Looking for geo-neutrinos with Borexino

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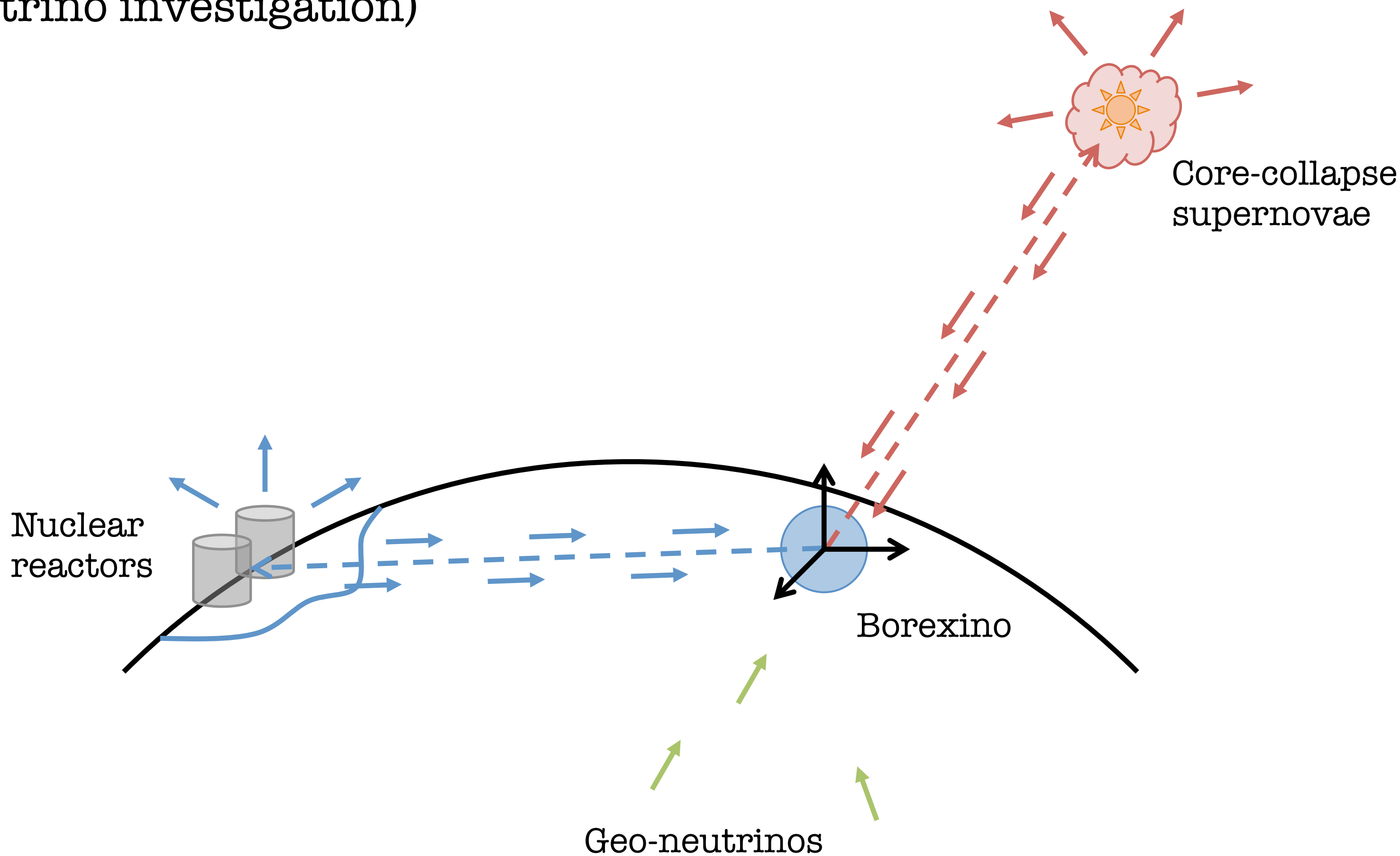
-- Anti-ν_e in Borexino --

-- Borexino is currently exposed to geo-neutrinos and nuclear reactors neutrinos (core-collapse supernovae?)

-- **Coming soon:** anti-ν_e from ^{144}Ce-^{144}Pr source (sterile neutrino investigation)



-- Why geo-neutrinos? --

-- Geo-neutrinos are messengers from the Earth interior

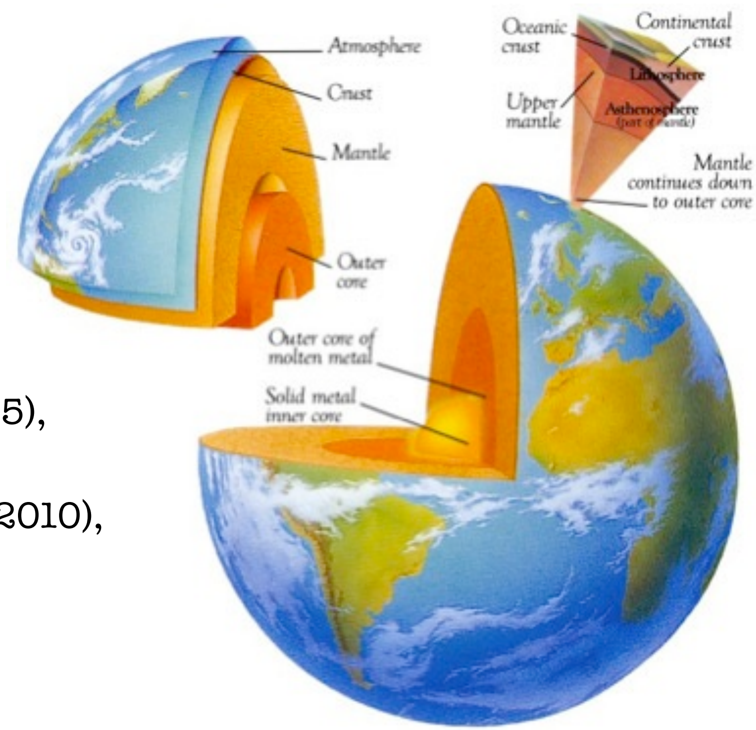
--> Especially of interest for the mantle knowledge

