Geo-neutrino results with Borexino

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-- Why geo-neutrinos? --

-- Geo-neutrinos are messengers from the Earth interior

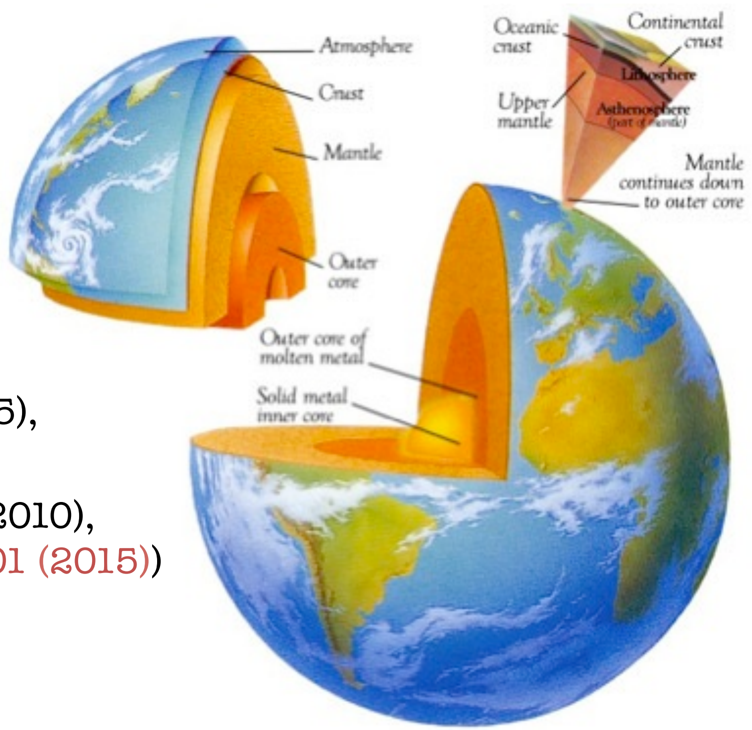
--> Especially of interest for the mantle knowledge

-- Radioactive decays inside the crust and the mantle of the Earth

--> ^{238}U, ^{235}U, ^{232}Th decay series as well as ^{40}K decay are involved and produced ν_e and anti-ν_e called geo-neutrinos

-- Differents Earth models exist (cosmo-chemical, geochemical, geodynamical etc...) and do not agree between themselves

--> Geo-neutrinos as a new source of information



-- Geo-neutrino measurements

--> KamLAND (Nature **436**, 499-503 (2005), Phys. Rev. D **88**, 033001 (2013))

--> Borexino (Phys. Lett. B **687**, 299-304 (2010), Phys. Lett. B **722**, 295-300 (2013), Phys. Rev. D **92**, 031101 (2015))

-- Which geo-neutrinos? --

-- Anti-ν_e detection through inverse β decay interactions
--> Threshold at 1.8 MeV

	^{238}U	^{235}U	^{232}Th	^{40}K($\bar{\nu}_e$)	^{40}K(ν_e)
$\tau_{1/2}$ (year)	4.47×10^9	7.04×10^8	1.40×10^{10}	1.28×10^9	1.28×10^9
Q (MeV)	51.7	46.4	42.7	1.311	1.505
$Q_{\bar{\nu}_e}$ (pJ)	0.634	0.325	0.358	0.103	-
$\# \bar{\nu}_e$	6	4	4	1	-
$\mathcal{R}_{\bar{\nu}_e}$ ($\bar{\nu}_e/(\mathrm{g} \cdot \mathrm{s})$)	7.46×10^4	3.20×10^5	1.63×10^4	2.31×10^5	-
$\# \nu_e$	-	-	-	-	1
$\mathcal{R}_{\nu_e}$ ($\nu_e/(\mathrm{g} \cdot \mathrm{s})$)	-	-	-	-	2.77×10^4
$E_{\max}$ (MeV)	3.26	1.23	2.25	1.311	0.044

-- Only anti-ν_e from **^{238}U** and **^{232}Th** decay series can be detected

-- Geo-neutrinos oscillation? --

-- Anti-ν_e from **^{238}U** and **^{232}Th** do oscillate

--> Survival probability of the geo-neutrinos:

$$P_{ee} = \cos^4\theta_{13}\left(1 - \sin^2(2\theta_{12})\sin^2\left(1.27\,\frac{\Delta m^2_{21}(\mathrm{eV}^2)L(\mathrm{m})}{E(\mathrm{MeV})}\right)\right) + \sin^4\theta_{13}$$

-- Oscillation length around 100 km << R_{Earth}

--> Reasonable assumption of an averaged survival probability:

$$\langle P_{ee}\rangle = \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right) + \sin^4\theta_{13} = 0.55 \pm 0.03$$

