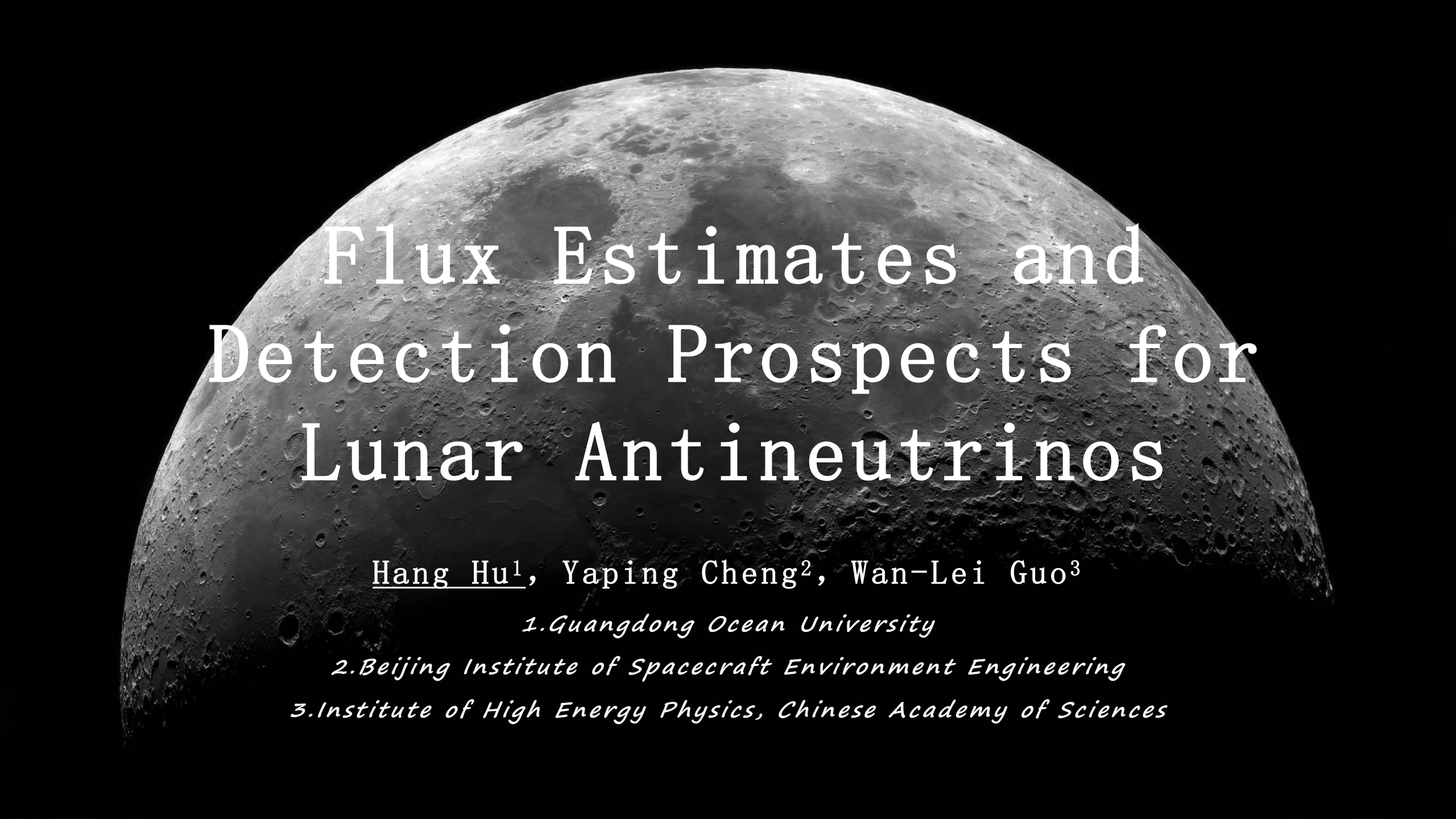


Flux Estimates and Detection Prospects for Lunar Antineutrinos

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Outline

1. Research Background

- Global lunar exploration (Chang'e, Artemis, ILRS, etc.)

2. Scientific Motivation

- Geological Significance: Probing U/Th/K distribution & lunar evolution

3. Lunar Interior Model & Flux Estimates

- Baseline Th distribution & Lunar density profile
- Antineutrino flux comparison (PKT vs. FHT)

4. Detection Channels & Event Rates

- Inverse Beta Decay (IBD)
- Radiochemical method (3He)
- Neutrino-electron Elastic Scattering (ES)

5. Summary & Conclusion

Research Background

- **Lunar exploration has gained increasing momentum in recent years**

➢ **China's Lunar Exploration Programs**
  - Chang'e-1 to Chang'e-6 missions
  - Future Chang'e-7 and Chang'e-8 missions
  - Crewed lunar landing
  - International Lunar Research Station (ILRS)

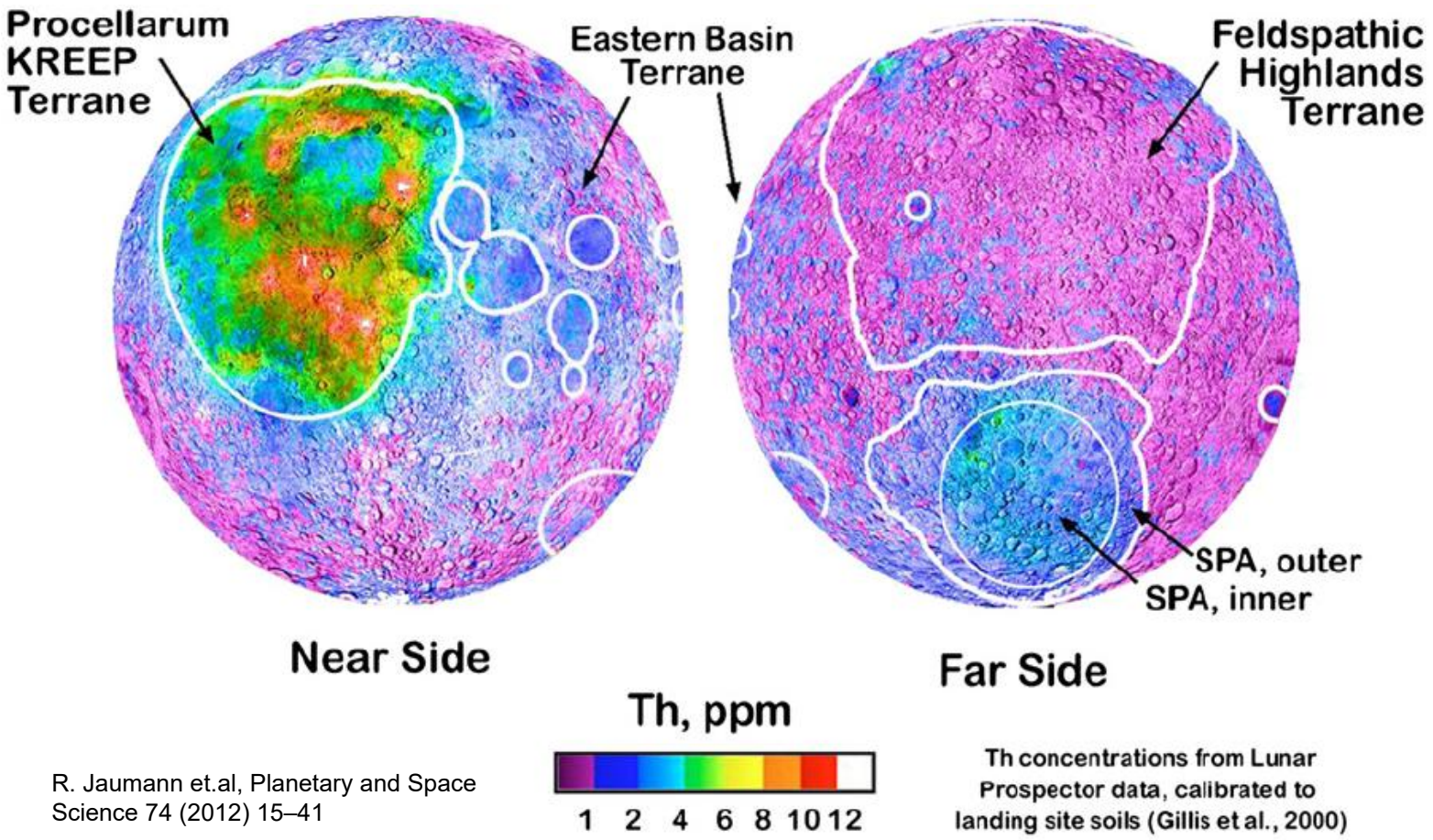
➢ **U.S. Return to the Moon : Artemis program**

