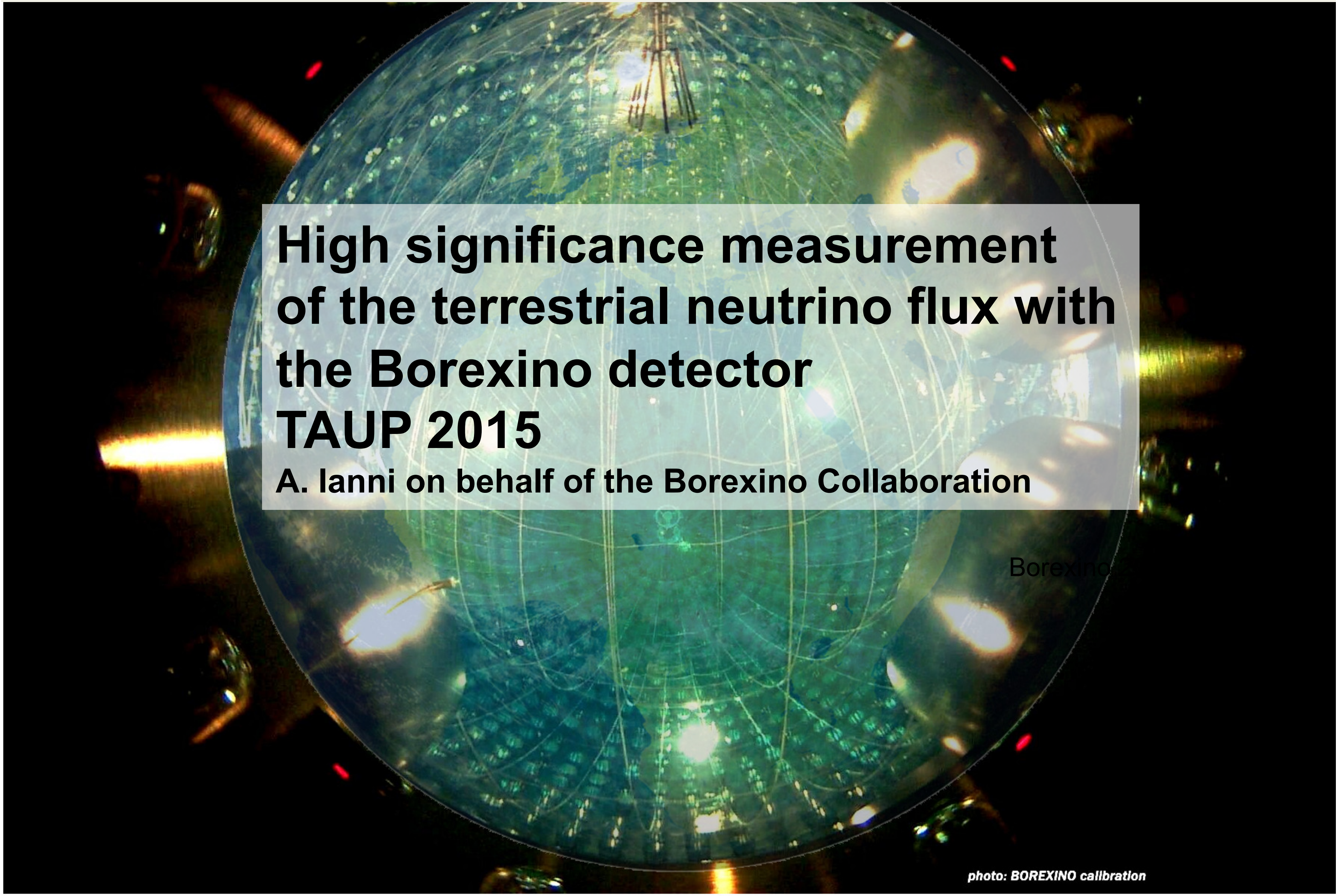
High significance measurement of the terrestrial neutrino flux with the Borexino detector

TAUP 2015

A. Ianni on behalf of the Borexino Collaboration



Geoneutrinos

- **Geoneutrinos**: electron anti-ν_e produced by β decay of long-lived radioactive elements in the Earth's crust and mantle

- Main sources are: ^{238}U, ^{232}Th and ^{40}K
  - in this context referred to as **heat producing elements (HPE)**

- These elements are distributed in the
  - Crust at ppm level (known by sampling)
  - In the Mantle at ppb (model dependent)
  - At present there is a large uncertainty on the total amount and distribution of these HPE

