Robust Geo-Neutrino Results

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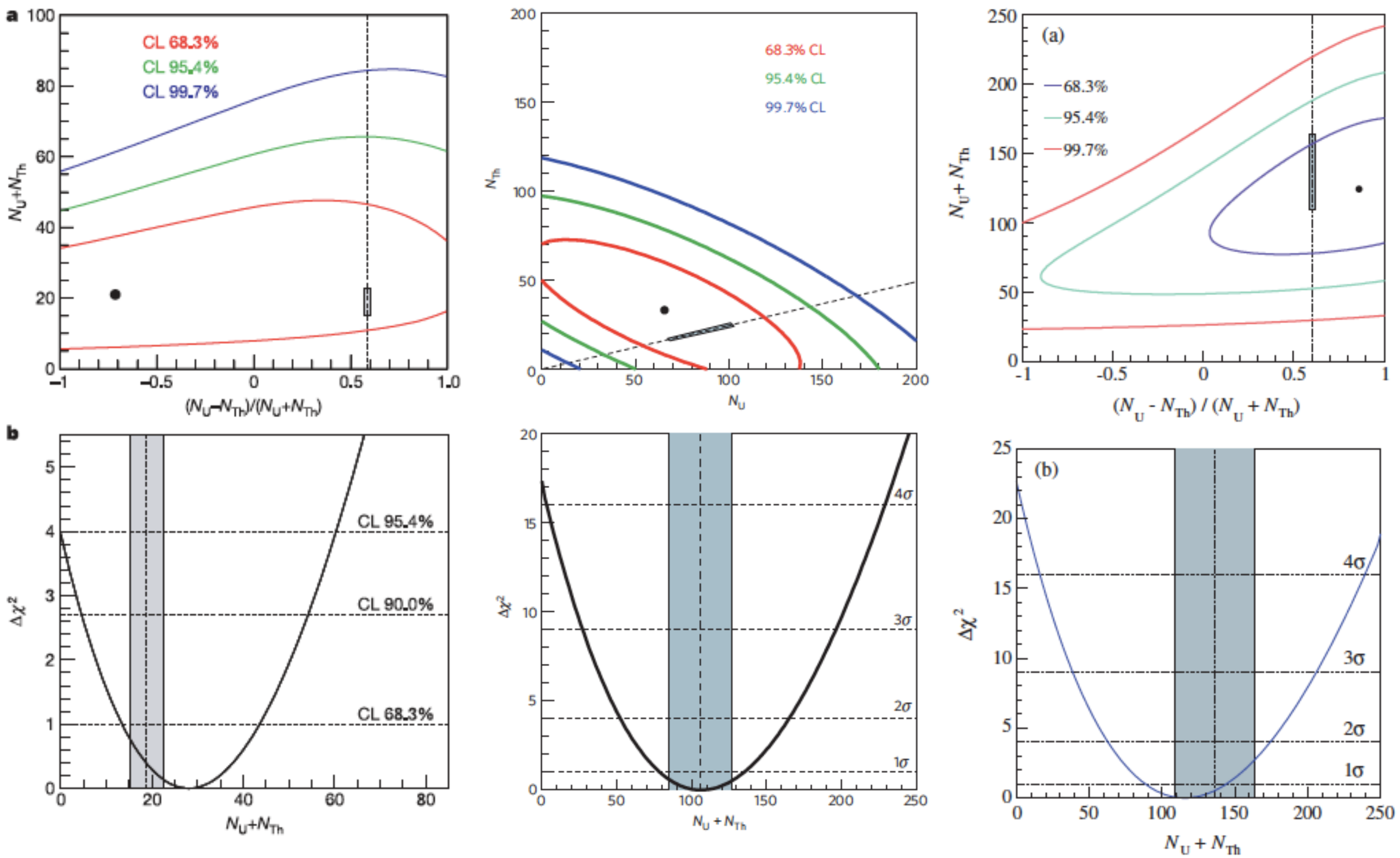
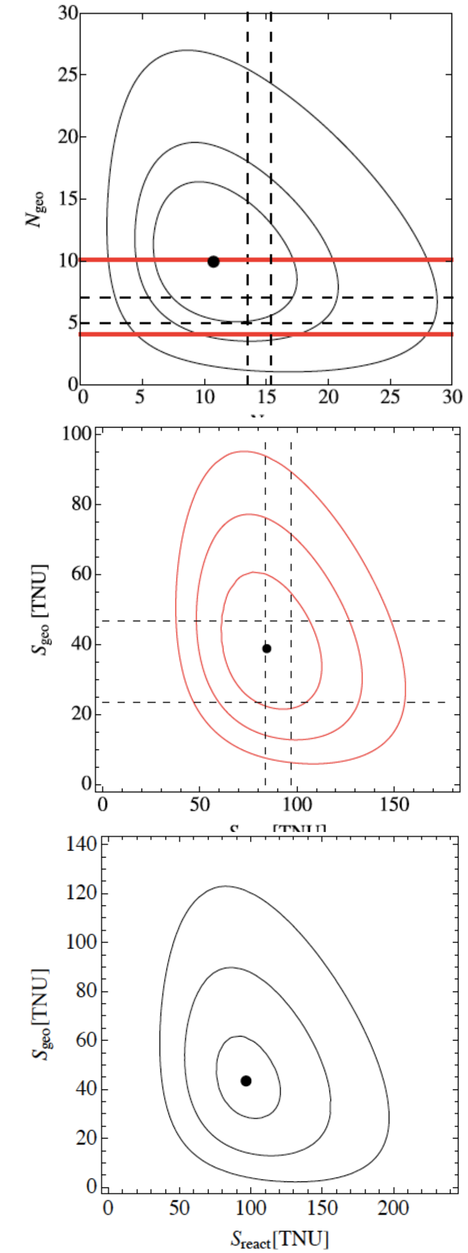
Spectacular Achievements