Goal: return humans to the Moon and establish a sustainable presence

➢ **Other Countries and Agencies:**

ESA, Japan(SELENE, SLIM), India, Russia: Luna

Motivation



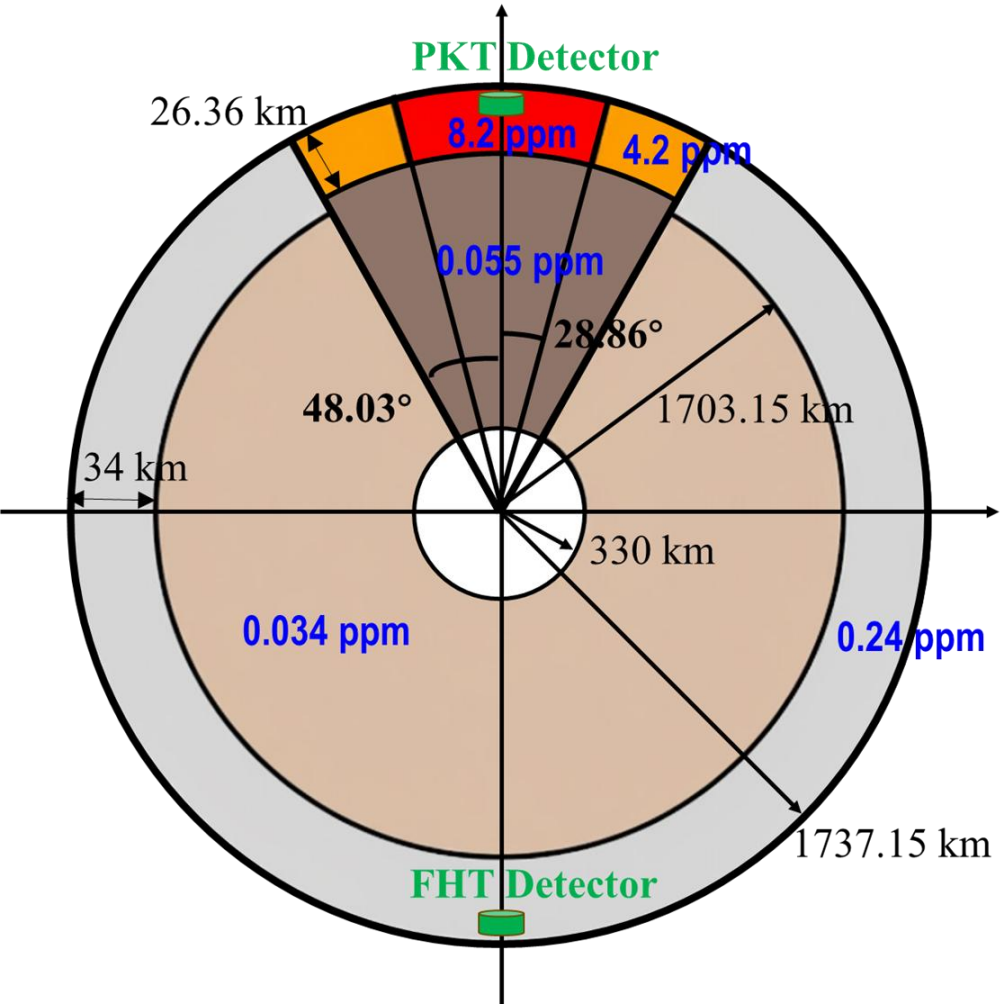
R. Jaumann et.al, Planetary and Space Science 74 (2012) 15–41

Three major lunar terranes

- Why are there such large spatial variations in Th distribution on the Moon?
- To understand the Moon's origin and thermal evolution, we must map the U/Th/K distribution.
- Lunar antineutrinos provide a unique, non-invasive probe to solve this problem.

TH/U/K Baseline Distributions

M. Laneuville et al. J. Geophys. Res. Planets 123, 3144–3166 (2018)



Schematic cross-section of the lunar internal structure and the baseline Th distribution

PKT Inner Crust: 8.2±4.0 ppm

Composition: corresponds to mafic impact-melt breccias
Magnetization: account for the lower magnetization in the central PKT

PKT Outer Crust: 4.2±2.5 ppm

Comparable to the lowest Th threshold for PKT boundaries

PKT Mantle: 0.055±0.018 ppm

Basis: Th concentrations in mare basalts
Assumption: Melt fractions of 5% and 10%
Bounds: 0.037 ppm (lower) – 0.073 ppm (upper)
Baseline: Mean of the two bounds

