Current status and prospects in solar neutrino field

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PHYSICS IN COLLISION 2022 - 08.09.2022

RWTH AACHEN UNIVERSITY
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QUARK - LEPTON
Tbilisi, Georgia, September 5-9, 2022

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OUTLINE

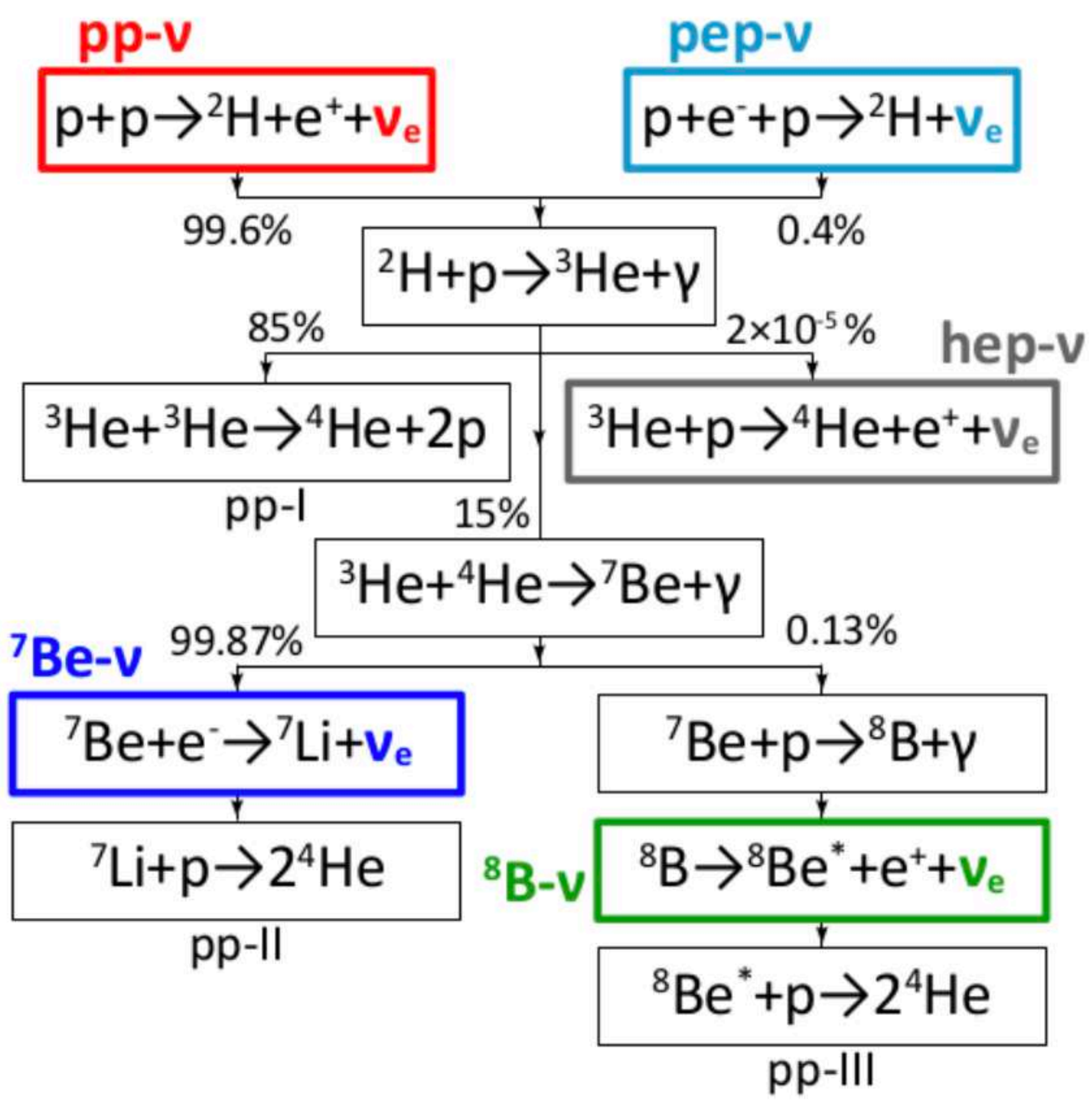
- Solar neutrinos
  - Thermonuclear processes
  - Detecting neutrinos
- Experimental activity:
  - Borexino
  - SuperKamiokande
  - SNO+
- Outlook: JUNO

SOLAR NEUTRINOS

The Sun is powered by two sequences of thermonuclear reactions, characterized by the same net reaction:

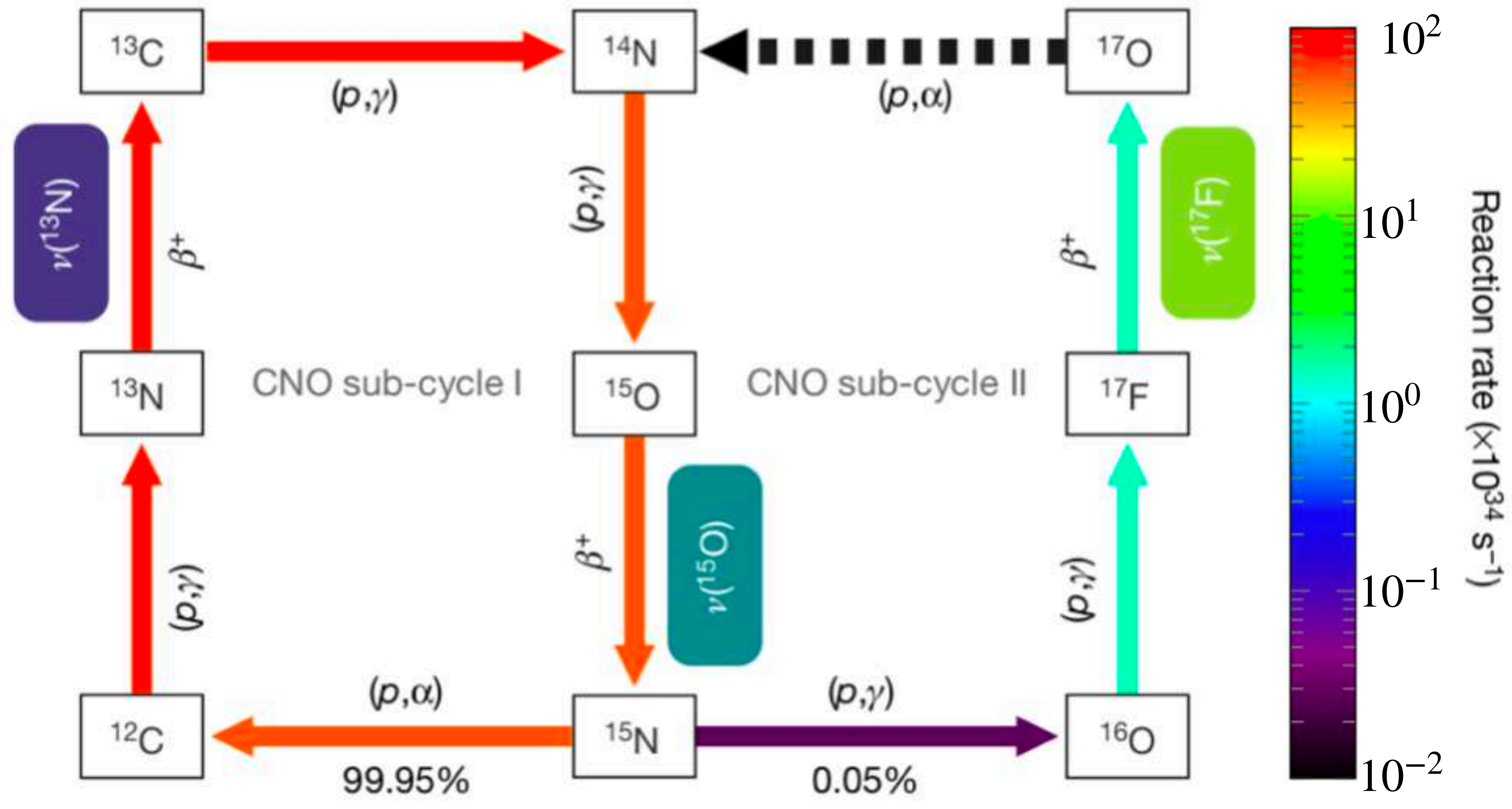
Net reaction: $4p \rightarrow \ {}^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$

pp chain



($\sim 99\,\%$ $E_\odot$)

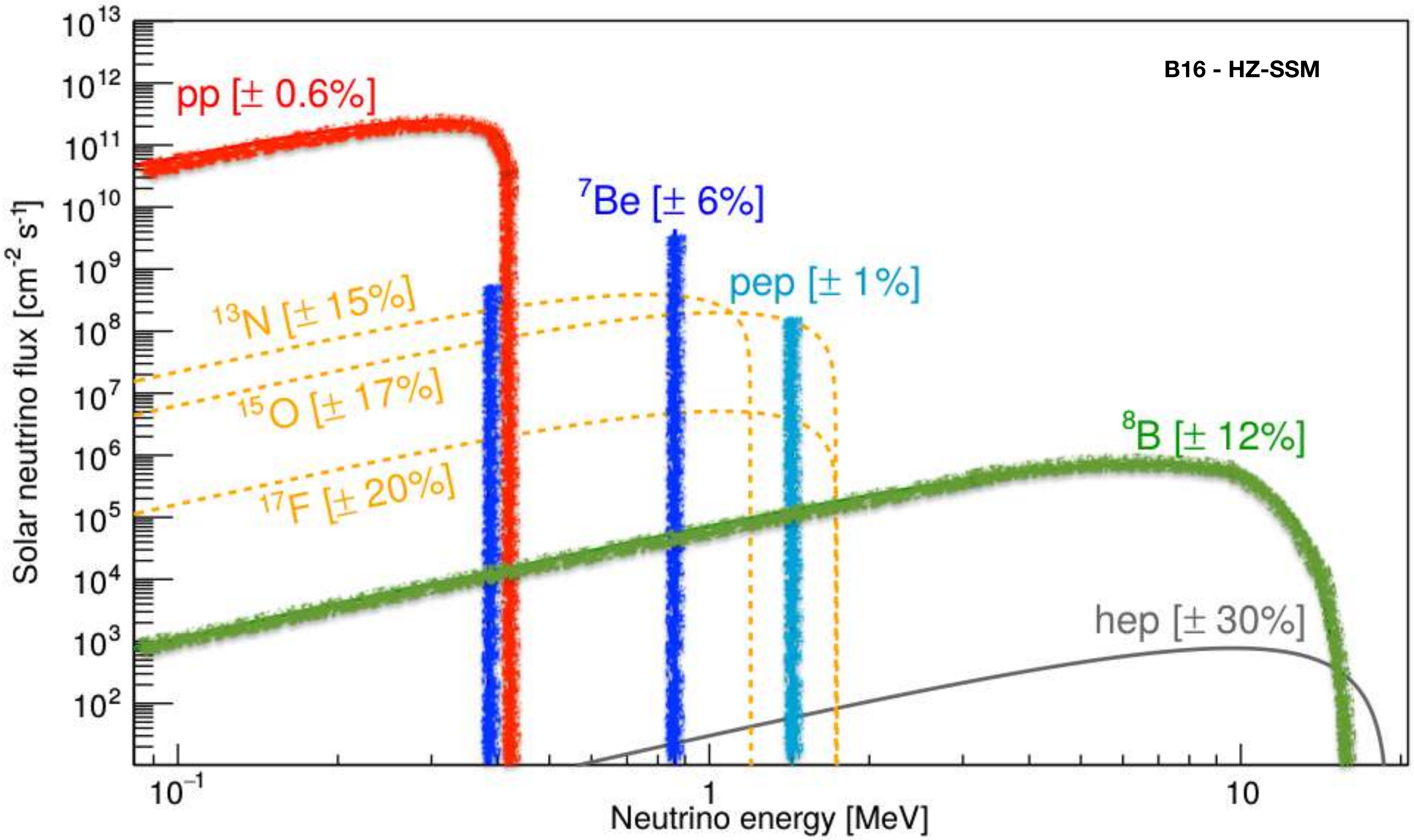
CNO cycle



($\sim 1\,\%$ $E_\odot$)

Dominant process in massive Stars

SOLAR NEUTRINOS - ENERGY SPECTRUM



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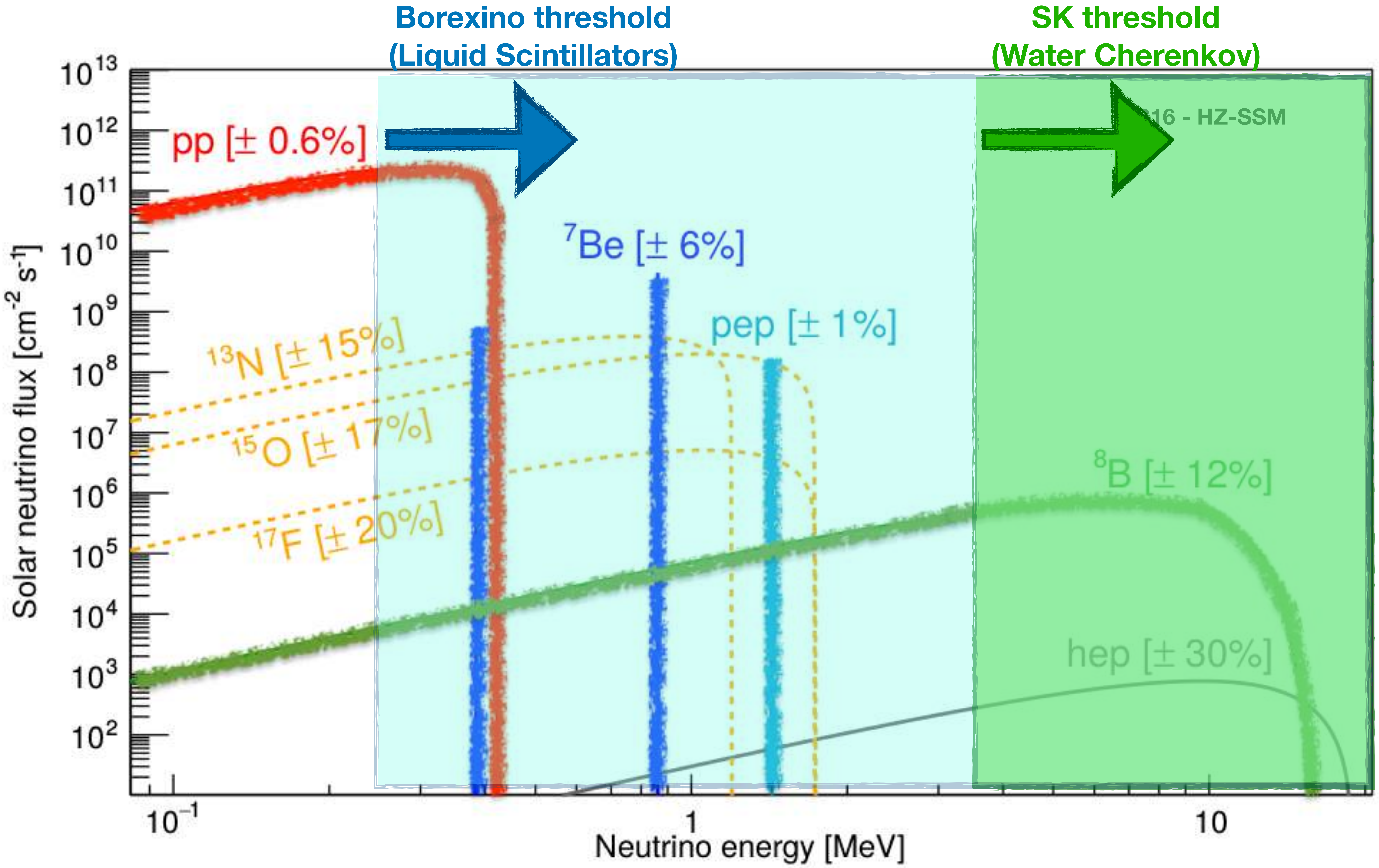

THE IMPORTANCE OF SOLAR NEUTRINOS

Solar neutrino problem → Intense experimental activity for solar neutrino detection (Homestake Kamiokande, SNO, Gallex, GNO, SAGE) → Proof of neutrino flavour conversion (+ atmospheric)

Solar neutrinos represent an important example of the connection between particle physics and astrophysics

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Neutrino physics:

- **Oscillation parameters**:
  - ☑ Solar sector (θ_{12}, Δm^2_{12} and global fits)
- **Matter effects:**
  - ☑ Earth: Day/Nighy asymmetry
  - ☑ Sun: Survival probability Pee (Upturn)
  - ☑ m_1/m_2 ordering
- **Beyond Standard Model Physics:**
  - ☑ Neutrino magnetic moment
  - ☑ Sterile neutrinos
  - ☑ Non-standard neutrino interactions

Solar and stellar physics:

- **Direct probe of thermonuclear processes:**
  - ☑ pp chain
  - ☑ CNO cycle
- **Thermodynamical stability** of the Sun
- **Unique probe to test Standard Solar Models:**
  - ☑ Metallicity puzzle

SOLAR PHYSICS: THE SOLAR METALLICITY PUZZLE

Metallicity: abundance of elements with Z>2 in the Sun (wrt Hydrogen)
Can be inferred from spectroscopic measurements of the photosphere

Evolution of **metal-to-hydrogen ratio (Z/X)**:

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

Perfect candidates to unravel the metallicity puzzle

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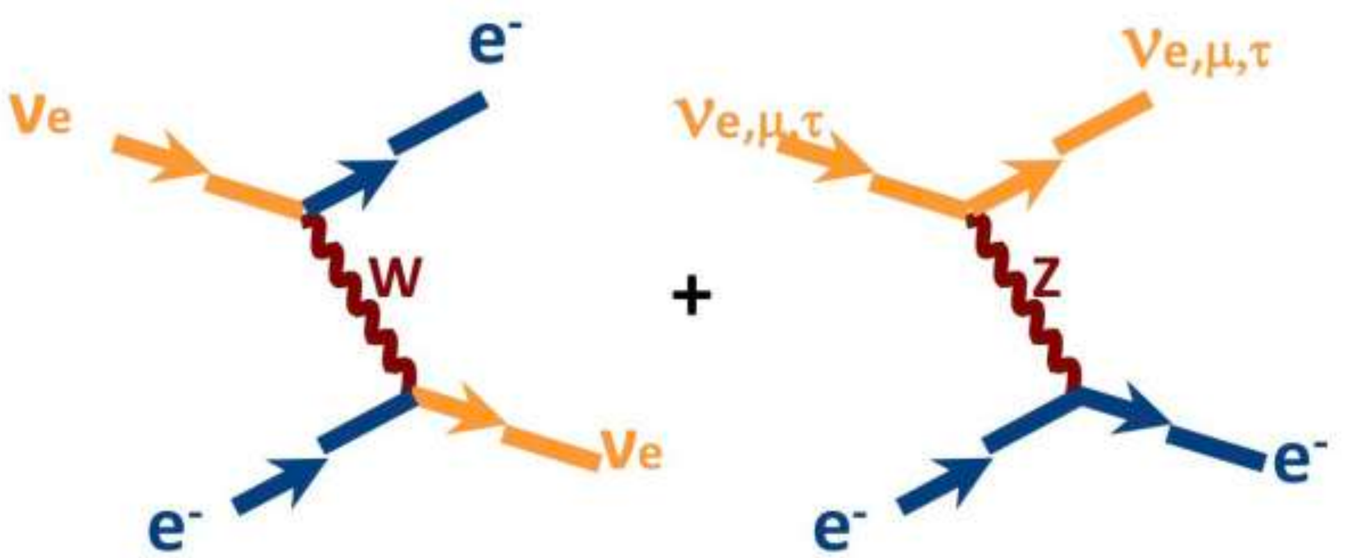
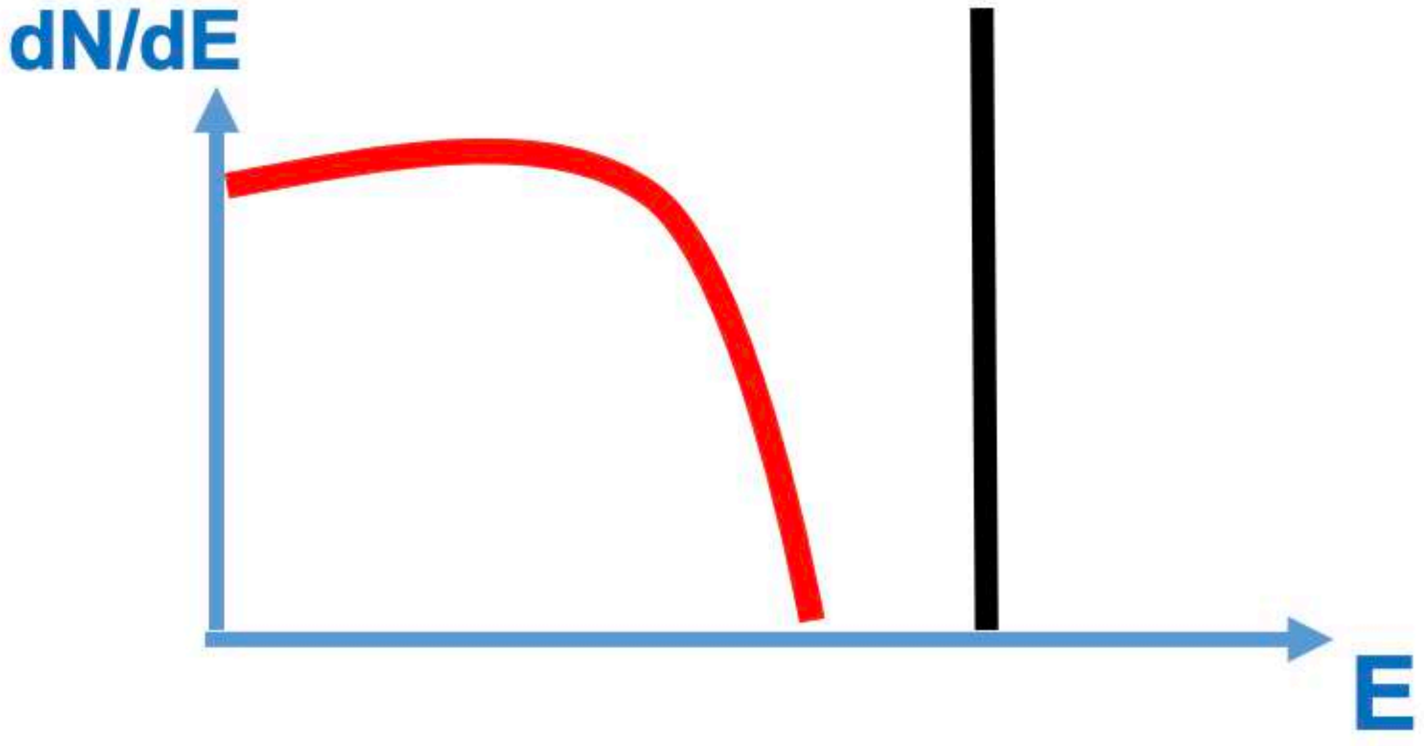
SOLAR NEUTRINOS - DETECTION CHANNEL

- *Detection channel:* **solar neutrino - electron elastic scattering (real time)** (both for liquid scintillators and Cherenkov detectors)



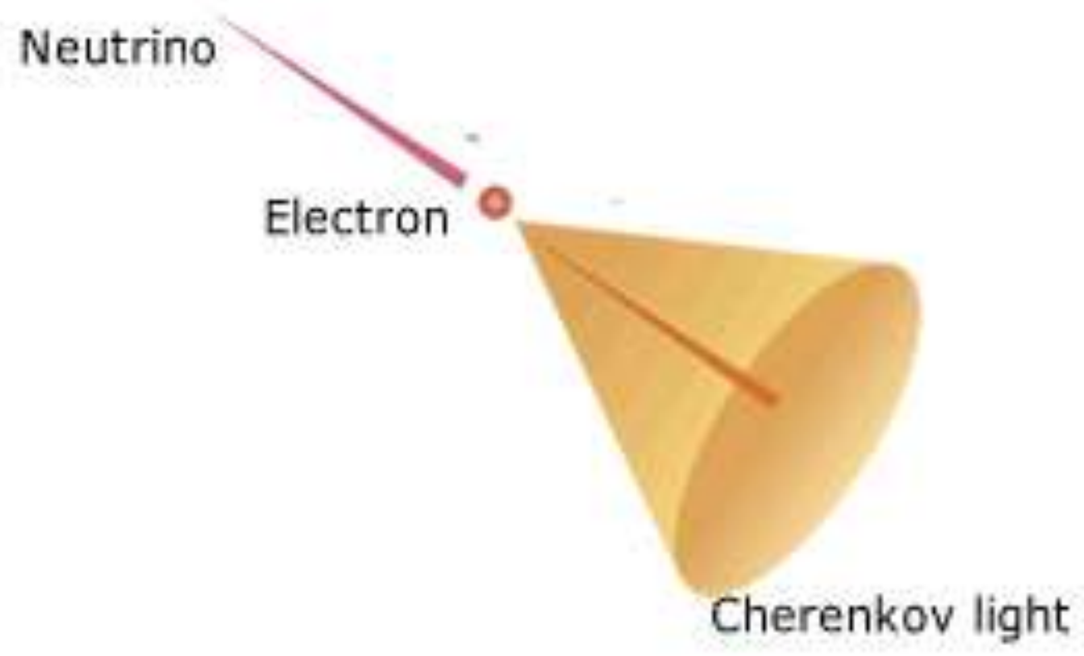
$$\sigma_{\nu_e} : \sigma_{\nu_{\mu,\tau}} :\cong 1 : 0.16$$

- *Sensitive to all neutrino flavours*
- *No intrinsic energy threshold*
- *Continuous energy spectrum:*



We see the energy **carried away by electrons**, not the **total neutrino energy**

- *LS - isotropic light*
- *Cherenkov - Directional information*



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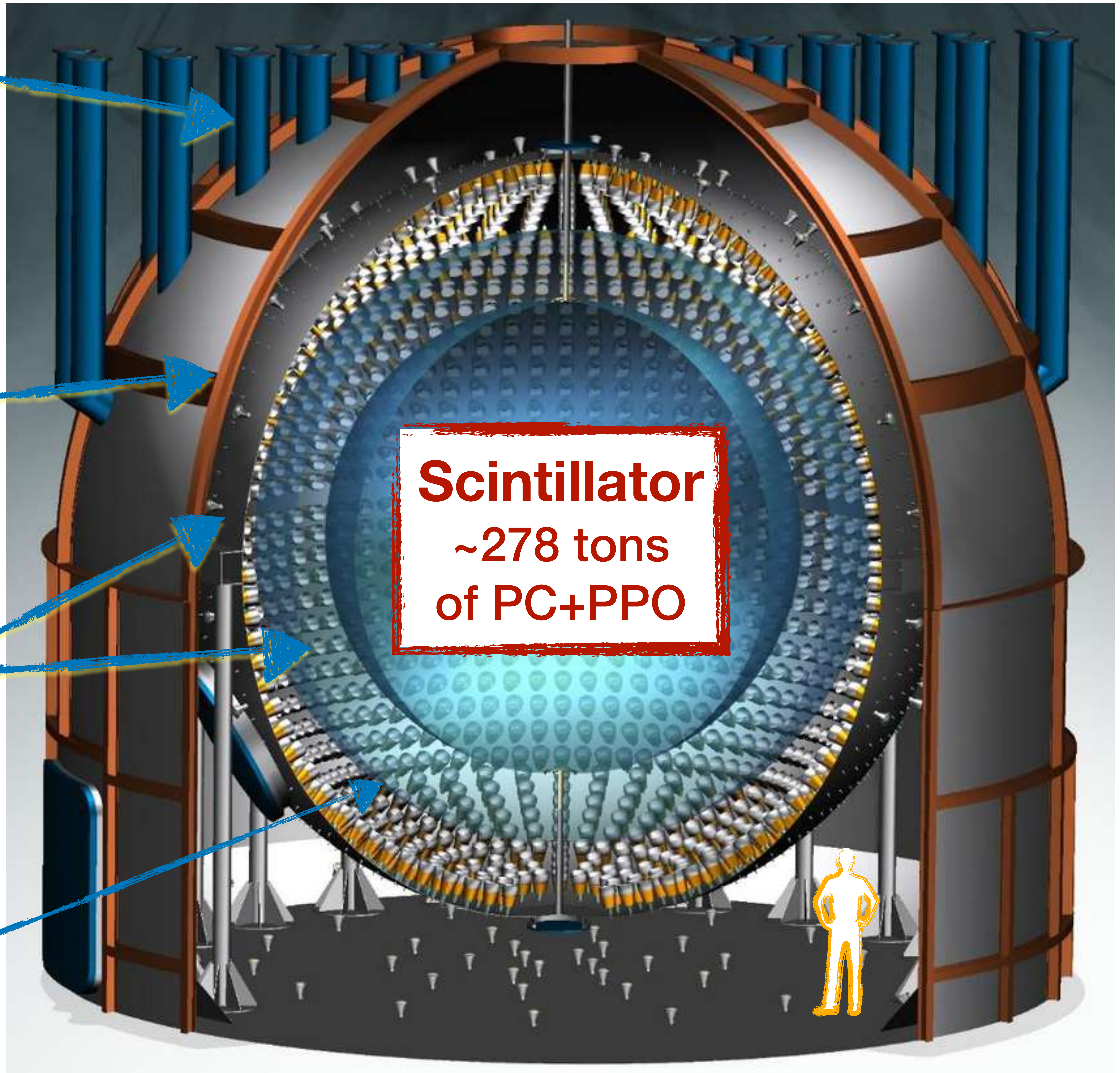
BOREXINO DETECTOR

Water tank: 2.8 kton of pure H_2O
γ & n shield
Cherenkov muon veto
280 PMTs in water

Stainless Steel Sphere:
2212 Internal PMTs

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

Buffer:
~900 tons of quenched scintillator



- *Location:* Laboratori Nazionali del Gran Sasso (LNGS), Italy
- *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)
- ☑ α/β discrimination capability via pulse shape discrimination

BOREXINO: THE LONG JOURNEY

- ☑ **1990**: Start of R&D for innovative radiopurity methods
- ☑ **1995**: Counting Test Facility (CTF) testing the radiopurity
- ☑ **1997**: Approval of the experiment
- ☑ **2007**: Begin of data taking

Purification campaign — **Purification campaign** — **Thermal insulation and active temperature control**

Phase-I (2007 - 2010) — Phase-II (2012 - 2016) — Phase-III (2016 - 2021)

Phase-I

Solar neutrinos:
- $^{7}Be\ \nu$: 1st observation (5%) + absence of day/night asymmetry;
- pep ν: 1st observation;
- 8B ν with low threshold;
- CNO ν : best limit;

Other:
- Geo-ν evidence > 4.5σ;

Phase-II

Solar neutrinos:
- pp ν: 1st observation;
- $^{7}Be\ \nu$ flux seasonal modulation;
- **Comprehensive measurement of pp-chain (Nature 2014 and 2018)**

Other:
- New limit on neutrino magnetic moment
- Geo-ν evidence > 5σ;

Phase-III

- **First direct experimental evidence of CNO neutrinos (Nature 2020)**
- **Updated CNO measurement (2022)**
- Comprehensive geoneutrino analysis

BOREXINO PHASE-II: PP CHAIN

Low Energy Region (LER) 0.19 - 2.93 MeV: $pp - \nu$ (10.5 %), $^7Be - \nu$ (2.7 %), and $pep - \nu$ ($> 5\sigma$)

High Energy Region (HER) 3.2 - 16 MeV: $^8B - \nu$ (8 % with 3 MeV threshold)

First limit on $CNO - \nu$ and $hep - \nu$

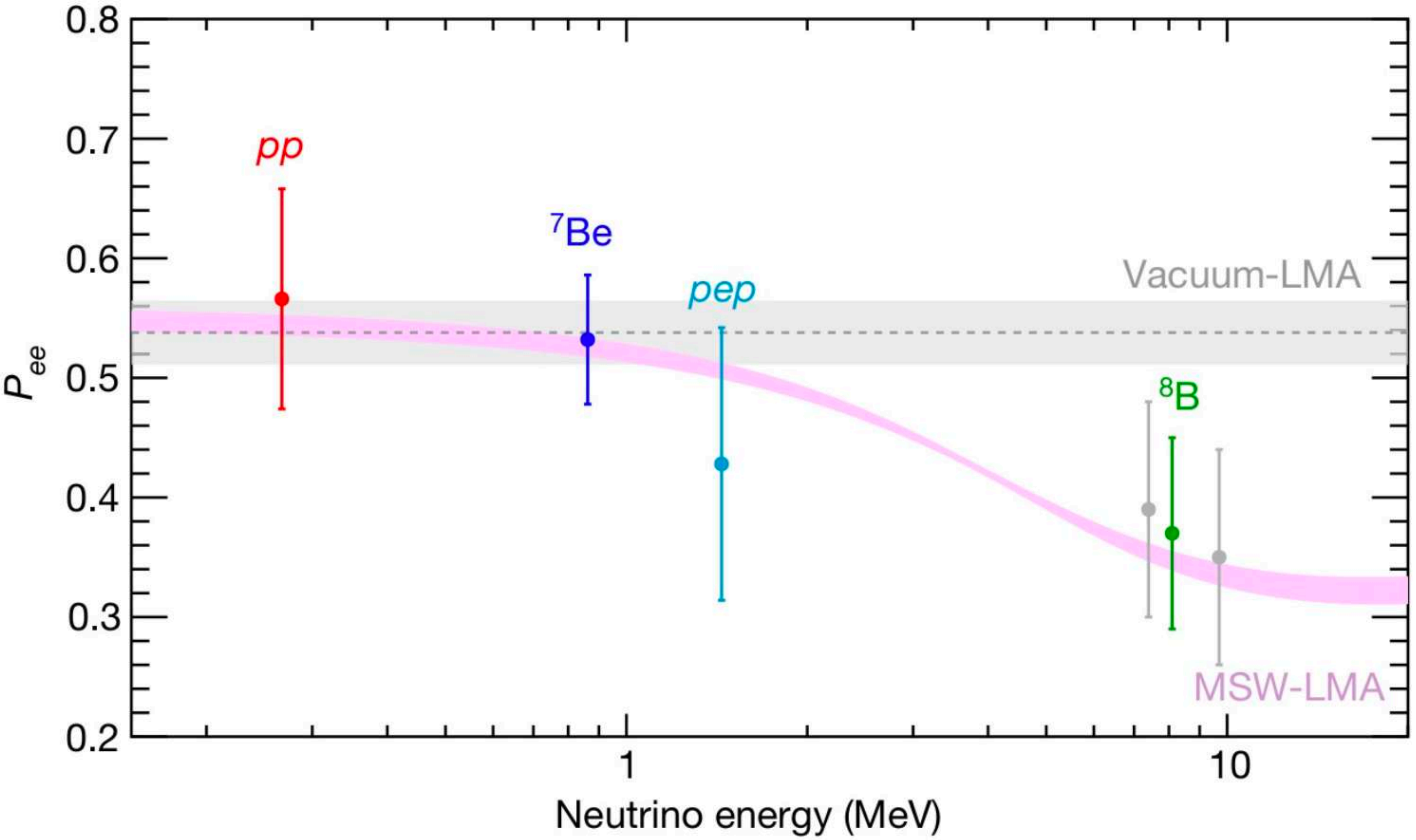
Neutrinos	References	Rate [cpd/100t]	Flux $[cm^{-2} \cdot s^{-1}]$
pp	Nature 2014, Nature 2018, PRD 2019	$134 \pm 10^{+6}_{-10}$	$6.1 \pm 0.5^{+0.3}_{-0.5} \cdot 10^{10}$
^7Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$4.99 \pm 0.11^{+0.06}_{-0.08} \cdot 10^9$
pep	PRL 2012, Nature 2018 PRD 2019	$2.7 \pm 0.4^{+0.1}_{-0.2}$	$1.3 \pm 0.3^{+0.1}_{-0.1} \cdot 10^8$
^8B	PRD 2010, Nature 2018, PRD 2020	$0.223^{+0.021}_{-0.022}$	$5.68 \pm 0.03^{+0.39}_{-0.41} \cdot 10^6$
hep	Nature 2018	< 0.002 (90% C.L.)	$< 2.2 \cdot 10^5$ (90% C.L.)
CNO	PRL 2010, Nature 2018	< 8.1 (95% C.L.)	$< 7.9 \cdot 10^8$ (95% C.L.)

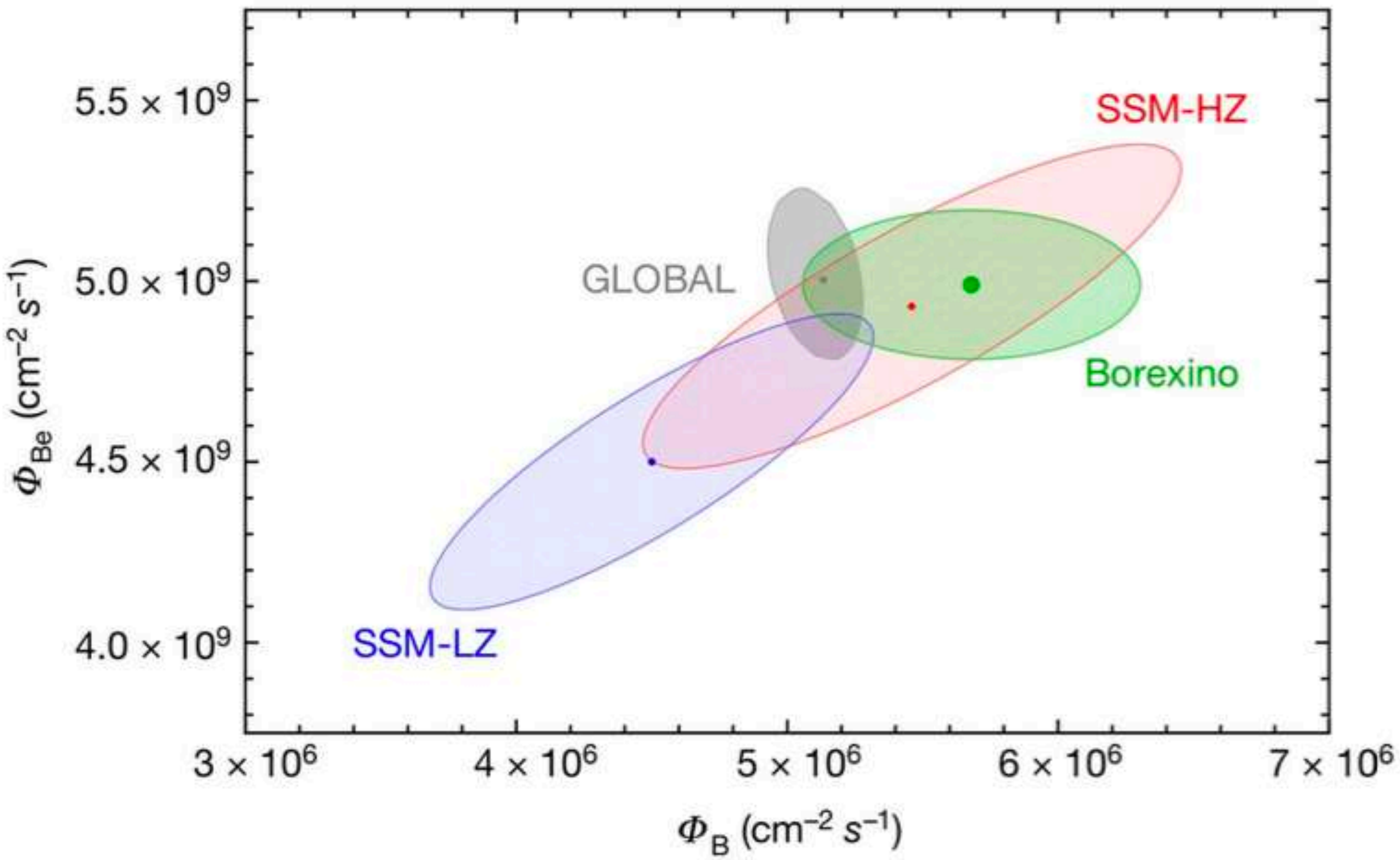
Upper limit only

BOREXINO PHASE-II: IMPLICATION OF THE RESULTS

Neutrino Luminosity: $L = 3.89^{+0.35}_{-0.42} \cdot 10^{33}$ erg s^{-1} in agreement with photon luminosity → thermodinamical stability of the Sun

Relative intensity ppII-ppI: $R_{I/II} = \dfrac{2\Phi(^7Be)}{\Phi(pp) - \Phi(^7Be)} = 0.178^{+0.027}_{-0.023}$ (in agreement with predicted values $R^{HZ}_{I/II} = 0.180 \pm 0.011$ and $R^{LZ}_{I/II} = 0.161 \pm 0.010$)





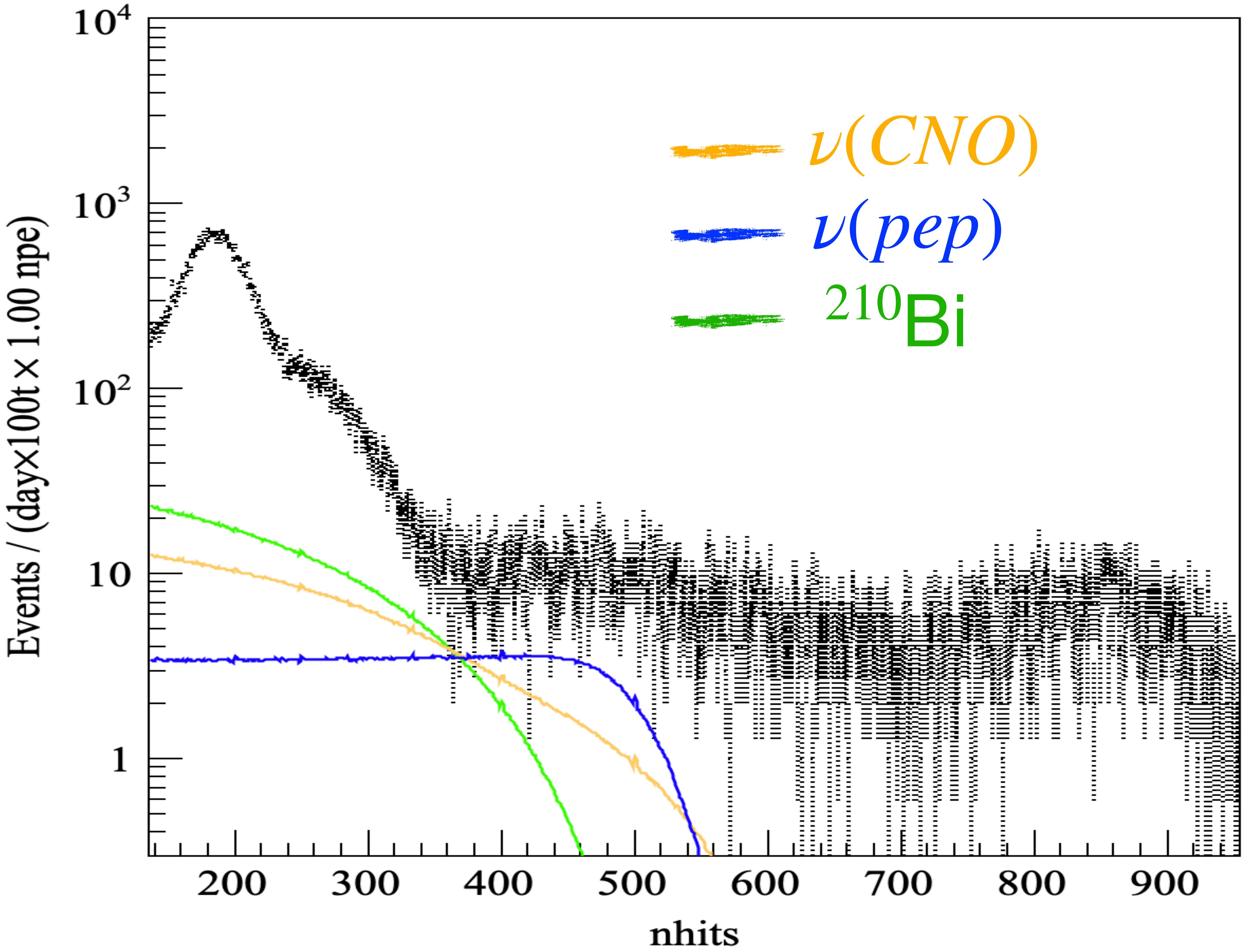
Survival probability with Borexino data only:
Vacuum-LMA model excluded at 98.2% CL

Indication towards HZ-SSM:
Low metallicity disfavoured at 1.8 σ

M. Agostini et al., Comprehensive measurement of pp-chain solar neutrinos, *Nature* 562 (2018) 505–510.

BOREXINO PHASE-III: CHALLENGES FOR CNO

- Low expected rate: 3-5 cpd/100 tons
- Spectral shape similar to $pep - \nu$ and ^{210}Bi



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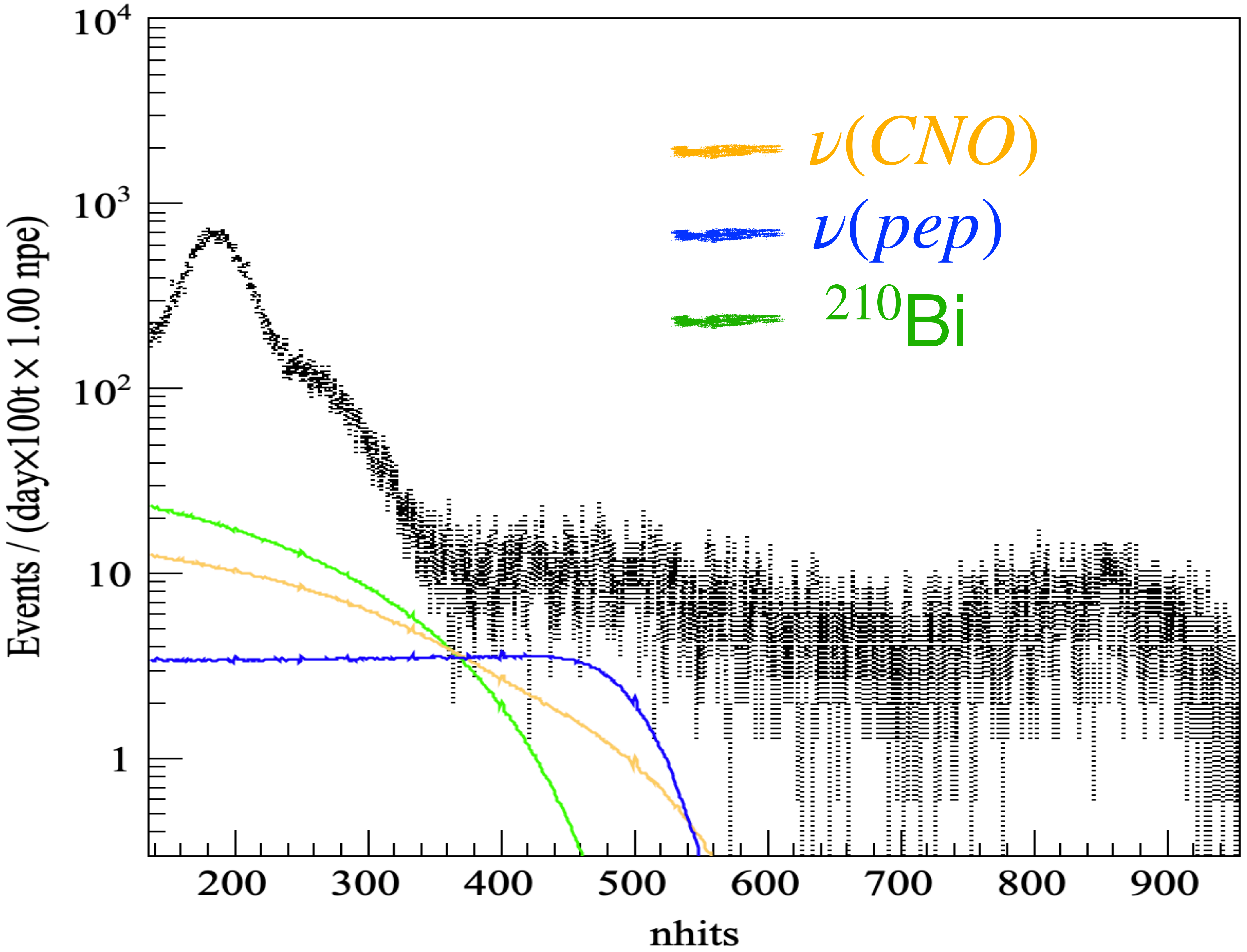
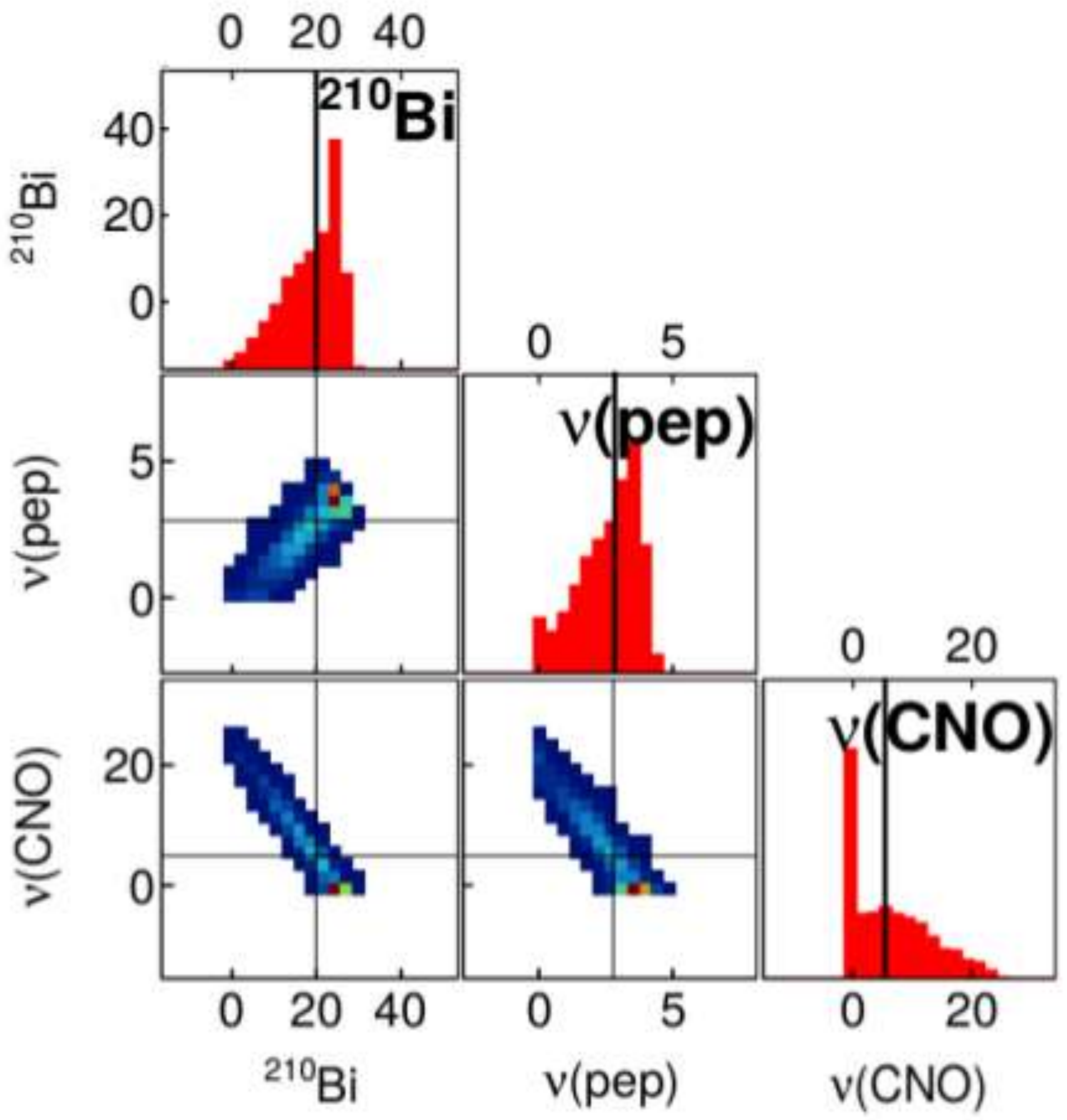


The strong anti-correlation…



… requires and **indipendent constraint**:

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

BOREXINO PHASE-III: CHALLENGES FOR CNO

^{210}**Bi** can be constrained exploiting the link with its daughter nucleus ^{210}Po:

$$^{210}\text{Pb} \xrightarrow[\beta\text{ decay}]{\tau \approx 32\text{ y}} {}^{210}\text{Bi} \xrightarrow[\beta\text{ decay}]{\tau \approx 7.23\text{ d}} {}^{210}\text{Po} \xrightarrow[\alpha\text{ decay}]{\tau \approx 199.1\text{ d}} {}^{206}\text{Pb}$$

^{210}Po is easier to identify:

- α decay → Alpha selection can be carried out on an event-by-event basis with an MLP variable
- Monoenergetic → Gaussian peak

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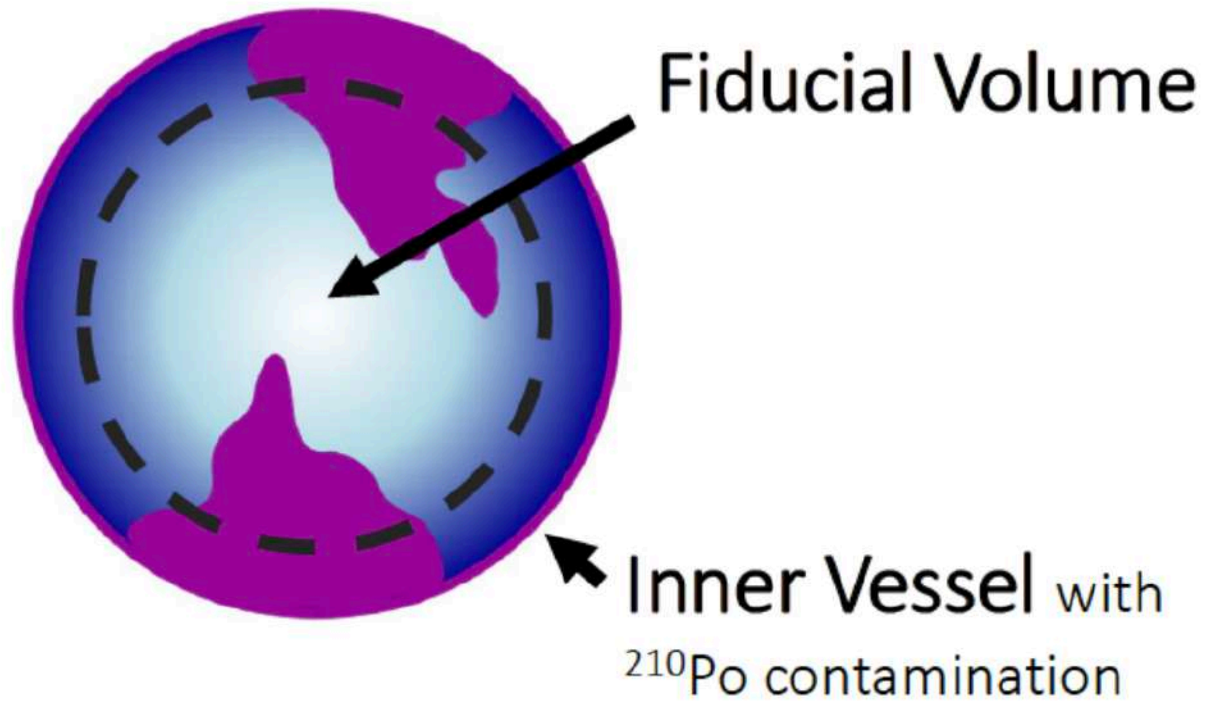
- α decay → Alpha selection can be carried out on an event-by-event basis with an MLP variable
- Monoenergetic → Gaussian peak

Life is not that easy:

Convective motions, triggered by temperature gradients, can contaminate the FV with unknown amount of out-of-equlibrium ^{210}Po, present on the nylon inner vessel.



This **breaks the secular equilibrium** of the ^{210}Pb chain!

$$R(^{210}\text{Po}) \geq R(^{210}\text{Bi})$$

We need to to **thermally insulate the detector** to stop convective motions!

