Solar neutrinos in liquid scintillator detectors: Borexino CNO measurement and JUNO sensitivity

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MATTER AND UNIVERSE 2023 - 14.09.2023

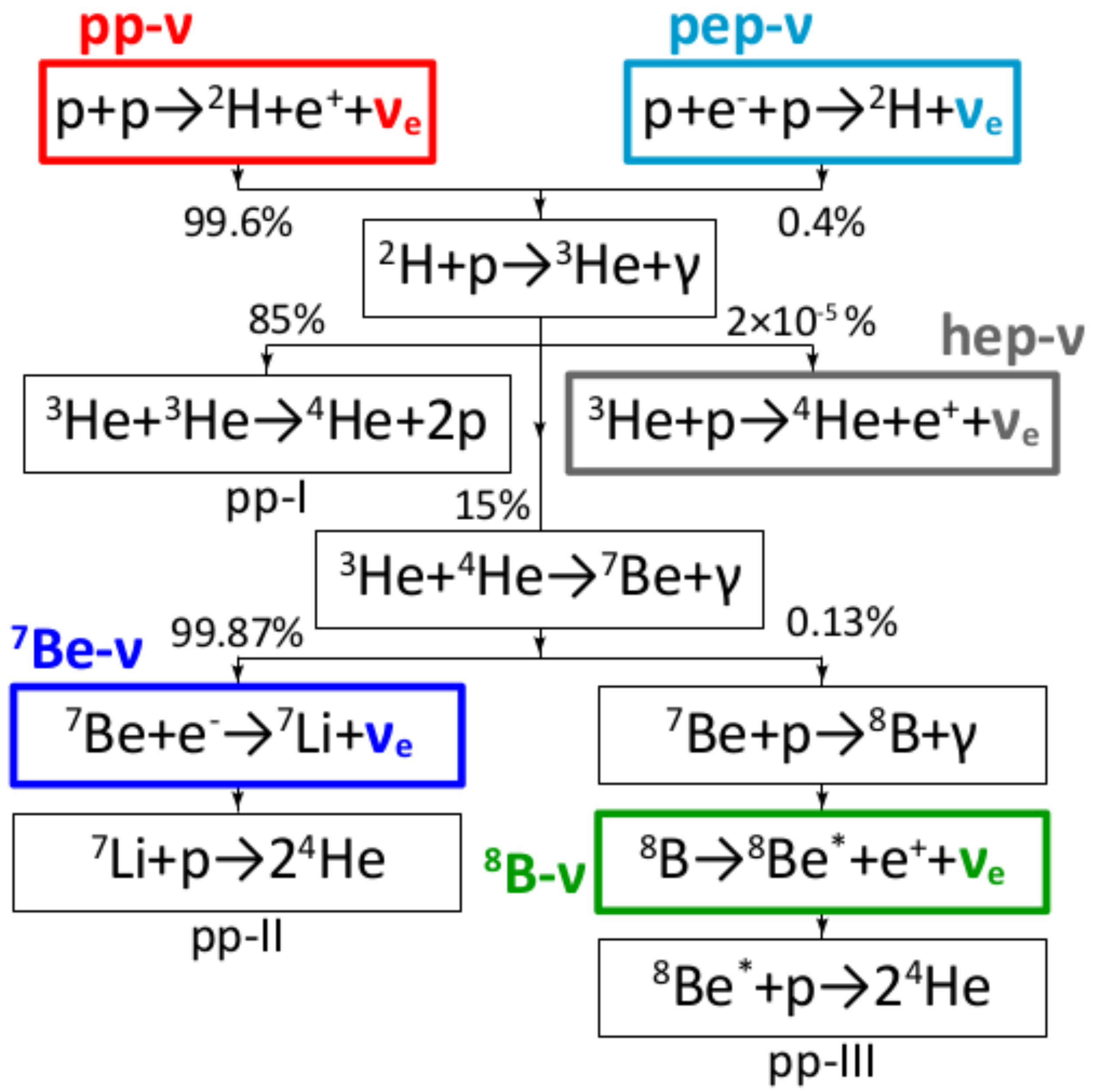
OUTLINE

- Solar neutrinos and importance of the CNO cycle
- CNO measurement with the Borexino detector
- Intermediate energy solar neutrinos sensitivity with the JUNO detector

SOLAR NEUTRINOS

Sun is powered by two sequences of thermonuclear reactions:

pp chain reaction (~$99\,\%$ $E_\odot$)



pp-ν

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

pep-ν

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

99.6%

0.4%

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

85%

$2\times10^{-5}\,\%$

hep-ν

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

pp-I

${}^3He+p \rightarrow {}^4He+e^++\nu_e$

15%

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

^{7}Be-ν

99.87%

0.13%

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

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

${}^7Li+p \rightarrow 2\,{}^4He$

pp-II

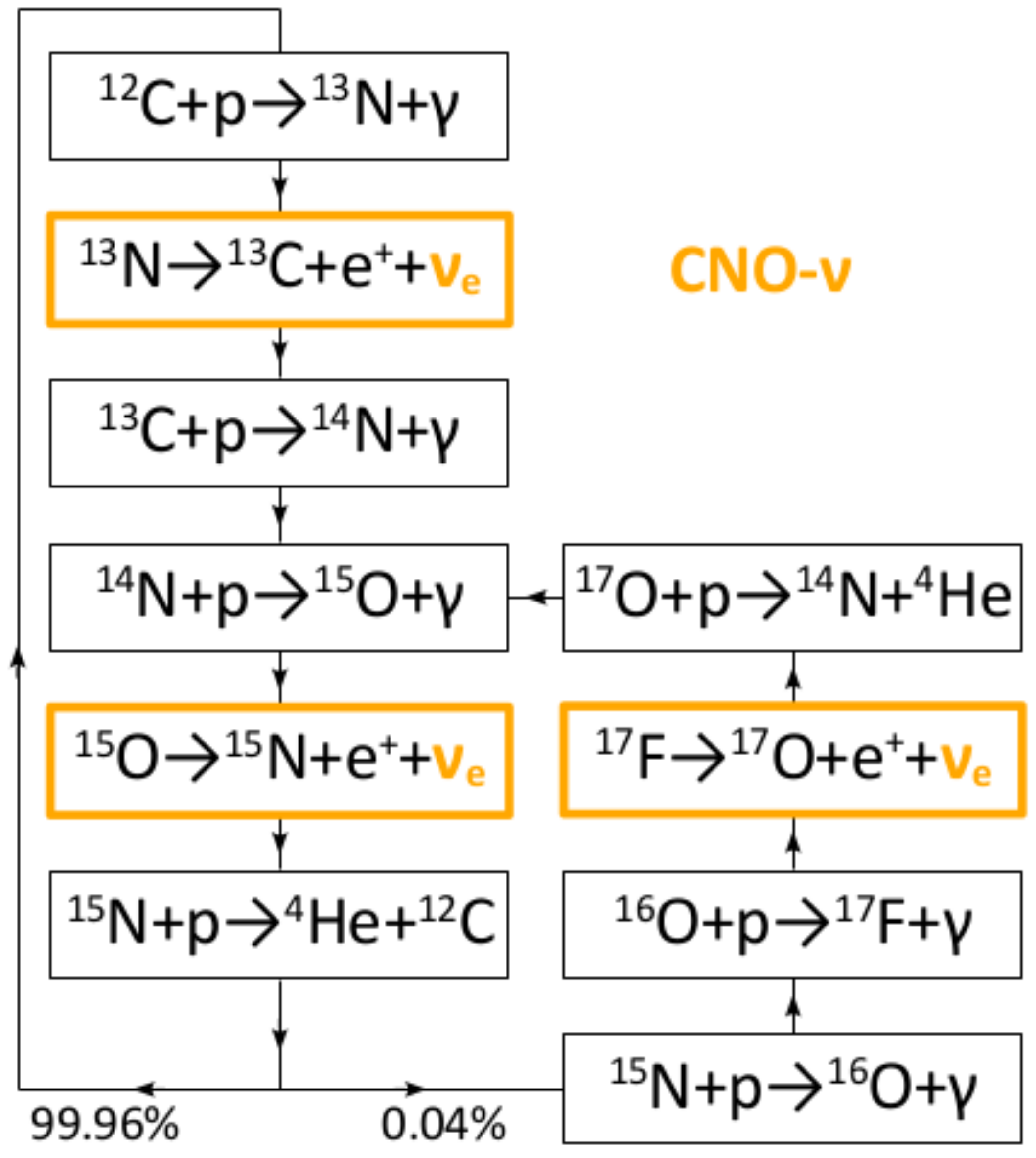
^{8}B-ν

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

${}^8Be^*+p \rightarrow 2\,{}^4He$

pp-III

CNO cycle (~$1\,\%$ $E_\odot$)



${}^{12}C+p \rightarrow {}^{13}N+\gamma$

${}^{13}N \rightarrow {}^{13}C+e^++\nu_e$

CNO-ν

${}^{13}C+p \rightarrow {}^{14}N+\gamma$

${}^{14}N+p \rightarrow {}^{15}O+\gamma$

${}^{17}O+p \rightarrow {}^{14}N+{}^4He$

${}^{15}O \rightarrow {}^{15}N+e^++\nu_e$

${}^{17}F \rightarrow {}^{17}O+e^++\nu_e$

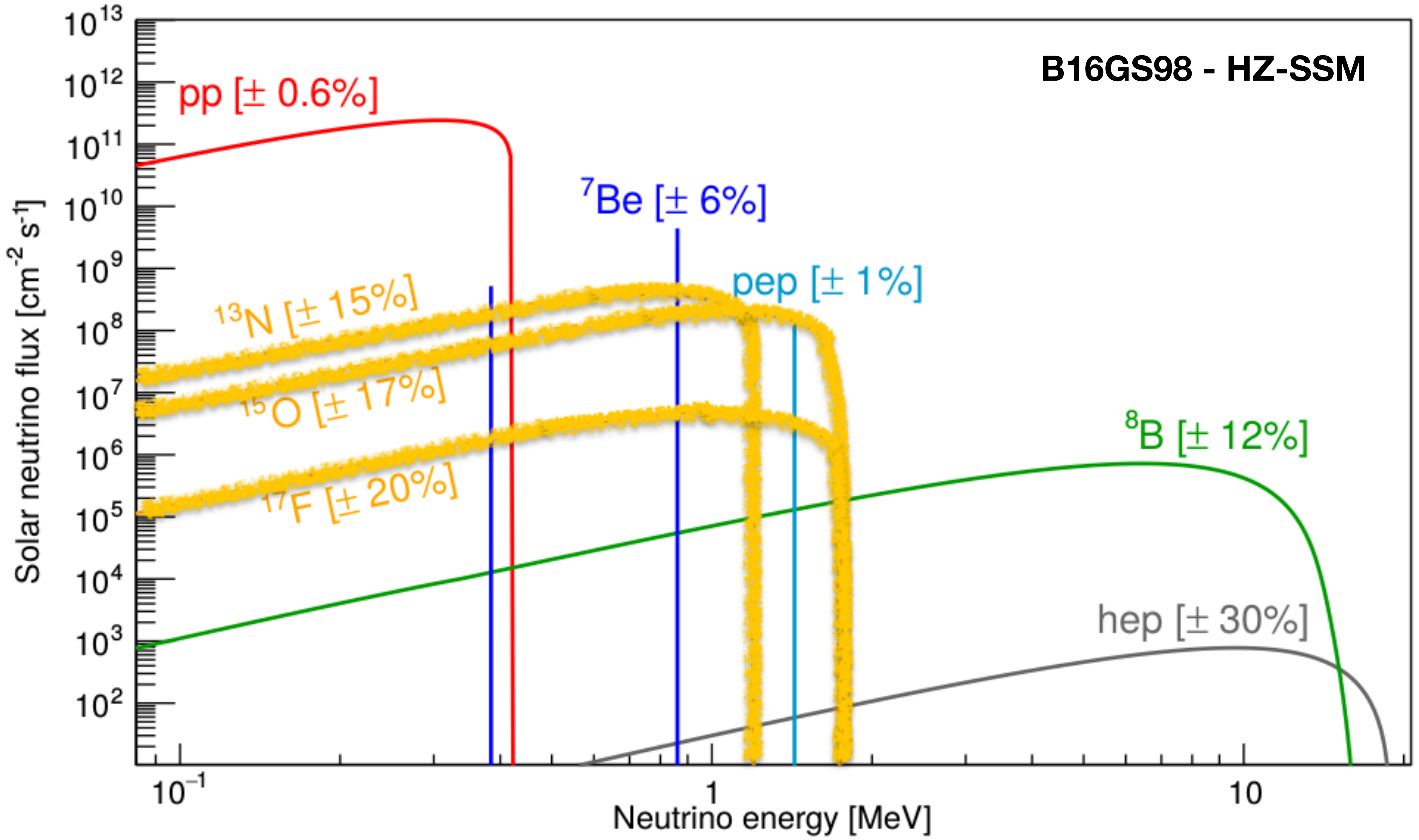
${}^{15}N+p \rightarrow {}^4He+{}^{12}C$

${}^{16}O+p \rightarrow {}^{17}F+\gamma$

${}^{15}N+p \rightarrow {}^{16}O+\gamma$

99.96%

0.04%

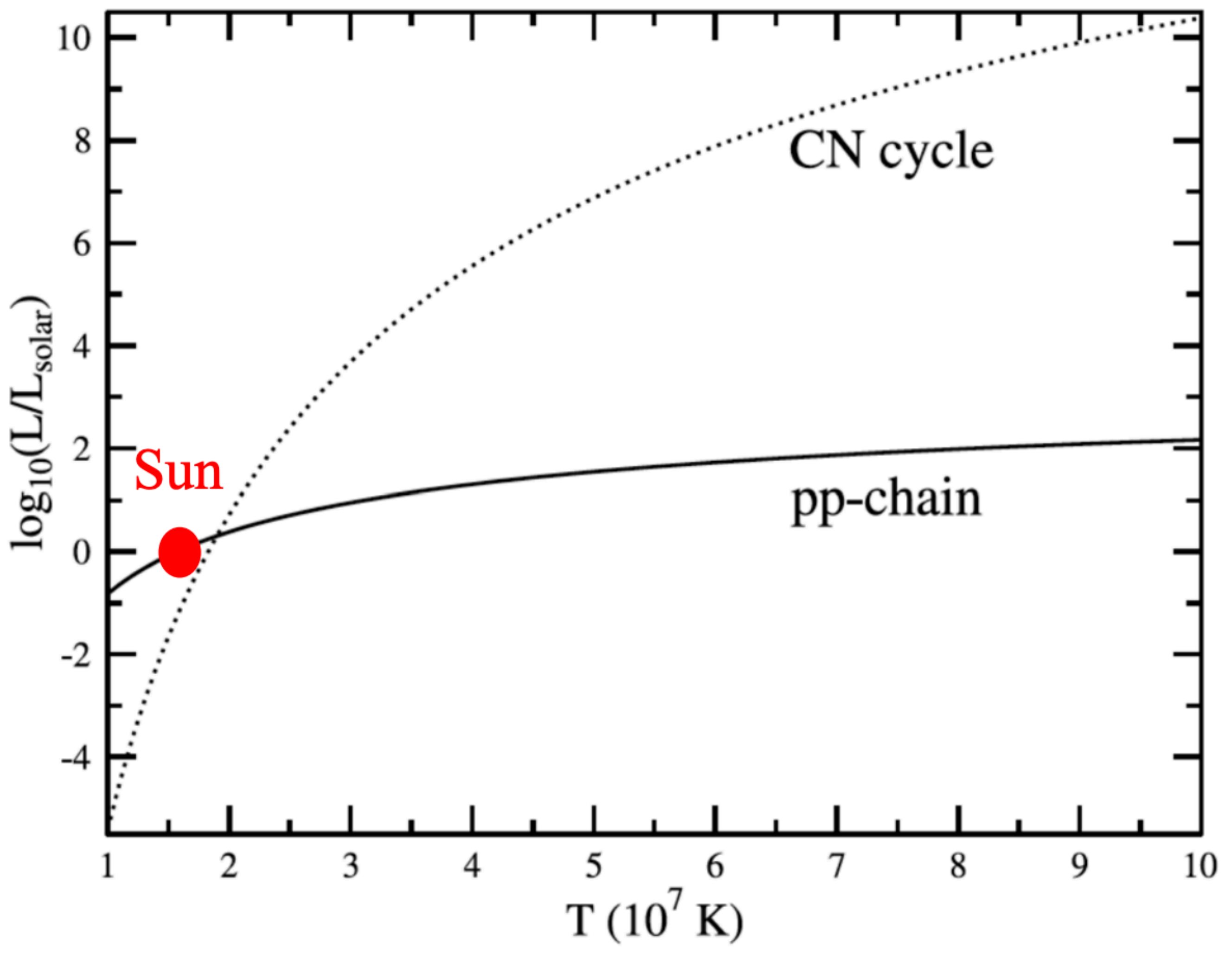


Net reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$

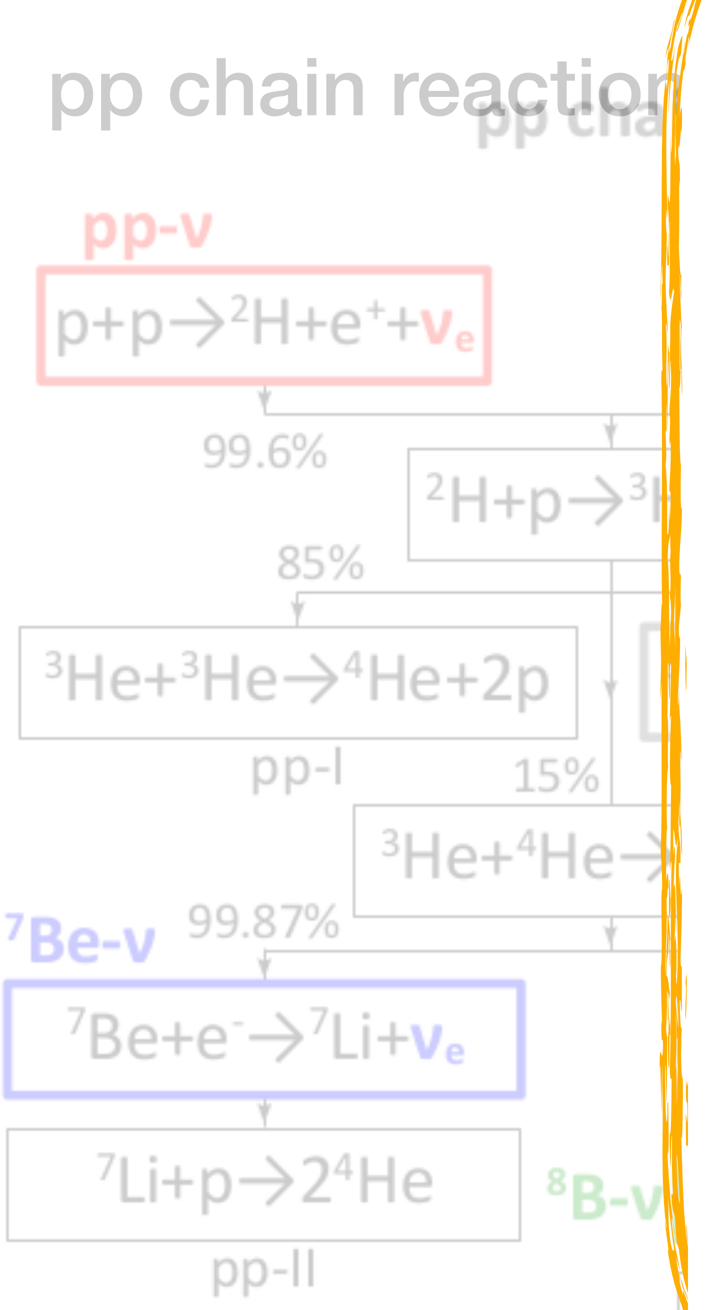
SOLAR NEUTRINOS

Sun is powered by two sequences of thermonuclear reactions:

The importance of CNO neutrinos



- **Proof of principle** of star energy production in the Sun via Carbon - Nitrogen - Oxygen (CNO) cycle
- CNO cycle is expected to be dominant for stars with $M \geq 1.3\ M_{\odot}$
- Sensitive to Sun's core **metallicity problem**


pp chain reaction

pp cha

pp-ν

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

99.6%

$^2H+p \rightarrow {}^3$

85%

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

pp-I

15%

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

^{7}Be-ν

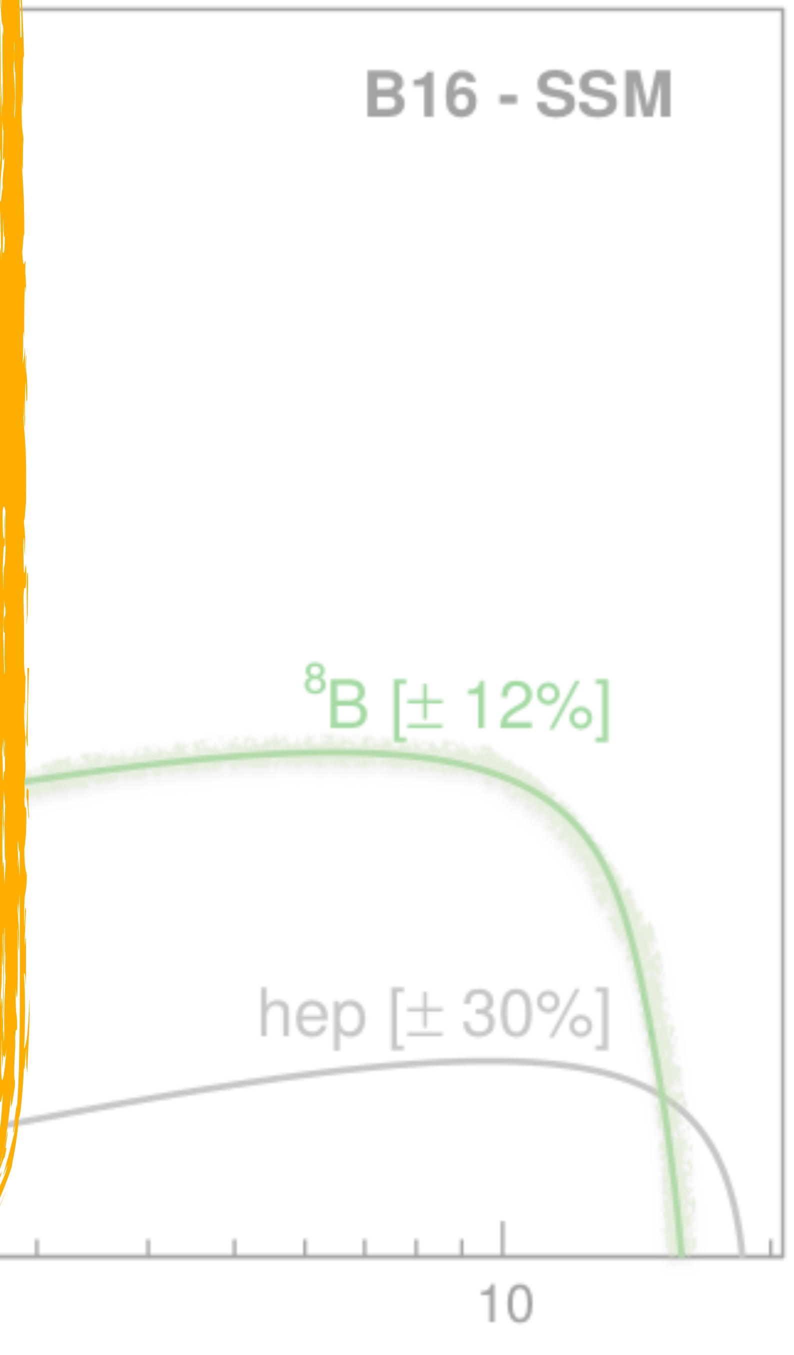
99.87%

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

$^7Li+p \rightarrow 2{}^4He$

pp-II

^{8}B-ν



Net reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$

BOREXINO DETECTOR

Water tank: 2.8 kton of pure H_2O
γ & n shield
Cherenkov muon veto

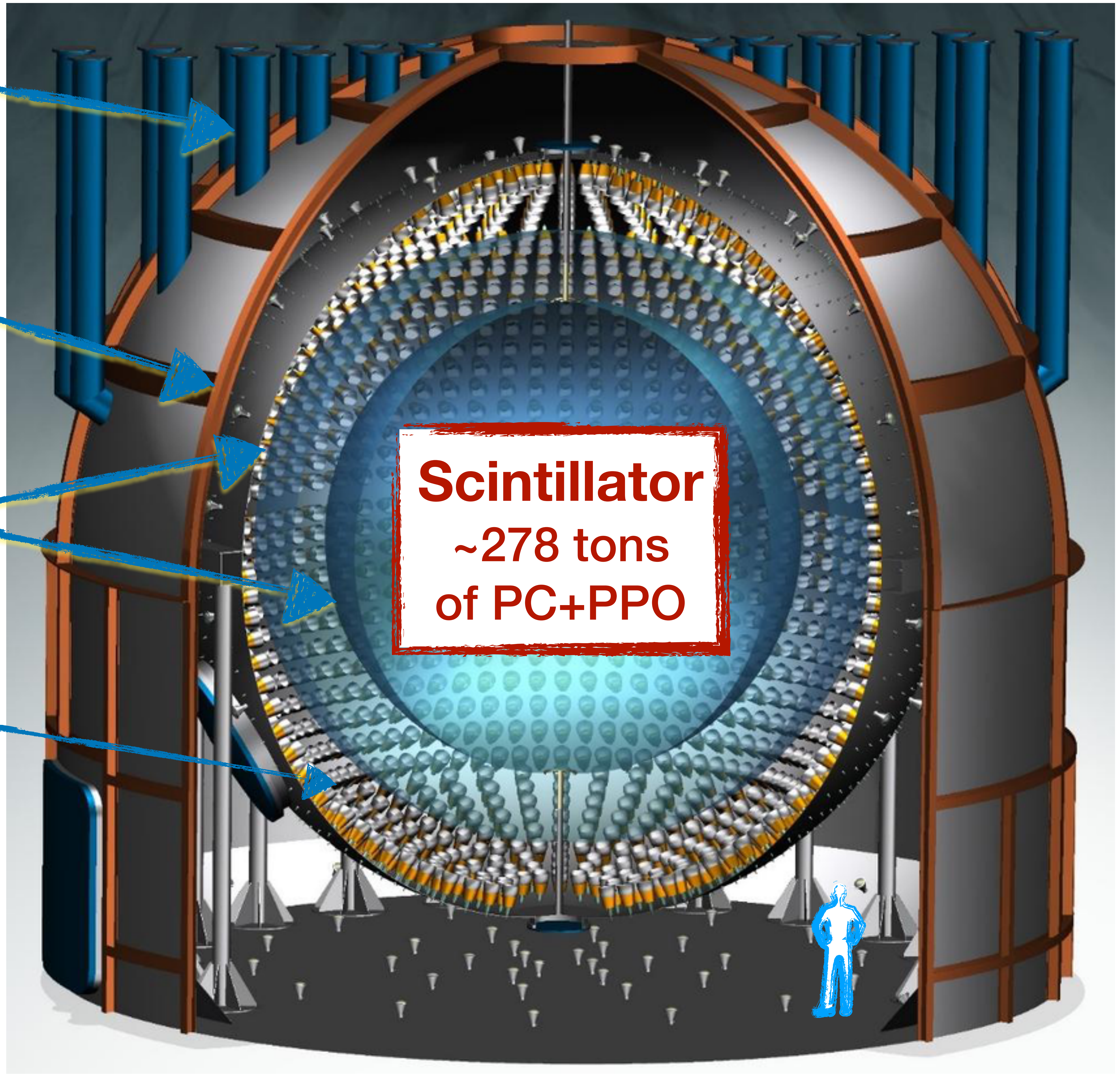
Stainless Steel Sphere:
2212 Internal PMTs

Nylon vessels:
r(Outer) = 5.5 m
r(Inner) = 4.25 m

Buffer:
~900 tons of quenched scintillator

Fiducial Volume:
$r < 2.8$ m & $(-1.8 < z < 2.2)$ m

- *Location:* Laboratori Nazionali del Gran Sasso (LNGS), Italy



Scintillator
~278 tons
of PC+PPO

- *Detection channel:* neutrino-electron elastic scattering
- *Unique features:*

☑ Unprecedented level of radiopurity:
$R(^{232}\text{Th}) < 7.2 \cdot 10^{-19}\ g/g$ and $R(^{238}\text{U}) < 9.5 \cdot 10^{-20}\ g/g$

☑ High eff. light yield (~500 p.e./MeV with 2000 PMTs)

☑ Low energy threshold

☑ Good energy (~6% at 1 MeV) and position resolution (~11 cm at 1 MeV)

DAQ timeline:

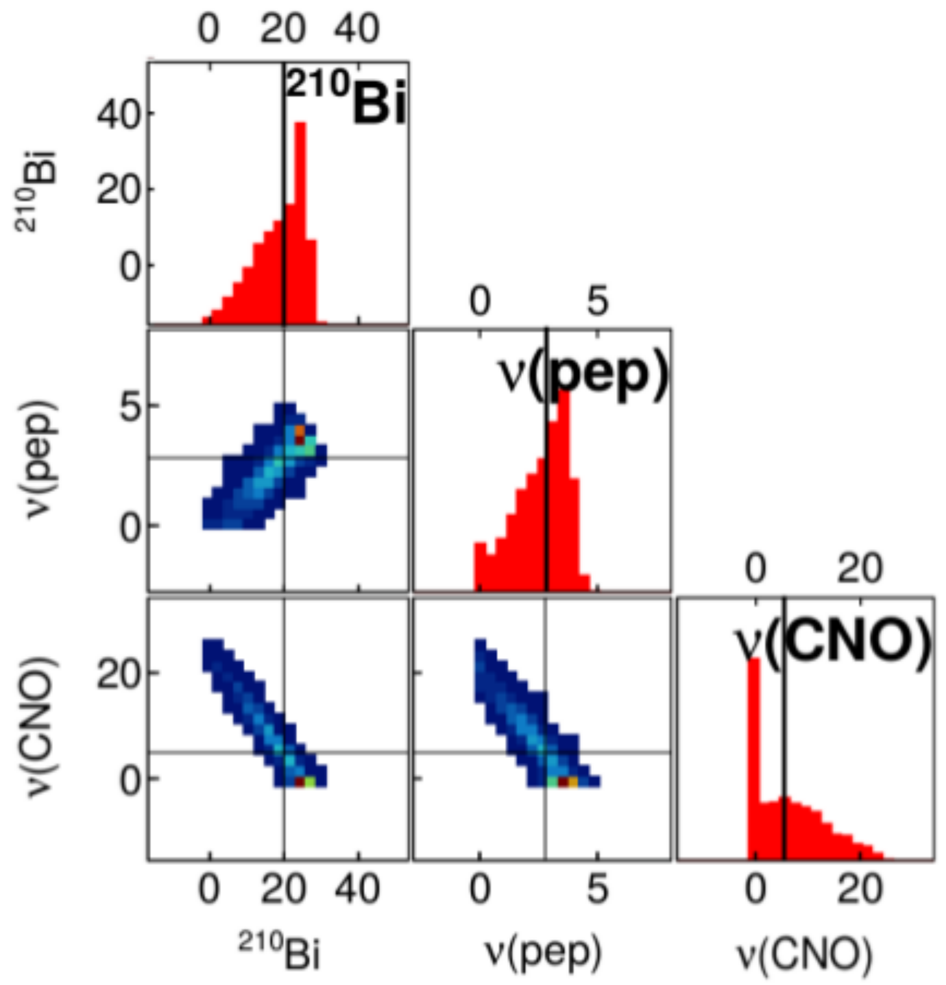
2007 **Phase-I (2007 - 2010):**
First observation of ^{7}Be-ν, pep-ν and ^{8}B-ν

2012 **Phase-II (2012 - 2016):**
Comprehensive measurement of pp-chain
(Nature 2014 and 2018)

2016 **Phase-III (2016 - 2021):**
- First direct experimental evidence of CNO neutrinos (Nature 2020)
- First Directional Measurement of sub-MeV Solar Neutrinos

CHALLENGES OF CNO MEASUREMENT

Most important backgrounds: ν(pep) and ^{210}Bi



Strong anti-correlation

Indipendent constraints:

- $\nu(pep) = 2.74 \pm 0.04$ **cpd/100t** (solar luminosity constraint + global analysis of solar data excluding Borexino Phase III);
- **^{210}Bi constraint is the main challenge of the analysis.**

^{210}Bi constrain through ^{210}Po:

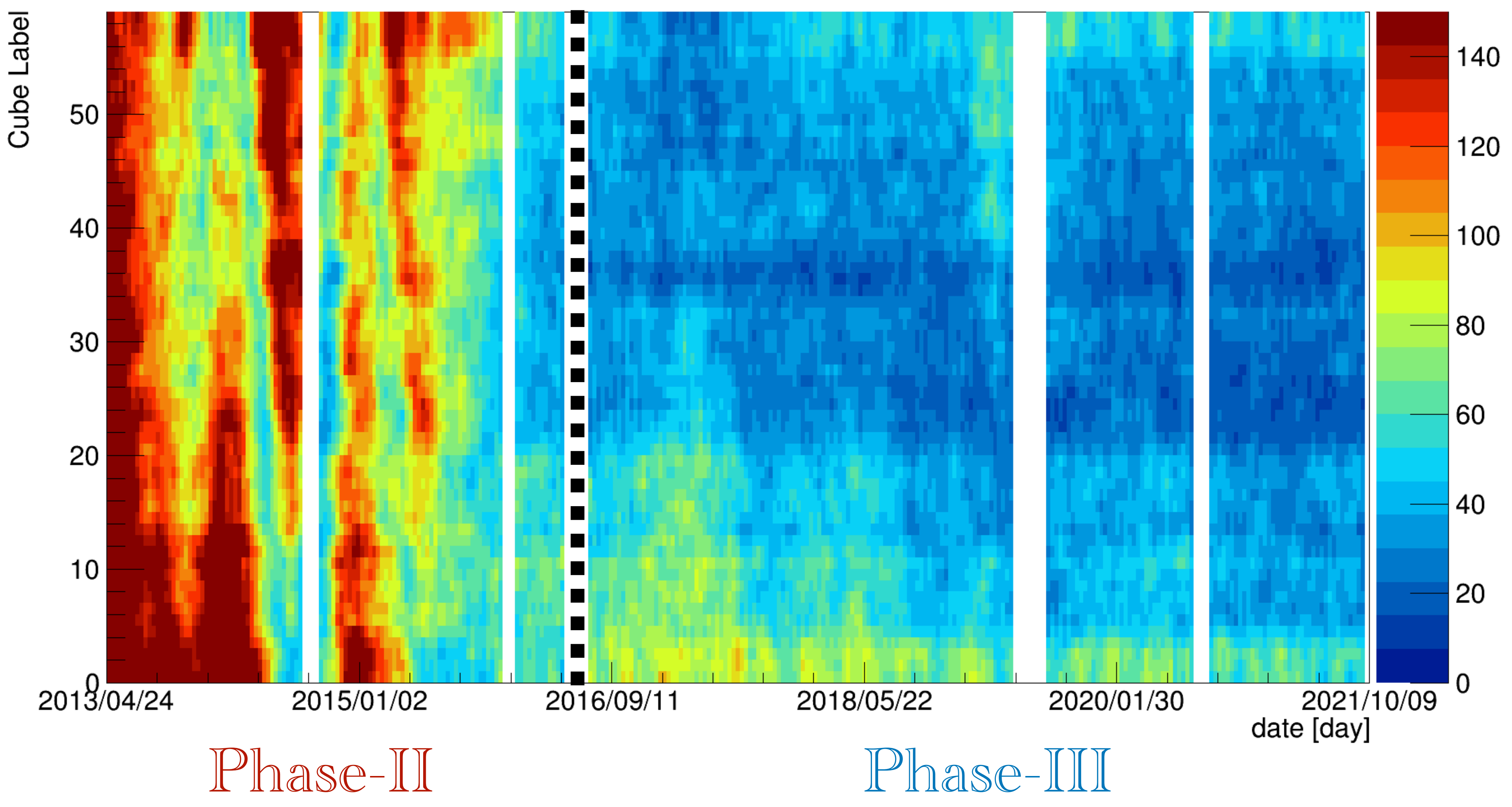
$$^{210}\text{Pb} \xrightarrow[Q_\beta = 63.5\text{ keV}]{\tau \approx 32\text{ y}} \boxed{^{210}\text{Bi} \xrightarrow[Q_\beta = 1160\text{ keV}]{\tau \approx 7.23\text{ d}} {}^{210}\text{Po}} \xrightarrow[Q_\alpha = 5.3\text{ MeV}]{\tau \approx 199.1\text{ d}} {}^{206}\text{Pb}$$

Temperature gradients inside the detector → Convective motions in the liquid scintillators → Unknown amount of out-of-equlibrium ^{210}Po inside the FV

Secular equilibrium is broken: $R(^{210}\text{Po}) \geq R(^{210}\text{Bi})$

Thermal insulation of the detector:

^{210}Po Rate [cpd/100t] in Cubes



Low Polonium Field (LPoF):

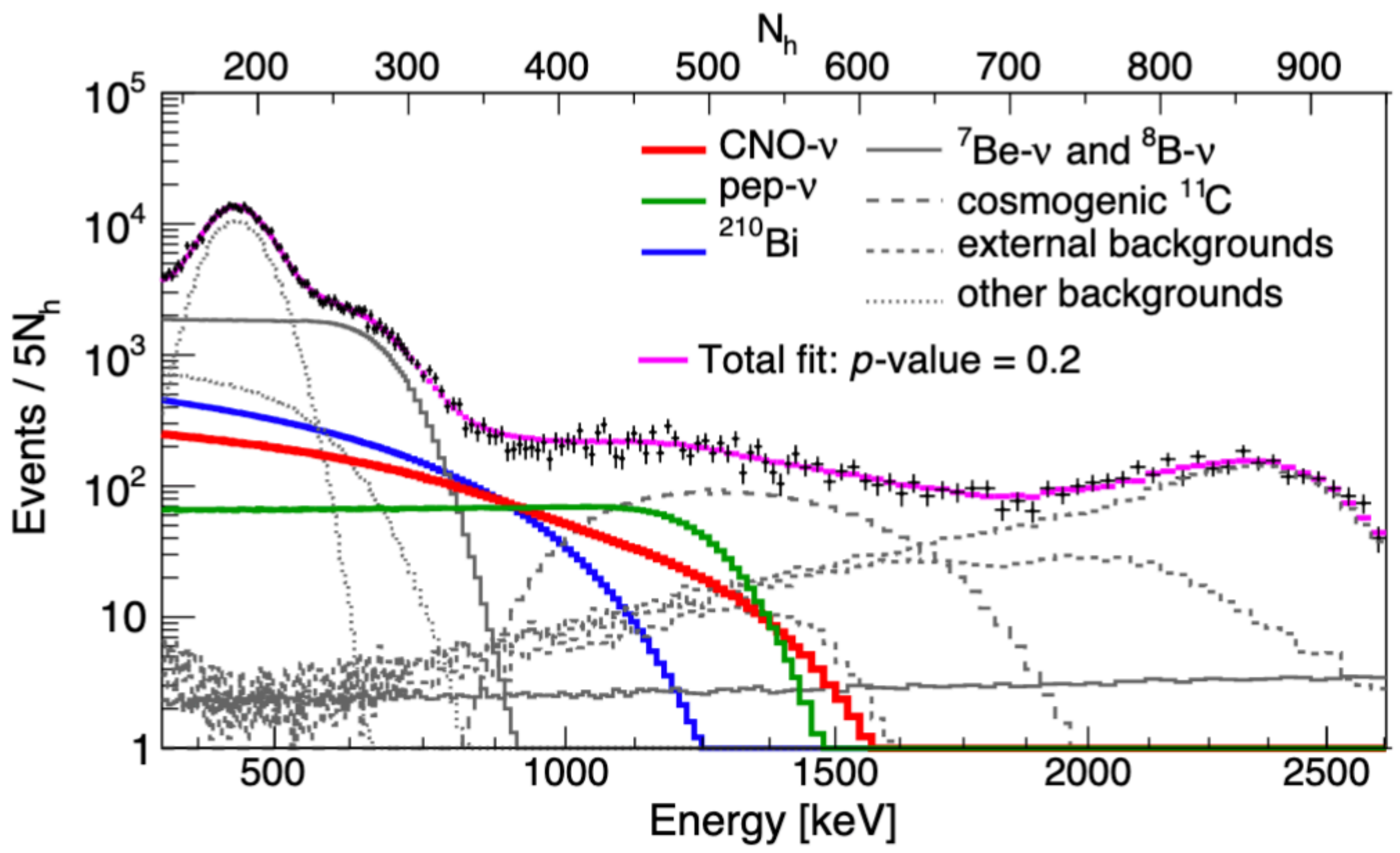
Region inside the FV where the additional ^{210}Po contribution is minimum

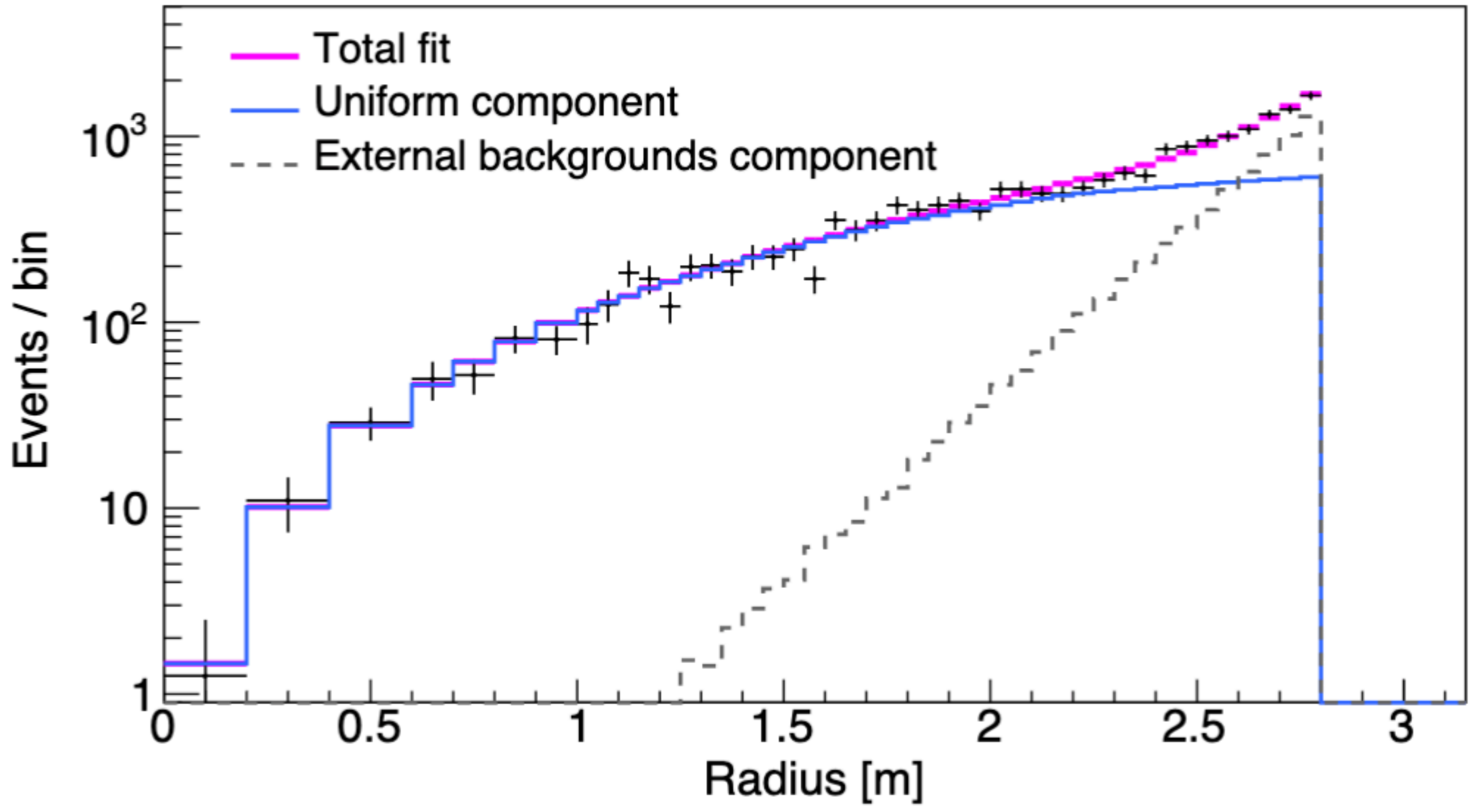
Upper limit:

$R(^{210}Bi) = 10.8 \pm 1.0$ **cpd/100t**

(11.3 ± 1.5 **cpd/100t for first CNO measurement**)

SPECTRAL FIT

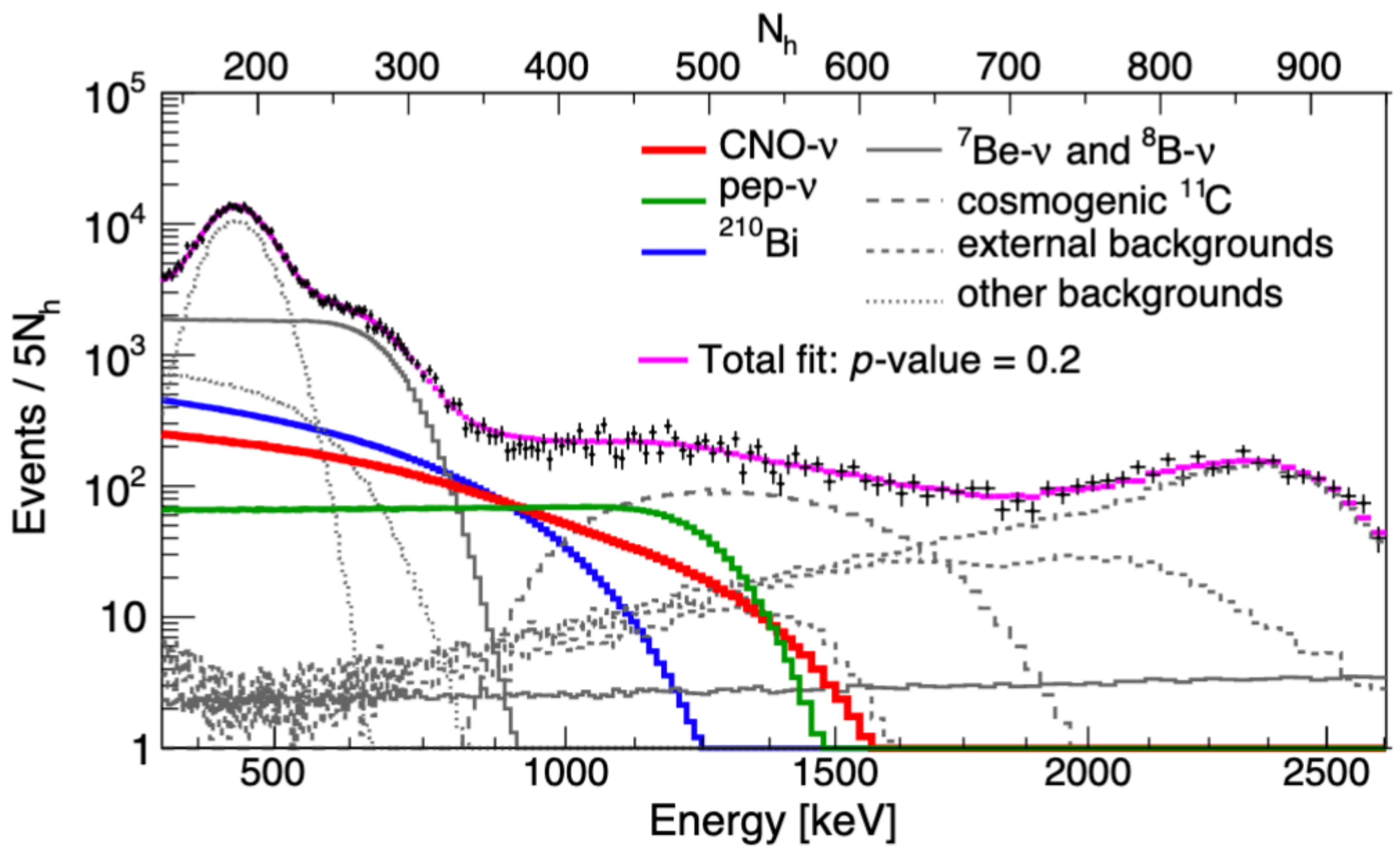


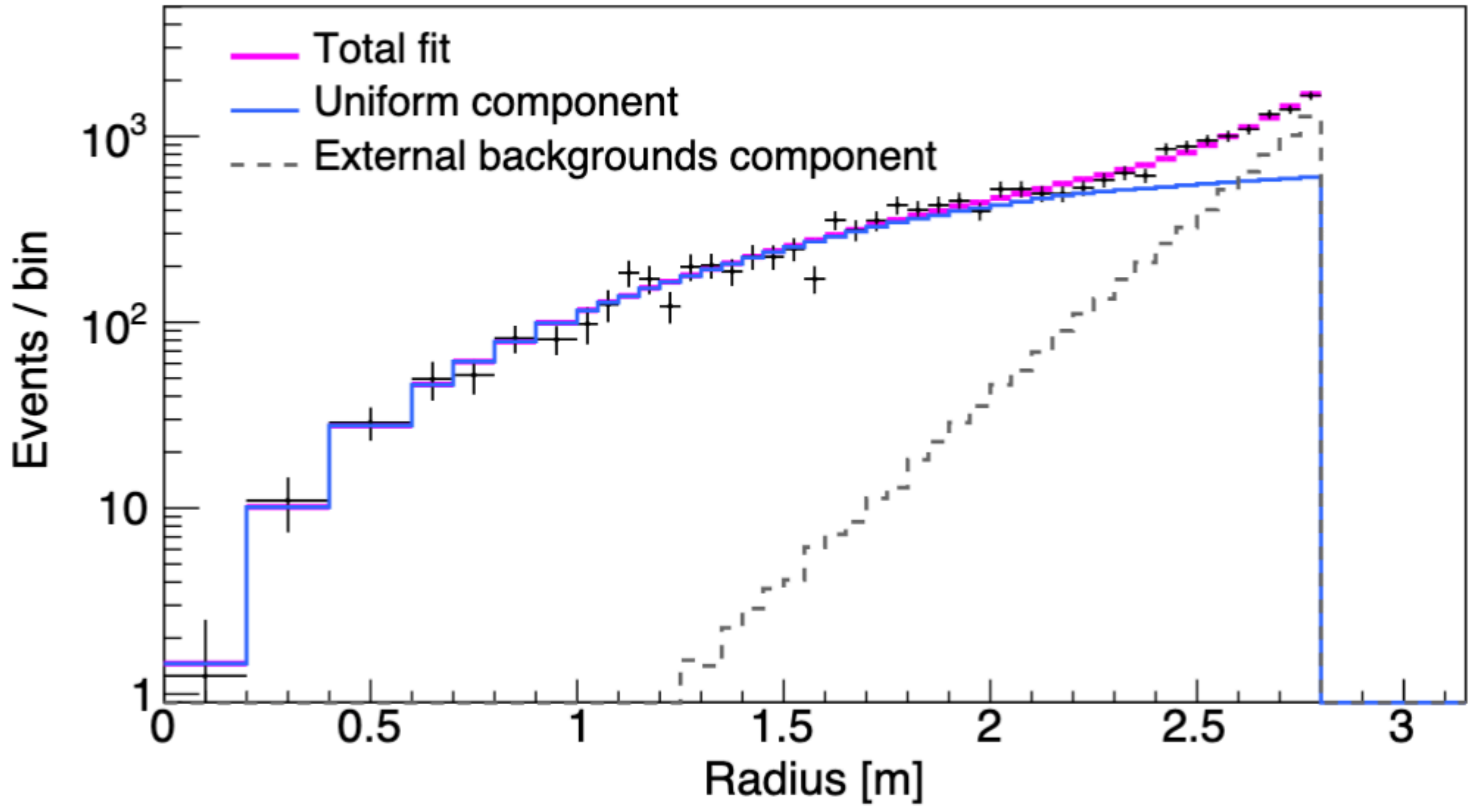


Multivariate spectral fit: interaction rates are obtained by maximizing a binned likelihood function

$$\mathscr{L}_{MV} = \mathscr{L}_E^{Tag} \cdot \mathscr{L}_E^{Sub} \cdot \mathscr{L}_R \cdot \mathscr{L}_{pep} \cdot \mathscr{L}_{^{210}Bi}$$

SPECTRAL FIT





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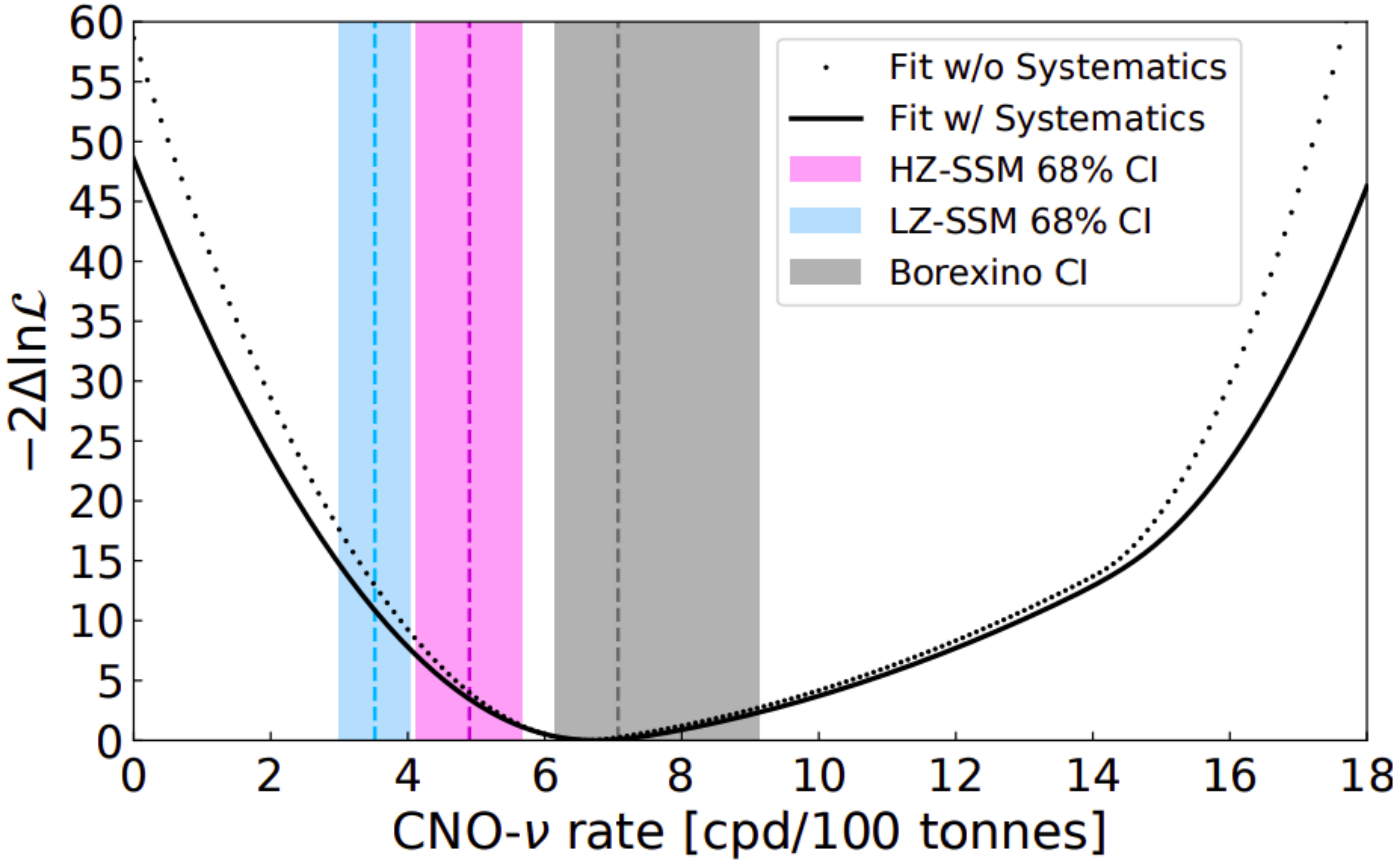

Results (stat. + syst.):

R(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t

$\phi(CNO) = 6.6^{+2.0}_{-0.9} \cdot \nu \cdot cm^{-2}s^{-1}$

no-CNO hypothesis rejected with **>7σ significance at 90% C.L.**

S. Appel et al. (Borexino Collaboration), Physical Review Letters. 129, 252701 (2022).

SPECTRAL FIT

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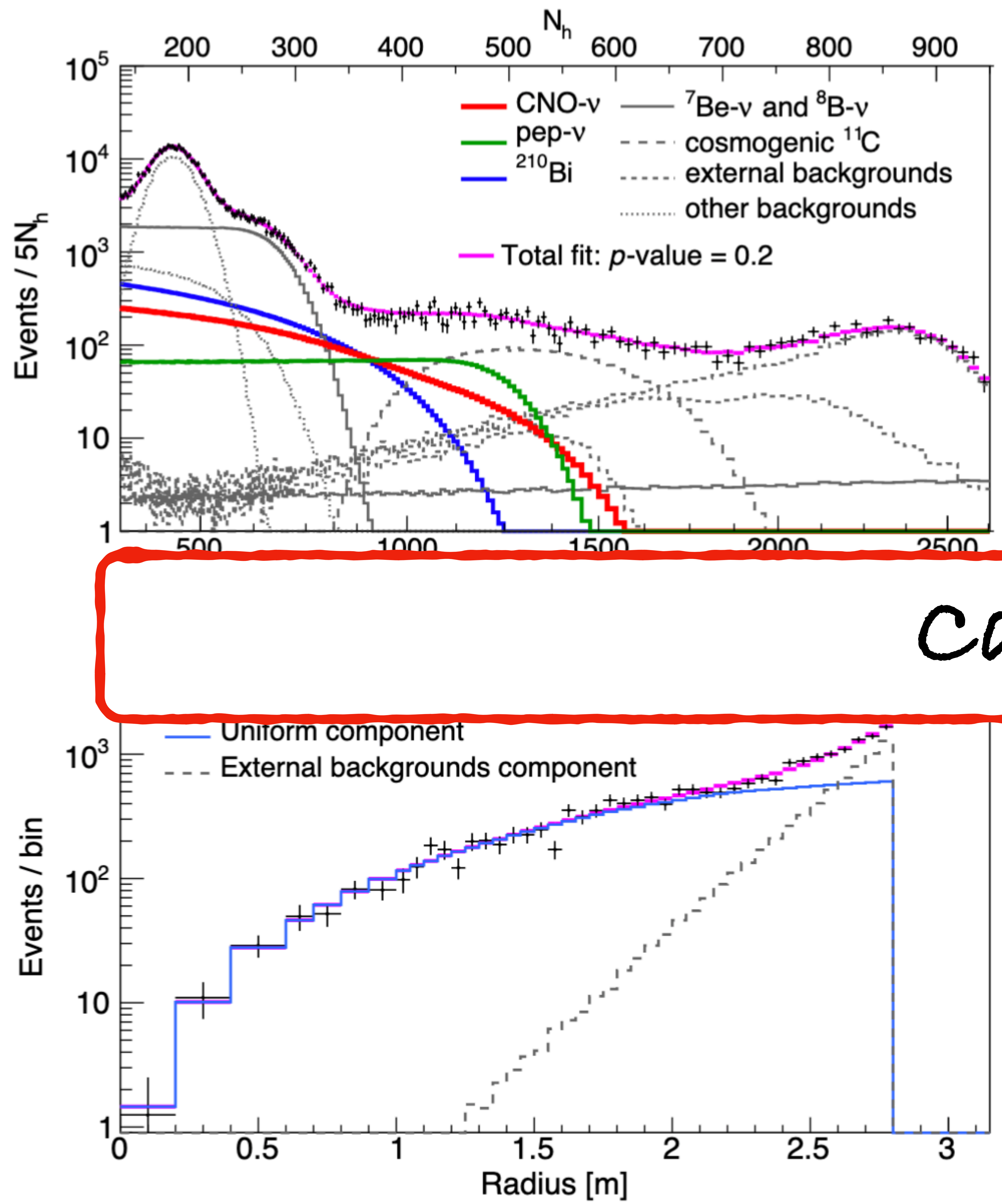

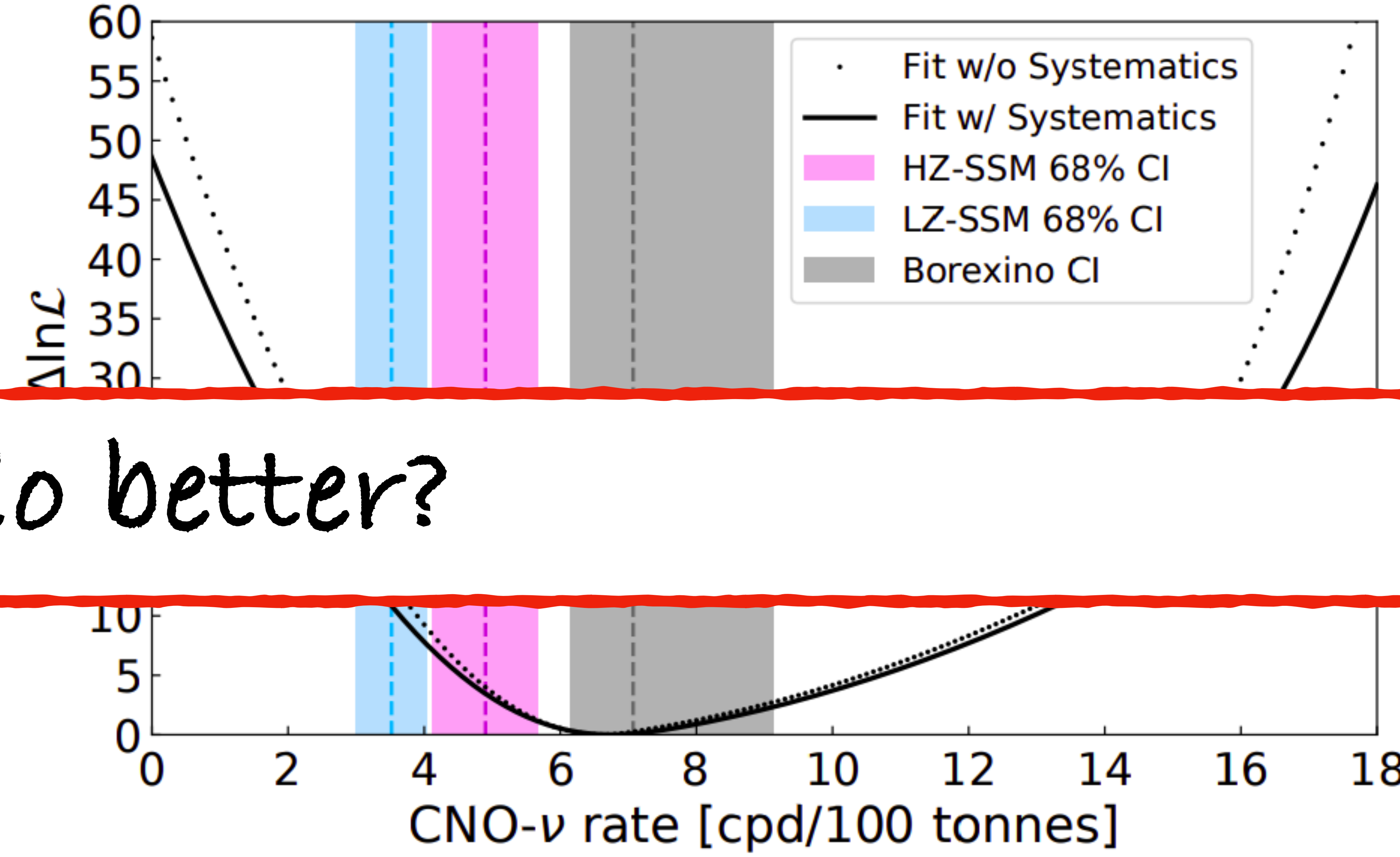

Can we do better?