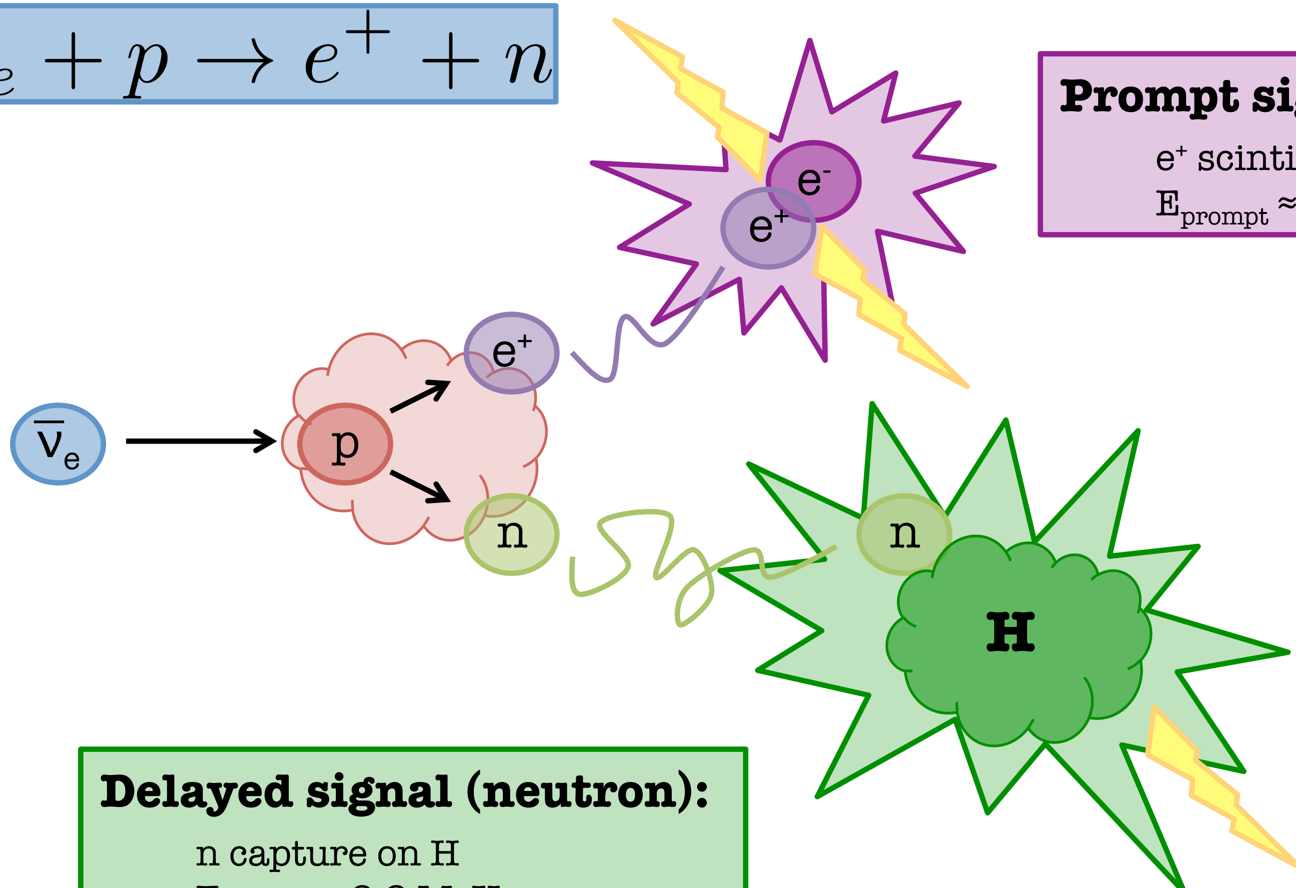
-- **WARNING:** not used for anti-ν_e from nuclear reactors (individual calculations)

Mixing angles and mass square differences are taken from Phys. Rev. D **89**, 093018 (2014)

-- Detecting anti-ν_e --

-- Anti-ν_e detection through inverse β decay interactions

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



Prompt signal (positron):

