Results from Borexino on Solar and Geo-Neutrino

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on behalf of:

Borexino Collaboration

06/22/2017

WIN2017

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Main purpose and achievements

The Borexino experiment is acquiring data since May 2007:
Its activity has been split in 2 phases by 6 cycles of water extraction to purify the Liquid Scintillator:

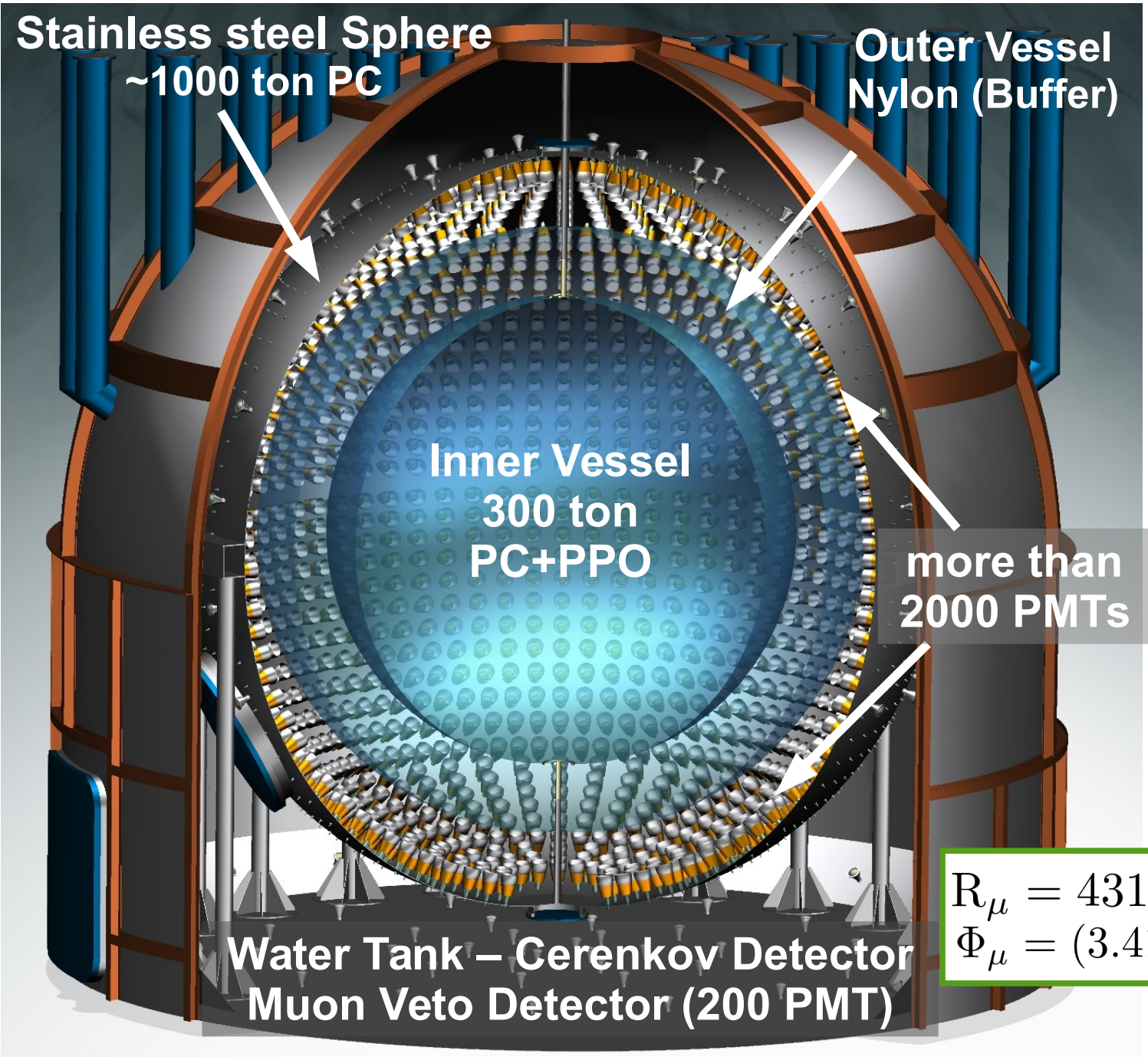
- **Phase I (2007- 2010):**
  - First measurement ^{7}**Be** neutrino Flux (862 keV) with 5% of accuracy
  - Exclusion of any night-day asymmetry
  - First direct observation of the **pep** electronic neutrino (1440 keV) and first limit on **CNO** flux.
  - Evidence of Seasonal Modulation of the fluxes
  - ^{8}**B** neutrino flux measurement at E > 3 MeV (transition energy)

- **Purification campaign (2010-2011):**
  - Unprecedented detector radio purity reached

- **Phase II (2012-2017)**
  - Direct measurement of **pp** neutrino flux
    Nature 512,383–386 (28 August 2014)
  - **Geoneutrinos** (phase I + phase II)
  - Seasonal Modulation Phase II
  - Thermal insulation to improve the background stability

Borexino Detector

The Detector



Light Yield:
500 p.e./MeV

$$\Delta E \sim 5\% \sqrt{E}$$

Shield: ~1400 m of rocks (3800 m w.e.)
The muon Flux reduction by factor 10^{-6}

$$R_\mu = 4310 \pm 2_{stat} \pm 10_{sys}\ d^{-1}$$
$$\Phi_\mu = (3.41 \pm 0.01) \times 10^{-4}\ m^{-2} s^{-1}$$

The Signal

1) *Nutrino-Electron* Scattering:

- Electrons accelerated by neutrinos or beta decay ionize the liquid scintillator (PC+PPO) that emit light by fluorescence

2) No Directionality:

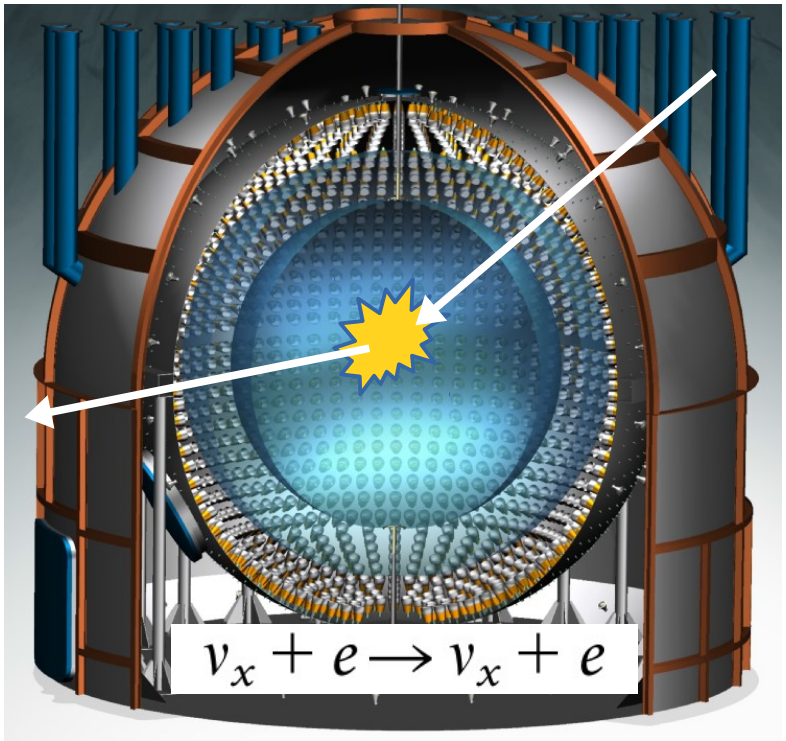
- The fluorescence light is isotropic event. It is not possible reconstruct the direction of the incident particles.

3) Pulse Shape Discrimination:

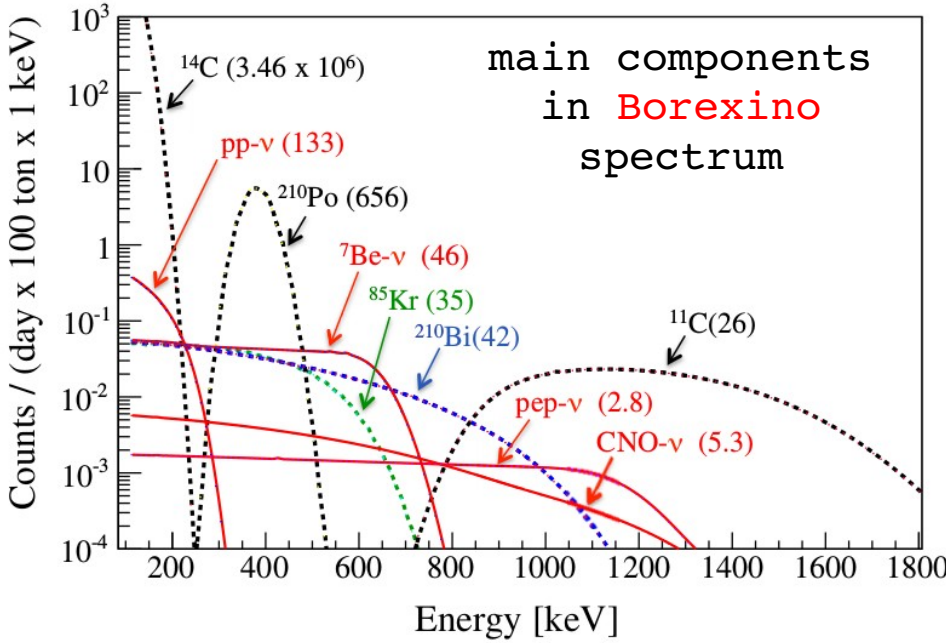
- It's possible to recognize the α particle from electron because of a longer pulse shape in time

4) Extremely low background required (Phase I):

- The radio-purity of Borexino is a unprecedented record.
  ^{238}U= (5.3 +/- 0.5) x10^{-18} g/g
  ^{232}Th= (3.8 +/- 0.8) x10^{-18} g/g

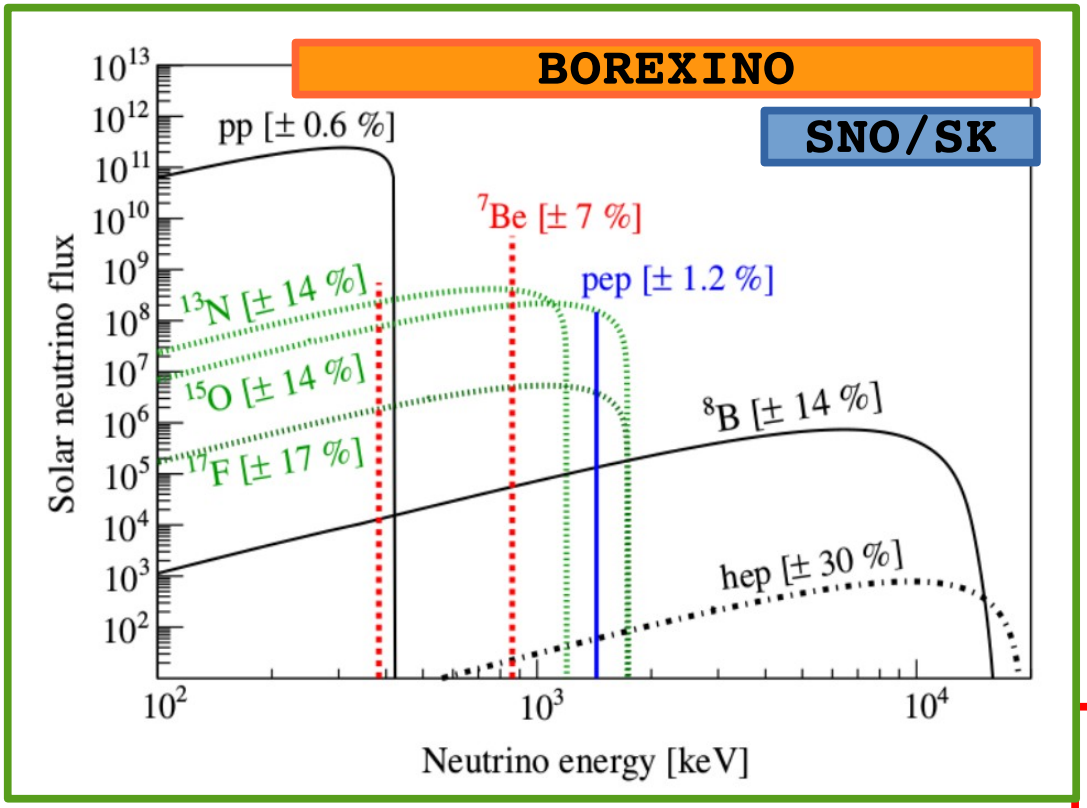


	Isotope	Decay Rate [cpd/100 ton]
Intrinsic in LS →	^{14}C	$(3.46 \pm 0.09) \times 10^6$
Reduced in Ph.II →	^{85}Kr	$(30.4 \pm 5.3 \pm 1.5)^{(a)}$
		$(31.2 \pm 1.7 \pm 4.7)^{(b)}$
	^{40}K	< 0.42 (95% C.L.)
	^{39}Ar	~0.4
	^{238}U	(0.57 ± 0.05)
	^{222}Rn	(1.72 ± 0.06)
Main Bkg ^7Be →	^{210}Bi	$(41.0 \pm 1.5 \pm 2.3)$
Main α-emitter →	^{210}Po	5×10^2–8×10^3
	^{232}Th	(0.13 ± 0.03)



Borexino Experiment
Solar Neutrinos

Solar Neutrinos

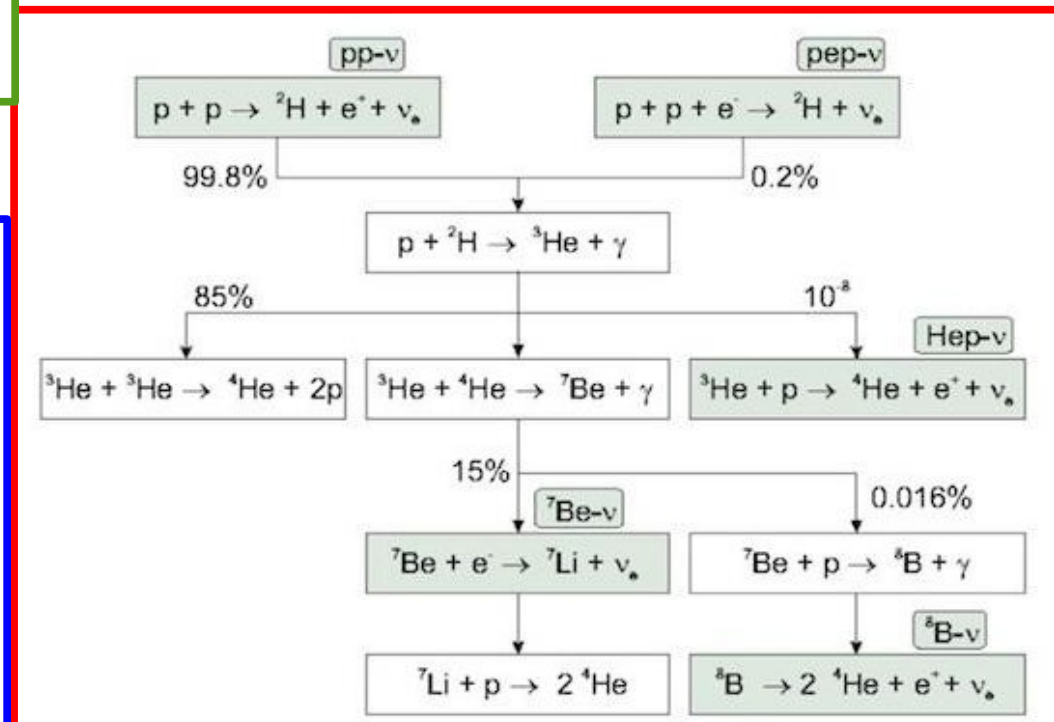


Borexino detector has been designed to measure the low energies spectra of Solar Neutrino (<3MeV).