BOREXINO PHASE-III: CHALLENGES FOR CNO

Towards stopping the convective currents:

- ☑ **Thermal insulation** with double layer of mineral wool installed in early 2016
- ☑ **Active temperature control system** (66 temperature probes)

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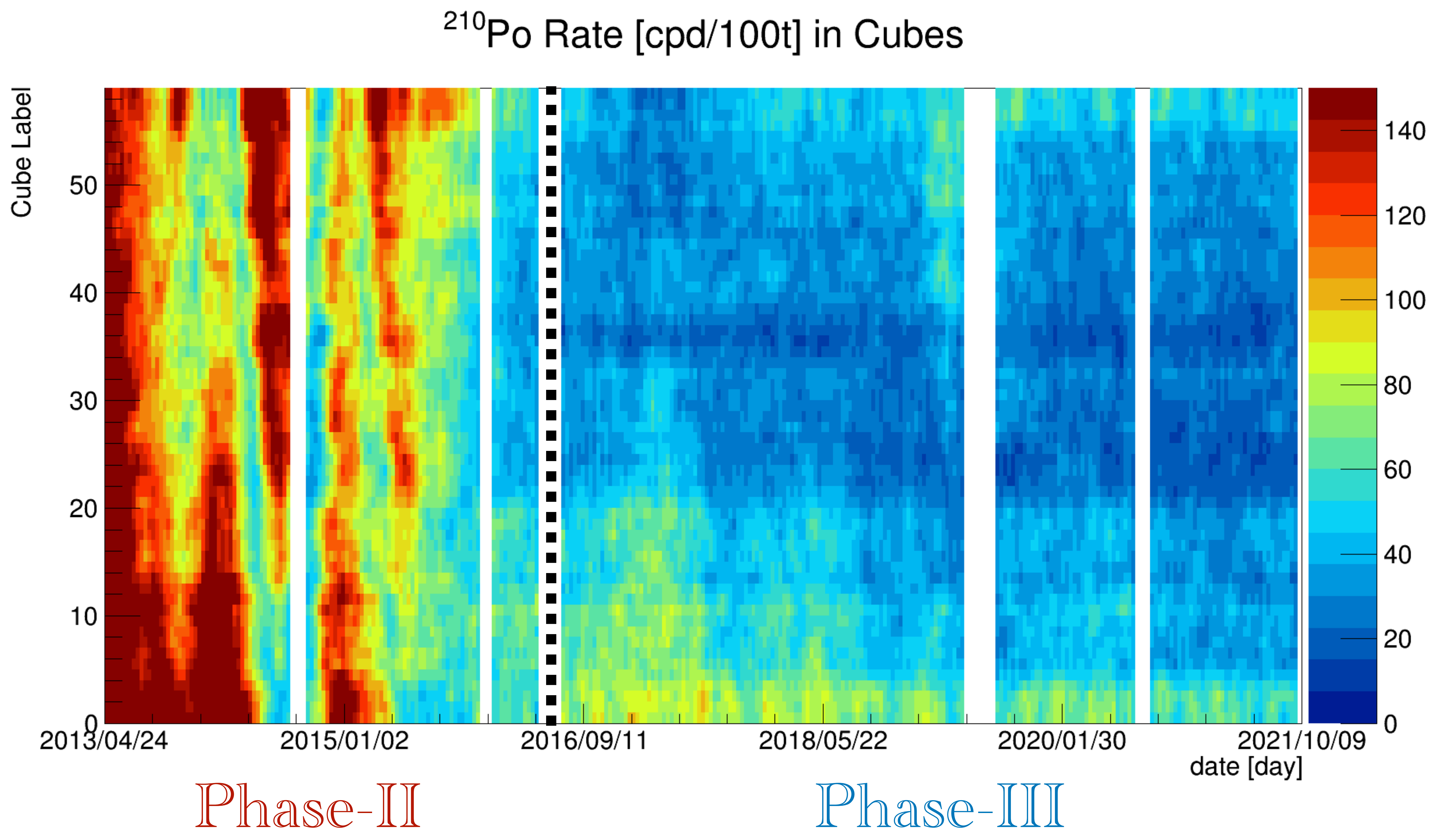
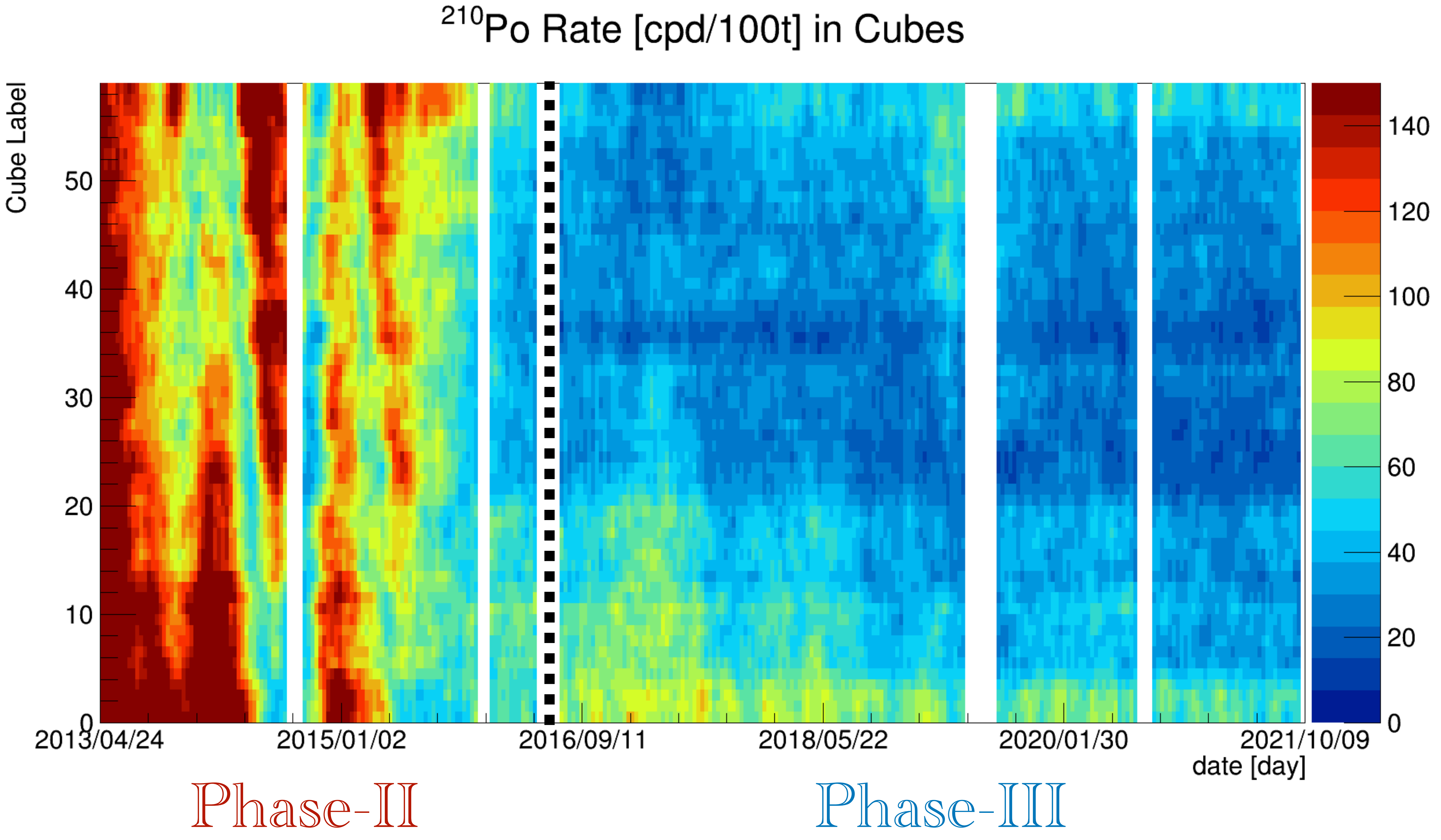
BOREXINO PHASE-III: CHALLENGES FOR CNO

A crucial achievement:

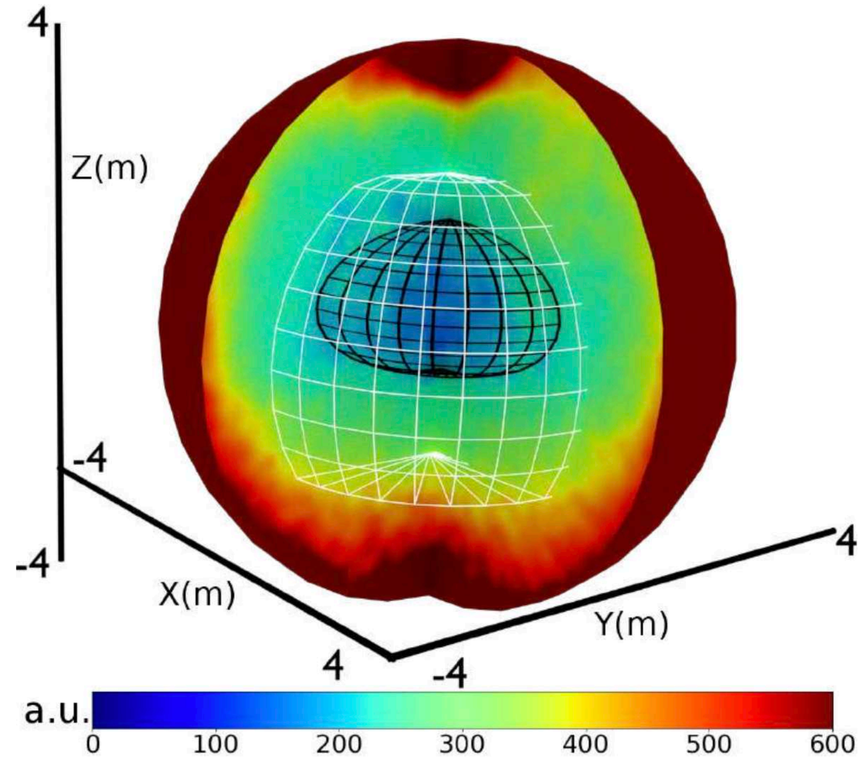


BOREXINO PHASE-III: CHALLENGES FOR CNO

A crucial achievement:



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

Two methods give consistent results, it is now possible to extract: $R(^{210}\text{Bi}) \leq R(^{210}\text{Po})$

BOREXINO PHASE-III: UPGRADED DATASET

Phase-III
(Nature 2020)

Data: July 2016 - February 2020

Monte Carlo: data - MC agreement stable until 2020

Bismuth constraint in the fit:
$R(^{210}Bi) = 11.5 \pm 1.3$ cpd/100t

First detection of CNO neutrinos
Borexino demonstrated how stars shine
(pp chain and CNO cycle)

Phase-III Complete
(submitted to PRL in 2022)

Data: January 2017 - October 2021
- ☑ **exposure increased** by ~ 33%;
- ☑ remove year 2016 where **contamination from unsupported ^{210}Po was still high**;

Monte Carlo: data - MC agreement improved for recent years(<1 % level)

Bismuth constraint in the fit:
$R(^{210}Bi) = 10.8 \pm 1.0$ cpd/100t

In 2021 temperature is even more stable:
- ➡ less unsupported ^{210}Po and larger LPoF
- ➡ **More stringent limit on ^{210}Bi**

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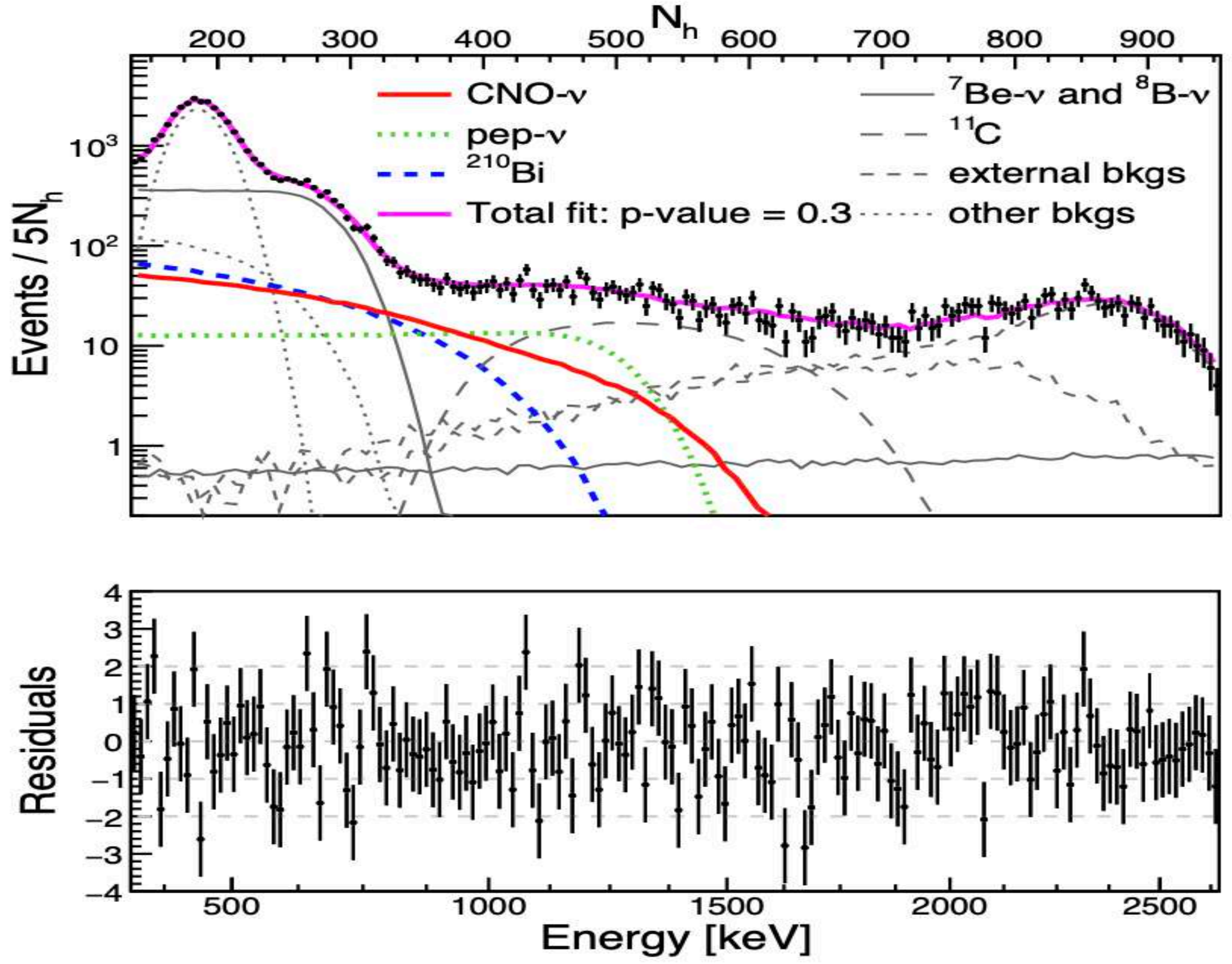
BOREXINO PHASE-III: THE MULTIVARIATE FIT

Neutrino interaction rates are obtained by maximizing a binned likelihood function:

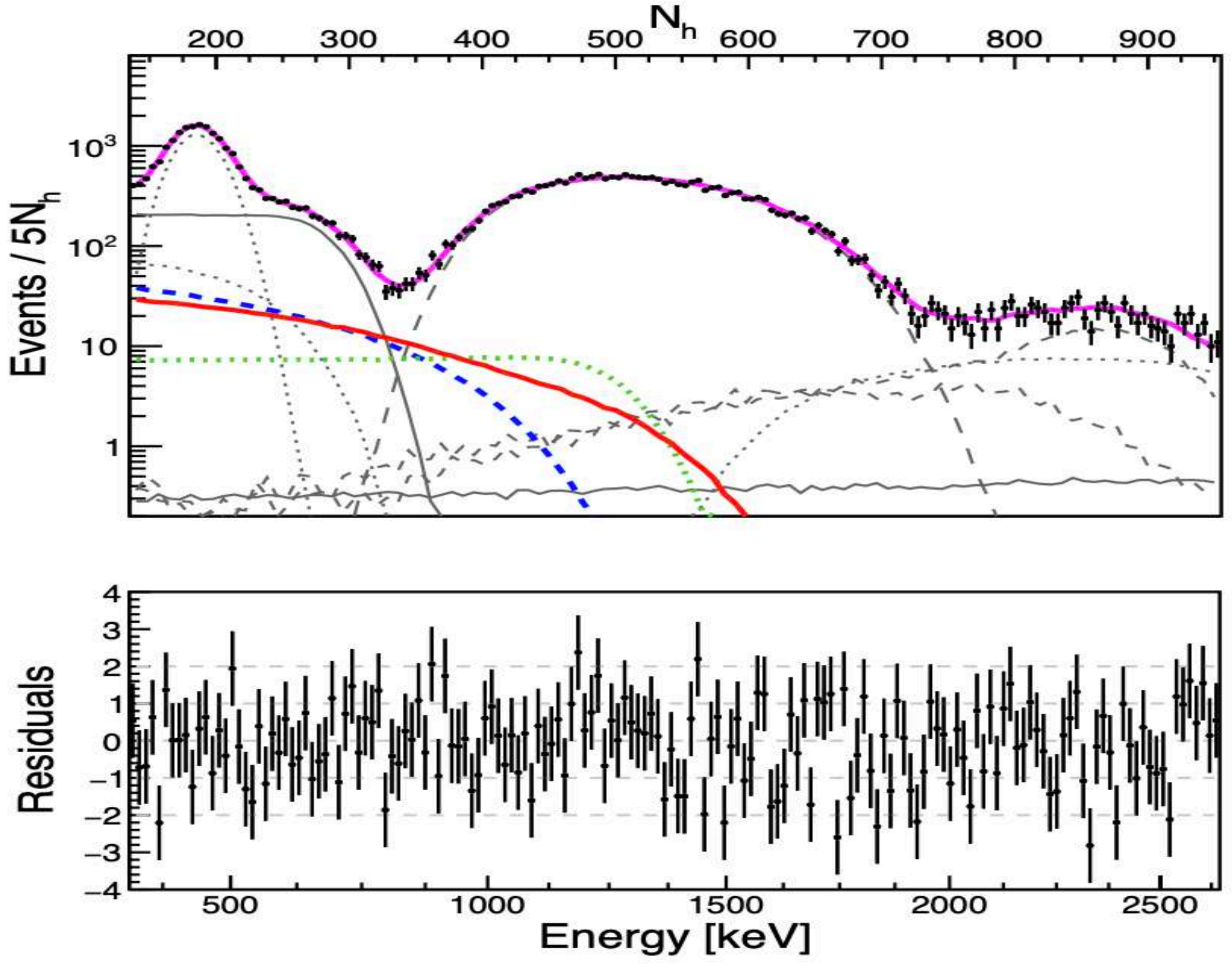
$$\mathscr{L}_{MV}(\vec{k} \mid \vec{\theta}) = \mathscr{L}_{TFC-sub}(\vec{k} \mid \vec{\theta}) \cdot \mathscr{L}_{TFC-tag}(\vec{k} \mid \vec{\theta}) \cdot \mathscr{L}_{Rad}(\vec{k} \mid \vec{\theta})$$

Where $\vec{k}$ = set of experimental data and $\vec{\theta}$ = set of parameters

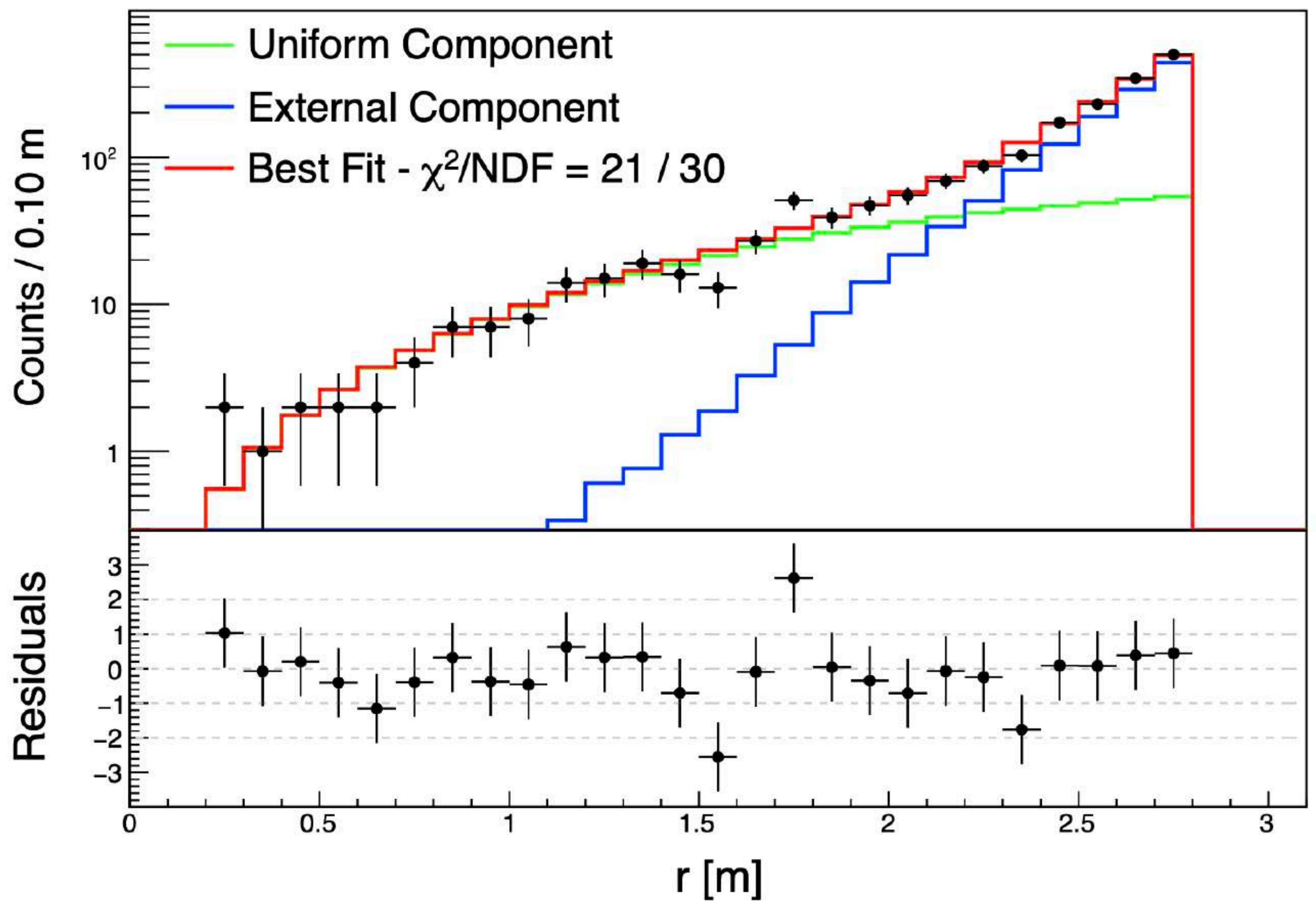
TFC-subtracted spectrum (depleted in ${}^{11}C$):
63.6% of exposure with 5.5% of ${}^{11}C$



TFC-tagged spectrum (enriched in ${}^{11}C$):
36.4% of exposure with 94.5% of ${}^{11}C$



Radial distribution:
Improve external backgrounds identification



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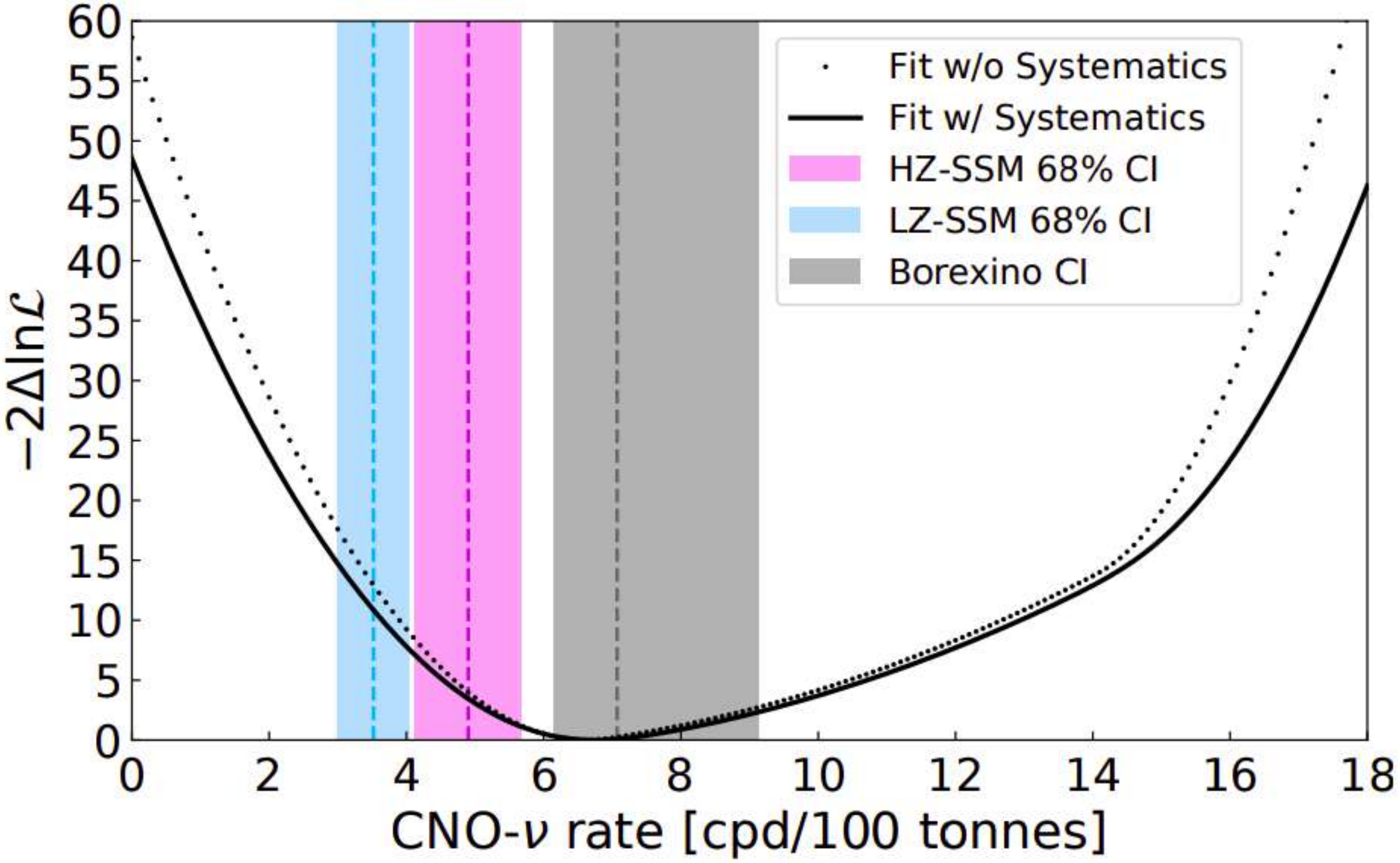
BOREXINO PHASE-III: LIKELIHOOD PROFILE

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: -0.4 +0.5 cpd/100t), **method of extraction and uniformity of ^{210}Bi upper limit** (included in the error on the constraint), and **N/O fixed ratio** in CNO spectral shape (negligible)



Results (stat. + syst.):

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

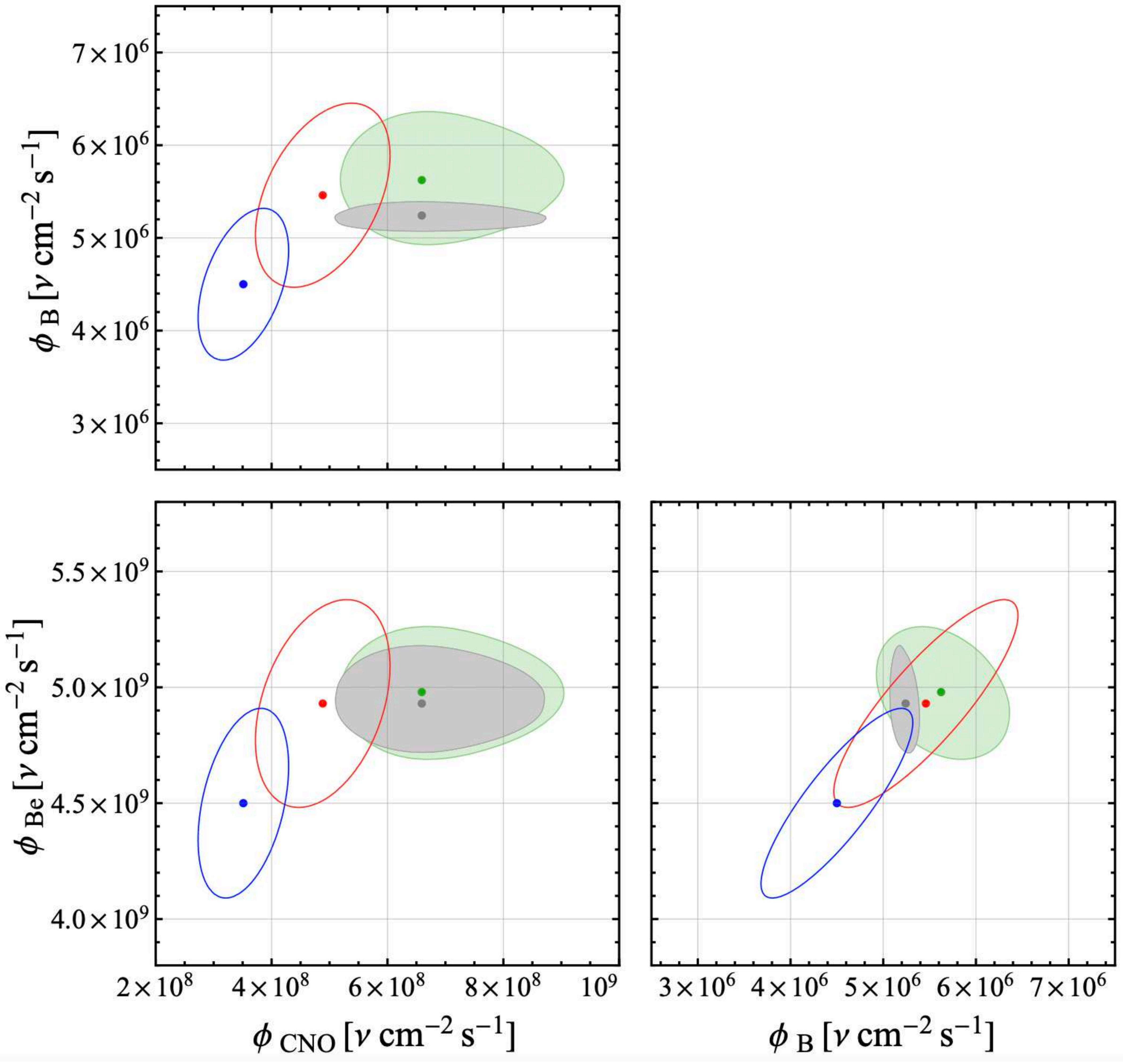
$$\phi(CNO) = 6.6^{+2.0}_{-0.9} \cdot \nu \cdot cm^{-2}s^{-1}$$

no-CNO hypotesis is rejected with a significance **better than 7σ at 90% C.L.**

S. Appel et al., Improved measurement of solar neutrinos from the Carbon-Nitrogen-Oxygen cycle by Borexino and its implications for the Standard Solar Model, *arXiv:2205.15975* (2022), and submitted to Phys. Rev. Lett.

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

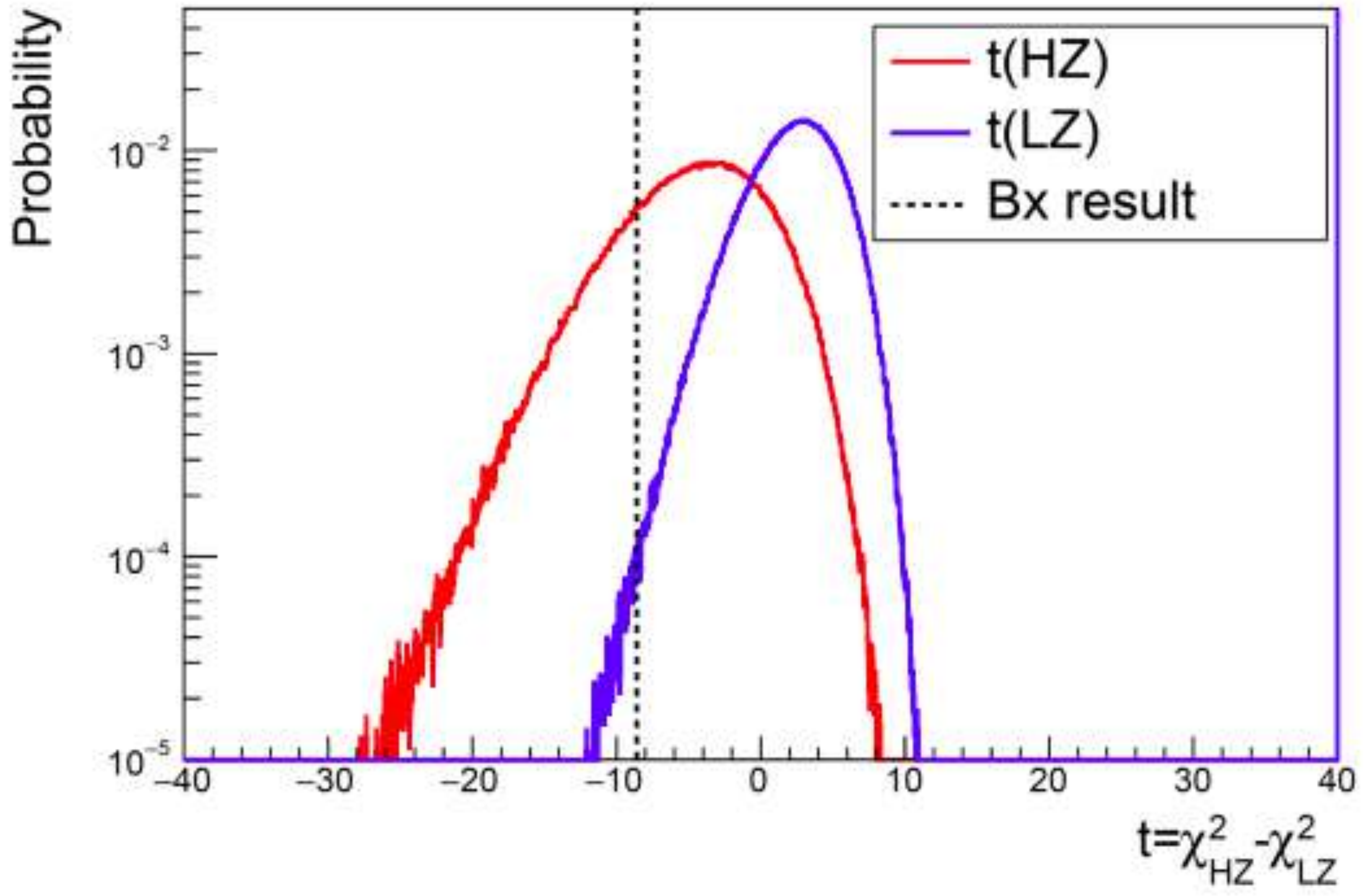
Frequentist hypothesis test based on a likelihood-ratio test statistics for SSM-LZ (null hypothesis H_0) and SSM-HZ (alternative hypothesis H_1)

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

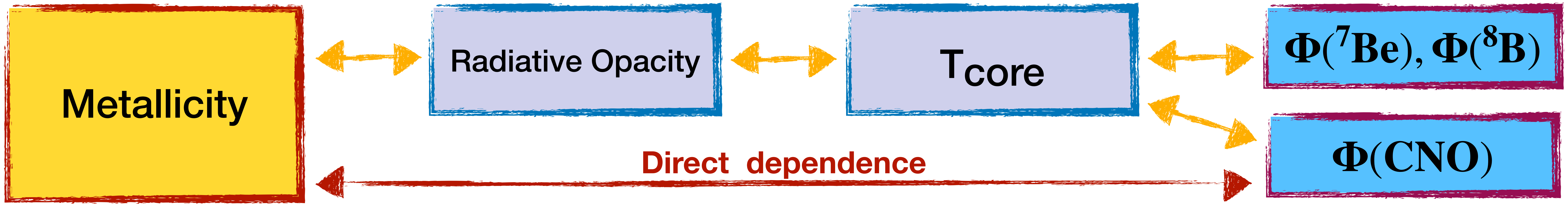
$$t = -2log[\mathscr{L}(HZ)/\mathscr{L}(LZ)] = \chi^2(HZ) - \chi^2(LZ)$$

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



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

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

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

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

Tcore ⟷ $\Phi(\mathrm{CNO})$

Metallicity ⟷ $\Phi(\mathrm{CNO})$: 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
$k = \tau_O/\tau_B \approx 0.83$

Reality is much more complicated than this…

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

Optimal k
$k = 0.769$

S-factors of nuclear properties

29 Elements abundances + Solar properties

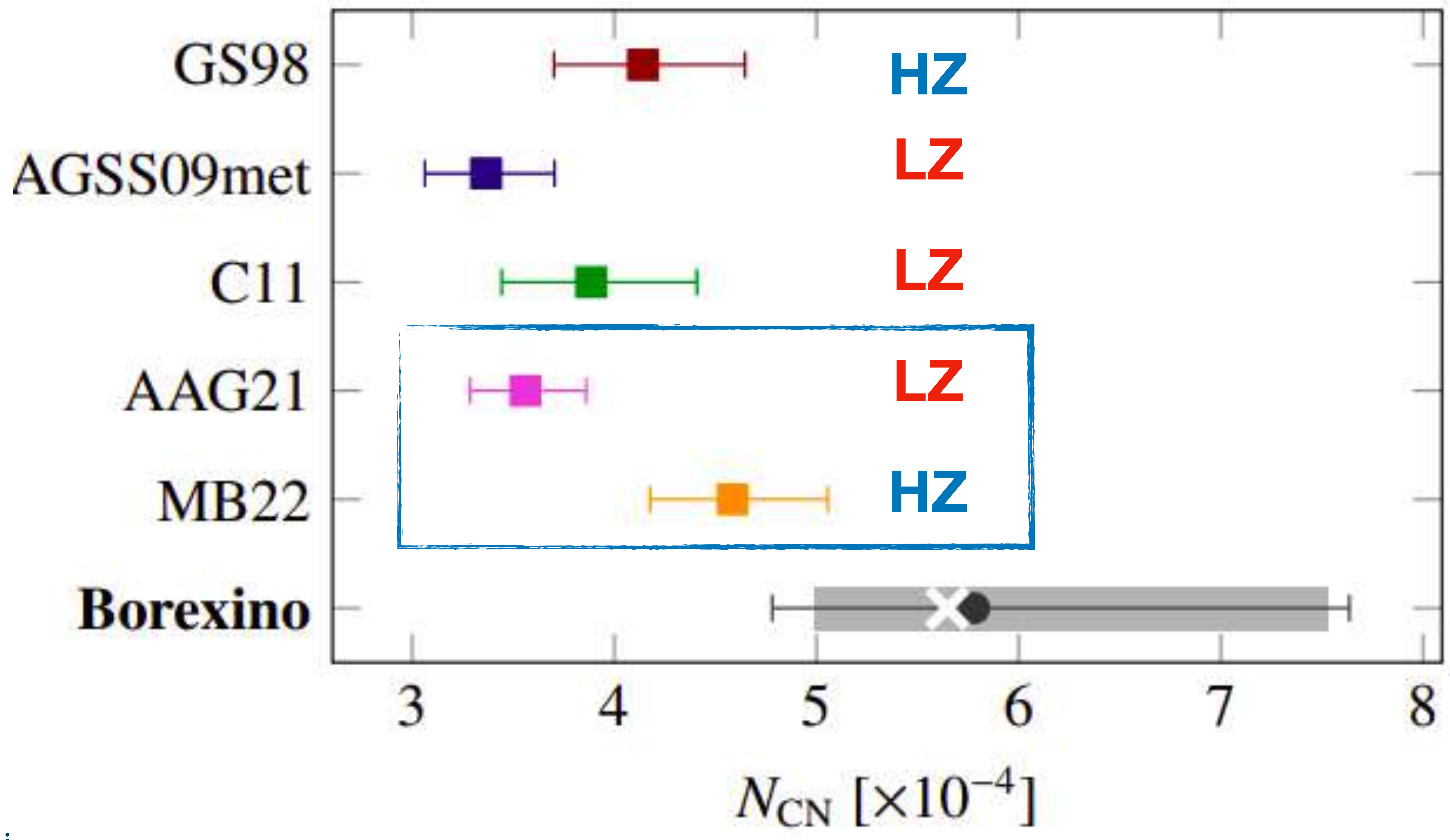
Diffusion

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

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

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**

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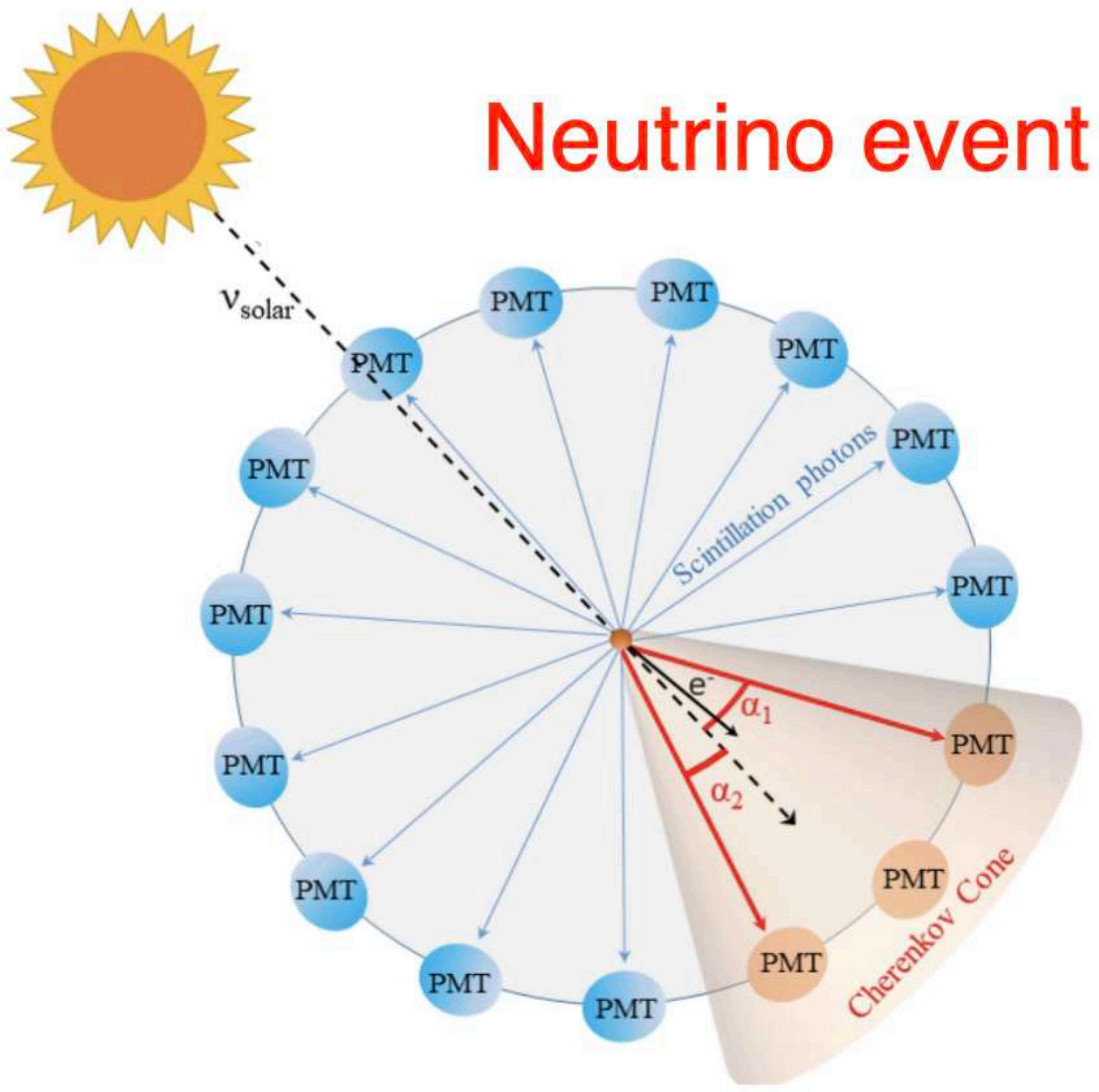
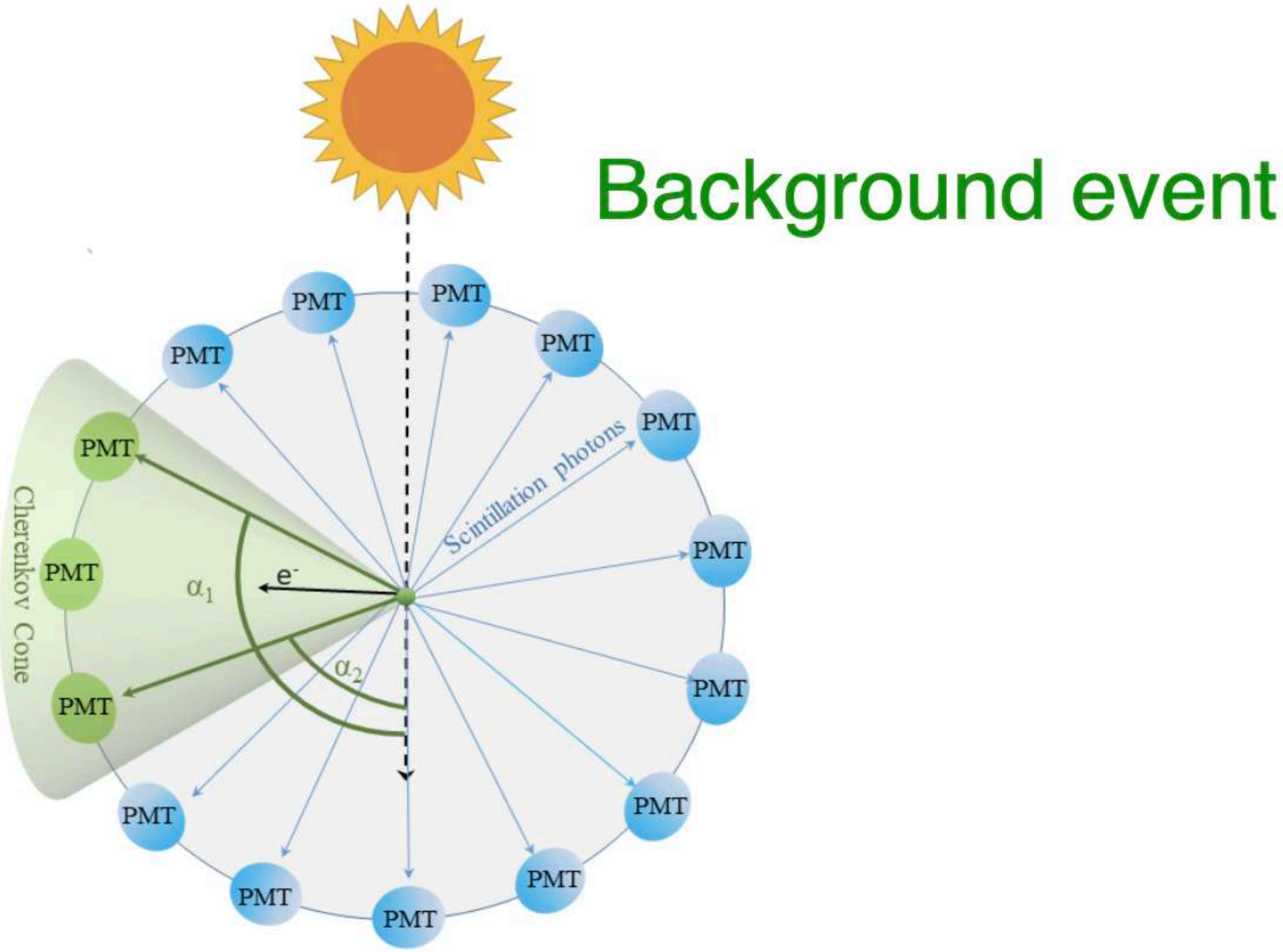
BOREXINO: FIRST DIRECTIONAL MEASUREMENT OF SUB-MEV SOLAR NEUTRINOS

CID: Correlated and Integrated Directionality

The idea





Correlated to Sun position:
non-flat cosα distribution (peak at cosα~0.75)

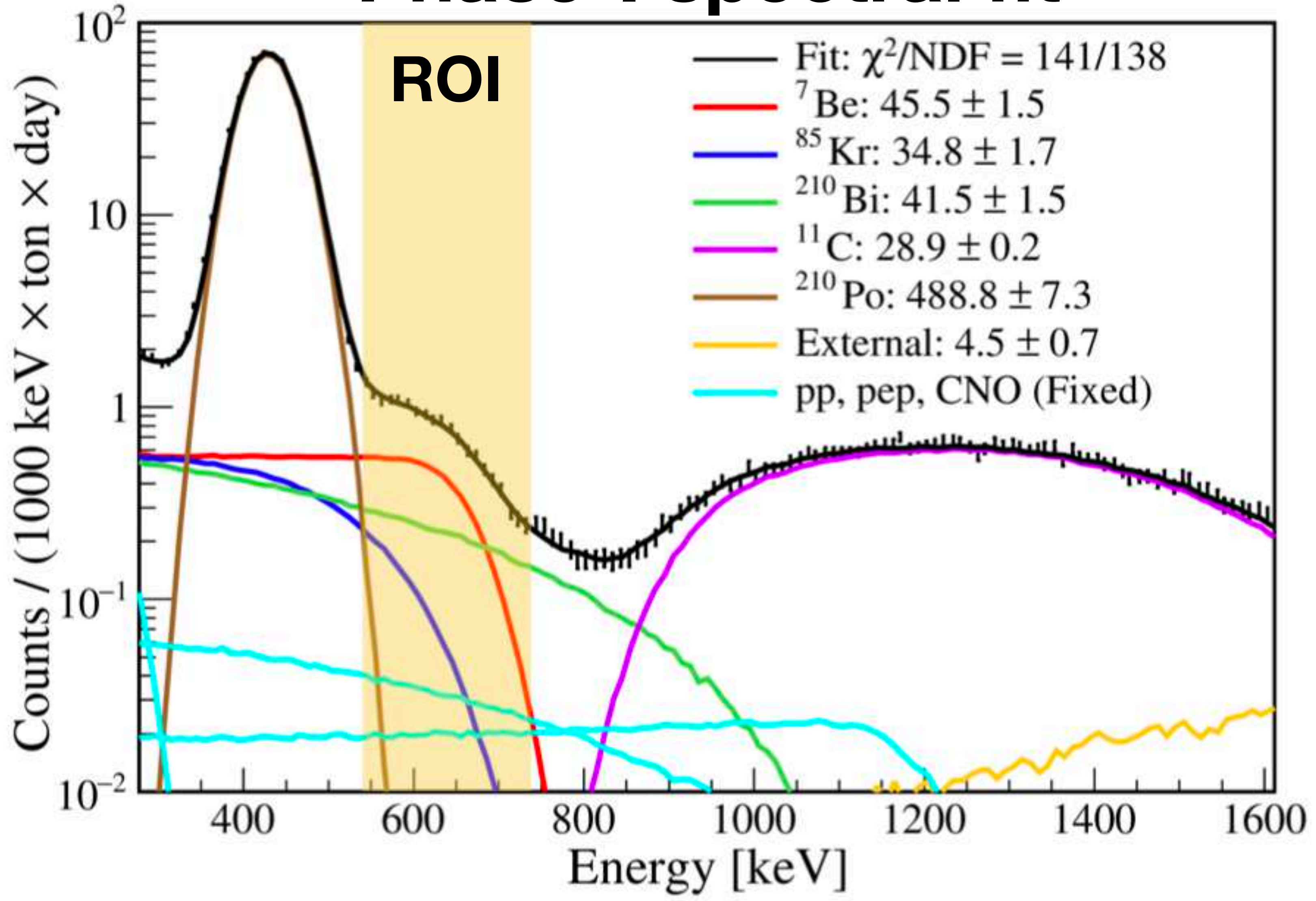
Non correlated to Sun position: **flat cosα distribution**

BOREXINO: FIRST DIRECTIONAL MEASUREMENT OF SUB-MEV SOLAR NEUTRINOS

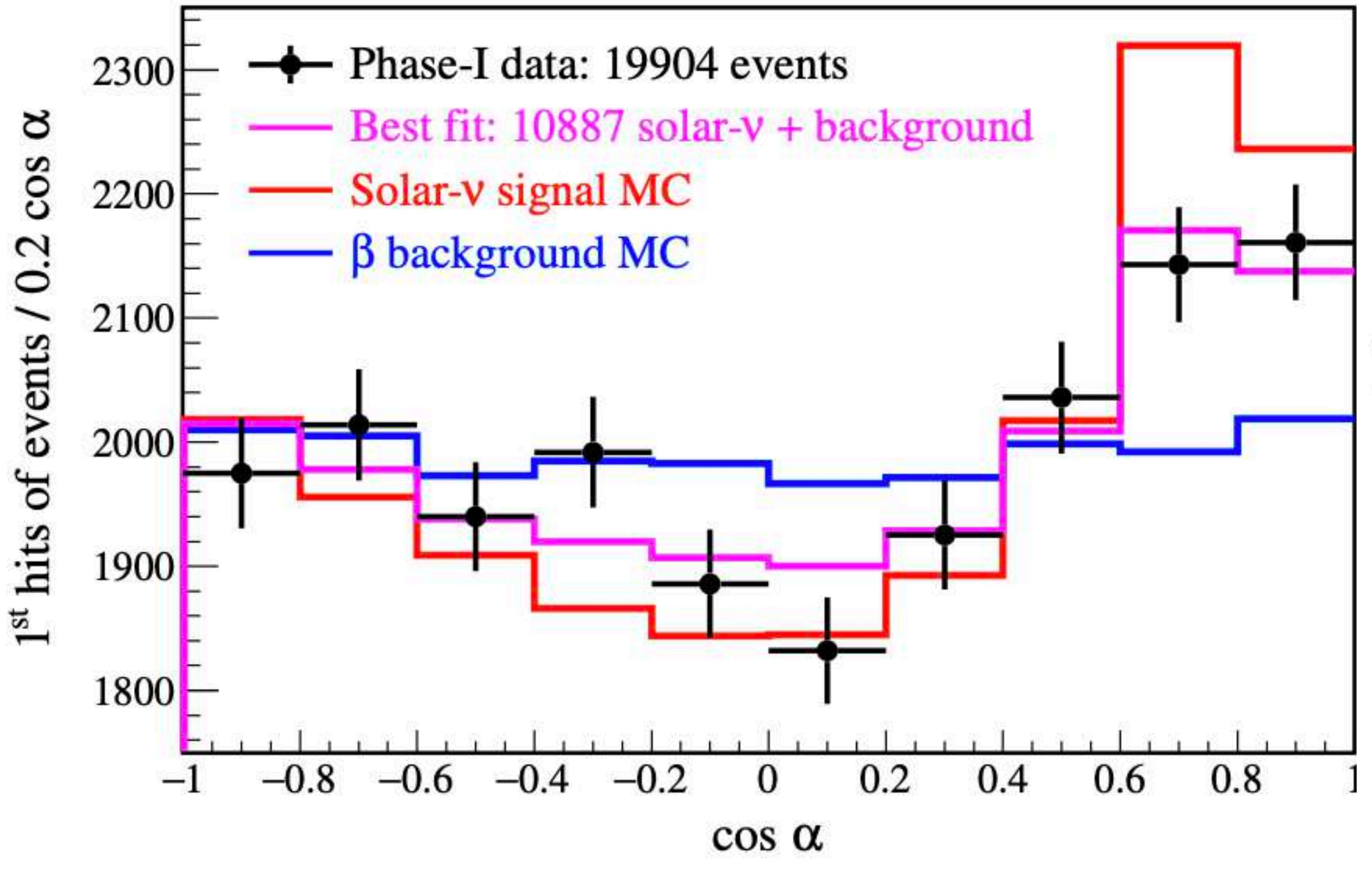
CID: Correlated and Integrated Directionality

Exploit 1st and 2nd hit of each event (characterized by a high fraction of Cherenkov light)

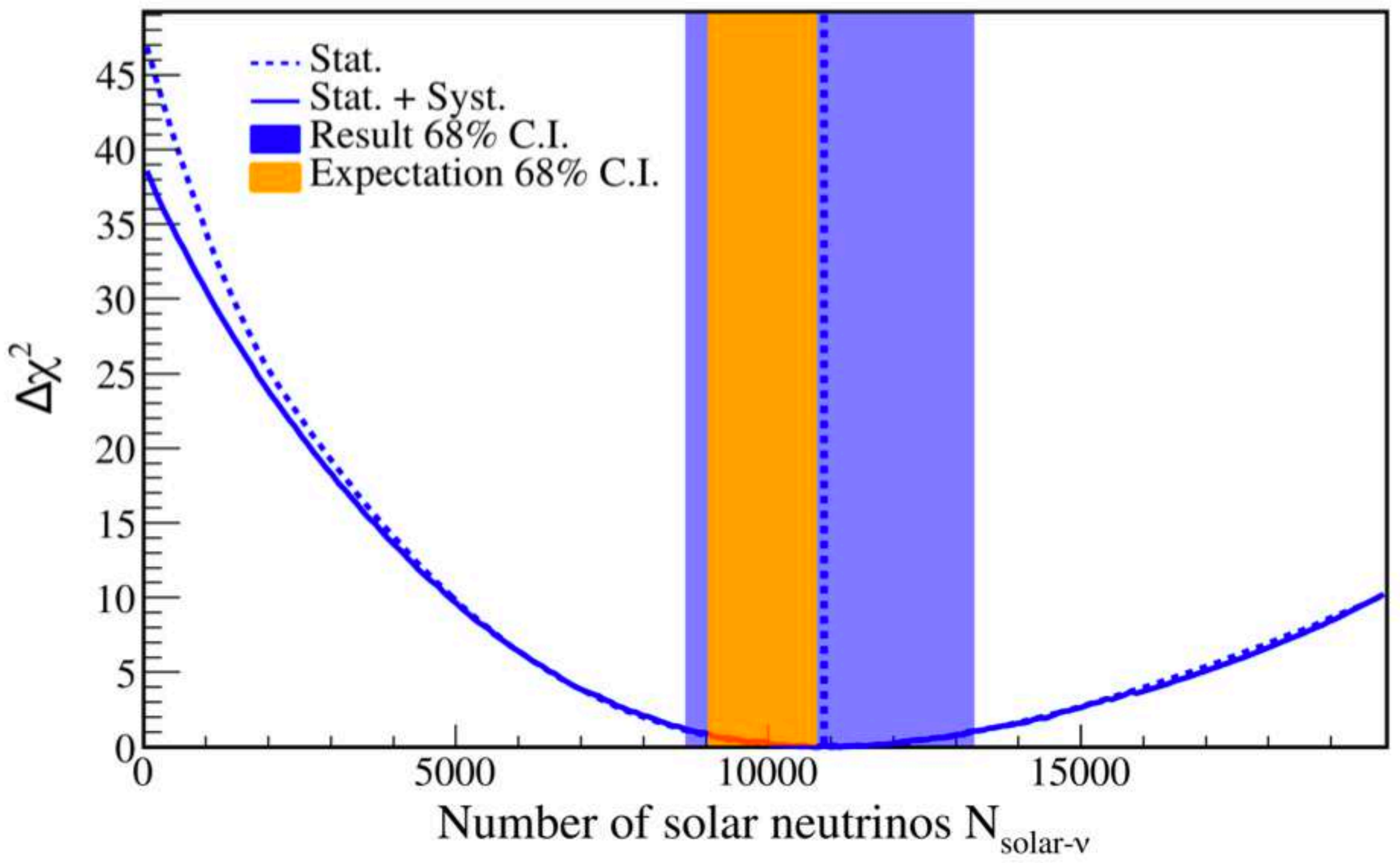
Phase-I spectral fit



cosα distribution



Results:



First directional measurement of sub-MeV solar neutrinos:

No-neutrino signal hypothesis ($N_{solar-\nu} = 0$) is **rejected with $> 5\sigma$**

$R(^7Be)_{CID} = 51.6^{+13.9}_{-12.5}$ cdp/100t (Compatible with SSM and spectral fit)

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.