-- Radioactive decays inside 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 are 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))

-- Which geo-neutrinos? --

-- Anti-ν_e detection through inverse beta 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** 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:

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

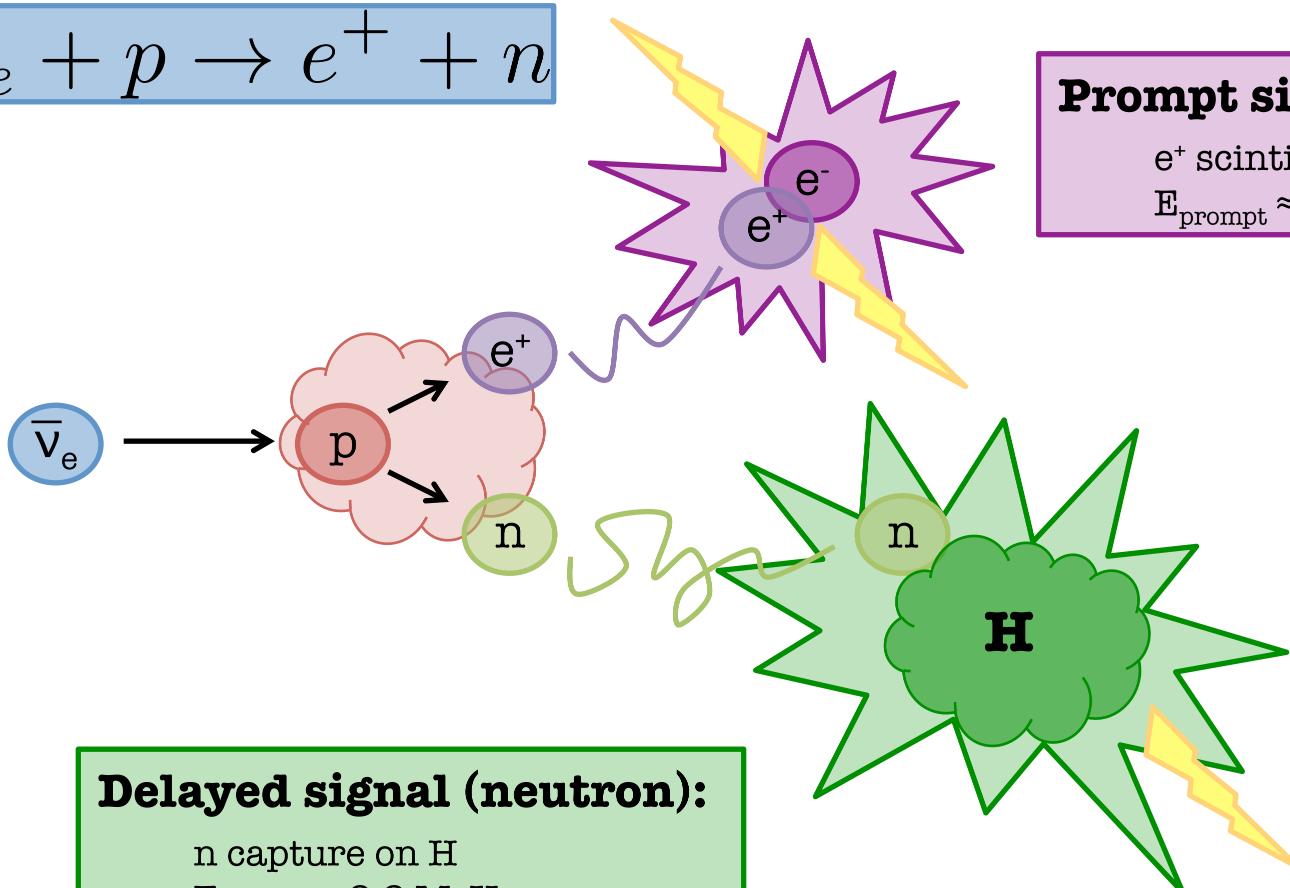
-- **WARNING:** not used for anti-ν_e from nuclear reactors (individual calculations)

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 beta 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