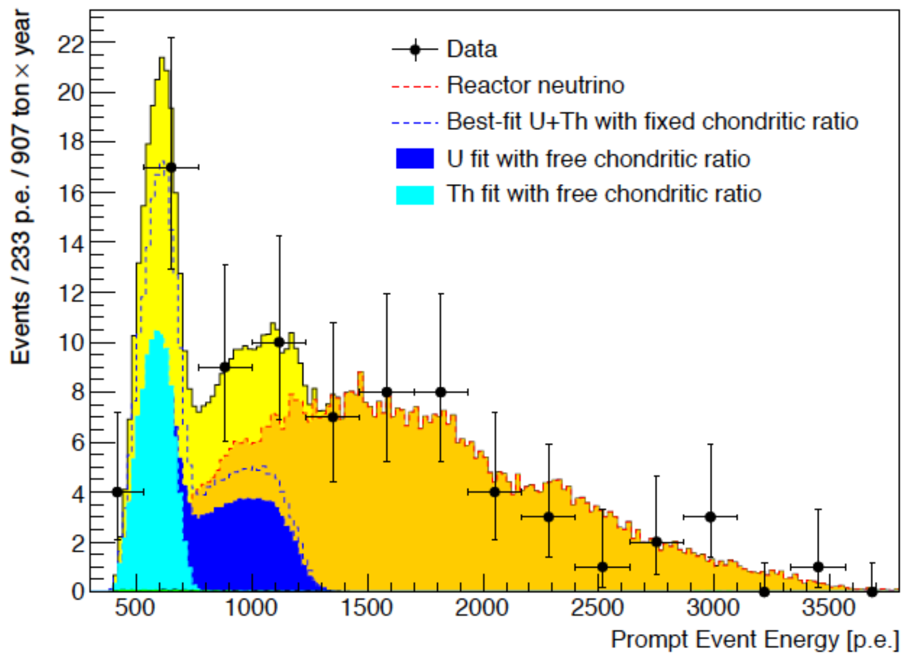


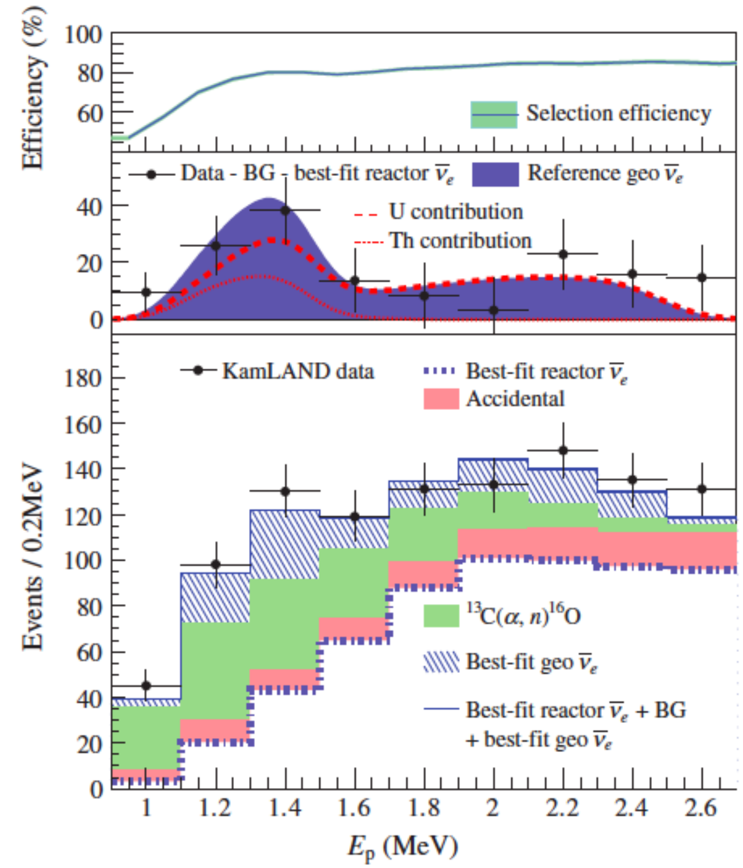
KamLAND data through the years



Borexino data through the years

Geo-neutrino Observations





