Hunting solar neutrinos:
New Results with Borexino Phase-II

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on behalf of the Borexino Collaboration

18.09.2017 | Erice School:
"Neutrinos in Cosmology, in Astro and in Particle and Nuclear Physics"
Erice, Italy

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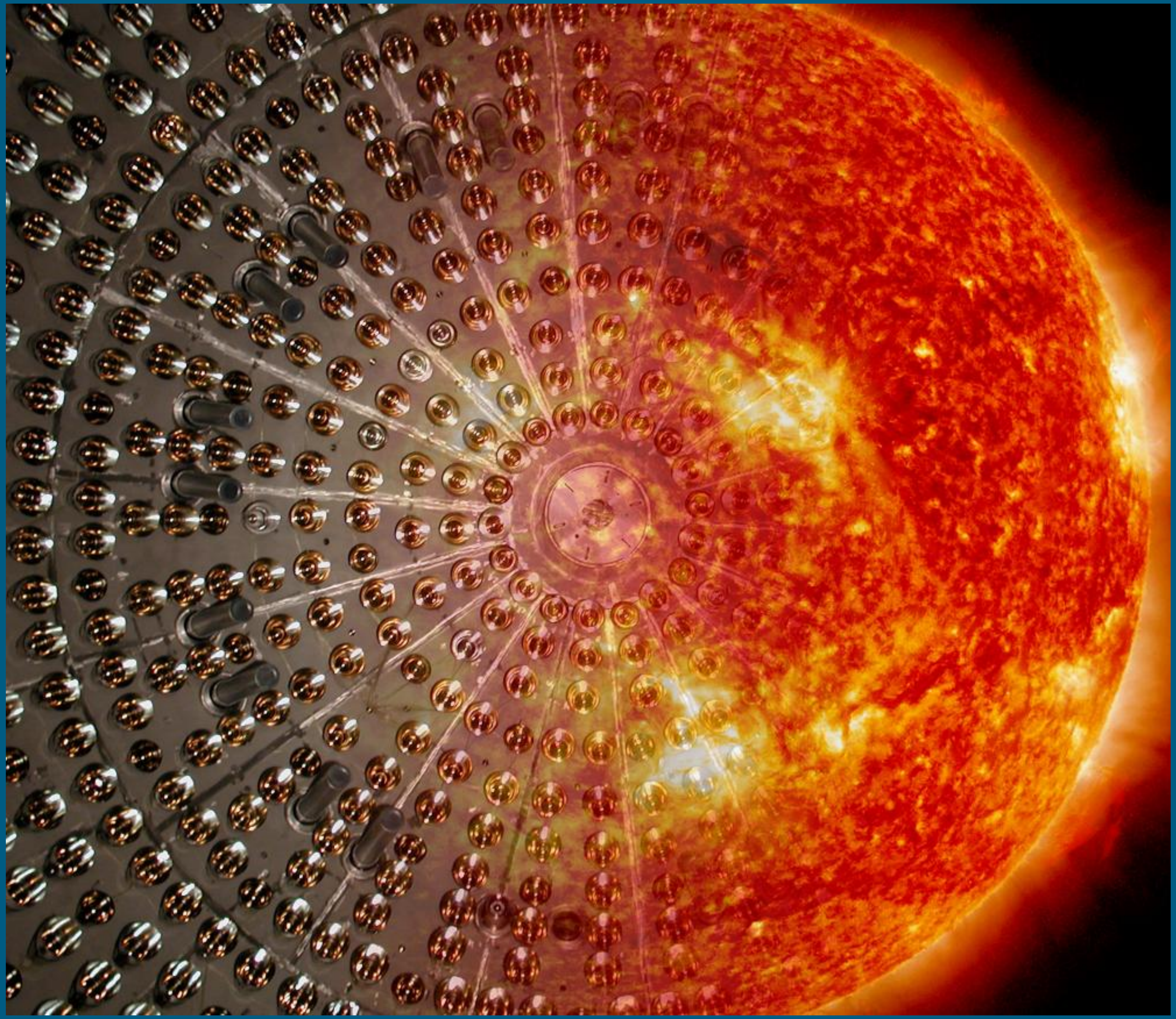
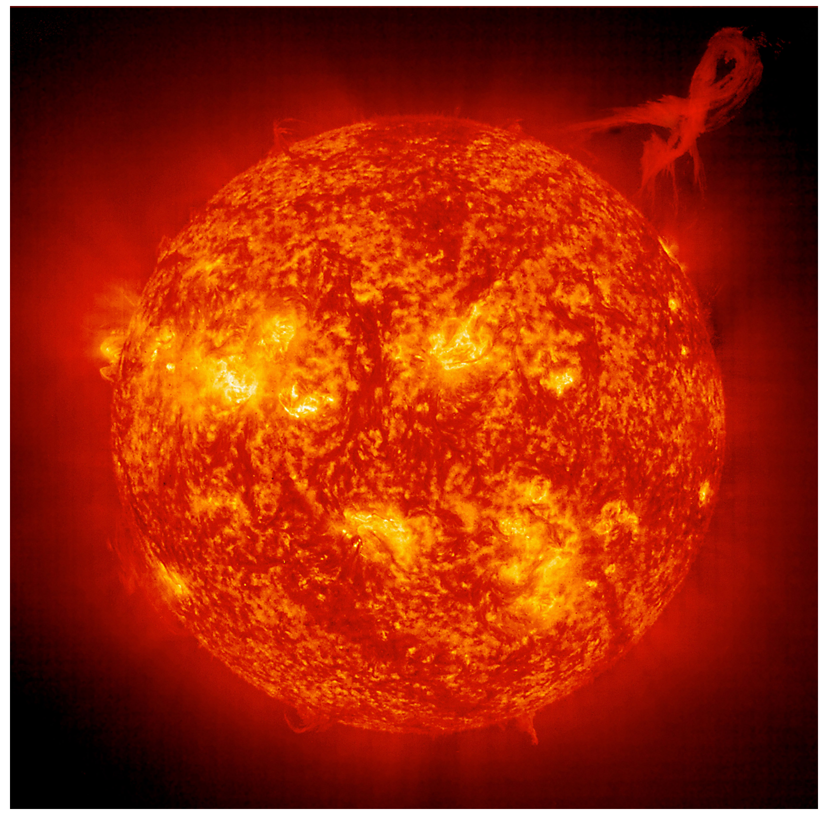


Scientific Motivation

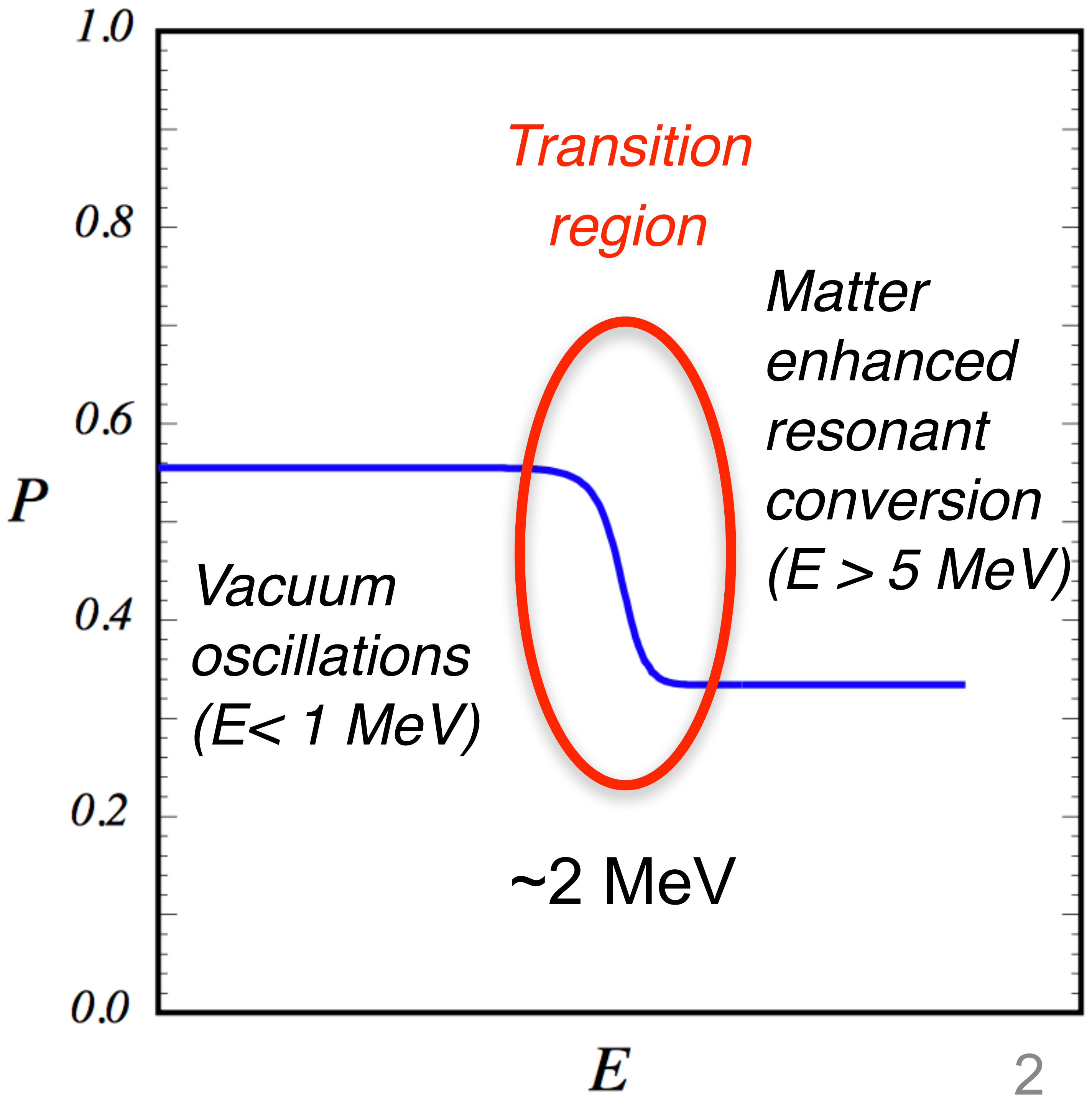

nasa.org

Studying the Sun with Neutrinos

- Energy production/loss mechanisms
- Testing stability of the Sun
- Metallicity problem
- Fusion rates (pp, CNO)

Studying Neutrinos with the Sun

- Neutrino oscillation parameters
- Magnetic moment of solar neutrinos
- Searching for deviations from MSW-LMA (large mixing angle Mikheyev-Smirnov-Wolfenstein effect) scenario of solar neutrino oscillations, especially in the transition region of P_{ee} (e.g. non-standard neutrino interactions models)



Bahcall & Pena-Garay:JHEP 0311:004 (2003)

Solar Neutrinos

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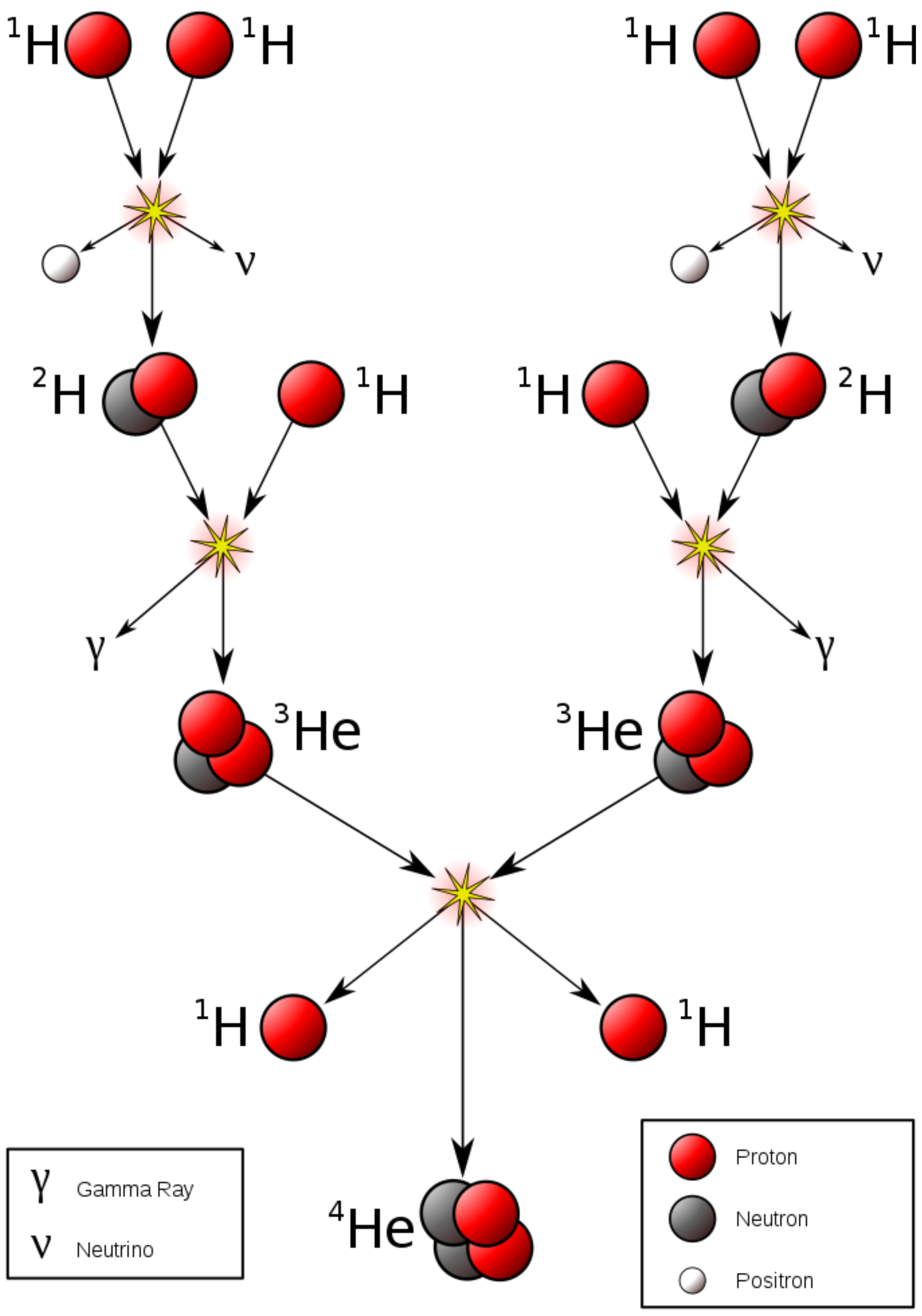
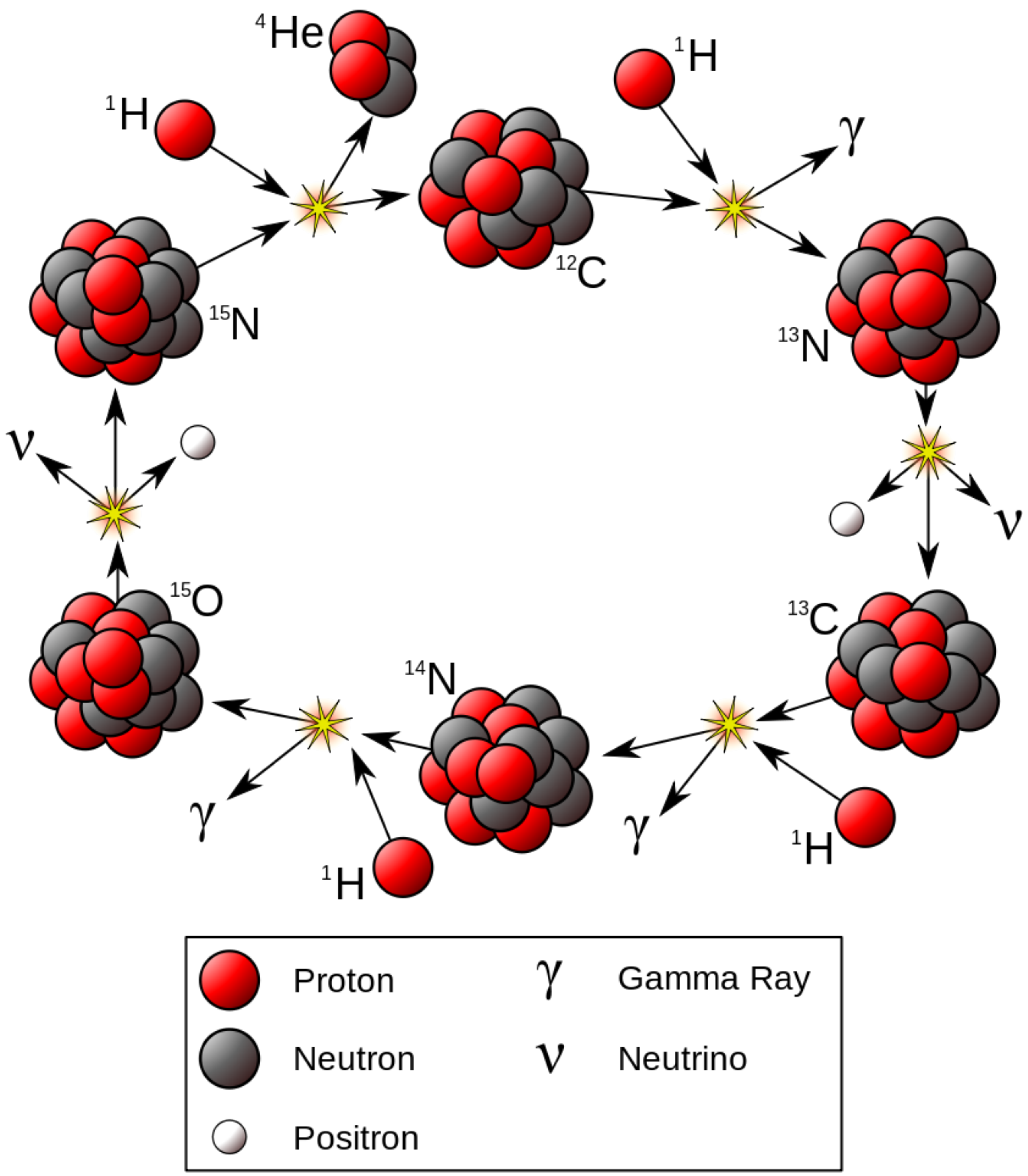
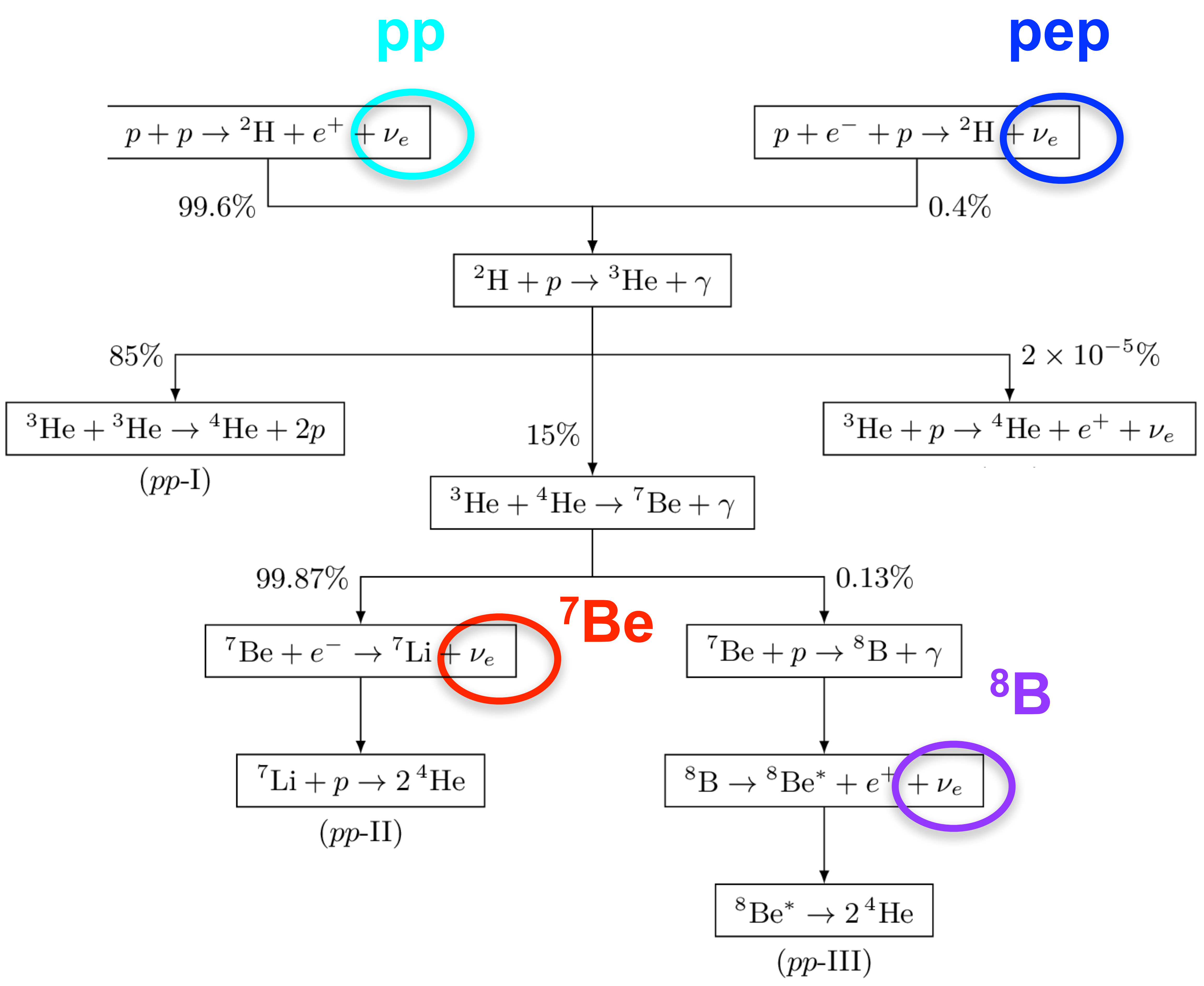
pp chain reaction (～99%)