BOREXINO: FIRST DIRECTIONAL MEASUREMENT OF SUB-MEV SOLAR NEUTRINOS

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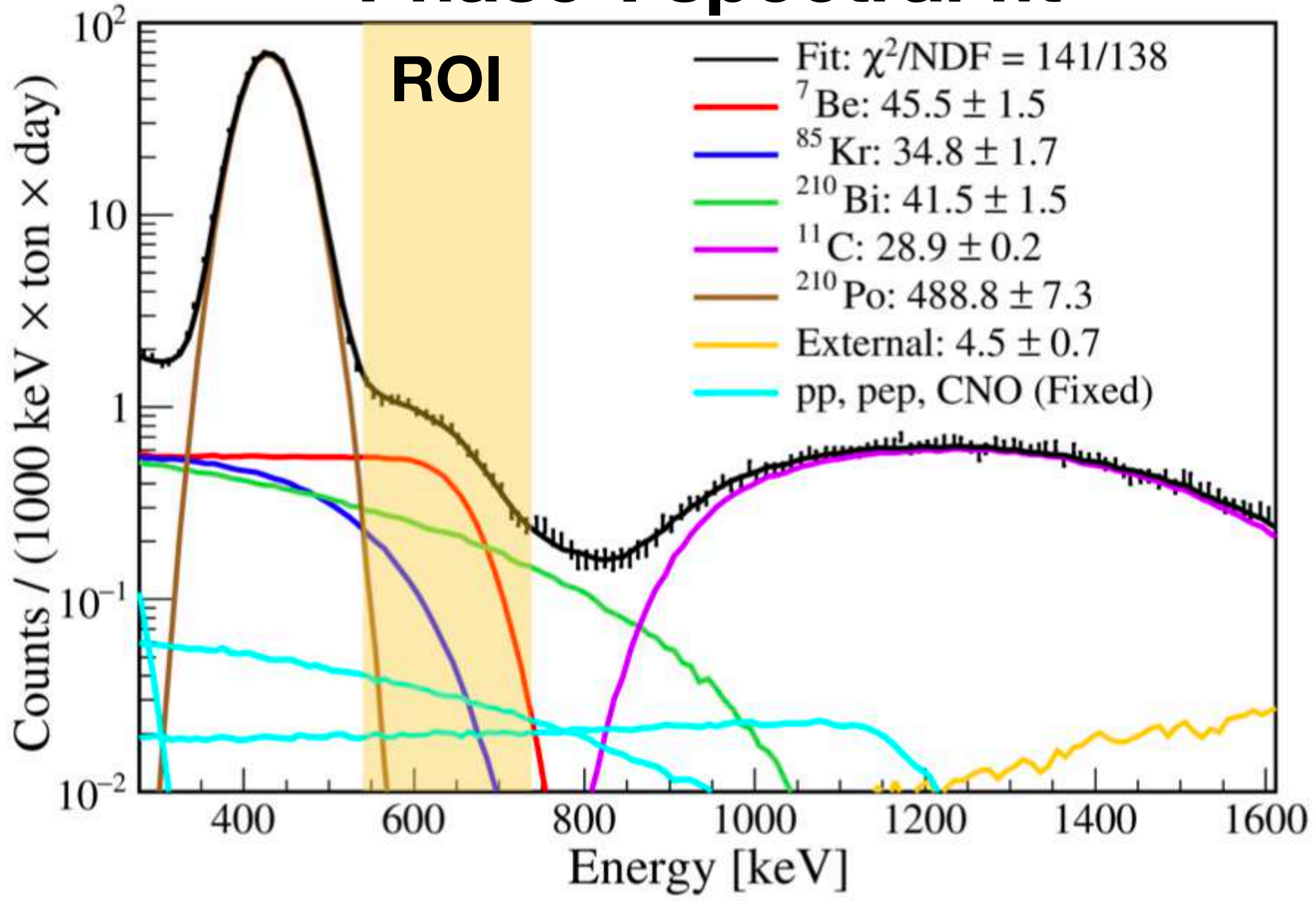
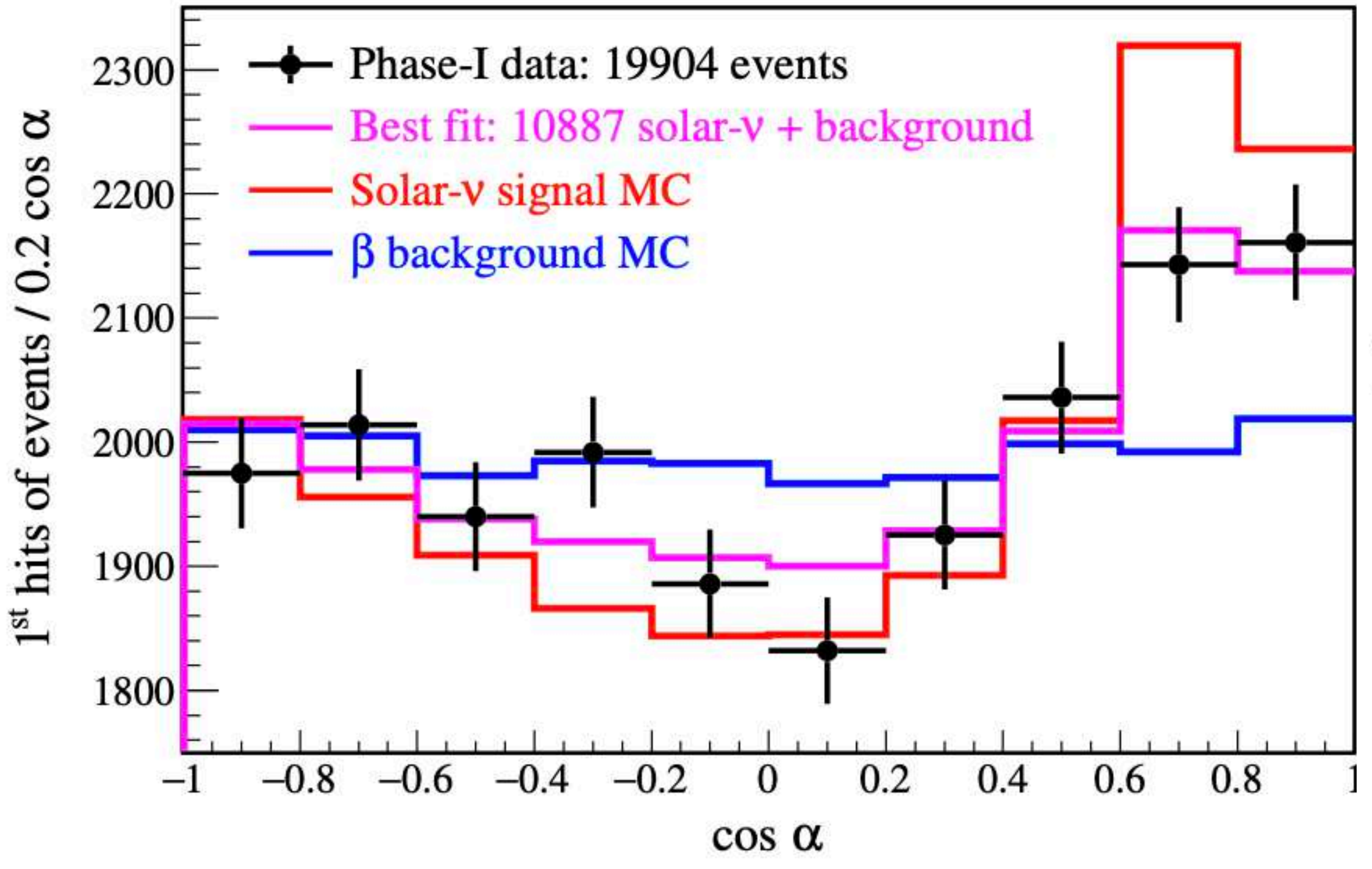
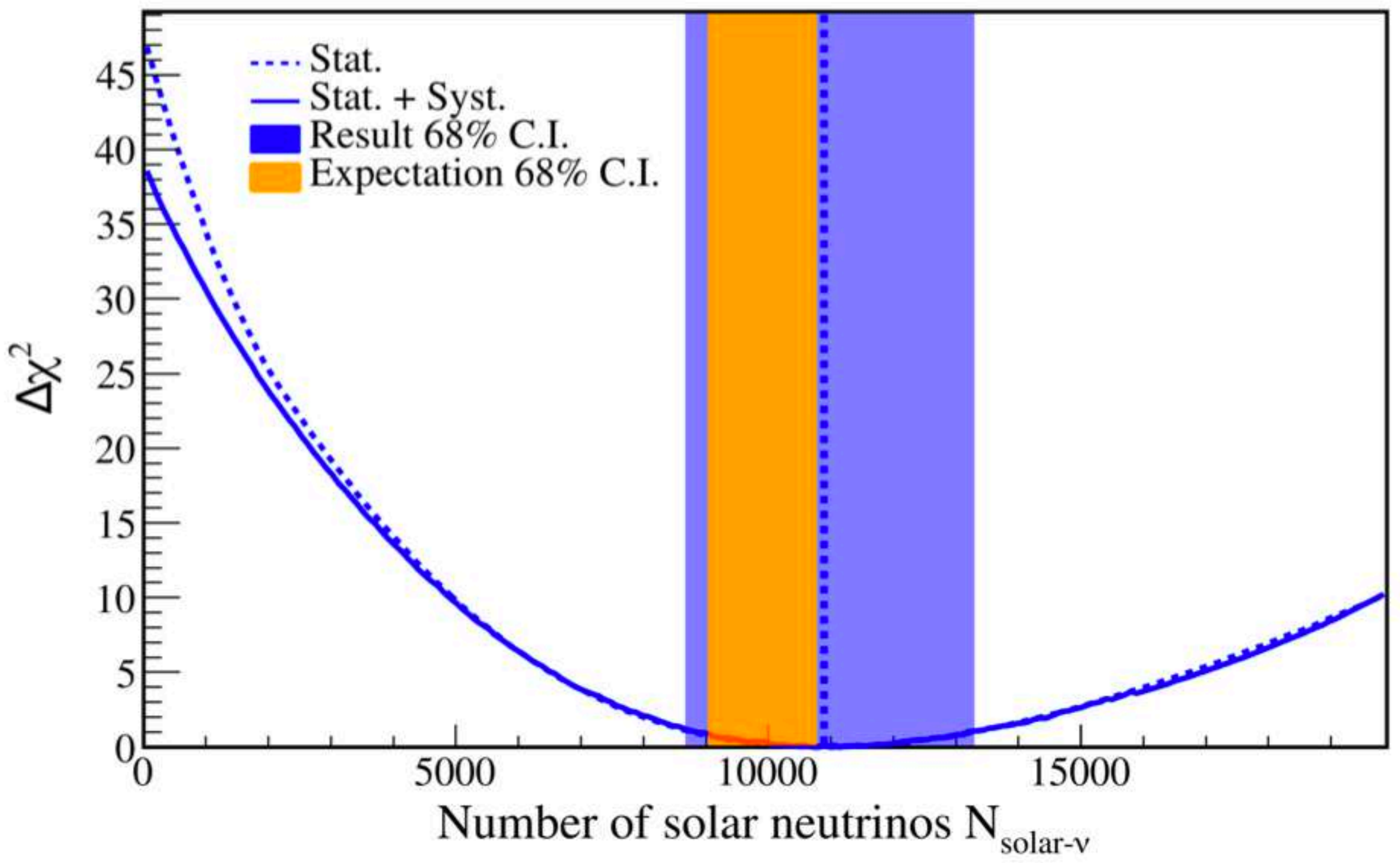


cosα distribution





Future perspectives:

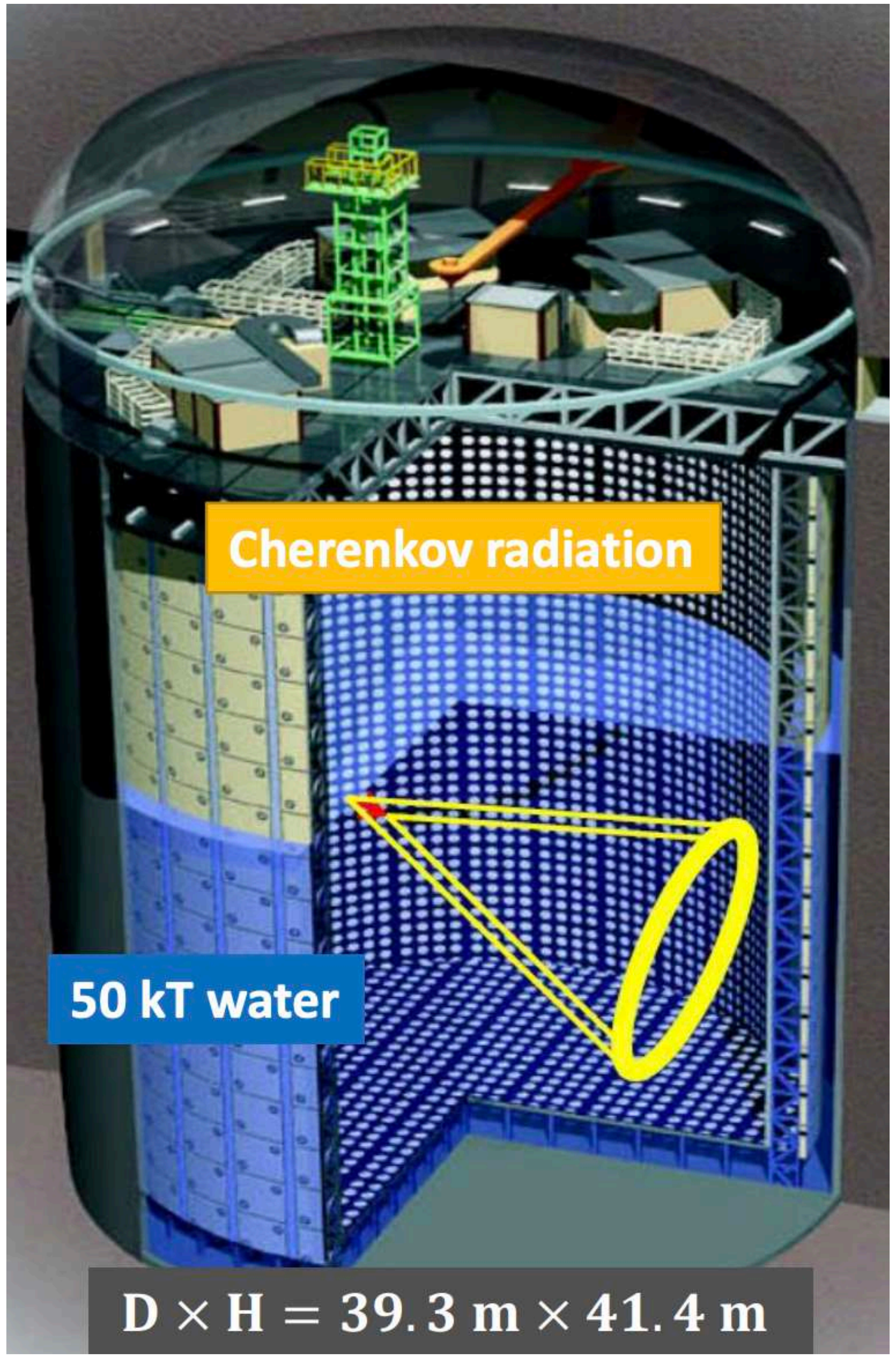
- ☑ Proof of principle for future detectors
- ☐ Extension to Borexino Phase-II and Phase-III
- ☐ CID for CNO neutrinos: additional constraint in the multivariate fit

OUTLINE

- Solar neutrinos
  - Thermonuclear processes
  - Detecting neutrinos
- **Experimental activity:**
  - Borexino
  - **SuperKamiokande**
  - SNO+
- Outlook: JUNO

Many thanks to Prof. Michael Smy for private communication

SUPER-KAMIOKANDE



(1)	96 97 98 99 00 01	02 03 04 05	06 07 08	09 10 11 12 13 14 15 16 17 18	19 20 21 22
(2)	SK-I	SK-II	SK-III	SK-IV	SK-V, SK-Gd
(3)	PMT 11,146 (40%)	5,182 (19%)	11,129 (40%)		
(4)	4.5 MeV	6.5 MeV	4.0 MeV	3.5 MeV	
(5)	1496 days	791 days	548 days	2970 days	

(1) Year, (2) SK phase, (3) Photo coverage [%], (4) Recoil electron kinetic energy [MeV], (5)Livetime for analysis

Water Cherenkov detector (~50 kton of ultrapure water)

- ✓ Directionality → backgrounds rejection
- ✗ Small Light Yield (wrt LS) ↔ worse resolution
- ✗ Few MeV energy threshold

Only ^{8}B neutrinos can be detected.

1. Effect of terrestrial matter densitiy: **D/N asymmetry**
2. Oscillation analysis: Δm^2_{21} and $\sin^2\theta_{21}$
3. Effect of solar matter in the Sun core: **"spectrum upturn"**

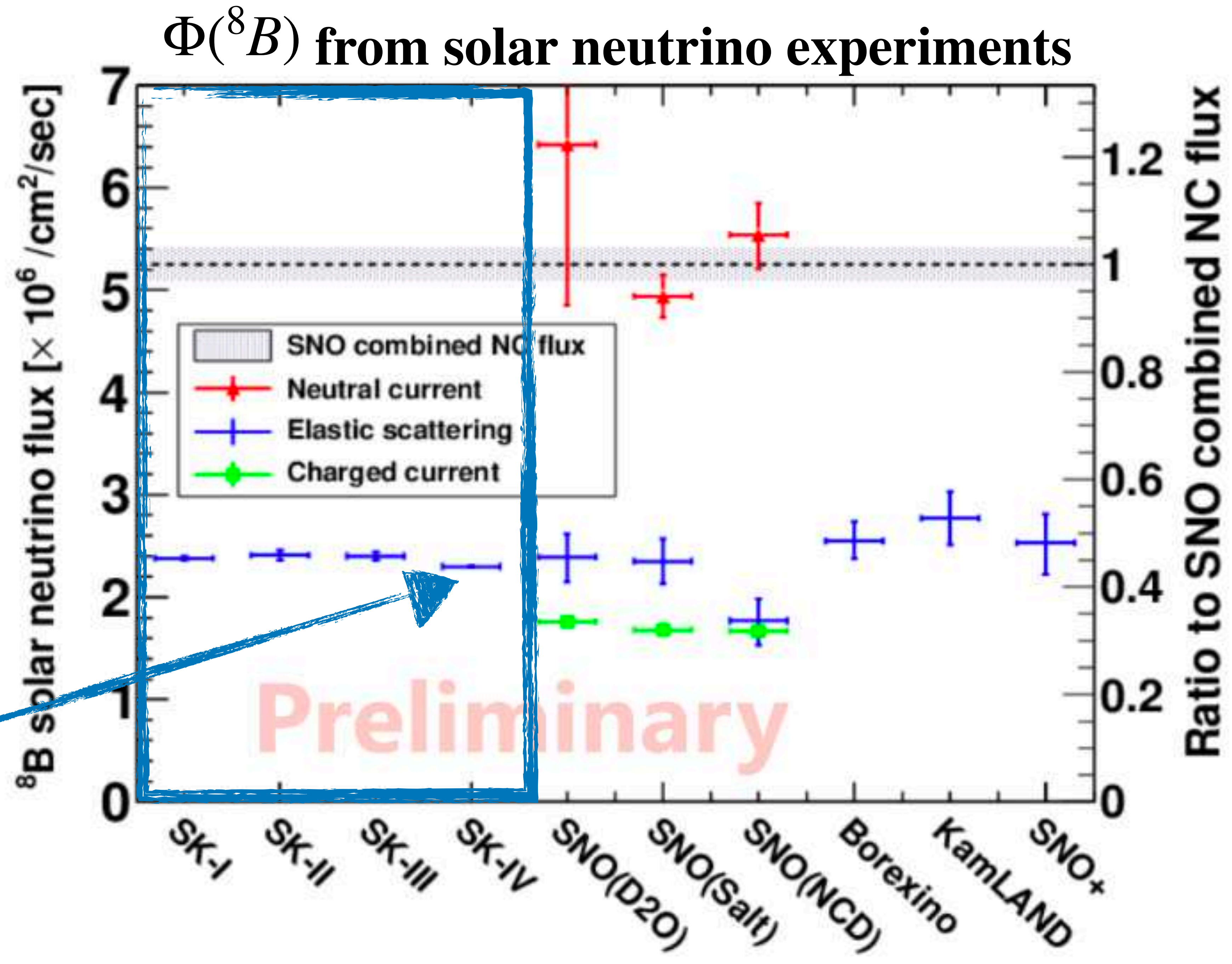
SUPER-KAMIOKANDE: 8B ANALYSIS

Precise measurement of ^{8}B:

Main upgrades of SK-IV:

- ☑ Removal of cosmogenic radioactive events (n-capture on H): +12% exposure
- ☑ Improved energy reconstruction and detector simulation: more spatially uniform detector response
- ☑ Low energy threshold **~3.2 MeV**

SK-IV: $\Phi(^{8}B) = 2.346 \pm 0.011$ (stat.) $\pm\, 0.043$ (syst.) $[10^{6}\ \text{cm}^{-2} s^{-1}]$



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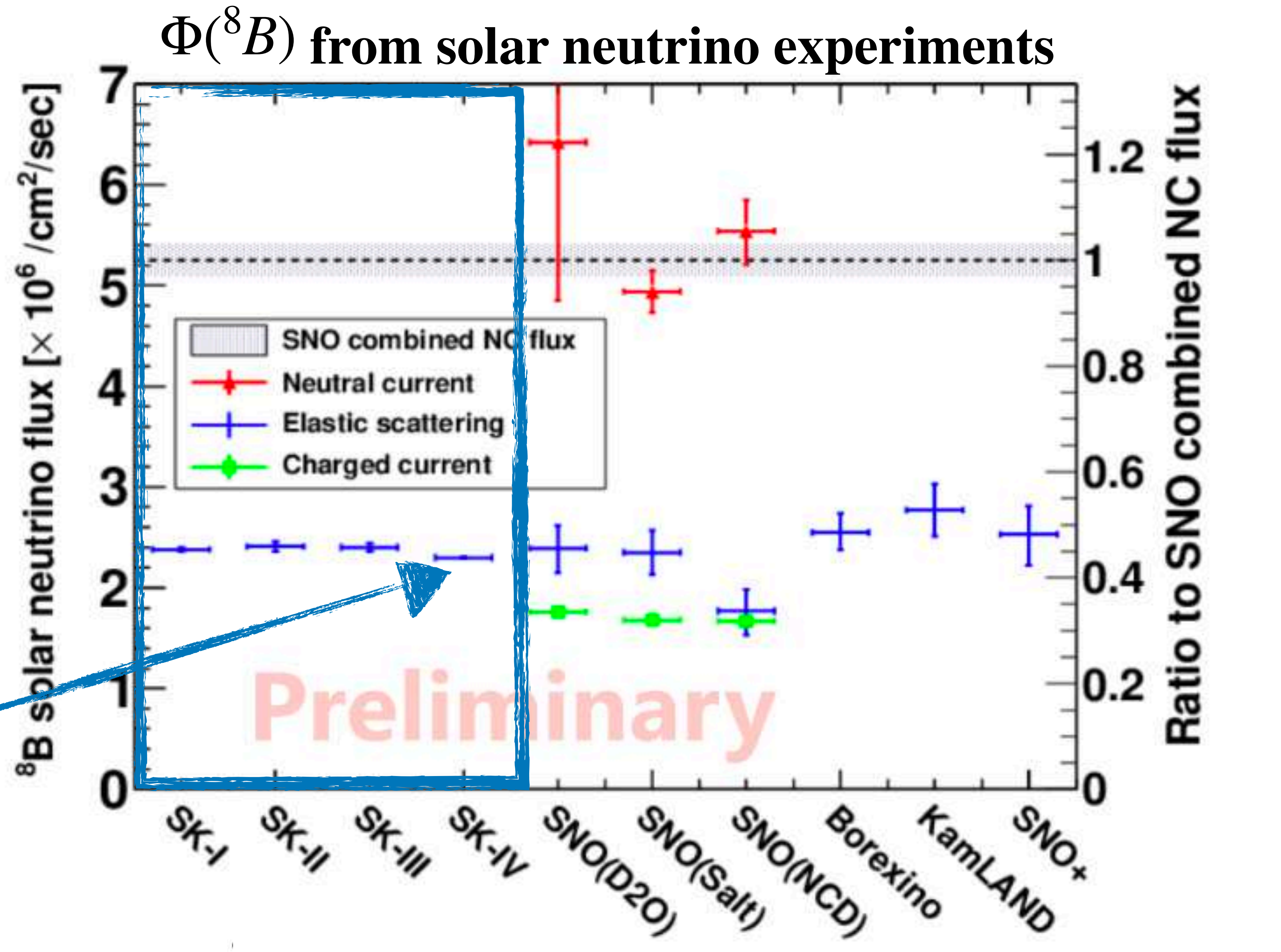
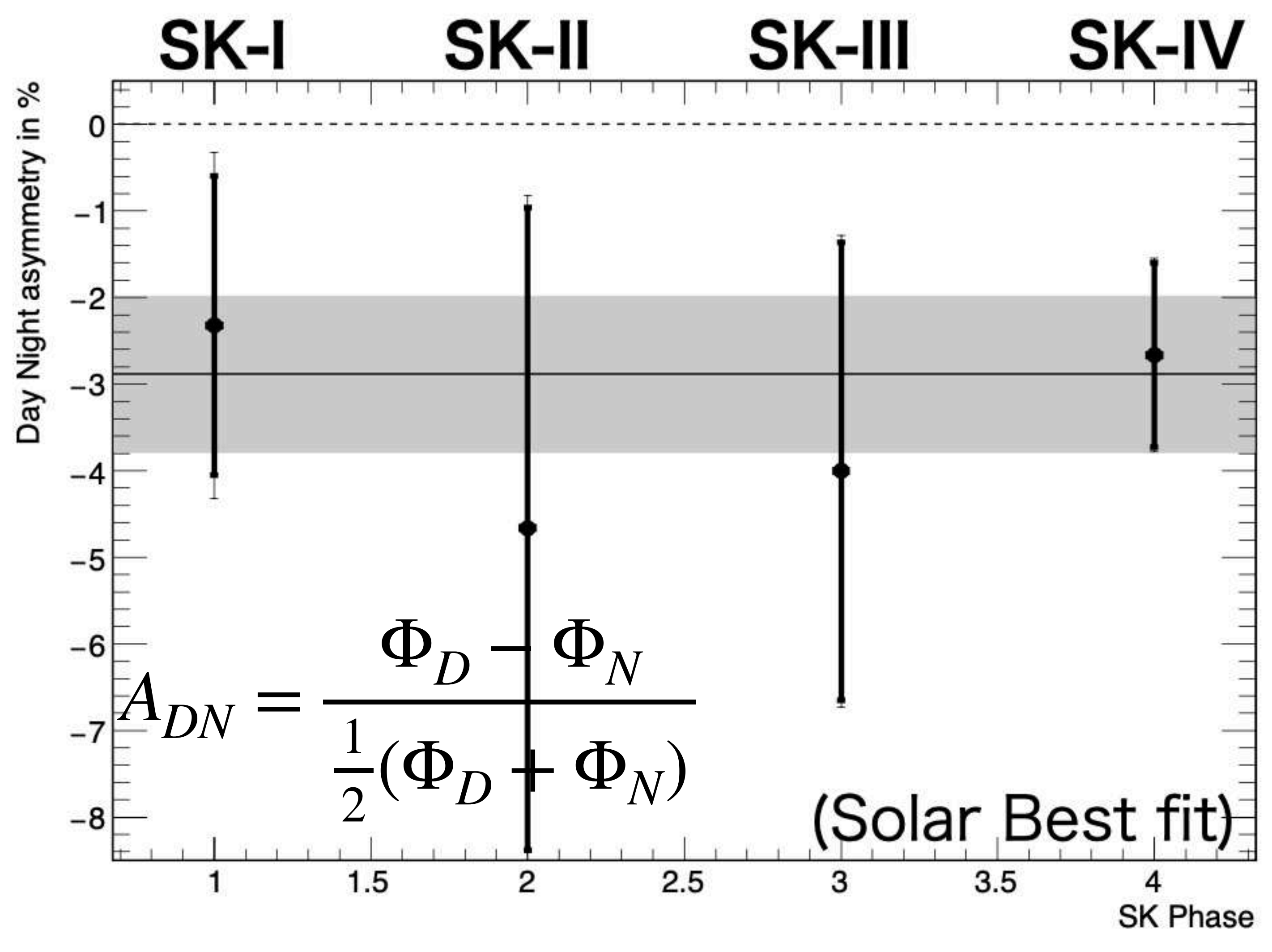
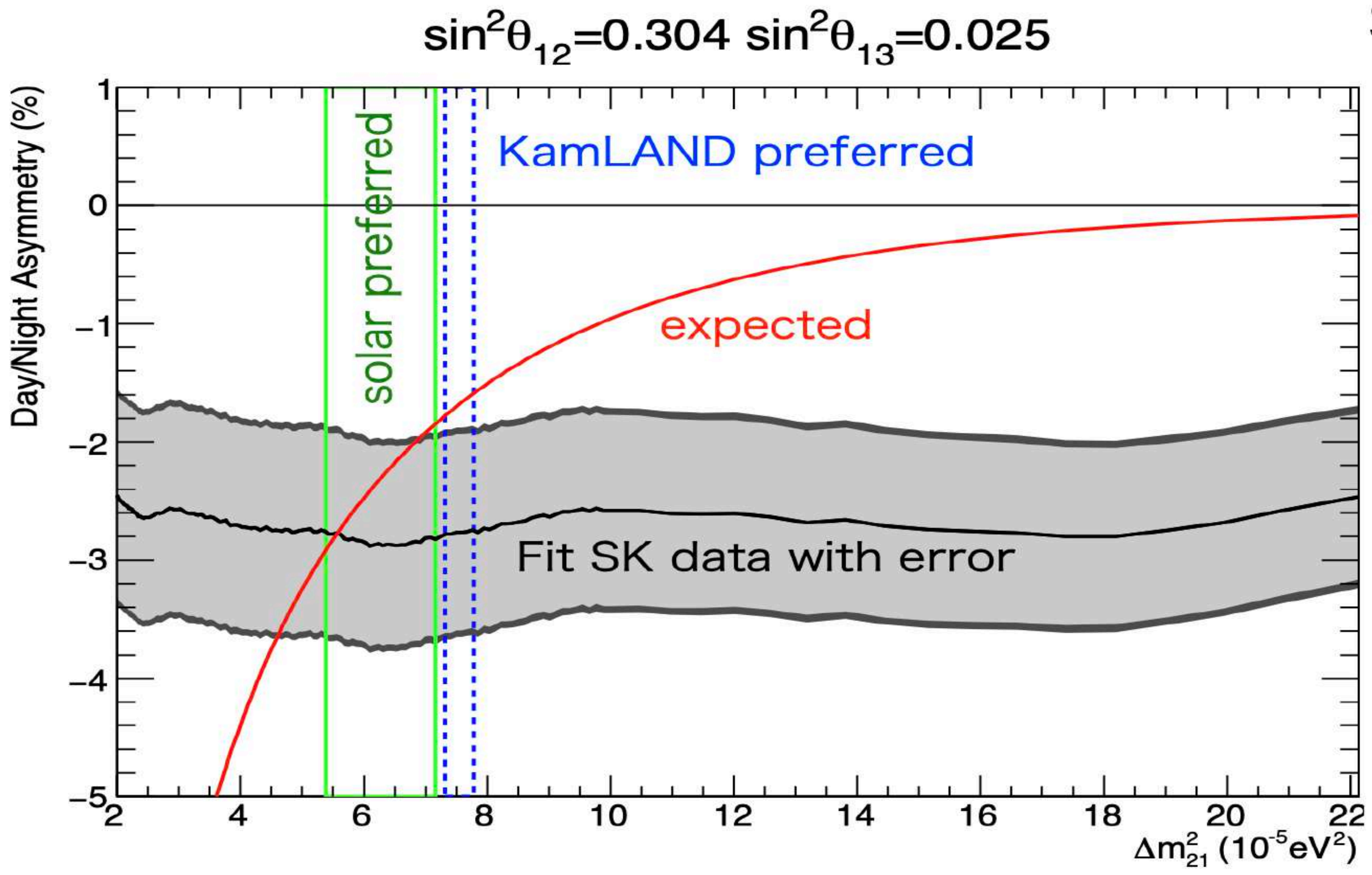


SK-IV: $\Phi(^{8}B) = 2.346 \pm 0.011$ (stat.) $\pm\, 0.043$ (syst.) $[10^6\ \mathrm{cm}^{-2} s^{-1}]$

1. Matter effect in the Earth: D/N asymmetry





Significance of D/N asymmetry:

3.2σ **for Solar Best fit**

3.1σ **for Global Best fit**

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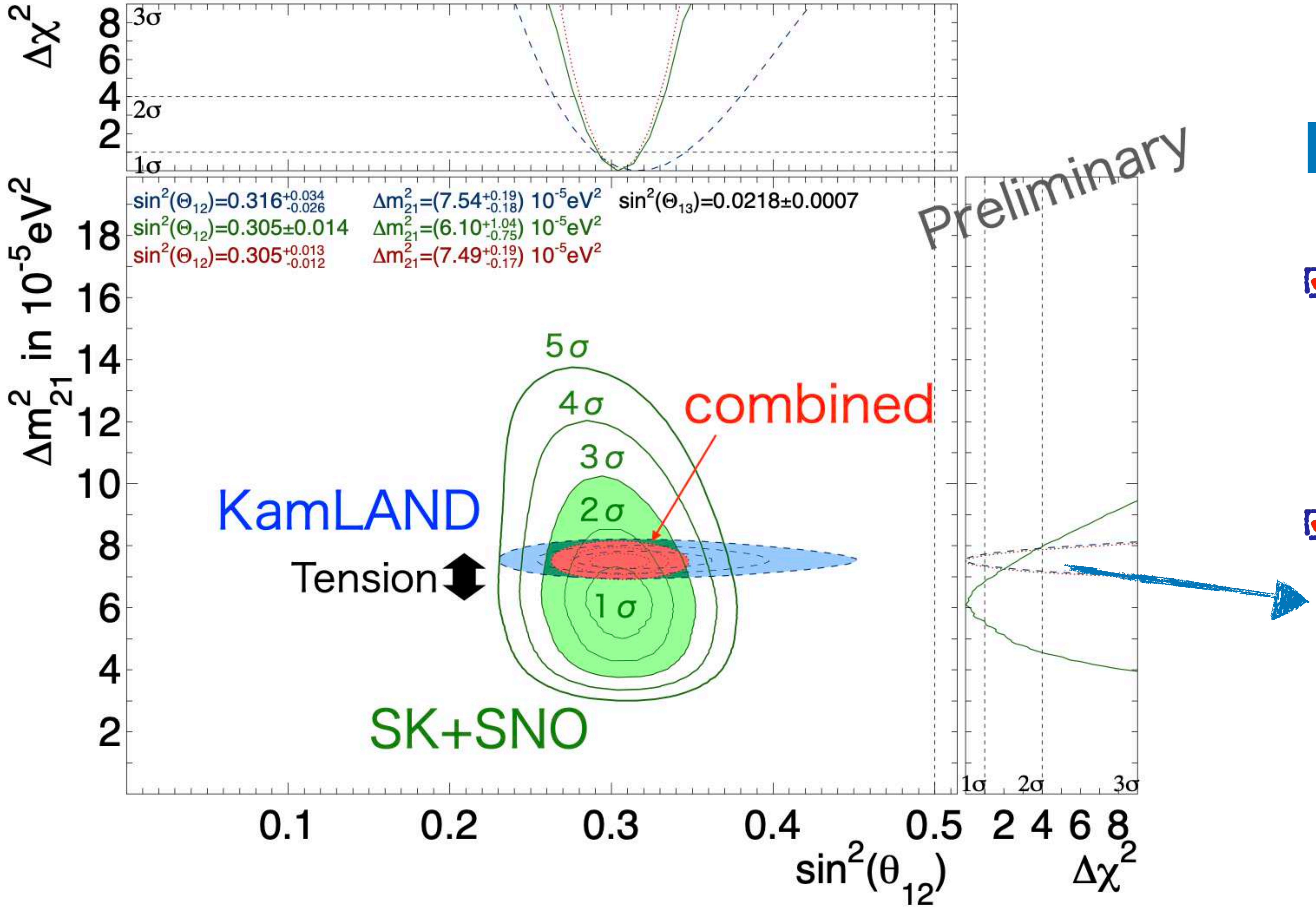
SUPER-KAMIOKANDE: 8B ANALYSIS

2. Oscillation analysis: Δm^2_{21} and $\sin^2\theta_{21}$



Results:

- **Updated fit** of solar neutrinos oscillation parameter:
  $\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \cdot 10^{-5}$ eV^2
  $\sin^2\theta_{21} = 0.305 \pm 0.014$

- **Reduced tension with KamLand** results (reactor anti-neutrinos) at **1.5σ** * (previously 2σ).
  *Addittion of SNO data does not improve the tension with KamLand

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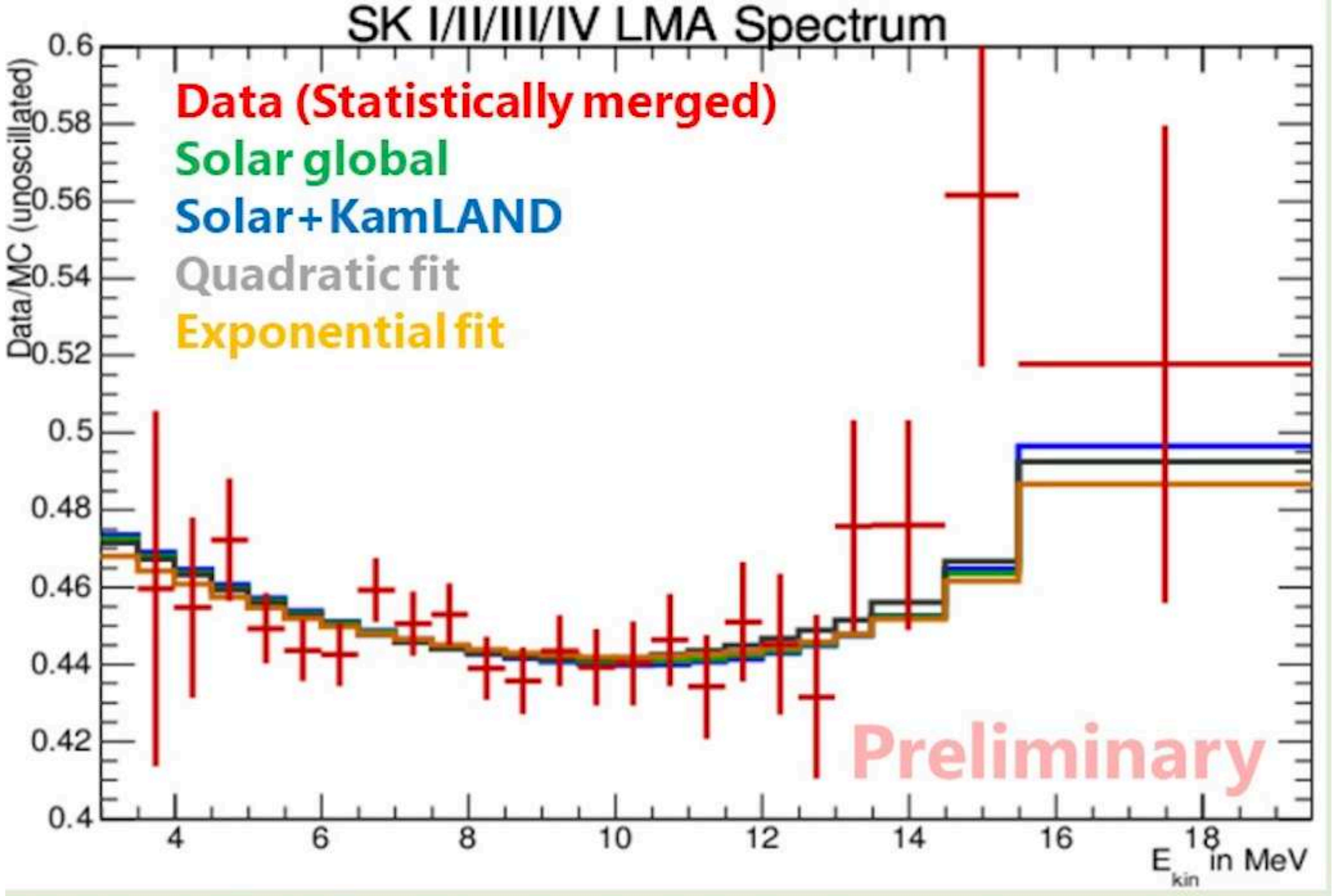
SUPER-KAMIOKANDE: 8B ANALYSIS

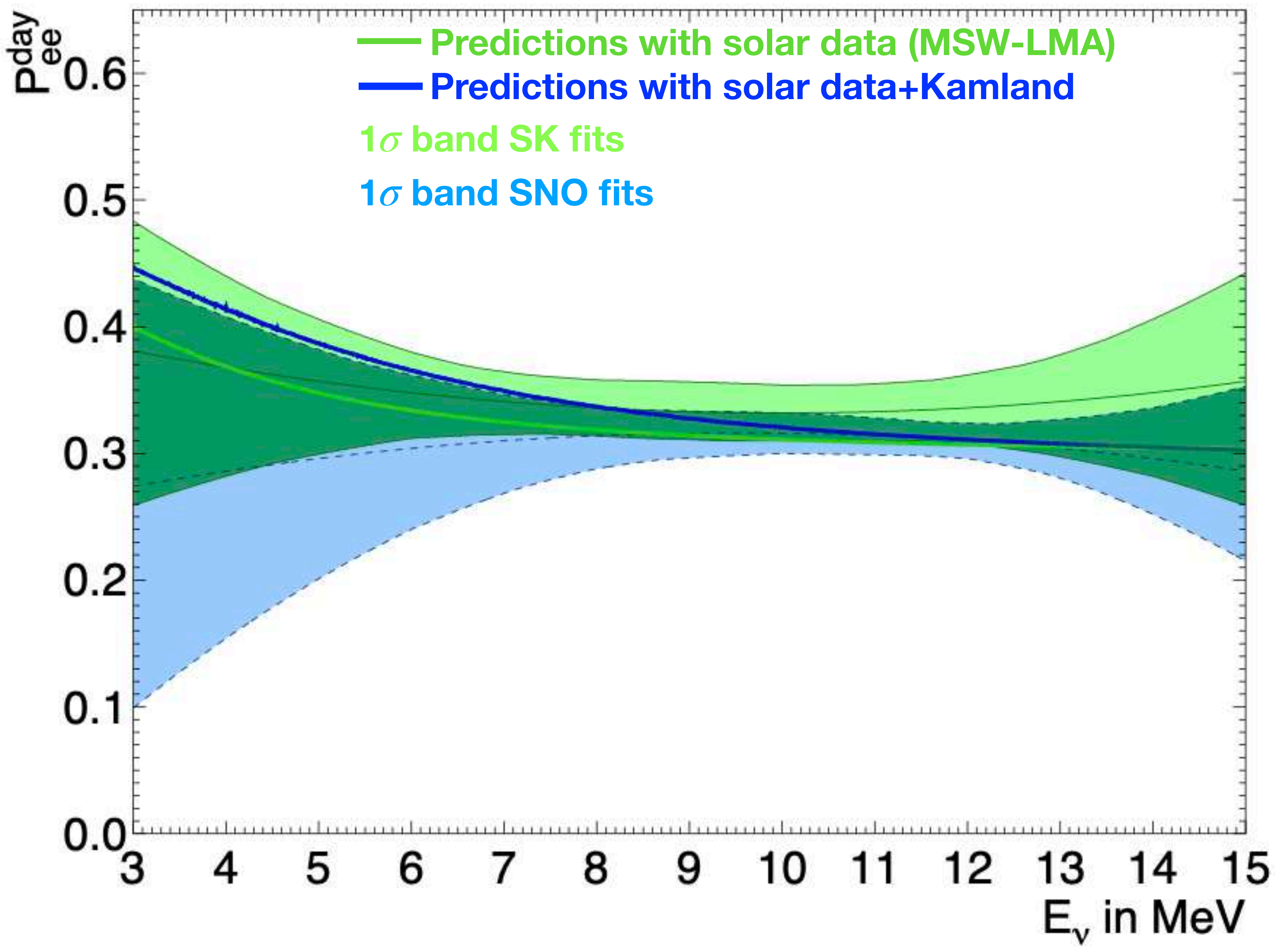
3. Matter effect in the core of the Sun: energy dependence of P_{ee}

$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{MeV} - 10\right) + c_2\left(\frac{E_\nu}{MeV} - 10\right)^2$$

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(e^{e_2(\frac{E_\nu}{MeV}-10)} - 1\right)$$

Combined spectra of SK I-II-III-IV:





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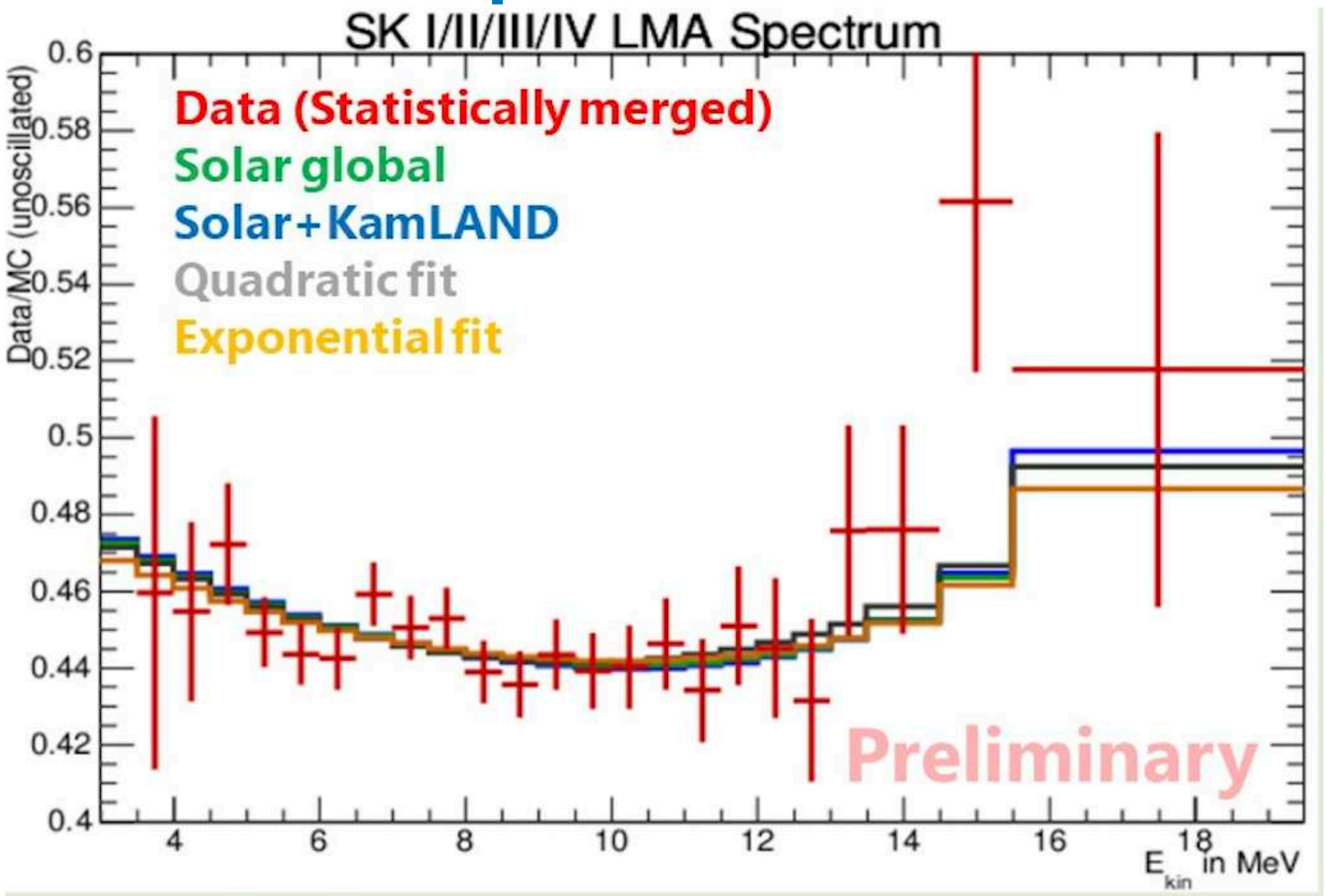
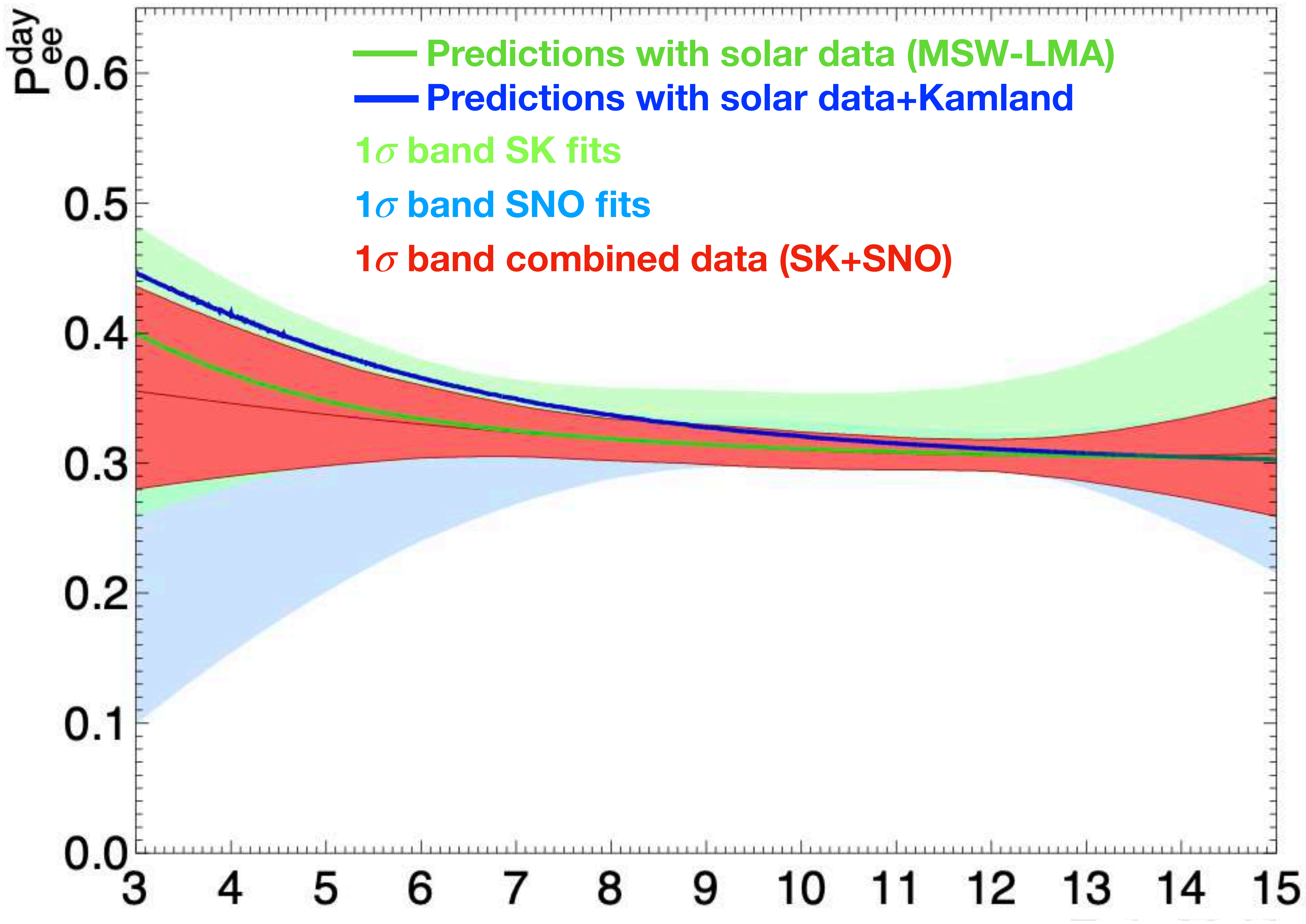




Upturn is slightly favoured, more data are needed

OUTLINE

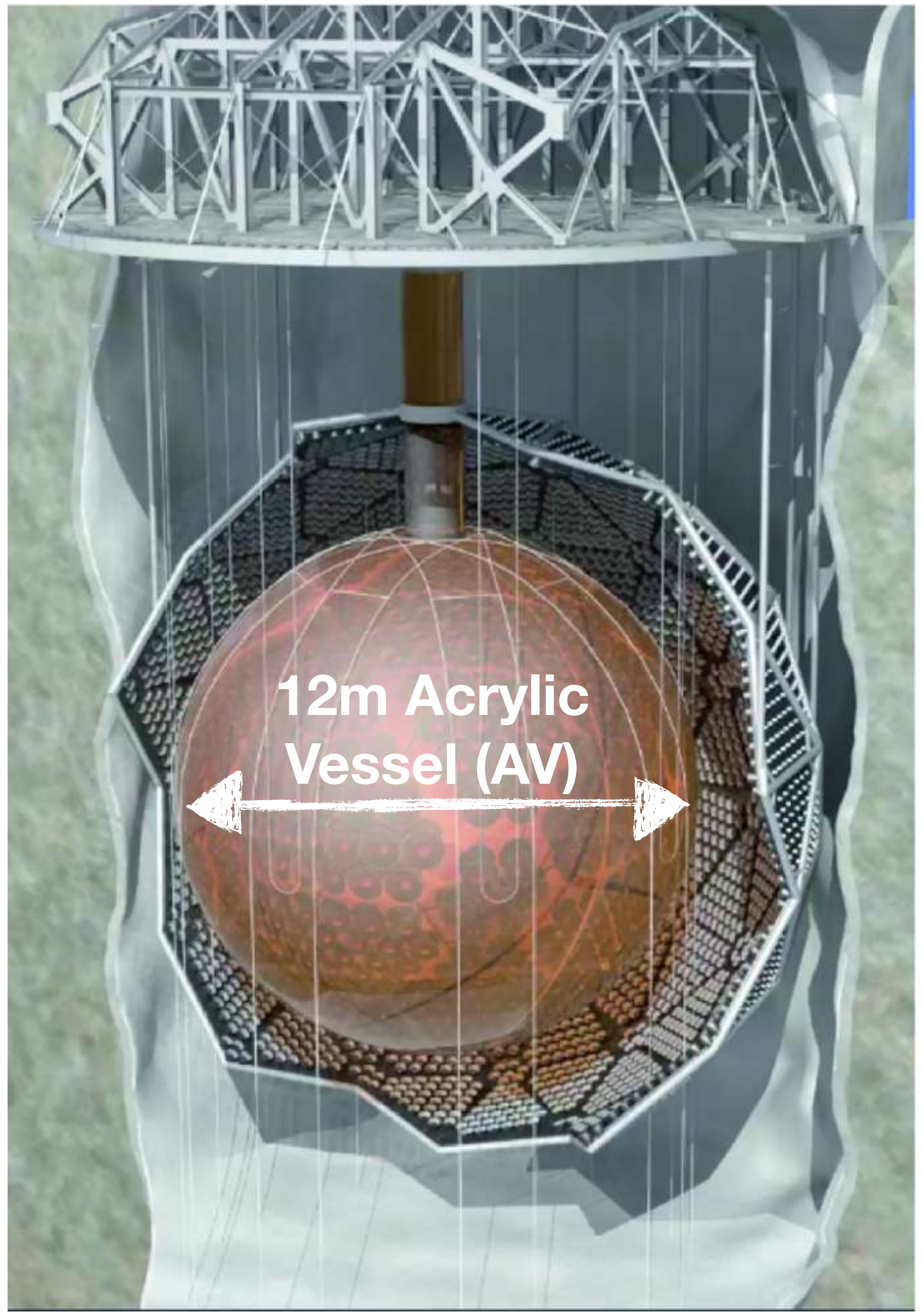
- Solar neutrinos
  - Thermonuclear processes
  - Detecting neutrinos
- **Experimental activity:**
  - Borexino
  - SuperKamiokande
  - **SNO+**
- Outlook: JUNO

Many thanks to Prof. Mark Chen for private communication

SNO+

Successor to **Sudbury Neutrino Observatory** (infastracture + renewd electronic chain)

Liquid scintillator detector Located at 6800 ft depth in SNOLAB (6000 m.w.e. translates to $\sim 3 \frac{\mu}{\text{hour}}$)



- Acrylic vessel (r = 6 m) is being filled with LS
- ~9400 PMTs (54% effective coverage)

Phases and status:

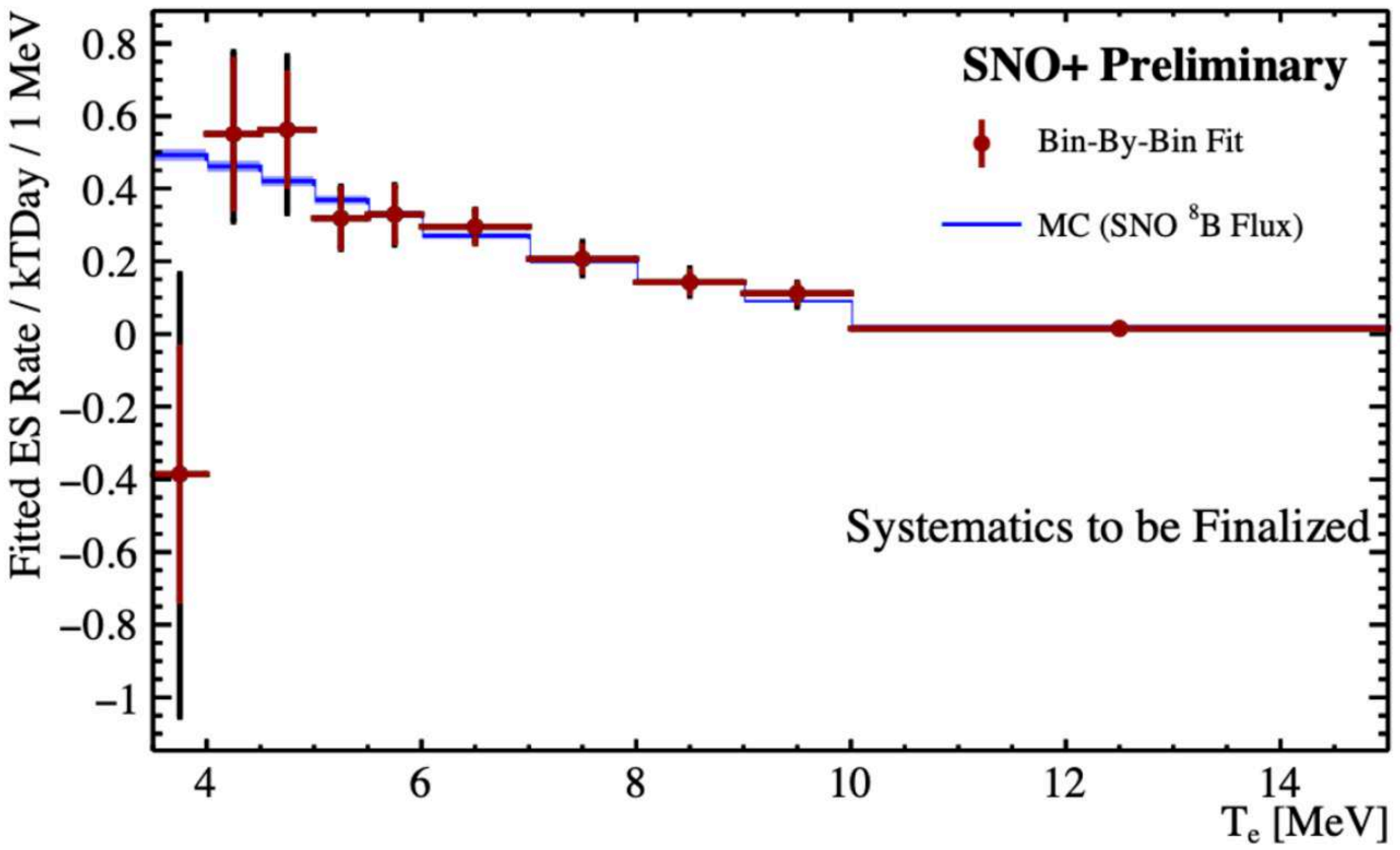
- ☑ **Pure water phase**: AV filled with 0.9 ktons of light water (May 2017 - July 2019)
- ☑ **Liquid Scintillator Phase (~780 tons)**:
  - ☑ “Partial fill” Phase (March 2020 - October 2020)
  - ☑ Filling completed (achieved in April 2022)
  - ☐ Tellurium Phase