Borexino data (2015)
5.9σ detection

KamLAND data (2013)
4.6σ detection

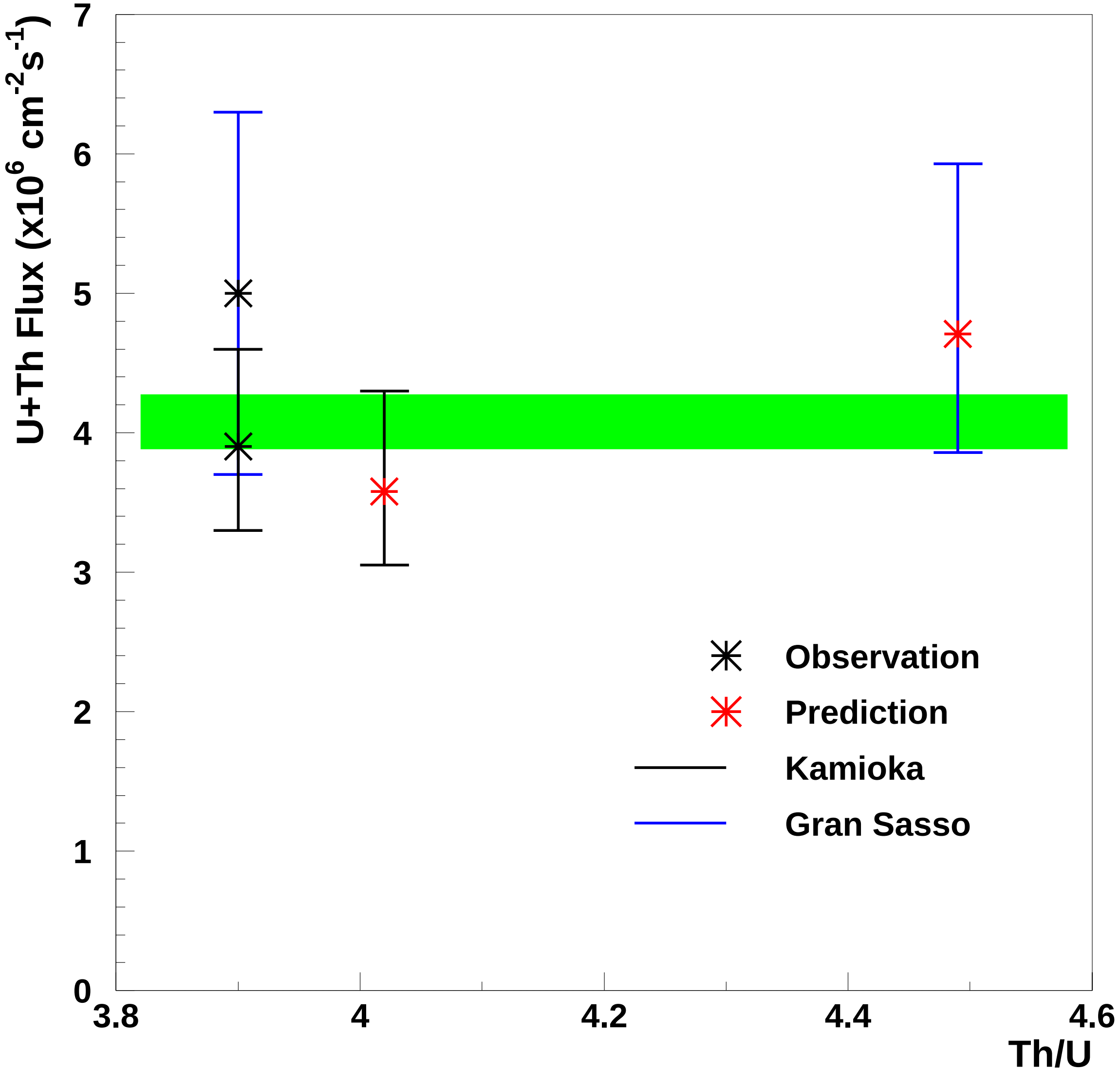
Geo-neutrinos conclusively observed at Japan and Italy