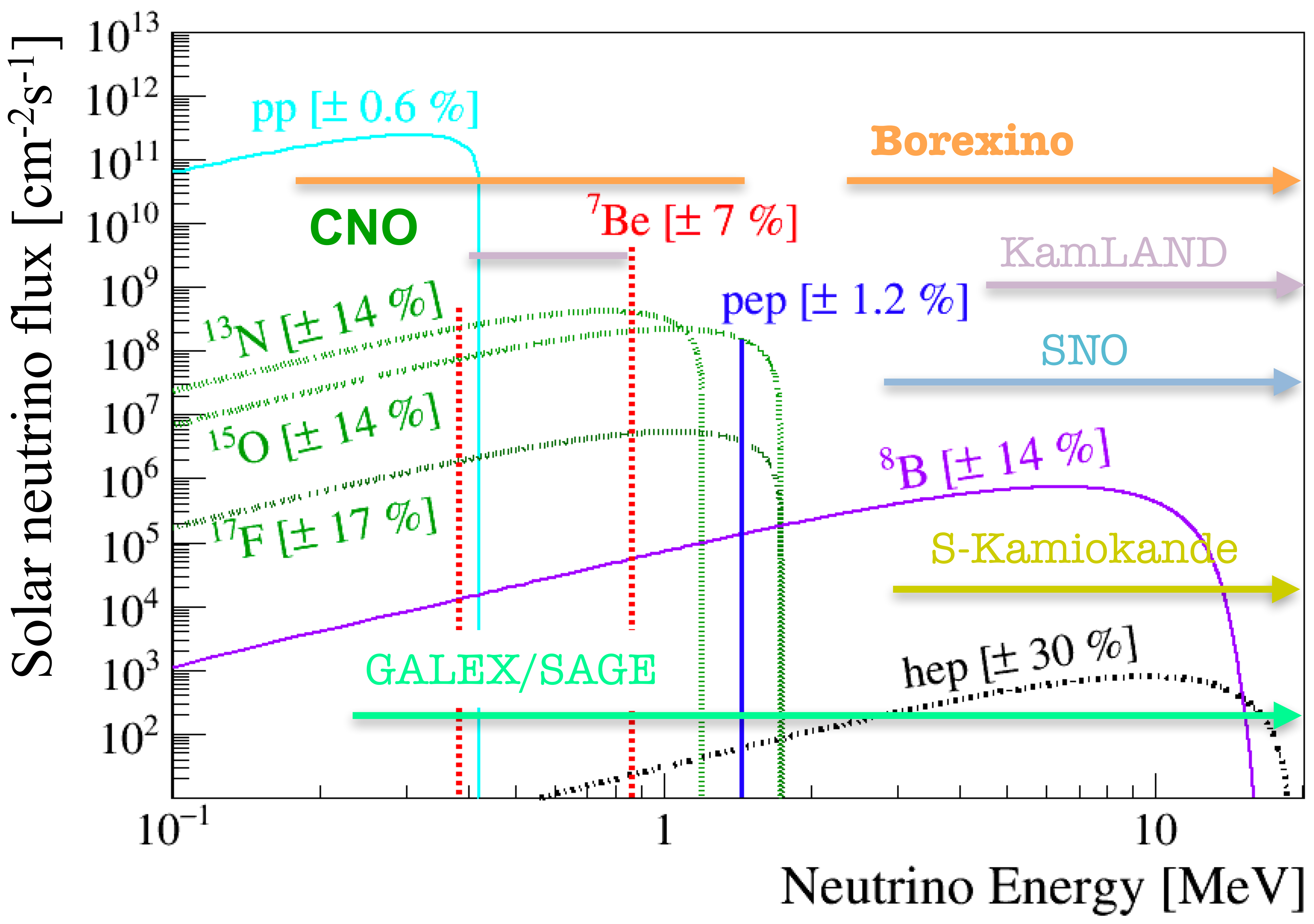
CNO cycle (＜1%)



Solar Neutrinos Spectrum

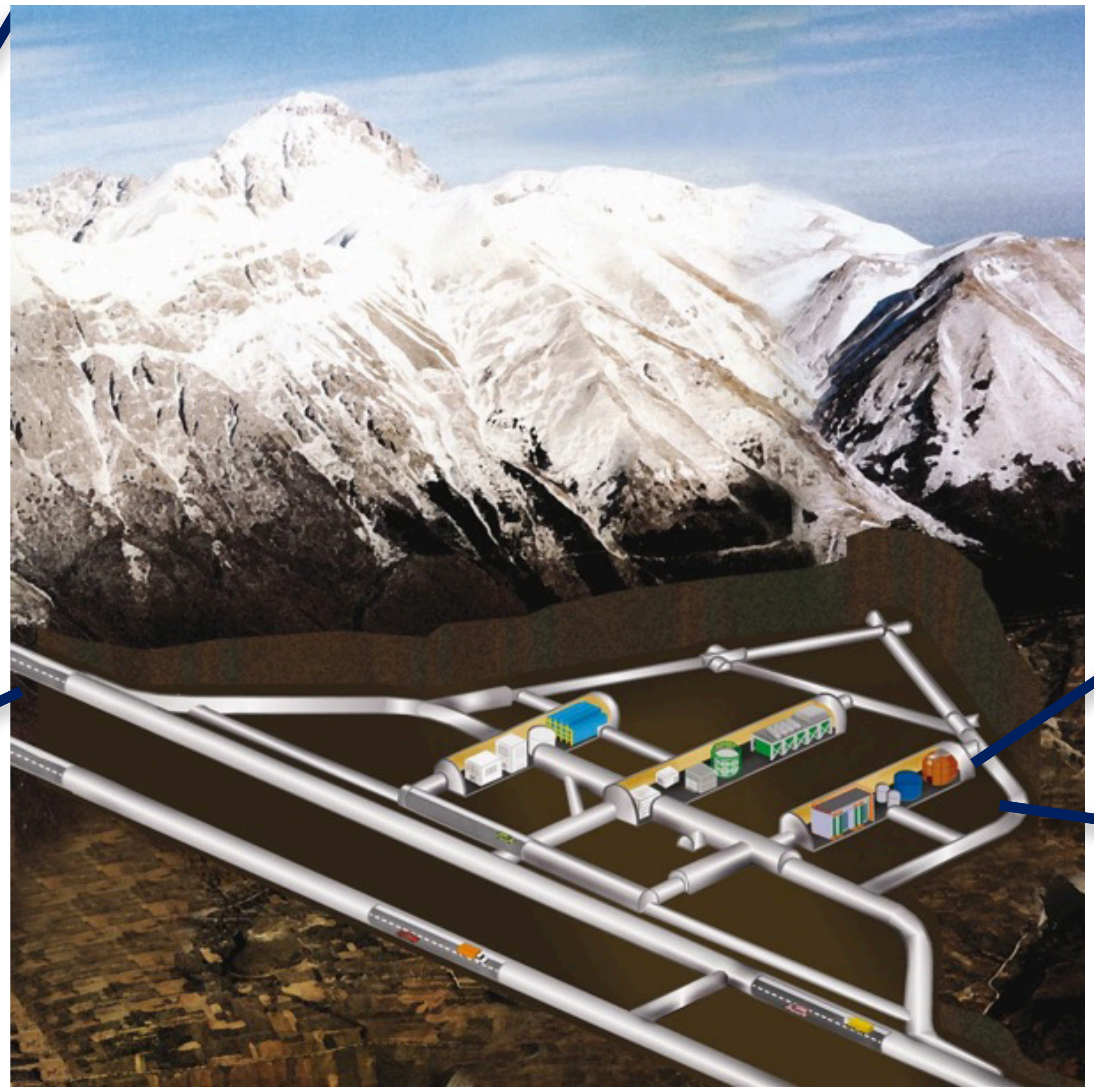


based on Standard Solar Model (SSM) uncertainties on flux



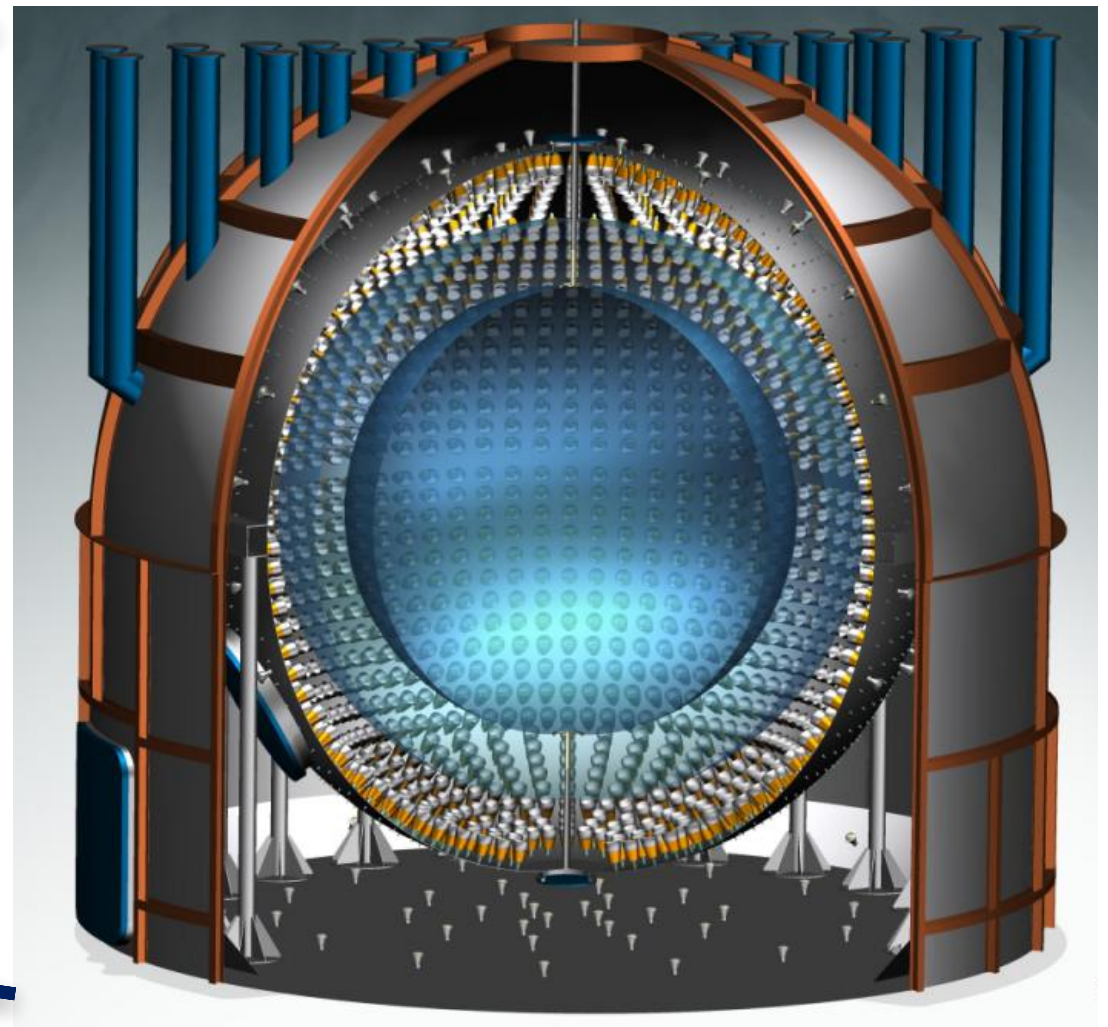
Borexino @ LNGS

Gran Sasso, Apennines, Abruzzo, Italy



Laboratori Nazionali di Gran Sasso

3800 m.w.e shielding against cosmic rays



Borexino detector at Hall C

Entrance to the LNGS

BOREXINO Detector

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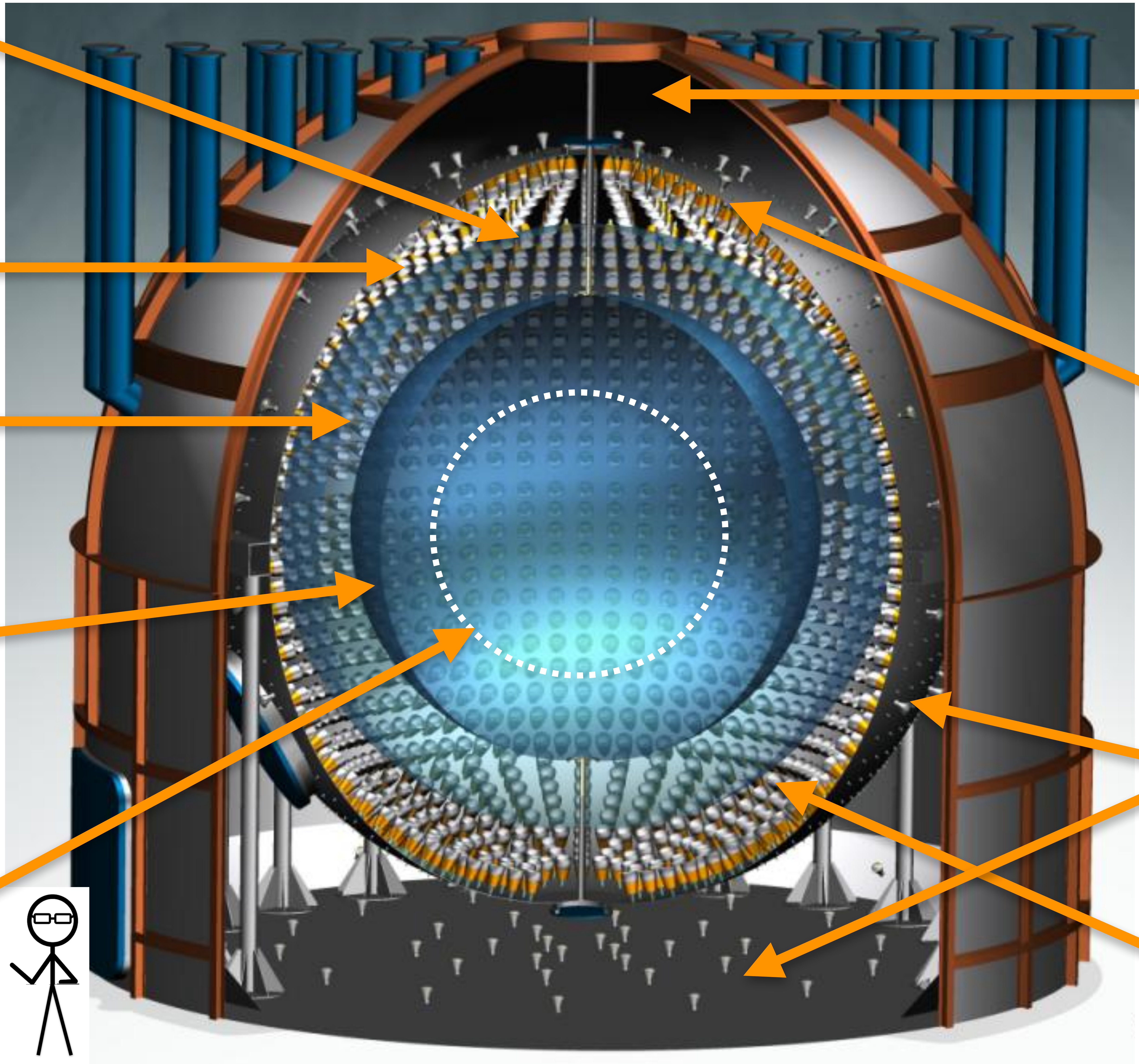
Nylon Outer Vessel
R = 5.5 m
Barrier for Rn
from steel, PMTs etc.

