Borexino对CNO太阳中微子的测量及其对标准太阳模型的影响

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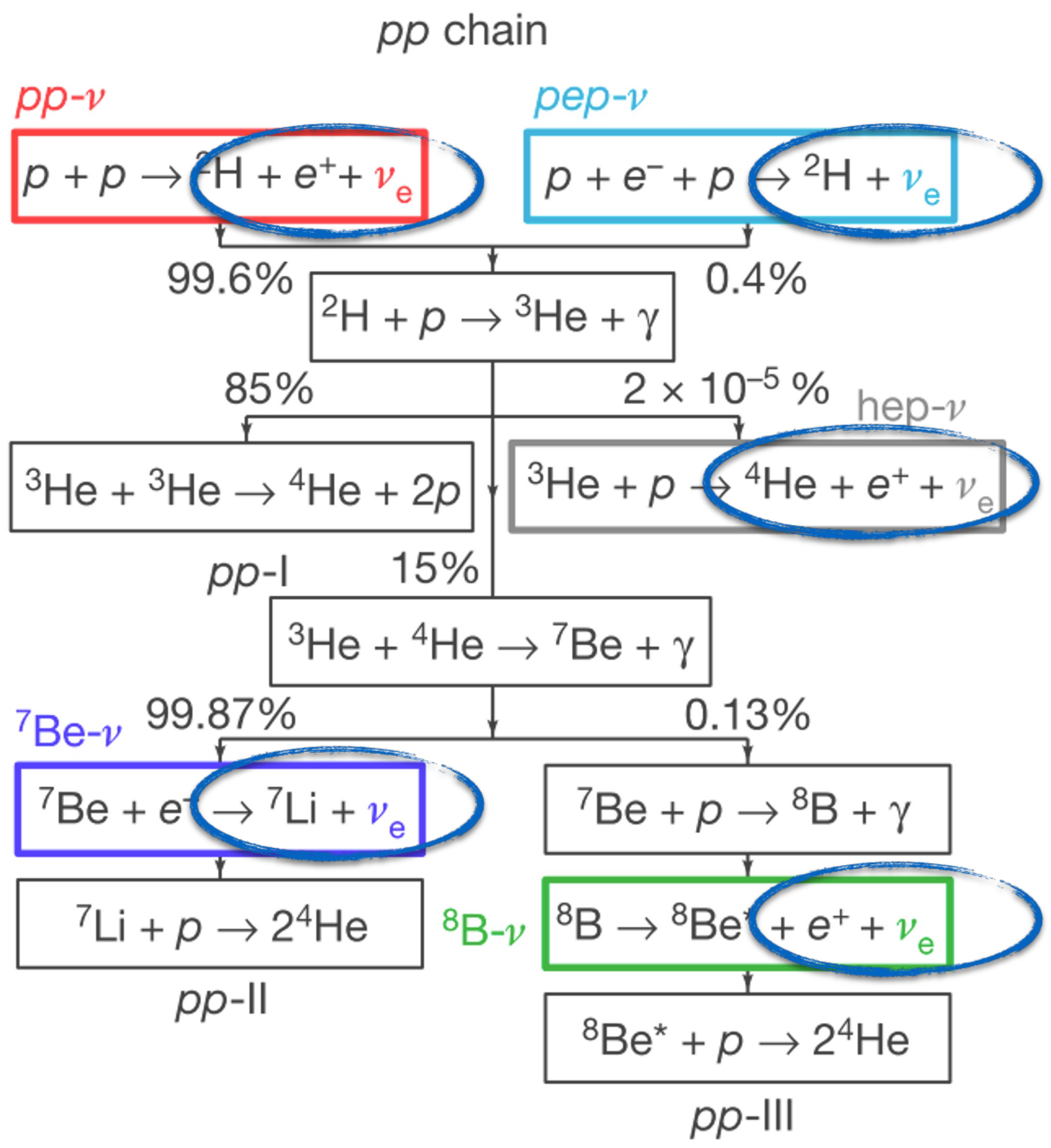
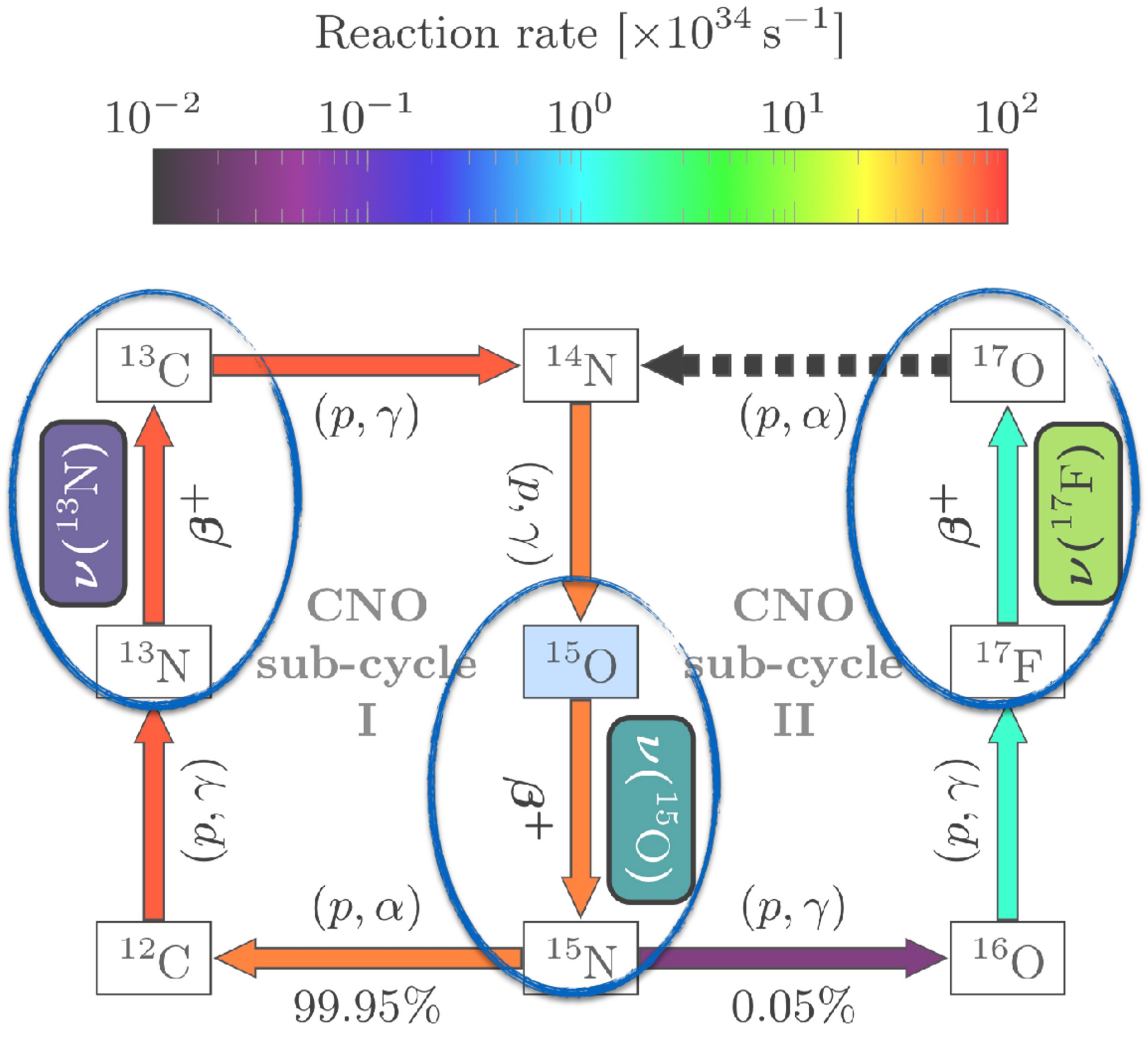
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会
2024年4月10日