e^+ scintillation + annihilation

$E_{prompt} \approx E_\nu - T_n - 0.8$ MeV

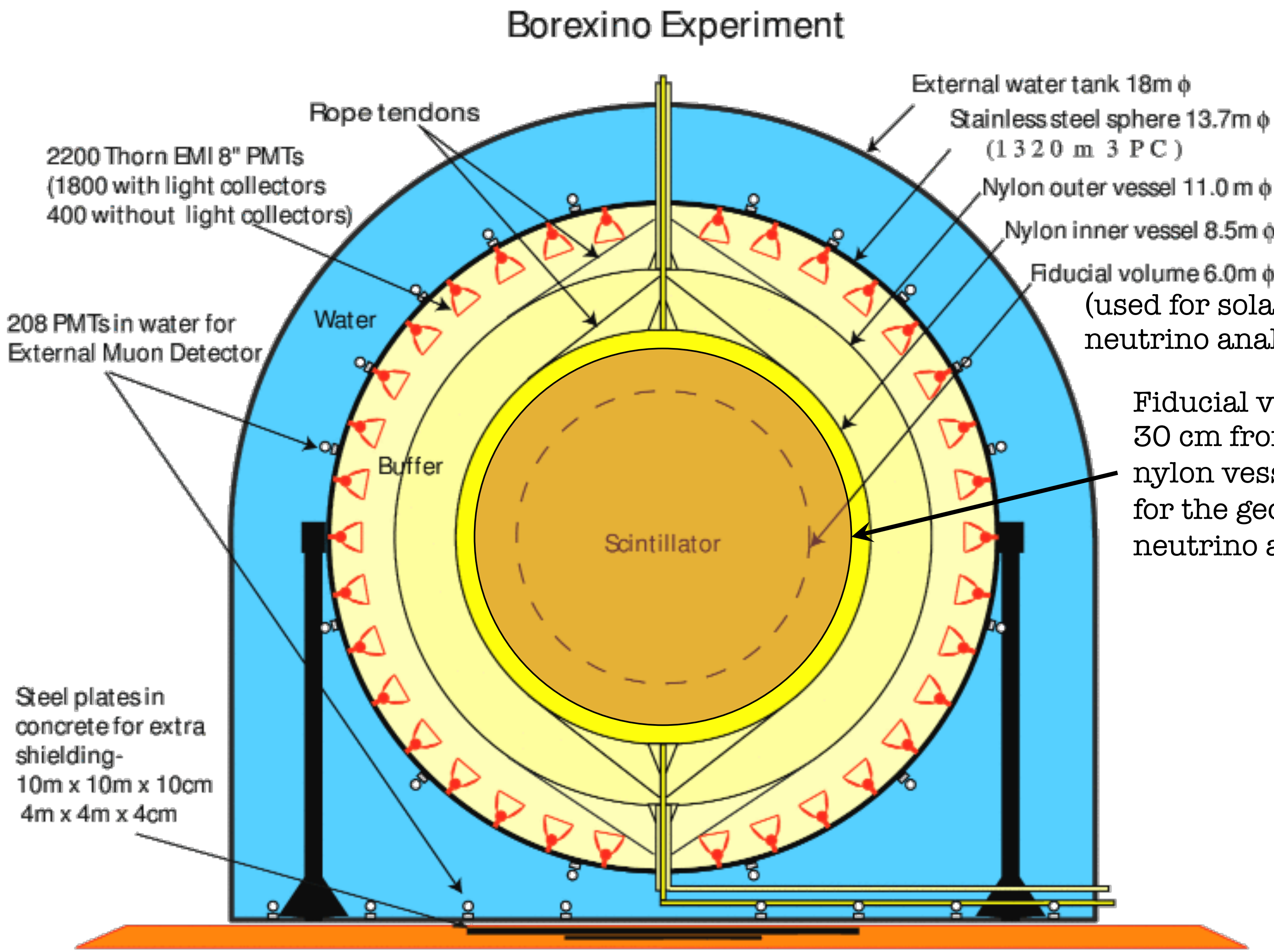
Delayed signal (neutron):

n capture on H

$E_{delayed} \approx 2.2$ MeV

$\Delta t \approx 260$ μs

-- The Borexino detector --



(used for solar neutrino analyses)

Fiducial volume 30 cm from the nylon vessel (used for the geo-neutrino analysis)

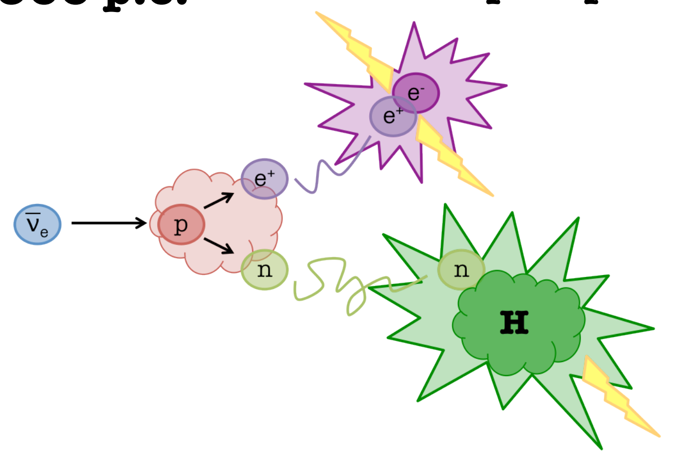
-- Selecting anti-ν_e --

1 MeV ≈ 500 p.e.

-- **Prompt signal:**
- -- $Q_{prompt} > 408$ p.e.
- -- Fiducial Volume Cut (FVC)

-- **Delayed signal:**
- -- $860 < Q_{delayed} < 1300$ p.e.

