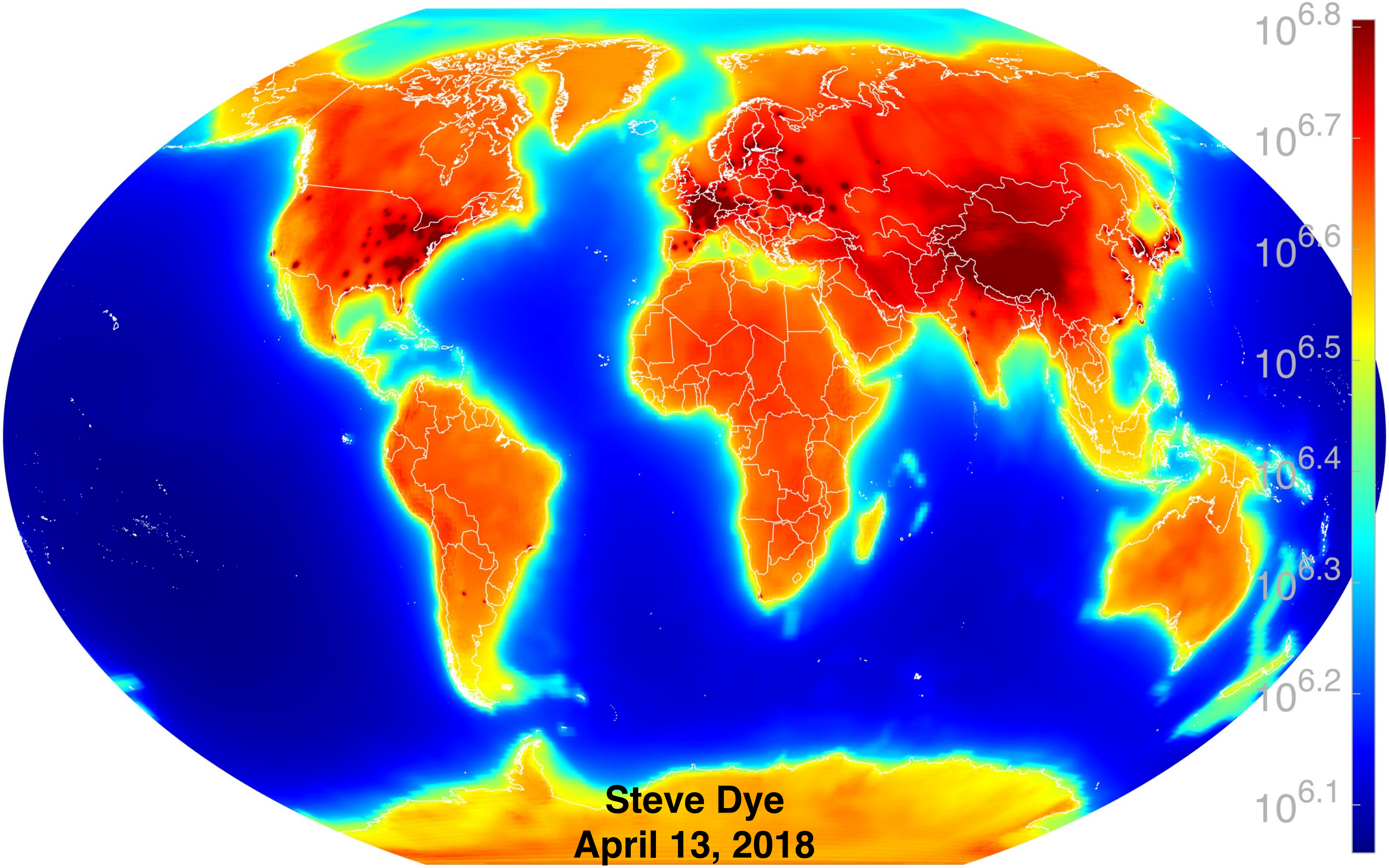
Antineutrinos for Theia



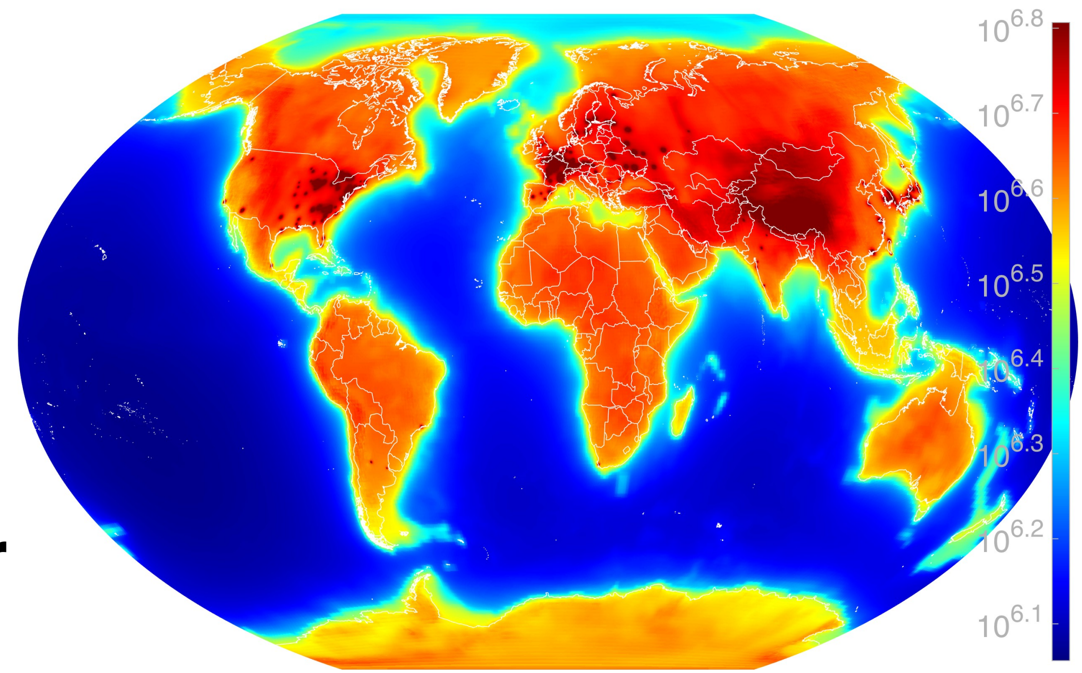
Steve Dye

April 13, 2018

Outline

- **2 - 10 MeV electron antineutrinos from reactors and Earth detected with IBD at Homestake**

- **Not discussing SNν or DSNB in this talk**



Estimated Anti-nu Signal

R_{total} = 77.2 TNU

$R_{reactor}$ = 33.3 TNU

$R_{closest}$ = 0.6 TNU
(0.8 % of total)