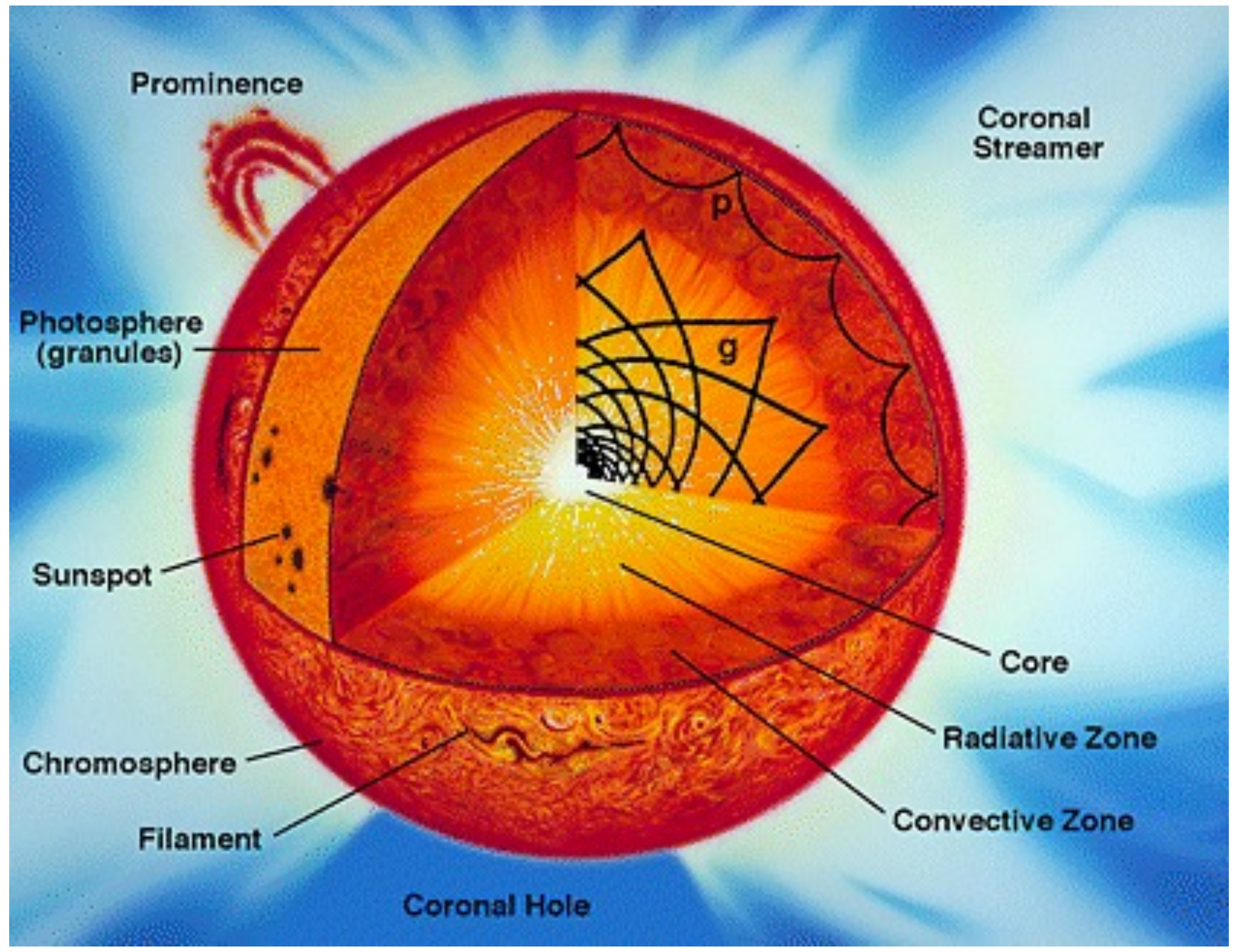
What is CNO cycle

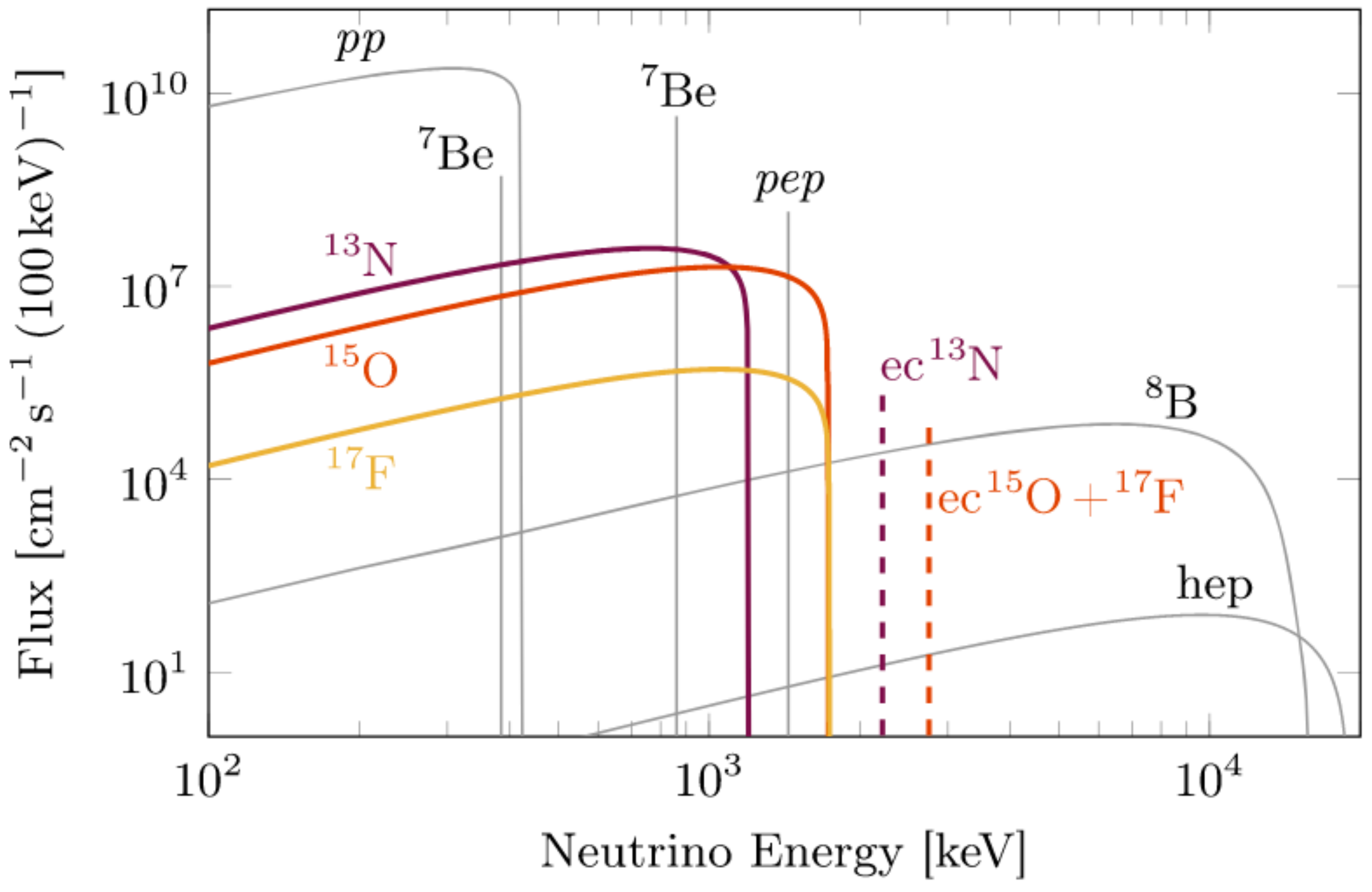


Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature



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





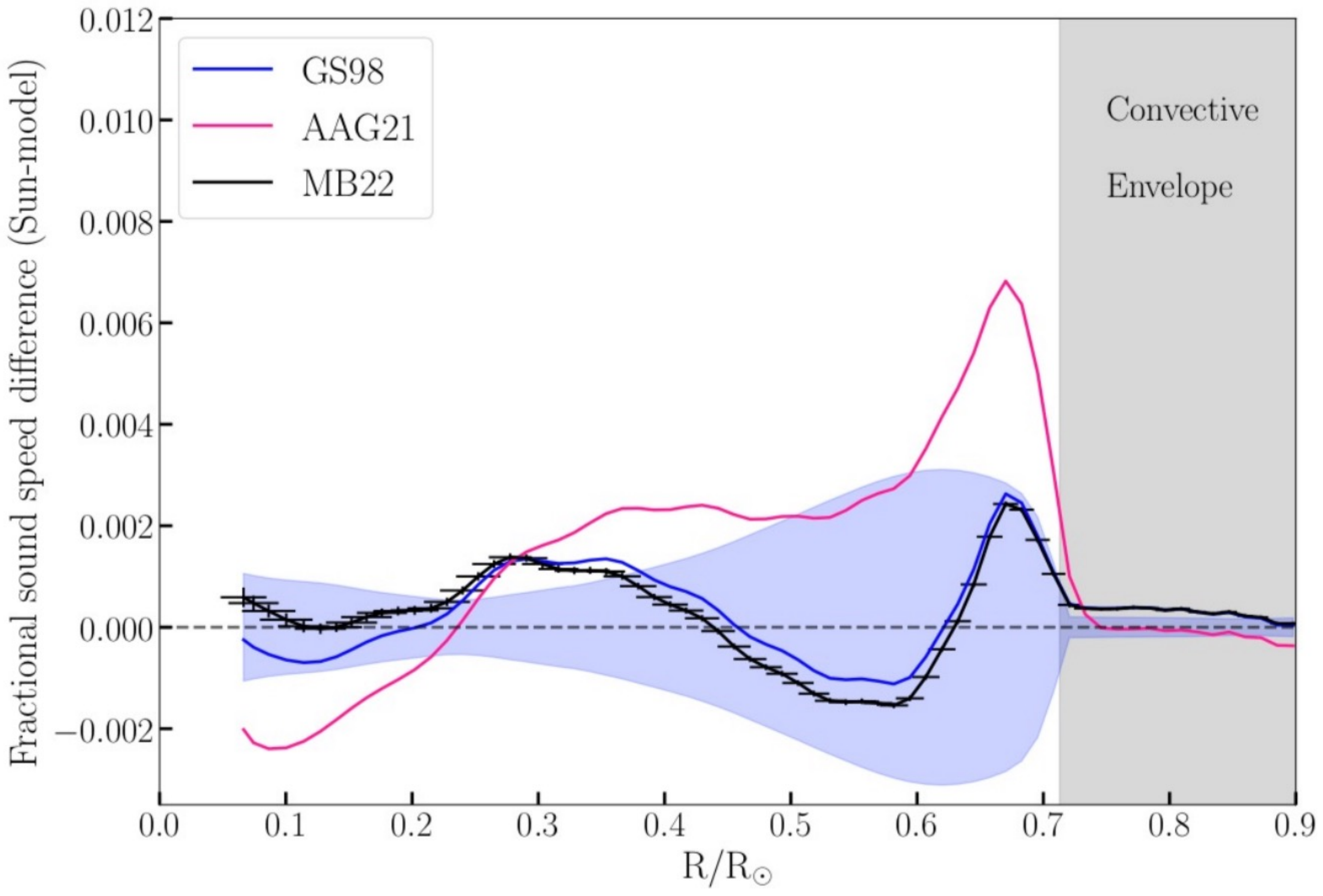
Agostini, M., K. Altenmüller, S. Appel, V. Atroshchenko, Z. Bagdasarian, D. Basilico, G. Bellini, et al. "Sensitivity to Neutrinos from the Solar CNO Cycle in Borexino." *European Physical Journal C* 80, no. 11 (November 26, 2020): 1091. https://doi.org/10.1140/epjc/s10052-020-08534-2.

- Two types of 4H=>^{4}He: pp-chain and CNO-cycle.
- Solar neutrinos are produced during the fusion.