Outer Buffer
PC + DMP quencher

Inner Buffer
PC + DMP quencher

Nylon Inner Vessel
R = 4.25 m
~ 300 tons of
liquid scintillator
(PC/PPO solution)

Fiducial volume
~100 tons (software cut)



Water tank:
R = 9 m, 2.1 kt of water
Shielding
Cherenkov muon veto

Stainless Steel Sphere:
R = 6.85 m
Buffer+ scint. container
PMTs support

208 Outer Detector PMTs

2212 Inward-facing PMTs

Borexino achievements so far

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

2007 — 2010 — 2012 — 2017

- ν (^{7}Be) flux
- ν (^{8}B) flux
- ν (pep) flux
- ν (CNO) limit

Improved radiopurity:
(6 cycles of scintillator purification)

- ^{85}Kr: reduced by ~4.6
- ^{210}Bi: reduced by ~2.3
- Th and U negligible:
  - ^{238}U: < 9.4 * 10^{-20} g/g (95% C.L.)
  - ^{232}Th: < 5.7 * 10^{-19} g/g (95% C.L.)

pp solar neutrinos

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

New results on the solar fluxes

- ν (^{7}Be) day-night asymmetry
- Neutrino magnetic moment limit
- Correlations with gravitational wave signals

Other recents results:

Geoneutrinos	> 5σ	DOI:10.1103/PhysRevD.92.031101
Gamma-ray burts correlation	No statistically significant excess over background	DOI:10.1016/j.astropartphys.2016.10.004
e charge conservation	> 6.6 10^{28} y @ 90% CL	DOI:10.1103/PhysRevLett.115.231802

Borexino achievements so far

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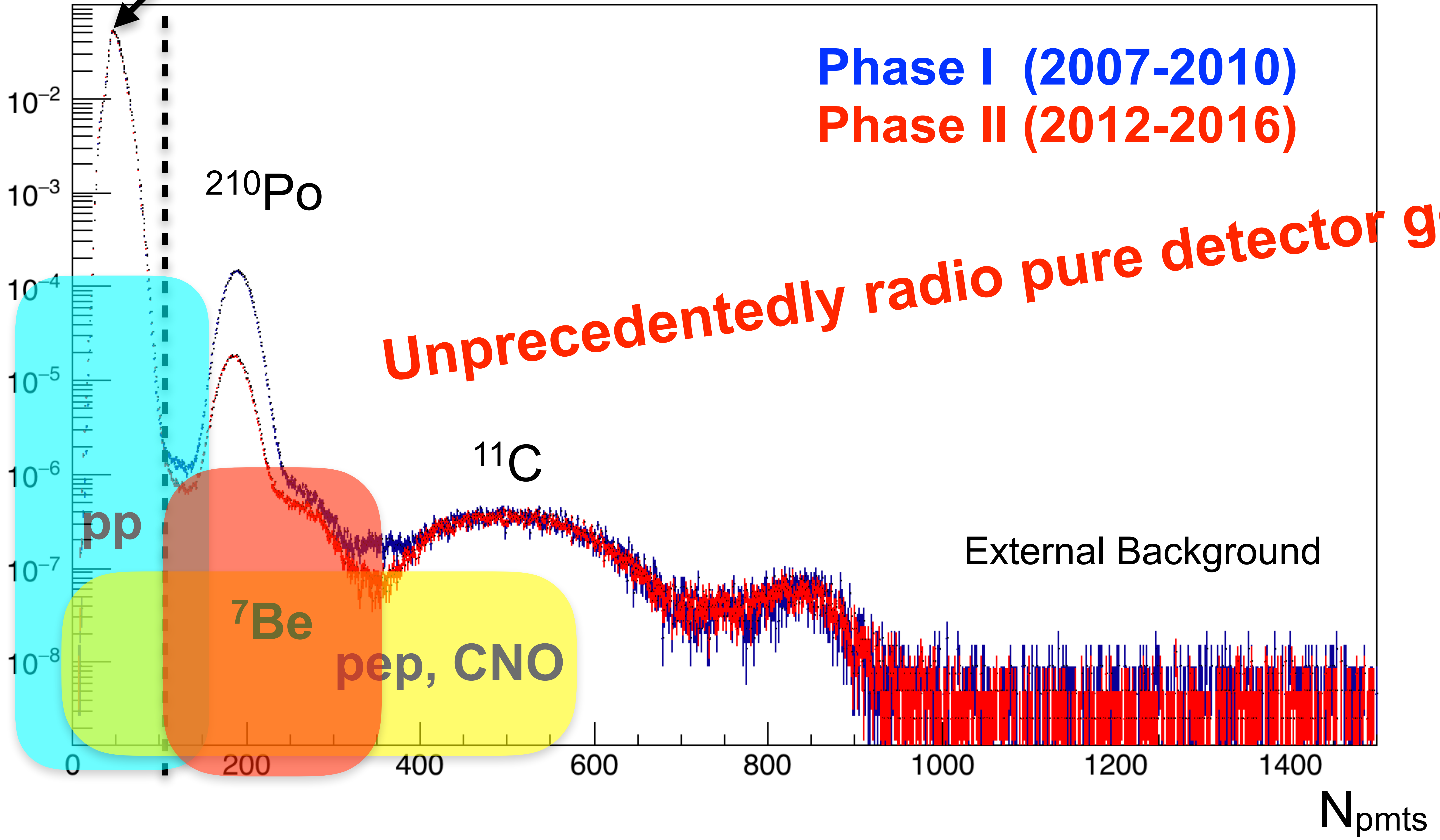
- **First measurement of the neutrinos from the primary proton-proton fusion process in the Sun** (Nature, Vol. 512 2014)
- **Seasonal modulations of the ^{7}Be solar neutrino rate** (Astroparticle Physics 92 (2017) 21);

New results on the solar fluxes

- **First Simultaneous Precision Spectroscopy of pp, ^{7}Be and pep Solar Neutrinos** (arXiv:1707.09279);
- **Improved measurement of ^{8}B solar neutrinos** (arXiv:1709.00756)

Comparison between Phase I and Phase II

^{14}C unavoidable in organic scintillator



A spectral fit needed to disentangle signals and background

Require spectral shapes of signals and backgrounds

Two approaches: Analytical & MC

to determine the reference spectral shapes of signal and background

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MonteCarlo

arXiV:1703.02291

PROS

Tuning of the MC parameters is done on calibration data which is completely independent from the data to be analyzed

CONS

More free parameters -> more prone to correlations

Analytical

Phys.Rev.D **89**, 112007 (2014)

CONS

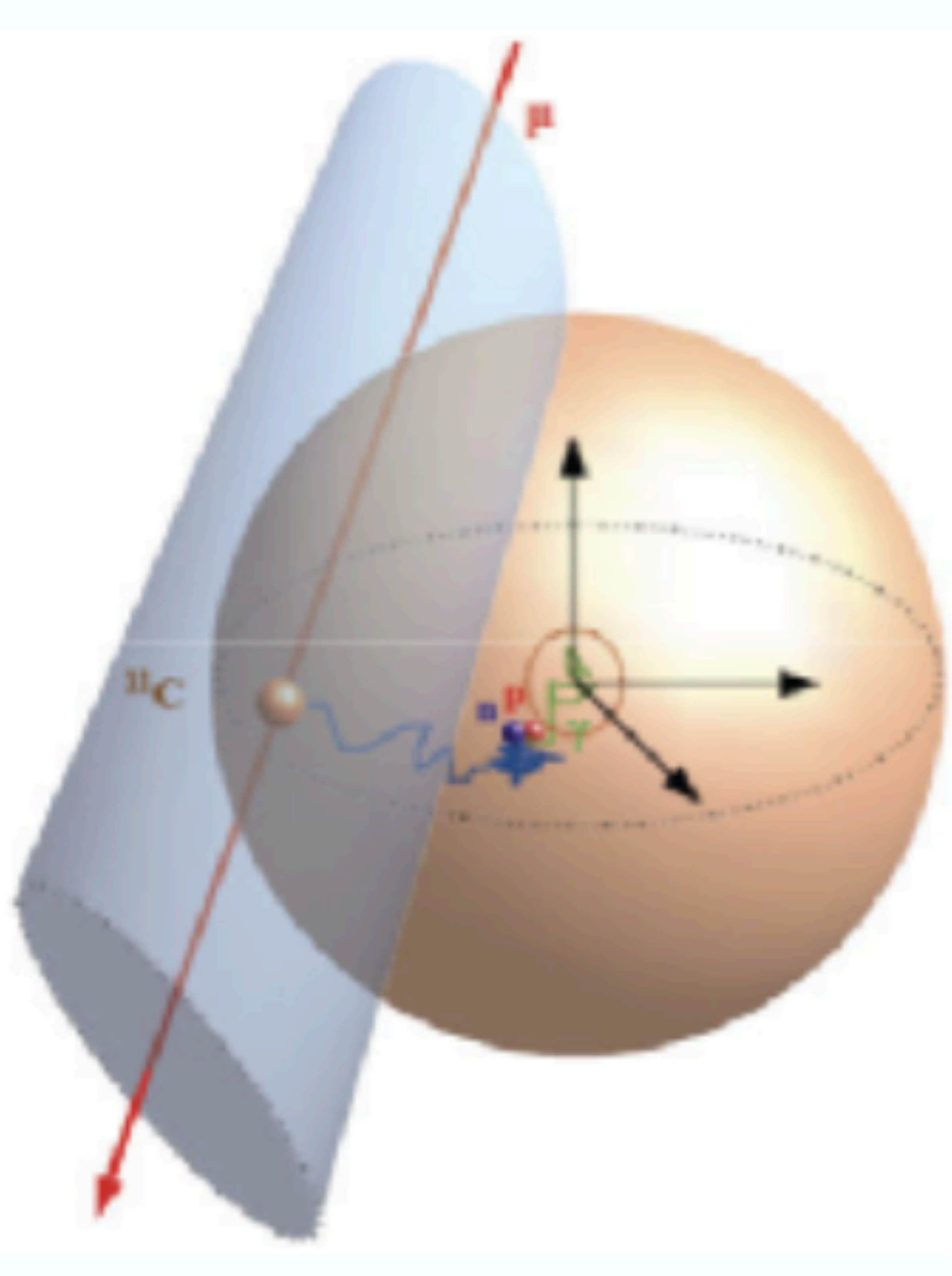
- Cannot take into account unknown variations of the detector properties
- Very high statistics to be simulated for ^{14}C

PROS

- More flexibility in case of unknown variations of the detector;
- Less problems in modelling ^{14}C
- Convolution of ideal spectral components with the solicited trigger spectrum

The two methods are complementary and provide internal cross-check to the analysis

Three Fold Coincidence (TFC)



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

$$n + p \rightarrow \mathrm{D} + \gamma_{2.2\,\mathrm{MeV}} \qquad (250\ \mu\mathrm{s})$$

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e \qquad (\sim 30\ \mathrm{min})$$

- Association of neutrons to a given μ track
- Veto region in space and time to exclude decay signatures from ^{11}C, associated to μ - n pairs
- 92% efficiency, 64% TFC subtracted exposure

The data set is divided in two spectra: one depleted in ^{11}C (TFC - subtracted) and one enriched in ^{11}C (TFC-tagged) which are then simultaneously fit

Multivariate fit

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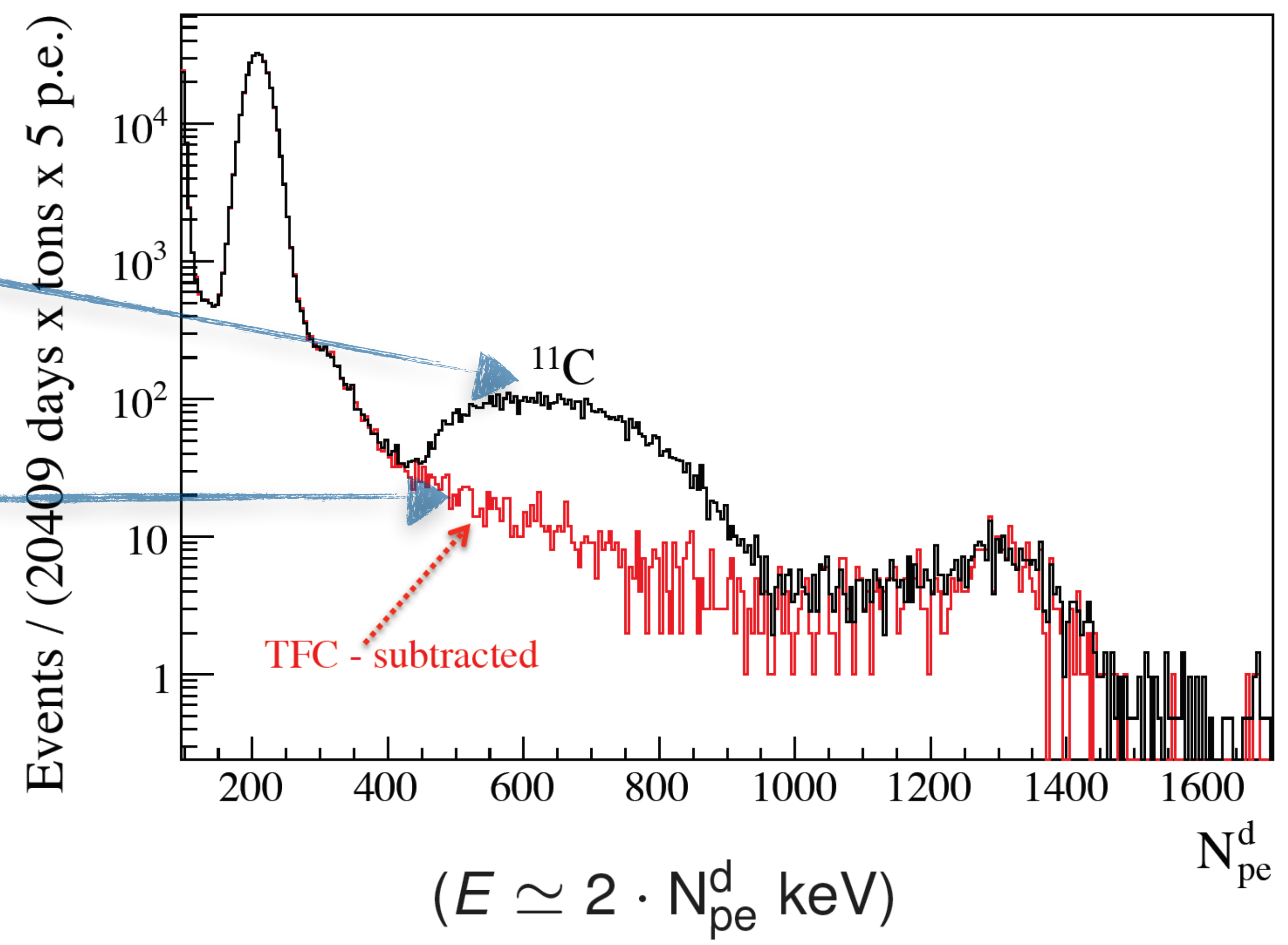
Three Fold Coincidence tagged energy spectrum

