Experimental Evidence of neutrinos produced in *the CNO fusion cycle* in the Sun with Borexino

Xuefeng Ding on behalf of Borexino Collaboration

Physics department, Princeton University, Princeton, NJ 08544, USA

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Borexino Collaboration

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INFN Istituto Nazionale di Fisica Nucleare

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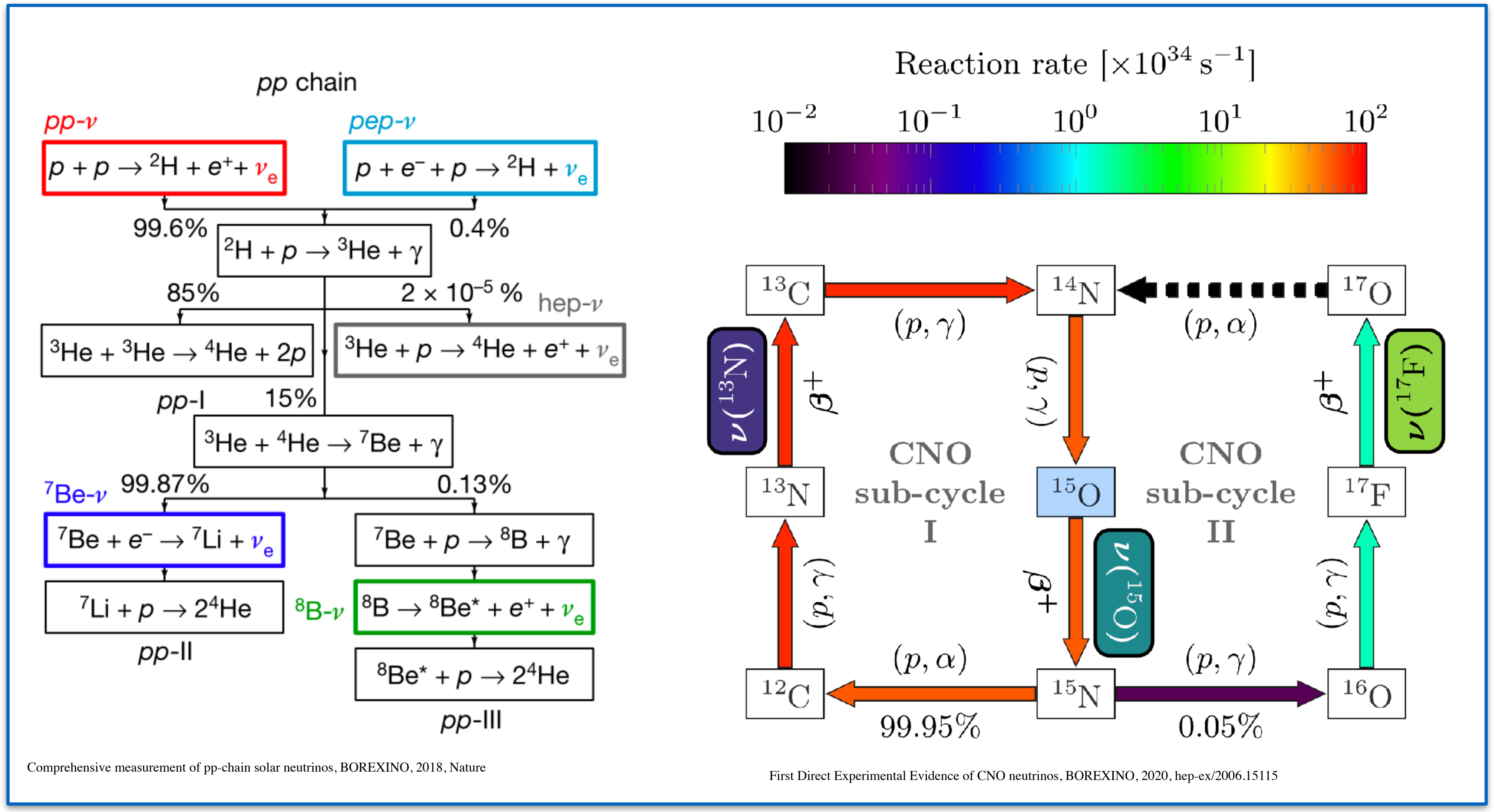
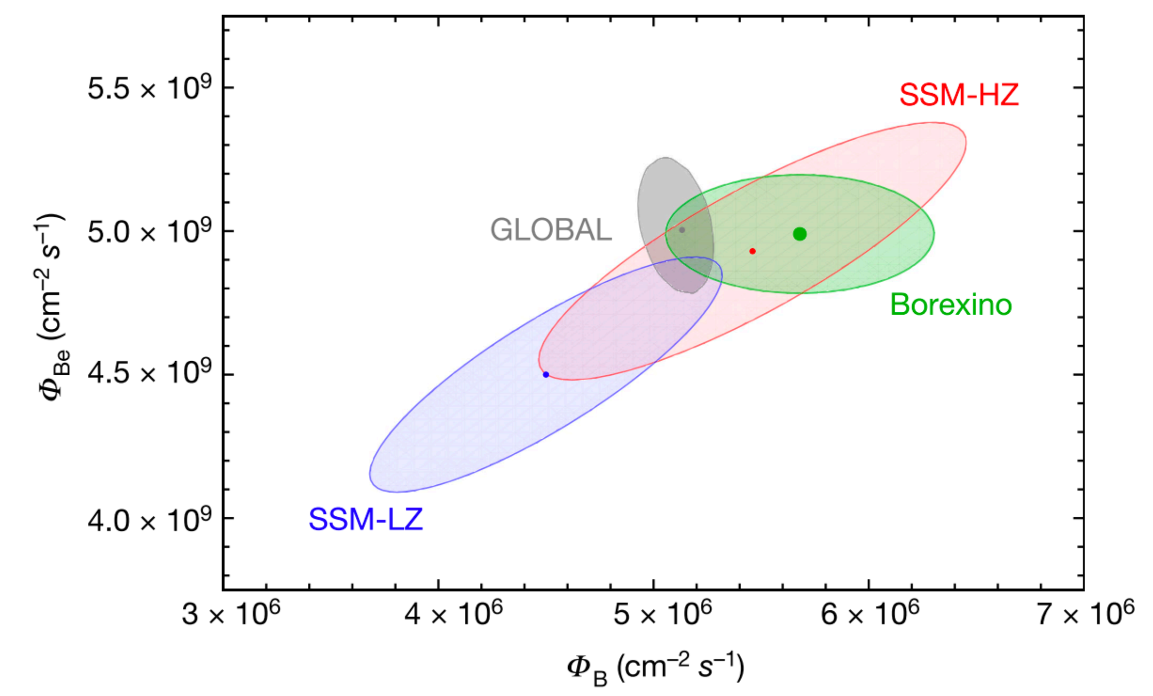
What is the CNO-cycle and Why

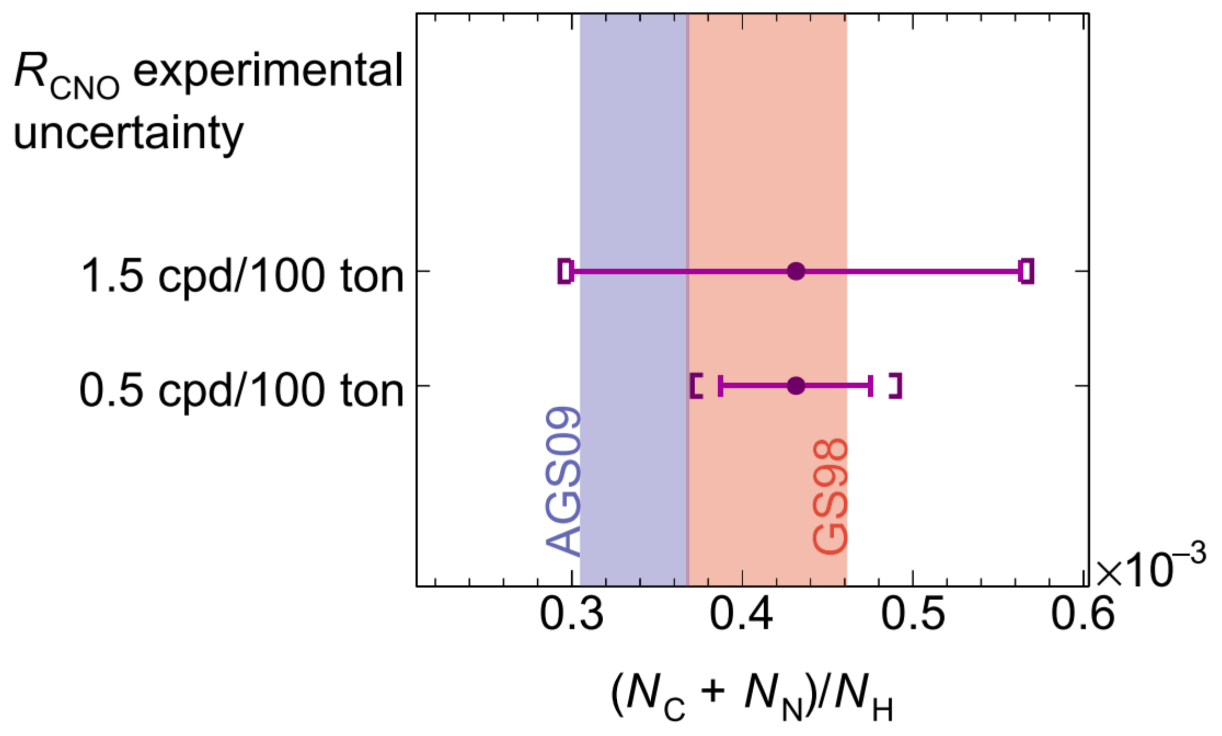
Two mechanisms how Sun convert hydrogen to helium





SSM-HZ vs SSM-LZ

Borexino Collaboration (2018). Comprehensive measurement of pp-chain solar neutrinos. Nature, 562(7728), 505–510. https://doi.org/10.1038/s41586-018-0624-y

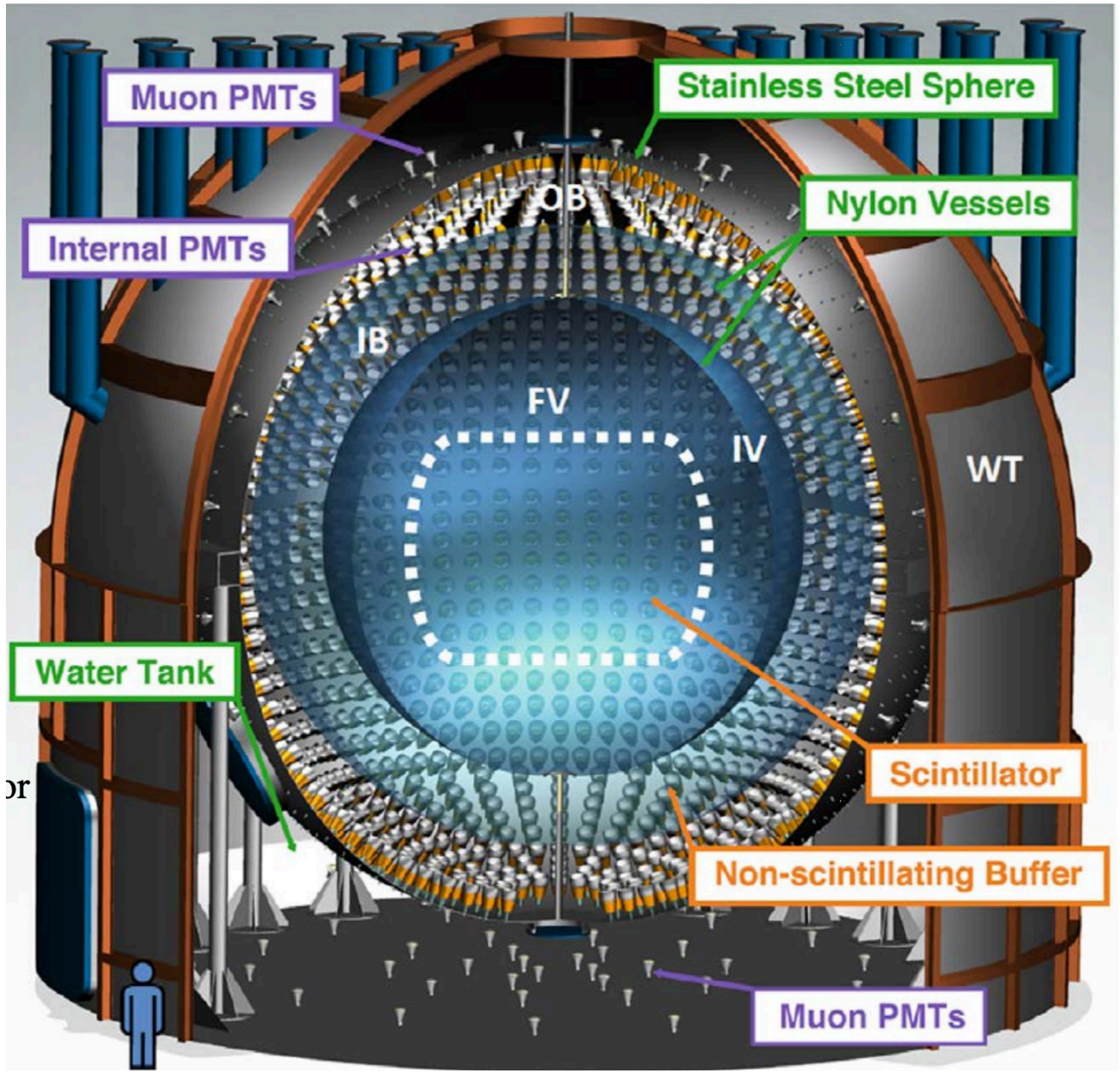


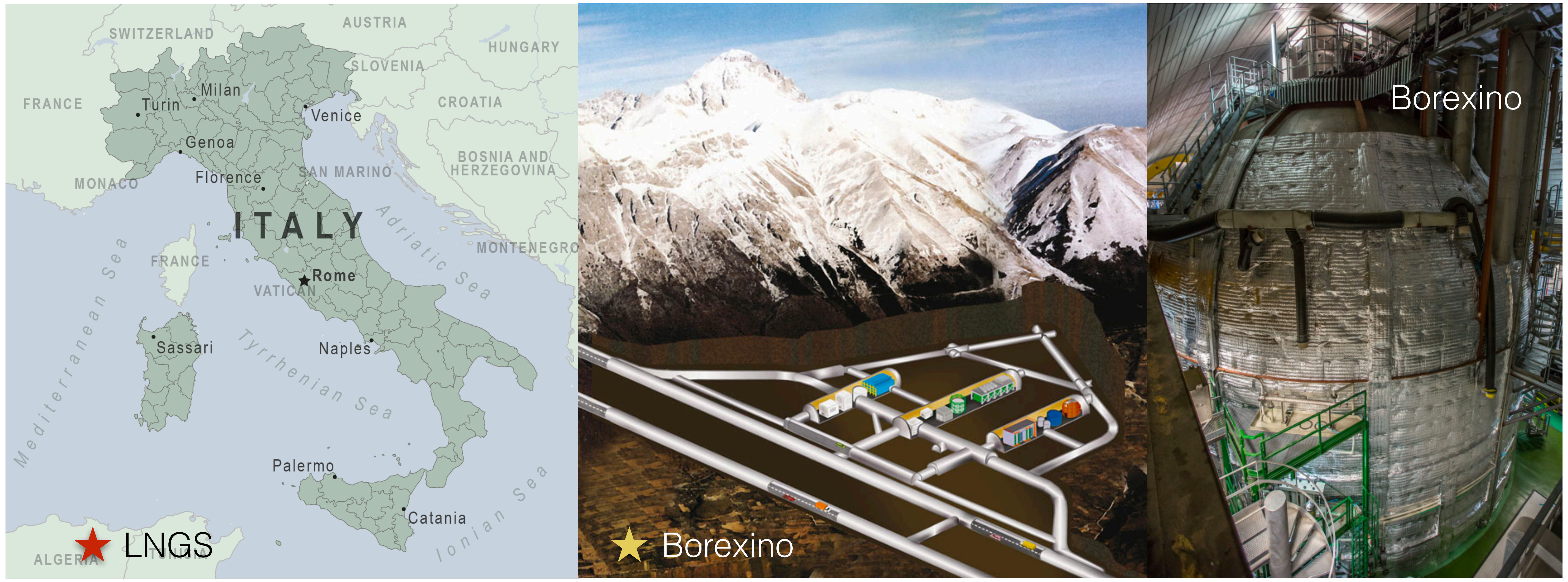
Determination of C+N abundances with CNO neutrino measurement

Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. European Physical Journal C, 80(11). https://doi.org/10.1140/epjc/s10052-020-08534-2

- CNO-cycle: one of two 4H=>^{4}He processes. **No exp. proof until this work.**
- SSM-HZ (helioseismology) vs LZ (spectroscopy): controversy about solar metallicity
- CNO neutrinos: **can be used to mesuare C&N abundances**