SNO+

Pure water Phase:

- $E_{th} = 3.5$ MeV
- Exposure $= 69.2$ kton · days

new result



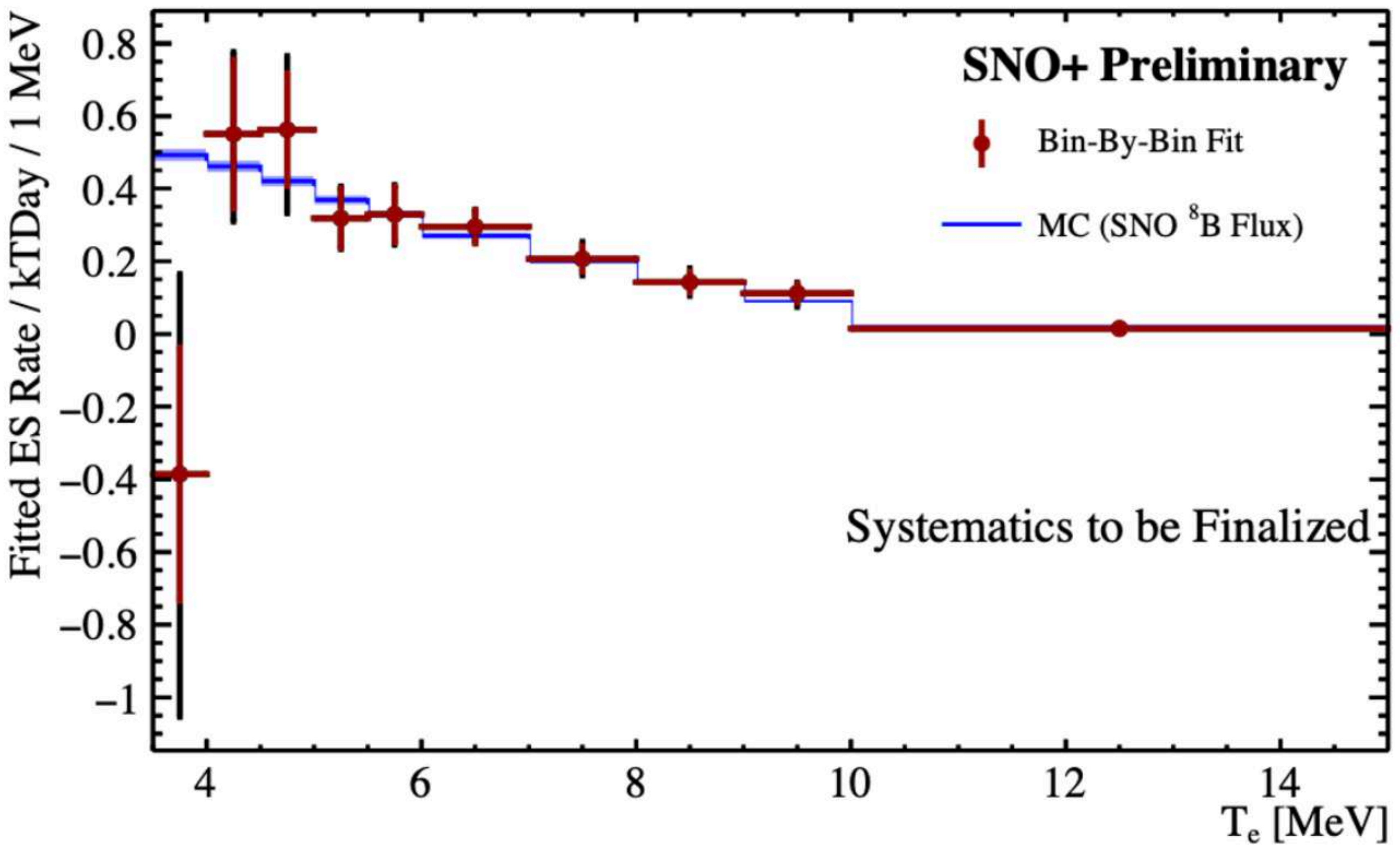
First solar neutrino result from SNO+ experiment

Good agreement with expectations

SNO+

Pure water Phase:

- $E_{th} = 3.5$ MeV
- Exposure $= 69.2$ kton · days



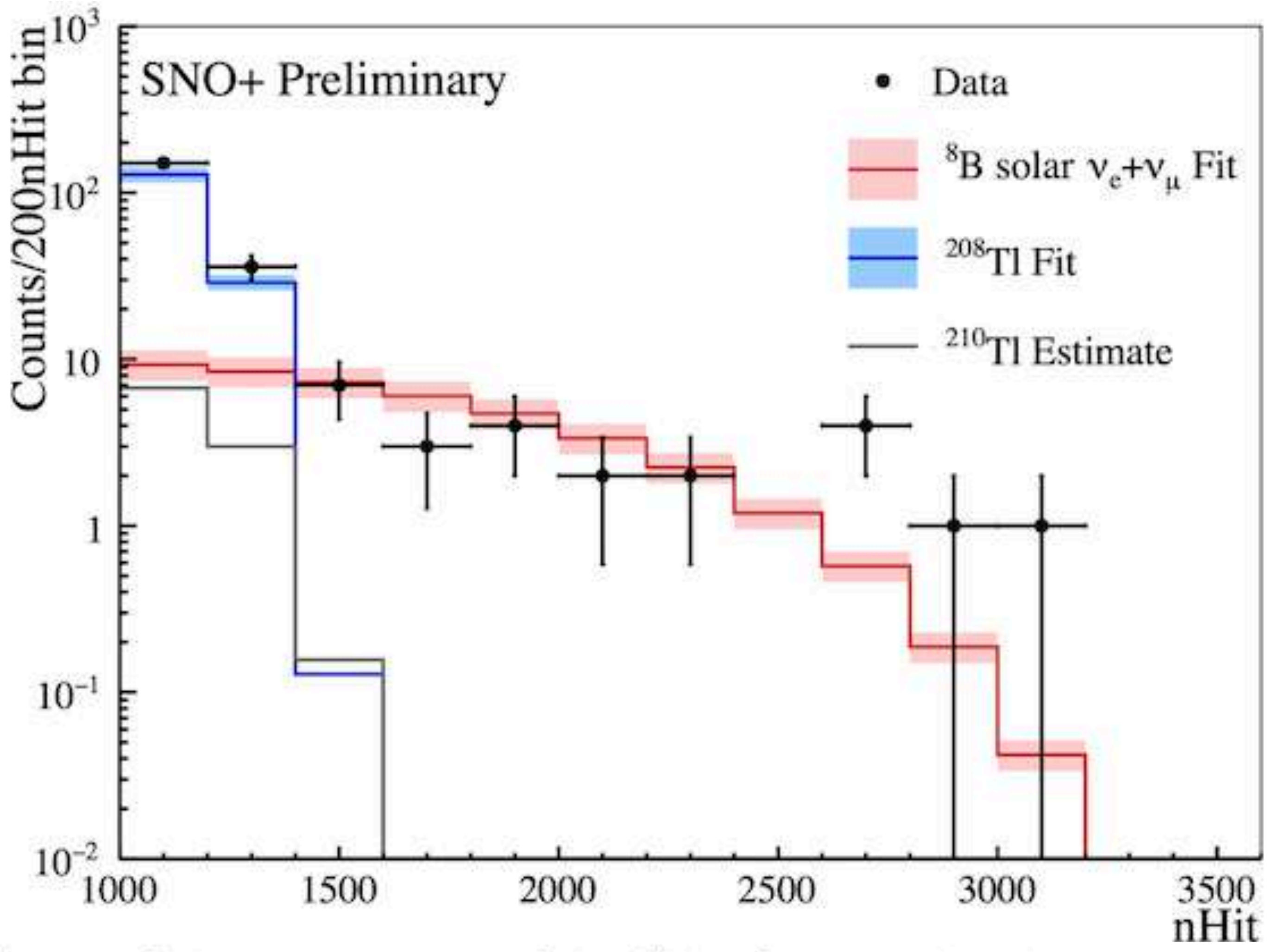
First solar neutrino result from SNO+ experiment

Good agreement with expectations

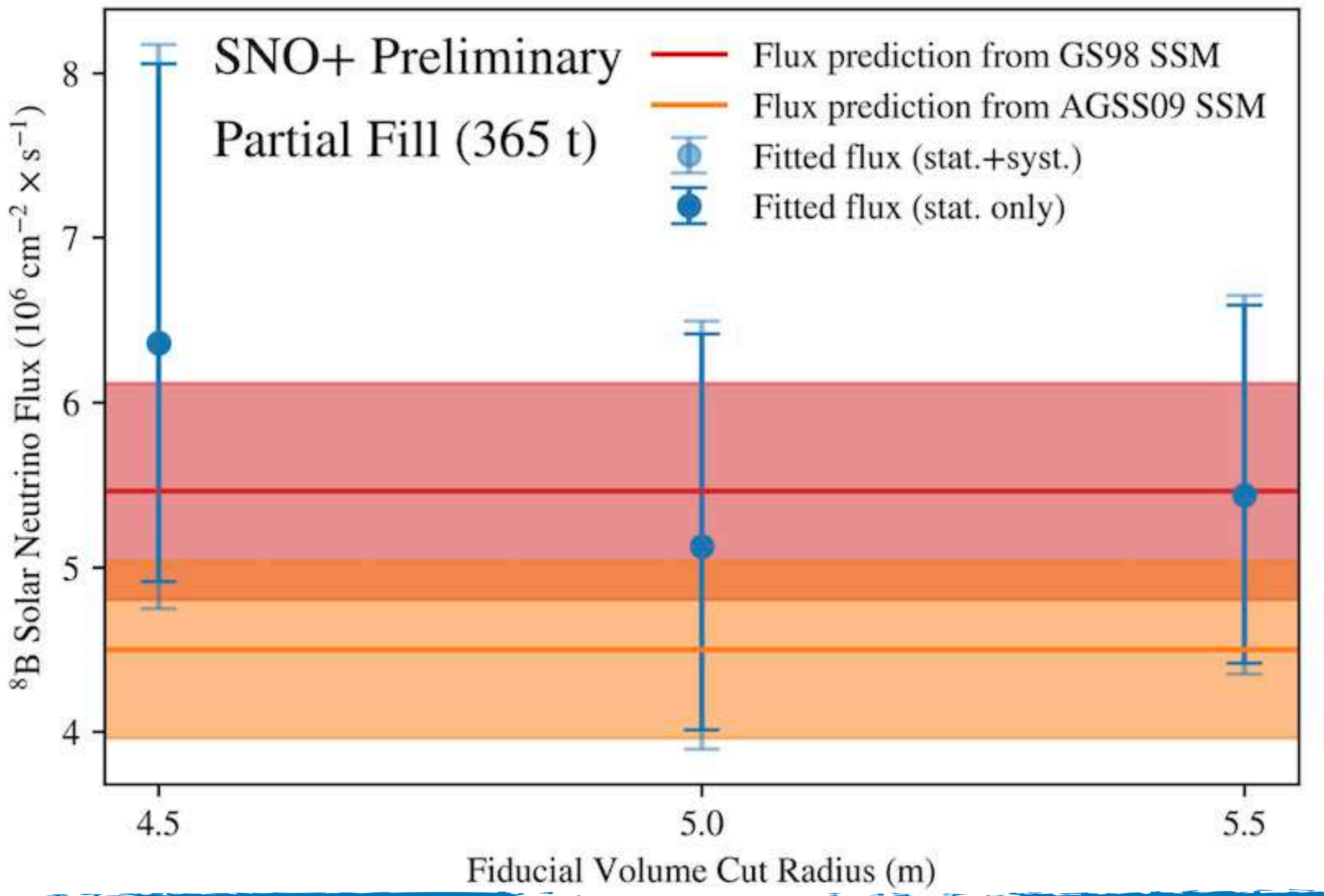
Partial Fill Phase:

- $E_{th} = 3$ MeV
- Exposure $= 92$ ton · years
- Multiple fiducial volumes selected (r = 4.5 m, r = 5 m, and r = 5.5 m)
- Only siginficant background: ^{210}Tl (from ^{238}U chain) and ^{208}Tl (from ^{232}Th chain)
- Systematic uncertainties on energy scale and resolution, position resolution evaluated with ^{214}Bi-^{214}Po coincidences

Unbinned and binned maximum likelihood spectral fits:



Number of solar neutrino events are **consistent with expectation in all FVs** (here reported the largest)

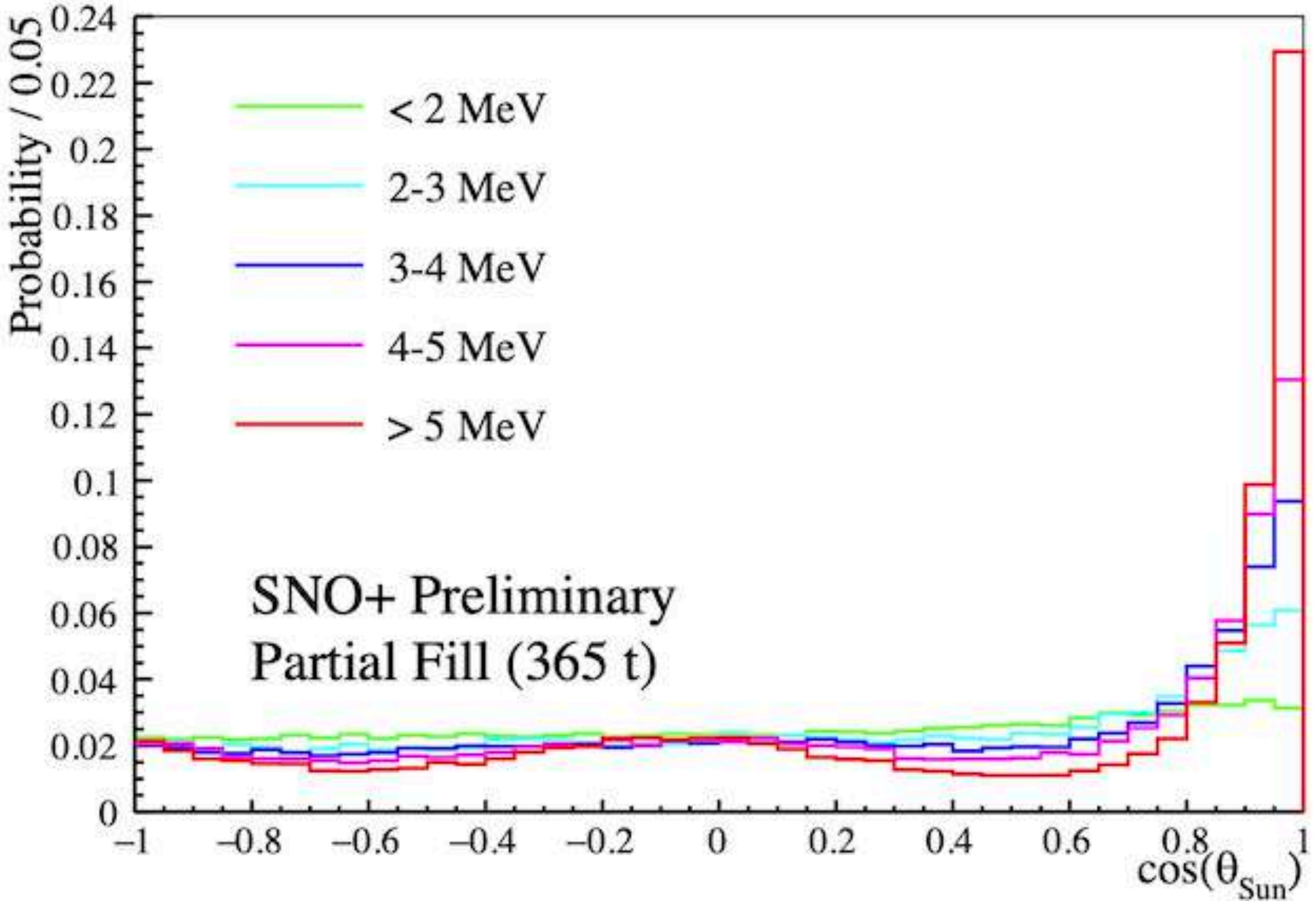


Extracted ^8B fluxes agree with **HZ** and **LZ** scenarios

SNO+ - DIRECTIONAL RECONSTRUCTION

MC predictions:

(Detector conditions form partial fill Phase)

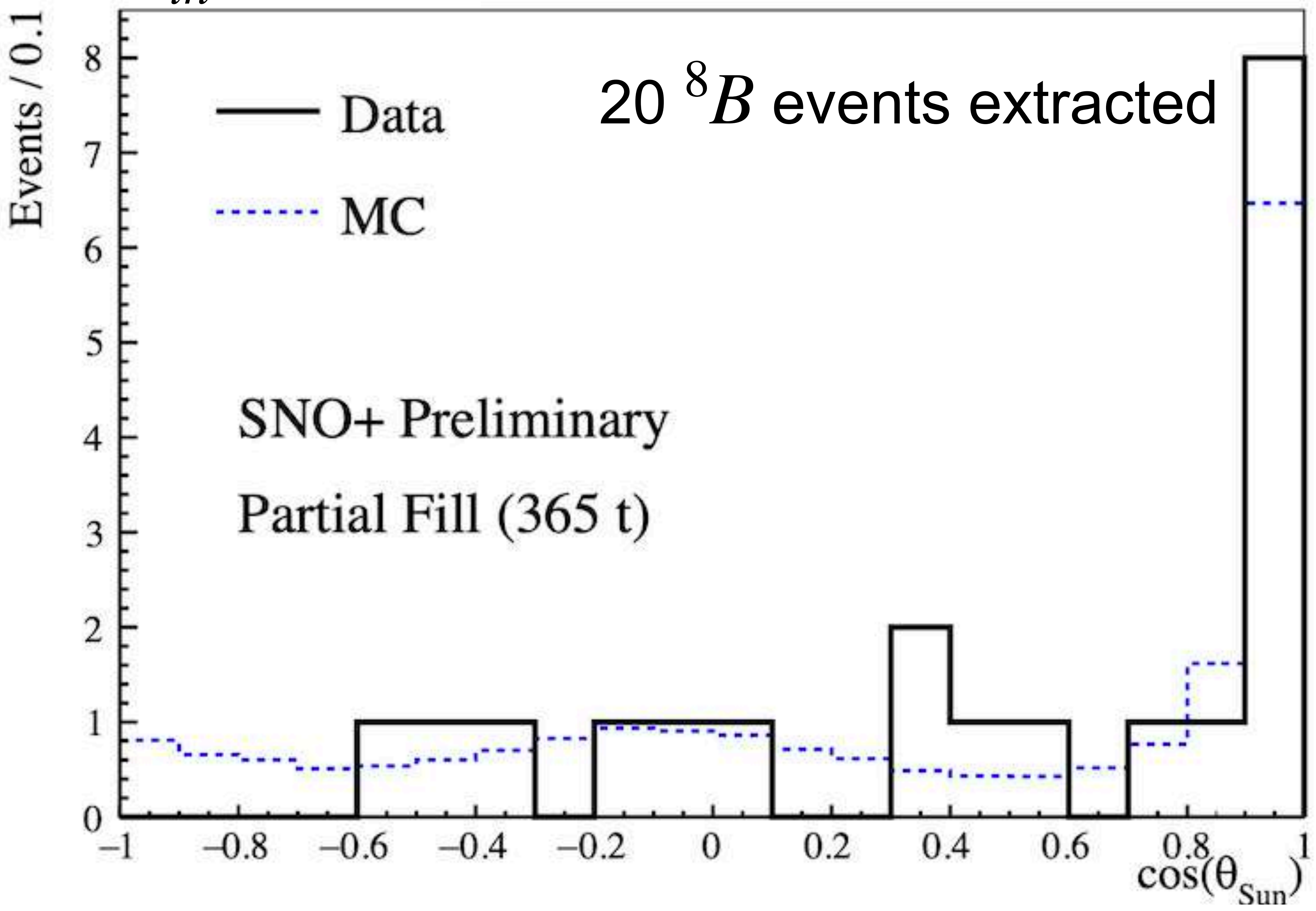


E > 5 MeV:

41% of events has $cos\theta_{\odot} > 0.8$

Results:

$E_{th} \sim 5$ MeV



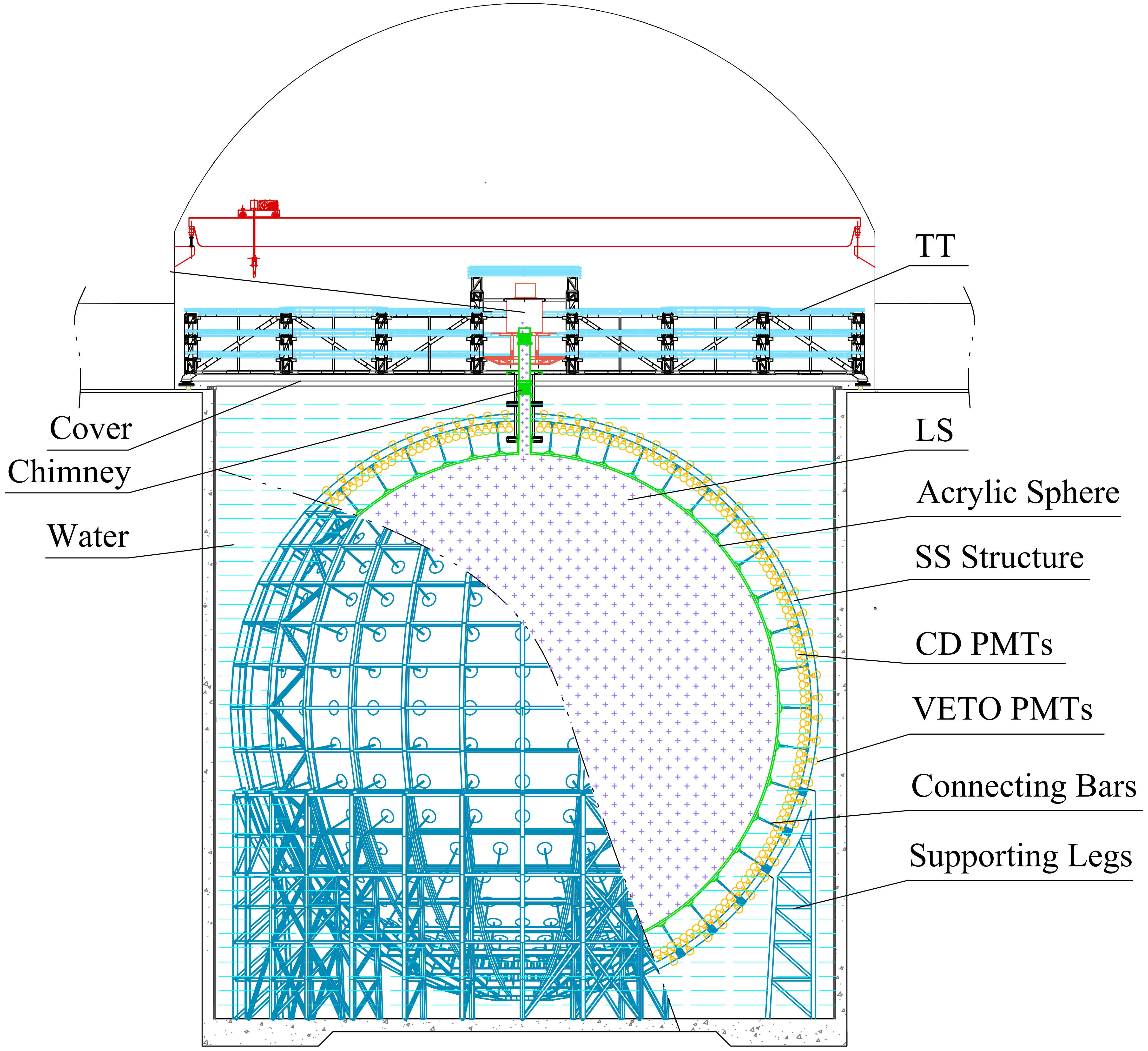
9 events are reconstructed with $cos\theta_{\odot} > 0.8$

First **event-by-event directional reconstruction** with LS detector

OUTLINE

- Solar neutrinos
  - Thermonuclear processes
  - Detecting neutrinos
- Experimental activity:
  - Borexino
  - SuperKamiokande
  - SNO+
- **Outlook: JUNO**

JUNO: SOLAR NEUTRINOS POTENTIAL



- ☑ **20 ktons LS** in Jiangmen (China)
- ☑ Construction will be completed by the end of 2023

→ **Sensitivity studies**

Huge **active mass** (~20 kton) and **excellent energy resoltuion** (~3% at 1 MeV)

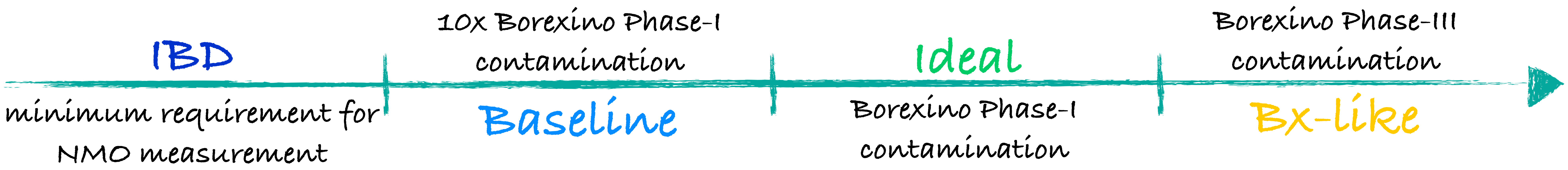
↓

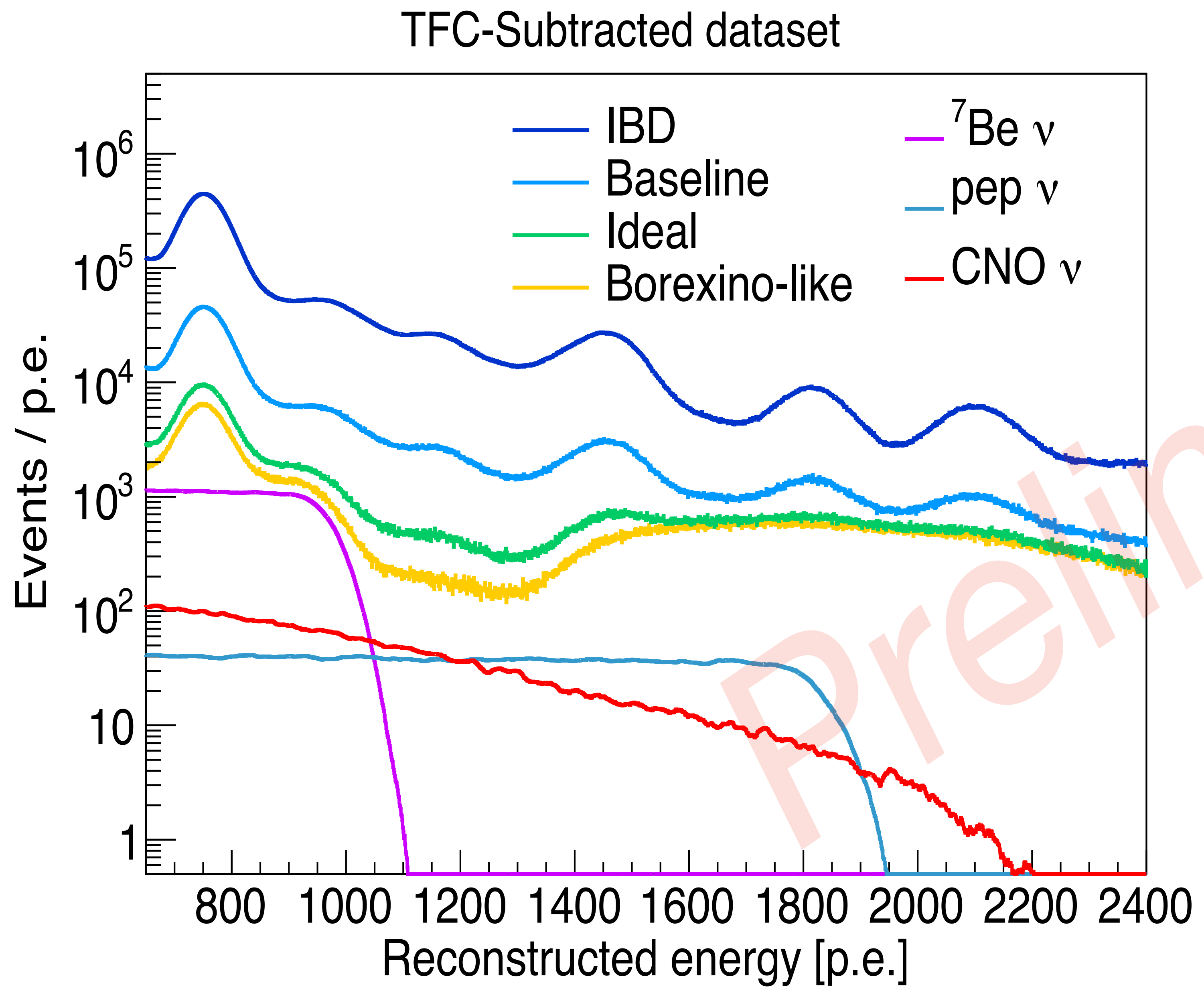
Potential to detect solar neutrinos with **unprecendented precision***.

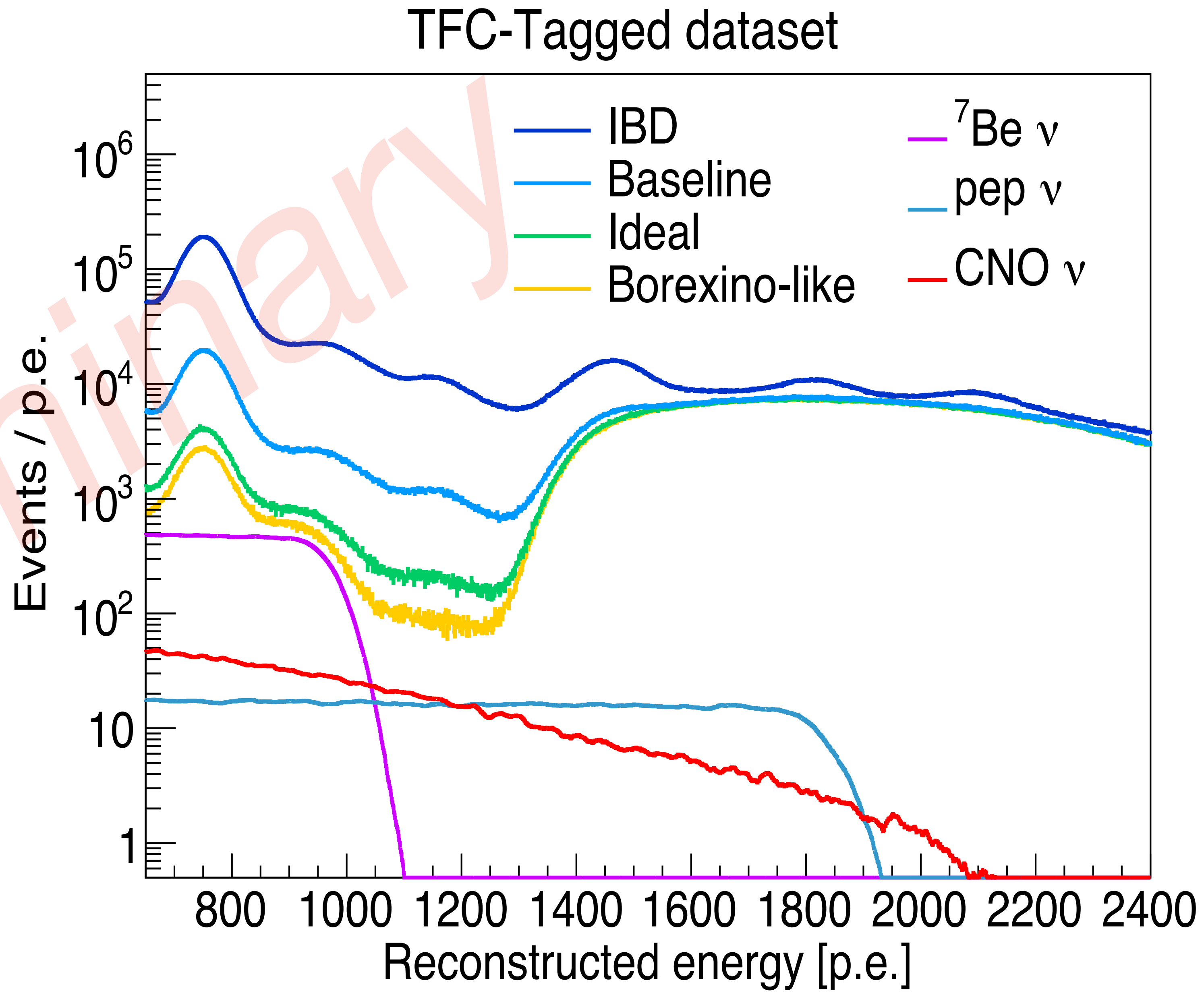
*Radiopurity needs to be carefully monitored

JUNO: INTERMEDIATE ENERGY SOLAR NEUTRINOS

Radio-purity scenarios considered (from worst to best):







Potential to improve current best results:

^{7}Be: after ~1 year can reach current best result (2.7%)

pep: after ~2 year can reach current best result (~17%)

CNO: pep constrained is crucial, 20% precision is achievable in 4 years (except for IBD scenario)

- Possible first independent measure of ^{13}N and ^{15}O

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JUNO: B8 ANALYSIS

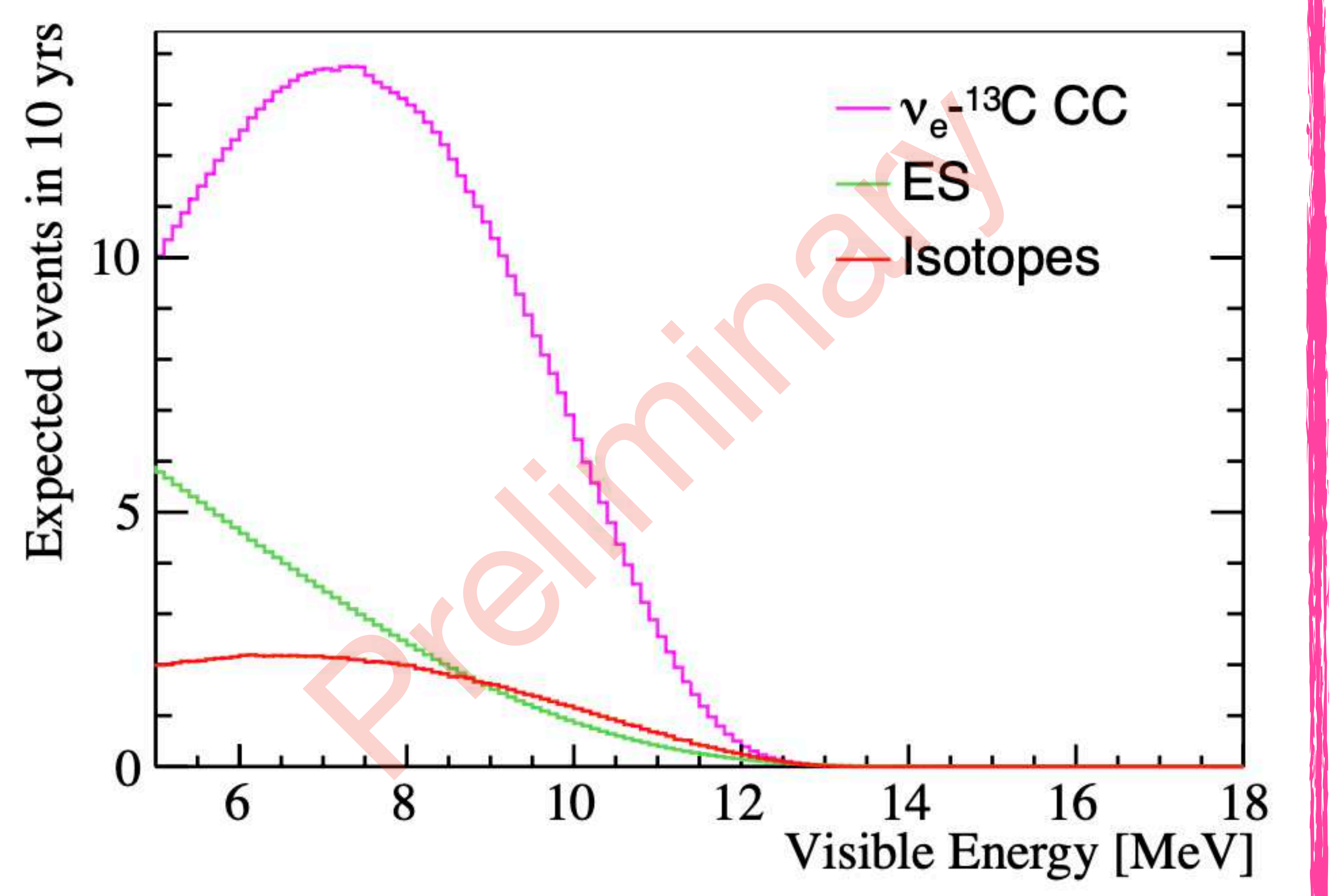
~0.2 ktons of ^{13}C in the LS → potential **model independent observation of B8 solar neutrino (CC, NC and ES)**

Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}\mathrm{N}$ decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \to \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

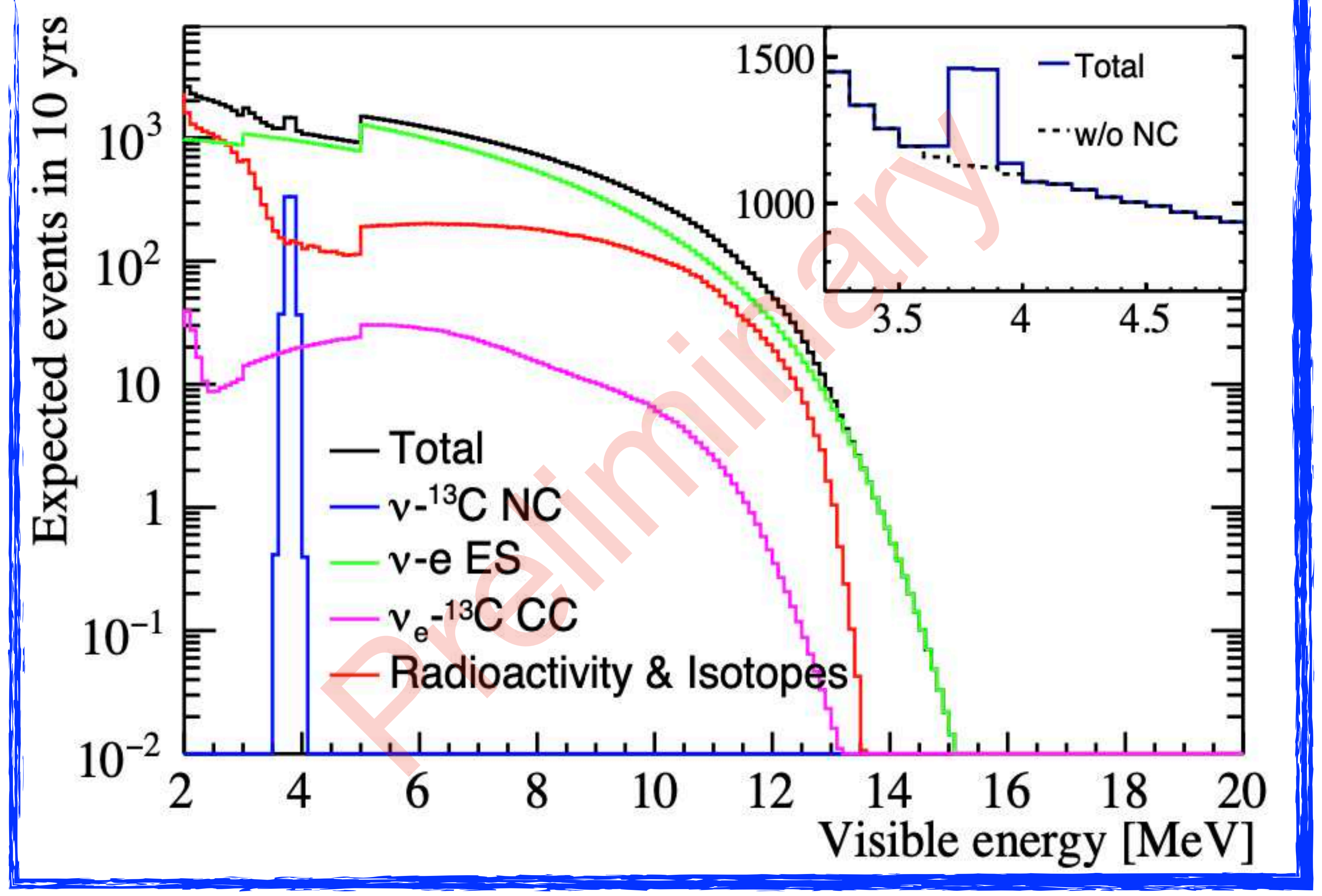
CC → Correlated events

NC, ES → Singles event

Spectrum of correlated events



Spectrum of singles events



Expected precision in 10 years:

B8 flux:

5% JUNO (better than SSM predictions)

3% JUNO+SNO (world best precision)

Oscillation parameters:

$sin^2(\theta_{12}) \to {}^{+9\%}_{-8\%}$

$\Delta m^2_{12} \to {}^{+25\%}_{-17\%}$

SUMMARY AND CONCLUSIONS

- ☑ Over the years, solar neutrinos have been of great use in understanding **Standard Solar Model and neutrino oscillations**

- ☑ Rich **experimental activity** in the solar neutrino field:
  - ☑ Borexino: **complete spectroscopy** of pp chain and CNO cycle, hints towards the solution of the **metallicity puzzle** and **first directional measurement** of sub-MeV solar neutrinos;
  - ☑ SuperKamiokande: effect of **solar and terrestrial matter**, **reduced tension** with Kamland on Δm^2_{21}
  - ☑ SNO+: first ^{8}**B measurement** and **first event-by-event directional reconstruction** with LS detector

- ☑ And more to come:
  - ☑ JUNO: potential to detect solar neutrinos with **unprecendented level of precision** (if radiopurity is kept under control)

- ☑ There are still open questions (solar-Kamland tension, metallicity, P_{ee} upturn…)

→ **Still a rich and active field**

THANK YOU FOR YOUR ATTENTION!

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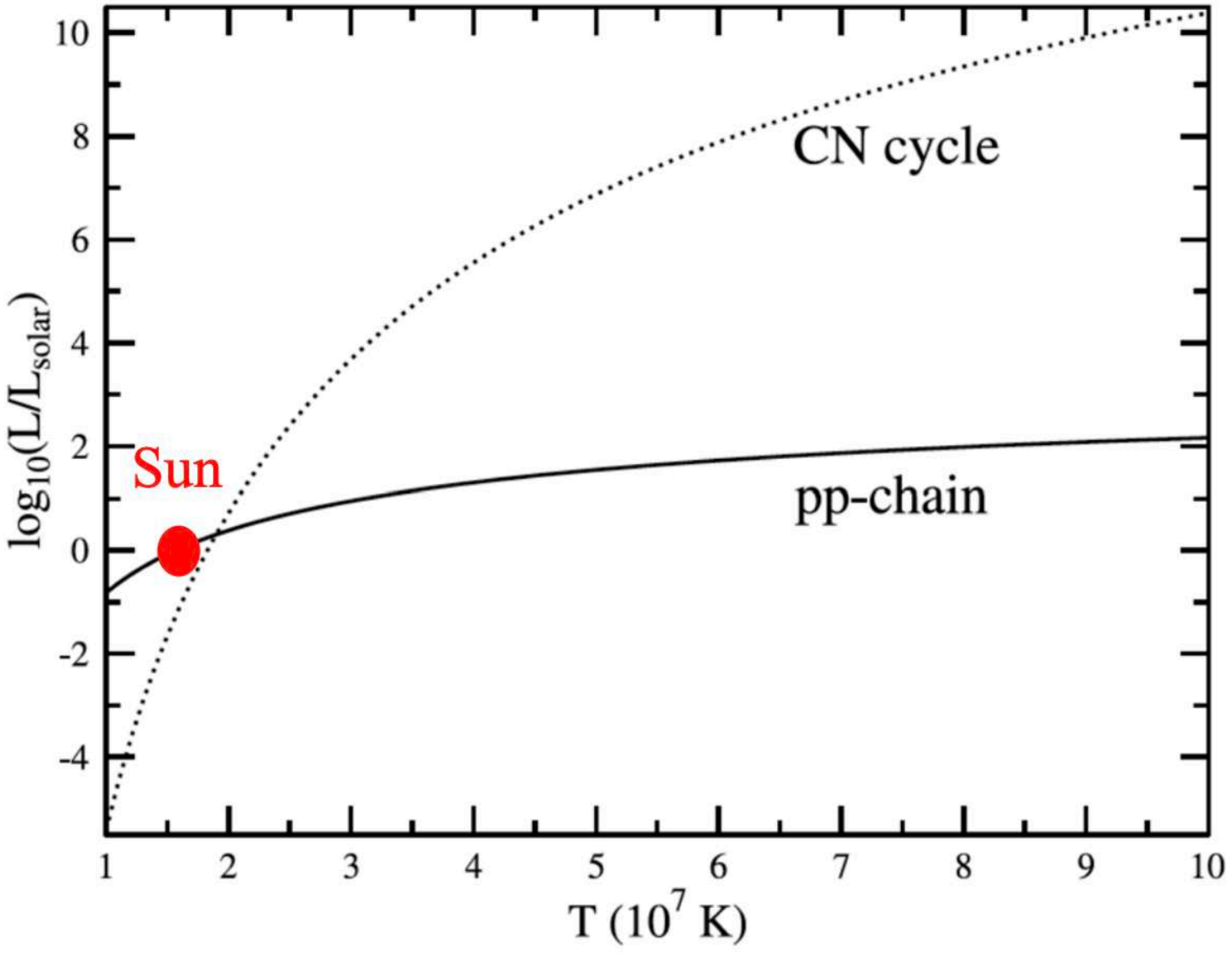
Forschungszentrum

BACKUP

SOLAR NEUTRINOS



The importance of CNO neutrinos:

- Proof of star energy production in the Sun via CNO cycle (observed for the first time in 2020 by Borexino)
- The CNO cycle is sub-dominant in the Sun, but is expected to be **dominant in more massive Stars**
- Can provide direct experimental information on the **solar metallicity**

NEUTRINO PHYSICS: MATTER EFFECT

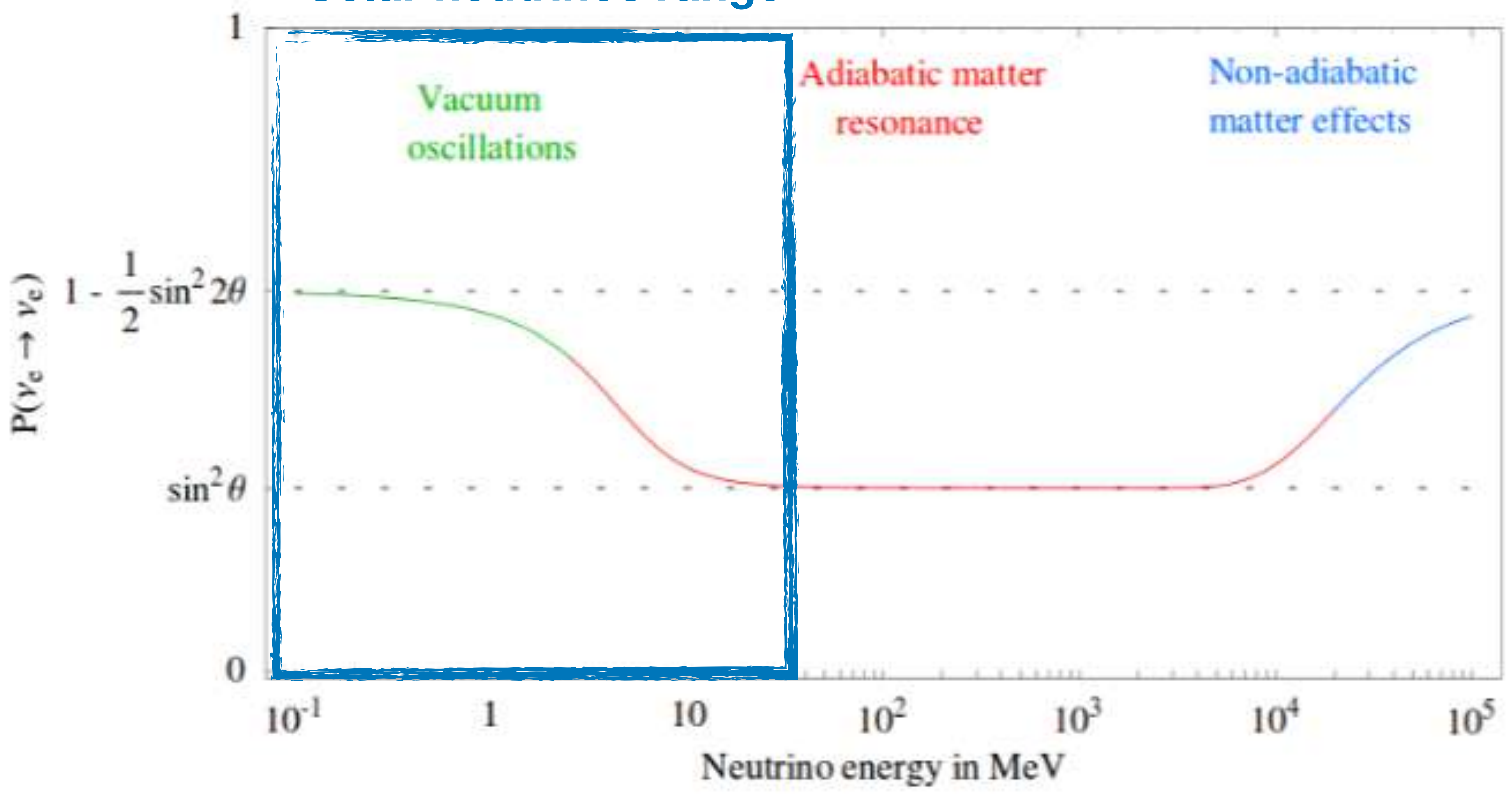
Flavor-dependent propagation → P_{ee}(Vacuum) $\neq$ P_{ee}(Matter)

MSW resonance mechanism (two-flavours scenario):

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_m \sin^2\left(\frac{\Delta m_m^2 L}{4E}\right) \qquad \Delta m_m^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - \epsilon_\odot)^2}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \epsilon_\odot)^2}$$

Solar neutrinos range



E ≤ 1 MeV**: Vaccum region** (marginal matter effect)

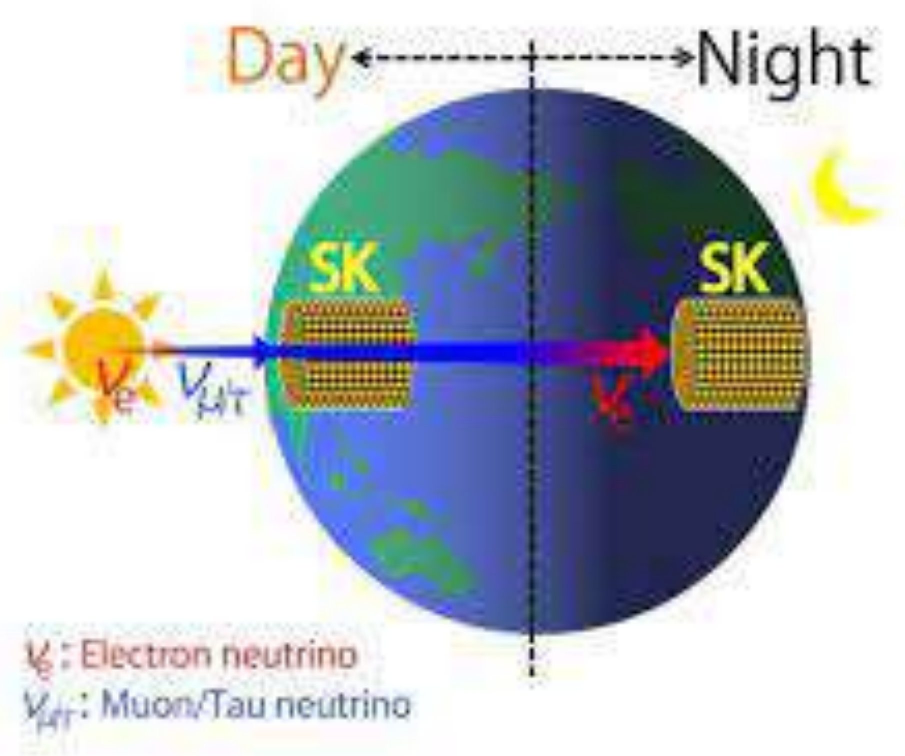
1 MeV $\leq$ E ≤ 15 MeV: **transition region (NSI), "upturn"**

E ≥ 15 MeV**: Matter enhanced resonant region**

Day/Night asymmetry: time variaton of Φ_{ν_s}

Coherent re-generation of ν_e during propagation through the Earth

Φ measured via ES → **effect enhanced in the night**



Method 1: straight calculation

$$A_{DN} = \frac{\Phi_D - \Phi_N}{\frac{1}{2}(\Phi_D + \Phi_N)}$$

Method 2: Amplitude fit

Add **amplitude scaling factor** (α) → $A_{DN} = A_i \times \alpha$

Likelihood function is maximed wrt signal, backgrounds and α

Method 2 gives great improvement in statistical error

MSW MECHANISM

Flavor dependent interaction potential:

$$V_\alpha = V_{CC}\delta_{\alpha e} + V_{NC} = \sqrt{2}G_F\left(N_e\delta_{\alpha e} - \frac{1}{2}N_n\right)$$

$$\alpha = e: \qquad V_e = V_{CC} + V_{NC} = \pm\sqrt{2}G_F\left(N_e - \frac{1}{2}N_n\right)$$

$$\alpha = \mu, \tau: \qquad V_\mu = V_\tau = V_{NC} = \mp\sqrt{2}G_F N_e$$

Different potential depending on flavours -> additional non zero phase

HM = Hamiltonian of interaction with matter

H = Hamiltonian of interaction in vacuum

$$\delta\phi_M = (H_M - H)t$$

$$\epsilon_\odot = \frac{\delta\phi_M}{\delta\phi_{Vacuum}} = \frac{\sqrt{2}G_F N_e}{\Delta m^2/2E} \approx \frac{7.5\times 10^{-5}\ \mathrm{eV}^2}{\Delta m^2}\left(\frac{E}{5\mathrm{MeV}}\right)\left(\frac{\rho}{100\mathrm{g/cm}^3}\right)$$

Estimator to quantify impact of matter effect

$$\begin{aligned} H = H_0 + H_M &\approx \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_{CC} & 0 \\ 0 & 0 \end{pmatrix} = \\ &= \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \frac{\sqrt{2}G_F N_e}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \\ &= \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta + \epsilon_\odot & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - \epsilon_\odot \end{pmatrix} \end{aligned}$$

Diagonalize H →

$$H = \frac{\Delta m_m^2}{4E}\begin{pmatrix} -\cos 2\theta_m & \sin 2\theta_m \\ \sin 2\theta_m & \cos 2\theta_m \end{pmatrix}$$

$$N_e^{res} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F} \approx 6.65\cdot 10^6 \frac{\Delta m^2\ [\mathrm{eV}]^2}{E\ [\mathrm{MeV}]} N_A \cos 2\theta\ [\mathrm{cm}]^{-3}$$

D/N ASYMMETRY

Two PDFs:

$p(\cos\theta_\odot, E)$ = angular shape expected for solar neutrinos of energy E

$u_i(\cos\theta_\odot)$ = angular shape expected for backgrounds in bin i

Method 1: straight calculation $A_{DN} = \frac{\Phi_D - \Phi_N}{\frac{1}{2}(\Phi_D + \Phi_N)}$

Method 2: Amplitude fit

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\text{bin}}} \prod_{\kappa=1}^{n_i} \left(B_i \cdot b_{i\kappa} + S \frac{\text{MC}_i}{\sum_j \text{MC}_j} \cdot s_{i\kappa} \right)$$

S = Signal

Bi = backgrounds

n_i events in energy bin i assigned to factor $s_{ik} = p(\cos\theta_{ik}, E_k)$ and

$b_{ik} = u_i(\cos\theta_{ik})$

MCi = number of events expected in bin i (using B8 and hep neutrinos)