Geoneutrinos and the Science of the Earth interior

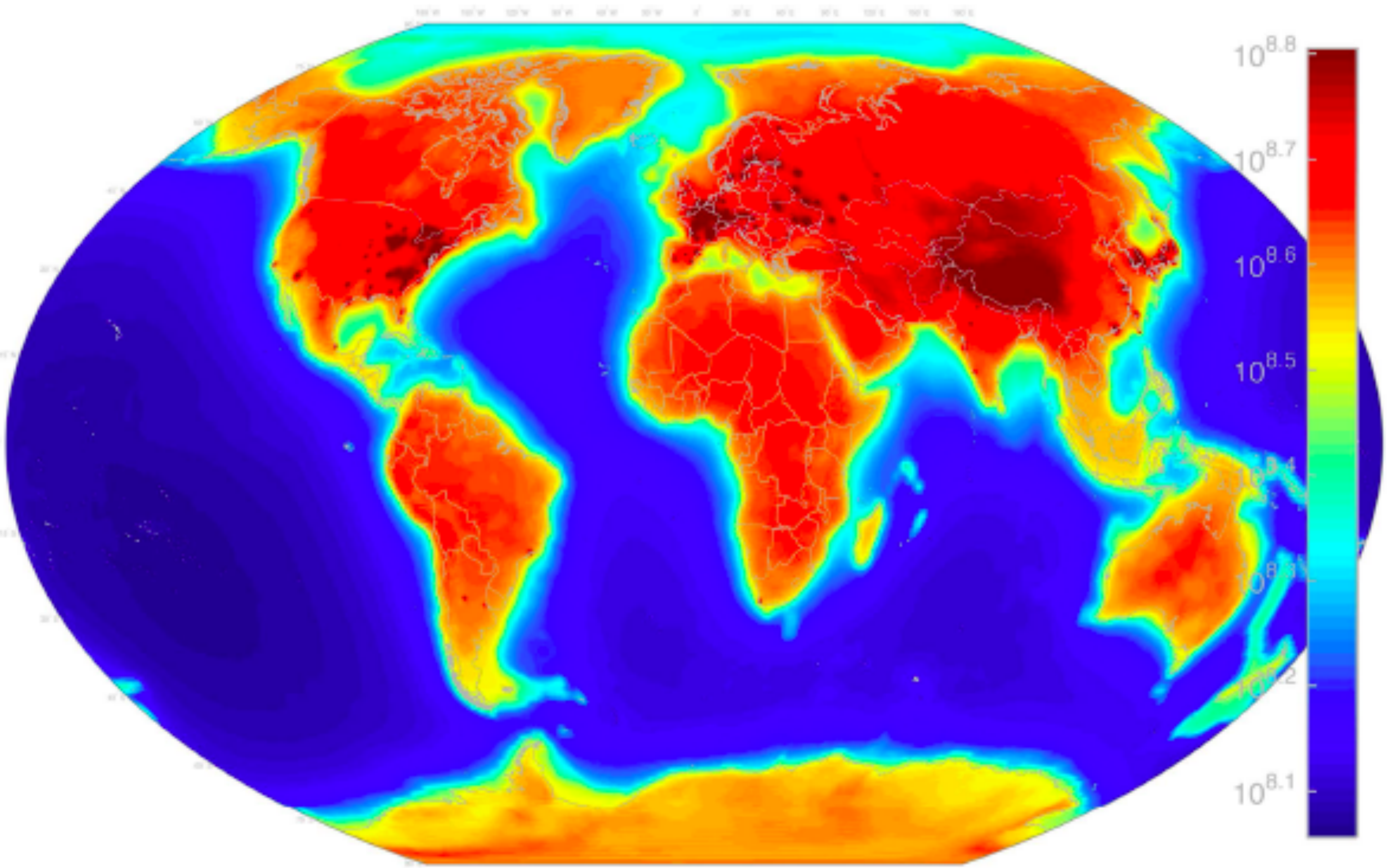
Detection of geoneutrinos could help give an answer to the following questions:

- How much U and Th are inside the Earth?
  - From other studies of the Earth's composition, the U abundance is determined to be 10 – 30 ng/g in the whole planet
- How this compares with the average solar system composition?
- What is the distribution of U and Th in crust vs mantle?
- How much of the heat flow from the Earth (31-47 TW) is due to radioactivity?
  - Using Th/U=3.9 and K/U=1.4×10^4 radiogenic power is model dependent and varies from 10 to >25 TW

History of papers on geoneutrinos

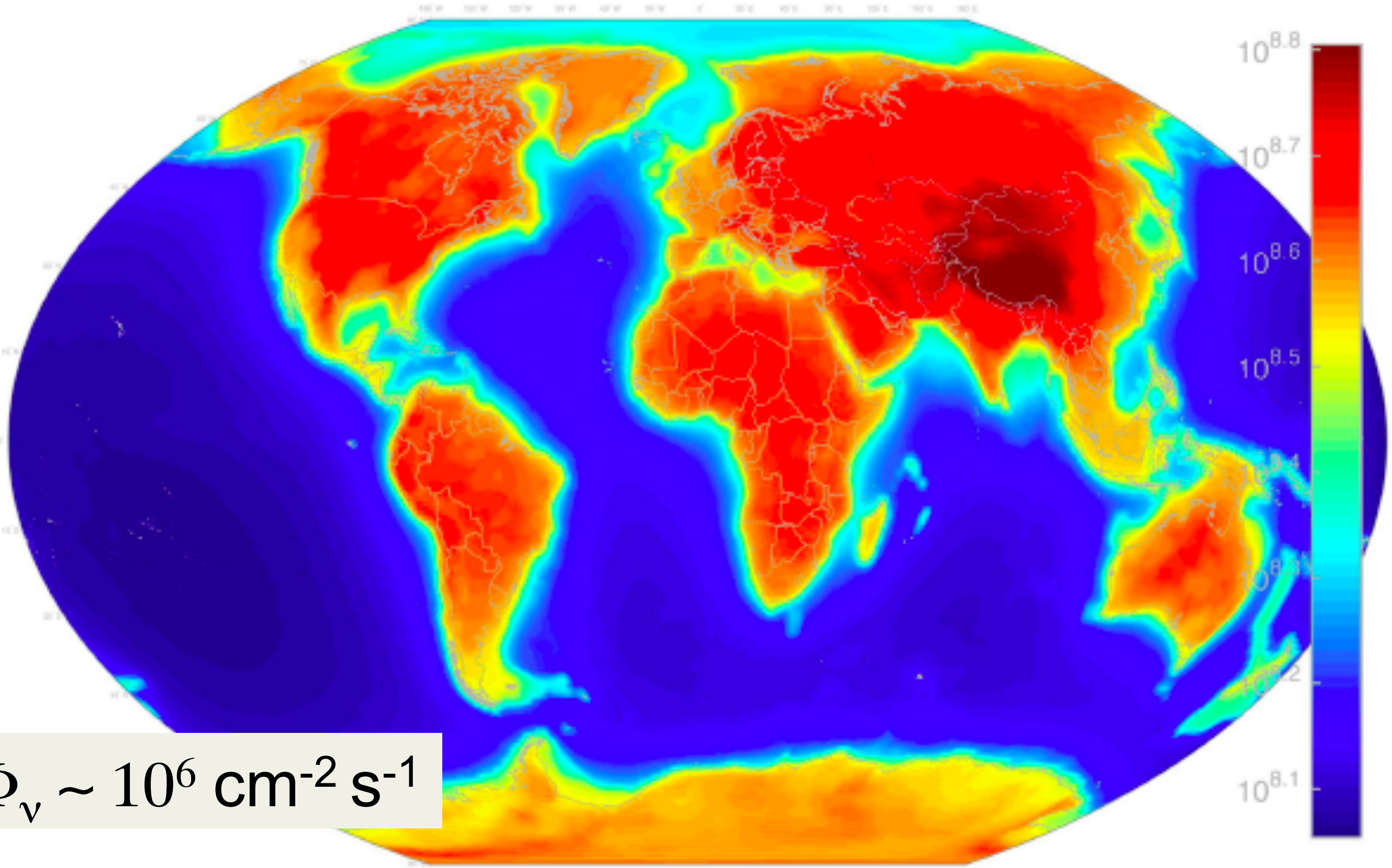
- Early papers:
  - G. Eder, Nucl. Phys. 78, 1966
  - G. Marx, Czech J. Phys. B19, 1969
  - L.M.Krauss, S.L.Glashow,D.M.Schramm, Nature 310, 1984
- Refresh early ideas in view of operating Borexino and KamLAND
  - R.S. Raghavan, et al., Phys. Rev. Lett. 80 (1998) 635
  - C.G.Rothschild, F. Calaprice, M. Chen, Geo. Res. Lett. 25 (1998) 1083
- First observations:
  - T. Araki, et al. KamLAND collaboration, Nature 436 (2005) 499
  - G. Bellini, et al. Borexino collaboration, Phys. Lett. B687 (2010) 299
- Most recent measurements:
  - A. Gando et al. KamLAND collaboration, Phys. Rev. D88 (2013) 033001
  - M. Agostini et al. Borexino collaboration, Phys. Rev. D 92 (2015) 031101(R)
    - THIS TALK