Borexino detector

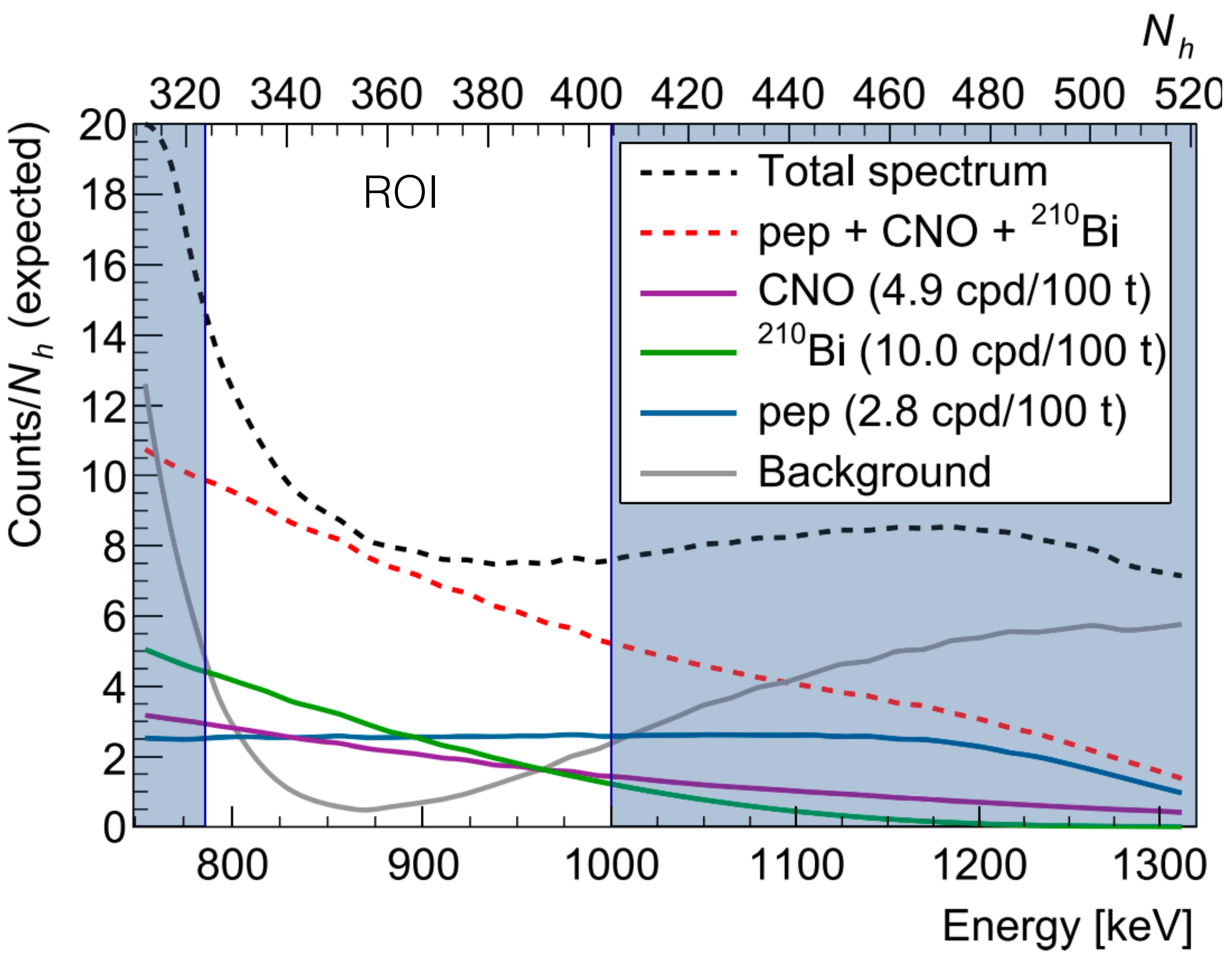




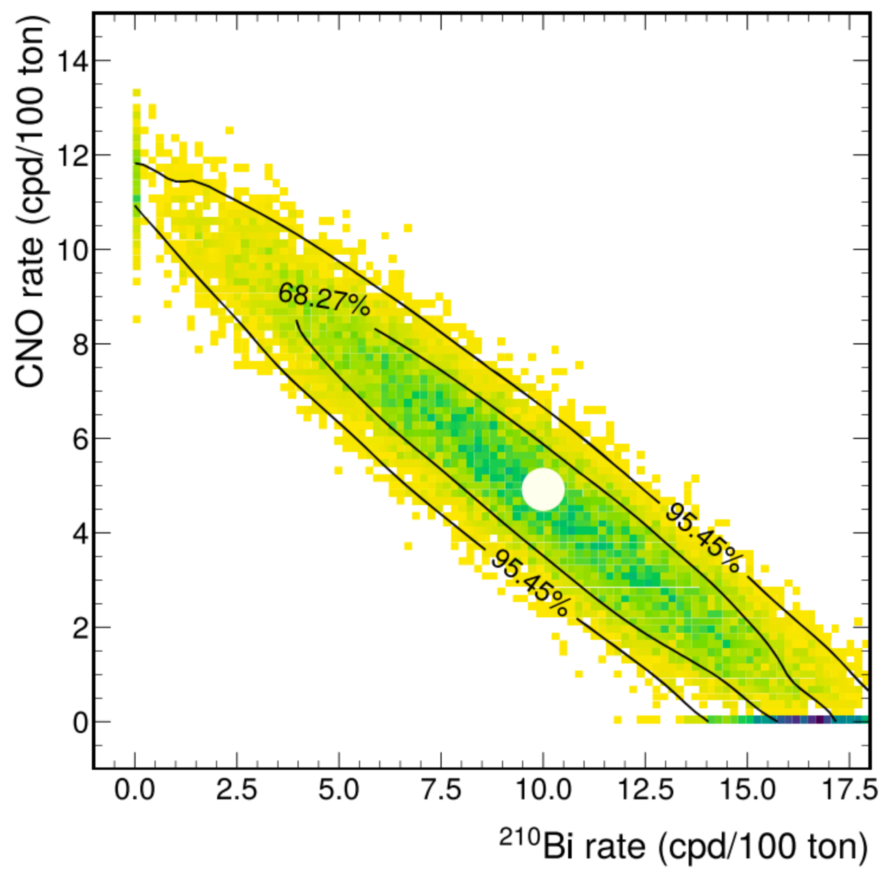
- Located at Hall C of LNGS, Italy.
- Active volume: 280 tons of liquid scintillator
- Detect solar neutrinos via elastic scattering off electrons of the scintillator, threshold at 60 keV

Sensitivity of Borexino to CNO neutrinos

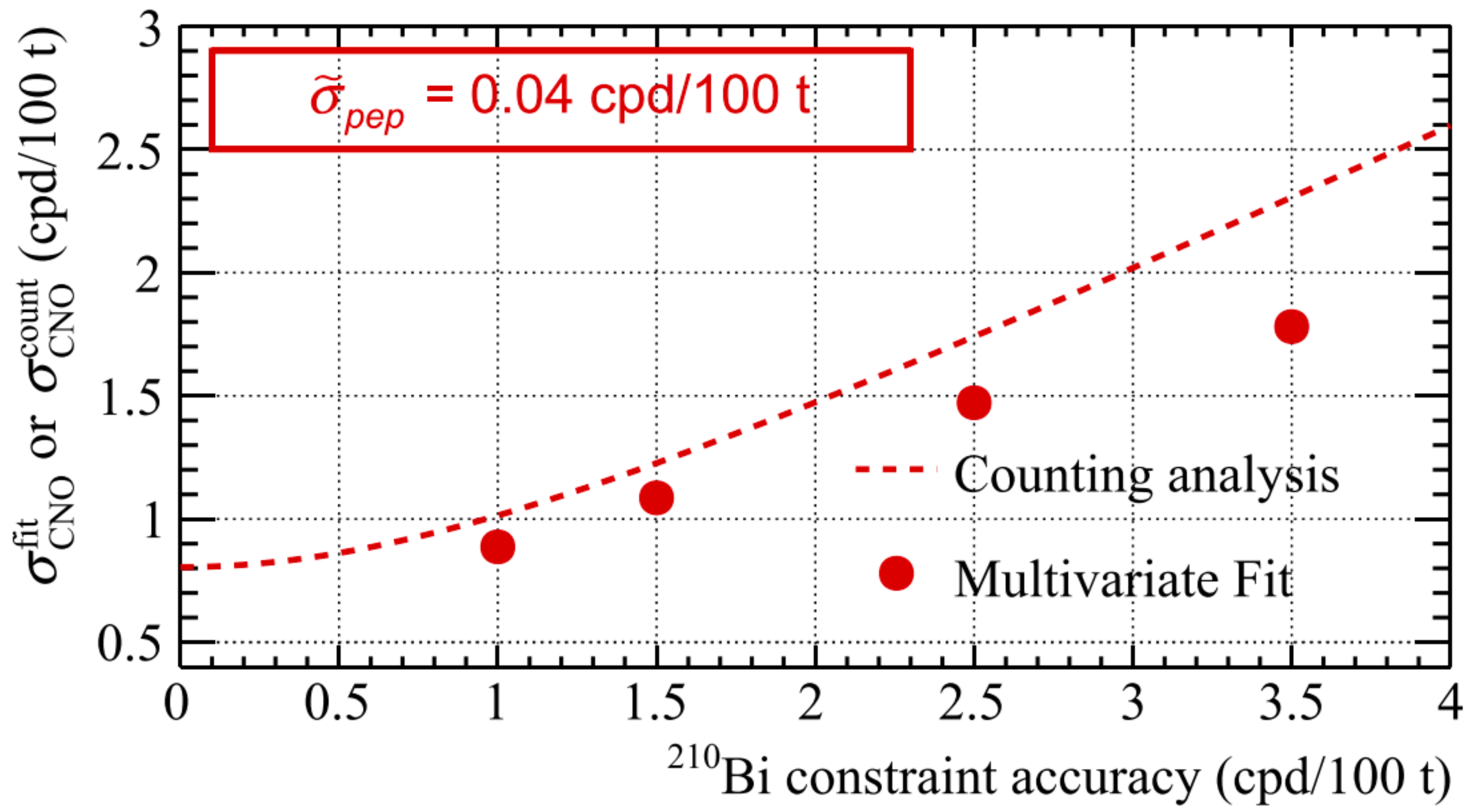
Shape of CNO and ^{210}Bi



Fit results of CNO and ^{210}Bi of toy MC datasets



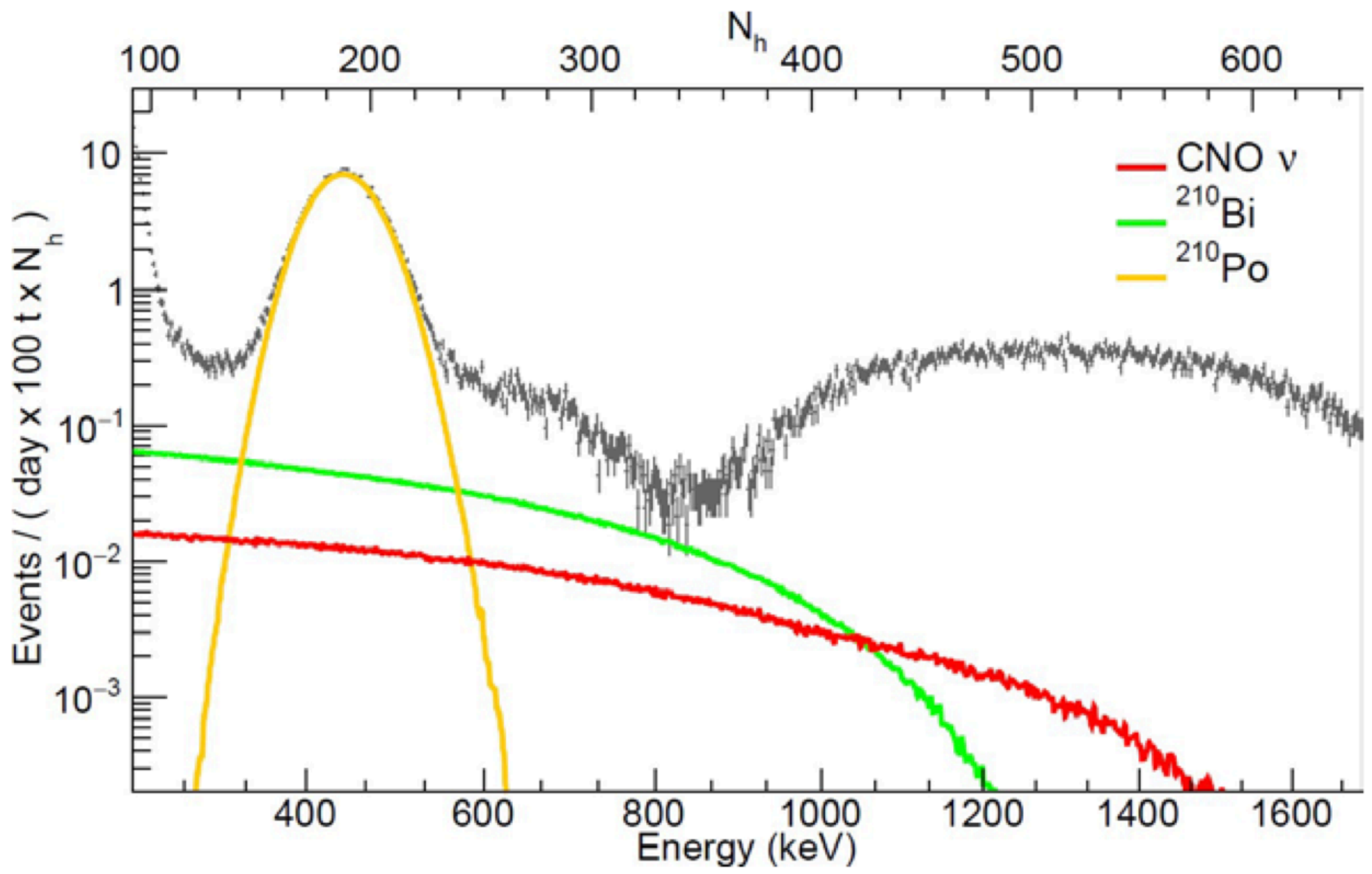
Comparison between expected precision from counting analysis and multivariate fit analysis



Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. European Physical Journal C, 80(11). https://doi.org/10.1140/epjc/s10052-020-08534-2

- ROI 0.8—1 MeV: 90% ^{210}Bi+pep + CNO; pep constrained according to global fit results (~1.4%)
- ^{210}Bi and CNO shapes very **similar**; ^{210}Bi fit results strongly **correlated** with CNO ν
- Major sensitivity comes from counting analysis in ROI

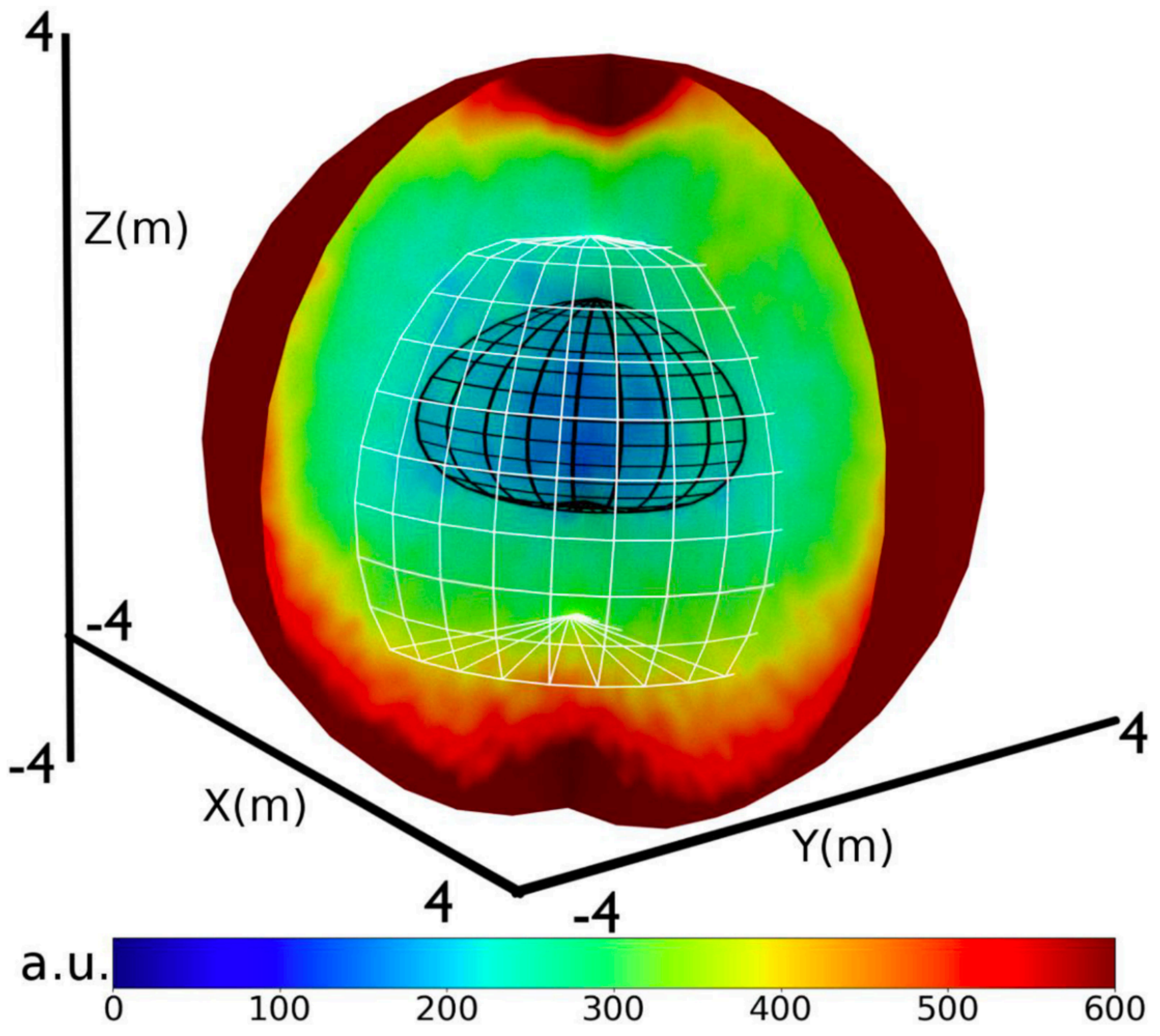
$$^{210}\mathrm{Pb} \xrightarrow[32\ \mathrm{y}]{\beta^-} \boxed{^{210}\mathrm{Bi} \xrightarrow[7.23\ \mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.1\ \mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}}$$



$R(^{210}\mathrm{Bi}) = $ "$R(^{210}\mathrm{Po})$"

Challenge: migrated ^{210}Po

Distribution of ^{210}Po events



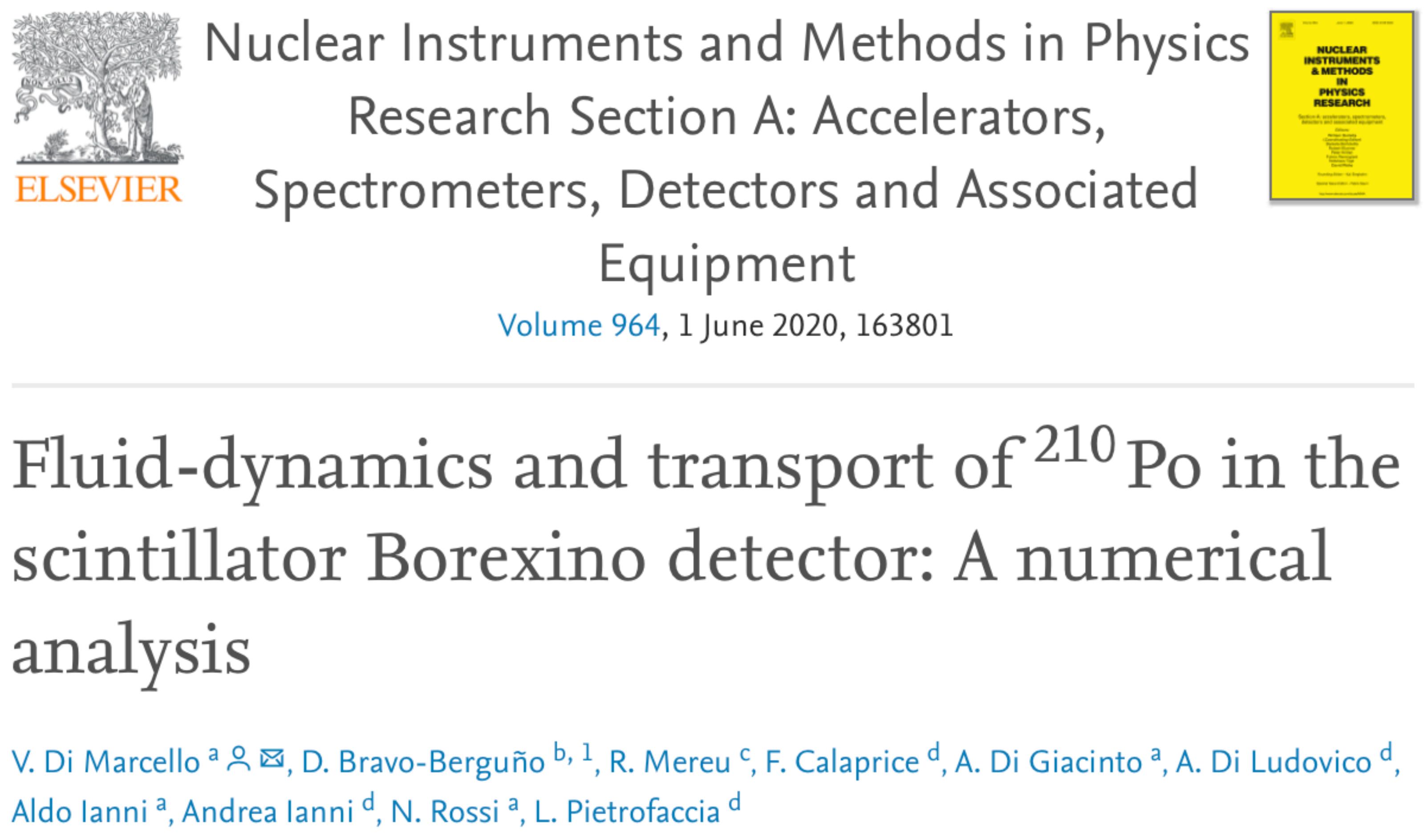
Extended Data Fig. 5 | The low polonium field in the Borexino scintillator. Three-dimensional view of the ^{210}Po activity inside the entire nylon vessel (see colour code). The innermost blue region contains the LPoF (black grid). The white grid is the software-defined fiducial volume. a.u., arbitrary units.