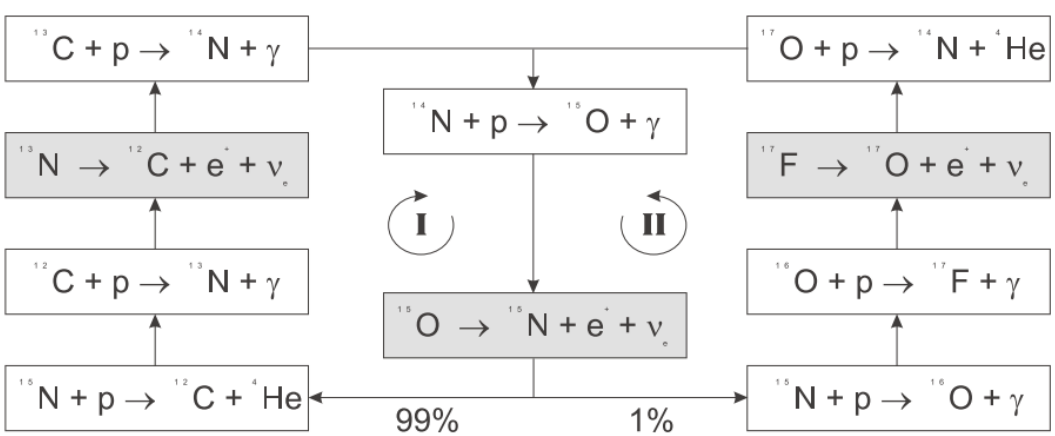
The electronic neutrinos are emitted by the nuclear reactions that provide the energy by means of:

- "pp-chain" (99%)
- "CNO bi-cycle" (1%)

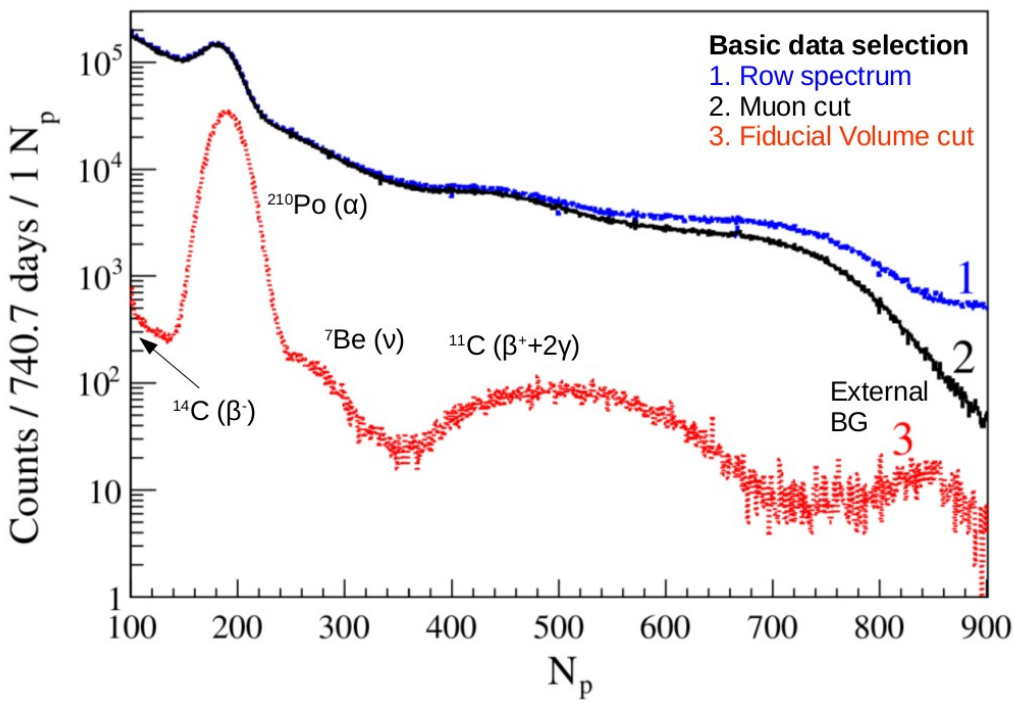
pp-chain

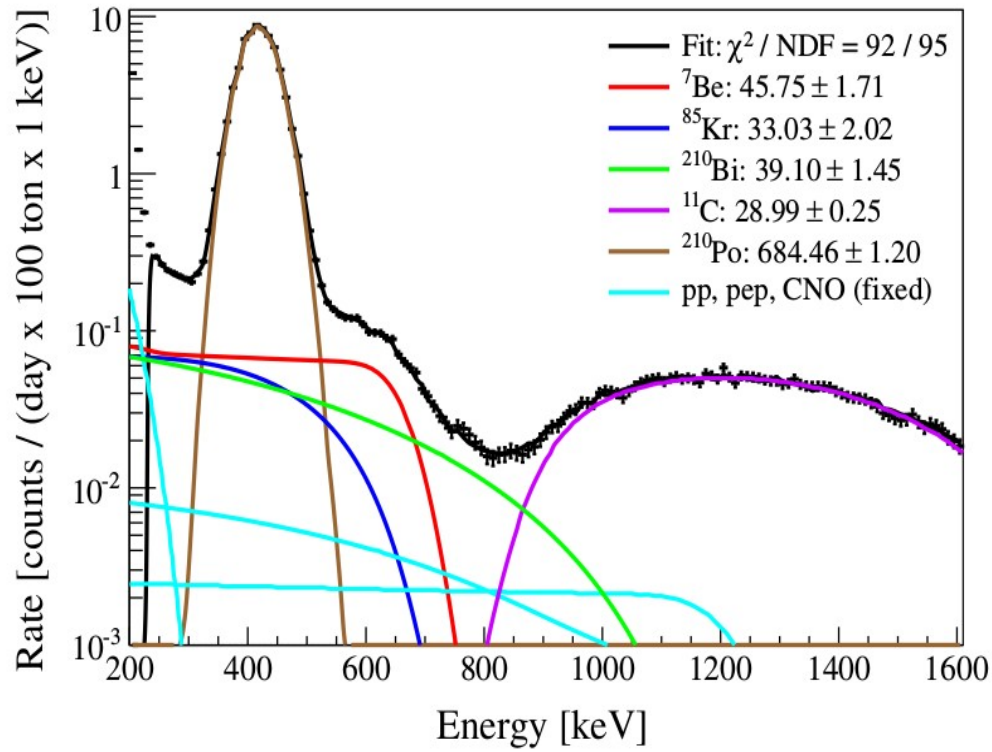


CNO cycle I CN CNO cycle II ON



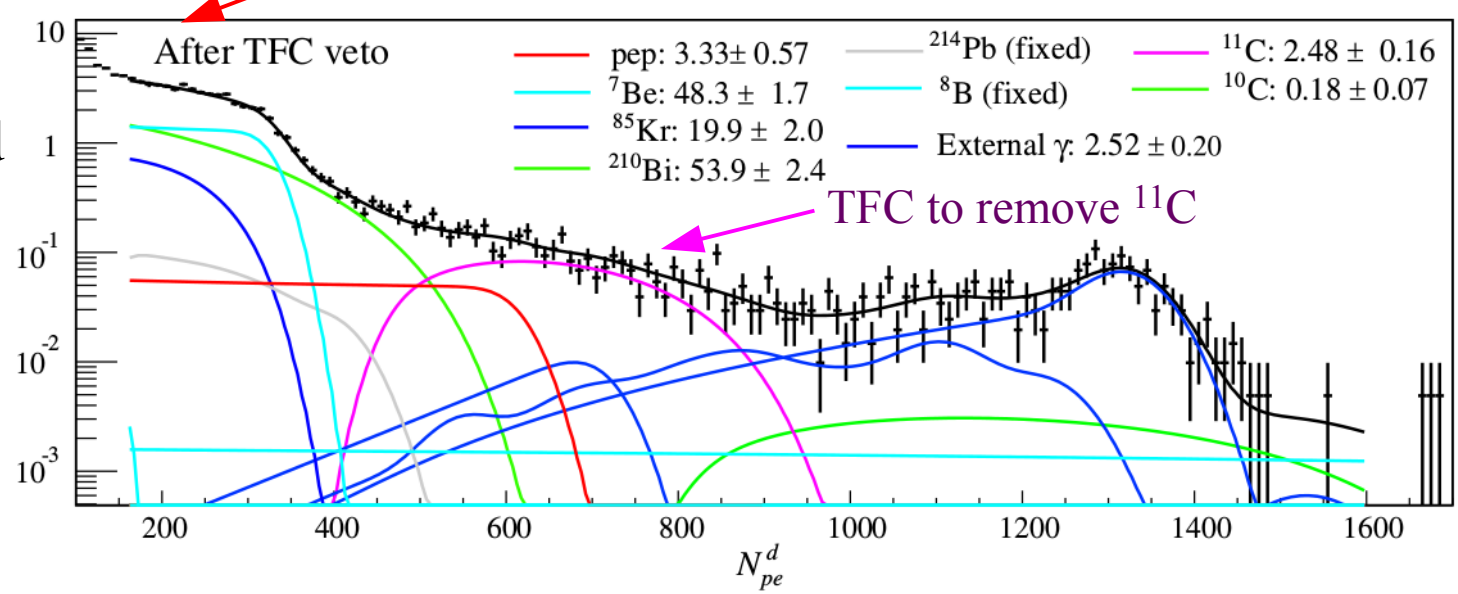
Event selection





α/β discrimination to remove ^{210}Po peak

We remove the events 300μs after each muon and the fiducial volume cut remove most of the external background showing the final shape of Borexino spectrum.

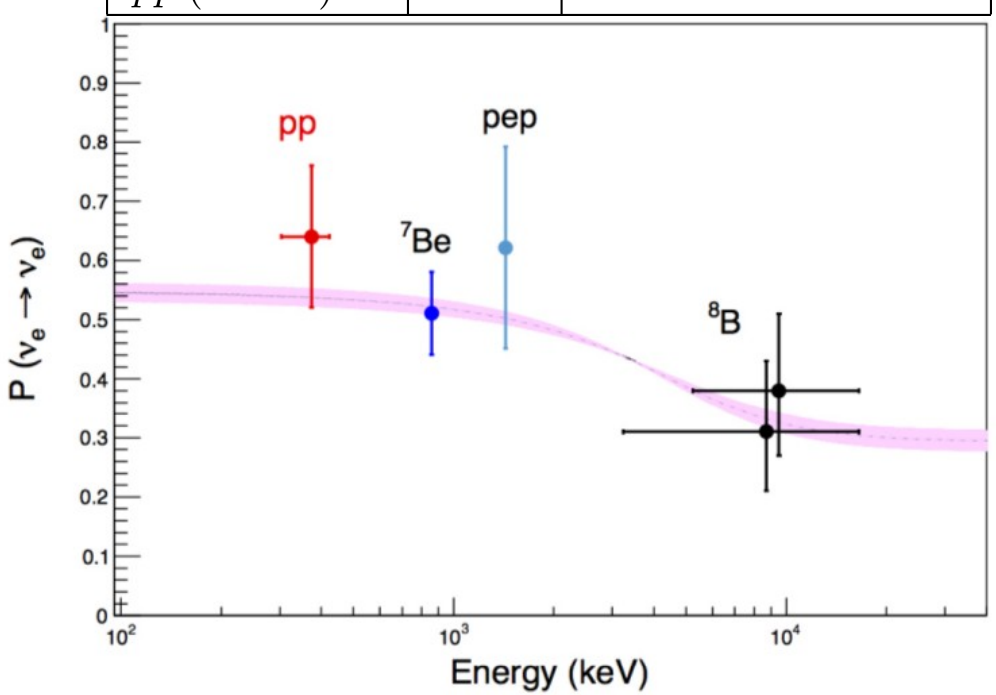


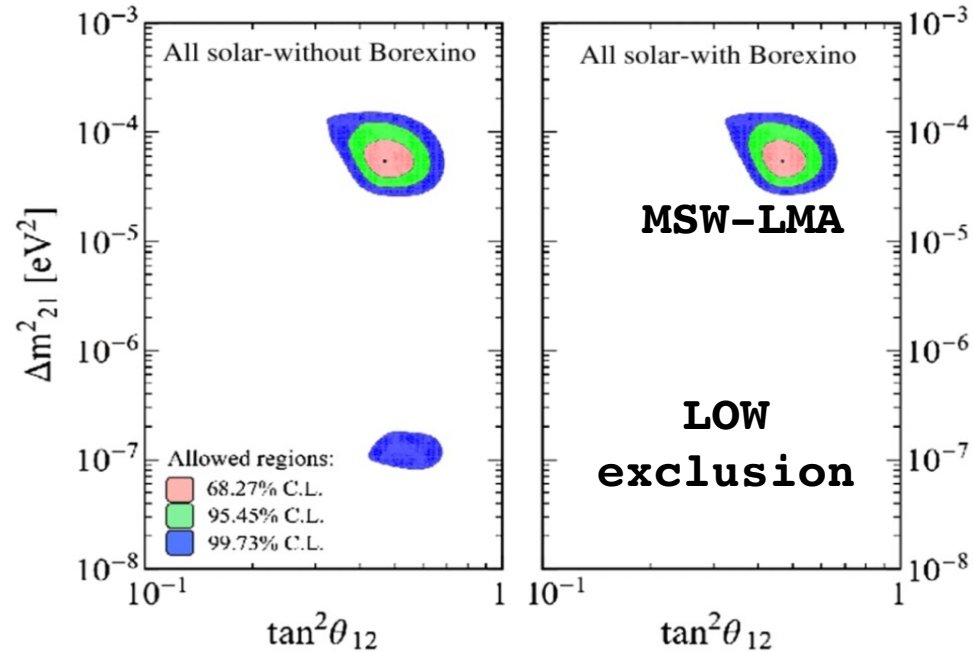
Borexino Results

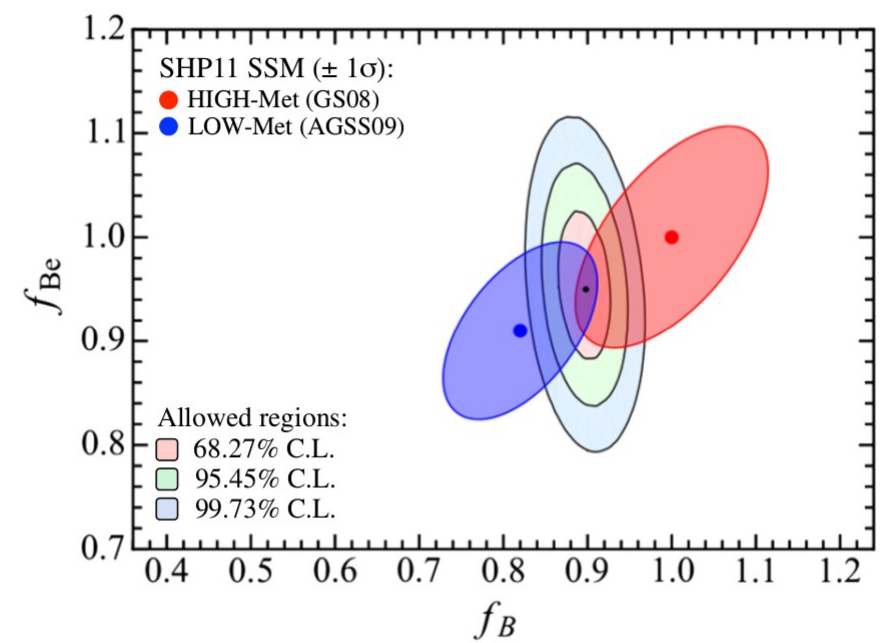
Borexino detector is the first neutrino detector able to perform a full spectroscopy of the solar neutrinos in real time, thanks to its incredible low background.