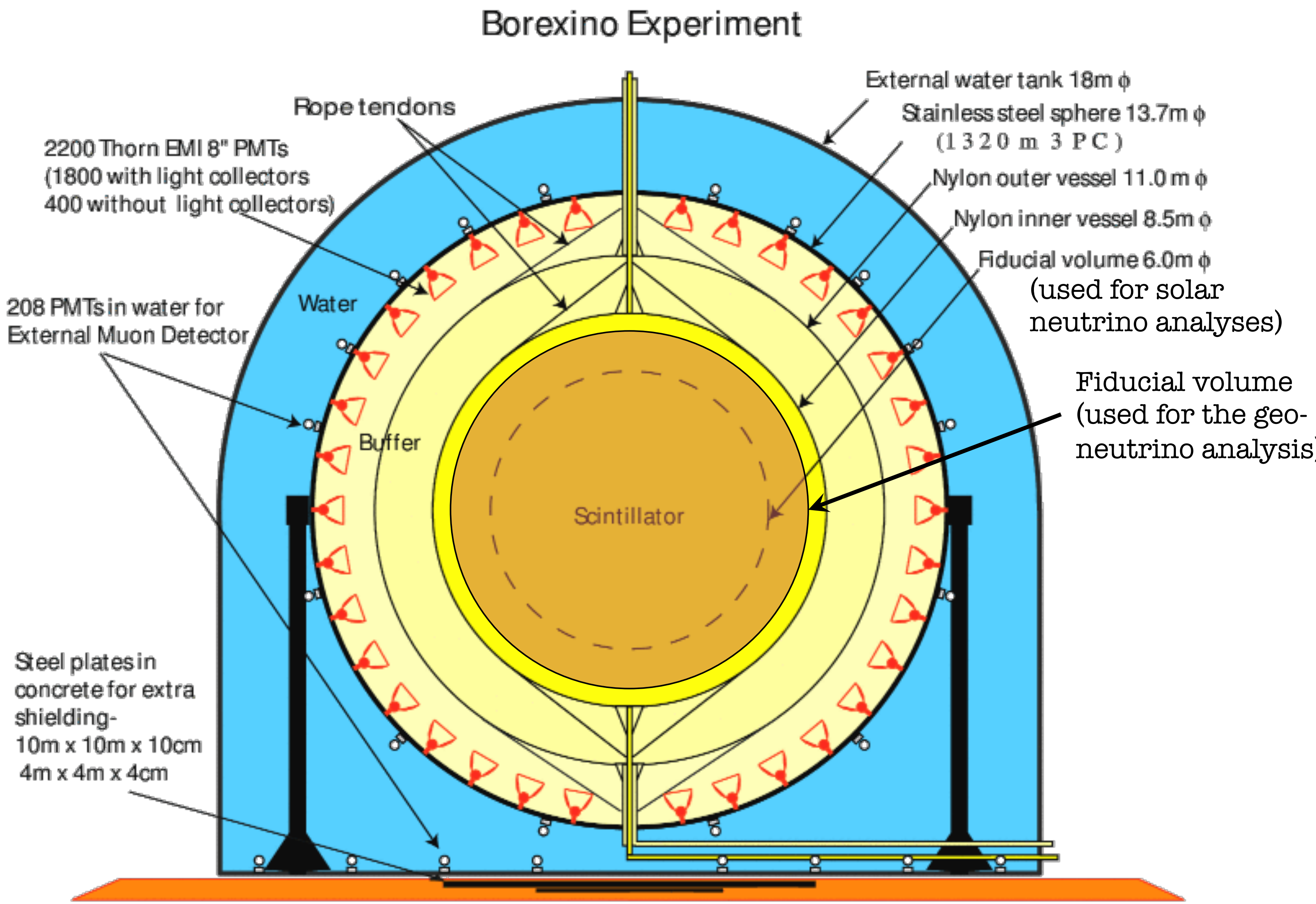
Delayed signal (neutron):

n capture on H

$E_{delayed} \approx 2.2$ MeV

$\Delta t = 254.5 \pm 1.8\ \mu s$

-- The Borexino detector --



-- Selecting anti-ν_e --

-- **Prompt signal:**

-- Q_{prompt} > 408 p.e.

-- Fiducial Volume Cut (FVC)

-- **Delayed signal:**

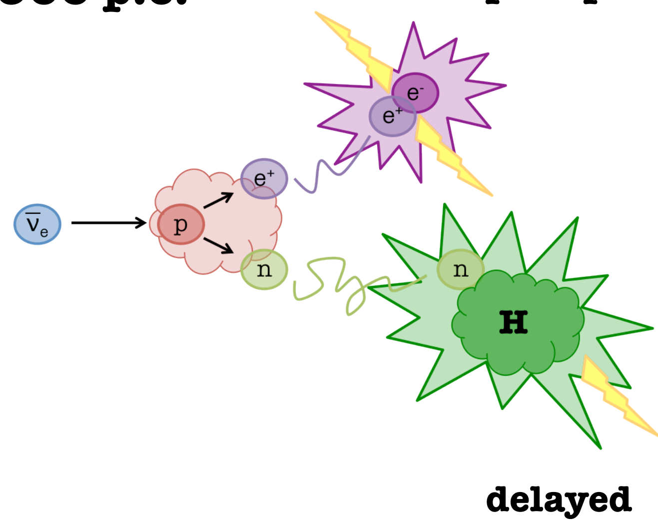
-- 860 < $Q_{delayed}$ < 1300 p.e.