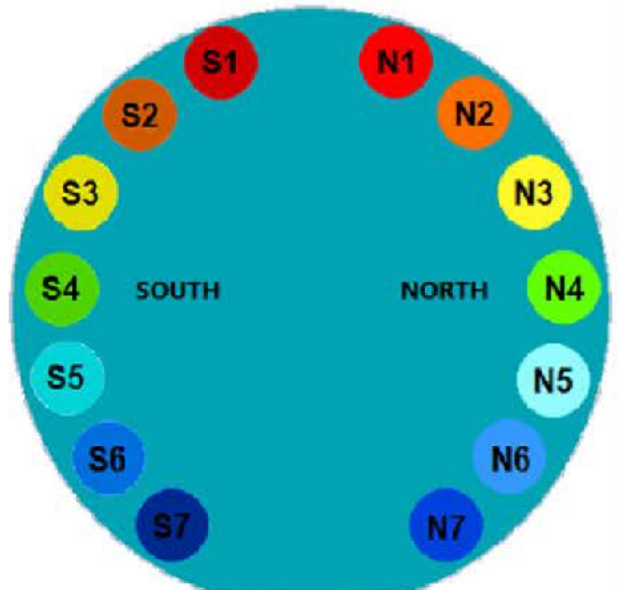
- Extra ^{210}Po brought into FV by convection & migration

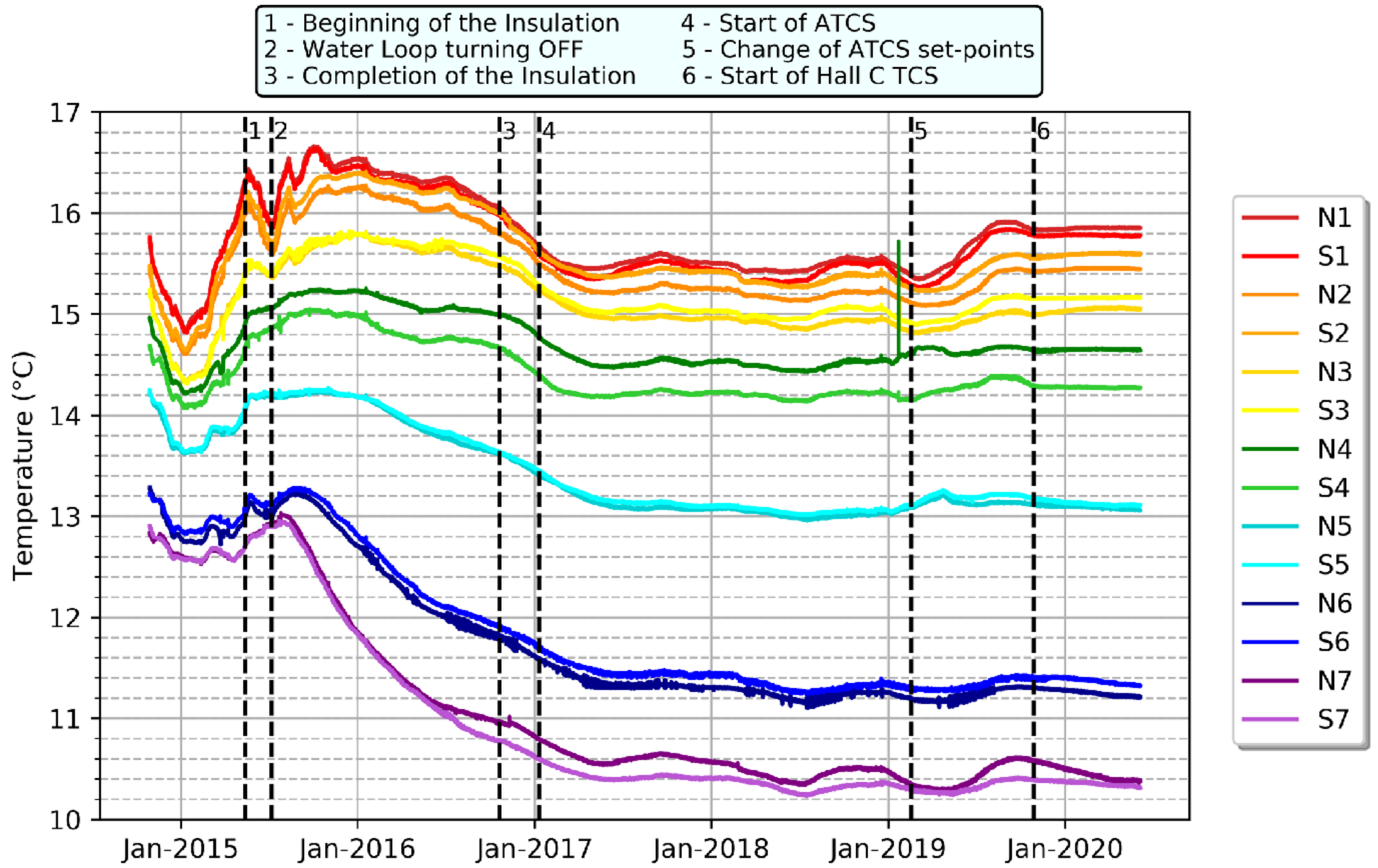
R(^{210}Bi) < R(^{210}Po) + migrated ^{210}Po

Efforts to stabilize detector thermal condition

First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



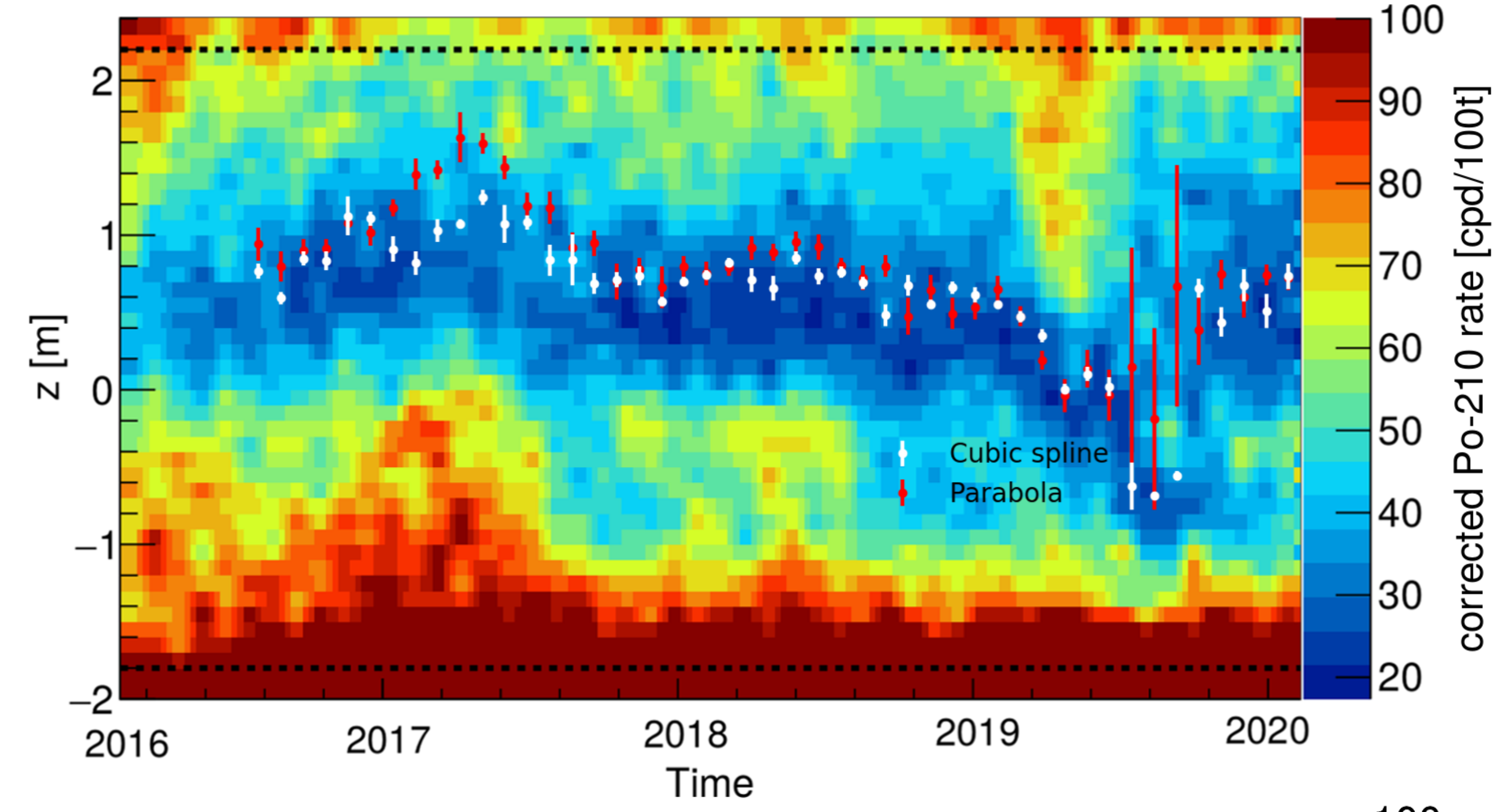


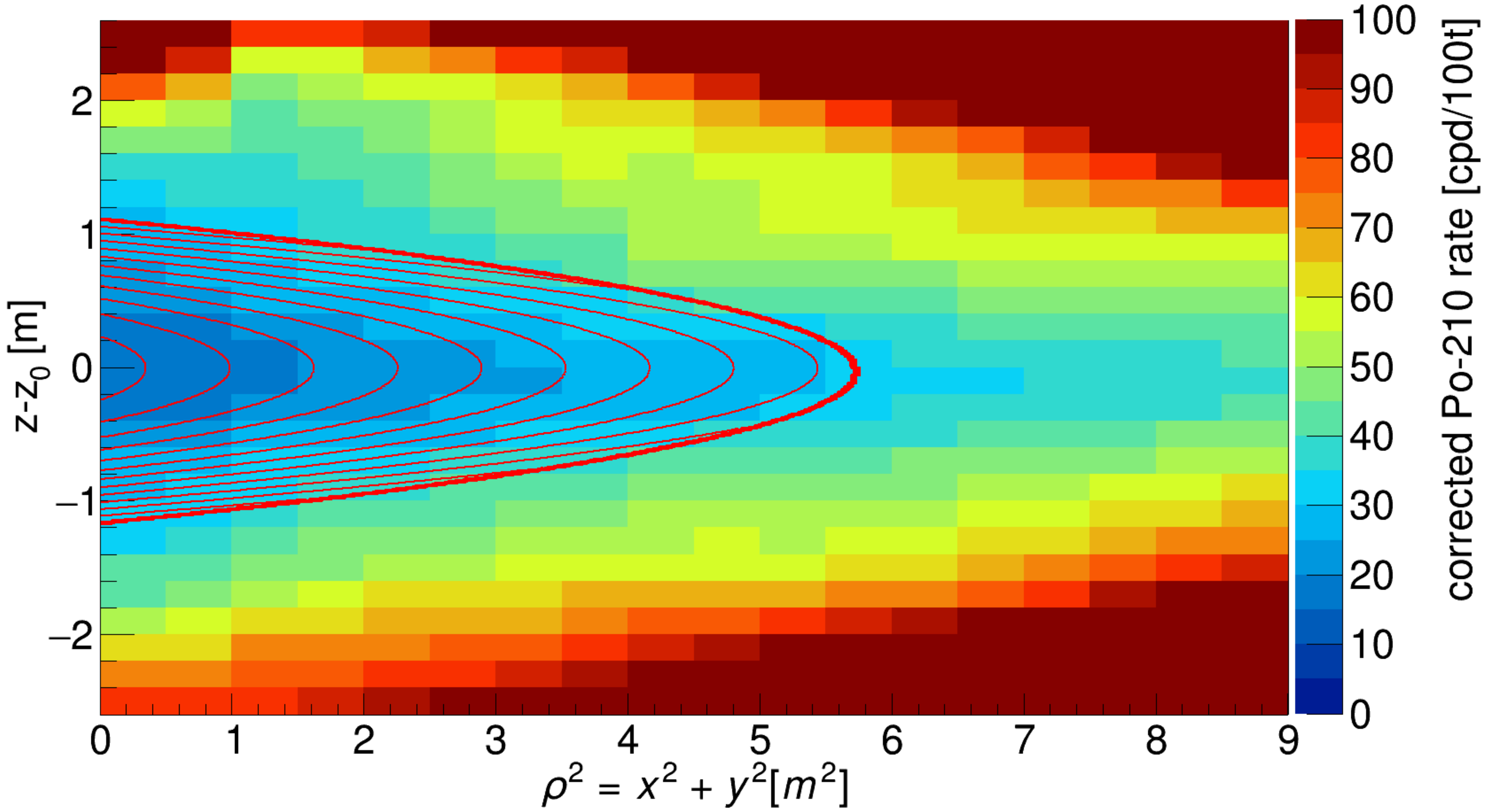


First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

- Double layer of mineral wool for insulation & Active Temperature Control System (ATCS) (2014—2016)
- Temperature Probes (2014—2016)
- Fluid dynamical simulations
- Hall C Temperature stabilization (2019)

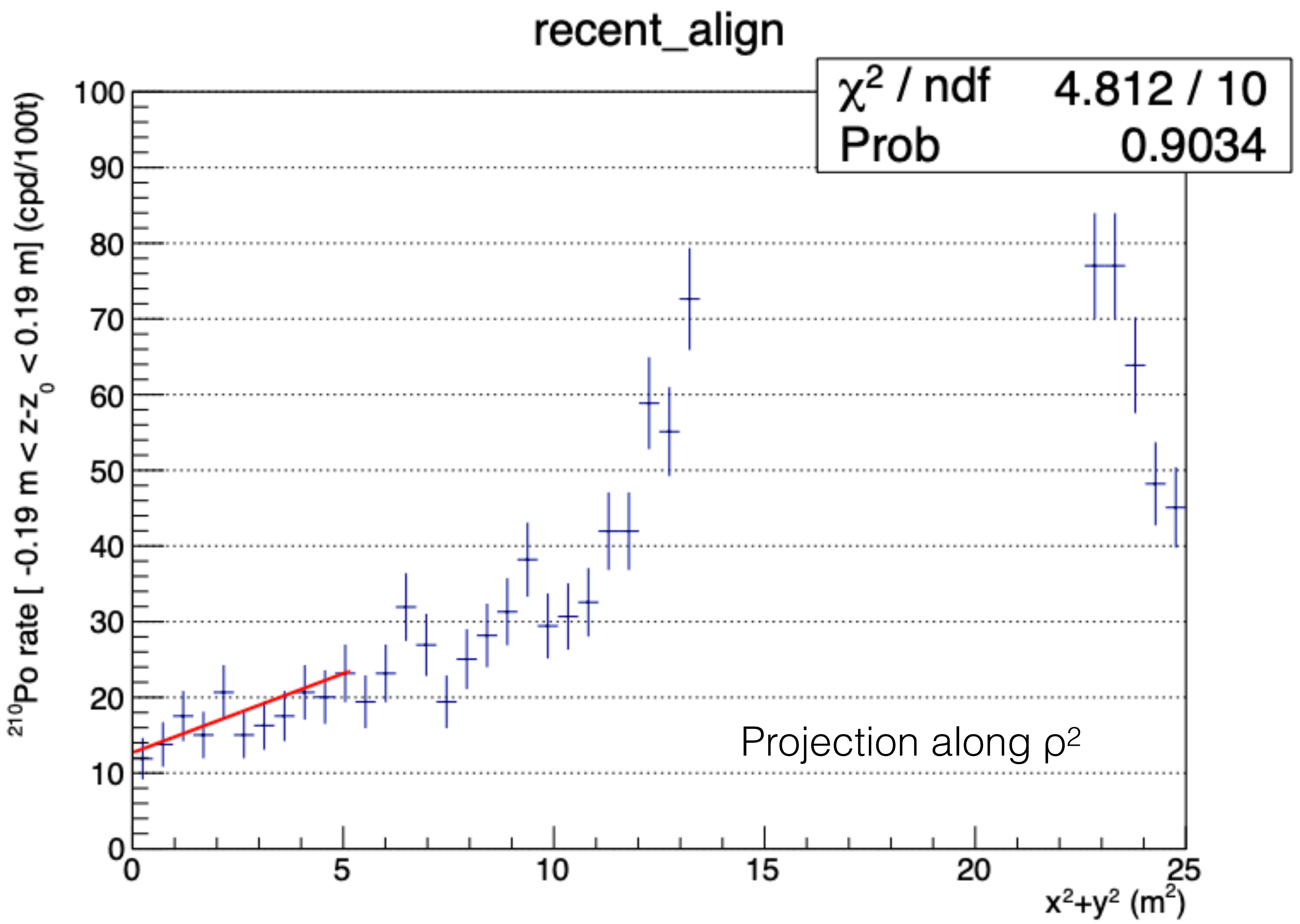
Low Polonium Field (LPoF) analysis

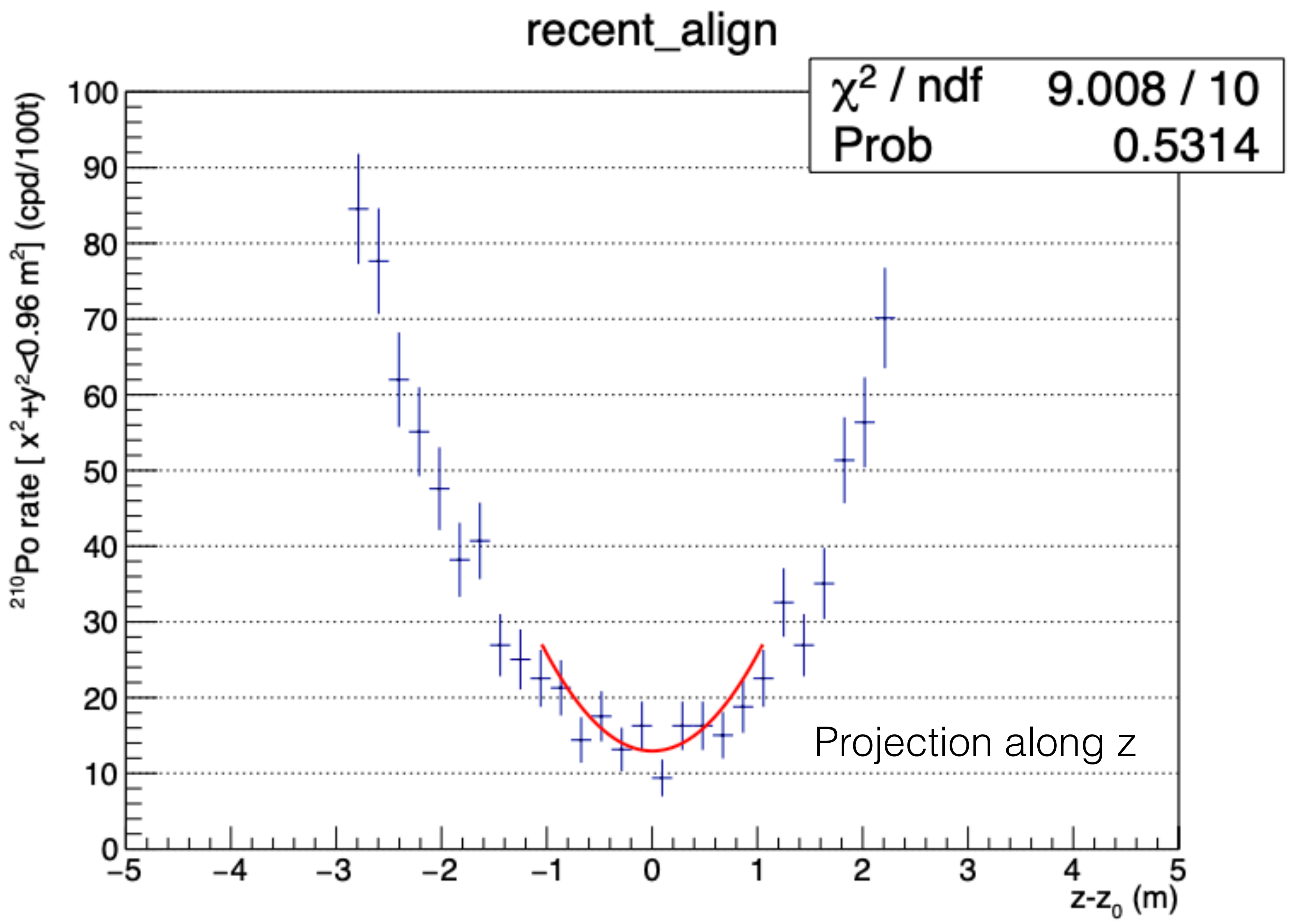




1. **Align** minimum vertical position
2. **Merge** aligned dataset
3. **Fit** merged data with parabolic func.