Neutrinos $R(\nu)$ [cpd/100 ton]		
^7Be	46.0	± 1.5 (stat) $^{+1.5}_{-1.6}$(sys)
^8B(3 -16 MeV)	0.22	± 0.04(stat)± 0.01(sys)
pep	3.1	± 0.6(stat)± 0.3(sys)
$CNO(limit)$	< 7.9	–
pp	144	± 13(stat)± 10(sys)

Neutrinos $\Phi(\nu)$ $[cm^{-2}s^{-1}]$		
^7Be $(\times 10^9)$	2.79	± 0.13
^8B $(\times 10^6)$	2.4	± 0.4(stat)± 0.1(sys)
pep $(\times 10^8)$	1.6	± 0.3
CNO $(\times 10^8)$	< 7.7	95% C.L.
pp $(\times 10^{10})$	6.6	± 0.7





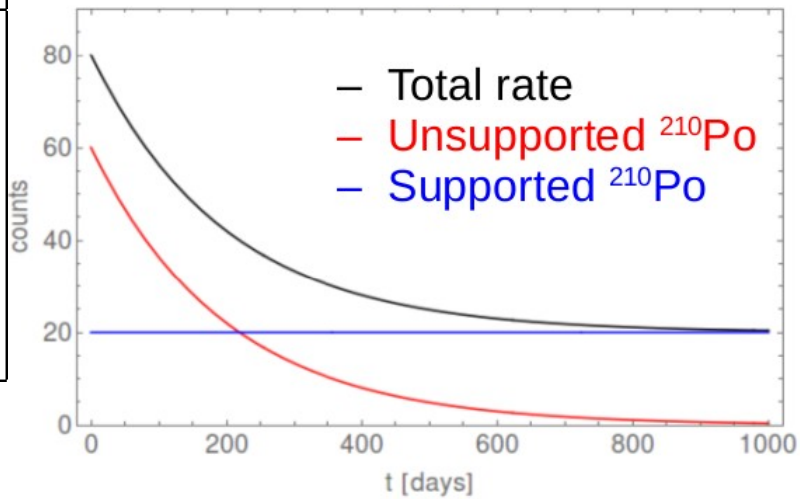


Borexino Background

The phase I has been characterized by a higher background and its time instability
The Phase II shows a much lower background rate and a very good stability in time, with exception of 210Po due to the convective motion inside the detector.

[cpd/100 ton]	phase I	Phase II (2014)
^{85}Kr	$31.2 \pm 1.7 \pm 4.7$	$1 \pm 9 \pm 3$
^{210}Po	684.5 ± 1.2	$583 \pm 2 \pm 12$
^{210}Bi	$41.0 \pm 1.5 \pm 2.3$	$27 \pm 8 \pm 3$
^{11}C	$28.5 \pm 0.2 \pm 0.7$	–
^{14}C $[Bq/100ton]$	–	40 ± 1
Pile-up ^{14}C	–	154 ± 10

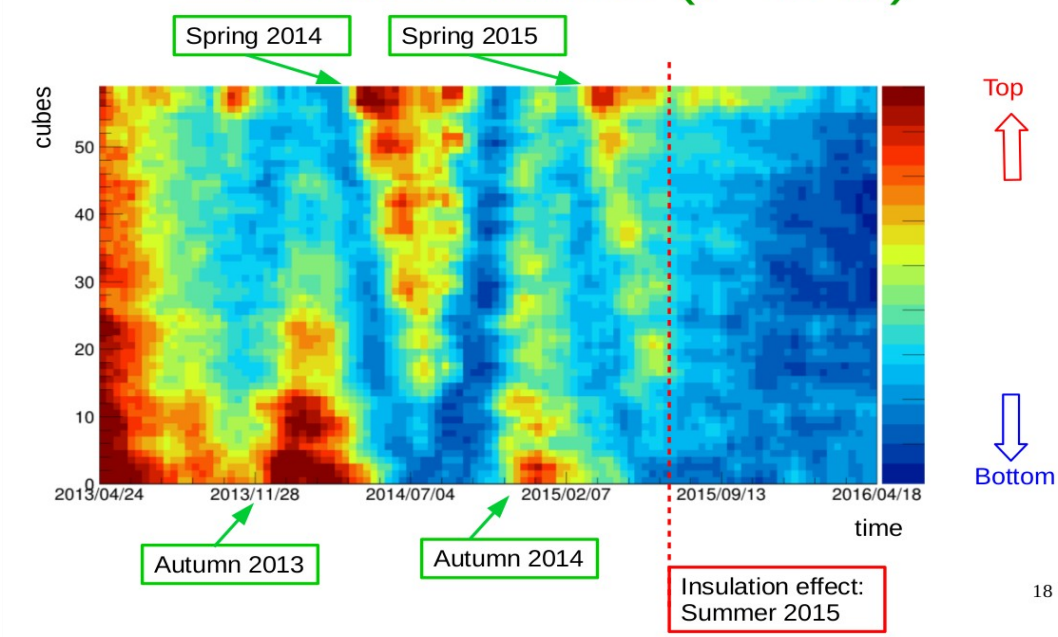
^{210}Pb (long lived) → ^{210}Bi (β) → ^{210}Po (α)



^{210}Bi main bkg for CNO (very high correlation!)

PRELIMINARY

^{210}Po in 60 cubes (r < 3 m)



Seasonal Modulation Phase 2

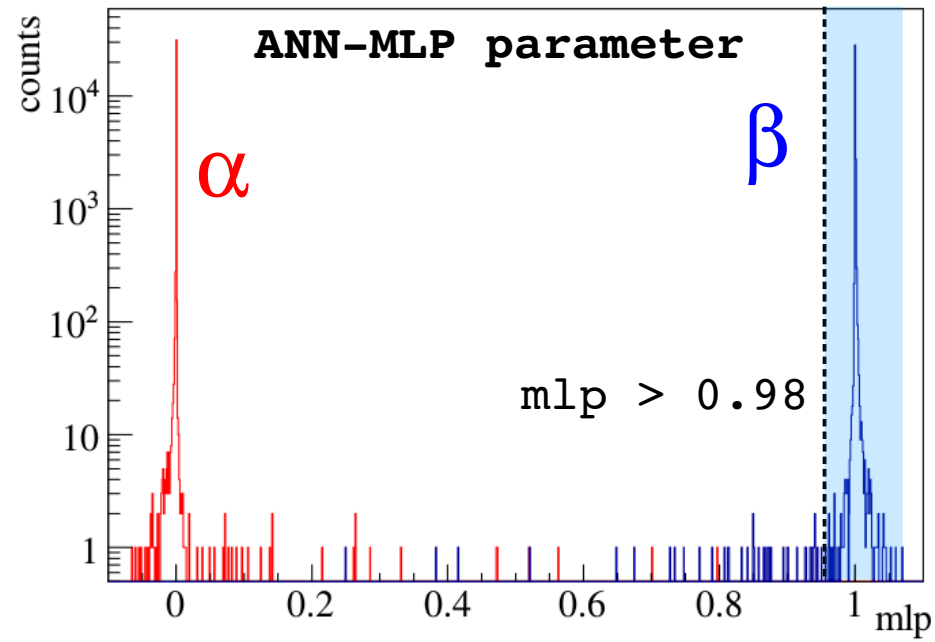
From Dec 2011 to Dec 2015: 4 years of data

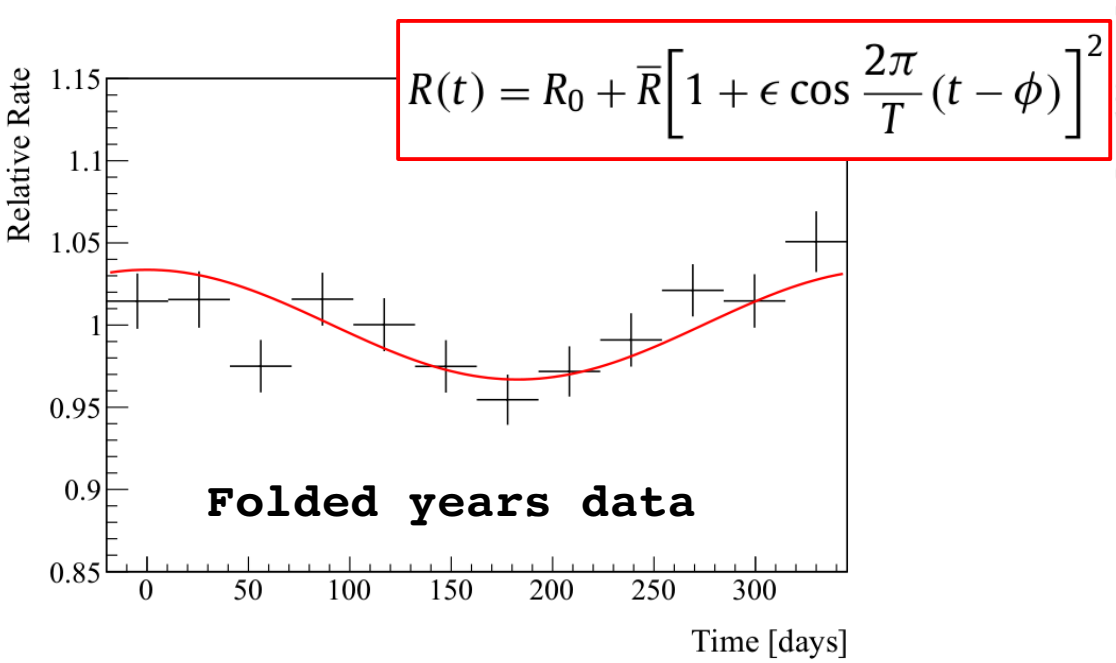
Data Analysis Method [Astropart.Phys. 92 (2017) 21-29]:

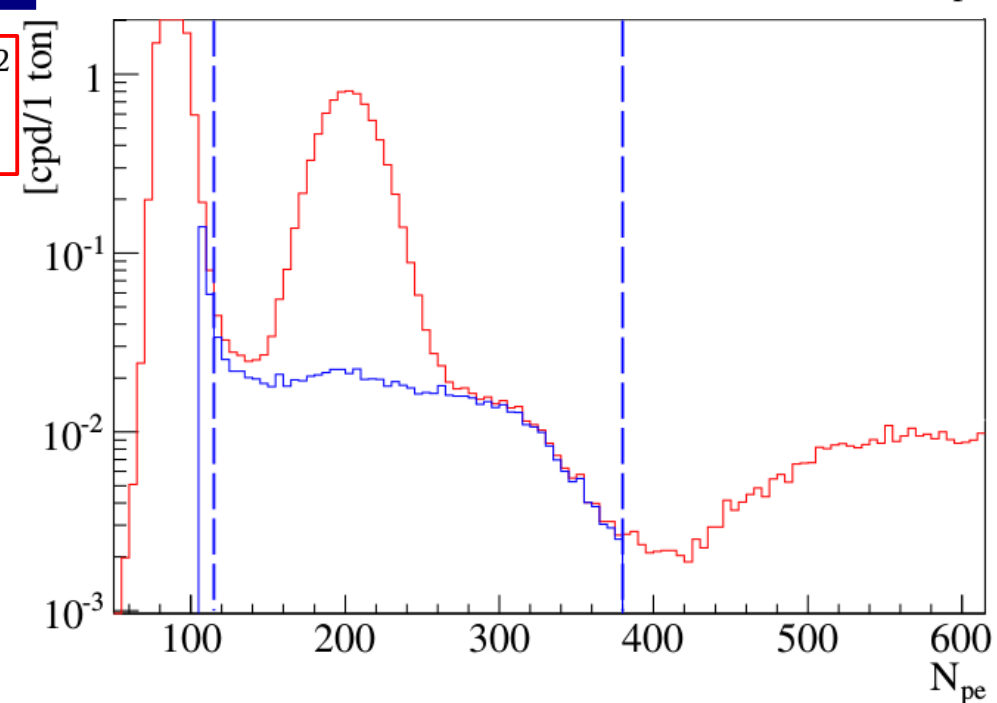
- Analytic Fit
- Lomb-Scargle (Fourier)
- Empirical Mode Decomposition (EMD)

Data Selection:

- Fiducial Volume 3m fixed radius
- New PSD based on ANN: Multilayer Perceptron (MLP)
- New Empirical Mode Decomposition algorithm (CEEMDAN)