Total antineutrino flux from the Earth (U + Th + reactors)



S.M. Usman, G.R. Jocher, S.T. Dye, W.F. McDonough & J.G. Learned
Scientific Reports, 1 September, 2015

Only geoneutrinos flux from U and Th



$\Phi_\nu \sim 10^6$ cm^{-2} s^{-1}

S.M. Usman, G.R. Jocher, S.T. Dye, W.F. McDonough & J.G. Learned
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Detection of geoneutrinos

At present the only practical method is the "well known" inverse β decay reaction exploited in massive low radioactivity liquid scintillators located underground

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

correlated prompt and delayed events

$$\downarrow$$

$$n + p \rightarrow d + \gamma(2.22\mathrm{MeV})$$

$$\mathrm{E}_{visible} = E_{\bar{\nu}_e} - 0.784\mathrm{MeV}$$

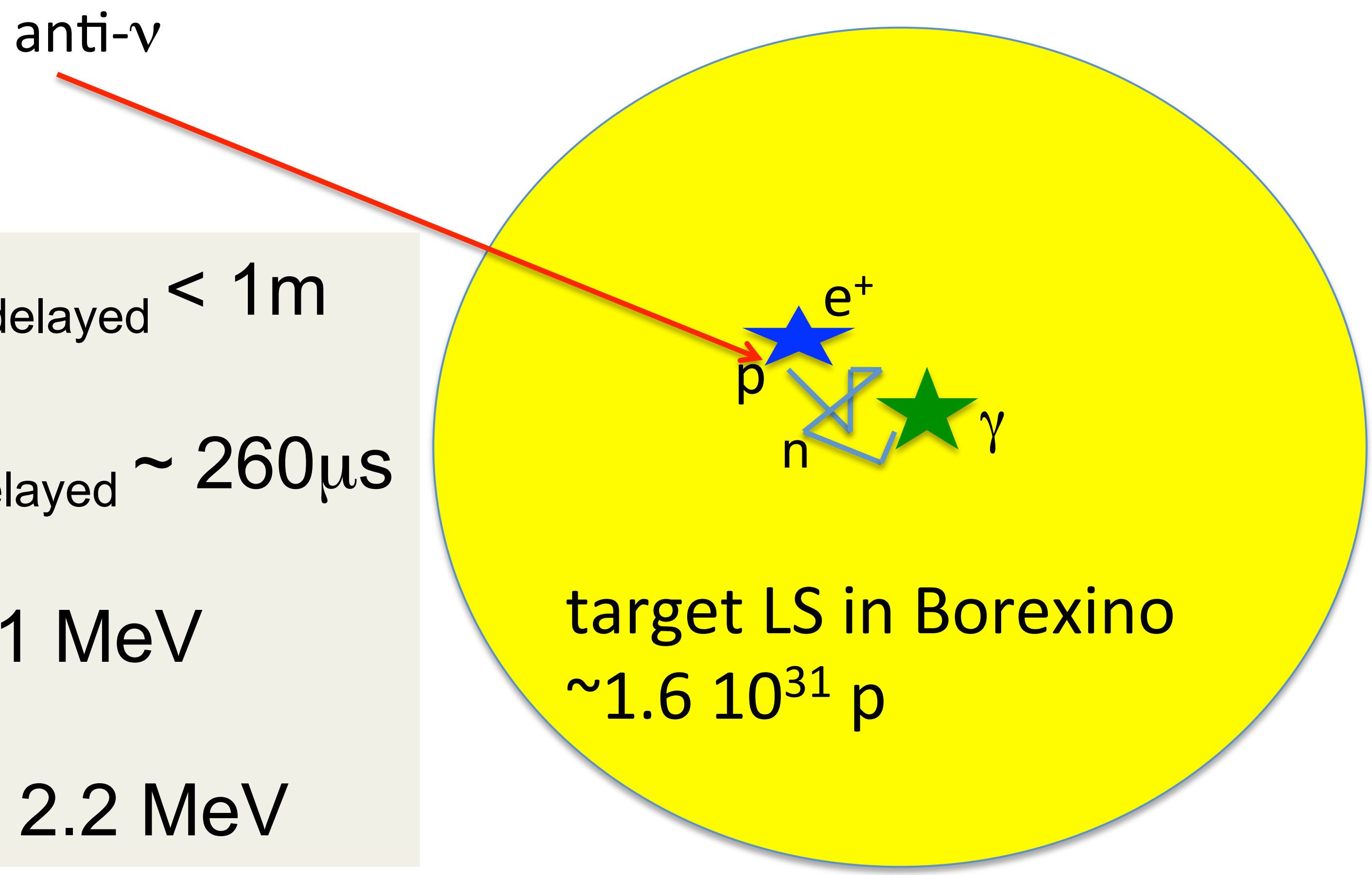
Topology of the anti-ν event

$\Delta R_{prompt\text{-}delayed} < 1\text{m}$

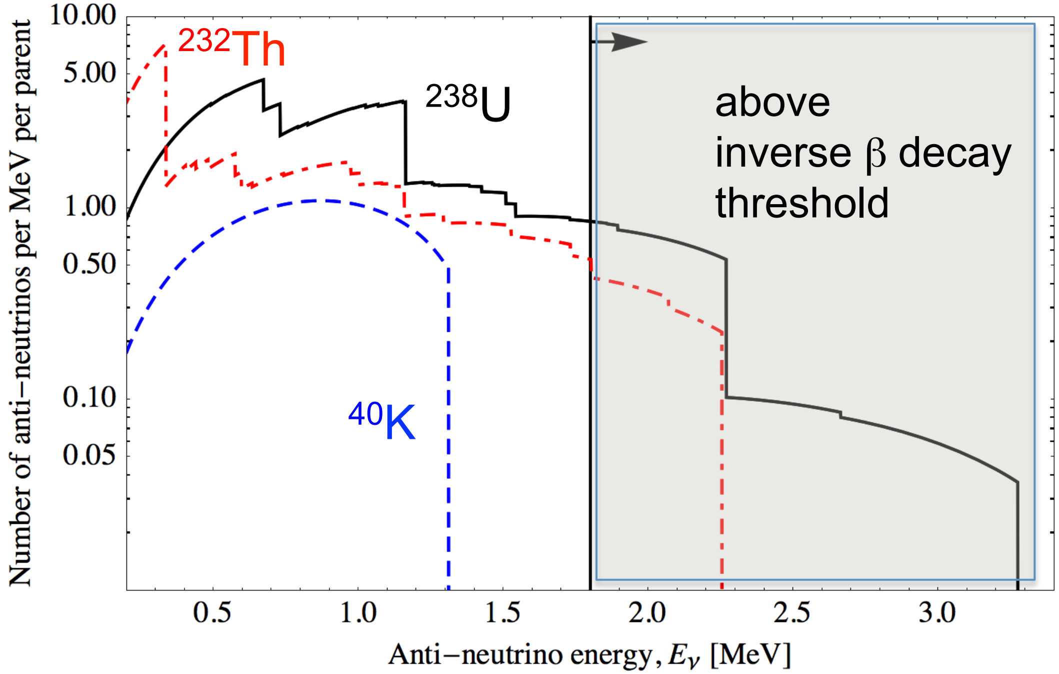
$\Delta t_{prompt\text{-}delayed} \sim 260\mu\text{s}$