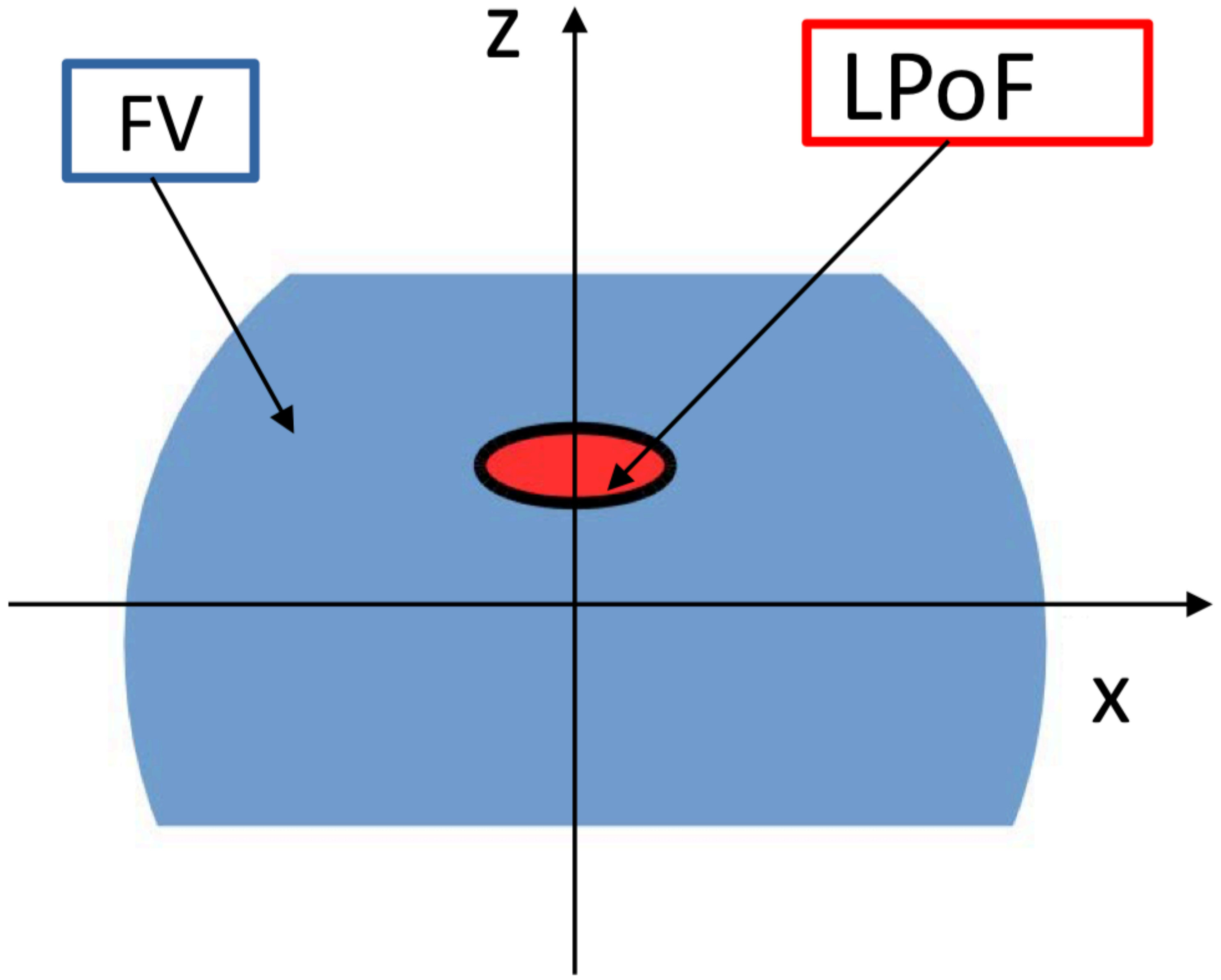
Result of LPoF analysis

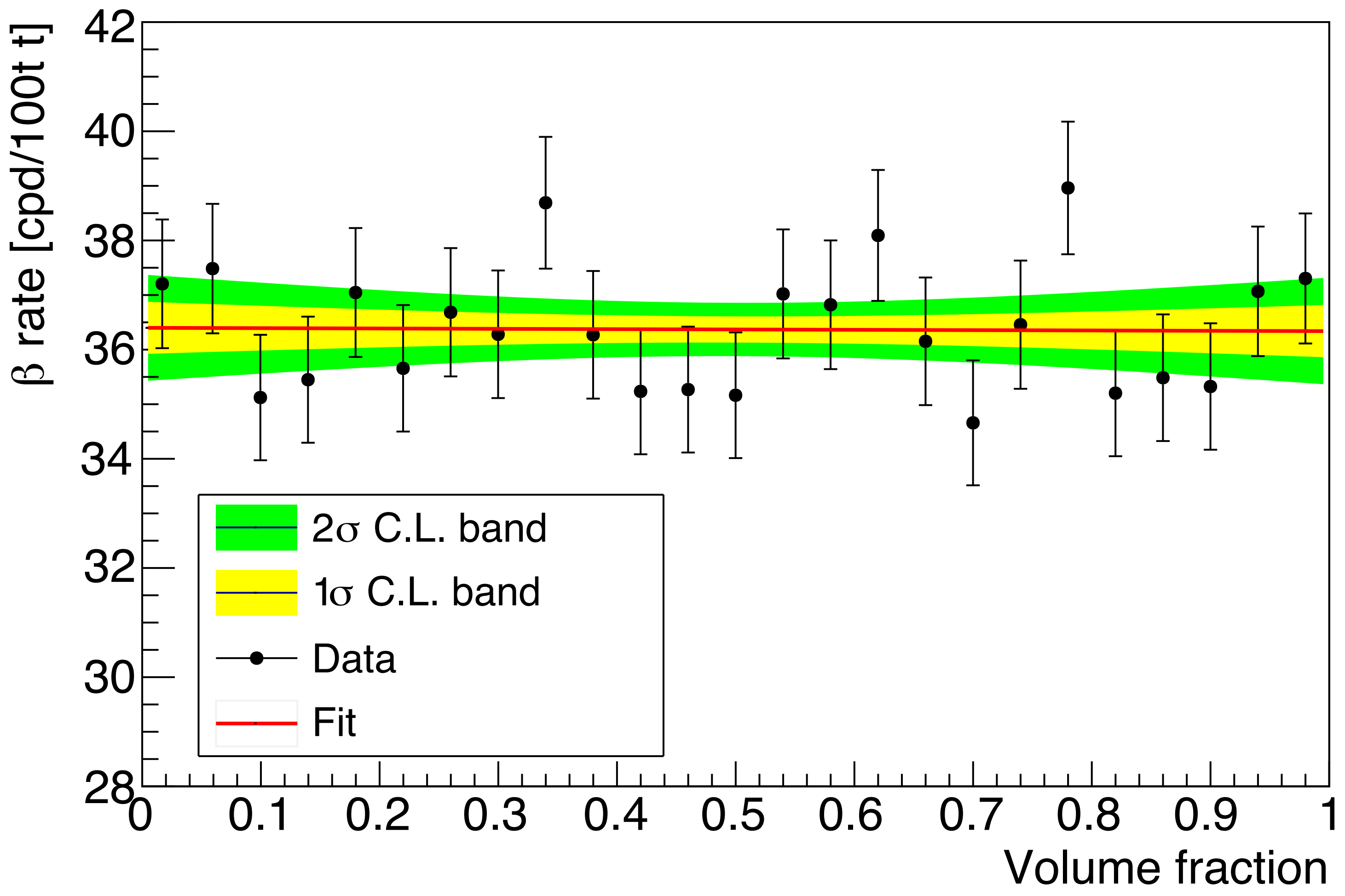




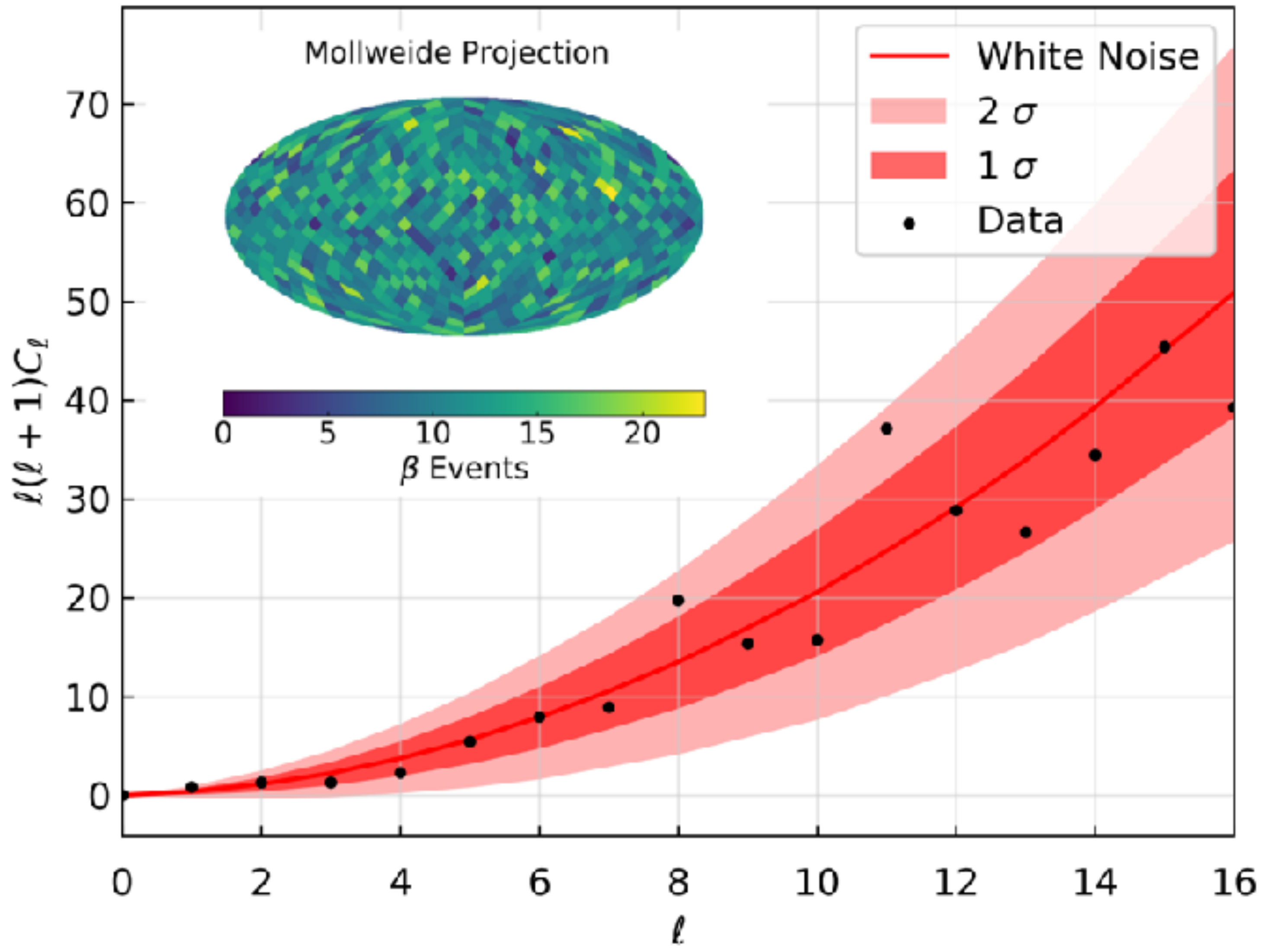
$R_{min}(cpd/100t)$	σ_{fit}	σ_{mass}	$\sigma_{binning}$	$\sigma_{^{210}Bi\ homog.}$	$\sigma_{\beta\ leak}$	σ_{Total}
11.5	0.88	0.36	0.31	See next slides	0.30	See next slides

^{210}Bi homogeneity systematics





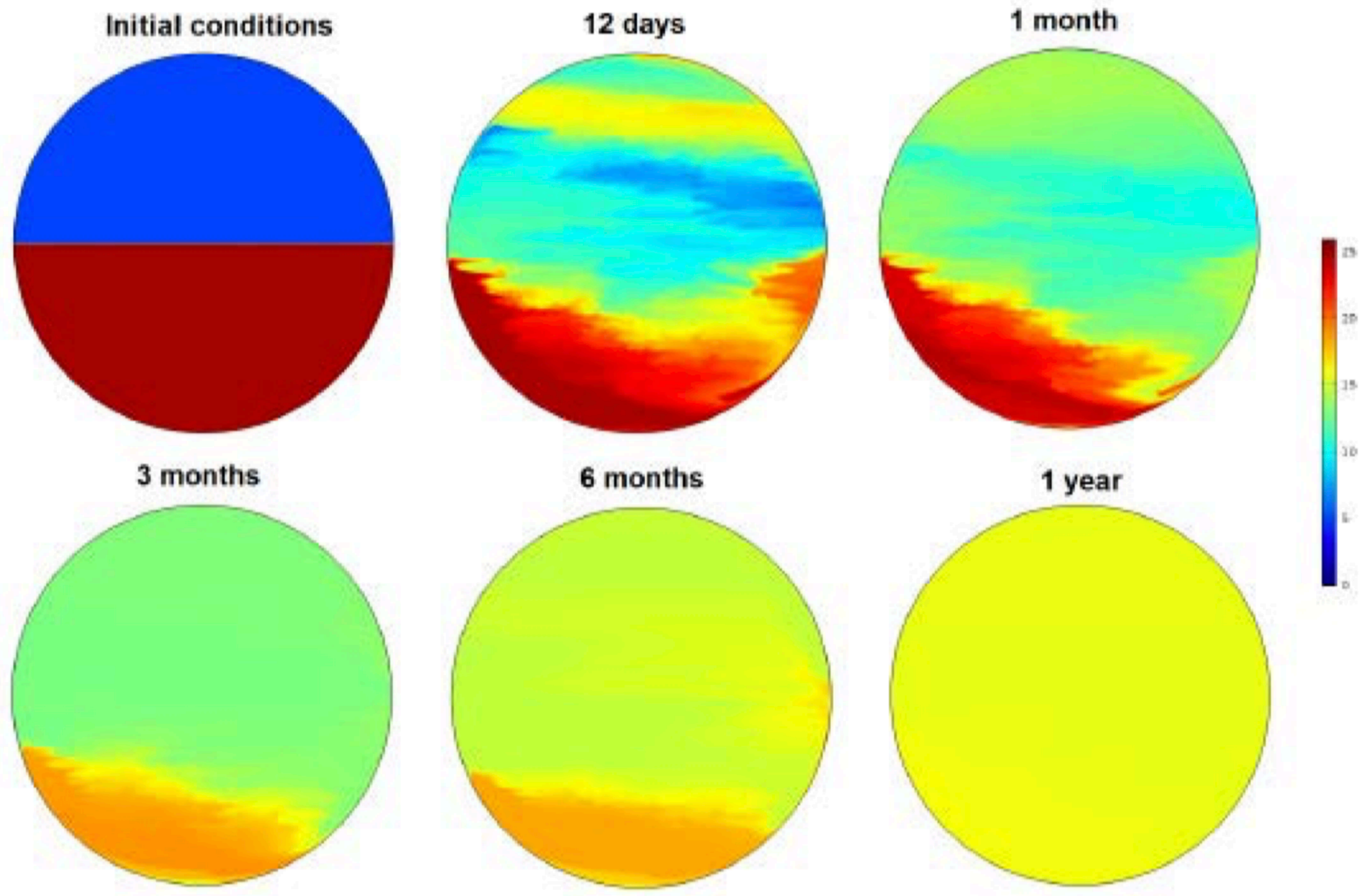
Radial part



Angular part

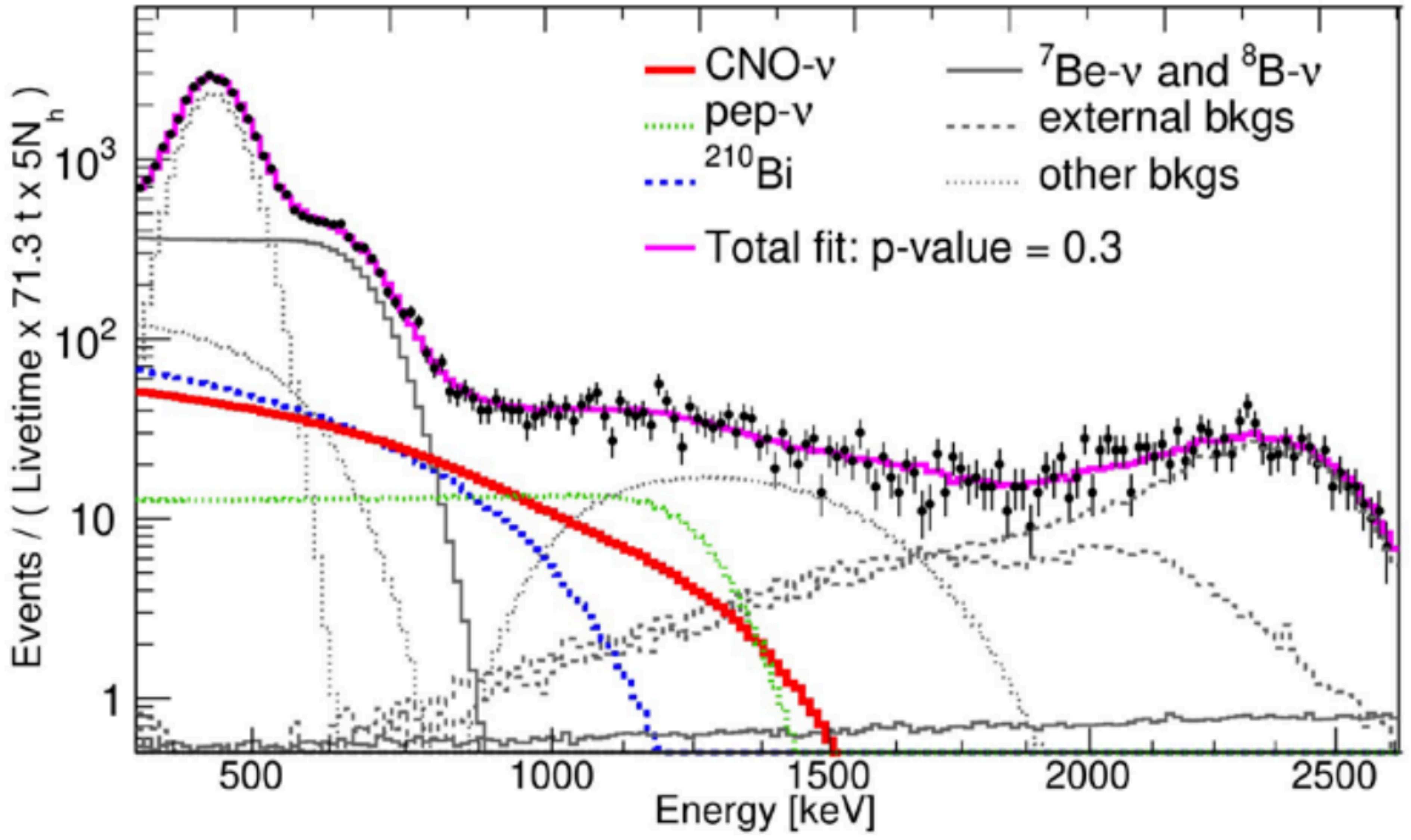
- R(^{210}Bi) constraint based on LPoF (20t)
- Extrapolate to "pep FV" (70t)
- Overall systematics: 0.78 cpd/100t