-- **Coincidence:**

-- 20 < Δt < 1280 μs

-- ΔR < 100 cm

1 MeV ≈ 500 p.e.



-- 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

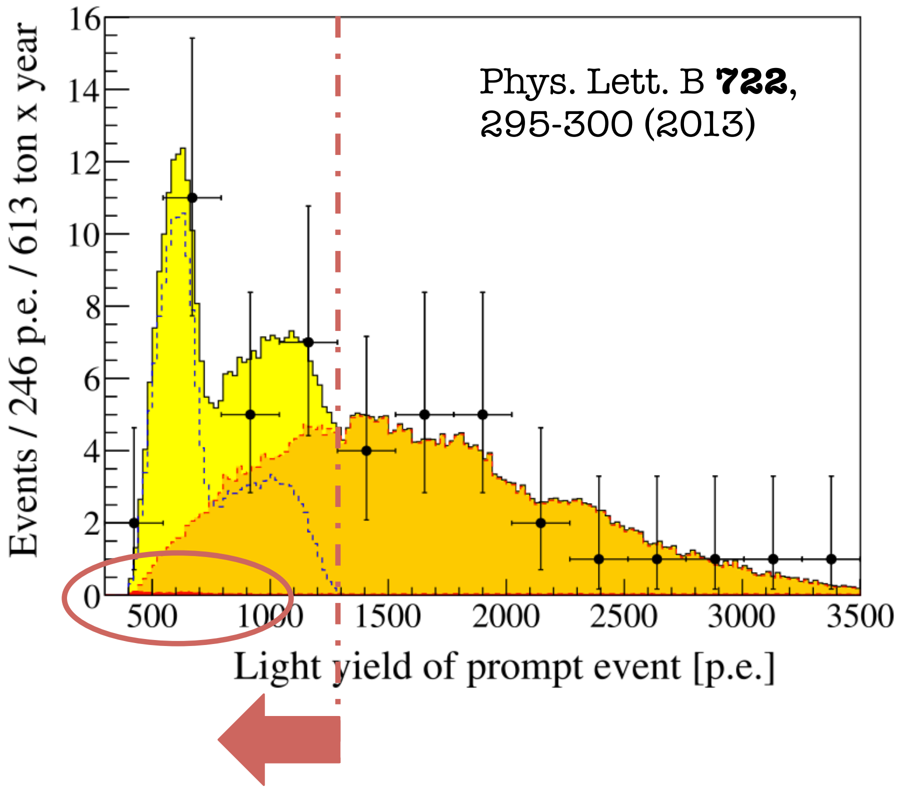
46 candidates

(between December 2007 and August 2012)

-- Anti-ν_e energy spectra --

-- Q_{prompt} spectrum contains both the geo-neutrino and the reactors neutrino components (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



Background source	Events
^{9}Li–^{8}He	0.25 ± 0.18
Fast n's (μ's in WT)	<0.07
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time corr. background	0.005 ± 0.012
(γ, n)	<0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α, n) in scintillator	0.13 ± 0.01
(α, n) in the buffer	<0.43
Total	0.70 ± 0.18

Very low background (except for reactor background)!

-- Reactor background --

-- Anti-ν_e from nuclear reactors are the main background

-- 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

Number of months considered

Exposure in month *m* and includes detector efficiency

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

Detector-reactor distance

Power fraction of component *i*

Effective thermal power of reactor *r* in month *m*

Average energy released per fission of component *i*

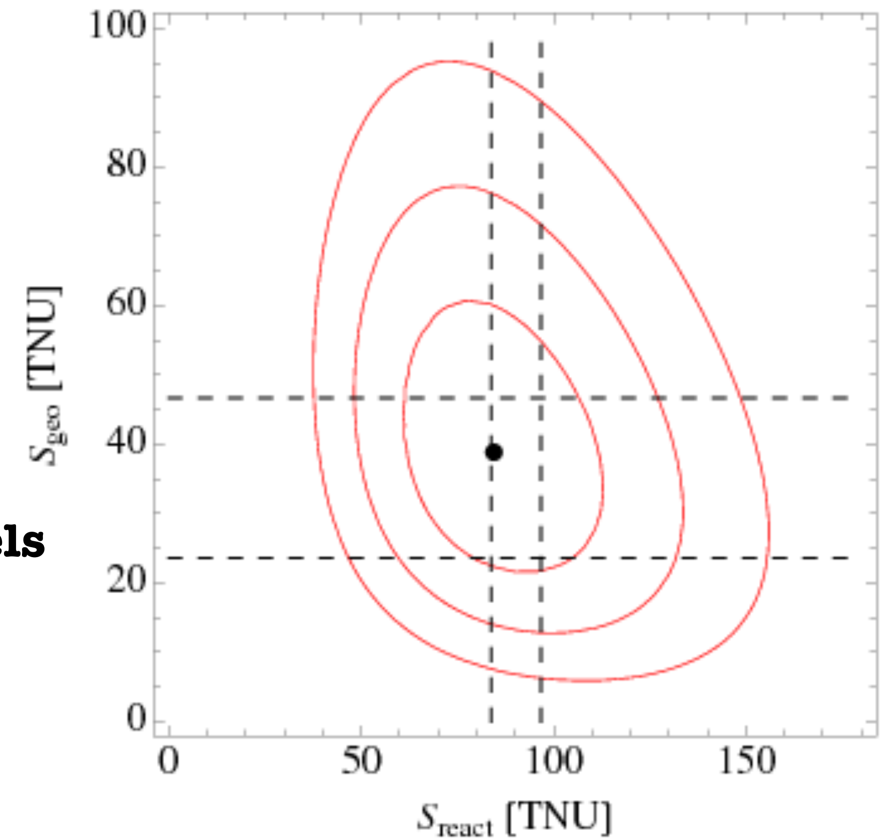
-- MC have been developed in order to take into account the 446 nuclear reactors running during the period of interest

-- Fit analysis --

-- Unbinned maximal likelihood method based on the prompt energy spectra of the candidates

-- The hypothesis that S_{geo} = 0 is rejected at 99.9989% C.L. (4.4 σ)

1σ expectation band
S_{react} = [83.2-97.3] TNU*



1σ expectation band
S_{geo} = [26.3-46.6] TNU* for different BSE geological models