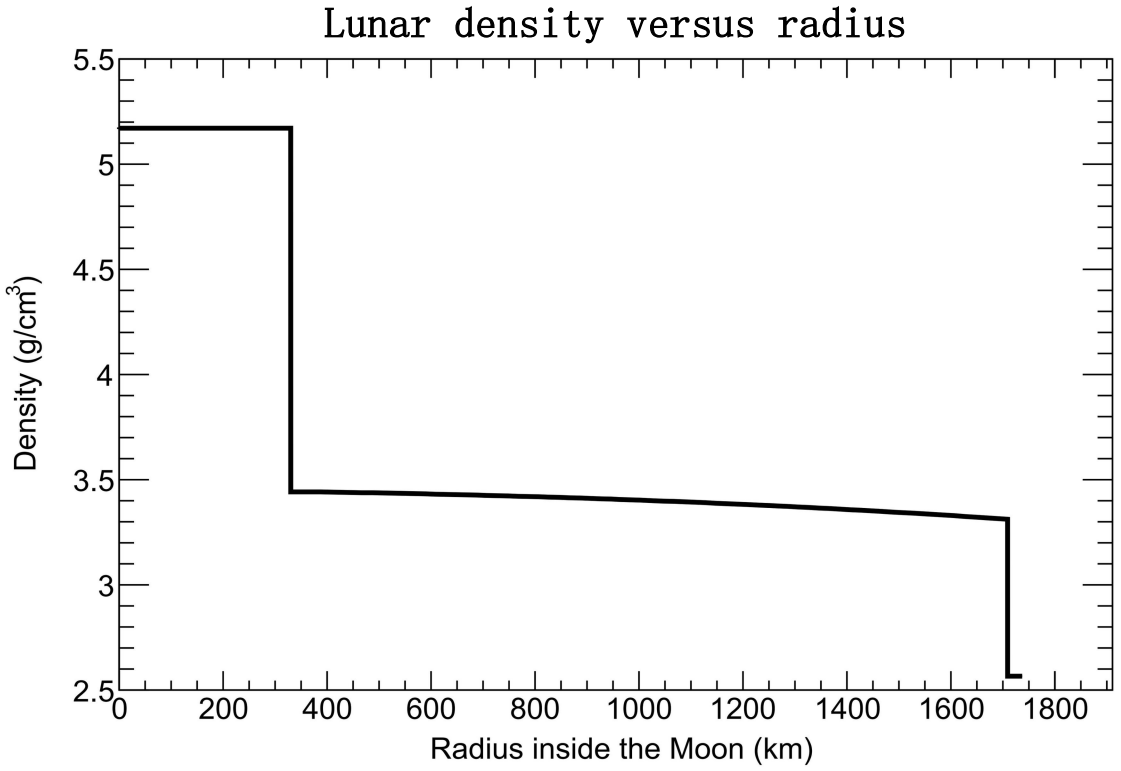
FHT Mantle: 0.034 ppm

Th mass balance with BSE (Bulk Silicate Earth) composition
BSE Th = 0.0776 ppm [W. F. McDonough, Geochimica et Cosmochimica Acta 422, 9-34 (2026)]

FHT Crust: 0.24±0.05 ppm

Upper layer (top 5 km): Aluminous layer (1.0 ± 0.3 ppm)
Middle layer: Anorthosite (0.05 ± 0.03 ppm)
Lower layer: SPA crust (1.5 ± 0.4 ppm)

Lunar Density Profile & Moon Structure



Thickness model

	model 1	model 2	model 3	model 4
highlands				
surface area (%)	77.53	77.53	77.53	77.53
mean elevation (km)	0.58	0.58	0.58	0.58
volume (m^3)	1.06×10^{18}	1.09×10^{18}	1.31×10^{18}	1.32×10^{18}
crustal thickness (km)	36.66	37.81	45.87	45.99
mass (kg)	2.71×10^{21}	2.95×10^{21}	3.37×10^{21}	3.57×10^{21}
silicate mass fraction (%)	3.75	4.08	4.66	4.94
average density (kg m^{-3})	2566	2711	2566	2712
PKT				
surface area (%)	16.56	16.56	16.56	16.56
mean elevation (km)	−1.49	−1.49	−1.49	−1.49
volume (m^3)	1.63×10^{17}	1.67×10^{17}	2.13×10^{17}	2.12×10^{17}
crustal thickness (km)	26.36	27.01	34.75	34.46
mass (kg)	4.22×10^{20}	4.57×10^{20}	5.53×10^{20}	5.80×10^{20}
silicate mass fraction (%)	0.58	0.63	0.77	0.80
average density (kg m^{-3})	2594	2742	2594	2742
SPA				
surface area (%)	5.91	5.91	5.91	5.91
mean elevation (km)	−3.37	−3.37	−3.37	−3.37
volume (m^3)	4.51×10^{16}	4.54×10^{16}	6.26×10^{16}	6.08×10^{16}
crustal thickness (km)	20.48	20.59	28.52	27.70
mass (kg)	1.18×10^{20}	1.26×10^{20}	1.64×10^{20}	1.68×10^{20}
silicate mass fraction (%)	0.16	0.17	0.23	0.23
average density (kg m^{-3})	2618	2766	2619	2767

rsta.royalsocietypublishing.org *Phil. Trans. R. Soc. A* **372**: 20130242

◆ Model Parameters:

- ✓ Density Profile: Based on Ref. [R.F. Garcia et al.,]; Top 28 km modified to 2.566 g/cm³ for consistency with Ref. [S. R. Taylor and M. A. Wieczorek].
- ✓ Core Radius: 330 km

Mass Calculation

- The Th abundances adopt the BSE Th abundance of 0.0776 ppm as a baseline

Reservoir	Mass (kg)	Mean Th (ppm)	Th mass (kg)
PKT Inner Crust	1.57×10^{20}	8.2	1.3×10^{15}
PKT Outer Crust	2.61×10^{20}	4.2	1.1×10^{15}
FHT Crust	2.84×10^{21}	0.24	6.7×10^{14}
PKT Mantle	1.16×10^{22}	0.055	6.4×10^{14}
FHT Mantle	5.77×10^{22}	0.034	1.9×10^{15}
Total	7.26×10^{22}	0.0776	5.6×10^{15}

- The U abundances adopt a mass(Th/U)=3.77

W. F. McDonough, Earth's composition: Origin, energy budget, and insights from geoneutrinos, Geochimica et Cosmochimica Acta 422, 9-34 (2026)

- The K abundances adopt a mass(K/Th)=460

LUNAR ANTINEUTRINO FLUXES

The differential neutrino flux $\phi_i(E_{\bar{\nu}_e}, \vec{d})$ at a detector position $\vec{d}$ can be calculated by integrating the contributions from all source volumes V within the Moon

$$\phi_i(E_{\bar{\nu}_e}, \vec{d}) = \int_V \frac{A_i(\vec{r})C_i}{\tau_i m_i} f_i(E_{\bar{\nu}_e}) P_{ee} \frac{\rho(\vec{r})}{4\pi|\vec{r}-\vec{d}|^2} dV$$

$A_i(\vec{r})$: the abundance of the ith HPEs at position $\vec{r}$

C_i, τ_i, m_i : the isotopic concentration, lifetime and mass of nucleus i

$\rho(\vec{r})$: lunar density

$f_i(E_{\bar{\nu}_e})$:the differential energy spectrum of the produced antineutrino per decay chain