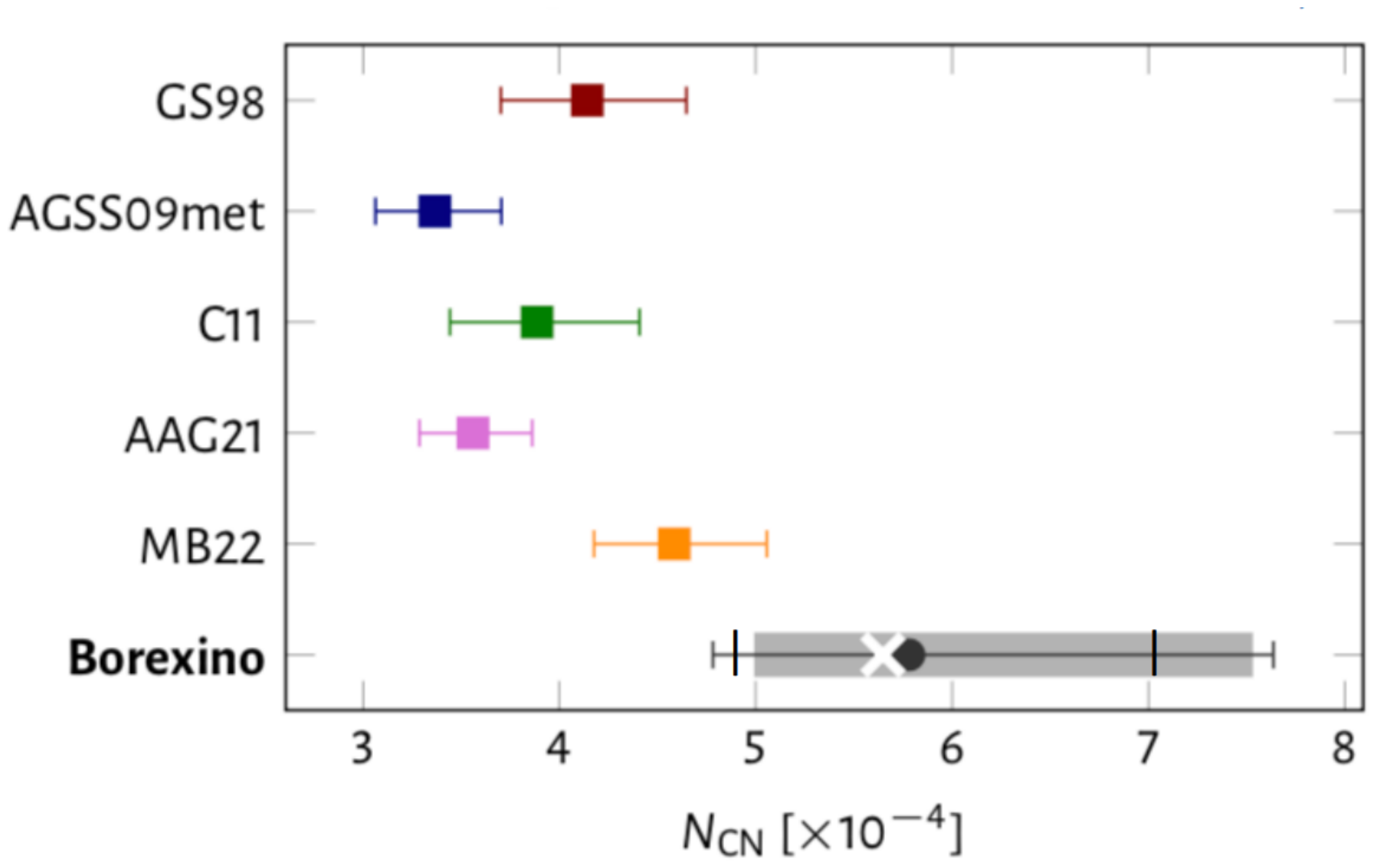
Motivation to measure CNO solar ν

- Study SSM. Test solar metallicity problem.
- Backgrounds and detector response are key points.

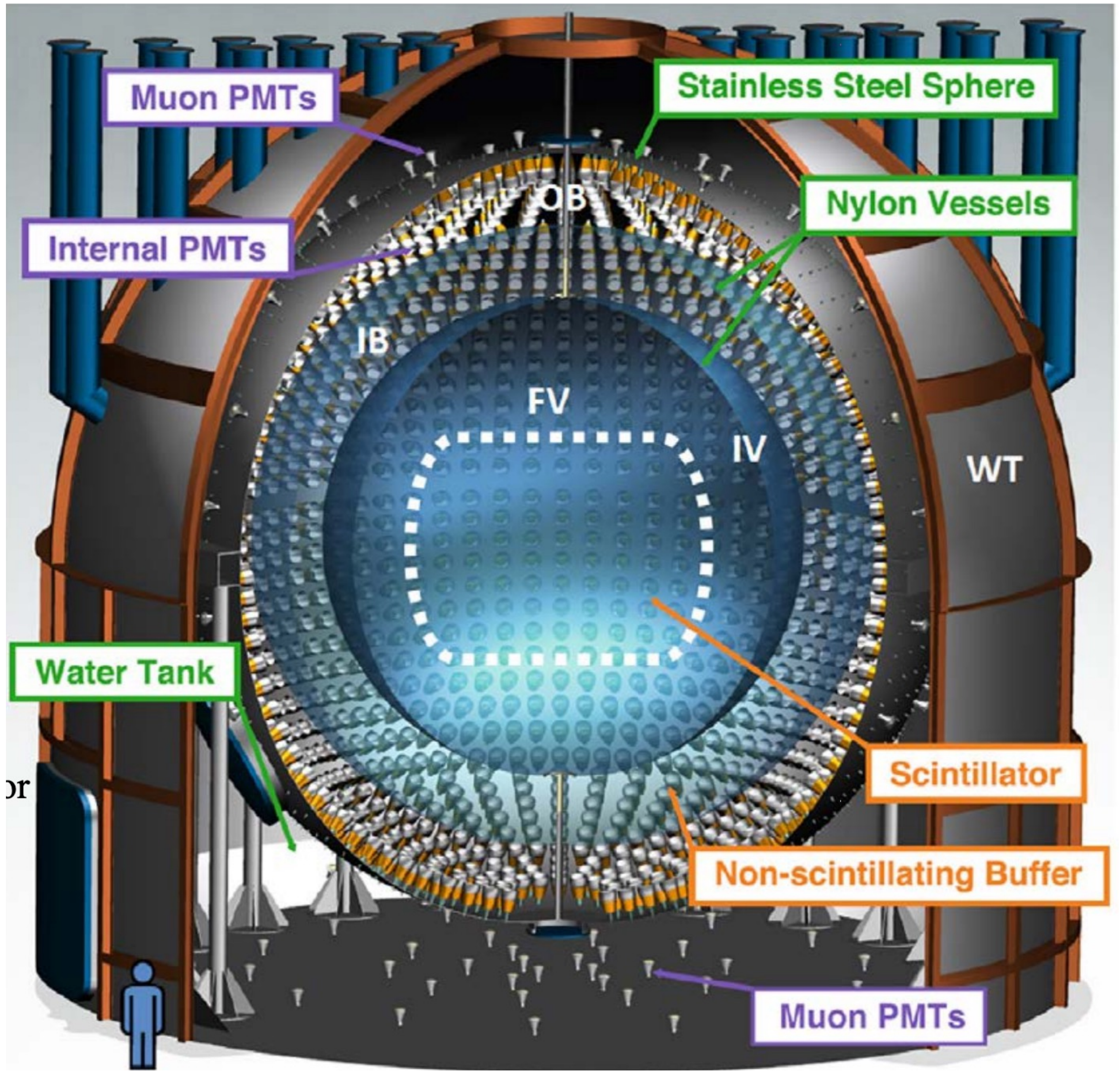
Consistency with helioseismology data



Determination of metallicity with solar neutrinos



Borexino detector



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

Physics program of Borexino

2007 May-2010 May
Phase-I

Be7 Phys. Rev. Lett. 107, 141302 (2011)
pep Phys. Rev. Lett. 108, 051302 (2012)
pp Nature 512, 383-386 (28 August 2014)
3 MeV B8 Phys.Rev.D82:033006 (2010)
geo-neutrino PLB 687, 299-340 (2010)
Day-night symmetry PLB 707-1,22-26, (2012)
…

