Solar Neutrino Physics with Borexino

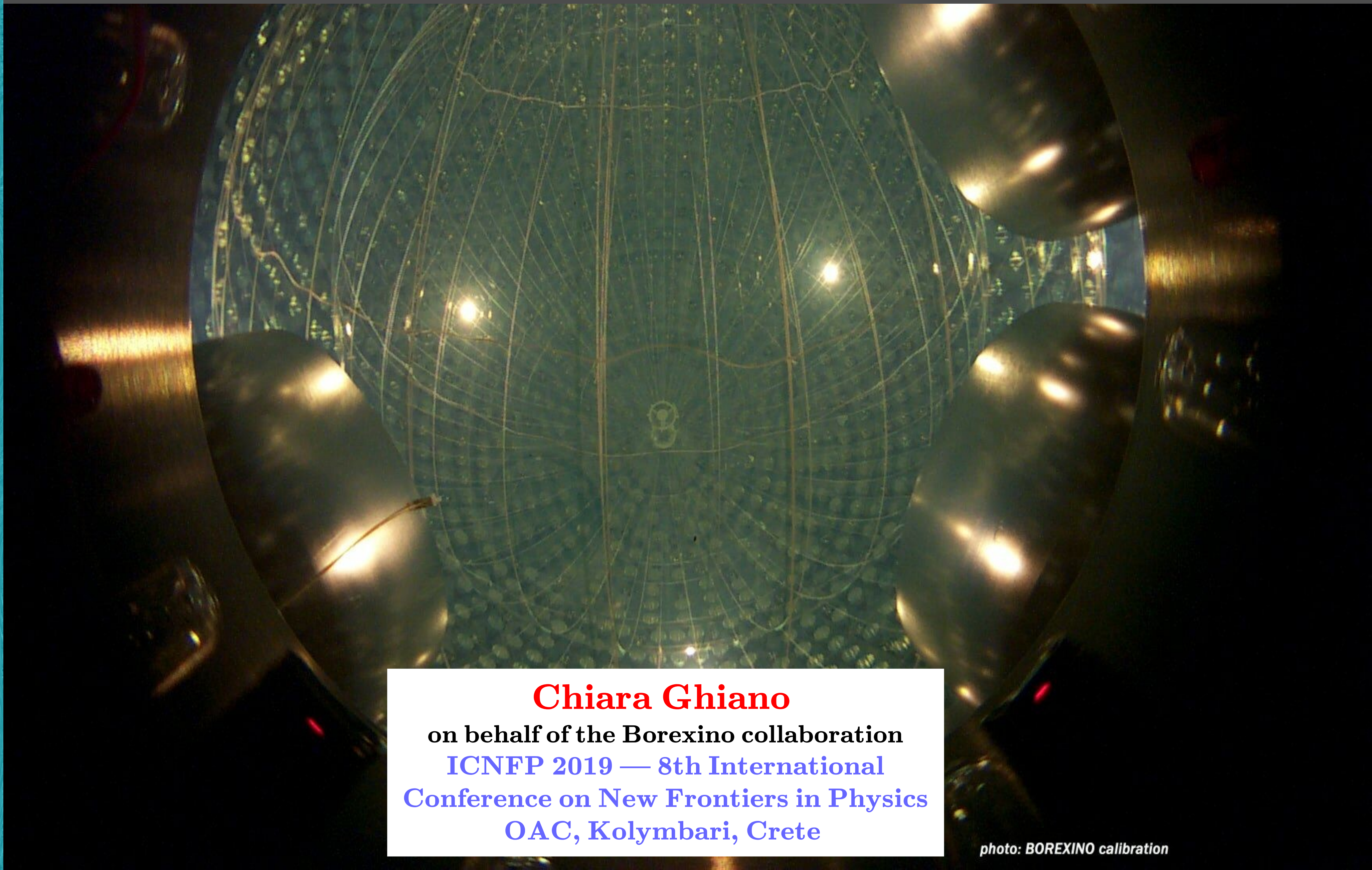


photo: BOREXINO calibration

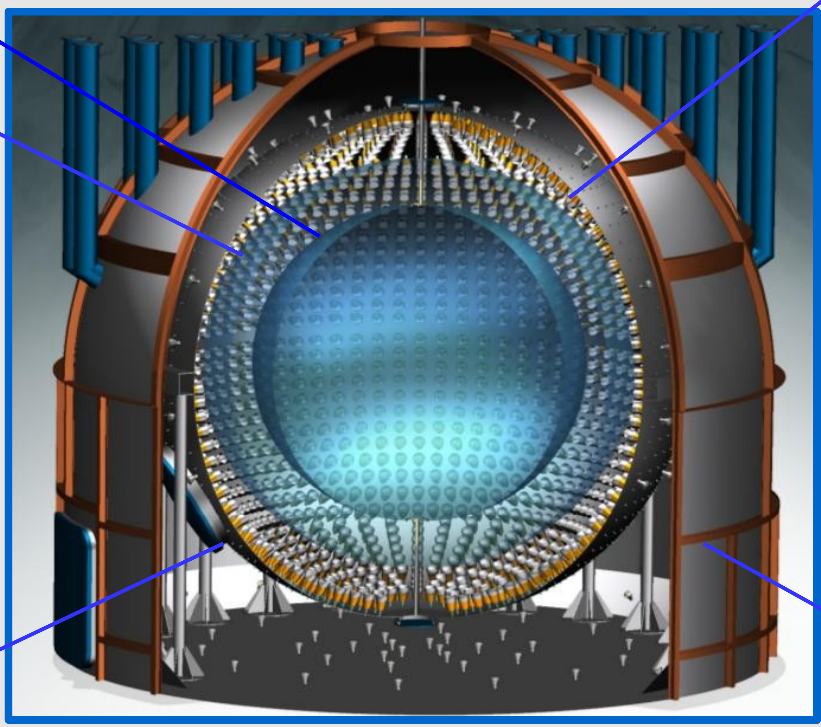
Chiara Ghiano
on behalf of the Borexino collaboration

ICNFP 2019 — 8th International Conference on New Frontiers in Physics
OAC, Kolymbari, Crete

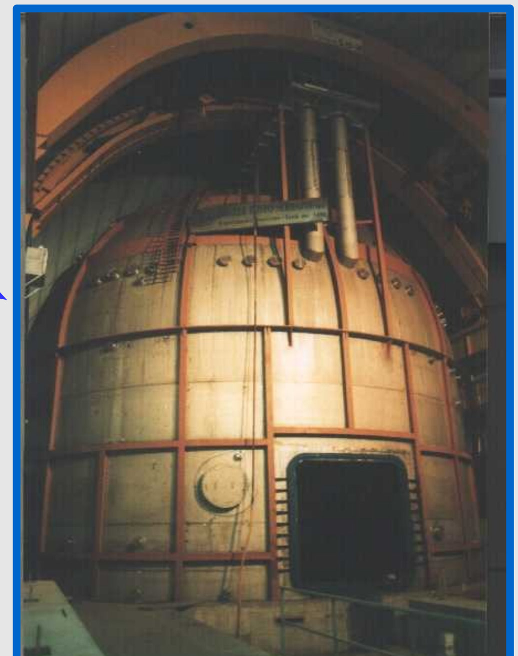
The BOREXINO detector

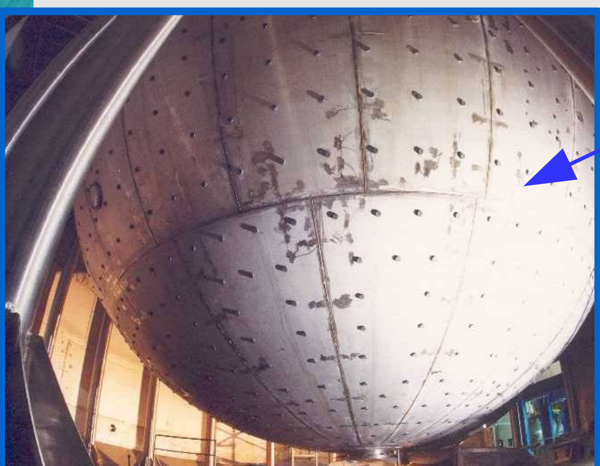
Two Nylon balloons 150 µm thick
Inner Vessel
(8.5 m, V = 340 m³)
Filled with 278 tons of scintillator
(PC @ 1.5 g/l of PPO)
Inner Buffer (11.5 m)
filled with PC + DMP

2212 8” ETL 9351
PMTs mounted inside the SSS



Water Tank
(d=18 m, V = 2400 m³)
Shielding from γ and n.
Water Cerenkov detector
(Muon Veto) 208 PMTs





Stainless Steel Sphere
(d= 13.7 m, Volume = 1340 m³)

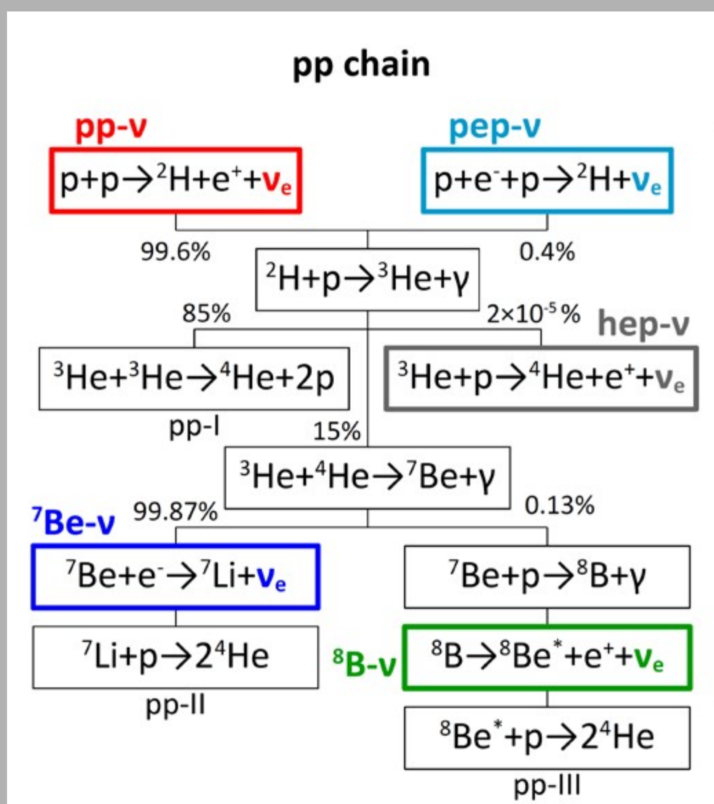
Solar fusion reactions

Fusion reactions in the Sun (and in H-burning stars) that convert H to He → produce ν

$$4p \rightarrow {}^4He + 2e^+ + 2\,\nu_e + 26.7\ MeV$$

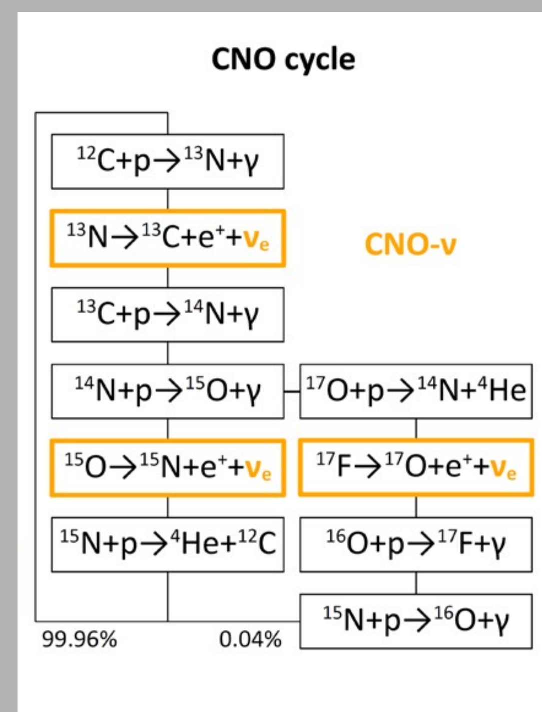
pp-chain (5 ν species)

> 99% energy production



CNO-cycle (3 ν species)

contribute <1% energy production
heavy star dominant



→ Still undetected!!!

Study the Sun with neutrinos
Study neutrinos with the Sun

(1) To measure solar neutrino flux → test Standard Solar Model

→ **Astrophysics interest: Solve solar metallicity Problem : tension between High Metallicity and Low Metallicity Solar Models**
(abundance of heavy elements in the Sun)

→ **Agreement between optical and neutrino luminosity: solar stability at 10^5 years scale**

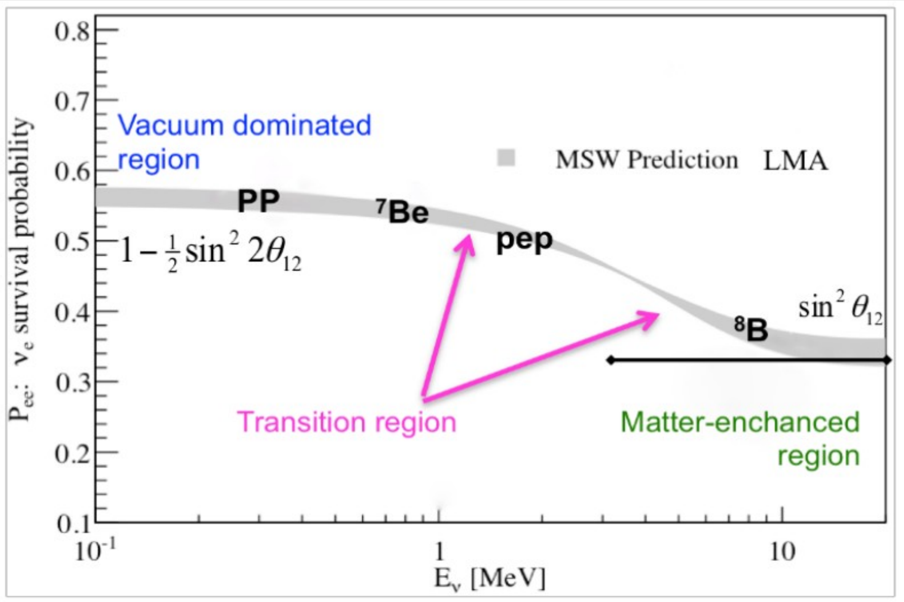
→ **Testing energy production mechanisms**

FLUX	B16-GS98	B16-AGSsmet	DIFF (HZ-LZ)/HZ
pp (10^{10} cm^{-2}s^{-1})	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} cm^{-2}s^{-1})	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} cm^{-2}s^{-1})	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} cm^{-2}s^{-1})	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} cm^{-2}s^{-1})	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} cm^{-2}s^{-1})	2.05(1±0.17)	1.44(1±0.16)	29.7%
^{17}F (10^{8} cm^{-2}s^{-1})	5.29(1±0.20)	3.26(1±0.18)	38.3%

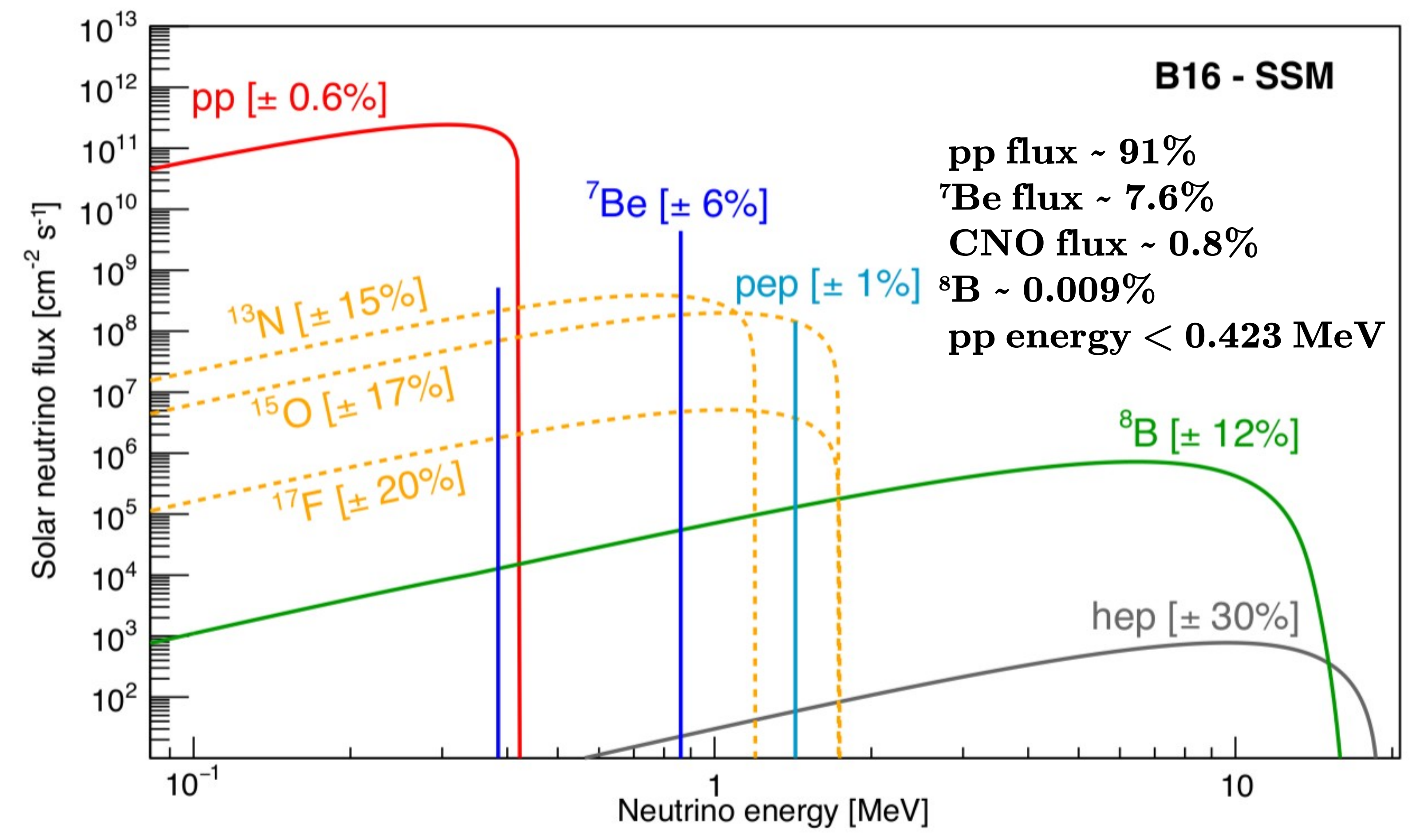
(2) Particle Physics interest → confirm LMA-MSW

Borexino can measure the P_{ee} (electron neutrino Survival probability) both in the matter-enhanced oscillation region and in the vacuum region.