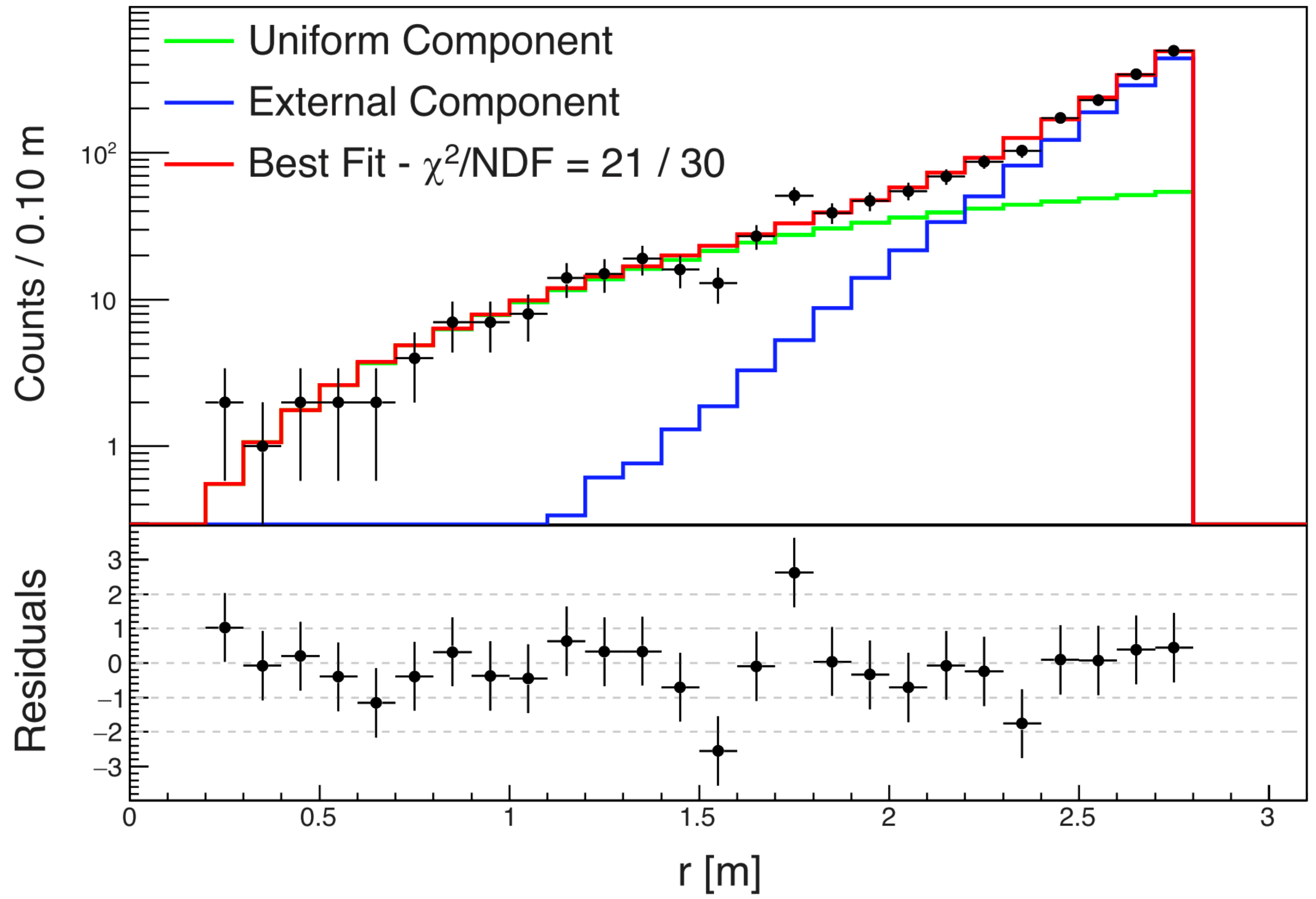
^{210}Pb / ^{210}Bi homogeneity: mixing arguments



- Before insulation, convection is strong.
- ^{210}Pb / ^{210}Bi should be totally mixed according to simulation.

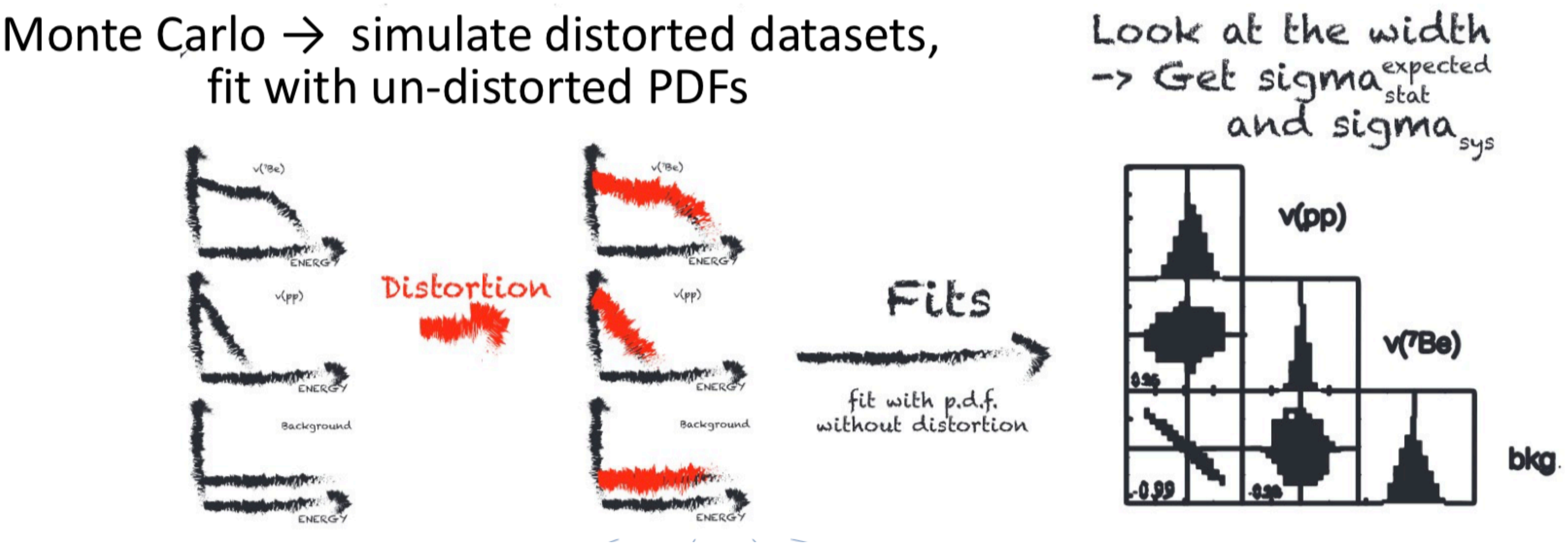
The Multivariate fit analysis





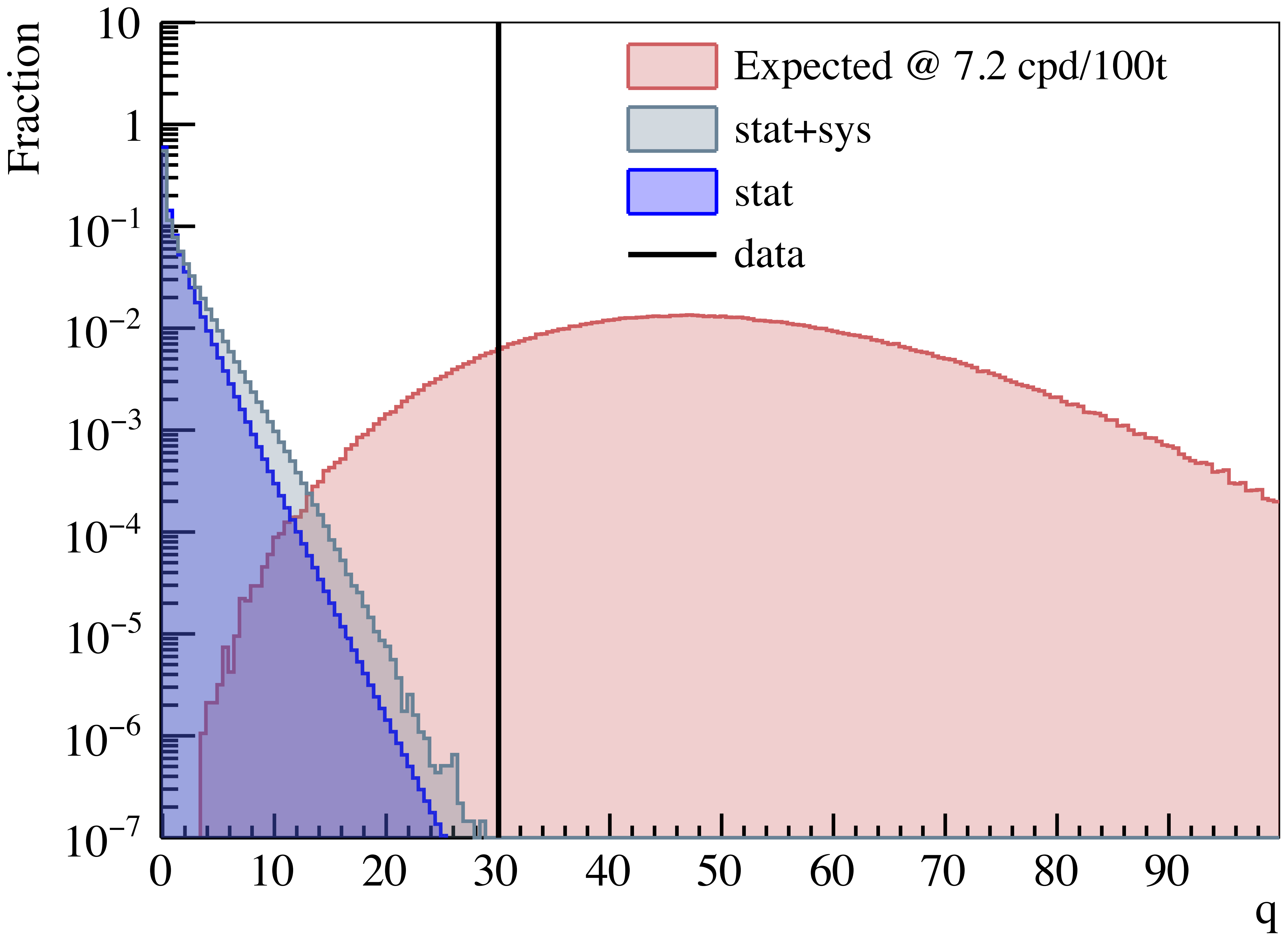
- Maximize likelihood built on distributions of event energy and position
- pep-ν constrained; ^{210}Bi upper limit imposed
- CNO ν: $7.2_{-1.7}^{+2.9}$ (stat.) cpd/100t

Evaluation of systematic uncertainty



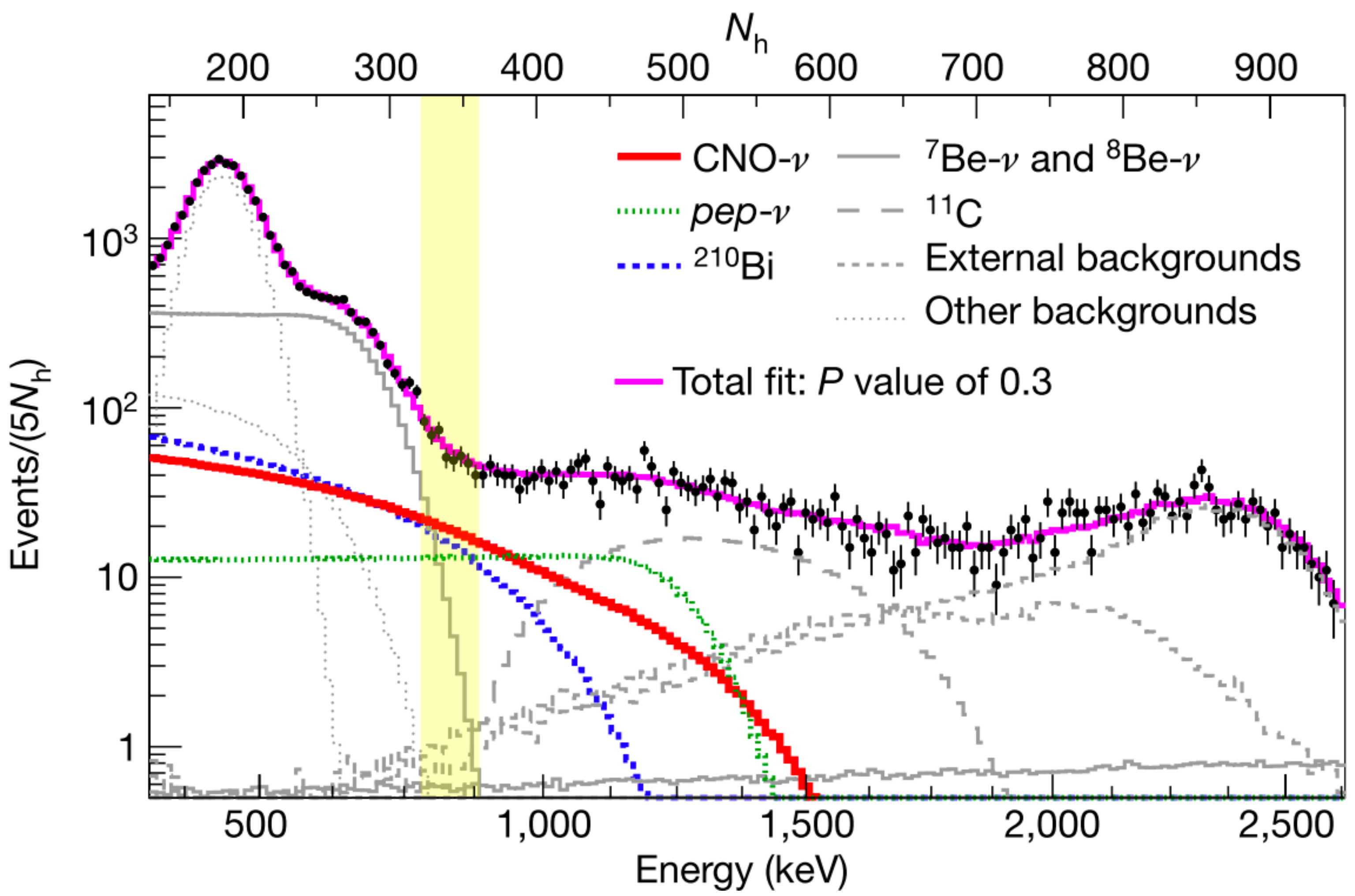
- Fit condition (negligible)
- Energy response function (energy scale, non-linearity, non-uniformity)
- ^{11}C and ^{210}Bi spectrum shapes
- CNO: $7.2\ _{-1.7}^{+3.0}$ (stat.+sys.) cpd/100t

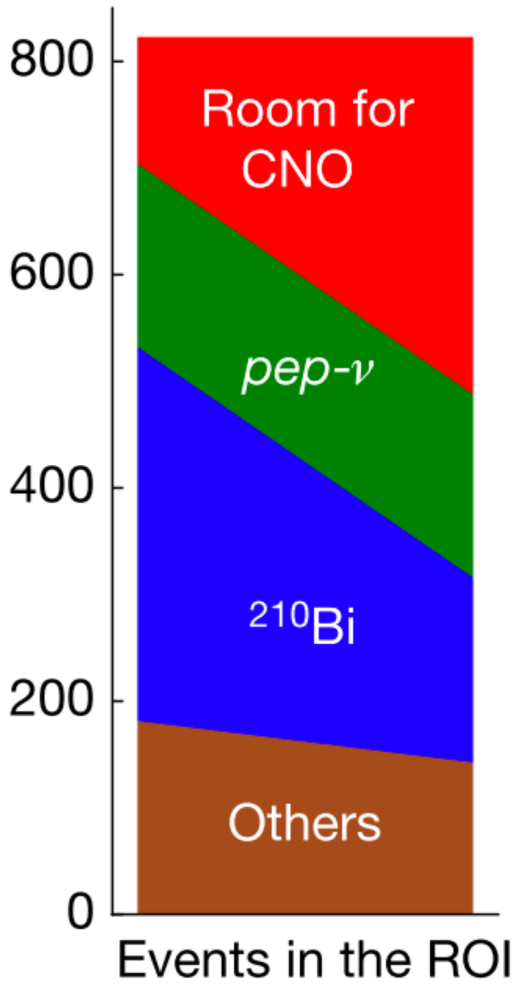
Test against no-CNO hypothesis



- Profile likelihood as the test statistic
- Use toy-MC method to get the distribution of test statistic. Evaluated p-value has statistical uncertainty.
- Simulated & Fitted 14million dataset
- **p-value < 5 σ @ 99% C. L.**

Cross-check with counting analysis





Species (S_i)	Events	Fraction
N	823 ± 28.7	
^{210}Bi	261.5 ± 29.6	0.31
ν(pep)	171.7 ± 2.4	0.21
$\nu(^{7}$Be)	86.8 ± 2.6	0.10
^{11}C	57.9 ± 5.8	0.07
Others	15.6 ± 1.6	0.02
$\sum_i S_i$	593.5 ± 30.4	0.71
$N - \sum_i S_i$	229.5 ± 41.8	0.29

- Count events in ROI (Yellow band)
- Subtract all backgrounds, rest is CNO
- R(CNO) = 5.6±1.6 (stat.+sys.) cpd/100t (~3.5 σ)
- Consistent with Full MV fit analysis