Results (stat. + syst.):
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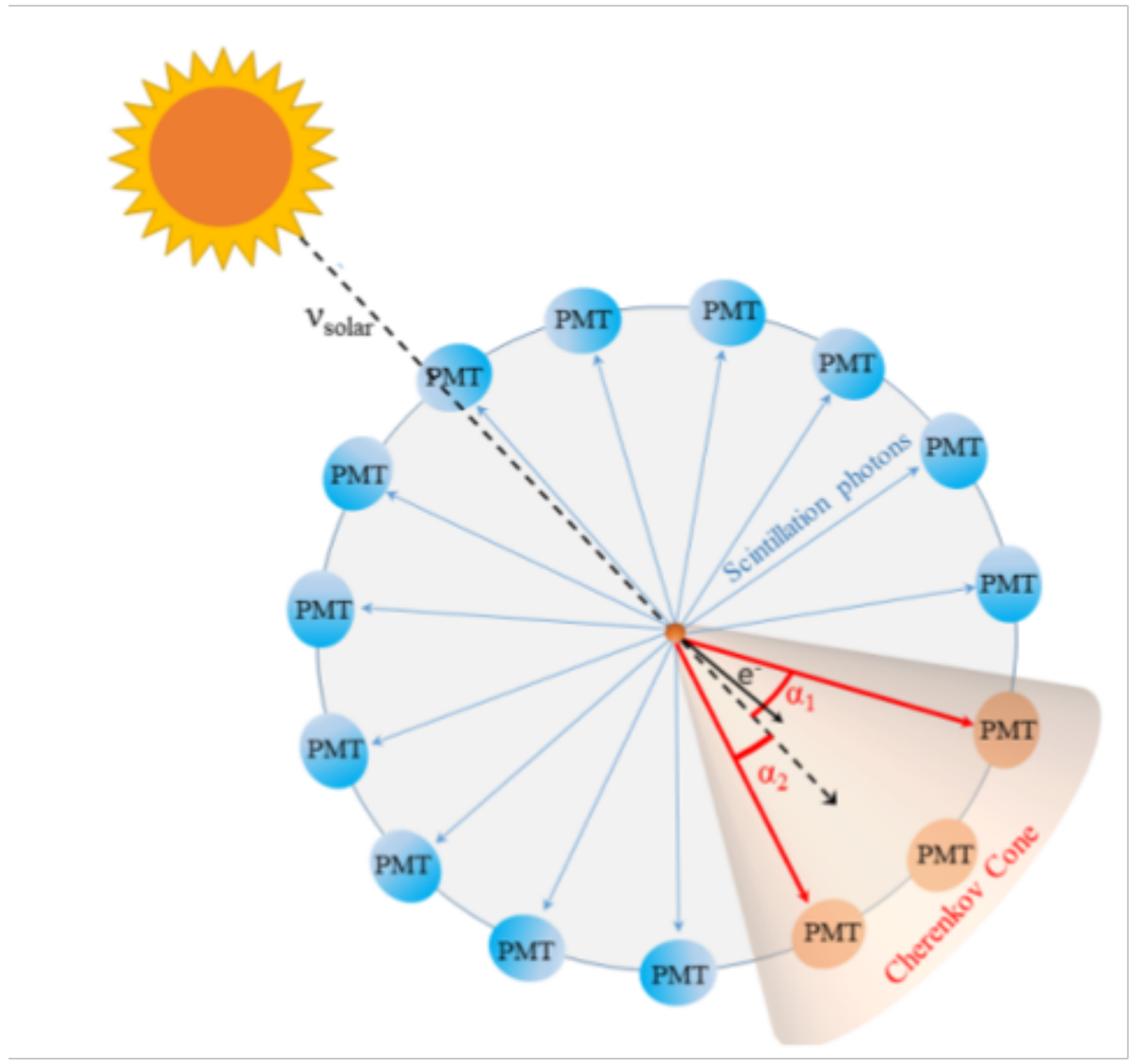
CORRELATED INTEGRATED DIRECTIONALITY (CID)

Newly developed method by Borexino:

First Directional Measurement of sub-MeV Solar Neutrinos with Borexino, *Phys. Rev. Lett*. 128 (2022) 091803.

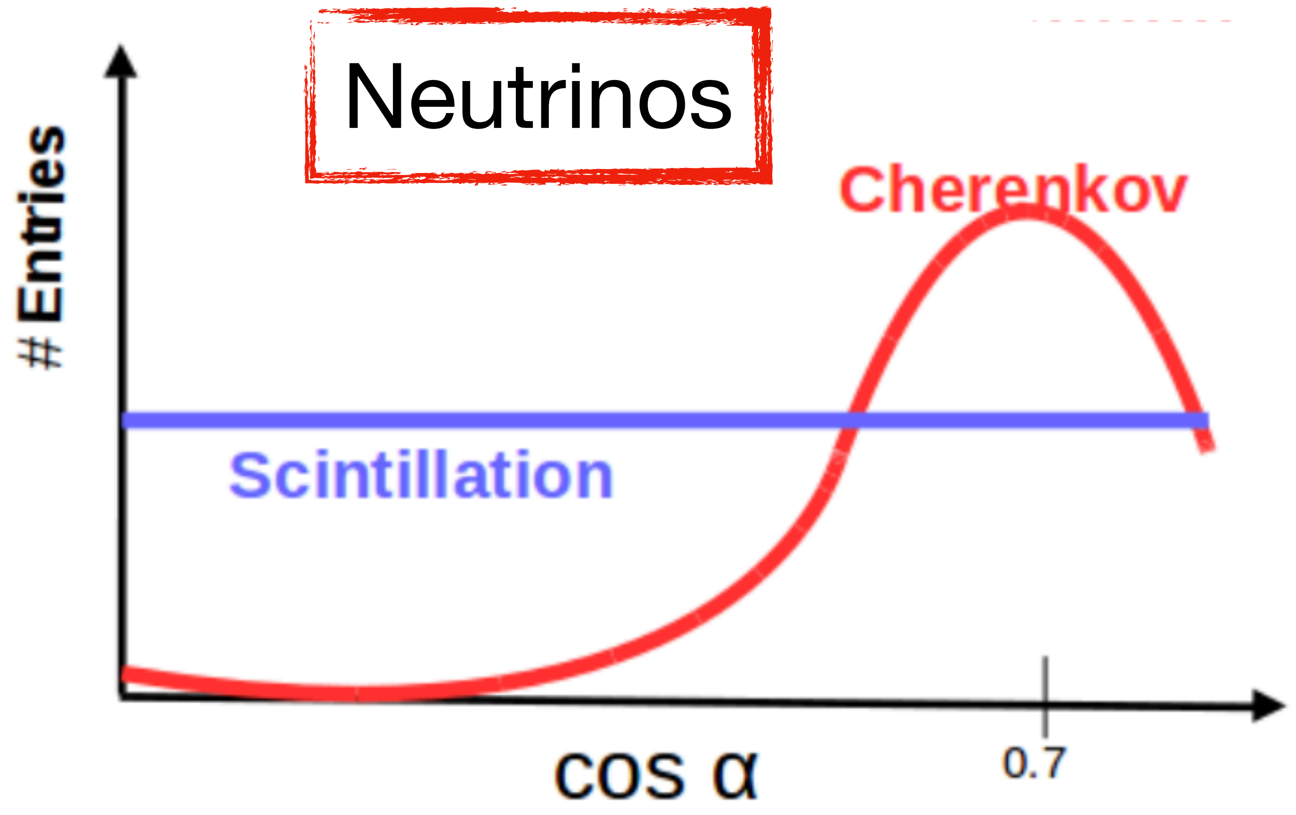
Correlated and Integrated Directionality for sub-MeV solar neutrinos in Borexino, *Phys. Rev. D* 105 (2022) 052002.

Exploit fast **Cherenkov light emission for** statistical separation of solar neutrinos and background



Neutrino Event:

Čerenkov light correlated to position of the Sun (non flat cosα)



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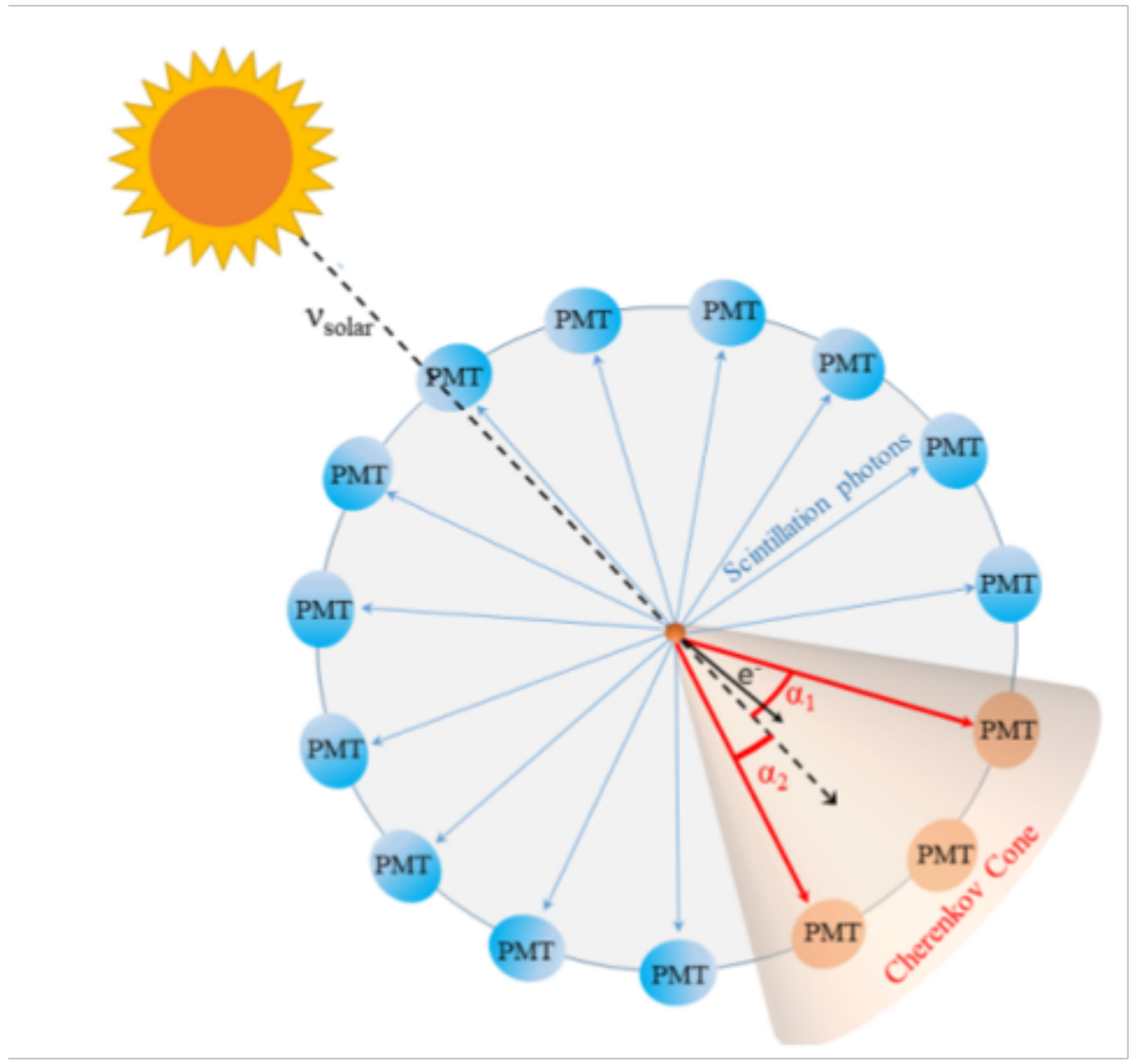

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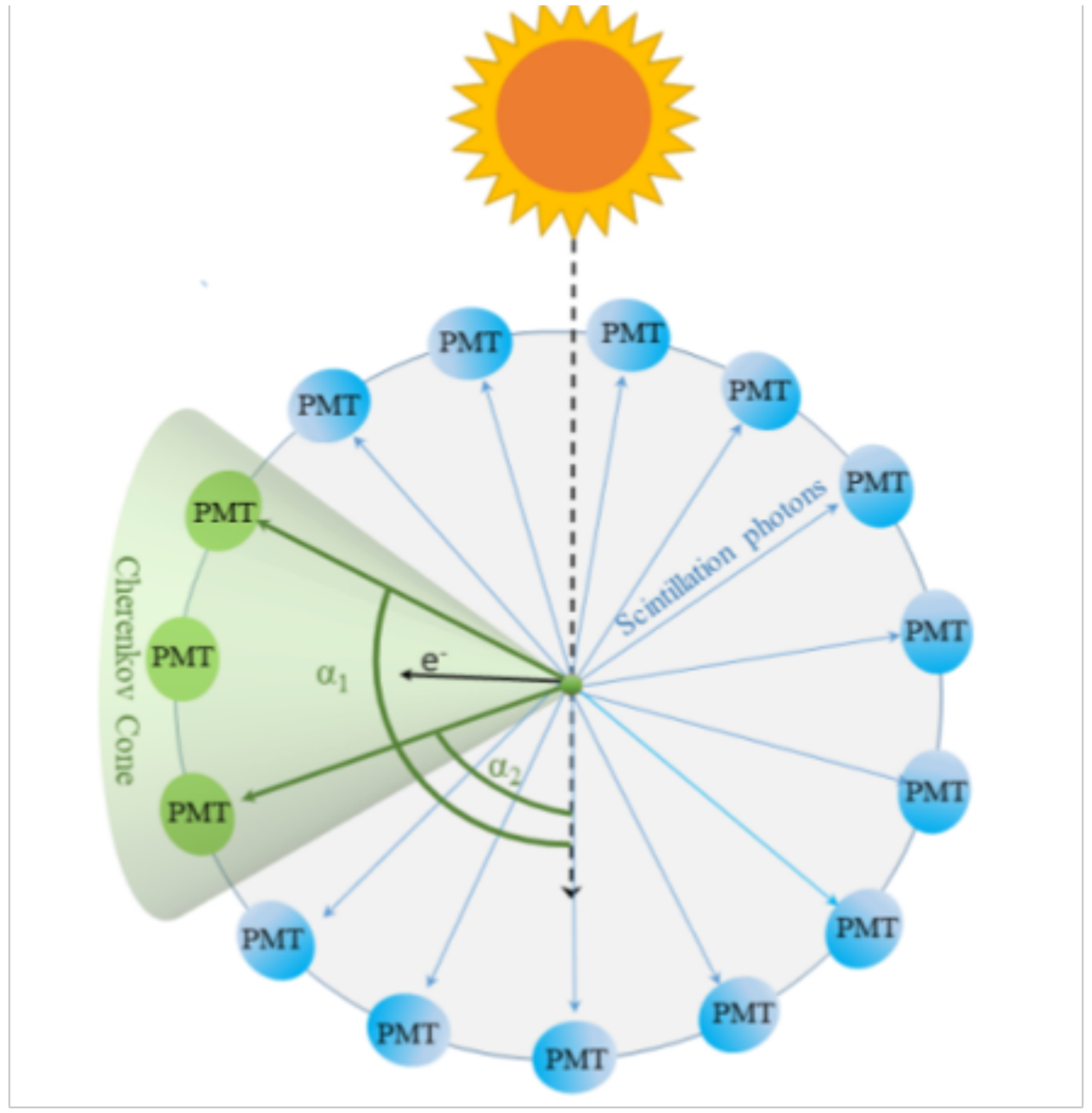
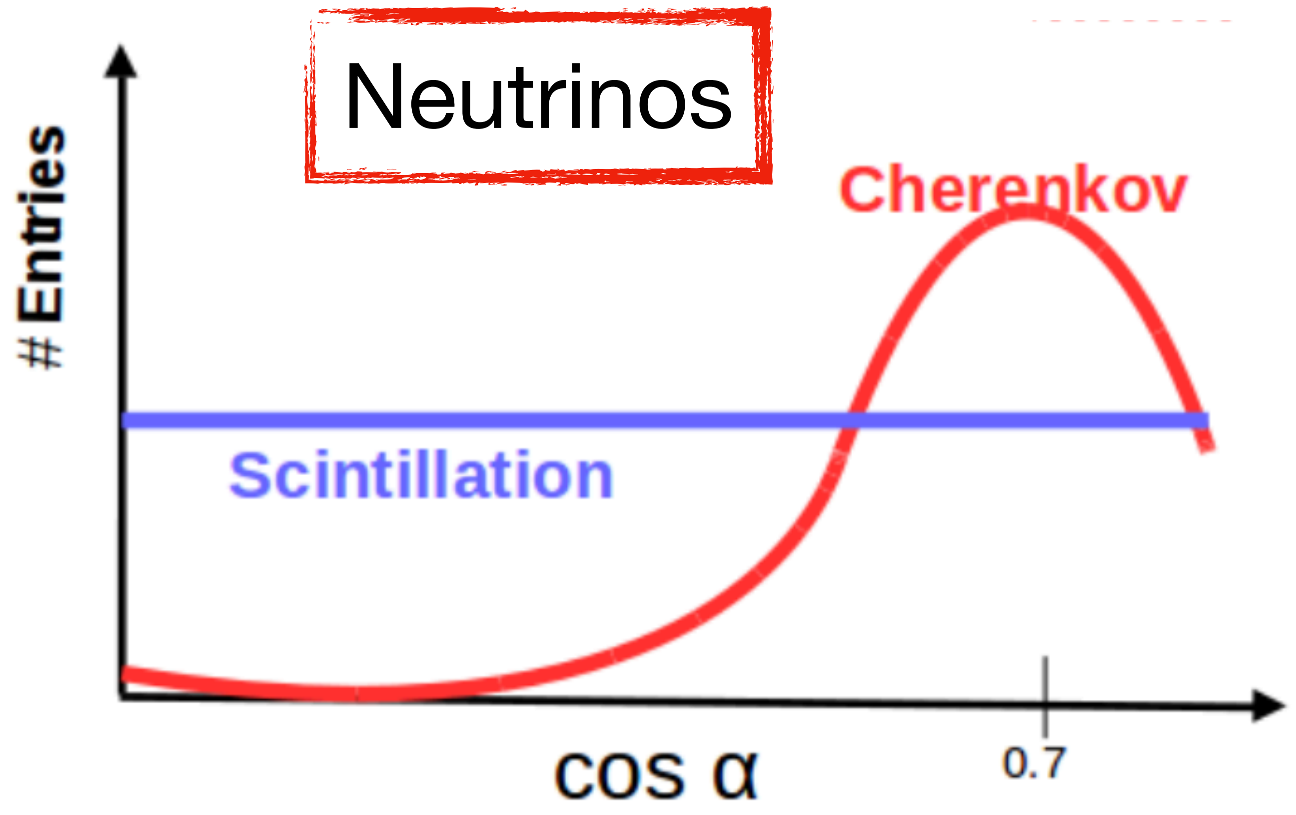
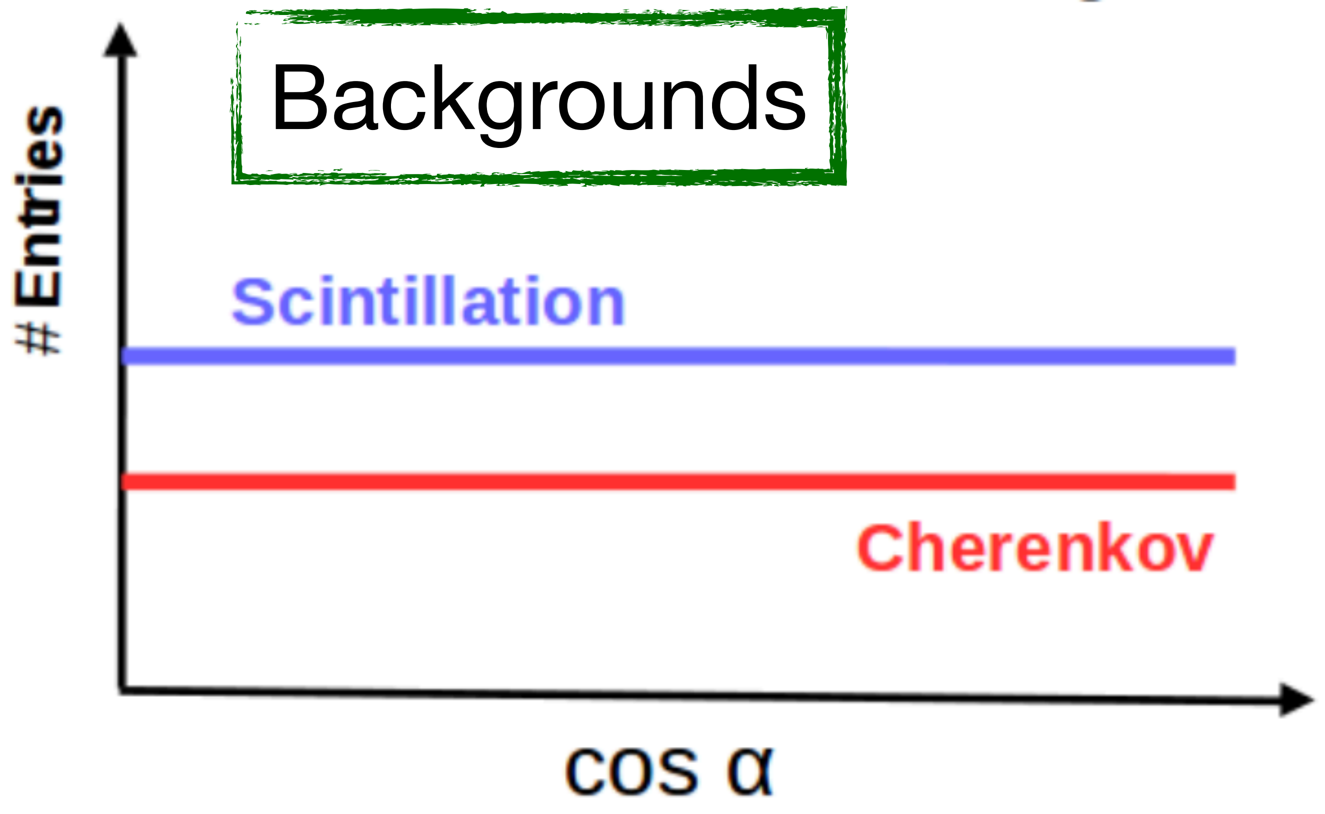


Background Event:

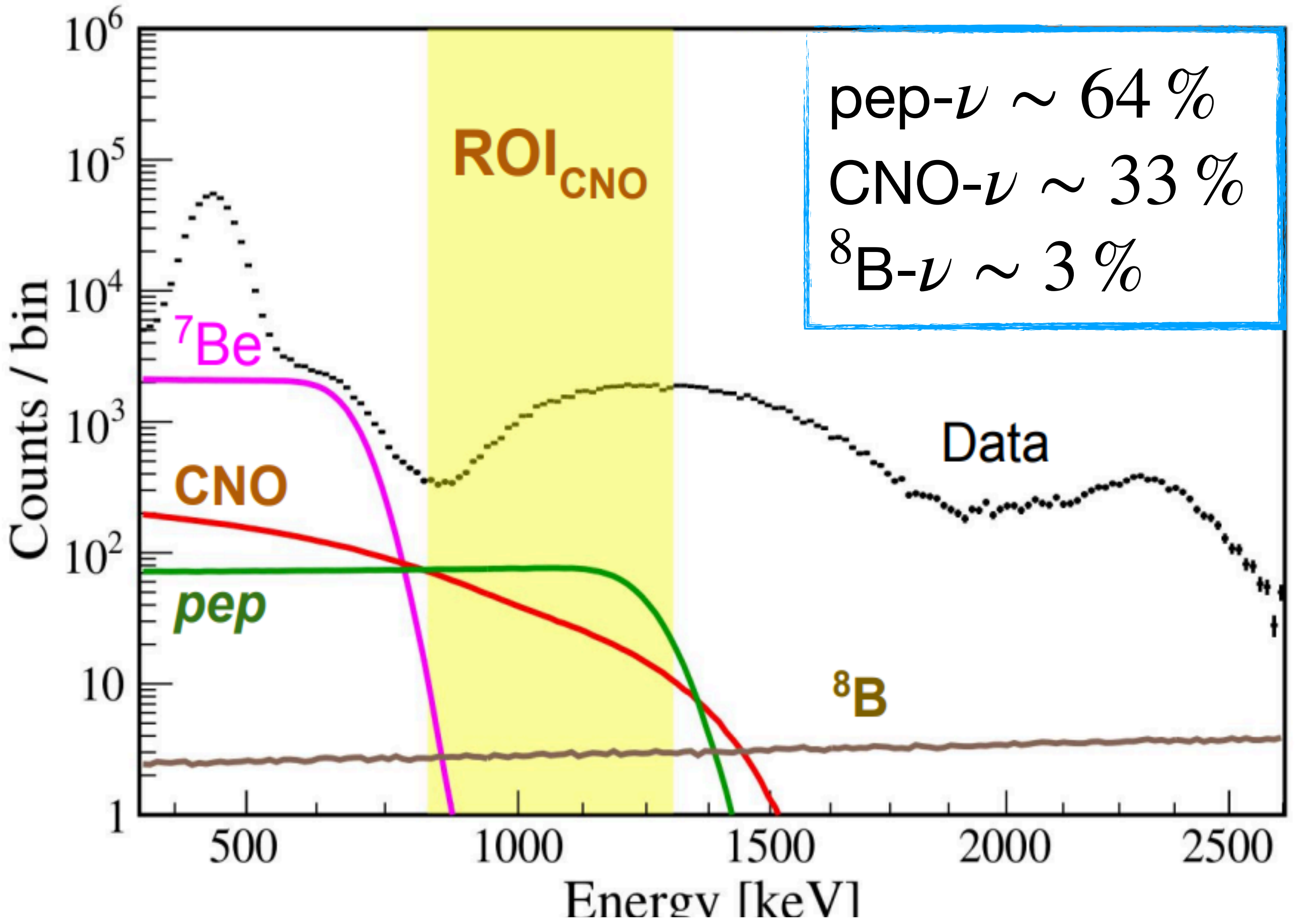
Čerenkov light uncorrelated to position of the Sun (flat cosα)