$E_{prompt} > 1\text{ MeV}$

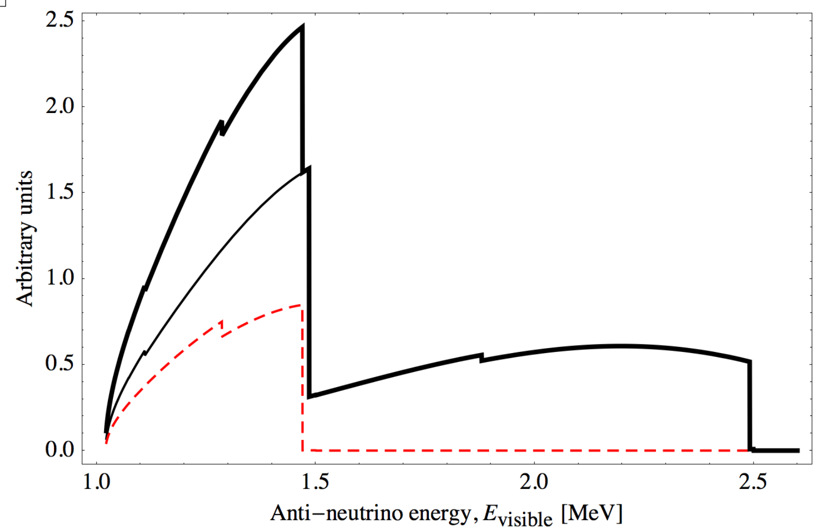
$E_{delayed} \sim 2.2\text{ MeV}$



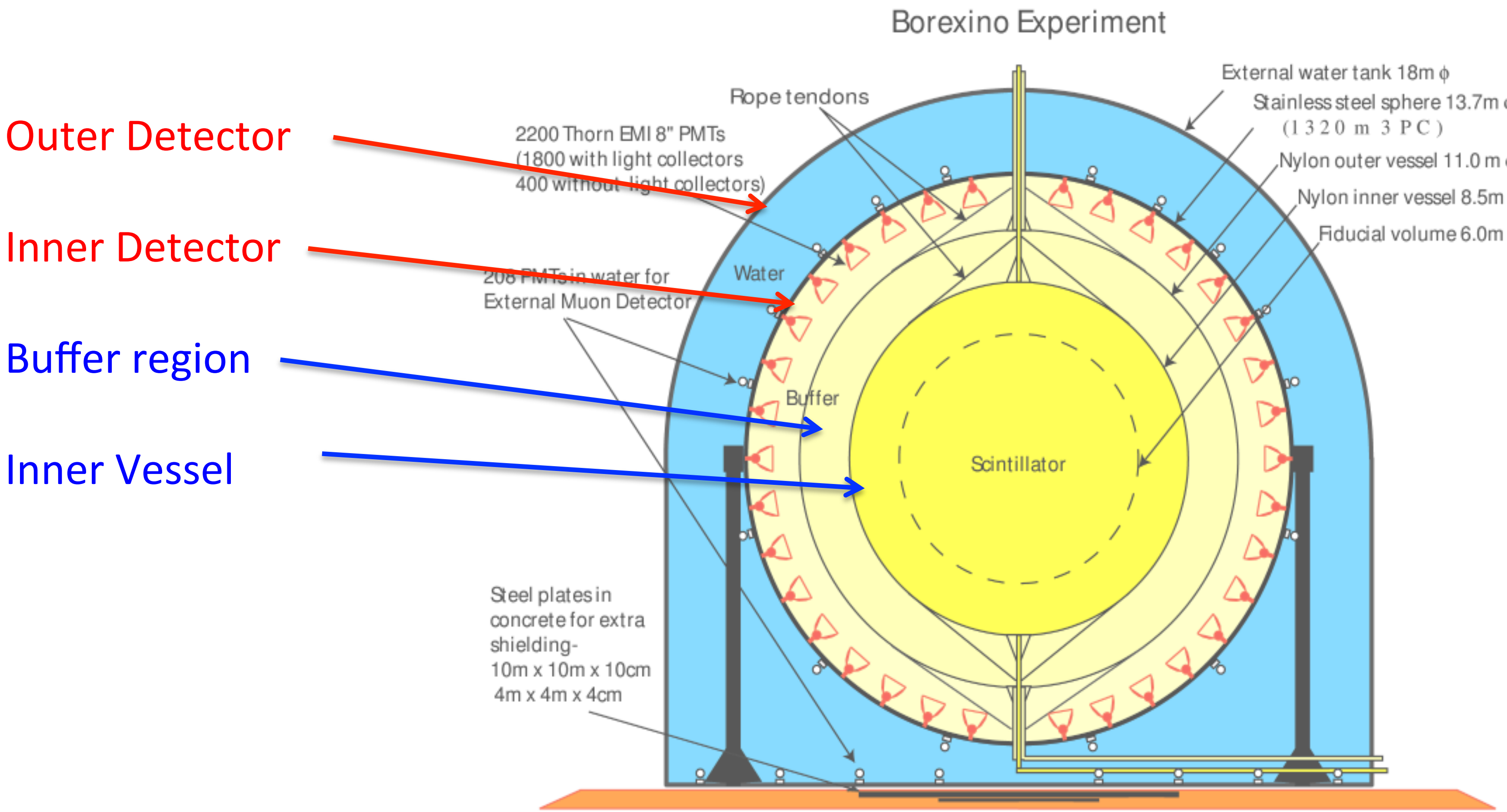
Energy spectrum



Visible spectrum



The Borexino detector



Backgrounds

- **Look for possible sources of *fake* anti-ν events**
  (prompt + delayed):

1. **Background induced from (α,n) and (γ,n) interactions**
    1. Mainly from $^{13}C(\alpha,n)^{16}O$ α from ^{210}Po (~14 cpd/ton)
    2. $^{214}Bi_{prompt}$ decay $^{214}Po_{delayed}(\alpha+\gamma)$ with 10^{-4} BR when radon in the detector after Water Extraction purification
2. **Muons**
    1. $\beta-$n emitters such as ^{9}Li and ^{8}He when muon detected in ID
        - Experimentally these events have a mean life of about 300ms
    2. High energy neutrons interacting on p or ^{12}C
3. **Accidental coincidences**
    1. Mainly below 1.5 MeV and from ^{214}Bi

Borexino 2015 data set

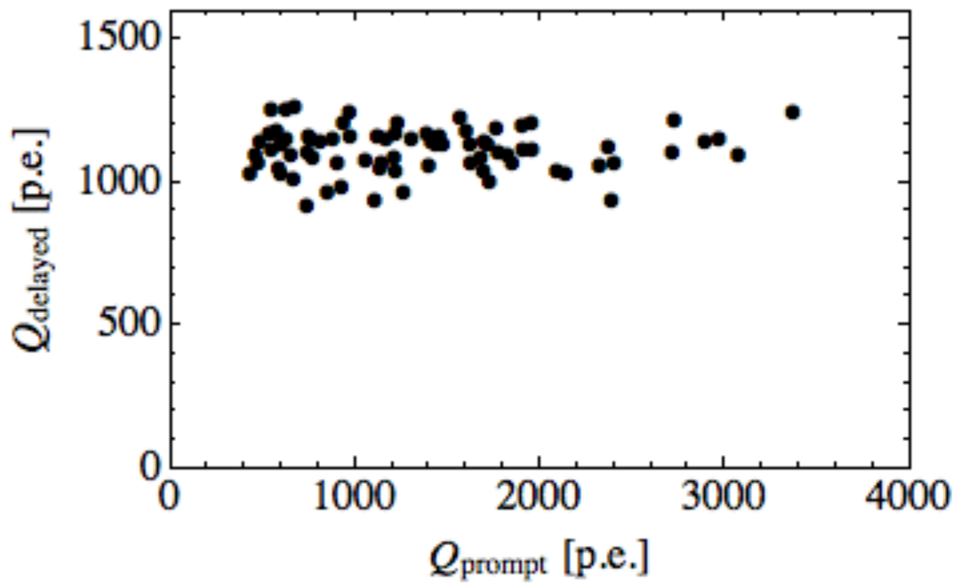
- December 15, 2007 – March 8, 2015
  - 2055.9 days
- Reject events 2ms after muon is detected in OD and 2s after muon in ID
  - Li-He events only 0.11% of total produced
- After muon cuts: 1841.9 days
  - $(5.5\pm0.3)\times10^{31}$ proton-year
- Physics cuts on
  - Prompt and delayed energy
  - Correlation space and time
  - Multiplicity: no neutron-like event within ±2ms wrt the candidate
  - PSD with Gatti filter
  - Fiducial volume (vertex of prompt >30cm away from nylon vessel)
- MC efficiency of cuts: 84.2±1.5 %

Candidates and Background

- 77 candidates passing selection cuts
- Background:

^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221±0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α,n) in scintillator	0.165±0.010
(α,n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	< 0.43
untagged muons	0.12±0.01
Fission in PMTs	0.032±0.003
^{214}Bi-^{214}Po	0.009±0.013
Total	$0.78^{+0.13}_{-0.10}$
	< 0.65(combined)

