Results from Borexino on solar and geo- neutrinos

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On behalf of the BOREXINO collaboration

Laboratori Nazionali del Gran Sasso

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The Borexino Collaboration

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Joint Institute for Nuclear Research

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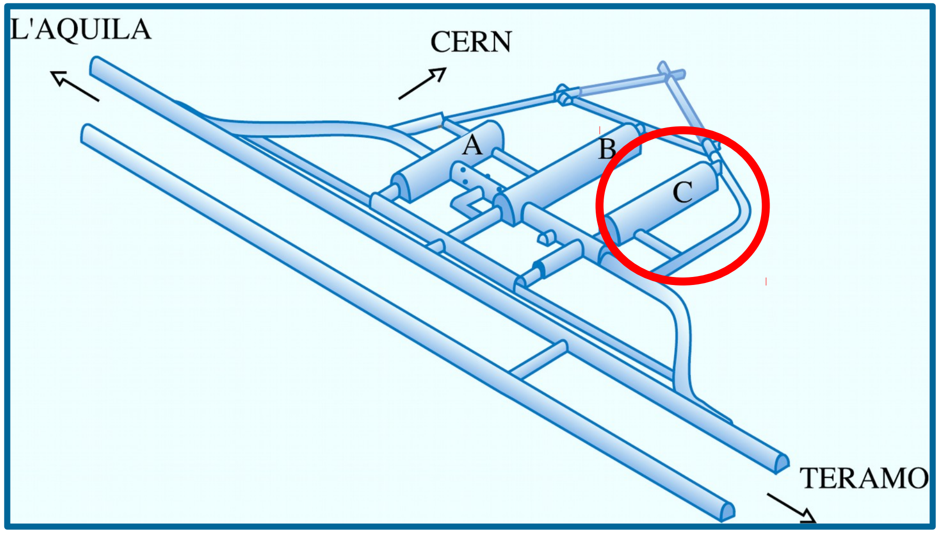
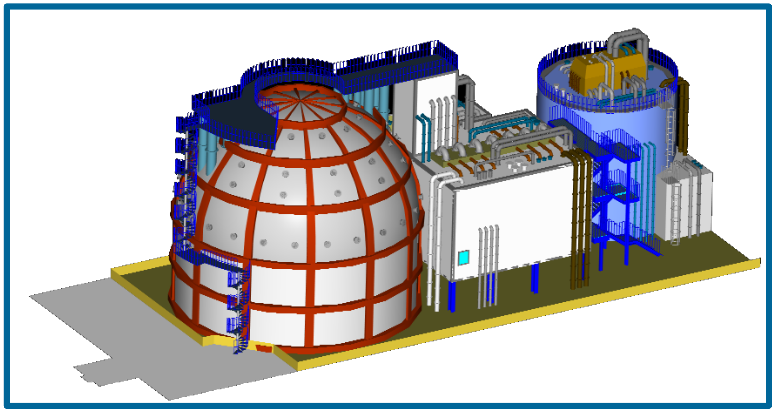
Solar Neutrino Physics

- **Solar neutrinos:**
  - Theoretical particle physics
  - Nuclear physics
  - Astrophysics
  - Astronomy
  - Experimental nuclear/particle physics

- Solar Neutrino problem can be considered solved
- Compare accurate observations with expectations of solar neutrinos (SSM): test models and understand something new.

Borexino is presently **the only detector able to measure** the solar neutrino interaction rate with neutrino **threshold** of **~ 150 keV** and to reconstruct the **energy spectrum** of the events.





Located in *Hall C*
Laboratori Nazionali del Gran Sasso (INFN)

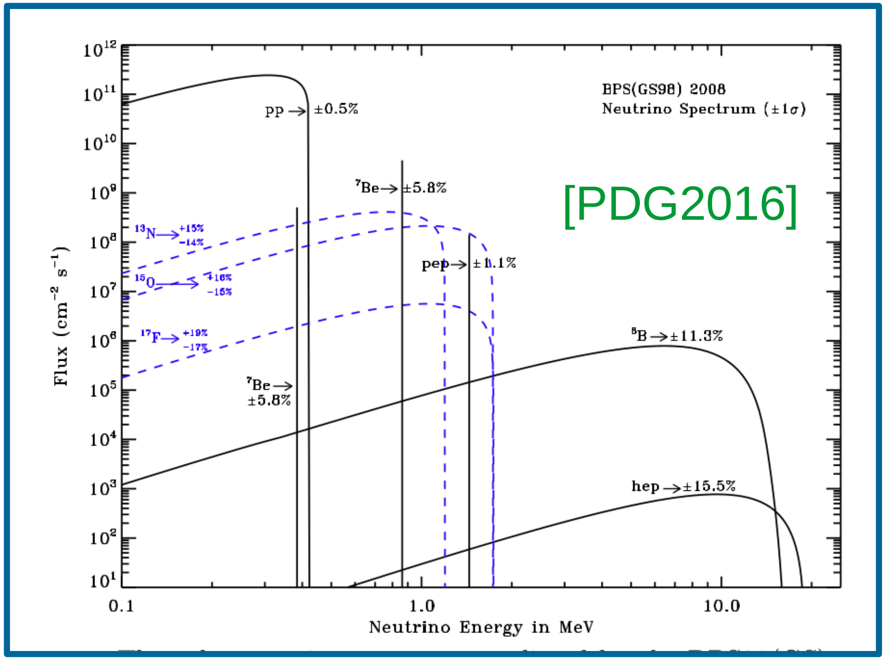
Nuclear Reactions and Neutrinos

PP chain (99% ☼)

PP-I (99.76%)	$p + p \rightarrow D + \beta^+ + \nu_e$ $p + D \rightarrow {}^3He + \gamma$ ${}^3He + {}^3He \rightarrow \alpha + 2p$
pep (0.24%)	$p + e^+ + p \rightarrow D + \nu_e$
PP-II (99.88%)	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$ ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ ${}^7Li + p \rightarrow 2\alpha$
PP-III (0.12%)	${}^7Be + p \rightarrow {}^8B + \gamma$ ${}^8B \rightarrow {}^8Be^* + \beta^+ + \nu_e$ ${}^8Be^* \rightarrow 2\alpha$
hep (PP-IV)	${}^3He + p \rightarrow \alpha + \beta^+ + \nu_e$
CNO-I (dominant)	${}^{12}C + p \rightarrow {}^{13}N + \gamma$ ${}^{13}N \rightarrow {}^{13}C + \beta^+ + \nu_e$ ${}^{13}C + p \rightarrow {}^{14}N + \gamma$ ${}^{14}N + p \rightarrow {}^{15}O + \gamma$ ${}^{15}O + {}^{15}N + \beta^+ + \nu_e$ ${}^{15}N + p \rightarrow {}^{12}C + \alpha$

CNO cycle (1% ☼)

Reaction	Abbr.	Flux ($cm^{-2}\ s^{-1}$)
$pp \rightarrow d\, e^+ \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \rightarrow d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
${}^3He\ p \rightarrow {}^4He\ e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
${}^7Be\ e^- \rightarrow {}^7Li\ \nu + (\gamma)$	${}^7Be$	$5.07(1 \pm 0.06) \times 10^{9}$
${}^8B \rightarrow {}^8Be^*\ e^+ \nu$	${}^8B$	$5.94(1 \pm 0.11) \times 10^{6}$
${}^{13}N \rightarrow {}^{13}C\ e^+ \nu$	${}^{13}N$	$2.88(1 \pm 0.15) \times 10^{8}$
${}^{15}O \rightarrow {}^{15}N\ e^+ \nu$	${}^{15}O$	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
${}^{17}F \rightarrow {}^{17}O\ e^+ \nu$	${}^{17}F$	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$