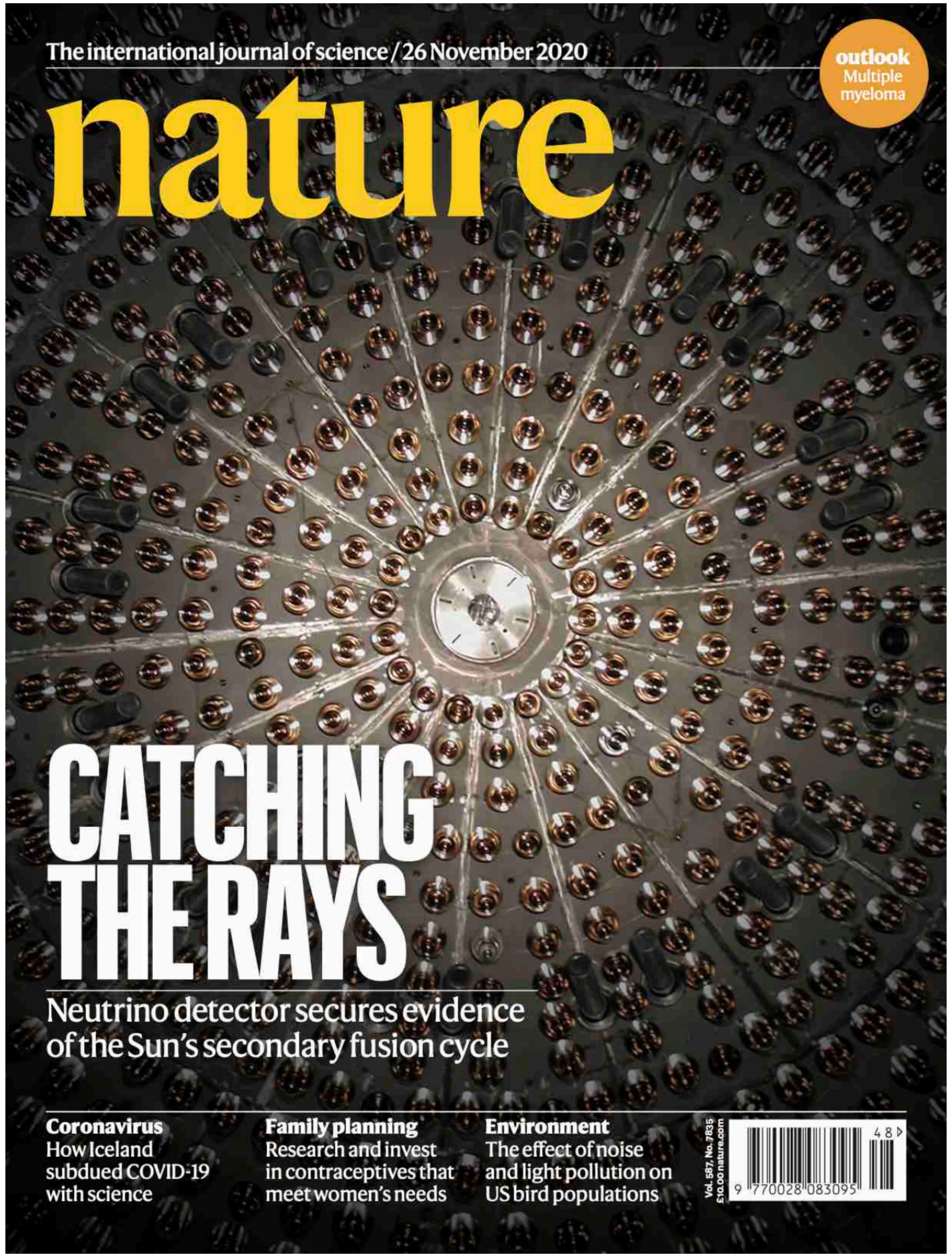
Discrimination against SSM-LZ

Expected CNO neutrino rate in Borexino

Solar ν	B16(GS98)-HZ cpd/100 ton	B16(AGSS09)-LZ cpd/100 ton
pp	131.1 ± 1.4	132.2 ± 1.4
^{7}Be	47.9 ± 2.8	43.7 ± 2.5
pep	2.74 ± 0.04	2.78 ± 0.04
CNO	4.92 ± 0.78	3.52 ± 0.52

- Compare pp, ^{7}Be, CNO, ^{8}B fluxes measured by Borexino with SSM-LZ in χ^2
- SSM-LZ rejected @ 2.1 σ

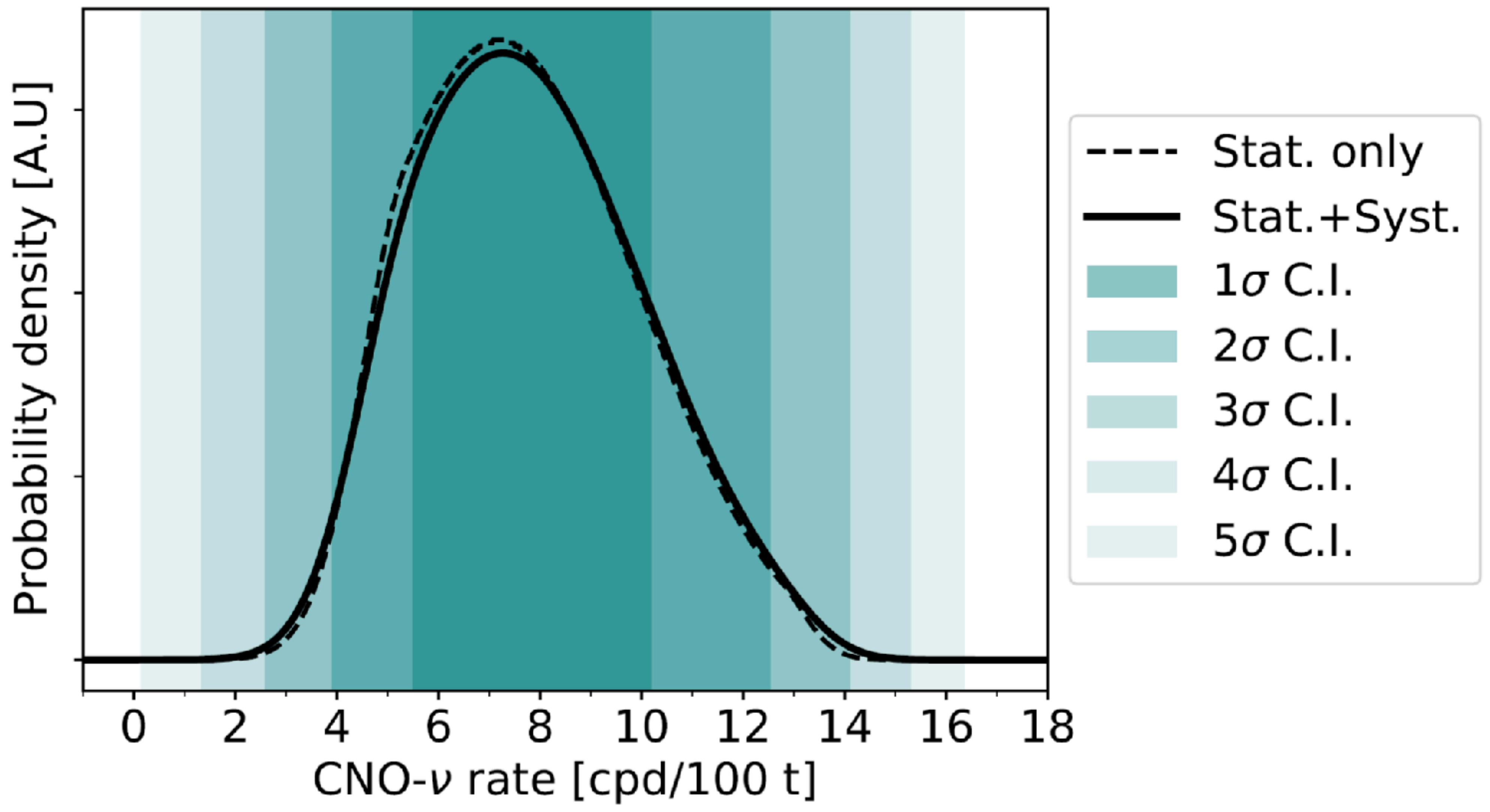
Conclusions

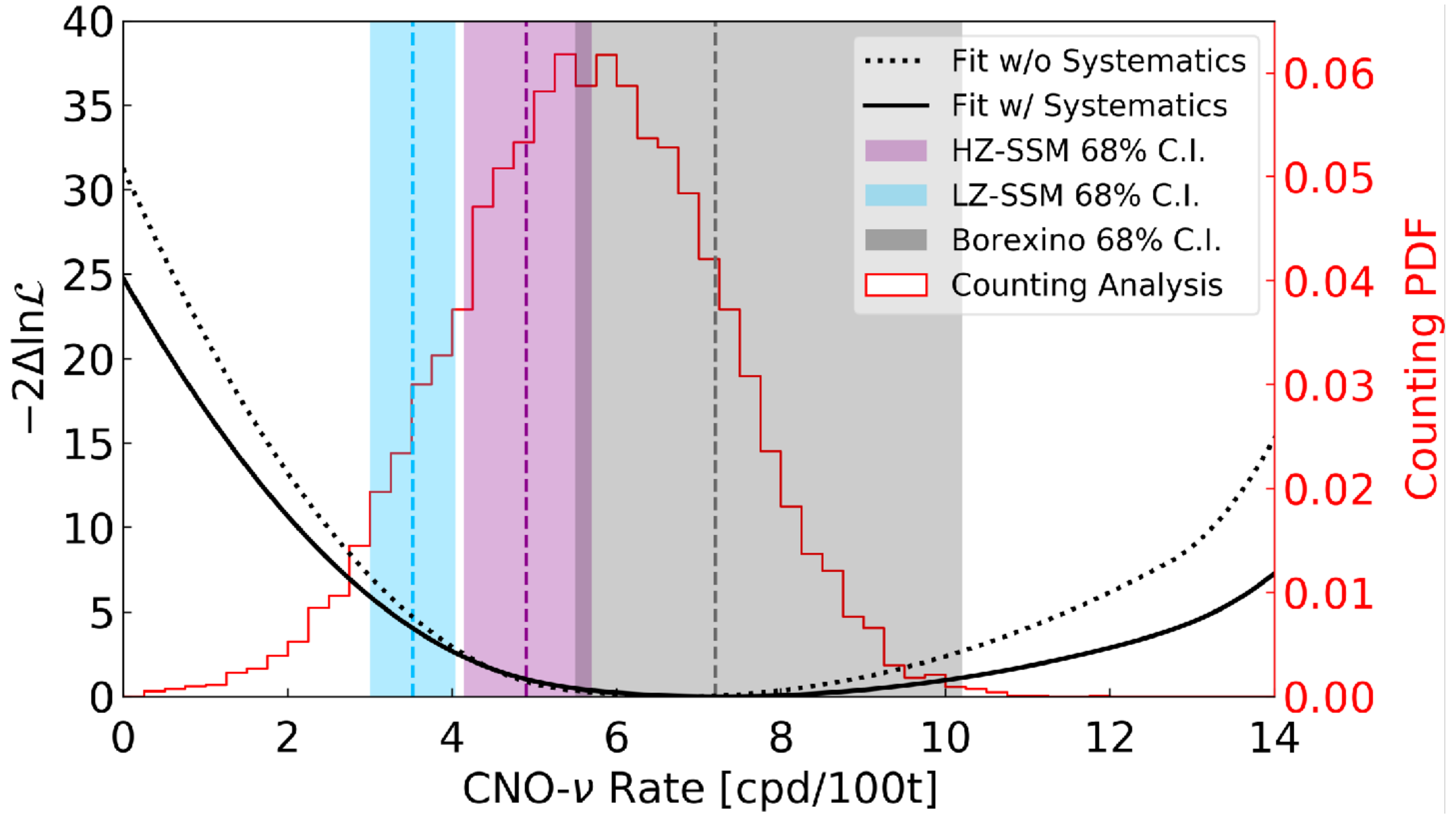


- No-CNO hypothesis rejected at 5 σ significance.
- CNO neutrino flux:
  $7.0_{-2.0}^{+3.0}$ (stat.+sys.) x 10^8 $cm^{-2}s^{-1}$
- Rejection to SSM-LZ: 2.1 σ.

Backup

The confidence interval — Multivariate fit



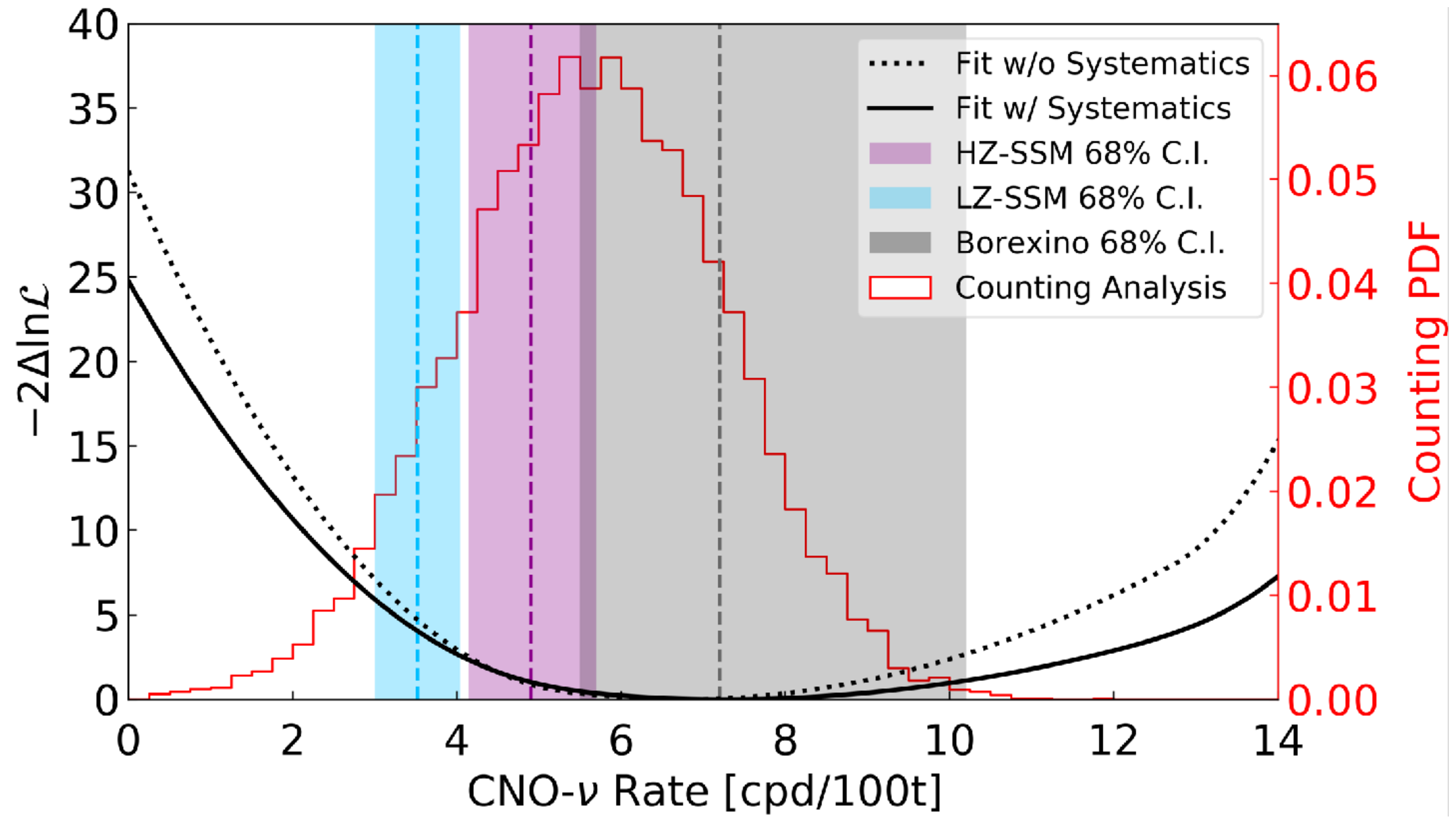


- Scan the test statistic over the CNO rate q(CNO).
- Convert q(CNO) to the P.D.F. of CNO rate according to p = C*exp(LL).
- Get 68% quantile as the 1 sigma Confidence Interval (C.I.)
- Smear the P.D.F. of CNO with systematic uncertainty ($_{-0.5}^{+0.6}$ cpd/100t)
- Get 68% quantile of the smeared P.D.F. as 1 sigma C.I. including systematic uncertainty.

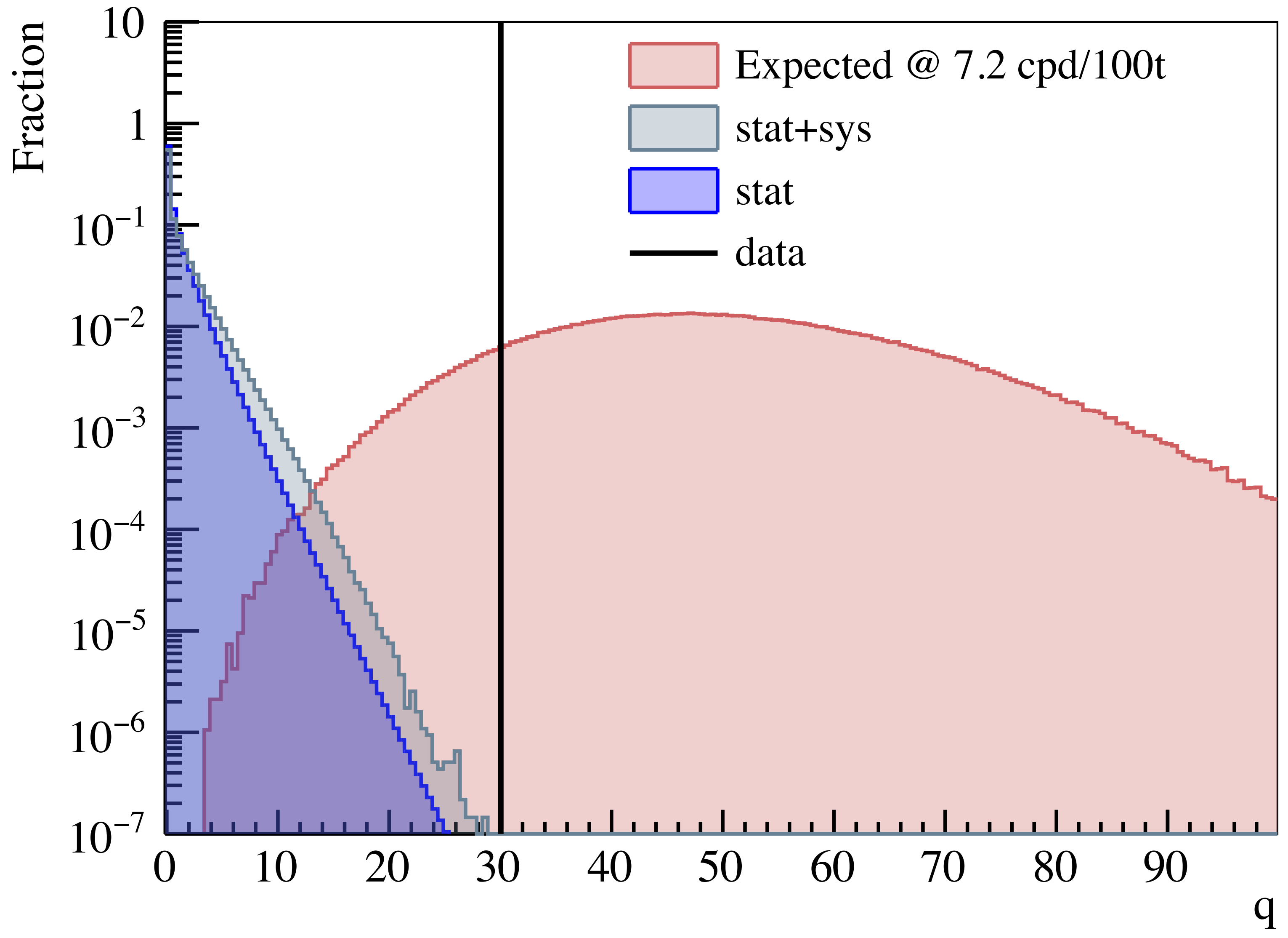
The Statistical analysis

- The statistical analysis has two objectives
  - Evaluate the confidence interval (counting + MV fit)
  - Evaluate the discovery significance (hypothesis test)

