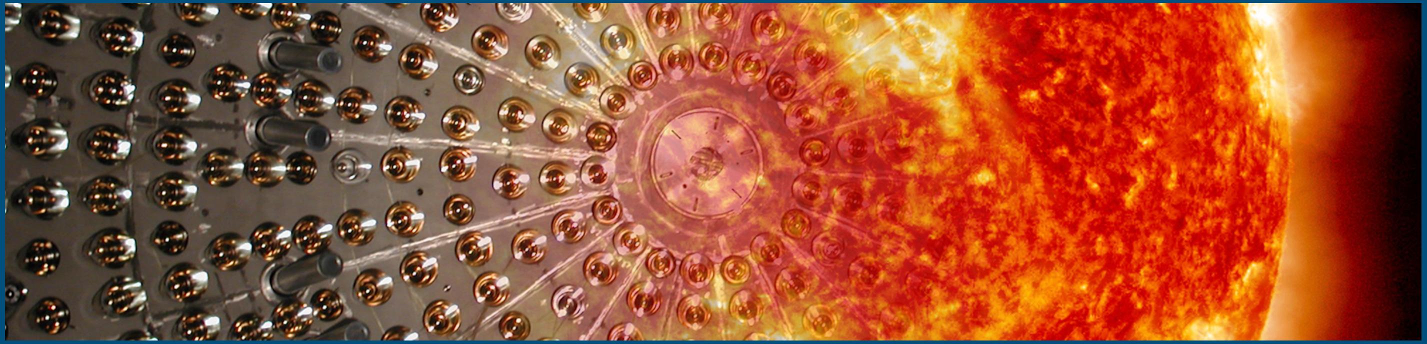
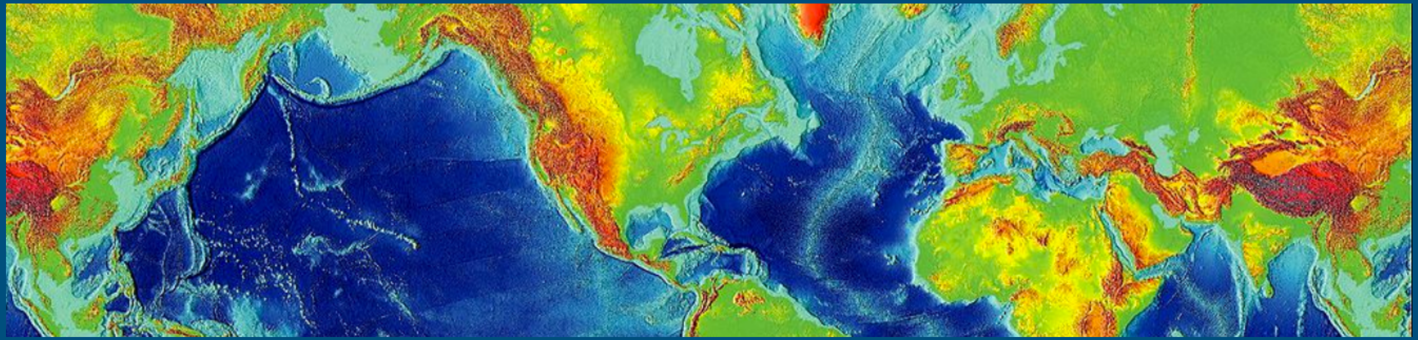
SYSTEMATIC ERRORS
IN BOREXINO SOLAR AND GEONEUTRINO ANALYSES

LIVIA LUDHOVA

IKP-2, FORSCHUNGSZENRUM JÜLCH
AND RWTH AACHEN UNIVERSITY,
GERMANY





NOVEMBER 1ST, 2018
VANCOUVER, CANADA

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

OUTLINE

1. Borexino **detector**, calibration, and Monte Carlo

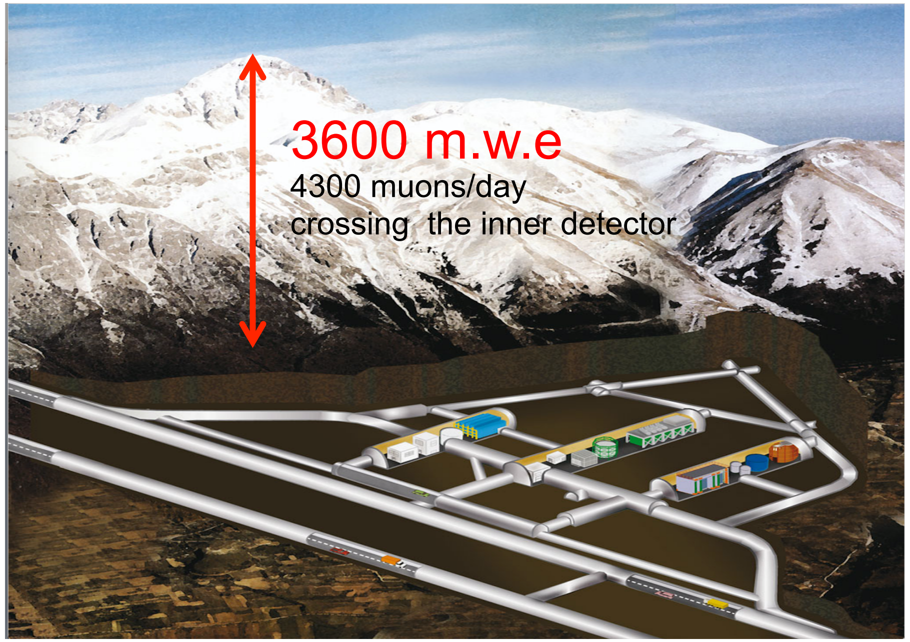
2. Latest **solar neutrino analysis** (Nature, October 25th, 2018)
   - ✓ Results summary
   - ✓ Main sources of systematic errros

NEW

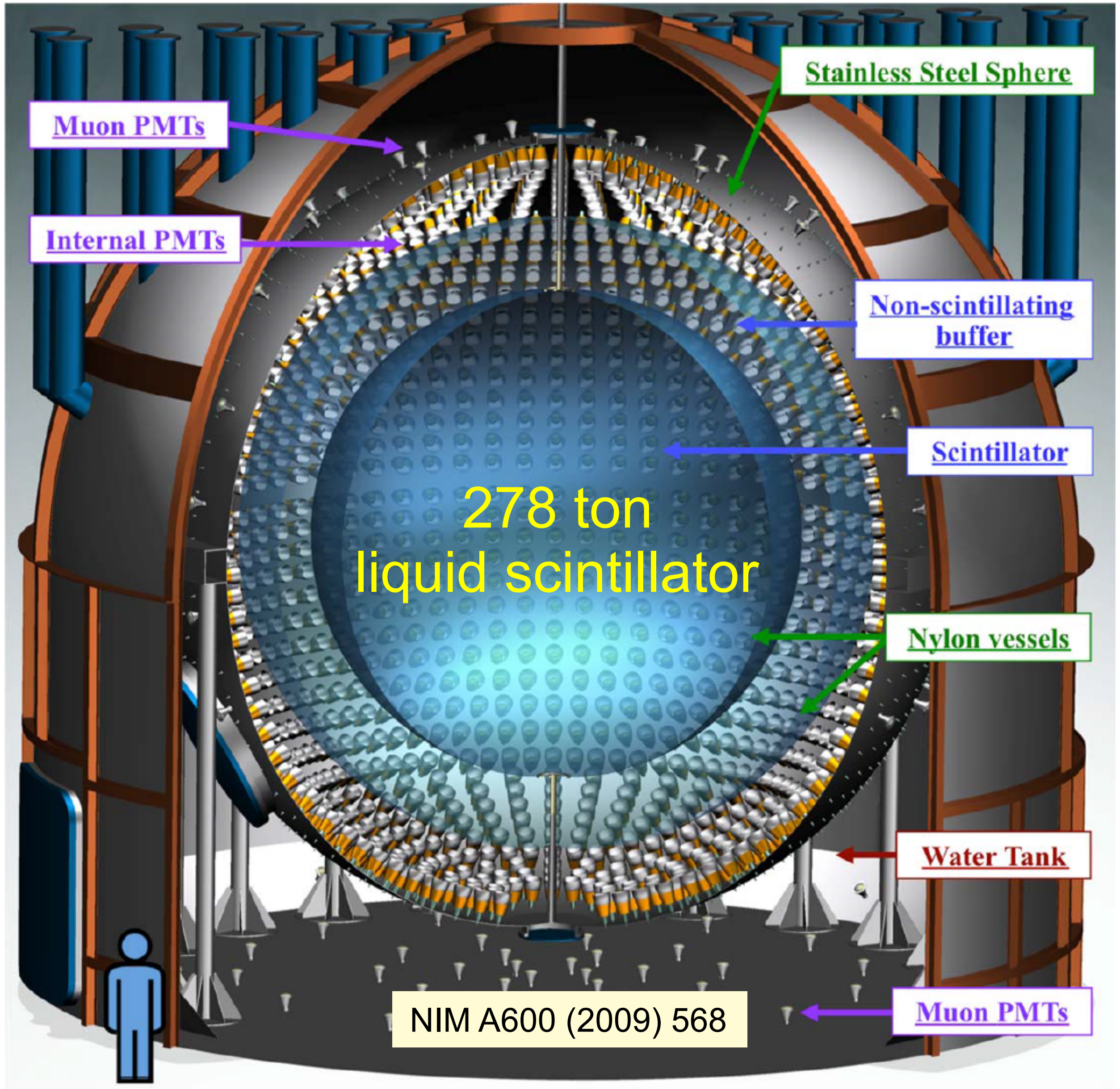
3. Latest **geoneutrino analysis** (PRD 92, 031101(R) (2015))
   - ✓ Results summary
   - ✓ Main critical issues in geoneutrino analysis

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy



- **the world radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g , $< 8 \times 10^{-20}$ g(U)/g
- **550 hit PMTs / MeV**
- energy reco: 5 keV (5%) @ 1 MeV
- position reco: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)

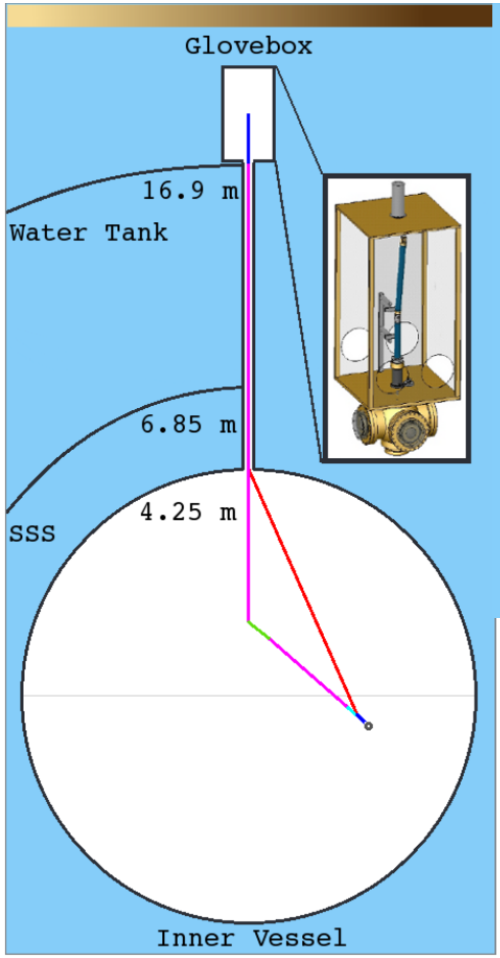


NIM A600 (2009) 568

Operating since 2007

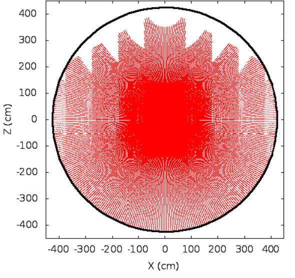
BOREXINO CALIBRATION

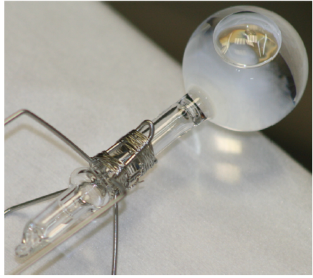
JINST 7 (2012) P10018

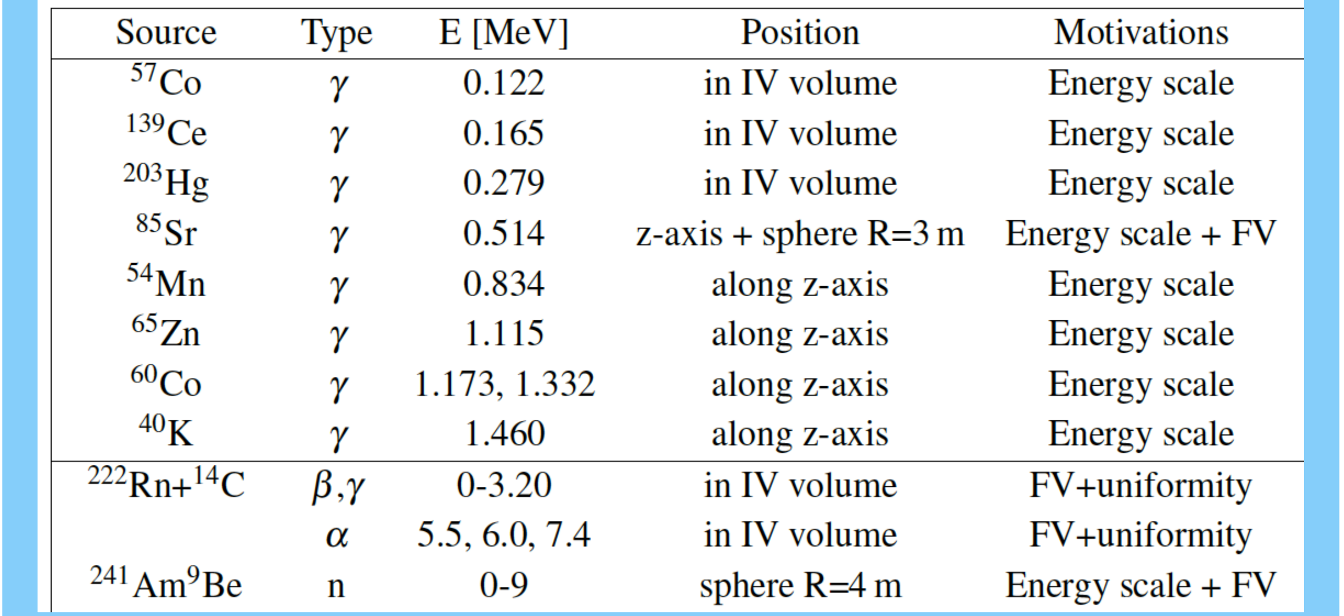


Internal calibration

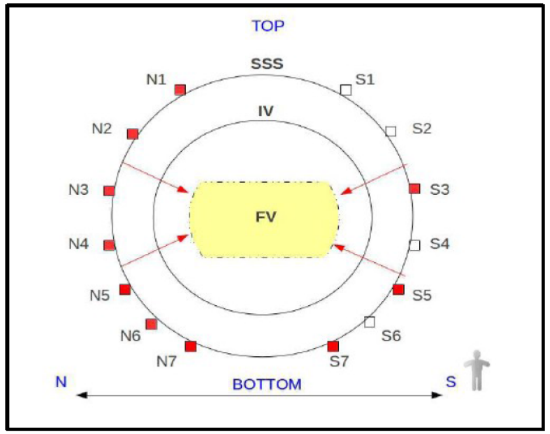
- ~300 points in the whole scintillator volume
- LED-based source positioning system







Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV

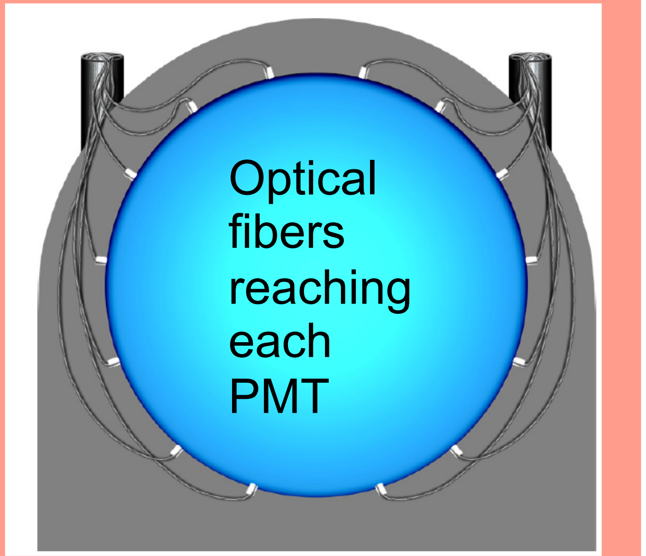


External calibration

9 positions with ^{228}Th source (γ 2.615 MeV)

Laser calibration

- PMT time equalisation
- PMT charge calibration (charge calib. also using ^{14}C)



Optical fibers reaching each PMT

BOREXINO MONTE CARLO

Astrop. Phys. 97 (2018) 136

Better than 1% (1.9%) precision
for all relevant quantities in the solar analysis <2 (>3) MeV

Geant-4 based

Tracking code

- Full detector geometry
- Energy loss
- Photon production & propagation

C++ Borexino custom

Electronics simulation

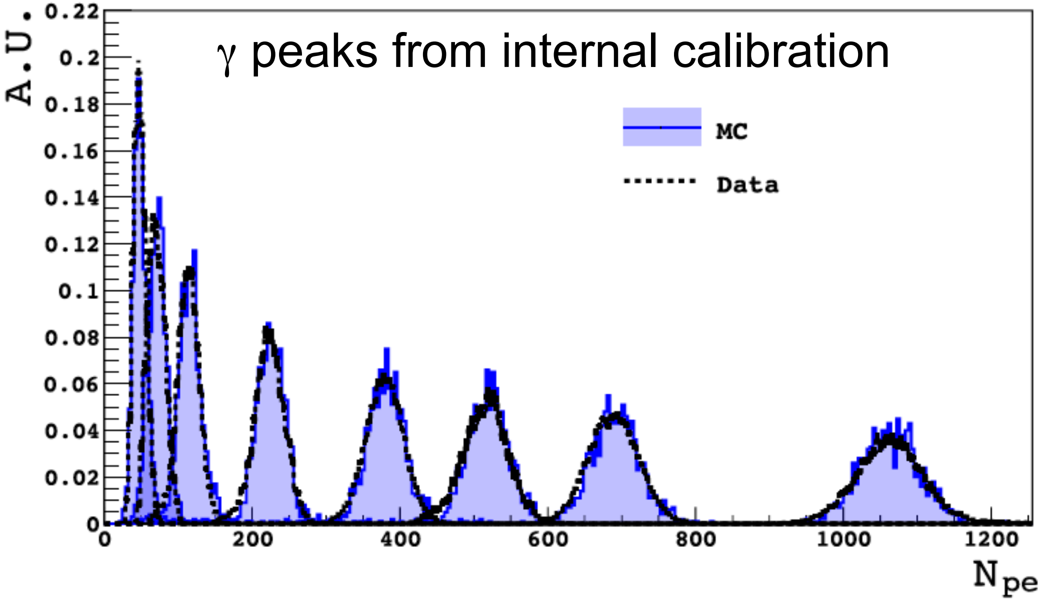
Follows real DAQ conditions

- PMT quality and calibration
- Dark noise
- Trigger condition
- Number of working channels on an event-by-event basis

Echidna: C++ Borexino custom

Reconstruction

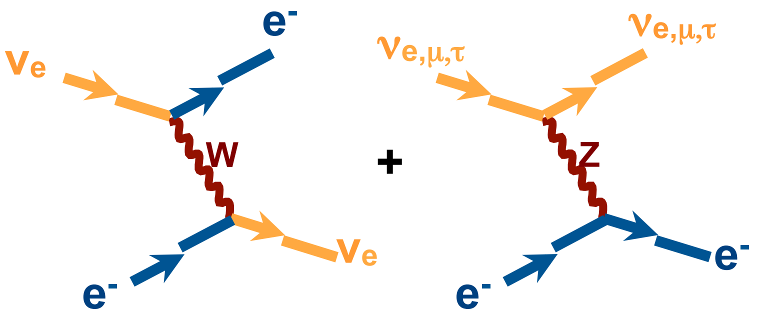
- Several energy estimators
- Position reconstruction
- Pulse-shape variables
- Output in the same format as reconstructed data files

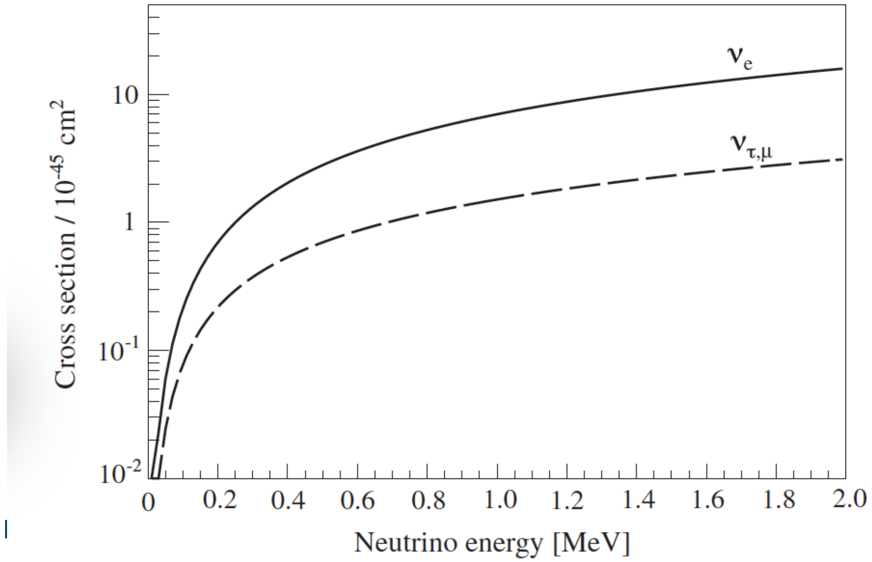


- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.
- **Biasing technique for external background.**
- **Simulation of pile-up events.**

NEUTRINO AND ANTINEUTRINO DETECTION

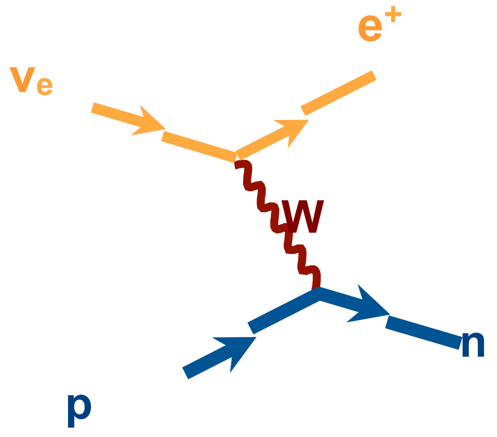
Neutrino detection:
elastic scattering off electrons



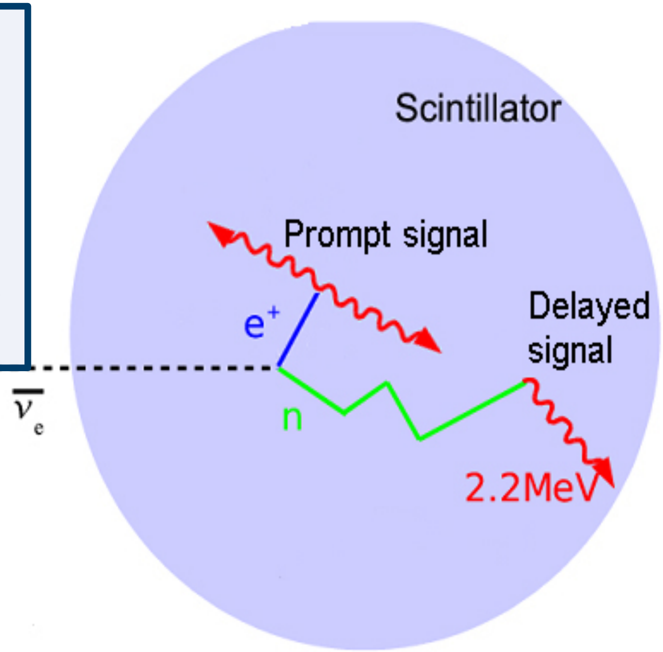


Antineutrino detection:
Inverse beta decay

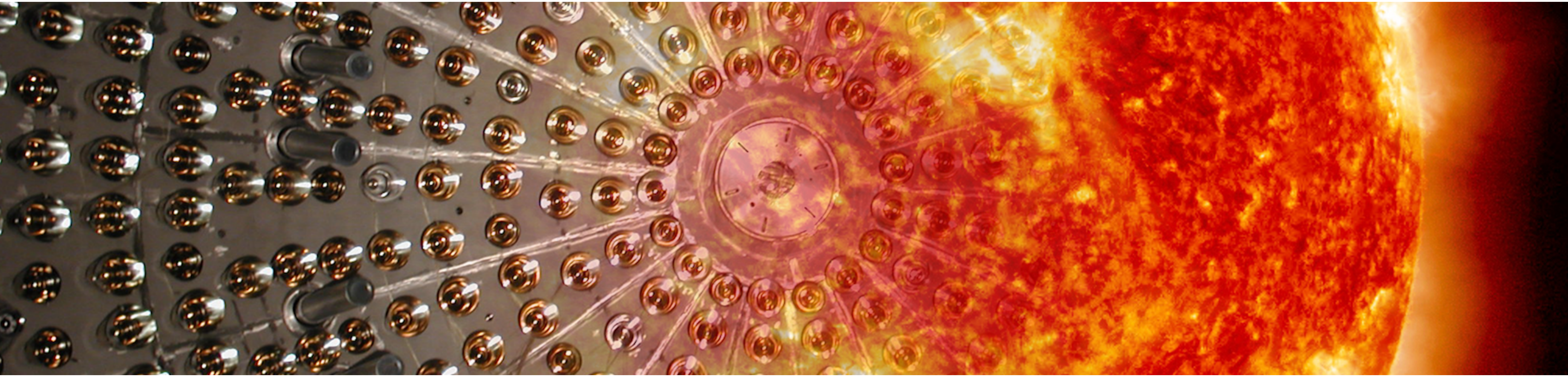
Energy threshold = 1.8 MeV
Electron flavour only
σ@ few MeV: ~10^{-42} cm^2
(~100 x more than scattering)



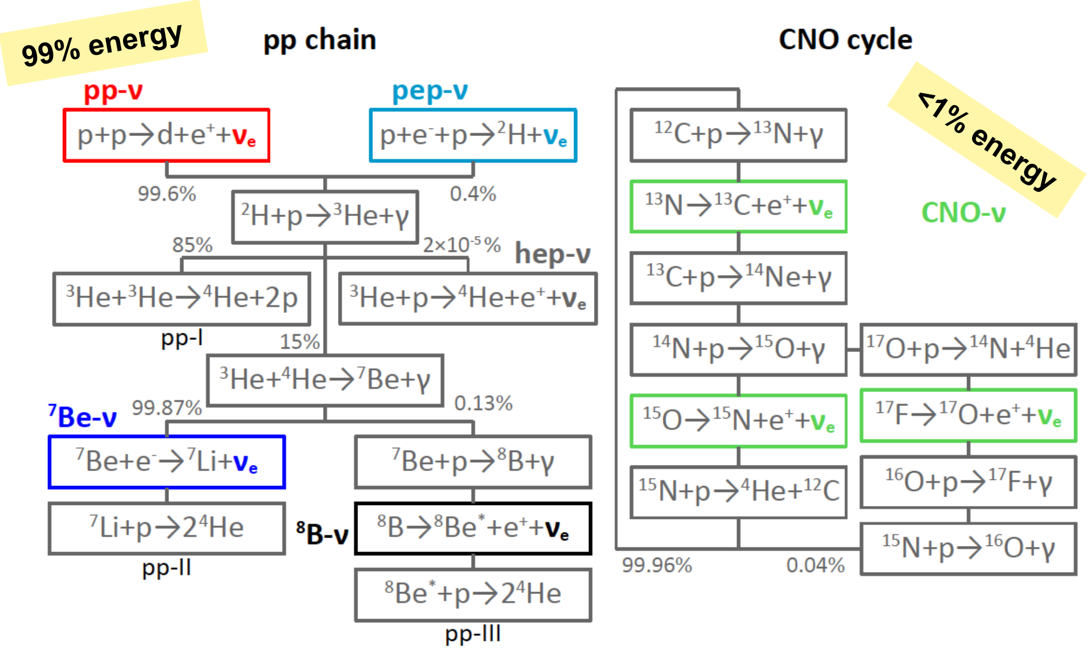
$$
\begin{aligned}
E_{prompt} &= E_{visible} \\
&= T_{e+} + 2 \times 511\ \text{keV} \\
&= E_{antinu} - 0.784\ \text{MeV}
\end{aligned}
$$