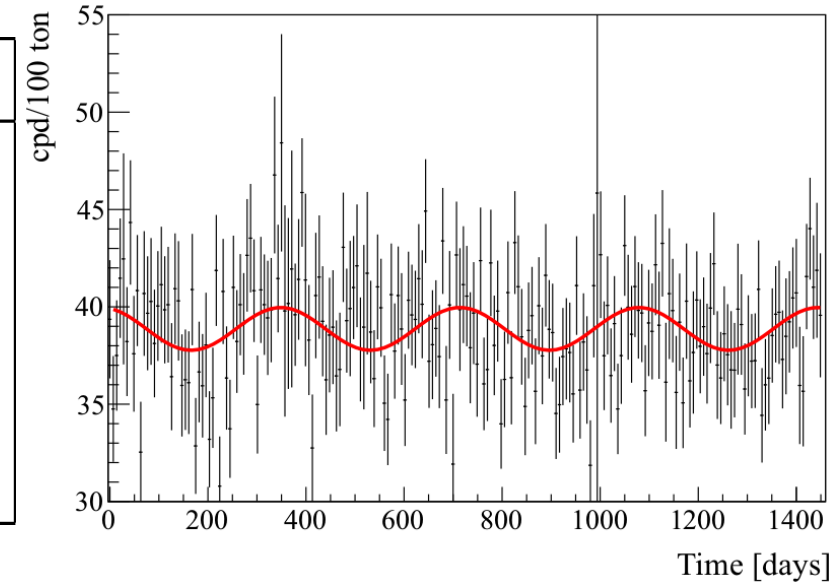




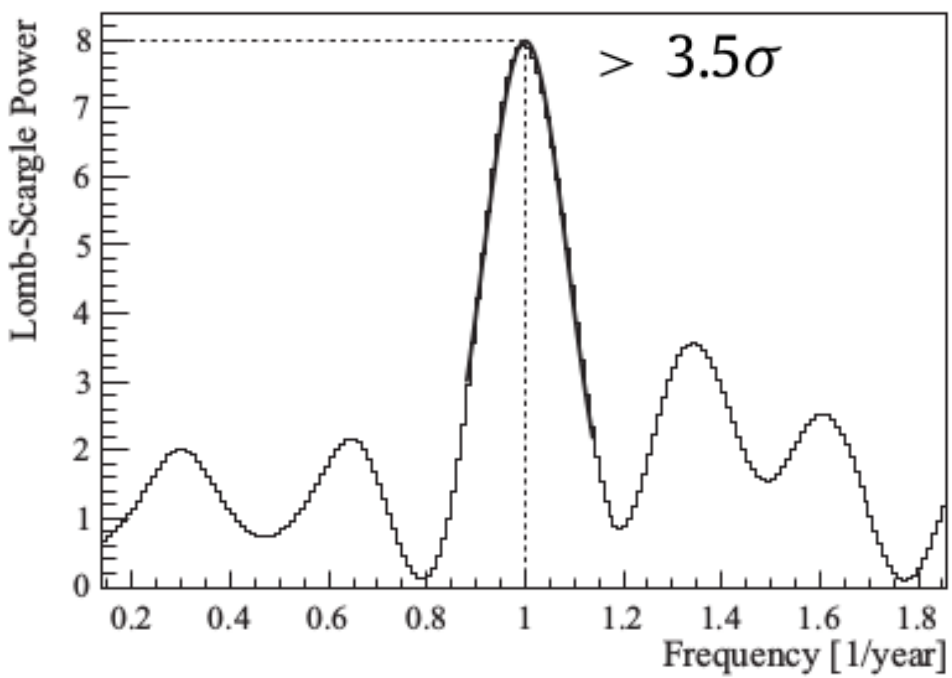
Seasonal Modulation Phase 2

Analytic and Lomb-Scargle

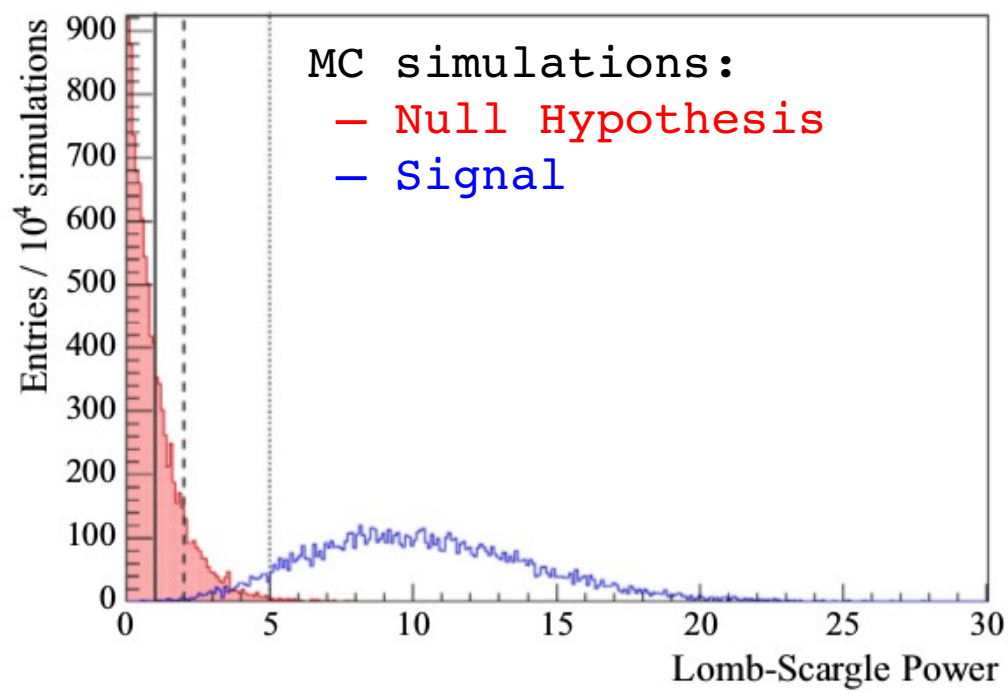
	Analytic	Lomb-Scargle
T [day]	367 ± 10	–
f [year^{-1}]	0.99 ± 0.03	$1.0 \pm 4\%$
$\varepsilon(\times 10^{-2})$	(1.74 ± 0.45)	1.43 ± 0.01
$\varepsilon(\%)$	$(7.1 \pm 1.9)\%$	$(5.7 \pm 0.4)\%$
ϕ [day]	-18 ± 24	no info



Fourier's Spectral Analysis



Statistical Significance (10^4 simul.)



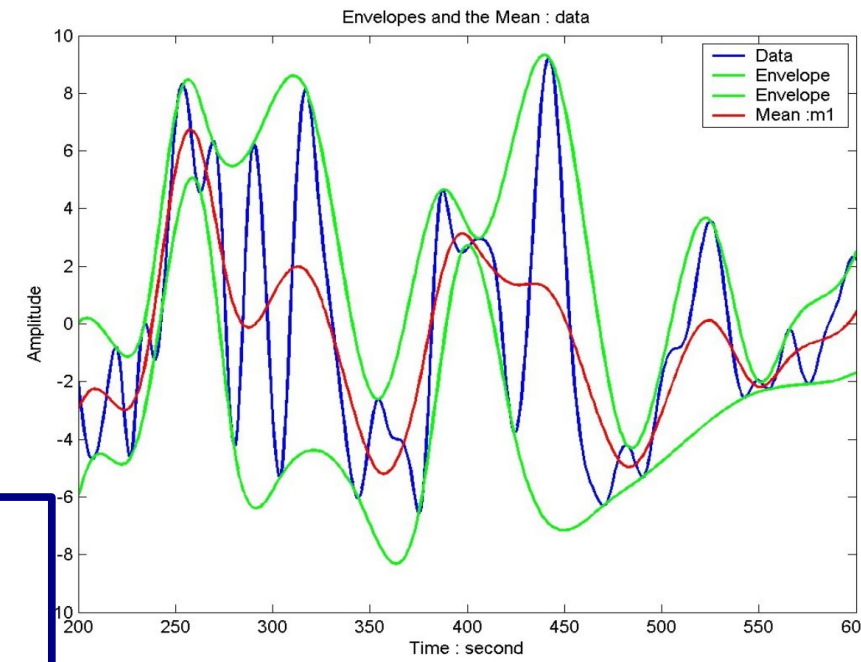
Empirical Mode Decomposition

Basic Ideas:

– "Sifting": To Decompose any time series in the "Intrinsic Mode Functions" (IMF).
– No analytical shapes assumed "a priori" (it works only with interpolated polynomials)
– Analytical Function to calculate the Instantaneous Frequency, Amplitude and phase.
– Toy Montecarlo to evaluate the statistical significance of the results.

Step 1. Set $k=0$ and find all extrema of $r_0 = x$.
Step 2. Interpolate between minima (maxima) of r_k to obtain the lower (upper) envelope e_{min} (e_{max}).
Step 3. Compute the mean envelope $m = (e_{min} + e_{max})/2$.
Step 4. Compute the IMF candidate $d_{k+1} = r_k - m$.
Step 5. Is d_{k+1} an IMF?
- Yes. Save d_{k+1}, compute the residue $r_{k+1} = x - \sum_{i=1}^{k} d_i$, do $k = k+1$, and treat r_k as input data in step 2.
- No. Treat d_{k+1} as input data in step 2.

Step 6. Continue until the final residue r_K satisfies some predefined stopping criterion.



Analytical Function z(t):

a(t) = time series (real part)

b(t) = Hilber Transform of a(t): $b(t) = \frac{1}{\pi} P \int_{t'} \frac{a(t')}{(t-t')} dt'$

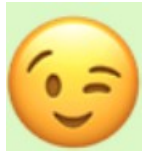
$$z(t) = a(t) + \mathrm{i}b(t) = A(t)e^{-\mathrm{i}\theta(t)}$$

$$A(t) = \sqrt{a^2(t) + b^2(t)}$$ Amplitude

$$\theta(t) = \arctan\left(\frac{b(t)}{a(t)}\right)$$ Inst. Phase

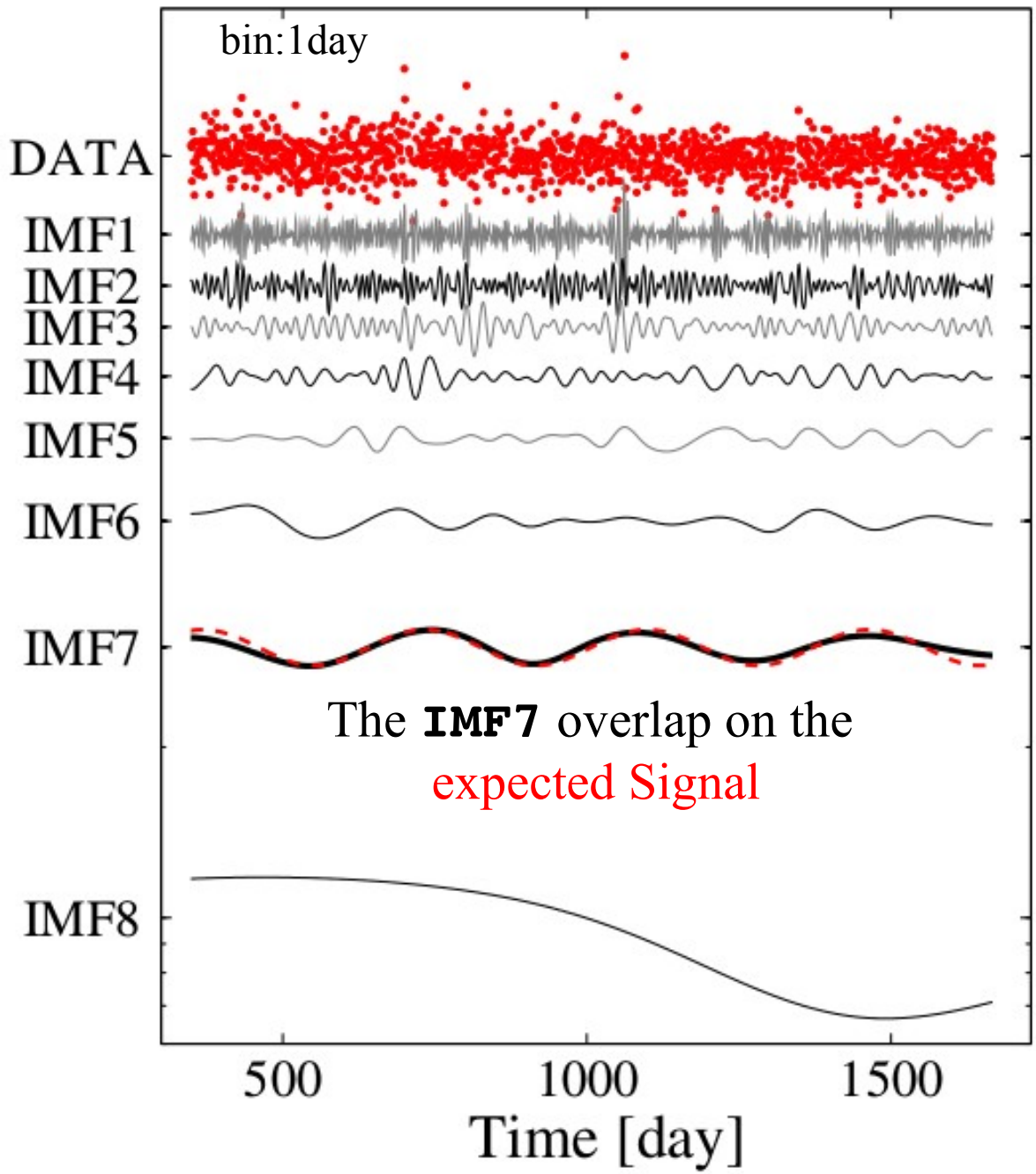
$$f(t) = \frac{\mathrm{d}\theta(t)}{\mathrm{d}t}$$ Inst. Frequency

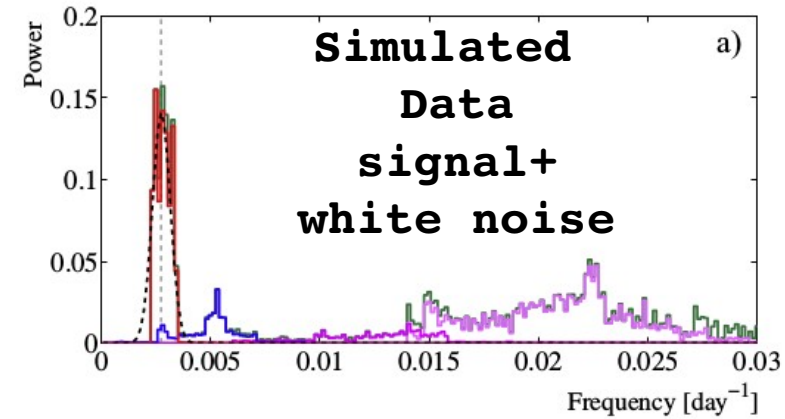
Just an rough idea!!
The life is not so easy