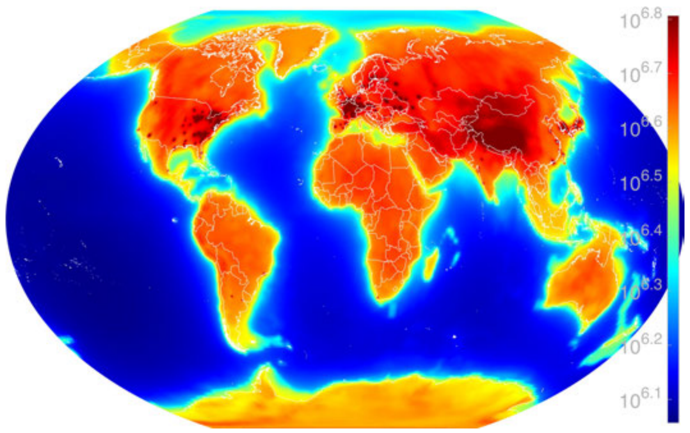
Assumptions and Model Dependence

- **Measured geo-neutrino rate (TNU) and spectrum (Th/U)**
- **If Th/U not resolved, assume Th/U (3.9) to go from rate to flux**
- **If source reservoirs not resolved, assume no core and use crust model to get mantle flux**
- **Radiogenic heating from mantle flux for model distributions**

- **Questions**
  - **Do assumptions and model dependence bias answers?**
  - **Are there assumption-free and model-independent measurements?**

Observations and Predictions Compatible





Predicted surface flux variation- AGM15

Geo-neutrino observations have not yet independently confirmed surface flux variation

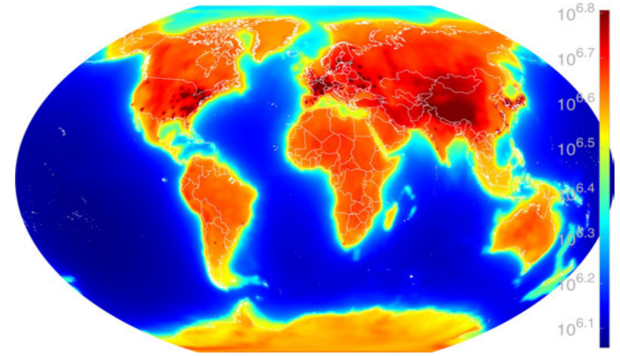
Constant Surface Flux/Rate Hypothesis

Flux

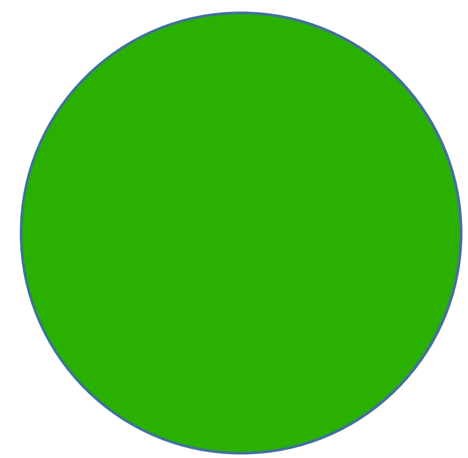
- Borexino 2015- $\phi_{U+Th} = 5.0 \pm 1.3\ cm^{-2}\mu s^{-1}$
- KamLAND 2016- $\phi_{U+Th} = 3.9 \pm 0.7\ cm^{-2}\mu s^{-1}$
- Weighted Average- $\phi_{U+Th} = 4.15 \pm 0.62\ cm^{-2}\mu s^{-1}$
- $\phi_{U} = 2.25 \pm 0.33\ cm^{-2}\mu s^{-1}$; $\phi_{Th} = 1.90 \pm 0.28\ cm^{-2}\mu s^{-1}$

Rate

- Borexino 2015- $R_{U+Th} = 43.5 \pm 11.8$ TNU
- KamLAND 2016- $R_{U+Th} = 34.9 \pm 6.0$ TNU
- Weighted Average- $R_{U+Th} = 37.2 \pm 5.5$ TNU
- $R_{U} = 29.6 \pm 4.4$ TNU; $R_{Th} = 7.6 \pm 1.1$ TNU



Predicted surface flux variation- AGM15



Measured surface flux/rate variation

Constant Surface Flux/Rate Hypothesis

Constant surface flux => constant HPE mass fractions

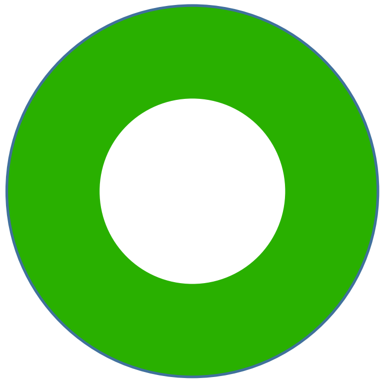
Uranium flux: ϕ_U = 2.25 ± 0.33 $cm^{-2}\mu s^{-1}$

Uranium mass fraction: a_U = 46 ± 7 ng/g*

Thorium mass fraction: a_{Th} = a_U Th/U (=3.9)

Potassium mass fraction: a_K = a_U K/U (=12000)