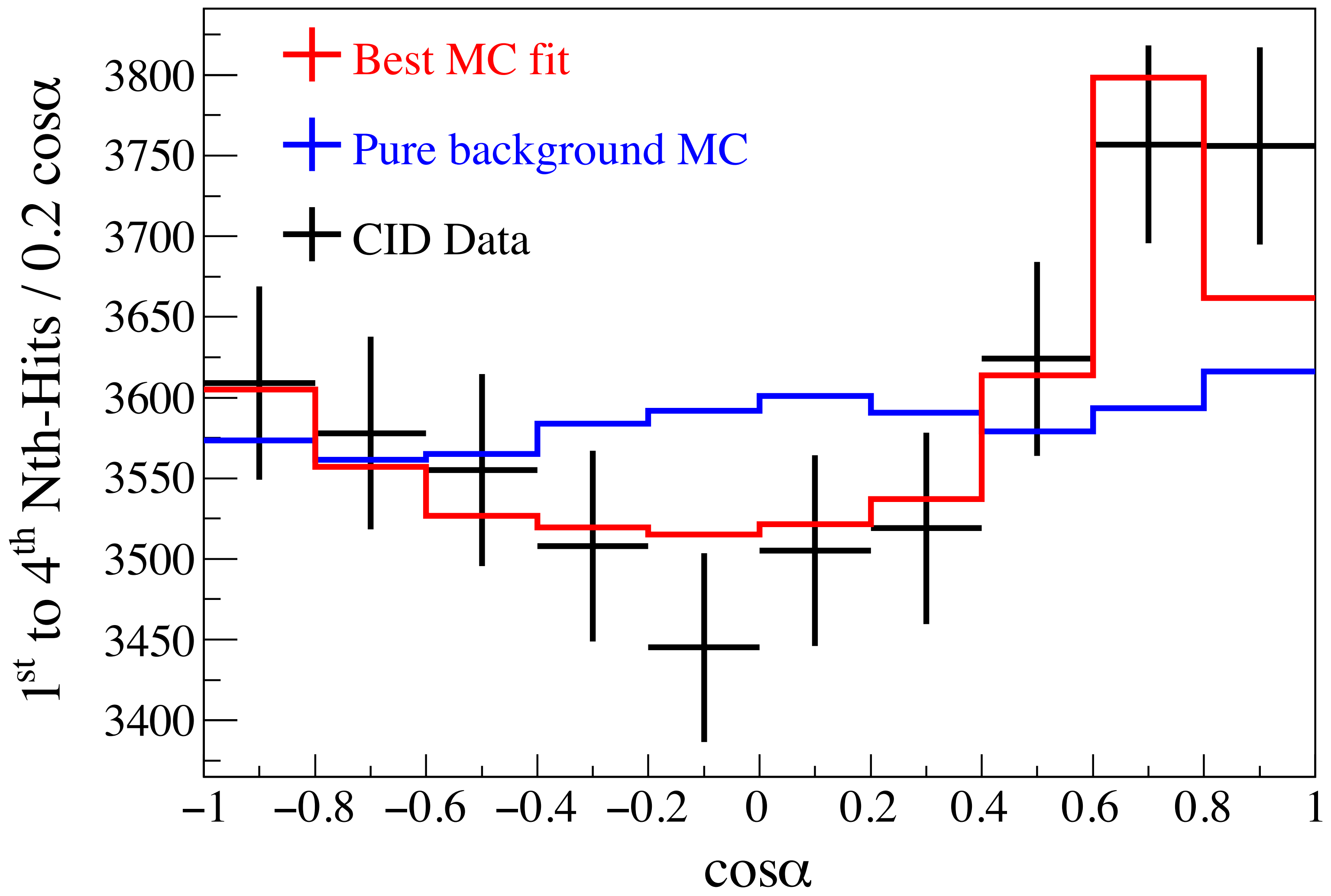


CORRELATED INTEGRATED DIRECTIONALITY (CID)

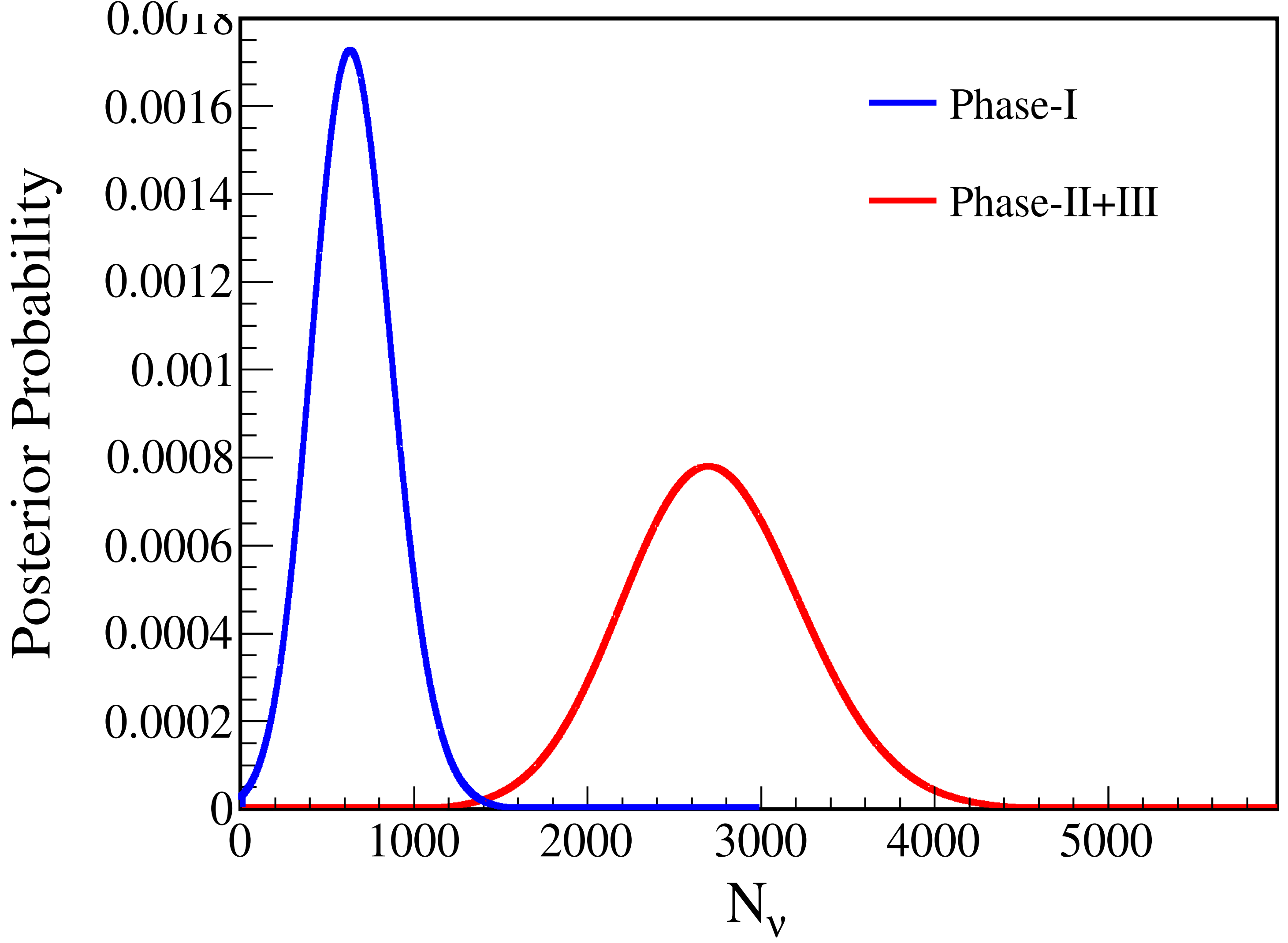
Region of Interest (ROI):



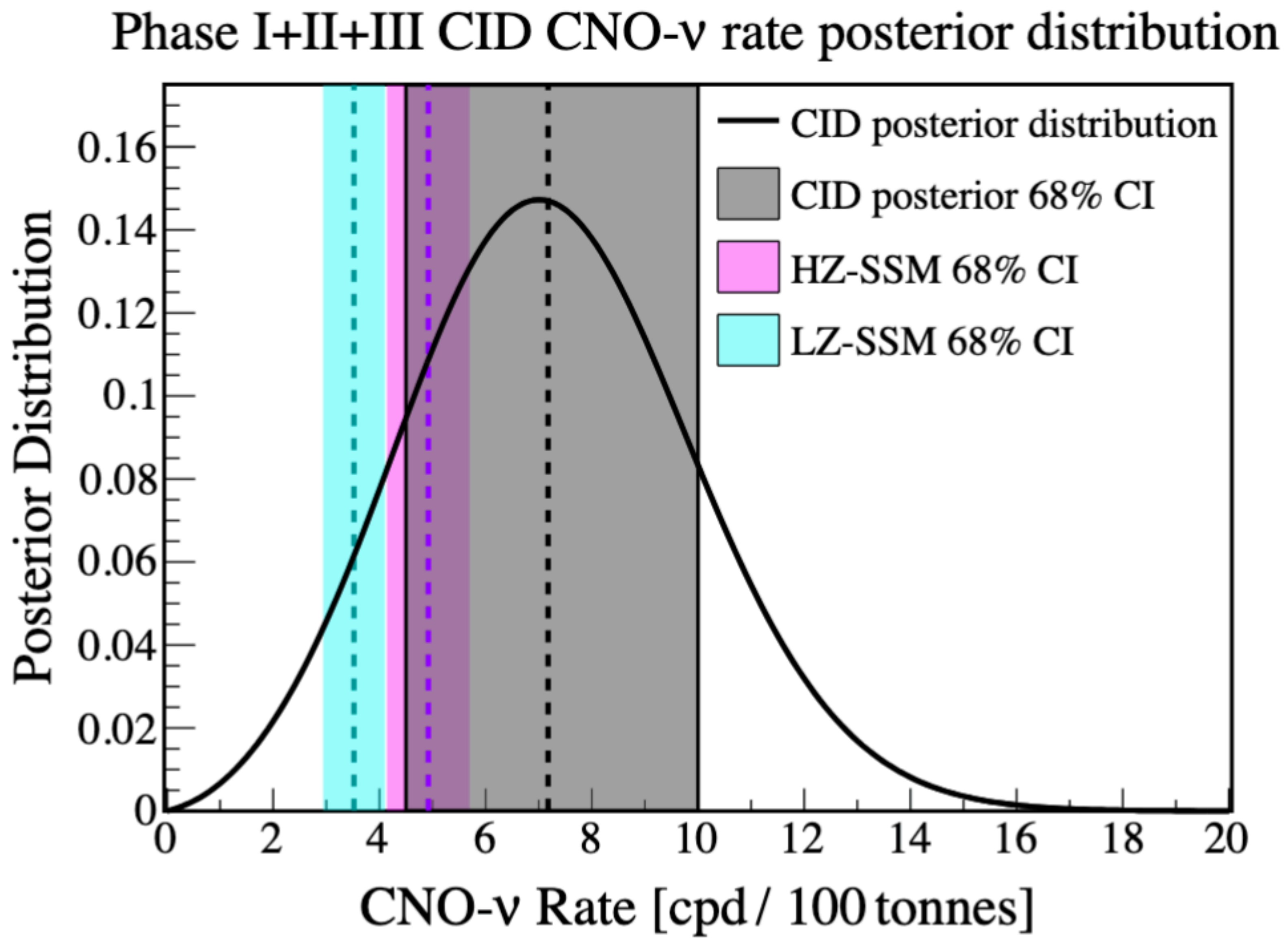
χ^2-fit to extract N_ν



N_ν posterior probability



- Constrain Non-CNO-ν to SSM
- combine all phases
- convert to rate



☑ **R(CNO) = $7.2^{+2.8}_{-2.7}$ cpd/100t**

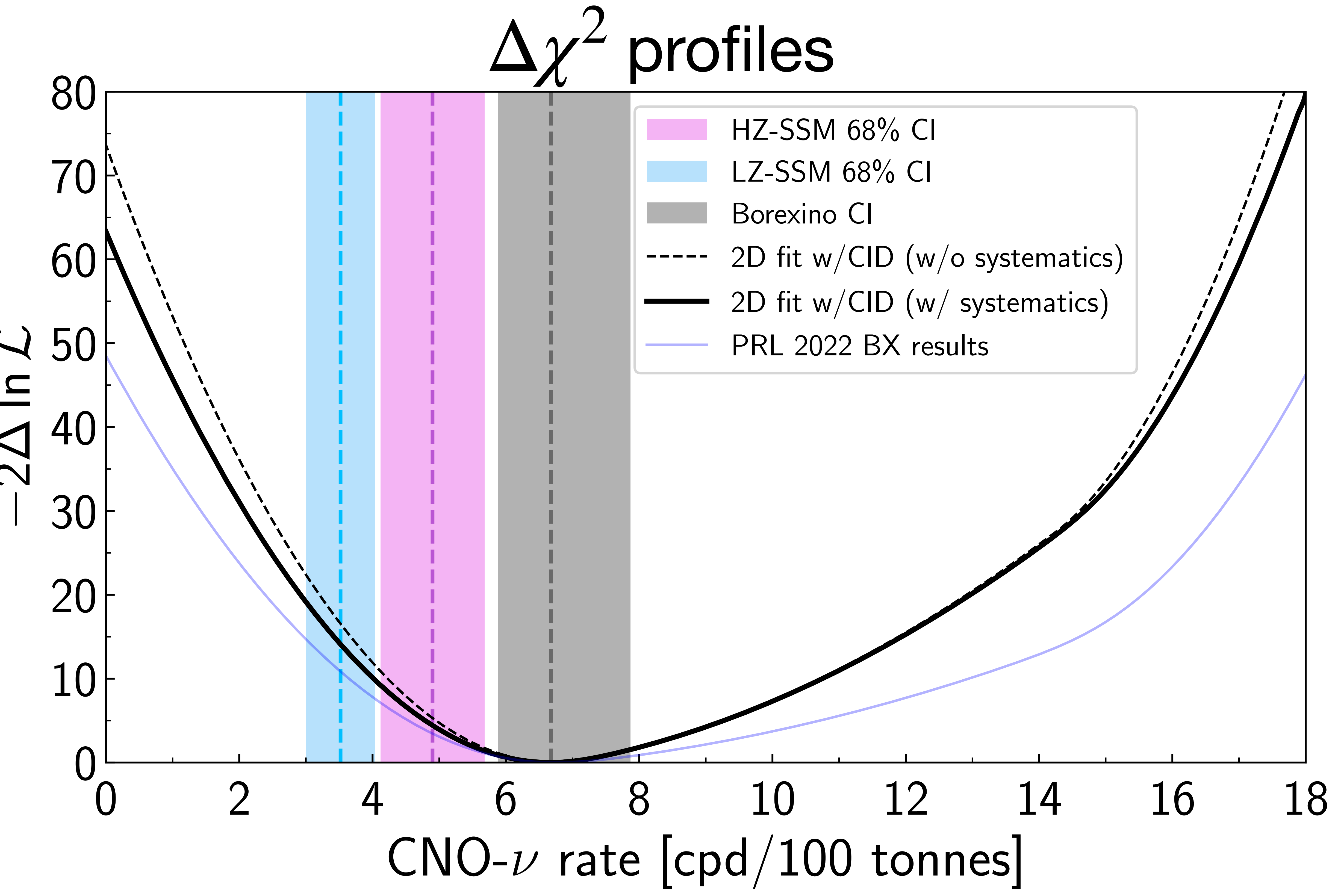
☑ No-CNO hypothesis disfavoured at $\sim 5.3\sigma$
without assumptions on backgrounds (^{210}Bi)

FINAL CNO RESULTS

Final Results of Borexino on CNO solar neutrinos, arXiv:2307.14636 [hep-ex]

Independent measurement of the **number of solar neutrino events** can be used an **external constraint** in the multivariate spectral fit

Combine the multivariate fitting routine with new CID measurement on CNO+pep solar neutrinos:



Borexino R(CNO) results:

First detection (2020):	R(CNO) = $7.2^{+3.0}_{-1.7}$ cpd/100t
Improved measurement (2022):	R(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t
Combined analysis (2023):	**R(CNO) = $6.7^{+1.2}_{-0.8}$ cpd/100t**

Most precise on CNO measurement so far
(Significance to no-CNO hypothesys > 8σ)

Solar implications:

☑ **Determination of C+N abundance** in the Sun using neutrinos

→ **(~2σ tension with SSM-LZ)**

☑ **Frequentist hypothesis test** based on a likelihood-ratio test statistics including only Borexino results

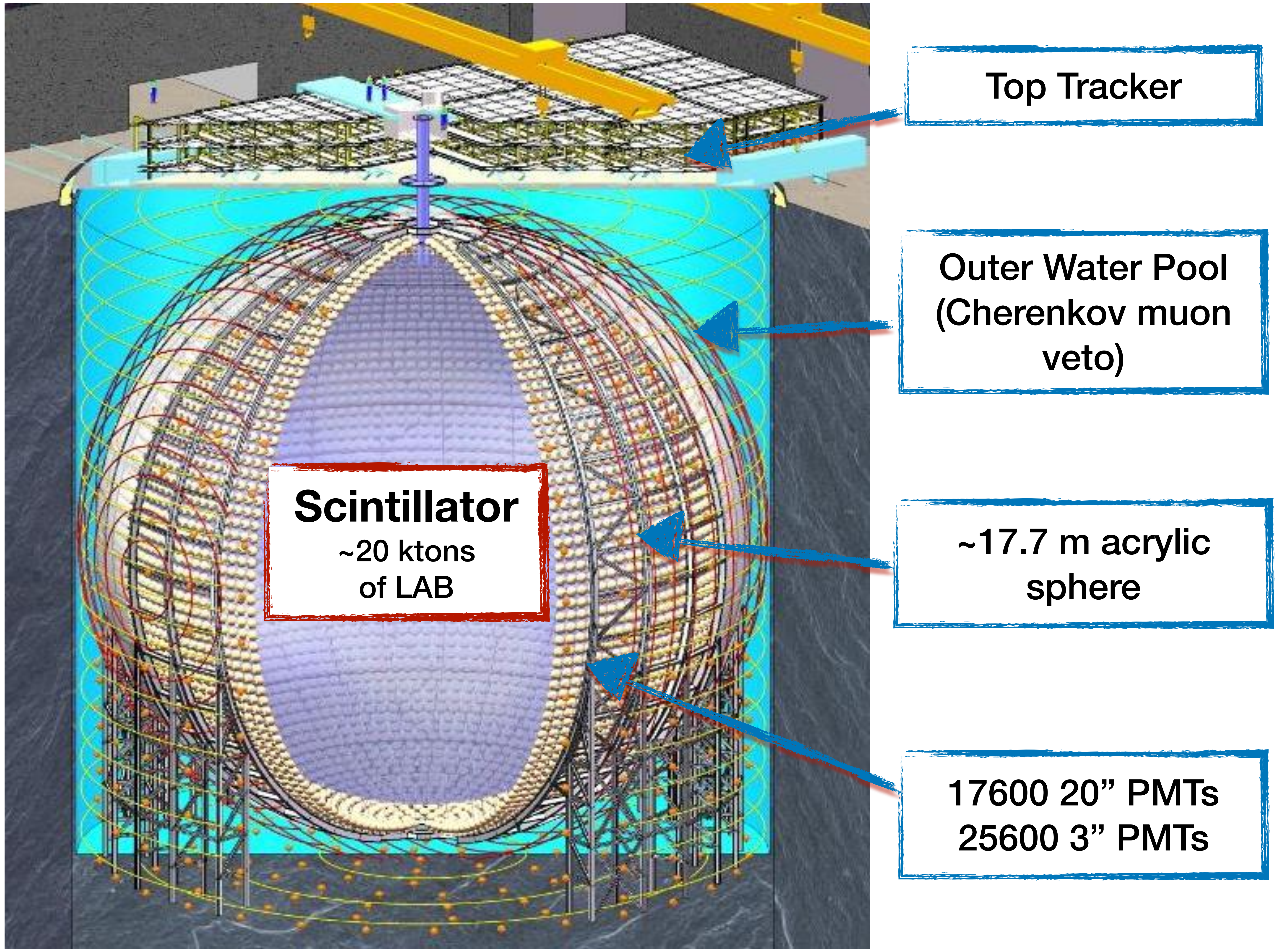
→ **(SSM-LZ disfavoured at ~3.2σ)**

OUTLINE

- Solar neutrinos and importance of CNO cycle
- CNO measurement with Borexino detector
- **Intermediate energy solar neutrinos sensitivity with JUNO detector**

THE JUNO DETECTOR

Construction (China) to be completed by the end of 2023



Scintillator
~20 ktons
of LAB

Top Tracker

Outer Water Pool (Cherenkov muon veto)

~17.7 m acrylic sphere

17600 20” PMTs
25600 3” PMTs

Main goal:

Neutrino mass ordering determination with reactor antineutrinos, through Inverse Beta Decay (IBD)

Characteristics:

✓ Radiopurity needs to be carefully monitored

✓ High eff. light yield (~1350 p.e./MeV)

✓ Excellent energy resolution (~3% at 1 MeV)

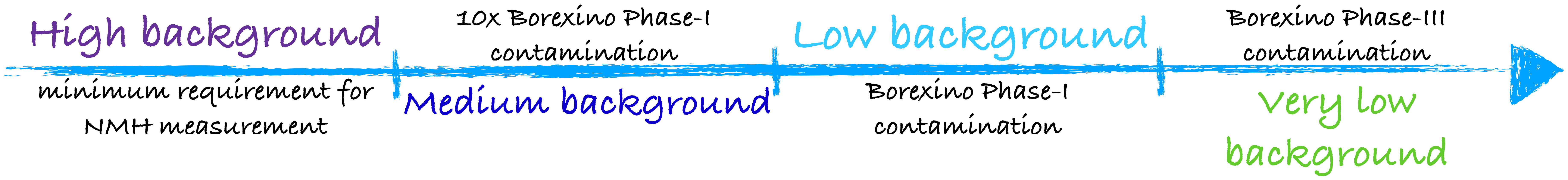
✗ No directional information

Potential to detect neutrinos from many sources, such as *Solar Neutrinos*

JUNO ENERGY SPECTRA

Juno sensitivity to 7Be, pep, and CNO solar neutrinos, arXiv:230303910 [hep-ex]

Radio-purity levels:
(from worst to best)

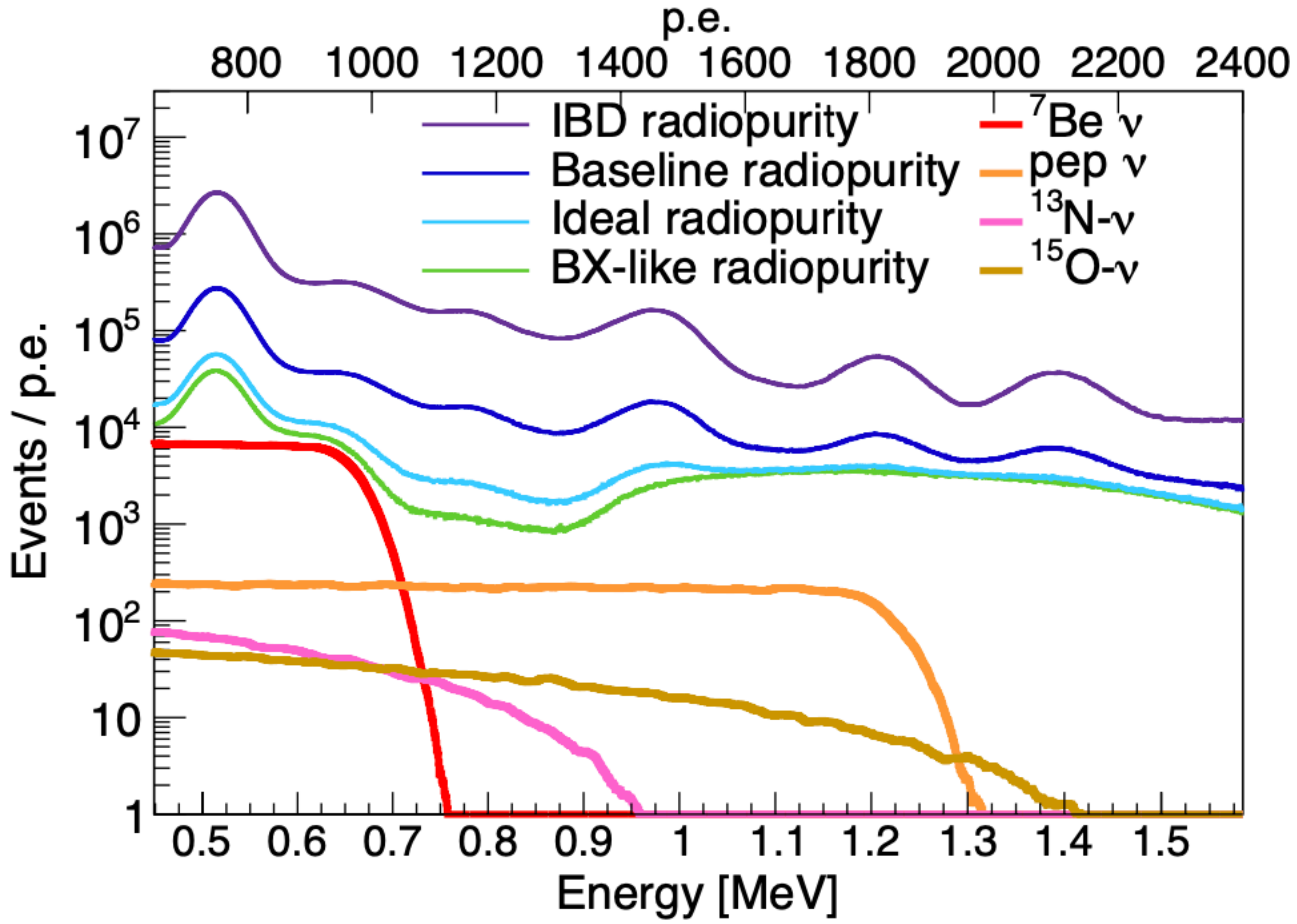


High background
minimum requirement for NMH measurement

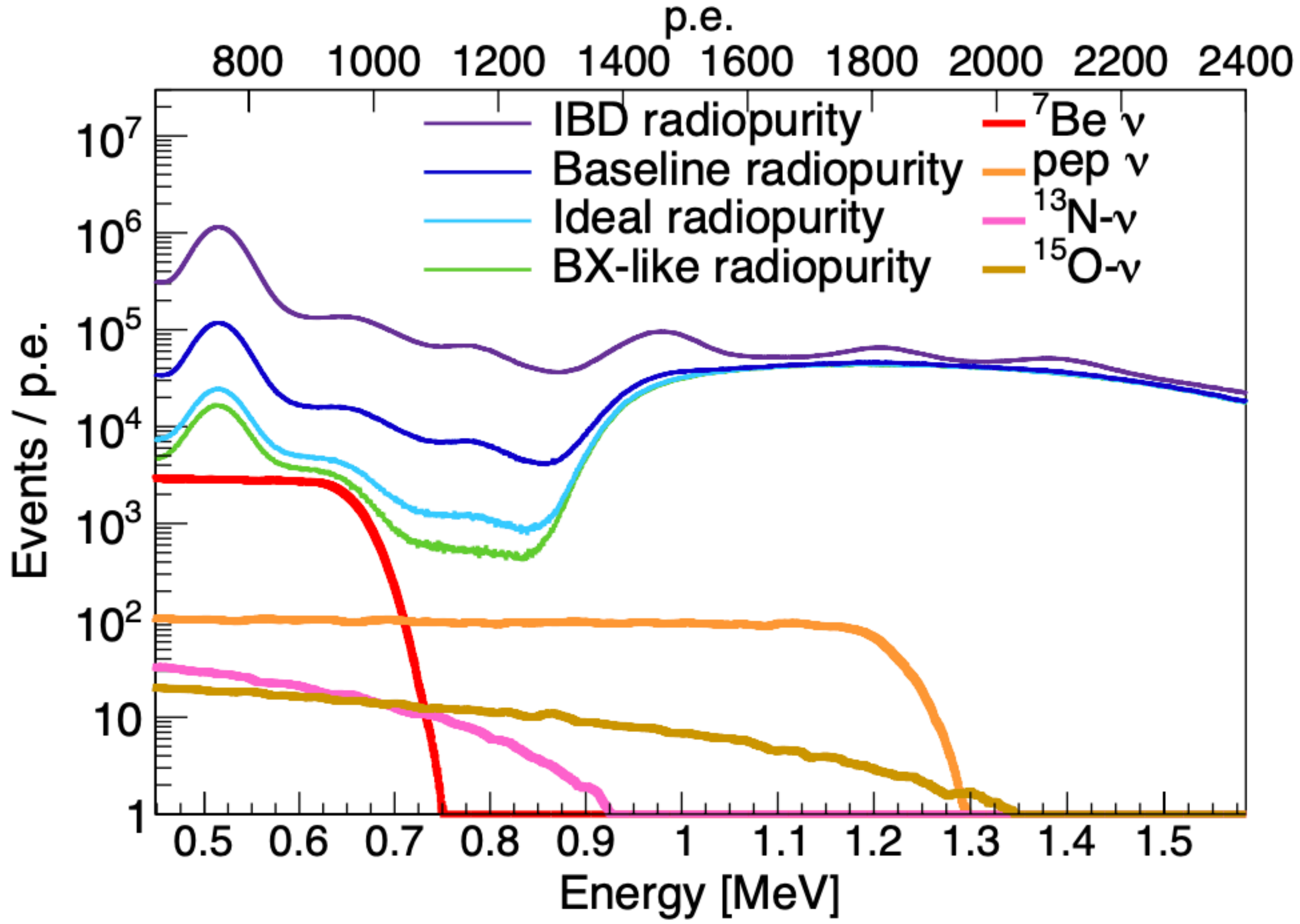
10x Borexino Phase-I contamination
Medium background