Likelihood maximized wrt S and B

$$s_{ik} = p(\cos\theta_{ik}, E_k) \times z_i(\alpha, t_k) \qquad z_i(\alpha, t) = \frac{1 + \alpha\left((1 + a_i) r_i(t)/r_i^{\text{av}} - 1\right)}{1 + \alpha \times a_i},$$

r_i = MC rate in bin I

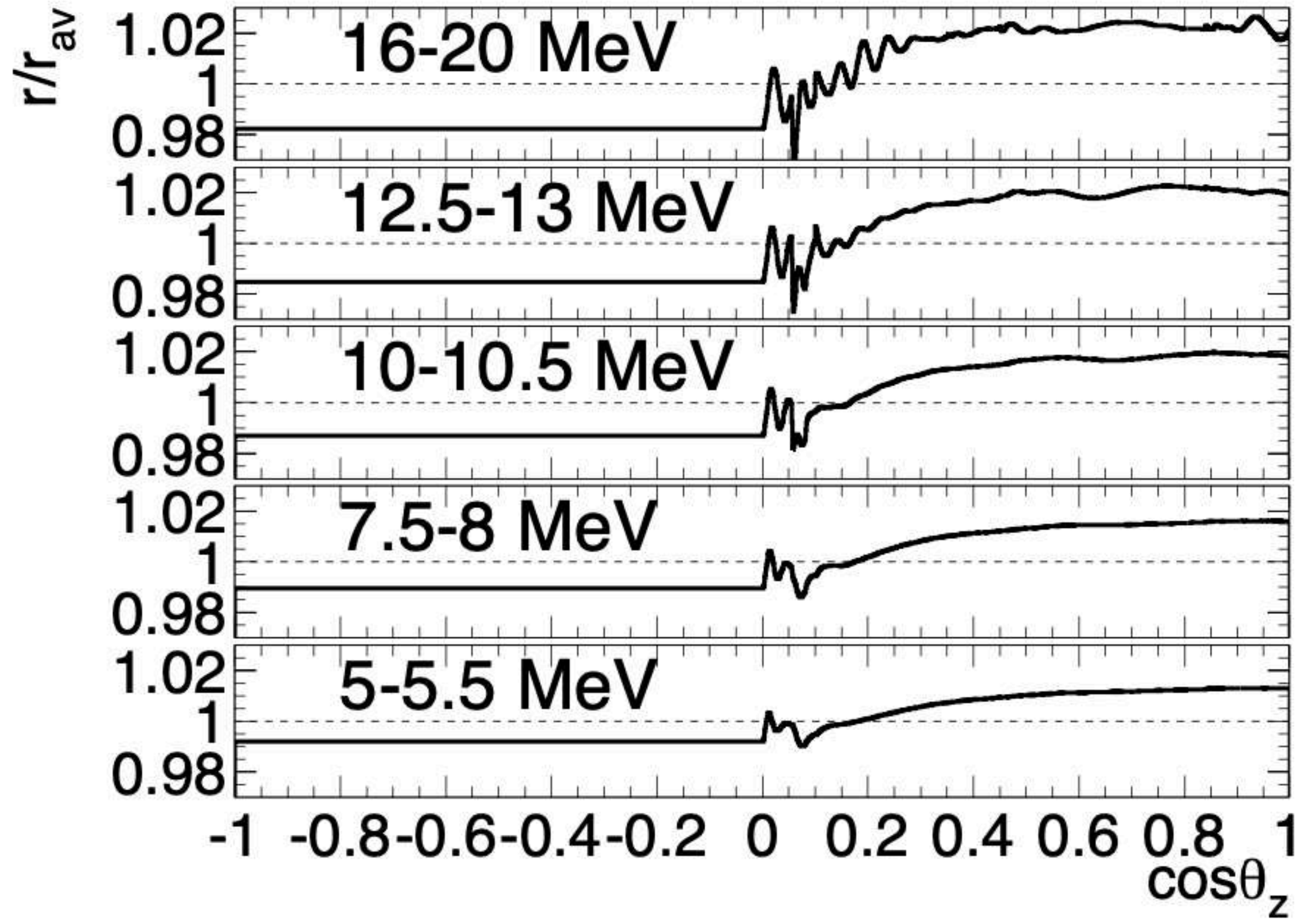
r^av = rate avaraged with livetime distribution (used to evaluate A_i)

a_i = effective asym param = 0.25*A_i*L_DN

with L_DN = (LD-LN)/(0.5(LD+LN))

→ $r'(\alpha, t) = z_i(\alpha, t) \times r_i^{av}$ t.c. r'(av) = r(av) and d/n asymm = A x α

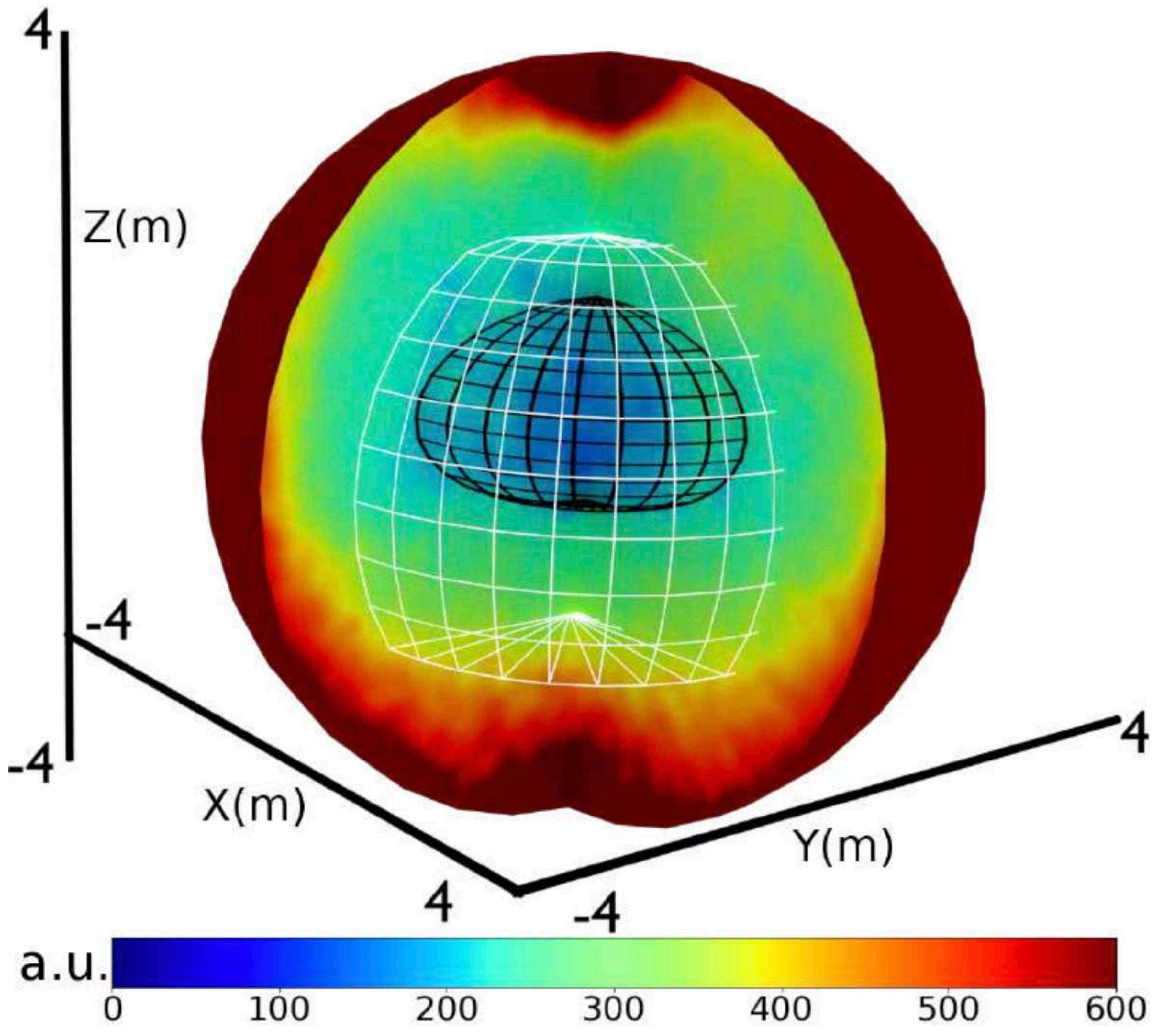
Likelihood maximized wrt S and B and α



$z_i(1, \cos\theta_z)$ as a function of different energy bins

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)

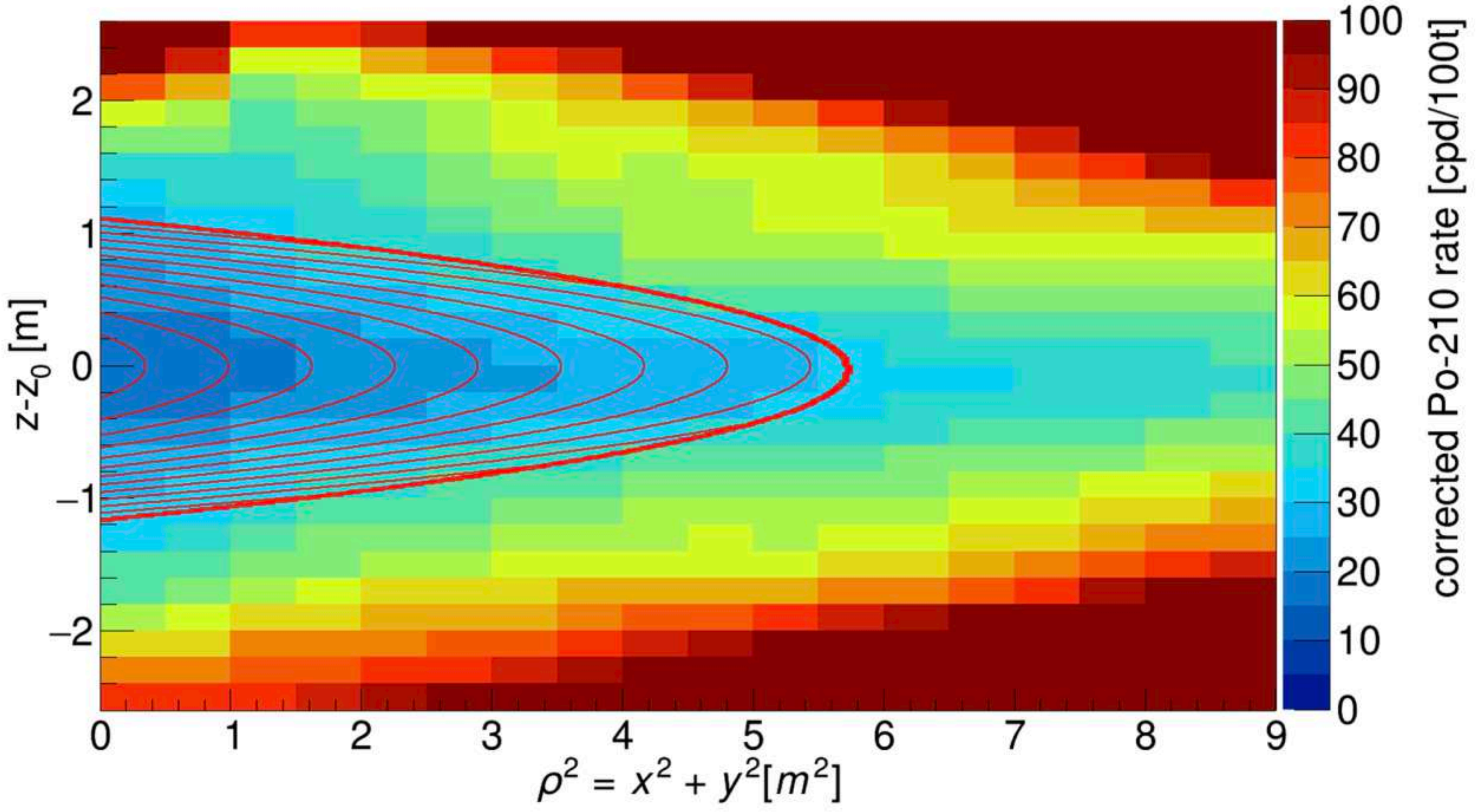
Cross-checked with fluid dynamic simulations

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

1) fitting LPoF with a 2D paraboloidal function:

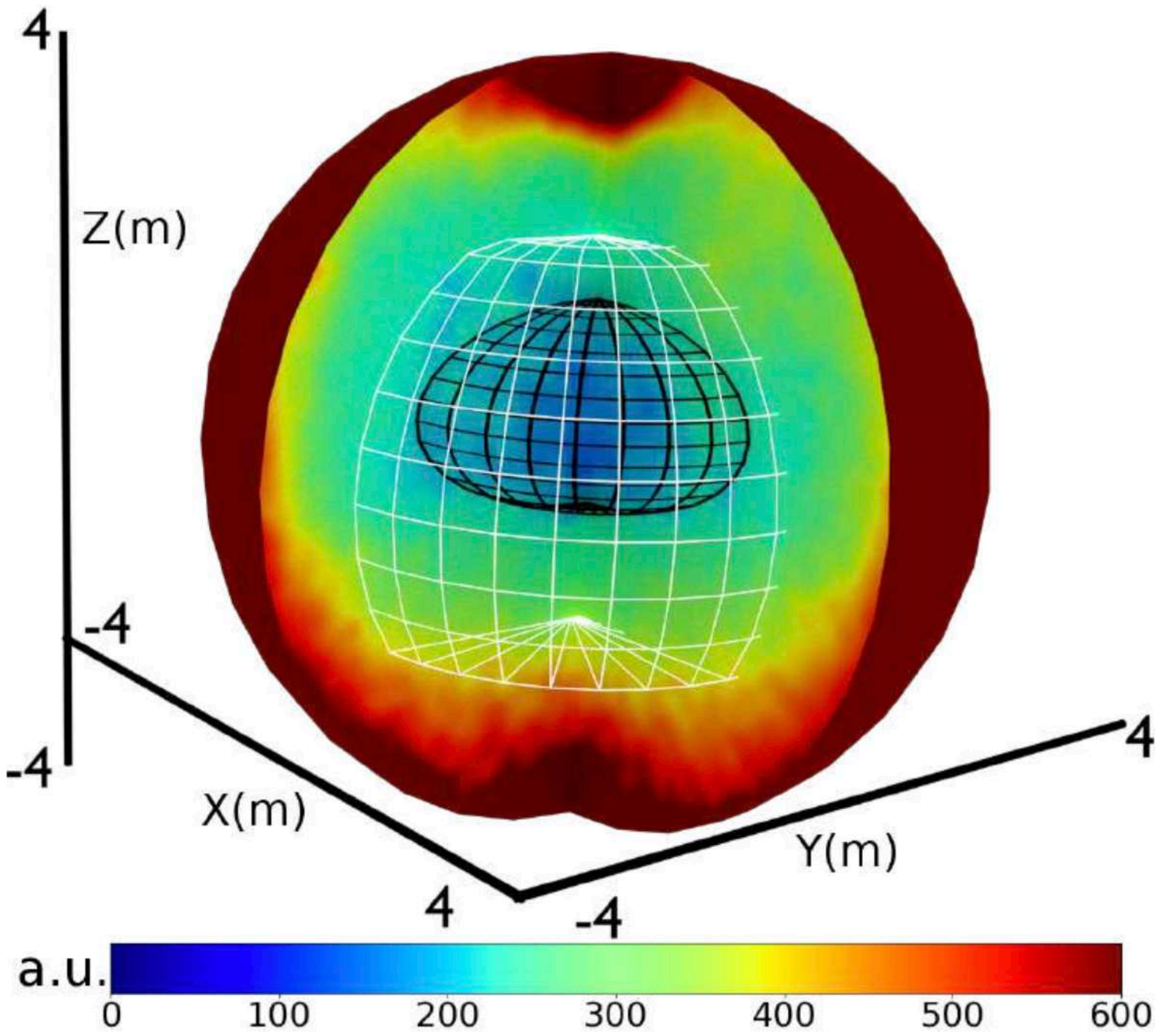
$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right)$$

- 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:



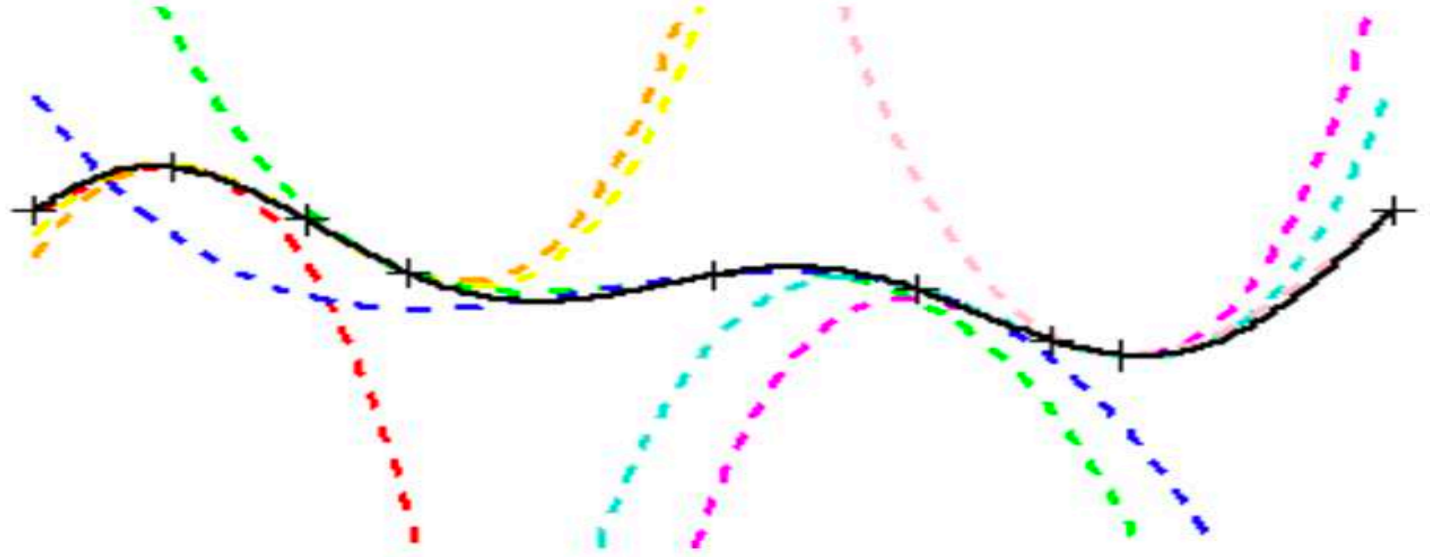
Low Polonium Field (LPoF):

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

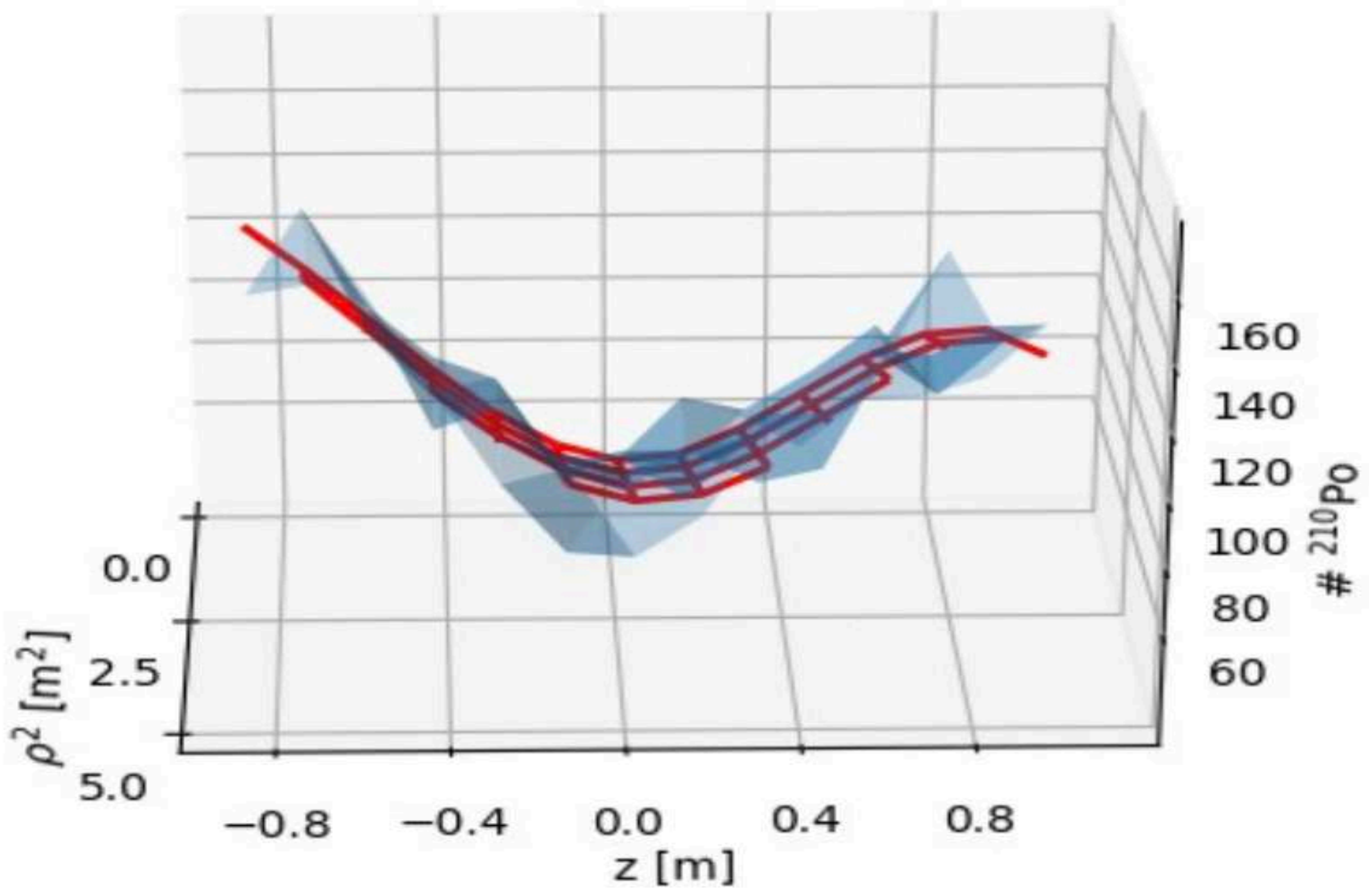
Cross-checked with fluid dynamic simulations

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

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

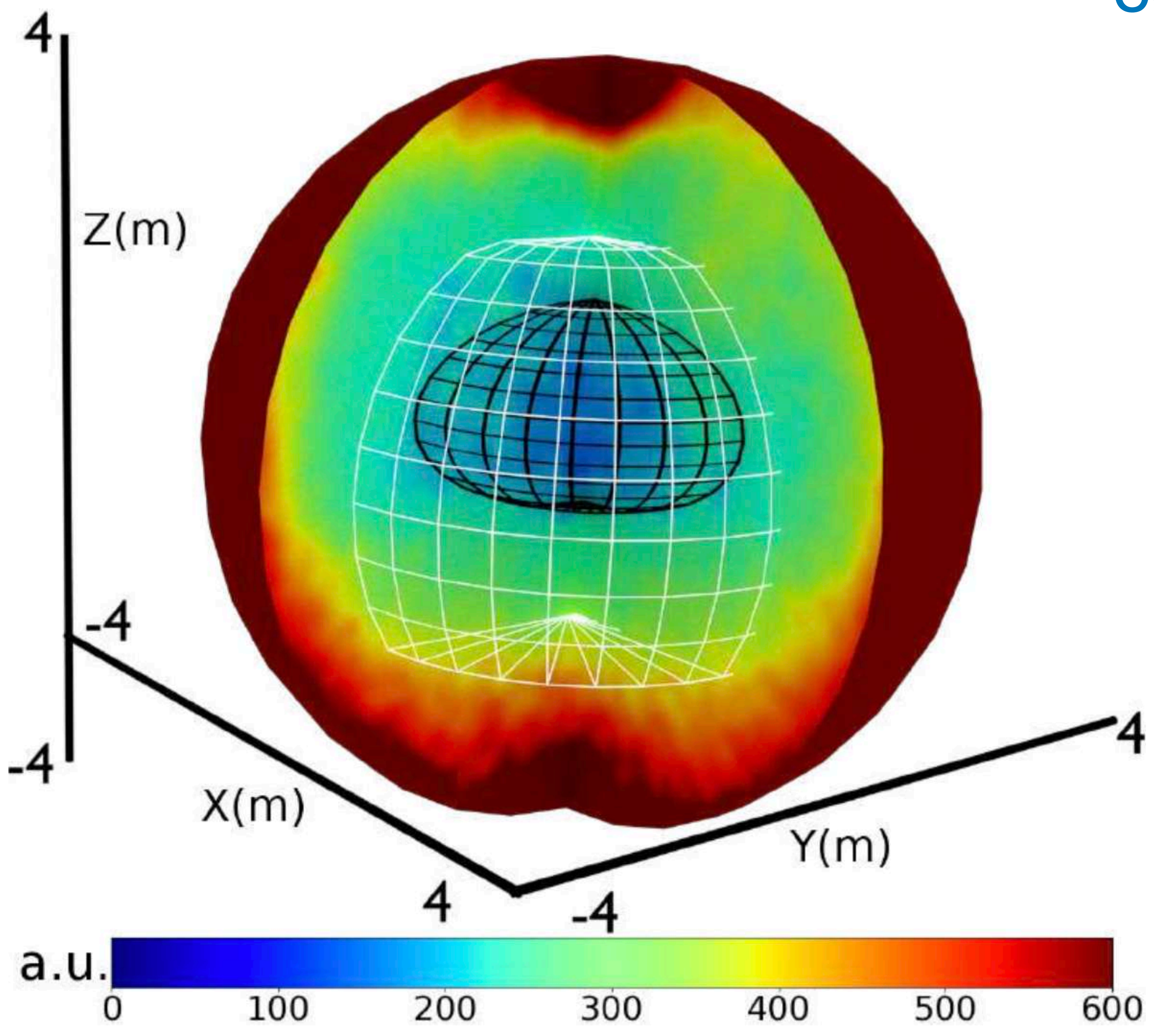


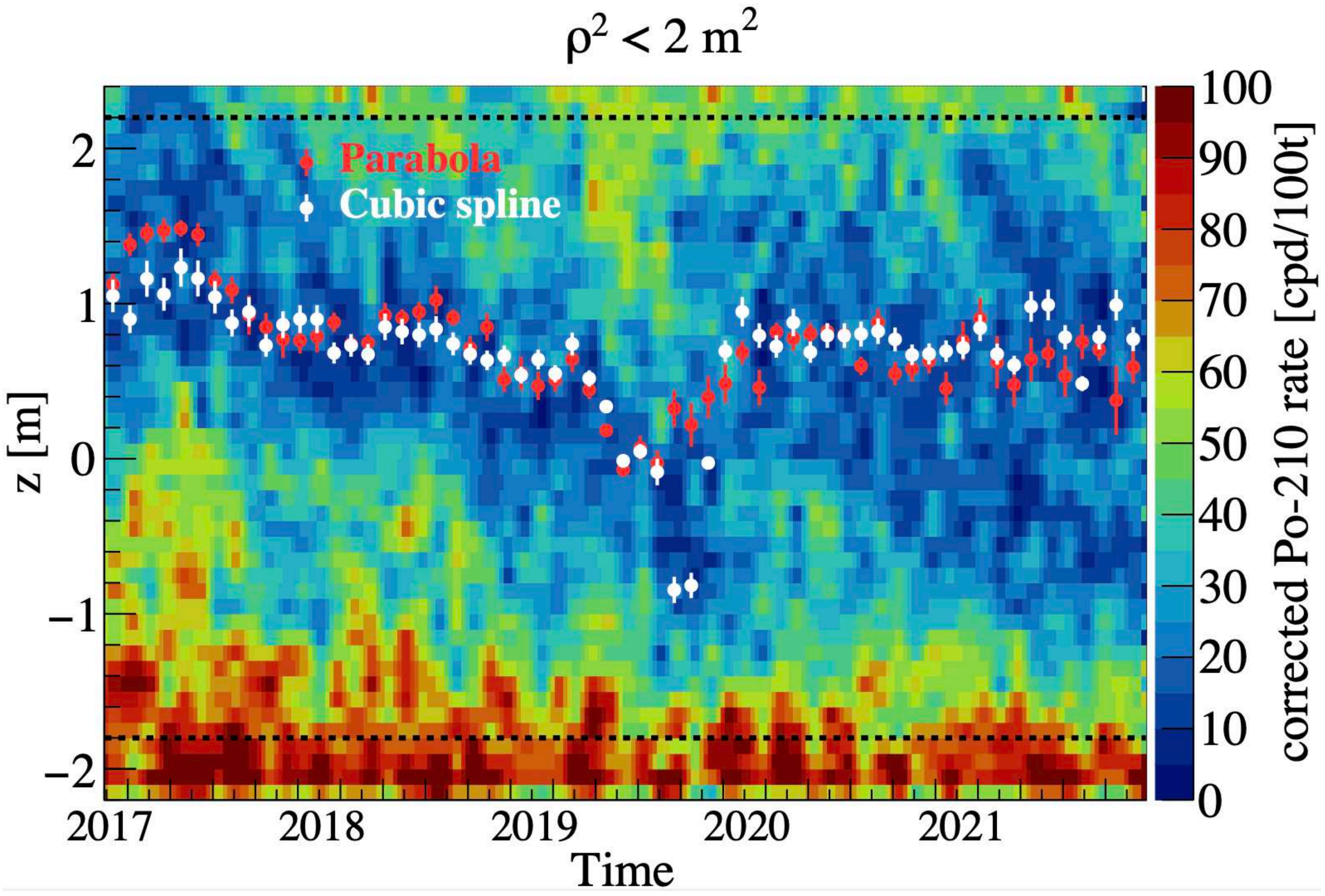
$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + spline(z)\right)$$



BOREXINO PHASE-III: 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)

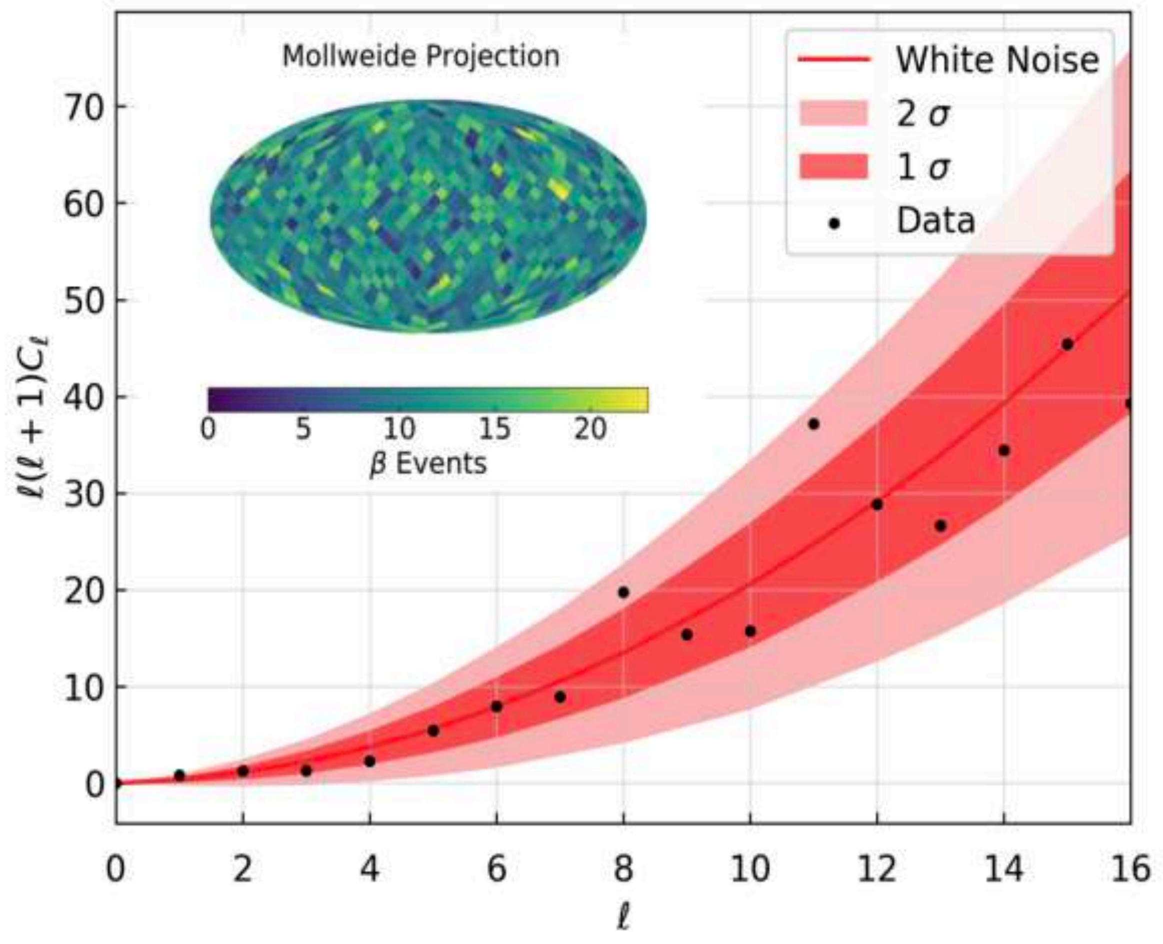
Cross-checked with fluid dynamic simulations

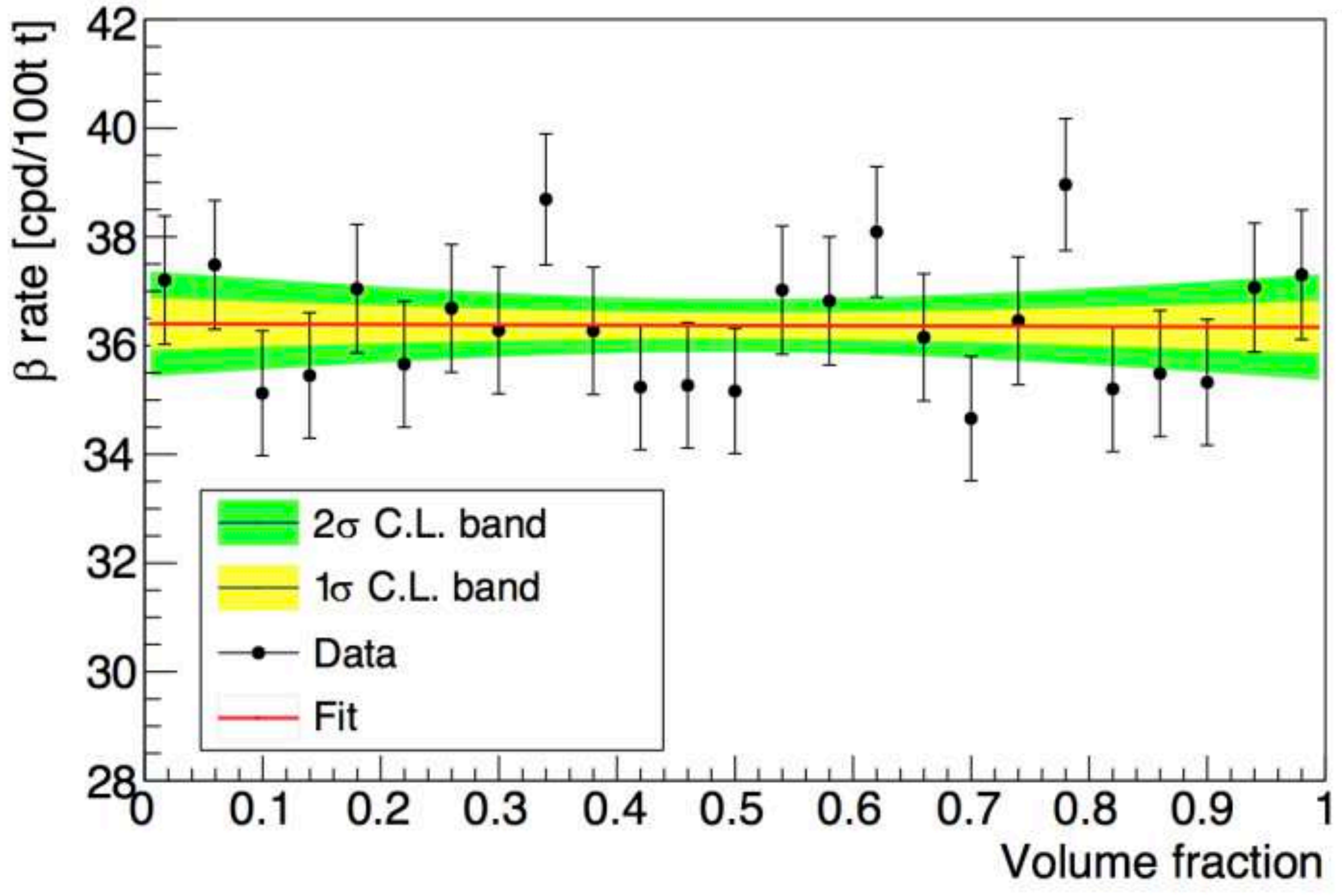
Two methods give consistent results:
it is now possible to extract: $R(^{210}\text{Bi}) \leq R(^{210}\text{Po})$

THE LOW POLONIUM FIELD

Systematics associated to ^{210}Bi constraint:

^{210}Bi uniformity: the upper limit can be extended to the FV only if ^{210}Bi is uniform in space and time





Angular distribution uniformity: ± 0.59 cpd/100t

Radial distribution uniformity: ± 0.52 cpd/100t

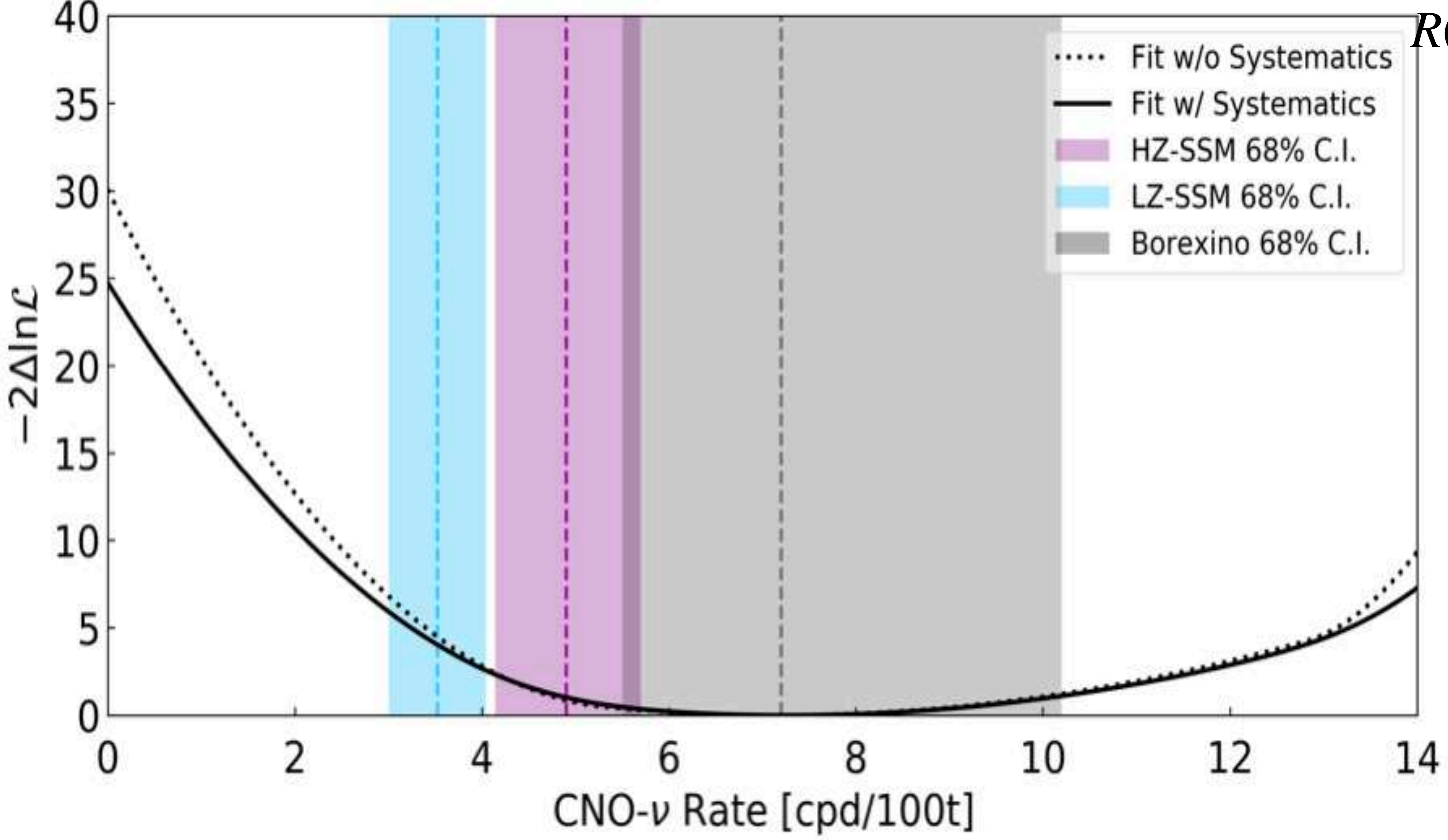
Other sources of systematics: mass, binning and β-leakage

$R_{min}(^{210}Po)$	$\sigma_{stat.}$	σ_{mass}	σ_{binw}	$\sigma_{Bi-homog}$	$\sigma_{\beta-leak}$	σ_{Total}
11.5	0.83	0.40	0.20	0.78	0.30	1.3

$R(^{210}\text{Bi}) \leq 11.5 \pm 1.3$ cpd/100t

BOREXINO PHASE-III: THE MULTIVARIATE FIT

log-likelihood profile



Constraints in the fit:

$R(^{210}\text{Bi}) \leq R(^{210}\text{Po}) = 11.5 \pm 1.3$ cpd/100t

$R(\text{pep}) = 2.74 \pm 0.04$ cpd/100t

Best fit result (stat. + syst.):

$R(CNO-\nu)$: $7.2^{+3.0}_{-1.7}$ **cpd/100 t**

$\Phi(CNO-\nu)$: $7.2^{+3.0}_{-2.0} \cdot 10^8$ ν/**cm²/s**

First detection of CNO neutrinos

no-CNO hypotesis rejected with a significance **better than 5σ at 90% C.L.**

M. Agostini et al. (Borexino Collaboration) **Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun** *Nature* 587 (2020)

Combining this result with other solar neutrino fluxes measured by Borexino and assuming th HZ-SSM predictions, the p-value(LZ-SSM) is 0.016.

The LZ-hypotesis is disfavoured at 2.1σ

BOREXINO PHASE-III: SYSTEMATIC UNCERTAINTY BUDGET

Many possible source of systematic error have been investigated:

- **Fitting method systematics**: we have performed the fit in ~650 different conditions and found great stability of the fit
- **Systematics associated to detector energy response**: non linearity (via calibration sources), light yield stability and spatial non uniformity (via cosmogenic neutrons), energy scale, and ^{210}Bi spectral shape.
  - Final systematic error associated to energy PDFs: **-0.4 +0.5 cpd/100t**
- **Method of extraction and uniformity of ^{210}Bi upper limit:** included in the error on the constraint;
- **N/O fixed ratio** in CNO spectral shape: found to be negligible

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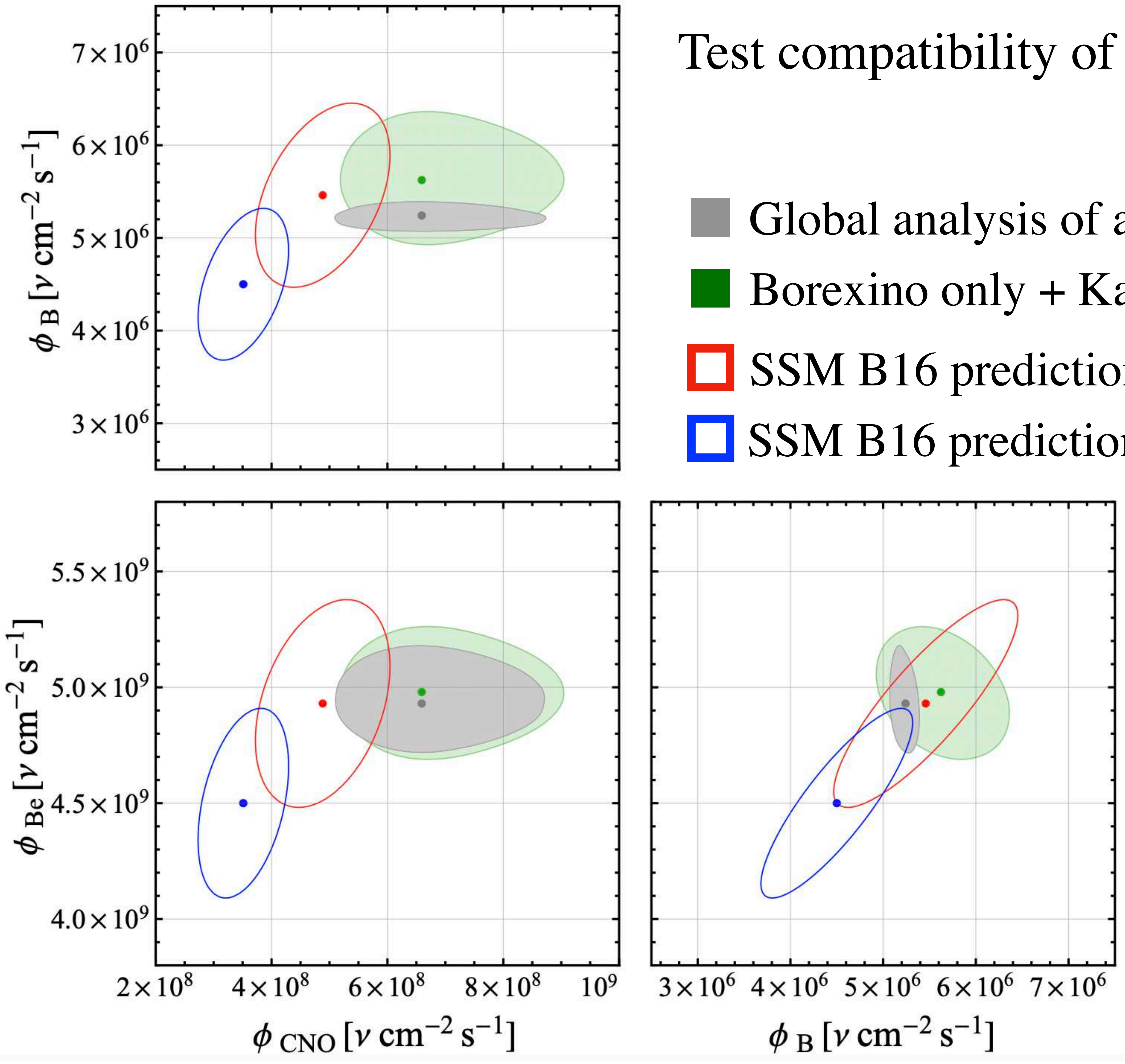
SOLAR IMPLICATIONS: GLOBAL ANALYSIS

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 $\bar{\nu}_e$
- Borexino only + Kamland reactor $\bar{\nu}_e$
- 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**

including the CNO measurement, p-value:

LZ-SSM vs **global analysis:** from 0.327 to 0.028

LZ-SSM vs **Bx+Kamland:** from 0.196 to 0.018

HZ-SSM compatible with both (**0.462** and **0.554**)

SOLAR IMPLICATIONS: C+N ABUNNDANCE

$$\frac{\Phi_B}{\Phi_B^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_B}$$

expansion of the SSM flux predictions →

explicit dependence of a given neutrino flux Φi from the input j in the form of a power-law

$$\frac{\Phi_i}{\Phi_i^{\mathrm{SSM}}} = \prod_j^{\mathrm{C,N}} x_j^{\alpha(i,j)} \times \prod_j^{\mathrm{env}} x_j^{\alpha(i,j)} \times \prod_j^{\mathrm{nucl}} x_j^{\alpha(i,j)} \times x_{\mathrm{diff}}^{\alpha(i,\mathrm{diff})}$$

x_j = SSM parameters normalized to their nominal values

$$\alpha(i,j) = \frac{\partial \ln\left(\Phi_i/\Phi_i^{\mathrm{SSM}}\right)}{\partial \ln x_j}$$

Calculated numerically

- *Nuclear*: i.e., the astrophisical S-factors of the nuclear processes involved in hydrogen burning (S_{11}, S_{33}, S_{34}, S_{e7}, S_{17}, S_{hep}, S_{114}, S_{116}, Tab. 2 left column)
- *Solar*: i.e., the Sun's astrophysical (Age, Luminosity) and non-nuclear properties (Diffusion length, Radiative opacity parametrization κ_A, κ_B [7] Tab. 2 right column)
- *metallicity*: the abundance of elements heavier than helium (Tab. 3)

The diffusion parameter is threated separately because has a twofold effect:

1. a change in the diffusion will affect the temperature stratification in the Sun
2. it will also affect the chemical composition profile

SOLAR IMPLICATIONS: C+N ABUNNDANCE

$$\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O - k\tau_B} \longrightarrow \frac{(\Phi_\mathrm{O}/\Phi_\mathrm{O}^\mathrm{SSM})}{(\Phi_\mathrm{B}/\Phi_\mathrm{B}^\mathrm{SSM})^k} = \prod_j^{\mathrm{C,N}} x_j^{\alpha(^{15}\mathrm{O},j)-k\,\alpha(^8\mathrm{B},j)} \times \prod_j^{\mathrm{env}} x_j^{\alpha(^{15}\mathrm{O},j)-k\,\alpha(^8\mathrm{B},j)} \times \prod_j^{\mathrm{nucl}} x_j^{\alpha(^{15}\mathrm{O},j)-k\,\alpha(^8\mathrm{B},j)} \times x_\mathrm{diff}^{\alpha(^{15}\mathrm{O},\mathrm{diff})-k\,\alpha(^8\mathrm{B},\mathrm{diff})}$$

The optimal value of k is chosen to minimize the contribution of the environmental parameters to the total uncertainty budget in the flux ratio

$$\mathrm{Var}\left[\frac{(\Phi_\mathrm{O}/\Phi_\mathrm{O}^\mathrm{SSM})}{(\Phi_\mathrm{B}/\Phi_\mathrm{B}^\mathrm{SSM})^k}\right]^{\mathrm{env}} = \sum_j^{\mathrm{env}} \left[\alpha(^{15}\mathrm{O},j) - k\alpha(^8\mathrm{B},j)\right]^2 (\delta x_j)^2$$

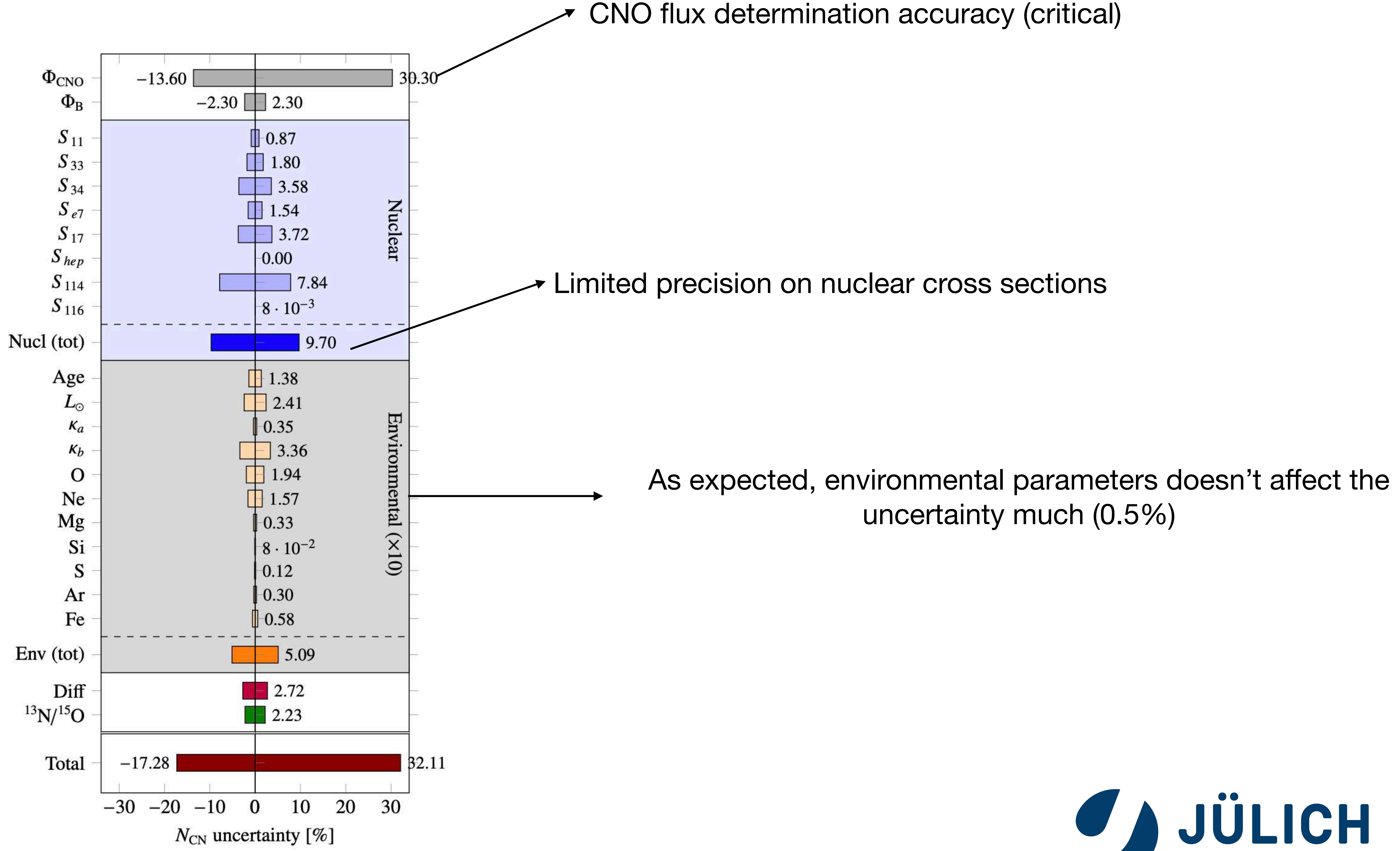
Minimizing this contribution k (0.769) is not so far away from the one obtained in the simplified calculation (0.83)

$$\frac{(\Phi_\mathrm{O}/\Phi_\mathrm{O}^\mathrm{SSM})}{(\Phi_\mathrm{B}/\Phi_\mathrm{B}^\mathrm{SSM})^{0.769}} =$$
$$x_\mathrm{C}^{0.802} x_\mathrm{N}^{0.204} x_D^{0.181}$$
$$\times \left[x_{S_{11}}^{-0.866} x_{S_{33}}^{0.345} x_{S_{34}}^{-0.689} x_{S_{e7}}^{0.769} x_{S_{17}}^{-0.791} x_{S_{hep}}^{0.000} x_{S_{114}}^{1.046} x_{S_{116}}^{0.001}\right] \quad \text{(nucl)}$$
$$\times \left[x_\mathrm{Age}^{0.313} x_{L_\odot}^{0.602} x_{\kappa_a}^{0.018} x_{\kappa_b}^{-0.050}\right] \quad \text{(env - solar)}$$
$$\times \left[x_\mathrm{O}^{0.006} x_\mathrm{Ne}^{-0.003} x_\mathrm{Mg}^{-0.003} x_\mathrm{Si}^{0.001} x_\mathrm{S}^{0.001} x_\mathrm{Ar}^{0.001} x_\mathrm{Fe}^{0.005}\right] \quad \text{(env - met)}$$

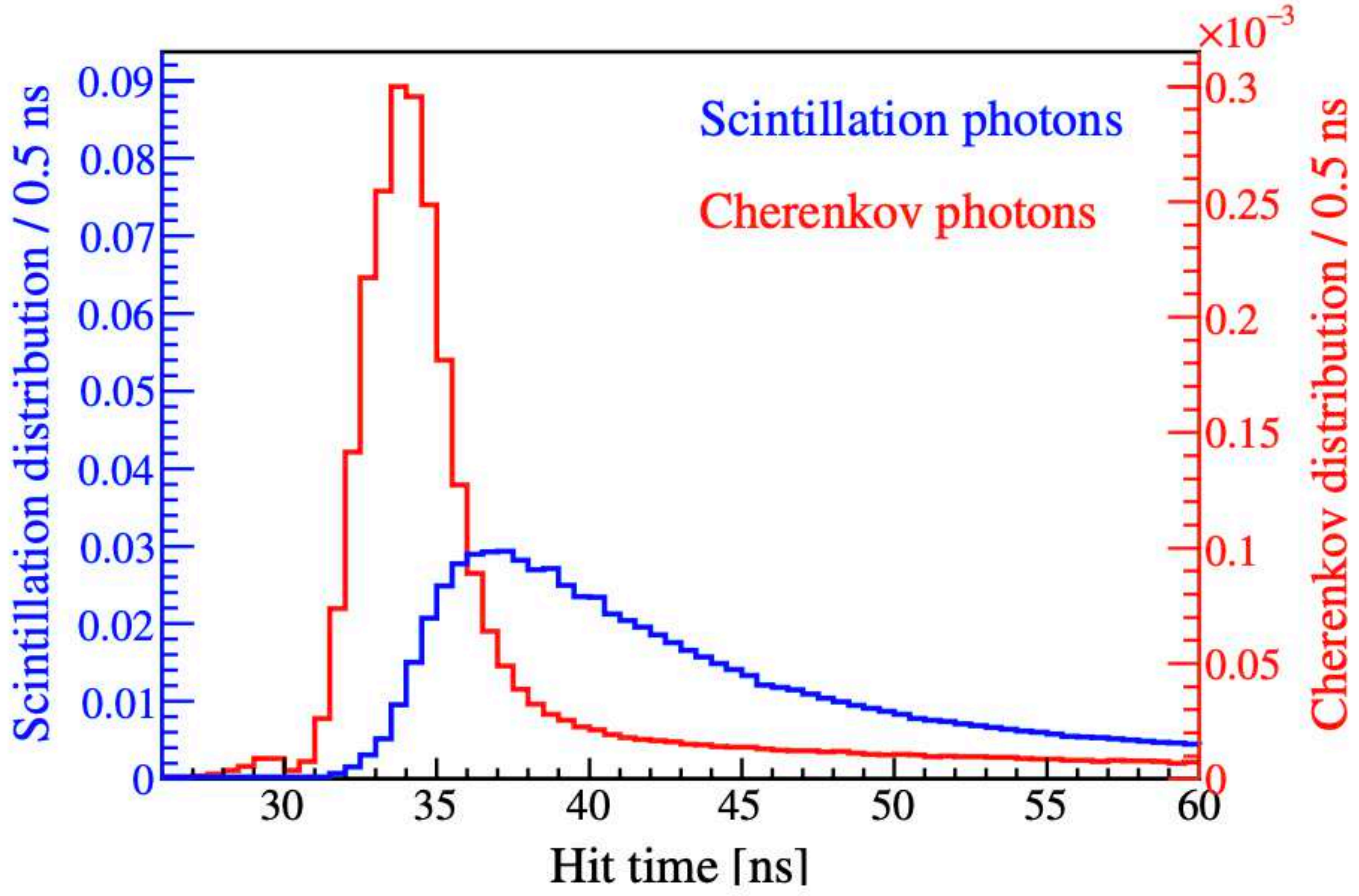
If power indices of x_C and x_N sum up to one, we can replace x_C* x_N with N_CN/N_CN(SSM)