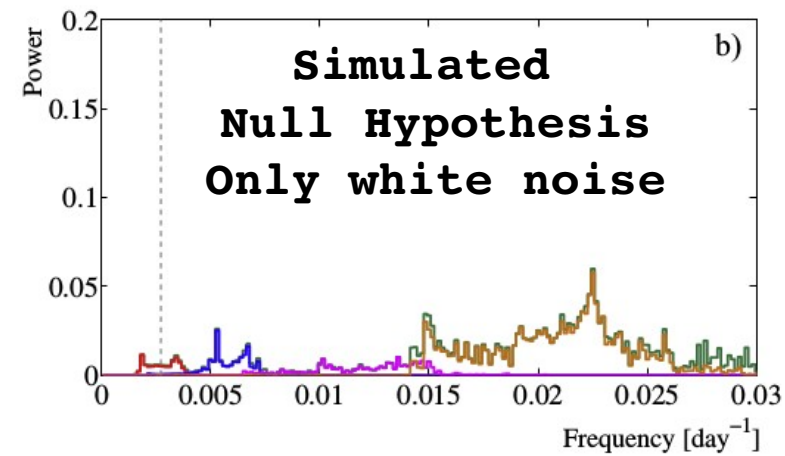


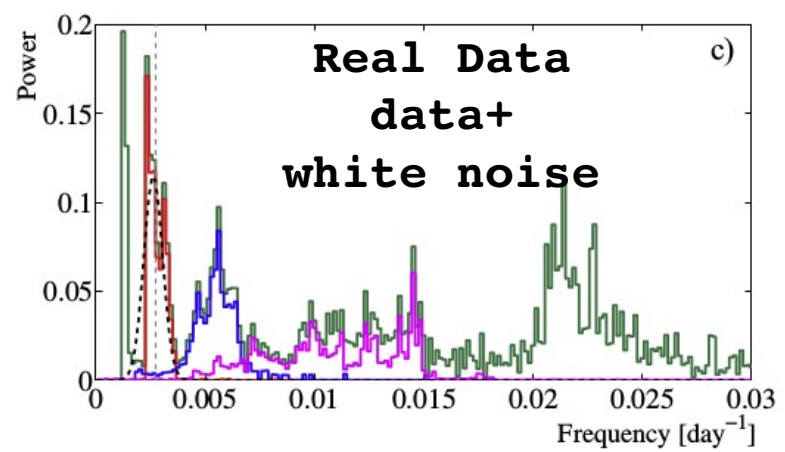
Seasonal Modulation Phase 2

Empirical Mode Decomposition Analysis

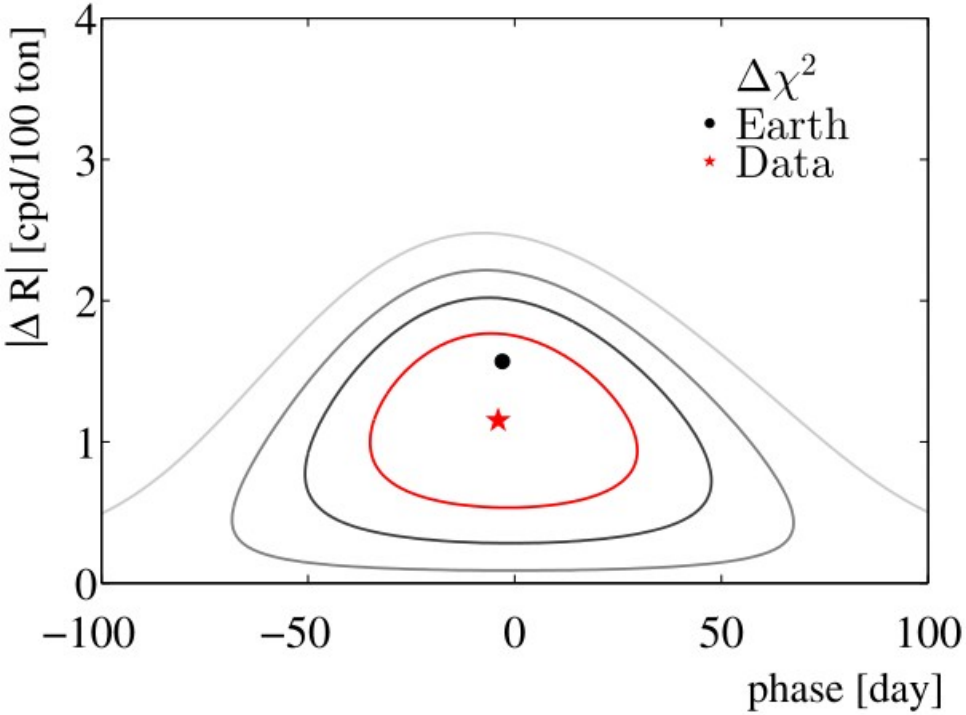


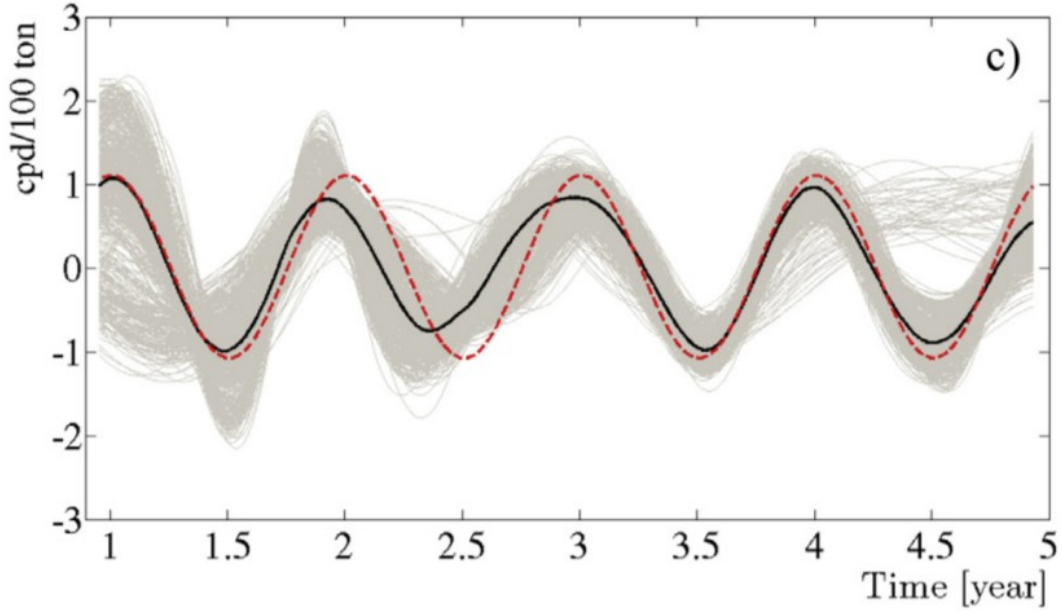






Seasonal Modulation Phase 2





	Simulated data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

	Analytic	Lomb-Scargle	CEEMDAN	Expected
T [day]	367 ± 10	–	351 ± 18	365.24
f [year^{-1}]	0.99 ± 0.03	$1.0 \pm 4\%$	1.04 ± 0.04	1.0
$\varepsilon(\times 10^{-2})$	(1.74 ± 0.45)	1.43 ± 0.01	1.68 ± 0.31	1.67
$\varepsilon(\%)$	$(7.1 \pm 1.9)\%$	$(5.7 \pm 0.4)\%$	$(6.7 \pm 1.2)\%$	6.7 %
ϕ [day]	-18 ± 24	–	14 ± 22	+3

Borexino Experiment
Geo-Neutrino

Geo-Neutrinos:

We call "Geo-neutrinos" the antineutrinos emitted by the beta-decay of:

$$^{238}U \rightarrow ^{206} Pb + 8\alpha + 8e^- + 6\overline{\nu}_e + 51.7MeV$$
$$^{232}Th \rightarrow ^{208} Pb + 6\alpha + 4e^- + 4\overline{\nu}_e + 42.8MeV$$
$$^{40}K \rightarrow ^{40} Ca + e^- + \overline{\nu}_e + 1.32MeV$$

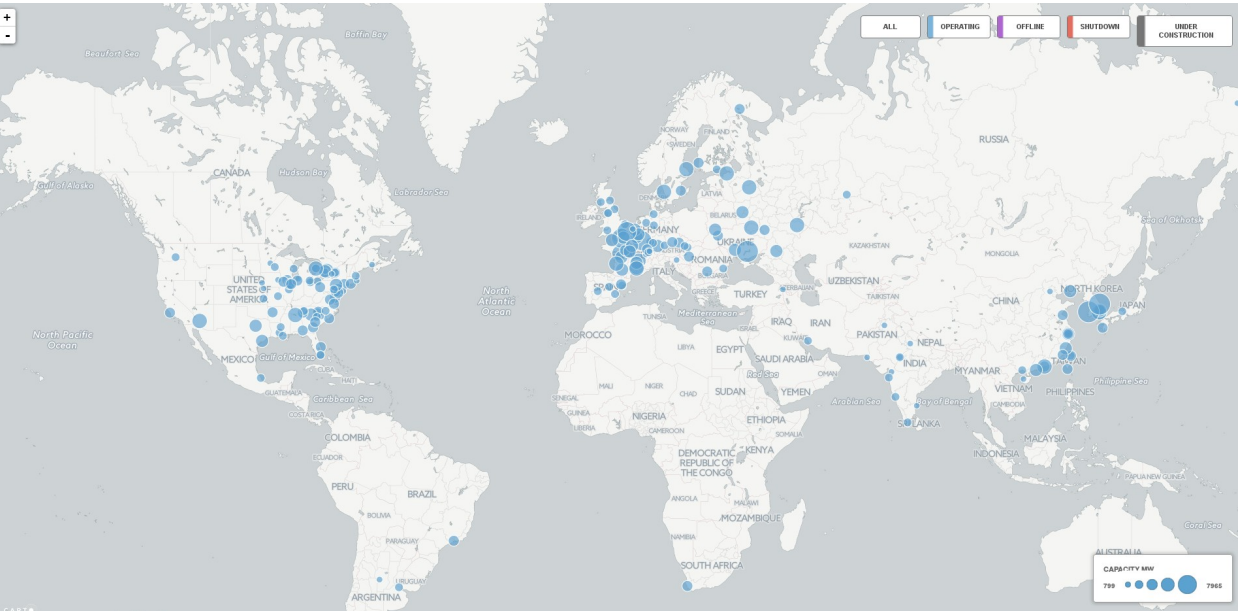
$$Th/U = 3.9$$
$$K/U = 1.2 \times 10^4$$

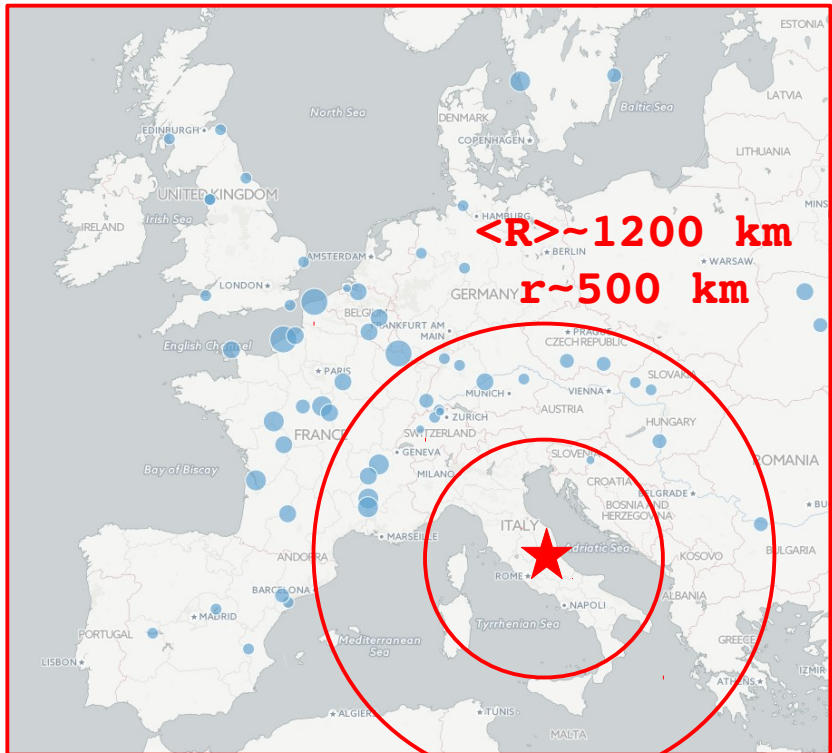
The geoneutrinos provide us an important information about radioactive element abundances in the interior of the Earth.

Nuclear plants Background:

The main background are the nuclear plants around the word. We consider 446 plants and their monthly nominal power provided by IAEA.

$$^{235}U :^{238} U :^{239} Pu :^{241} Pu = 0.542 : 0.411 : 0.022 : 0.0243$$





Borexino Signal:

- Dataset phase 1+ phase 2: 15 Dec 2007 → 8 March 2015
- Fiducial Volume: (613+/-26) ton
- Dynamic Fiducial Volume (30cm away from the vessel)
- Detection by means inverse beta decay:

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

- Event Energy Threshold: 1.806 MeV

"prompt signal": e^+

energy loss T_{e+} +

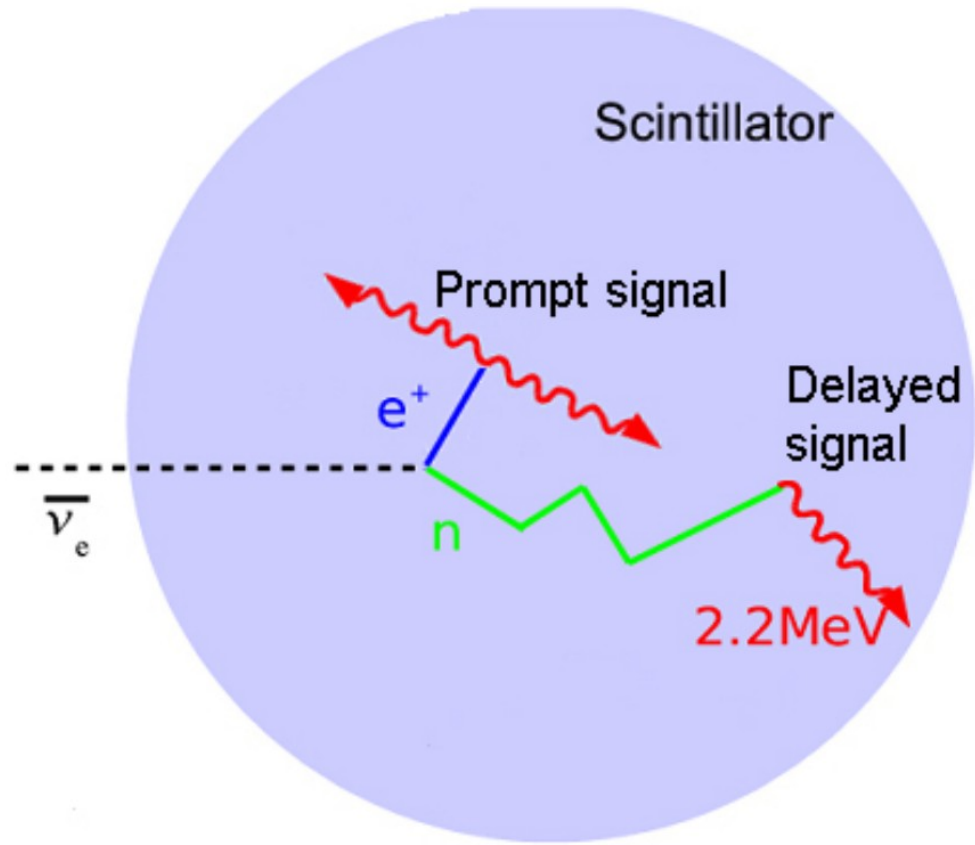
annihilation (2 x 0.511 MeV)