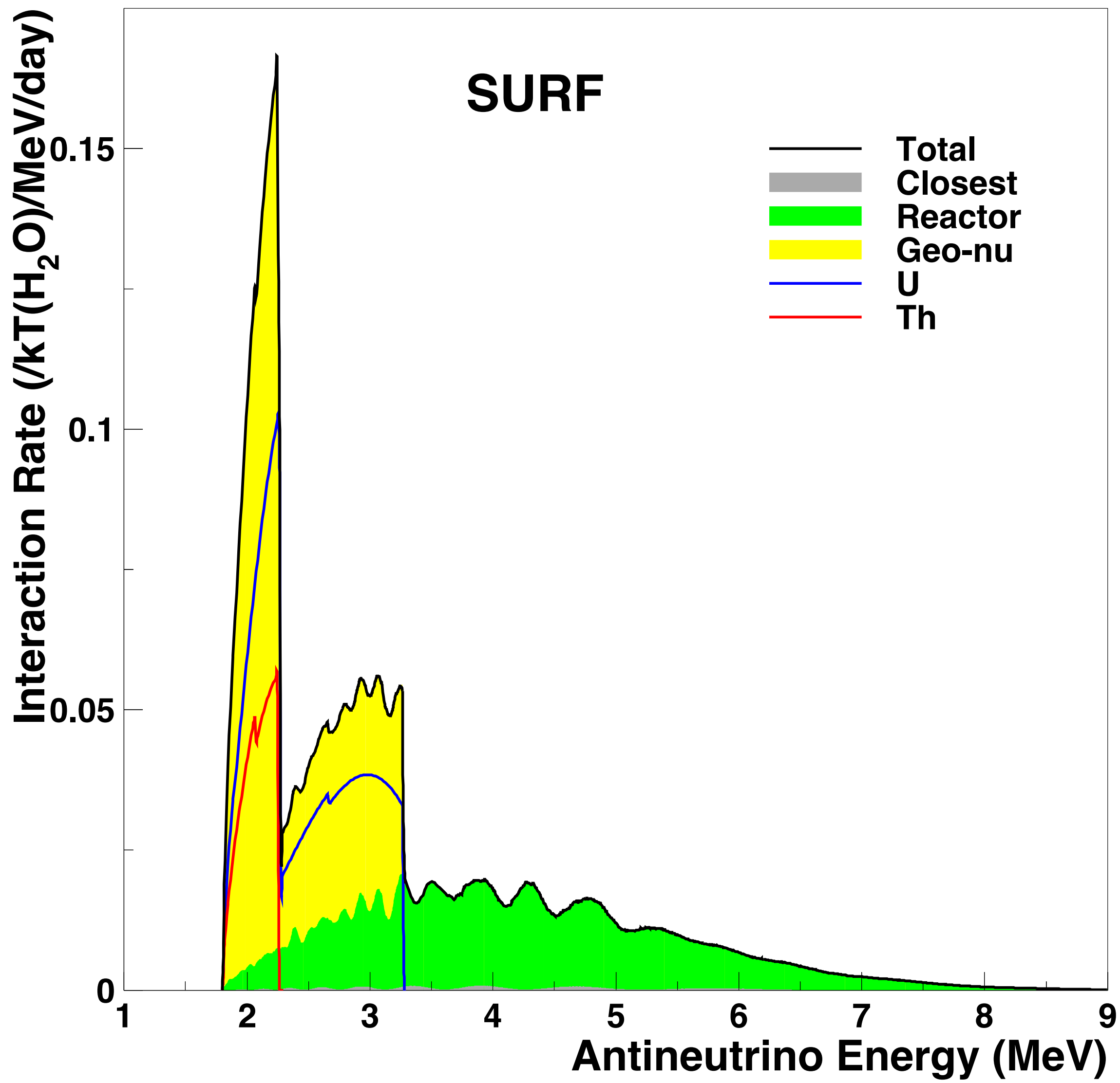
$D_{closest}$ = 699.93 km

$R_{E < 3.275 MeV}$ = 52.0 TNU

R_{geo} = 43.9 TNU
(U = 34.4, Th = 9.6)

Th/U_{geo} = 4.2

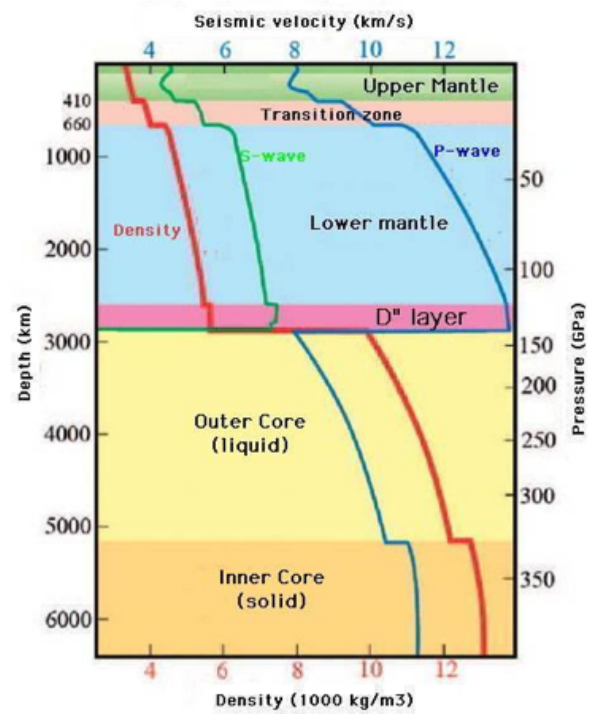
1 TNU = 1 event/10^{32} free protons/year
1 kT H_2O contains 0.668559x10^{32} free protons