→ **testing the LMA (Large Mixing Angle) - MSW Oscillation (matter effects) analysis solution to Neutrino oscillations (energy dependent day/night effects)**



Solar Neutrinos Flux on Earth



pp flux ~ 91%

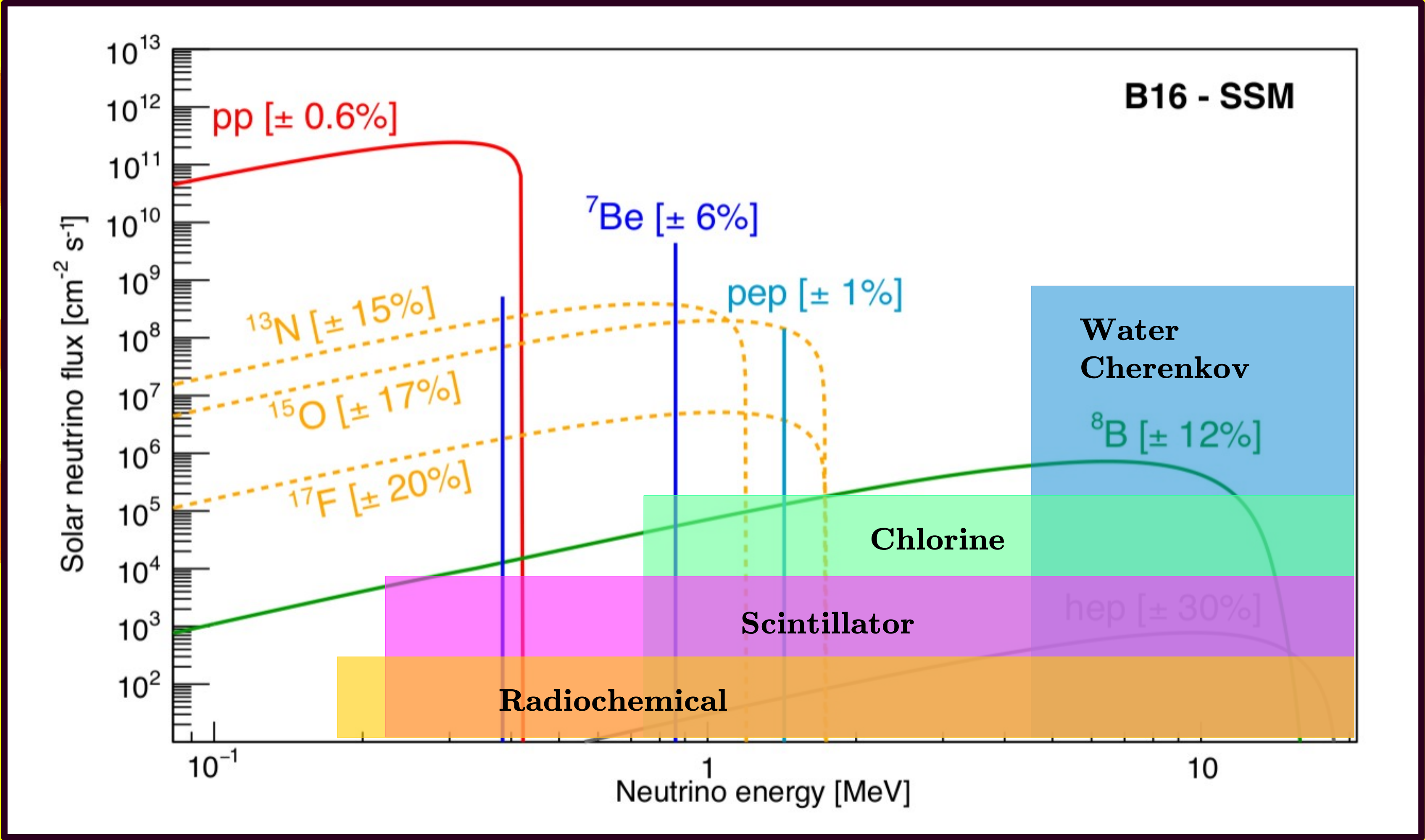
^{7}Be flux ~ 7.6%

CNO flux ~ 0.8%

^{8}B ~ 0.009%

pp energy < 0.423 MeV

Solar Neutrinos Flux on Earth



Borexino performance

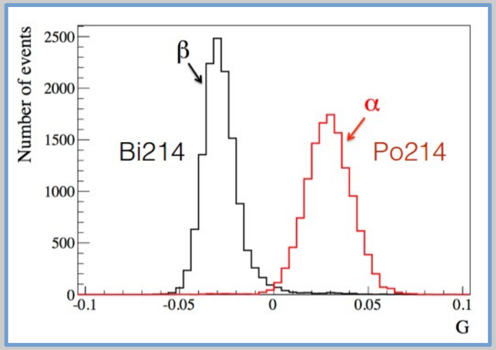
The Borexino PMTs detect the scintillation light produced by electrons scattered by Neutrinos

For each scintillation event Borexino records:

- **Number of collected photons** (Photoelectron yield 500 p.e./MeV)
  $\rightarrow$ **Energy**
  Good energy resolution ~ 5% @ 1MeV

- **Time of arrival of photons** $\rightarrow$ **Position reconstruction** (by T.O.F.)
  Good position reconstruction ~10cm @ 1 MeV

  $\rightarrow$ **For α and β^+ we can apply the pulse shape discrimination α / β, $\beta^+ \beta^-$**



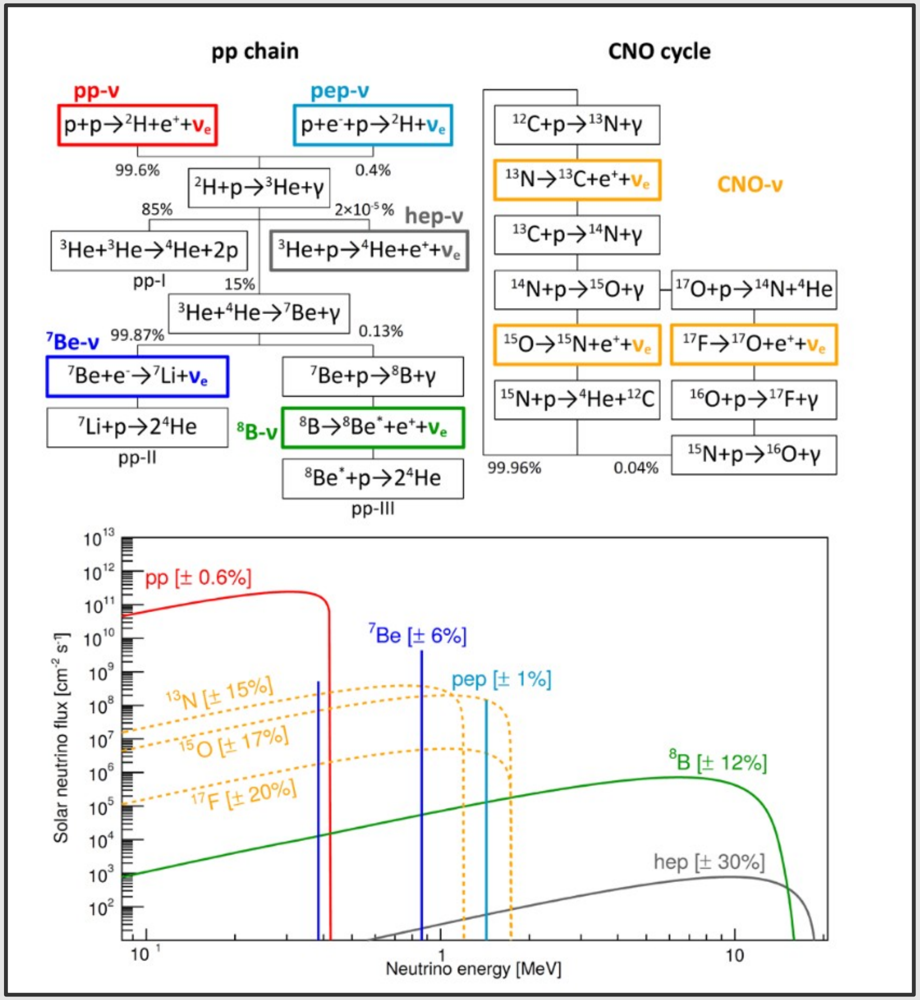
Drawbacks $\rightarrow$ No directionality

$\rightarrow$ **Crucial point: Extreme low background required!!!**

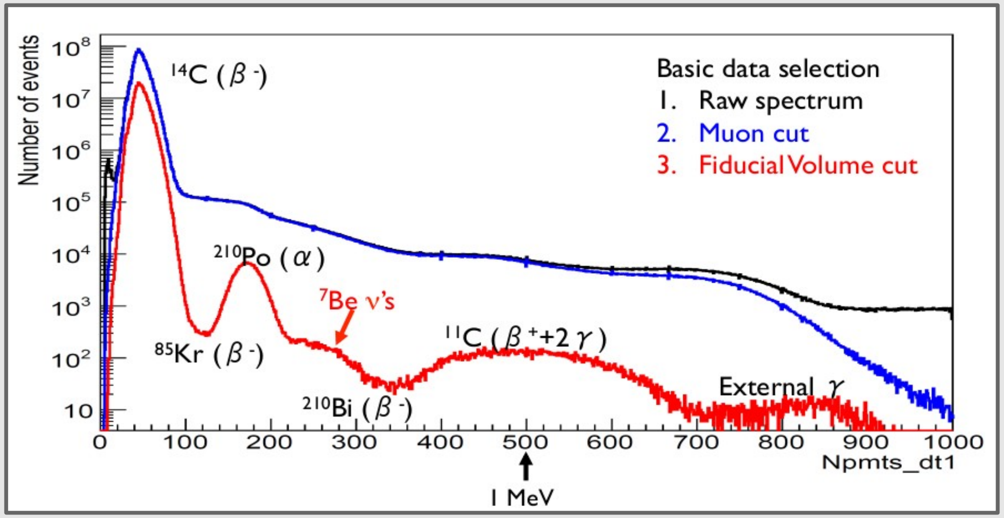
- **Very low energy threshold (~<100 keV)**

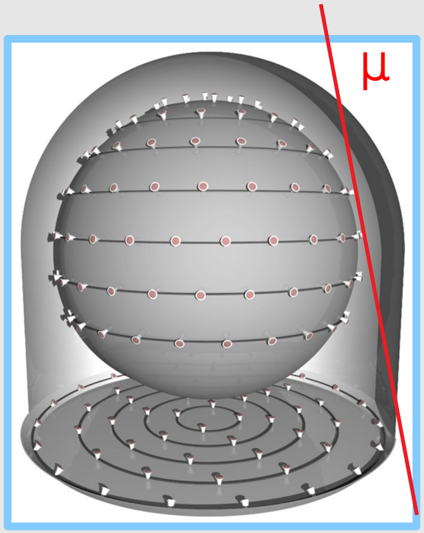
Solar Neutrino Detection: Elastic Scattering

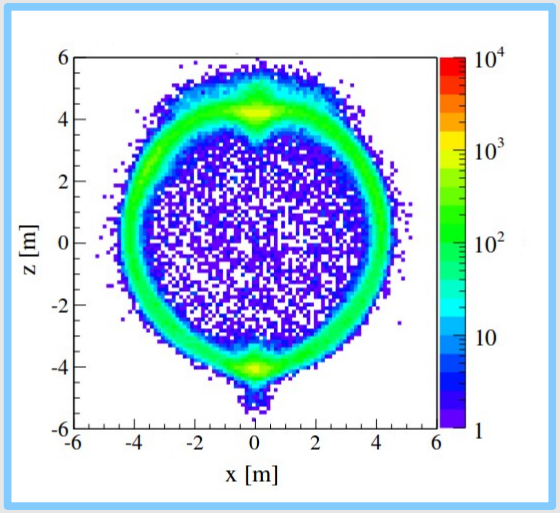
(1) Theory: Solar neutrino spectrum



(2) Data: Electron recoil spectrum in Borexino $\rightarrow$ $\nu +$ backgrounds







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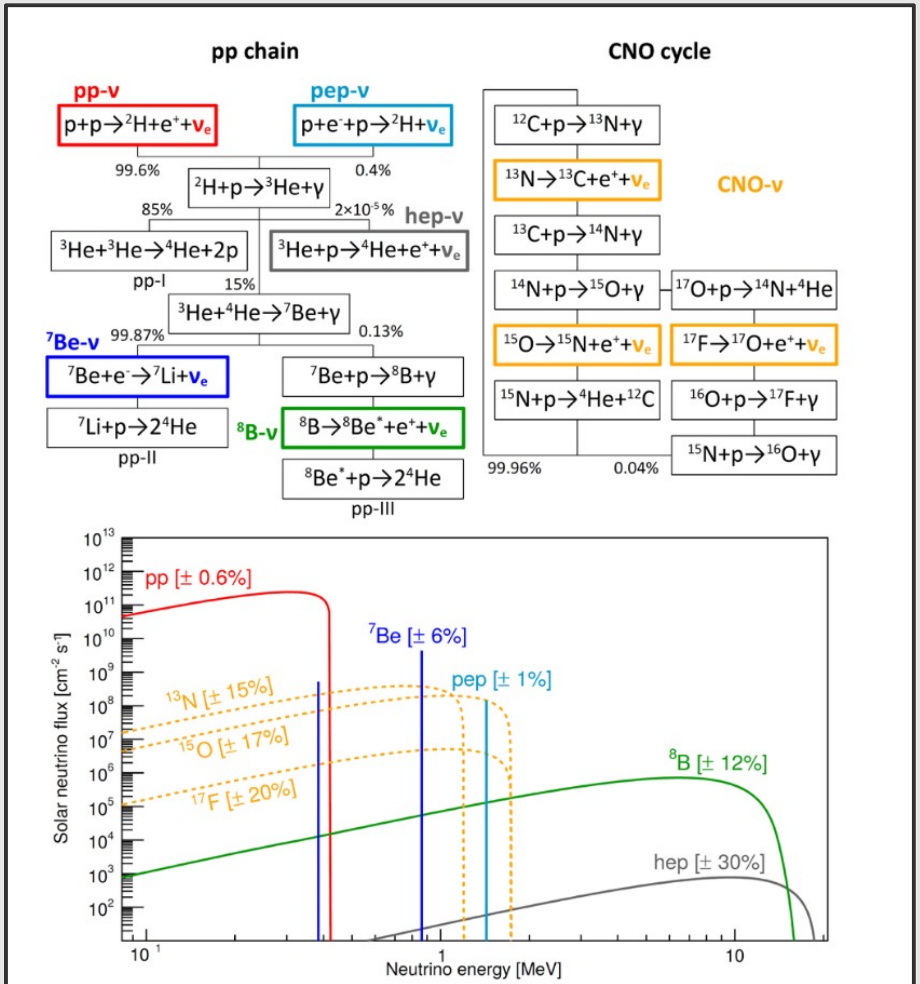
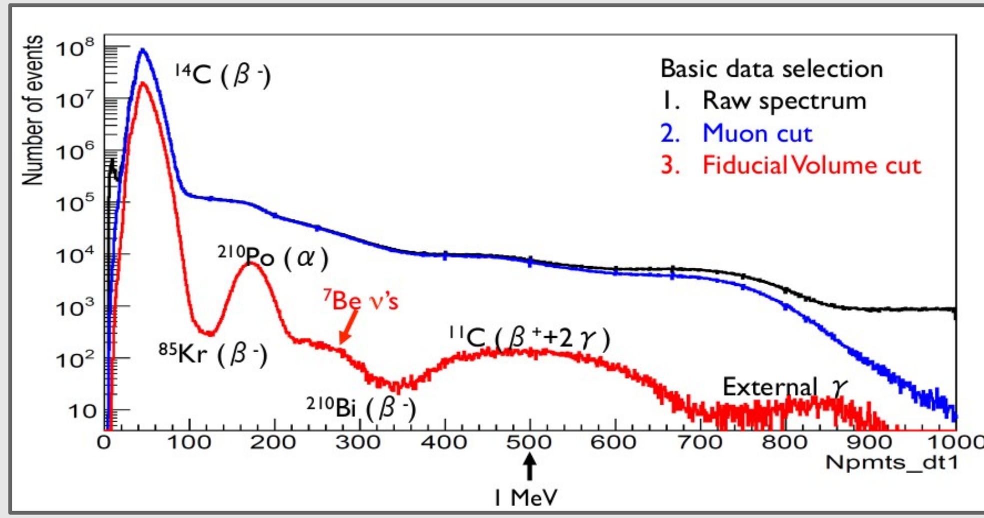
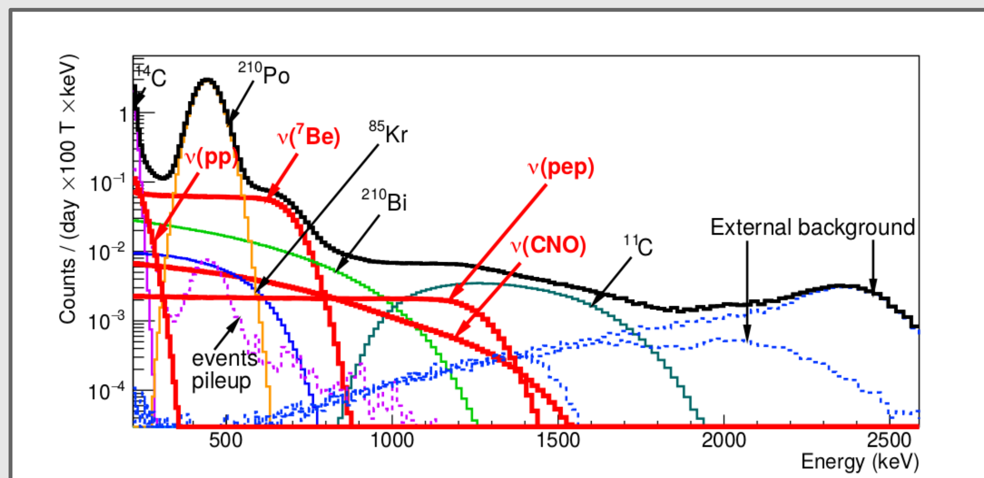


(2) Data: Electron recoil spectrum in Borexino → ν + backgrounds



(3) Fit → ν + backgrounds rates



Borexino Achievements so far

Purification I | **Purification II** | **External Tank Insulation**

Phase I (2007-2010) — **2010** — **2012** — **Phase II (2012-2016)** — **Phase III**

Phase I (2007-2010)

- **$\nu(^7Be)$ flux** [1-3]
- **$\nu(^8B)$ flux** [4]
- **ν(pep) flux** [5]
- **ν(CNO) limit** [5]
- **$\nu(^7Be)$ day-night asymmetry**[6]
- Limit on NMM [1]
- **First Geo-ν observation at $> 4\sigma$** [7]
- Detailed study of the cosmogenics in LS
- Limits on rare processes
- Muon seasonal mod.