-- **Coincidence:**
- -- $20 < \Delta t < 1280$ μs
- -- $\Delta R < 100$ cm



-- 2 s dead time window applied after an internal muon and 2 ms dead time window applied after an external muon

-- No neutron event in the 2 ms time window before the prompt signal and in the 2 ms time window after the delayed signal

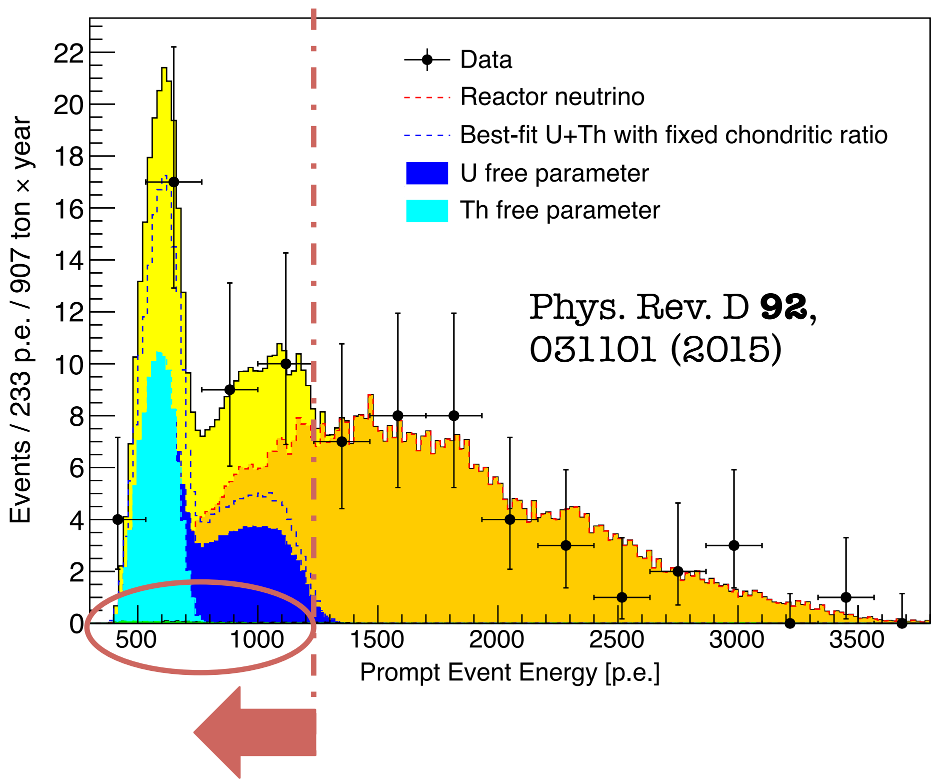
77 candidates

(2056 days of data taking between December 2007 and March 2015, 1842 days after muon cuts, exposure of 5.5×10^{31} proton×year)

-- Anti-ν_e energy spectra --

-- Q_{prompt} spectrum contains both the geo-neutrino and the anti-ν_e from nuclear reactors (and the backgrounds)

--> Since $E_{max}(^{238}U)$ = 3.26 MeV and $E_{max}(^{232}Th)$ = 2.25 MeV, geo-neutrinos stand in the 4 first bins of the Q_{prompt} spectrum



^{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)

Very low background (except for reactor background)!

-- Reactor background --

-- Anti-ν_e from nuclear reactors are the main background (despite Italy is a nuclear free country)

-- Estimation of the expected number of events from the spectral components of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu

Number of nuclear reactors considered (R)

Number of months considered (M)

Exposure in month *m* and includes detector efficiency (η_m)

$$N_{\mathrm{react}} = \sum_{r=1}^{R} \sum_{m=1}^{M} \frac{\eta_m}{4\pi L_r^2} P_{rm} \times \int \mathrm{d}E_{\bar{\nu}_e} \sum_{i=1}^{4} \frac{f_i}{E_i} \phi_i(E_{\bar{\nu}_e}) \sigma(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}, L_r)$$

Detector-reactor distance (L_r)

Power fraction of component *i* (f_i)

Effective thermal power of reactor *r* in month *m* (P_{rm})

Average energy released per fission of component *i* (E_i)

-- Monte Carlo have been developed in order to take into account the 446 nuclear reactors running during the period of interest

-- Fit analysis --

-- Unbinned maximum likelihood fit of the prompt energy spectrum of our anti-ν_e candidates (background components constrained)

-- Assuming a Th/U mass ratio of 3.9 (also called chondritic ratio), our best fit values are:

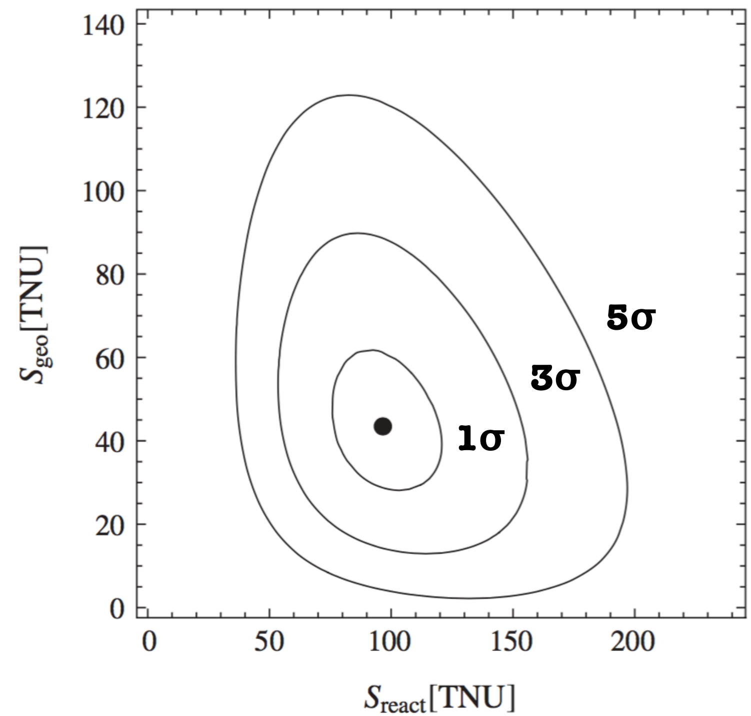
$\mathbf{N_{geo} = 23.7^{+6.5}_{-5.7}\ (stat)\ ^{+0.9}_{-0.6}\ (syst)}$

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

which, in terms of TNU*, becomes:

$\mathbf{S_{geo} = 43.5^{+11.8}_{-10.4}\ (stat)\ ^{+2.7}_{-2.4}\ (syst)}$

$S_{react} = 96.6^{+15.6}_{-14.2}\ (stat)\ ^{+4.9}_{-5.0}\ (syst)$



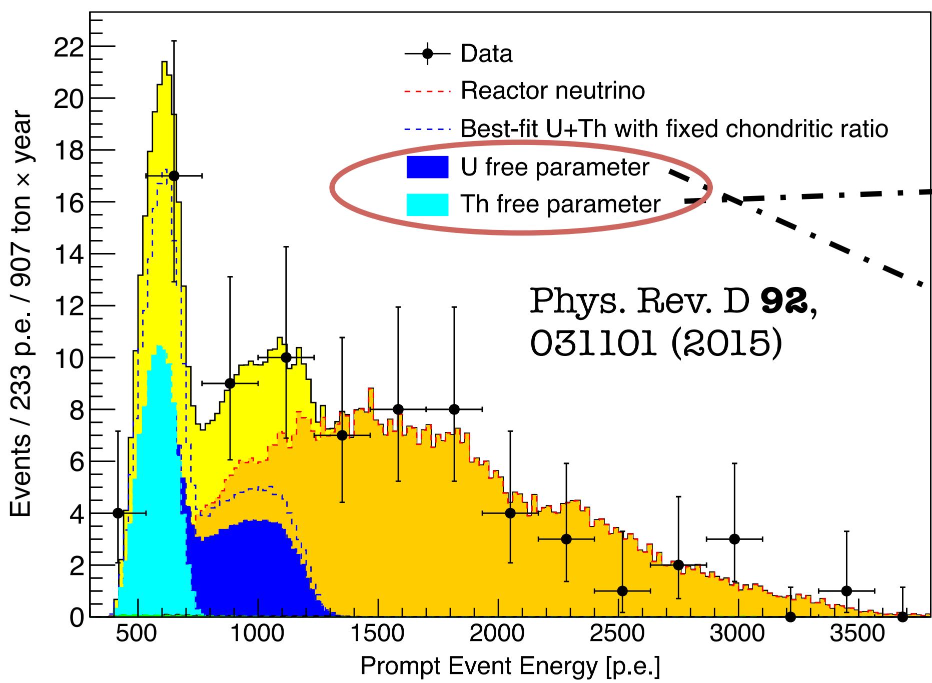
The hypothesis that S_{geo} = 0 is rejected at 5.9 σ

* 1 TNU = 1 event detected over 1 year exposure of 10^{32} target protons at 100 % efficiency