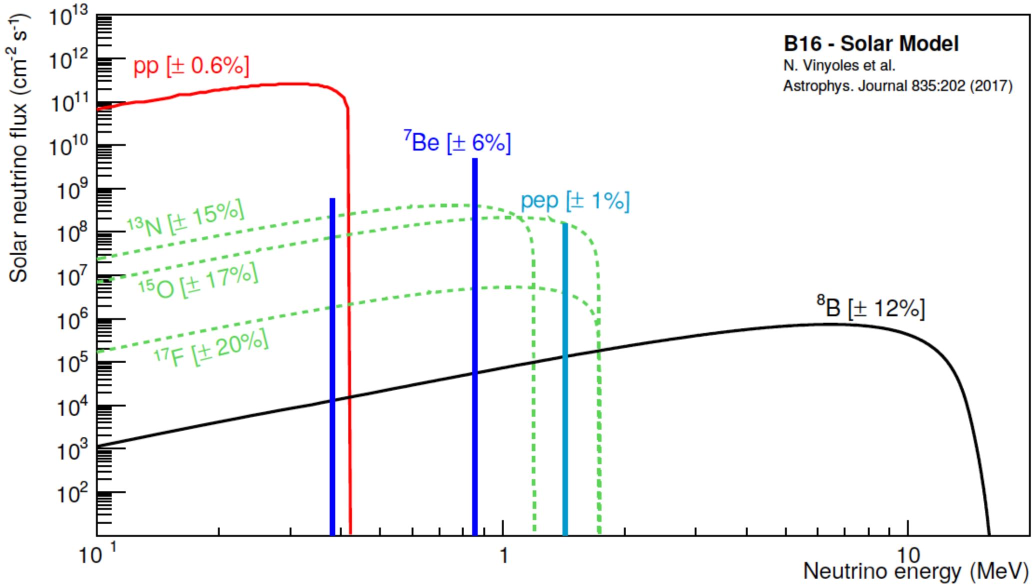


SOLAR NEUTRINOS



SOLAR NEUTRINOS AND WHY TO STUDY THEM





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

Solar and stellar physics

- Direct probe of **nuclear fusion**
- Testing **thermodynamical stability** of the Sun
- **Standard Solar Models**
  - ✓ Helioseimology
  - ✓ High-Z and Low-Z models (different ϕ_ν prediction)
  - ✓ Metallicity problem

Neutrino physics

- **Survival probability** and its upturn
- Matter effects
- Testing LMA-MSW predictions
- Searches for **new physics**
- Solar mixing angle and global fits of **oscillation parameters**

LATEST SOLAR-ν RESULTS

Spectroscopy of all pp-cycle neutrinos at once

Low Energy Region (LER) 0.19 – 2.93 MeV:

pp (9.5%), **^{7}Be** (2.7%), ***pep*** (>5σ)

High Energy Region (HER) 3.2 – 16 MeV:

^{8}B (3 MeV threshold, 8%)

- First Borexino limit on **hep** neutrinos
- Limit on **CNO cycle** neutrinos
- Neutrino and elmag luminosity in agreement

ARTICLE

Nature Oct 25th 2018

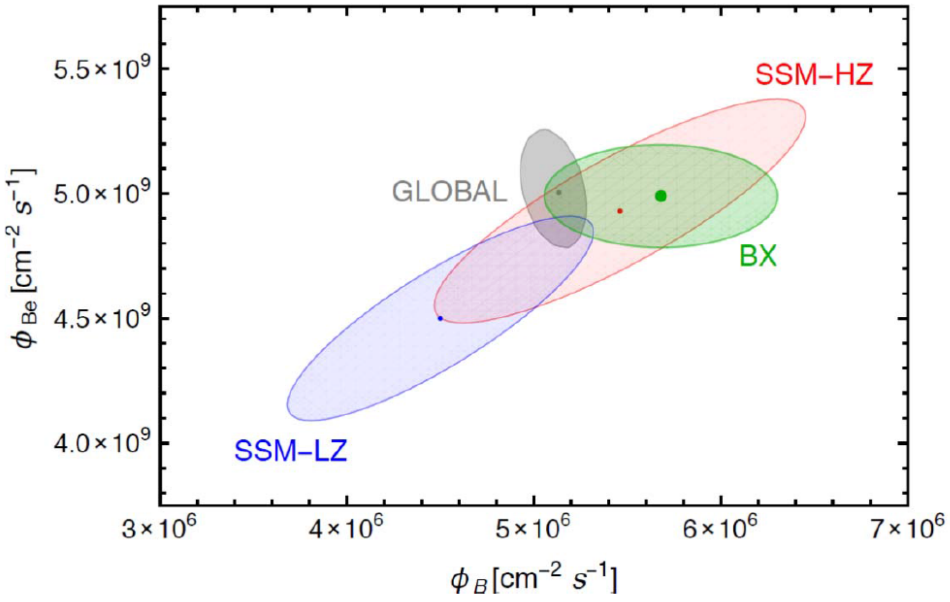
https://doi.org/10.1038/s41586-018-0624-y

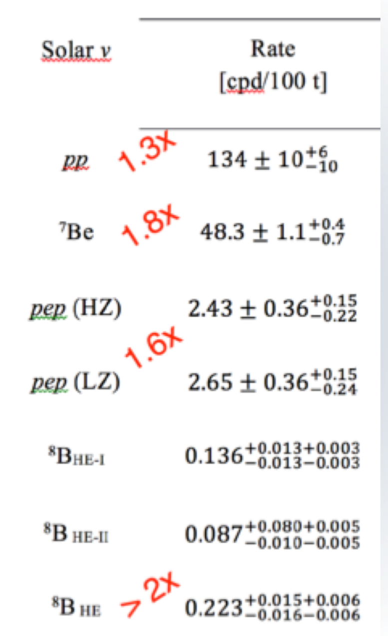
Comprehensive measurement of *pp*-chain solar neutrinos

NEW

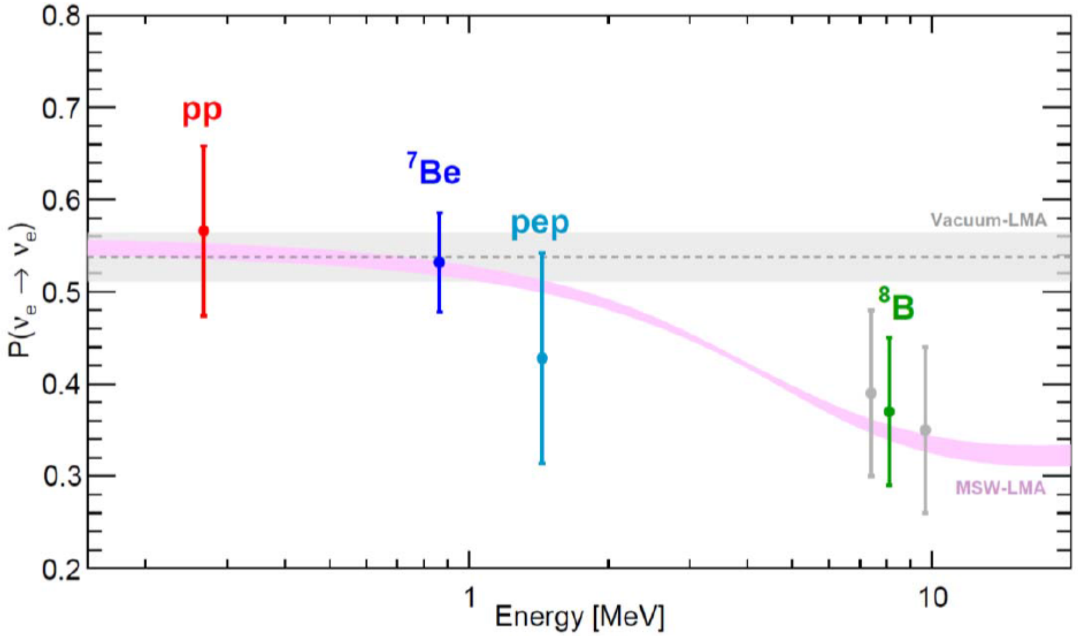
The Borexino Collaboration*

- Indication towards **HZ Standard Solar Models**
- BR(pp_{II}/pp_I)=<^{3}He+^{4}He>/<^{3}He+^{3}He> = 0.18±0.03
- Survival probabilities at different energies in both vacuum and matter domains
- **Vacuum-LMA model excluded at 98.2% CL**





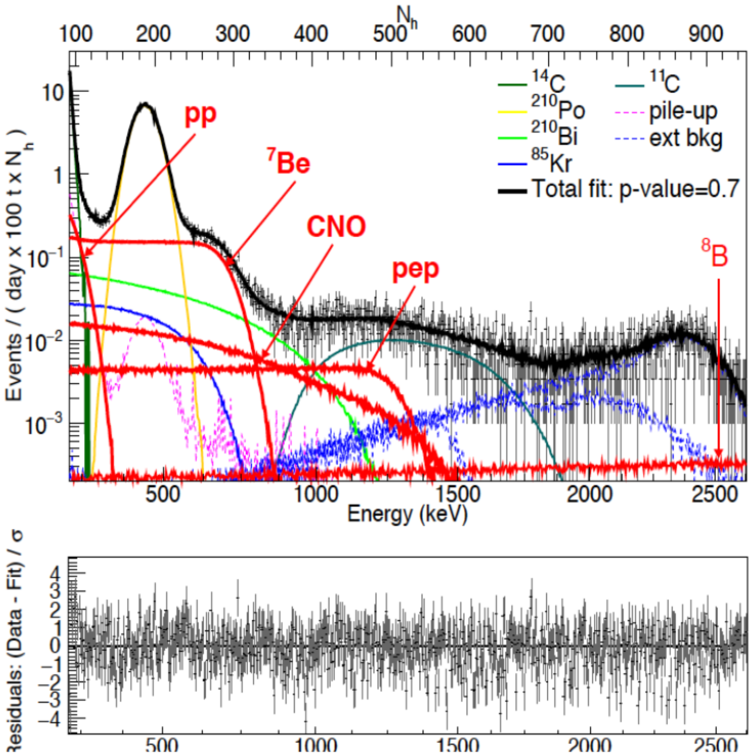
Solar ν		Rate [cpd/100 t]
pp	1.3x	$134 \pm 10^{+6}_{-10}$
^{7}Be	1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)		$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)	1.6x	$2.65 \pm 0.36^{+0.15}_{-0.24}$
$^8B_{HE\text{-}I}$		$0.136^{+0.013+0.003}_{-0.013-0.003}$
$^8B_{HE\text{-}II}$		$0.087^{+0.080+0.005}_{-0.010-0.005}$
$^8B_{HE}$	>2x	$0.223^{+0.015+0.006}_{-0.016-0.006}$

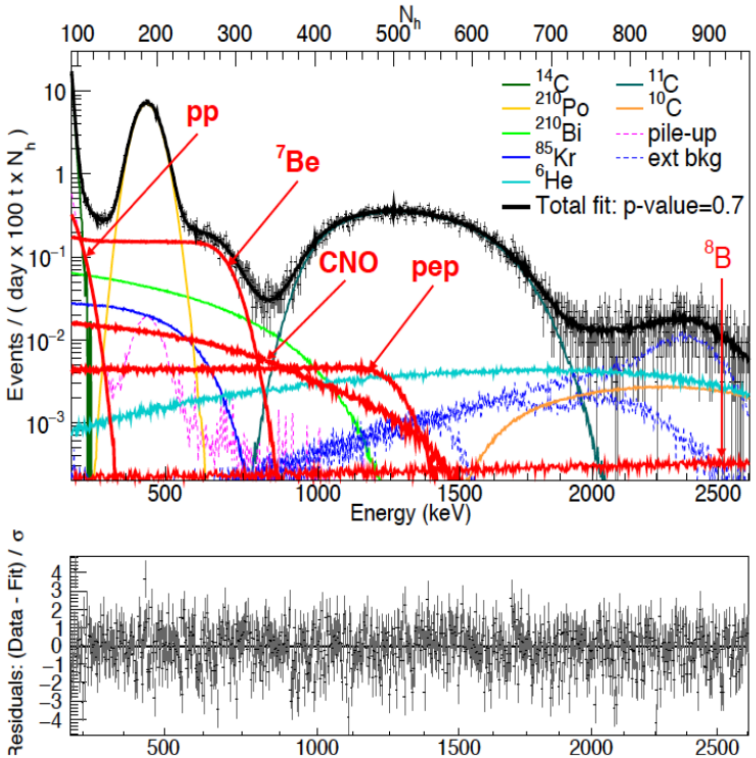


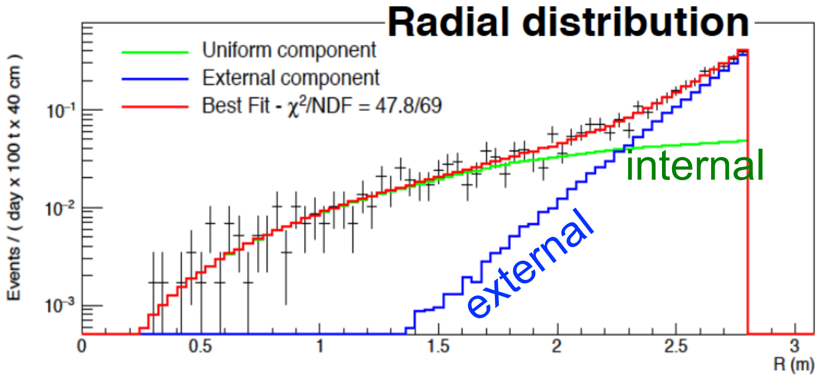
LOW ENERGY REGION (LER): MULTIVARIATE SPECTRAL FIT

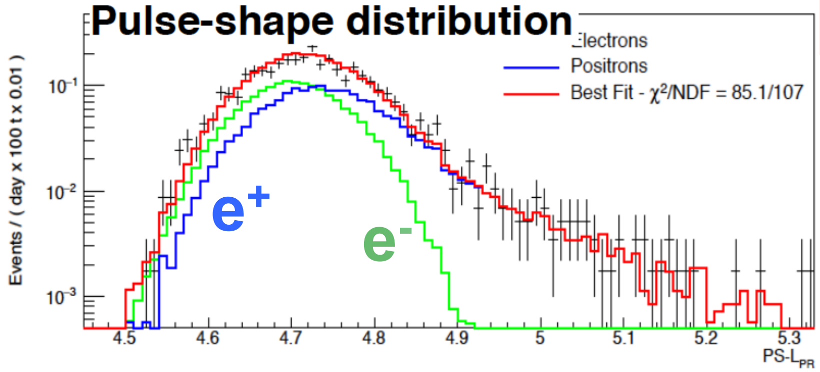
Results on *pp*, ^{7}Be, *pep*, and limit on CNO solar neutrinos

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






Radial distribution


Pulse-shape distribution

- 1291.51 days of Borexino Phase II
- Selection cuts in 71.3 ton FV

2 energy spectra

TFC-subtracted:

64% of exposure, 8% of ^{11}C

TFC-tagged:

46% of exposure, 92% of ^{11}C

Pulse-shape distribution

^{11}C(e+)/e- discrimination

Constraining ^{11}C in the TFC-subtracted spectrum

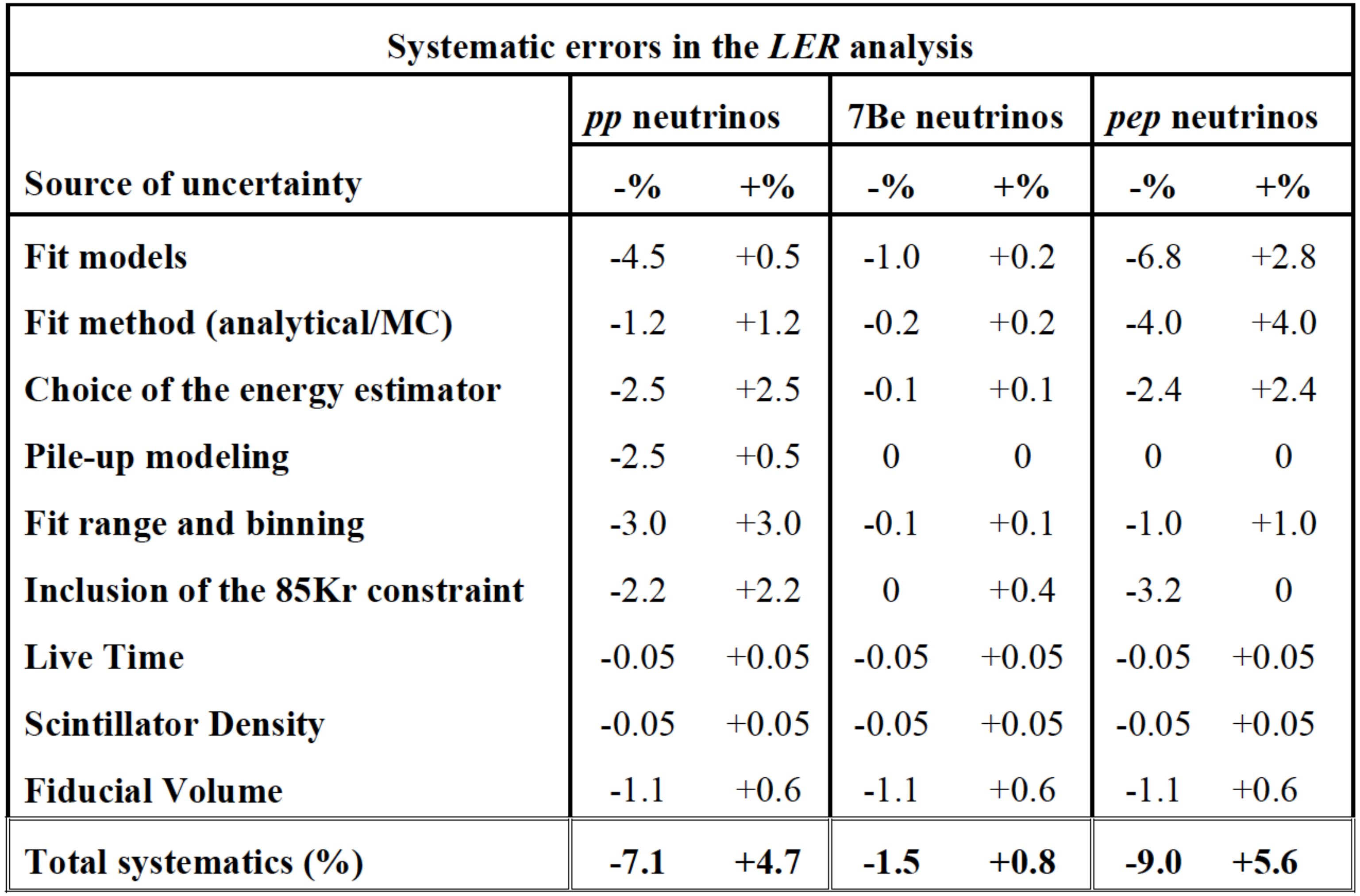
Radial distribution:

To better disentangle external background from internal signal

MC-based and analytical fit of the energy spectra

- Complementarity
- Thousands of fits
- Differences included in sys error

SYSTEMATIC ERRORS IN LER



Systematic errors in the *LER* analysis

Source of uncertainty	***pp*** **neutrinos**		**7Be neutrinos**		***pep*** **neutrinos**	
	-%	**+%**	**-%**	**+%**	**-%**	**+%**
Fit models	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/MC)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the 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
Inclusion of the 85Kr 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**

Fit models:
the shapes of fit functions are varied within the uncertainties allowed by the calibration data.

Fit methods:
analytical approach versus Monte Carlo shapes of the spectral components.

Energy estimators
#triggered PMTs in a fixed time window, #of hits, #photoelectrons.

Pile-up modelling:
Synthetic pile-up vs convolution with with random data spectrum.

^{85}Kr constraint:
Constrained based on the ^{85}Kr -> ^{85m}Rb fast coincidence (BR = 0.43%).

Fiducial Volume:
Position reconstruction precision based on calibration data.

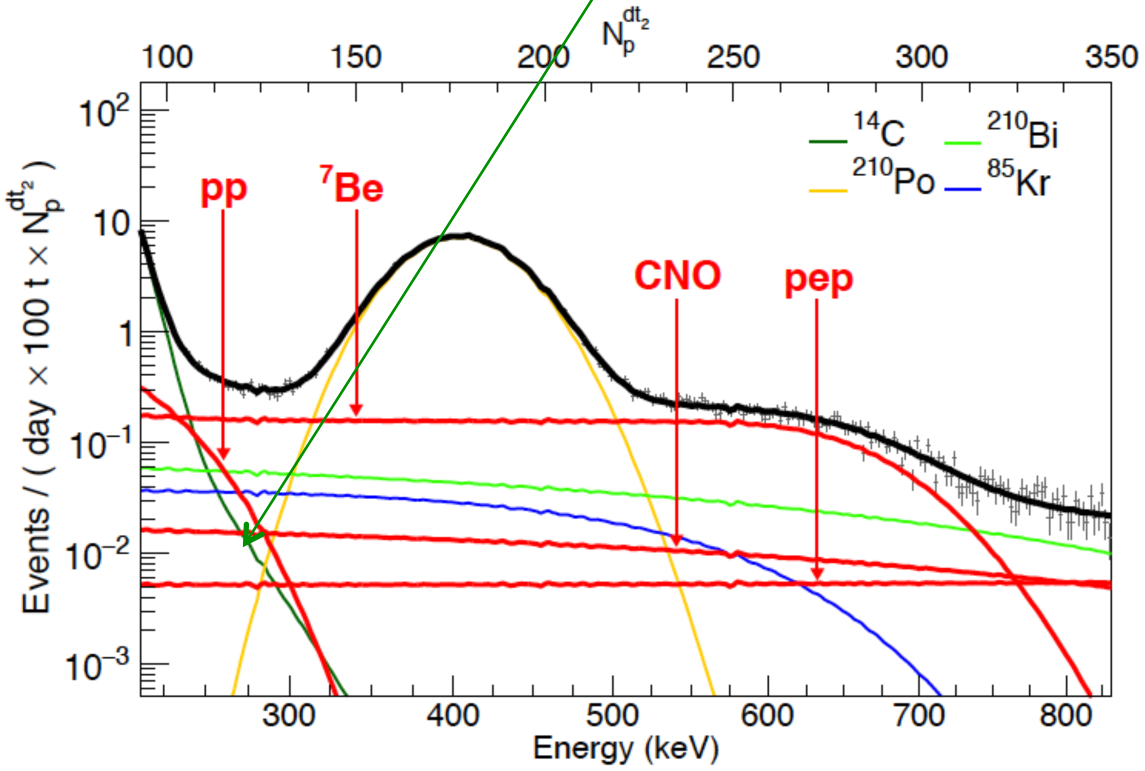
^{14}C-DOMINATED PILE-UP

Critical for *pp* neutrinos: multiple events reconstructed as a single event

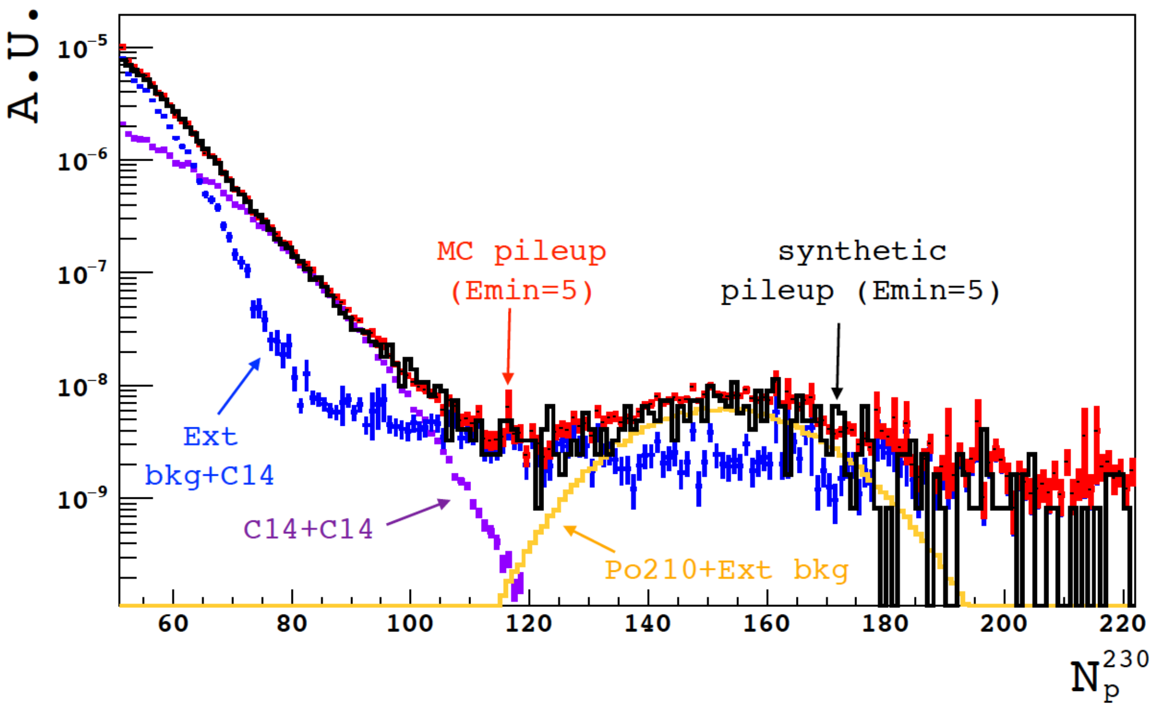
Borexino has 10^{-18} g/g of ^{14}C

40 ± 2 counts / s / 100 ton

Method A: convolution of all spectral shapes with random data spectrum (mostly visible as a **kink in ^{14}C spectrum**)



Method B: synthetic pile-up as a separate PDF, with constrained shape and rate (1. MC- and 2. data- based PDF construction)



THREE-FOLD COINCIDENCE (TFC) TO TAG ^{11}C

Critical for *pep* and CNO neutrinos

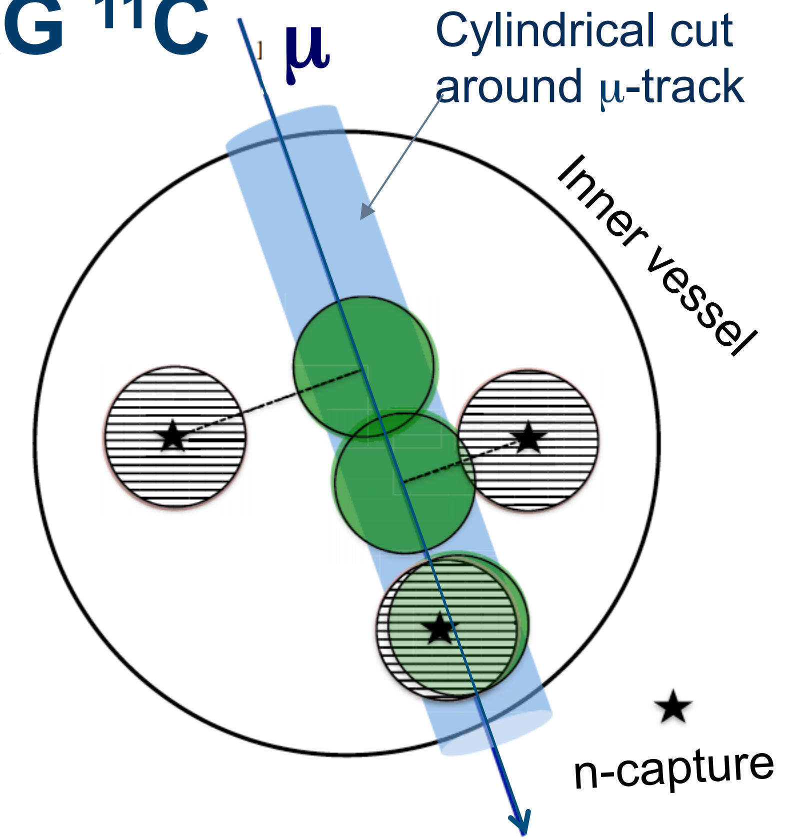
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$
$\tau \sim 30$ min

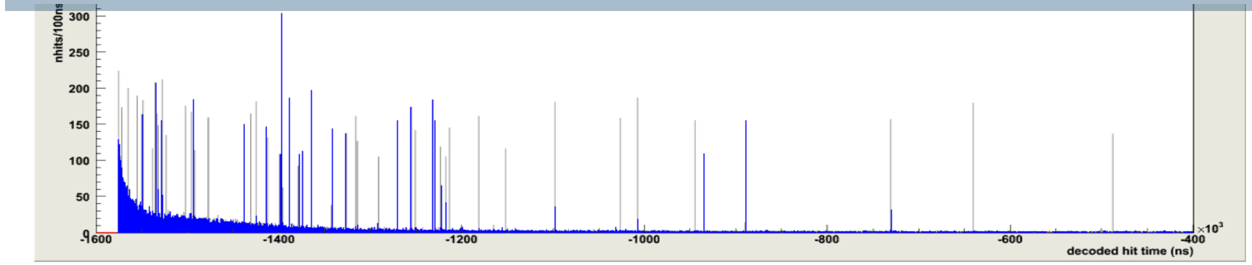
$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim 260\ \mu s$

Muon detection ε = 99.992%:

- Outer Detector triggers
- Cluster of hits in Outer Detector data
- Pulse-shape of Inner Detector data



Neutron detection: after each ID μ, 1.6 ms gate is opened to detect neutrons: example with several tens of neutrons.