2010–2012

Improved radiopurity: (6 cycles of scintillator purification)

- ^{85}Kr reduced by ~4.6
- ^{210}Bi: reduced by ~2.3
- **Th and U negligible (~10^{-19} g/g)**

Phase II (2012-2016)

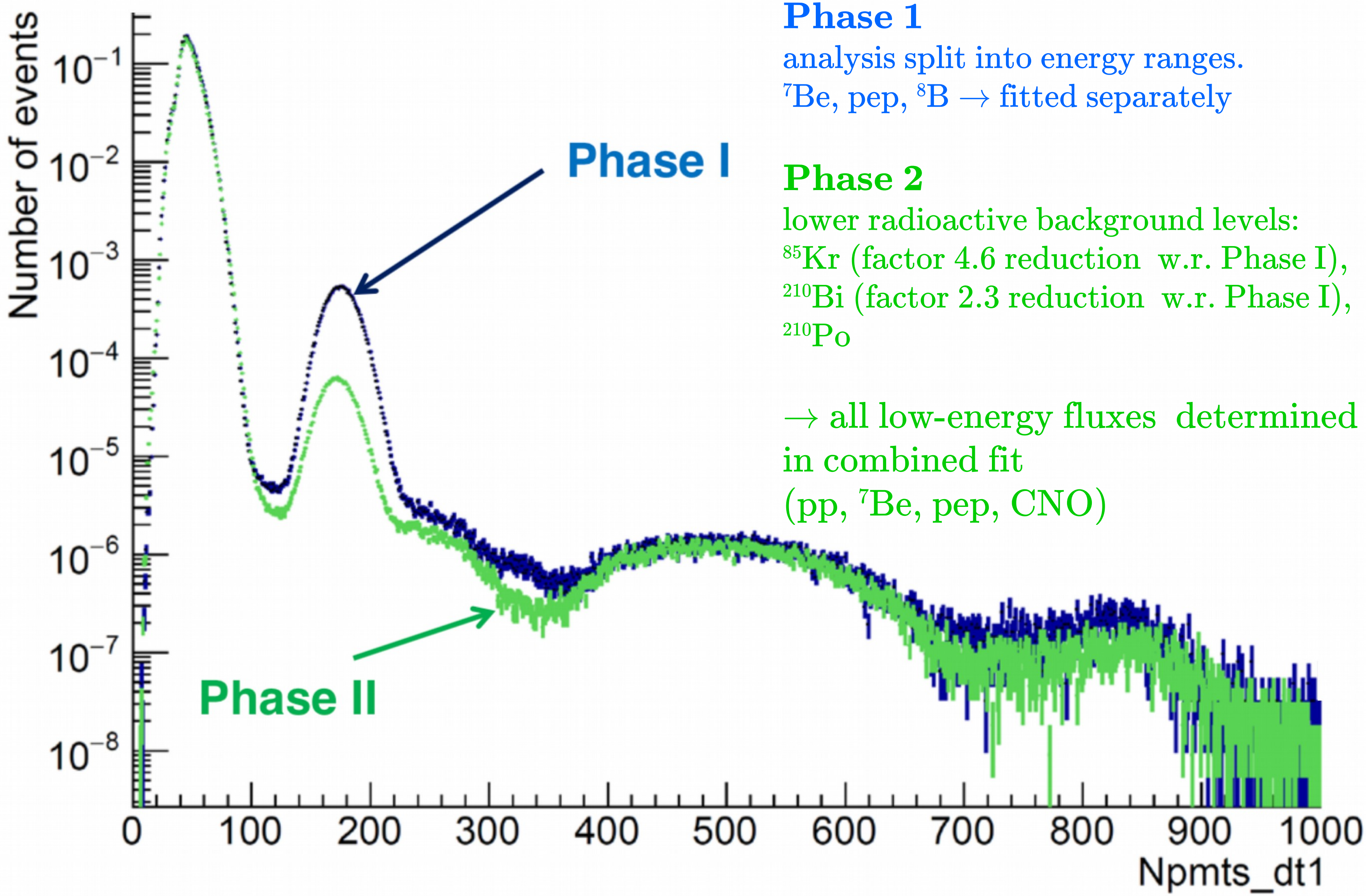
- **pp solar neutrinos** [8]
- New results on the solar fluxes 1st global spectral fit @(0.186-2.97) MeV! **Simultaneous measurement of pp, ^7Be, pep neutrinos** [9]
- Seasonal modulation of ^7Be [10]
- New limit on neutrino magnetic moment [11]
- **Improved ^8B measurement** [12]
- Geoneutrinos evidence at 5σ [13]
- Modulations of the CosmicMuon Signal in Ten Years of Borexino Data[14]
- **Comprehensive measurement of pp-chain solar neutrinos**[15]
- Constraints on NSNI from Borexino Phase-II[16]

Phase III

- The detector has been stabilized in temperature; **Attempt to search for CNO neutrinos** in progress

[1] DOI: 10.1103/PhysRevLett.101.091302;
[2] DOI: 10.1016/j.physletb.2007.09.054;
[3] DOI: 10.1103/PhysRevLett.107.141302;
[4] DOI: 10.1103/PhysRevD.82.033006;
[5] DOI: 10.1103/PhysRevLett.108.051302;
[6] DOI: 10.1016/j.physletb.2011.11.025;
[7] DOI: 10.1016/j.physletb.2013.04.030;
[8] Nature 512 (2014) 383, doi:10.1038/nature13702;
[9] arXiv: 1707.09355;
[10] Astr. Phys. 92 (2017) 21, doi:10.1016/j.astropartphys.2017.04.004;
[11] doi:10.1103/PhysRevD.96.091103;
[12] arXiv: 0808.2868;
[13] DOI:10.1103/PhysRevD.92.031101
[14] arXiv:1808.04207v3 (2018)
[15] Nature 562, 505–510 (2018)
[16] arXiv:1905.03512v1

Phase I vs Phase II



Phase 1

analysis split into energy ranges.

^{7}Be, pep, ^{8}B → fitted separately

Phase 2

lower radioactive background levels:

^{85}Kr (factor 4.6 reduction w.r. Phase I),

^{210}Bi (factor 2.3 reduction w.r. Phase I),

^{210}Po

→ all low-energy fluxes determined in combined fit (pp, ^{7}Be, pep, CNO)

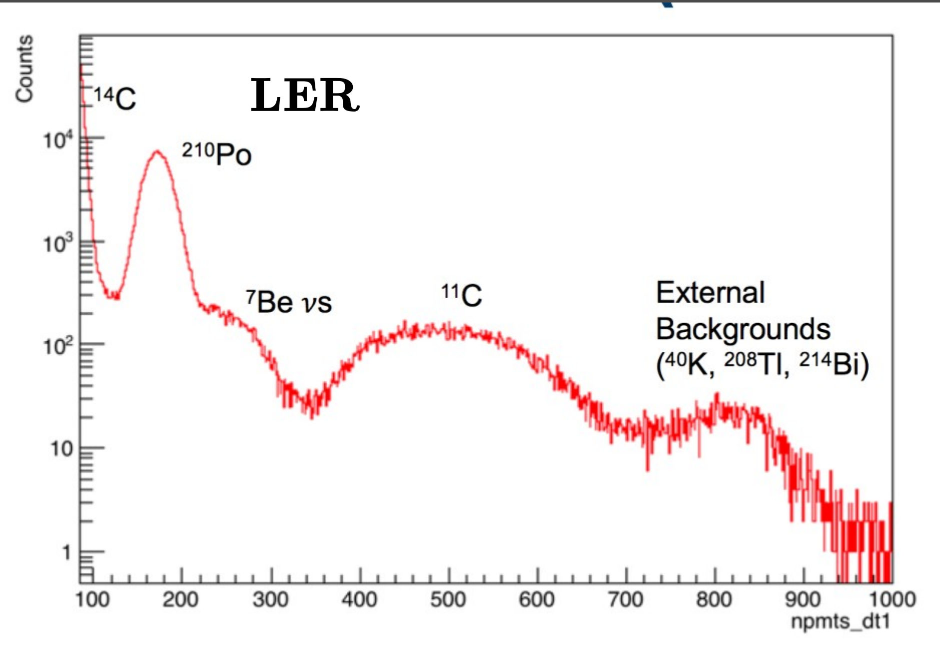
Comprehensive measurement of pp-chain solar neutrinos

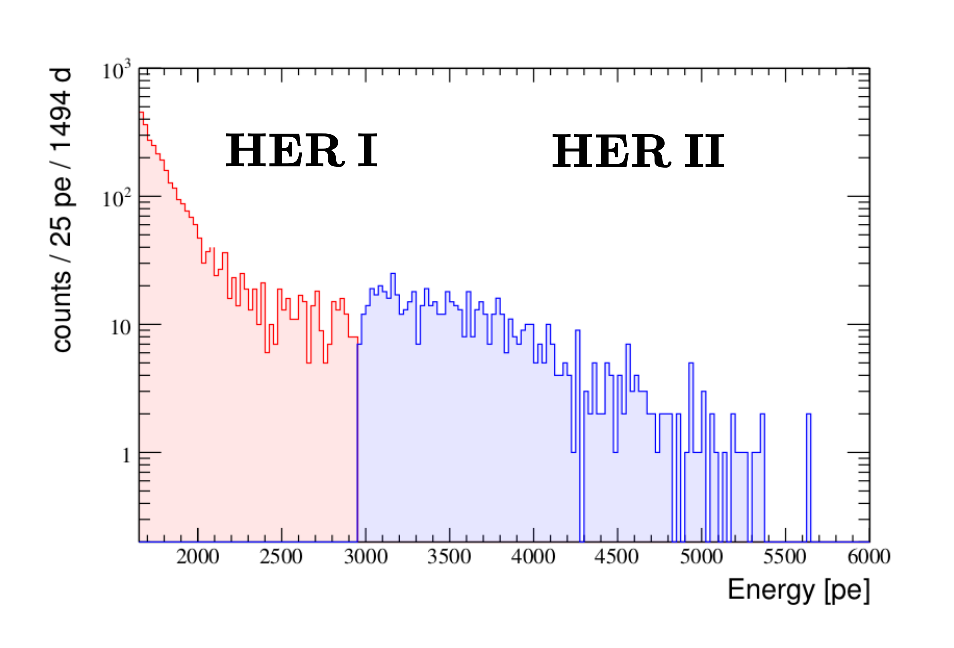
Analysis performed in two energy ranges:

- **LER → pp, pep, ^{7}Be, CNO**
  (0.19 - 2.93 MeV)
  Exposure: 1291.51 days × 71.3 t
  First simultaneous extraction of pp, pep and ^{7}Be rates

- **HER → ^{8}B, hep**
  (3.2 - 16 MeV)
  HER-I (3.2 – 5.7 MeV)
  HER-II (5.7 – 16 MeV)
  no natural long-lived radioactive background above 5 MeV
  Exposure HER-I: 2062.4 days ×227.8 t
  Exposure HER-II: 2062.4 days ×266.0 t
  Lowest energy threshold

→ HER and LER have different backgrounds





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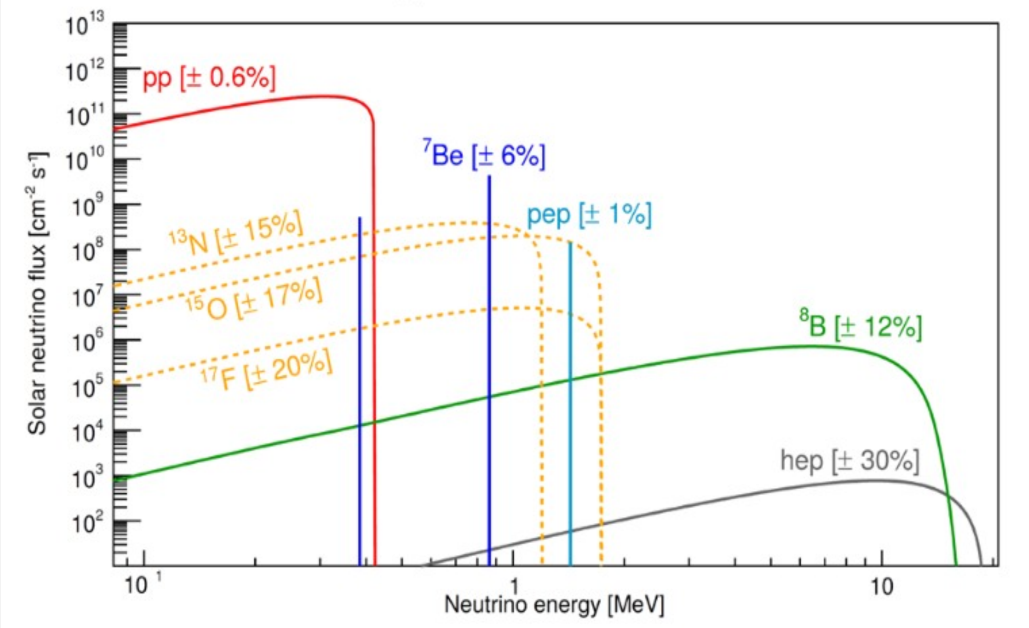


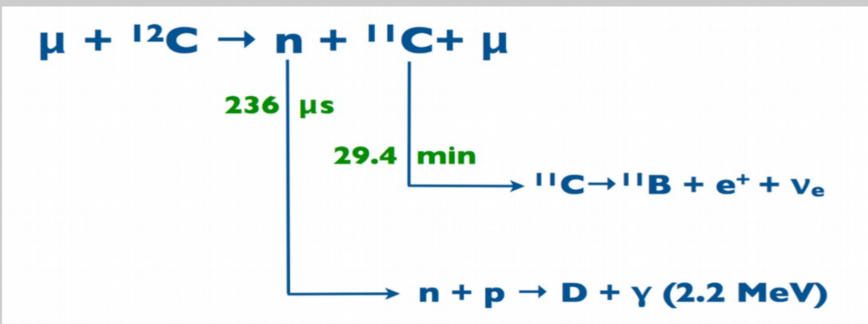
→ HER and LER have different backgrounds

^{11}C background rejection $\quad ^{11}C \rightarrow ^{11}Be + e^{+} + \nu_e$

Three-fold Coincidence technique (TFC) for ^{11}C tagging

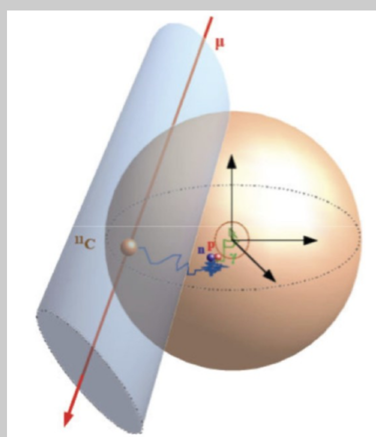
suppression of cosmogenic ^{11}C (e$^+$) ($\tau = 29.4$ min)

- Space-time correlation between muon track, neutron capture, ^{11}C decay



- (92±4)% ^{11}C-tagging effiency
- (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum

- ^{11}C rate: 27 → 2.5 cpd/100tons

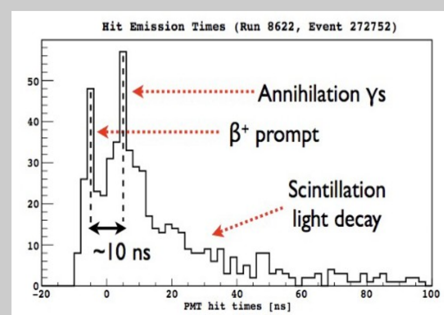


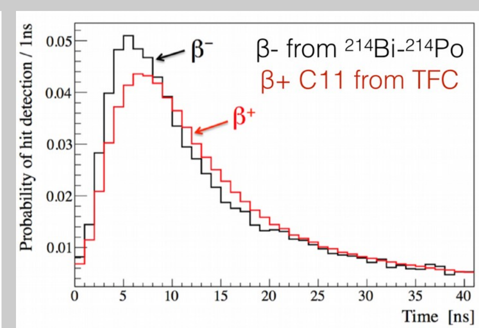
PULSE SHAPE technique to discriminate $\beta^{-}\beta^{+}$ events

- e$^+$ can form ortho-positronium with 50% probability and ~3ns lifetime in Borexino's scintillator

- formation of different pulse shapes for electrons and positrons
  → distribution of scintillation time signal for e$^+$ delayed with rispect to e$^-$
  → different event topology (energy deposit is not point-like because of the two annihilation gammas)

  → use such difference to discriminate e$^+$/e$^-$ events

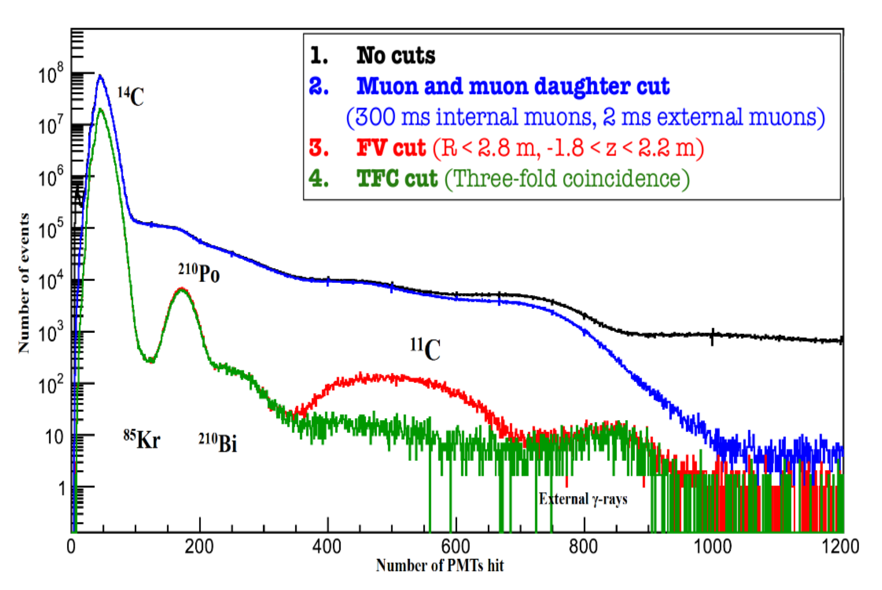




Multivariate approach

Main analysis variable is **visible energy**

→ **Spectral fit: fit of known signal and background spectra to the data spectrum to extract neutrino rates**
→ **Multivariate fit analysis** includes further variables in analysis fit, originally developed for pep-neutrino analysis (2012)



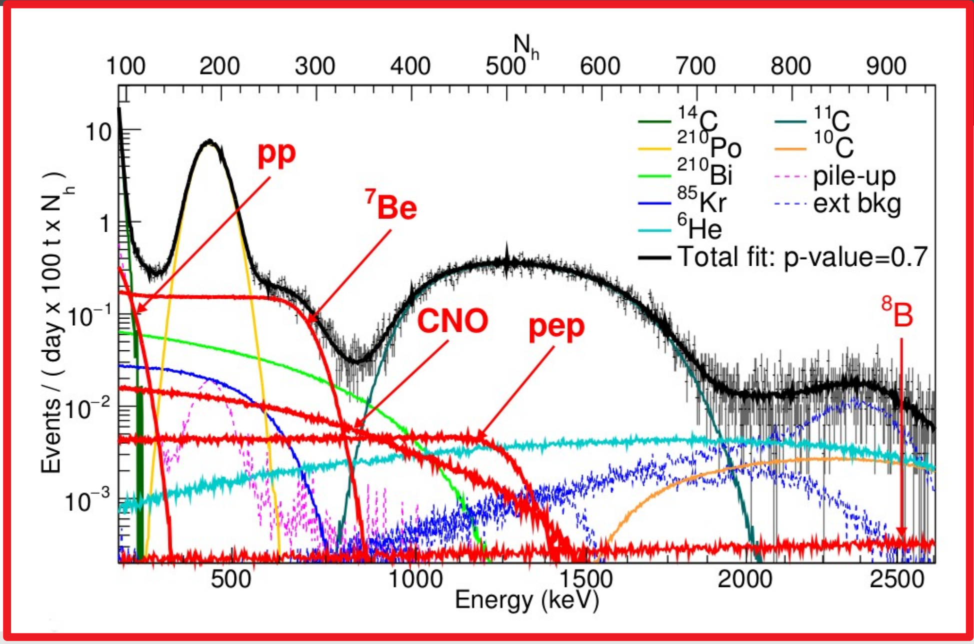
Tecnique consists in including in the likelihood:

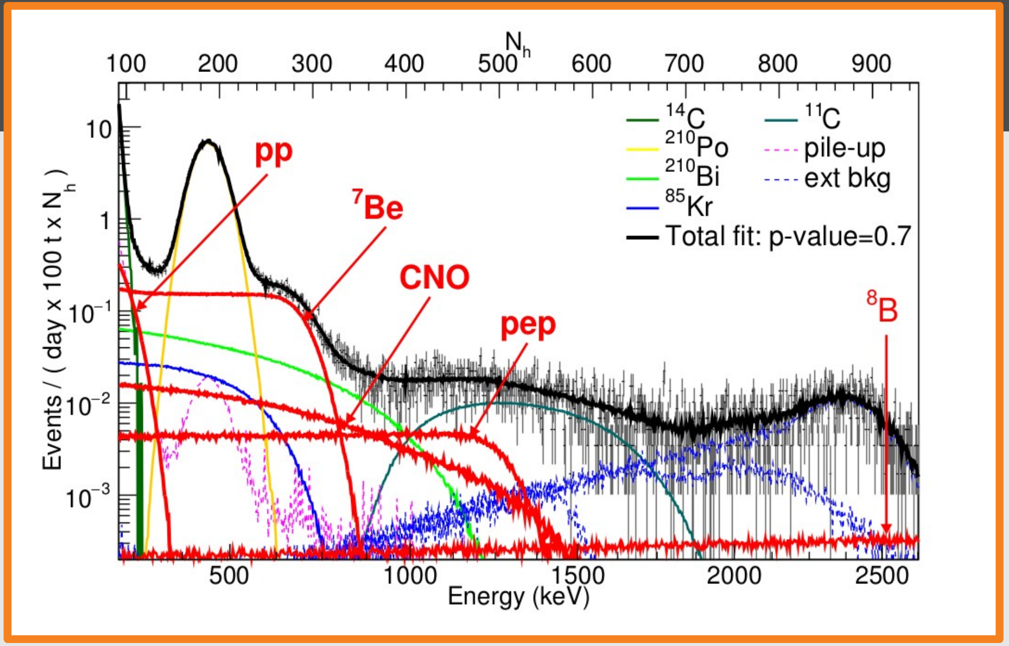
- **2 energy spectra**
  TFC-subtracted: 64% of exposure, 8% of ^{11}C
  TFC-tagged: 46% of exposure, 92% of ^{11}C