$E_{prompt} = E_{geonu} - 0.784$ MeV

"delayed signal": neutron

neutron thermalisation & capture on protons, emission of **2.2 MeV γ**

τ ~ 250 μs

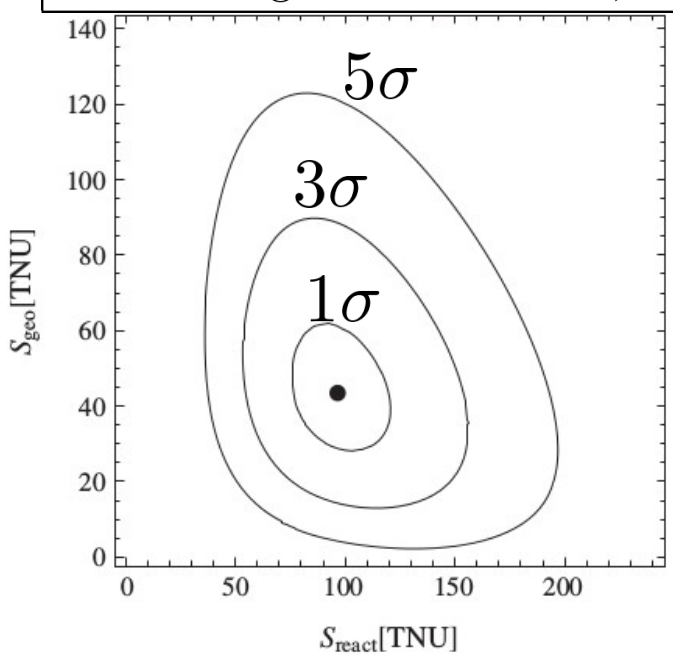


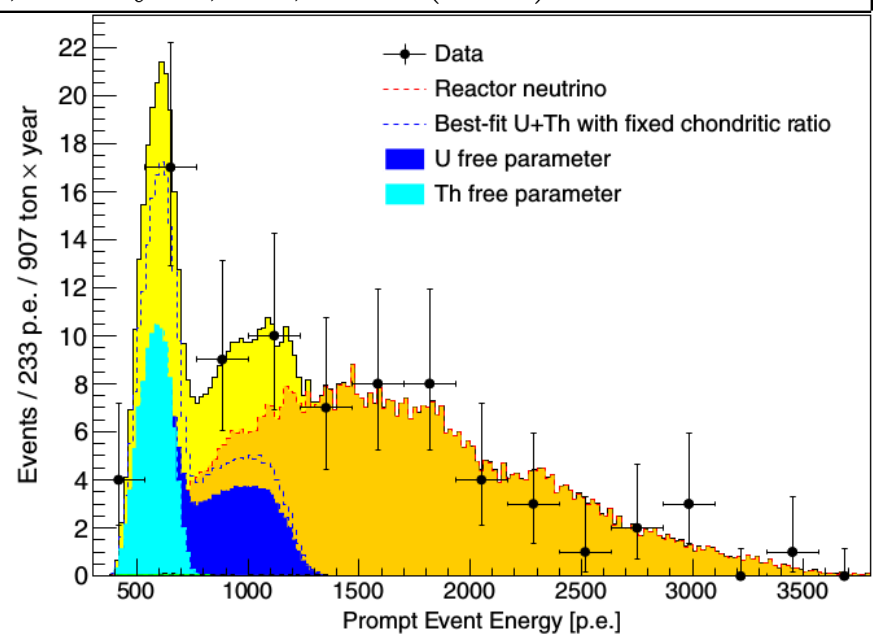
Borexino Results

Final fit of Prompt events spectrum. Background NON-antineutrino <1%.
The Th and U spectral shapes have been generated by mean of MC.
Null Hypothesis of geoneutrinos excluded at 5.9 σ.

Geo-Neutrinos (2015) $\sim 2055.9 day$		
	events	TNU $[\mathrm{ev}/10^{32} p/yr]$
$S_\nu\ Tot$	77	–
S_{geo}	$23.7\ ^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$	$43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$
$S_{geo}\ LOC^*$	–	9.7 ± 1.3
$S_{geo}\ LOC + ROC^{**}$	–	23.4 ± 2.8
$S_{geo}\ Mantle$	–	$20.9\ ^{+15.1}_{-10.3}$
S_{reac}	$52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(sys)$	$96.6^{+15.6}_{-14.2}(stat)^{+4.9}_{-5.0}(sys)$

*M.Coltorti *et al.* Earth Planet Sc. Lett. **293**, 259 (2010)
Y.Huang *et al.* Geochem., Geophys., Geosyst., **14, 2003 (2013)





Borexino Results

Assuming the chondritic mass ratio the fluxes of geoneutrinos are:

$$\phi(U) = (2.7 \pm 0.7) \times 10^6\ cm^{-2}\ s^{-1}$$

$$\phi(Th) = (2.3 \pm 0.6) \times 10^6\ cm^{-2}\ s^{-1}$$

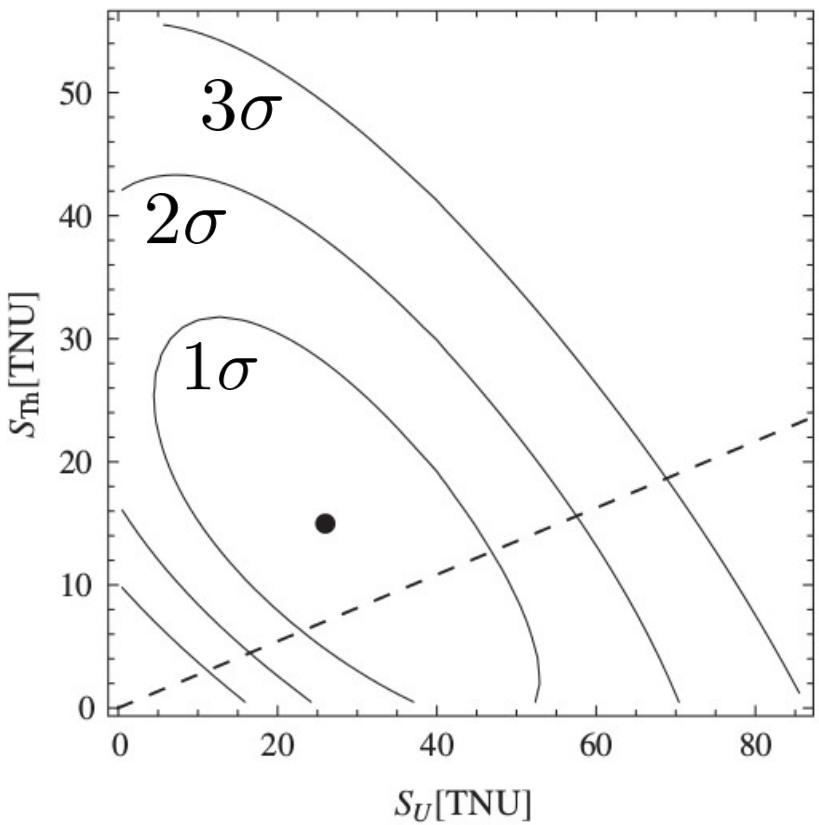
We can make an estimation of the radiogenic heat between 23-36 TW.

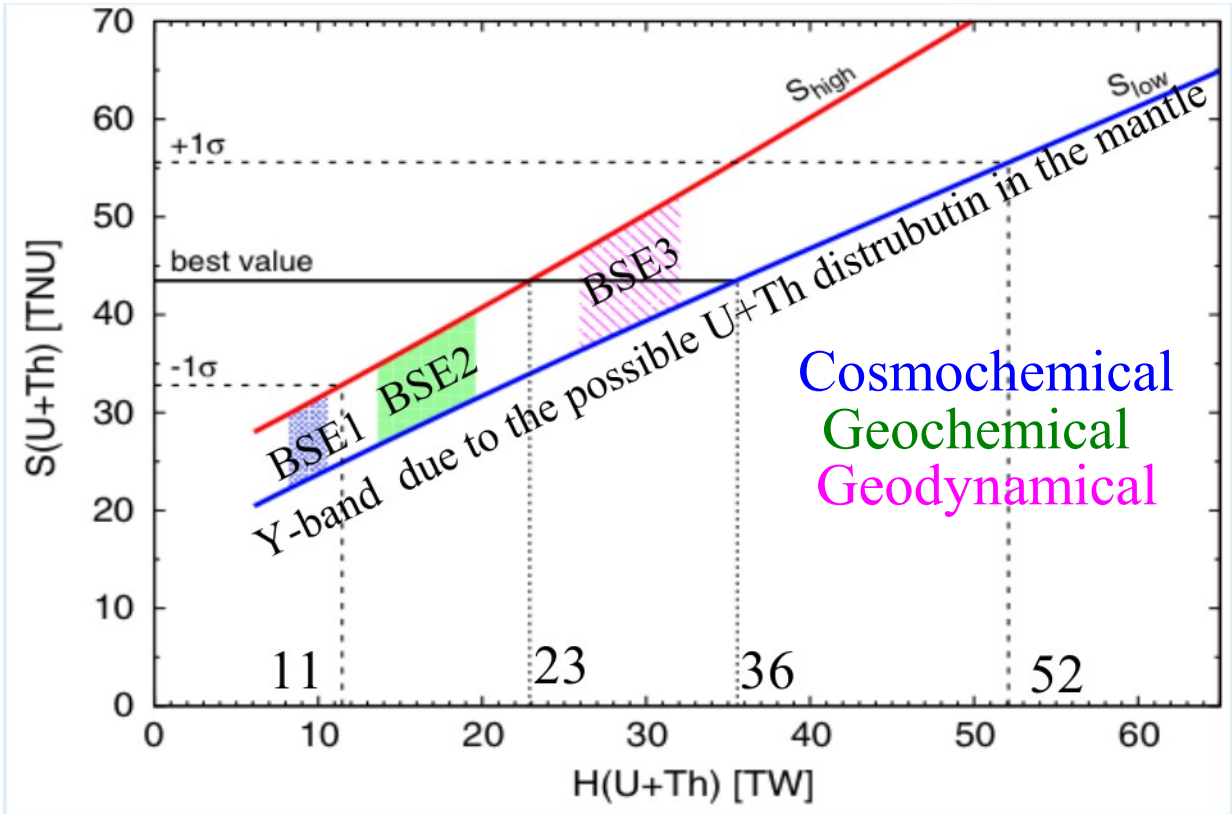
The Best fit within 1σ is 11-52 TW

Taking into account the potassium chondritic mass ratio K/U=10^4, the total Earth's radiogenic power is:

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

while the total power is P_{tot}= 47+/-2 TW.





the Borexino Collaboration

INFN

Milano

München

Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

JINR Dubna

Virginia Tech

Houston

Paris

Moscow

Los Angeles

Princeton

UMass Amherst

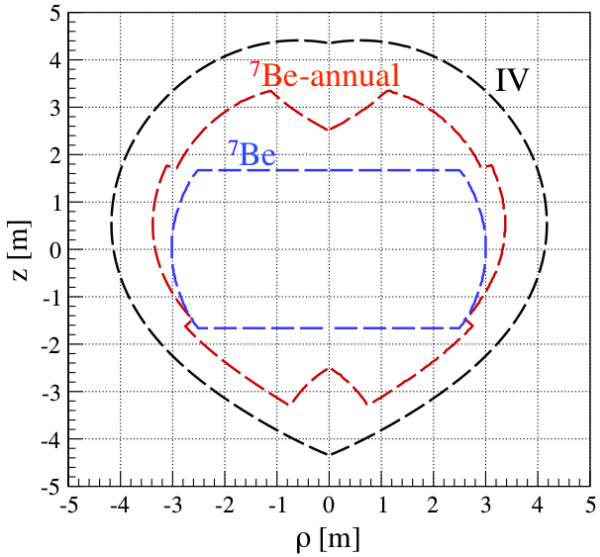
St. Petersburg

Kurchatov Moscow

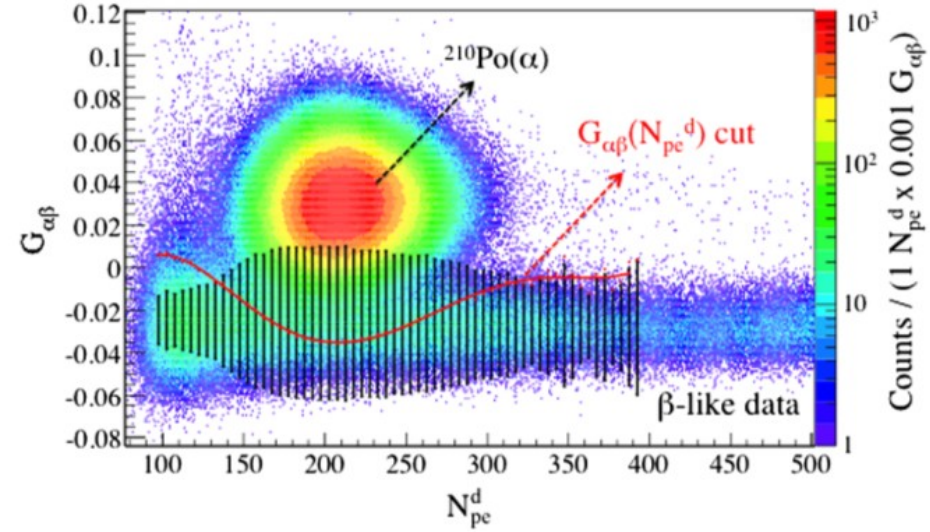

Thank you!