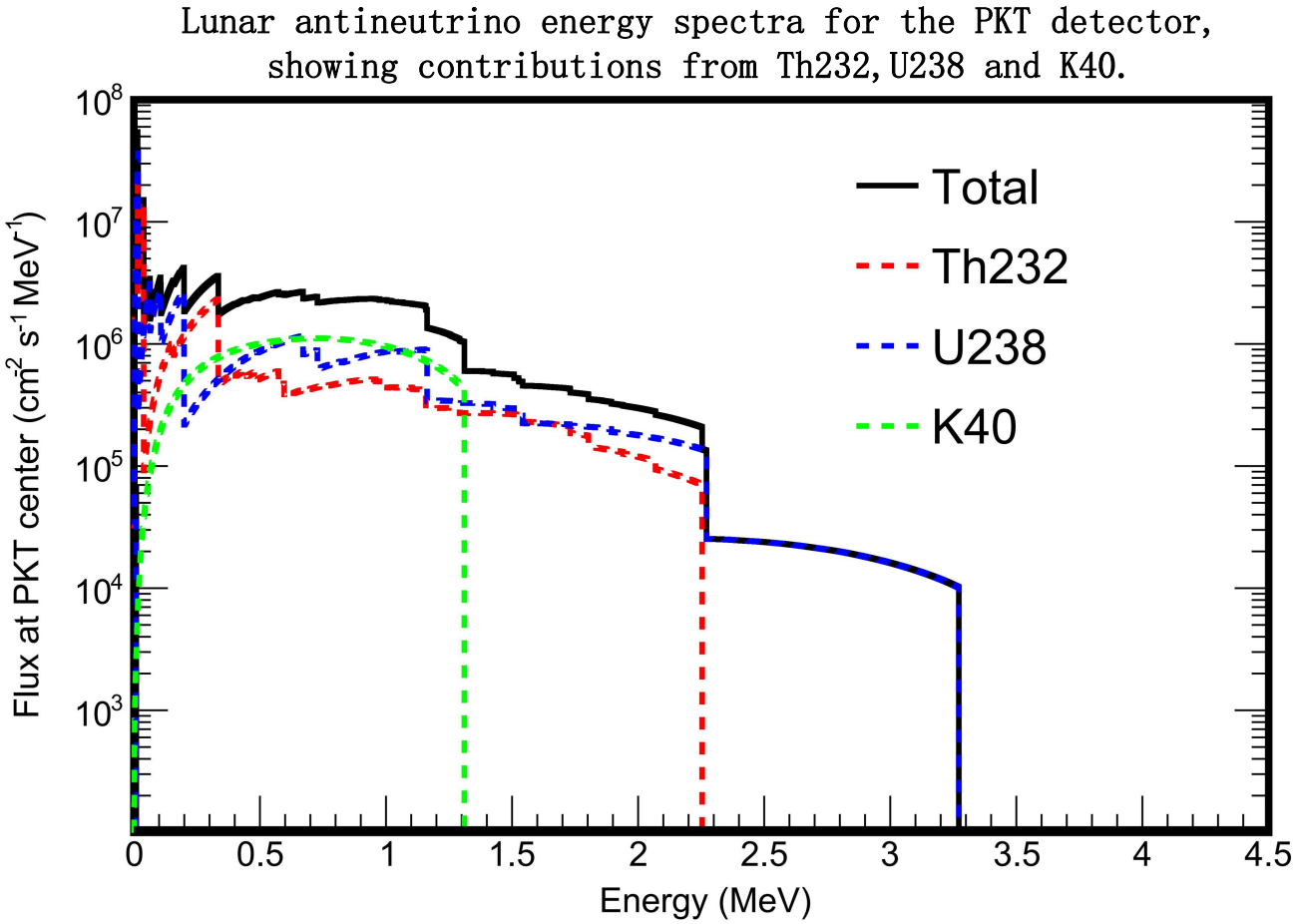
P_{ee}: the electron antineutrino survival probability

$$P_{ee} = 1 - \sin^2 2\theta_{13}[\cos^2\theta_{12} \cdot \Delta_{31} + \sin^2\theta_{12} \cdot \Delta_{32}] - \cos^4\theta_{13}\sin^2 2\theta_{12} \cdot \Delta_{21}$$

$$\Delta_{ij} = \sin^2\left(\frac{1.27 \cdot |\Delta m_{ij}^2| \cdot |\vec{r}-\vec{d}|}{E_{\bar{\nu}_e}}\right)$$

$\sin^2 2\theta_{13} = 0.0851, \sin^2\theta_{12} = 0.3092,$
$\Delta m_{21}^2 = 7.50 \times 10^{-5}\text{eV}^2, \Delta m_{21}^2 = 2.513 \times 10^{-3}\text{eV}^2$

Antineutrino energy spectra at Detector



□ PKT Detector (Highest Flux):

- Total Flux: $\mathbf{3.9 \times 10^6\ cm^{-2}s^{-1}}$
- U/Th Contributions:

U238: $\mathbf{1.6 \times 10^6\ cm^{-2}s^{-1}}$ (**KamLAND**: $\mathbf{2.34 \times 10^6\ cm^{-2}s^{-1}}$)

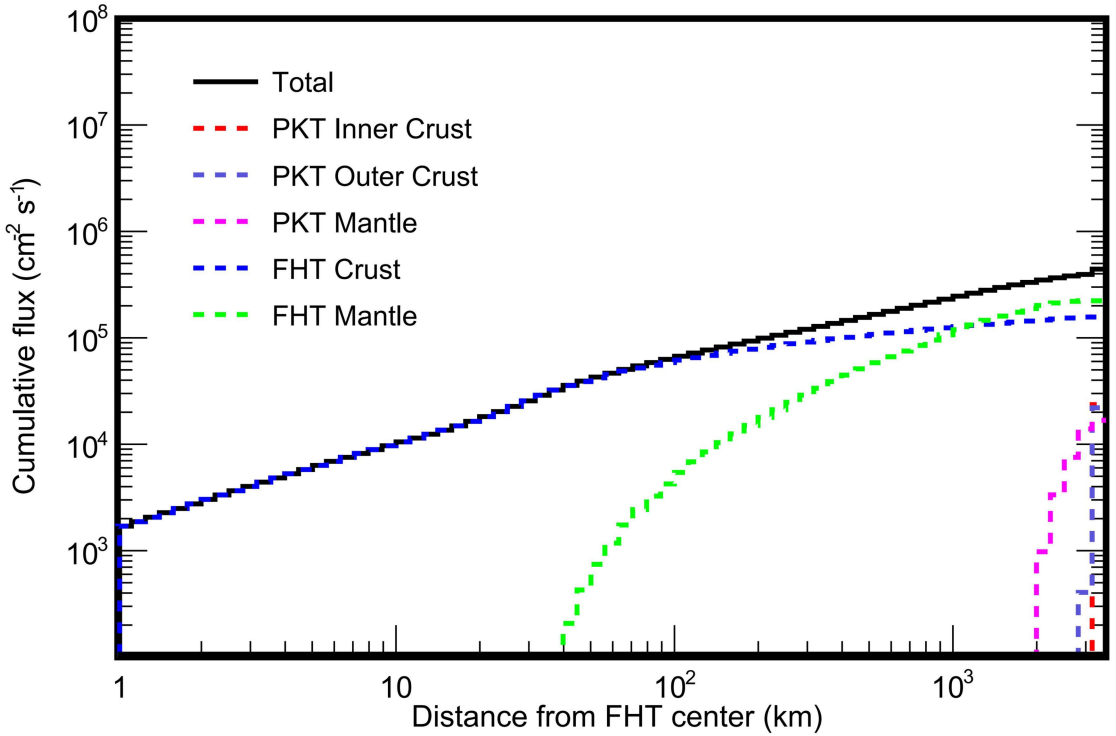
Th232: $\mathbf{1.3 \times 10^6\ cm^{-2}s^{-1}}$ (**KamLAND**: $\mathbf{1.98 \times 10^6\ cm^{-2}s^{-1}}$)