Anti-neutrino Candidates

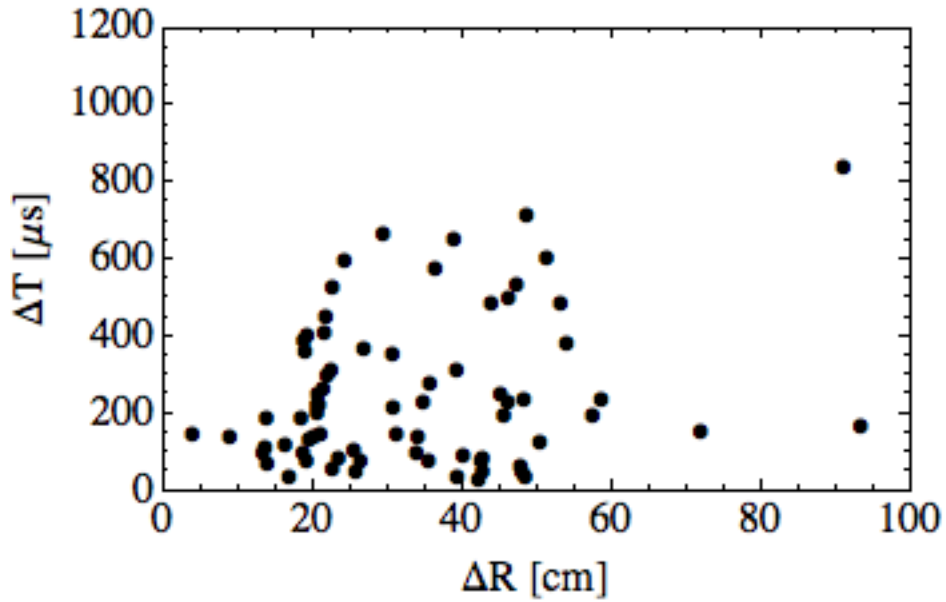


Q_{prompt} > 408 p.e. (1.022 MeV)

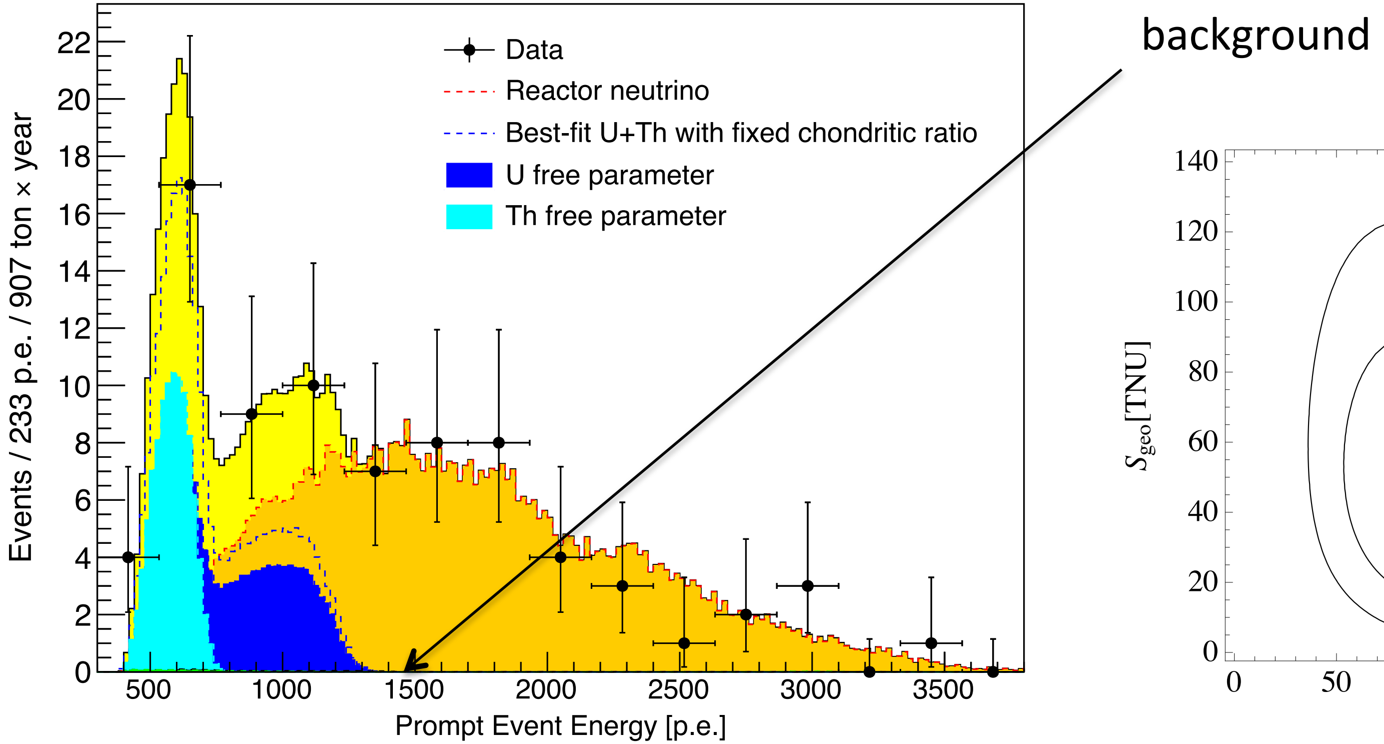
860 p.e. < $Q_{delayed}$ < 1300 p.e.