Geo-neutrino Signal Estimate- I

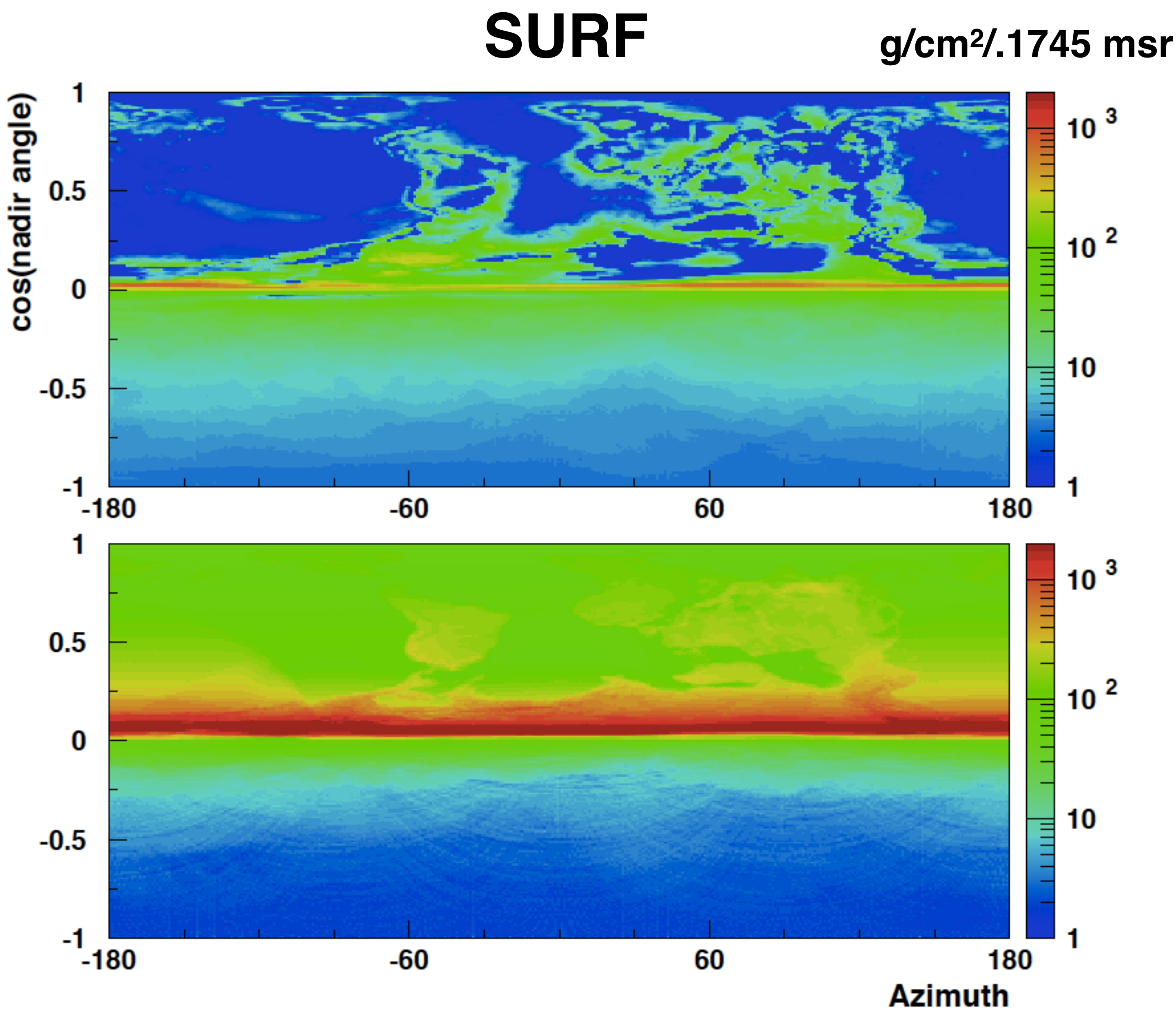
Geophysics

- K, Th, U in silicate mantle and crust not in metallic core
- 8 geophysical reservoirs defined by seismology in mantle and crust
- Map directions of mass per area per solid angle, or geophysical response, of each reservoir
- Relatively well known (± few %) compared with abundances of K, Th, U in each reservoir