Radiogenic power: P = 44 ± 7 TW

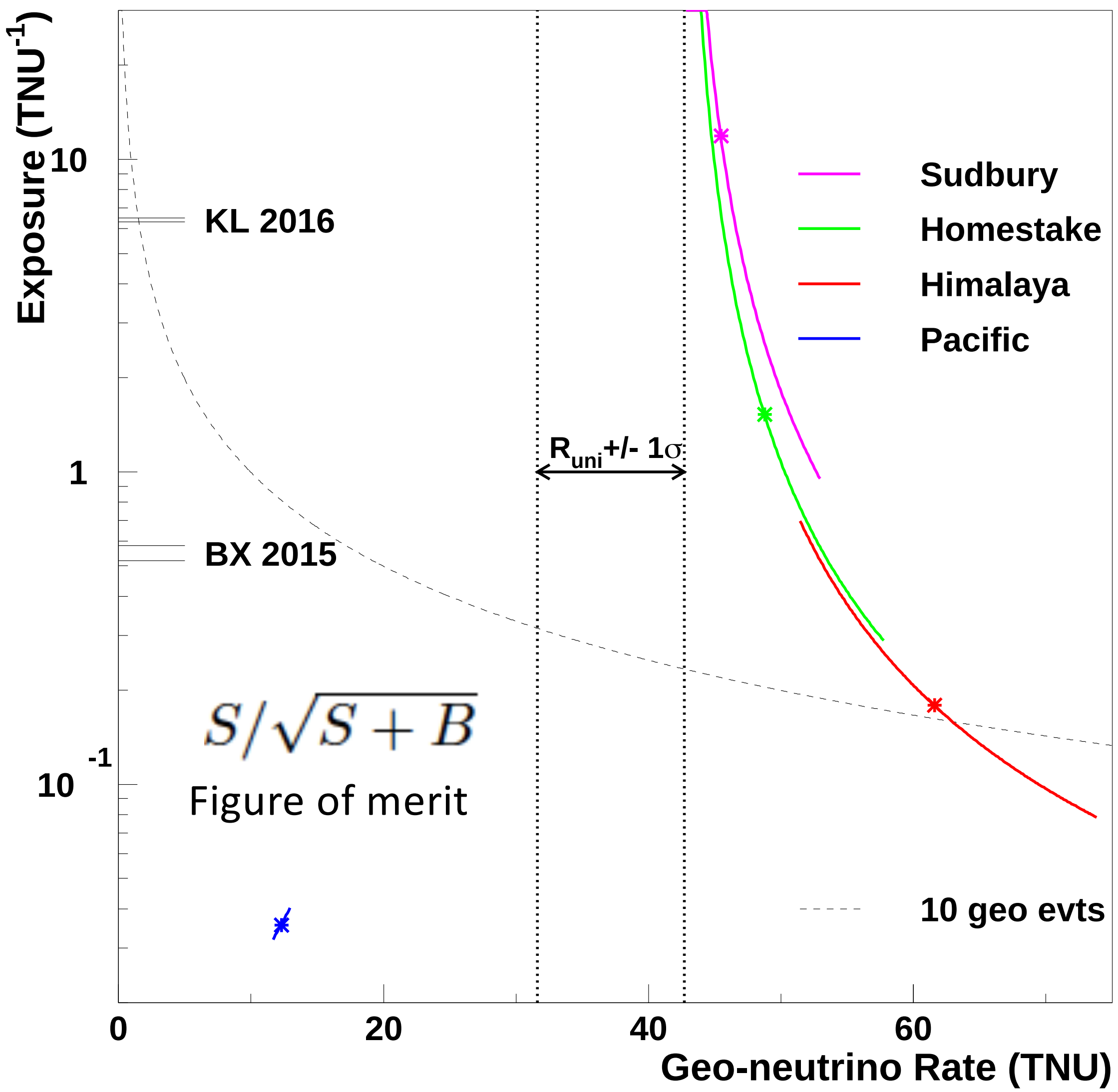


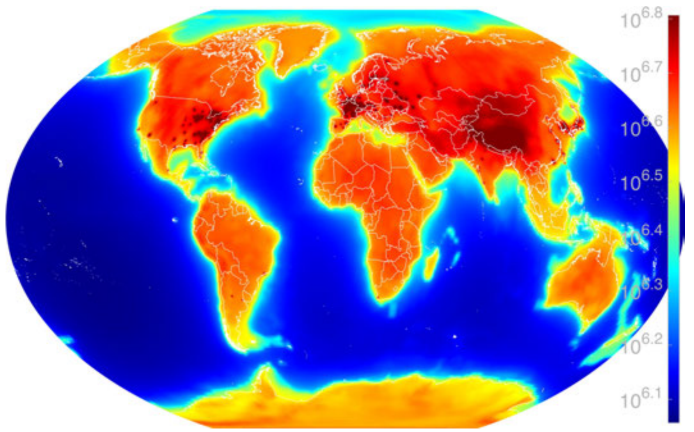
Measured Heat Flux: P = 47 ± 2 TW
(Davies and Davies, 2010)