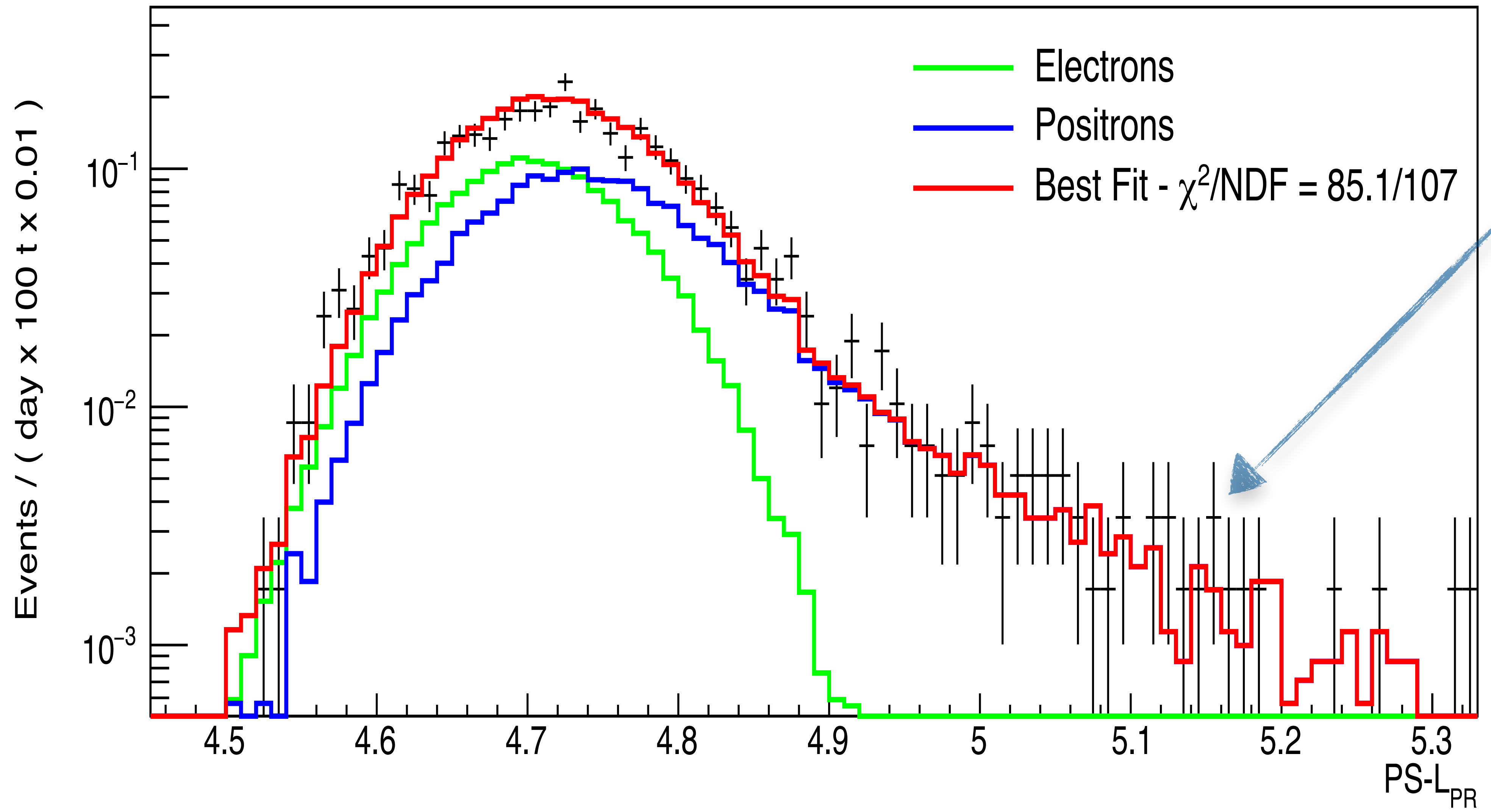


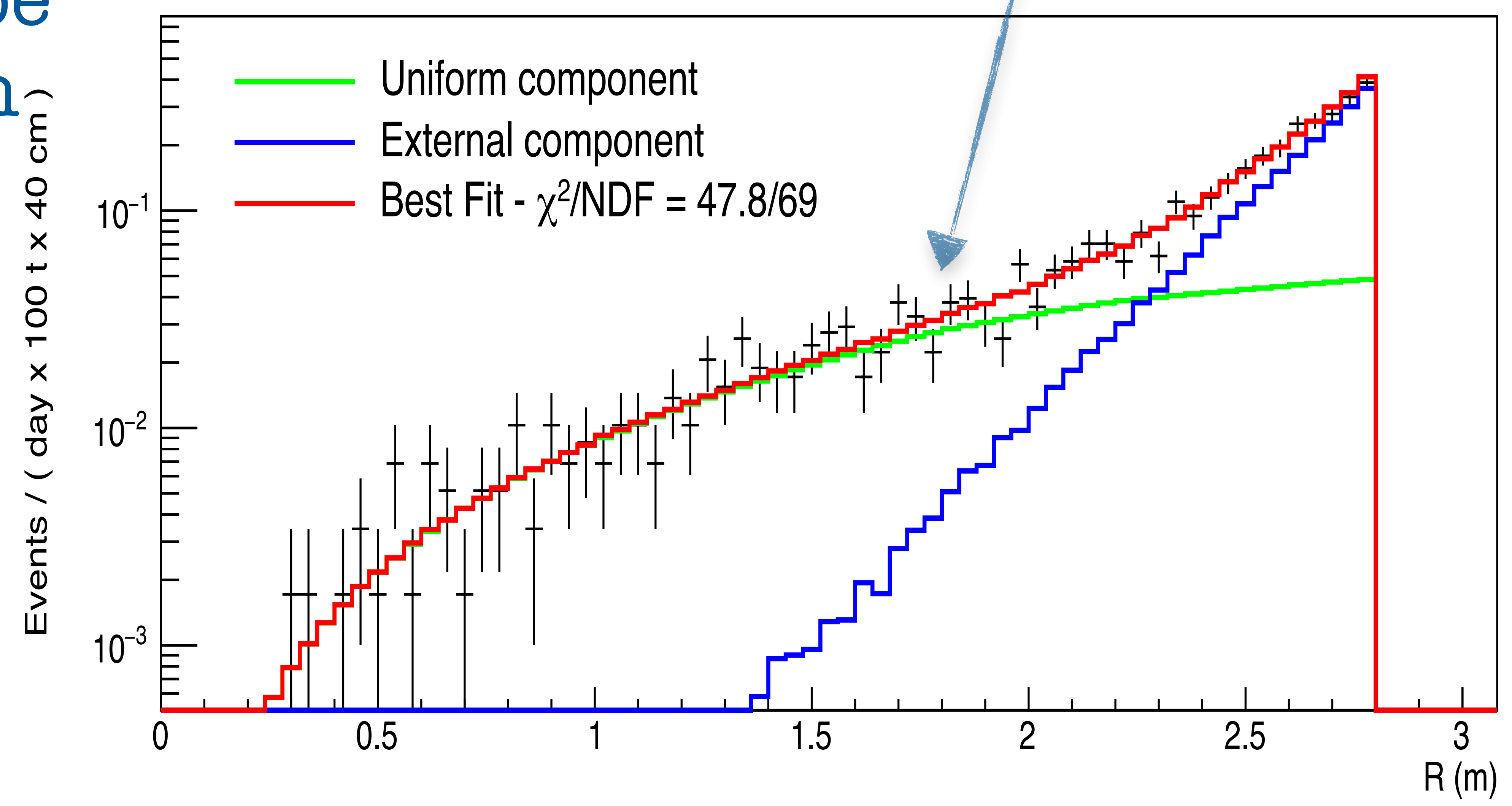
Energy spectrum after Three Fold Coincidence veto

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

Radial Distribution

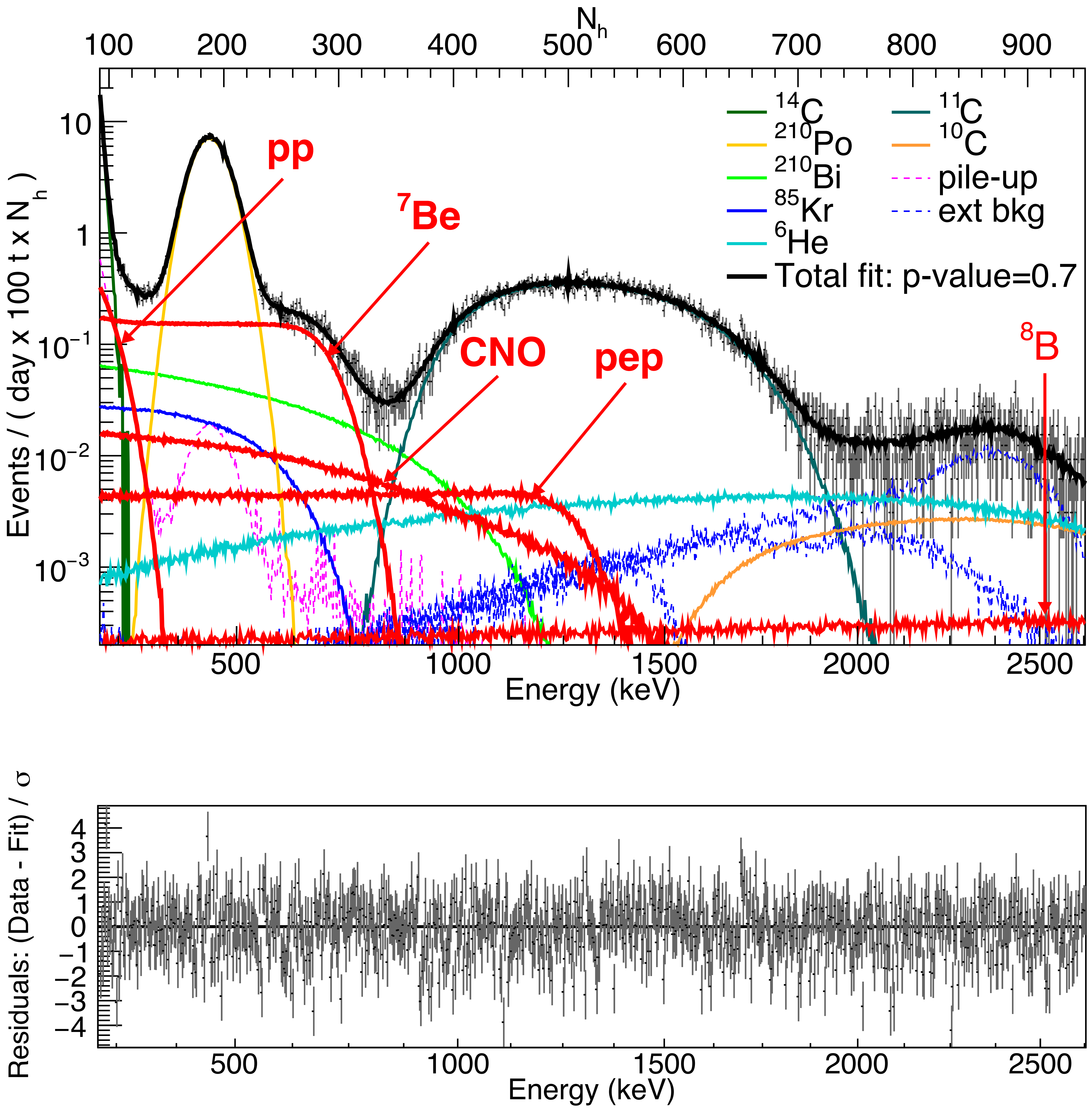
e^+/e^- **p**ulse-**s**hape discrimination



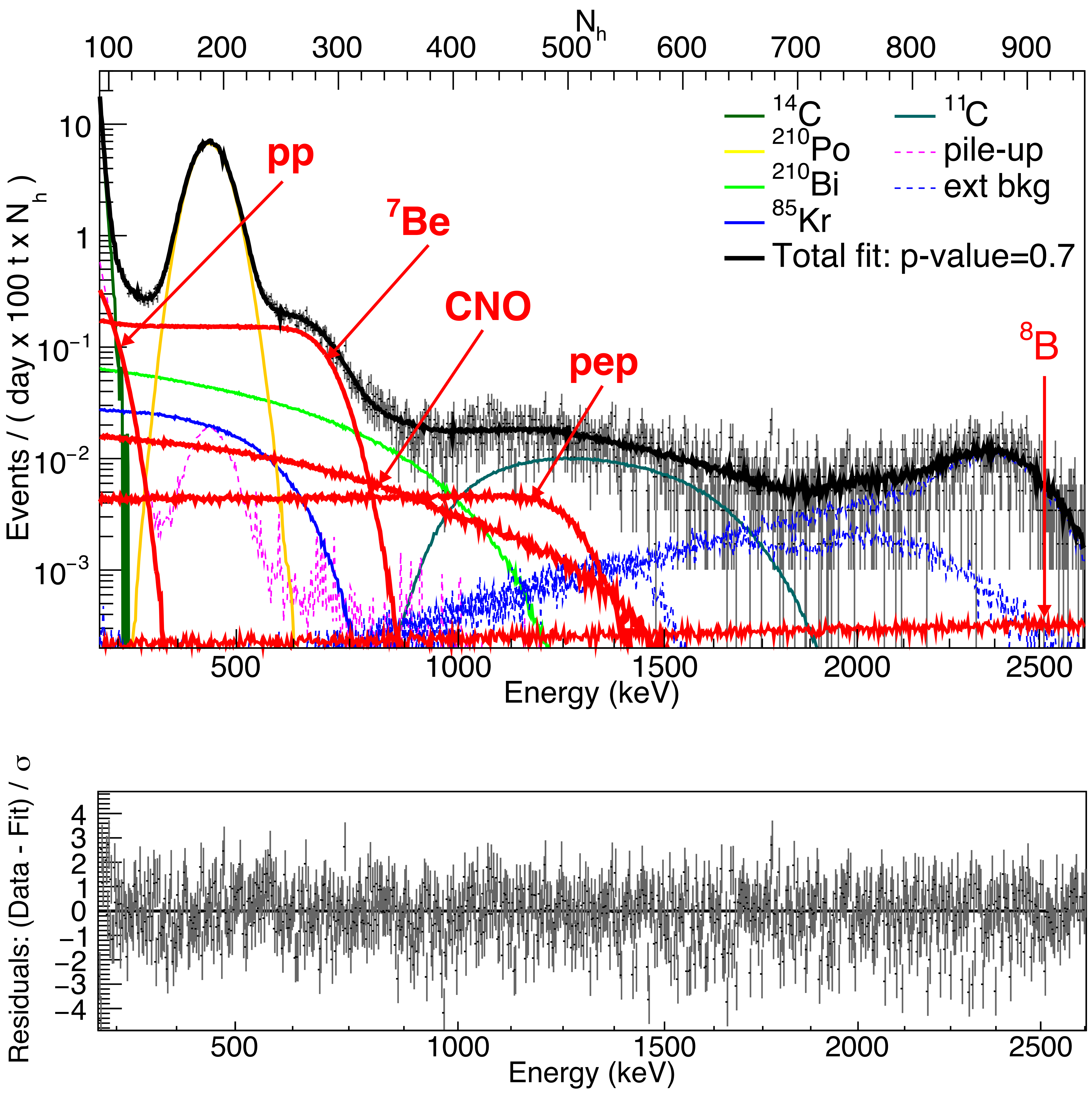


Monte Carlo spectral fit

TFC tagged energy spectrum



TFC subtracted energy spectrum



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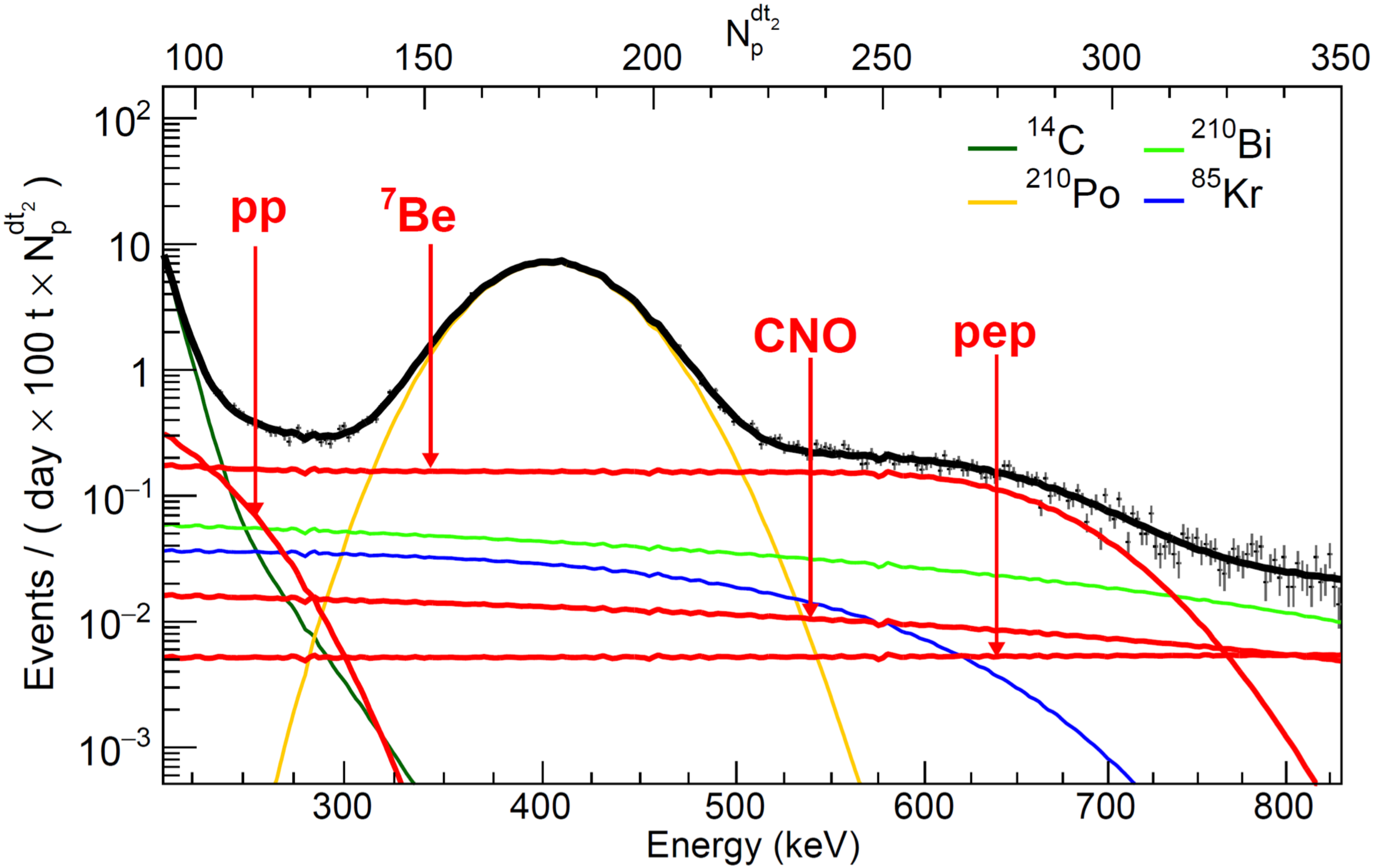
Analytical fit (zoom at low energies)