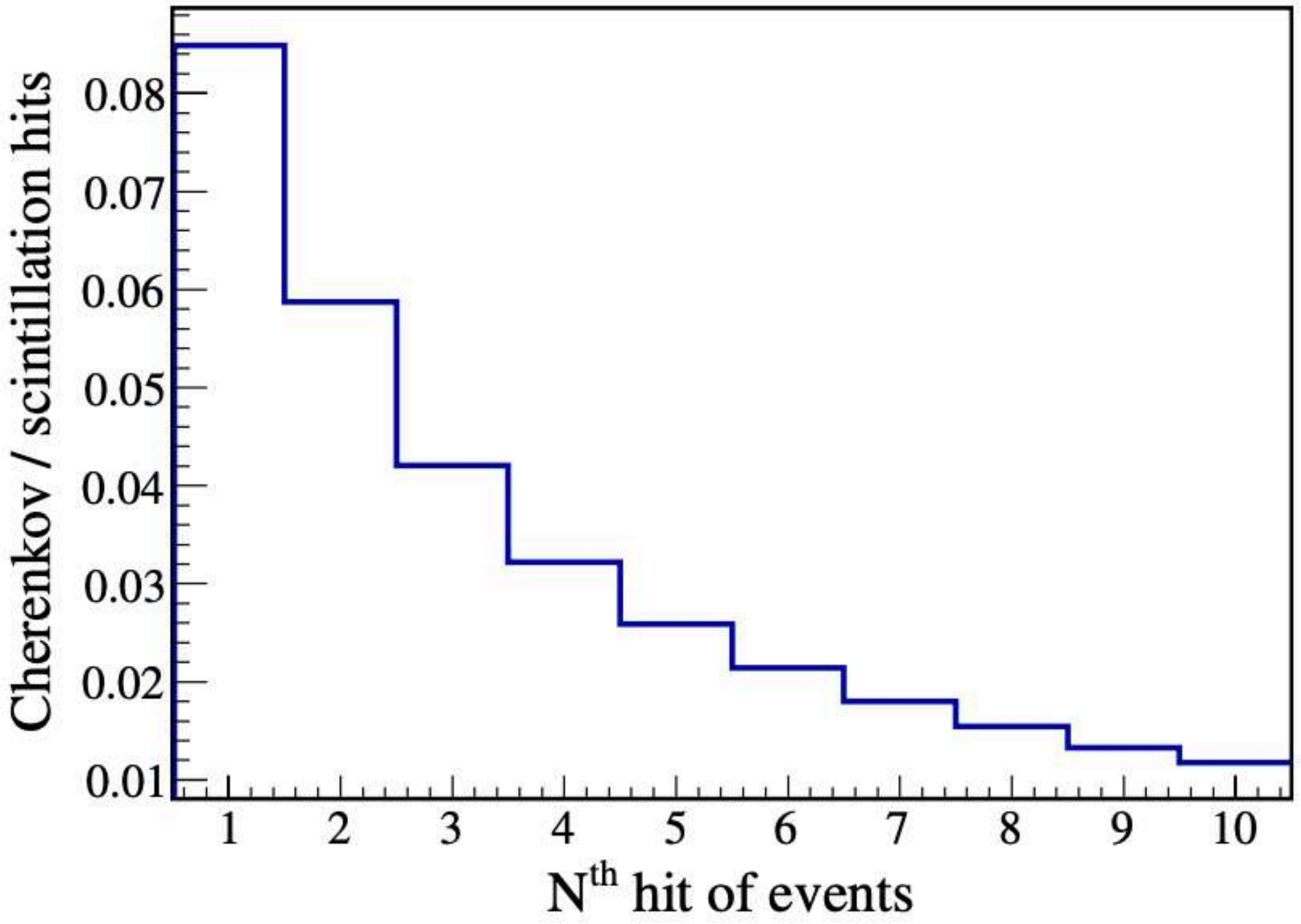
SOLAR IMPLICATIONS: C+N ABUNNDANCE

Error budget on N_CN



BOREXINO: FIRST DIRECTIONAL MEASUREMENT OF SUB-MEV SOLAR NEUTRINOS



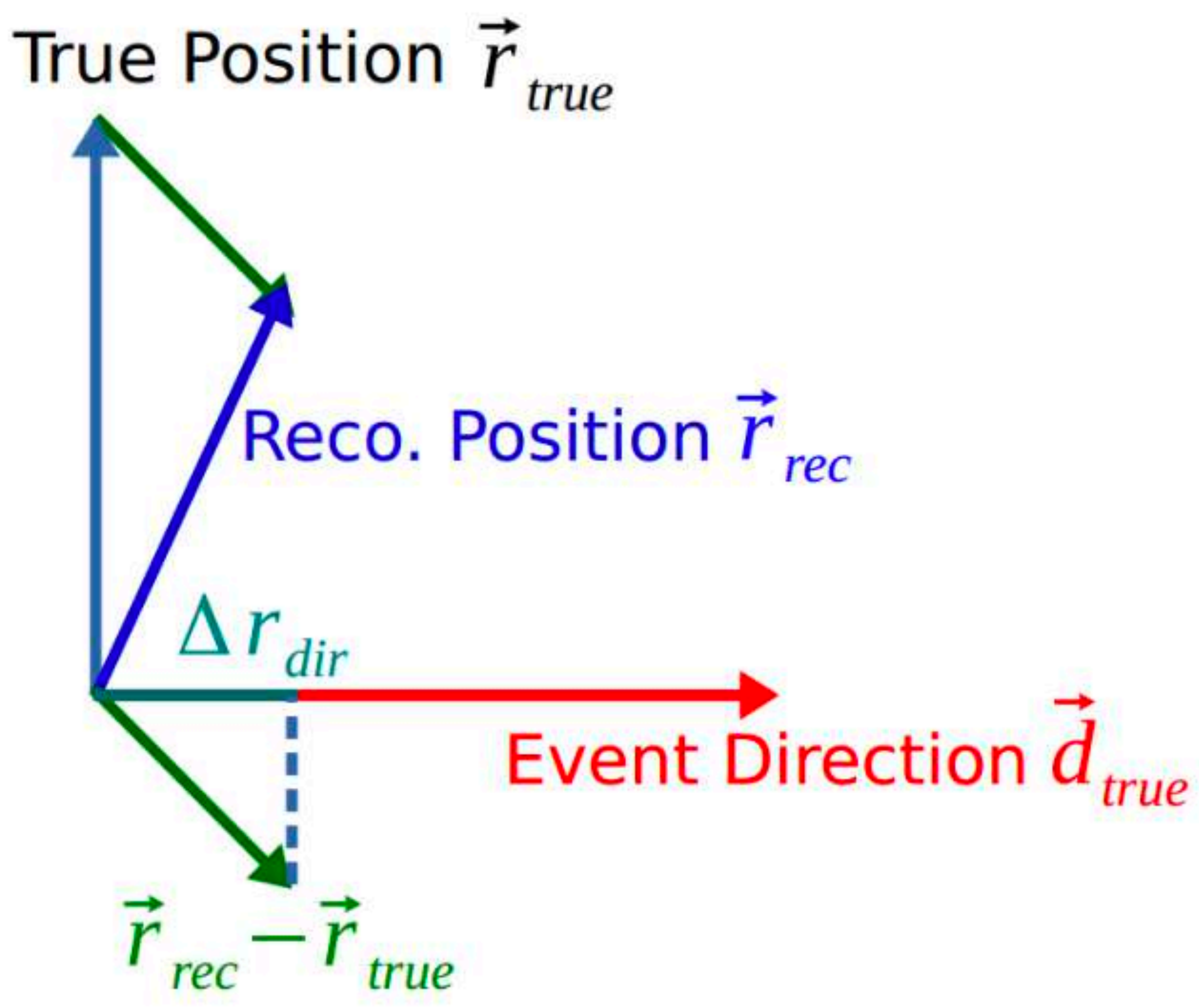


Main source of systematics

(1) bias between the true and the reconstructed positions of the recoil electron in its direction (left as a **free nuisance parameter in the fit**)

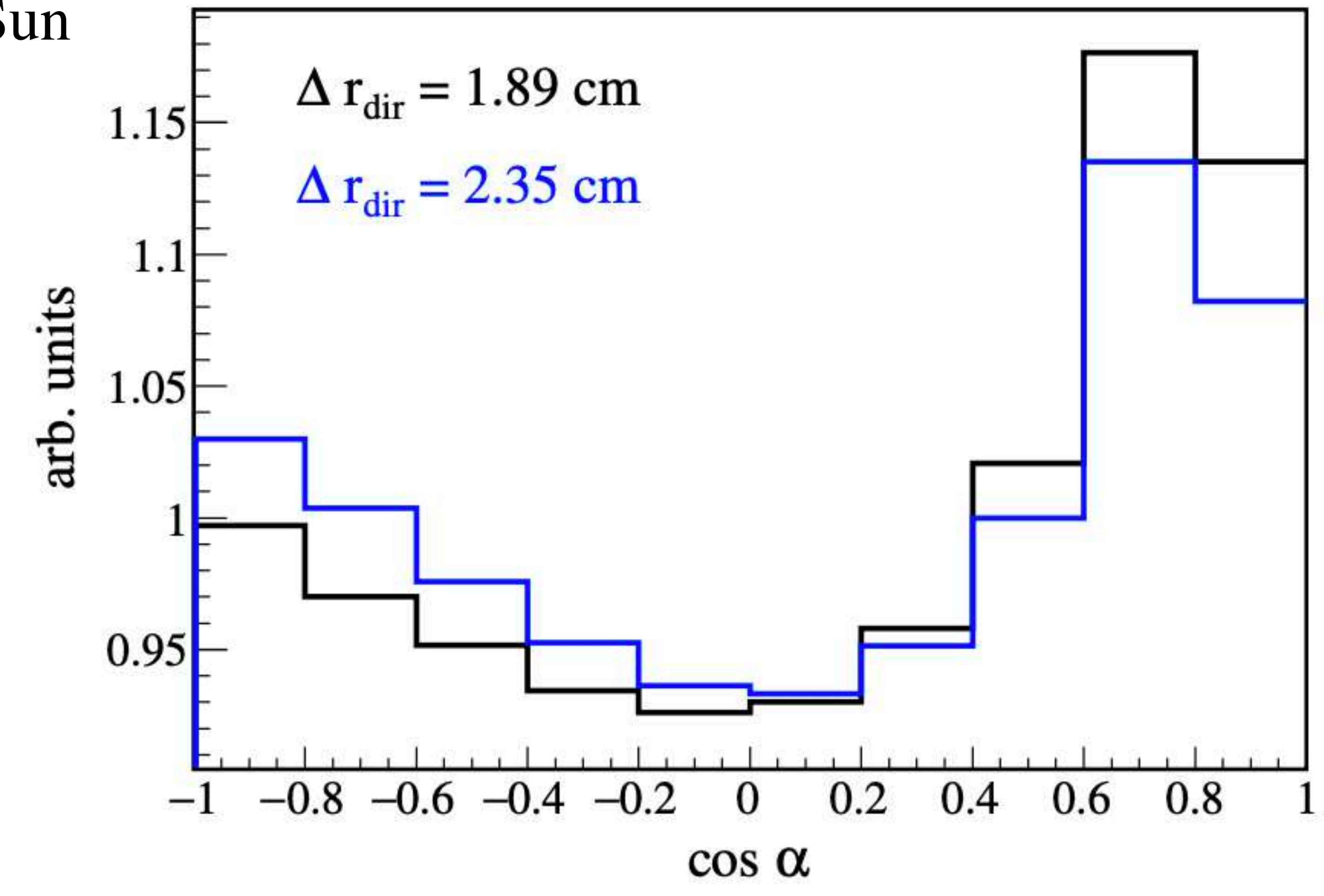
(2) large relative uncertainty of 36% on the effective Cherenkov group velocity correction obtained from gamma calibration sources (nuisance parameter)

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



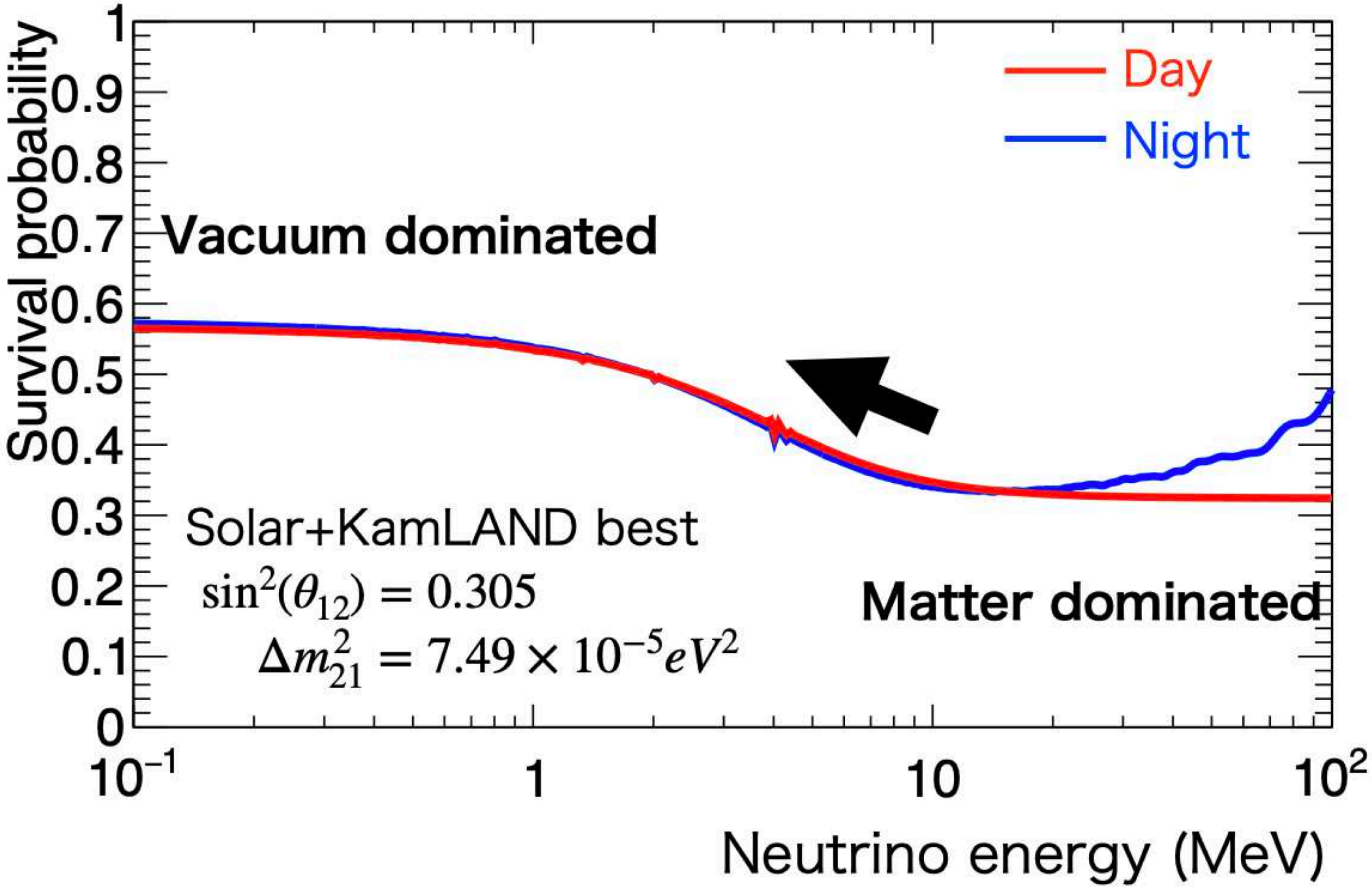
Source	Uncertainty [%]
Choice of N^{th} Hit	4.8
Selection of PMTs	5.9
Choice of histogram binning	4.2
Total for $N_{\mathrm{solar}-\nu}$	8.7
Exposure	4.6
MLP variable	1.0
CNO and *pep* rates	$^{+2.3}_{-1.2}$
Total for $R(^7\mathrm{Be})$	$^{+10.1}_{-10.0}$

This effect is not present in background, in which the true electron direction is not correlated to the position of the Sun



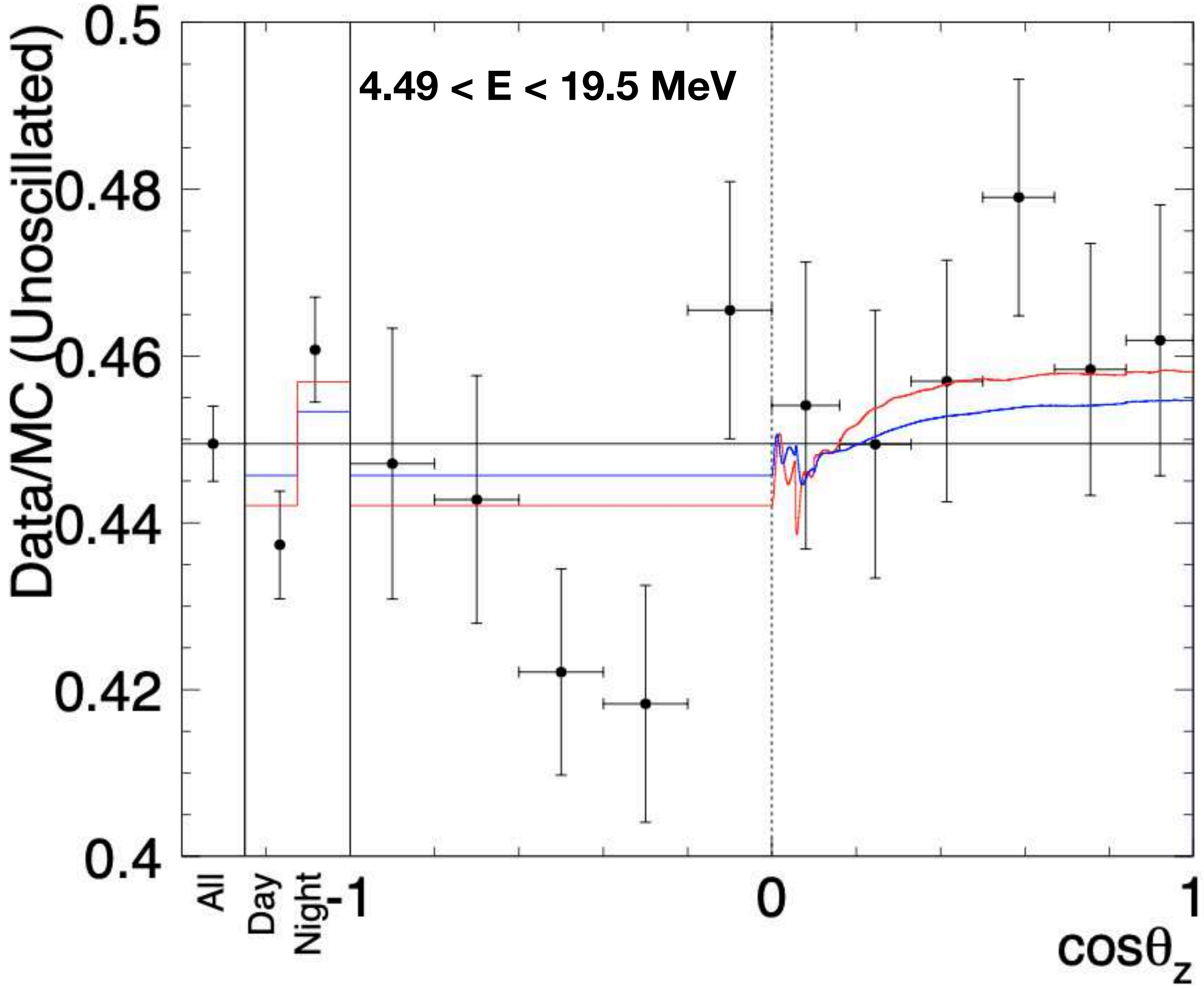
SUPERKAMIOKANDE

Neutrino oscillation (MSW-LMA)

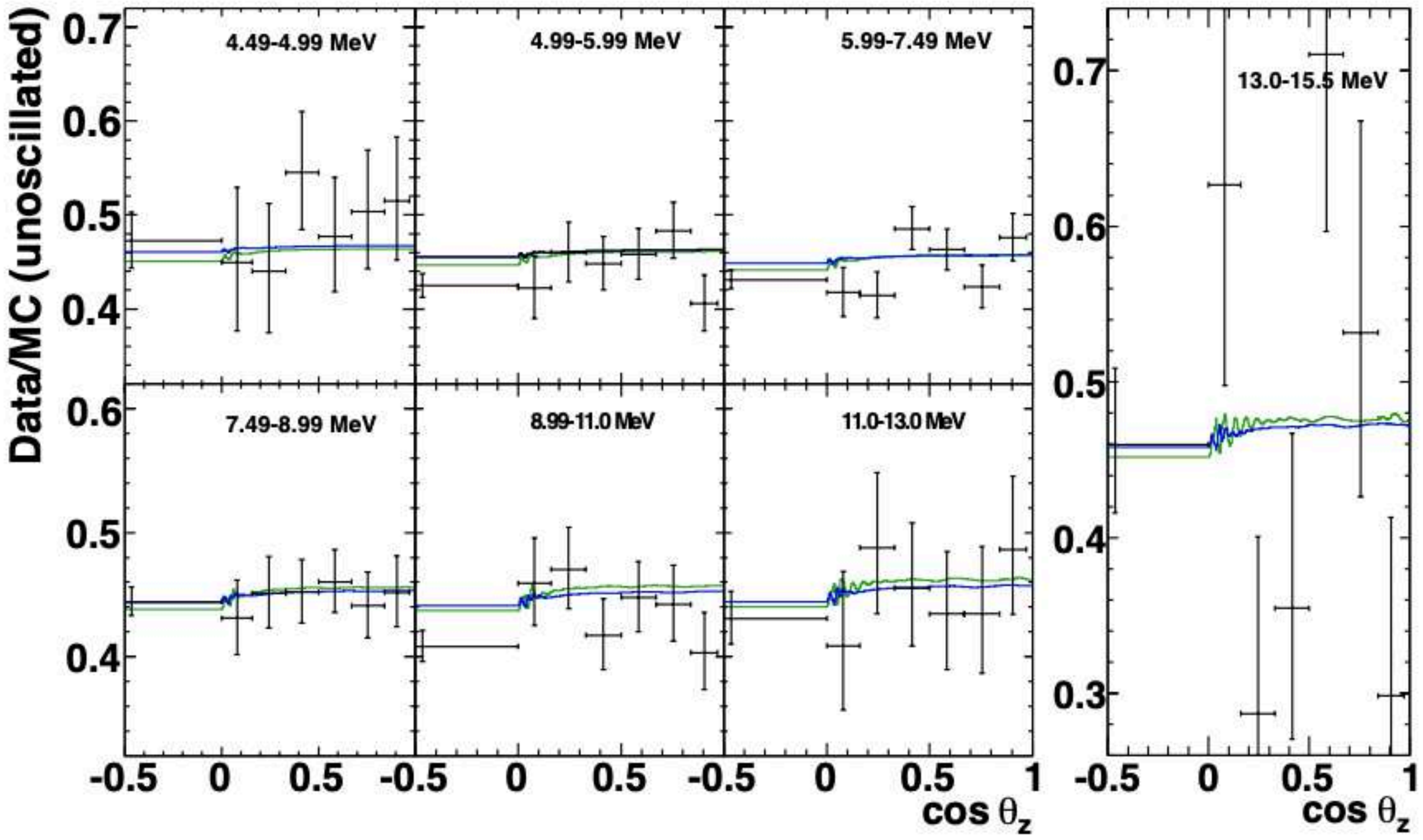


SK-IV

Solar zenith angle dependence of solar data/MC(unoscill) interaction rate ratio



Predictions with solar neutrino and solar neutrino+kamland



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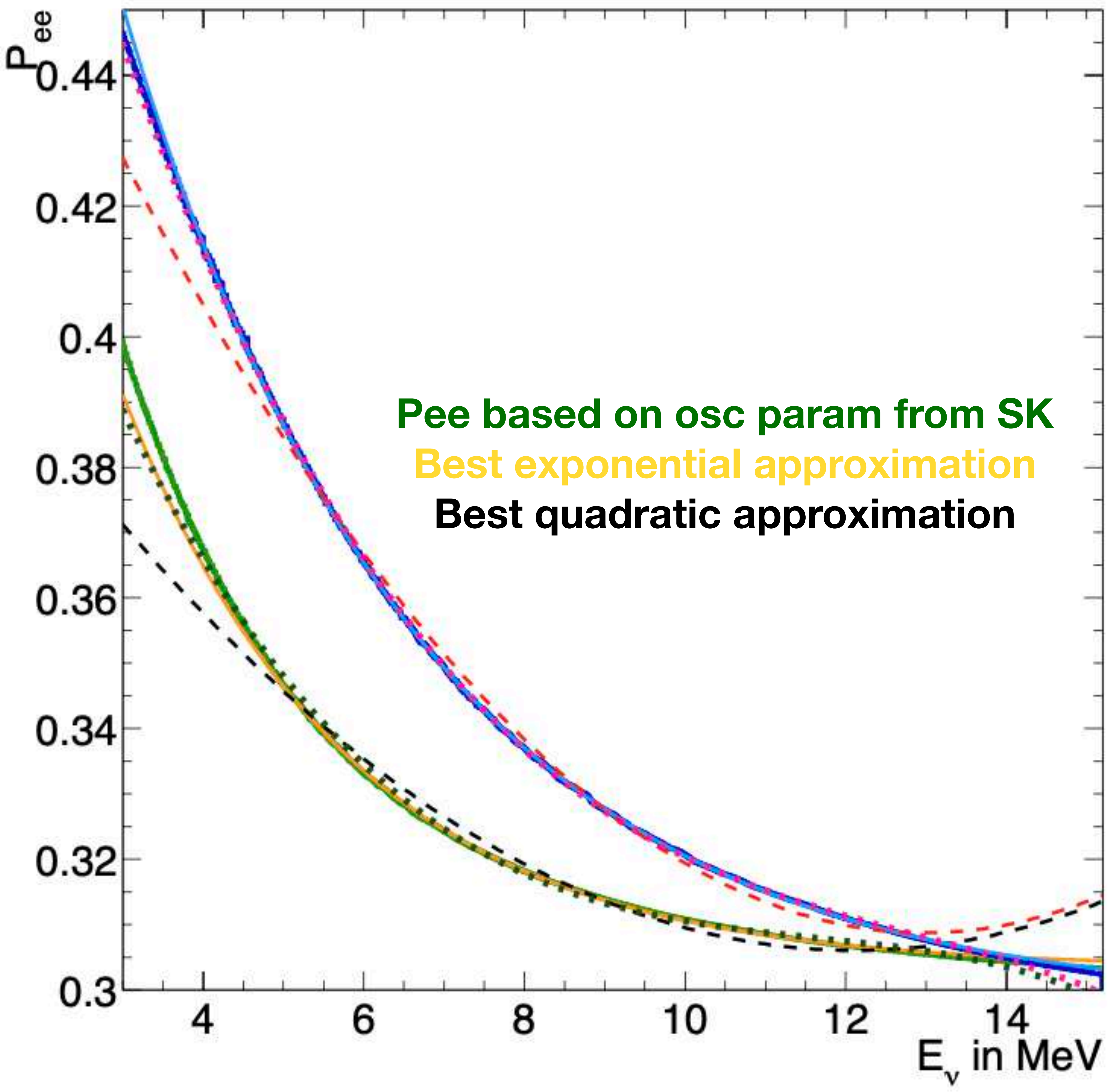
SUPER-KAMIOKANDE: 8B ANALYSIS

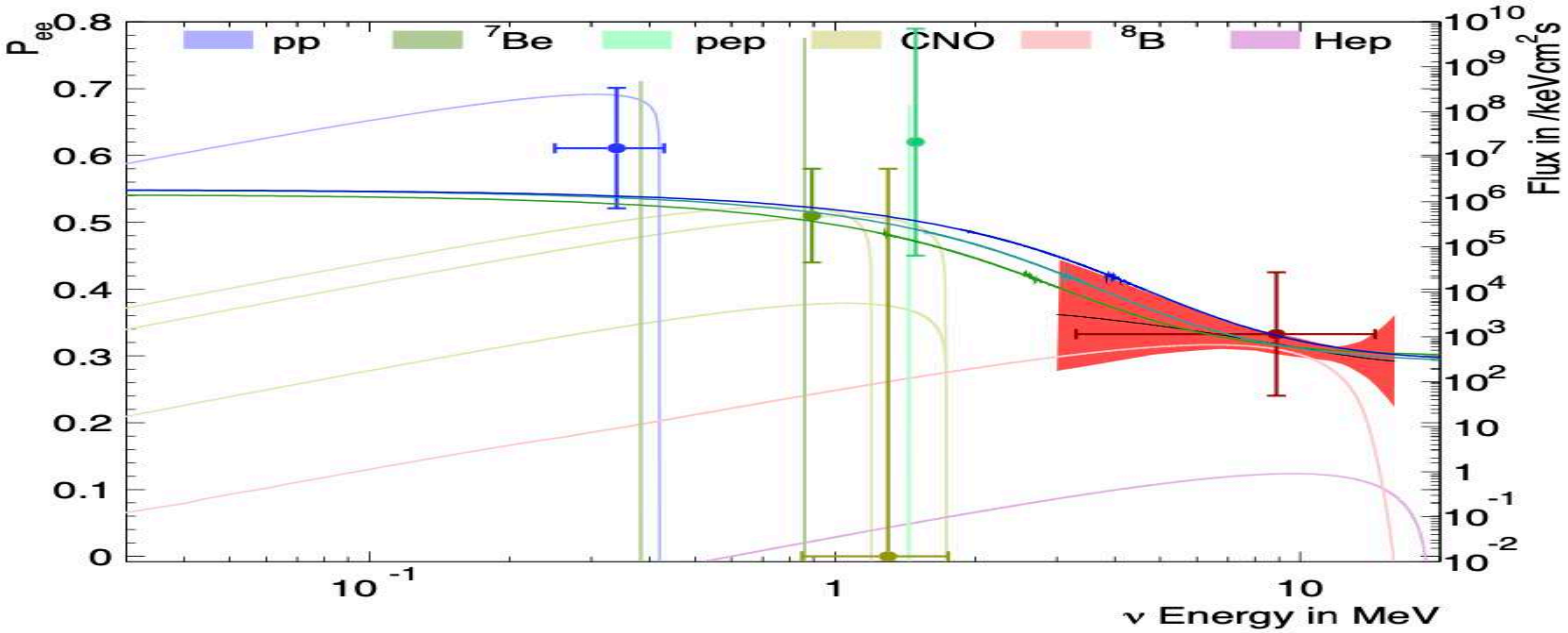
2. Matter effect in the core of the Sun: energy dependence of P_{ee}



Exponential approximation reproduce better the Pee (in blue solar nu + Kamland)

SUPER-KAMIOKANDE: 8B ANALYSIS

2. Matter effect in the core of the Sun: energy dependence of P_{ee}



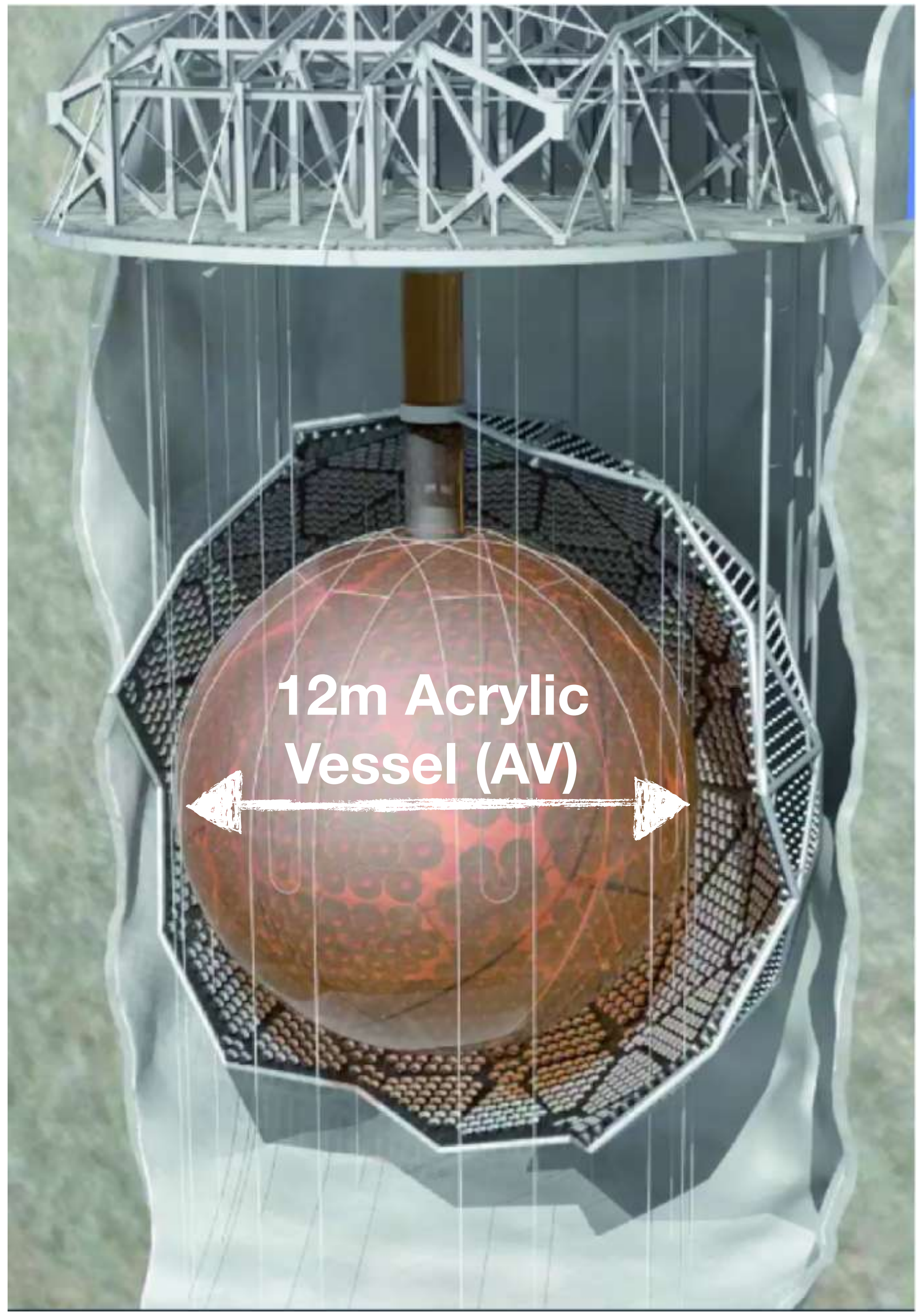
Good agreement between the MSW curves and SK+SNO combined allowed band

Upturn is slightly favoured, more data are needed

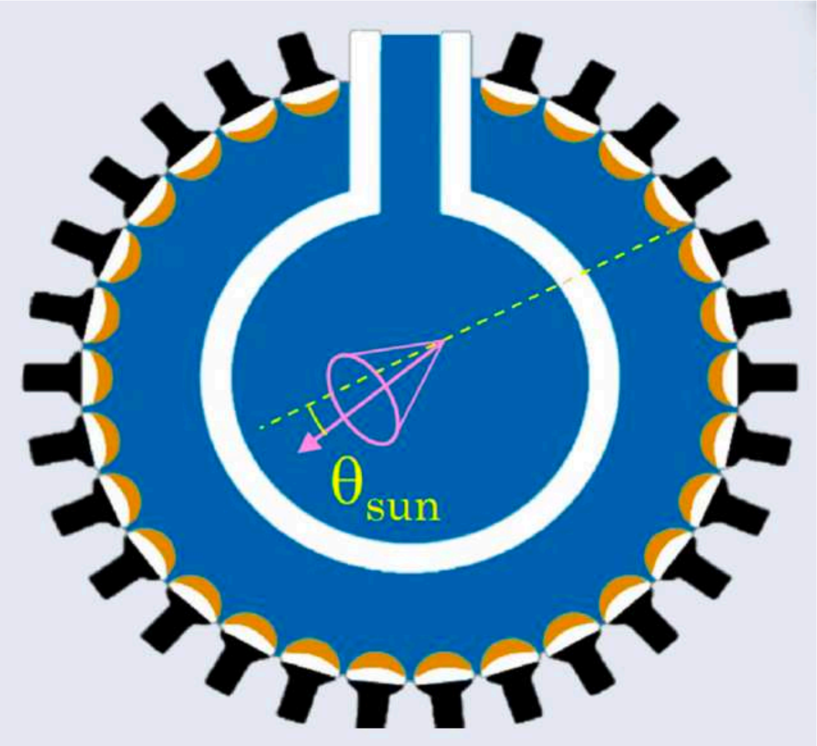
SNO+

SNO+

Liquid scintillator detector Located at 6800 ft depth in SNOLAB (6000 m.w.e. translates to $\sim 3 \frac{\mu}{\text{hour}}$)



- Acrylic vessel (r = 6 m) is being filled with LS
- ~9400 PMTs (54% effective coverage)
- Dataset acquired during **water commission phase**: AV filled with 0.9 ktons of light water (opposed to D_2O used in SNO)



$cos\theta_{\odot}$ = angle between event reconstructed direction and direction of the sun

Analysis overview:

Recoiling electron direction is correlated with Sun: $R(\nu_S)$ is extracted by fitting $cos\theta_{\odot}$ distributions

Dataset: May - December 2017 (Exposure $= 69.2$ kton · days)

Selection cuts summary:

Selection	Passing Triggers
Total	12 447 734 554
Low-level cuts	4 547 357 090
Trigger Efficiency	126 207 227
Fit Valid	31 491 305
Fiducial Volume	6 958 079
Hit Timing	2 752 332
Isotropy	2 496 747
Energy	820

FV: r < 5.3 m
r < 4.2 m (13% of livetime)

5 MeV $< E <$ 15 MeV

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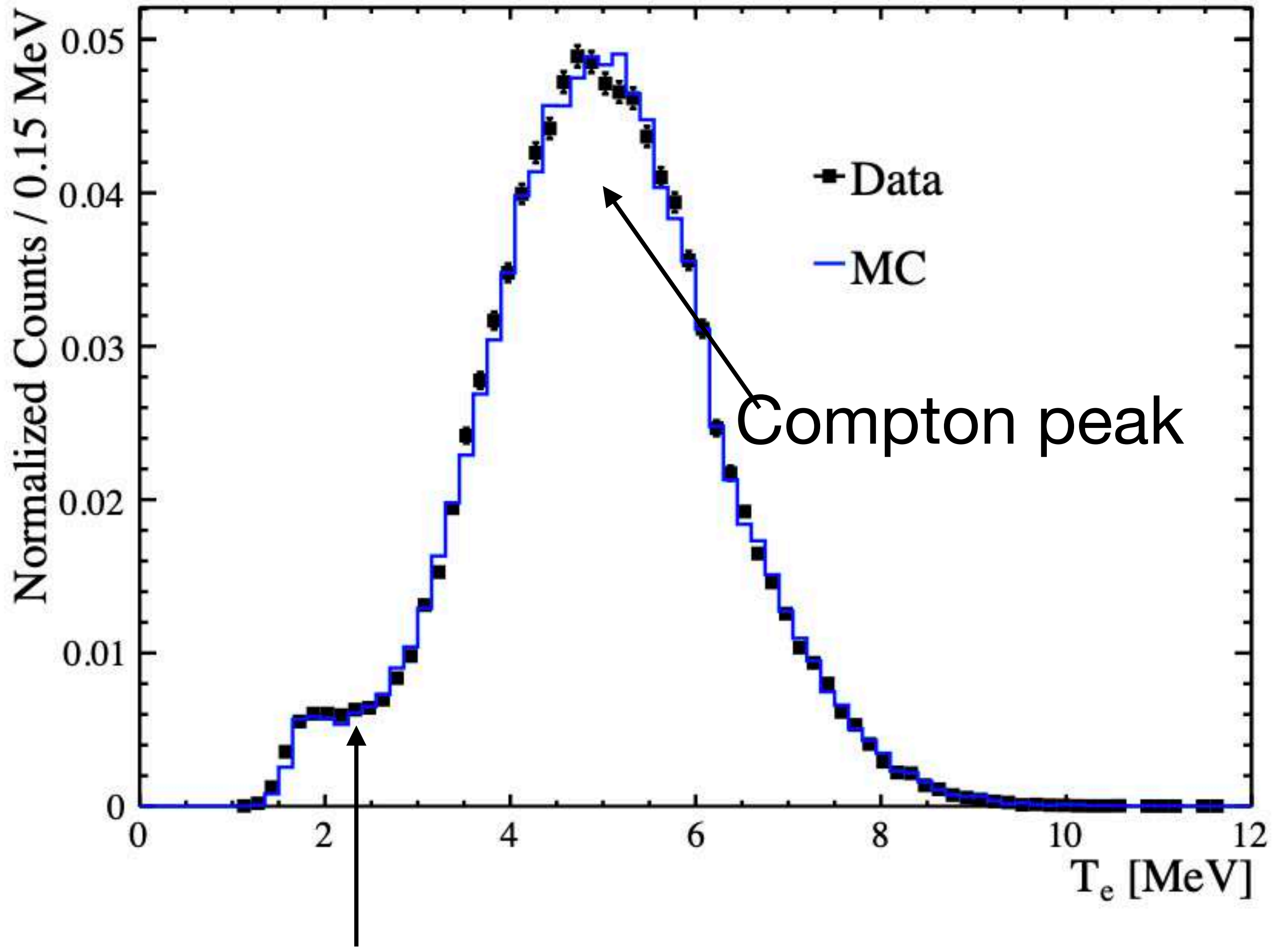
SNO+

Calibrations

^{16}N source (6.1 MeV gamma)

Direction

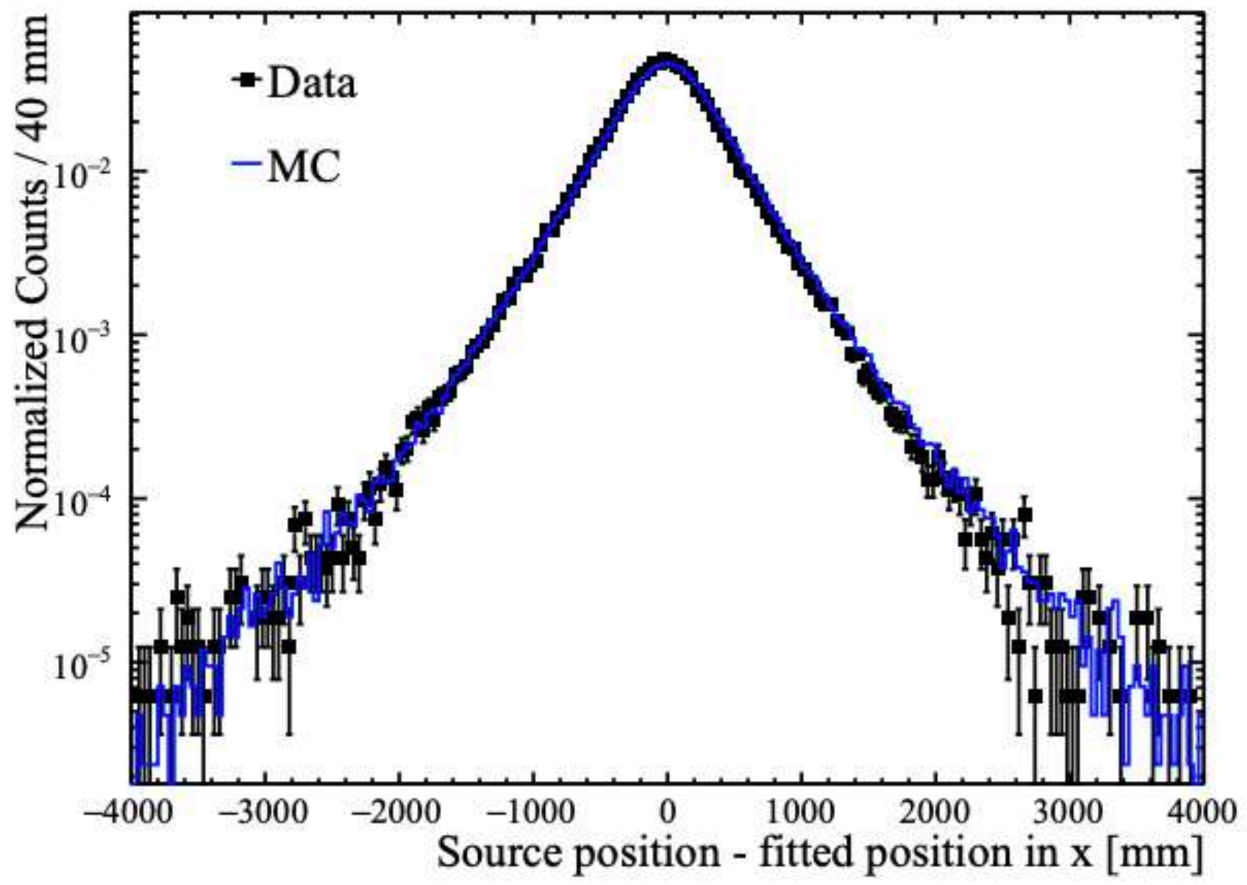
Energy



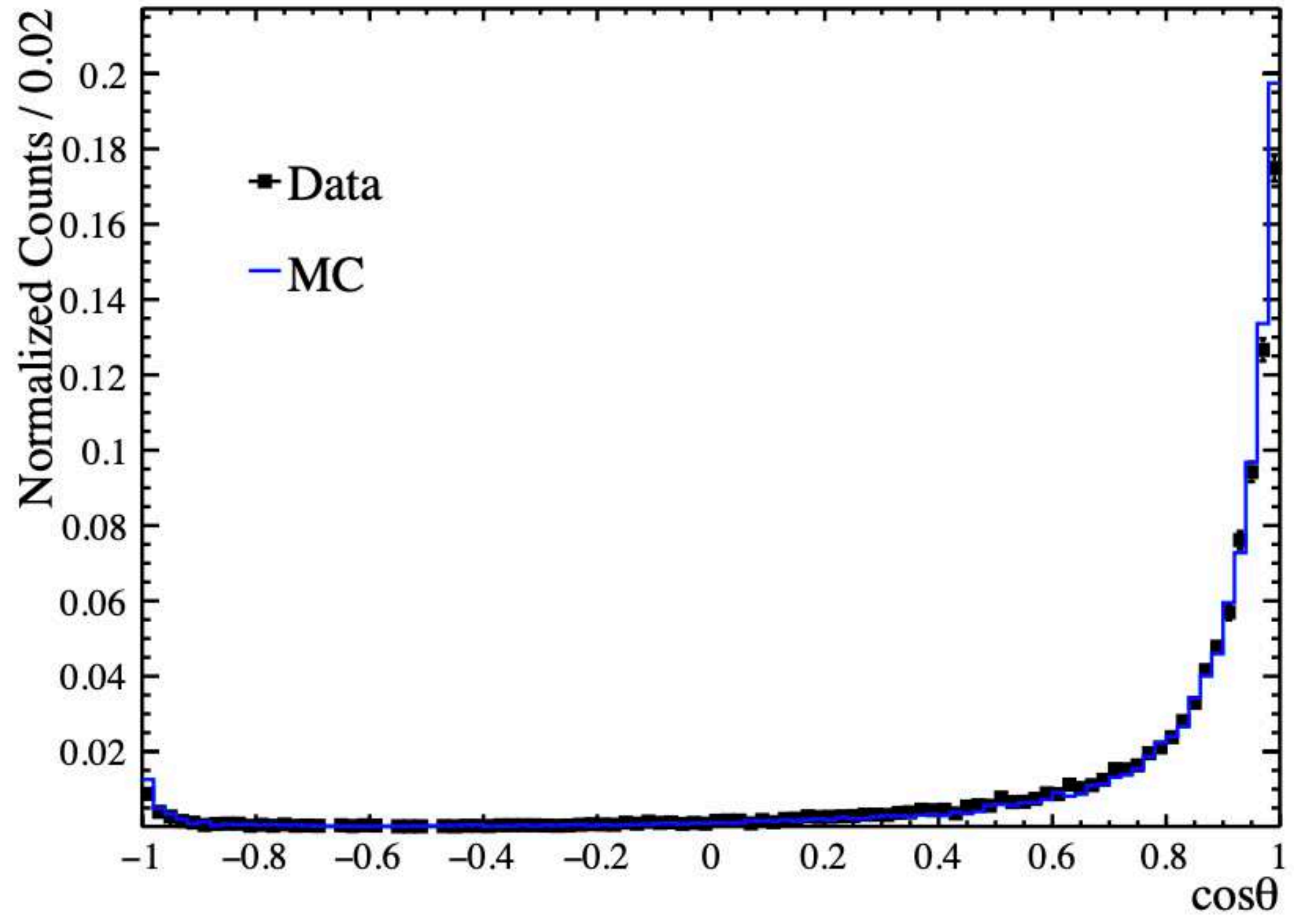
Compton peak

En deposition in source container

x



cos0



SNO+

Selection cuts

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Isotropy	2 496 747
Energy	820

Remove events originating from instrumental effects

23 PMTs fired in a 100 ns coincidence window

Select only events for which vertex reconstruction fit converged (can not converge in an optically complicated region as outside AV)

At least 55% of PMT signal in a time window of 7.5 ns (remove residual bckgs from external components)

Isotropy is parametrised with factor β_{14} (determined via legandre polinomial of angular distribution of PMT signals) ->

$-0.12 < \beta_{14} < 0.95$

SNO+

Likelihood function

$$\mathcal{L}(S, \mathbf{B}, \delta_\theta | \mathbf{n}, \mu_\theta, \sigma_\theta) =$$
$$\mathcal{N}(\delta_\theta, \mu_\theta, \sigma_\theta) \prod_{j=0}^{N_E} \prod_{i=0}^{N_\theta} \text{Pois}\left(n_{ij},\ B_j + S\, p_{ij}(\delta_\theta)\right)$$

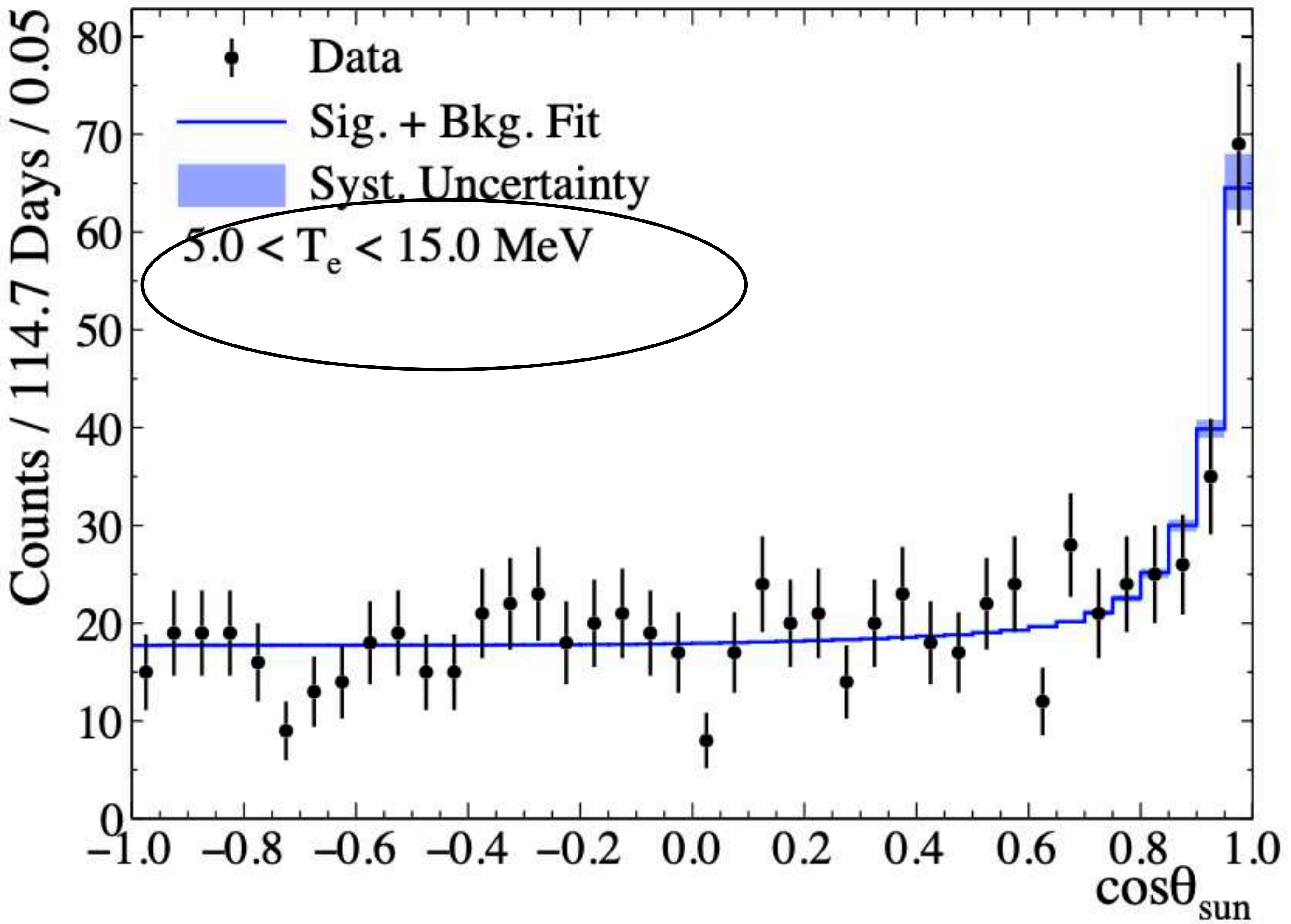
- N_E energy bins
- N_theta radial bins
- S = solar neutrino interaction rate
- B_j = bkgs rate in each energy bin
- N = Normalized gaussian distribution:
  - delta_theta = angular resolution parameter. Adjustment to angular distribution (treated as nuisance parameter)
  - mu_theta/sigma_theta = best fit/constraint on delta from calibrations
- n_ij = number of observed counts
- p_ij = PDF for a given angular delta

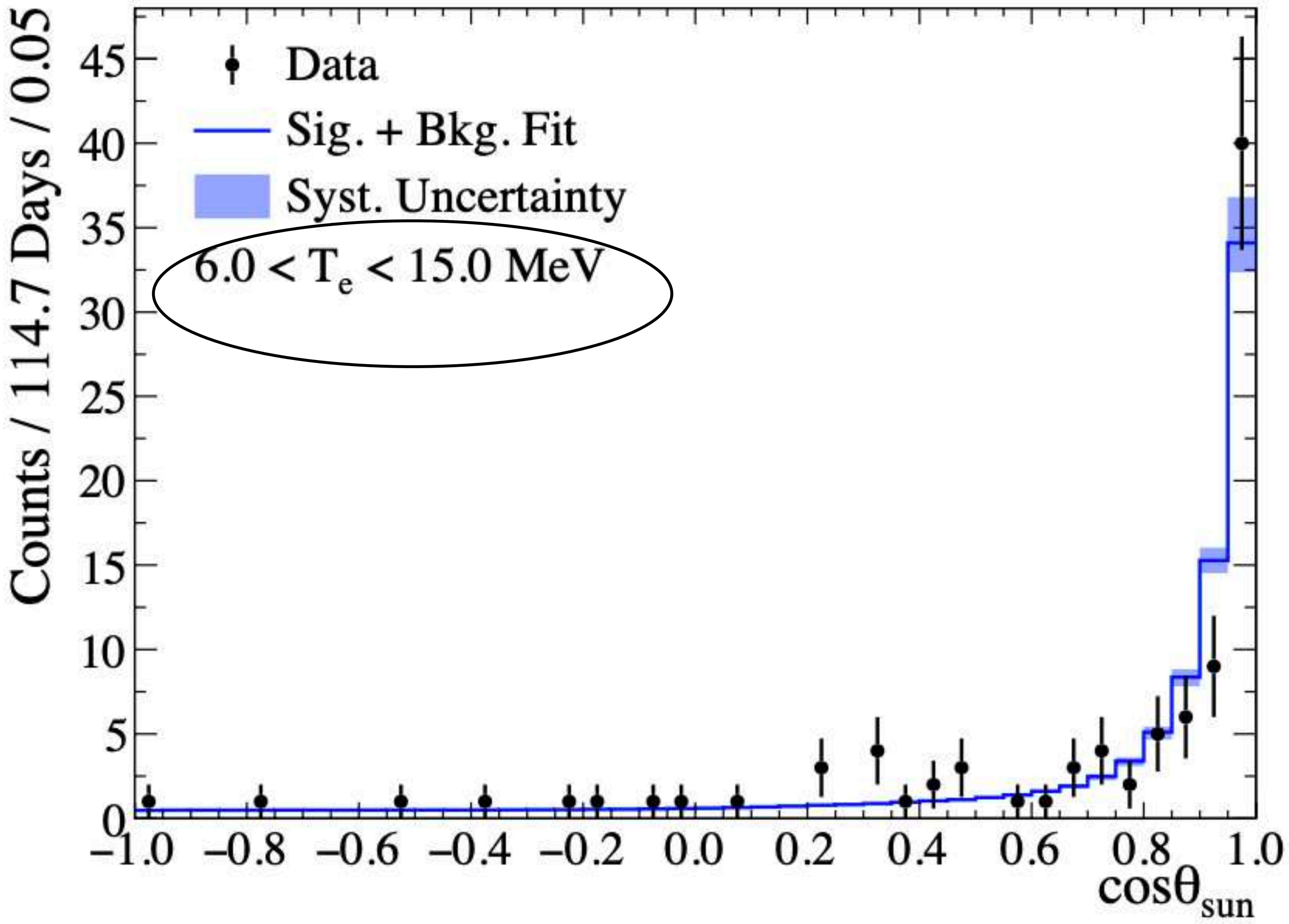
Systematics are treated by varying reconstructed quantities for each simulated events -> distorted PDFs

Systematic	Effect
Energy Scale	3.9%
Fiducial Volume	2.8%
Angular Resolution	1.7%
Mixing Parameters	1.4%
Energy Resolution	0.4%
Total	5.0%