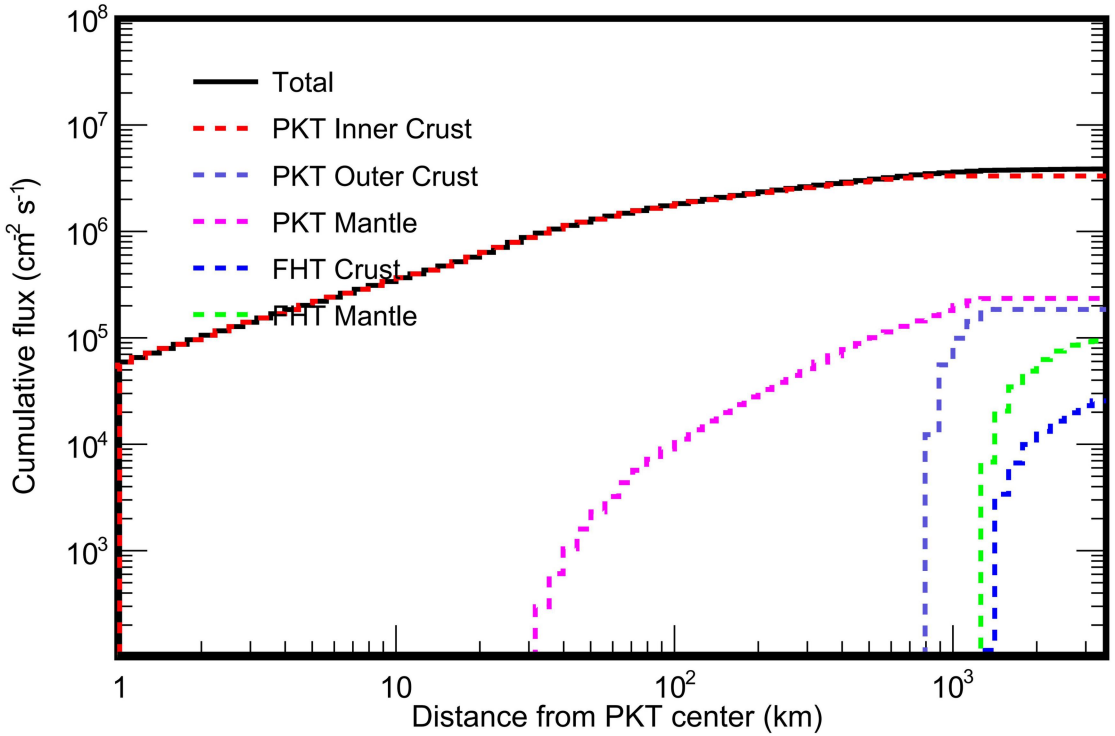
◆ FHT Detector (Lowest Flux):

- Total Flux: $\mathbf{4.4 \times 10^6\ cm^{-2}s^{-1}}$ (8.7× lower than PKT)

With the averaged survival probability $\langle P_{ee} \rangle \approx \mathbf{0.5486}$ the flux differ from the above values by less than 4%.

Cumulative antineutrino fluxes





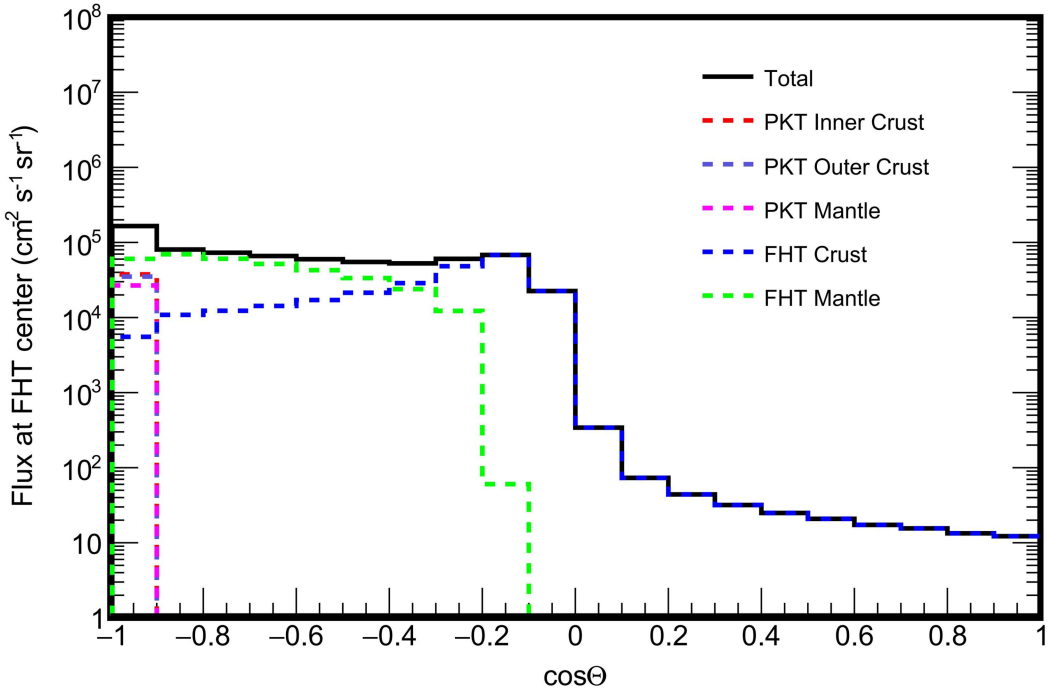
➢ FHT Detector

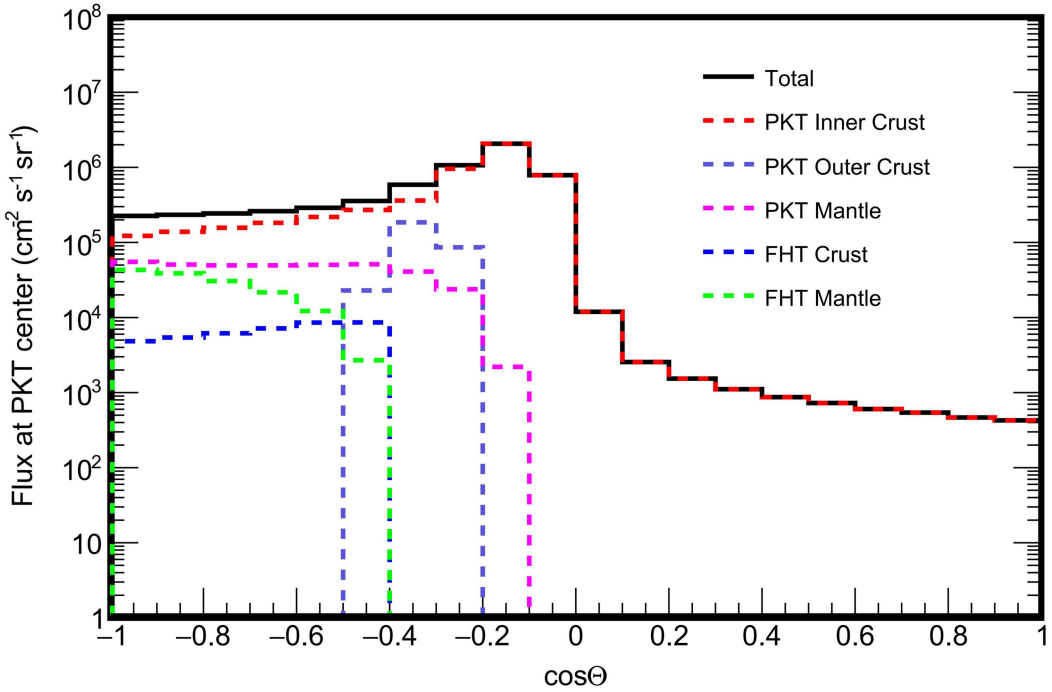
- ✦ $< 100\,km$: FHT crust dominates
- ✦ At $1000\,km$: Contributions from FHT crust and underlying mantle become equal.
- ✦ **Reason:** Larger mantle volume compensates for lower emissivity.