- **pulse shape analysis for β^+/β^- separation**
  Pulse-shape discriminator (PSD) of e^+/e^- :
  (^{11}C decays emiting β^+) based on the difference of the scintillation time profile for e^- and e^+

- **Radial distribution**
  To better disentangle external background from internal contaminants

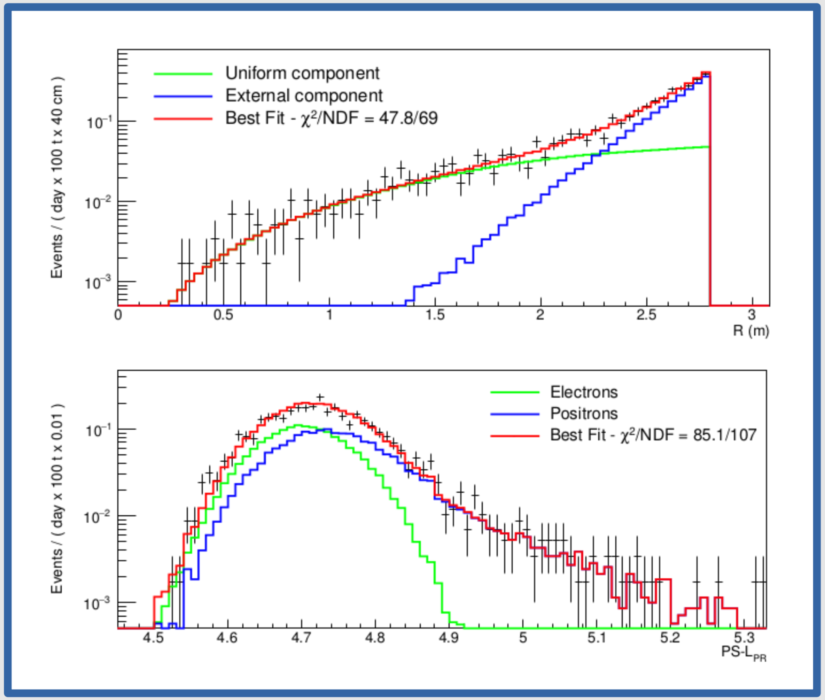
Multivariate analysis





Multivariate Likelihood Definition:

$$\mathcal{L}_{\mathcal{MV}}(\theta) = \mathcal{L}_{tag}(\theta)\cdot\mathcal{L}_{sub}(\theta)\cdot\mathcal{L}_{\mathcal{PS}}(\theta)\cdot\mathcal{L}_{\mathcal{Rad}}(\theta)$$



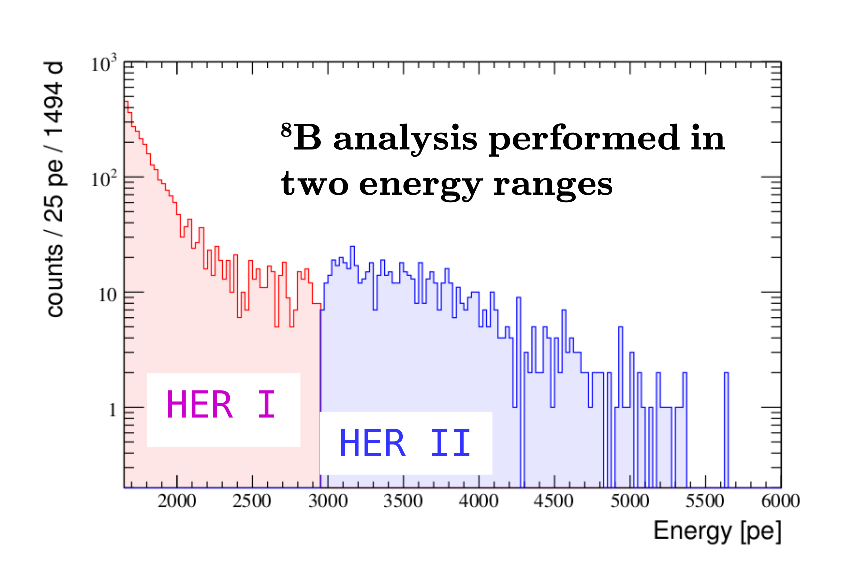
- **2 energy spectra**
  - →TFC tagged energy spectrum
  - → Energy spectrum after TFC veto
- **Radial Distribution** → To better disentangle external background from internal contaminants
- **Pulse Shape Analysis**

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure

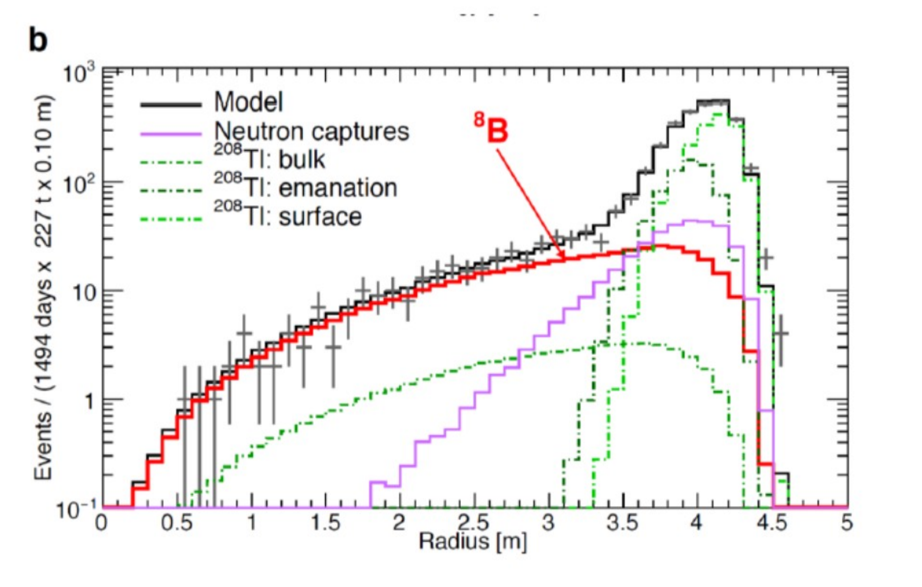
- **Fit done on radial distribution in two energy ranges**
  HER-1 (3.2 -5.7 MeV)
  HER-2 (5.7-16 MeV)
  No natural radioactivity expected above 5 MeV
- Data-set: January 2008 - December 2016
  Total exposure: 1.5 kton years ;
  (x 11.5 of the Phase I analysis)
- No FV cut
- Better understanding of backgrounds (external γs, cosmogenic)

  Gamma due to n capture
  n produced through (a,n) reaction
  ^{208}Tl from ^{232}Th of the vessel and in the scintillator bulk
  PDF from MonteCarlo

- Lowest energy threshold among Real Time Detectors



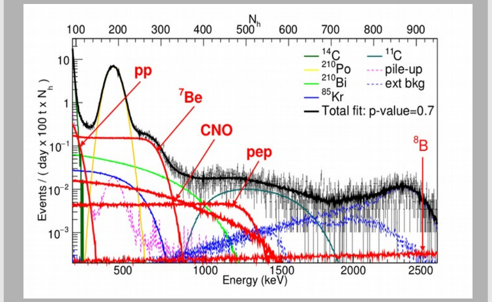
fit of the radial distribution of the events in the HER1



BX Phase II Results → Nature Paper

- **pp neutrinos**: improved accuracy respect to previous Borexino results
- **^{7}Be neutrinos**: 2.7% precision, twice more accurate than SSM predictions
- **pep neutrinos**: significance $> 5\sigma$ for the first time (constraining CNO rate)
- **CNO neutrinos**: confirmed previous Borexino result, best upper limit available

First Simultaneous Precision Spectroscopy of pp, ^{7}Be, and pep Solar Neutrinos with Borexino Phase-II



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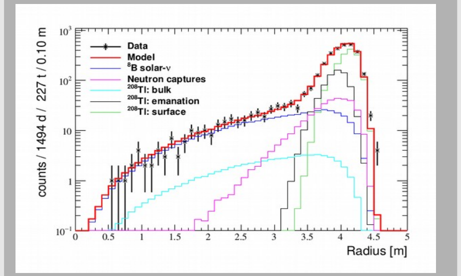
Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure

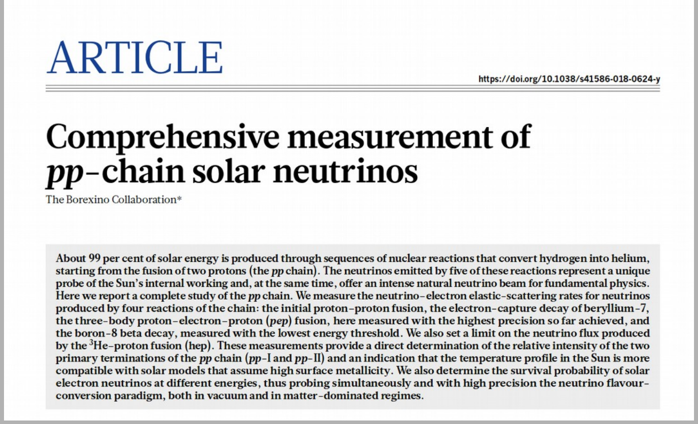


$\nu(^8\text{B})$ indipendent measurement

→

Comprehensive measurement of pp-chain solar neutrinos

Nature volume 562, pages 505–510 (2018)



ARTICLE

https://doi.org/10.1038/s41586-018-0624-y

Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration*

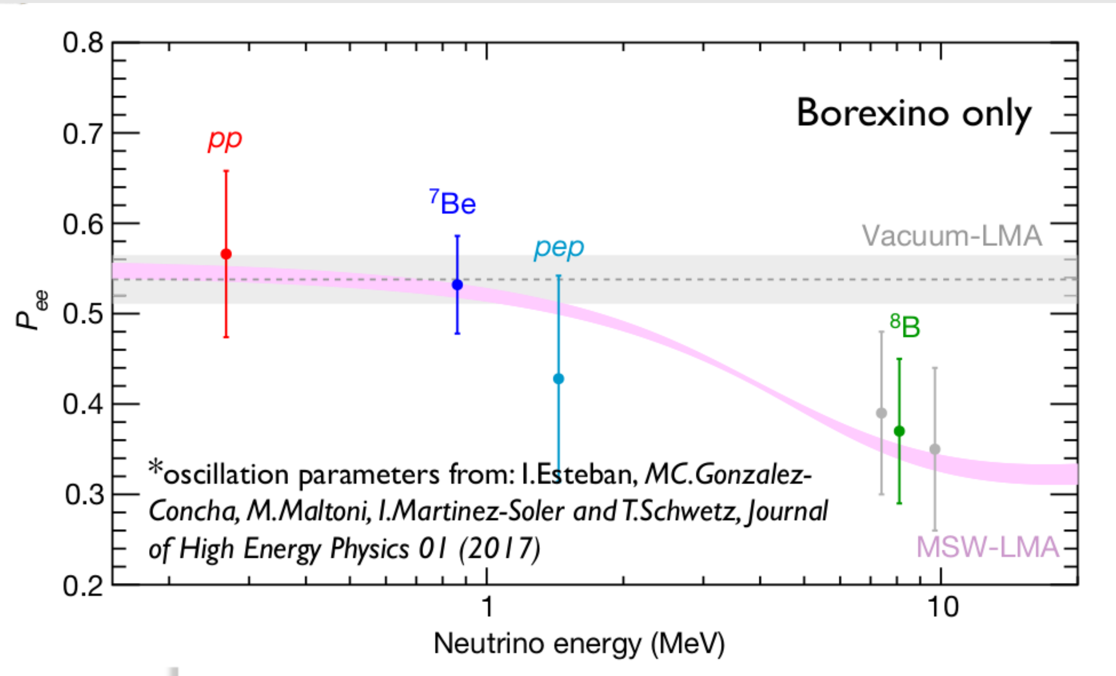
About 99 per cent of solar energy is produced through sequences of nuclear reactions that convert hydrogen into helium, starting from the fusion of two protons (the *pp* chain). The neutrinos emitted by five of these reactions represent a unique probe of the Sun's internal working and, at the same time, offer an intense natural neutrino beam for fundamental physics. Here we report a complete study of the *pp* chain. We measure the neutrino–electron elastic-scattering rates for neutrinos produced by four reactions of the chain: the initial proton–proton fusion, the electron-capture decay of beryllium-7, the three-body proton–electron–proton (*pep*) fusion, here measured with the highest precision so far achieved, and the boron-8 beta decay, measured with the lowest energy threshold. We also set a limit on the neutrino flux produced by the ^{3}He–proton fusion (hep). These measurements provide a direct determination of the relative intensity of the two primary terminations of the *pp* chain (*pp*-I and *pp*-II) and an indication that the temperature profile in the Sun is more compatible with solar models that assume high surface metallicity. We also determine the survival probability of solar electron neutrinos at different energies, thus probing simultaneously and with high precision the neutrino flavour-conversion paradigm, both in vacuum and in matter-dominated regimes.

BX Phase II Results

All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

	Phase I (cpd/100t)	Phase II (cpd/100t)	Uncertainty reduction
pp	$144 \pm 13 \pm 10$	$134 \pm 10^{+6}_{-10}$	1.3
^{7}Be	$48.3 \pm 2.0 \pm 0.9$	$48.3 \pm 1.1^{+0.4}_{-0.7}$	1.8
pep	$3.1 \pm 0.6 \pm 0.3$	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	1.6
^{8}B	$0.217 \pm 0.038 \pm 0.008$	$0.223^{+0.015}_{-0.016} \pm 0.006$	2.4
CNO	< 7.9 (95 % C.L.)	< 8.1 (95 % C.L.)	

Global analysis:
electron neutrino survival probability



From the measured interacton rates and assuming HZ-SSM fluxes we get:

$P_{ee}(pp)=0.57\pm0.10$
$P_{ee}(^7Be,862KeV)=0.53\pm0.05$
$P_{ee}(pep)=0.53\pm0.05$
$P_{ee}(^8B)=0.36\pm0.8$ $<E_\nu>=8.7$ MeV

→ Only experiment to simultaneously test neutrino flavour conversion both in the vacuum and in the matter-dominated regimes

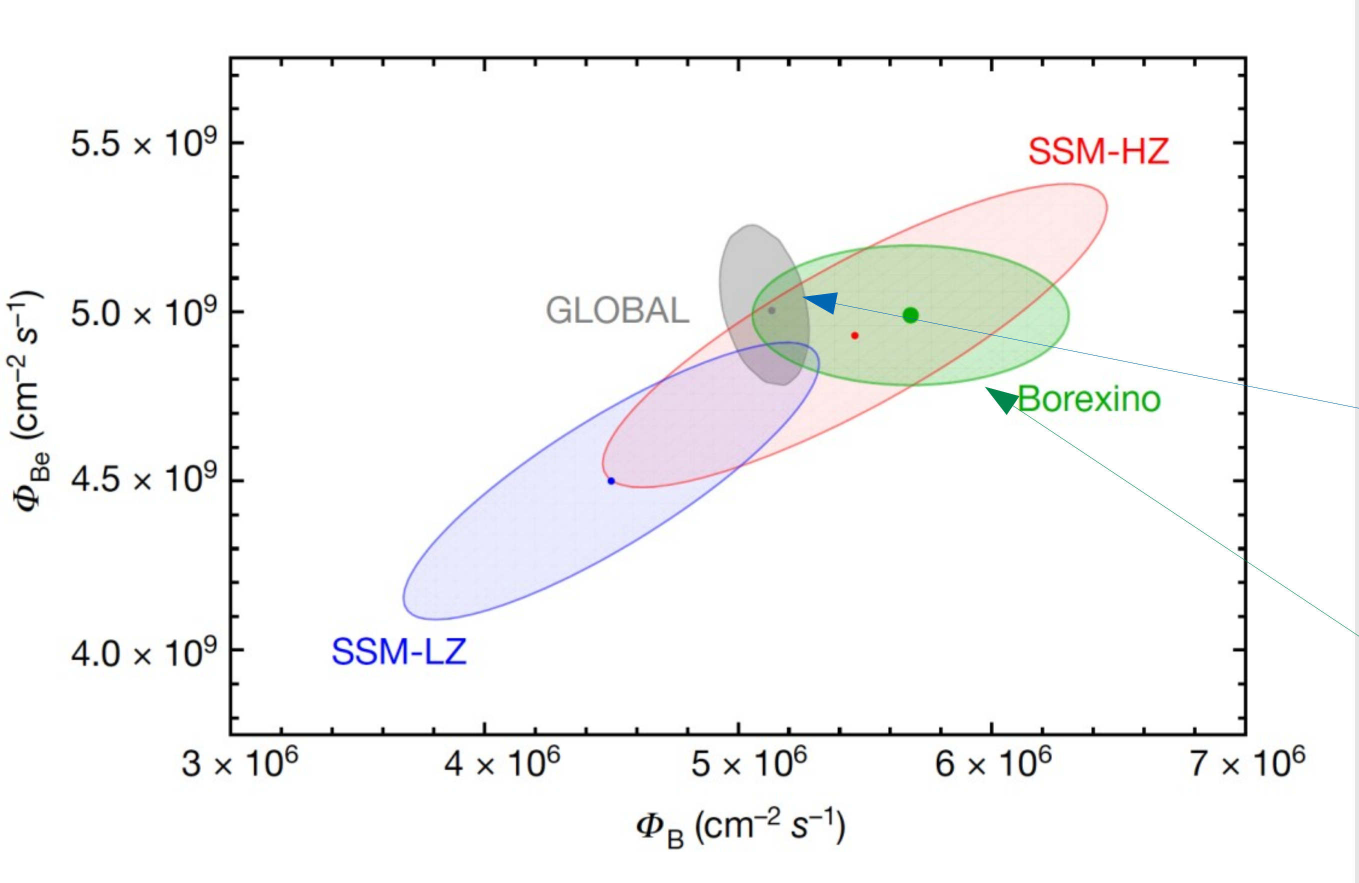
→ Most precise in the low-energy range(vacuum oscillations)

→ Excellent agreement with MSW-LMA solution

→ Rejection of vacuum LMA hypothesis at 98.2%

Global analysis: metallicity

The metallicity determines the opacity of solar plasma and, as a cosequence, regulates the central T of the Sun and the Branching Ratios of the different pp- chain terminations



Global fit of all solar, Kamland reactors, and new Borexino results

Borexino+other solars and Kamland Global fit
Hints about HZ is weaker

Borexino only:
Hints in favor of HZ

LZ is disfavoured at 96.6%

note: only 1 σ theoretical uncertainty in the plot
$\rightarrow$ important to reduce the theoretical uncertainty