First simultaneous precision spectroscopy of pp, ^{7}Be and pep: Overview

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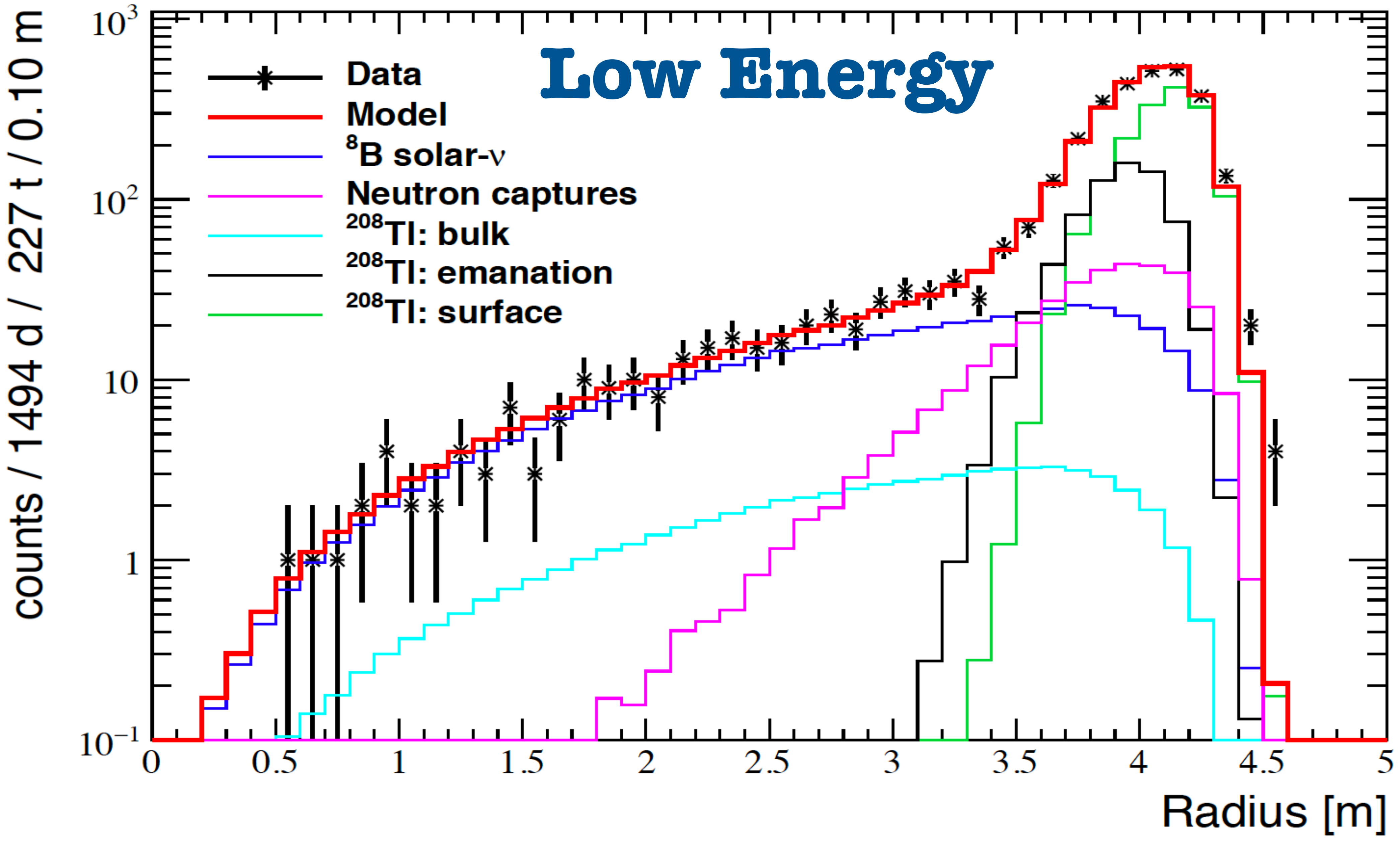
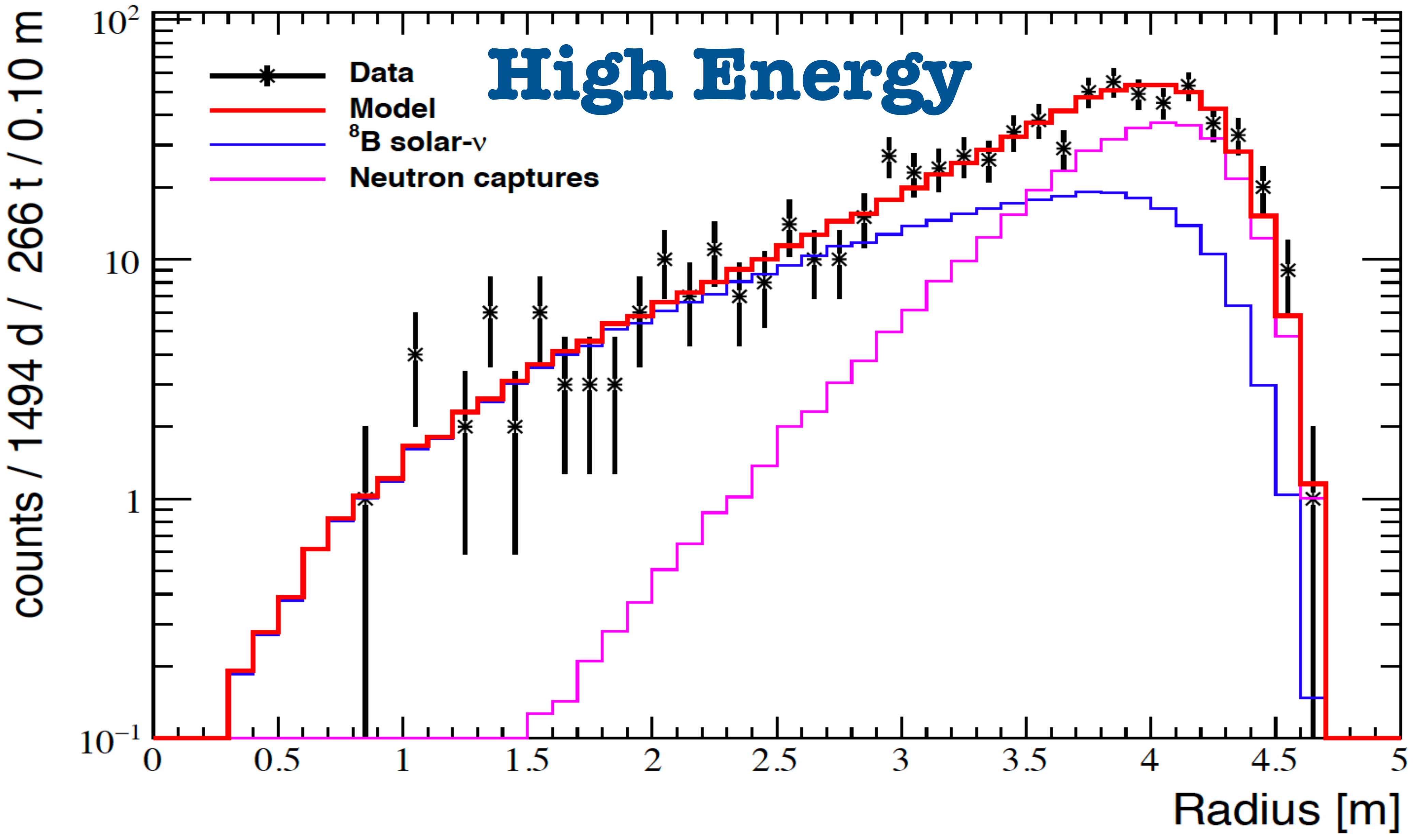
- **Data-set:** Dec 14th 2011- May 21st 2016;
- **Total exposure**: 1291.51 days x 71.3 tons (1.6 times Phase I data);
- **Fit range**: (0.19-2.93) MeV;

- CNO rate constrained to HZ-value (and to LZ-value);
- Fit performed both with the Monte Carlo and the Analytical methods;
- Different conditions of the fit (energy variable, range, binning, with or without ^{85}Kr constraint..);
- The final numbers are the average values obtained in different conditions;
- Differences are quoted as systematic error.

Improved measurement of ^{8}B neutrinos:
Overview

- **Data-set:** January 2008 - December 2016 (Purification period removed)
- **Total exposure**: 1.5 kton x years (**11.5-fold** increase from Phase I results)
- **Fit range**: 3.2 -17 MeV
- **Extending the fiducial mass** (~ 100 t) to the entire active mass (~ 300 t)
- Fit performed with the MonteCarlo fit, split into Low Energy ([1650, 2950] p.e.) and High Energy ([2950, 8500] p.e.) ranges at 5 MeV for proper handling of the background;





Improvements

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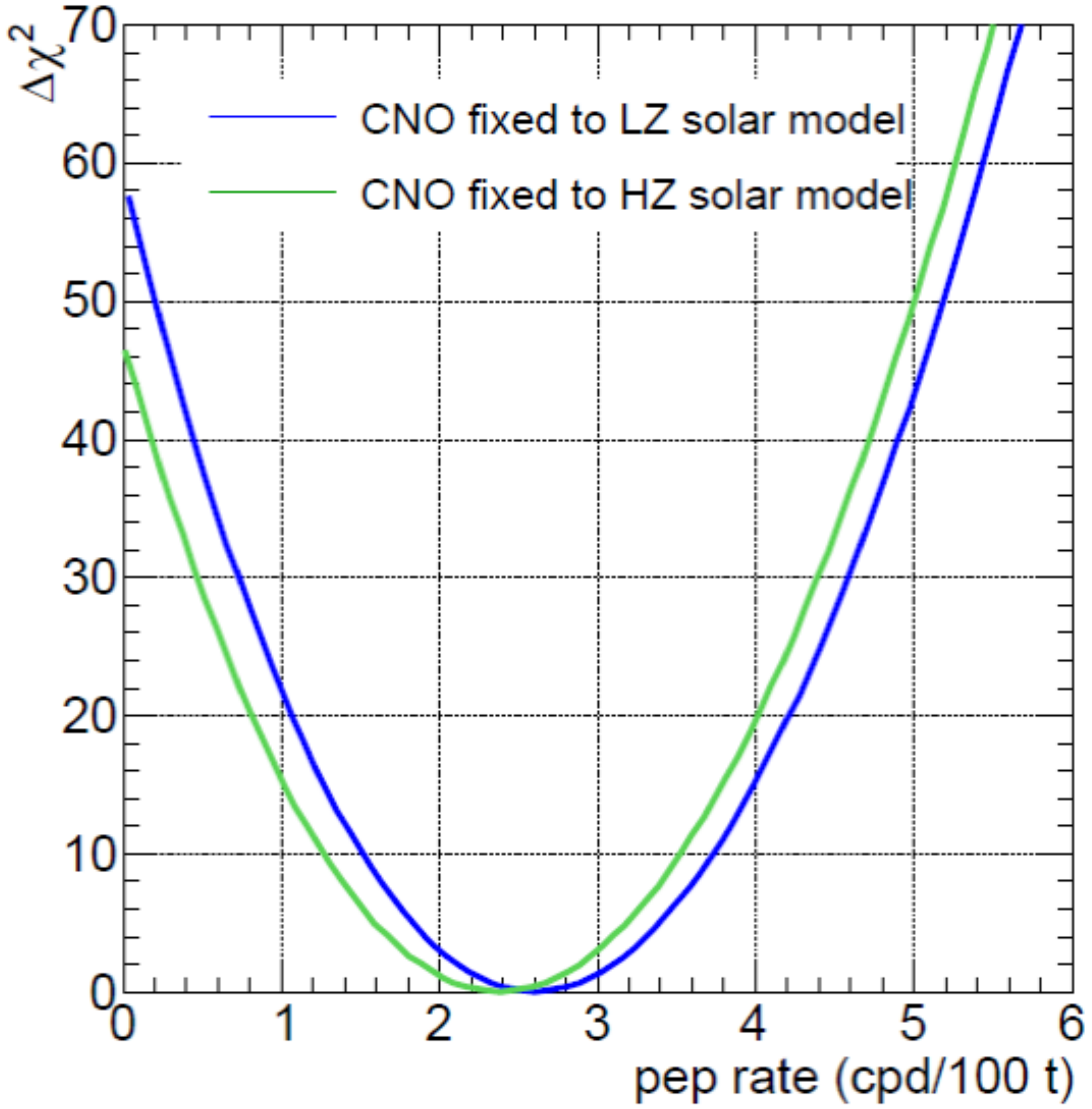
All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

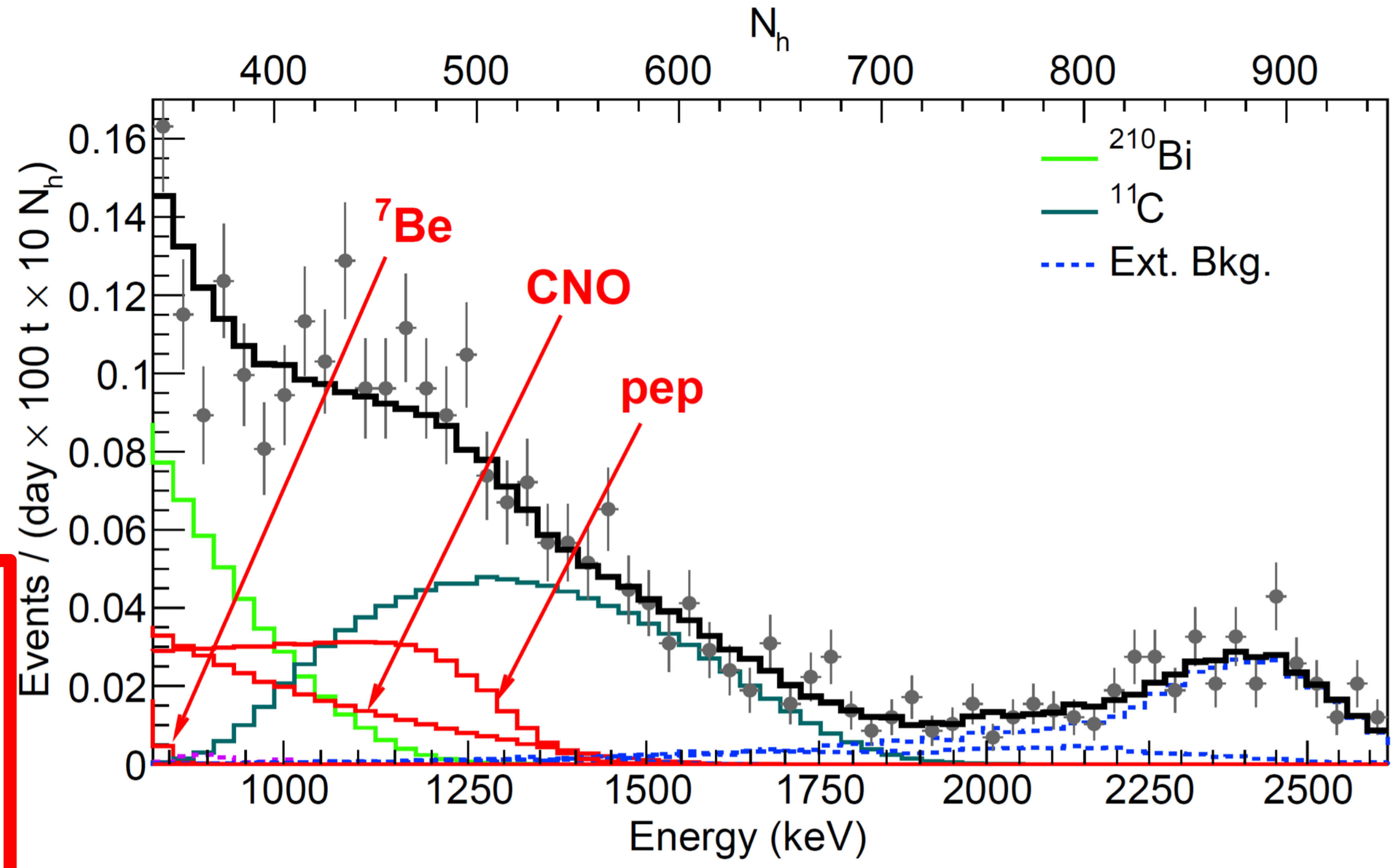
	Previous BX results (cpd/100t)	This work (cpd/100t)	Uncertainty reduction
pp	144 ± 13 ± 10	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be	48.3± 2.0 ± 0.9	$48.3 \pm 1.1^{+0.4}_{-0.7}$ 2.7% precision	0.57
pep	3.1 ± 0.6 ± 0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61
^{8}B	0.217 ± 0.038 ± 0.008	$0.220^{+0.015}_{-0.016} \pm 0.006$	0.42

Implications of the new results



>5σ evidence of **pep signal** (including systematic errors)

pep ν shoulder after the stringent cuts on FV and on the pulse-shape variable PS_L_{PR}