2010-2011
Purification +
Calibration

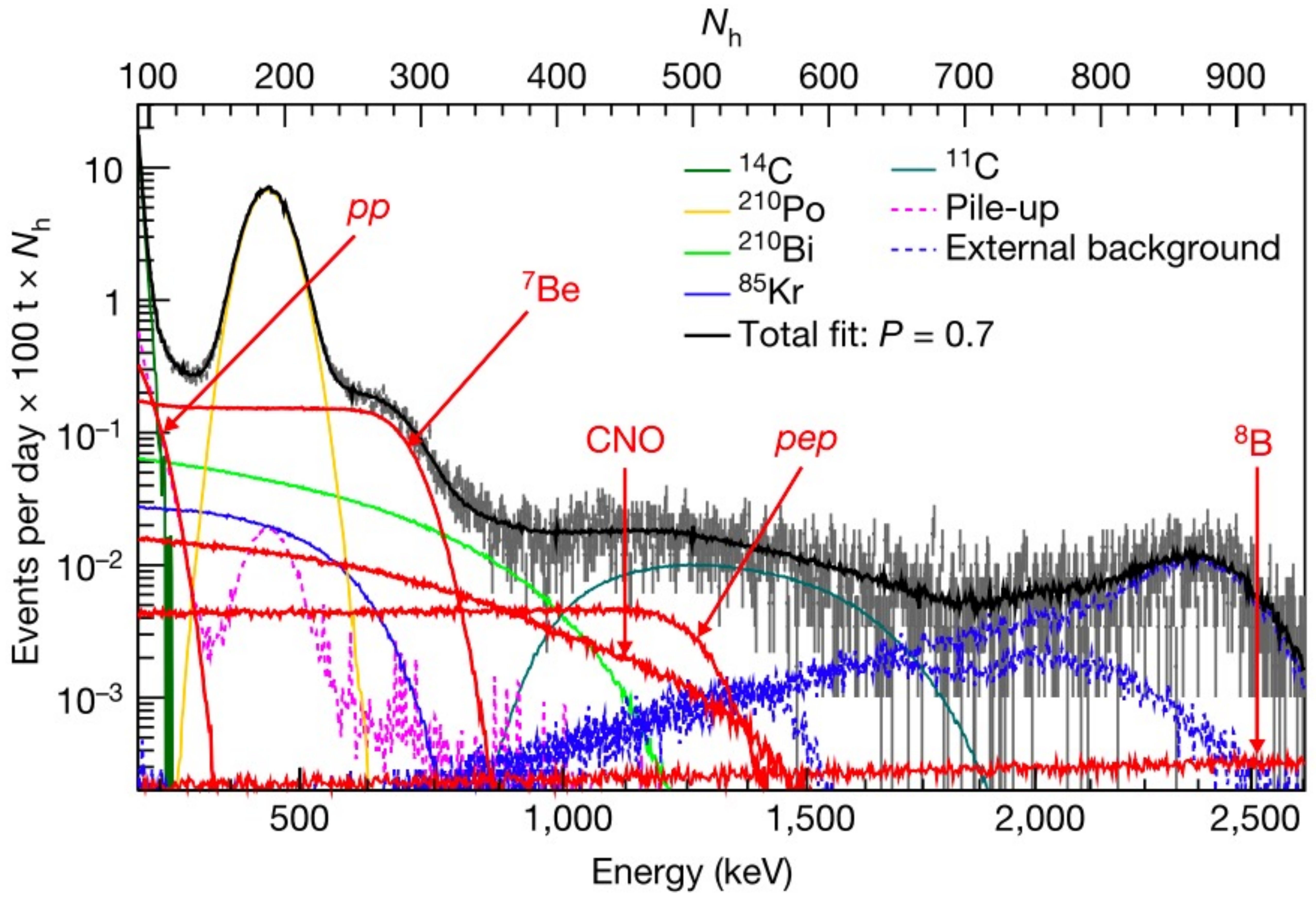
2011 Dec-2016 May
Phase-II

pp+Be7+pep+CNO+^{8}B Nature 2018, PRD 100, 082004, PRD 101.062001
neutrino magnetic moment PRD 96, 091103 (2017)
gravitational wave ApJ 850-21 (2017)
Be7 seasonal modulation AP, 92, 21-29 (2017)
gamma ray burst AP, 86, 11-17, (2017)
electric charge conservation PRL 115,231802(2017)
geo-neutrino PRD 93, 031101 (2015)
…

2016 June - 2021 October
Phase-III

Experimental evidence of CNO neutrinos, Nature 2020
Sensitivity to CNO neutrinos, EPJC 80, 10912020
Search for low energy neutrinos from astrophysical sources, ApJ 102509, 2020
…