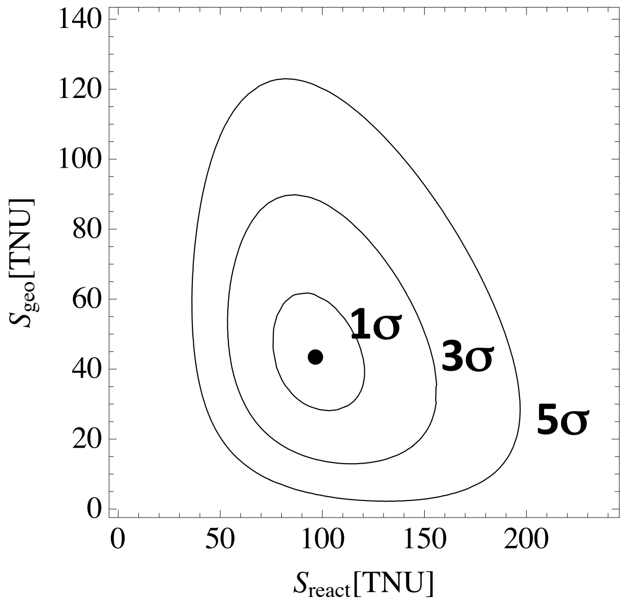
ΔR < 100 cm

20 μs < ΔT < 1280 μs



Unbinned likelihood fit



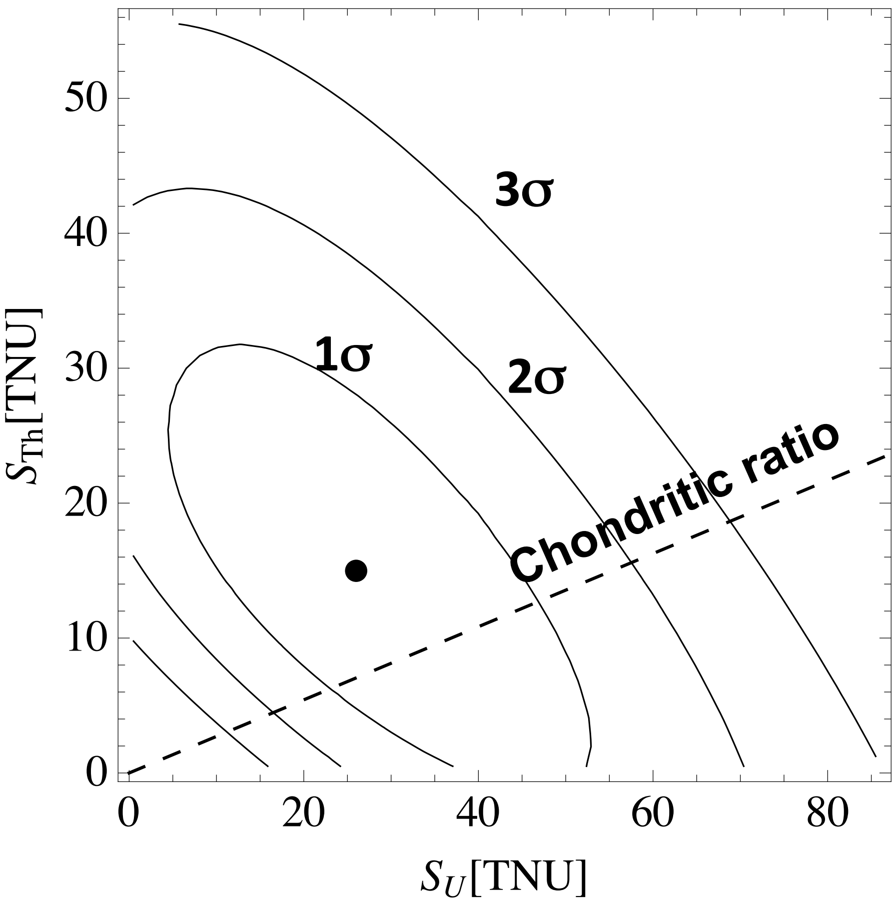


$N_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$

$N_{react} = 52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(sys)$

Null hypothesis rejected at 3.6×10^{-9}

Disentangle U vs Th



$N_{geo}(U) = 14.2^{+10.2}_{-9.1}$

$N_{geo}(Th) = 8.2^{+6.2}_{-6.3}$

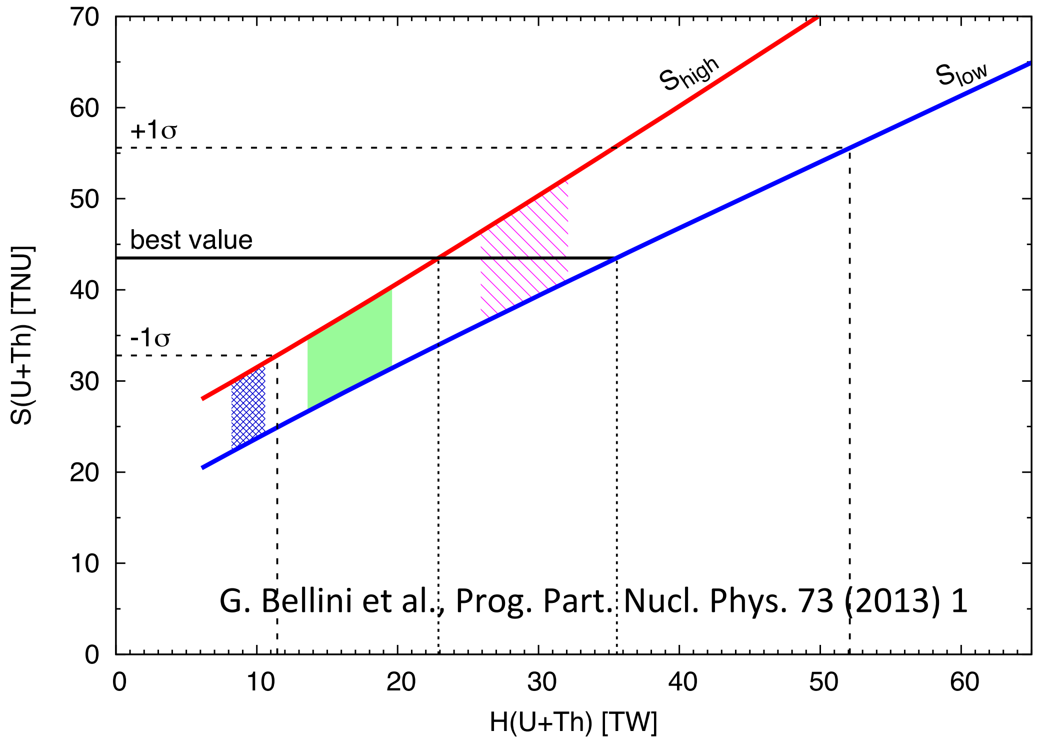
$N_{react} = 54.1^{+9.2}_{-8.5}$

Signal from the Mantle

- Using a detailed computation of the contribution from the crust by Y. Huang and collaborators:
  - S_{geo}(crust) = 23.4±2.8 TNU (1TNU = 1 event/year/10^{32}protons)
- Borexino geoneutrino signal:
  - $S_{geo}=43.5^{+12.1}_{-10.7}$ TNU
- Considering the experimental likelihood profile for S_{geo} and a gaussian profile for S_{crust}
- We obtain:
  - $S_{mantle}= S_{geo} - S_{crust} = 20.1^{15.1}_{10.3}$ TNU
  - Out of 77 candidates, 13 from the crust and 11 from the mantle
- The hypothesis $S_{mantle} = 0$ is rejected at 98% C.L.