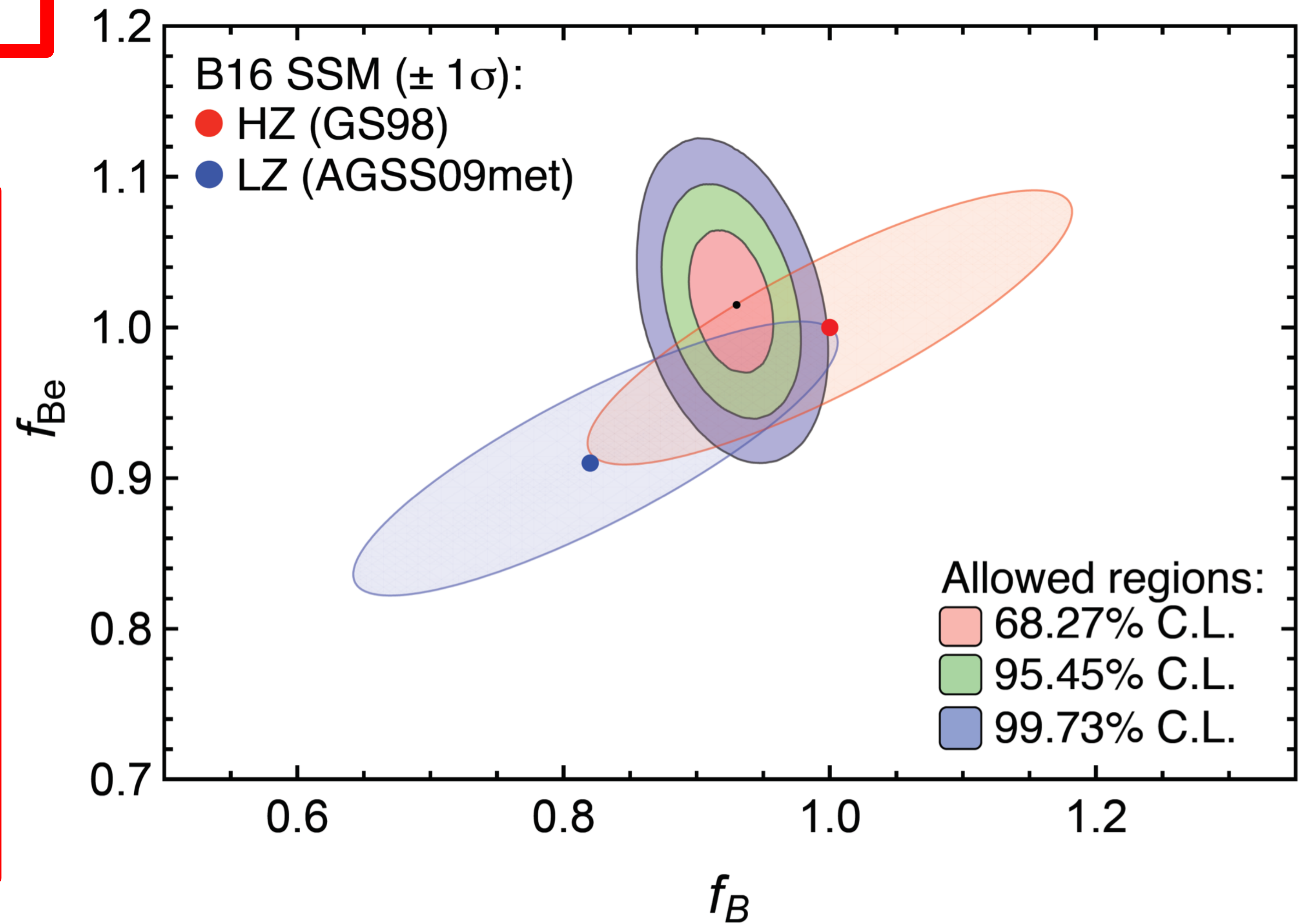


- The new Borexino results on ^{7}Be and ^{8}B neutrino rates seem to give a hint towards the High Metallicity hypothesis
  - p-value (HZ)= 0.87
  - p-value (LZ)= 0.11

$$f_{Be} = \frac{\Phi(Be)}{\Phi(Be)_{HZ}} = 1.01 \pm 0.03$$

$$f_B = \frac{\Phi(B)}{\Phi(B)_{HZ}} = 0.93 \pm 0.02$$

We are now largely dominated by the theoretical error



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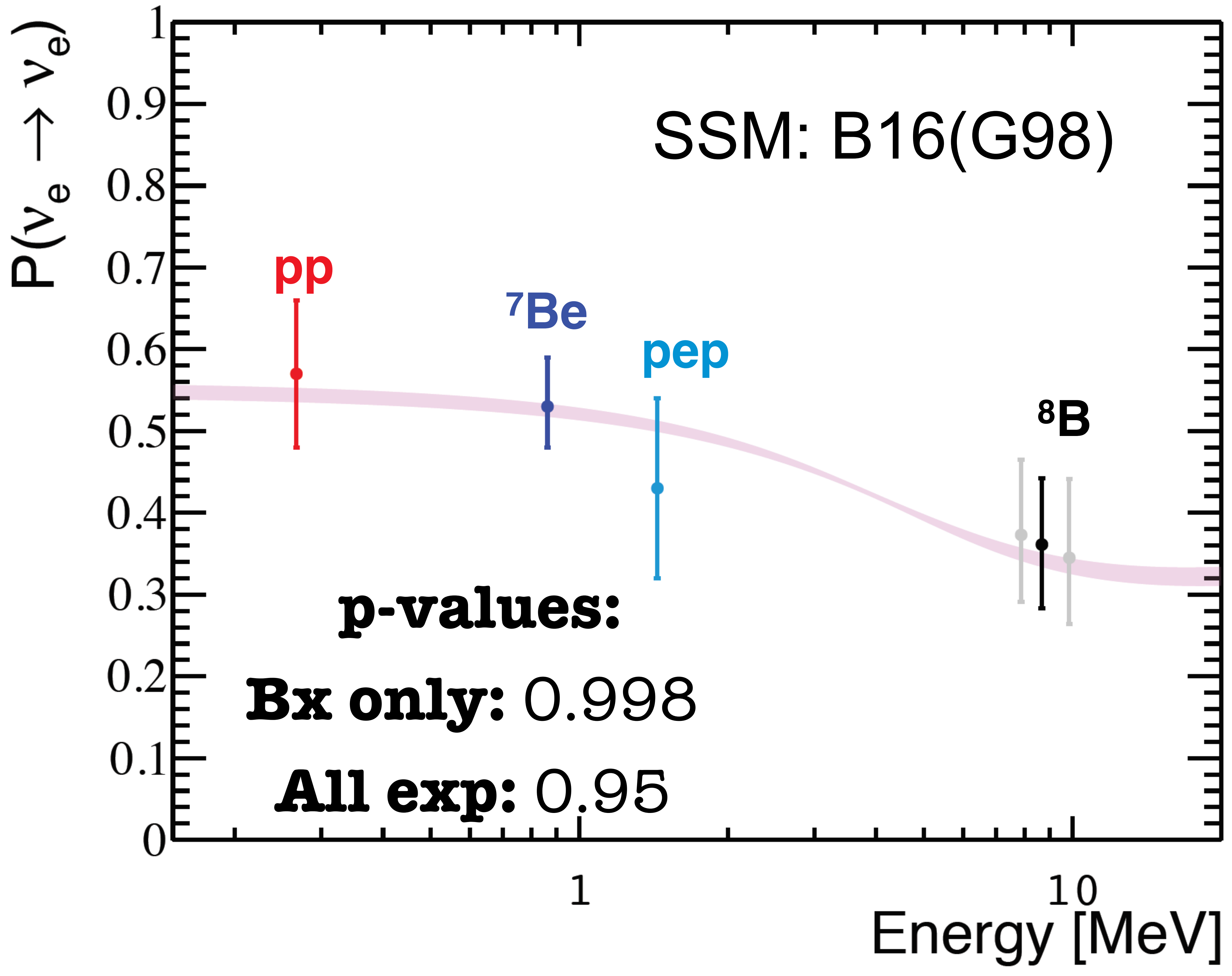
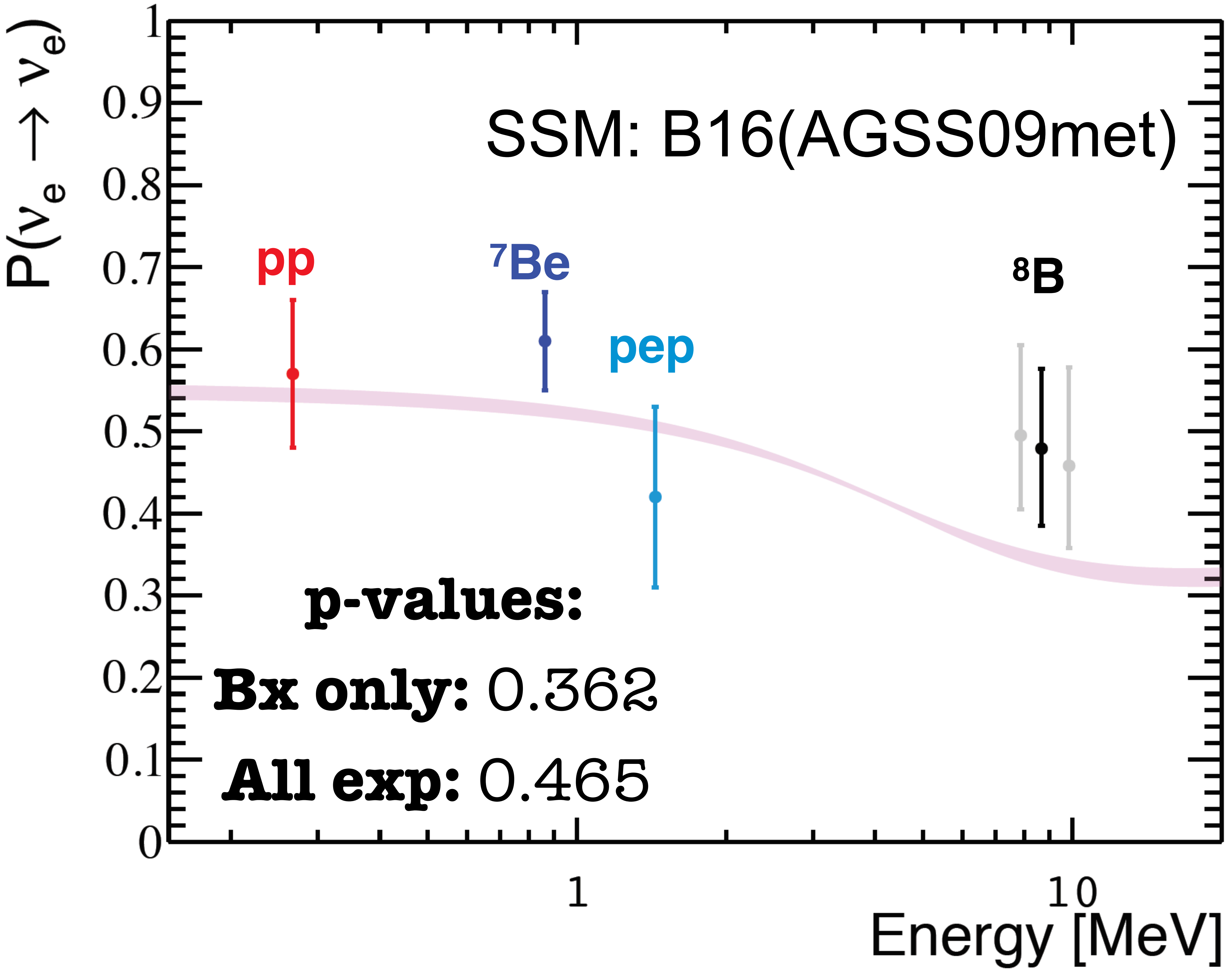
Survival Probability

High Metallicity



Low Metallicity



Conclusions

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Borexino has gone well beyond its original goal providing a complete study of solar neutrinos from the entire proton-proton chain

The newest results feature

- First simultaneous extraction of pp, pep and ^{7}Be neutrino rate from the same multivariate fit;
- Improved precision in all flux measurements (notably ^{7}Be precision is now 2.7%);
- >5σ evidence of the pep neutrino signal;
- Lowest energy threshold among real time measurements of ^{8}B;
- Hint towards the High Metallicity hypothesis

Borexino Collaboration

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UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

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

Università degli Studi di Ferrara

The University of California UCLA

TECHNISCHE UNIVERSITÄT DRESDEN

APC

Studium Generale Civitatis Perusii

POLITECNICO MILANO 1863

Thanks

Erice, Sicily

Svaneti, Georgia

Jvari Monastery, Georgia

Back-up slides

Comparison with the theoretical predictions

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Rates

Solar ν	Borexino results Rate [cpd/100 t]	Expected-HZ Rate [cpd/100 t]	Expected-LZ Rate [cpd/100 t]
pp	$134 \pm 10\ ^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.3
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05

Fluxes Φ

Solar ν	Borexino results Flux [cm^{-2}s^{-1}]	Expected-HZ Flux [cm^{-2}s^{-1}]	Expected-LZ Flux [cm^{-2}s^{-1}]
pp	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	$5.98\,(1 \pm 0.006) \times 10^{10}$	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	$4.93\,(1 \pm 0.06) \times 10^{9}$	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$

*oscillation parameters from: I.Esteban, MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)
**neutrino fluxes from: N.Vinyole,A.Serenelli, F.Villante, S.Basu, J.Bergstrom,M.C.Gonzalez-Garcia, M.Maltoni, C.Pena-Garay, N.Song, Astr.Jour. 835,202 (2017)

Systematic errors of pp, ^{7}Be and pep

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Two methods to take into account pile-up:

Effects of non perfect modelling of the detector response; Uncertainty on theoretical input spectra (^{210}Bi);

^{85}Kr constrained to be <7.5cpd/100t (95% C.L.) (from ^{85}Kr-^{85}Rb delayed coincidences)

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 modelling	-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	-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

Borexino background rates

Background species	Rate (cpd/100t)
^{14}C (Bq/100t)	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

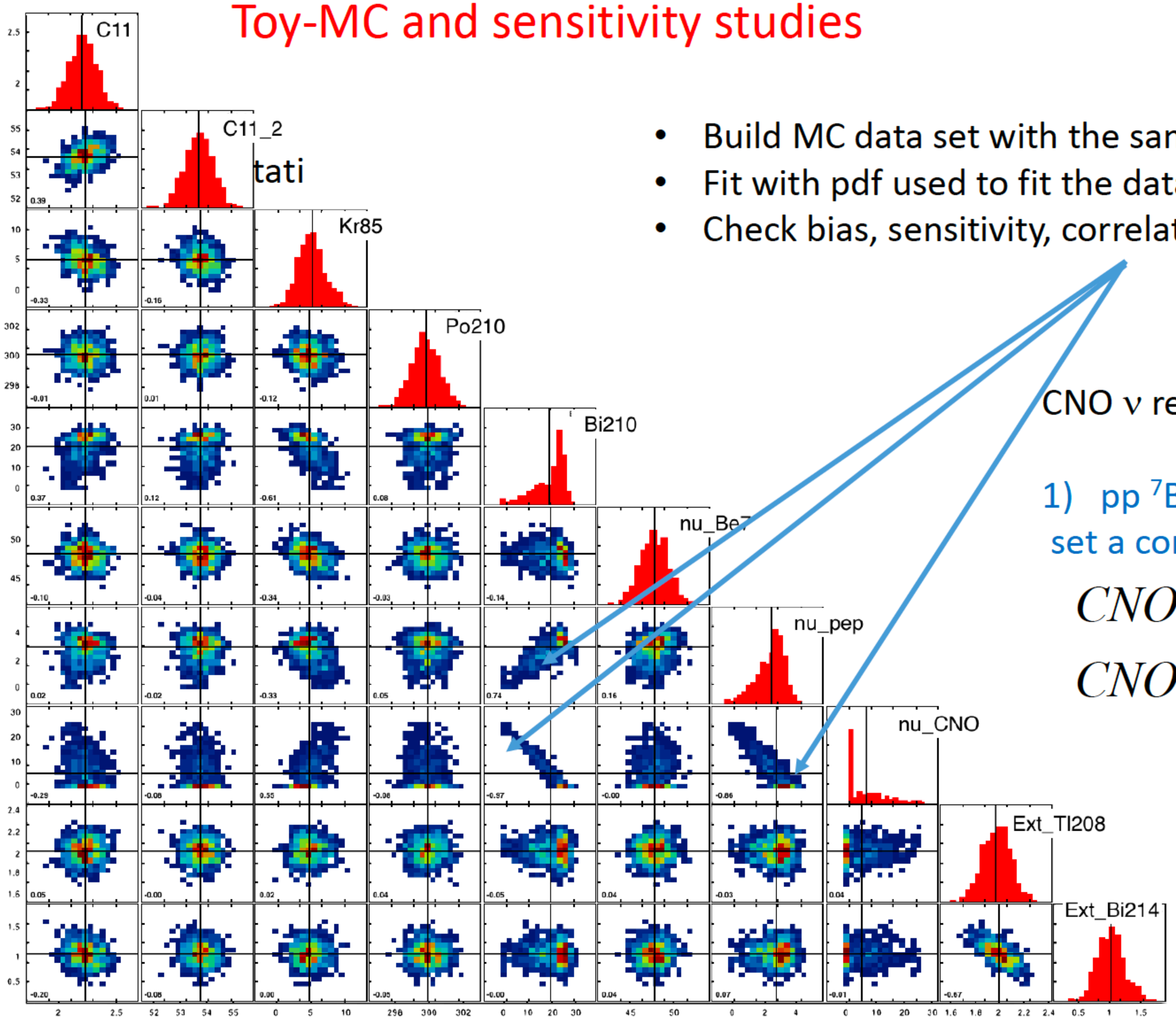
Factor 4.6 reduction with respect to Phase-I