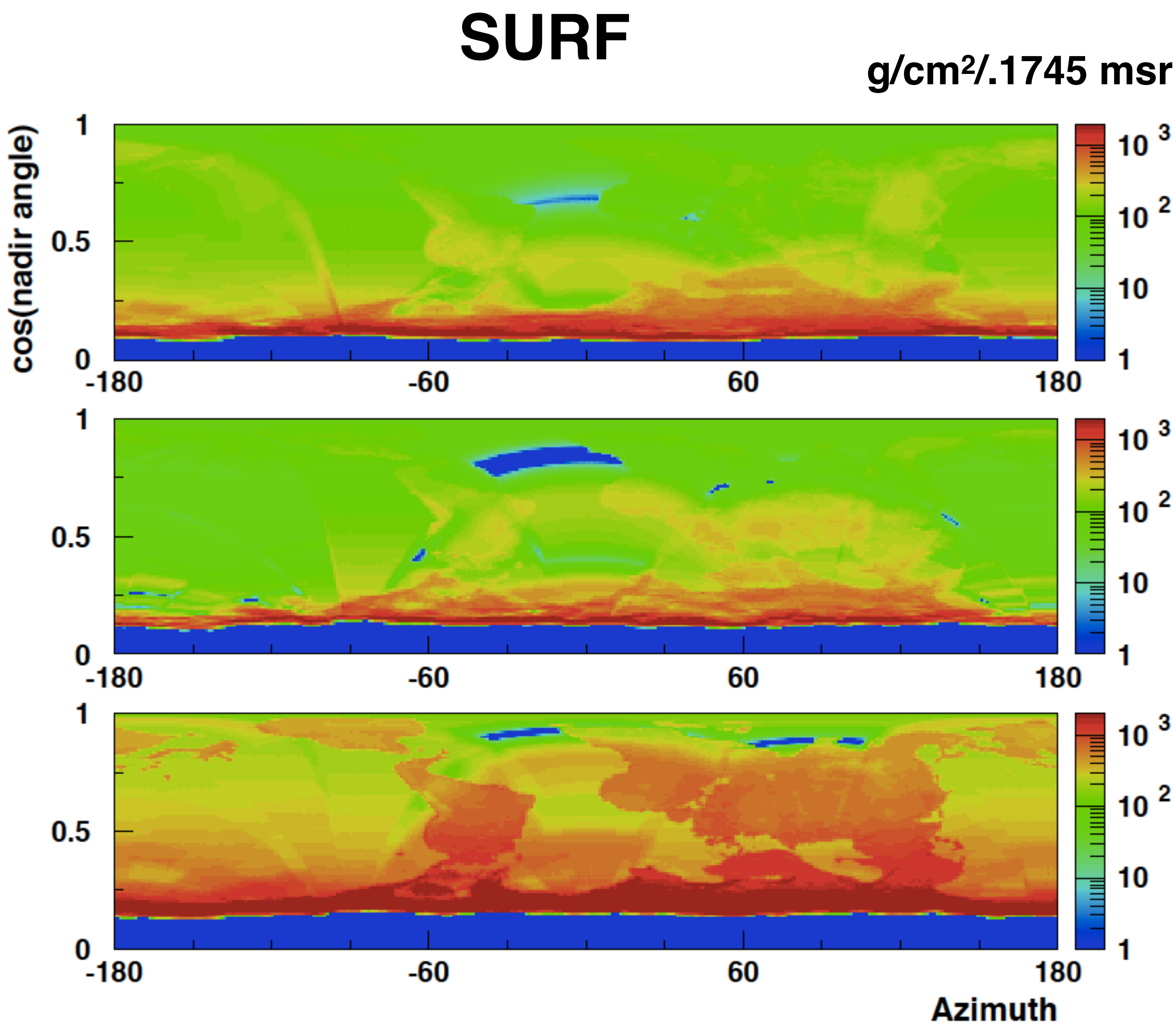
Geophysical Response

- **Sediment**
- **Upper Continental Crust**



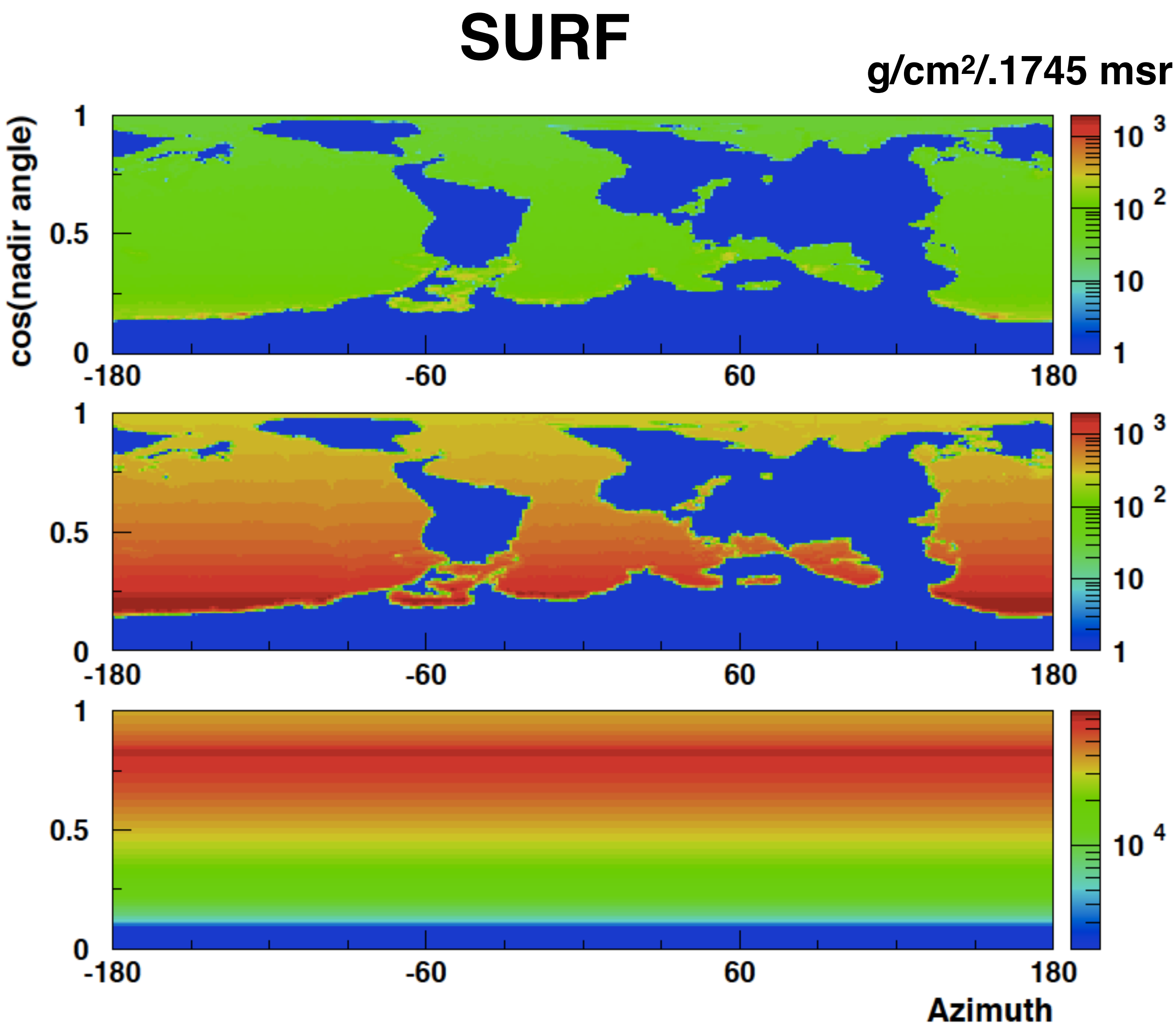
Geophysical Response

- **Middle CC**
- **Lower CC**
- **Continental Lithospheric Mantle**



Geophysical Response

- **Ocean Crust**
- **LID**
- **Mantle**



Geo-neutrino Signal Estimate- II

Geochemistry

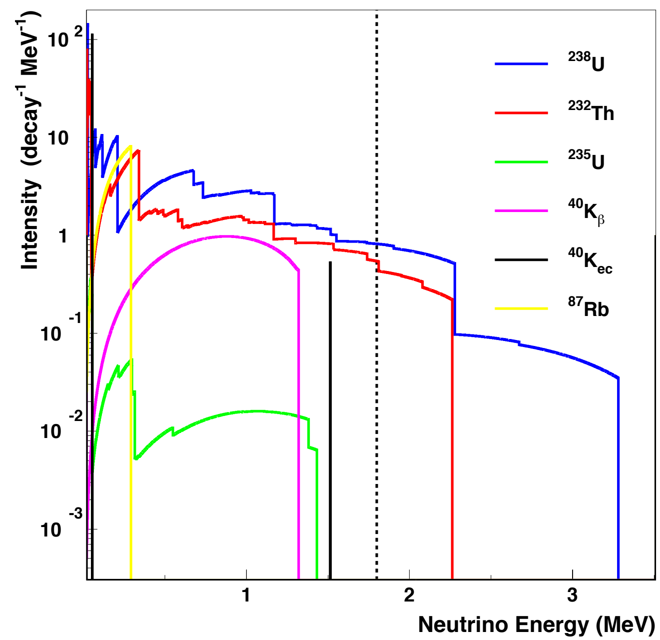
- **Abundances of K, Th, U in 8 reservoirs assumed uniform- although assuredly heterogeneities**
- **Requires input from models: silicate earth and crust**
- **Largest source of error (± few 10 %)**

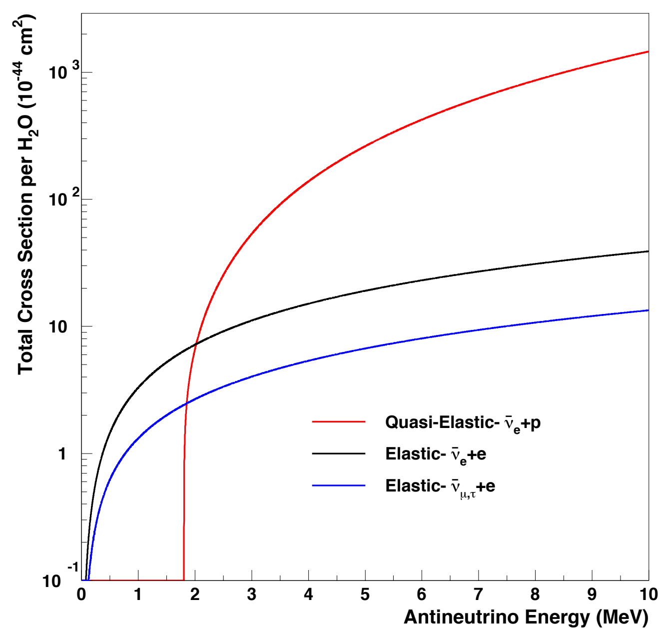
Reservoir/Isotope	U (μg/g)	Th (μg/g)	K (wt. %)
Upper continental crust	2.7 ± 0.6	10.5 ± 1.1	2.3 ± 0.2
Middle continental crust	1.3 ± 0.4	6.5 ± 0.5	1.9 ± 0.3
Lower continental crust	0.20 ± 0.11	1.3 ± 0.9	0.71 ± 0.28
Continental lithospheric mantle	0.045 ± 0.035	0.24 ± 0.19	0.04 ± 0.03
Sediment	1.7 ± 0.1	8.1 ± 0.6	1.8 ± 0.1
Oceanic crust	0.07 ± 0.02	0.21 ± 0.06	0.07 ± 0.02
Mantle (no radioactivity in core)	0.011 ± 0.009	0.036 ± 0.033	0.016 ± 0.013

Geo-neutrino Signal Estimate- III

Physics

- **Activities of K, Th, U well known (/g/s). Assume secular equilibrium for Th & U decay series**
- **Beta decay spectra, intensities, and branching ratios well known**
- **Average survival probability for distributed sources well known**
- **Antineutrino IBD (& ES) cross section(s) well known**
- **Relatively well known (± few %) compared with abundances of K, Th, U in each reservoir**