Borexino Results

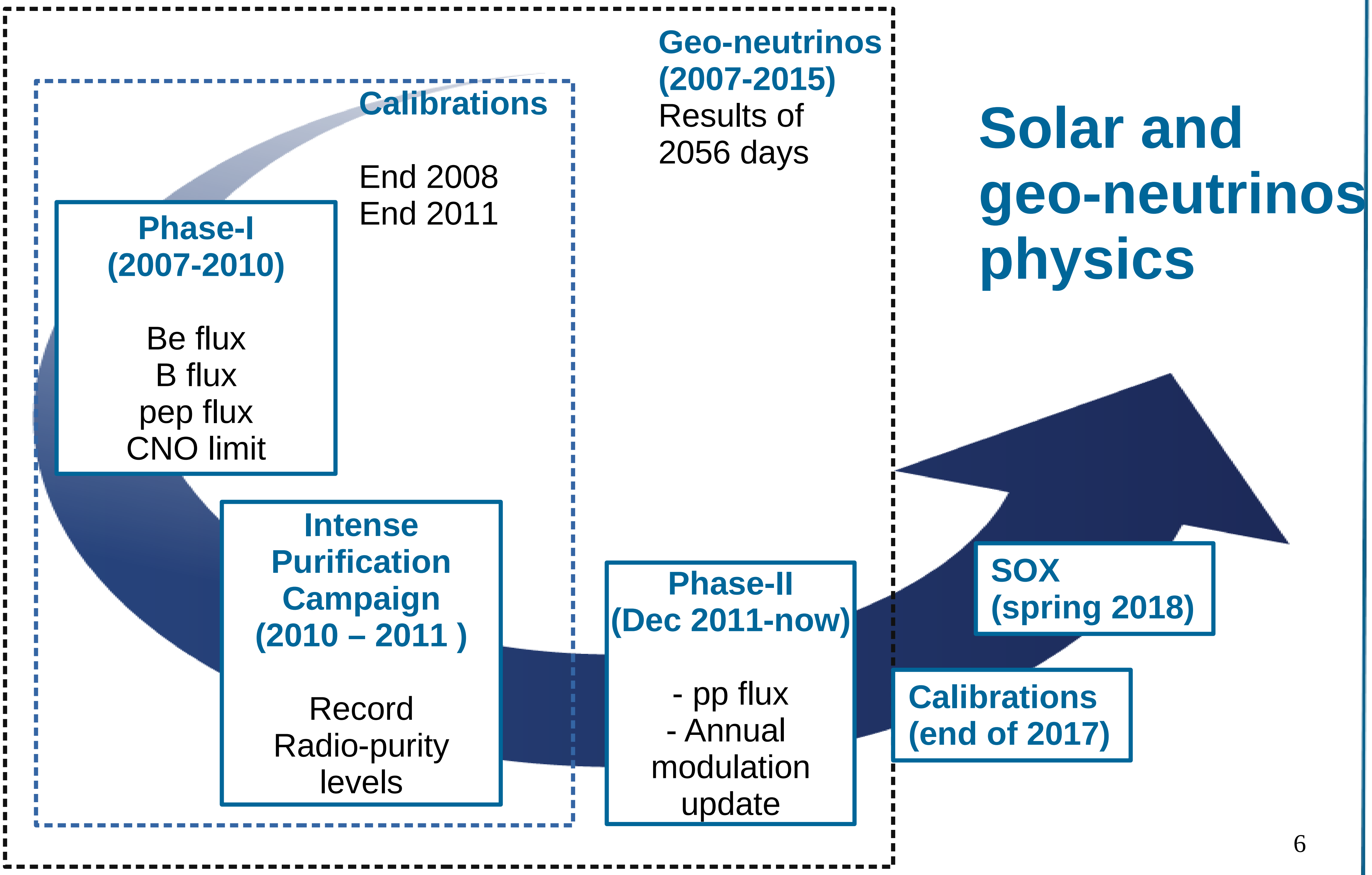
Solar physics results:

- First measurement of the interaction rate of the ^{7}Be (862 keV) neutrinos (5% accuracy) [Phys.Rev.Lett. 107 (2011) 141302]
- Exclusion of any significant day-night asymmetry of the ^{7}Be solar neutrino flux [Phys.Lett. B707 (2012) 22-26]
- Annual modulation observation of the ^{7}Be neutrino flux (recently updated) [Astropart.Phys. 92 (2017) 21-29]
- First direct observation of the mono-energetic 1440 keV pep solar neutrinos [Phys.Rev.Lett. 108 (2012) 051302]
- Set of the strongest upper limit of the CNO solar neutrinos flux [ibid.]
- Measure of the ^{8}B solar neutrinos with an energy threshold of 3 MeV [Phys.Rev. D82 (2010) 033006]
- First spectroscopical observation of pp neutrinos [Nature 512 (2014) no.7515, 383-386]

Other results:

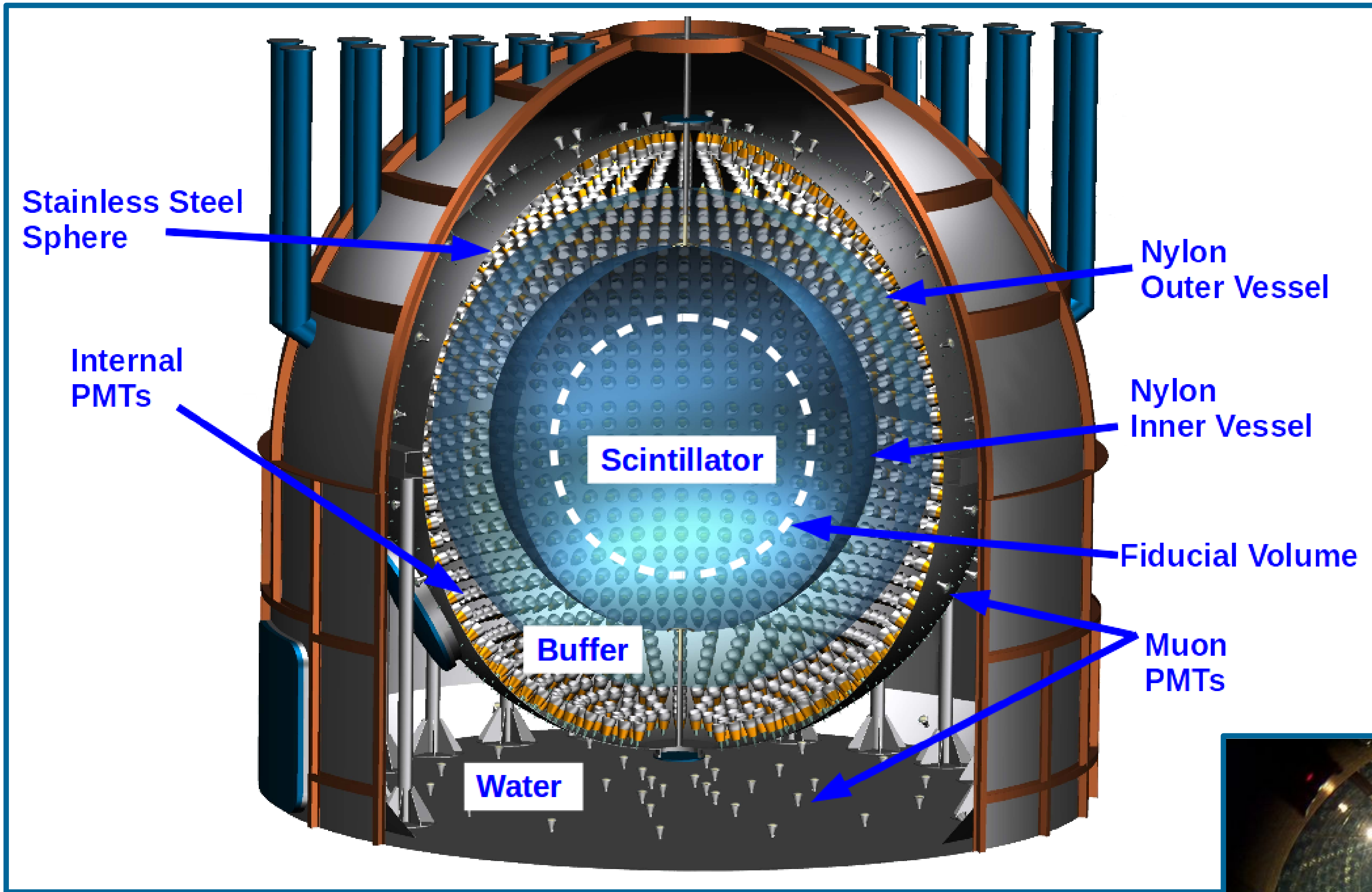
- 5σ geo-netrinos detection
- **Rare processess (recent):** Charge conservation [Phys.Rev.Lett. 115 (2015) 231802], Low-energy neutrinos with GRB [Astropart.Phys. 86 (2017) 11-17] and GW [arXiv:1706.10176].

Timeline



Calibrations
End 2008
End 2011
Geo-neutrinos
(2007-2015)
Results of
2056 days
Solar and
geo-neutrinos
physics
Phase-I
(2007-2010)
Be flux
B flux
pep flux
CNO limit
Intense
Purification
Campaign
(2010 – 2011)
Record
Radio-purity
levels
Phase-II
(Dec 2011-now)
- pp flux
- Annual
modulation
update
SOX
(spring 2018)
Calibrations
(end of 2017)

The Detector

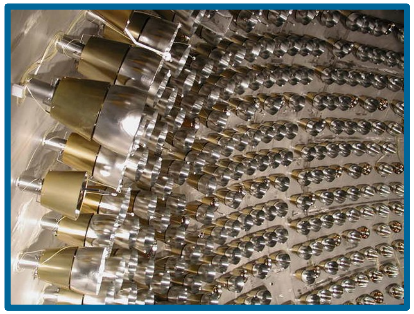


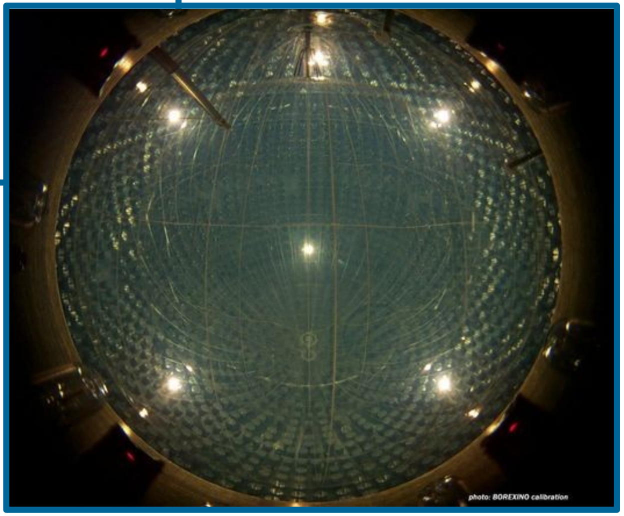
13.7 m stainless sphere:
~ 1300 tons of Pseudocumene (PC)
~300 tons Inner Vessel scintillator (PC+PPO)