S_{geo} = 38.8 ± 12.0 TNU

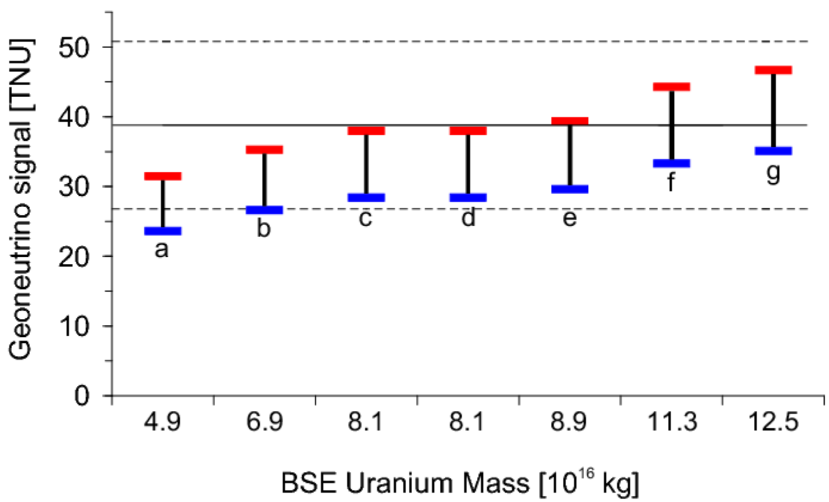
* 1 TNU = 1 event detected over 1 year exposure of 10^{32} target protons at 100 % efficiency

-- BSE geological models --

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

-- Different BSE models:
- Cosmochemical
- Geochemical
- 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} = 38.8 ± 12.0 TNU from the Borexino fit analysis

Borexino results in agreement with BSE models

-- Accessing geo-neutrinos from the mantle --

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

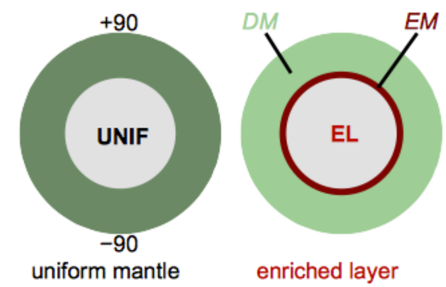
-- Borexino:
- S_{geo} (total) = 38.8 ± 12.0 TNU
- S_{geo} (crust) = 23.4 ± 2.8 TNU

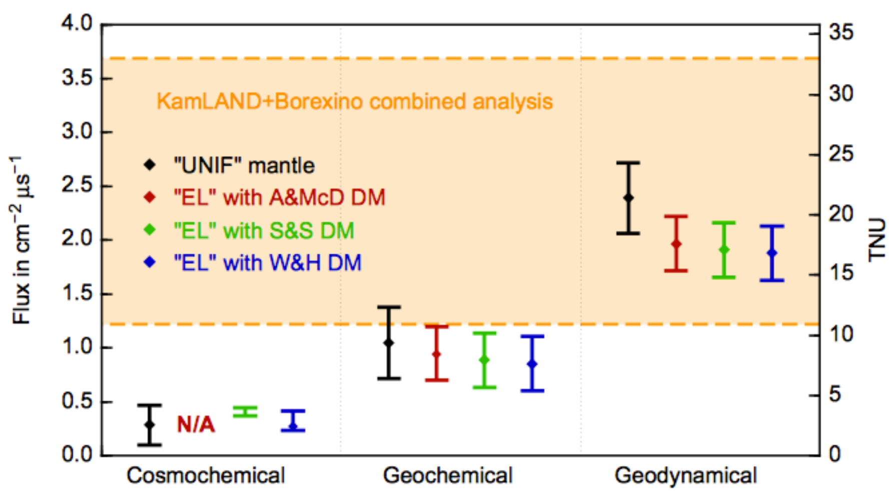
} **S_{geo} (mantle) = 15.4 ± 12.3 TNU**

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

-- Combined (Sramek et al. (2013), Ludhova and Zavatarelli (2013))

-- Discrimination between different models is not yet possible, even when combining Borexino and KamLAND





-- Fit analysis with Th/U ratio left free --

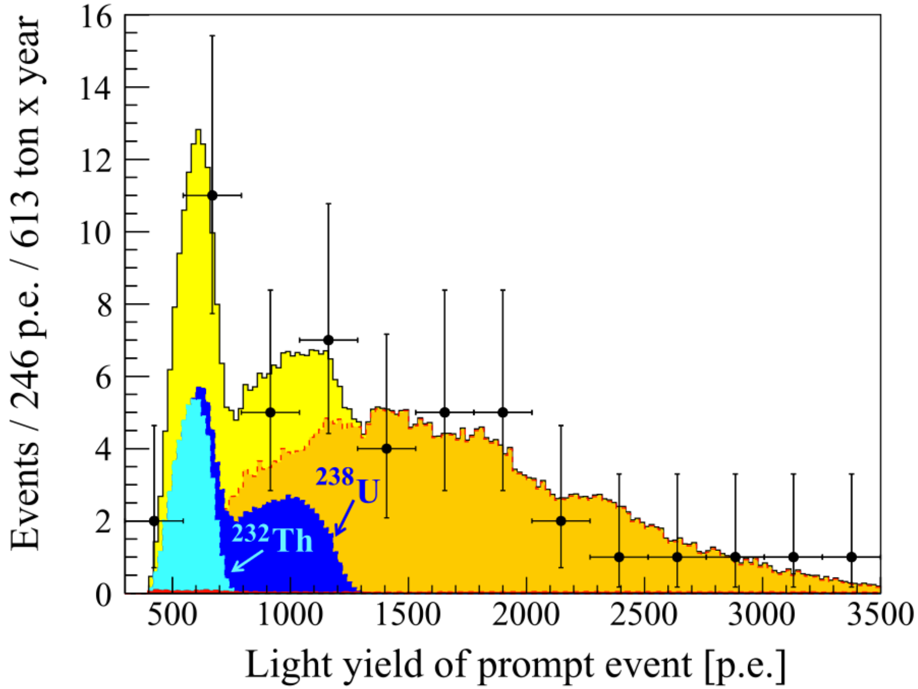
-- Fit of U and Th spectra independently