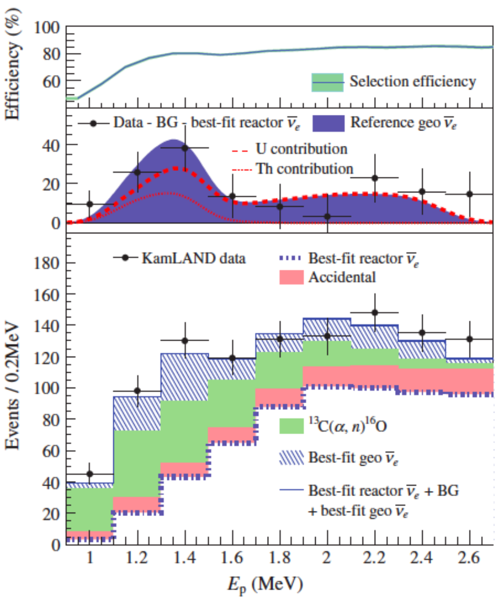
Geo-neutrino Observations- Flux

Kamioka, Japan

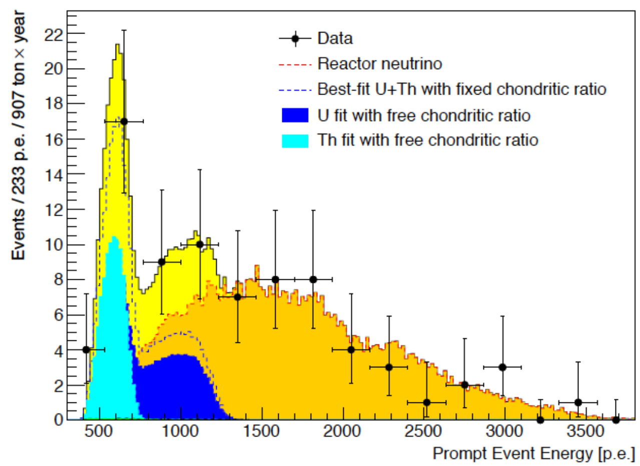
Mar 2002 - present

Gran Sasso, Italy

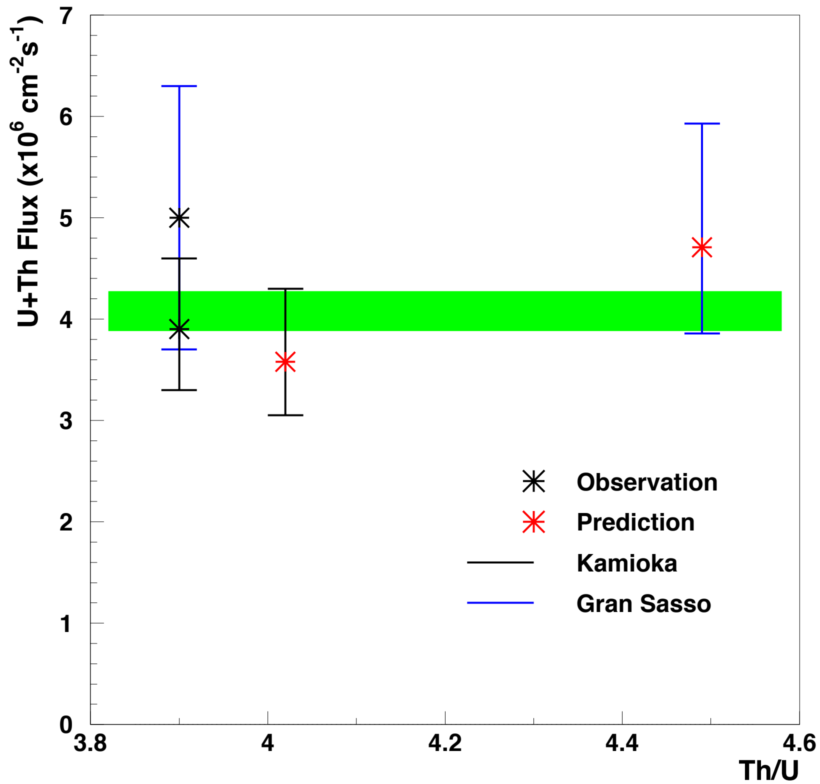
Dec 2007 - present

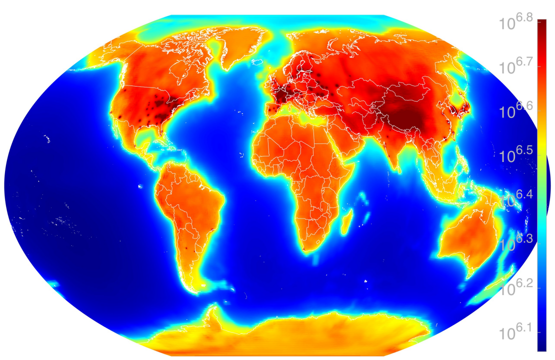


KamLAND data (2013)
4.6σ detection



Borexino data (2015)
5.9σ detection

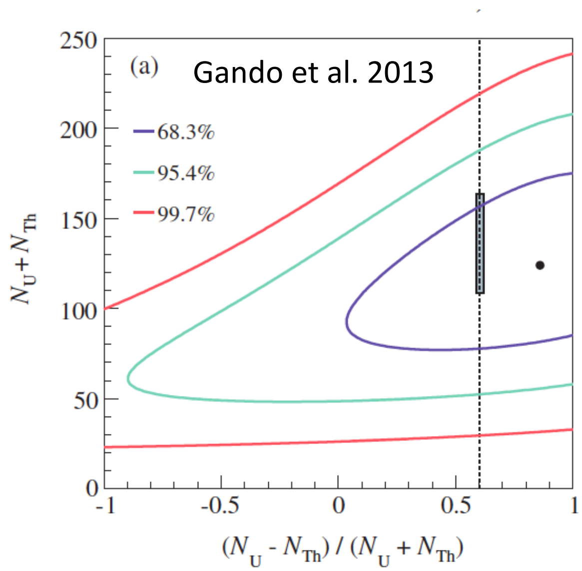




Predicted surface flux variation not yet observed

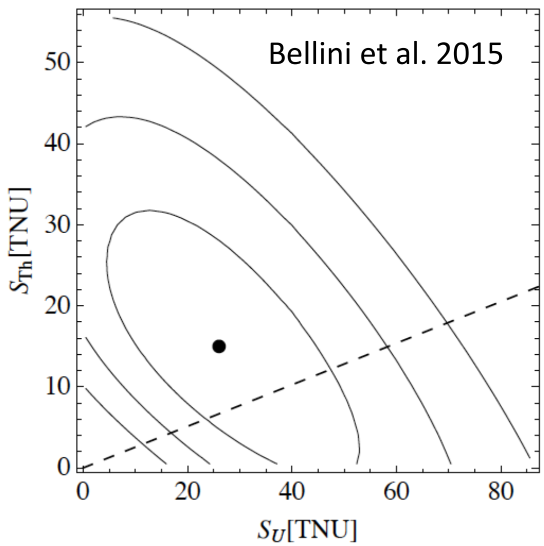
Geo-neutrino Observations- Spectrum

Kamioka, Japan
Mar 2002 - present

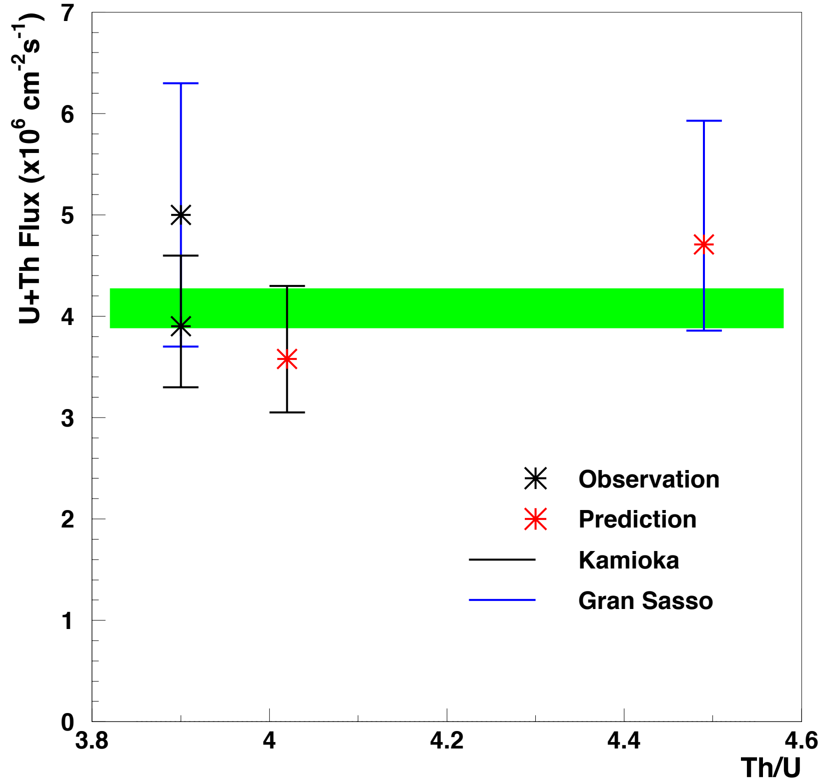


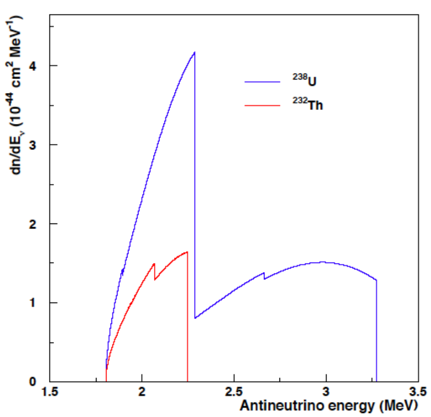
KamLAND data (2013)
consistent with N_{Th}= 0