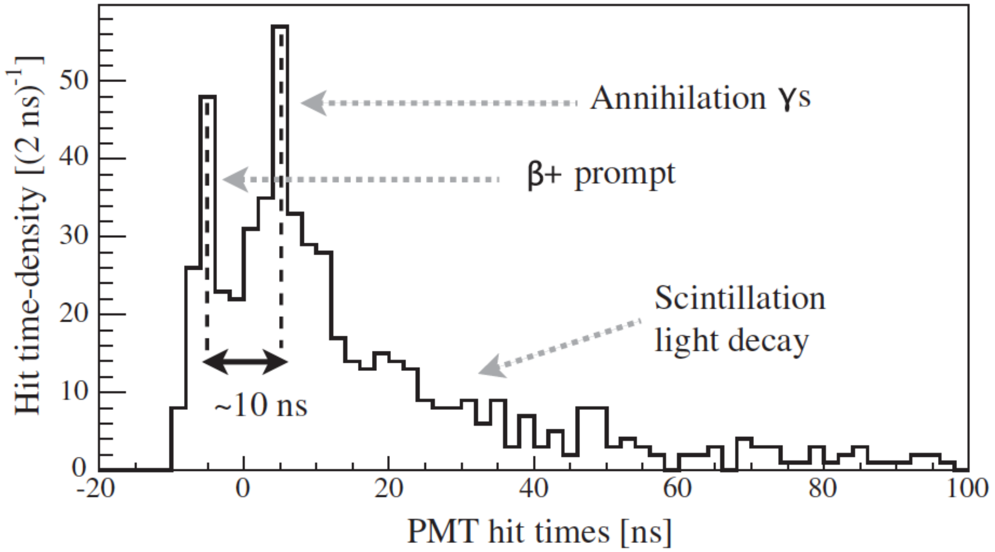
Exposure divided to 2 categories:
TFC-tagged (46% of exposure, 92% of ^{11}C)
TFC-subtracted (64% of exposure, 8% of ^{11}C)

Likelihood that a certain event is ^{11}C uses in input time and space correlations between subsequent muons and cosmogenic neutrons.

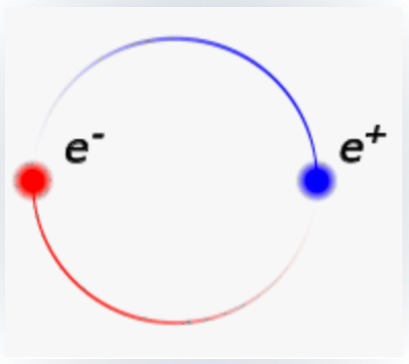
ELECTRON-POSITRON PULSE SHAPE DISCRIMINATION

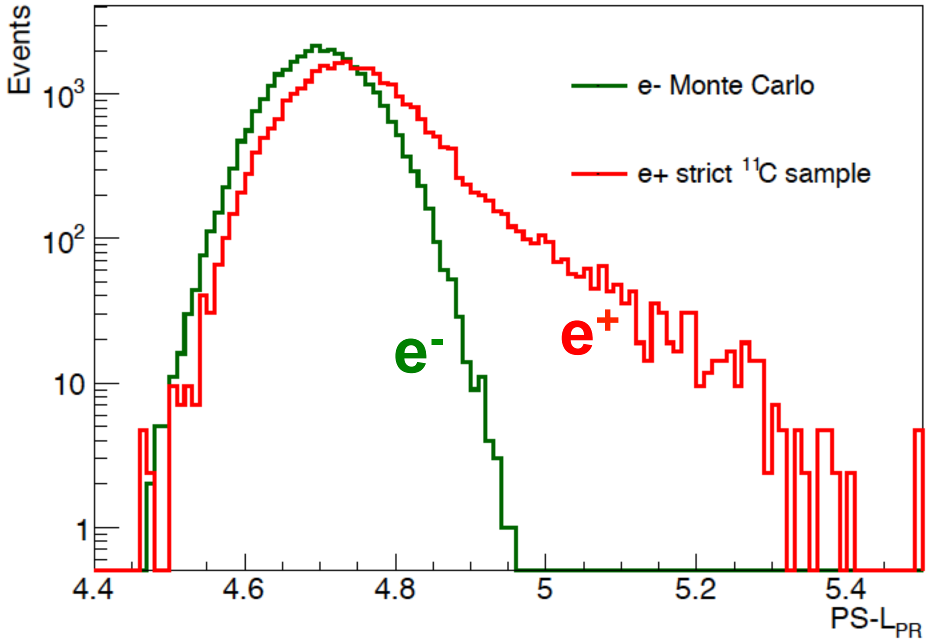
Critical for *pep* and CNO neutrinos

in ~50% of the cases, e^+ annihilation is delayed by ortho-positronium formation (τ ~3ns);



Single ortho-positronium event, in which annihilation occurs in 10 ns after o-Po formation





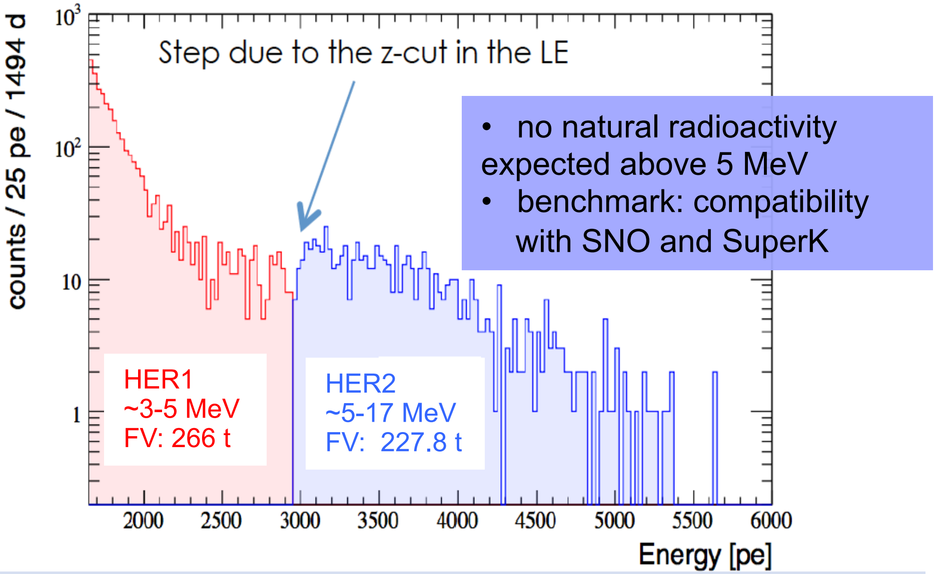
Pulse shape estimator:
normalized likelihood of the position reconstruction algorithm that uses light emission profiles for electrons.

Used to pin-down the remaining $^{11}C(e^+)$ in the TFC-subtracted spectrum.

HIGH ENERGY REGION (HER) ANALYSIS

Results on ^{8}B solar neutrinos

Analysis in 2 energy regions



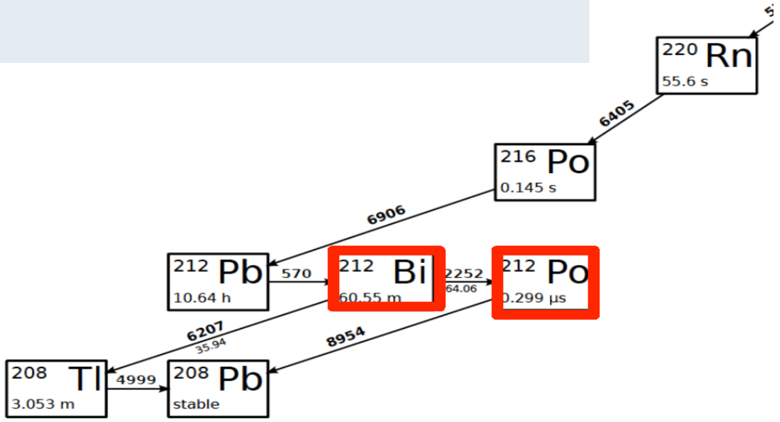
- no natural radioactivity expected above 5 MeV
- benchmark: compatibility with SNO and SuperK

Backgrounds after selection cuts (neutron, cosmogenics, TFC(^{10}C), ^{214}Bi-^{214}Po, random coincidence)

HER1
- ✓ cosmogenic ^{11}Be
- ✓ ^{208}Tl (bulk , emanation and vessel surface)
- ✓ γ's from n-captures

HER2
- ✓ cosmogenic ^{11}Be
- ✓ γ's from n-captures

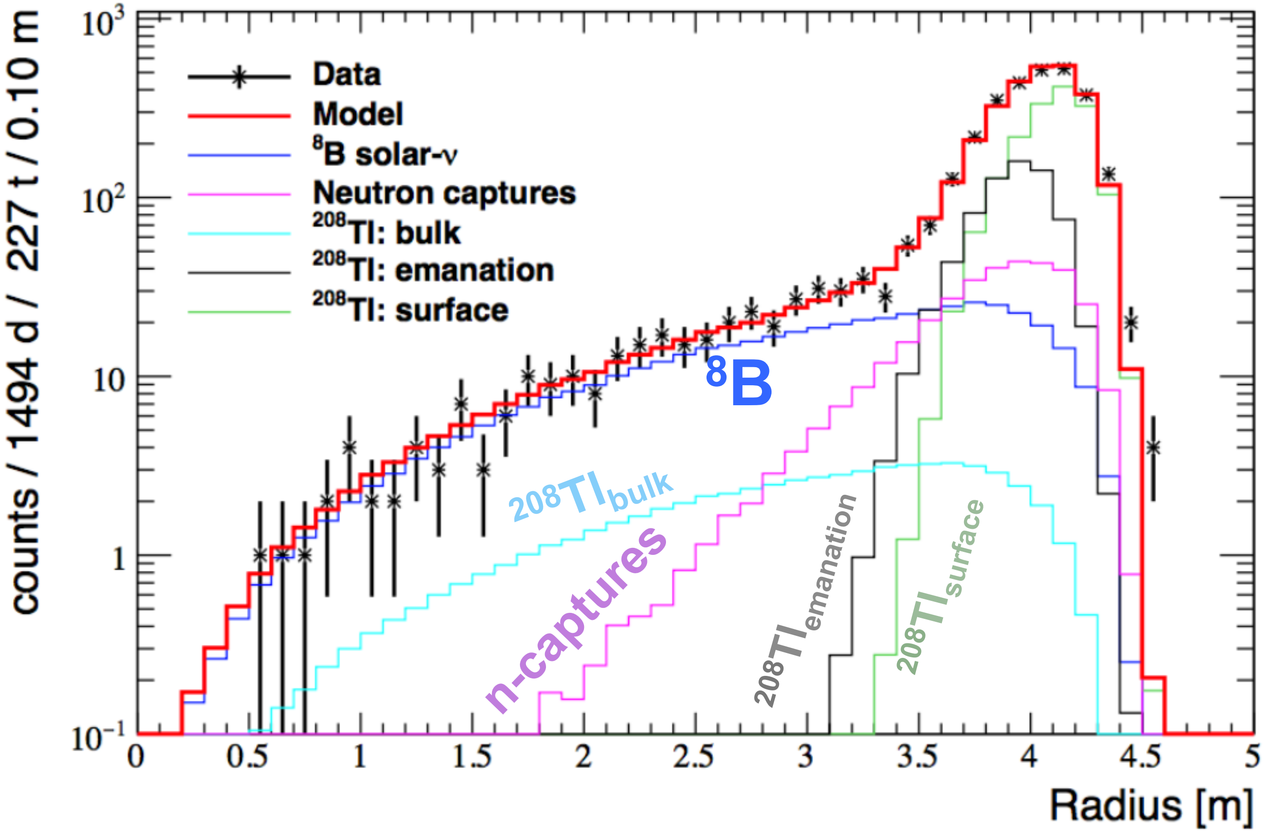
- Almost all scintillator volume used in the analysis.
- Factor 2 improvement wrt PRD 82 (2010) 033006.
- 5x lower internal ^{208}Tl background estimated from ^{212}Bi-^{212}Po coincidences within 3 m radius.
- Two components of the external ^{208}Tl background: pure surface and due to ^{220}Rn emanation.
- Identified new source of background: γ's from neutrons captured on materials different than H,C. The source of neutrons are (α,n) reactions and fissions from U and Th chains.
- New estimation of the ^{11}Be background compatible with 0.



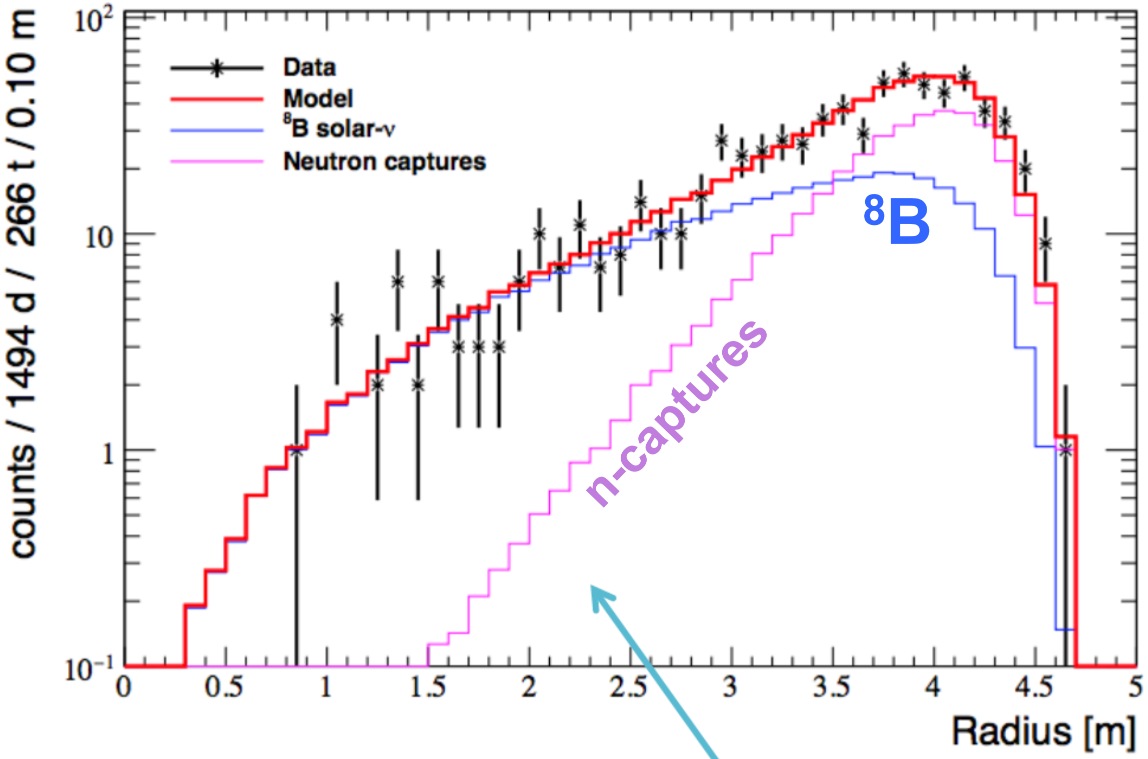
RADIAL FITS IN HER1 AND HER2

No use of energy spectra is a choice: no assumptions on the $P_{ee}(E_\nu)$ shape