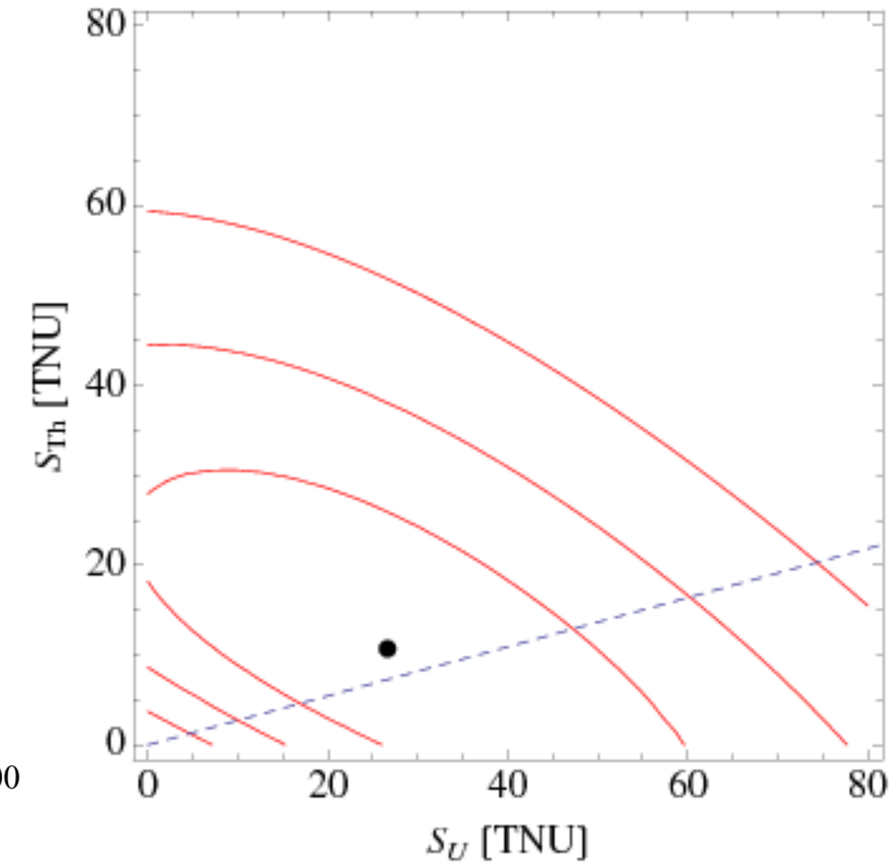
S_U = 26.5 ± 19.5 TNU

S_{Th} = 10.6 ± 12.7 TNU

-- Th/U ratio left free in the fit

--> Best fit value compatible with the chondritic value of 3.9





-- Conclusion and perspectives --

-- Geo-neutrinos are of interest, especially for the mantle knowledge
--> Borexino helps geoscience to better understand our planet

-- 2 years more of statistics
--> Borexino alone should be able to reach the 5σ signal

-- Future large scale detectors coming up soon
--> SNO+
--> JUNO
--> LENA
--> Hanohano

-- Anti-ν_e from ^{144}Ce-^{144}Pr decays --> SOX --

-- Several anomalies to be understood

① LSND and MiniBooNE

② Radiochemical solar experiments (GALLEX and SAGE)

③ Short baseline reactor experiments

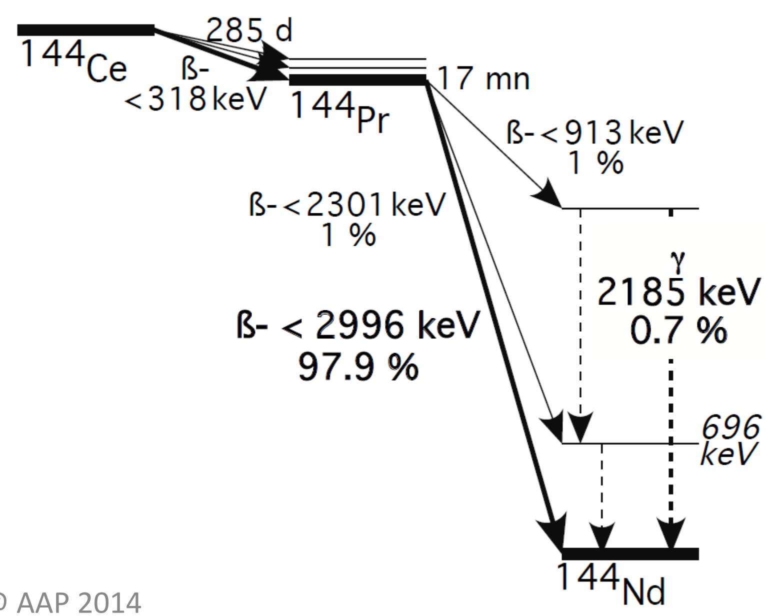
-- Investigation on a possible new neutrino oscillation

--> **SOX** experiment (Short Oscillations with BoreXino)

How? Bringing a 100 kCi ^{144}Ce-^{144}Pr source (anti-ν_e emitter) below Borexino and looking for the L/E pattern