Gran Sasso, Italy
Dec 2007 - present

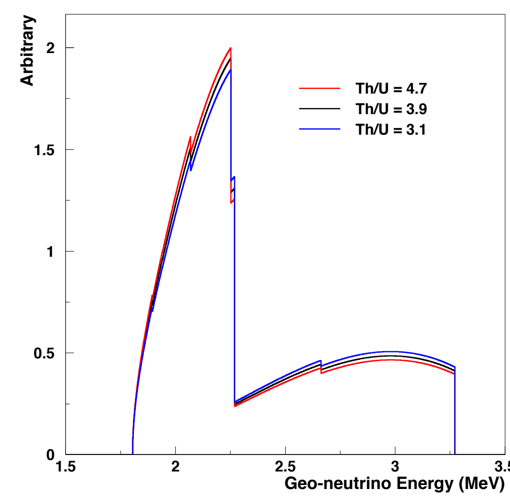


Borexino data (2015)
consistent with S_{Th}= 0





Spectral components (Th/U) not yet resolved



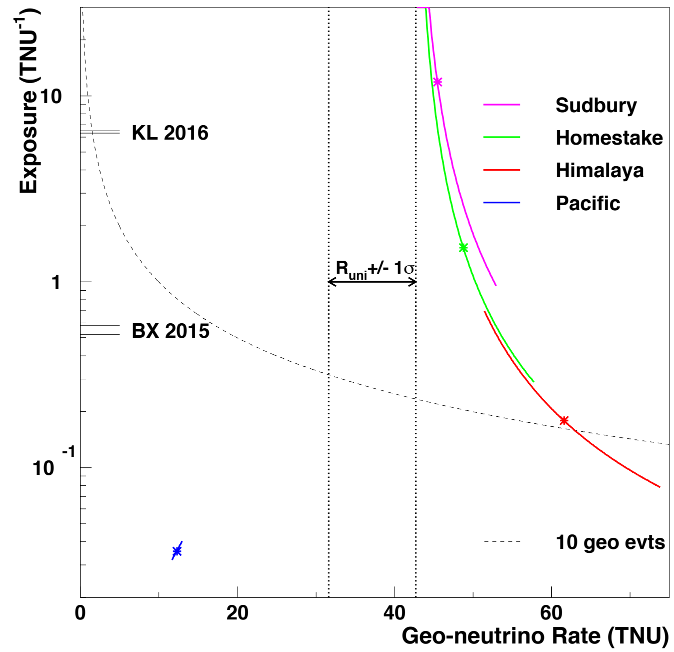
Geo-neutrino Observation Status

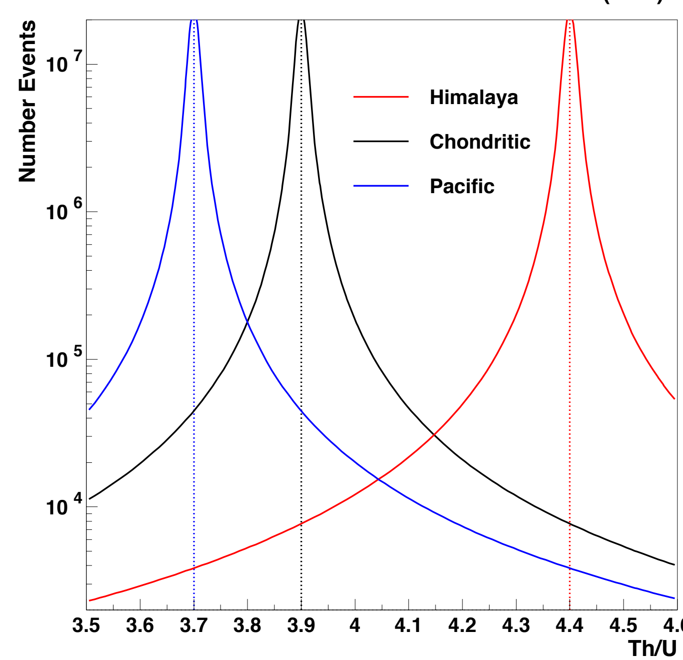
	Rate	Spectrum	Flux	Variation	Power	Dir
U + Th	>5σ	Th/U < 17	Th/U=3.9		model	
K	K/U		K/U		K/U	
Crust	model		model		model	
Mantle	model		model		model	
LLSVP/ULVZ						
Core						

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

Theia Geo-nu Opportunities

- **Observed signal rate depends on yet-to-be-determined detection efficiency**
- **Assume for now 80% flat in energy**
- **At 30 kT fiducial expect ≈ (44 x 30 x 2/3 x 4/5 =) 700 IBD events per year**
- **Measure *R* different from KamLAND and Borexino (≈ 1 year of Theia)**
- **Resolve spectral components (Th/U) (≈ 10 years of Theia)**

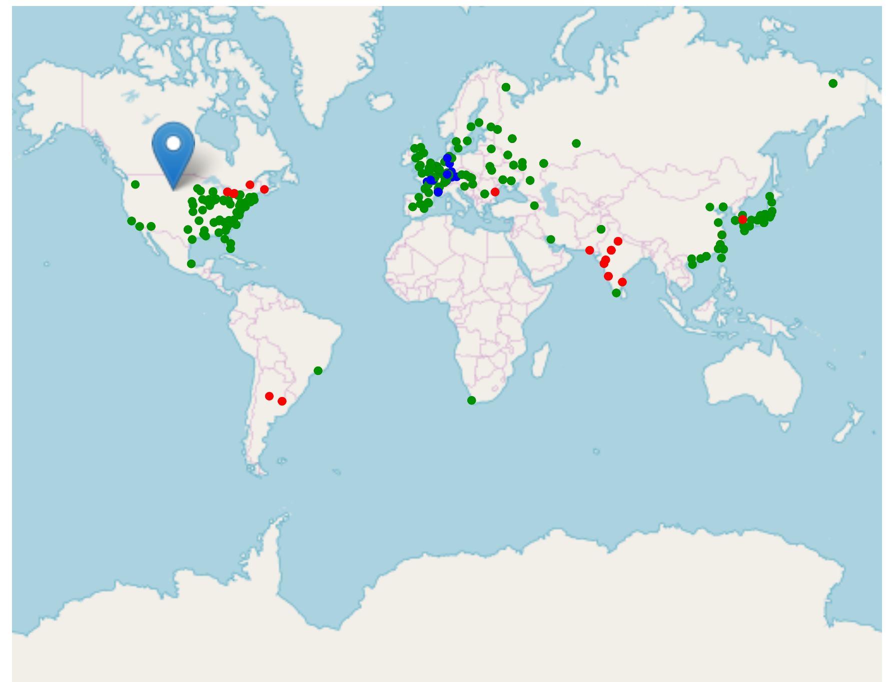




Reactor Antineutrino Signal- I

GIS/Operator

- **Location, power, load, fuel**
- **450 power reactor cores (IAEA)**
- **Core types by fuel**
- **Relatively well known (± few %)**



LEU: BWR, PWR, GCR, etc.