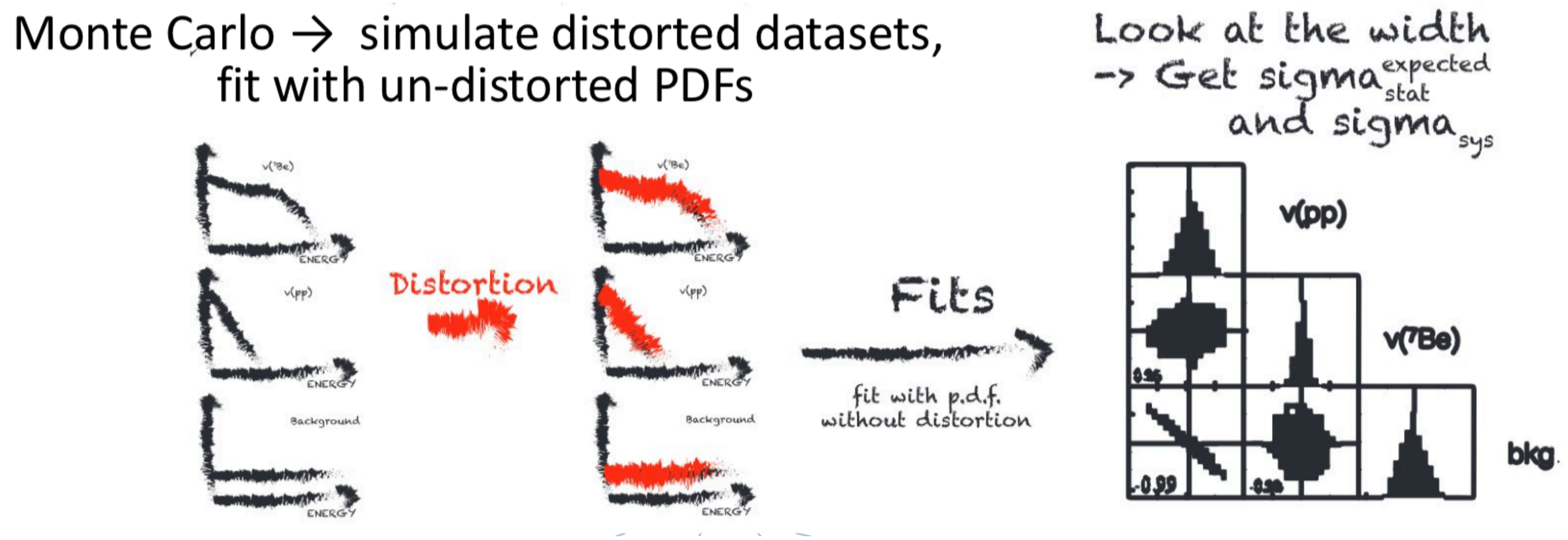
Confidence interval



Discovery significance



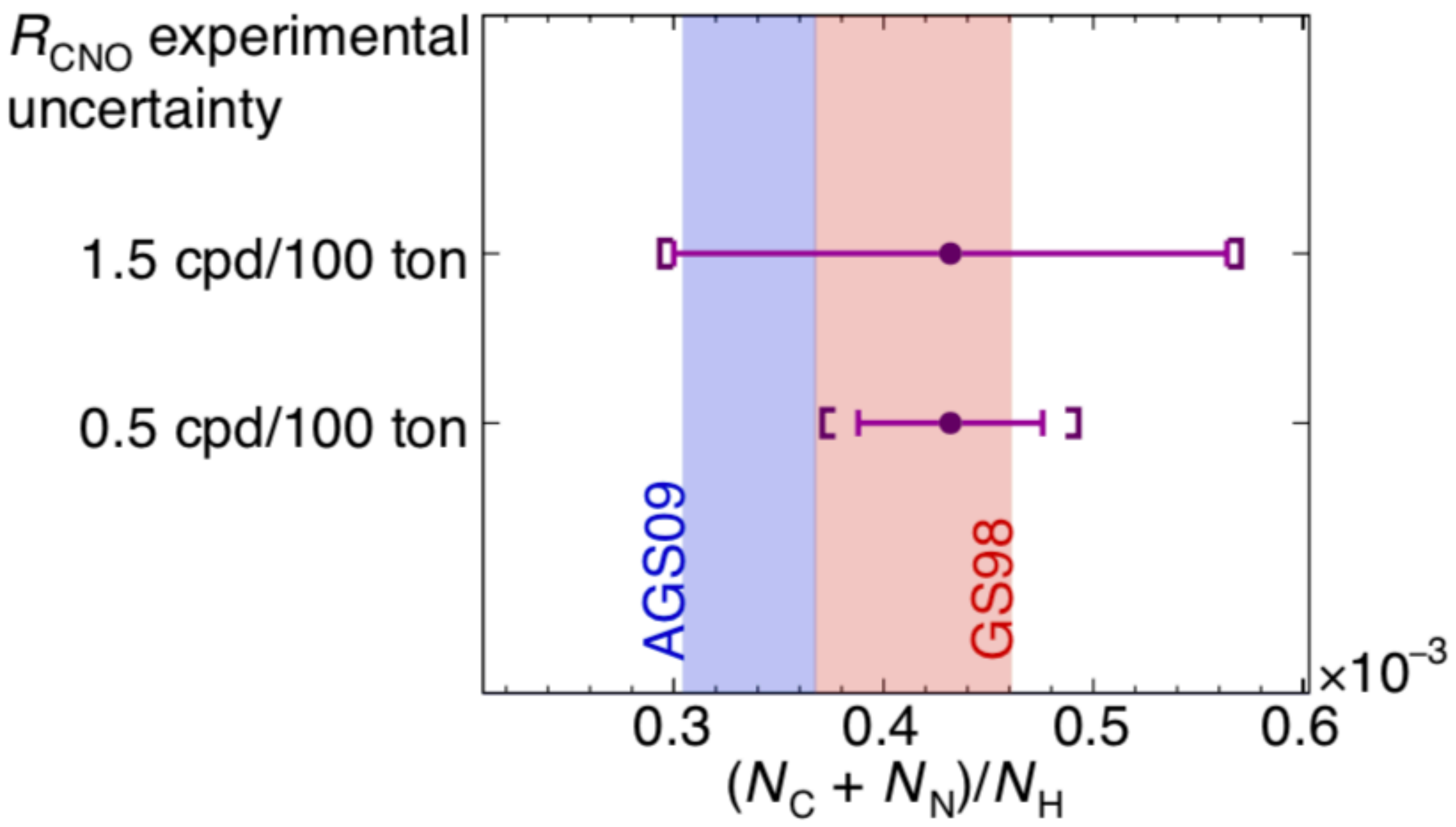
The systematic uncertainty



- Using the Cousins & Highland, or hybrid frequentist-Bayesian method.
  - Define list of known inaccuracy type and magnitude (energy function, LY 0.23%, non-uniformity 0.28% and NL 0.4%; ^{11}C deformation 2.3%; ^{210}Bi shape 18%)
  - Simulate distorted datasets and fit with un-distorted PDF
  - Subtract quadratically width of distribution of results with 0-systemics.

Use CNO to measure C & N abundances

(Expected, MC only)

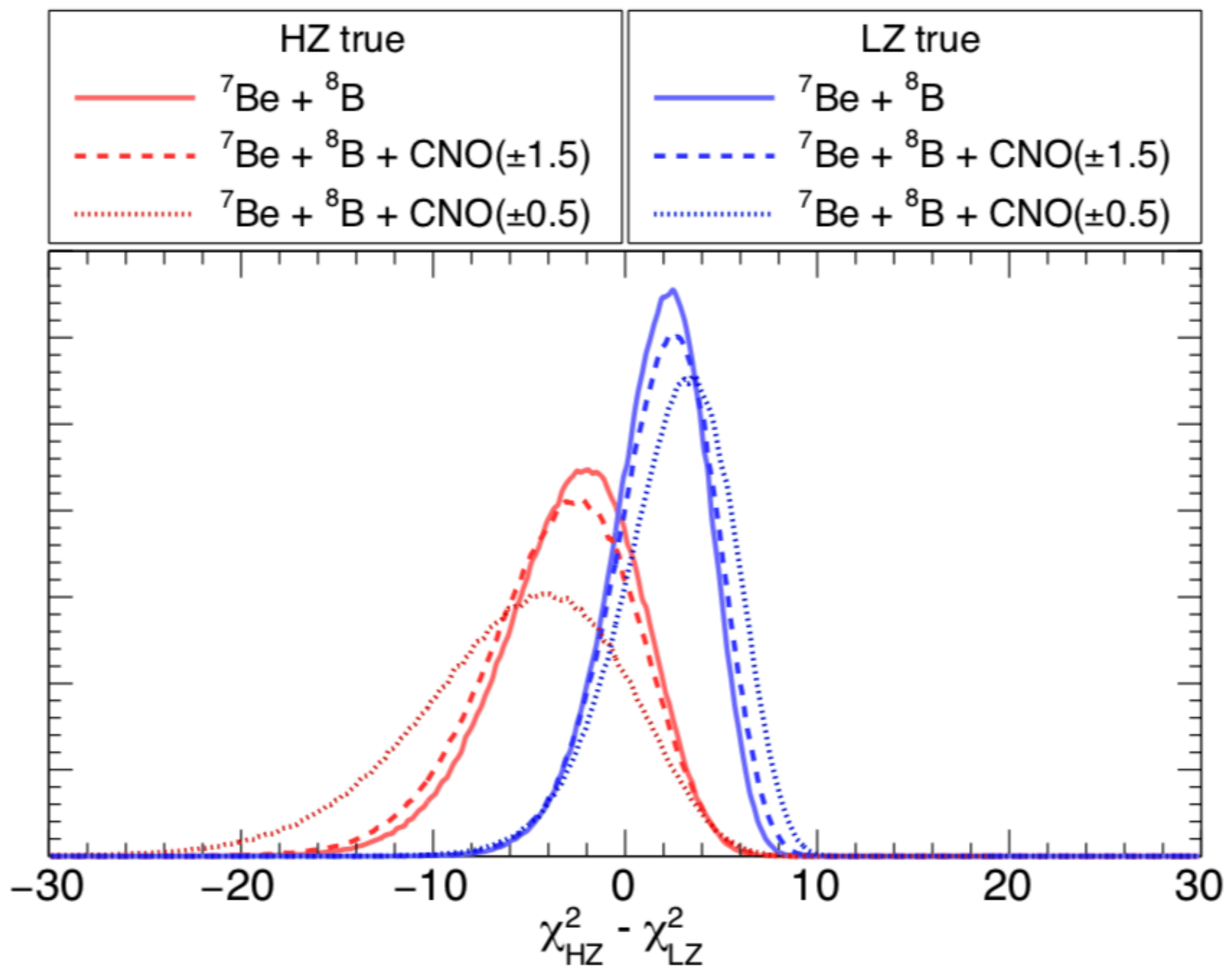


Sensitivity to neutrinos from the solar CNO cycle in Borexino, arXiv 2005.12829

- pp-chain solar neutrino fluxes depend on solar core temperature
- CNO cycle solar neutrino fluxes depend on temperature + C & N abundances.
- Combine two to measurement C & N abundances directly

Use CNO to do hypothesis test

(Expected, MC only)

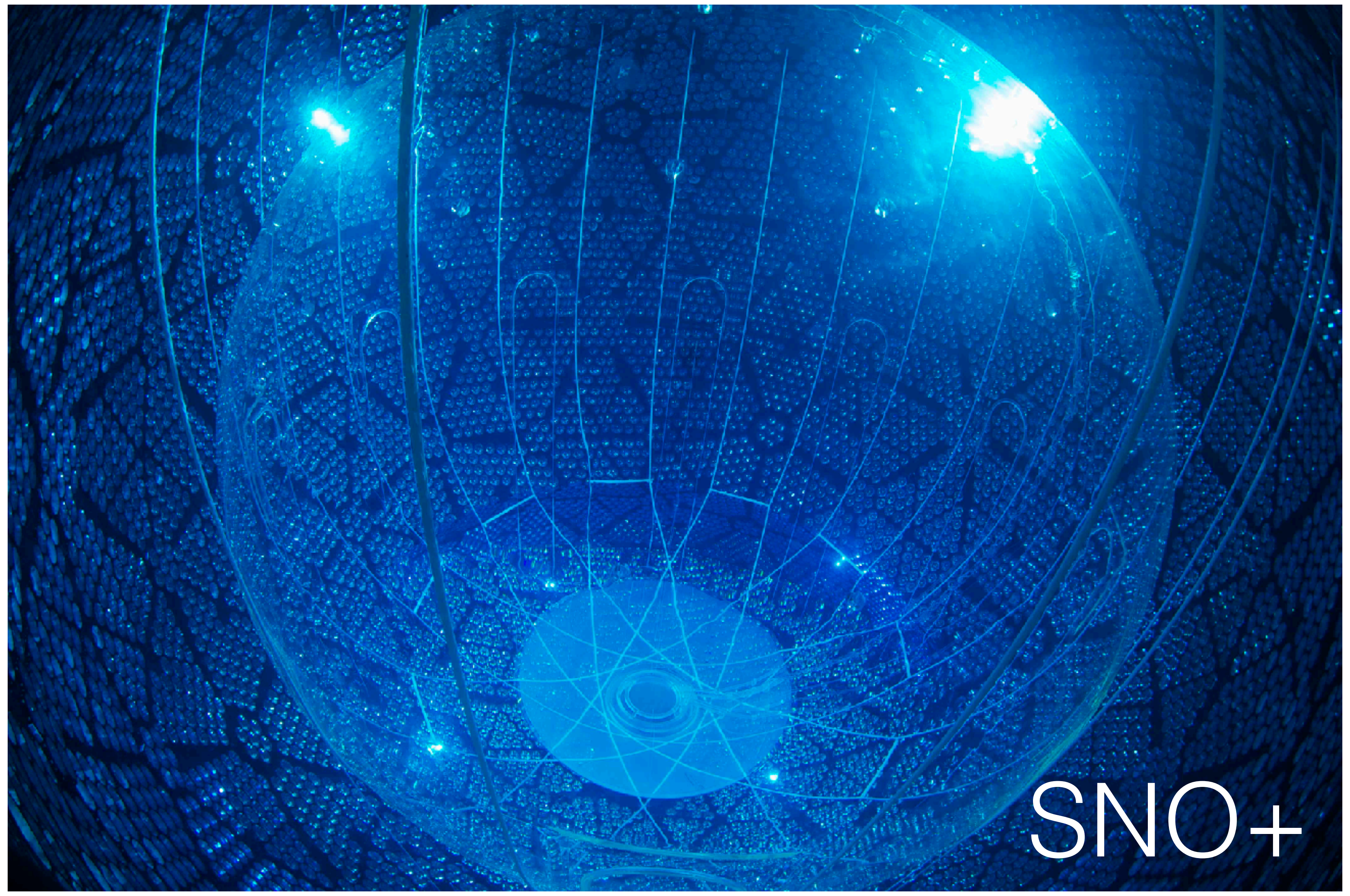


Sensitivity to neutrinos from the solar CNO cycle in Borexino, arXiv 2005.12829

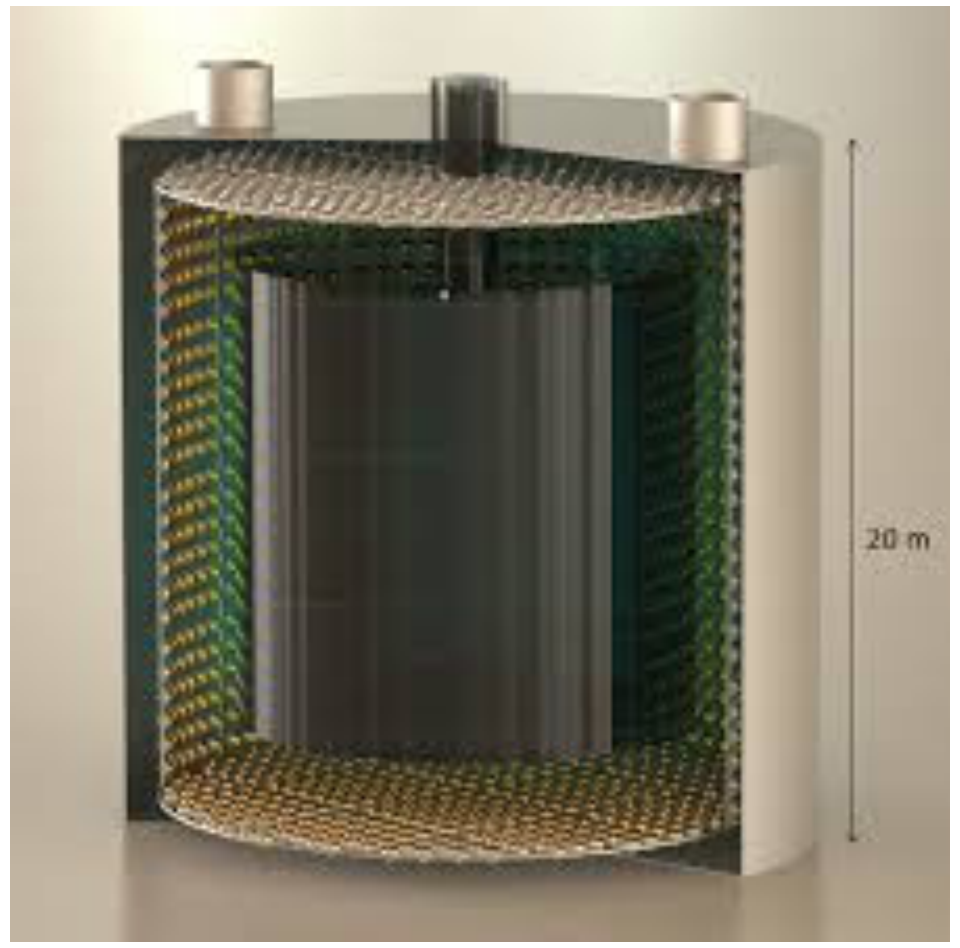
Solar ν	B16(GS98)-HZ cpd/100 ton	B16(AGSS09)-LZ cpd/100 ton	Borexino Results cpd/100 ton
pp	131.1 ± 1.4	132.2 ± 1.4	$134 \pm 10^{+6}_{-10}$
^{7}Be	47.9 ± 2.8	43.7 ± 2.5	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep	2.74 ± 0.04	2.78 ± 0.04	$2.43 \pm 0.36^{+0.15}_{-0.22}$(HZ)
			$2.65 \pm 0.36^{+0.15}_{-0.24}$ (LZ)
CNO	4.92 ± 0.78	3.52 ± 0.52	< 8.1 (95% C.L.)