When? End of 2015

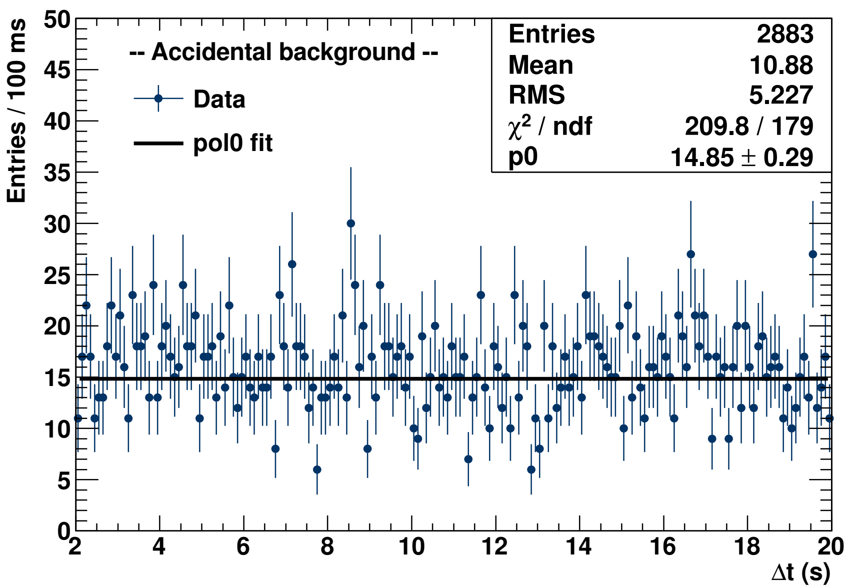
STAY TUNED!

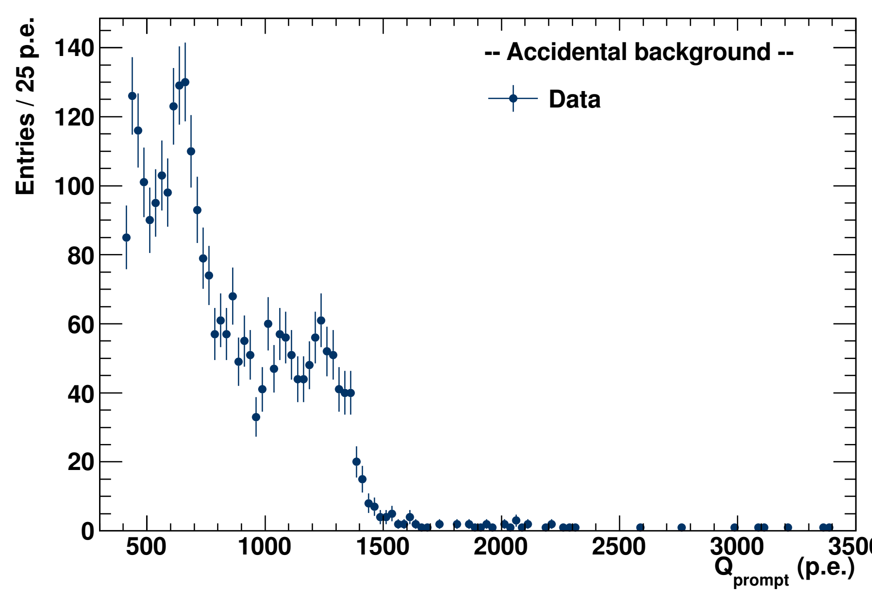


Thank you for your attention

-- Accidental background --

-- Looking for the off time coincidence in the [2 s, 20 s] range after the prompt signal