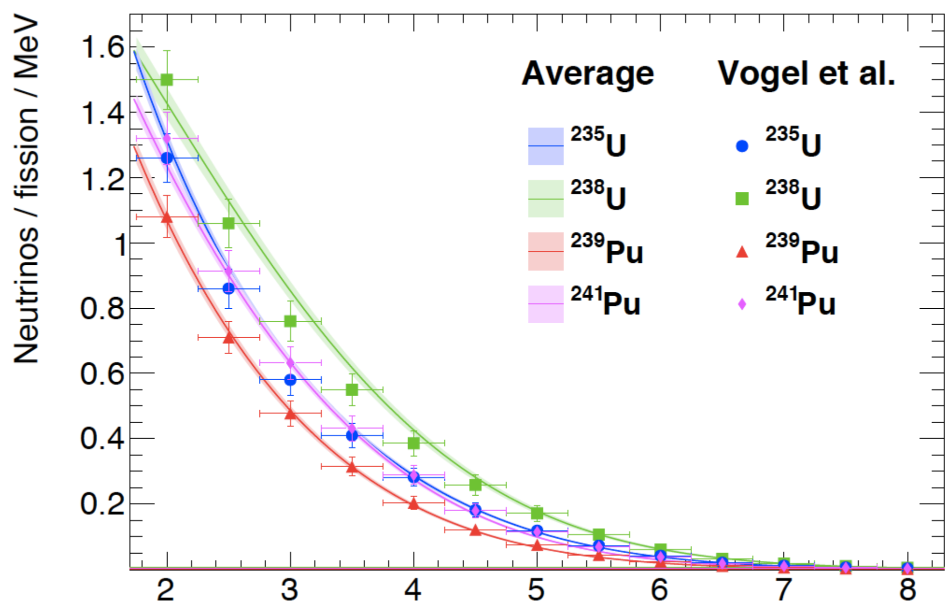
SEU: PHWR

LEU+MOX

Reactor Antineutrino Signal- II

Nuclear Physics

- **Fissile isotopes- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
- **Take weighted average of conversion and summation data**
- **Calculate energy per fission**
- **Assume mid-cycle fission fractions**
- **Relatively well known (± few %)**



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  "LEU": {
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  "SEU": {
    "U235": 0.52,
    "U238": 0.05,
    "PU239": 0.42,
    "PU241": 0.01
  },
  "LEU_MOX": {
    "U235": 0.39,
    "U238": 0.08,
    "PU239": 0.42,
    "PU241": 0.11

"FISSION_ENERGIES": {
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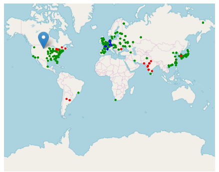
  "U238": 204.997,
  "PU239": 210.927,
  "PU241": 213.416