Seasonal Modulation Phase 1

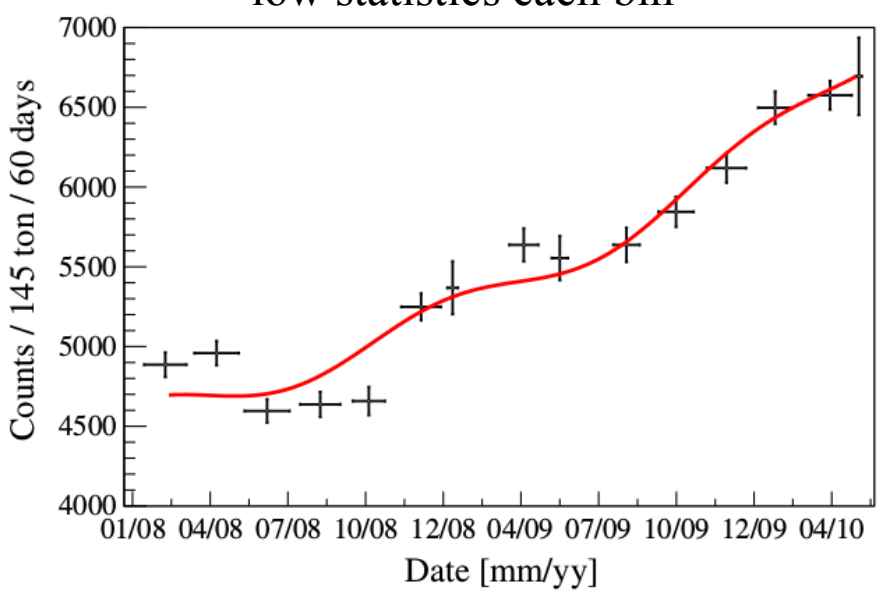
Larger fiducial volume thanks to the Dynamic FV



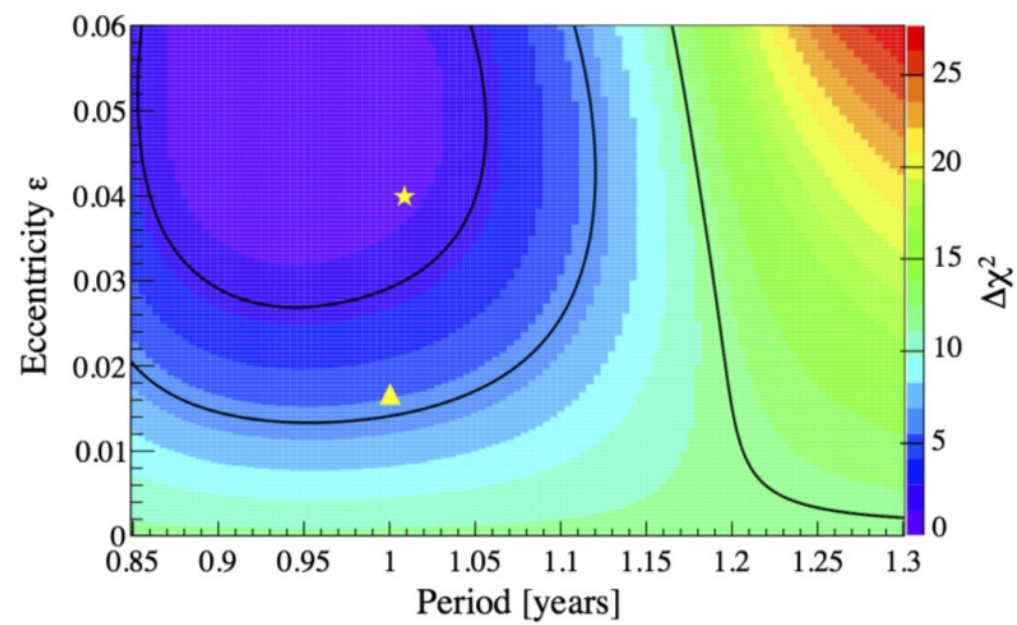
Hard cut α/β on Gatti parameter (PSD): strong reduction of beta events.



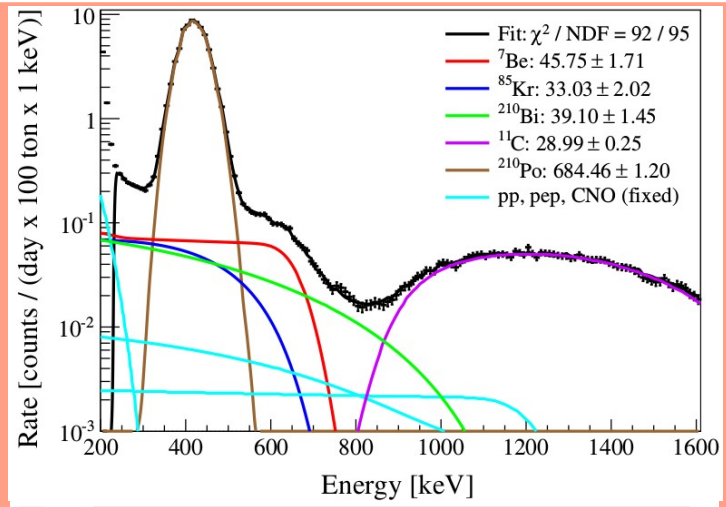
Background instable in time:
we cannot sum data in different years.
low statistics each bin

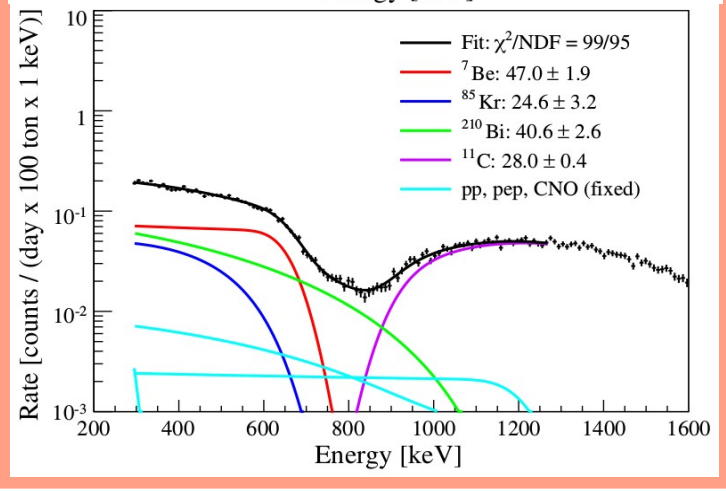


$$R(t) = R_0 + R_{\mathrm{Bi}} e^{\Lambda_{\mathrm{Bi}} t} + \bar{R}\left[1 + 2\varepsilon \cos\left(\frac{2\pi t}{T} - \phi\right)\right]$$



Borexino Phase I Results:





ν ^{7}Be:

PRL 107, 1411302 (2011)
PHYSICAL REVIEW D 89, 112007 (2014)

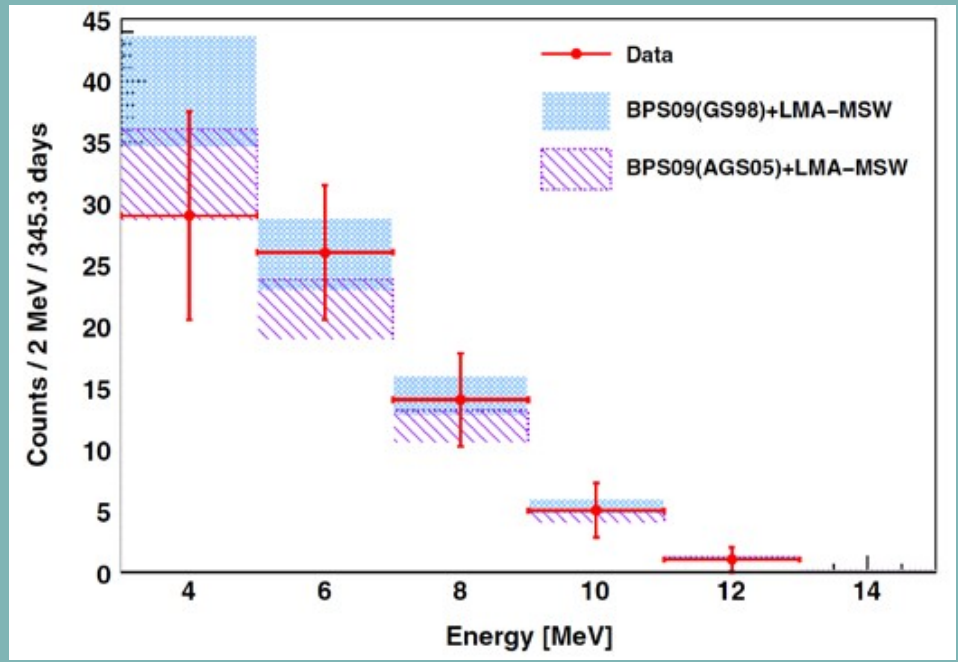
TABLE I. Average fit results [counts/(day · 100 ton)].

^{7}Be	$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$
^{85}Kr	$31.2 \pm 1.7(\text{stat}) \pm 4.7(\text{syst})$
^{210}Bi	$41.0 \pm 1.5(\text{stat}) \pm 2.3(\text{syst})$
^{11}C	$28.5 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$

ν ^{8}B:

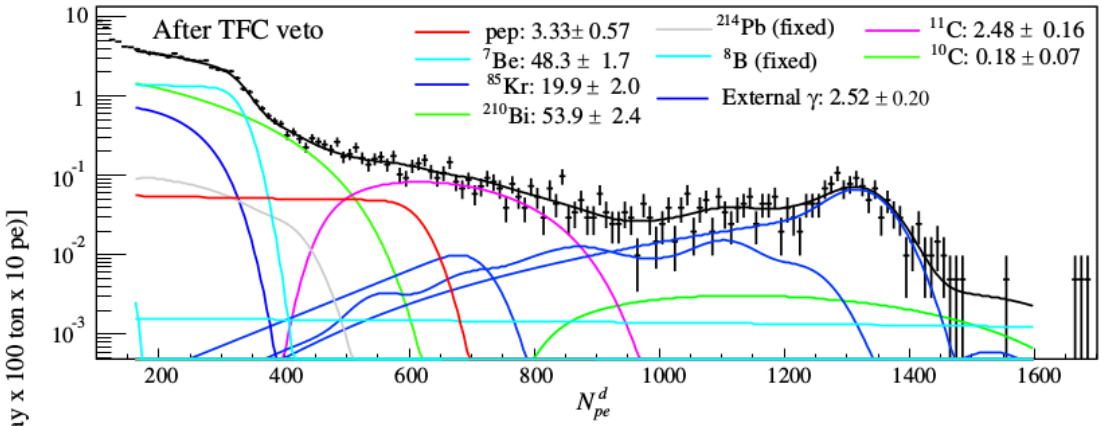
Phys.Rev.D 82, 0330066 (2010)

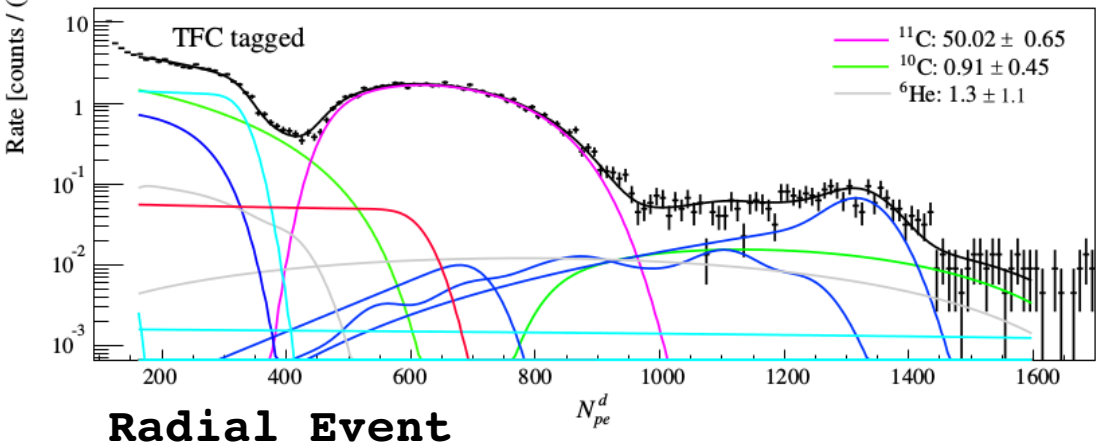
	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	$0.22 \pm 0.04 \pm 0.01$	$0.13 \pm 0.02 \pm 0.01$
Φ^{ES}_{exp} [10^6 cm^{-2} s^{-1}]	$2.4 \pm 0.4 \pm 0.1$	$2.7 \pm 0.4 \pm 0.2$
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88 ± 0.19	1.08 ± 0.23



Pep-CNO

TFC and C11 subtraction Fit





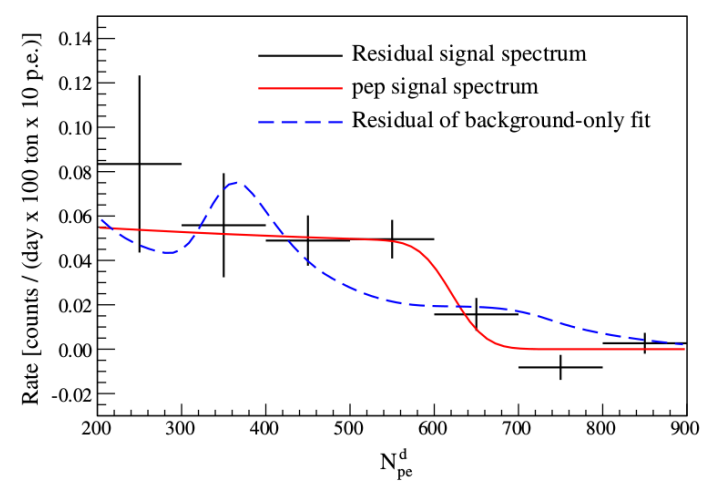
Procedure:

- Multivariate Fit:
  - ➔ Spectrum w/ and w/o ^{11}C
  - ➔ Radial Distribution
- Boosted Decision Tree:
  - ➔ Pulse Shape discrimination positron and electron
- Strong Bi210 and pep correlation with CNO

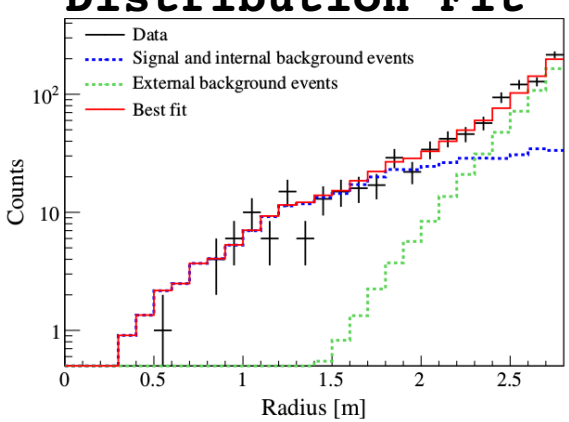
last column gives the ratio between our measurement and the high metallicity (GS98) SSM [9].