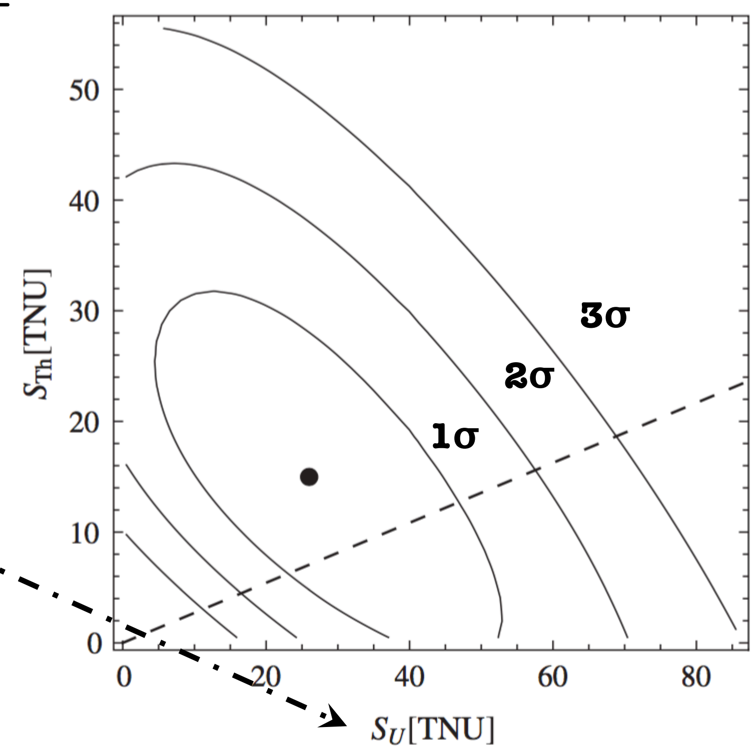
-- Fit analysis with U and Th left free --

-- Fit leaving the U and Th spectral contributions as free parameters

-- Demonstration of the possibility to discriminate the contributions from U and Th
--> Larger exposure needed



Phys. Rev. D **92**, 031101 (2015)



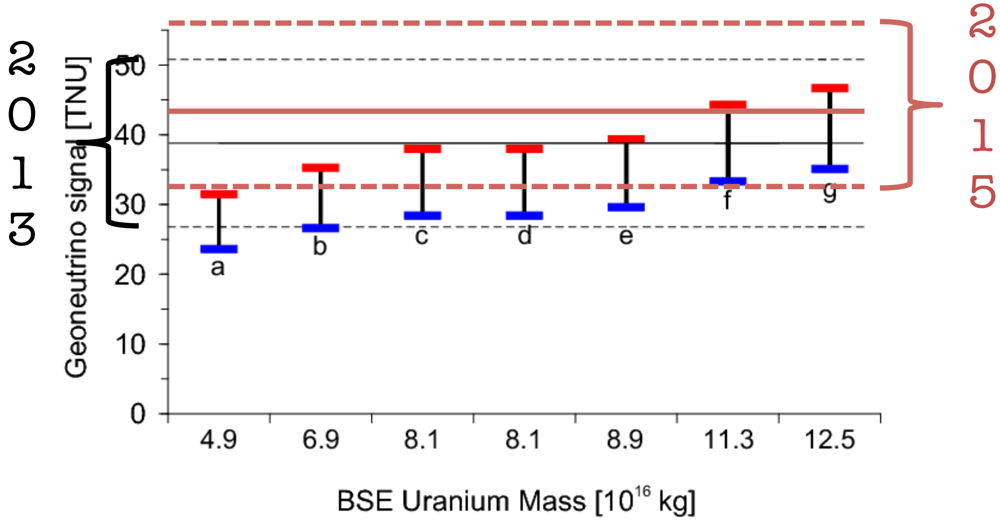
Best fit value compatible with the chondritic ratio of 3.9

-- BSE geological models --

-- Bulk Silicate Earth (BSE) models describe both the crust and the mantle

-- Different BSE models:
1) Cosmochemical
2) Geochemical
3) Geodynamical

BSE S_{geo} [TNU]		Model
- Low -	- High -	
23.6	31.44	Javoy et al. (2010) (a)
26.6	35.24	Lyubetskaya & Korenaga (2007) (b)
28.4	37.94	McDonough & Sun (1995) (c)
28.4	37.94	Allegre et al. (1995) (d)
29.6	39.34	Palme & O'Neil (2004) (e)
33.3	44.24	Anderson (2007) (f)
35.1	46.64	Turcotte & Schubert (2002) (g)