More than 2000 PMTs:
34% Coverage
Light Yield = 500 PE/MeV

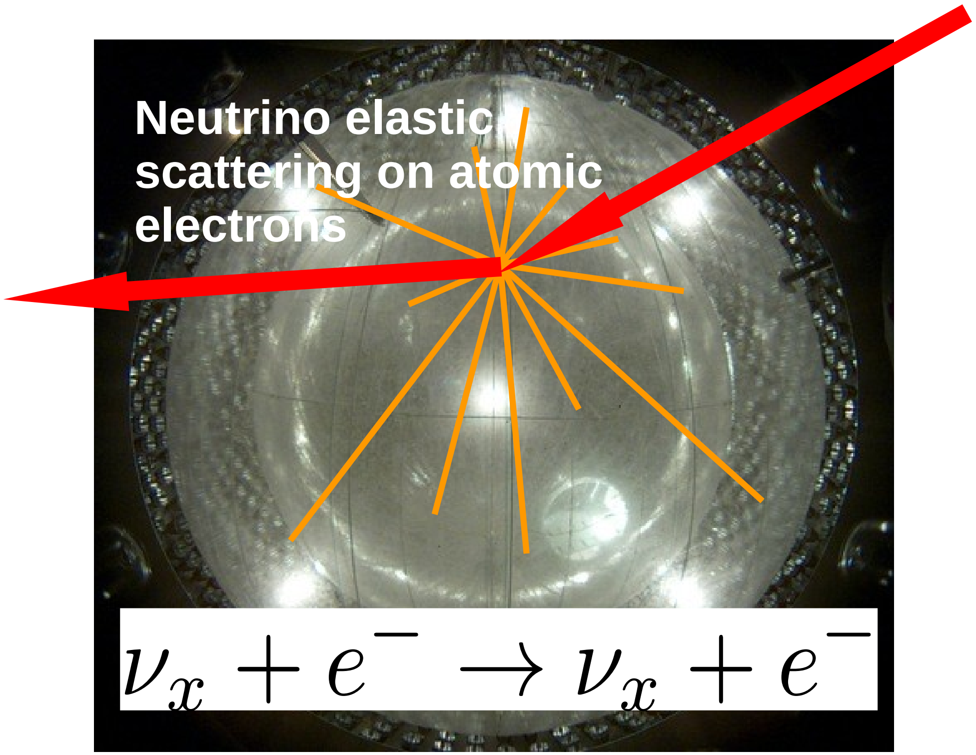
Cherenkov muon veto
~200 PMTs

Very (very) low background:
- Nitrogen stripping
- Distillation
- Water Extraction

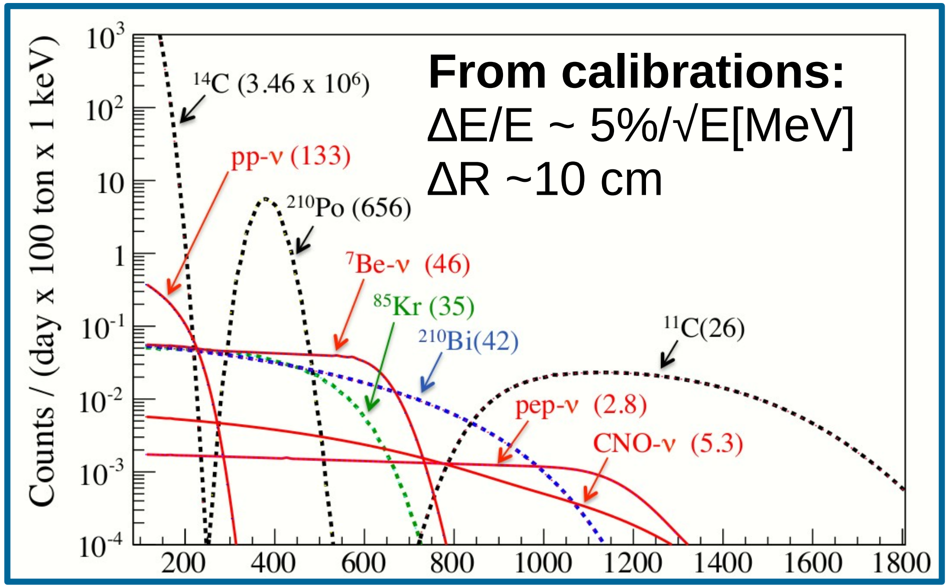




The Signal



$$\nu_x + e^- \rightarrow \nu_x + e^-$$



From calibrations:
ΔE/E ~ 5%/√E[MeV]
ΔR ~10 cm

Comparison of major contaminants

[cpd/100t]	Phase-I	Phase-II
^{210}Po	>2000	~50
^{210}Bi	~40	x2 less
^{85}Kr	~30	x(5-6) less

Phase-II

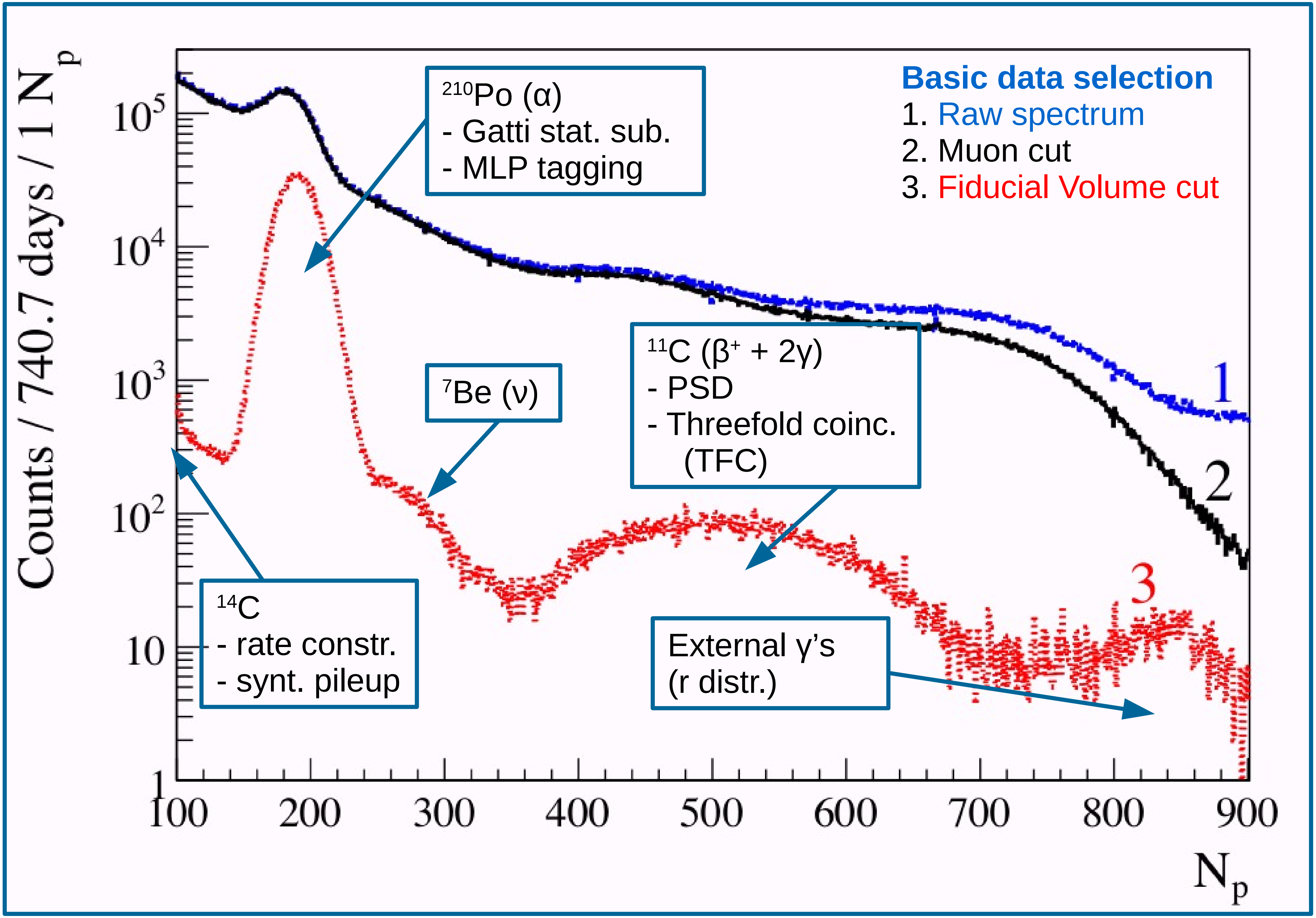
^{238}U (Bi-Po 214)
< 9.7 x 10 -19 g/g (95% CL)

^{232}Th (Bi-Po 212)
< 1.2 x 10 -18 g/g (95% CL)

^{40}K no evidence (TBD)