Factor 2.3 reduction with respect to Phase-I

Statistical and systematical errors added in quadrature

Sensitivity Studies

Toy-MC and sensitivity studies



- Build MC data set with the same exposure as in the data
- Fit with pdf used to fit the data
- Check bias, sensitivity, correlations

Analysis strategy:

CNO ν recoil and ^{210}Bi: very similar energy spectrum

1) pp ^{7}Be pep flux measurement:
set a constraint of the CNO rate to the HZ and LZ values

$$CNO\ HZ \quad 4.92 \pm 0.56 \quad cpd/100t$$

$$CNO\ LZ \quad 3.52 \pm 0.37 \quad cpd/100t$$

2) Upper limit CNO ν flux:
we set a constraint on the ratio pp/pep

$$R(pp/pep) \quad 47.5 \pm 1.2$$

Cosmogenic Isotopes

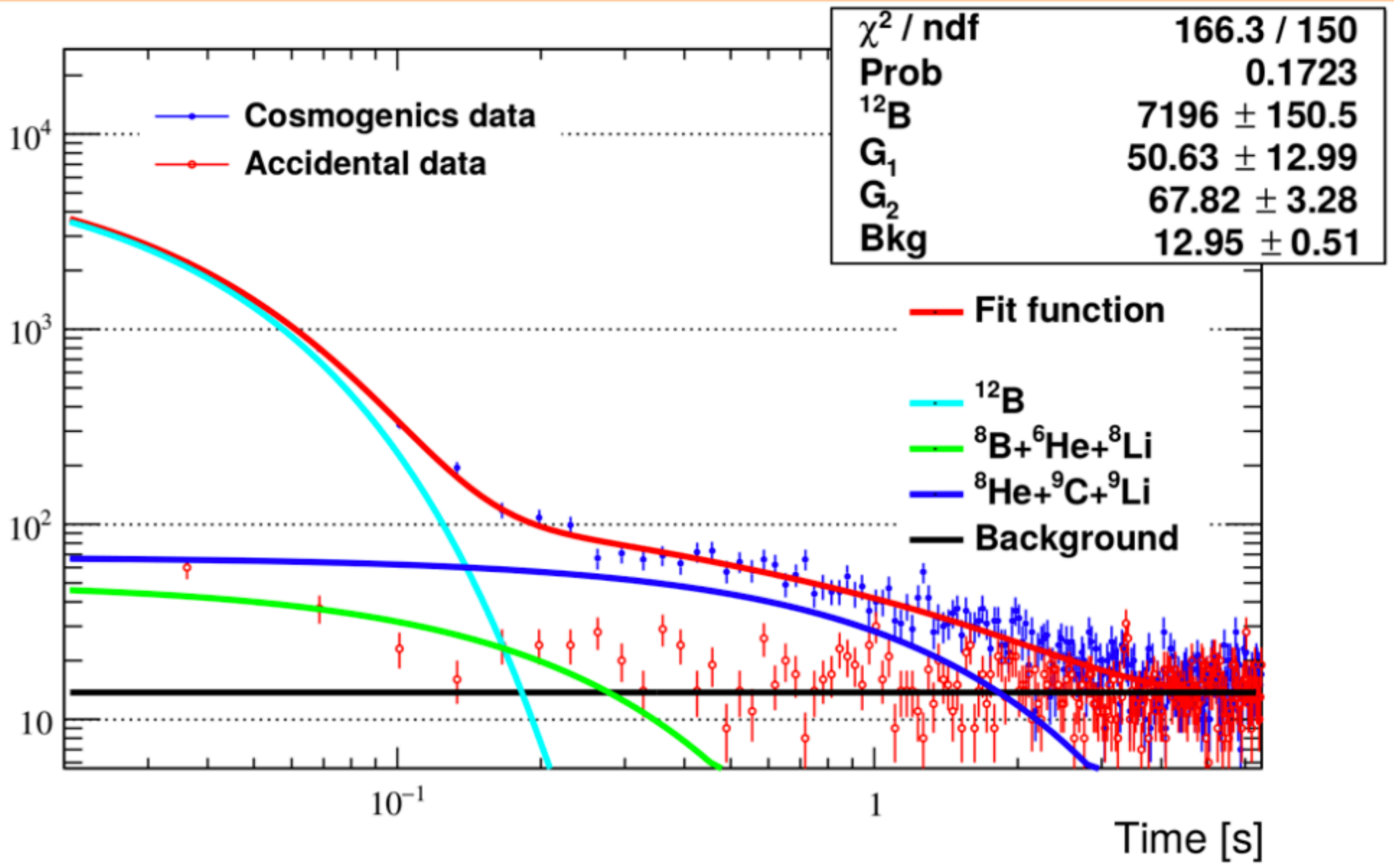
Isotopes	τ	Q [MeV]	Decay	Expected Rate [cpd/100 t]	Fraction $> 3\ MeV$	Expected Rate $> 3\ MeV$ [cpd/100 t]	Measured Rate $> 3\ MeV$ [cpd/100 t]
^{12}B	0.03 s	13.4	β^-	1.41 ± 0.04	0.886	1.25 ± 0.03	1.48 ± 0.06
^{8}He	0.17 s	10.6	β^-	0.026 ± 0.012	0.898	$(1.8 \pm 0.3)\times10^{-1}$	$(1.7 \pm 0.5)\times10^{-1}$
^{9}C	0.19 s	16.5	β^+	0.096 ± 0.031	0.965		
^{9}Li	0.26 s	13.6	β^-	0.071 ± 0.005	0.932		
^{8}B	1.11 s	18.0	β^+	0.273 ± 0.062	0.938	$(6.0 \pm 0.8)\times10^{-1}$	$(5.1 \pm 0.7)\times10^{-1}$
^{6}He	1.17 s	3.5	β^-	NA	0.009		
^{8}Li	1.21 s	16.0	β^-	0.40 ± 0.07	0.875		
^{10}C	27.8 s	3.6	β^+	0.54 ± 0.04	0.012	$(6.5\pm0.5)\times10^{-3}$	$(6.6\pm1.8)\times10^{-3}$
^{11}Be	19.9 s	11.5	β^-	0.035 ± 0.006	0.902	$(3.2 \pm 0.5)\times10^{-2}$	$(3.6\pm3.5)\times10^{-2}$

6.5 s veto

TFC

Untaggable

Extrapolation of the cosmogenic contribution after the 6.5 s time window, with a fit of the time profile of events following a muon



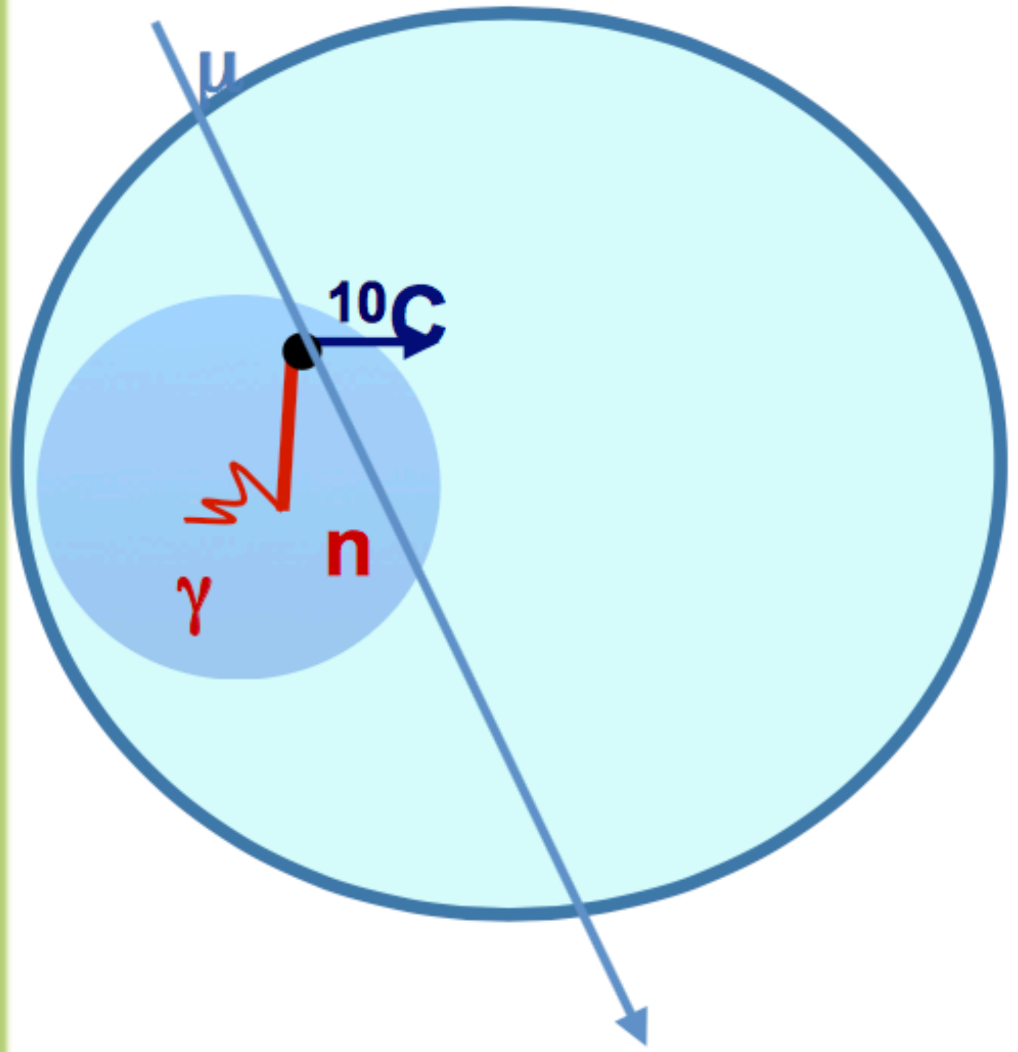
Cosmogenic Isotopes

Isotopes	τ	Q [MeV]	Decay	Expected Rate [cpd/100 t]	Fraction $> 3\ MeV$	Expected Rate $> 3\ MeV$ [cpd/100 t]	Measured Rate $> 3\ MeV$ [cpd/100 t]
^{12}B	0.03 s	13.4	β^-	1.41 ± 0.04	0.886	1.25 ± 0.03	1.48 ± 0.06
^{8}He	0.17 s	10.6	β^-	0.026 ± 0.012	0.898		
^{9}C	0.19 s	16.5	β^+	0.096 ± 0.031	0.965	$(1.8 \pm 0.3) \times 10^{-1}$	$(1.7 \pm 0.5) \times 10^{-1}$
^{9}Li	0.26 s	13.6	β^-	0.071 ± 0.005	0.932		
^{8}B	1.11 s	18.0	β^+	0.273 ± 0.062	0.938		
^{6}He	1.17 s	3.5	β^-	NA	0.009	$(6.0 \pm 0.8) \times 10^{-1}$	$(5.1 \pm 0.7) \times 10^{-1}$
^{8}Li	1.21 s	16.0	β^-	0.40 ± 0.07	0.875		
^{10}C	27.8 s	3.6	β^+	0.54 ± 0.04	0.012	$(6.5 \pm 0.5) \times 10^{-3}$	$(6.6 \pm 1.8) \times 10^{-3}$
^{11}Be	19.9 s	11.5	β^-	0.035 ± 0.006	0.902	$(3.2 \pm 0.5) \times 10^{-2}$	$(3.6 \pm 3.5) \times 10^{-2}$

6.5 s veto

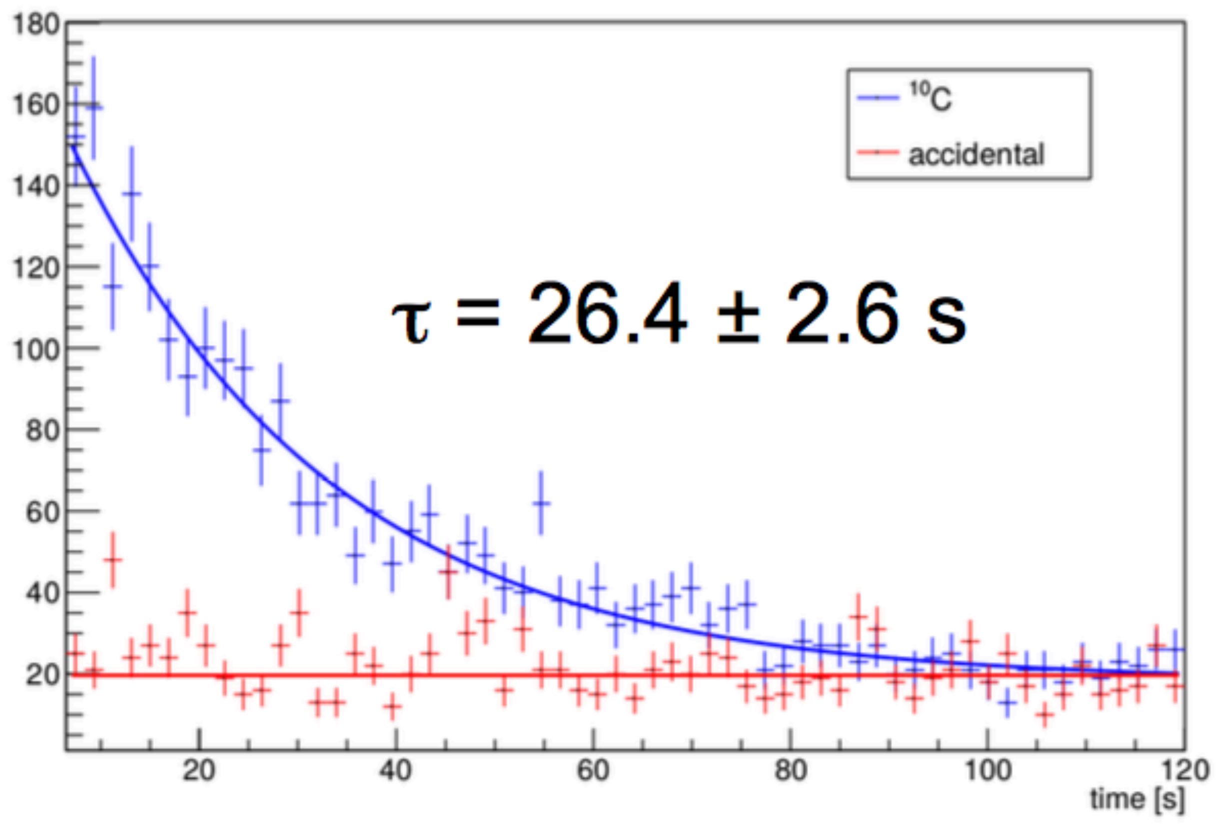
TFC

Untaggable



Fraction of ^{10}C with Q > 1650 pe = 1.6%

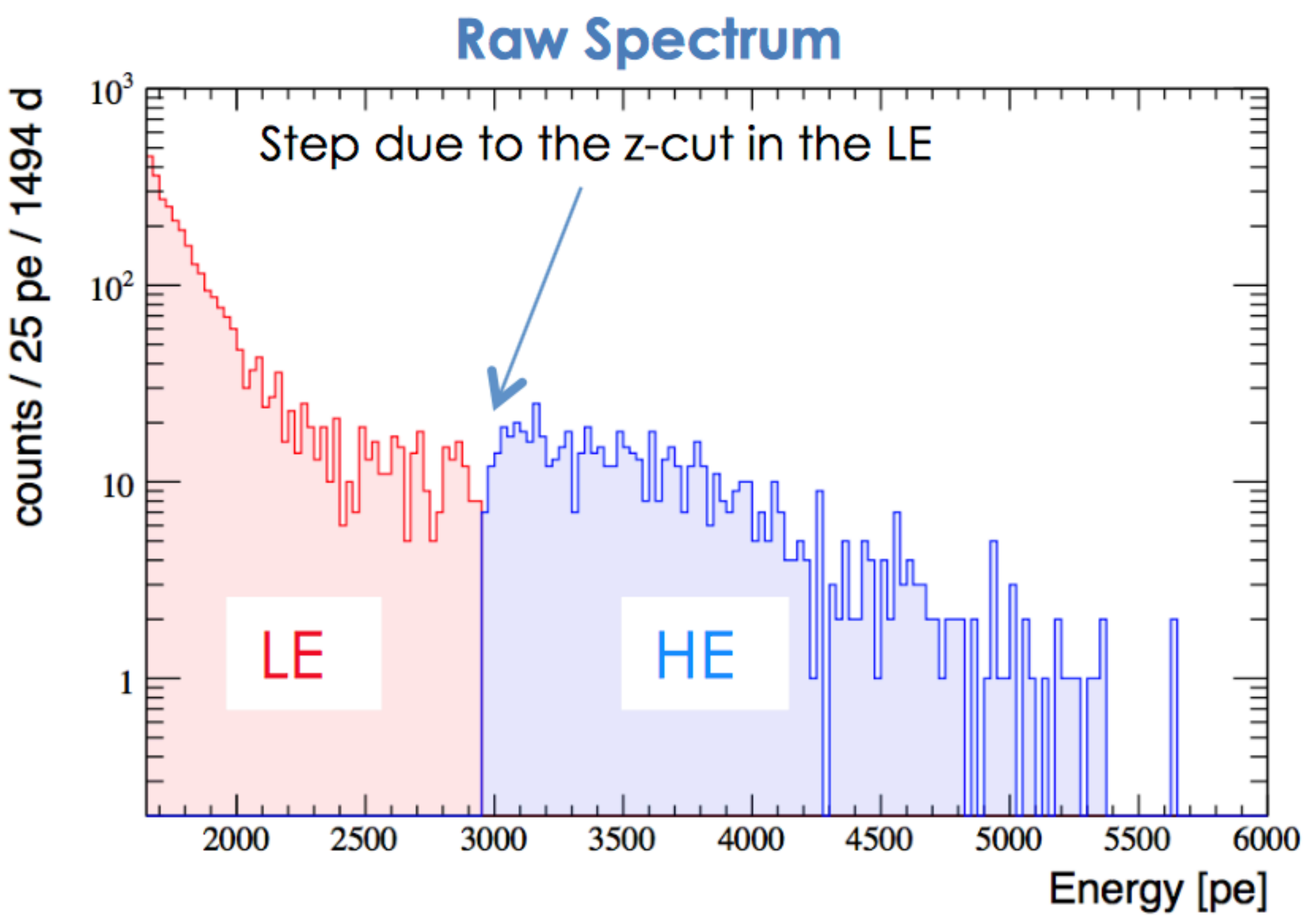
Three Fold Coincidence:
- Sphere radius = 0.8 m
- Veto time window: 120 s
- Tag efficiency = 92.5^{+7}_{-20}%
- Total **visible ^{10}C rate** = **$0.48^{+0.04}_{-0.11}$** cpd/100 t