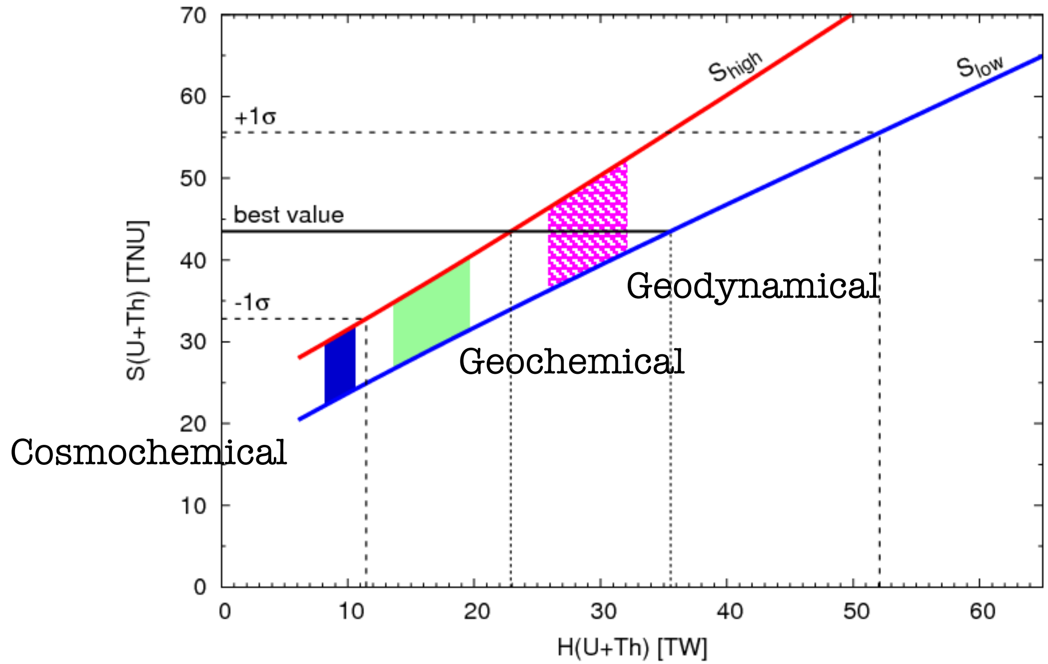


1σ expectation band
$S_{geo} = 43.5^{+12.1}_{-10.7}$ TNU from the Borexino fit analysis

Borexino results in agreement with BSE models

-- Radiogenic heat --

-- Understanding the Earth's energy budget
-- Radiogenic heat production for U and Th between 23 and 36 TW



-- Assuming a chondritic ratio of 3.9 and $m(K)/m(U) = 10^4$, the total terrestrial radiogenic power is:

$$\mathbf{P(U + Th + K) = 33^{+28}_{-20}\ TW}$$

(to be compared with the global terrestrial power $P_{tot} = 47 \pm 2$ TW)

-- Accessing geo-neutrinos from the mantle --

-- Measured signal = BSE signal = crust signal + mantle signal
where crust* = local crust (LOC) + rest of the crust (ROC)

-- Borexino:
- S_{geo} (total) = $43.5^{+12.1}_{-10.7}$ TNU
- S_{geo} (crust) = 23.4 ± 2.8 TNU

S_{geo} (mantle) = $20.9^{+15.1}_{-10.3}$ TNU

-- KamLAND:
- **S_{geo} (mantle) = 5.0 ± 7.3 TNU**

➡ **The hypothesis that S_{geo} (mantle) = 0 is rejected at 98% C.L.**

*Investigated in Coltorti *et al.* Geochim. Cosmochim. Acta **75**, 2271 (2011) and Huang *et al.* Geochem., Geophys., Geosyst. **14**, 2003-2029 (2013)

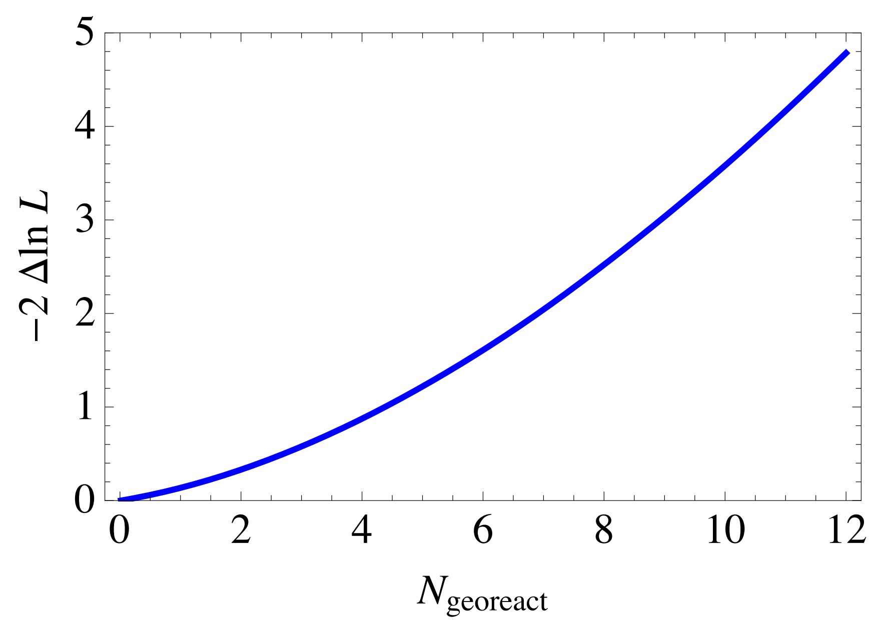
-- Investigation on a possible georeactor (new!) --

Is there a natural nuclear reactor standing inside the Earth?