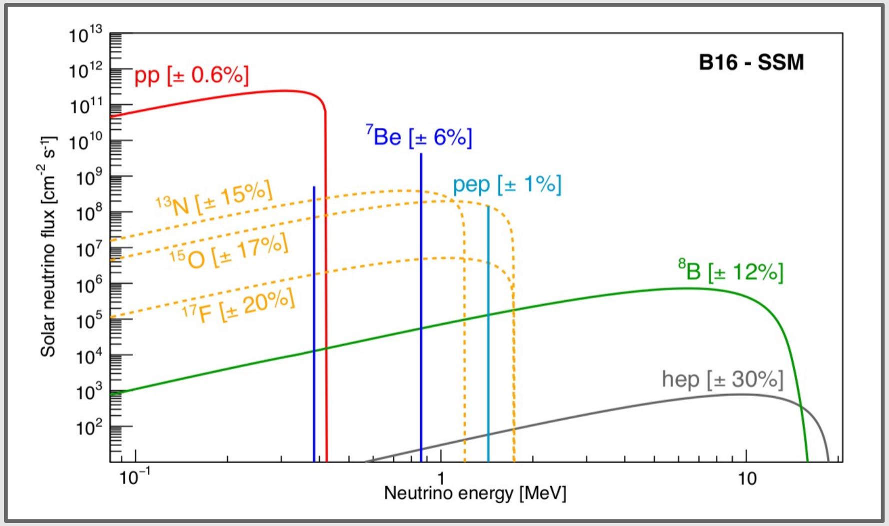
Key to the Solar metallicity : CNO flux

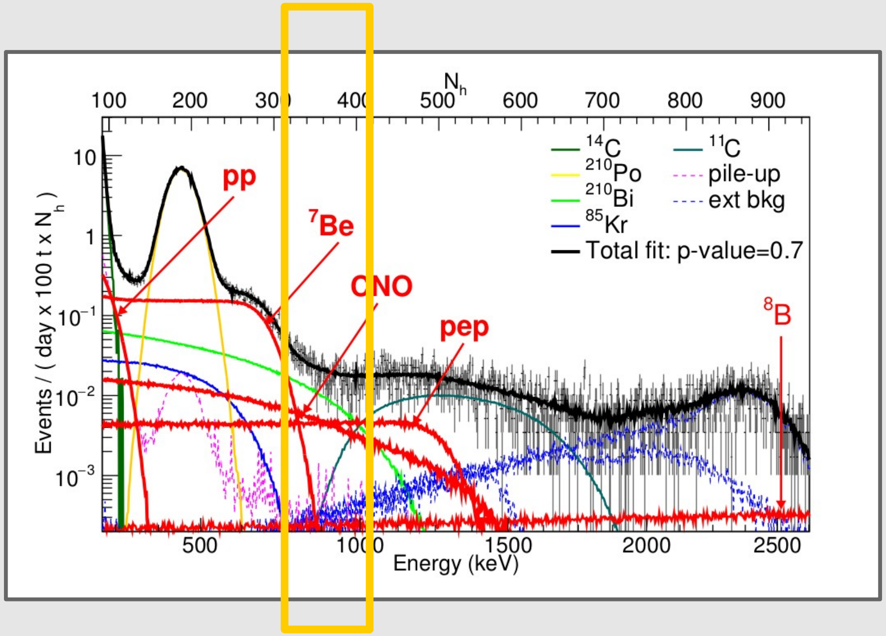
Motivations:

- **CNO neutrinos have never been detected**
  According to astrophisical models, CNO cycle is responsible of ~1% of the solar luminosity and it is the main mechanism of energy generation in massive stars

- **CNO neutrinos measurement will allows to complete the SSM and stellar astrophysics**

- help solar physicists to solve the **solar metallicity problem**





Expected CNO rate (MSW-LMA):
High metallicity
(B16)GS98 $R_{CNO} = 4.91 \pm 0.55$ cpd/100 t
Low Metallicity
(B16)AGSS09 $R_{CNO} = 3.52 \pm 0.37$ cpd/100 t

Borexino: $\Phi(CNO) < 7.9 \times 10^8$ **cm^{-2} s^{-1} (95% C.L.)**
$R(CNO) < 8.1$ **cpd/100 t (95% C.L.)**

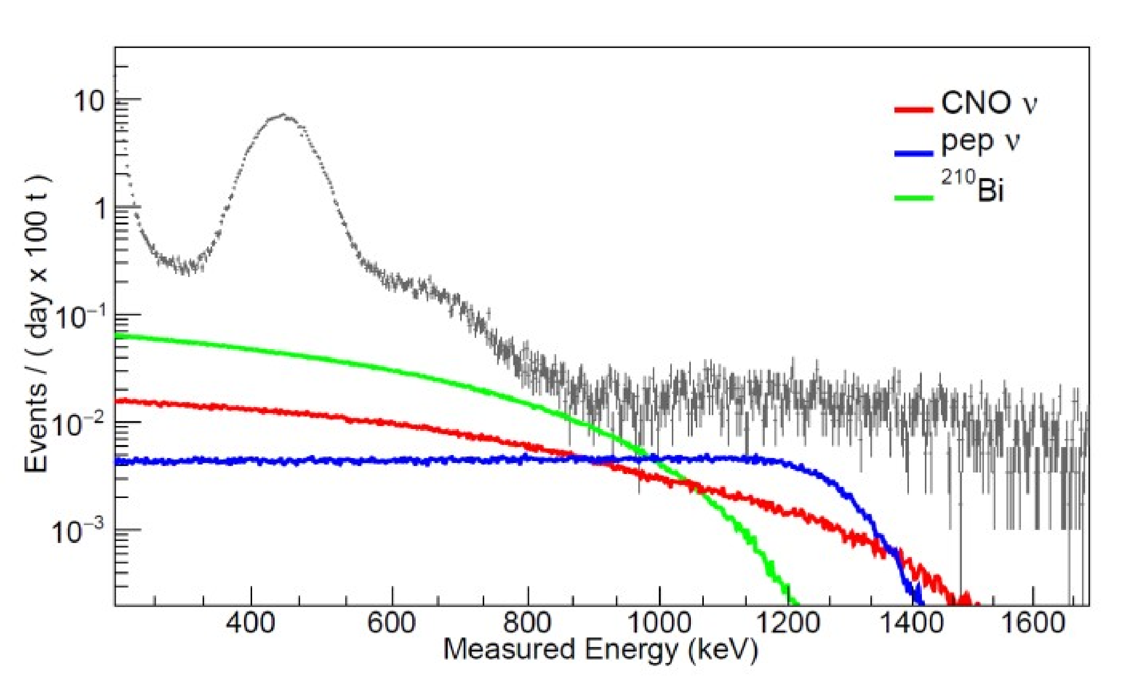
Key to the Solar metallicity : CNO flux

The detection of CNO neutrinos in Borexino is challenging:

- ★ The low flux of CNO neutrinos (CNO cycle responsible of $\approx 1\%$ of the total Solar Power)
- ★ The absence of prominent spectral features
- ★ Anticorrelation with ^{210}Bi and pep ν

Note also the low rate:
→ **R(CNO)** expected ~ 3-5 cpd/100ton
→ **R(^{210}Bi)** ~ 20 cpd/100ton
→ **R(pep)** ~ 2.7 cpd/100ton

The spectral fit returns only the sum of the components, if both are left free!



Borexino data
CNO ν expected spectrum
^{210}Bi spectrum
pep ν spectrum

→ Strict anticorrelation between CNO ν, pep ν and ^{210}Bi

Key to the Solar metallicity : CNO flux
Strategy

★ **(1) Measure the ^{210}Po rate to costrain ^{210}Bi and remove degeneracy with CNO spectrum**

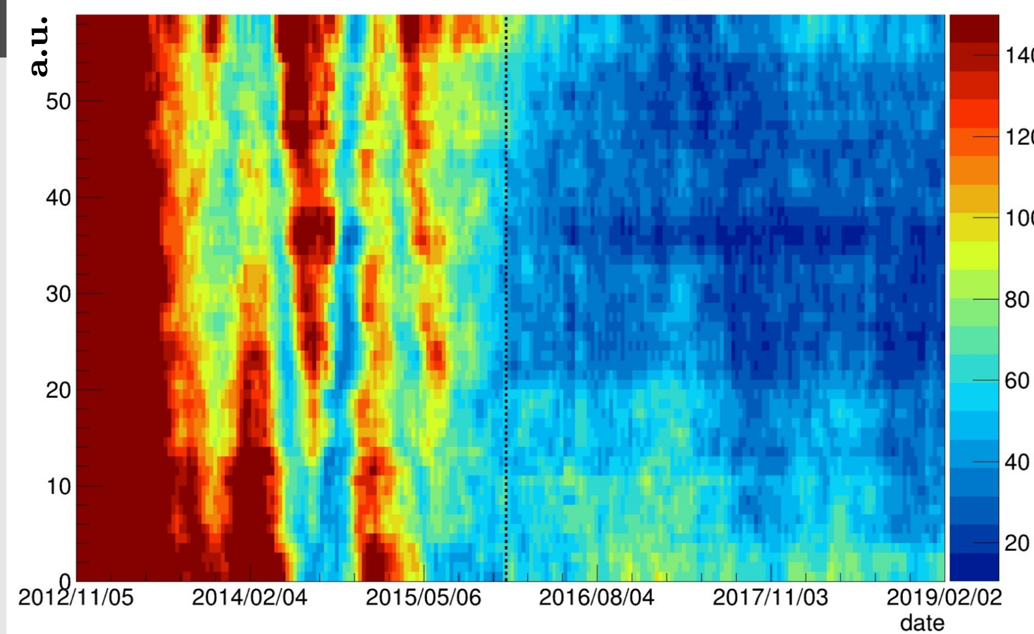
$$^{210}\mathrm{Pb} \xrightarrow[32\ \mathrm{y}]{\beta^-} \boxed{^{210}\mathrm{Bi} \xrightarrow[7.23\ \mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.1\ \mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}}$$

^{210}**Po** is "easier" to identify wrt ^{210}Bi:
- Monoenergetic decay → "gaussian" peak
- α decay → pulse shape discrimination

If the ^{210}**Bi** is in radioactive equilibrium with ^{210}Po, an independent measurement of the latter decay rate gives directly the ^{210}Bi.

^{210}**Bi** homogeneity is required → Thermal insulation for preventing convective motions and **background** mixing

Background rate in the ROI



(2) Temperature stabilization for preventing Background mixing
We observed ^{210}Po leaching out the nylon vessel and moving into the FV due to convection motions
→ Thermal insulation &temperature control of the detector to reduce and control thermal gradients

(3) Purification
further purification of the LS by water extraction to reduce ^{210}**Bi**

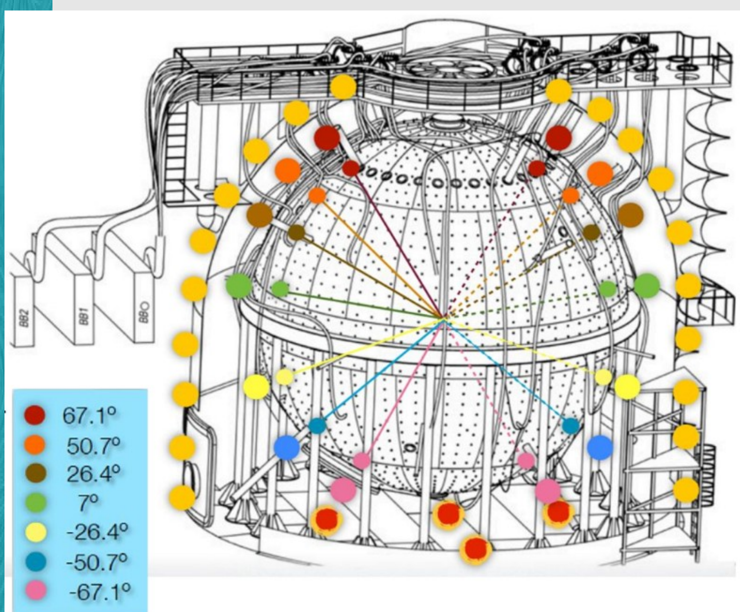
Temperature stabilization

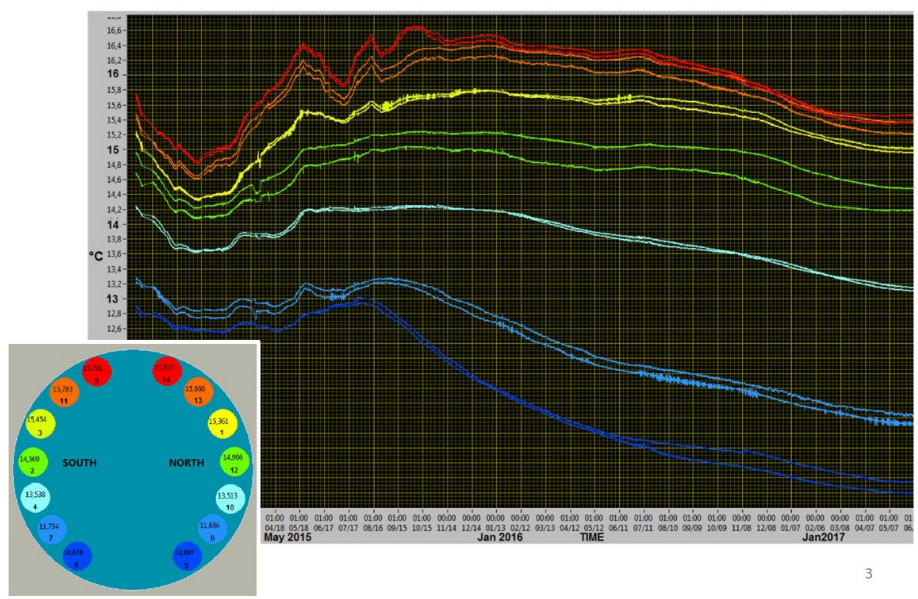
Hardware

→ Insulation with rock wool (2015)
→ Active T control system

Monitoring

→ 54 temperature probes located both in the buffer and in the external tank and at different levels

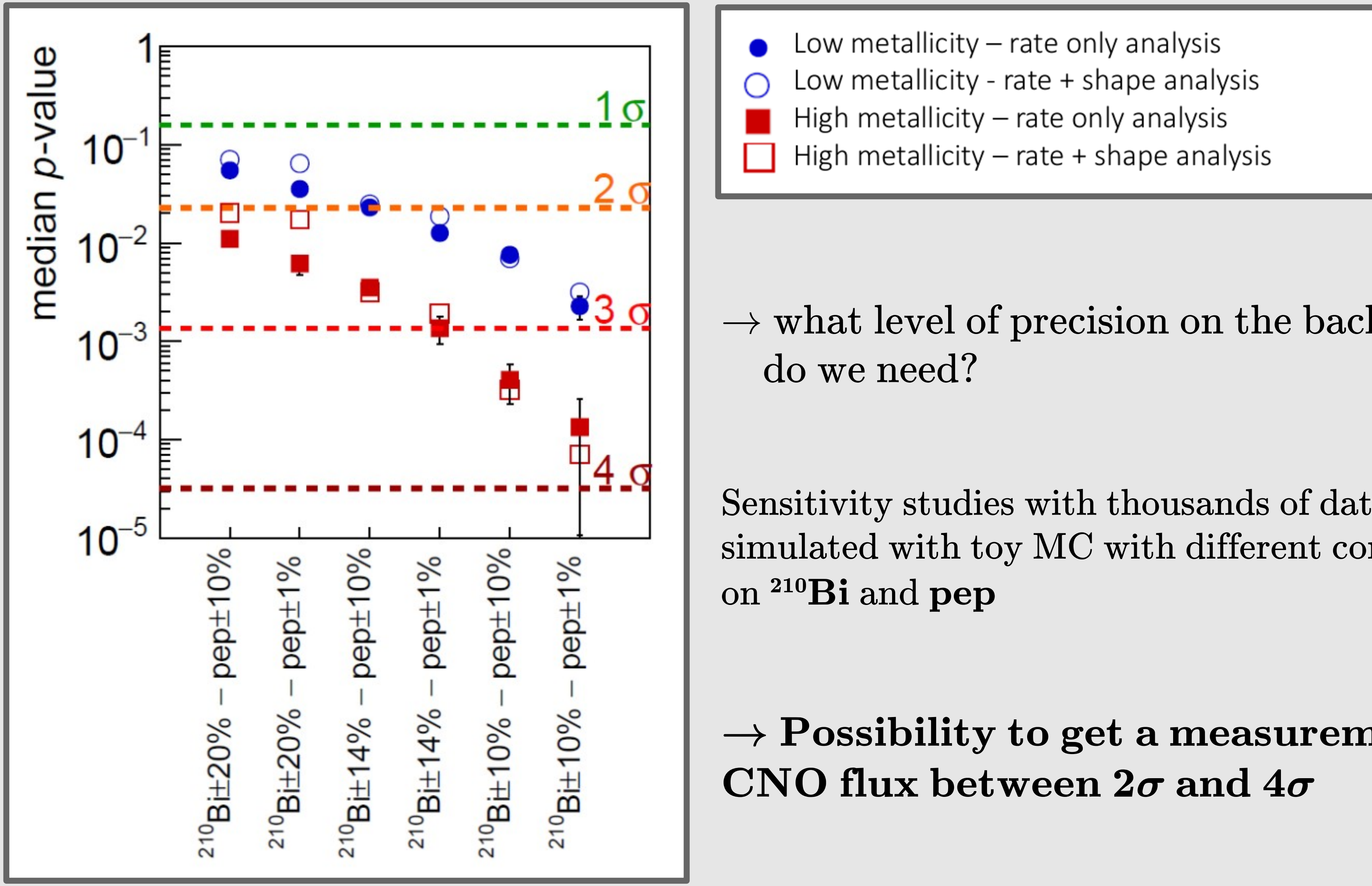




Results

→ The T profile has stabilized after insulation
→ We are collecting data in these stable conditions to verify our capability to tag ^{210}Bi from ^{210}Po

Sensitivity to CNO ν detection



→ what level of precision on the background do we need?