Constant surface flux hypothesis is compatible with fully radiogenic heat model of Earth

$$^* \quad a_U = \frac{\phi_{U+Th}}{(l_U + l_{Th}\mathrm{Th/U}) < P_{ee} > G}$$

Measuring a Rate Different from Constant Rate

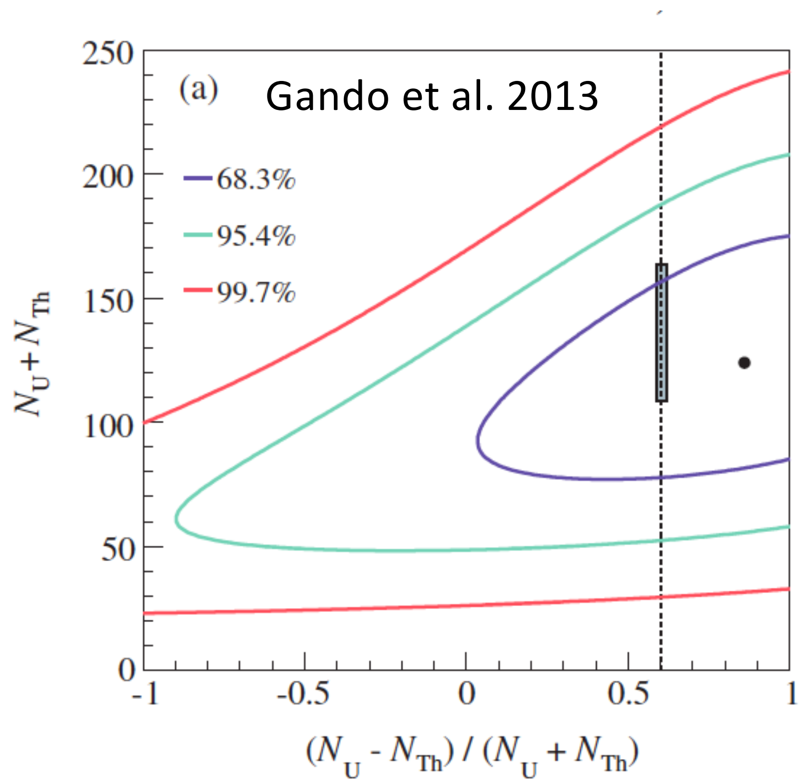




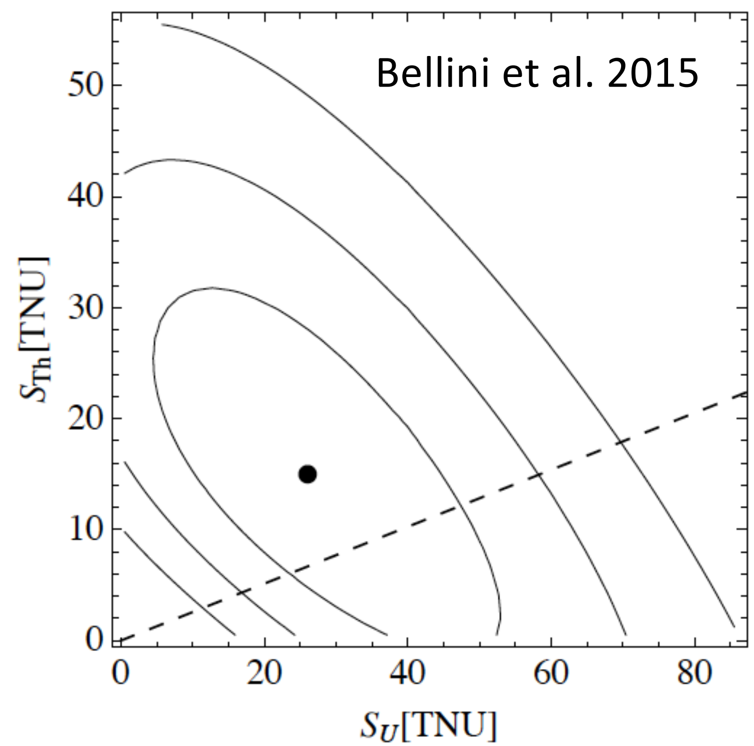
Predicted surface flux variation- AGM15

Geo-neutrino observations of about 1 TNU^{-1} at selected sites should resolve surface rate variation