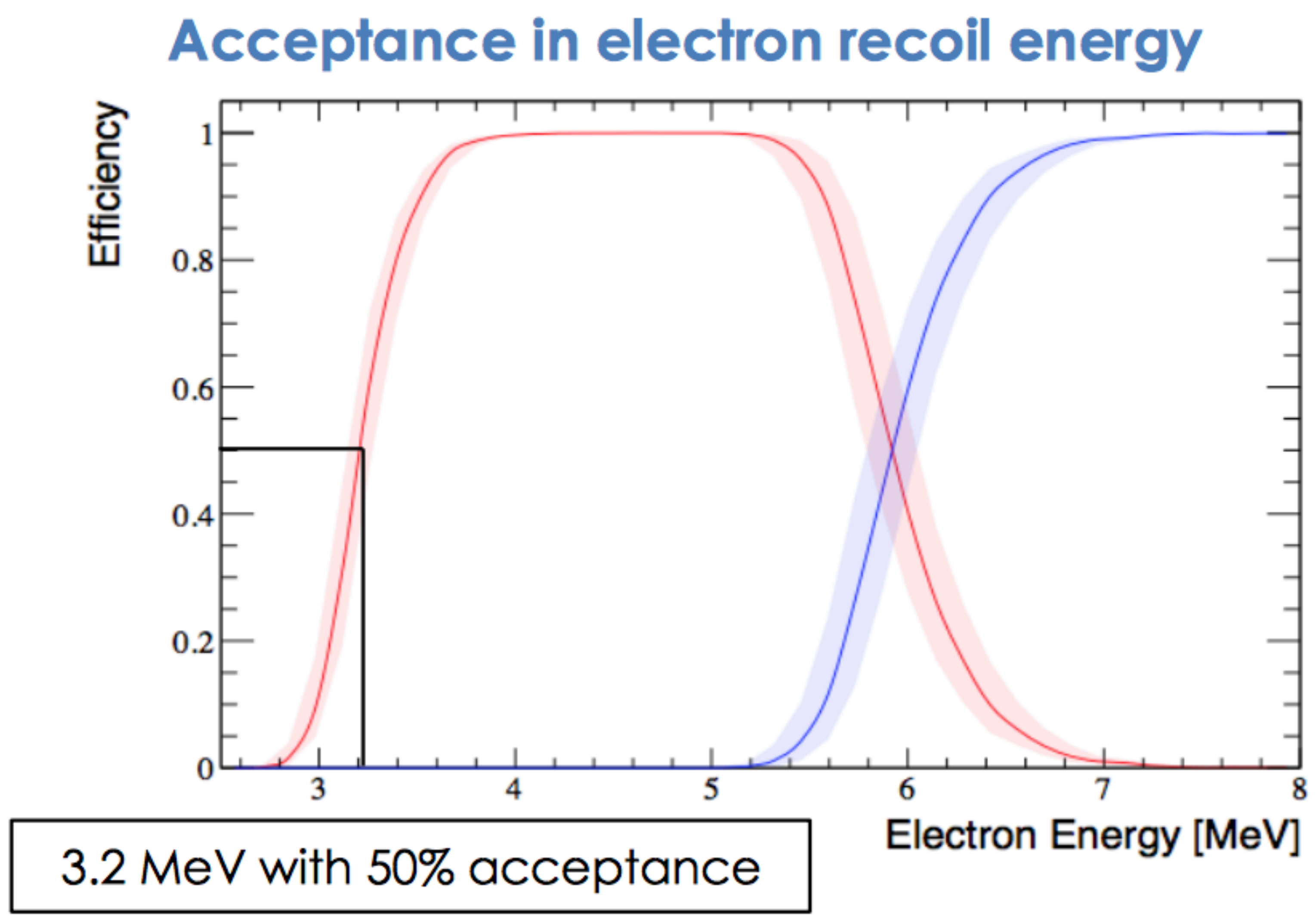


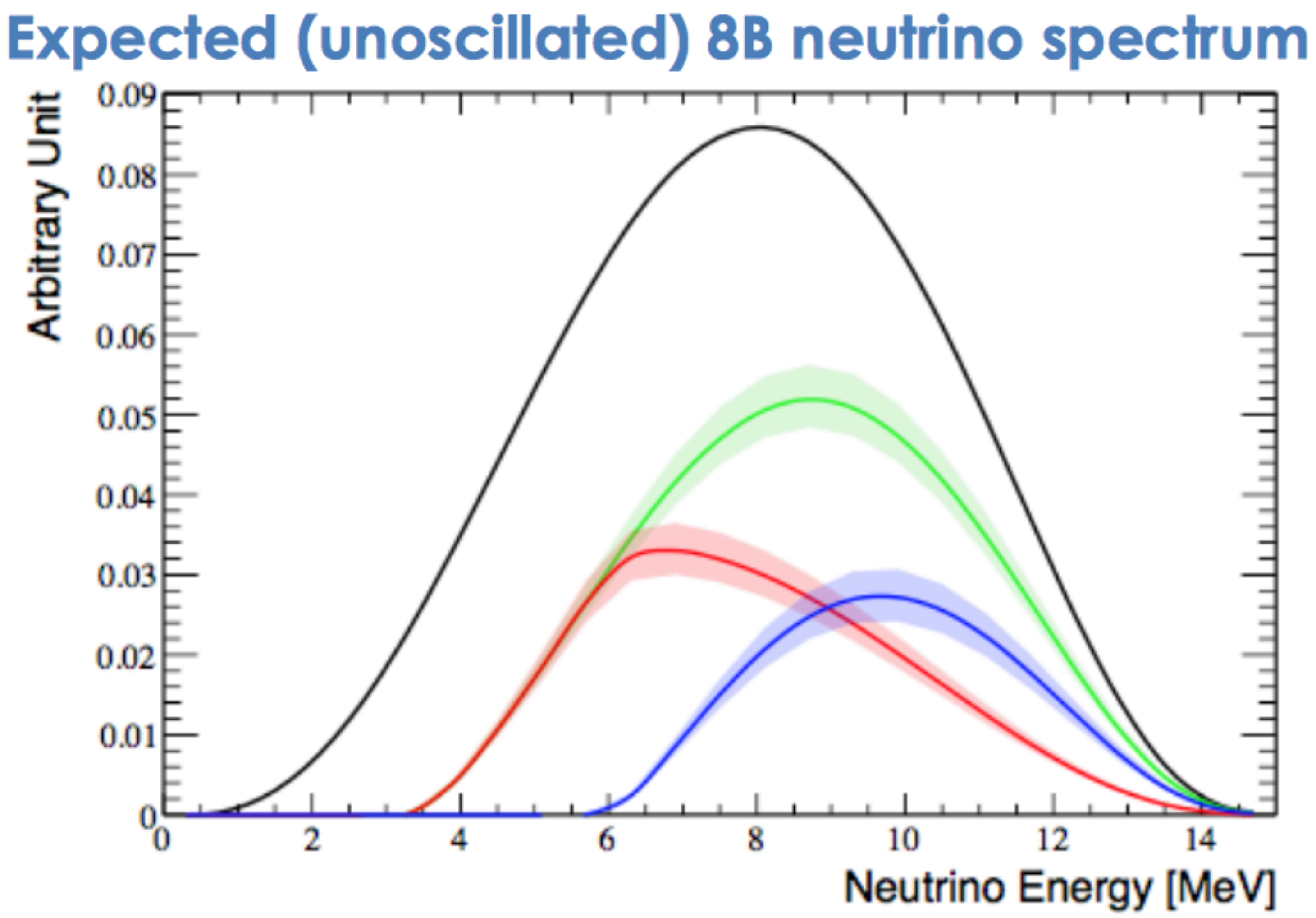
Dominant **invisible channel**, ^{12}C(p,t)^{10}C: **~10^{-2}** cpd/100 t

Low and High Energy Ranges

Splitting the sample at 2950 npe (> 5 MeV): no natural radioactivity expected above this threshold



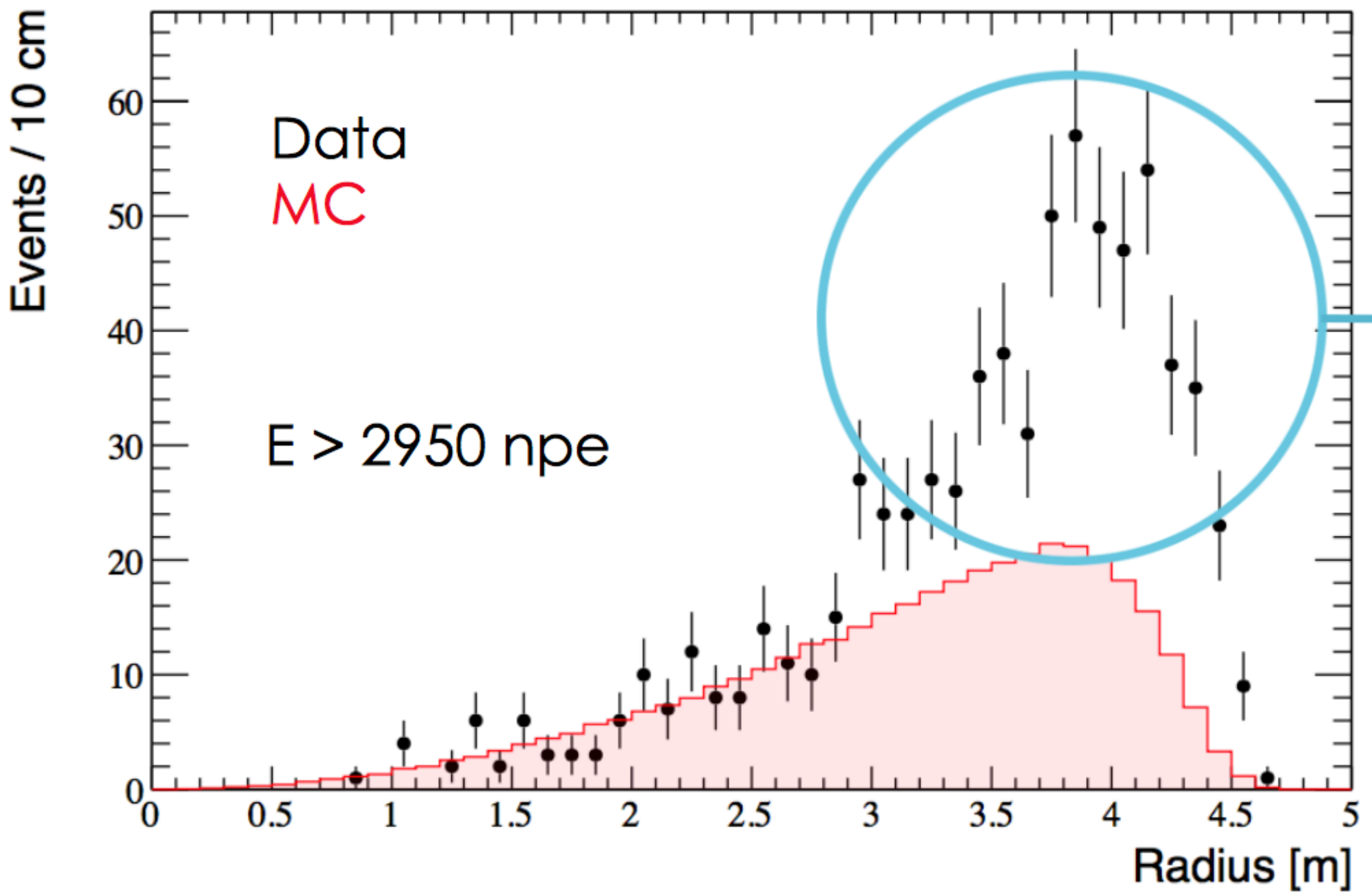




Mean neutrino energies:

LE: 7.9 MeV
HE: 9.9 MeV
LE+HE: 8.7 MeV

High Energy External Background

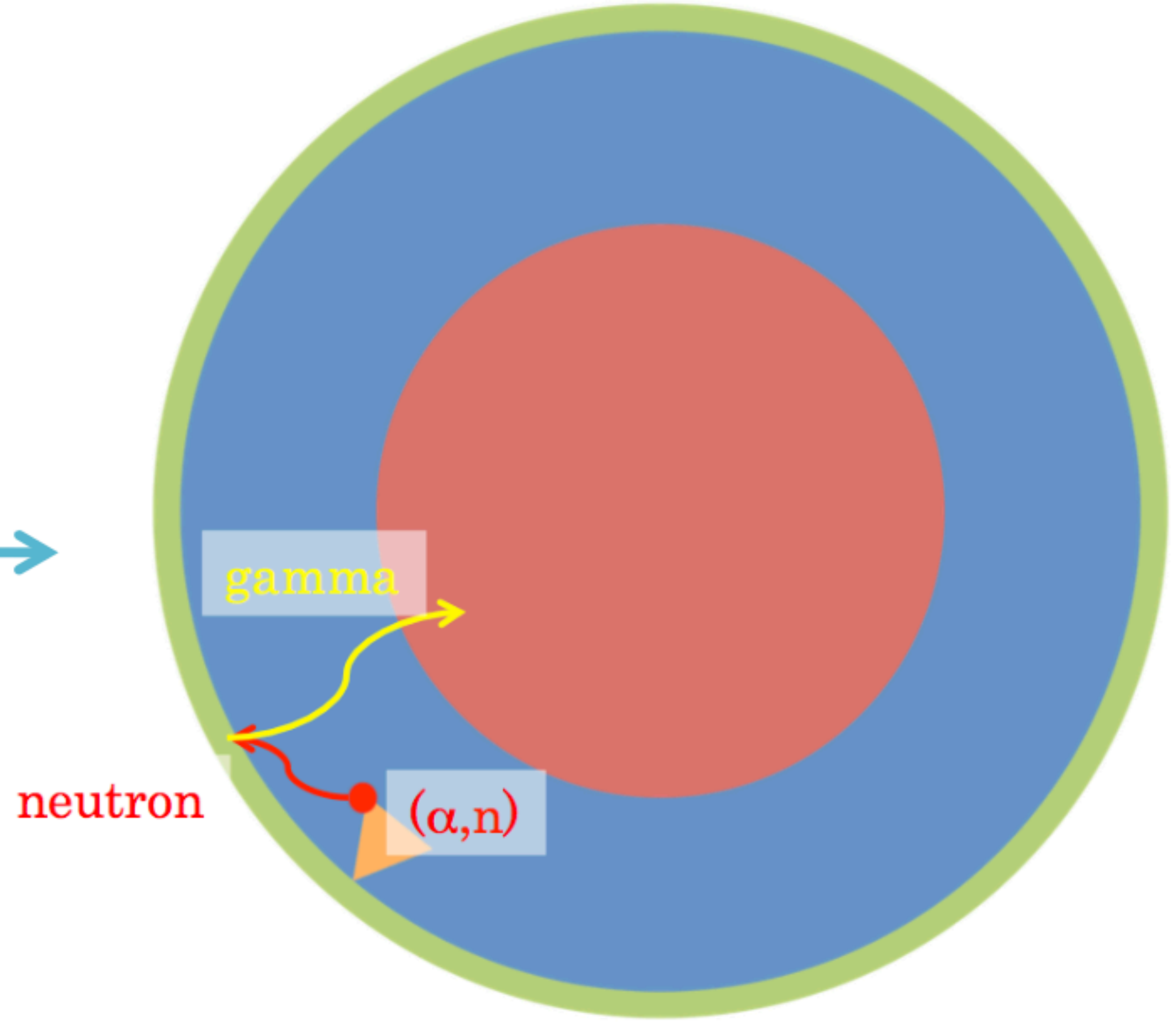


Excess **not compatible** with a **bulk** distribution

Not compatible with events from the **vessel nylon**: 5 MeV is the max Q-value from natural β-decay radioactivity (^{208}Tl)

Hypothesis:

- External background from **neutron captures** on elements different from H and C
- Neutron sources: **(α, n)** reactions and **fissions** from U and Th chains
- Neutron capture material candidates: **SSS**, PMTs, support structures



Systematic Errors and Results

JÜLICH FORSCHUNGSZENTRUM

Source	LE σ	HE σ	LE+HE σ
Active mass	2.0	2.0	2.0
Energy Scale	0.5	4.9	1.7
z-cut	0.7	0.0	0.4
Live Time	0.05	0.05	0.05
Scintillator density	0.5	0.5	0.5
Total	2.2	5.3	2.7

Addition tests:

- pdf radial distortion: ±3%
- Emanation vessel shift: ±1%
- Response functions for the emanation component generated at 6 cm from the vessel (instead of 1 cm)
- Binning dependence

None of these potential systematic sources affected the measured ^8B rate outside 1 statistical sigma

Expected rate in the LE+HE range:
0.211± 0.025 cpd/100t
(Assuming B16(G98) SSM and MSW+LMA)

$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}$$

$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}$$

$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}$$

	Super Kamiokande	Previous BX results	NEW BX results
^8B flux [10^6 cm^{-2} s^{-1}]	2.345 ±0.014 ±0.036	2.4 ±0.4	2.55 ±0.18 ±0.07