Sensitivity studies with thousands of data-sets simulated with toy MC with different constraints on ^{210}**Bi** and **pep**

→ Possibility to get a measurement of CNO flux between 2σ and 4σ

Conclusions and Outlook

★ **We are approaching 12 years of Borexino running with**

→ Unprecedented backgrounds
→ A new wide range multivariate fit strategy
→ Low-background techniques developed

★ **Borexino alone has performed the full spectroscopy of pp-chain neutrinos**

→ improved precision in all flux measurements
→ ^{7}Be (862+384) precision 2.7 % (stat+sys)
→ 5σ evidence of pep Neutrinos for the first time
→ Improved ^{8}B measurement
→ Borexino has slight preference to High Metallicity at 96.6 % C. L.
→ Exclusion of Vacuum-LMA scenario at 98.2 % C. L.
→ Simultaneous test of the P_{ee} in the vacuum and matter dominated region;

→ test of Sun's nuclear processes and its long term stability

★ **CNO Sensitivity and Measurement under investigation**

→ Current Best Limit: Φ (CNO) < 7.9×10 cm^{-2} s^{-1} (95 % C.L.)
→ Future: Continue data taking with stable condititions to attempt a CNO measurement

BOREXINO COLLABORATION

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

Virginia Tech

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

University of Houston

Universität Hamburg

APC

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH Forschungszentrum

POLITECNICO MILANO 1863

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

University of Massachusetts Amherst

Università degli Studi di Perugia

Università degli Studi di Ferrara

TECHNISCHE UNIVERSITÄT DRESDEN

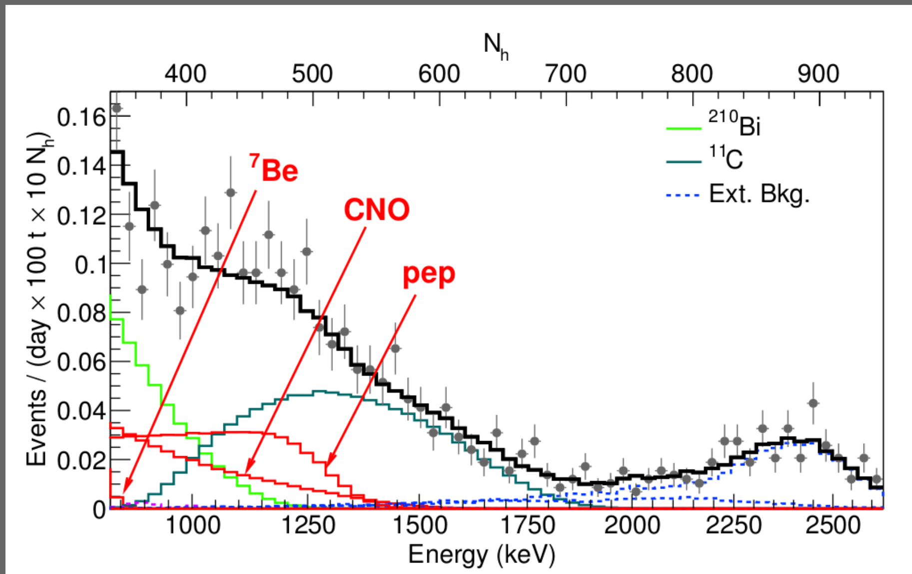
University of California (UCLA)

Joint Institute for Nuclear Research

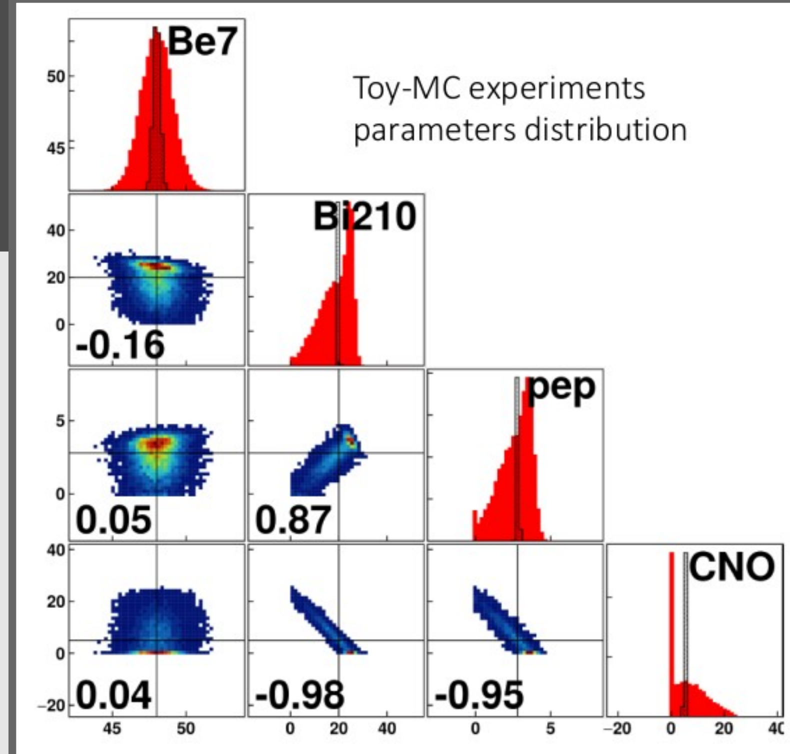
GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare

Backup slides

Evidence of pep ν signal

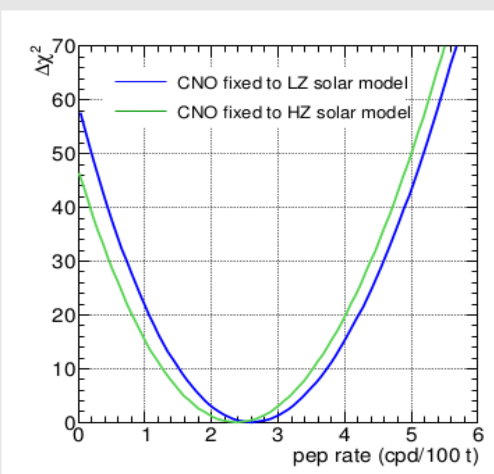


Applying more stringent cuts on FV and on the pulse-shape variable we can actually see the pep ν shoulder!



Sensitivity studied from distribution of maximum likelihood estimators obtained from simulated datasets

→ **Clear correlation between CNO, ^{210}Bi and pep**



Break **^{210}Bi – pep - CNO** correlation by fixing the CNO rate to:

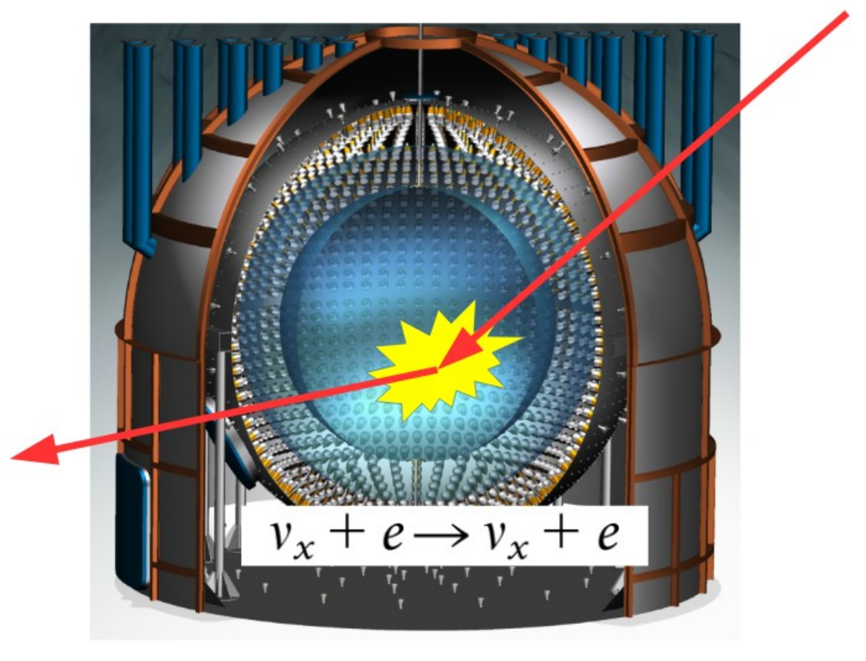
R_{CNO} (HZ) = 4.92 ± 0.55 cpd/100t

R_{CNO} (LZ)= 3.52 ± 0.37 cpd/100t

→ 5σ evidence of pep signal

(including systematic errors)

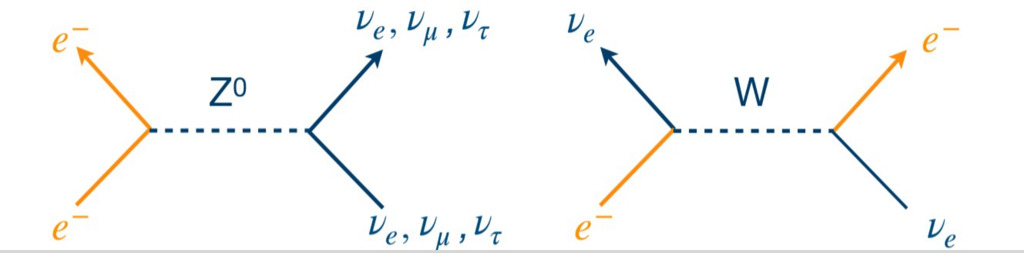
The Borexino signal



Mainly a solar neutrino experiment:
$\boldsymbol{\nu_e + e \rightarrow \nu_e + e}$
in an organic liquid scintillator
But can detect also **anti-neutrinos**
(Geo, Reactors, SuperNova)

✯ Neutrinos

Elastic scattering on electrons:
$\nu + e^- \rightarrow \nu + e^-$
Mono energetic ν produce characteristic shoulder



@1-2 MeV for electron flavour: σ ~10^{-44} cm^2
for μ,τ flavours: σ is ~6x smaller

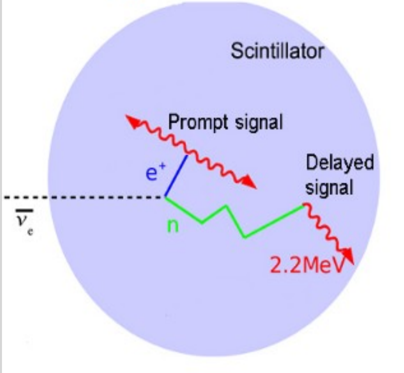
✯ Electron anti neutrinos

Inverse β-decay on p

$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$n \rightarrow p + d + \gamma(2.2MeV)$$
(250 μsec)

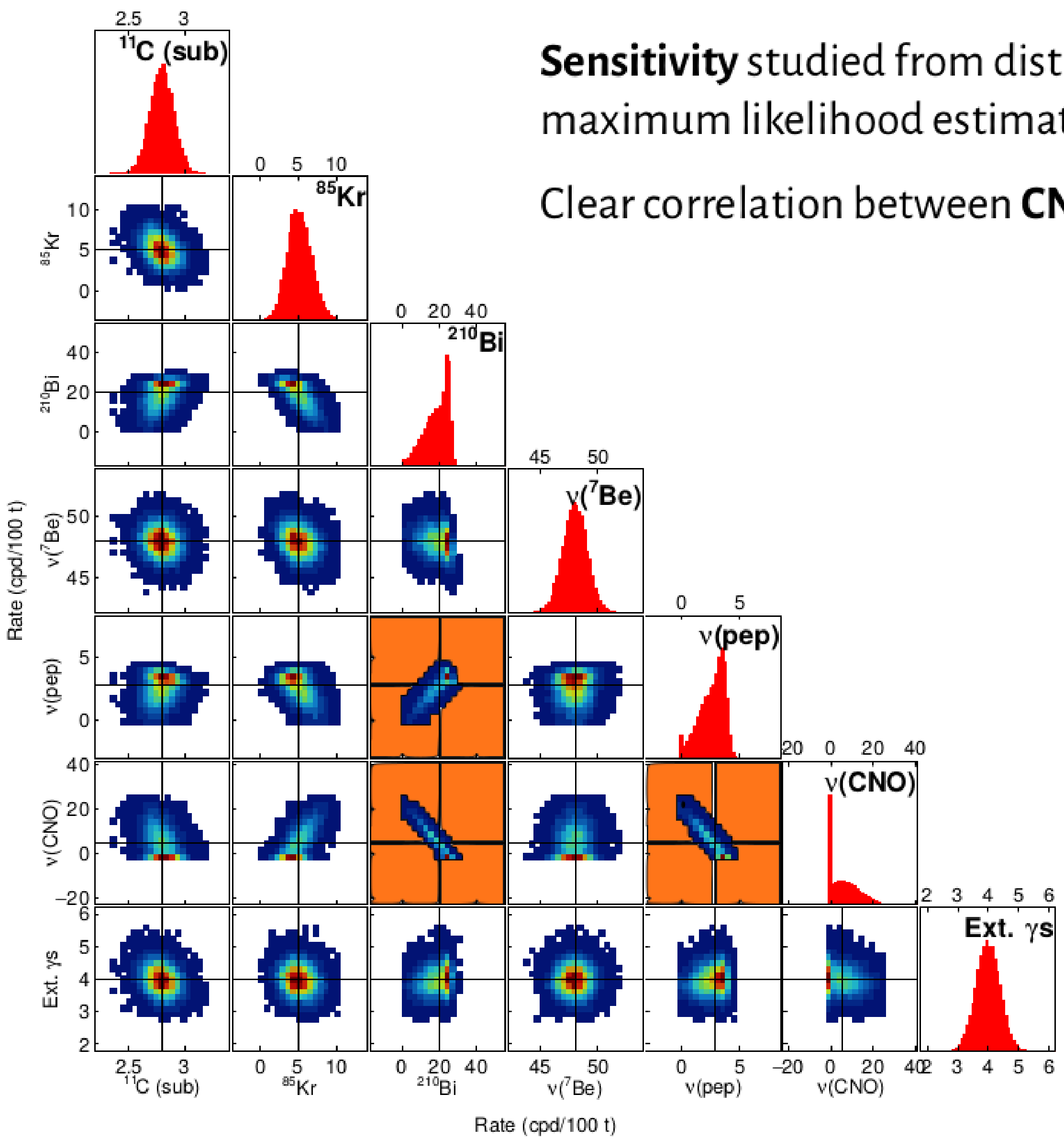
Energy threshold
= 1.8 MeV

Electron flavour only
σ @ few MeV ~10^{-42} cm^2
(~100 x more than scattering)

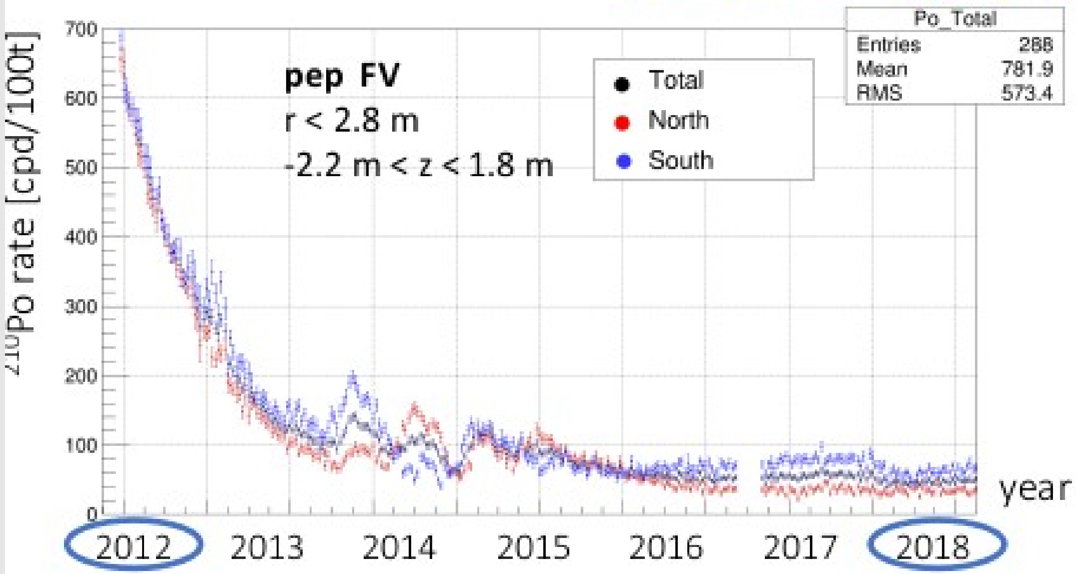


Sensitivity studied from distribution of maximum likelihood estimators obtained from **simulated datasets**

Clear correlation between **CNO, ^{210}Bi and *pep***



^{210}Po rate evolution in time



Decreasing trend:
^{210}Po out of equilibrium!
(1400 cpd/100ton at beginning of 2012)

Irregular/"oscillating" trends: possibly due to scintillator temperature variations (seasonally correlated)

$$R_{\rm Po}(t) = (A - B)e^{-t/\tau_{\rm Po}} + B \qquad \tau_{\rm Po} \approx 200 \text{ days}$$

A: "unsupported term", out of equilibrium

B: **"supported term", directly related to the ^{210}Bi parent** → Waiting for the plateau! ($t \to \infty$)

Core of the analysis: understand the validity and the features of this relation, quantifying this B-term.

Background issues

Source of contamination		Typical flux	Borexino requirements	Strategy (hardware)	Strategy (softw.)	Result phase 1	Result phase 2
μ	cosmic	~200 $s^{-1}m^{-2}$ @ sea level	< $10^{-10} s^{-1}m^{-2}$	Underground, water detector	Cherenkov PS analysis	< 10^{-10} eff > 0.9992	< 10^{-10} eff > 0.9992
γ	Rock	--	--	water	FV	negligible	negligible
γ	PMT, SSS	--	--	buffer	FV	negligible	negligible
^{14}C	Intrinsic PC	~ 10^{-12} g/g	~ 10^{-18} g/g	selectioon	threshold	~2 10^{18} g/g	~2 10^{18} g/g
^{238}U ^{232}Th	**Dust, metallic**	**10^{-5}-10^{-6} g/g**	**< 10^{-16} g/g**	**Distillation WE, filtration, mat. Selection, cleanliness**	**Tagging α/β**	**1.6+-0.1 10^{-17} g/g** **5.1+-1 10^{-18} g/g**	**< 9.4 10^{-20} g/g** **< 5.7 10 $^{-19}$ g/g**
^{7}Be	cosmogenic	~ 3 10^{-2} Bq/t	< 10^{-6} Bq/t	distillation	--	Not seen	Not seen
^{40}K	Dust, PPO	~2 10^{-6}g/g (dust)	< 10^{-18} g/g	Distillation, WE	--	Not seen	Not seen
^{210}Po	Surface cont. from ^{222}Rn		< 1c/d/t	Distillation, WE, filtration, cleanliness	fit	May '07 70 c/d/t Jan '10 ~1 c/d/t	< 1 c/d/t
^{222}Rn	Emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	< 10 cpd 100 t	N_2 stripping cleanliness	Tagging α/β	< 1 cpd 100t	< 0.1 cpd 100t
^{39}Ar	Air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr	<< ^{85}Kr
^{85}Kr	Air, nuclear weapons	1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	30 +-5 cpd/100t	< 7 cpd/100 t
^{210}Bi	Surface cont. from ^{220}Rn	--	--	Water extraction	fit	10-50 cpd/100t	~17 cpd/100 t

BX Phase II Results
arXiv : 1707.09279

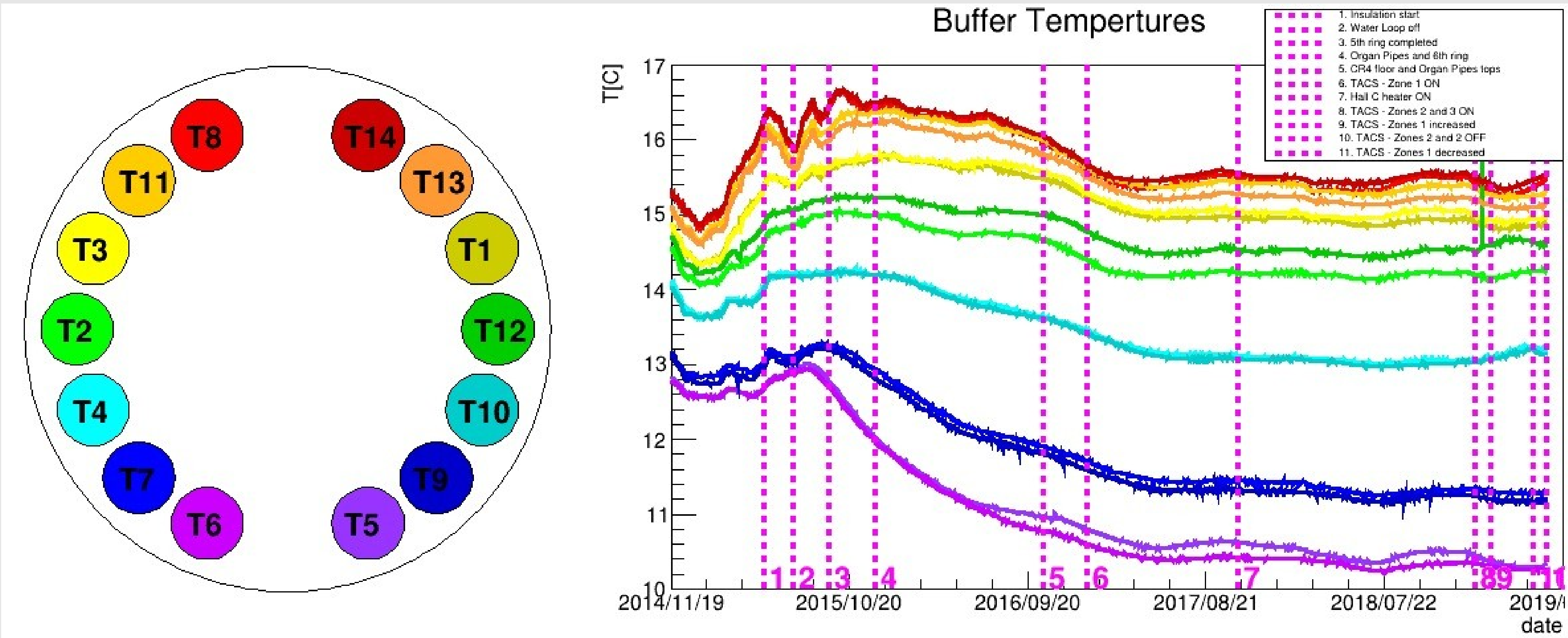
Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	131.1 ± 1.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.2 ± 1.4	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.11\ ^{+0.06}_{-0.08}) \times 10^{9}$	47.9 ± 2.8	$4.93\,(1 \pm 0.06) \times 10^{9}$	43.7 ± 2.5	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	2.74 ± 0.04	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.04	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	2.74 ± 0.04	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.04	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)	4.92 ± 0.55	$4.88\,(1 \pm 0.11) \times 10^{8}$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^{8}$