➢ PKT Detector:

- ✦ $< 1000\,km$: PKT inner crust contributes almost all antineutrinos.
- ✦ **Reason:** High emissivity and lateral extent encompasses most high HPE sources within intermediate distances.

Angular distributions





➢ Constraining Boundaries (PKT):

PKT Outer crust give a significant contribution in the range $-0.4 < \cos\theta < -0.3$.
Helps verify heat source distribution models.

➢ Signal Separation (FHT):

- **Crust:** Peaks at near-horizontal ($\cos\theta = 0$)
- **Mantle:** Dominates below horizontal ($\cos\theta < -0.4$)

Enables lunar interior tomography.

➢ Futher : Background Subtraction & Deep Probe:

◦Subtracts solar/reactor neutrino backgrounds.
◦Probes deeper structures (core, HPE asymmetries).

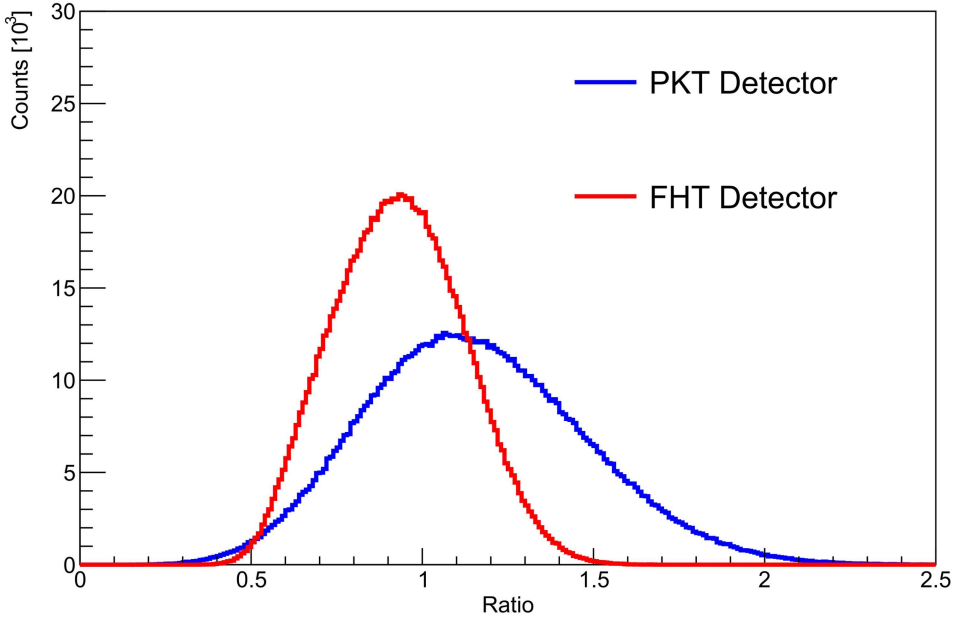
Impact Th abundance uncertainties

Th Abundance Uncertainties

DOI: 10.1029/2018JE005742

$$M_{BSM} \times \mathbf{0.0776} = M_{PIC} \times \mathbf{8.2} + M_{POC} \times \mathbf{4.2} + M_{FC} \times \mathbf{0.235} + M_{PM} \times \mathbf{0.055} + M_{FM} \times XXX$$

10% ± 4.0 ± 2.5 ± 0.049 ± 0.018



Distributions of the predicted lunar antineutrino fluxes at the PKT and FHT sites, normalized to the baseline values, showing the impact of Th abundance uncertainties

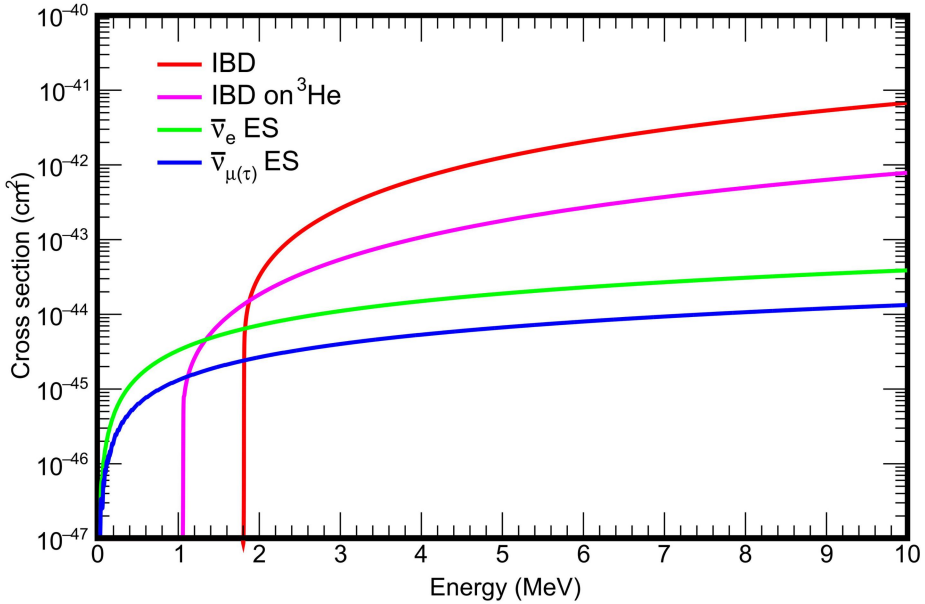
➢ Monte Carlo Sampling :

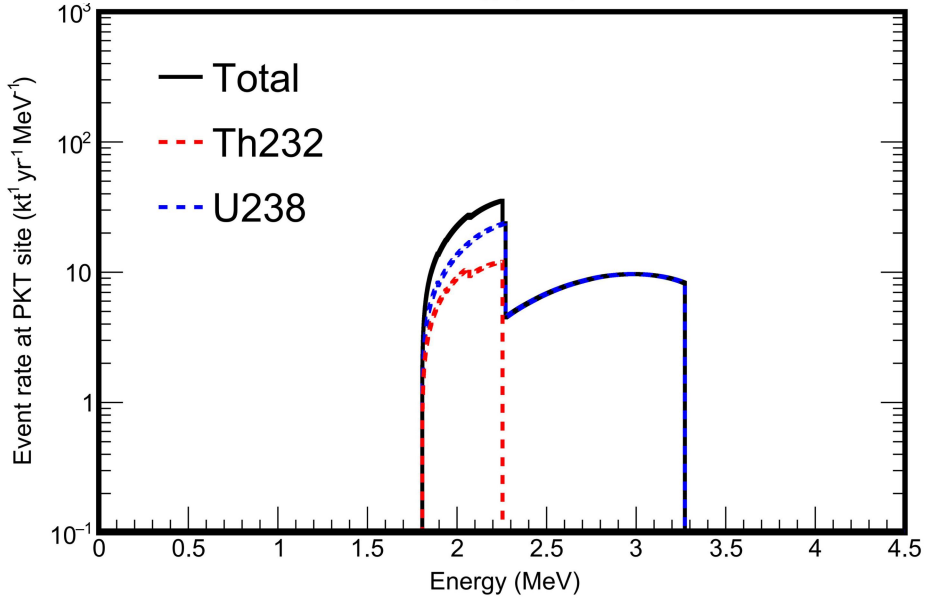
- 10^6 random samplings based on Th uncertainties
- Most predicted fluxes fall within 0.5-2.0× the baseline values
- Slightly deviate from unity for constrained by geological order