HER1: ~3-5 MeV

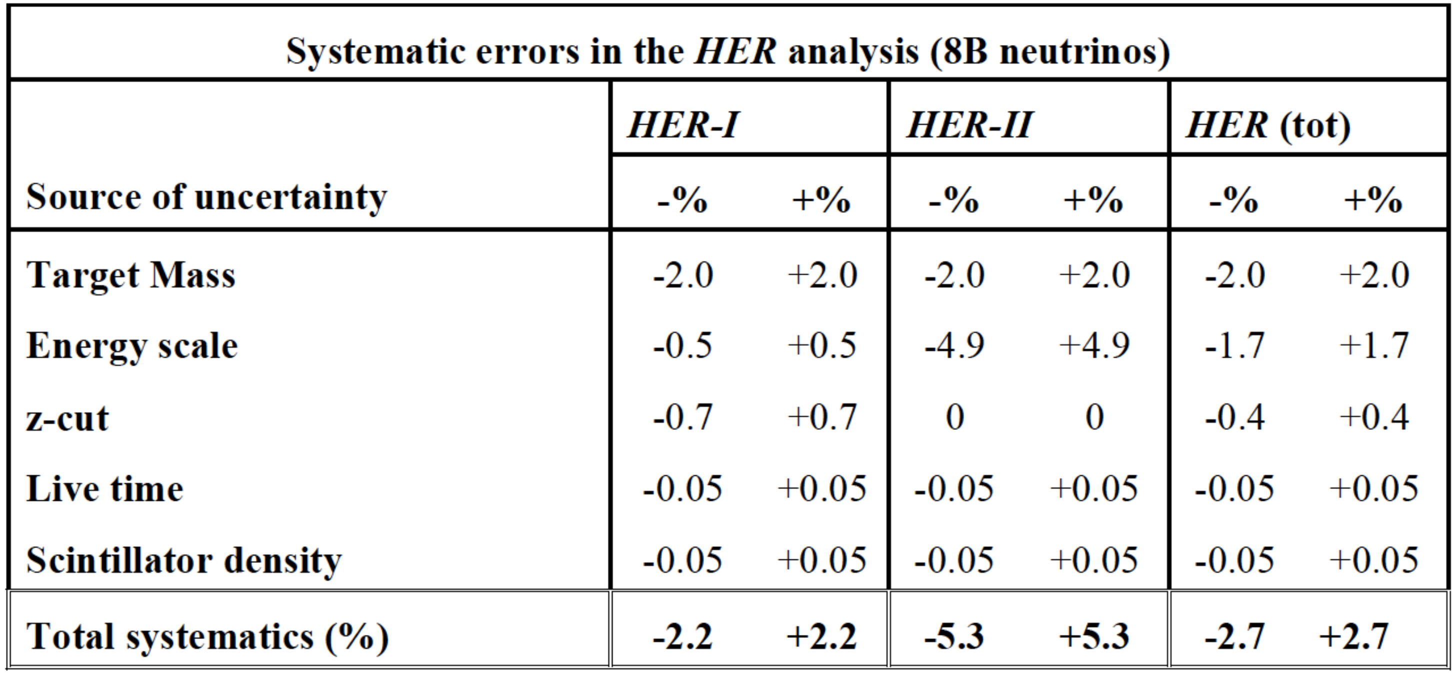


HER2: ~5-17 MeV



In the previous analysis this component was erroneously neglected

RESULTS AND SYSTEMATIC ERRORS IN HER



Systematic errors in the *HER* analysis (8B neutrinos)

	HER-I		*HER-II*		*HER* (tot)	
Source of uncertainty	-%	+%	-%	+%	-%	+%
Target Mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
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
Total systematics (%)	**-2.2**	**+2.2**	**-5.3**	**+5.3**	**-2.7**	**+2.7**

Additionally studied:

- PDF's radial distortion +3%.
- Emanation vessel shift +1%.
- Distortion of the emanation PDF's.
- Binning dependence.

SuperKamiokande	2.345 ±0.014 ±0.036 x 10^6 cm^{-2} s^{-1}
BX 2010	2.4 ±0.4 x10^6 cm^{-2} s^{-1}
This measurement	**2.55 ±0.18 ±0.07 x 10^6 cm^{-2} s^{-1}**

QUEST FOR CNO SOLAR NEUTRINOS

^{210}Bi and CNO correlated

- external constraint on ^{210}Bi from ^{210}Po (time) needed

$$^{210}\text{Pb} \xrightarrow{\beta\ (63\ \text{KeV})} {}^{210}\text{Bi} \xrightarrow{\beta} {}^{210}\text{Po} \xrightarrow{\alpha} {}^{206}\text{Pb}$$

$T_{1/2}$=22y — 5 days — 138 days — stable

F. Villante et al., Phys. Lett. B 701 (2011)

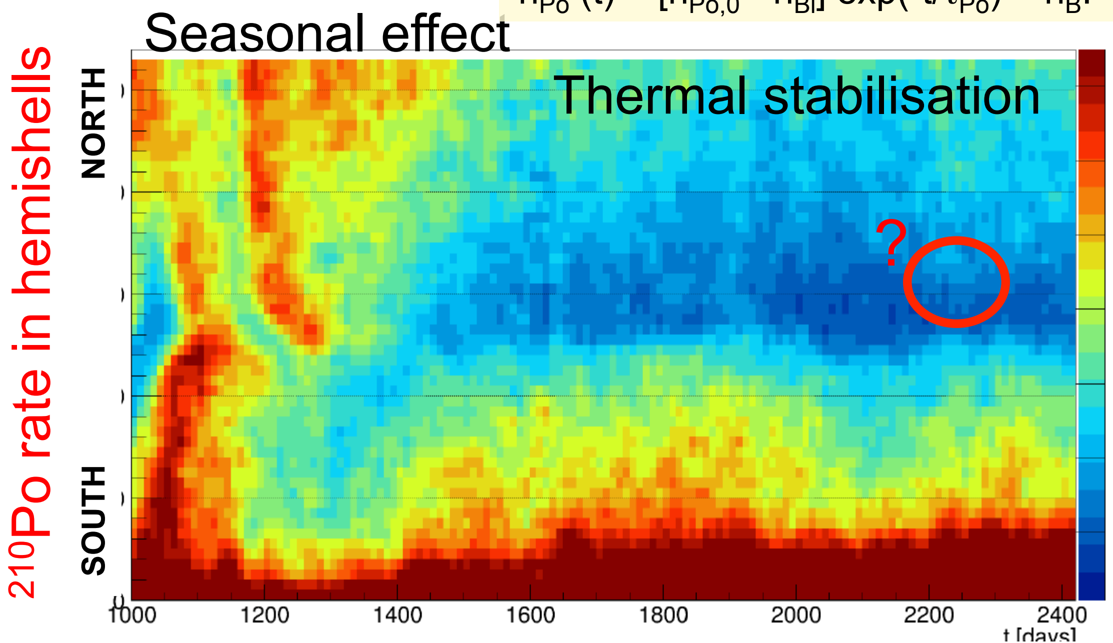
Not in equilibrium

R(^{210}Po, Dec 2011) ~1400 cpd/100 ton

R(^{210}Bi, Phase II) = 17.5 + 1.9 cpd/100 ton fit with CNO constrained to SSM

- Nylon vessel holding the scintillator is a source of ^{210}Po
  - ✓ diffusion slow -> ^{210}Po cannot penetrate to the FV
  - ✓ block convection -> **thermal stabilisation**

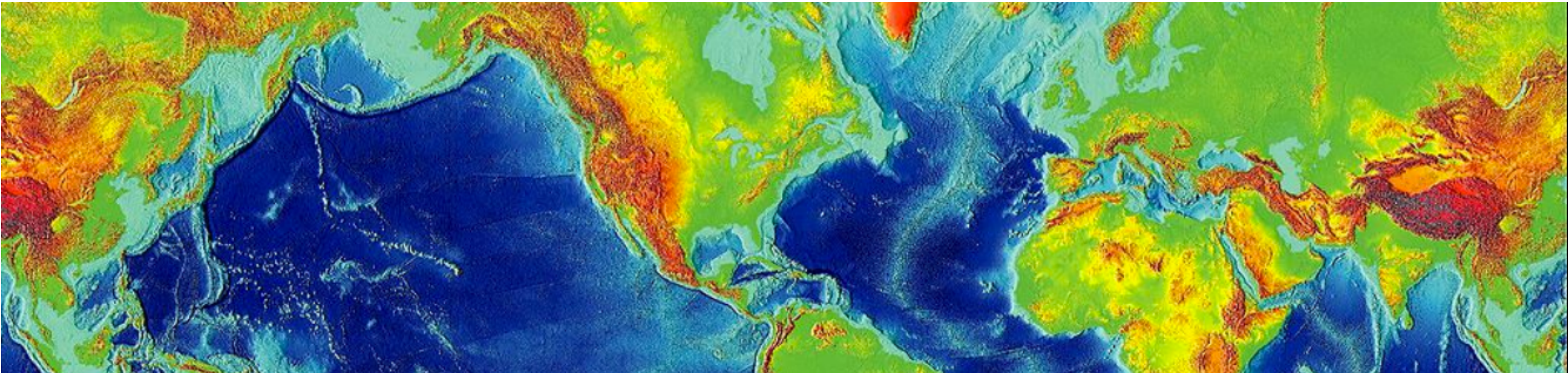
$n_{Po}(t) = [n_{Po,0} - n_{Bi}] \exp(-t/\tau_{Po}) + n_B$: at regime R(^{210}Po) = R(^{210}Bi)



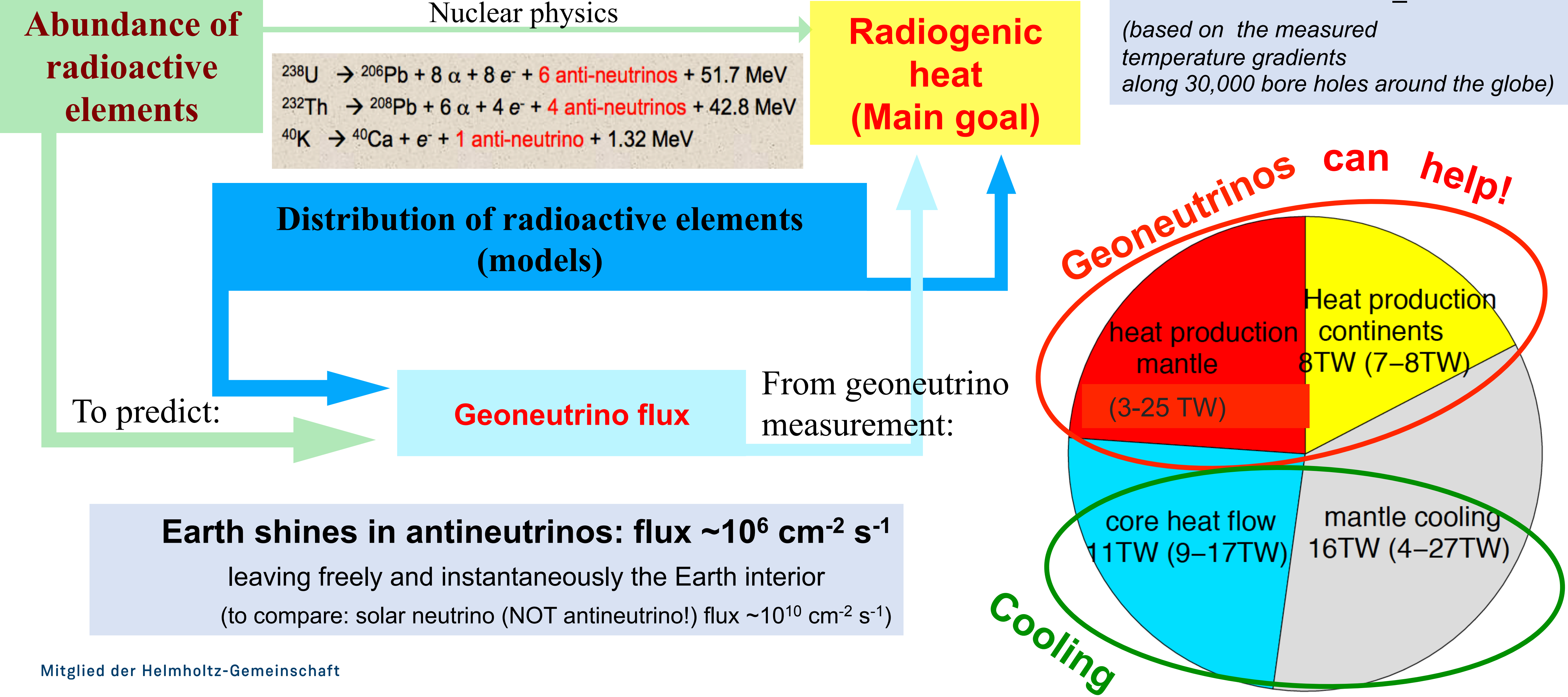
Strategy

- identify portion of the detector in which ^{210}Bi rate low, stable, and known
- additional water extraction campaign for further ^{210}Bi reduction

GEONEUTRINOS



GEONEUTRINOS AND WHY TO STUDY THEM



Abundance of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Radiogenic heat (Main goal)

Distribution of radioactive elements (models)

To predict:

Geoneutrino flux

From geoneutrino measurement:

Surface heat flux: 47 ± 3 TW

(based on the measured temperature gradients along 30,000 bore holes around the globe)