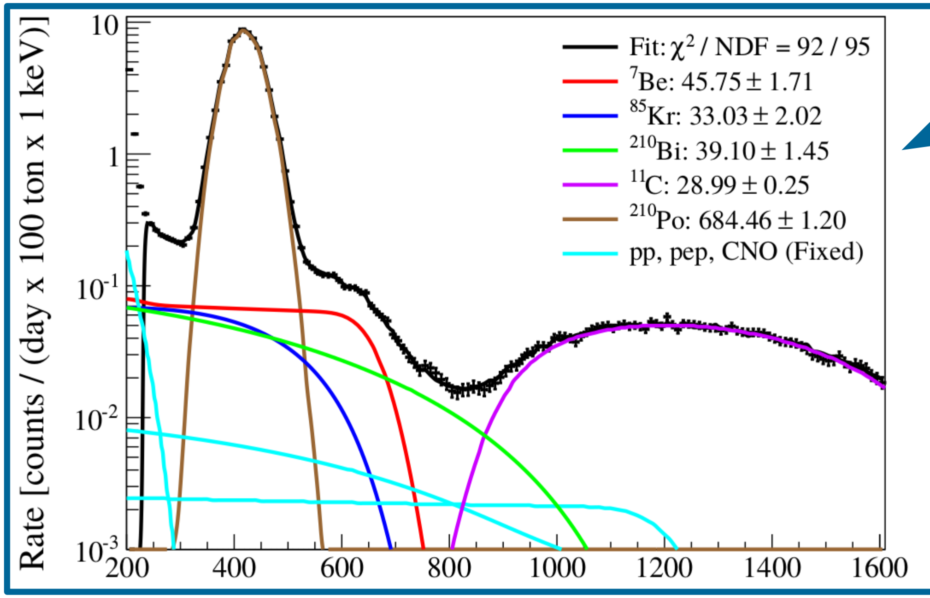
^{39}Ar << ^{85}Kr

The Borexino Spectrum (Phase-I)

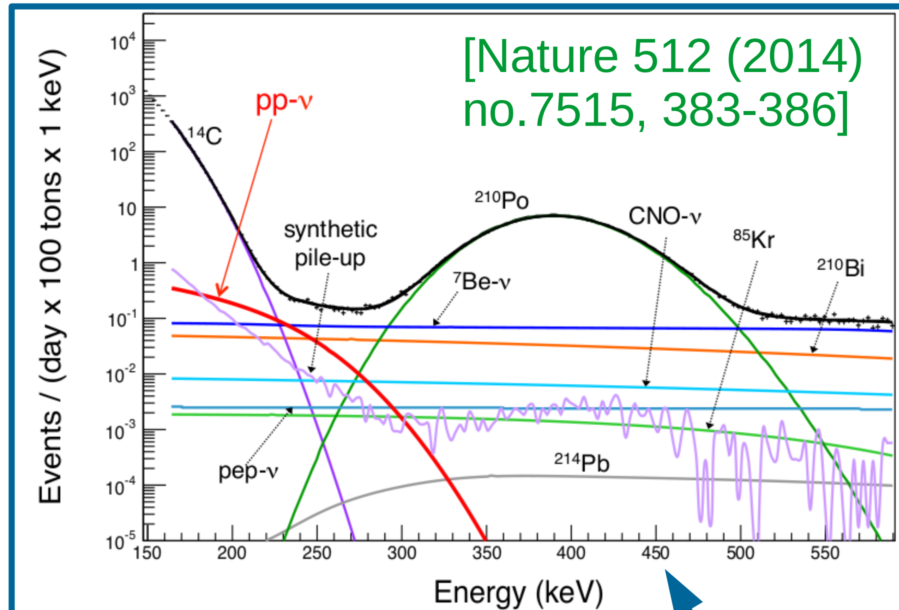


Spectral fit results 1

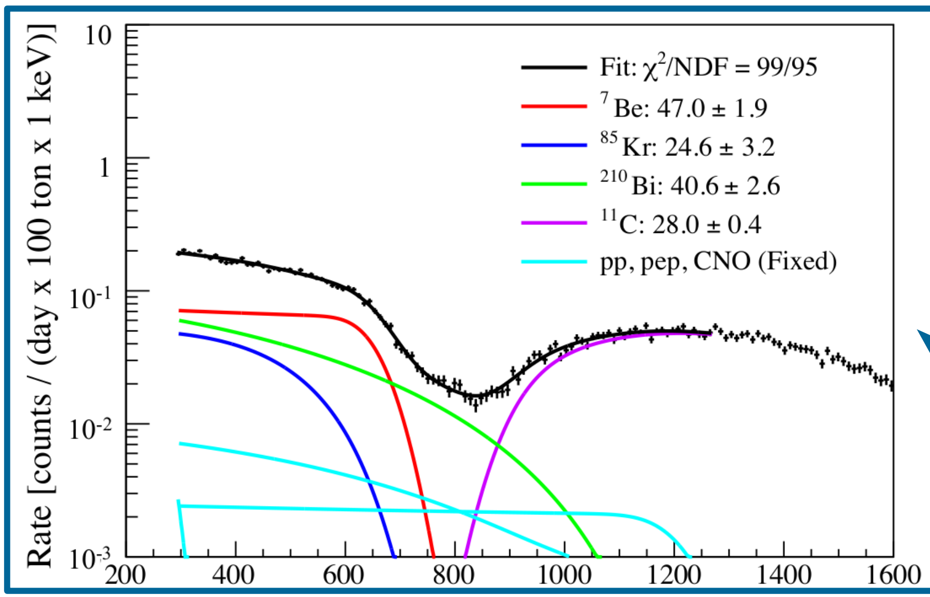
[Phys.Rev. D89 (2014) no.11, 112007]



^{7}Be region energy spectrum With ^{210}Po alpha peak



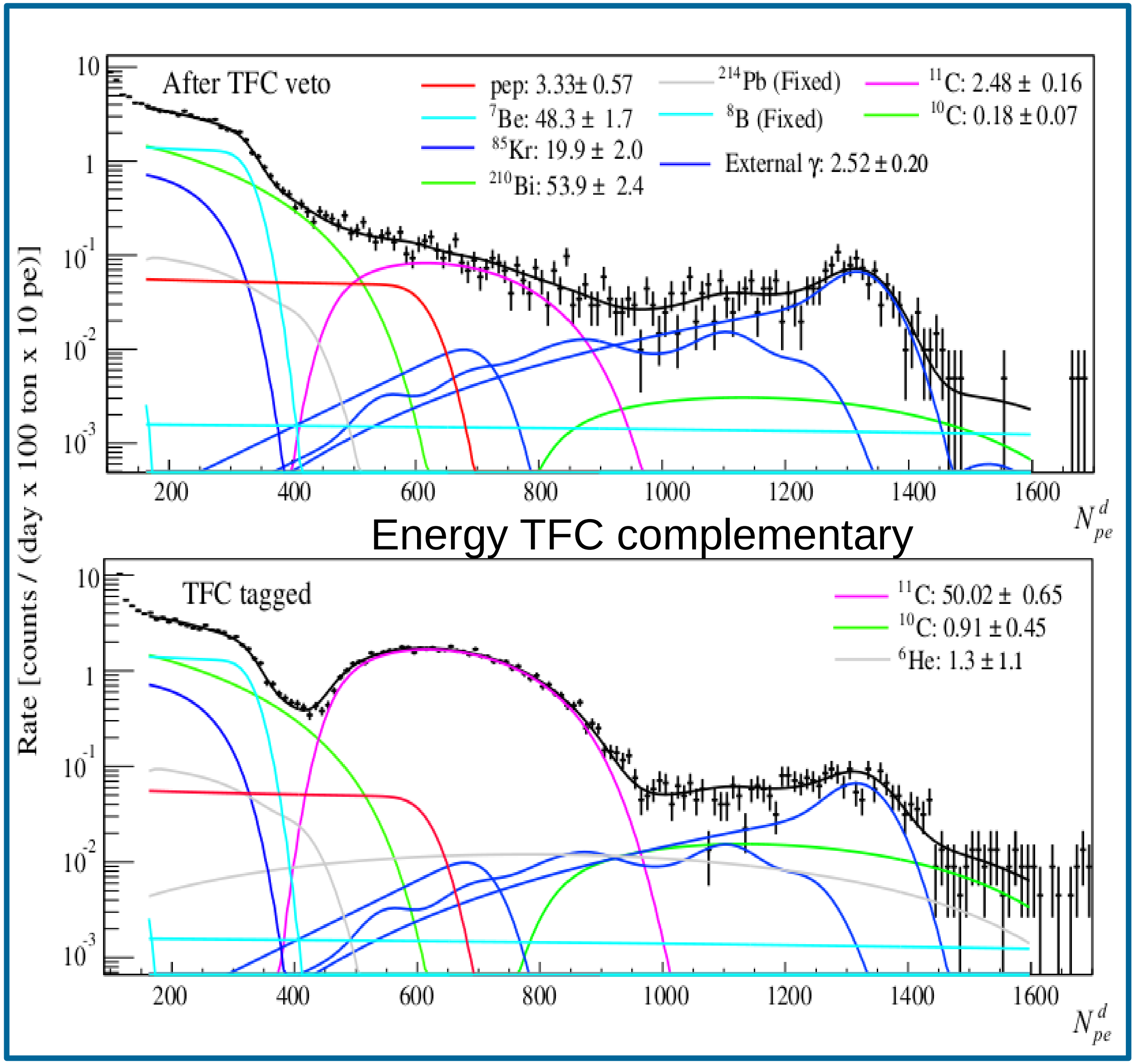
PP low energy fit



^{7}Be region energy spectrum Without ^{210}Po alpha peak

Spectral fit results 2

Energy TFC tagged



Energy TFC complementary

Fit Methods:

Analytical
- different energy estimators
- different response modelings

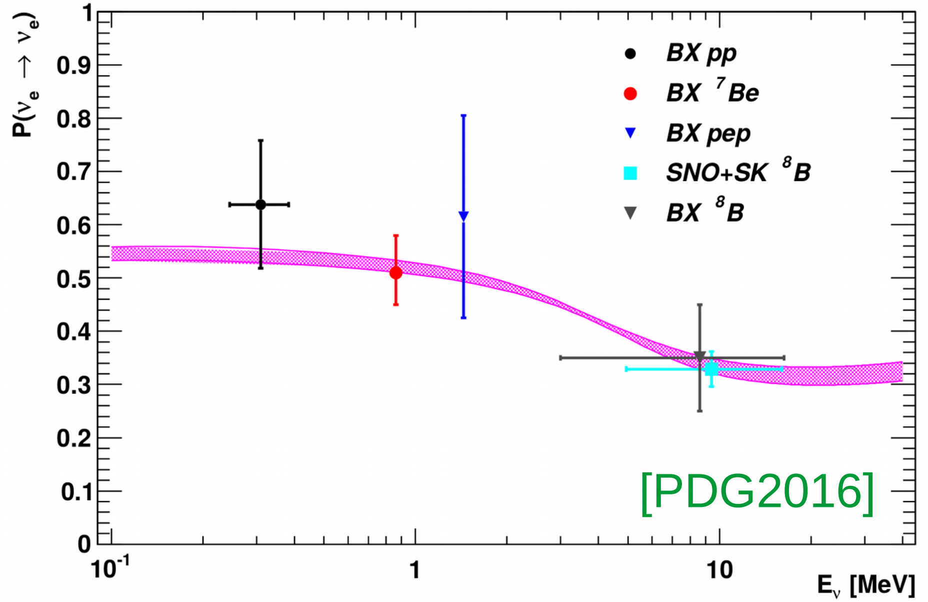
Monte Carlo
- detailed MC modeling tuned on calibrations (new MC recently published)

Multivariate approach (Maximal sensitivity)
- Energy TFC tagged
- Energy TFC complementary
- Radial Distribution
- Pulse shape likelihood

[Phys.Rev. D89 (2014) no.11, 112007]

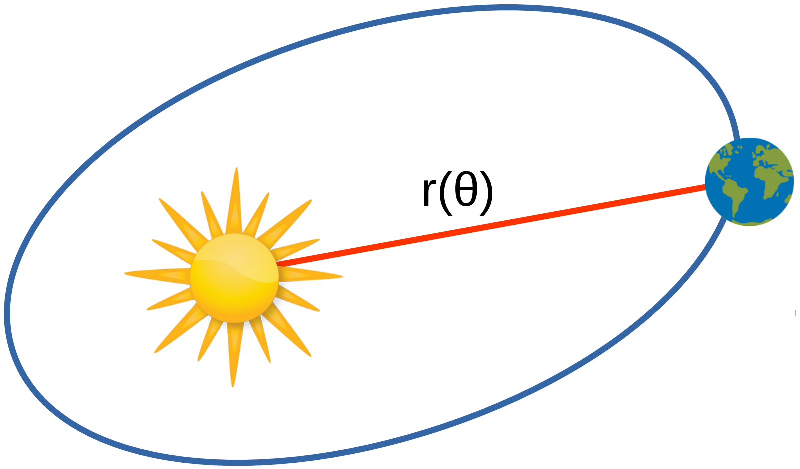
Solar neutrinos with Borexino

Neutrino species	Interaction rate [cpd/100t]	Flux [cm $^{-2}$ s $^{-1}$]	References
^{7}Be (863 keV)	46.0 ± 1.5 +1.5 -1.6	3.1 ± 0.15 x 10^{9}	[Phys.Rev.Lett. 107 (2011) 141302]
pep (1442 keV) CNO	3.1 ± 0.6 ± 0.3 < 7.9 (95% CL)	1.6 ± 0.6 x 10^{8} <7.7 x 10^{8} (95% CL)	[Phys.Rev.Lett. 108 (2012) 051302]
^{8}B(> 3 MeV)	0.22 ± 0.04 ± 0.01	2.4 ± 0.4 ± 0.1 x 10^{6}	[Phys.Rev. D82 (2010) 033006]
pp	144 ± 13 ± 10	6.6 ± 0.7 x 10^{10}	[Nature 512 (2014) no.7515, 383-386]



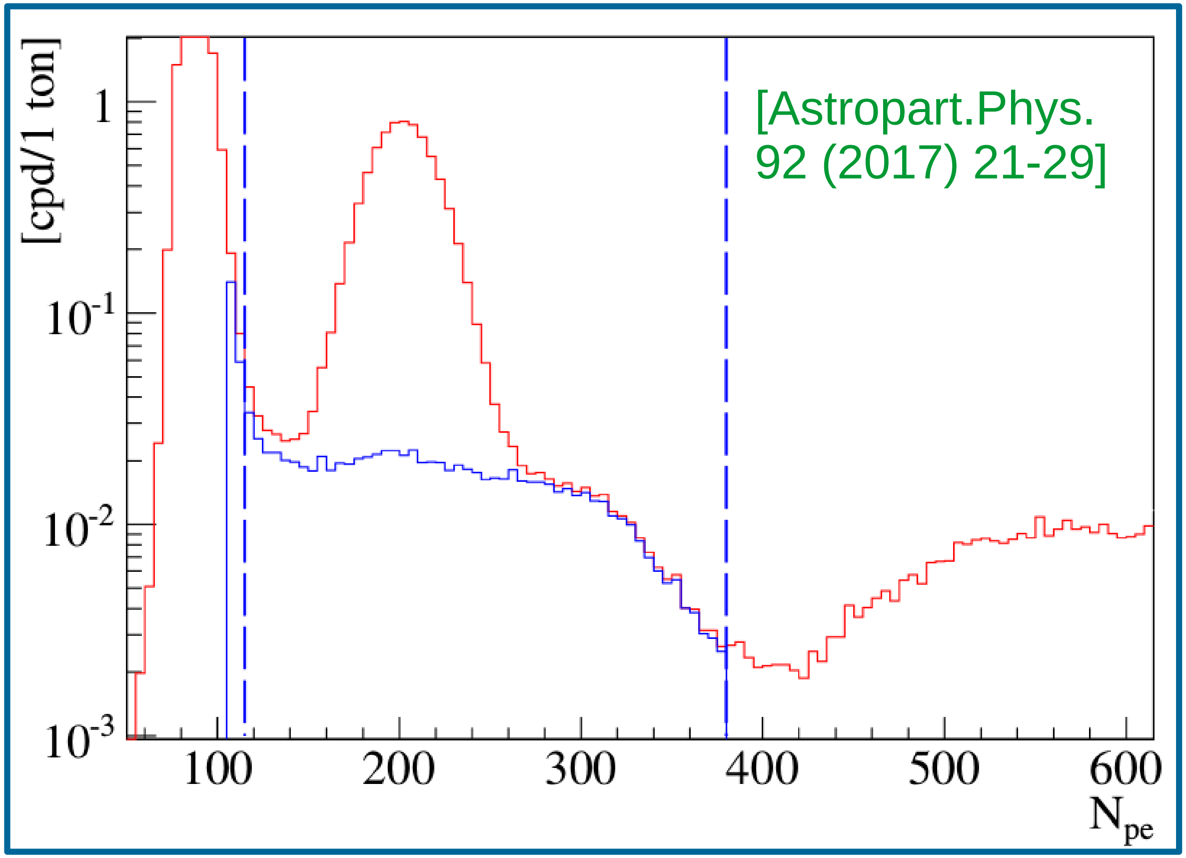
P_{ee} survival probability in the MSW-LMA scenario with Borexino data only!

^{7}Be seasonal modulation



Earth orbit eccentricity = 0.0167
Corresponds to ~3.4% modulation amplitude in the solar neutrino flux

$$\Phi_\nu \simeq \frac{1}{\bar{r}^2}[1 + 2\epsilon \cos(2\pi(t - t_0)/T)]$$



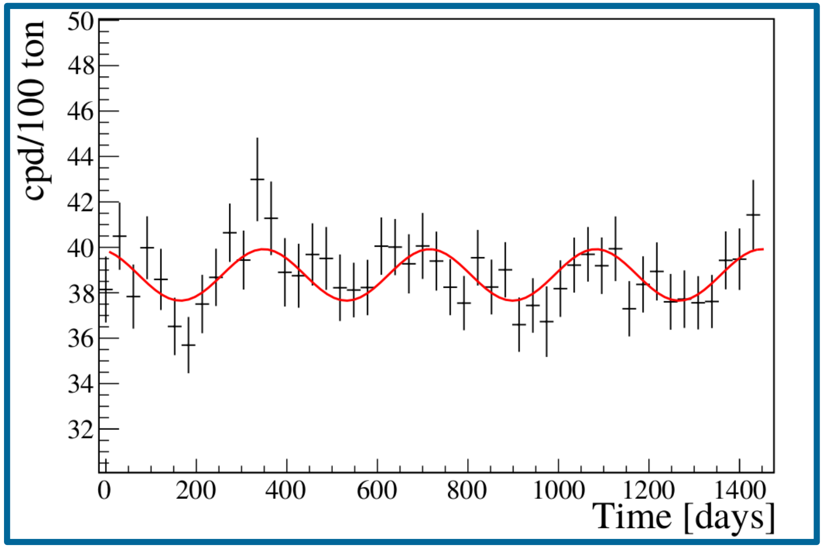
Event Selection:

Wide range including mostly the ^{7}**Be shoulder.**

^{210}**Po alphas tagged and removed** with a high efficiency PSD based on *Multi-Layer Perceptron* (**MLP**) trained with ^{214}Bi-Po coincidences from ^{222}Rn during the water extraction

Recent Results

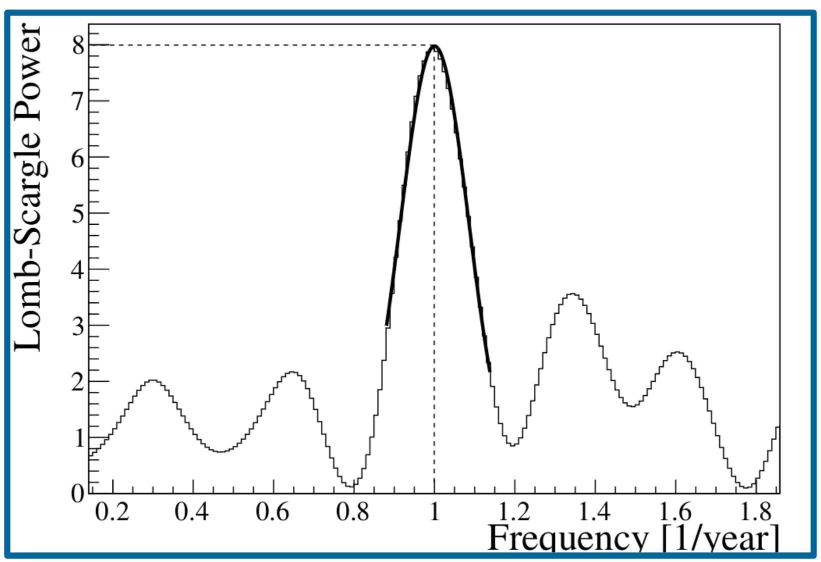
I) Sinusoidal fit



The **period**, **amplitude**, and **phase** of the observed time evolution of the signal are **consistent with its solar origin**, and **the absence of an annual modulation is rejected at 99.99% C.L.**

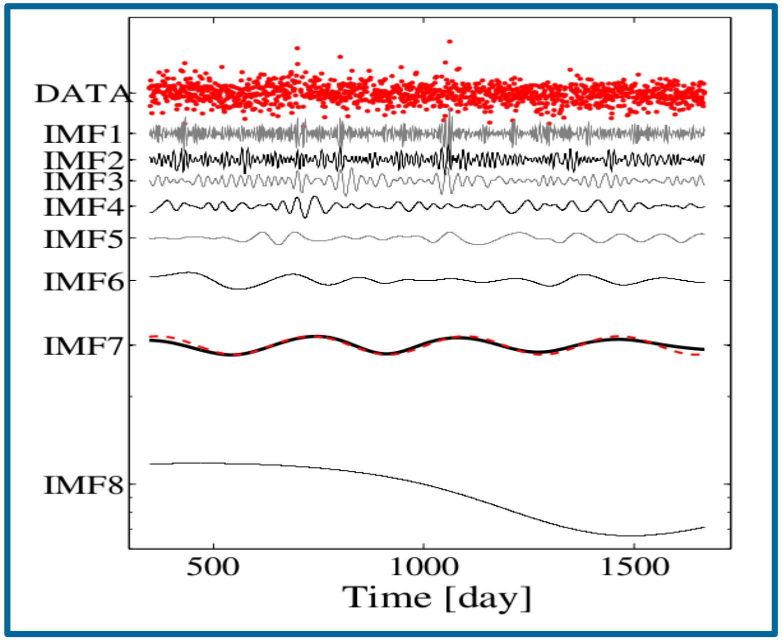
	Simulated Data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

2) Lomb-Scargle



[Astropart.Phys. 92 (2017) 21-29]

3) Empirical Mode Decomposition



Three methods, all in agreement!

Sensitivity to CNO: a challenge

Motivations:

- According to astrophisical models, CNO cycle is responsible of ~1% of the solar luminosity. Main mechanism of energy generation in massive stars.
- Its measurement will allows us to complete the SSM and stellar astrophysics.
- A solution for the *solar metallicity problem*. Relative species predicted by nuclear physics, absolute abundance still unknown.

Experimental issues:

- Low rate expected in Borexino: **~5 cpd/100t (HZ)**
  ~3 cpd/100t (LZ)

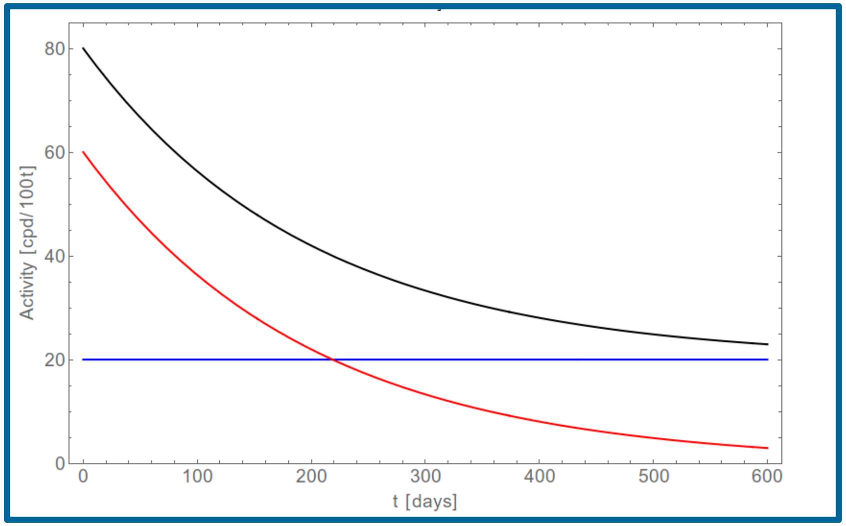
- Very low and almost degenerate with ^{210}Bi beta spectrum

- Same region as **pep** (but correlation **pp-pep** can help!)

^{210}Bi independent constraint

^{210}Pb (β^-, τ = 32y) → ^{210}Bi (β^-, τ = 7d) → ^{210}Po (α, τ = 200d)

- Assuming the secular equilibrium the ^{210}Bi rate can be determined by the ^{210}Po rate [F. Villante et al. Phys.Lett. B701 (2011) 336-341]:



Example:

– Total rate A(t)
– *Unsupported* ^{210}Po term A_0
– *^{210}Bi-supported* ^{210}Po term B_0

$$A(t) = (A_0 - B_0)e^{-t/\tau_{Po}} + B_0$$

- Contaminants must be homogeneous.
- A **stable temperature vertical gradient** is required to **prevent motions** of the contaminants in the FV through convection. Pure diffusive regime cannot bring contaminants (^{210}Po) towards the center before it decays