^{85}**Kr**: Factor 4.6 reduction with respect to Phase-I
^{210}**Bi**: Factor 2.3 reduction with respect to Phase-I

Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

Source of uncertainty	*pp*		^{7}Be		*pep*	
	−%	+%	−%	+%	−%	+%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6

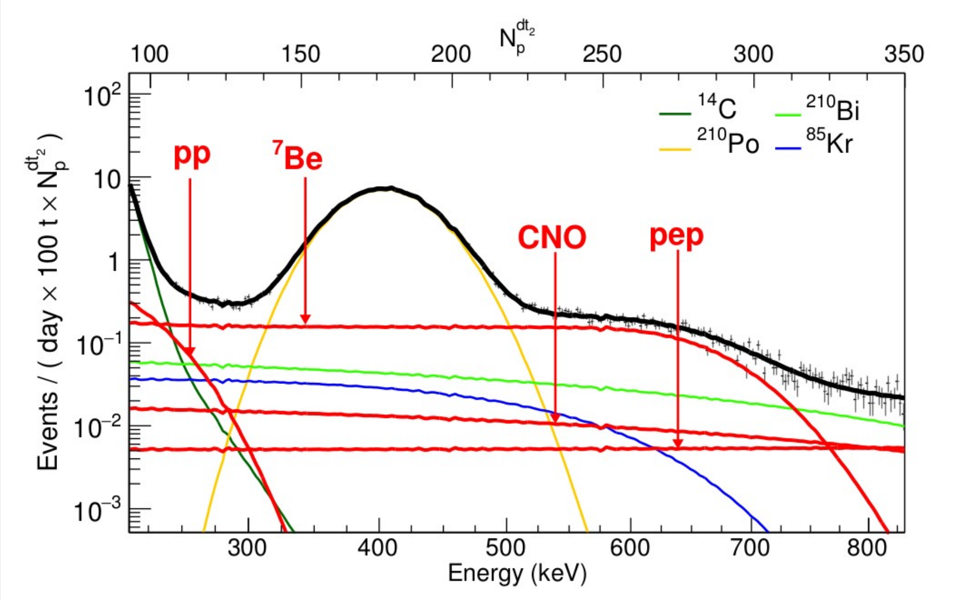
Temperature stabilization

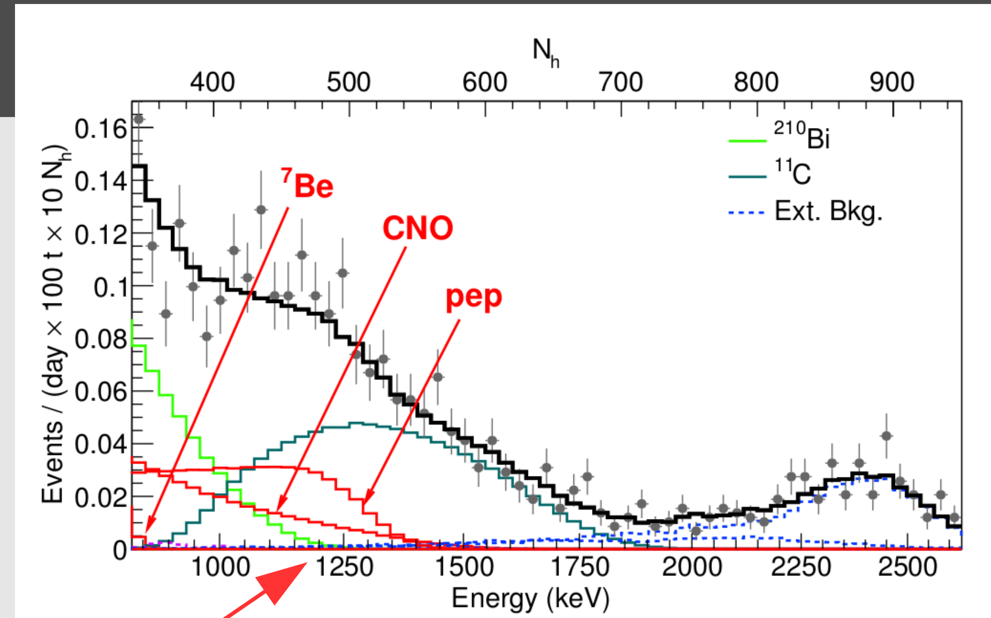


(1)insulation started
(2)Water Loop turned off
(3)5th ring insulation completed ,
(4)Organ Pipes and 6th ring insulation completed,
(5)CR4 floor and Top Organ Pipes insulation completed,
(6)Temperature Active Control System tests started
(7)Hall C active control started.

Fit results

Zoom into low-energy part of the spectrum





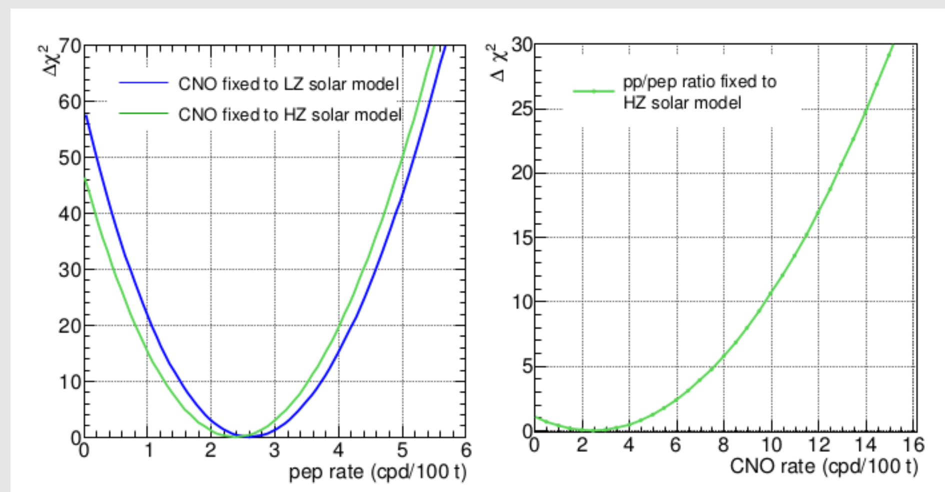
Pep-neutrino characteristic shoulder is made visible by applying more stringent cuts (R<2.8 m and L_{PS}<4.8)

^{7}**Be** → precision improved beyond 3% level

pp → absolute precision improved by 10%

pep → >5σ evidence in LZ/HZ, including systematics

CNO → slightly worse limit because of less stringent assumptions on pep rate



Seasonal modulations of the ^{7}Be solar neutrino rate

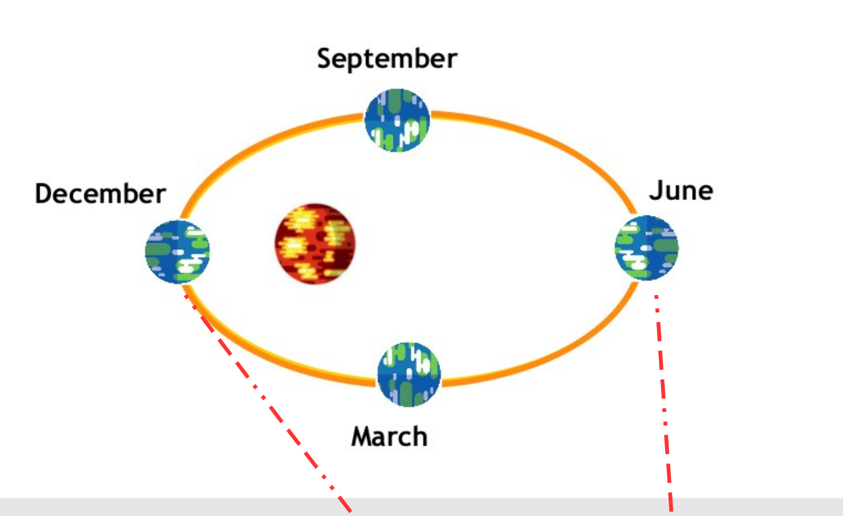
Astroparticle Physics 92 (2017)

Search for the seasonal variations of the neutrino interaction rate due to the varying distance L(t) between Sun and Earth during the year

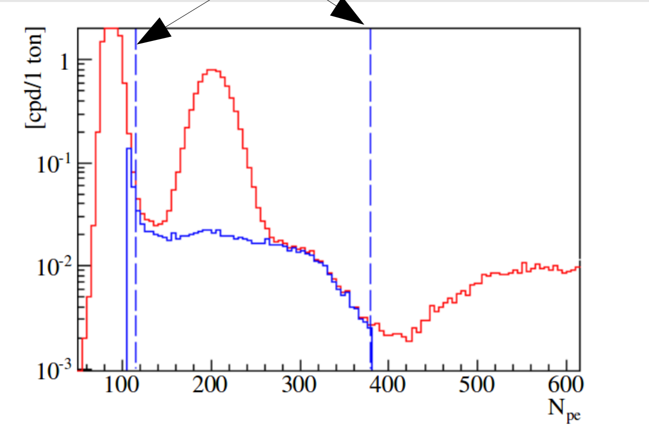
→ Confirms the solar origin of the observed signal

→ Measurement of the astronomic year with solar neutrinos

→ The absence of an annual modulation is rejected at 99.99% C.L.



Only the events in the energy range: 215keV-715 keV



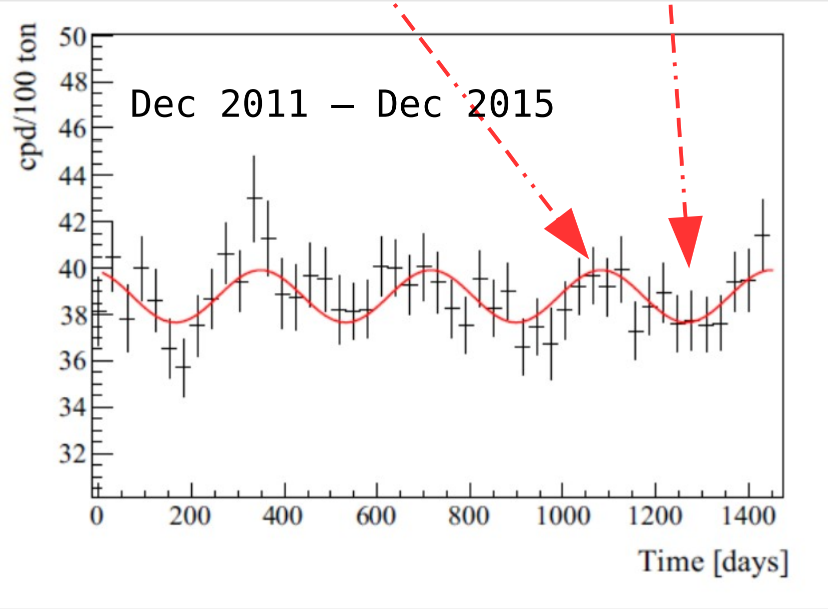
After ^{210}Po subtraction by pulse-shape discrimination

Fit to the evolution of the rate in time (bin of 30 days)

$\varepsilon = 1.74 \pm 0.45$ %

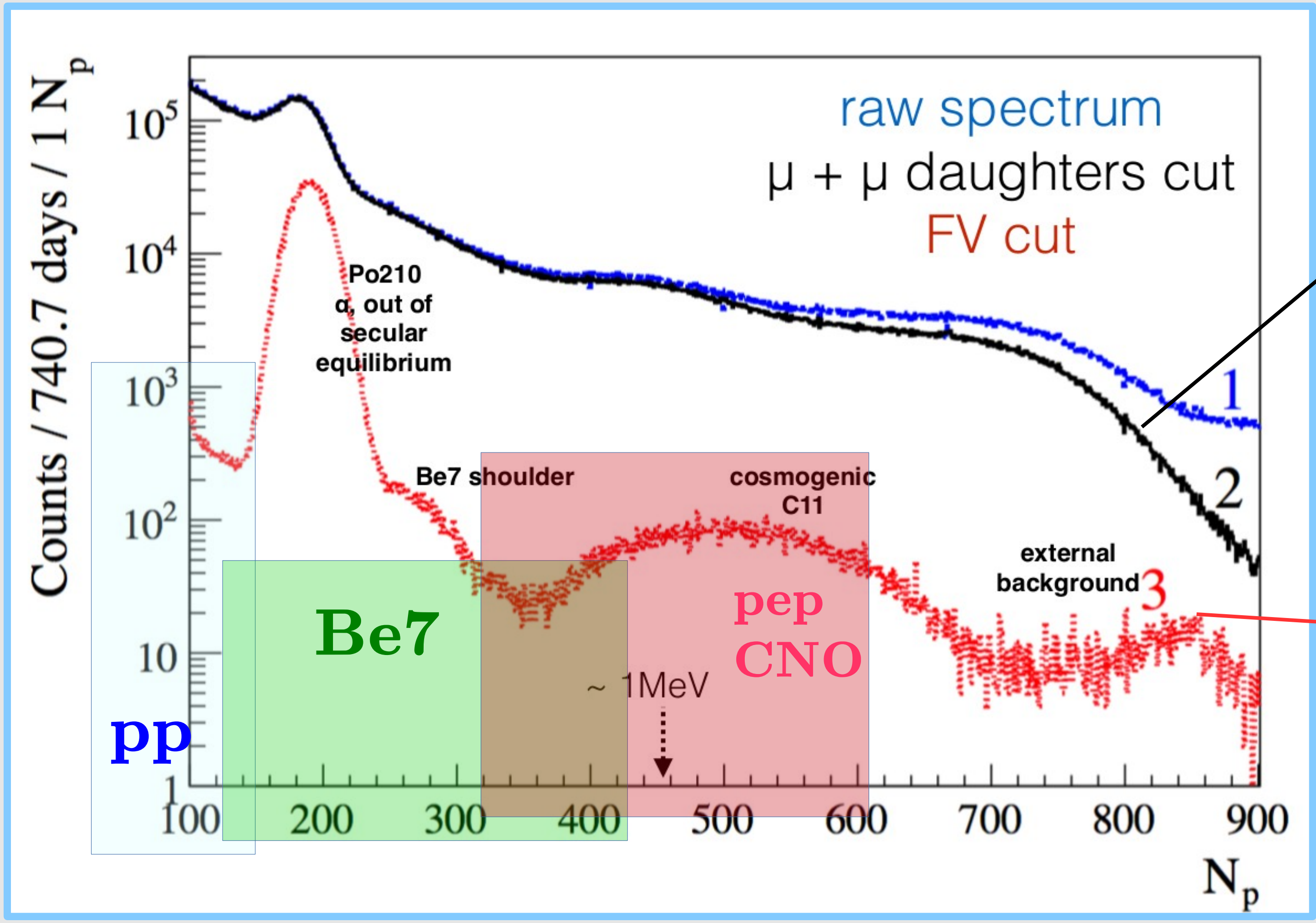
$T = 367 \pm 10$ days

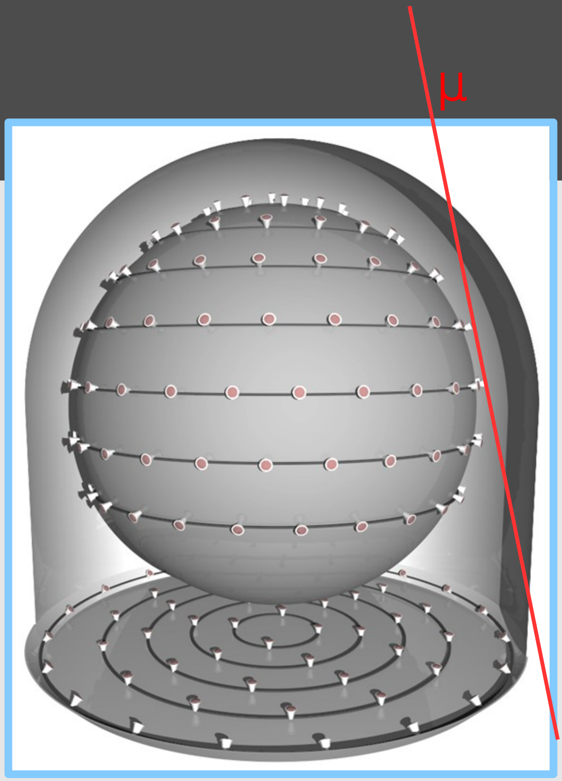
$\Phi = -18 \pm 24$ days

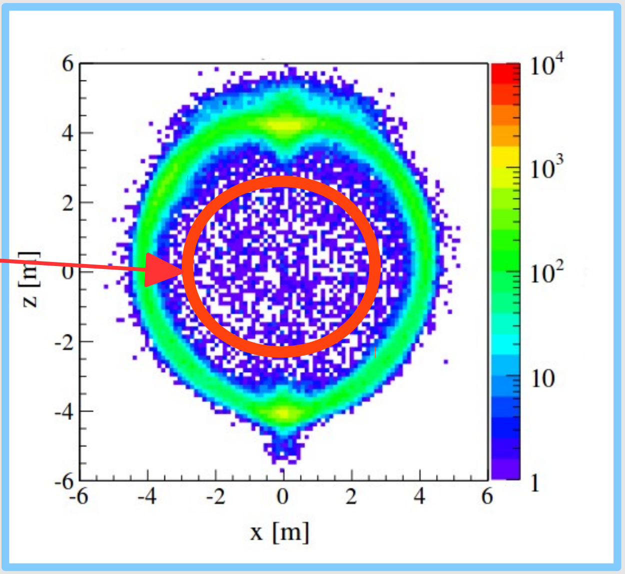


Borexino visible energy spectrum and background rejection

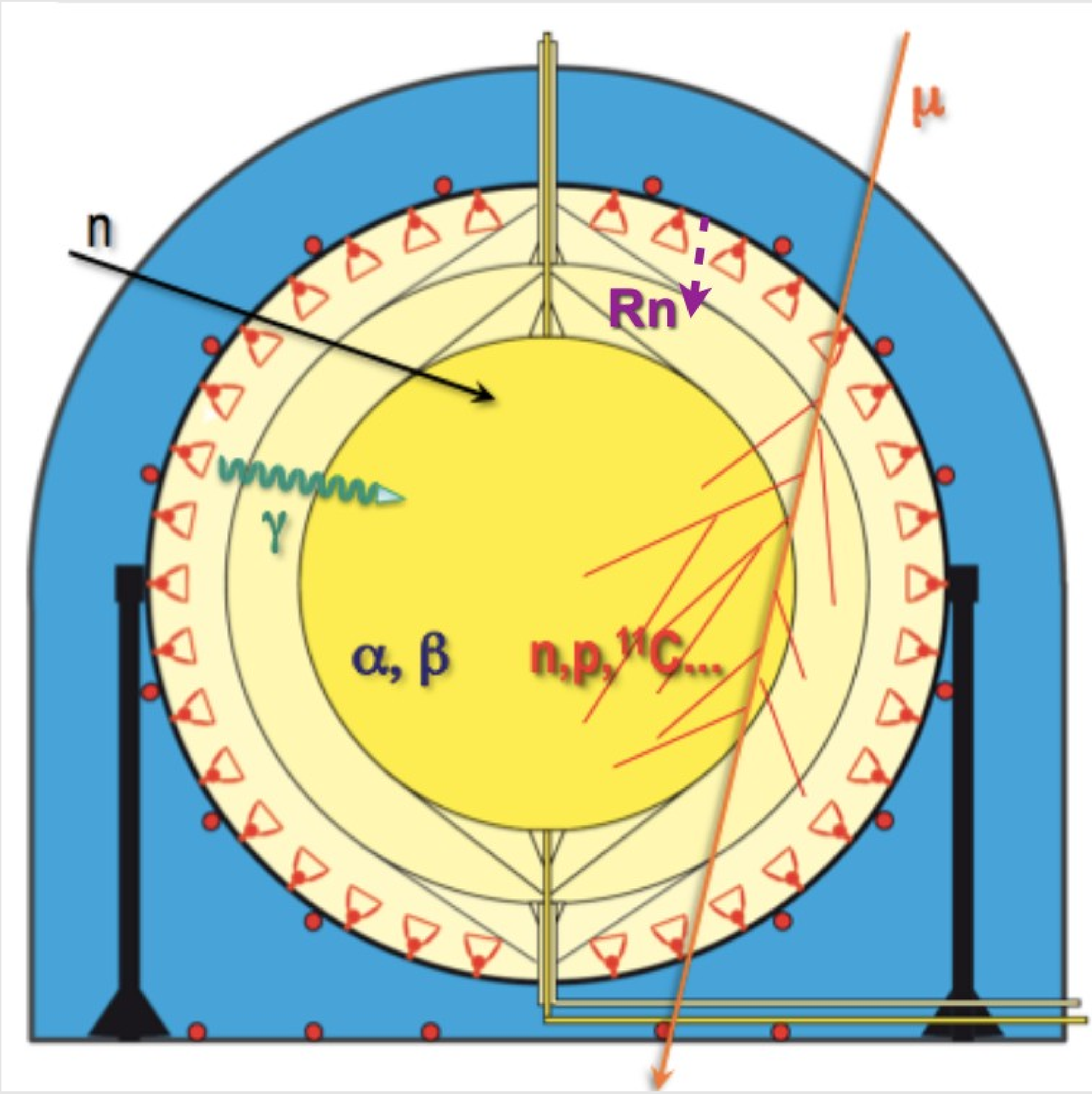
(1) Raw spectrum
(2) External and internal muon veto
(veto of 300 ms after a muon in OD)
(3) Fiducial volume cut for removing external background