Observing Geo-neutrino Spectrum



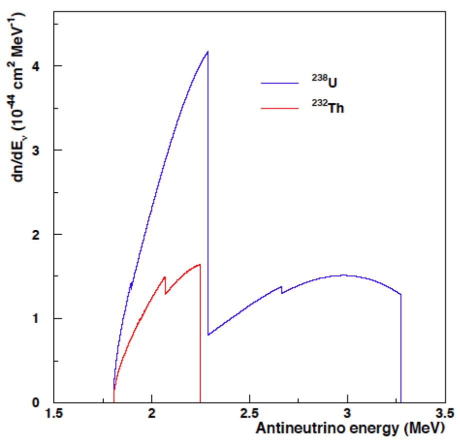
KamLAND data (2013) consistent with N_{Th}= 0

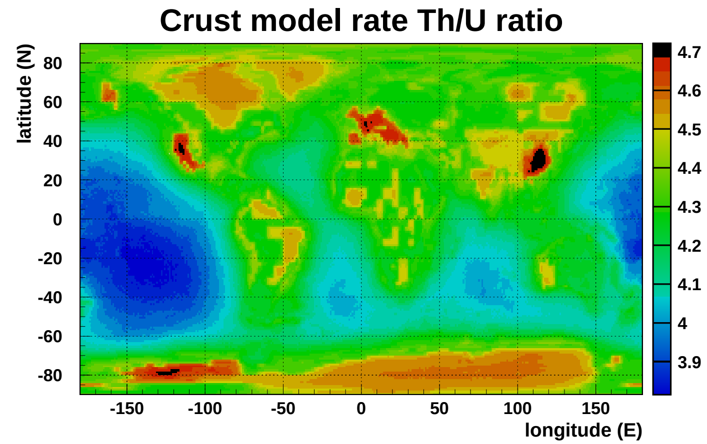


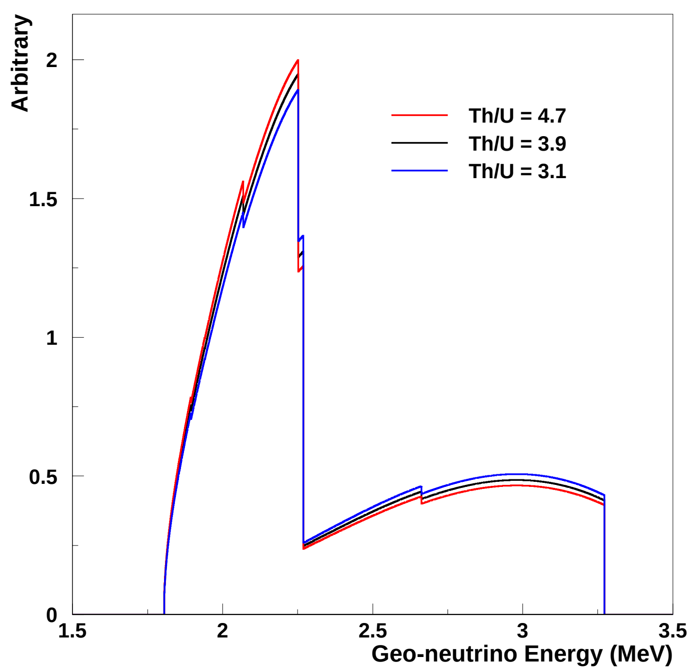
Borexino data (2015) consistent with S_{Th}= 0