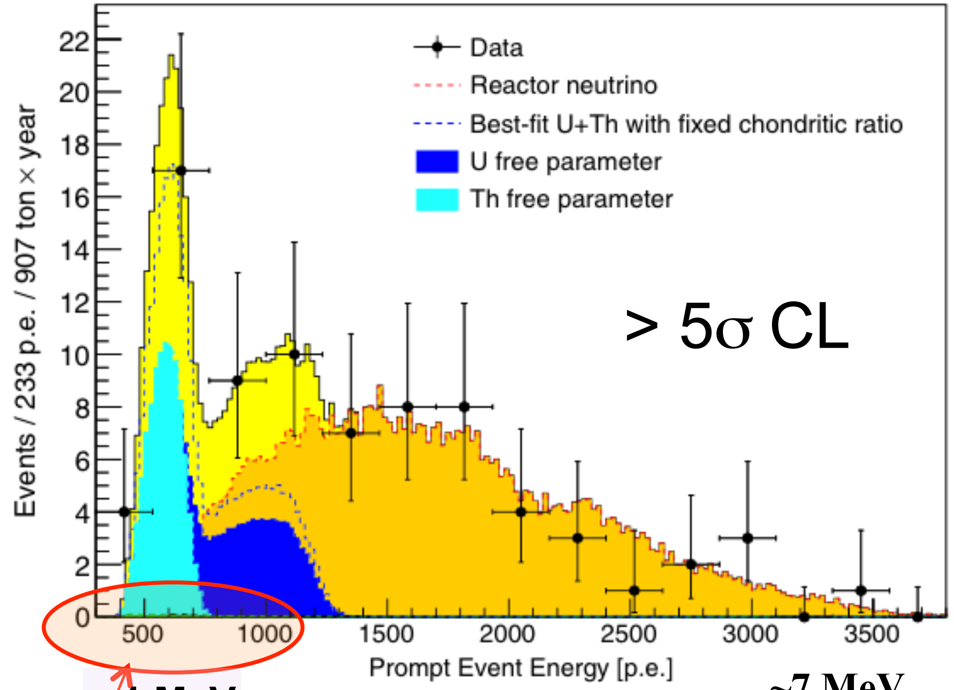
Earth shines in antineutrinos: flux ~10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

(to compare: solar neutrino (NOT antineutrino!) flux ~10^{10} cm^{-2} s^{-1})

GEONEUTRINO RESULTS AND ANALYSIS

Borexino 2015: **$23.7^{+6.5}$ (stat) $^{+0.9}$ (sys)** geonu's



> 5σ CL

~1 MeV

~7 MeV

PRD 92 (2015) 031101 (R)

- ✓ Non-antineutrino background almost invisible!
- ✓ 5.5 x 10^{31} target-proton year

- Unbinned maximum likelihood fit of 77 candidates.
- Non-antineutrino background almost negligible (< 1 event) and constrained in the fit.
- Reactor background left free in the fit: results compatible with expectations.
- 2 kinds of fit:
  - ✓ U/Th left free;
  - ✓ U/Th constrained to chondritic value.
- **Statistical error largely dominates systematic uncertainty** (reactor spectra, uncertainty of backgrounds, and detector response).

New update with ~20% precision under preparation.

First geologically significant results available but more statistics needed!

Important new tool for future experiments

BACKGROUNDS

B) Non-antineutrino background

1) Cosmogenic background

- ^{9}Li and ^{8}He ($T_{1/2}$ = 119/178 ms)
- decay: β(prompt) + neutron (delayed);
- **fast neutrons**

  scattered protons (prompt)

Estimated by studying coincidences detected AFTER muons.

2) Accidental coincidences;

Estimated from OFF-time coincidences.

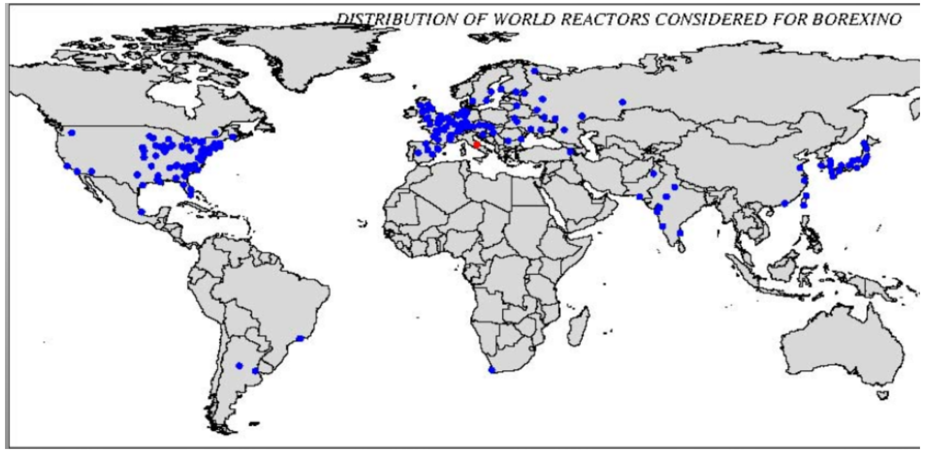
3) Due to the internal radioactivity:

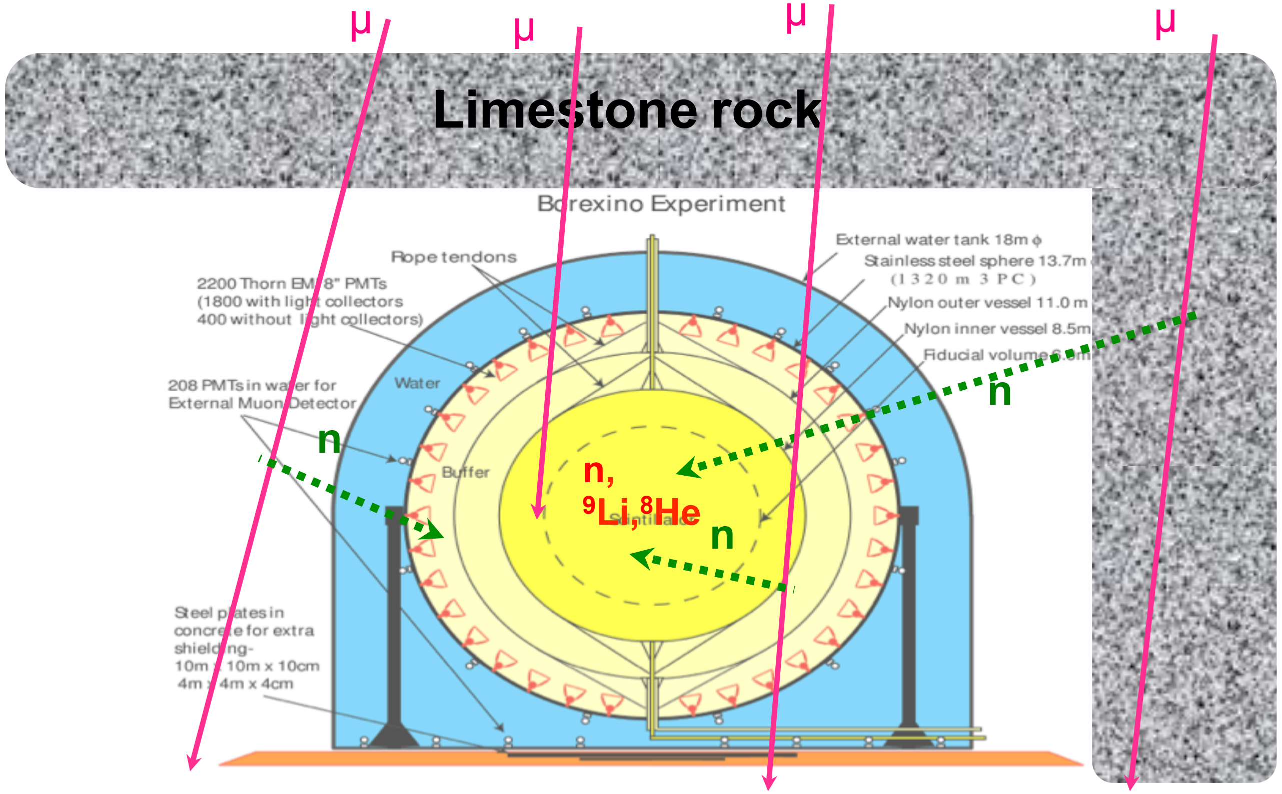
(α, n) reactions: $^{13}C(\alpha, n)^{16}O$

Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated from $^{210}Po(\alpha)$ and ^{13}C contaminations, cross section.

A) Reactor antineutrino background





KEY POINTS AND SUMMARY

Solar neutrinos:

Spectral multivariate fit (radial and pulse shape e^{+}/e^{-} distributions):

- *pp* neutrinos: ^{14}C and its pile-up.
- ^{7}Be neutrinos: ^{210}Bi out of equilibrium with ^{238}U chain, ^{85}Kr; low levels of ^{238}U and ^{232}Th.
- *pep* neutrinos: cosmogenic $^{11}C(e^{+})$: TFC technique and e^{+}/e^{-} discrimination.
- CNO neutrinos: cosmogenic $^{11}C(e^{+})$, correlations with ^{210}Bi and *pep* (*pp*/*pep* ratio constraint)

Radial fit:

- ^{8}B neutrinos: cosmogenics and external backgrounds.

Geoneutrinos:

- Statistics is an issue -> large detectors.
- Cosmogenic ^{9}Li-^{8}He as (β + neutron) emitters: depth of the laboratory.
- ^{210}Po out of equilibrium -> danger of (α, n) background.
- Reactor antineutrinos.
- Key: local geology to subtract the crustal (to get the mantle) contribution.

Thank you!

Victoria, BC, Canada, October 2018

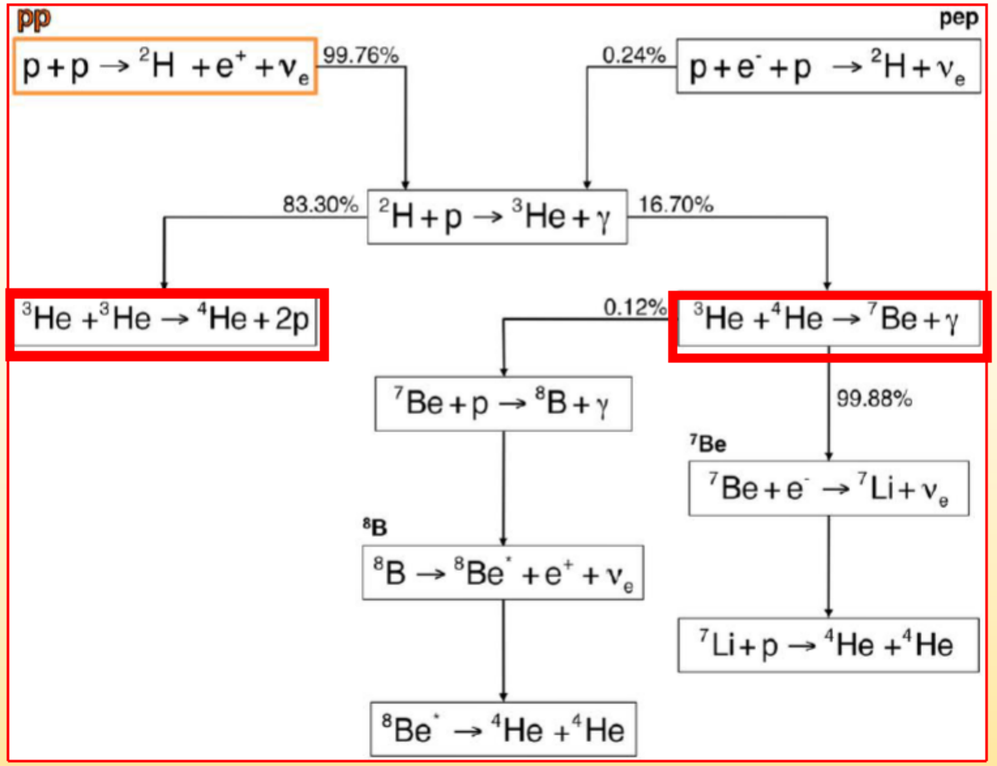
Back up slides

Solar ν	Rate [cpd/100 t]	Flux – non-oscillated [cm^{-2} s^{-1}]	Flux – e-equivalent [cm^{-2} s^{-1}]
pp 1.3x	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5})\times10^{10}$	$(4.2 \pm 0.3^{+0.2}_{-0.3})\times10^{10}$
^{7}Be 1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08})\times10^{9}$	$(3.15 \pm 0.07^{+0.03}_{-0.05})\times10^{9}$
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12})\times10^{8}$	$(0.78 \pm 0.12^{+0.05}_{-0.07})\times10^{8}$
1.6x *pep* (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13})\times10^{8}$	$(0.85 \pm 0.12^{+0.05}_{-0.08})\times10^{8}$
^{8}B$_{\text{HE-I}}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$(2.66^{+0.25+0.06}_{-0.25-0.06}) \times 10^{6}$
^{8}B HE-II	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$(2.44^{+0.22+0.14}_{-0.28-0.14}) \times 10^{6}$
^{8}B HE >2x	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$(2.57^{+0.17+0.07}_{-0.18-0.07})\times10^{6}$

Implication of the results: probe solar fusion with R

$$R = \frac{Rate(^3He + ^3He)}{Rate(^3He + ^4He)}$$

Reaction from the main pp chain



pp

$p + p \rightarrow {}^2H + e^+ + \nu_e$ 99.76%

pep

0.24% $p + e^- + p \rightarrow {}^2H + \nu_e$

83.30% ${}^2H + p \rightarrow {}^3He + \gamma$ 16.70%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

0.12% ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + p \rightarrow {}^8B + \gamma$

99.88%

^{7}Be

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

^{8}B

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^7Li + p \rightarrow {}^4He + {}^4He$