Low background
Borexino Phase-I contamination

Borexino Phase-III contamination
very low background



TFC subtracted



TFC tagged

Signals:

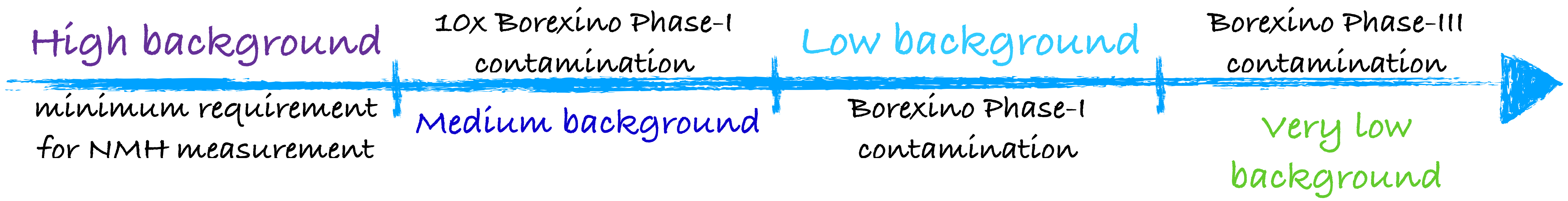
intermediate energy solar neutrinos (**Be7, pep, and CNO**)

Backgrounds:

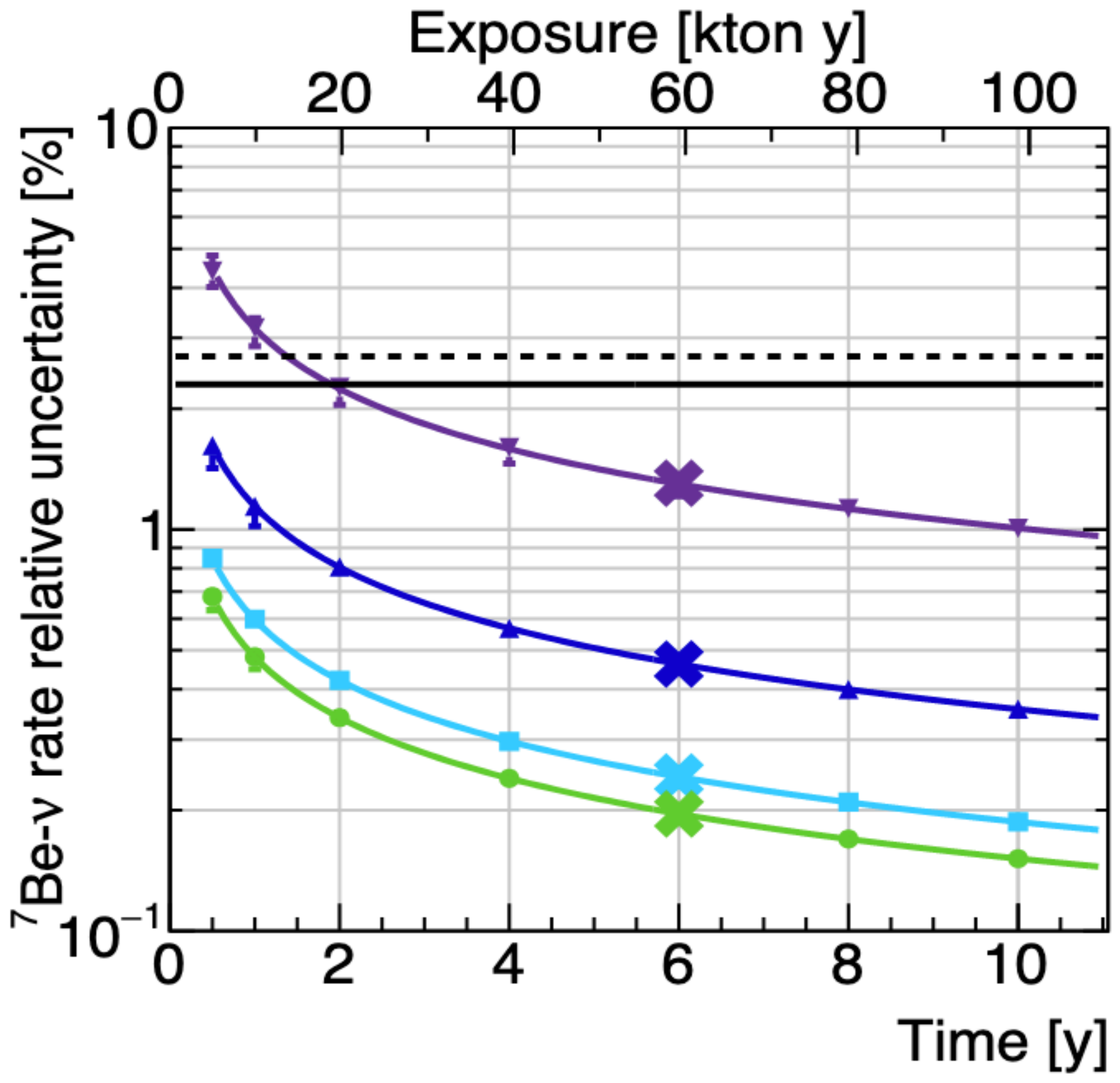
- **Internal:** ^{210}Bi, ^{210}Po, ^{85}Kr, ^{40}K, ^{232}Th chain, ^{238}U chain
- **Cosmogenic:** ^{11}C, ^{6}He, ^{10}C
- **External:** removed via fiducial volume cut

Interaction rates are extracted by means of a **binned poisson likelihood optimisation**, simultaneously fitting TFC subtracted and tagged energy spectra

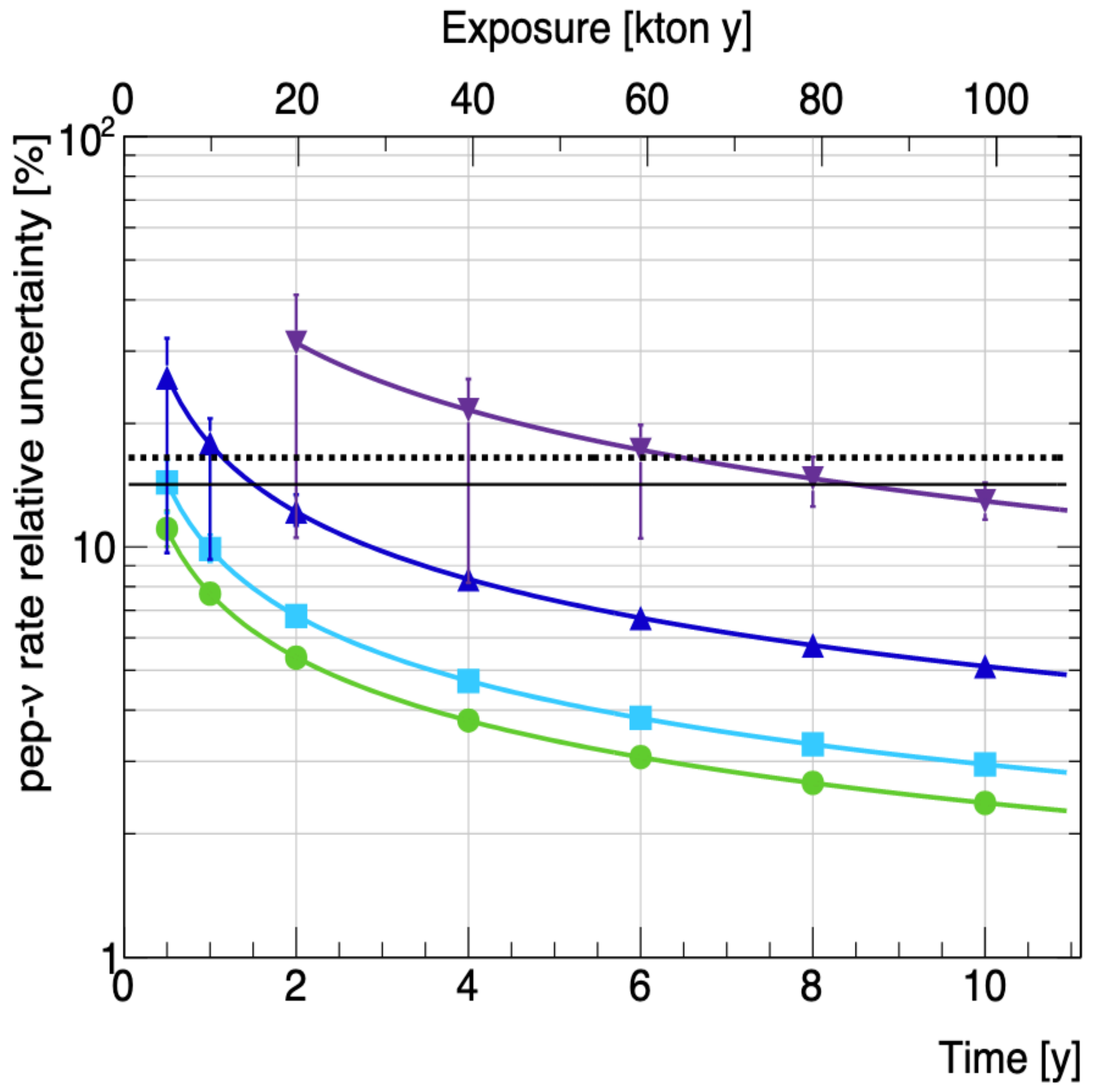
SENSITIVITY STUDIES


High background
minimum requirement for NMH measurement
10x Borexino Phase-I contamination
Medium background
Low background
Borexino Phase-I contamination
Borexino Phase-III contamination
Very low background

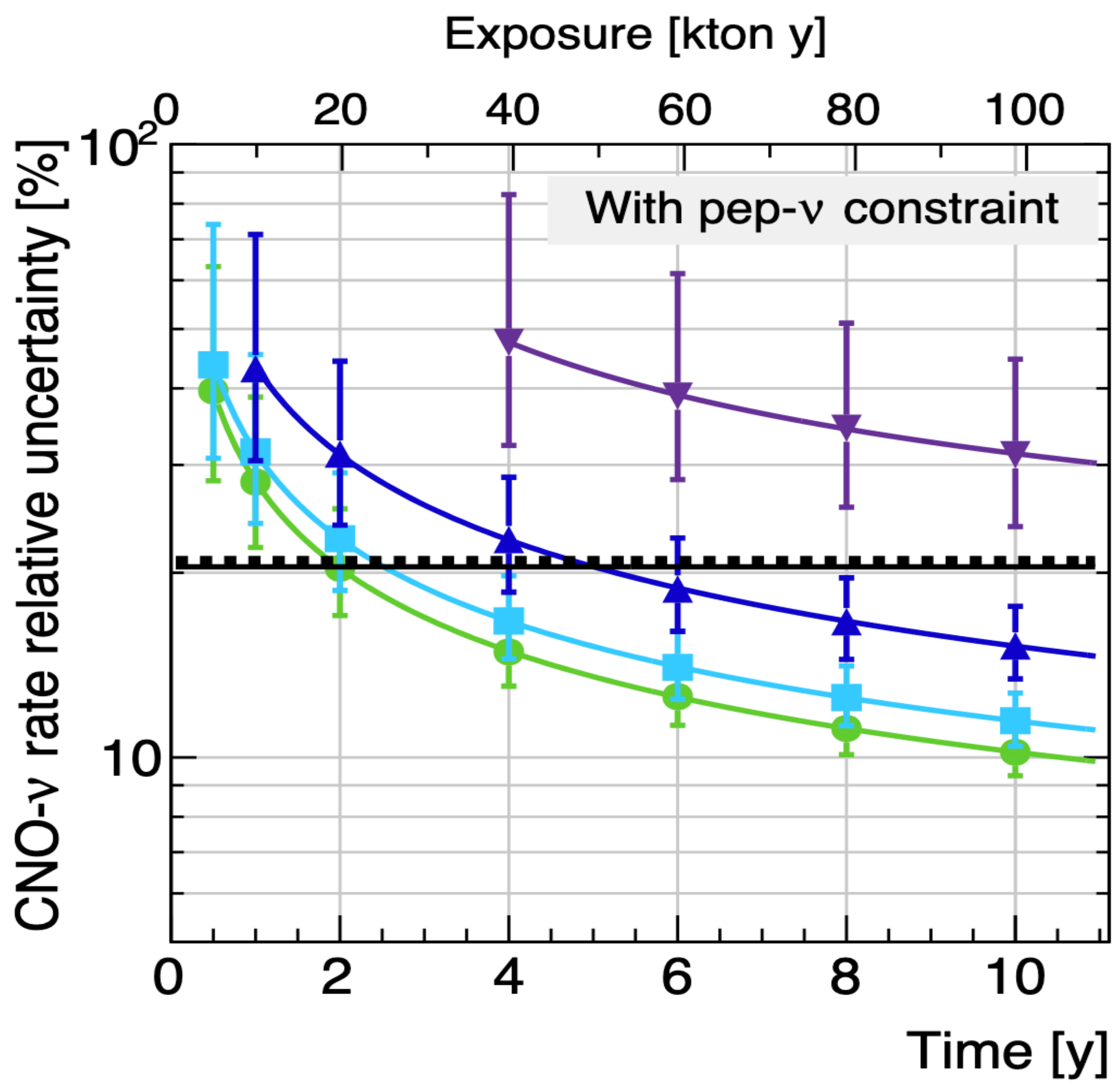
$^7\text{Be} - \nu$



$\text{pep} - \nu$



$\text{CNO} - \nu$



- ☑ JUNO has the potential to **reach and surpass current best precision** for intermediate energy solar neutrino measurements
- ☑ In all radiopurity scenarios (except IBD), JUNO has the potential to detect for the first time **single CNO components ($^{13}\text{N} - \nu$ and $^{15}\text{O} - \nu$)**
- ☐ Onoing work to **include CID method** for CNO precise measurement…

SUMMARY AND CONCLUSIONS

- ☑ **Solar neutrinos** are a crucial ingredient for a complete understanding of the reactions taking place in the Sun.

- ☑ Over more than 10 years of data taking, Borexino has performed a complete spectroscopy of solar neutrinos (pp-chain and CNO cycle).

- ☑ Directionality measurement, using the **Correlated Integrated Directionality (CID) method** for solar neutrinos:
  - **Independet CNO measurement**: R(CNO) = $7.2^{+2.8}_{-2.7}$ cpd/100t.
  - Spectral fit result: R(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t.
  - **Combined analysis** leads to unprecendented precision: R(CNO) = $6.7^{+1.2}_{-0.8}$ cpd/100t.

- ☑ **Sensitivity studies** confirm the **outstanding JUNO performances for solar-ν spectroscopy** (^{7}Be-ν, pep-ν, CNO-ν), depending on radiopurity scenarios:
  - expected uncertainty on ^{7}Be, pep and CNO neutrinos will significantly improve with respect to the current best results
  - ^{13}N-ν and ^{15}O-ν can be detected separately for the first time

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

THANK YOU FOR YOUR ATTENTION!

BACKUP

SOLAR PHYSICS: THE SOLAR METALLICITY PUZZLE

Metallicity: abundance of elements with $Z > 2$ in the Sun (wrt Hydrogen), quantified with **metal-to-hydrogen ratio (Z/X)**.
Can be inferred from spectroscopic measurements of the photosphere.

High Metallicity

(1998) **Z/X(GS98) = 0.023**
- **HZ-Scenario**
- Helioseismology ✓

→

Low Metallicity

(2009) **Z/X(AGS09) = 0.018**
- **LZ-Scenario**
- Helioseismology ✗

→

Low Metallicity

(2021) **Z/X(AG21) = 0.0187**
- **LZ-Scenario**
- Helioseismology ✗

→

High Metallicity

(2022) **Z/X(MB22) = 0.0225**
- **HZ-Scenario**
- Helioseismology ✓

Solar neutrino fluxes depends on the metallicity input in SSM:

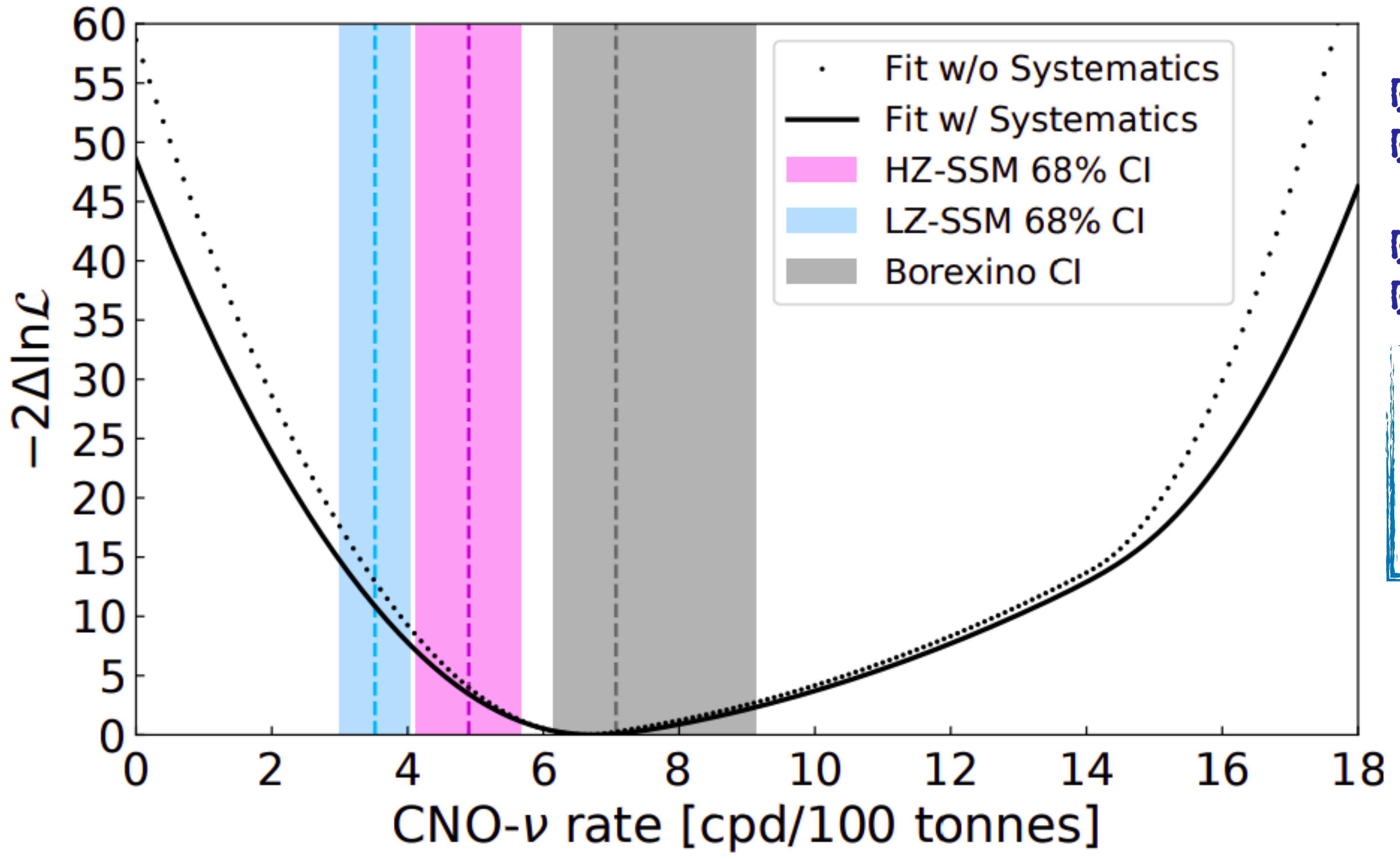
Flux	**BGS98 (HZ) [cm^{-2}s^{-1}]**	**AGSS09 (LZ) [cm^{-2}s^{-1}]**	**% diff**
pp	$5.98(1 \pm 0.006) \cdot 10^{10}$	$6.03(1 \pm 0.005) \cdot 10^{10}$	0.83
pep	$1.44(1 \pm 0.01) \cdot 10^{8}$	$1.46(1 \pm 0.009) \cdot 10^{9}$	1.4
^{7}Be	$4.93(1 \pm 0.006) \cdot 10^{10}$	$4.50(1 \pm 0.06) \cdot 10^{10}$	8.7
^{8}B	$5.45(1 \pm 0.12) \cdot 10^{6}$	$4.50(1 \pm 0.12) \cdot 10^{6}$	17.4
^{13}N	$2.78(1 \pm 0.15) \cdot 10^{8}$	$2.04(1 \pm 0.14) \cdot 10^{8}$	26.6
^{15}O	$2.05(1 \pm 0.17) \cdot 10^{8}$	$1.44(1 \pm 0.16) \cdot 10^{8}$	29.8
^{17}F	$5.29(1 \pm 0.20) \cdot 10^{6}$	$3.26(1 \pm 0.18) \cdot 10^{6}$	38.6
All CNO	$4.88(1 \pm 0.16) \cdot 10^{8}$	$3.51(1 \pm 0.15) \cdot 10^{8}$	28.1

^{7}**Be**, ^{8}**B**, and **CNO neutrinos** are the best candidates to unravel the metallicity puzzle

LATEST CNO MEASUREMENT

- ☑ **Phase-III Dataset:** January 2017 - October 2021: exposure increased by ~ 33% (wrt first CNO measurement);
- ☑ **Monte Carlo:**
  - ☑ data - MC agreement improved
  - ☑ Improved energy non linearities and non-uniformities estimation (based on cosmogenic neutrons) for systematics evaluation
- ☑ In 2021 temperature is more stable, thus less unsupported ^{210}Po (and larger LPoF)

→ **More stringent limit on ^{210}Bi:** $R(^{210}Bi) = 10.8 \pm 1.0$ **cpd/100t** ($R(^{210}Bi) = 11.3 \pm 1.5$ cpd/100t for first CNO measurement)



Sources of systematic error:

- ☑ **fitting method systematics** (great stability of the fit)
- ☑ **detector energy response** (non linearity, light yield stability and spatial non uniformity, energy scale, and ^{210}Bi spectral shape)
- ☑ **method of extraction and uniformity of ^{210}Bi upper limit**
- ☑ **N/O fixed ratio** in CNO spectral shape (negligible)

Results (stat. + syst.):

R(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t

$$\phi(CNO) = 6.6^{+2.0}_{-0.9} \cdot \nu \cdot cm^{-2}s^{-1}$$

→

no-CNO hypotesis rejected with **>7σ significance at 90% C.L.**

Solar implications:

- ☑ First **determination of C+N abundance** in the Sun using neutrinos

→ **(~2σ tension with SSM-LZ)**

- ☑ **Frequentist hypothesis test** based on a likelihood-ratio test statistics including only Borexino results

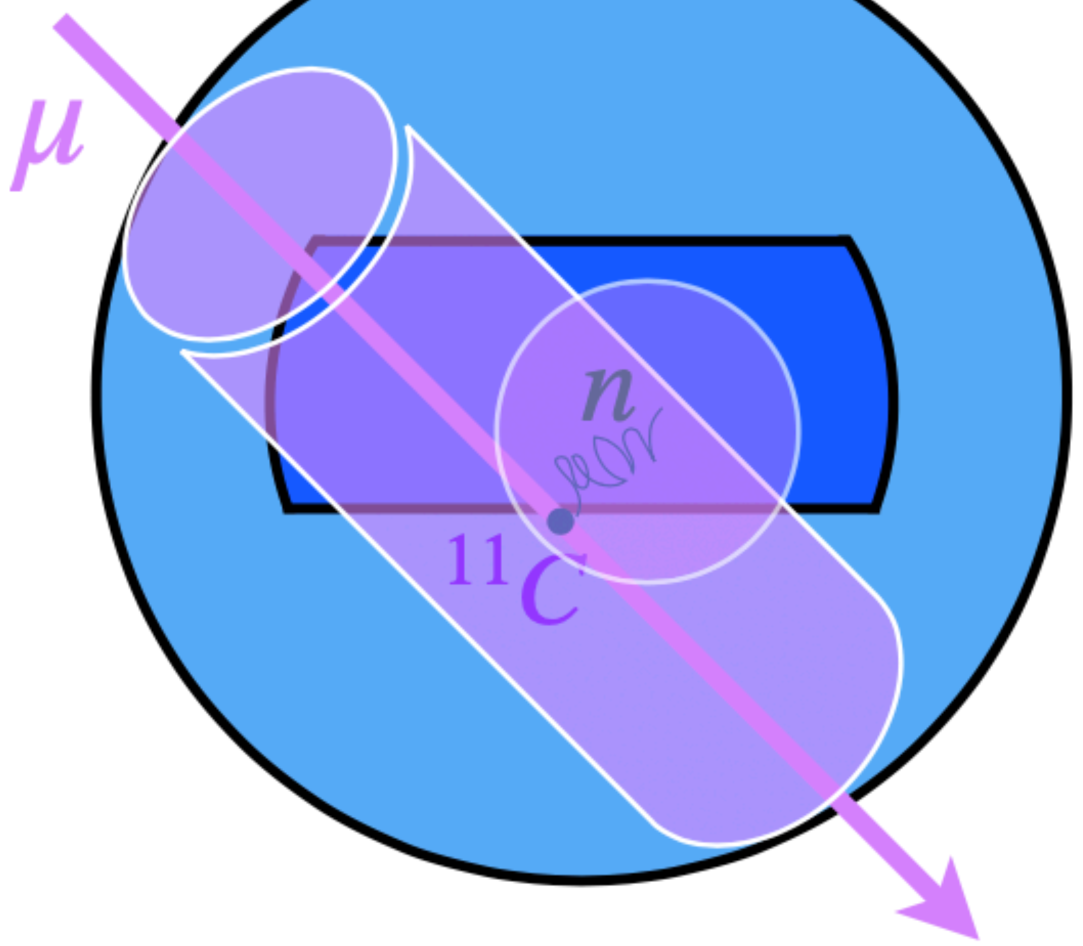
→ **(SSM-LZ disfavoured at ~3.1σ)**

- **Signal**: CNO solar neutrinos

- **Backgrounds**:
  - **Internal backgrounds**: ^{210}Bi, ^{210}Po, ^{85}Kr
  - **External backgrounds**: γ's produced from ^{208}Tl , ^{214}Bi and ^{40}K nuclei (mainly from the stainless steel sphere and PMTs)
  - **Cosmogenic backgrounds**: mainly ^{11}C produced by cosmic muons spallations, identified via **three fold coincidence (TFC)**

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

$${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e \qquad n + p \rightarrow d + \gamma_{2.2\ MeV}$$

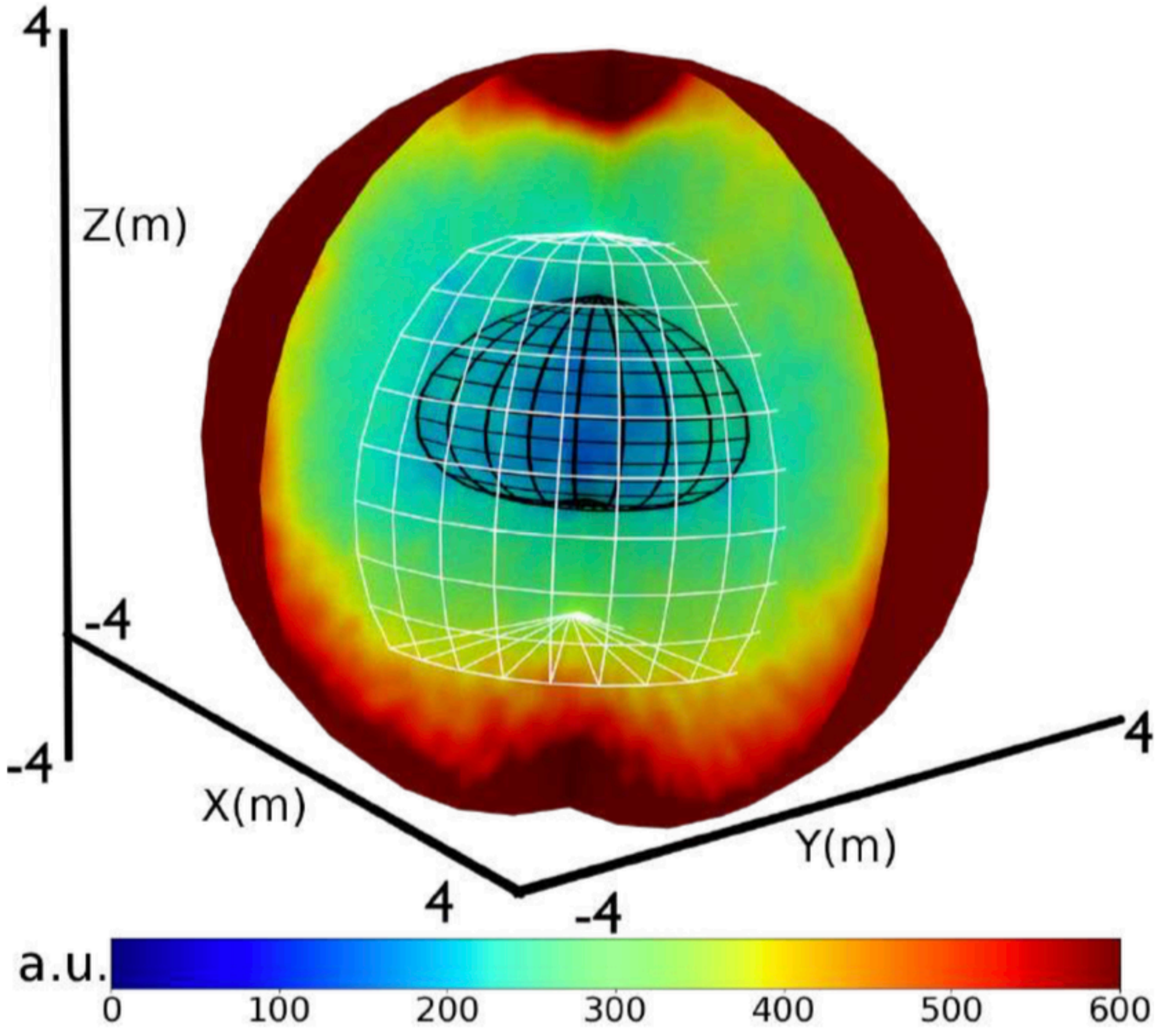


Data-set divided in two samples:
TFC-tagged (enriched in ^{11}C) and
TFC-subtracted (depleted in ^{11}C)