Borexino backgrounds



internal radioactivity
traces of radioisotopes in the scintillator (U,Th,^{40}K)

Internal

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

External

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure

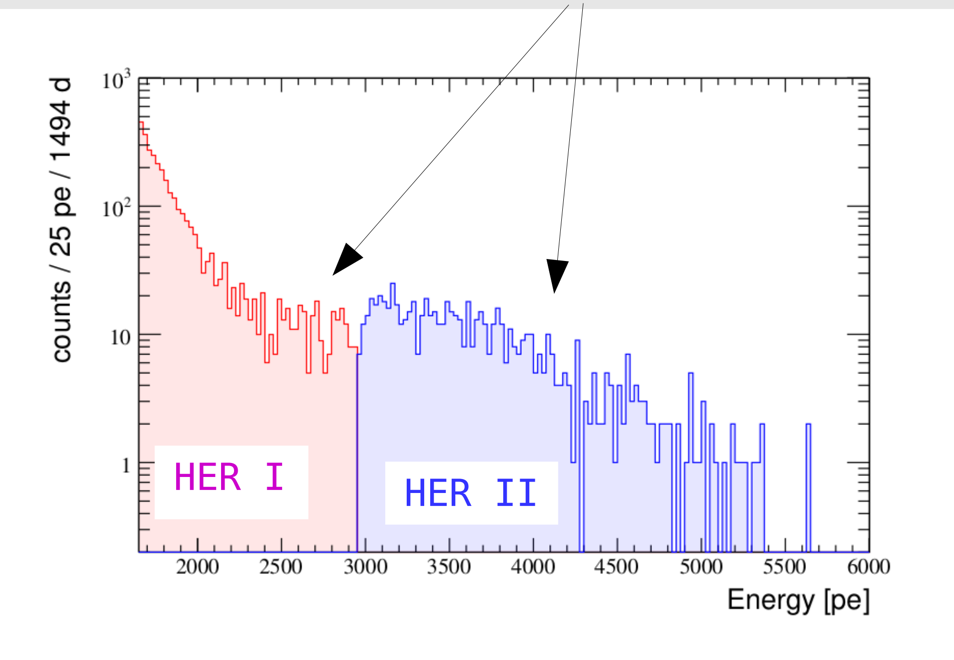
what is improved in analysis:

- ★ **Fit done on radial distribution in two energy ranges**
  HER-1 (3.2 -5.7 MeV)
  HER-2 (5.7-16 MeV)

  No natural radioactivity expected above 5 MeV

- ★ Data-set: January 2008 - December 2016 (Purification period removed)
- ★ No FV cut
- ★ Total exposure: 1.5 kton years ; (x 11.5 of the Phase I analysis)
- ★ Better understanding of backgrounds (external γs, cosmogenic)
- ★ Lowest energy threshold among Real Time Detectors

^{8}B analysis performed in two energy ranges



Selection cuts (27.6% dead time)

- ✓ Removed muons
- ✓ Neutron cut: 2 ms after all muons
- ✓ Cosmogenics cut: 6.5 after all internal muons (^{12}B, ^{8}He, ^{9}C, ^{9}Li, ^{8}B, ^{6}He, ^{8}Li)
  ^{10}C TFC cut: 120 s, 0.8 m radius sphere around neutrons
- ✓ Fast coincidence cut: no ^{214}Bi-^{214}Po
- ✓ Coincidence cut: no events closer than 5 s

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure

arXiv:1709.00756

- Radial Fit not Energy Fit → Not to assume shape of survival probability P_{ee}
- radial information used to discriminate signals from external backgrounds

- Deep study of backgrounds close to the vessel border:
  - U/Th chain elements on the vessel (only ^{208}Tl ranges above 3.2 MeV)
  - emanation of ^{220}Rn from the vessel → additional ^{208}Tl component
  - high-energy gamma-rays from neutron capture on Fe/C

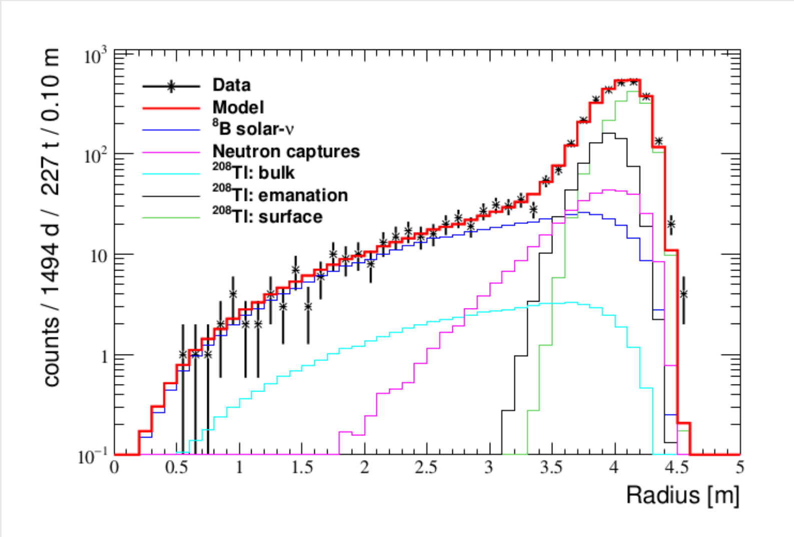
Rate = $0.223^{+0.015+0.006}_{-0.016-0.006}$ cpd/100t

Flux = $(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^6$ cm^{-2} s^{-1}

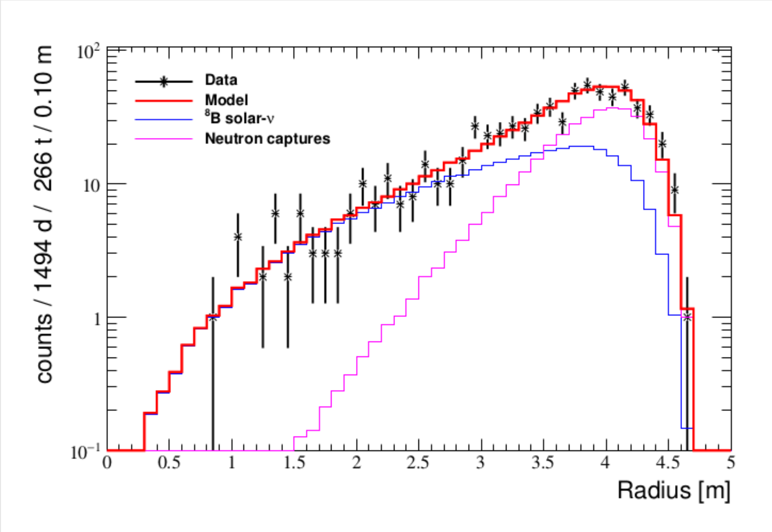
Theoretical predictions

Flux=
$5.46(1.0\pm0.12) \times 10^6$ cm^{-2} s^{-1} (HZ)
$4.50(1.0\pm0.12) \times 10^6$ cm^{-2} s^{-1} (LZ)

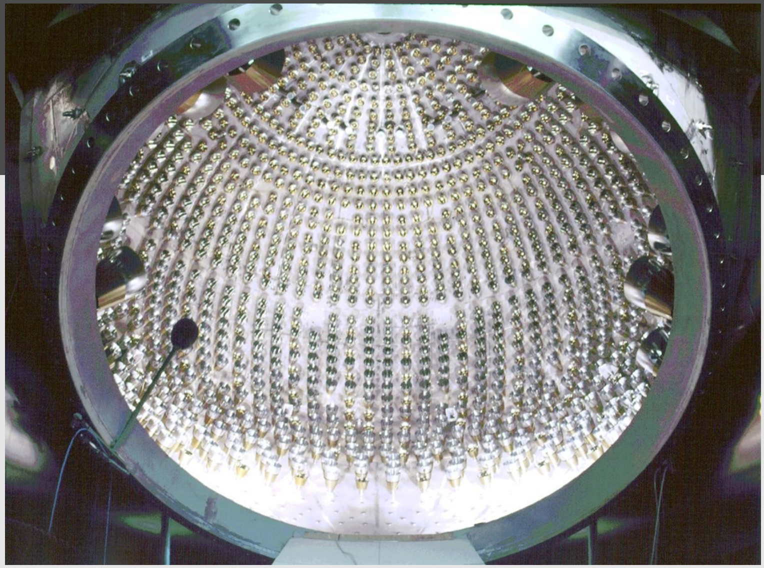
HER II Fit: [2950, 8500] p.e. > 5.7 MeV



HER I Fit: [1650, 2950] p.e 3.2 to 5.7 MeV



Signal and backgrounds

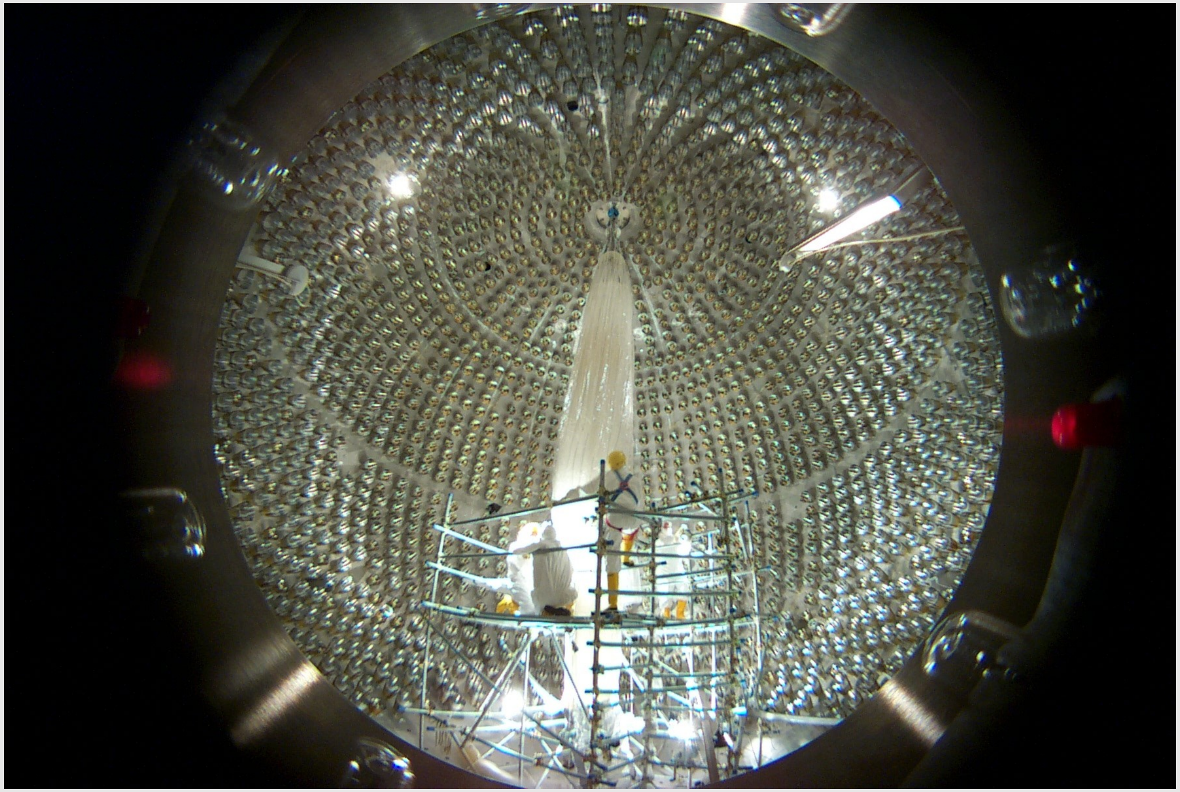


Expected ~50 events/day on 100ton of liquid scintillator from neutrinos ~ $6\ 10^{-9}$ **Bq/kg**

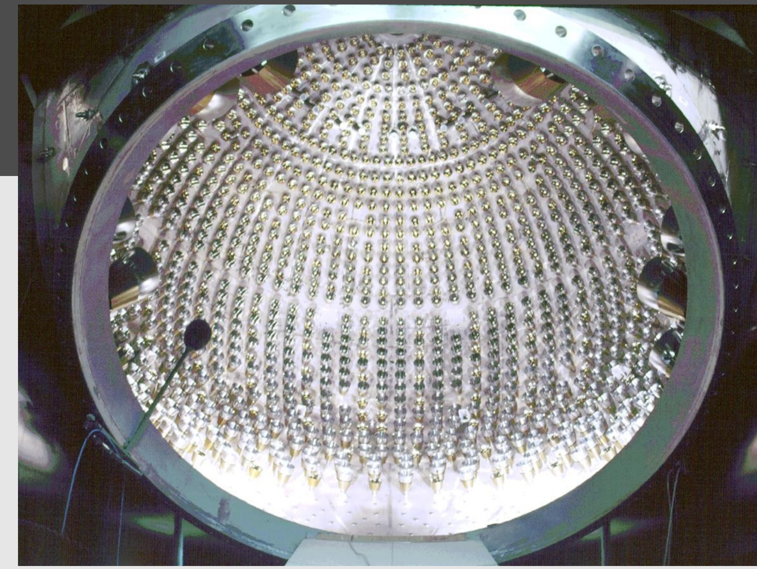
But

- Natural water is **~10 Bq/Kg** in **^{238}U**, **^{232}Th** and **^{40}K**
- Air is **~10 Bq/m³** in **^{39}Ar**, **^{85}Kr** and **^{222}Rn**
- Typical rock is **~100-1000 Bq/m³** in **^{238}U**, **^{232}Th** and **^{40}K**

→ Borexino's scintillator must be 9/10 orders of magnitude less radioactive than anything on Earth!



Signal and backgrounds



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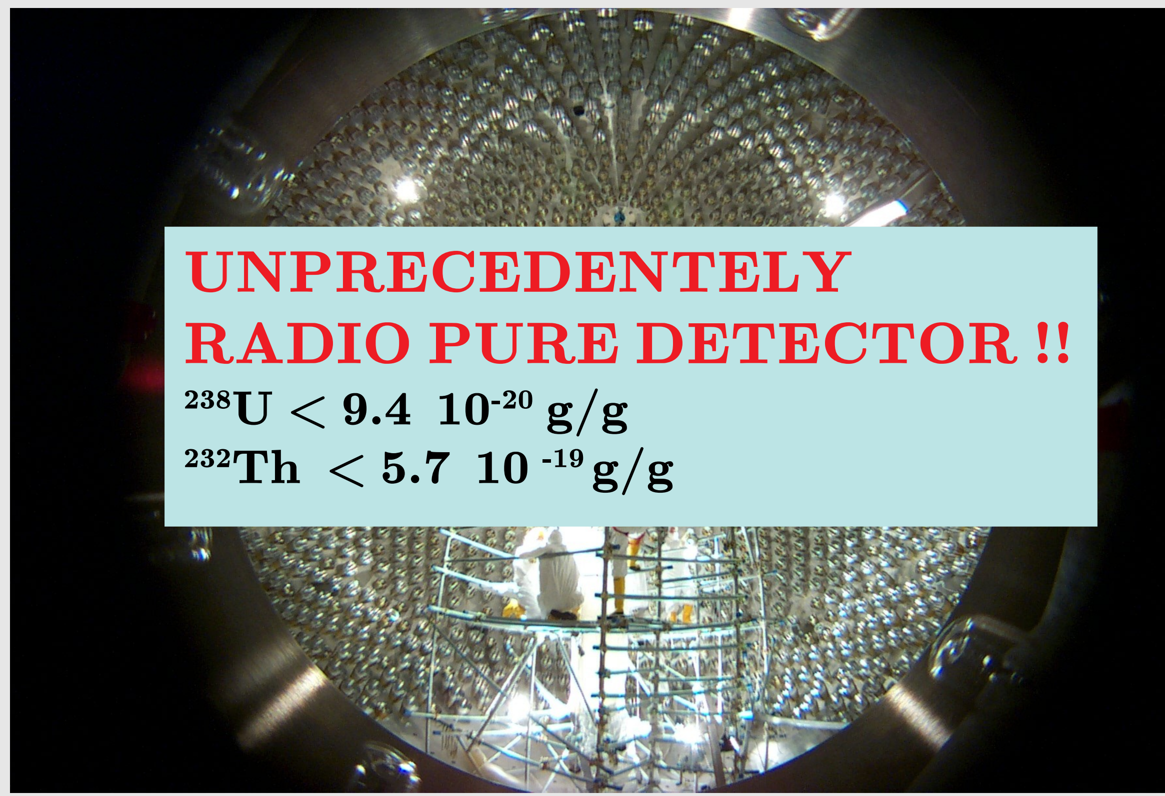
HOW??

→ Principle of graded shielding: materials get more pure towards the detector core

→ purification of target mass

15 years of work to reach the required Radio-purity



UNPRECEDENTELY RADIO PURE DETECTOR !!

^{238}U < 9.4 10^{-20} g/g

^{232}Th < 5.7 10^{-19} g/g