The thermal insulation and temperature active control system

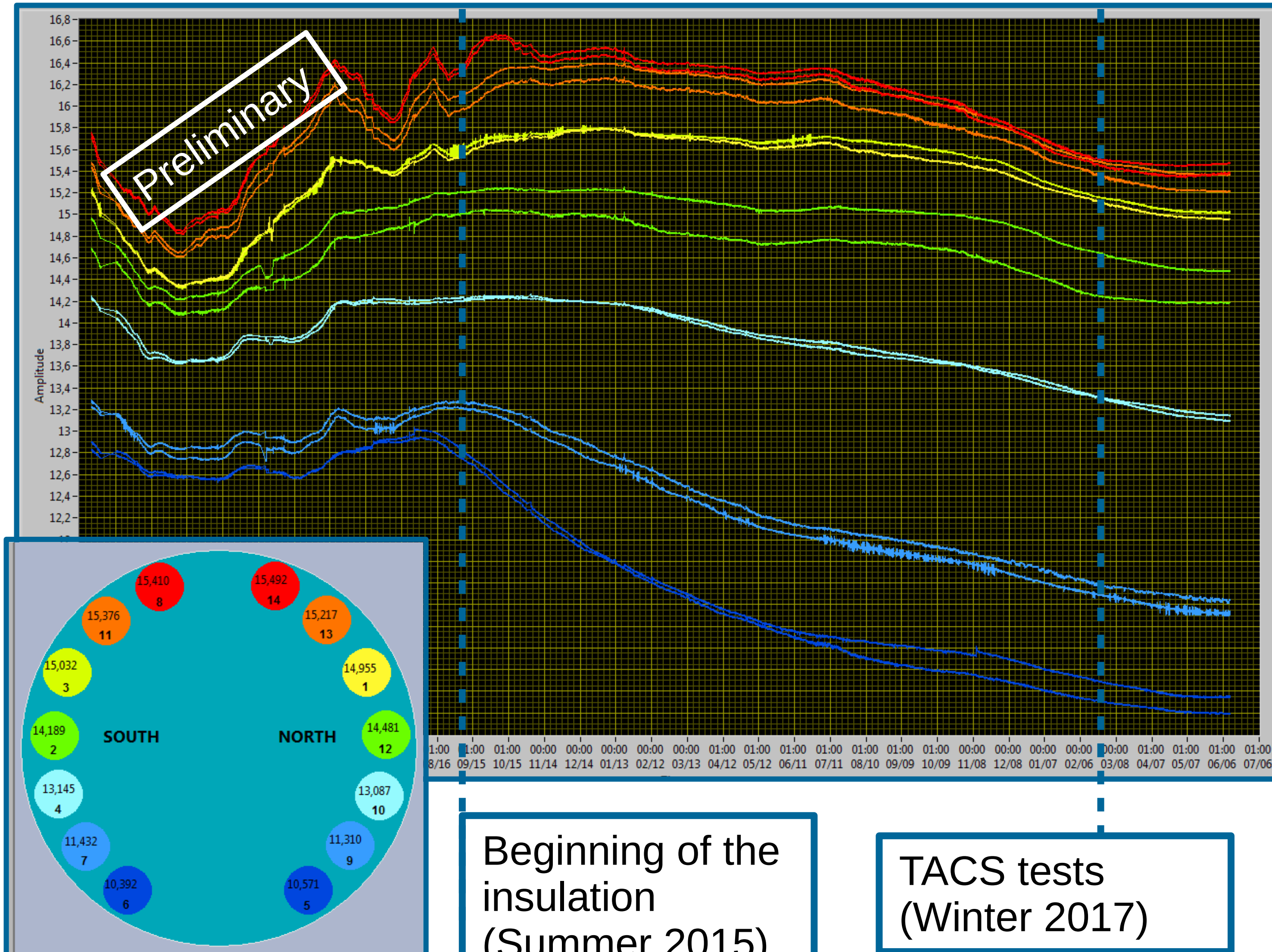
Before thermal insulation

After thermal insulation

- Since the end of 2015 the detector is surrounded by a thick layer of **rock wool**
- The dome of Borexino is equipped with a **water coil** able to provide heat for compensating the heat sink from the bottom (rock at ~6°C)

Temperature evolutions

Coils of the TACS system before the insulation

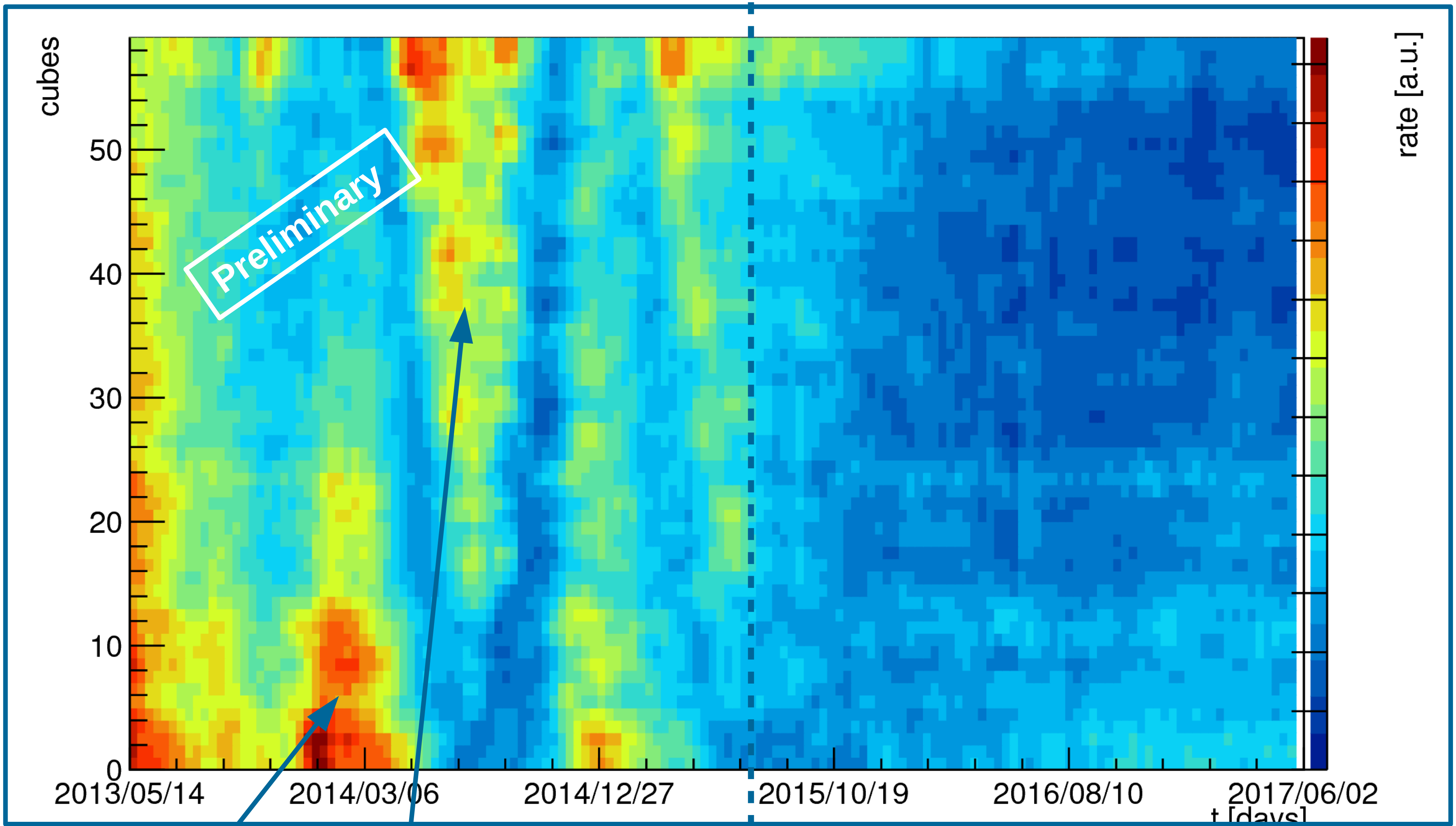


Sensors on the Sphere

Beginning of the insulation (Summer 2015)

TACS tests (Winter 2017)

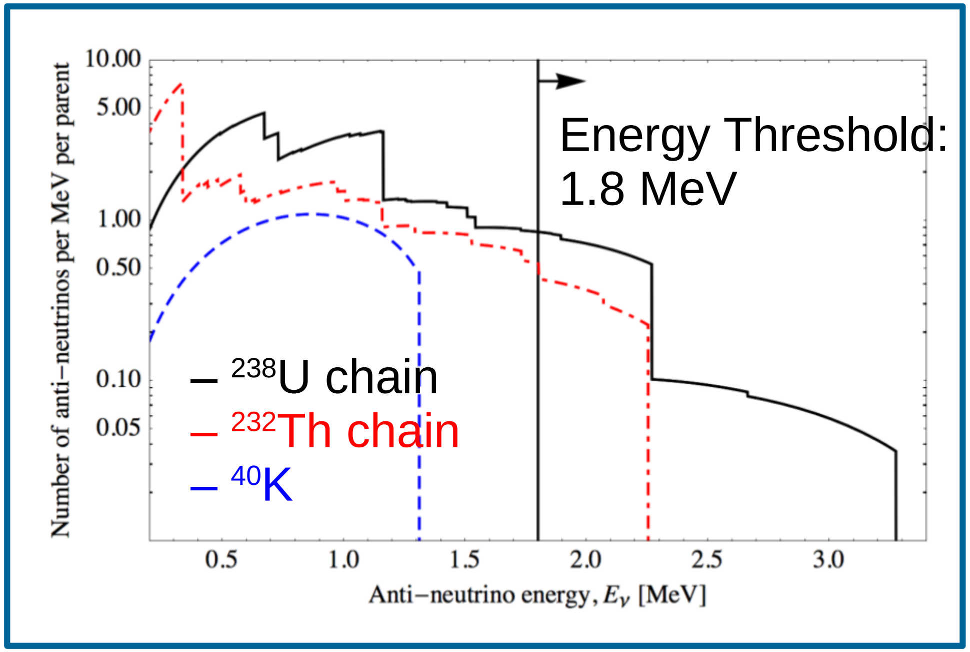
Background Evolutions



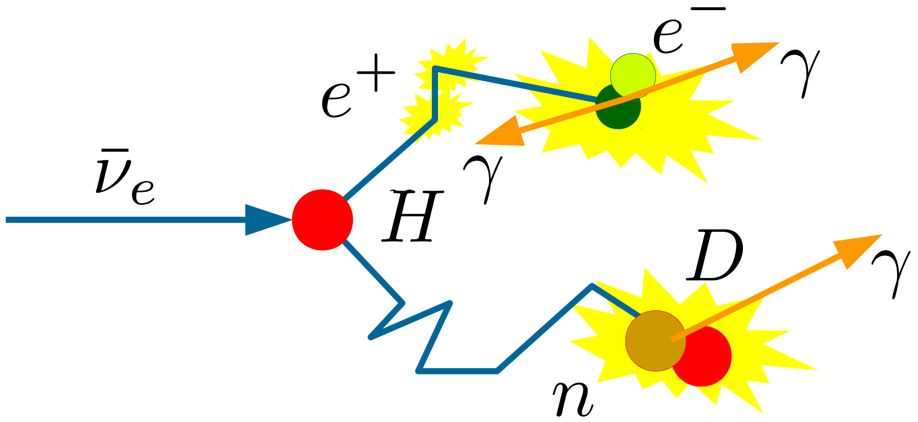
Convective motions before the insulation

Beginning of the insulation (Summer 2015)