-- Monte Carlo built such that $^{235}U/^{238}U$ = 0.75/0.25 (Pu set to 0)
-- Fit above 1510 p.e. in order to get rid of the geo-neutrino spectrum
-- Background components normalized, reactor component constrained to the theoretical value

$N_{georeact}$ < 8.4 (10.5) events at 90% C.L. (95% C.L.)

$P_{georeact}$ < 3.4 (4.2) TW at 90% C.L. (95% C.L.)



-- Conclusion --

-- We report an updated measurement of geo-neutrinos with Borexino

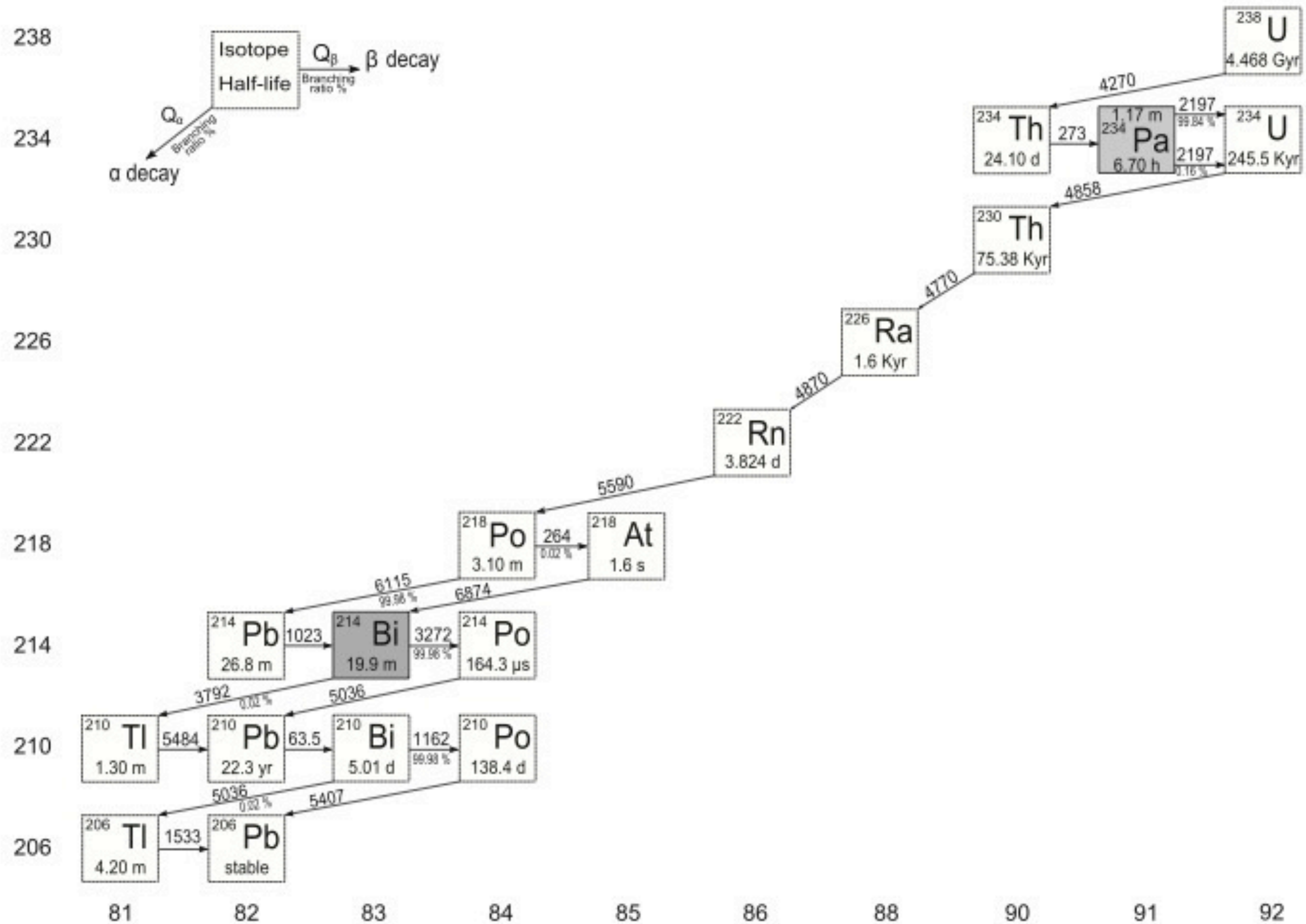
-- From 2056 days of data taking, Borexino alone is able:
--> to reject the null geo-neutrino signal at 5.9 σ
--> to claim a geo-neutrino signal from the mantle at 98% C.L.
--> to restrict the radiogenic heat production for U and Th between 23 and 36 TW

-- Signal-to-background ratio of the order of 100
--> Real time spectroscopy of anti-ν_e

-- **Upper limit for a 3.4 TW georeactor (4.2 TW) at 90% C.L. (95% C.L.)**

Thank you for your attention

-- ^{238}U decay chain --



-- ^{232}Th decay chain --