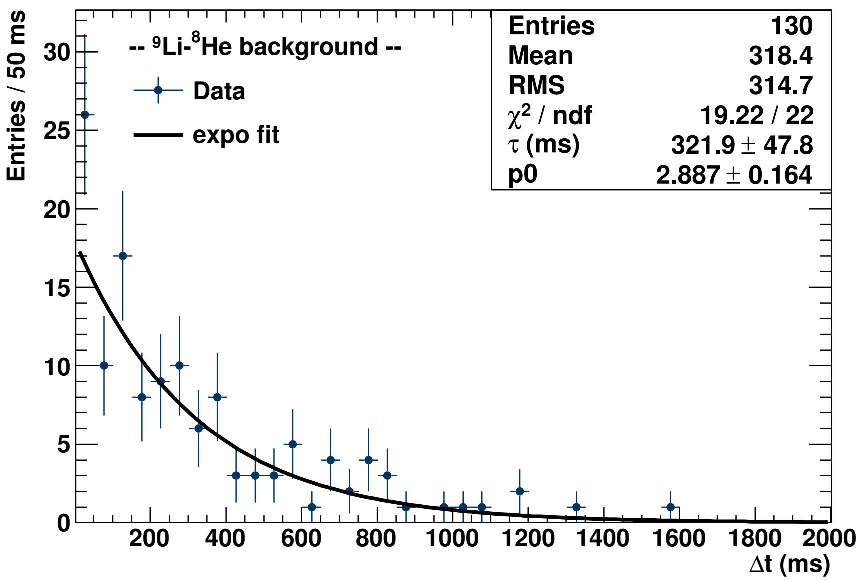


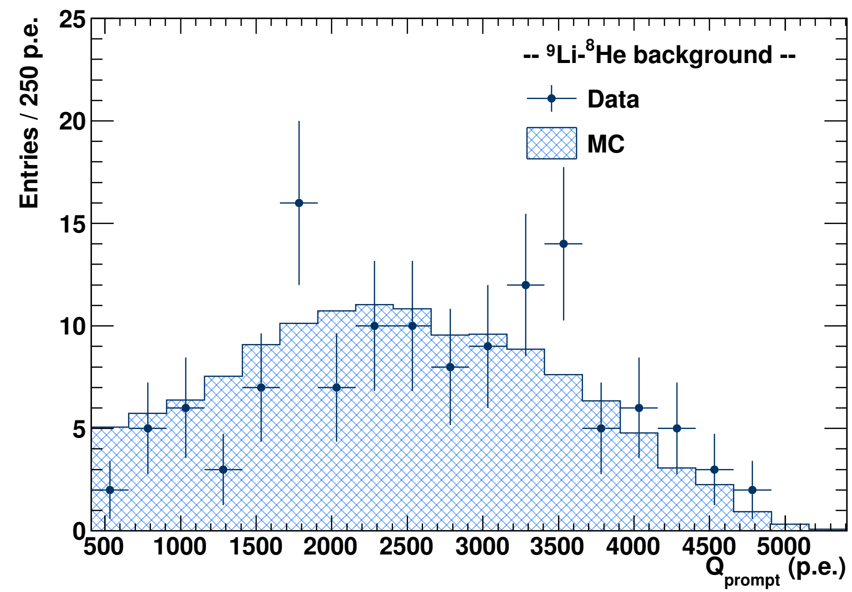


-- Δt distribution between prompt signal and delayed signal

-- ^{9}Li-^{8}He background --

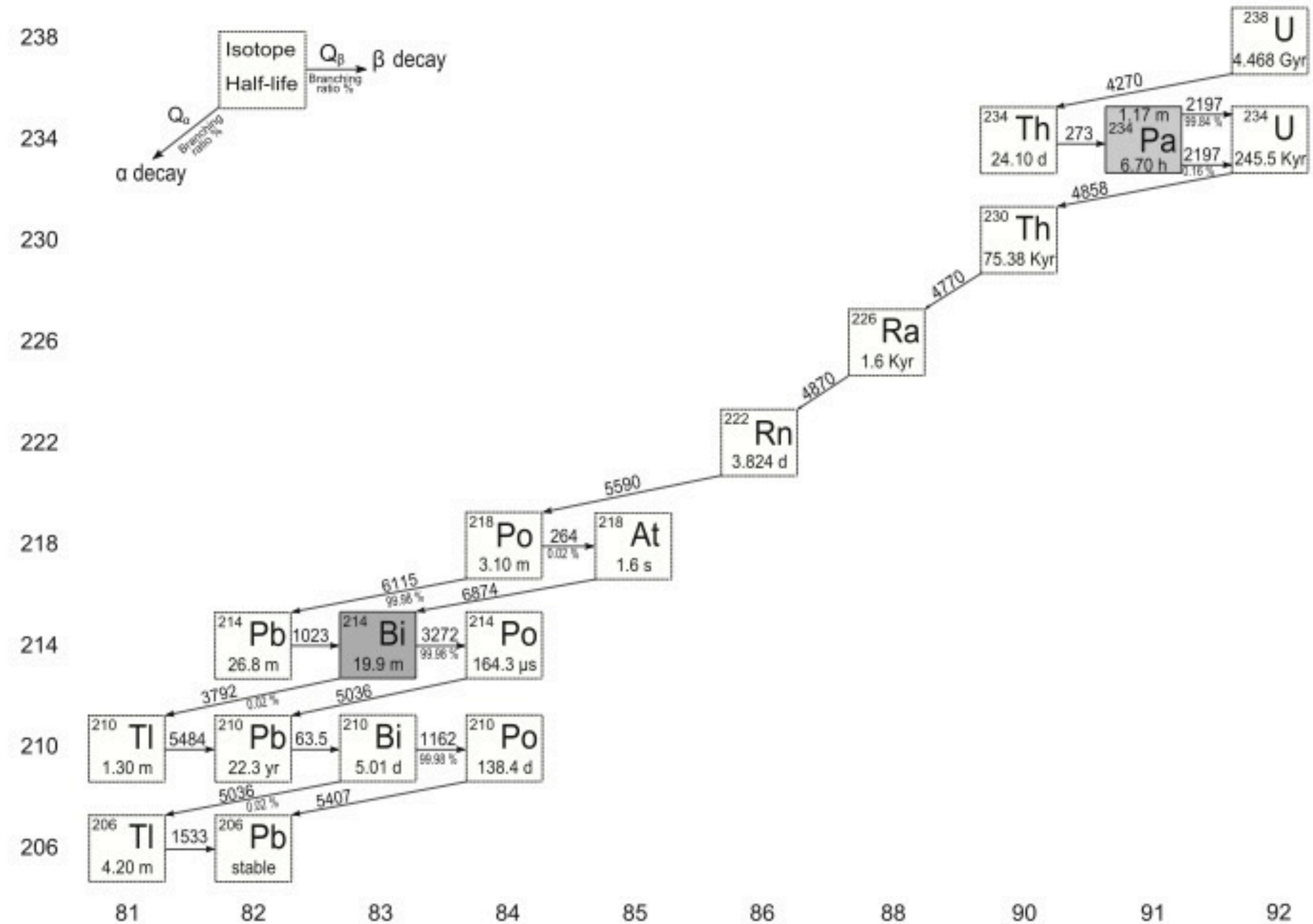
-- Same anti-ν_e cuts except that we are now looking in the [2 ms, 2 s] range after an internal muon





-- Δt distribution between internal muon and prompt signal

-- ^{238}U decay chain --



-- ^{232}Th decay chain --