Reactor Antineutrino Signal- III

Neutrino Physics

- **Apply IBD cross section**
- **Apply oscillations explicitly for each core distance**
- **Sum contributions of all cores**
- **Estimated precision (± 6 %)**


```
"OSCILLATION_PARAMETERS": {
  "s2t12": 0.297,
  "dmsq21": 0.0000737,
  "s2t13Normal": 0.0215,
  "s2t13Inverted": 0.0216,
  "dmsq31Normal": 0.00256,
  "dmsq31Inverted": 0.0024663
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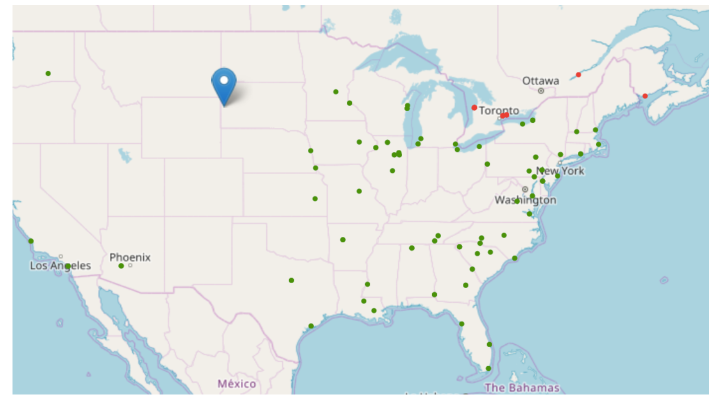
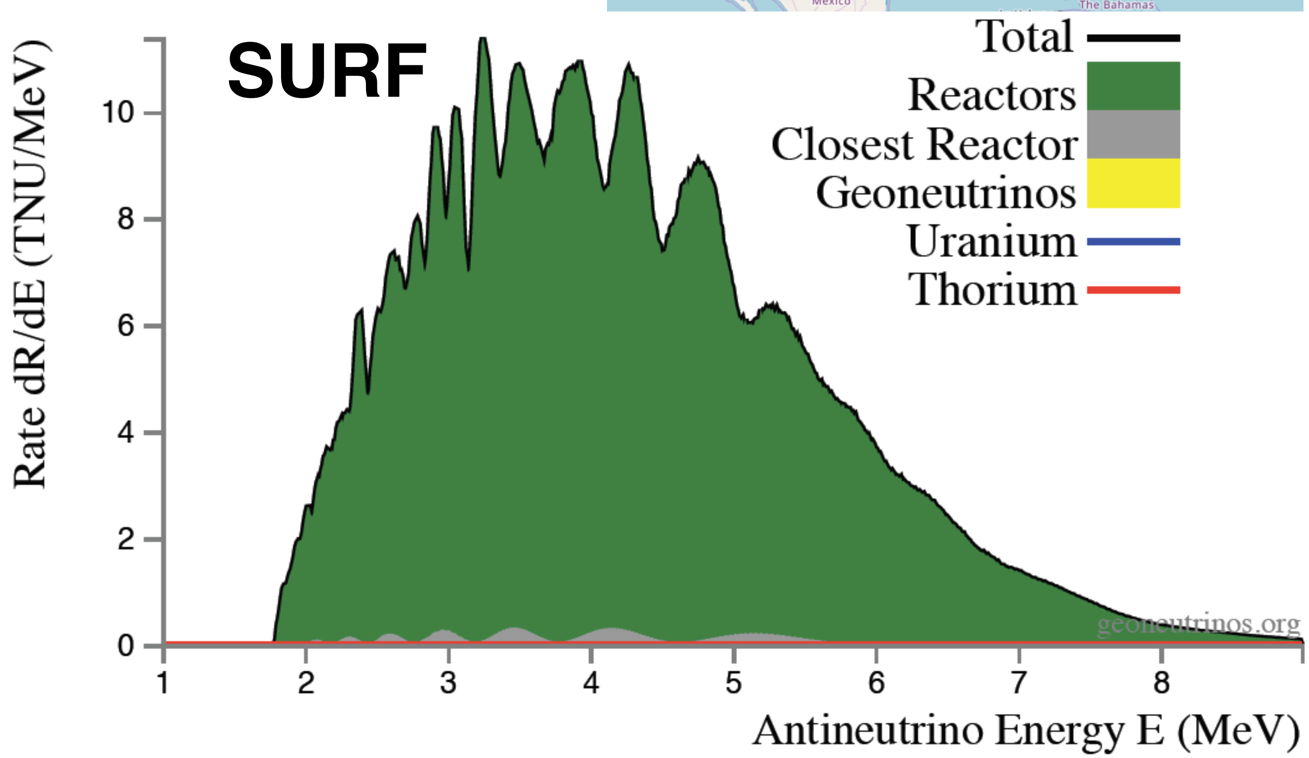
PDG values





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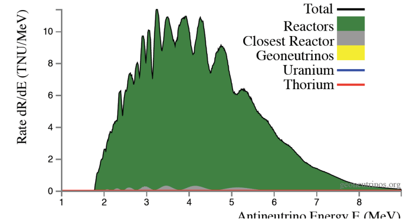
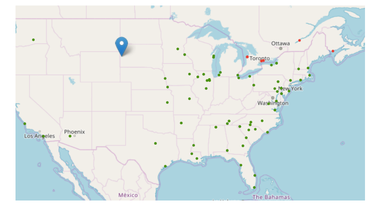
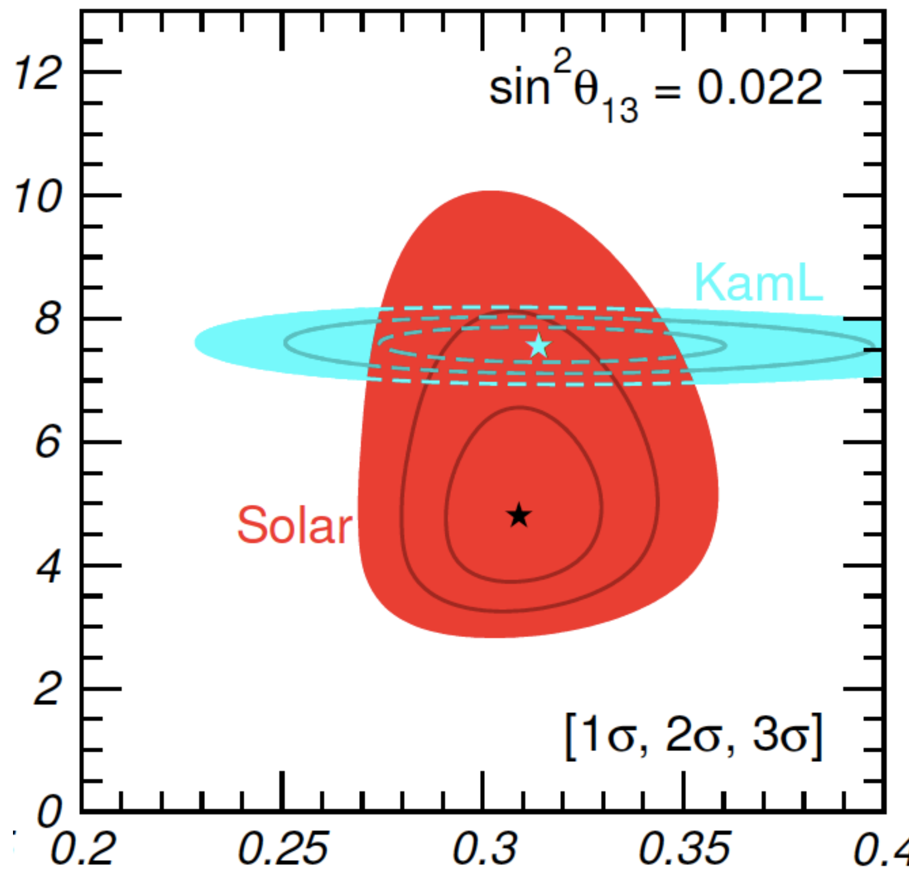
- **Observed spectrum depends on yet-to-be-determined energy resolution**

- **Teal P: Compare Δm^2_{21} reactor and Δm^2_{21} solar in same detector**







Maltoni & Smirnov 2017 $\sin^2\theta_{12}$

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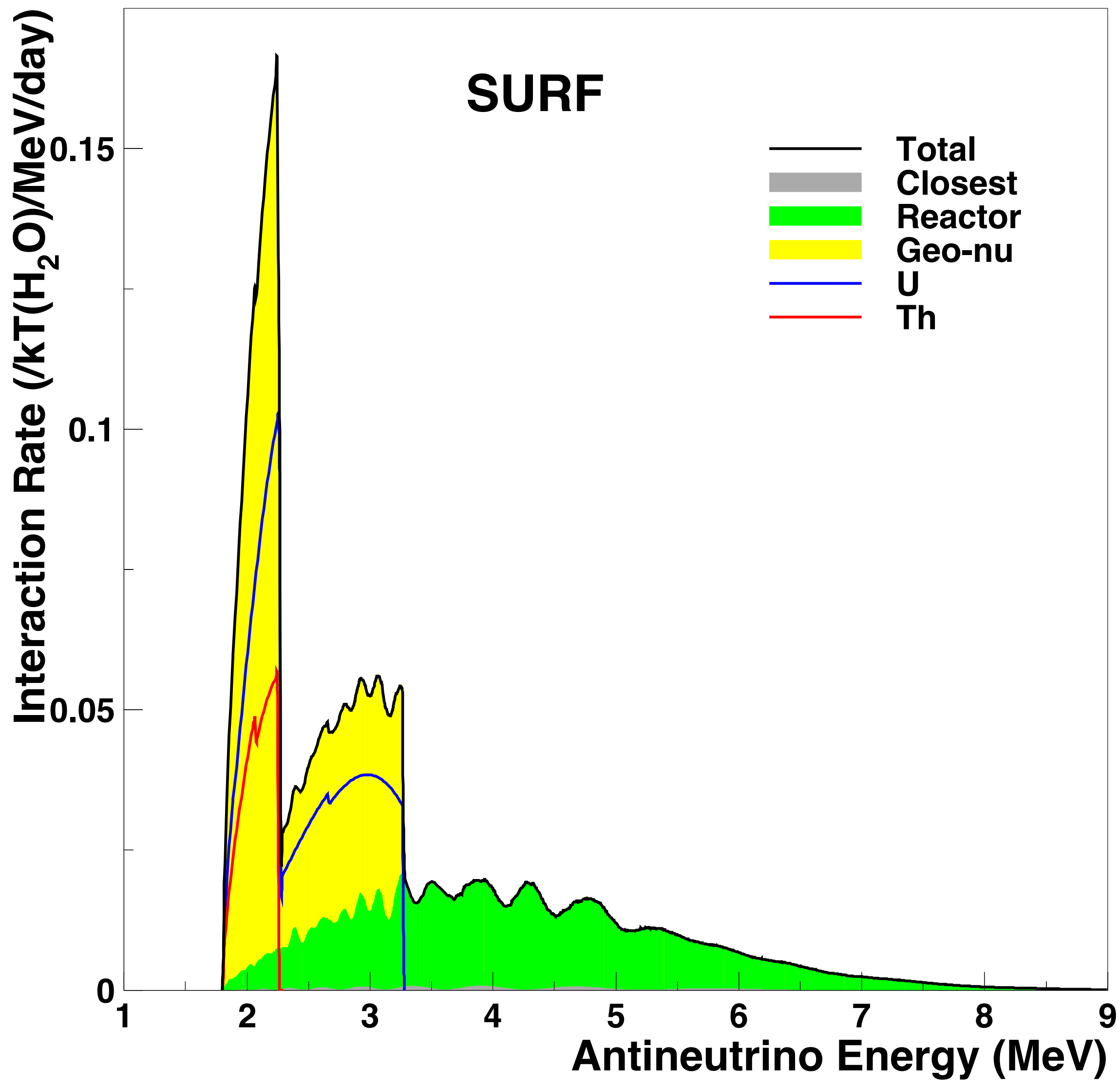

Conclusion

- **Geo- and reactor antineutrino rates in Theia potentially many hundreds per year**
- **Geo-neutrino rate ≠ KL or BX**
- **Geo-neutrino Th/U ≠ 3.9**
- **Reactor $\Delta m^2_{21} \stackrel{?}{=}$ solar Δm^2_{21}**
- **Direction???**