  - **pp-chain Solar neutrinos**: $pep - \nu$ and $^{7}Be - \nu$

THE LOW POLONIUM FIELD

In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:



Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

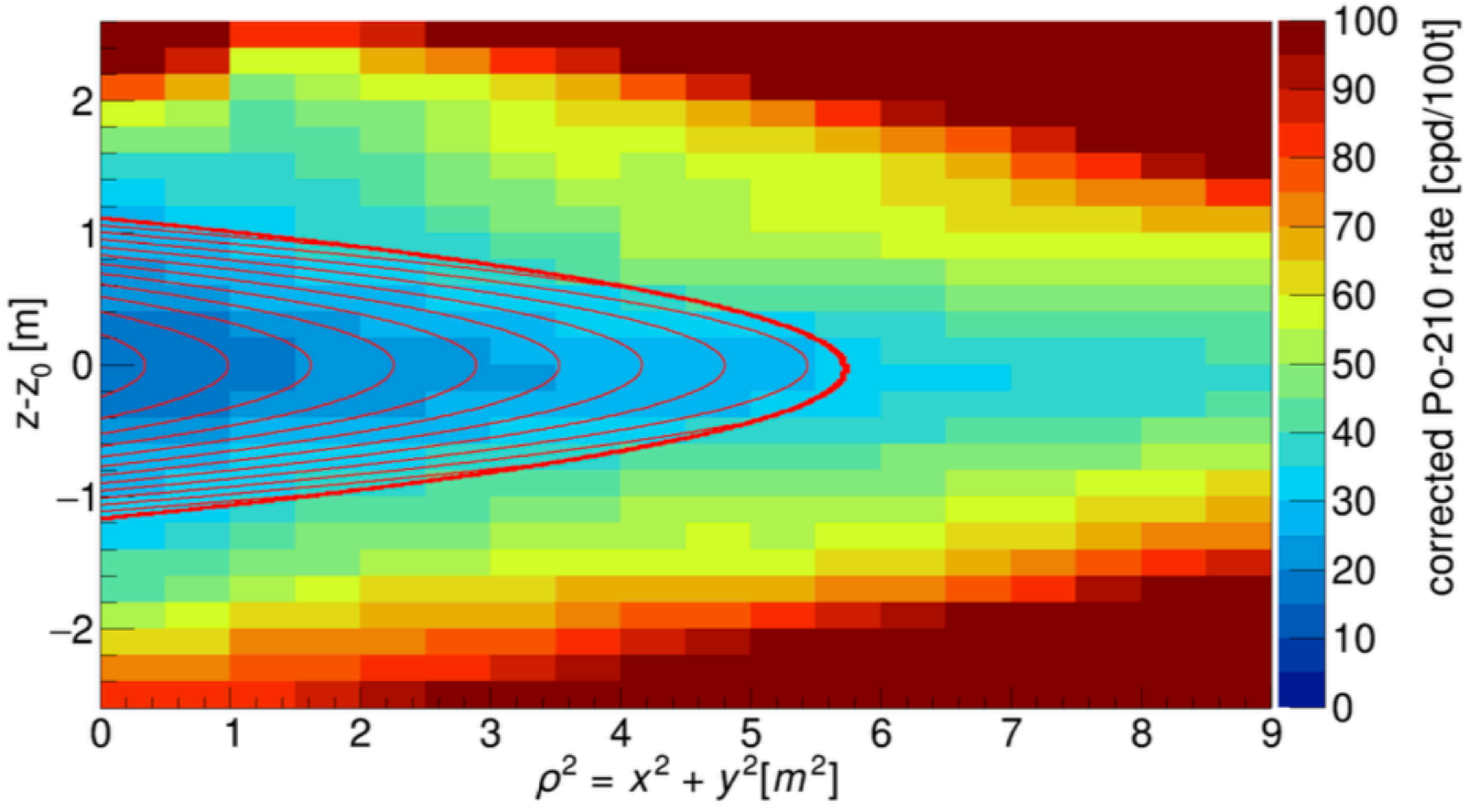
Cross-checked with fluid dynamic simulations

^{210}Po minimum is determined with **two methods**:

1) fitting LPoF with a 2D paraboloidal function:

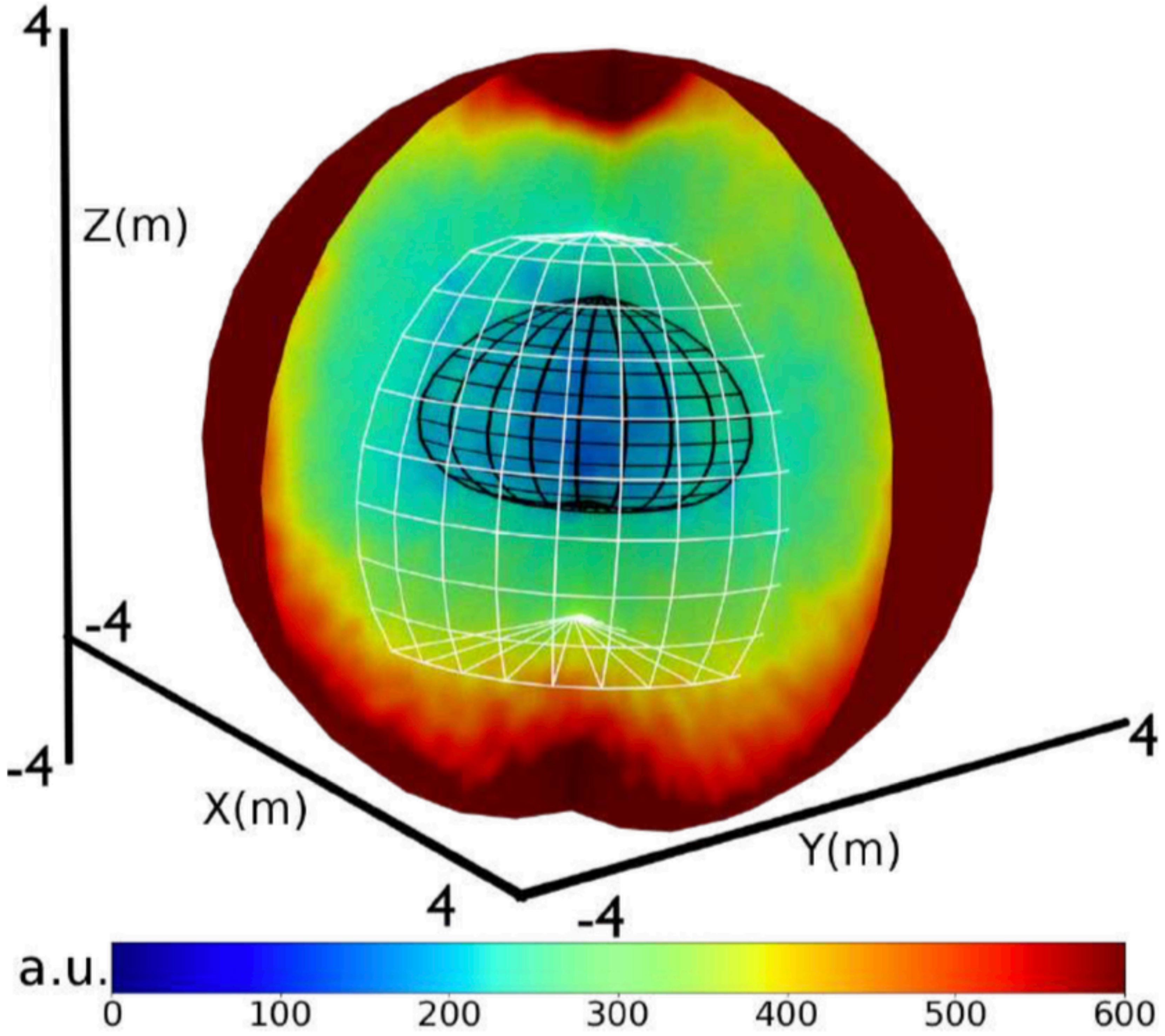
$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right)$$

- Fit performed in data bins of one month: extract z_0 position vs time
- Sum up the time bins, alignin distributions wrt z_0
  - **Aligned dataset:** blindly align data according to z_0 from previous month to minimize possible biases



THE LOW POLONIUM FIELD

In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:



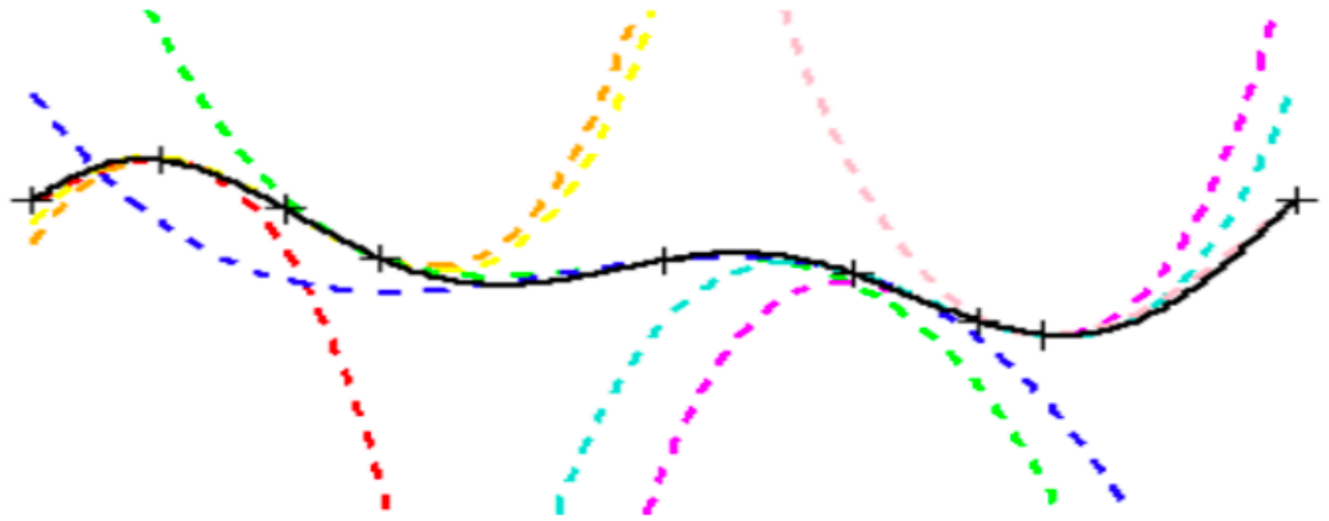
Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

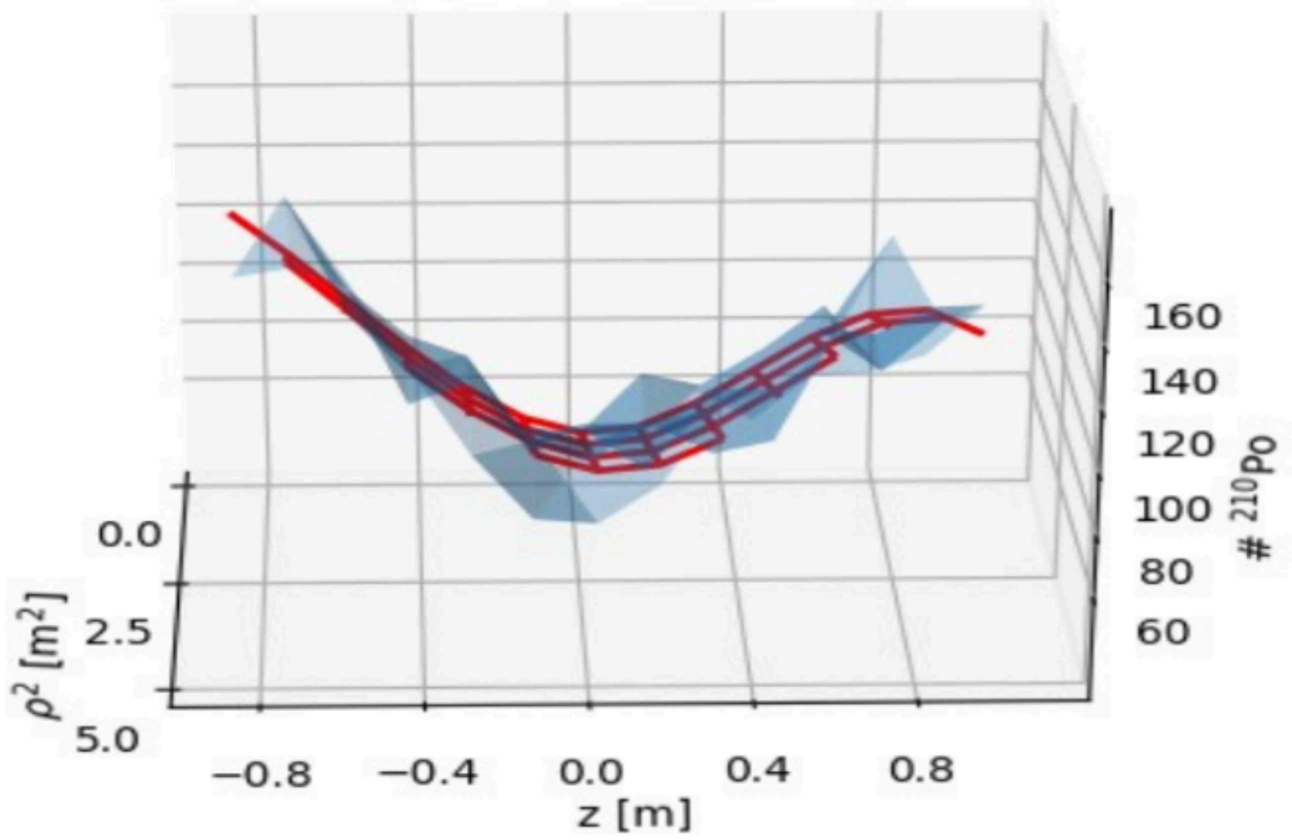
Cross-checked with fluid dynamic simulations

^{210}Po minimum is determined with **two methods**:

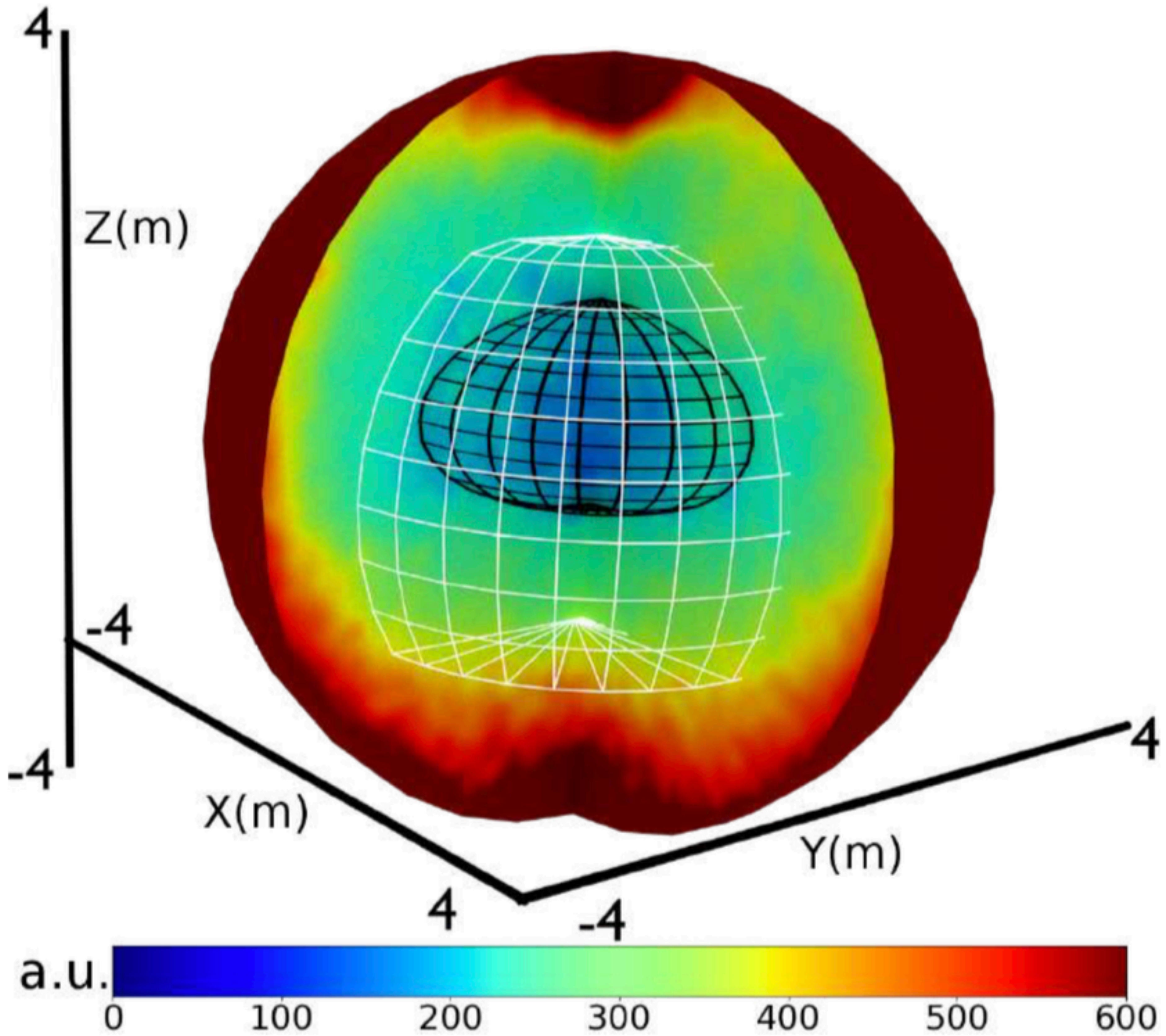
2) fitting LPoF with splines (cubic functions defined by *knots*) along z:

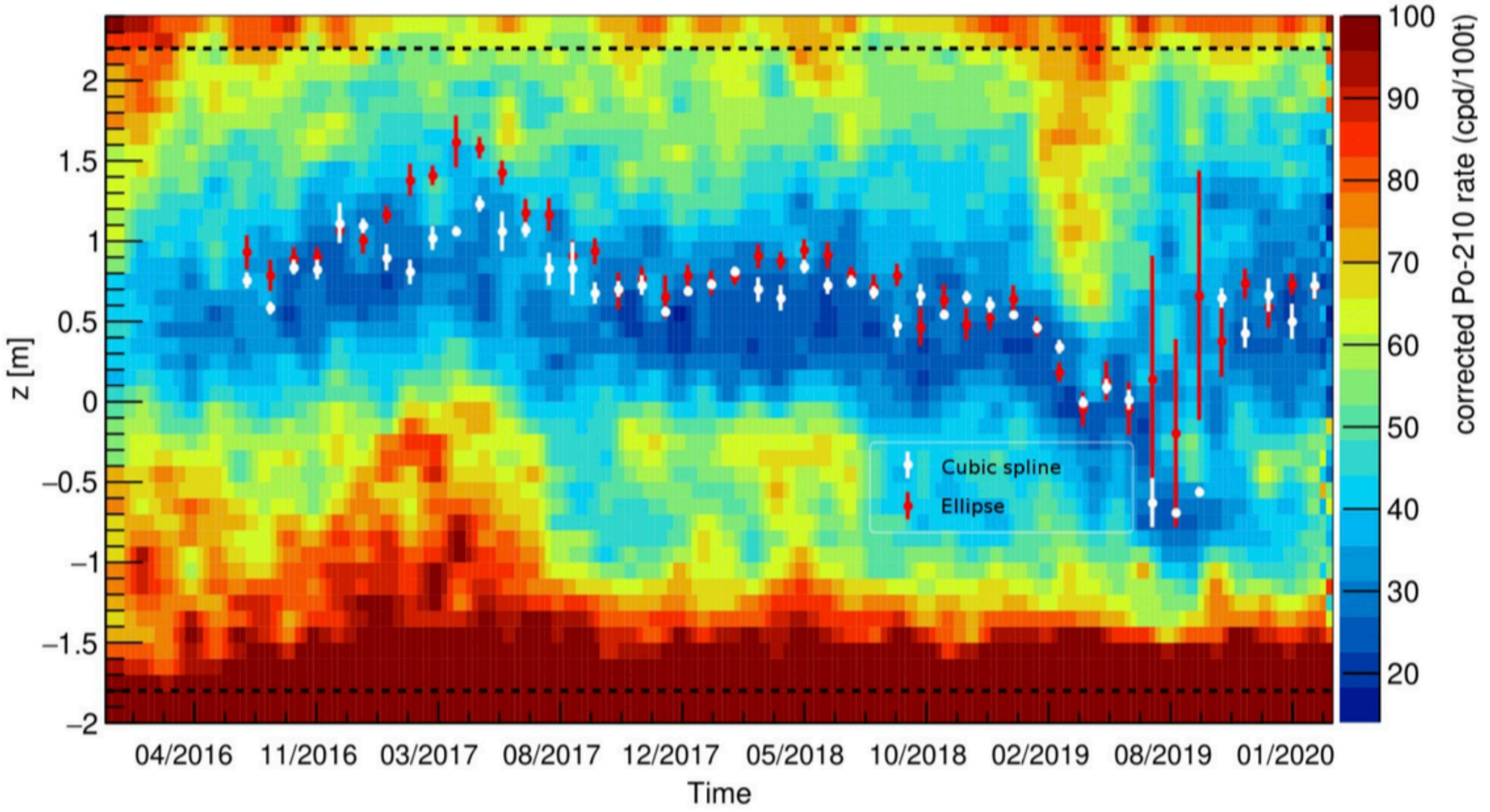


$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + spline(z)\right)$$



In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:





Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

Cross-checked with fluid dynamic simulations

The two methods give consistent results:

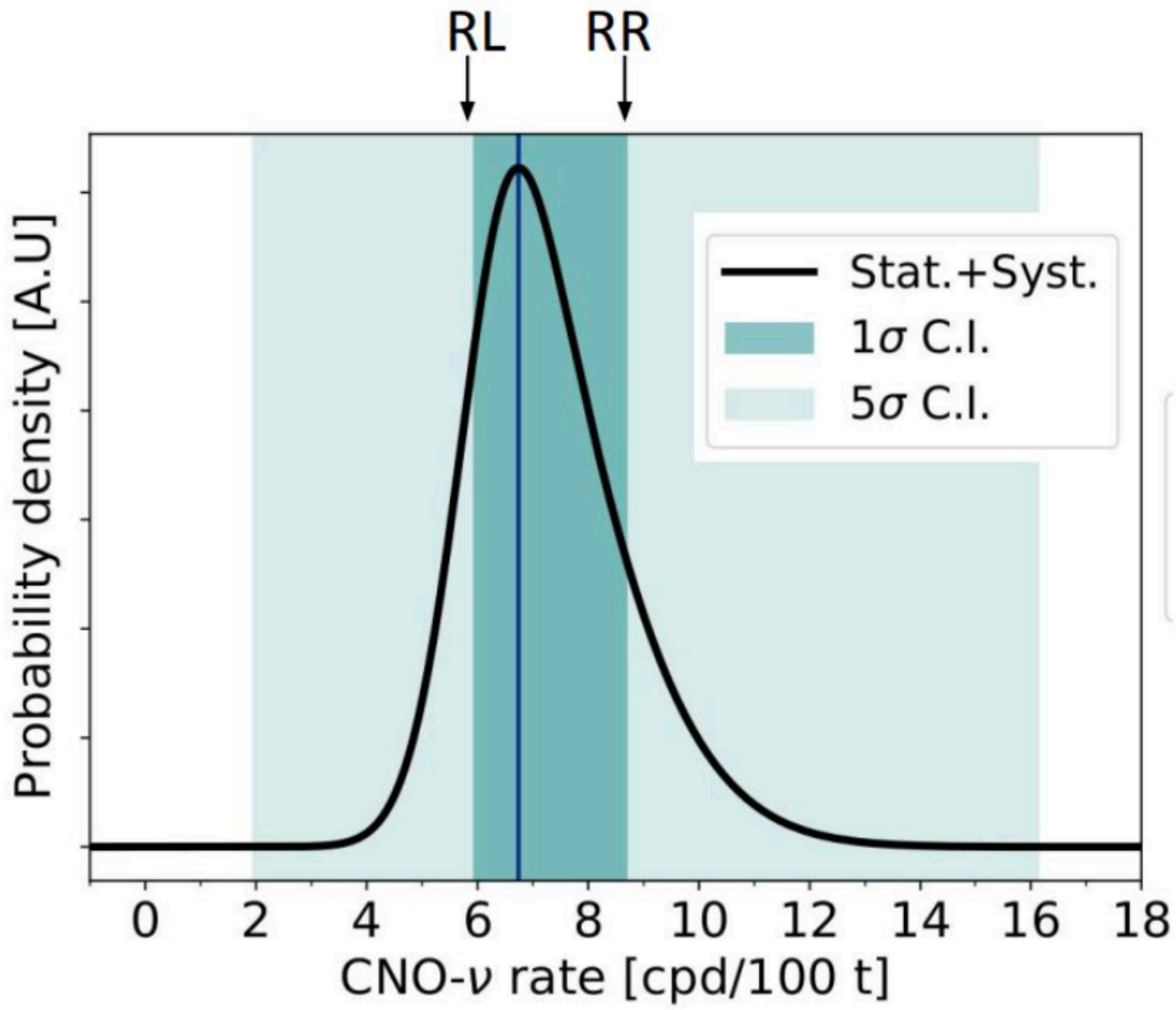
$R(^{210}\text{Bi}) \leq R(^{210}\text{Po}) = 11.5 \pm 1.0$ cpd/100t

Quantiles approach for CNO confidence interval

Procedure: quantiles of the CNO likelihood profile assuming Wilks approximation (same as 2020 CNO Nature paper)

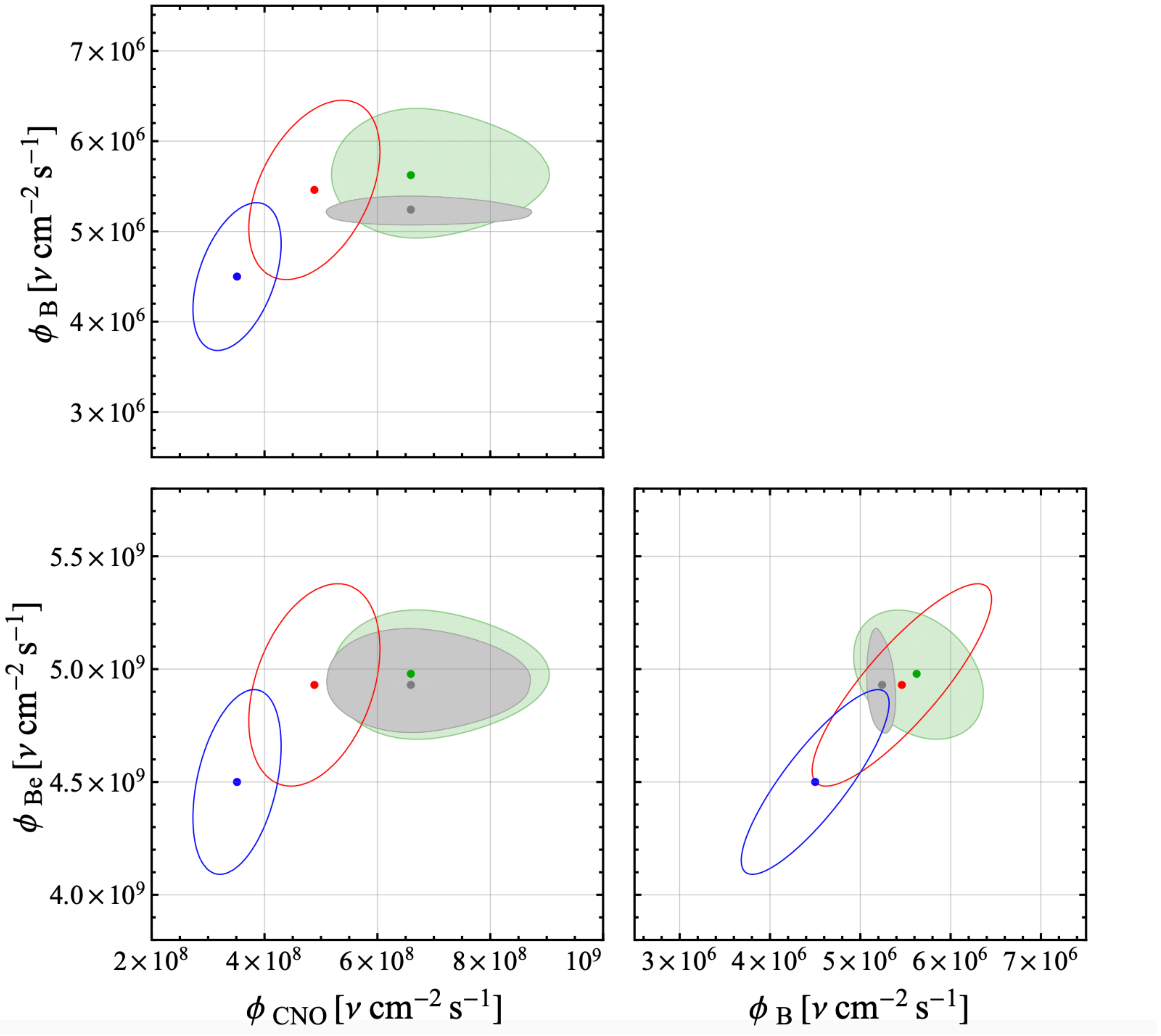
Central value → mode value: maximum of CNO rate likelihood / minimum of CNO rate $\Delta\chi^2$
C.I.→ calculating quantile of CNO density probability starting from the tail, separately for the left side and from the right side.