Borexino and geo-neutrinos

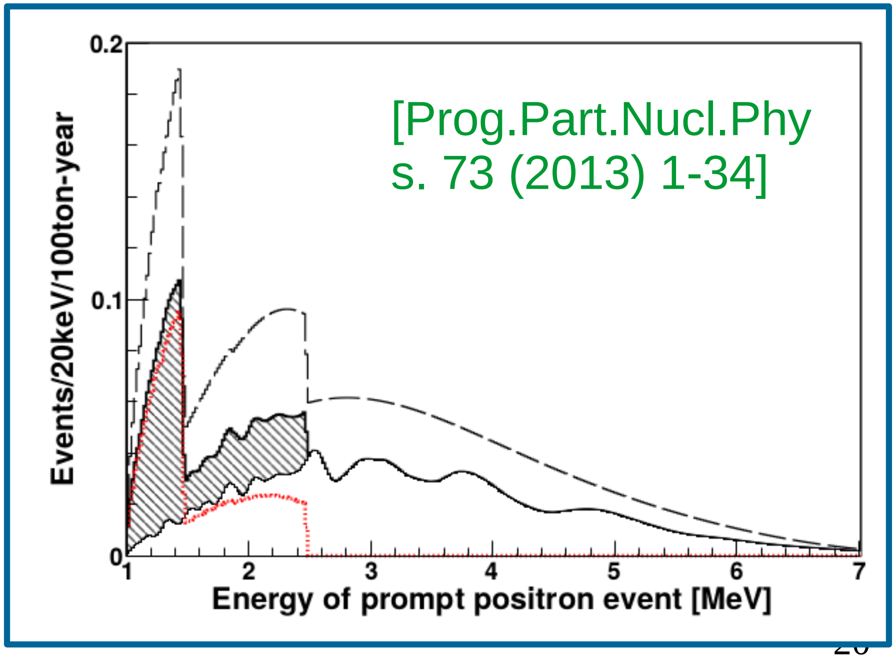


Signal in Borexino: inverse beta



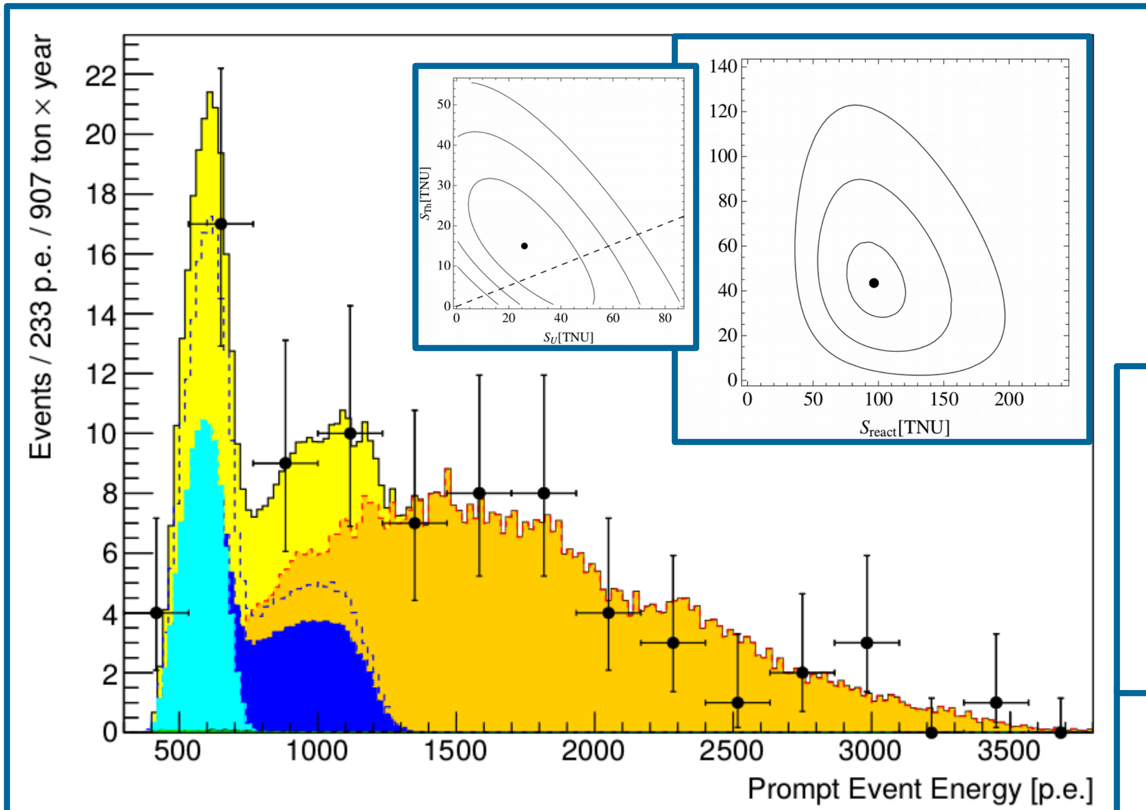
Geo-neutrinos are emitted by long-lived radioactive decays in the Earth.

Why important?
- Energy for plate tectonics
- Mantle composizion
- contribution to W_{Earth}
- Th/U ratio (solar system formation)
- Geo-reactor (?)



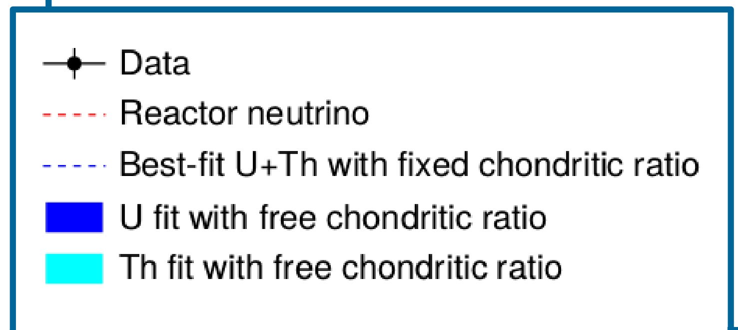
Expected spectrum: geo-nu + reactors

Geo-neutrino results

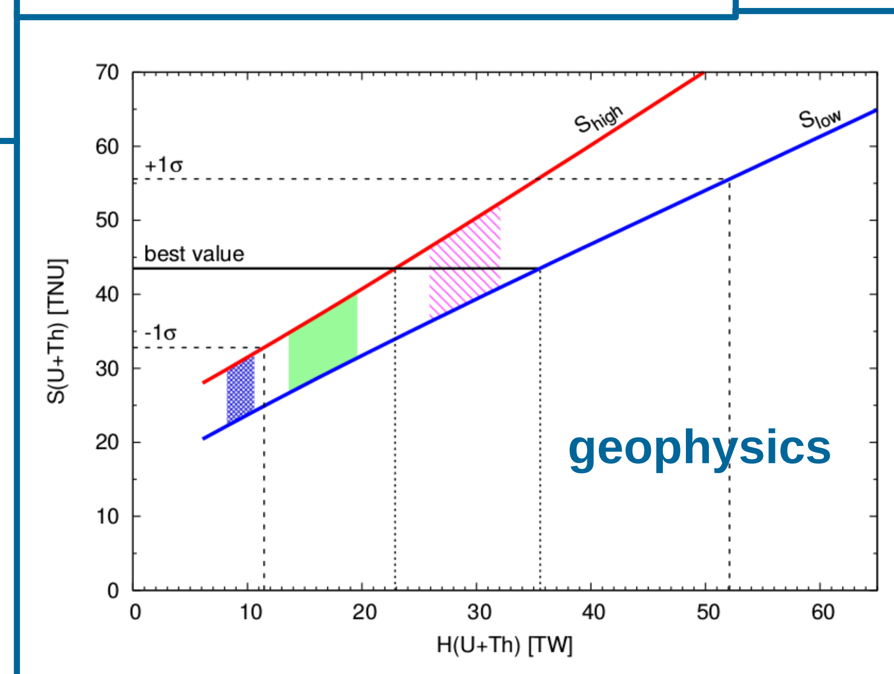


Spectral fit:
- geo-neutrinos vs. reactors
- Th/U free and fixed **chondritic ratio**
- geo-reactor upperlimit

[Phys.Rev. D92 (2015) no.3, 031101]



Geo-neutrino signal in Borexino from U and Th as a function of radiogenic heat released in radioactive decays of U and T



Earth thermal power:
(U + T h + K) = 33^{+28}_{-20} TW (radiogenic only),
to be compared with the global terrestrial power output P_{tot} = 47 ± 2 TW

Present and near future

- **New Monte Carlo** (emission, propagation, electronics): energy response and time distribution <1% (calibrations) in between 100 keV and several MeV [arXiv:1704.02291]. (Global fit)
- **Improvement of the analytical methods**: new response modelings. (Global fit).
- **New fitting tools** and fitting **strategies.**
- **Phase-II: ~5 year of high quality** and **low background**. Future program:

  Step-I: Precision measurement of ^{7}Be, pep, pp and CNO limit **(coming soon!)**

  Step-II: New release of ^{8}B at low threshold (>3MeV)

  Step-III: Fighting for Improvement of the CNO sensitivity.
- **Update of geo-neutrinos**
- **Other measurement:** neutrino magnetic moment update
- **SOX project (2018) – Short Baseline Oscillation (in this conference)**

Thank you for your attention.