Radiogenic heat [1]

Understanding the Earth's energy budget is a fundamental question for plate tectonics, mantle convection and geodynamo

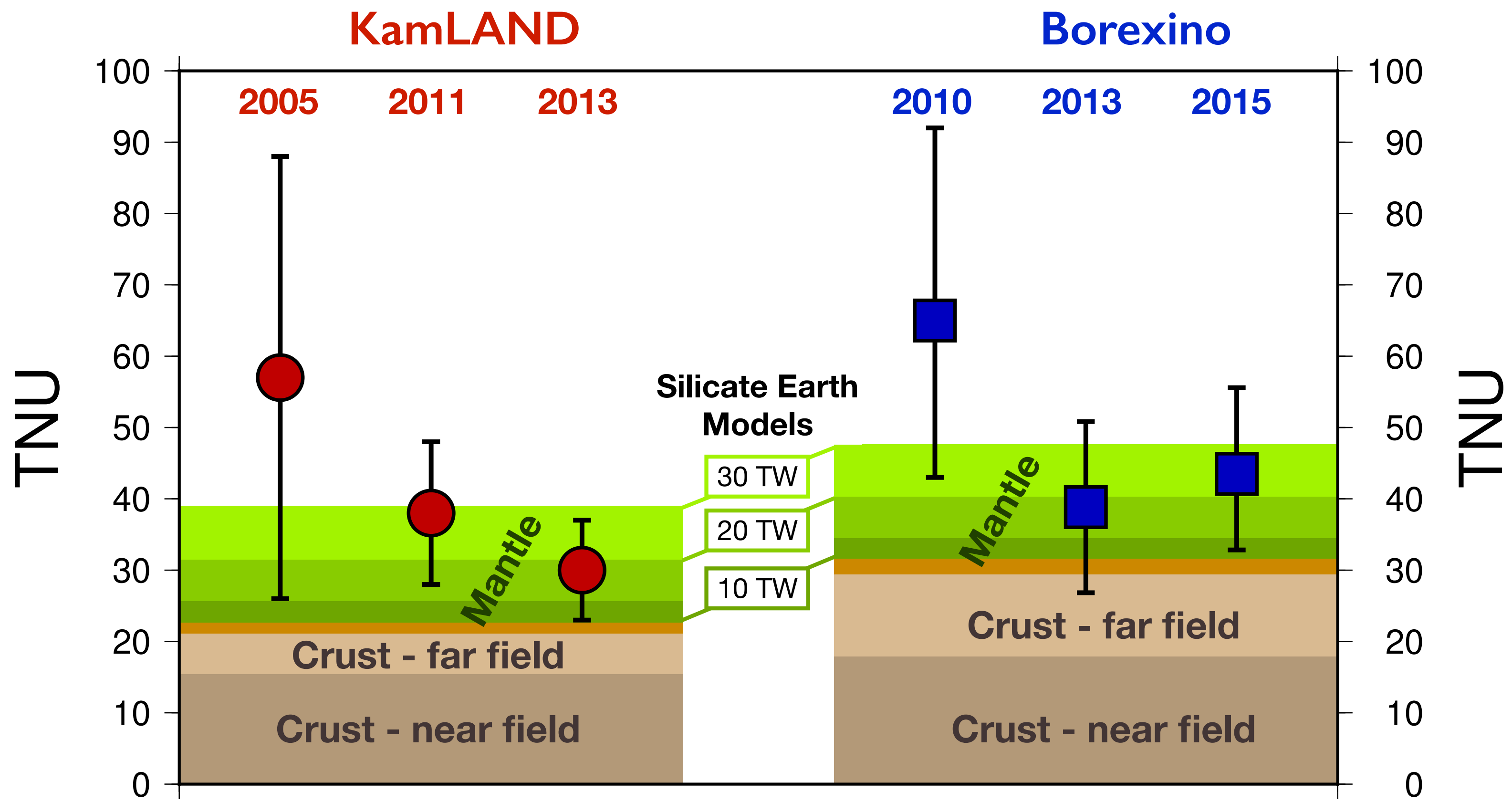


Present data restricts the radiogenic heat to 23 – 36 TW for the best-fit and 11 – 52 TW for 1σ range (S_{geo}= $43.5^{+12.1}_{-10.7}$ TNU)

Using the chondritic ratio Th/U=3.9 and m(K)/m(U) = 10^4 the total radiogenic heat is 33^{+28}_{-20} TW

Cosmochemical (rad. power ~ 10 TW, Th/U=3.5), geochemical (~ 20 TW, Th/U=3.9) and geodynamical (~ 30 TW) models shown in the plot

Radiogenic heat [2]



W.F. McDonough and O. Sramek, Envirn. Earth, Sci (2014) 71
W.F. McDonough private comunication based on Scientific Reports, 1 September, 2015

Conclusions

- Borexino has measured geoneutrinos at **5.9σ**
- Signal-to-background ~ 100 for such a measurement in Borexino
- Geoneutrino fluxes are (chondritic scenario):
  - **$\Phi(U) = (2.7\pm0.7)\times10^6$ $cm^{-2}s^{-1}$**
  - **$\Phi(Th) = (2.3\pm0.6)\times10^6$ $cm^{-2}s^{-1}$**
- The null hypothesis for a non-zero signal from the mantle is excluded at **98% C.L.**
- At present, the uncertainty in the relative abundance of U and Th is limited only by statistics
- **Geoneutrino observations are providing direct measurements of radiogenic heat produced in the Earth**

Spares

Characteristics of the radioactive decays

Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	E_{max} [MeV]	ε_H [W/kg]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	51.7	4.47	3.26	$0.95 \cdot 10^{-4}$	$7.41 \cdot 10^{7}$
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	42.8	14.0	2.25	$0.27 \cdot 10^{-4}$	$1.63 \cdot 10^{7}$
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$	1.32	1.28	1.31	$0.36 \cdot 10^{-8}$	$2.69 \cdot 10^{4}$

- These decays produce heat and **neutrinos**

Likelihood profiles