- 1σ C.I. left boundary: Rate RL such as area from 0 to RL is (1-0.68)/2 ~ 0.16
- 1σ C.I. right boundary: Rate RR such as area from RR to ∞ is (1-0.68)/2 ~ 0.16



SOLAR IMPLICATIONS: GLOBAL ANALYSIS

Results of **global analysis** fits in Φ_B, Φ_{Be}, and Φ_{CNO} planes



Test compatibility of solar ν data with SSM B16 predictions:

- ■ Global analysis of all solar neutrino + Kamland reactor $\overline{\nu}_e$
- 🟩 Borexino only + Kamland reactor $\overline{\nu}_e$
- 🟥 SSM B16 predictions using HZ inputs (GS98)
- 🟦 SSM B16 predictions using LZ inputs (AGSS09met)

Agreement with SSM-HZ predictions.
Small **tension** (adding CNO results) **with SSM-LZ**

SOLAR IMPLICATIONS: HZ VS LZ TENSION

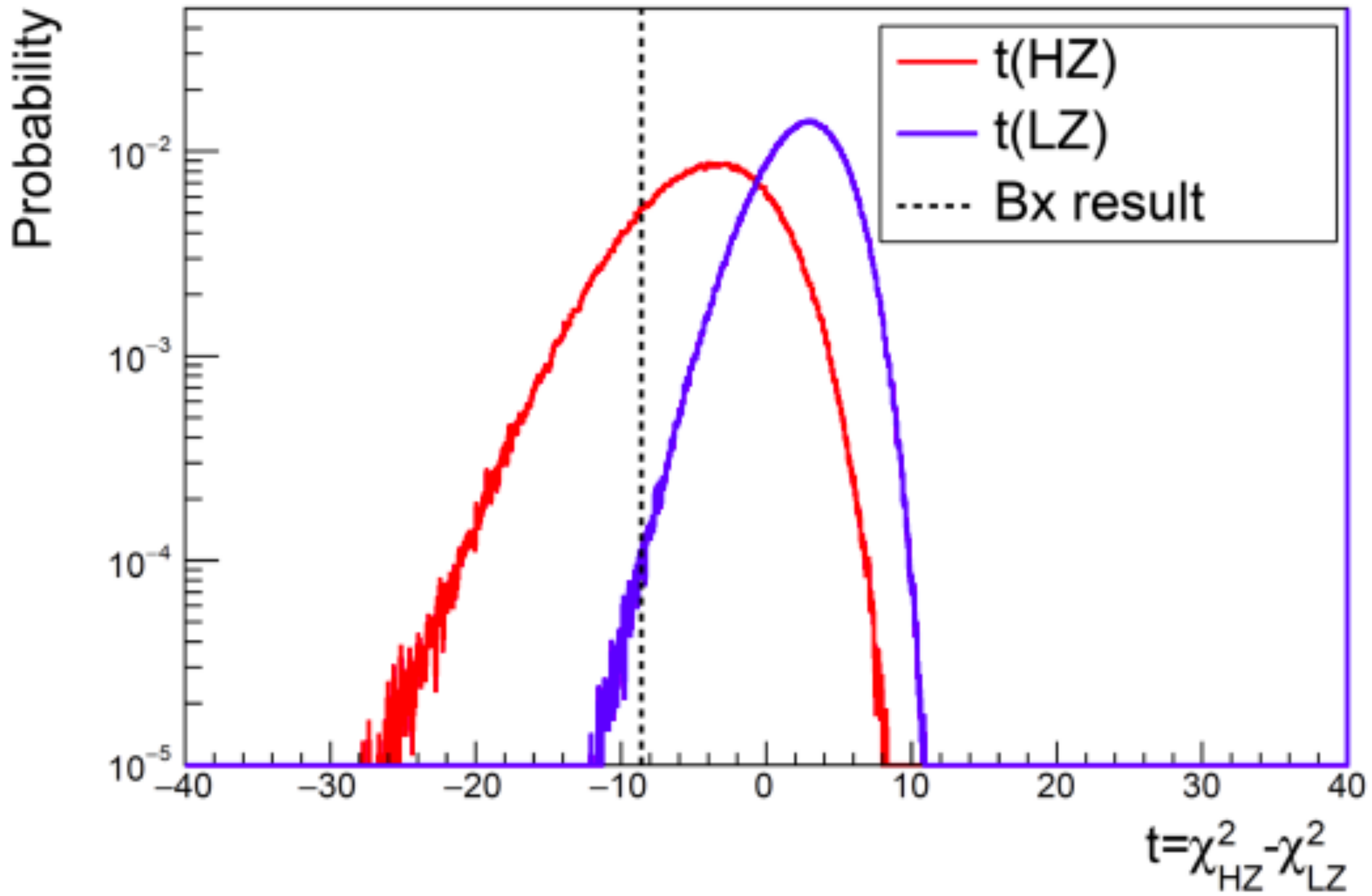
Frequentist hypothesis test based on a likelihood-ratio test statistics for SSM-LZ (null hypothesis H_0) and SSM-HZ (alternative hypothesis H_1)

Test statistics t is built using only ^8B, ^7Be, and CNO Borexino's results:

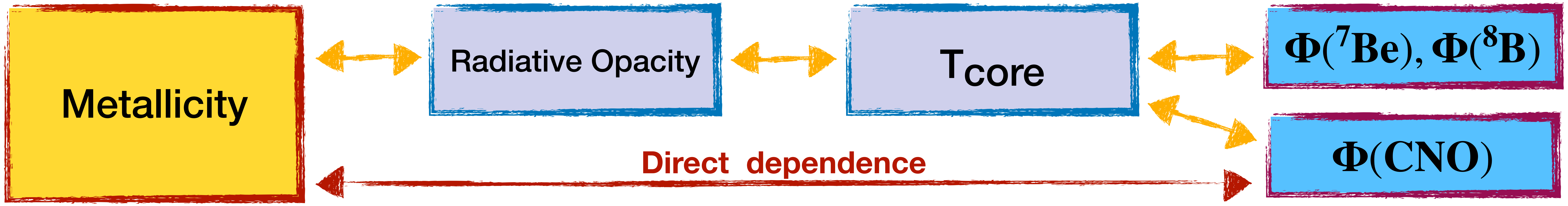
$$t = -2log[\mathscr{L}(HZ)/\mathscr{L}(LZ)] = \chi^2(HZ) - \chi^2(LZ)$$

Model and experimental uncertainties included

Assuming SSM-HZ, Borexino results (^7Be, ^8B and CNO) **disfavour SSM-LZ at ~3.1σ.**



SOLAR IMPLICATIONS: C+N ABUNNDANCE



Metallicity

Radiative Opacity

Tcore

$\Phi(^7\mathrm{Be}), \Phi(^8\mathrm{B})$

$\Phi(\mathrm{CNO})$

Direct dependence

$$\frac{\Phi_i}{\Phi_i^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_i}$$

$$\frac{\Phi_B}{\Phi_B^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_B} \qquad \tau_{^8B} \approx 24$$

$$\frac{\Phi_O}{\Phi_O^{SSM}} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O} \qquad \tau_{^{15}O} \approx 20$$

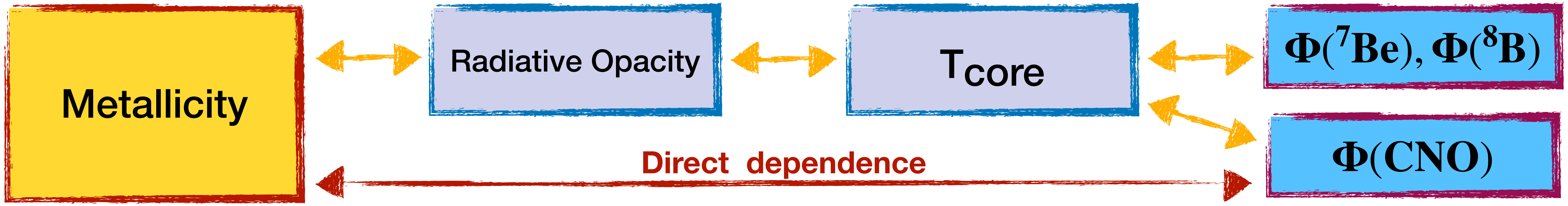
Φ_B **as thermometer**

$$\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O - k\tau_B}$$

k to minimize impact of T_C

$k = \tau_O/\tau_B \approx 0.83$

SOLAR IMPLICATIONS: C+N ABUNNDANCE



Metallicity

Radiative Opacity

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$\Phi(^7\mathrm{Be}), \Phi(^8\mathrm{B})$

$\Phi(\mathrm{CNO})$

Direct dependence

$$\frac{\Phi_i}{\Phi_i^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_i}$$

$$\frac{\Phi_B}{\Phi_B^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_B} \qquad \tau_{^8B} \approx 24$$

$$\frac{\Phi_O}{\Phi_O^{SSM}} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O} \qquad \tau_{^{15}O} \approx 20$$

Φ_B as thermometer

$$\boxed{\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O - k\tau_B}}$$

k to minimize impact of T$_C$
$k = \tau_O/\tau_B \approx 0.83$

Reality is much more complicated than this…

$$\boxed{\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{N_{CN}}{N_{CN}^{SSM}} \cdot [1 \pm (0.097(\mathrm{nucl}) + 0.005(\mathrm{env}) + 0.027(\mathrm{diff})]}$$

S-factors of nuclear properties

31 Elements abundances + Solar properties

Diffusion

Optimal k
$k = 0.769$

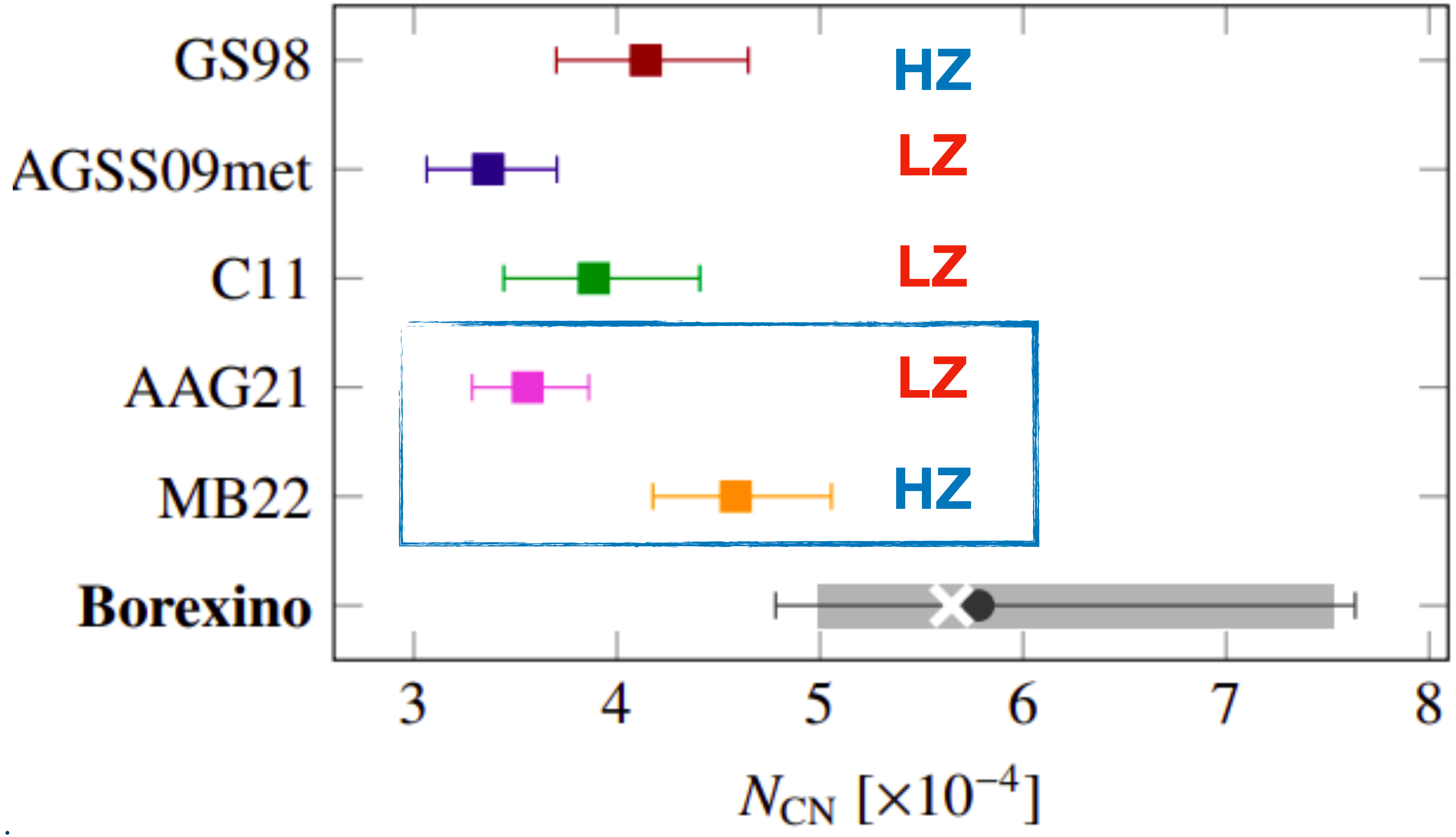
SOLAR IMPLICATIONS: C+N ABUNNDANCE

With $(\Phi_B/\Phi_B^{SSM}) = 0.96 \pm 0.03$ from global analysis and $(\Phi_O/\Phi_O^{SSM}) = 1.35^{+0.41}_{-0.18}$ from CNO measurement

$$\boxed{N_{CN} = (5.78^{+1.86}_{-1.00}) \cdot 10^{-4}}$$

First **determination of C+N abundance** in the Sun using neutrinos

Can be directly compared with measurements from solar photosphere



● Calculation performed with B16-GS98

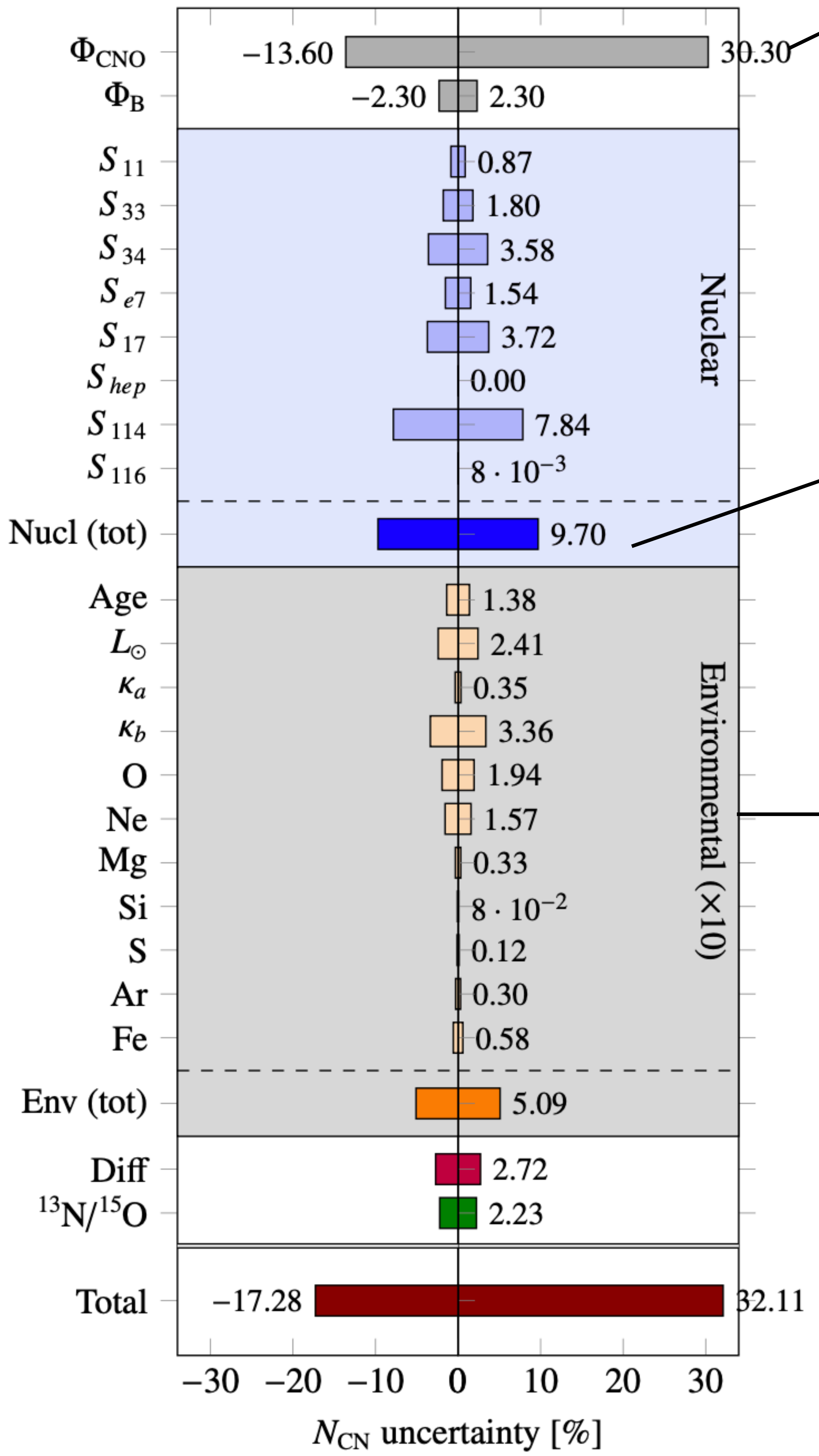
× Calculation performed with B16-AGSS09met

Agreement with SSM-HZ predictions.

Moderate ~2σ **tension with SSM-LZ**

SOLAR IMPLICATIONS: C+N ABUNNDANCE

Error budget on N_CN

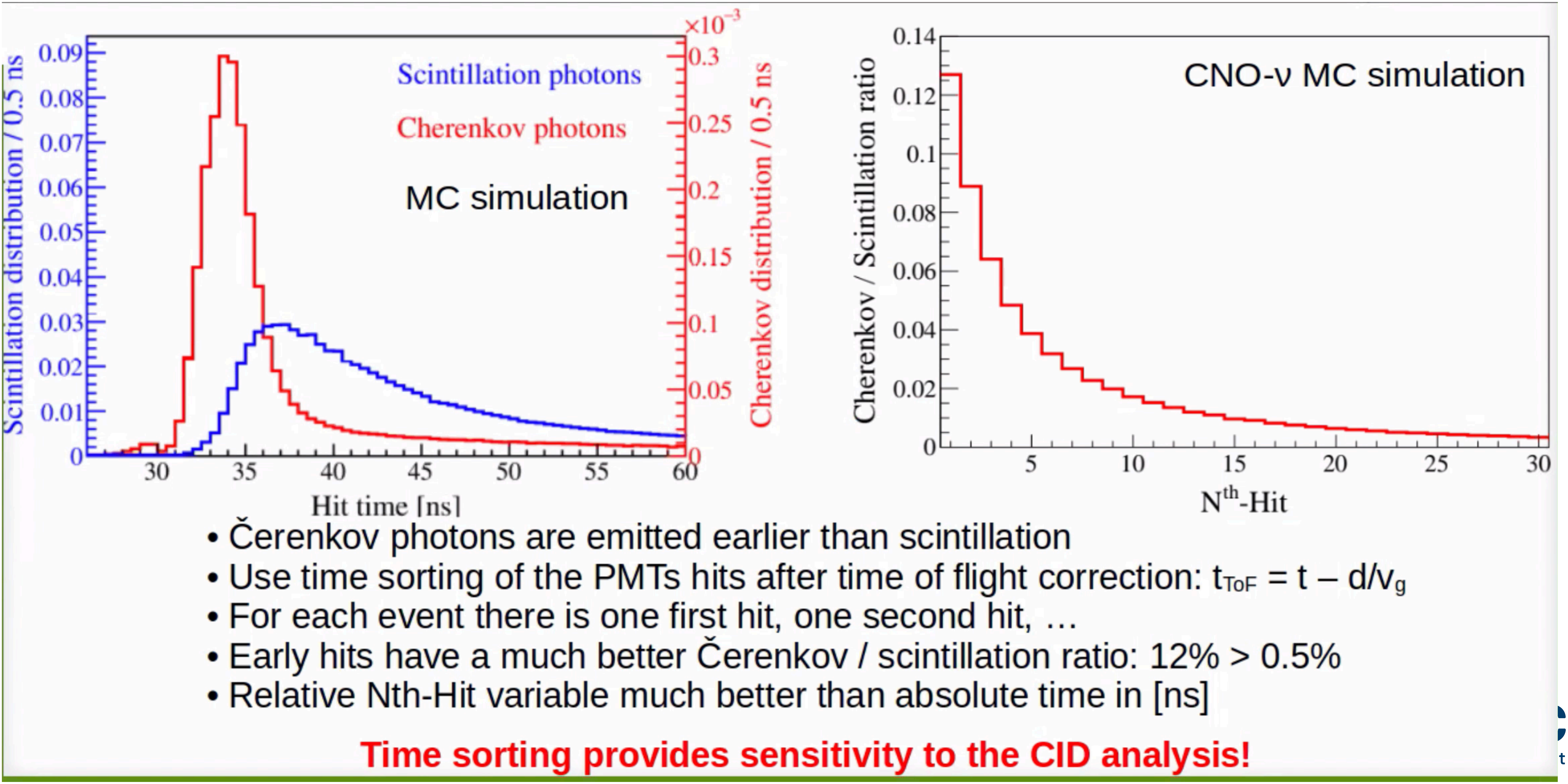


CNO flux determination accuracy (critical)

Limited precision on nuclear cross sections

As expected, environmental parameters doesn't affect the uncertainty much (0.5%)

Scintillation and Cherenkov detected photons (hits) are indistinguishable on an event-by-event basis:



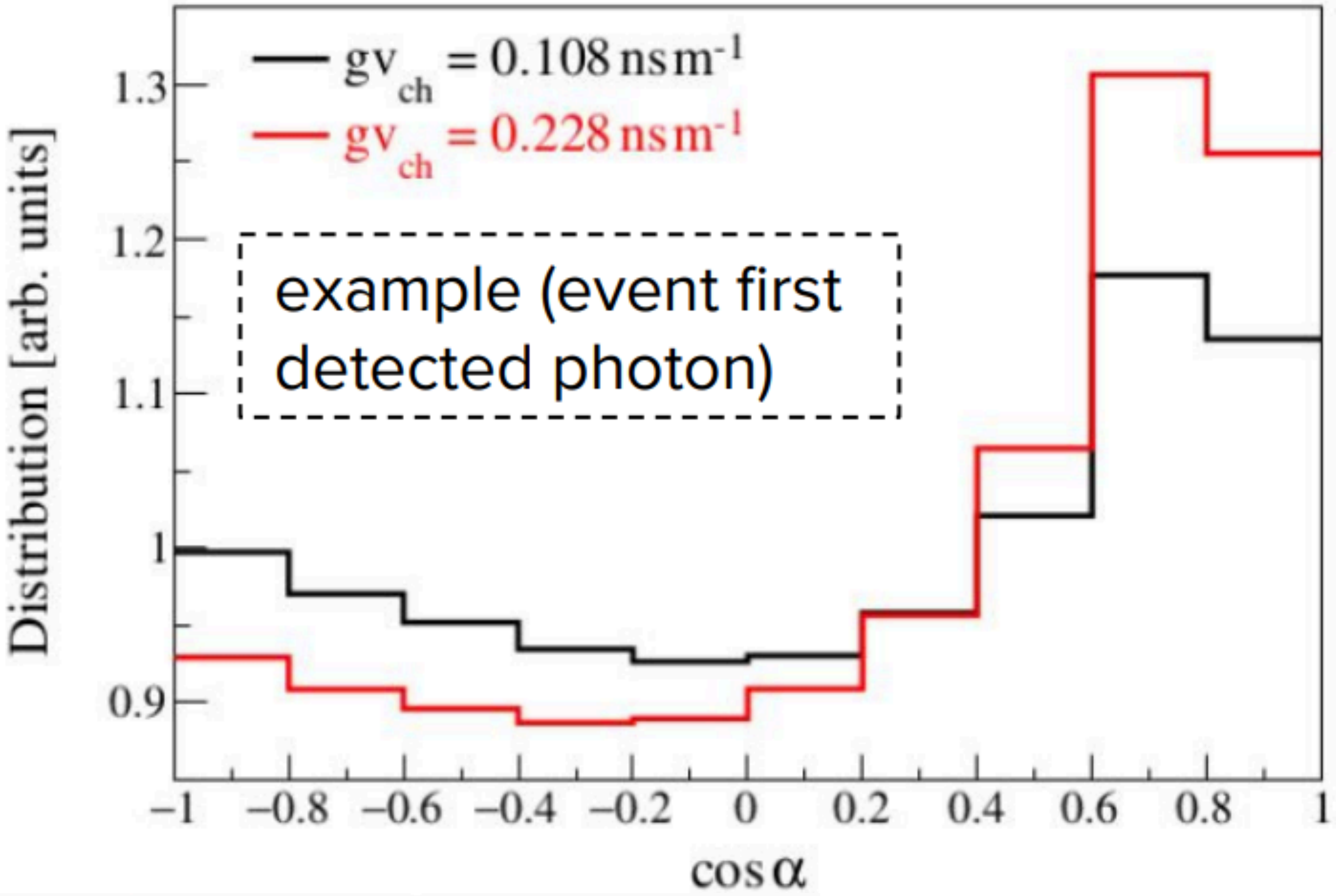
- Čerenkov photons are emitted earlier than scintillation
- Use time sorting of the PMTs hits after time of flight correction: $t_{ToF} = t - d/v_g$
- For each event there is one first hit, one second hit, …
- Early hits have a much better Čerenkov / scintillation ratio: 12% > 0.5%
- Relative Nth-Hit variable much better than absolute time in [ns]

Time sorting provides sensitivity to the CID analysis!