SNO+

Energy ranges





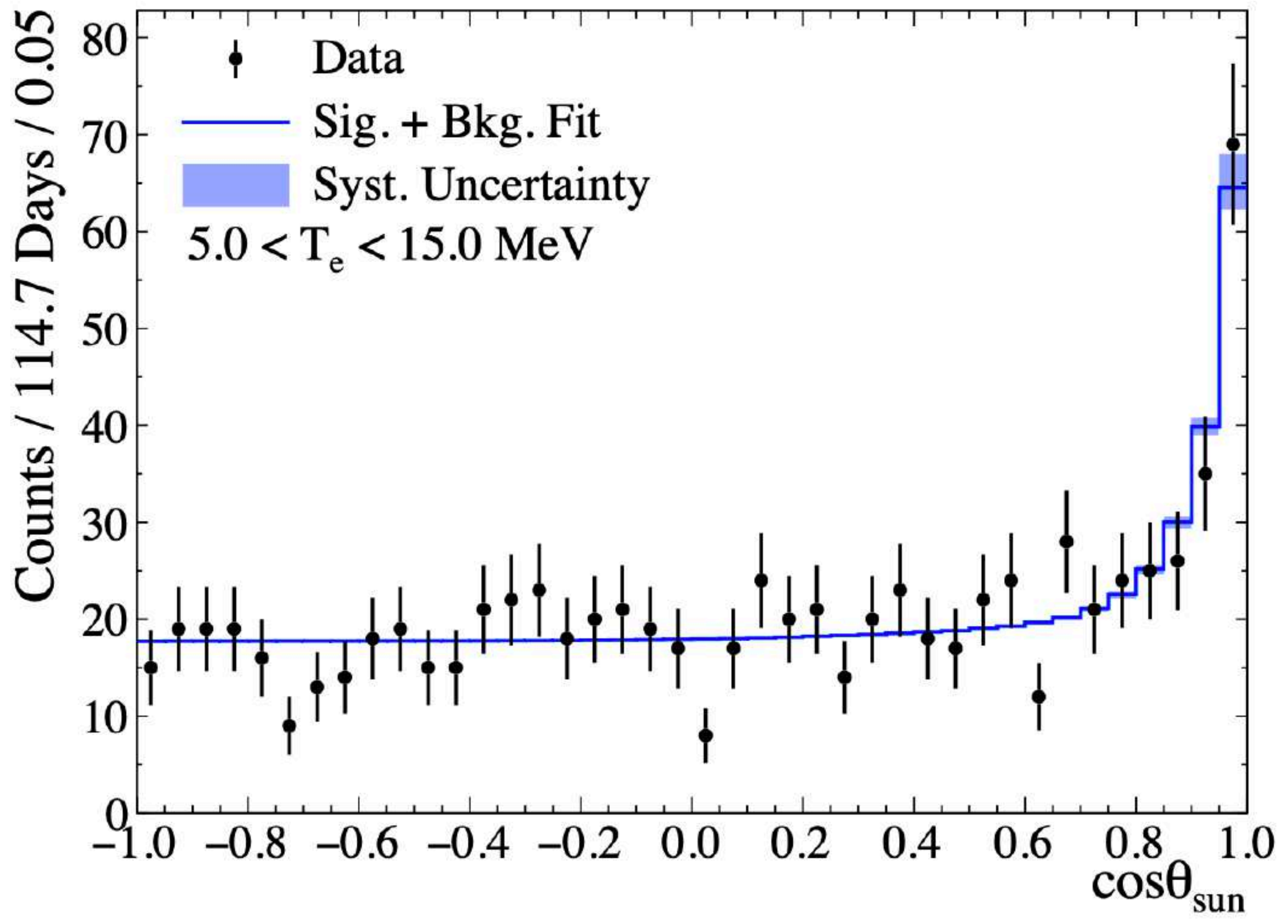
Reduced bkg removing 5 MeV bin

SNO+

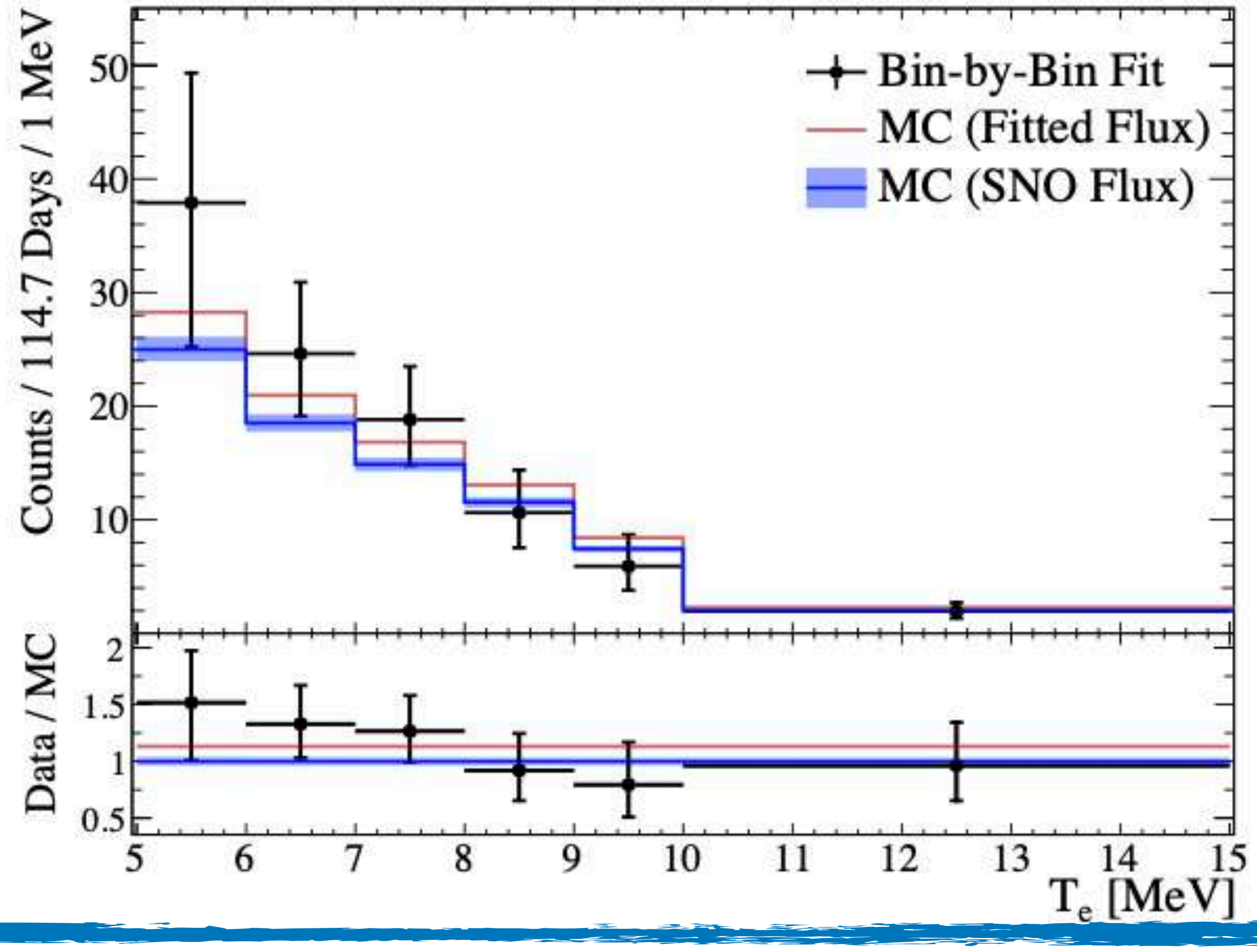
Results:

$E_{th} = 5$ MeV
Exposure $= 69.2$ kton · days

Fit of $cos\theta_{\odot}$ distribution in each energy bin



Best fit flux by maximizing the Ls from the fit in each energy bin



Assuming purely ν_e flux:

$$\Phi_{ES} = 2.53^{+0.31}_{-0.28}\ \text{(stat.)}^{+0.13}_{-0.10}\ \text{(syst.)}\ [10^6\ \text{cm}^{-2}s^{-1}]$$

Consistent with $\Phi_{ES}(SK)$

Including solar neutrino oscillations:

$$\Phi(^8B) = 5.95^{+0.75}_{-0.71}\ \text{(stat.)}^{+0.28}_{-0.30}\ \text{(syst.)}\ [10^6\ \text{cm}^{-2}s^{-1}]$$

Consistent with $\Phi_{SNO}(^8B) = 5.25 \pm 0.20\ [10^6\ \text{cm}^{-2}s^{-1}]$

First solar neutrino results from SNO+ experiment

$E_{th} = 5$ MeV: ultra pure sample (mainly thanks to cosmic muon shielding)
Accurate measurement with little exposure
(Lowest bkg ES measurement of solar neutrinos in a water Cherenkov detector)

Best fit:

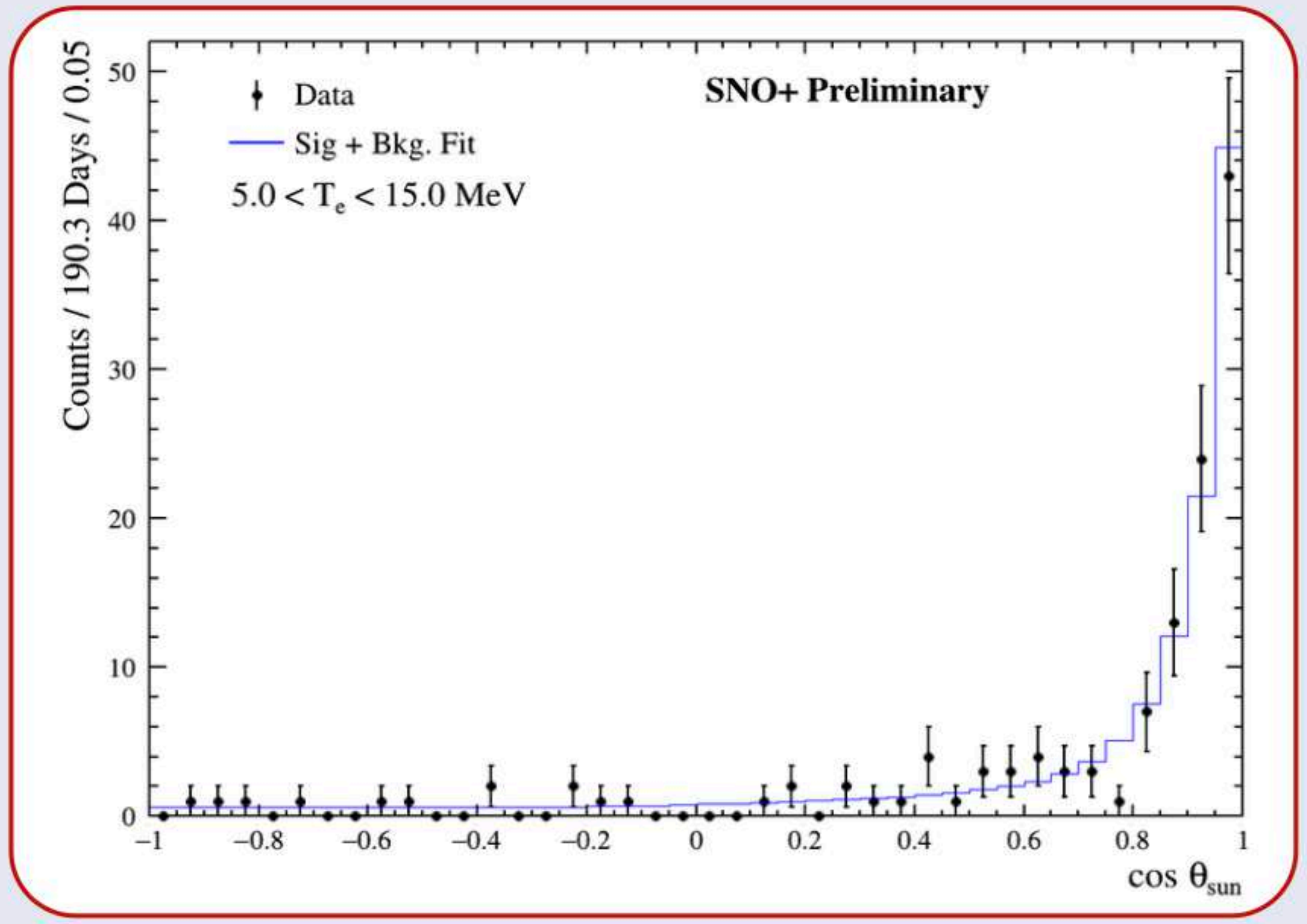
$$R(\text{bkgs}) = 0.25^{+0.09}_{-0.07}\,\frac{\text{events}}{\text{kt-days}} < R(\nu_S) = 1.03^{+0.13}_{-0.12}\,\frac{\text{events}}{\text{kt-days}}$$

Ongoing work to **reduce energy threshold to 3.5 MeV** with different fiducial volume selection

SNO+

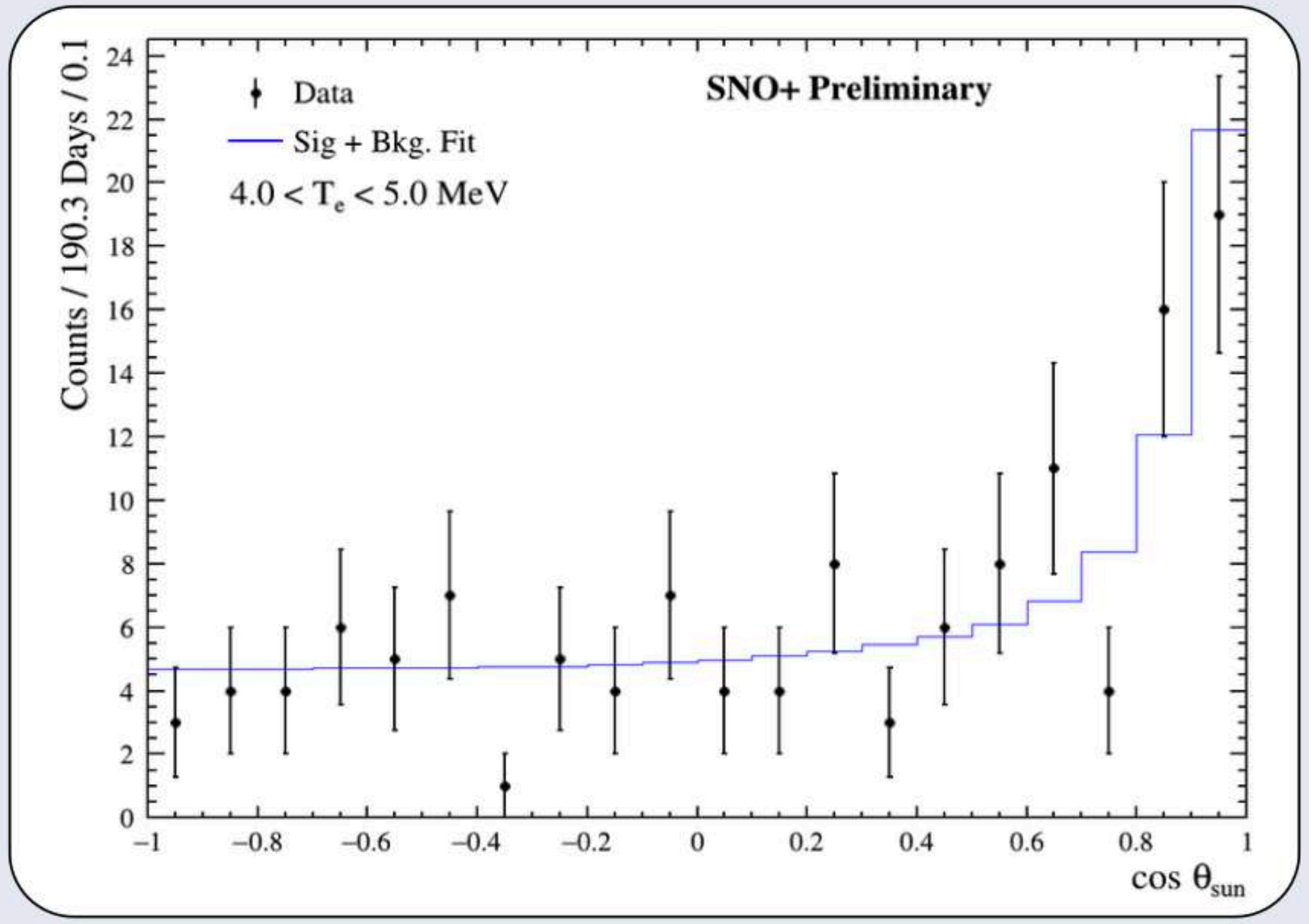
Energy ranges

FV: R < 5m



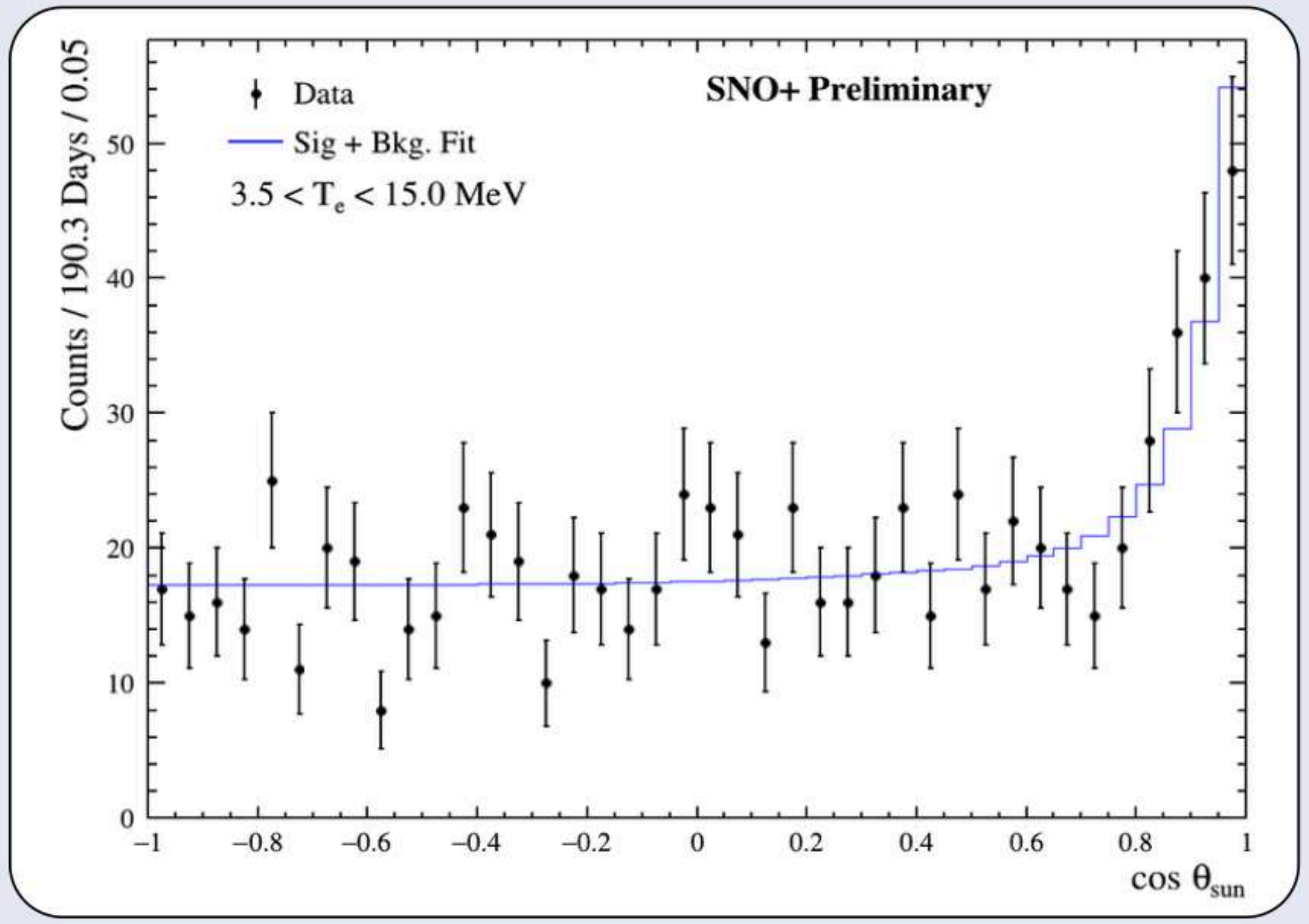
Using a 5m fiducial volume, there is a very pure sample of ES events from 5-15 MeV

Reduced FV: (R <4.6m, and R <4.2m when z>0)



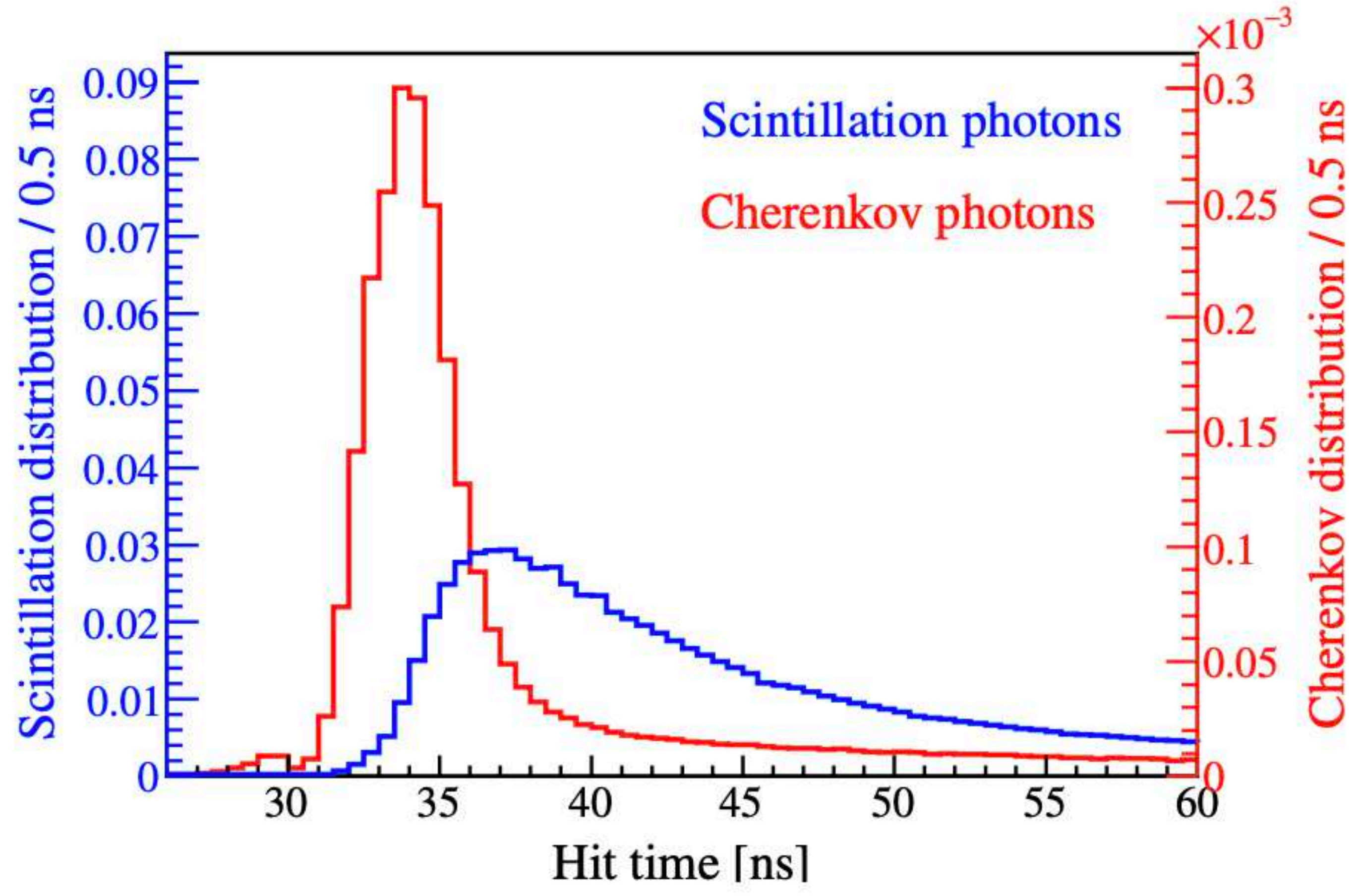
Applying a tighter fiducial cut, there is still a resolvable solar signal in the 4-5 MeV bin

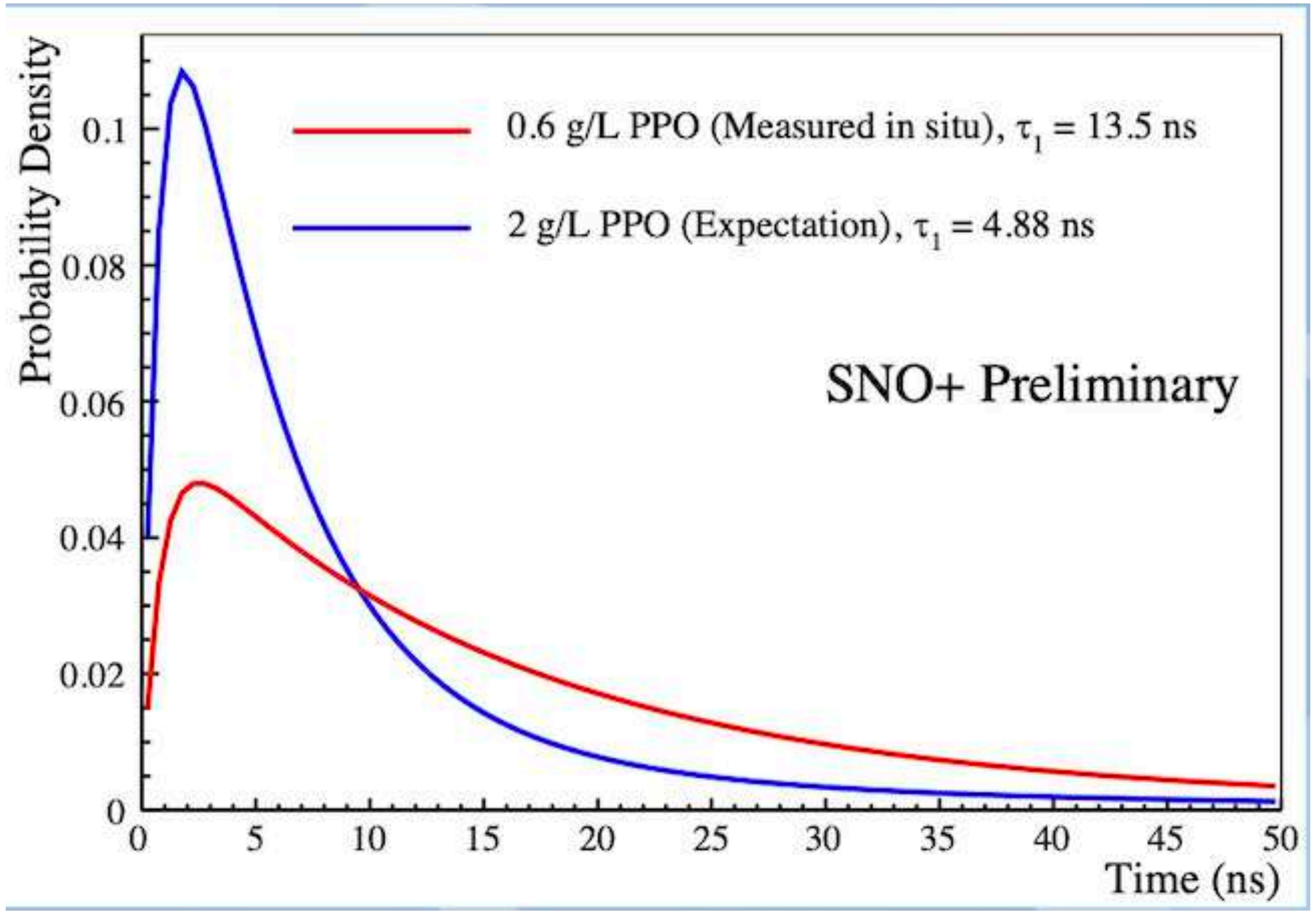
Reduced FV: (R <4.6m, and R <4.2m when z>0)



In this reduced fiducial volume, the data has a modest flat background contribution from 3.5-15 MeV

SNO+ - DIRECTIONALITY





The slower the scintillation signal -> the better the separation between Cherenkov and LS light

More dilute mixtures have slower profile

Low concentration scintillator provide perfect opportunity for directionality

JUNO

3. Statistical tools

Three fold coincidence (TFC) algorithm [4]:

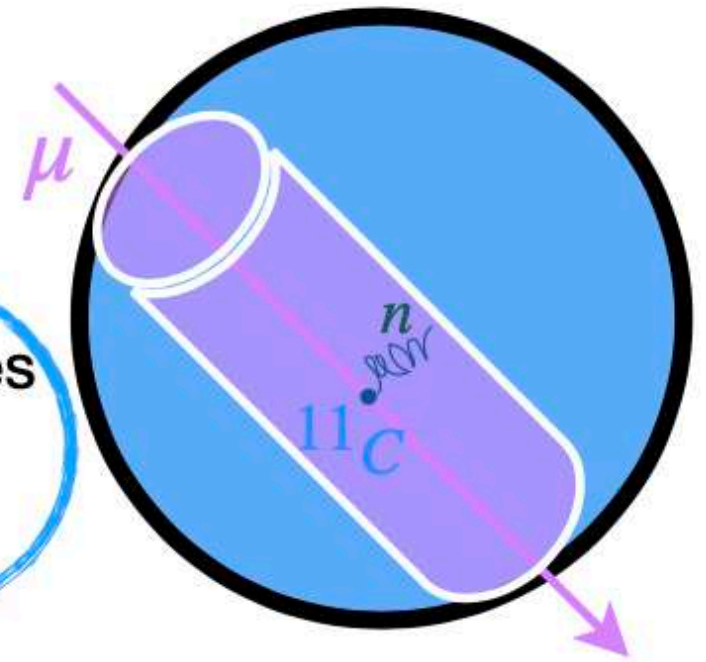
Identify cosmogenic backgrounds finding the space-time correlations between ^{11}C decay, n capture, and parent muon:

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

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

Data-set divided in two complementary samples to be fitted simultaneously:

TFC-tagged and TFC-subtracted



Relevant parameters:

Tagging Power (TP): percentage of correctly identified cosmogenic events

SubtractedExposure (SE): remaining exposure in the TFC-subtracted dataset

Sensitivity Tools:

β/γ backgrounds are indistinguishable from neutrino signal on an event by event basis → Two independent spectral fit (JUST & MUST) are used to extract signals (agreement at $\sim 10^{-4}$ level)

Estimate JUNO's sensitivity:

I. Generate Monte Carlo PDFs

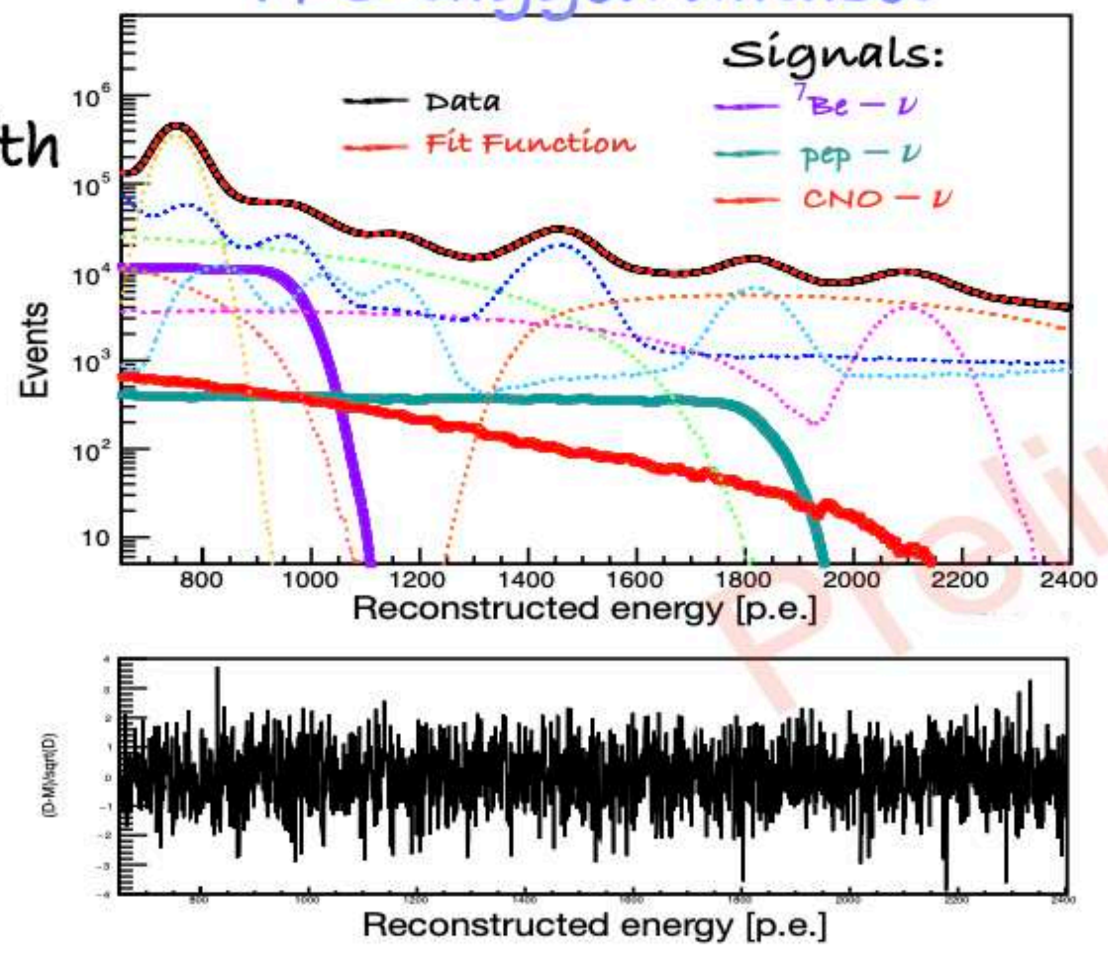
II. Create thousands toy-experiments with poissoninan sampling for each PDF

III. Simultanoeus fit based on binned Poisson likelihood:

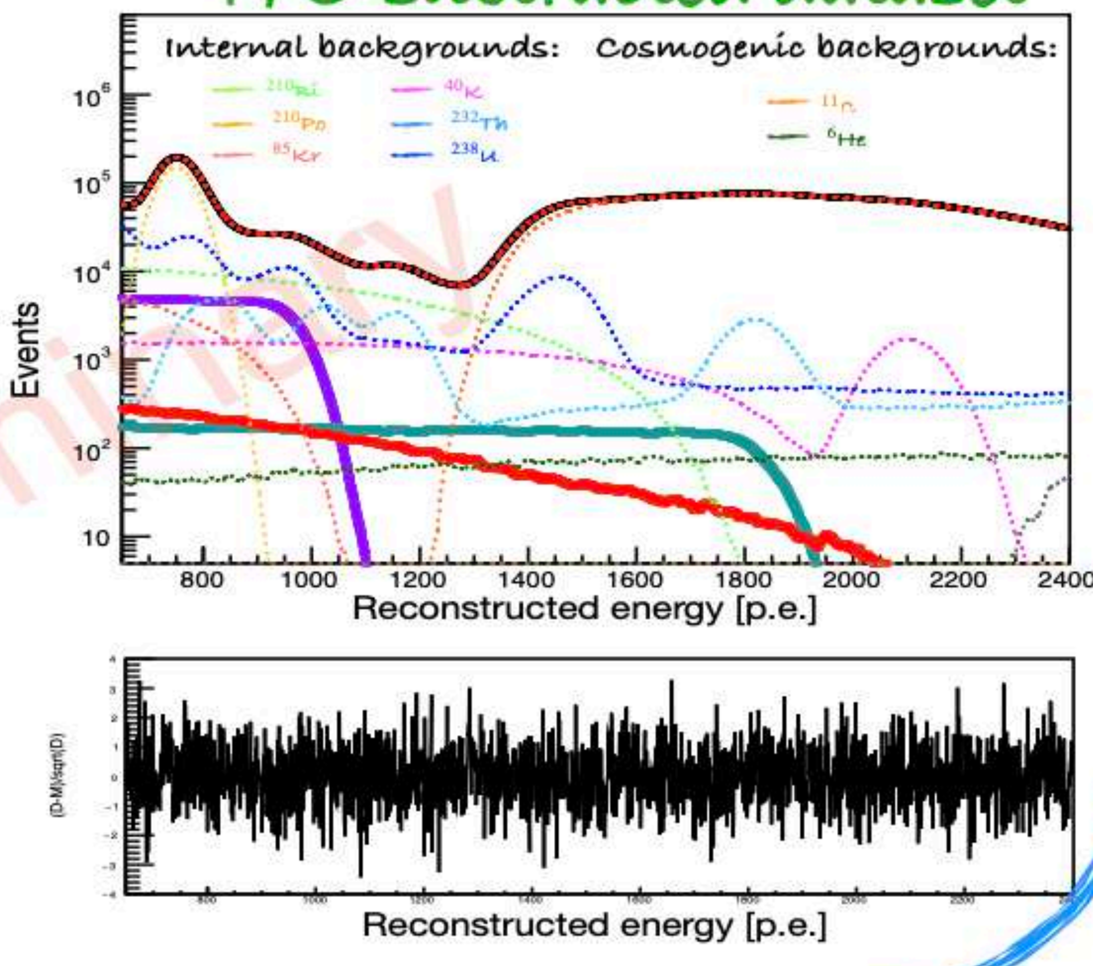
$$\mathscr{L}(\vec{k} \mid \vec{\lambda}(\vec{N})) = \prod_{j=Sub}^{Tag} \mathscr{L}_j(\vec{k} \mid \vec{\lambda}(\vec{N}))$$

$$= \prod_{j=Sub}^{Tag} \prod_{i=1}^{n} \frac{\lambda_{i,j}^{k_{i,j}}}{k_{i,j}!} \cdot e^{-\lambda_{i,j}}$$

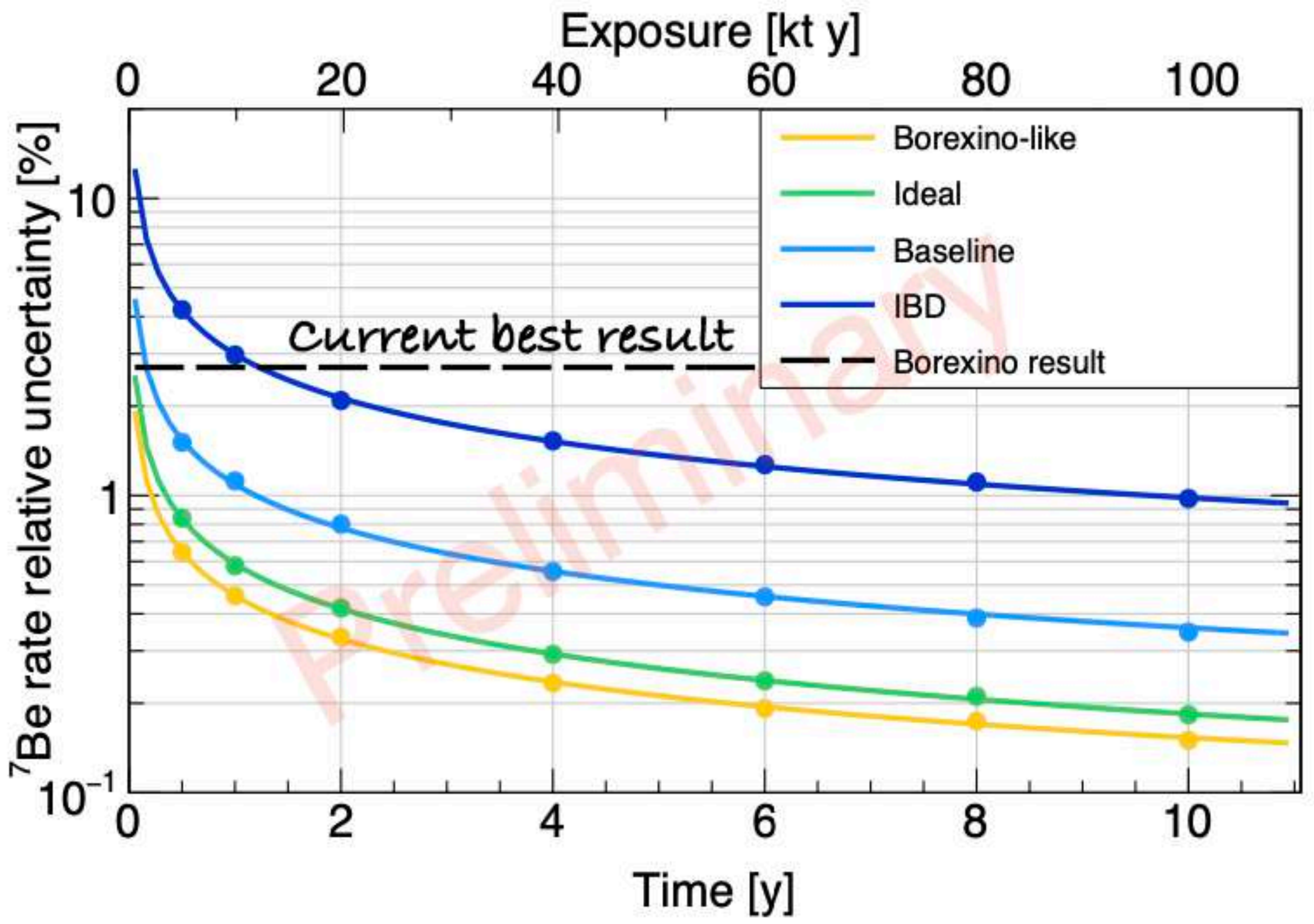
TFC-tagged dataset



TFC-subtracted dataset



^{7}Be neutrinos



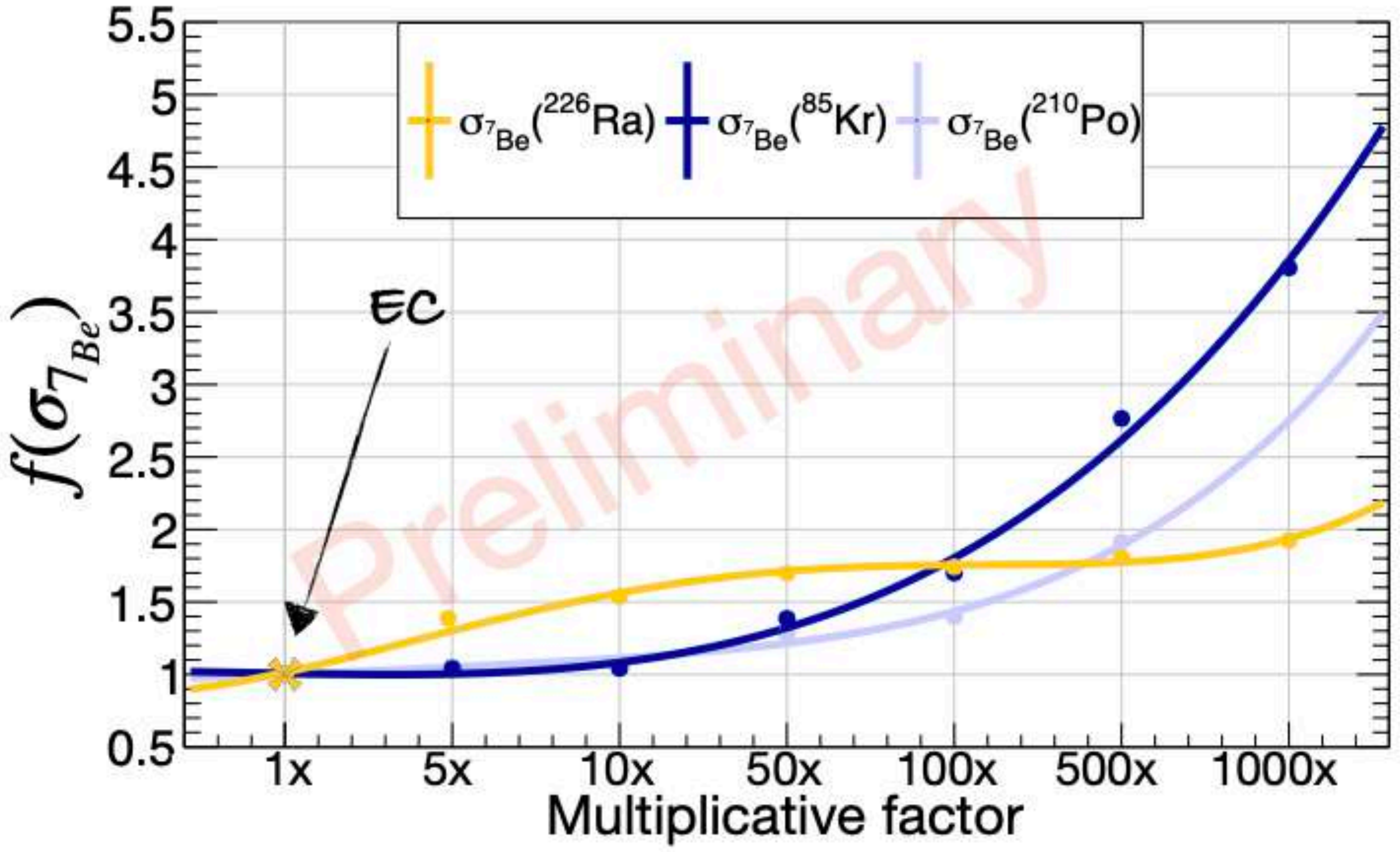
After 1 year of data-taking JUNO can **reach and overcome current best result** (2.7%).

Most critical backgrounds: ^{85}Kr, ^{226}Ra, ^{210}Po

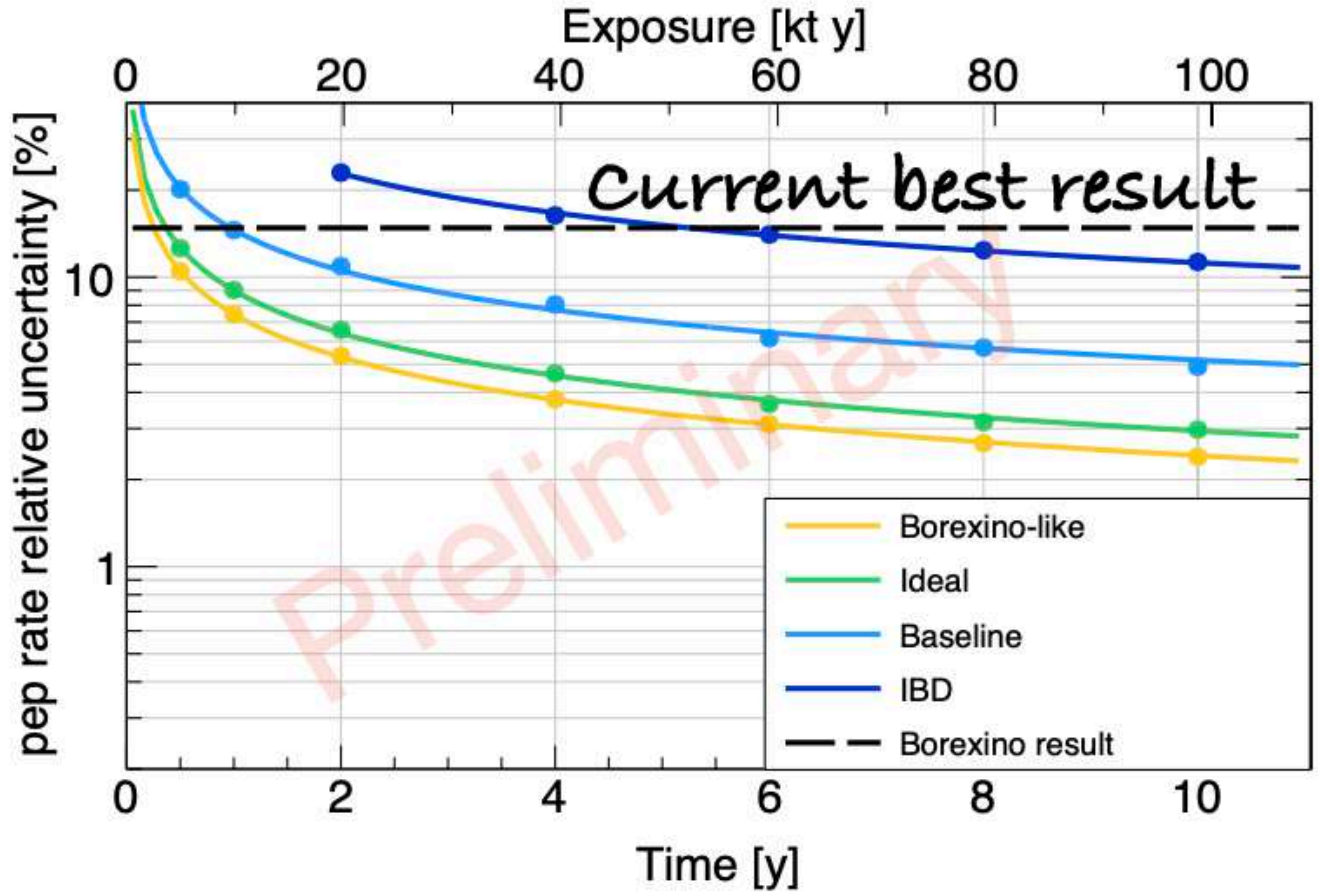
Starting from Expected Contamination (EC) in baseline scenario evaluate $f(\sigma_{Rel})$ to test different background contamination (as multiplicative factor i):

$$f(\sigma_{^7Be}) = \frac{\sigma_{^7Be}(i \times EC)}{\sigma_{^7Be}(EC)}$$

$i = 1,5,10,50,100,500,1000$



pep neutrinos



After 2 year of data-taking (except for IBD scenario) JUNO can **reach and overcome current best result** (14.8%).

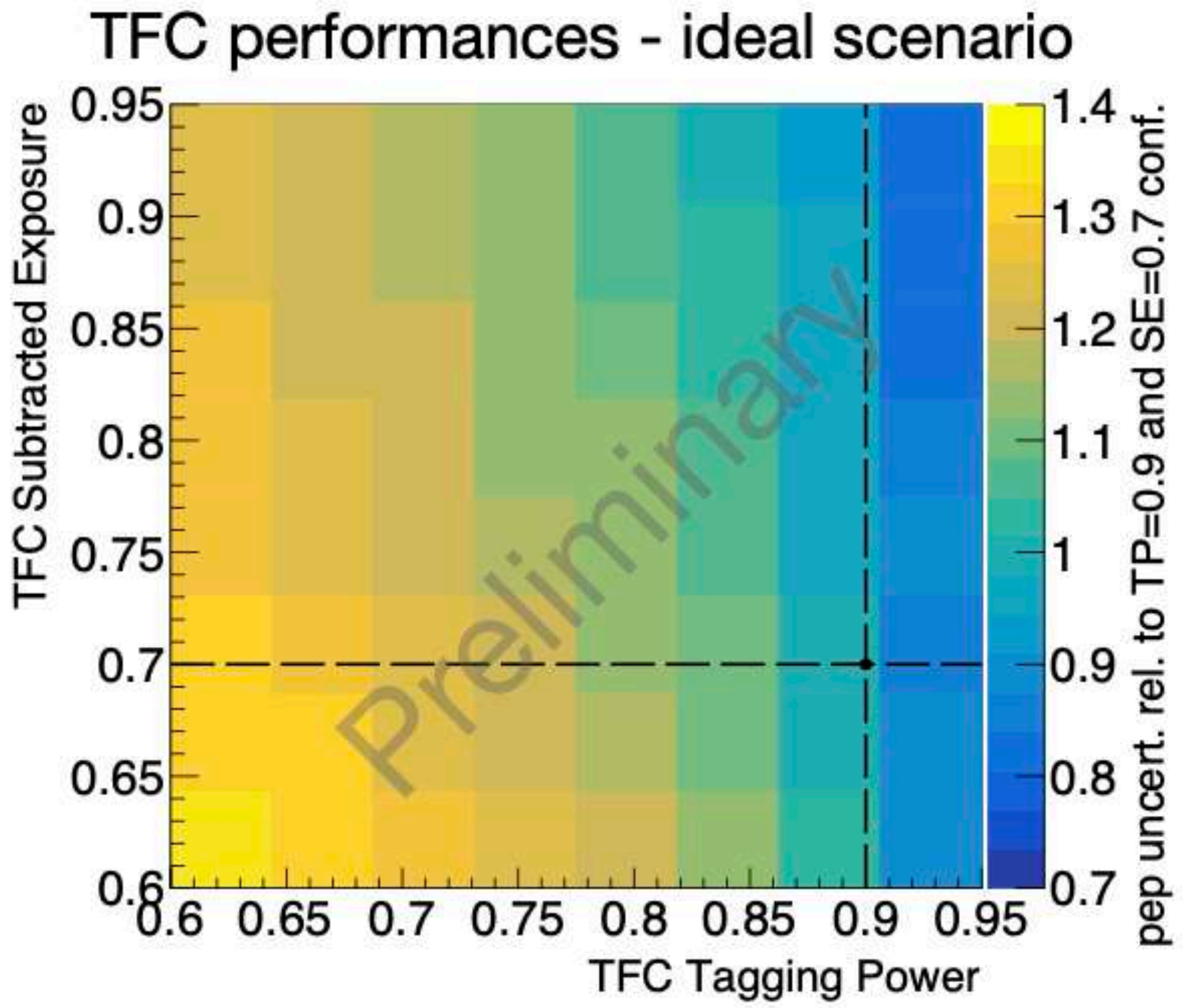
Most critical background: ^{11}C

Impact of TFC performances:

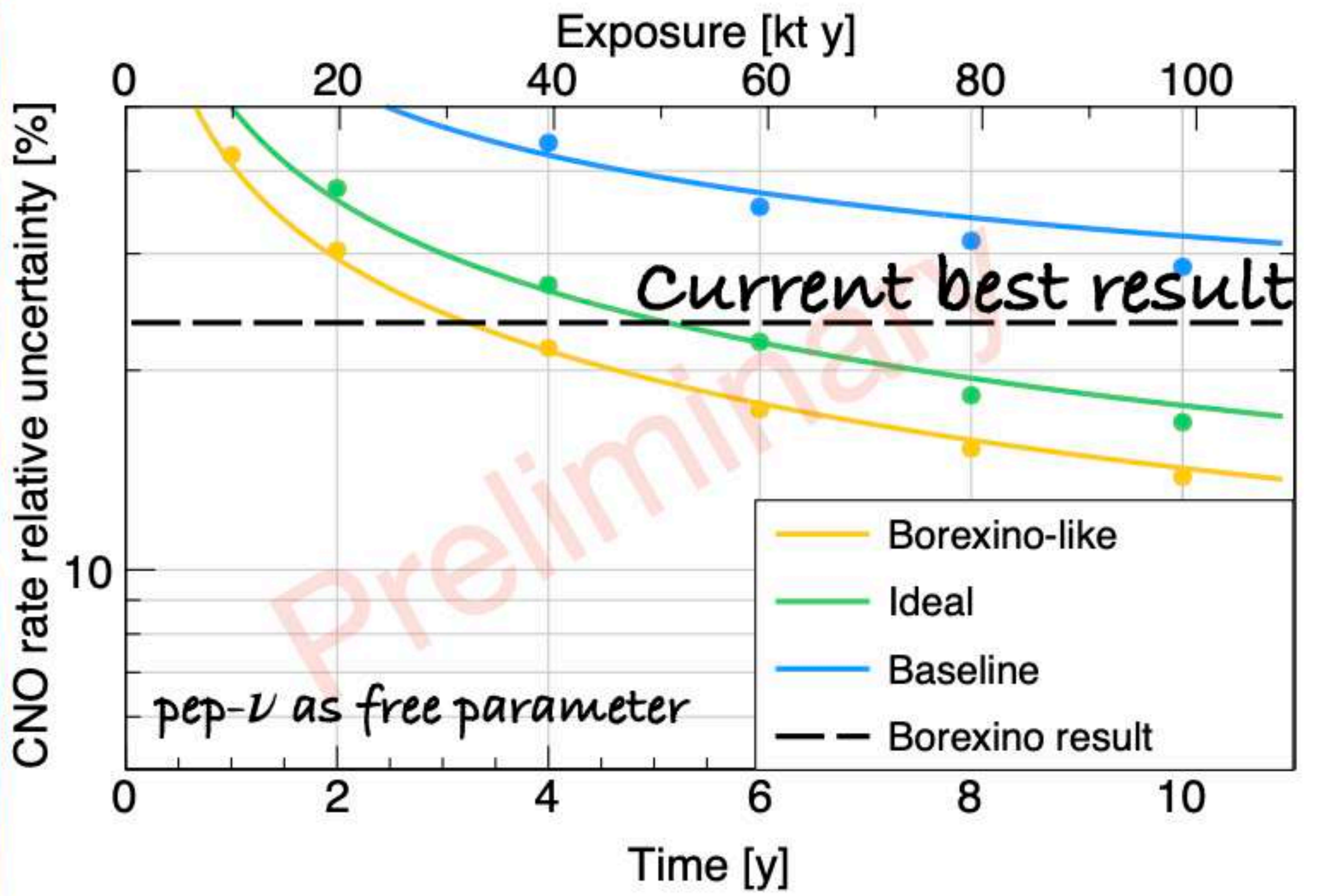
$$0.6 < i < 0.95$$

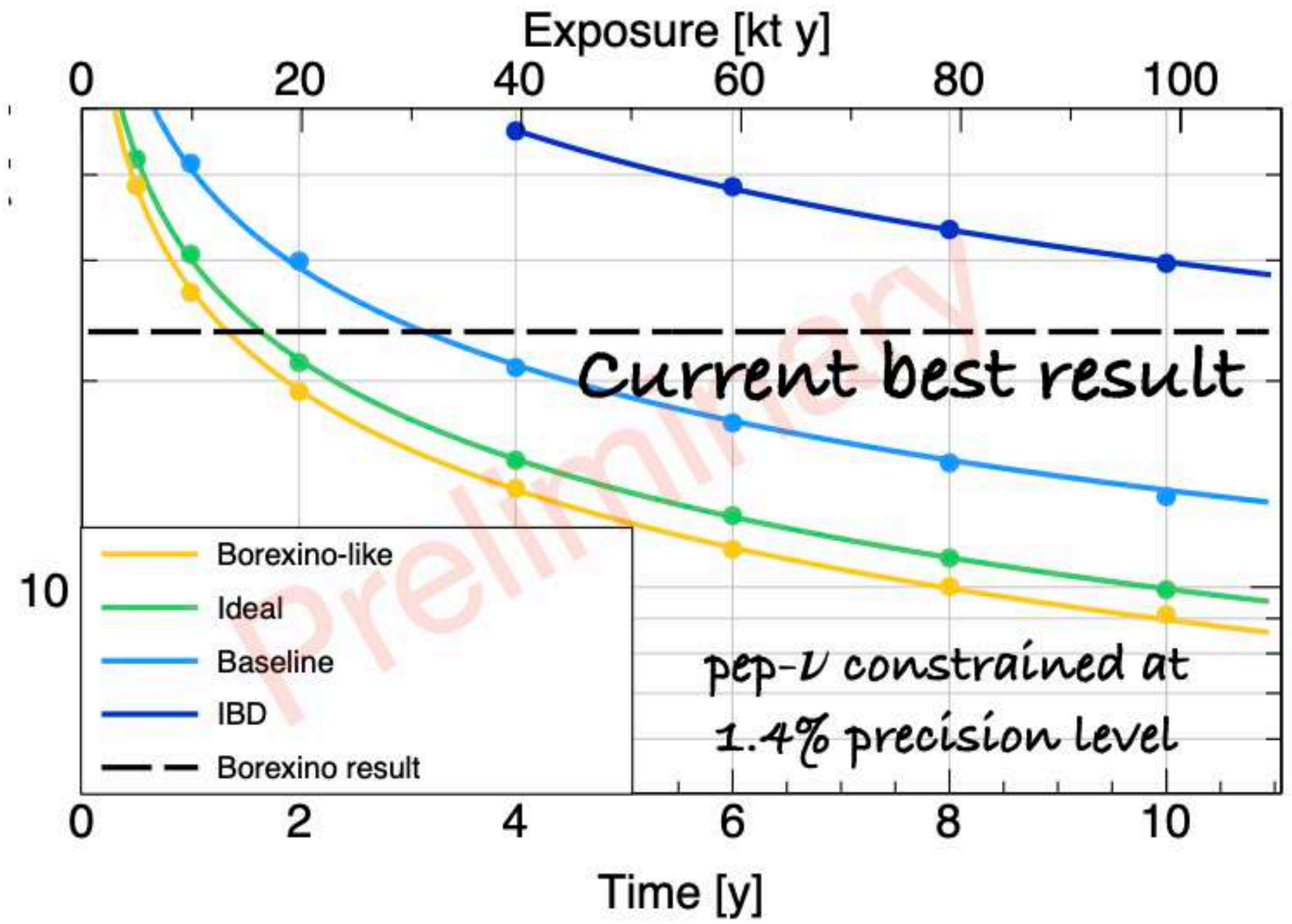
with $i = TP, SE$

- TFC performances are more important in most radiopure scenarios
- Efficient identification of ^{11}C (TP) is more relevant than high fraction of events in the TFC-Sub spectrum (SE)