ν	Interaction rate [counts/(day · 100 ton)]	Solar-ν flux [10^8 cm^{-2} s^{-1}]	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2
CNO	<7.9 ($<7.1_{stat\ only}$)	<7.7	<1.5

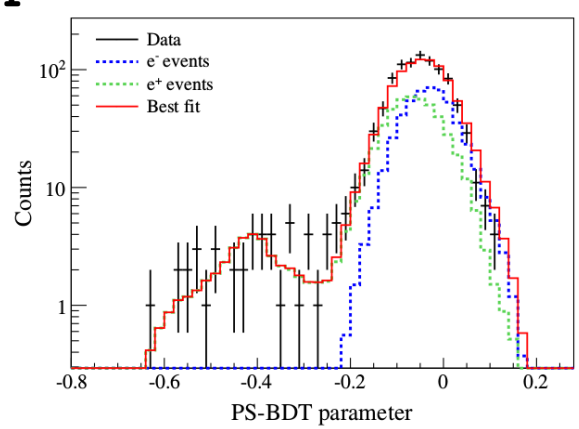
Fit of Residual Spectrum



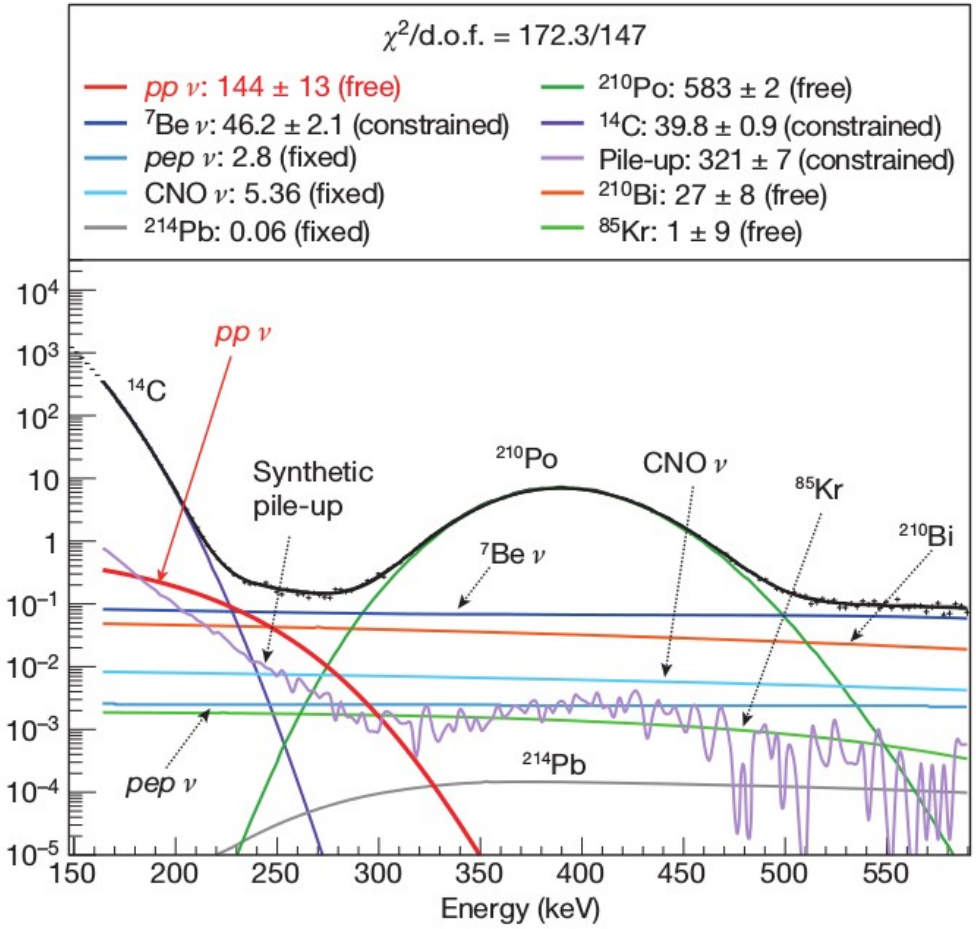
Radial Event Distribution Fit



positron/electron PSD



pp neutrino



Phase II Borexino background: [cpd/100 ton]

^{85}Kr: 1 +/- 9 (stat)
+/-3 (sys)

^{210}Bi: 27 +/- 8 (stat)
+/- 3 (sys)

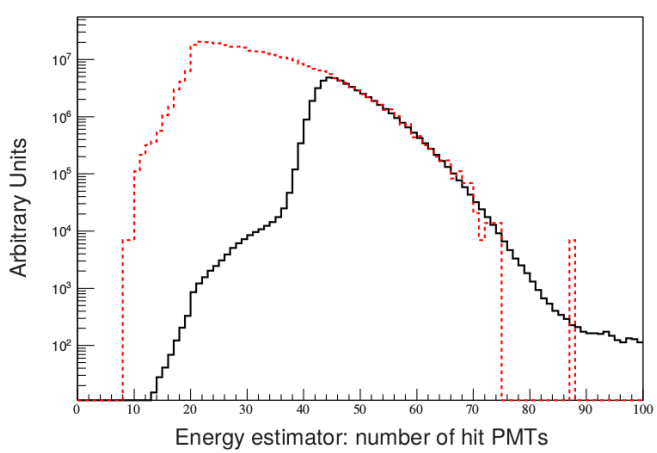
^{210}Po: 583 +/- 2 (stat)
+/- 12 (sys)

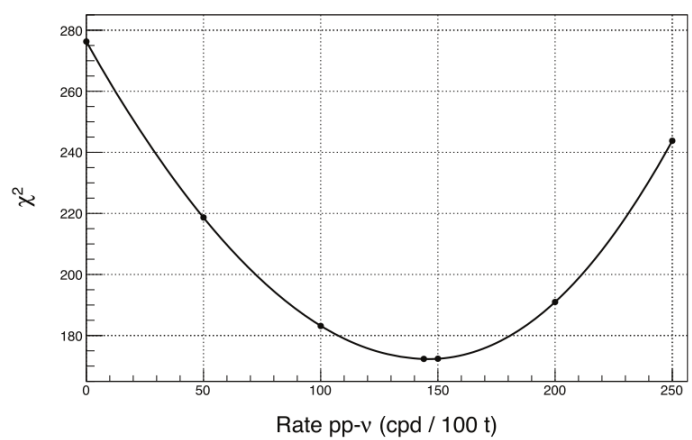
R(pp) = 144 +/- 13 (stat)
+/- 10 (sys)

Nature 512,383–386 (28 August 2014)

R(^{14}C) = 40 +/-1 Bq/100t
(independent measurement)

Synthetic pile-up R(^{14}C):
154+/-10 cpd/100 ton
(whole spectrum)





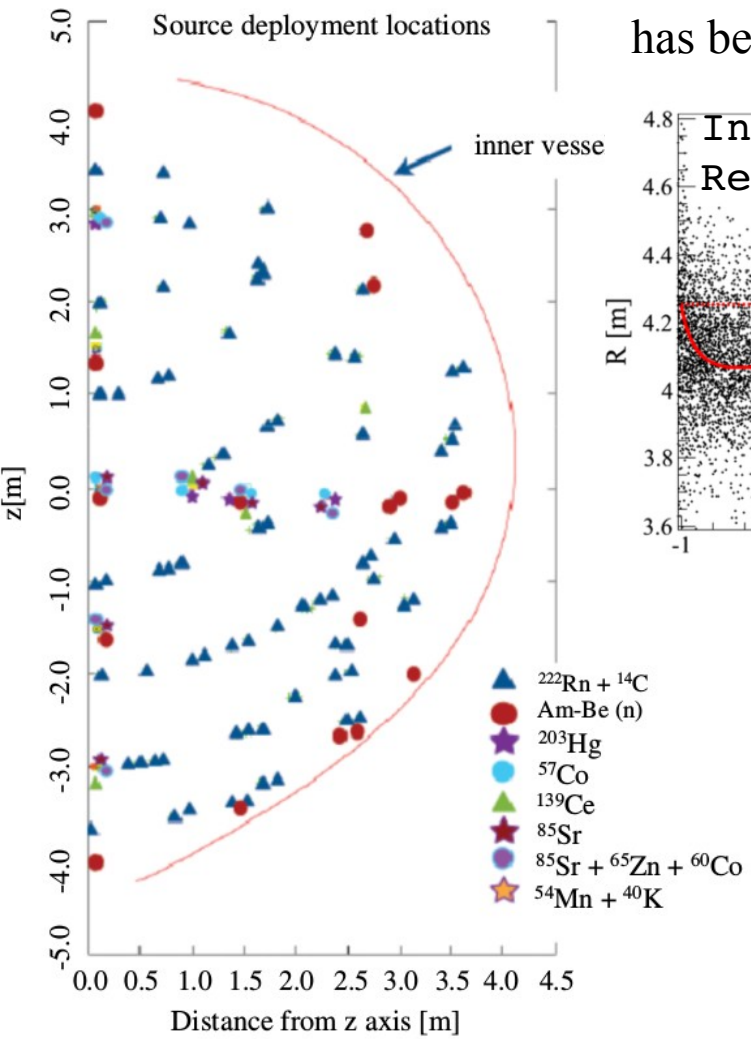
Calibration Campaign

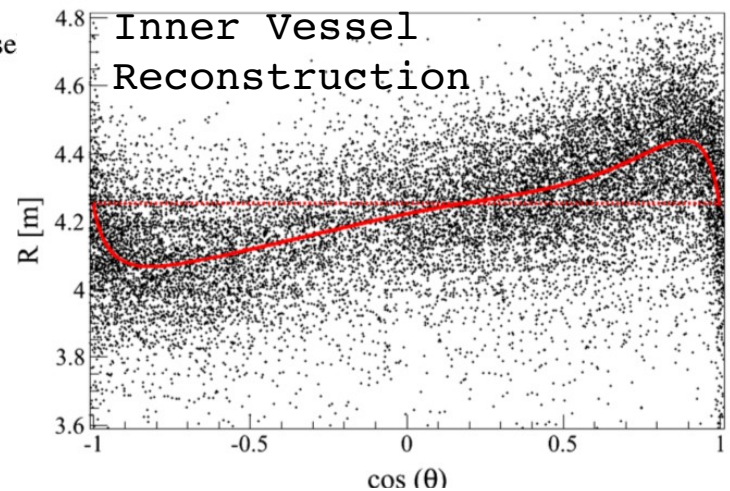
– The Calibration have been performed by means of the standard sources with a telescopic arm inserted within the Inner Vessel.

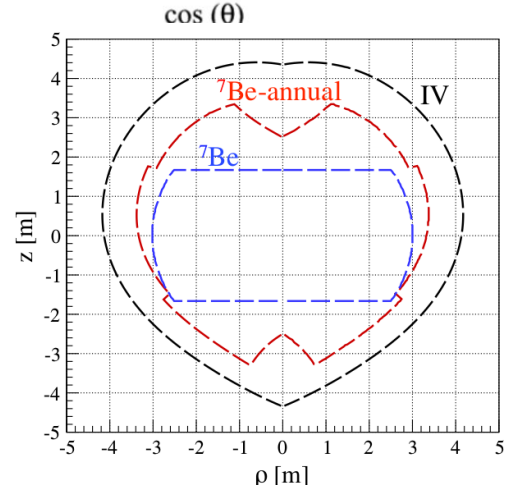
– The Full energy scale has been covered. Energy resolution: $\Delta E \sim 5\% \sqrt{E}$

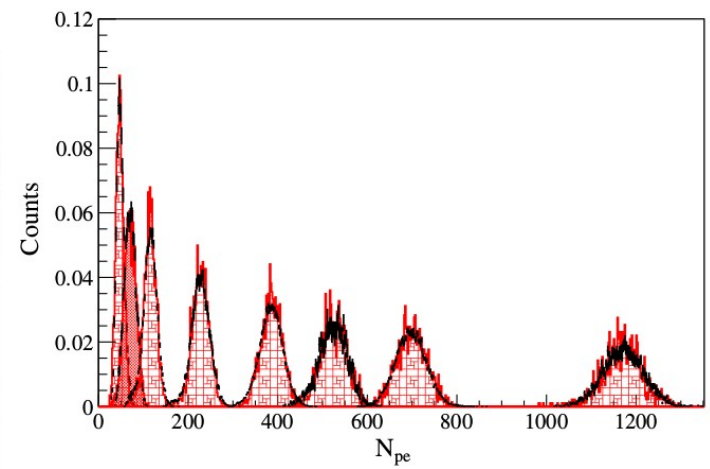
– The position reconstruction has been calibrated putting the source in different position.

– Selecting the energy range 800-900 keV by means of the events present on Vessel, a Dynamic reconstruction of its profile has been done.









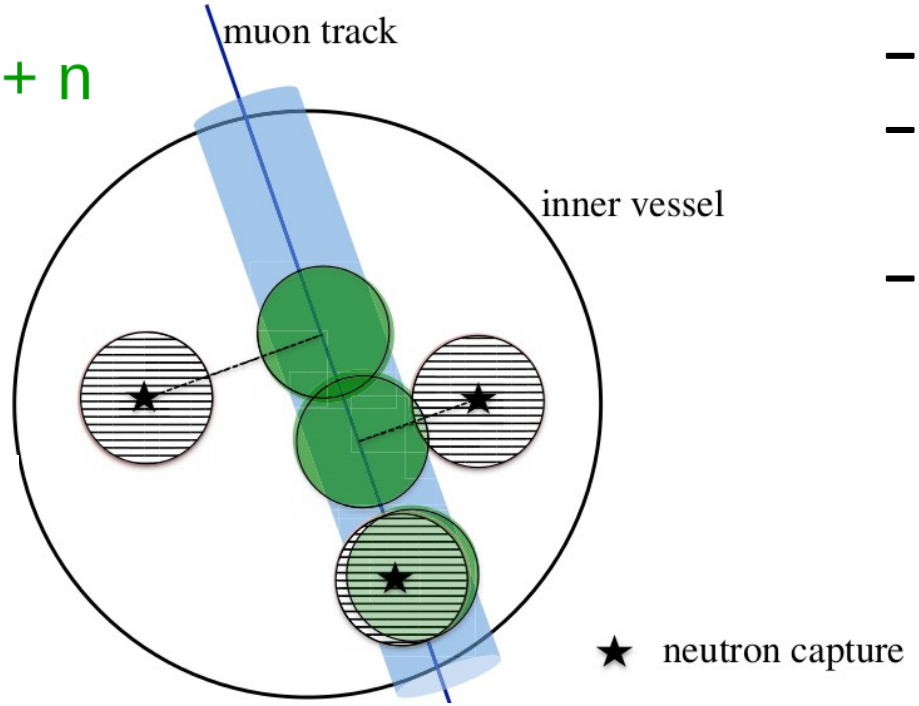
Isotope Inner vessel	Type	Energy [keV]
^{57}Co	γ	122 + 14 (89%)
^{57}Co	γ	136 (11%)
^{139}Ce	γ	165
^{203}Hg	γ	279
^{85}Sr	γ	514
^{54}Mn	γ	834
^{65}Zn	γ	1115
^{60}Co	γ	1173, 1332
^{40}K	γ	1460
^{222}Rn	α β	0–3200
^{14}C	β	0-156
^{241}Am–^{9}Be	neutrons	< 11000
	γ (H)	2233
	γ (^{12}C)	4946
Outer buffer		
^{228}Th (^{208}Tl)	γ	2615

3) TFC – Three Fold Coincidence

[1]
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

[2]
${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
(~30 min)

[3]
$H + n \rightarrow D + \gamma$
2.2 Mev (250 μs)



- Muon Tracking
- Neutron Capture

- Veto on cylindrical + spherical volumes around the neutrons