➢ BSE Th Abundance Sensitivity:

- BSE Th varied from 0.0626 to 0.094 ppm (baseline: 0.0776 ppm).
- FHT Flux: 3.2×10^5 to 5.8×10^5 $\mathbf{cm^{-2}s^{-1}}$ ($\pm$30% deviation)
  Controlled by PKT inner crust (8.2$\pm$4.0 ppm, large uncertainty).
- PKT Flux: Stable at 3.9×10^5 $\mathbf{cm^{-2}s^{-1}}$ (little variation).
  Nearly half from FHT crust (0.24$\pm$0.05 ppm, small uncertainty)

EVENT RATE ESTIMATES: IBD@H





liquid scintillator detector composed of 88% C12 and 12% H by weight

1. Detection Channel: IBD

- **Reaction:** $\bar{\nu}_e + p \rightarrow e^+ + n$
- ✅ **Advantage:** Excellent background rejection (prompt-delayed coincidence)
- ⚠️ **Limitation:** 1.806 MeV threshold ➡️ Blind to $^{40}\mathrm{K}$
- 🎯 **Sensitive to:** $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ chains

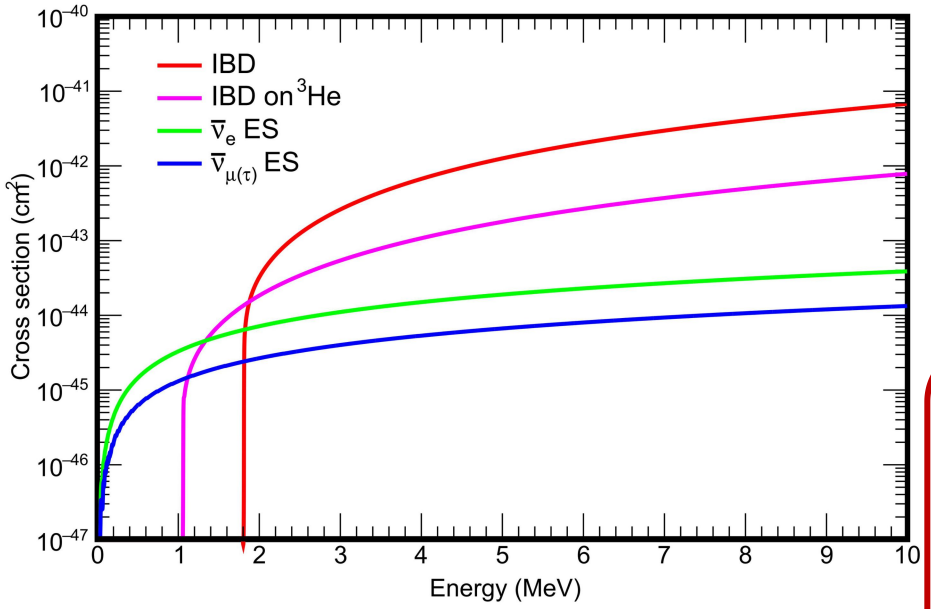
2. Expected Event Rates (PKT vs. FHT)

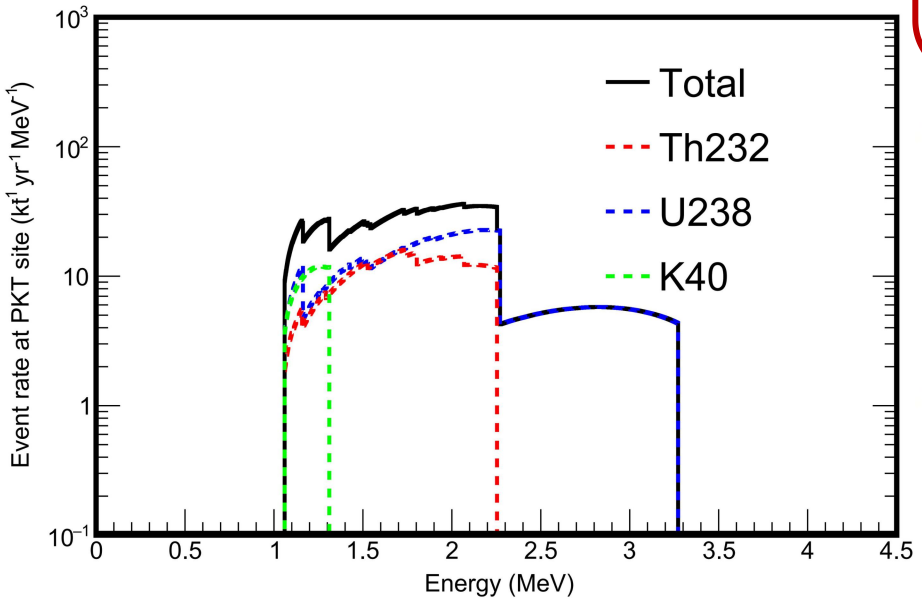
- **PKT Site: 19 kt^{-1} yr^{-1}** *(Dominated by $^{238}\mathrm{U}$: 15 kt^{-1} yr^{-1})*
- **FHT Site: 8.7× lower** than PKT

3. Crucial Comparison

- **Lunar Signal:** $\sim$19 kt^{-1} yr^{-1}
- **Earth Signal:** $\sim$0.001 kt^{-1} yr^{-1}
- 💡 *Lunar signal is vastly superior!*