${}^8Be^* \rightarrow {}^4He + {}^4He$

$$R = \frac{2\,\Phi(^7Be)}{\Phi(pp) - \Phi(^7Be)}$$

Expected values: (C. Pena Garay, private comm,)

$$R = 0.180 \pm 0.011 \quad HZ$$

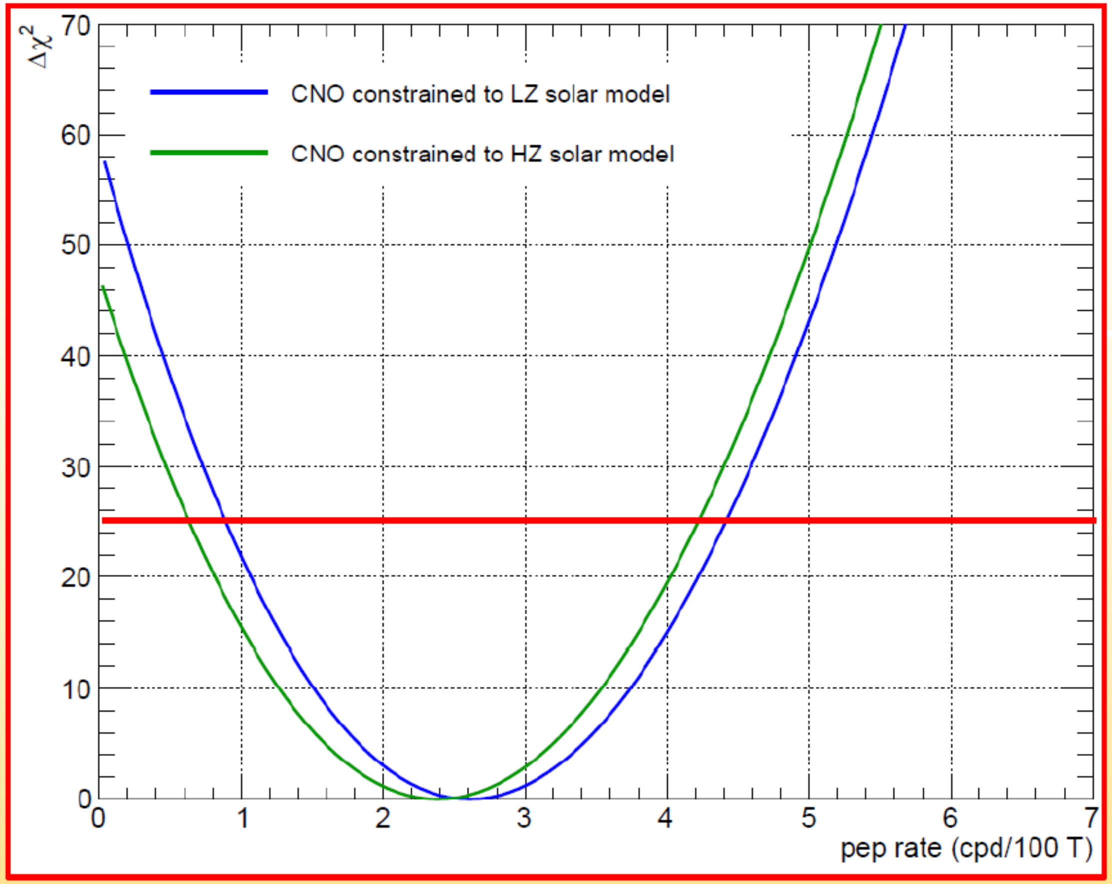
$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

$$R(BRX) = 0.178^{+0.027}_{-0.023}$$

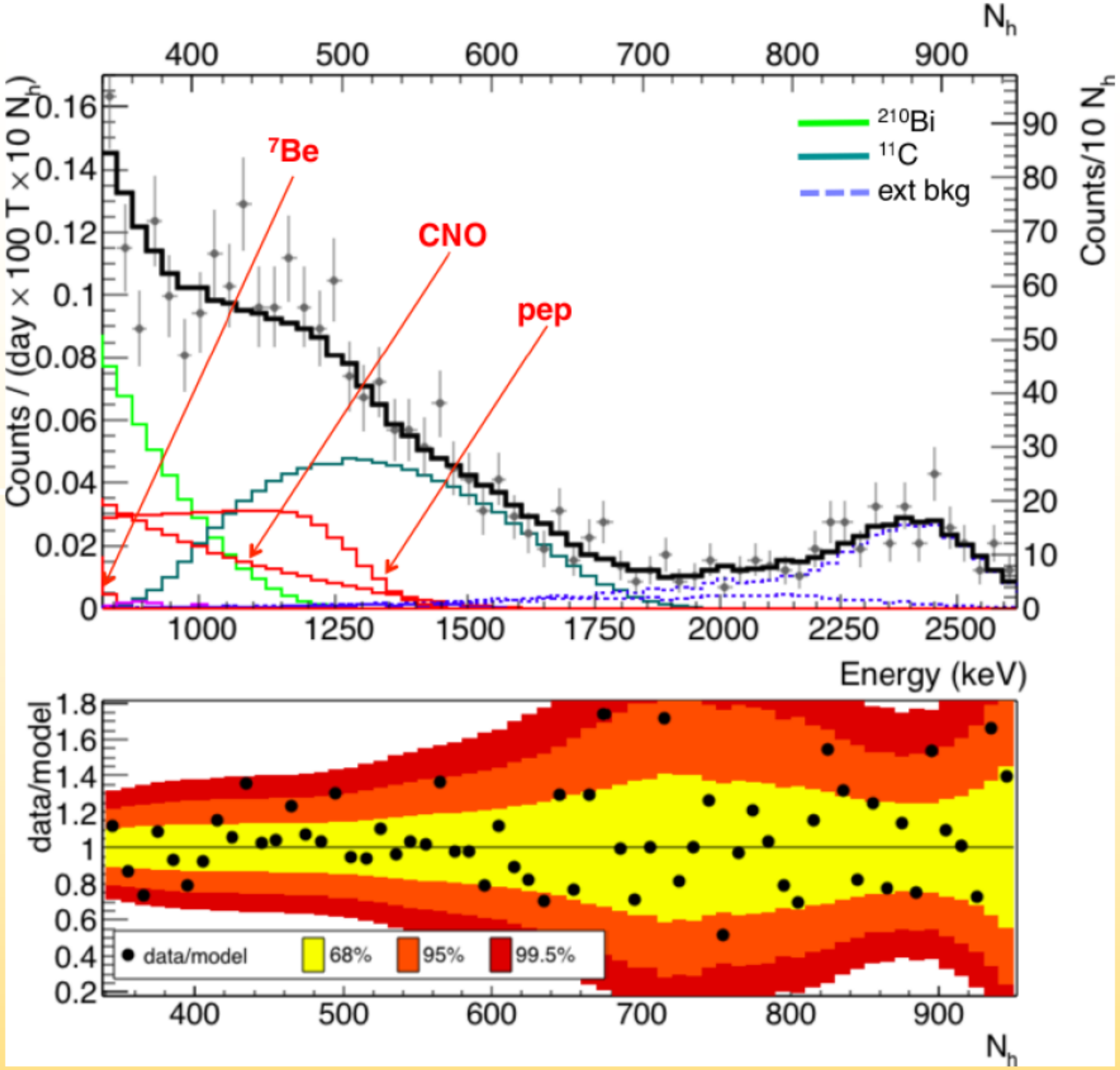
5 σ evidence of pep solar ν (including systematics uncertainties)

Likelihood profile resulting from the multivariate fit



Select innermost β- like events

Radius<2.4 PS-LPR<4.8



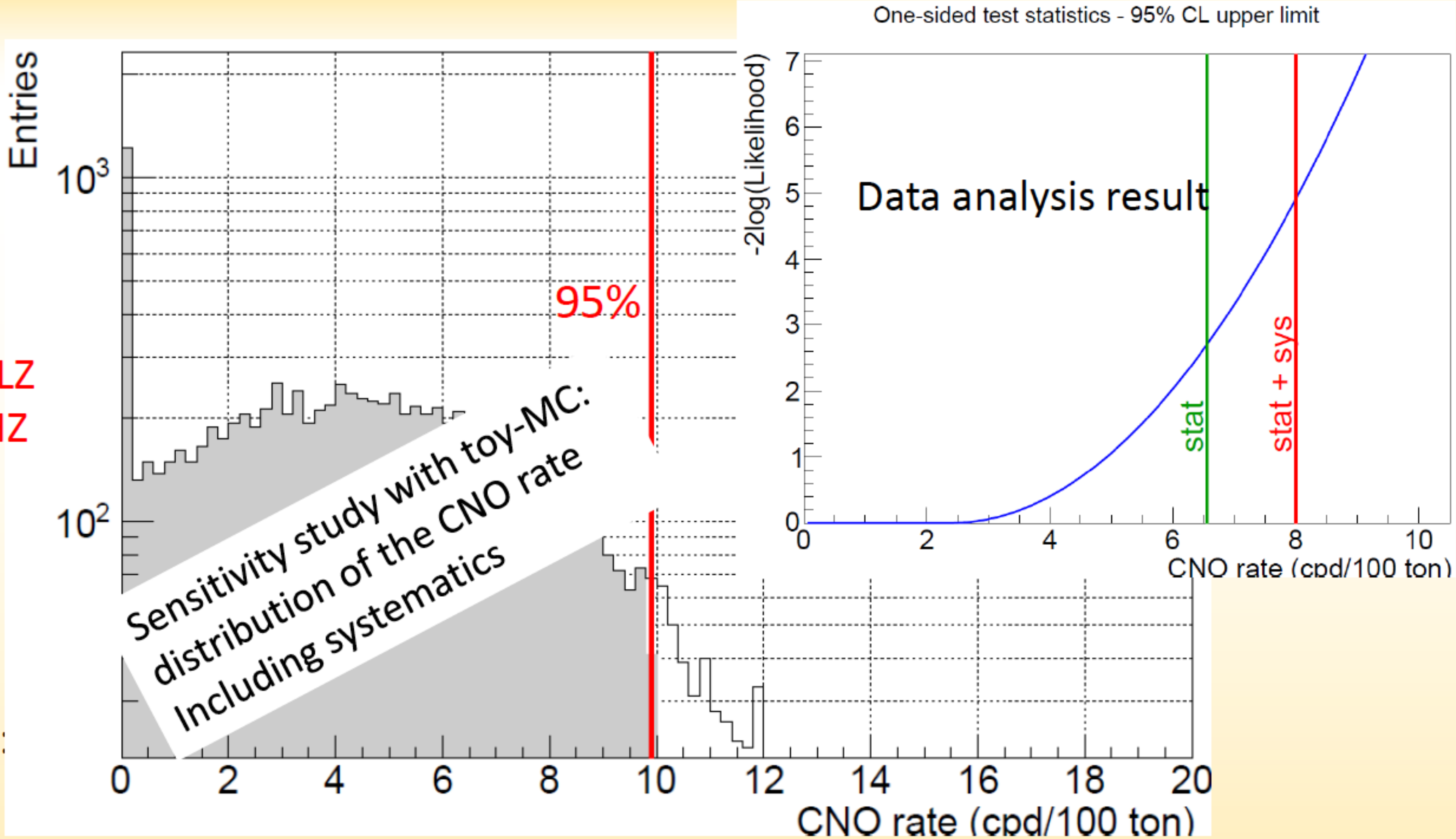
Upper limit on the CNO flux

- Set a constrain to the ratio pp/pep
- Very well know in the solar model
- Include oscillations LMA-MSW
- Toy MC study of the sensitivity :

the median 95% CL is 9 cpd/100t for LZ
10 cpd/100t for HZ

95% C.L. limit on the CNO n rate
8.1 cpd/100t
including systematics errors

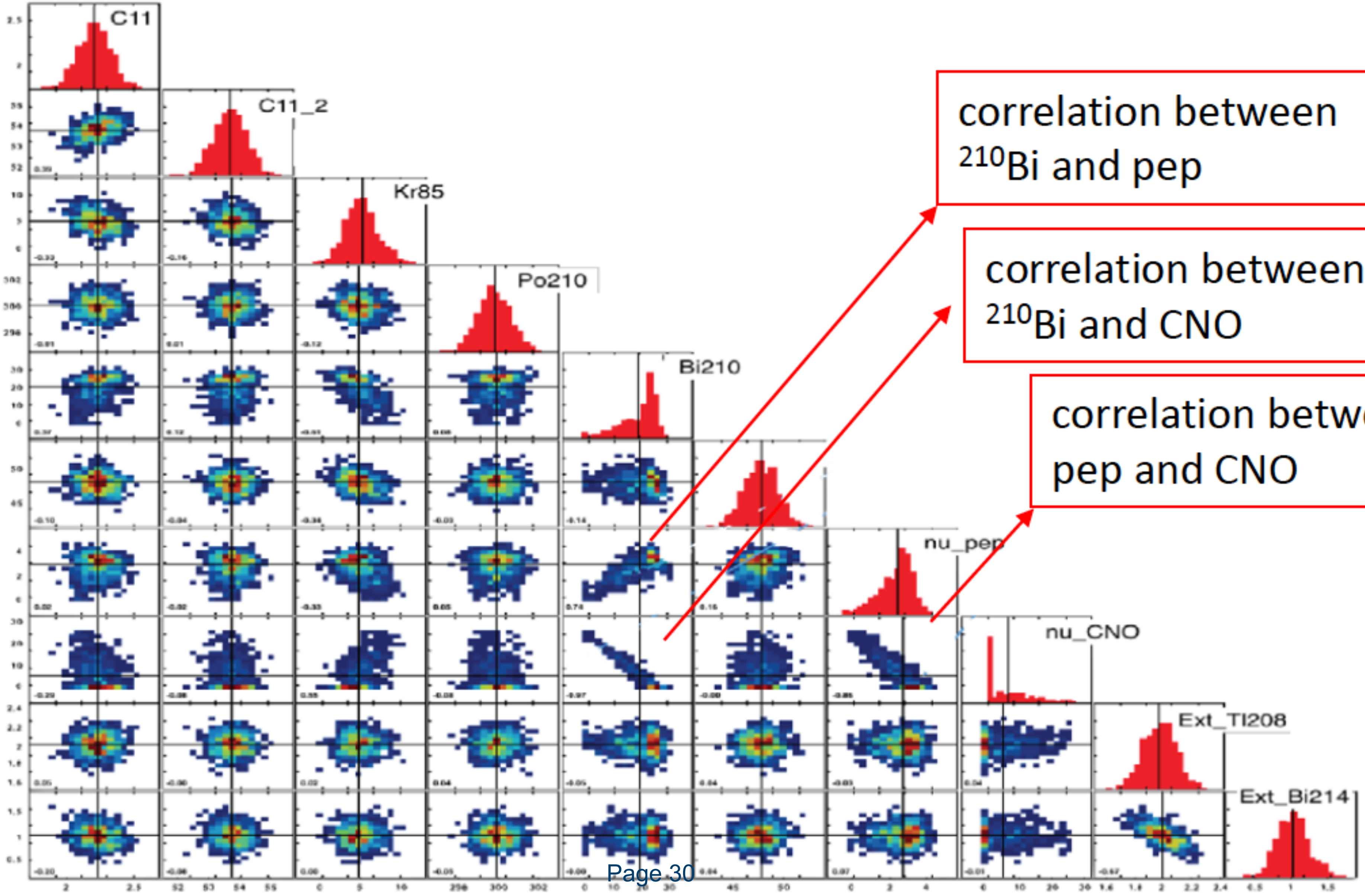
Previous limit (set by Borexino Phase I):
7.9 cpd/100t


Sensitivity study with toy-MC: distribution of the CNO rate Including systematics

Data analysis result

	Borexino result	Expected HZ	Expected LZ
CNO ν	**< 8.1 95%C.L cpd/100t**	**4.91 +-0.56 cpd/100t**	**3.62 +- 0.37 cpd/100t**

SENSITIVITY STUDIES



correlation between ^{210}Bi and pep

correlation between ^{210}Bi and CNO

correlation between pep and CNO