- Standard hypothesis test

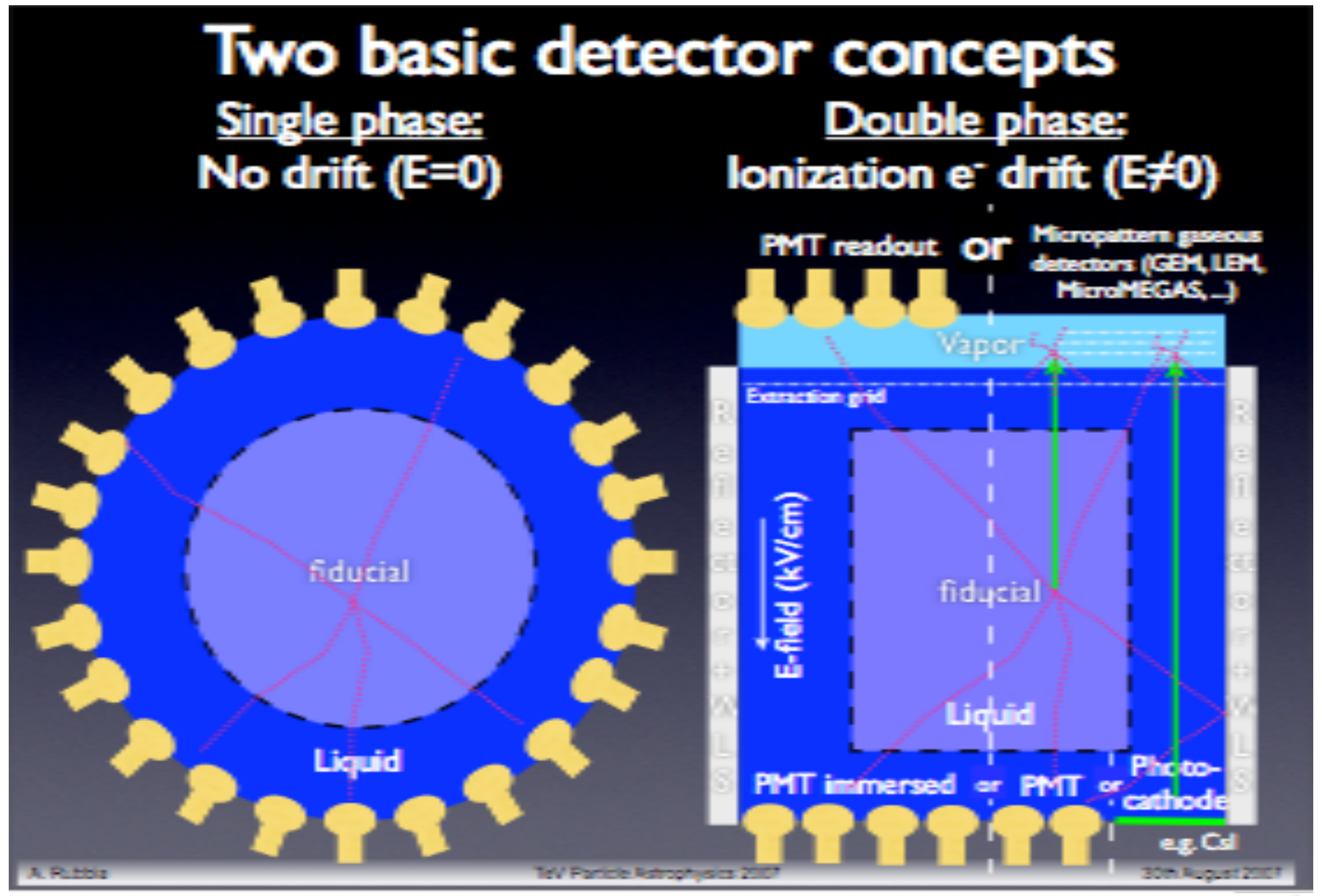
Future experiments



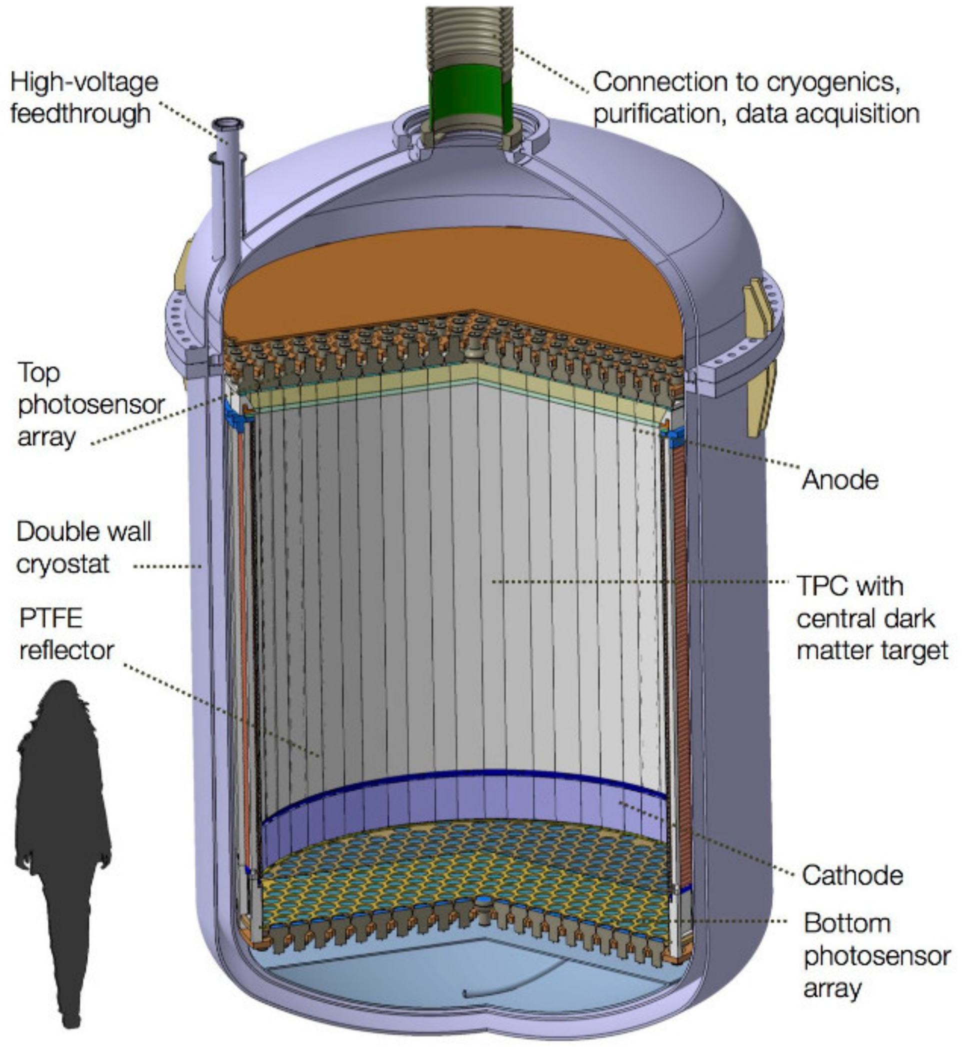
Jingping Neutrino Experiment



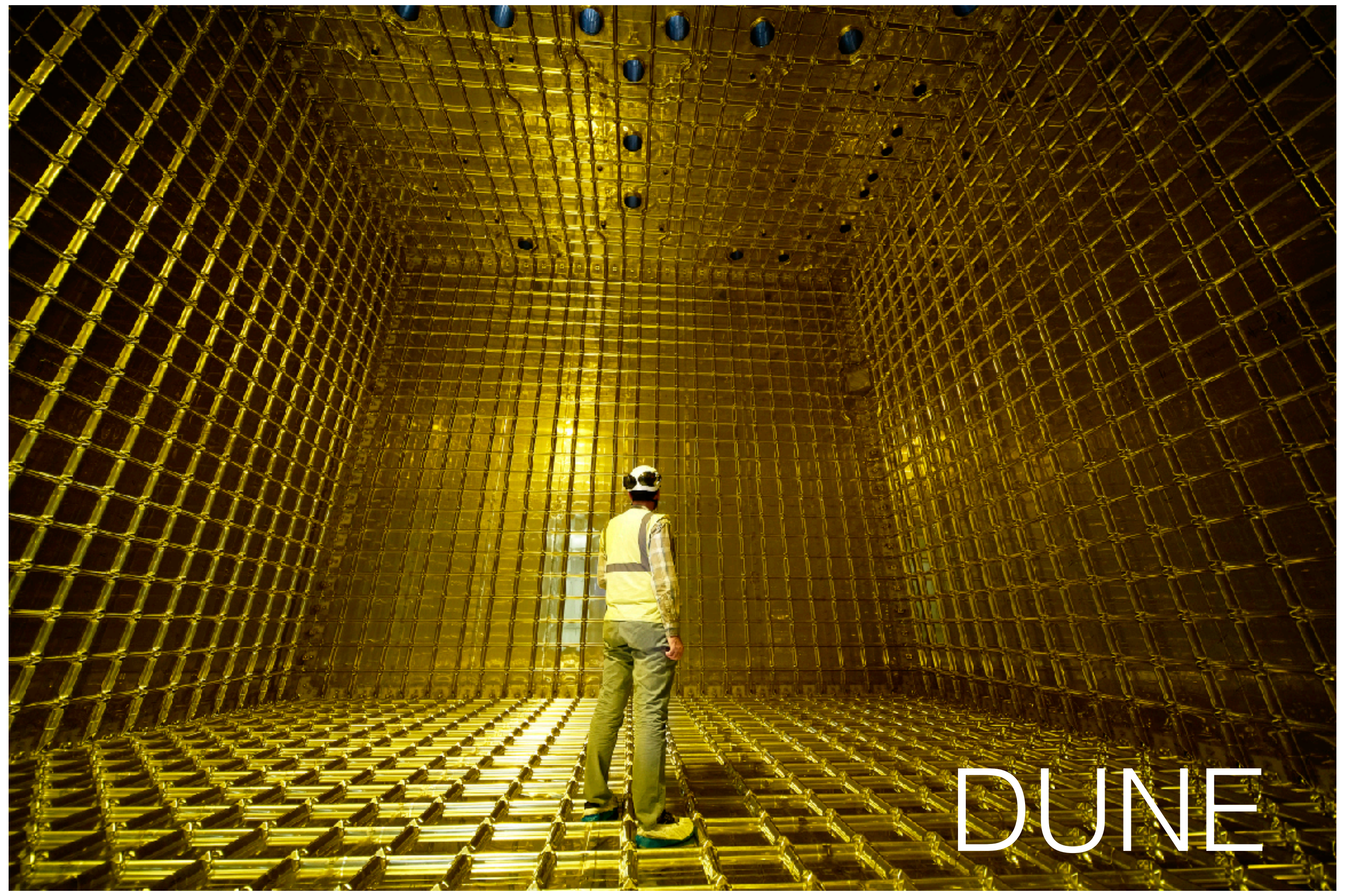
- SNO+: existing, deep
- JPNE: directionality
- LAr/LXe: no ^{11}C, high energy resolution



ARDM



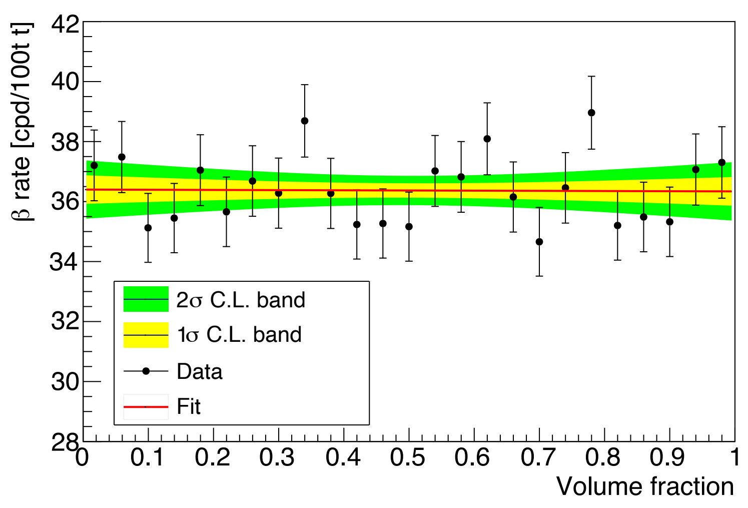
DARWIN

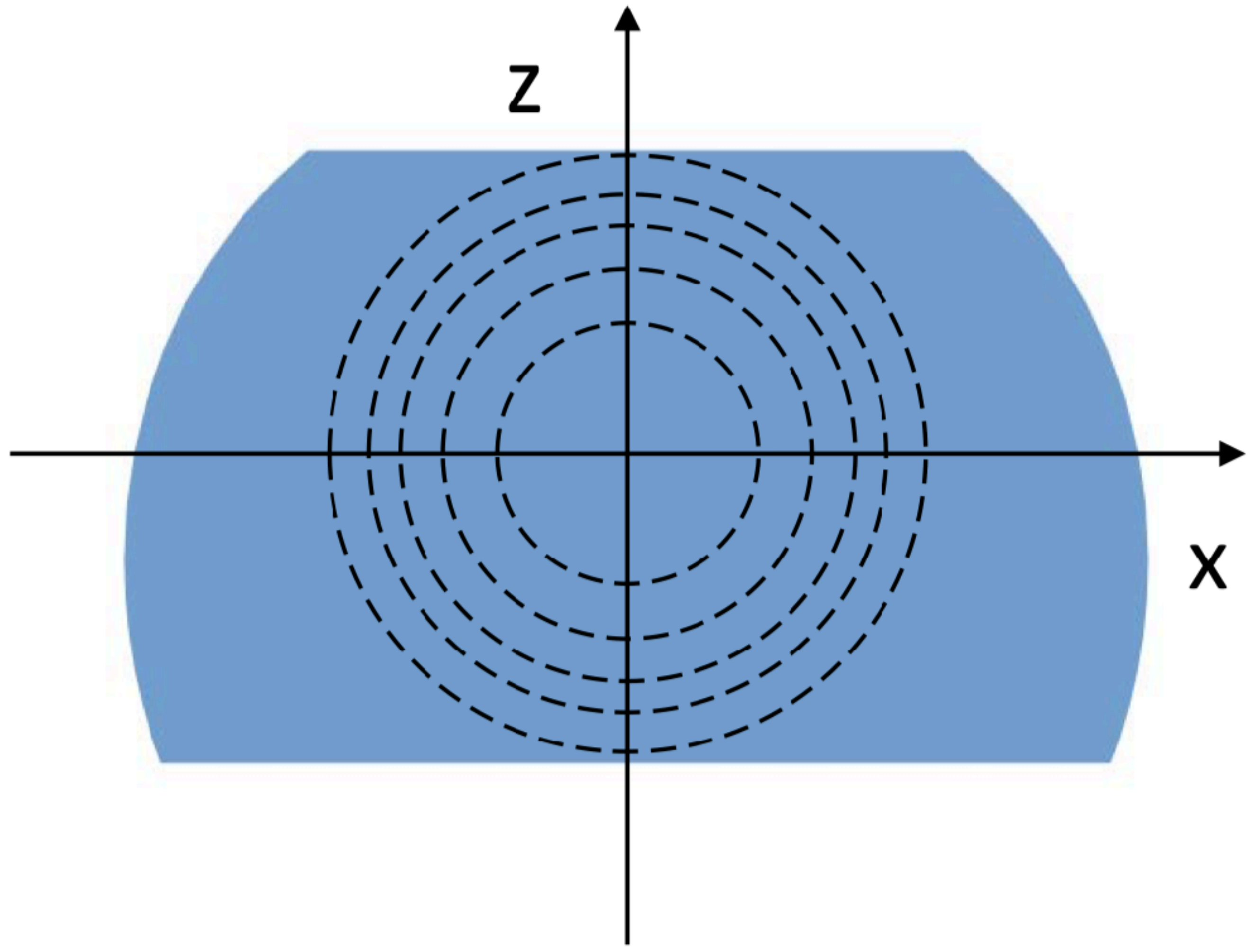


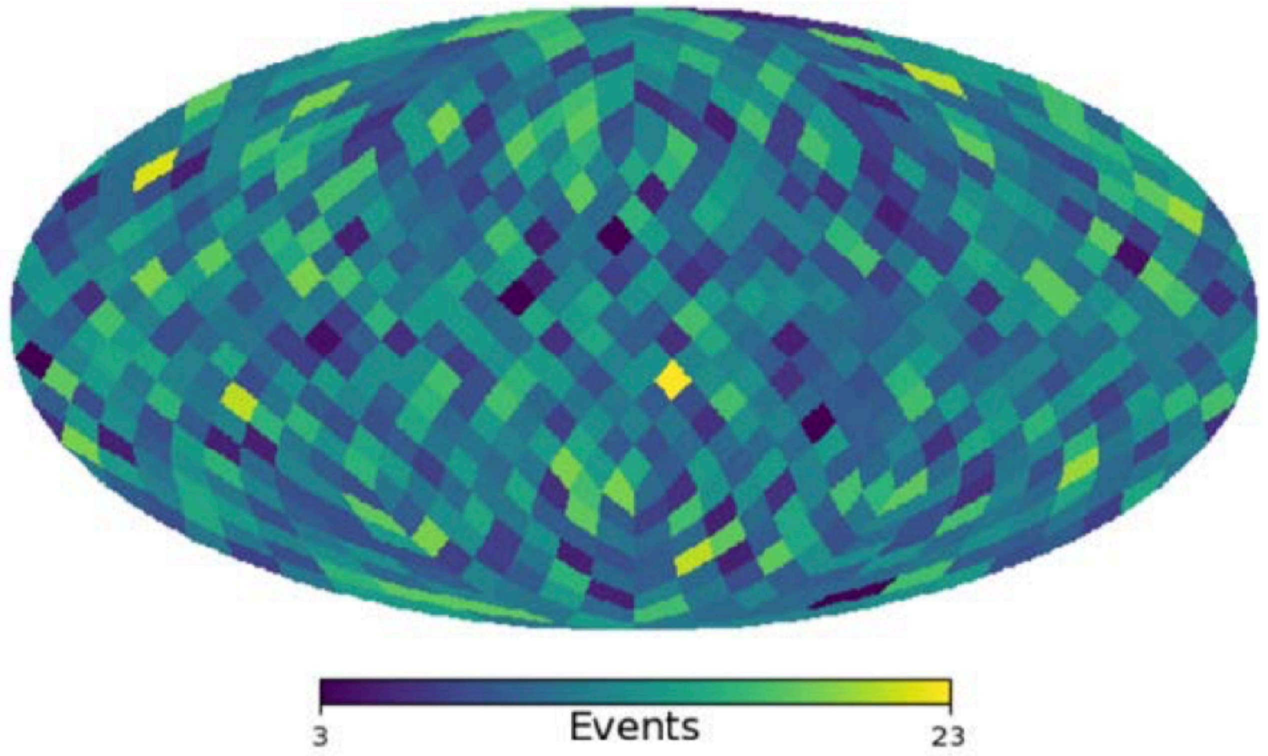
Radial β analysis + **Angular β analysis**

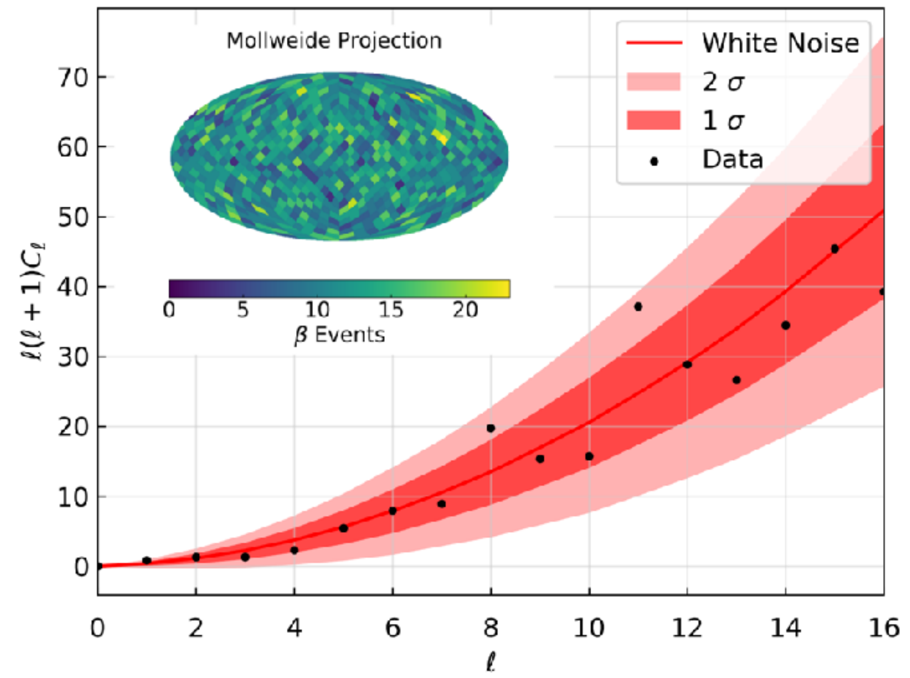
Radial shells

Spherical harmonics decomposition









0.51 cpd/100t

0.59 cpd/100t

Overall ^{210}Bi spatial uniformity systematics: 0.78 cpd/100t