EVENT RATE ESTIMATES: IBD@He3

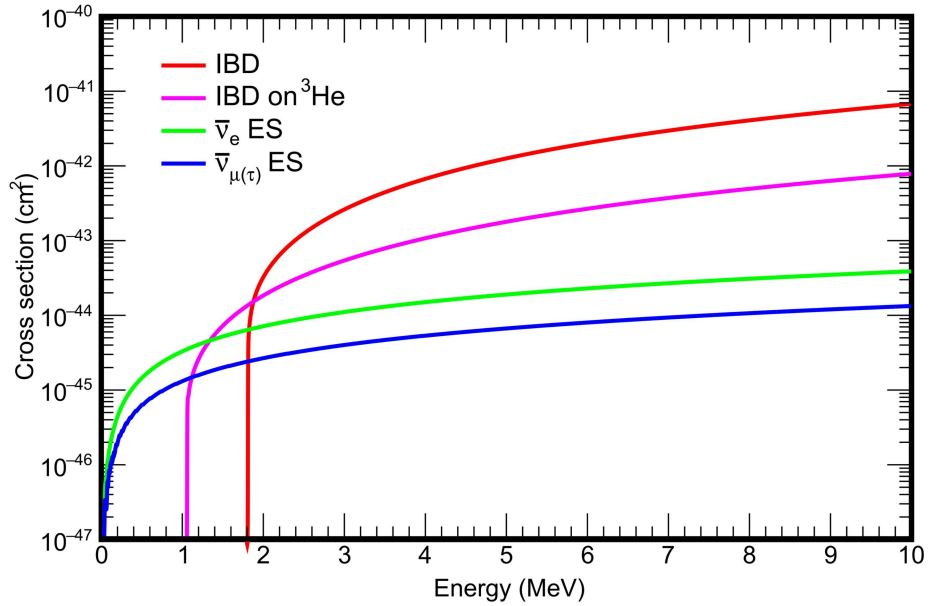


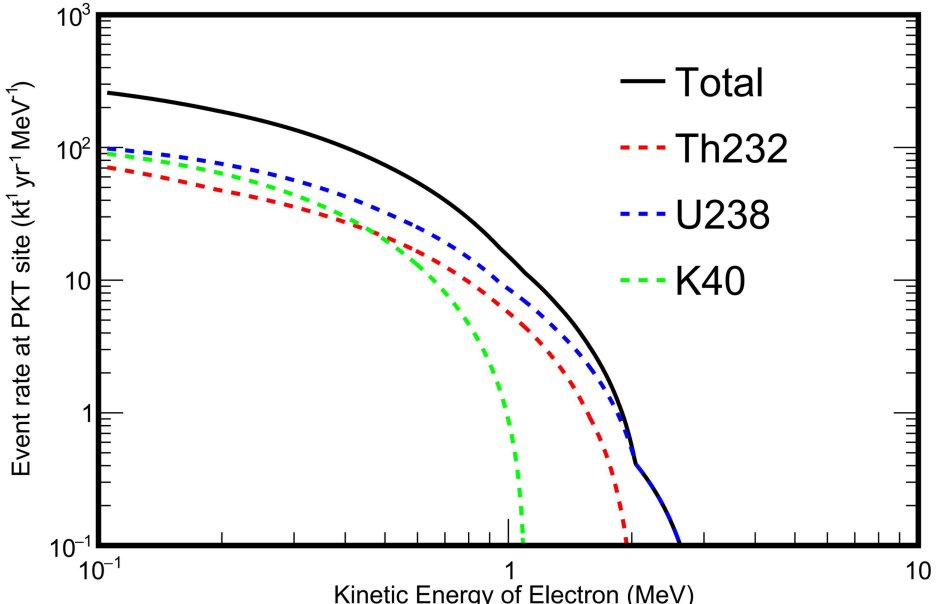


J. Golak, R. Skibi´nski, K. Topolnicki, H. Wita la, A. Grassi, H. Kamada and L. E. Marcucci, Momentum space treatment of inclusive neutrino scattering off the deuteron and trinucleons, Phys. Rev. C **98**, no. 1, 015501 (2018)

- **Reaction & Method:**
  - $\bar{\nu}_e + {}^3\mathrm{He} \rightarrow e^+ + {}^3\mathrm{H}$ (CC reaction)
  - *Analogy:* Similar to Homestake chlorine detector; measures accumulated ^{3}H.
- **Key Advantages:**
  - **Low Threshold (1.041 MeV):** Captures the high-energy tail of ^{40}K (unlike IBD).
  - **Lunar Resource:** $\sim 6.5 \times 10^5$ tons of ^{3}He in lunar regolith (from solar wind).
  - **Accumulation Effect:** ^{3}H (half-life 12.32 yrs) accumulates over time.
- **Expected Yield (1 kt target, 10 yrs):**
  - **Total:** $\sim 3.0 \times 10^2$ atoms
  - **Contributions:** ^{238}U (180), ^{232}Th (100), ^{40}K (19)
- **Technical Challenge:**
  - Cosmic-ray backgrounds: $n + {}^3\mathrm{He} \rightarrow p + {}^3\mathrm{H}$ and $\mu^- + {}^3\mathrm{He} \rightarrow \nu_\mu + {}^3\mathrm{H}$.

EVENT RATE ESTIMATES:ES@e





- **Reaction & Feature:**
  - $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$
  - **No energy threshold** ➡️ Sensitive to full spectra (crucial for $^{40}\mathrm{K}$).
  - All flavors ($\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$) participate.
- **High Event Rate:**
  - Expected overall rate: $1.2 \times 10^2\ \mathrm{kt}^{-1}\mathrm{yr}^{-1}$ (higher than IBD).
  - Contributions: U (49), Th (33), K (34).
  - *Reason:* Abundant target electrons + extra contributions from μ and τ flavors.
- **The Catch: Solar Neutrino Background**
  - Solar neutrino flux exceeds lunar flux by **orders of magnitude**.
  - **Mitigation:** Applying a 0.7 MeV threshold reduces rate to **13 $\mathrm{kt}^{-1}\mathrm{yr}^{-1}$**, but it's still below the solar background.
  - **Future need:** Directional reconstruction (currently unachievable).

Summary

- **Flux Estimates:**
  - **PKT (High-flux):** $3.9 \times 10^6\ \mathrm{cm^{-2}s^{-1}}$ (Dominated by inner crust).
  - **FHT (Low-flux):** $4.4 \times 10^5\ \mathrm{cm^{-2}s^{-1}}$ (Mixed crust & mantle).
  - *Uncertainty:* Most predicted fluxes fall within **2×** of baseline values.
- **Directional Detection:**
  - Can resolve crust and mantle contributions (e.g., FHT).
- **Detection Channels (PKT Rates):**
  - **IBD:** 19 $\mathrm{kt^{-1}yr^{-1}}$
  - **^{3}He:** 39 $\mathrm{kt^{-1}yr^{-1}}$
  - **ES:** 13 $\mathrm{kt^{-1}yr^{-1}}$ *(with 0.7 MeV threshold)*
  - *(Note: FHT rates are **8.7× lower** than PKT).*
- **Ultimate Goal:**
  - A lunar antineutrino observatory provides a **non-invasive probe** to resolve the Moon's formation, differentiation, and thermal evolution.

For more details, see our published paper.

Chinese Physics C Vol. 51, No. 1 (2027) 013001

Flux estimates and detection prospects for lunar antineutrinos*

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Abstract: The distribution of heat-producing elements (U, Th, K) within the Moon is critical for understanding its thermal evolution and formation history. Based on a refined lunar interior model, we calculate the lunar antineutrino fluxes from radioactive decays of these elements at two representative detector locations that bracket the expected signal intensity. The maximum flux is found to be slightly lower than the geoneutrino flux for the KamLAND site on Earth, while the minimum flux is approximately a factor of 9 lower than this maximum value. We also compute the expected event rates for lunar antineutrinos using three detection channels.

Keywords: geoneutrino, liquid scintillator detector, lunar antineutrinos

DOI: 10.1088/1674-1137/aea82c **CSTR:** 32044.14.ChinesePhysicsC.51013001

Thanks