Th geo-neutrinos certainly present but not yet resolved at 1 (1.6?)σ

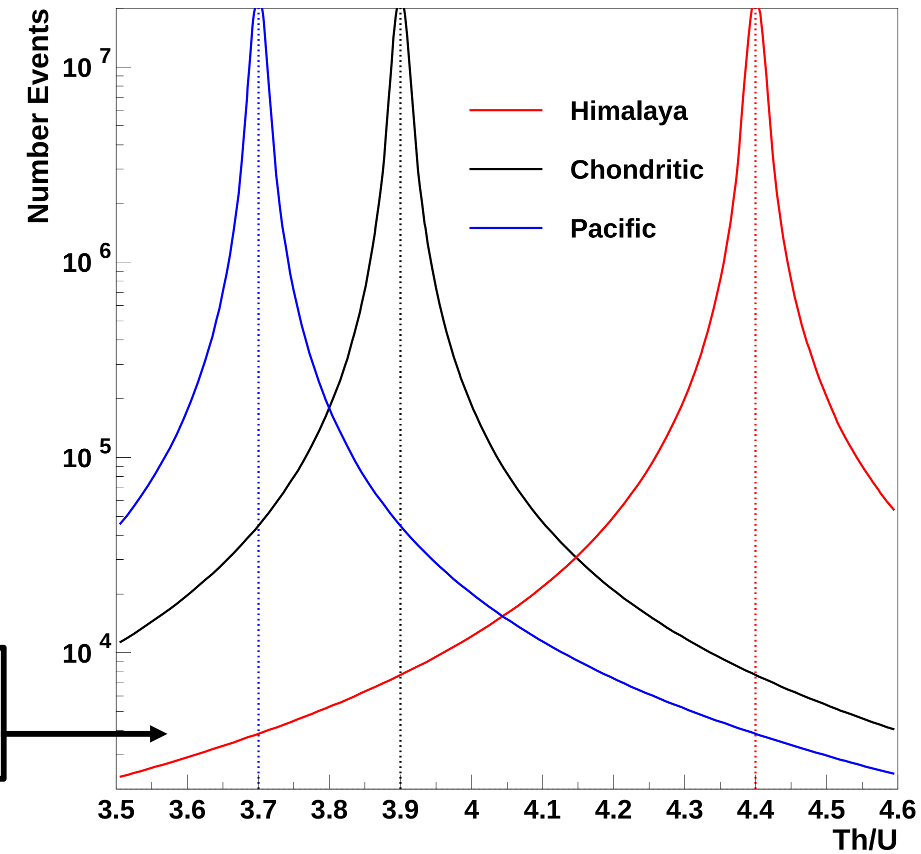
Measuring Different Th/U







Poisson statistics
σ = √N



Geo-neutrino observations of about 100 TNU^{-1} at selected sites should resolve Th/U variation

Status of Geo-Neutrino Observations

	Rate	Spectrum	Flux	Variation	Power	Dir
U + Th	>5σ	Th/U < 17	Th/U=3.9		model	
K	K/U		K/U		K/U	
Crust	model		model		model	
Mantle	model		model		model	
LLSVP/ULVZ						
Core						

Demonstrated/Completed
Assumption and/or Model-dependent result
Opportunity

Assumption-Free Model-Independent Results

- Rule out constant surface rate hypothesis
  - Observations at selected sites (Himalaya, Pacific, …)
  - Exposure requirements not demanding (1 TNU^{-1})
  - Independently confirm fractionation of HPE between crust and mantle
- Rule out constant spectral shape hypothesis
  - Observations at selected sites (Himalaya, Pacific, …)
  - Exposure requirements demanding (100 TNU^{-1})
  - Independently confirm differential fractionation of HPE between crust and mantle
- Direction measurements
  - Imaging of inverse beta decay is scintillating liquid
  - Resolving elastic electron scattering in high pressure TPC

Constant Mantle Assumption

- **Measure mantle and crust rates with multiple observations**
- **Requires one crust estimate with small absolute error**

Rate Analysis

- T = C + M + R + B
- Total (T) = Crust (C) + Mantle (M) + Reactor (R) + Background (B)
- R and B are estimated with good precision
- Signal (S) = Total (T) – Reactor (R) – Background (B)
- Signal (S) = Crust (C) + Mantle (M)
- S = C + M

Rate Analysis

- $S_1 = C_1 + M$
- $S_2 = C_2 + M$
- $C_2 = C_1 + (S_2 - S_1)$
- $\delta C_2 = \{ (\delta C_1)^2 + (\delta S_2)^2 + (\delta S_1)^2 \}^{1/2}$
- $\delta M = \{ (\delta S_1)^2 + (\delta C_1)^2 \}^{1/2}$
- δS_1 and δS_2 from Poisson statistics
- If Number of events (N) is very high, then $\delta M \approx \delta C_2 \approx \delta C_1$

Rate Analysis

- $\delta M \cong \delta C_2 \cong \delta C_1$
- Applies to any site C_2, C_3, C_4 … C_N
- Just minimize δC at one site
- Crust studies realize 15% - 20% error at continental sites
- If $C_{cont} \approx 40$ TNU, then $\delta C_{cont} \approx \delta M \approx \delta C_N \approx 6$ TNU
- Model-dependent
- What about ocean?

Rate Analysis

- Set $C_{ocean} \pm \delta C_{ocean} = 3 \pm 1$ TNU (error exaggerated)
- $\delta C_{ocean} \approx \delta M \approx \delta C_N \approx 1$ TNU
- But statistics not infinitely large
- Assume $N_{ocean} = 100$ (10%)
- $\delta C_N = \{ (\delta C_{ocean})^2 + (\delta S_N)^2 + (\delta S_{ocean})^2 \}^{1/2}$
- If S_N and C_N continental, then $\delta C_N = \{ (1)^2 + S_N{}^2/N + (1)^2 \}^{1/2} \lessapprox 2.5$ TNU
- If $N_N = 400$ and $S_N = 40$ TNU, continental crust signals C_N measured to ≈ 6%
- Mantle signal M measured to ≈ 25%
- Precision improves as N_N increases

Conclusions

- Geo-neutrino observations making spectacular progress
- Most results use Th/U=3.9 signal shape assumption
- Further analyses depend on crust modeling
- Constant rate hypothesis still allowed- can rule out with modest exposures at selected sites (Himalaya, Pacific, …)
- Constant shape hypothesis still allowed- can rule out with demanding expoures at selected sites (Himalaya, Pacific, …)
- Direction measurements should really help
- Constant mantle assumption enables crust and mantle rate measurements
- Future looks very good!