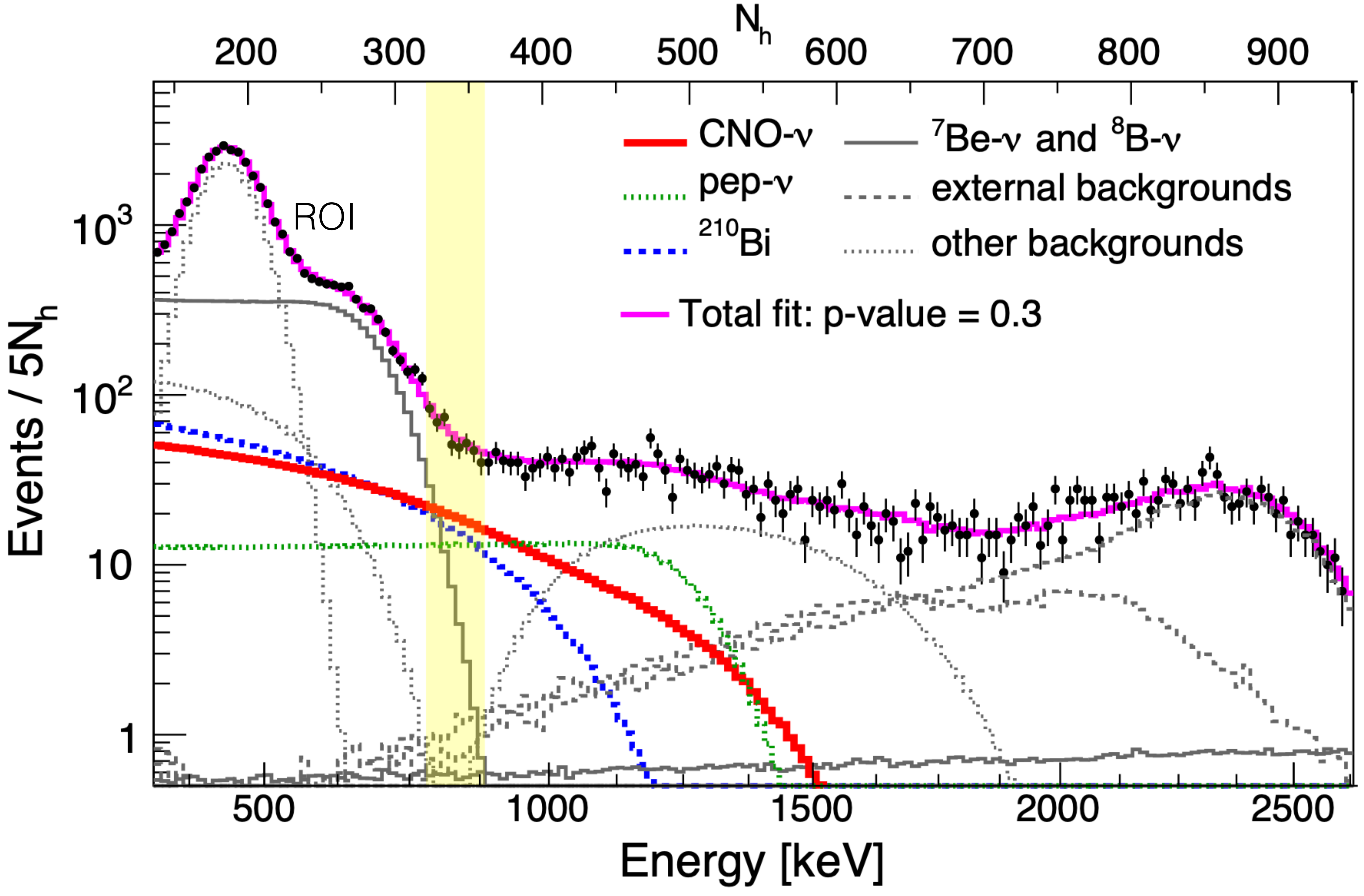
Signals and backgrounds in Borexino



- Recoil electron induced by solar neutrinos (*pp*, ^{7}Be, CNO, *pep*, ^{8}B)
- Internal natural radioactivity (^{210}Po, ^{210}Bi, ^{85}Kr)
- External natural radioactivity
- Cosmogenic radioactivity (^{11}C)
- Pile-ups