CID method: nuisance parameters

$[v_g(\check{C}er) - v_g(scint)]_{data} \neq [v_g(\check{C}er) - v_g(scint)]_{MC}$ To tune this difference introduce gvc

1) **Group velocity of Cherenkov photons**, relative to scintillation, at MC level: $\mathbf{t_{corrected} = t_{MC} - gv_{ch} d_{MC}}$



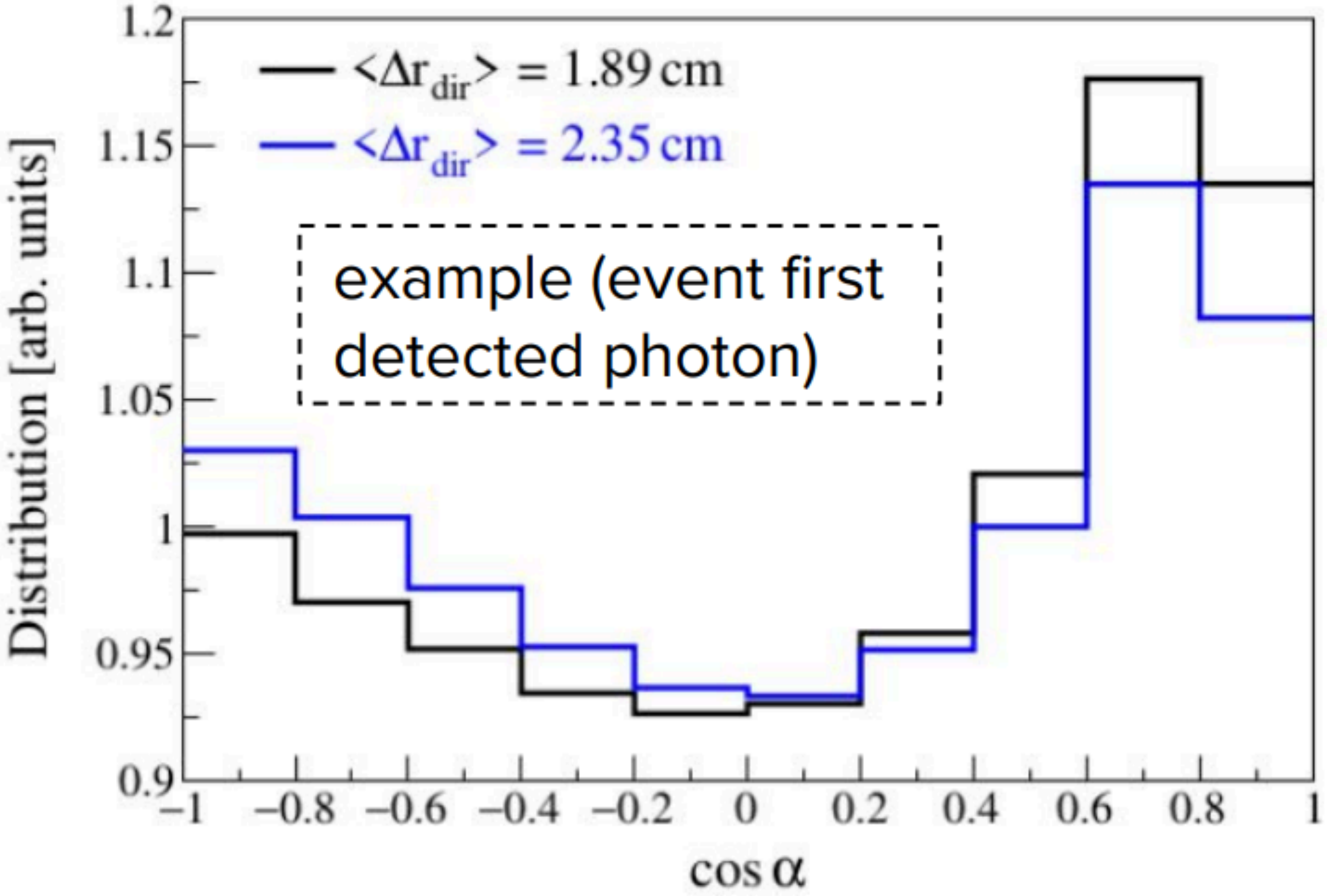
Calibrate value of gv_{ch}, such that:

$[v_g(\check{C}er) - v_g(scint)]_{data} = [v_g(\check{C}er) + 1/gv_{ch} - v_g(scint)]_{MC}$

Can be calibrated: 7Be shoulder ROI

→ **constrained** nuisance parameter in CNO analysis

2) Small **bias in position reconstruction** in direction of the solar neutrino **Δr** due to Cherenkov hits

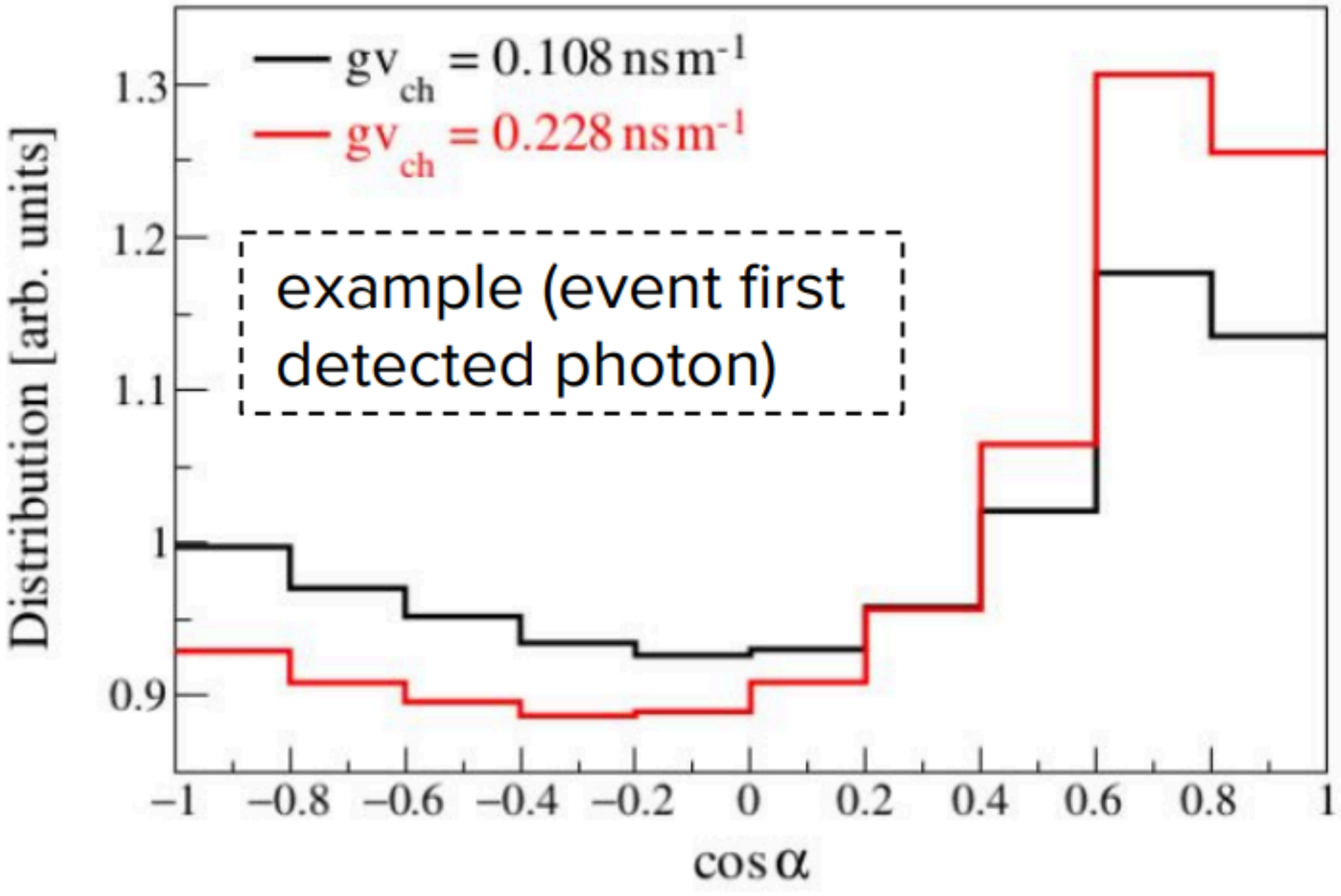


Cannot be calibrated: no dedicated e- Cherenkov calibration source

→ **free** nuisance parameter in CNO analysis

CID method: nuisance parameters

1) **Group velocity of Cherenkov photons**, relative to scintillation, at MC level: $\mathbf{t_{corrected} = t_{MC} - gv_{ch} d_{MC}}$



example (event first detected photon)

Can be calibrated: 7Be shoulder ROI

→ **constrained** nuisance parameter in CNO analysis

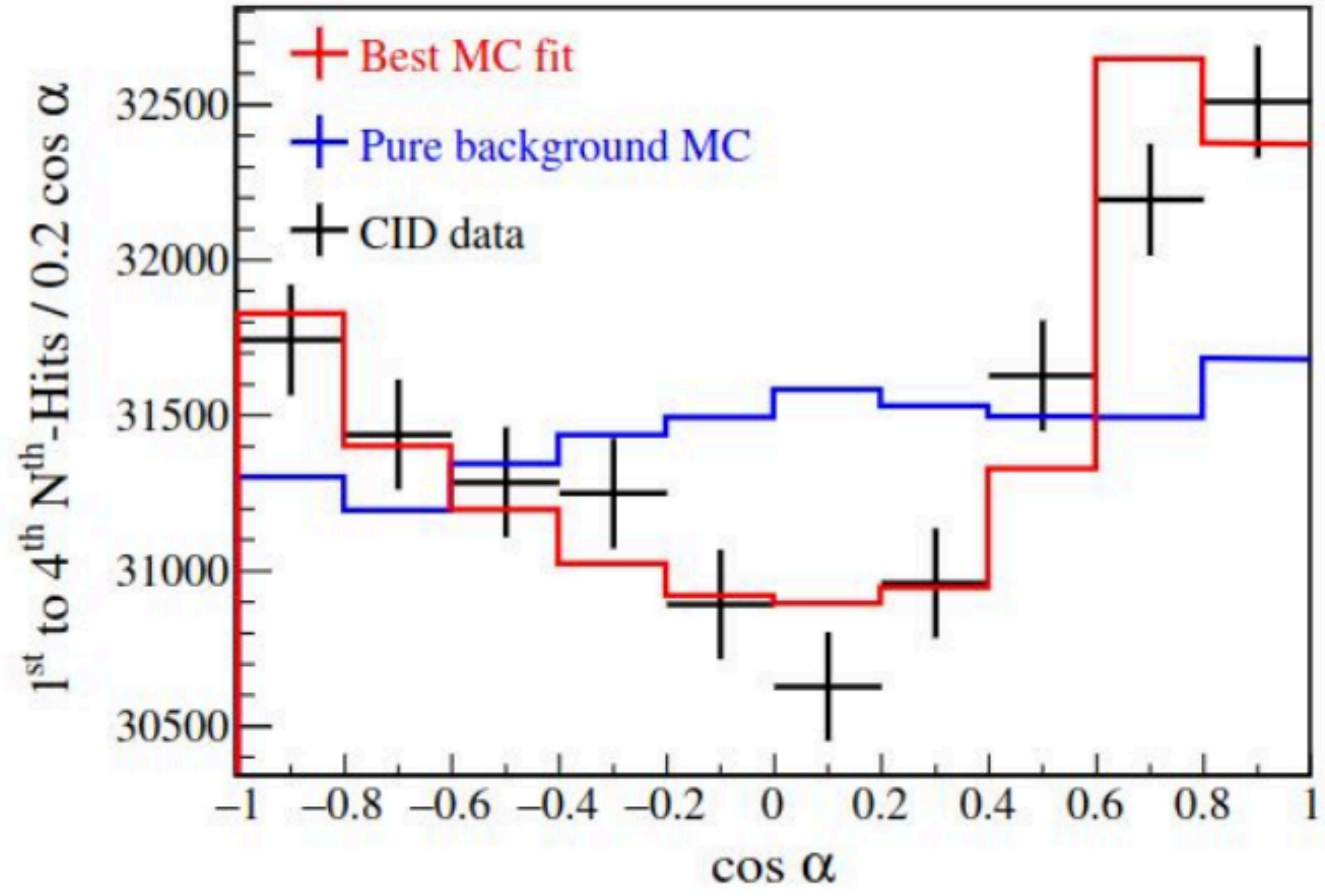
$$\chi^2_{\mathrm{gv_{ch}}}(N_\nu, \mathrm{gv_{ch}}, \Delta r_{\mathrm{dir}}) = \sum_{n=1}^{\mathrm{N^{th}\text{-}hit(max)}} \sum_{i=1}^{I} \left(\frac{\left(N \cdot M_i^n - D_i^n\right)^2}{N \cdot M_i^n + N^2 \cdot M_i^n} \right) - 2\ln\left(P(N_\nu)\right)$$

- $\boldsymbol{M_i^n}$, $\boldsymbol{D_i^n}$: MC and data in cos α for i-th bin and n-th hit

→ ν contribution to M_i^n explicitly depends on gv$_{ch}$, N_ν Δr$_{dir}$

- $\boldsymbol{N_\nu}$ constrained by SSM
- **Δr$_{dir}$** free to vary

cos α fit (1 to 4 hit)



CID method: nuisance parameters, $\mathrm{gv_{ch}}$ calibration

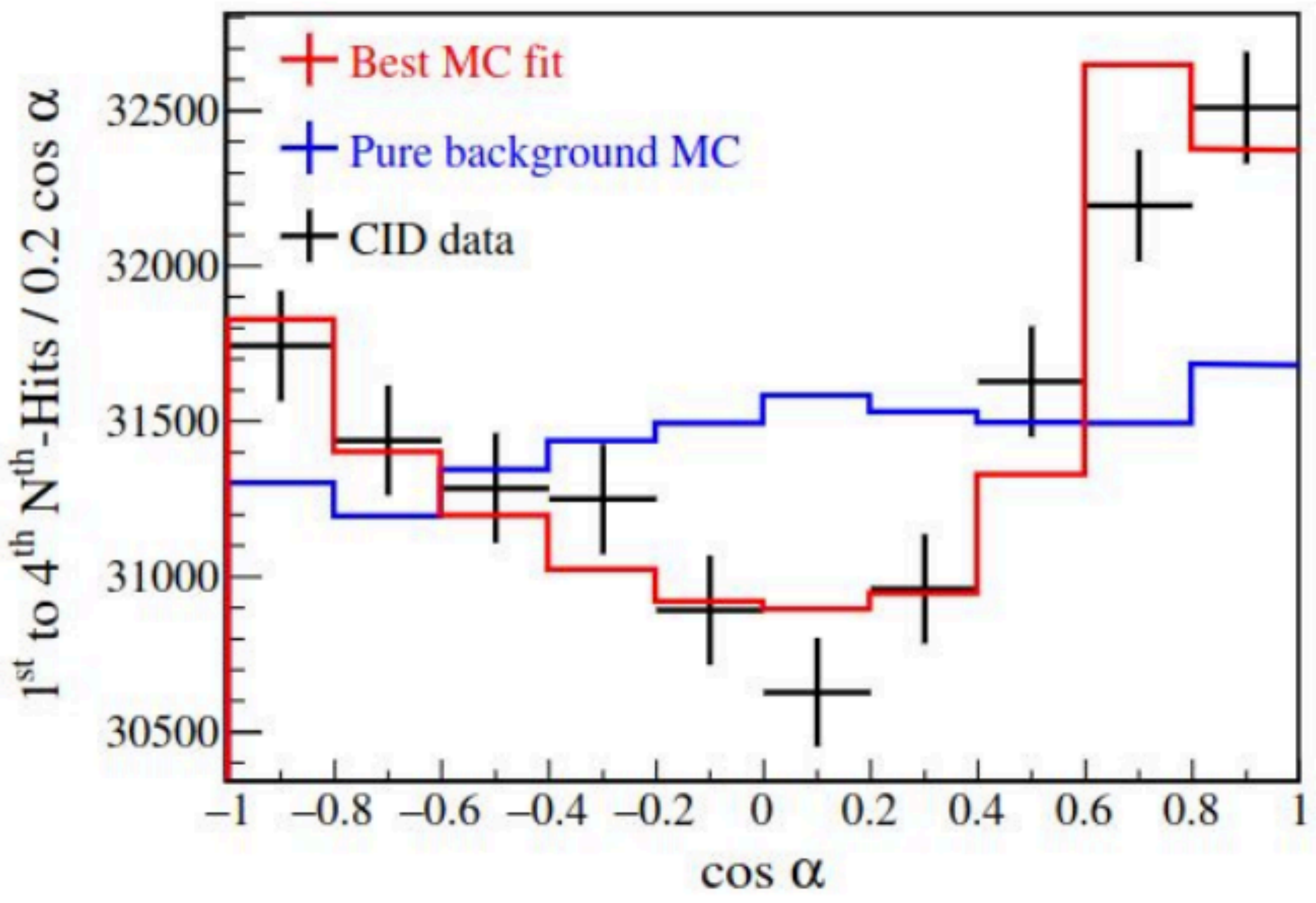
How to extract $\mathrm{gv_{ch}}$? 7Be shoulder ROI (0.5 MeV $\lesssim T_e \lesssim$ 0.8 MeV), rich in neutrinos

$$\chi^2_{\mathrm{gv_{ch}}}(N_\nu, \mathrm{gv_{ch}}, \Delta r_{\mathrm{dir}}) =$$

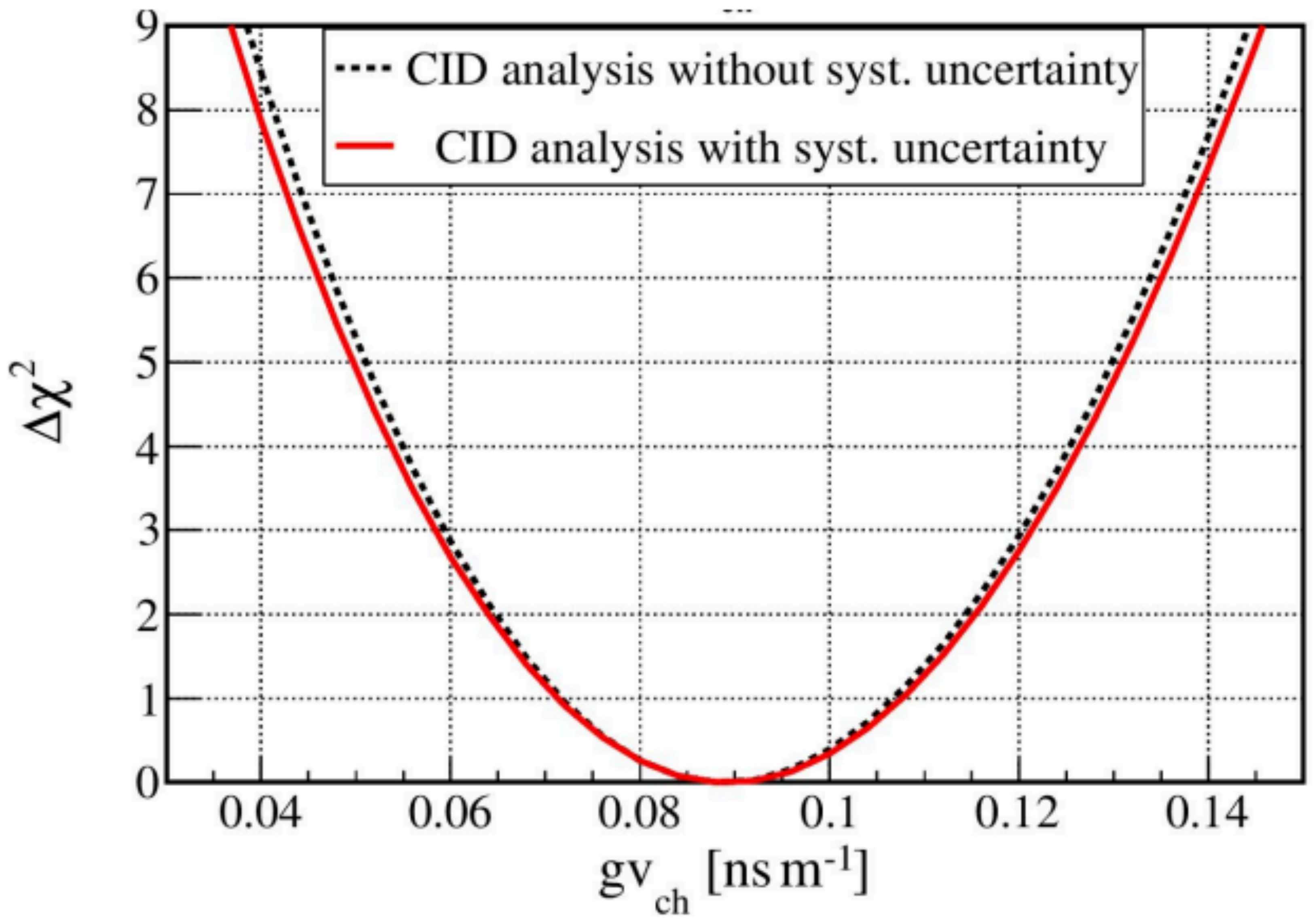
$$= \sum_{n=1}^{\mathrm{N^{th}\text{-}hit(max)}} \sum_{i=1}^{I} \left(\frac{\left(\mathcal{N} \cdot M_i^n - D_i^n\right)^2}{\mathcal{N} \cdot M_i^n + \mathcal{N}^2 \cdot M_i^n} \right) - 2\ln\left(P(N_\nu)\right)$$

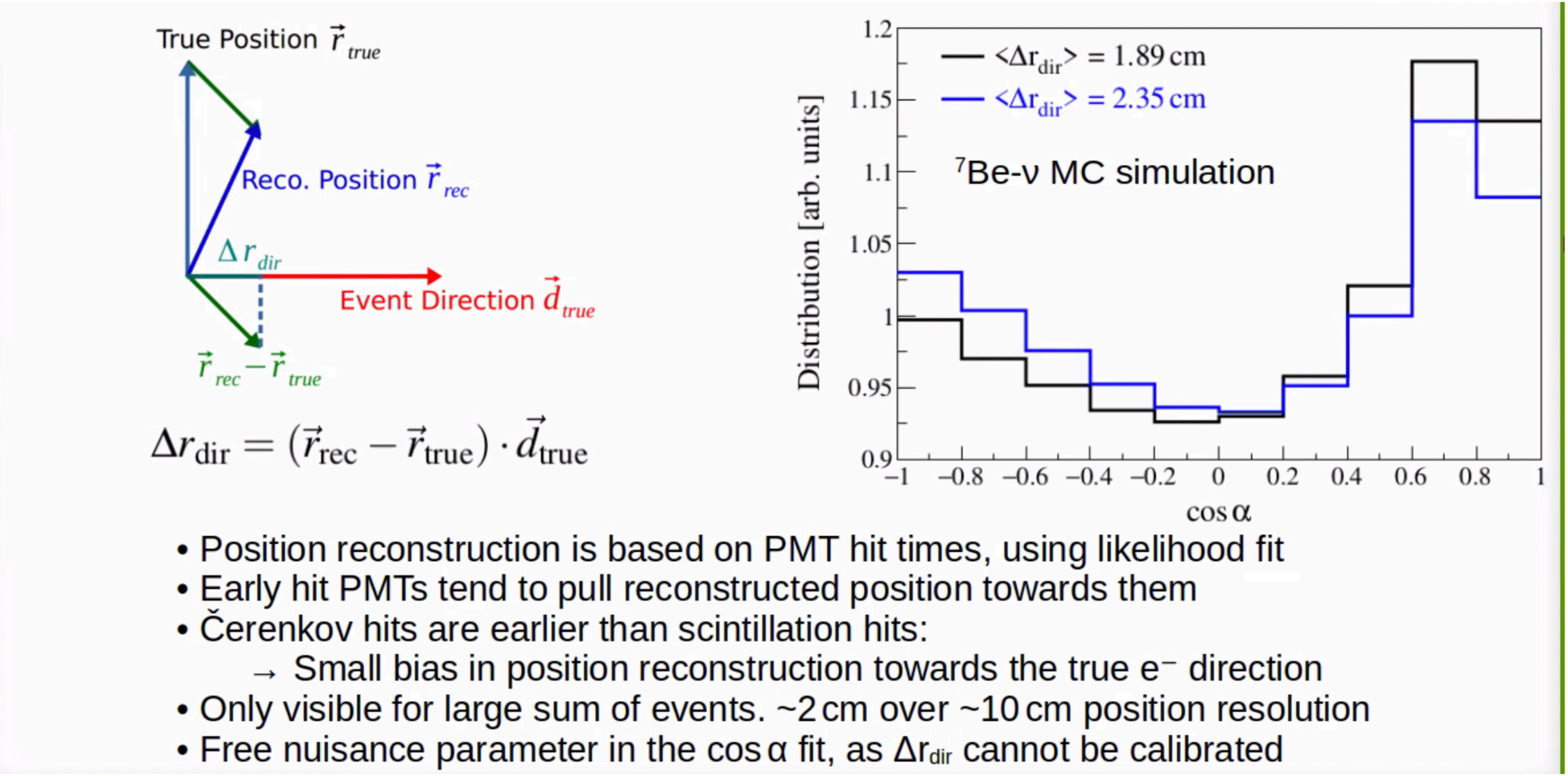
- **M_i^n, D_i^n**: MC and data in cos α distrib. for i-th bin and n-th hits
➔ ν contribution to M_i^n explicitly depends on $\mathrm{gv_{ch}}$, N_ν Δr_{dir}
- **N_ν** constrained by SSM
- **Δr_{dir}** free to vary

cos α fit (1 to 4 hit)



Δχ² profile for $\mathrm{gv_{ch}}$



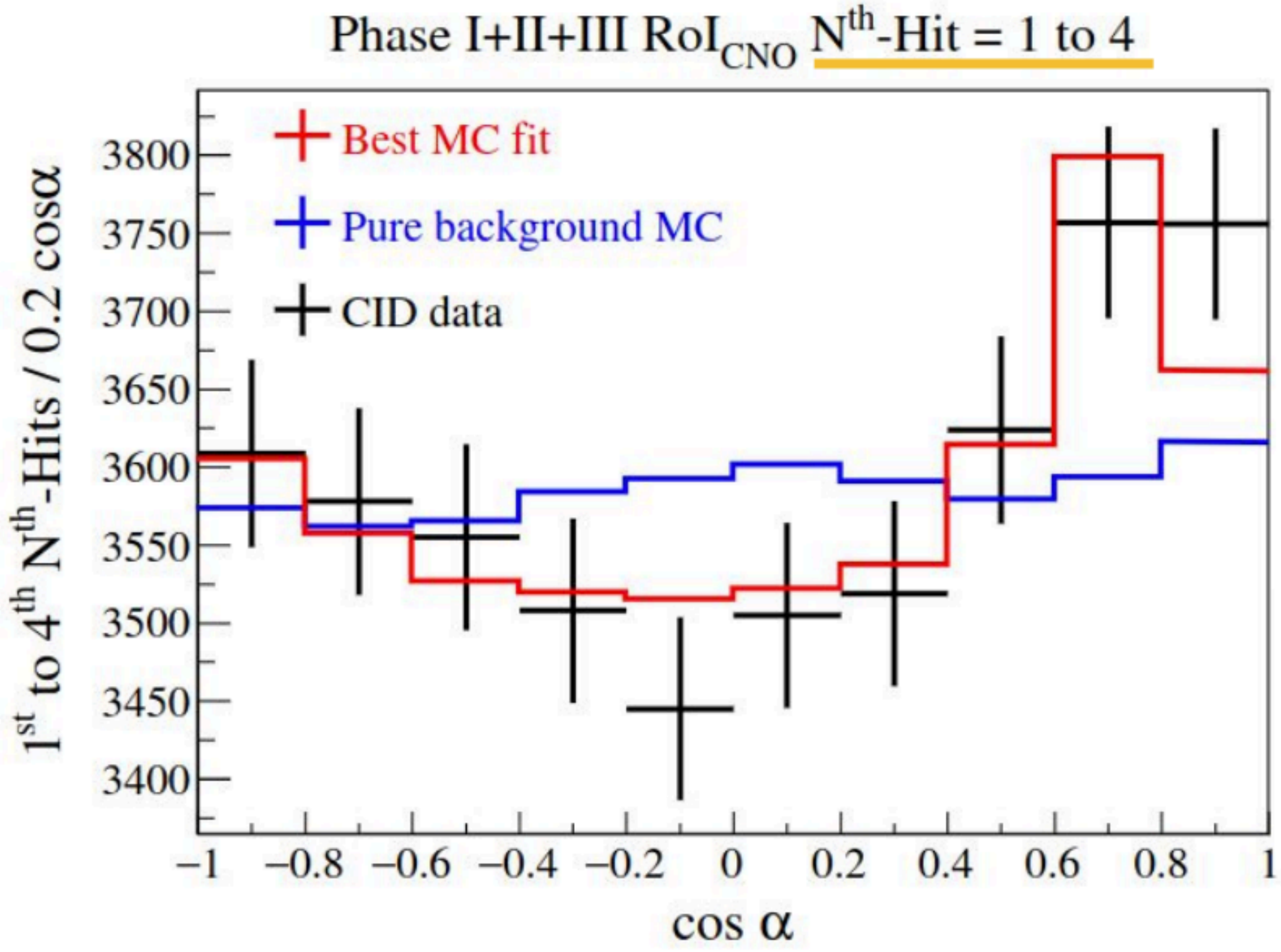


$$\Delta r_{\mathrm{dir}} = (\vec{r}_{\mathrm{rec}} - \vec{r}_{\mathrm{true}}) \cdot \vec{d}_{\mathrm{true}}$$

- Position reconstruction is based on PMT hit times, using likelihood fit
- Early hit PMTs tend to pull reconstructed position towards them
- Čerenkov hits are earlier than scintillation hits:
  - → Small bias in position reconstruction towards the true e^- direction
- Only visible for large sum of events. ~2 cm over ~10 cm position resolution
- Free nuisance parameter in the cos α fit, as Δr_{dir} cannot be calibrated

cos α fit in CNO ROI

gv_{ch} calibration **unlocks** the CID analysis on the whole Borexino dataset and without 210Bi constraint
Events cosα distribution in the CNO ROI ➜ **obtain number of ν ($N_\nu=N_{CNO}+N_{pep}+N_{8B}$) and background** events



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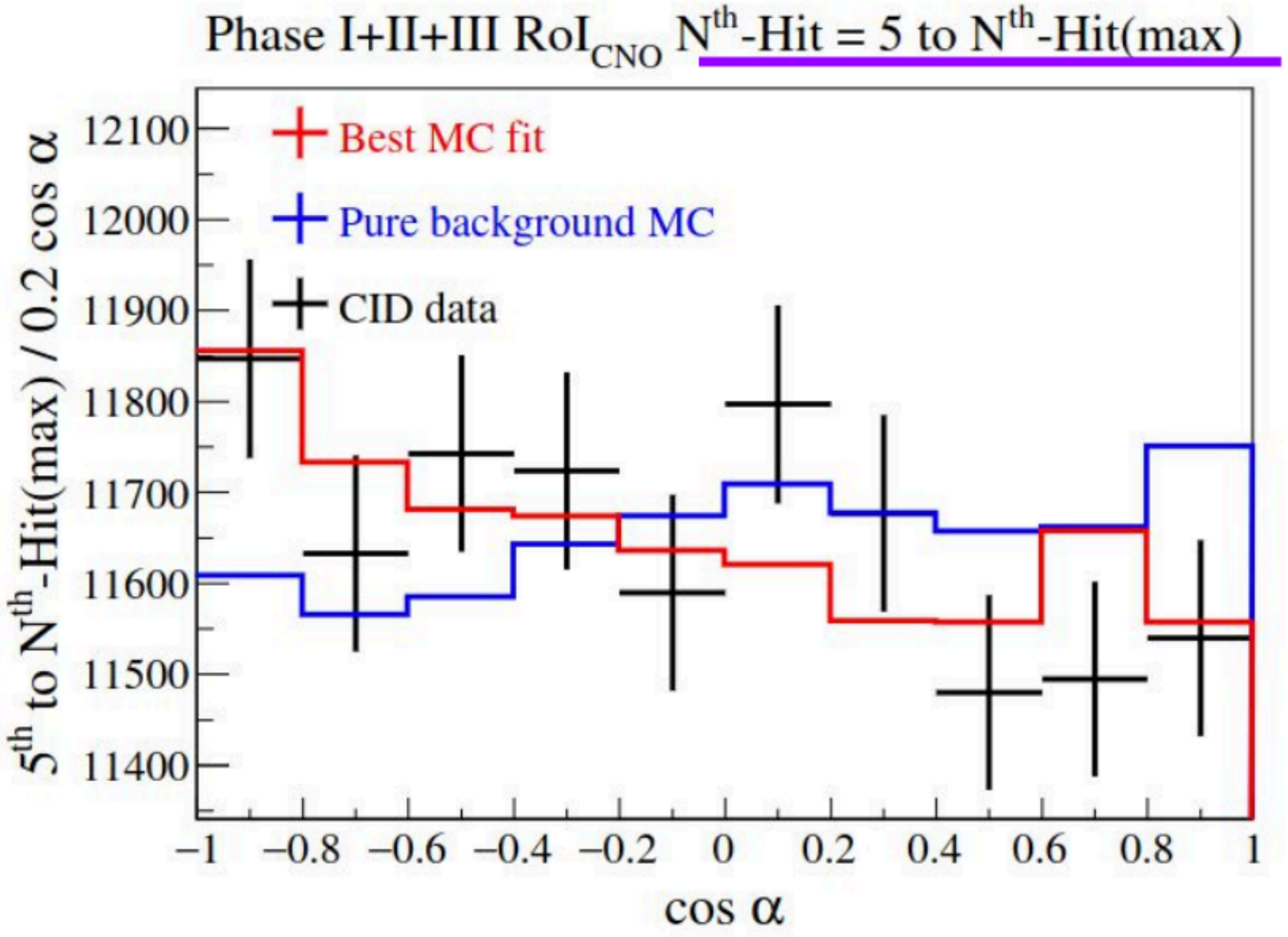

Earliest 4 hits: direct Cherenkov information (peak for neutrinos at cos α ~ 0.75)

Later hits: indirect directionality information via Δr_{dir}

N13

O15

Radiopurity scenario

— BX-like — Ideal — Baseline — IBD

dashed: w/ *pep* constraint
solid: w/o *pep* constraint