CNO neutrinos



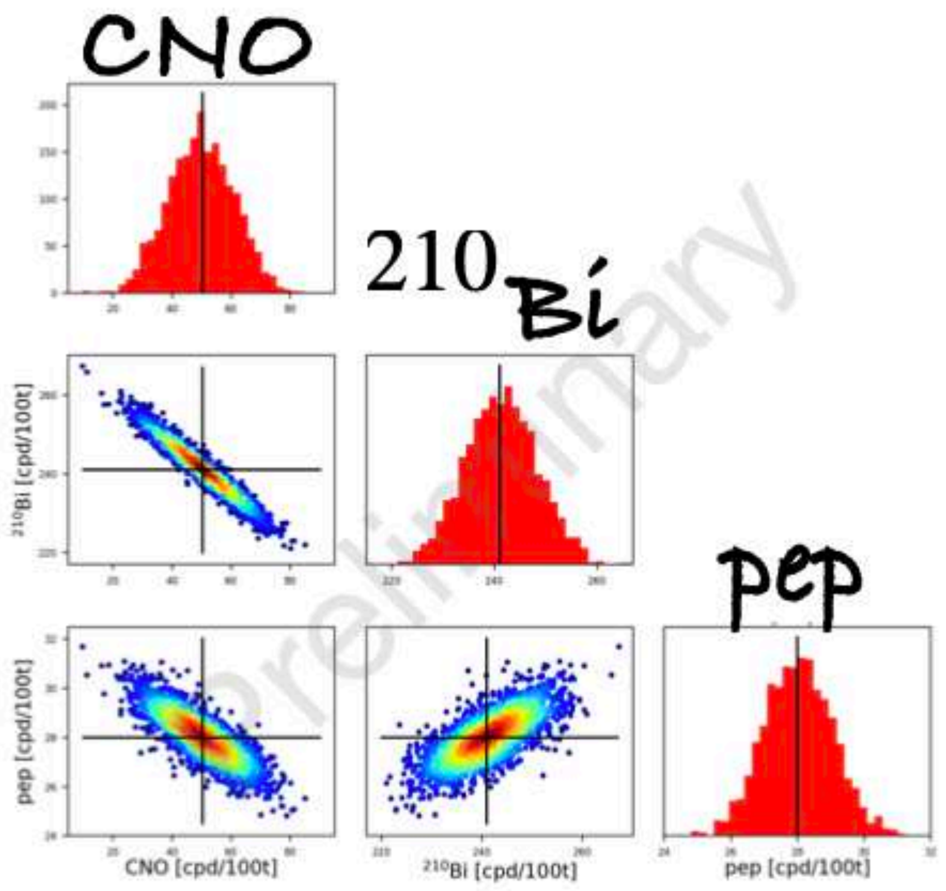


Constraint on pep-ν is crucial for CNO detection. CNO rate can be identified with precision better than 20% (except for IBD scenario)

Most critical backgrounds: ^{210}Bi, pep-ν (and ^{11}C)

CNO spectral shape degeneracy with pep-ν and ^{210}Bi translates in a strong anti-correlation that affect the sensitivity:

- Constraint on pep-ν is crucial
- Constraint on ^{210}Bi is foreseen



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JUNO: B8 SIGNALS

CC: senstive to electron flavour neutrinos
NC: sensitive to all flavours (with identical cross section)
ES: sensitive to all flavours (with different cross section)

No.		Channels	Threshold [MeV]	Signal	Event numbers (200 kt×yr)
1	CC	$\nu_e + ^{12}\mathrm{C} \to e^- + ^{12}\mathrm{N}\,(1^+;\mathrm{gnd})$ [32]	16.827	$e^- + ^{12}\mathrm{N}$ decay(β^+, Q=17.338 MeV)	0.43
2	CC	$\nu_e + ^{13}\mathrm{C} \to e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$ [33]	2.2	$e^- + ^{13}\mathrm{N}$ decay(β^+, Q=2.22 MeV)	3929
3	CC	$\nu_e + ^{13}\mathrm{C} \to e^- + ^{13}\mathrm{N}\,(\frac{3}{2}^-;3.5\,\mathrm{MeV})$ [33]	5.7	e^-+p	2464
4	NC	$\nu_x + ^{12}\mathrm{C} \to \nu_x + ^{12}\mathrm{C}\,(1^+;15.11\,\mathrm{MeV})$ [32]	15.1	γ	4.8
5	NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + n + ^{12}\mathrm{C}\,(2^+;4.44\,\mathrm{MeV})$ [34]	6.864	$\gamma + n$ capture	65
6	NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + ^{13}\mathrm{C}\,(\frac{1}{2}^+;3.089\,\mathrm{MeV})$ [33]	3.089	γ	14
7	NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$ [33]	3.685	γ	3032
8	NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + ^{13}\mathrm{C}\,(\frac{5}{2}^+;3.854\,\mathrm{MeV})$ [33]	3.854	γ	2.8
9	ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5

Only CC with ok threshold: coincidence of prompt electron and delayd positron (from N13 beta+ decay)

Dominant NC reaction (The one with neutron is overwhelmed by reactor IBDs)

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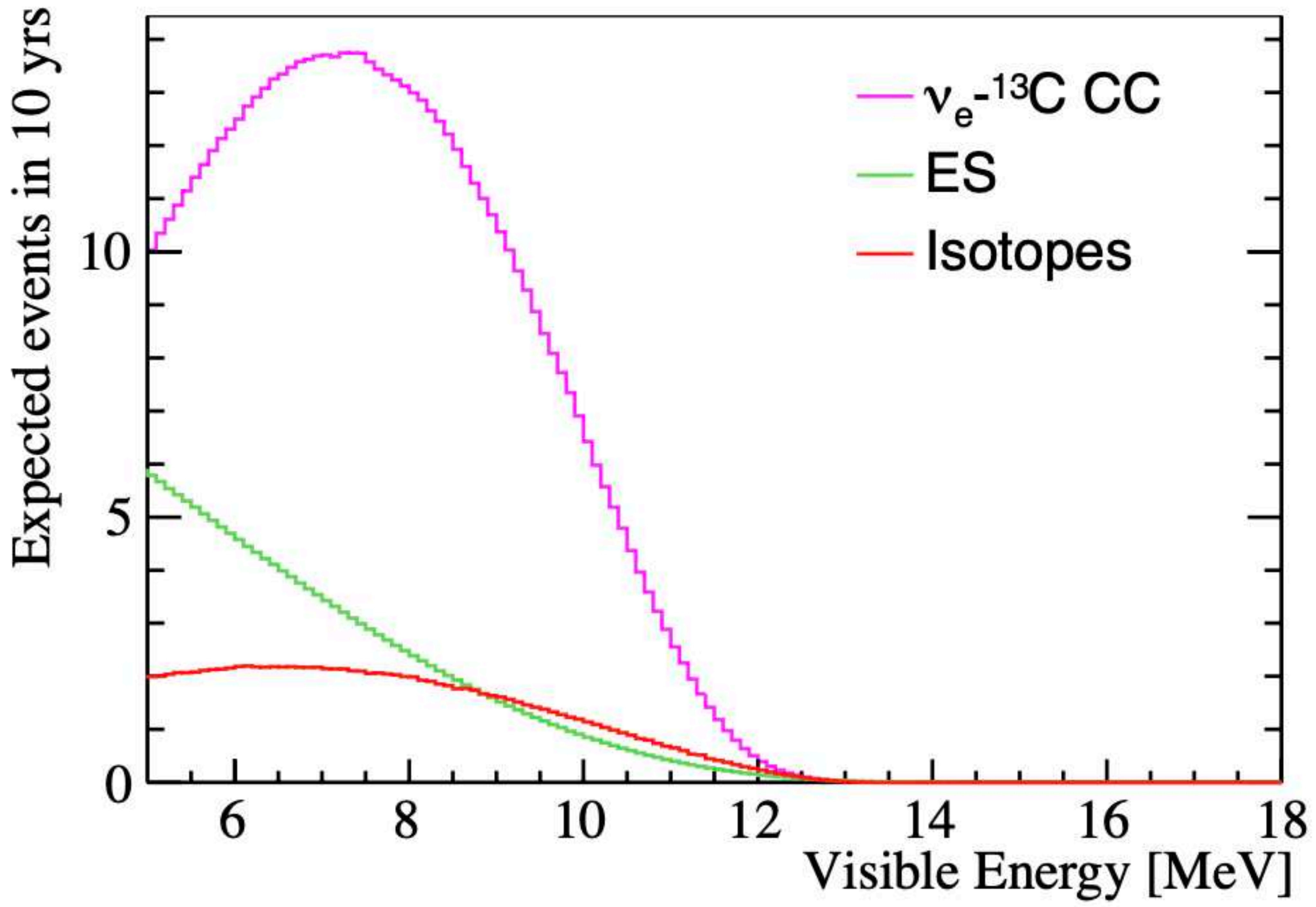
JUNO: CC

	Cuts	Signal efficiency	Signal	Solar ES	Muon-induced isotopes	
				Accidental	Accidental	Correlated
–	–	–	3929	–	–	–
Time cut	$\Delta T < 900$ s	65%	1487	10^{10}	10^{13}	10^{12}
Energy cut	5 MeV $< E_p <$14 MeV 1 MeV $< E_d <$ 2 MeV	79% 91%	2287	10^9	10^{10}	10^9
Fiducial volume Cut	R < 16.5 m [27]	81%	3182	10^7	10^7	10^8
Vertex cut	$\Delta d < 0.47$ m	87%	1293	328	10^5	10^6
Muon veto	Muon and TFC veto [27]	50%	647	164	53	58
Combined	–	17%	647	275		

Accidental:
Promt = natural radioactivity
Delayd = muon induced signal
Correlated:
Promt = muon induced signal (10C, 6He …))
Delayd = muon induced signal (11C)



CC interactions (after selection cuts) ~

Accidental coincidence of solar neutrino (ES)
164 events
Muon induced isotopes
53 accidentals + 58 correlated

FOM = S/SQRT(S+B) = 21!

5 MeV < E < 14 MeV
FV => R < 16.5 m

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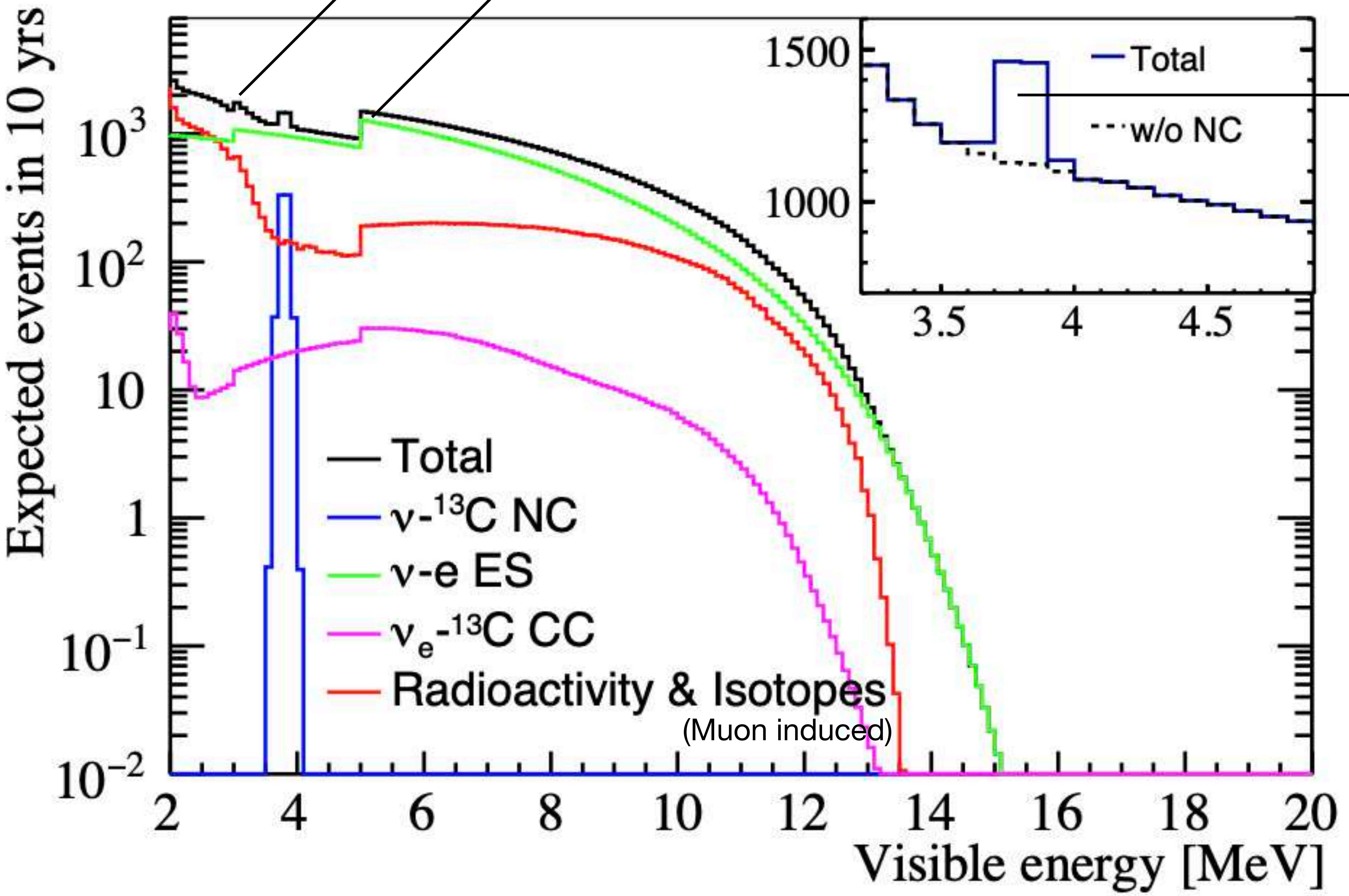
JUNO: NC

Different FVs: r<13 m (2-3 MeV), r<15 m (3-5 MeV) and r < 16.5 m (>5 MeV)



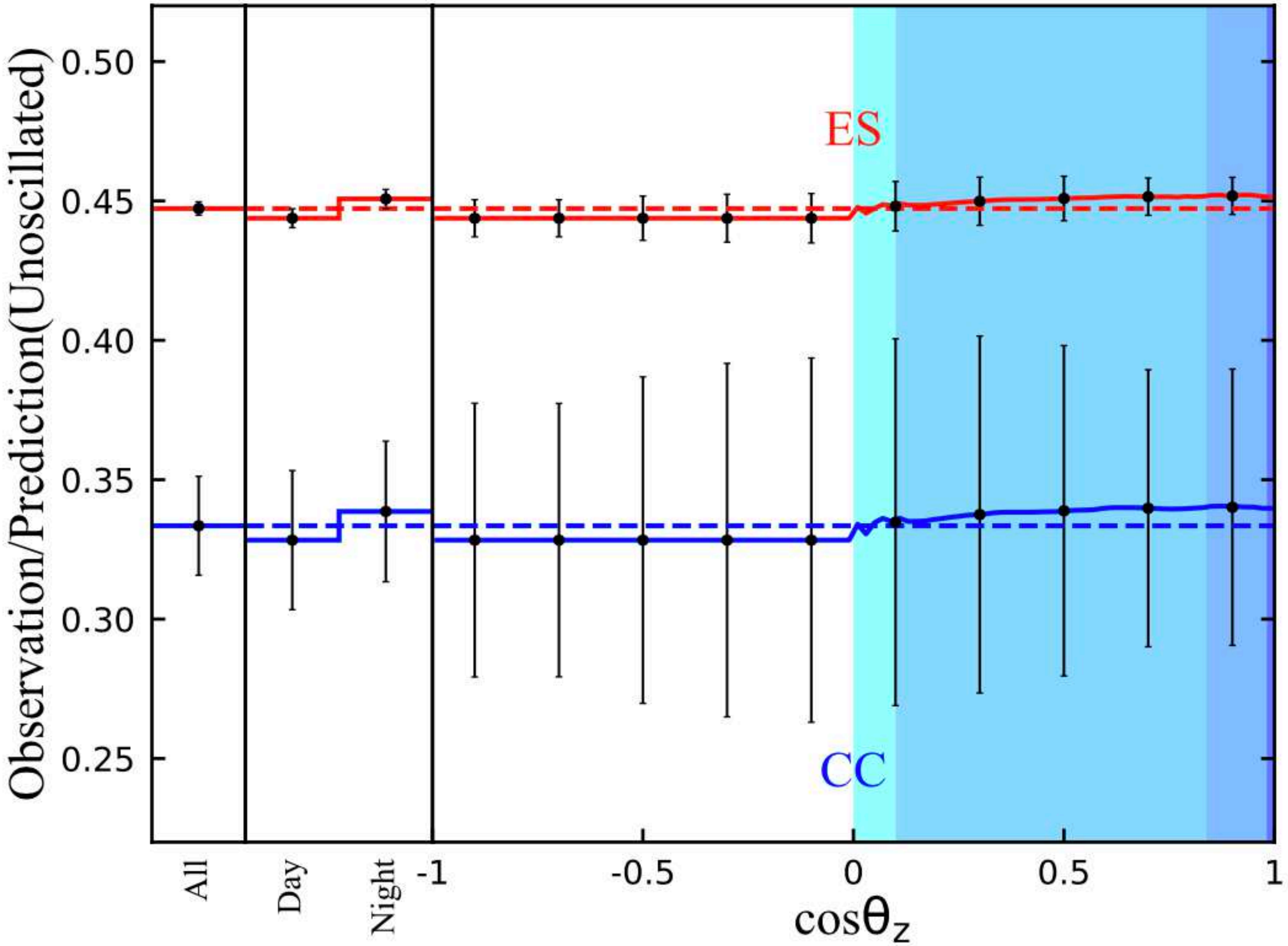
Peak of NC events!

(Promising)

2 MeV < E < 16 MeV

JUNO: D/N

Ratios of events rate w and w/o matter effect (as a function of zenith angle) for ES and CC

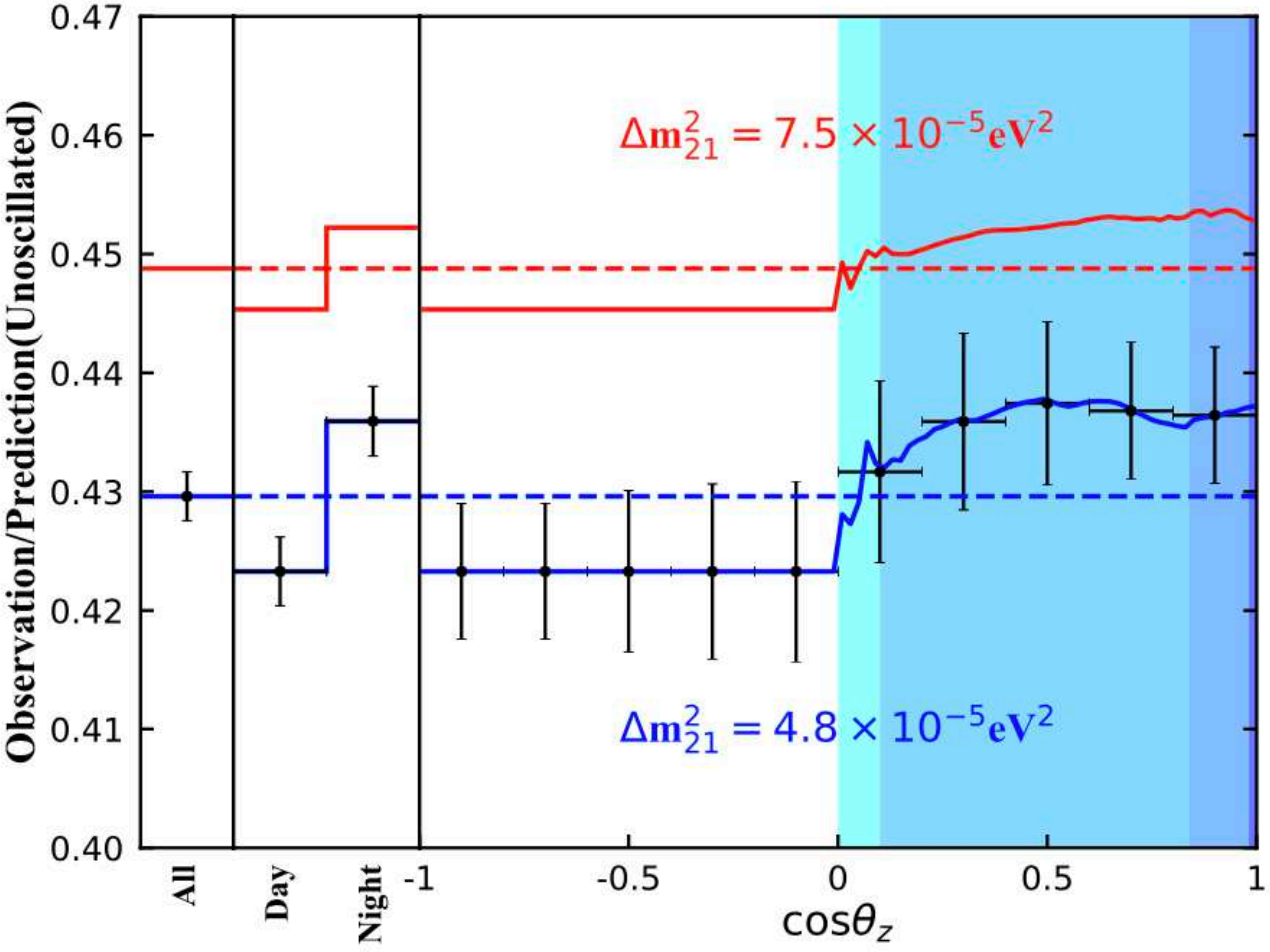


Dashed lines = average over whole angle range

If DM2 = 7.5 *10^-5 eV^2, in 2-16 MeV Range:
A_DN (CC) = -3.1%
A_DN (ES) = -1.6%

If DM2 = 6.1 *10^-5 eV^2, in 2-16 MeV Range:
A_DN (CC) = -4.2 %
A_DN (ES) = -2.2 %

JUNO: D/N

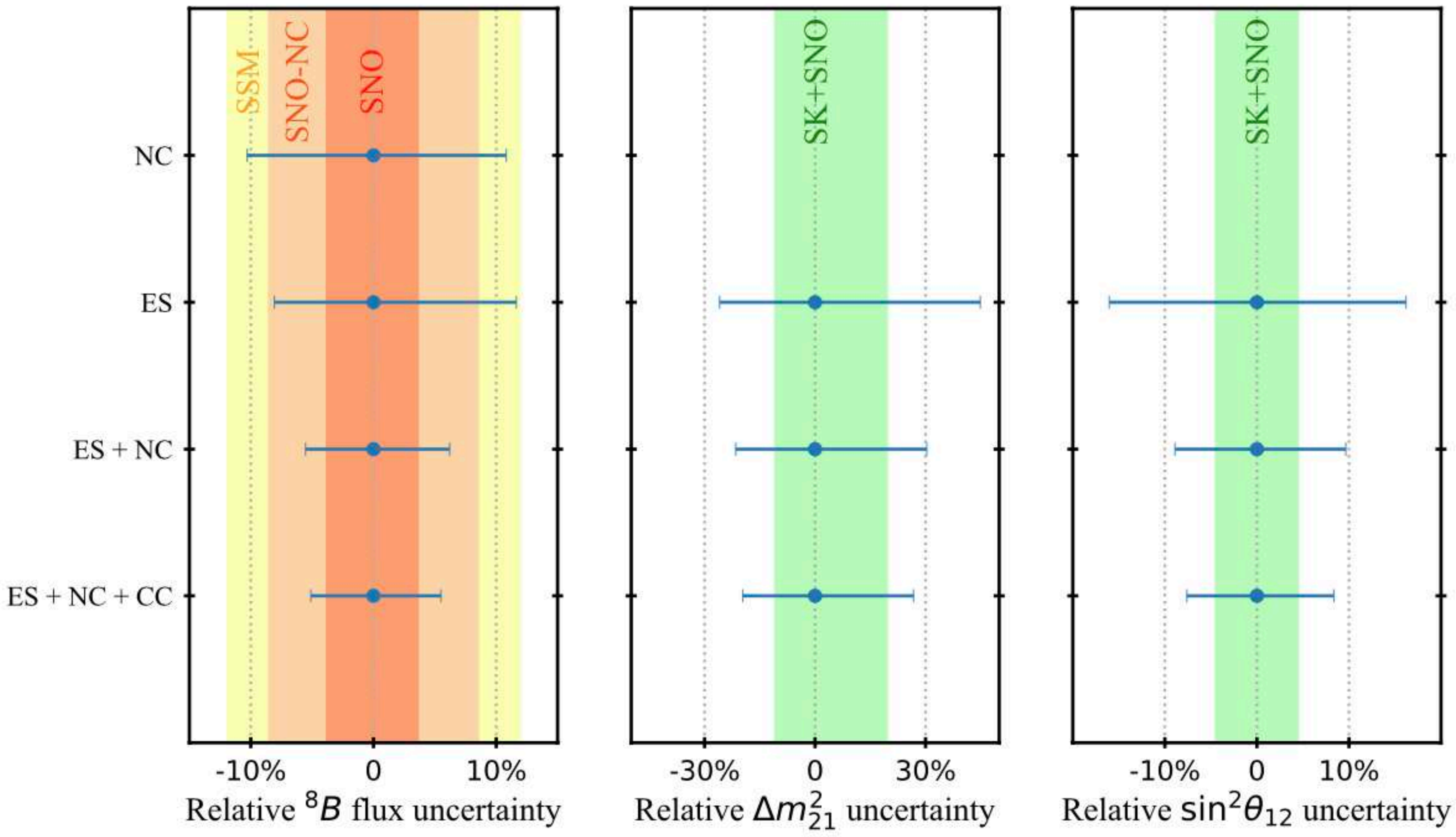


If DM2 = 4.8 *10^-5 eV^2:

Energy	Exposure	Day	Night	A_{DN}
2~3 MeV	41 kt·y	4334	4428	(-2.1 ±3.2)%
3~5 MeV	51 kt·y	8686	8906	(-2.5 ±1.7)%
5~16 MeV	84 kt·y	17058	17644	(-3.4 ±1.2)%
2~16 MeV	N/A	30078	30977	(-2.9±0.9)%

If DM2 = 7.5 *10^-5 eV^2, in 2-16 MeV Range:
A_DN = -1.6 pm 0.9%

JUNO: D/N



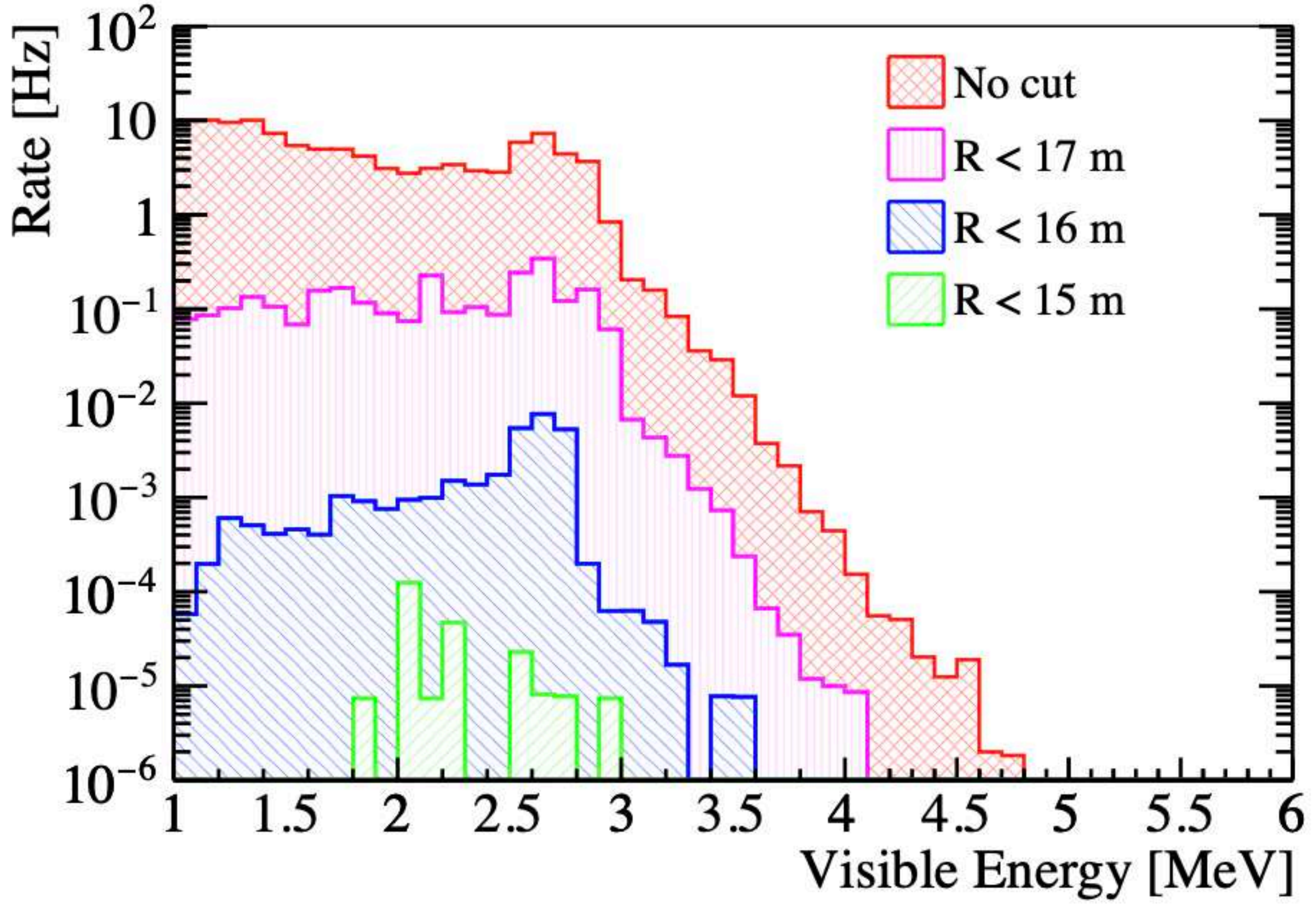
SSM
SNO-NC
SNO
SK+SNO
SK+SNO
NC
ES
ES + NC
ES + NC + CC
-10%
0
10%
Relative ^8B flux uncertainty
-30%
0
30%
Relative Δm^2_{21} uncertainty
-10%
0
10%
Relative $\sin^2\theta_{12}$ uncertainty

JUNO: SOLAR NEUTRINOS POTENTIAL

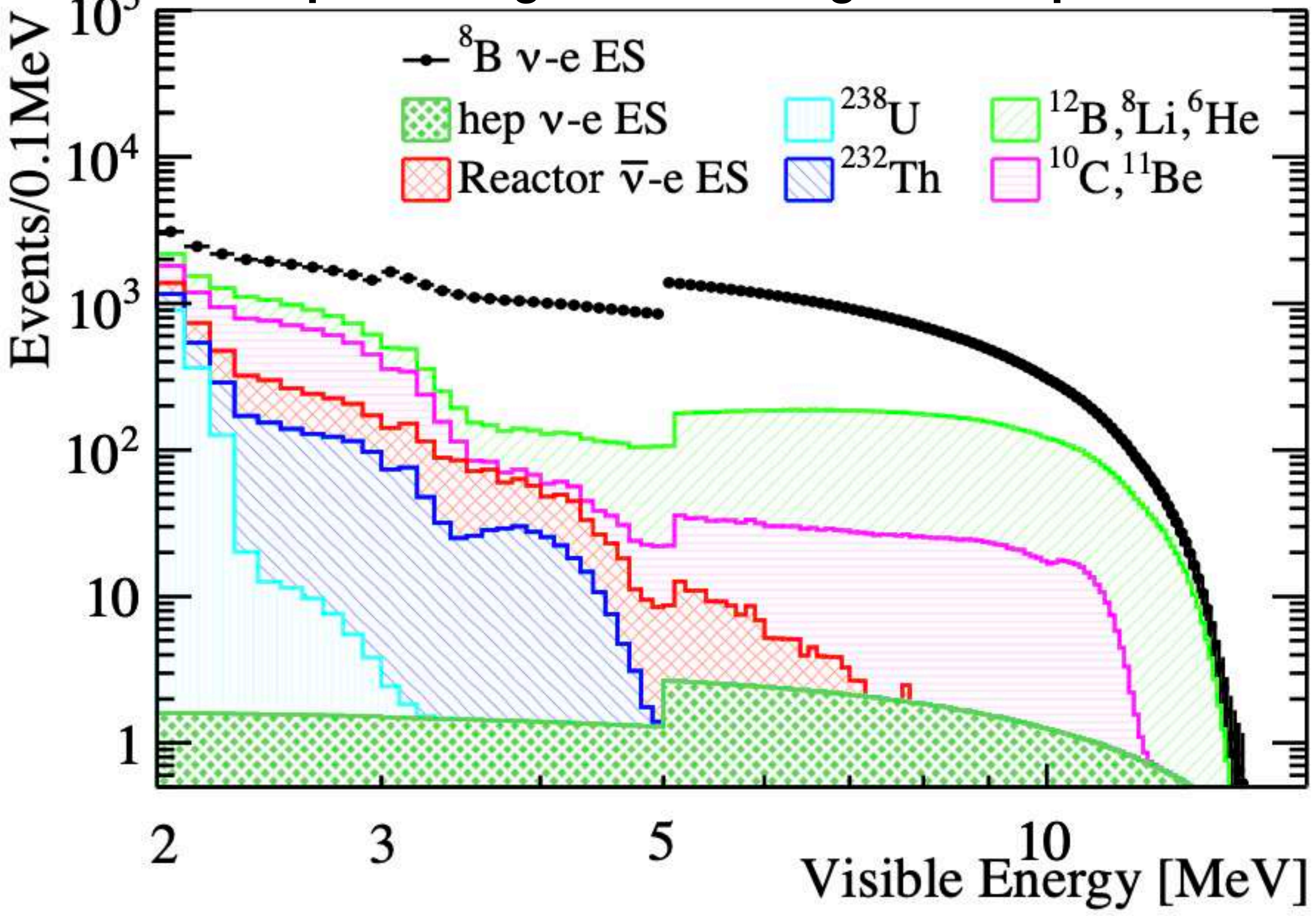
Boron-8 analysis:

energy threshold can be reduced to **2 MeV** (with specifically devised FV cuts bkgs are suppresed to 0.5% wrt signals)
Potential observation of B8 neutrinos CC and NC interactions (in 10 years)

External backgfrounds contribution with different FV cuts



Expected signal and backgrounds spectra

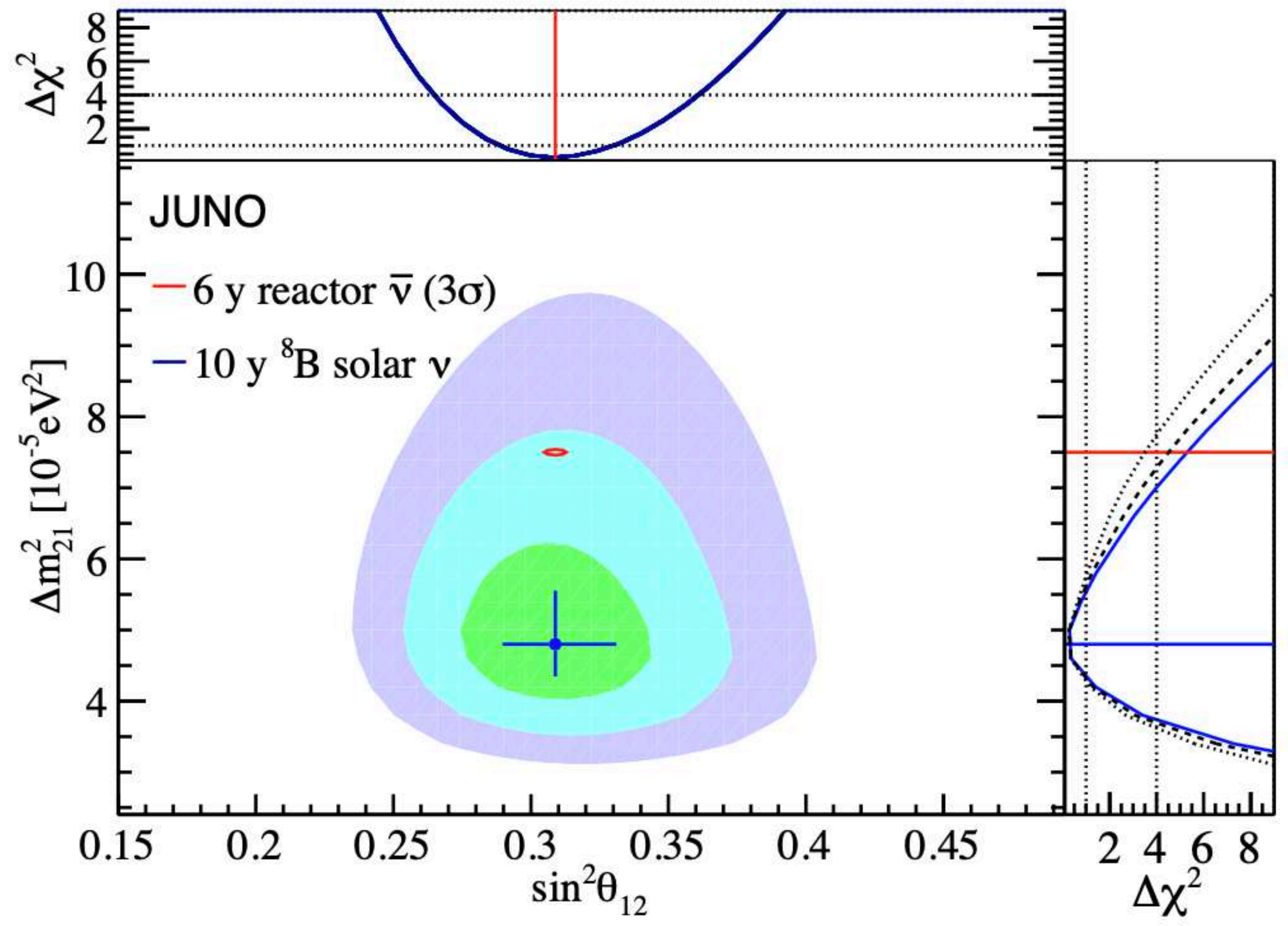


JUNO: SOLAR NEUTRINOS POTENTIAL

D/N asymmetry:

- If $\Delta m^2_{21} = 4.8 \cdot 10^{-5}$ eV^2 and $E_{th} = 2$ MeV, JUNO has the potential to observe D/N asymmetry with **3σ significance** (2.8σ for less optimistic scenarios)
- Different A_{DN} values contribute to Δm^2_{21} determination

Oscillation parameters Δm^2_{21} and $\sin^2\theta_{21}$:

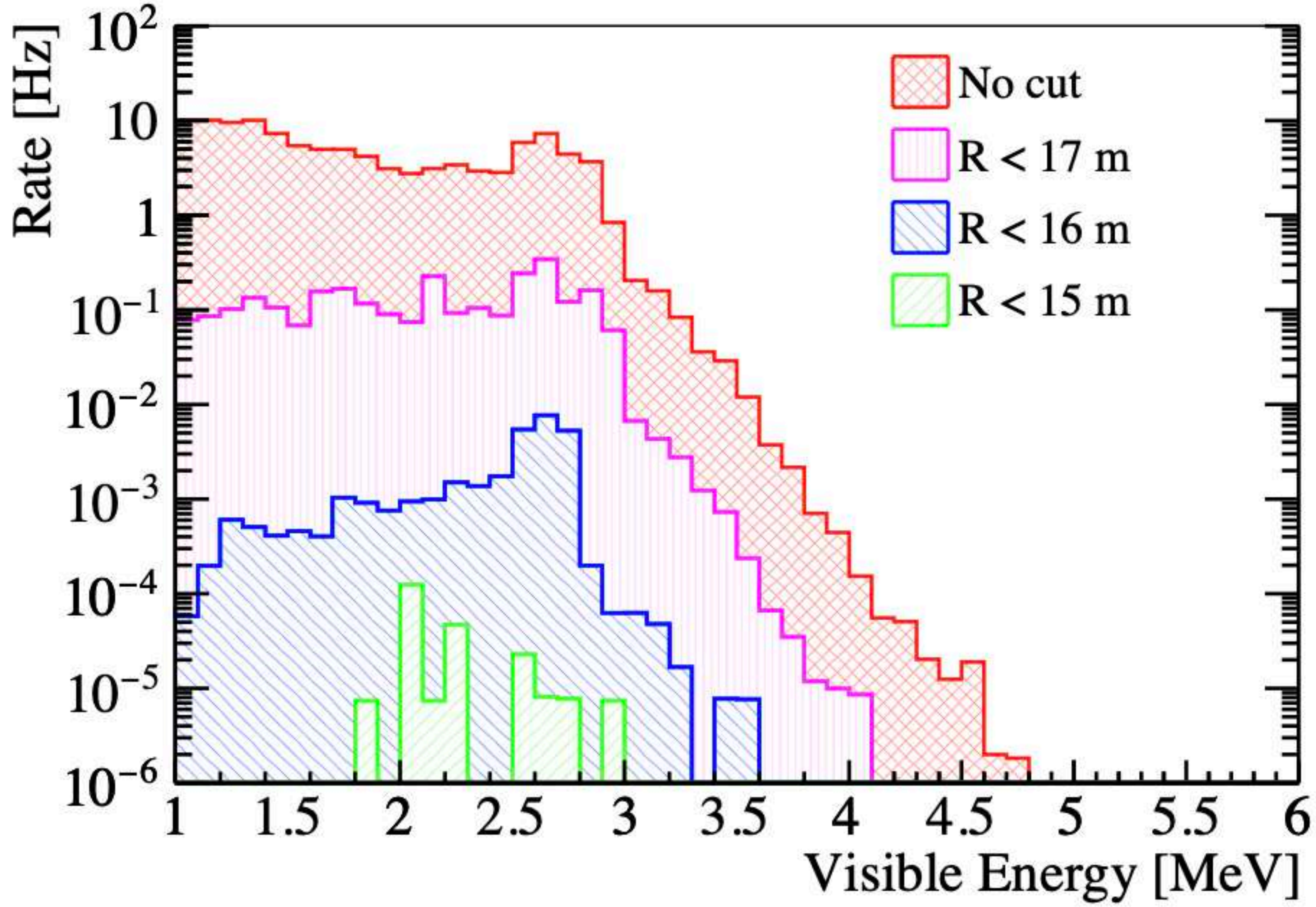


Discrimination sensitivity between the two possible Δm^2_{21} values highly depends on radiopurity:

- Ideal - $\approx 2.3\sigma$ ($\Delta\chi^2 \sim 5.3$)
- Out-of-equilibrium ^{210}Po - $\approx 2.1\sigma$ ($\Delta\chi^2 \sim 4.5$)
- IBD - $\approx 1.9\sigma$ ($\Delta\chi^2 \sim 3.5$)

A. Abusleme et al., Feasibility and physics potential of detecting 8B solar neutrinos at JUNO, *Chinese Physics C* 45 (2021) 1.

JUNO: EXTERNAL BKGS



Energy dependet fiducial volume cut

- $2 < E_{\mathrm{vis}} \leq 3$ MeV, $r < 13$ m, 7.9 kt target mass;
- $3 < E_{\mathrm{vis}} \leq 5$ MeV, $r < 15$ m, 12.2 kt target mass;
- $E_{\mathrm{vis}} > 5$ MeV, $r < 16.5$ m, 16.2 kt target mass.

JUNO: INTERNAL BKGS

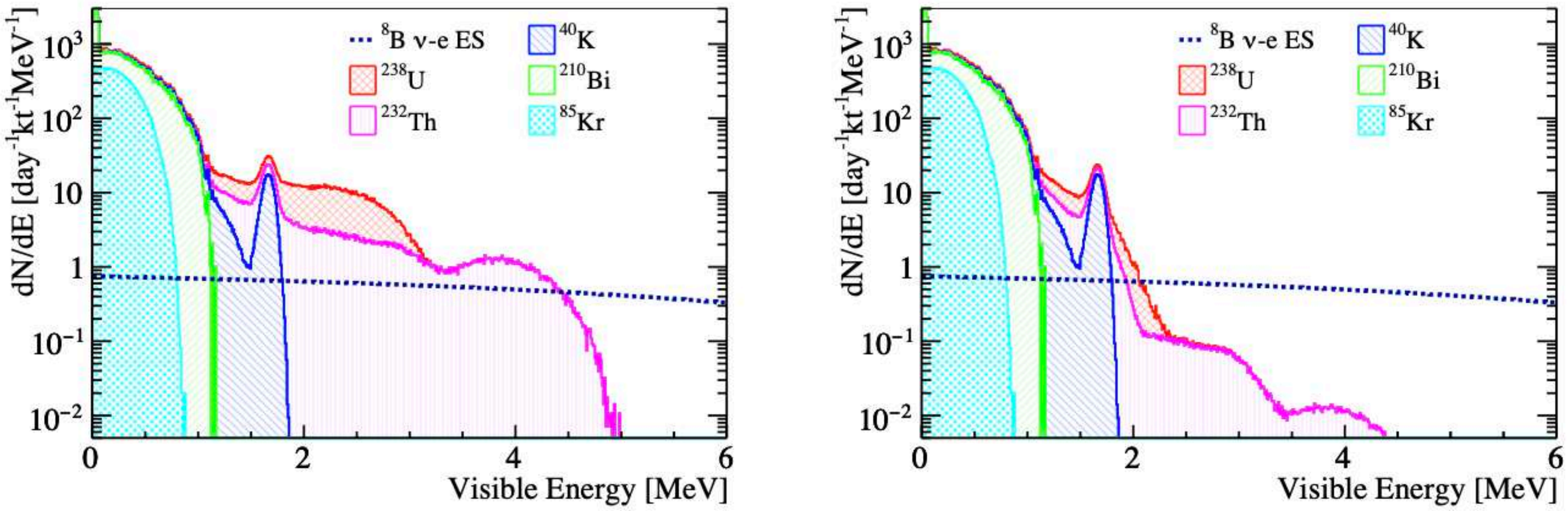


Figure 8: Internal radioactivity background compared with ^{8}B signal before (left) and after (right) time, space and energy correlation cuts to remove the Bi-Po/Bi-Tl cascade decays. The events in the 3 – 5 MeV energy range are dominated by ^{208}Tl decays, while those between 2 and 3 MeV are from ^{214}Bi and ^{212}Bi.

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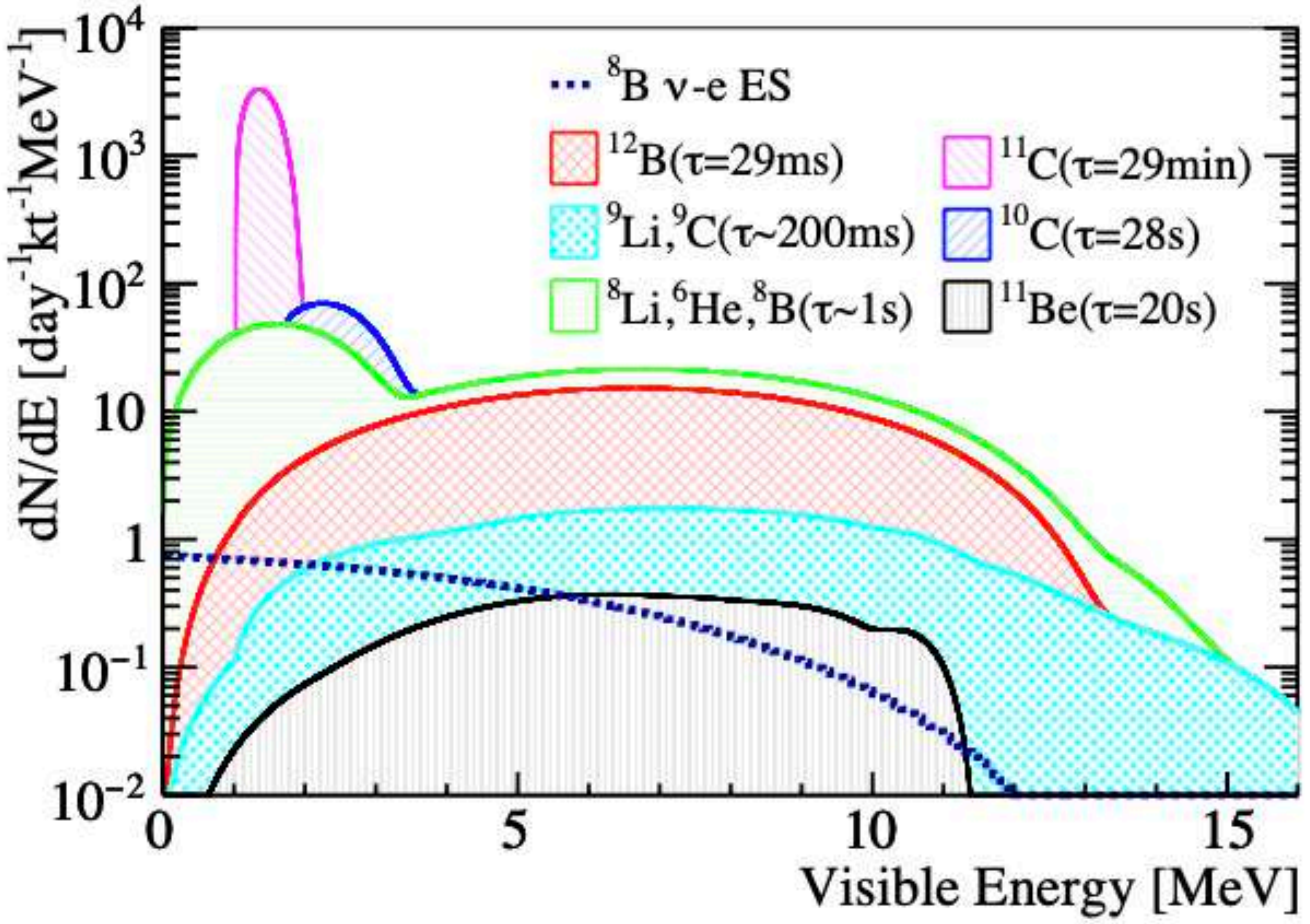
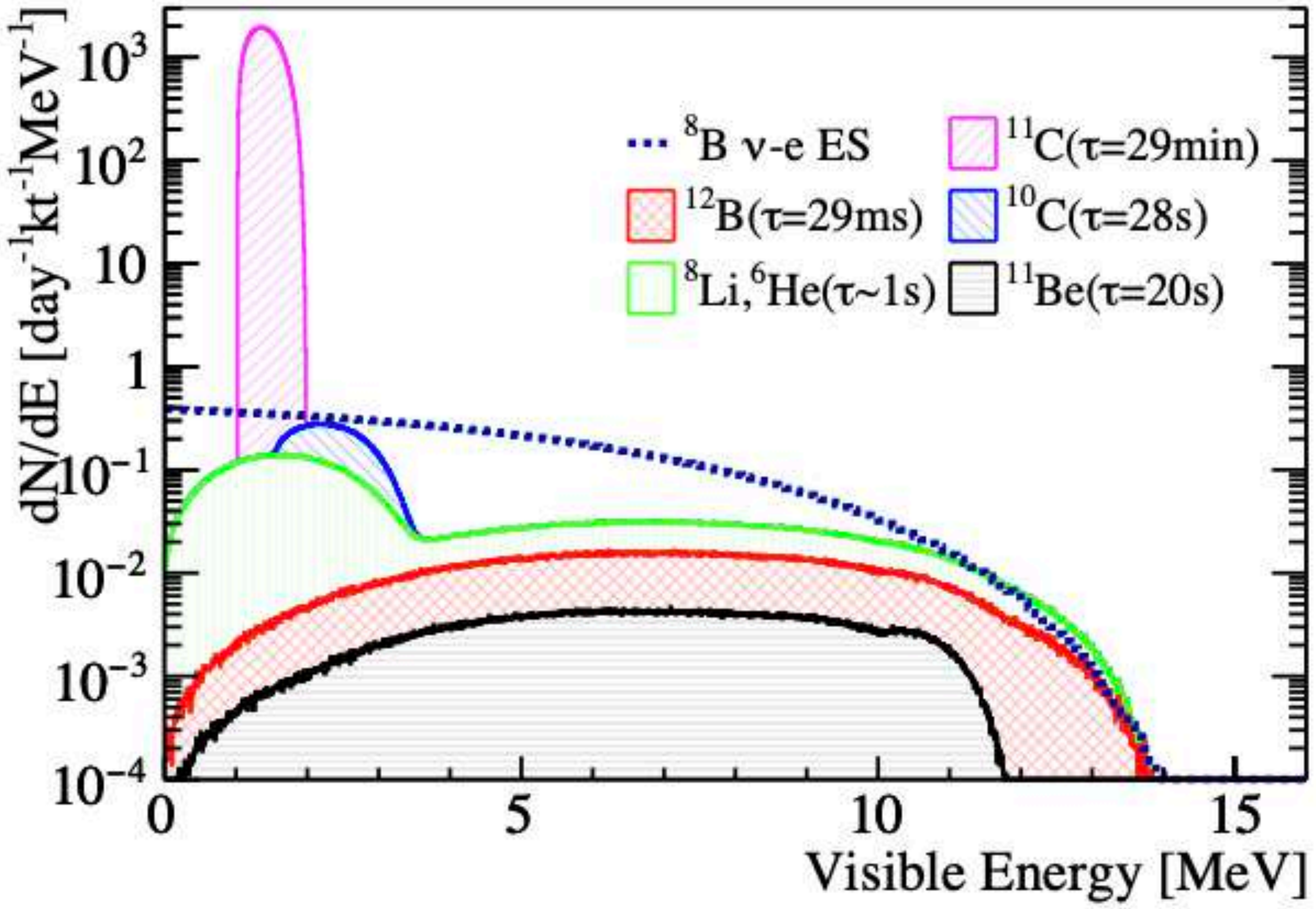
JUNO: COMSOGENIC BKGS



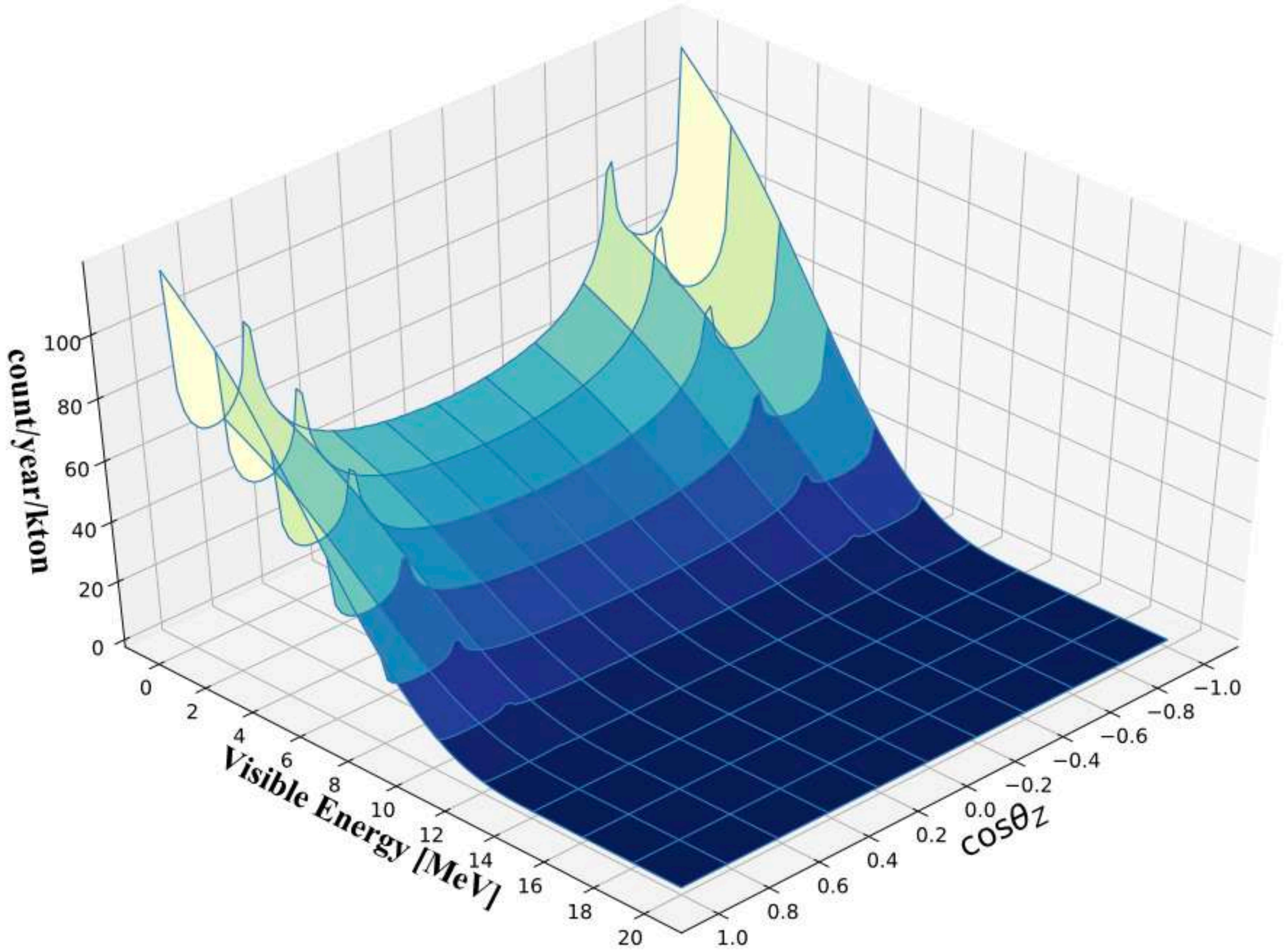
cylindrical veto along the muon track + TFC cut



JUNO: SIGNAL AND BKGS

cpd/kt	FV	^{8}B signal eff.	^{12}B	^{8}Li	^{10}C	^{6}He	^{11}Be	^{238}U	^{232}Th	$\overline{\nu}$-e ES	Total bkg.	Signal rate at $\Delta m_{21}^{2\star}$	Signal rate at $\Delta m_{21}^{2\dagger}$
(2, 3) MeV	7.9 kt	~51%	0.005	0.006	0.141	0.084	0.002	0.050	0.050	0.049	0.39	0.32	0.30
(3, 5) MeV	12.2 kt	~41%	0.013	0.018	0.014	0.008	0.005	0	0.012	0.016	0.09	0.42	0.39
(5, 16) MeV	16.2 kt	~52%	0.065	0.085	0	0	0.023	0	0	0.002	0.17	0.61	0.59
Syst. error	1%	<1%	3%	10%	3%	10%	1%	1%	2%				

JUNO: D/N



count/year/kton
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Visible Energy [MeV]
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
cosθz