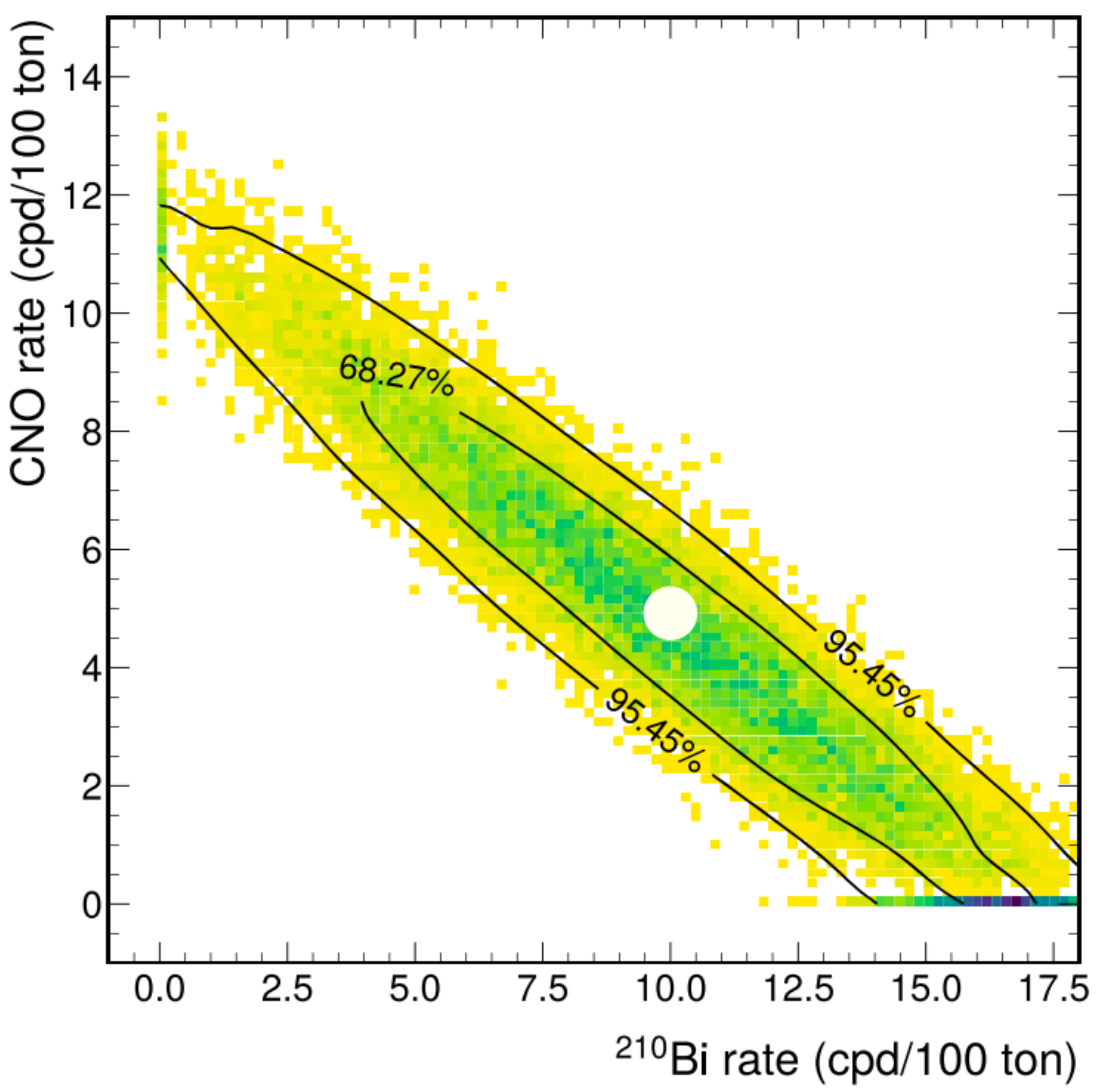
Measuring CNO with Borexino

Shape of CNO and ^{210}Bi



First detection of solar neutrinos from CNO cycle with Borexino. G. Ranucci. Neutrino 2020

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

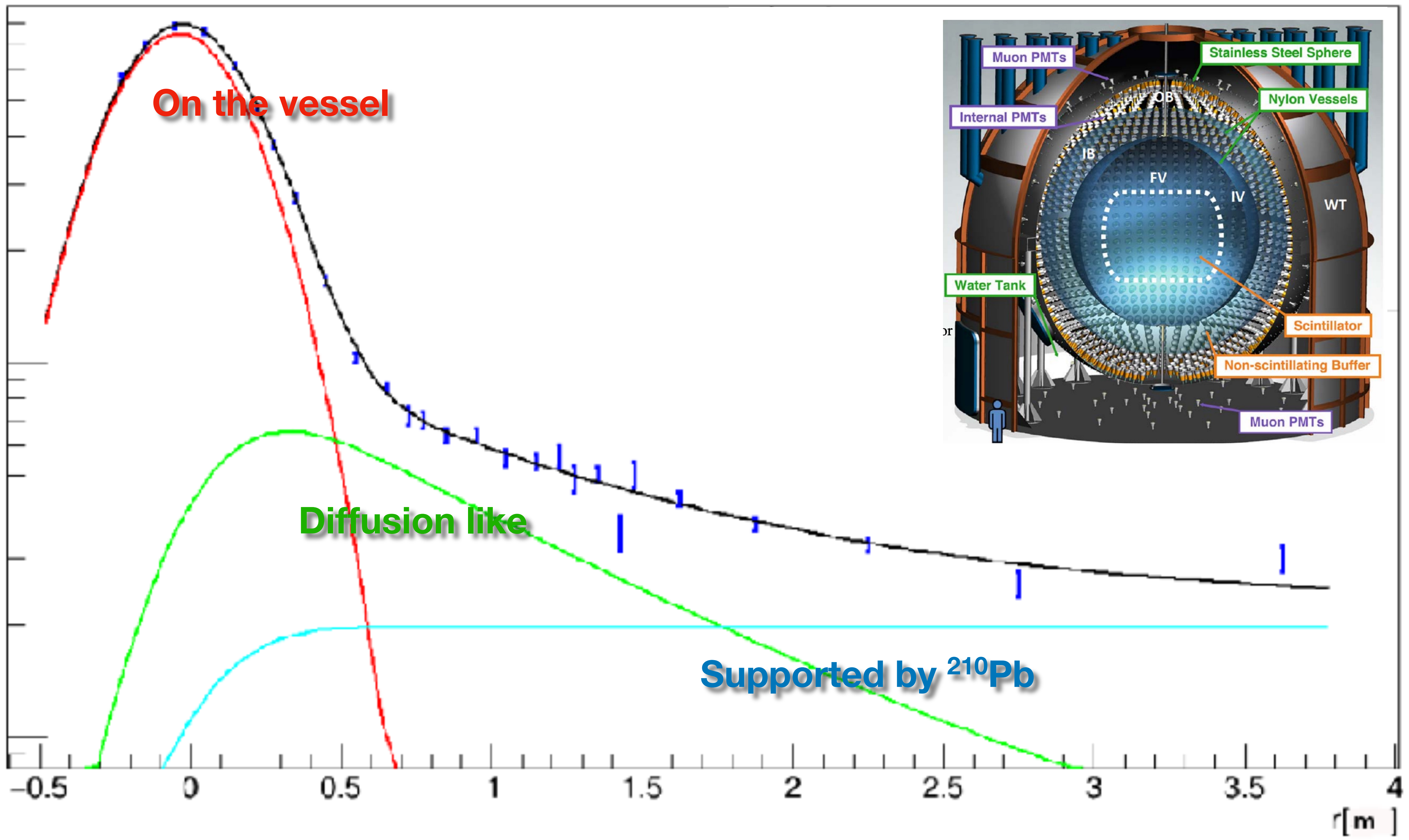


Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. European Physical Journal C, 80(11). https://doi.org/10.1140/epjc/s10052-020-08534-2

- Bulk sensitivity from 0.8—1 MeV. With pep fixed, 0.6 ^{210}Bi+CNO is known well.
- **Once ^{210}Bi is determined, CNO will be measured.**

How to measure ^{210}Bi

Distribution of ^{210}Po events



- ^{210}Po is the decay daughter of ^{210}Bi;
- $^{210}Bi = {}^{210}Po$ @ secular equilibrium;
- Extra ^{210}Po brought into FV by convection & migration:

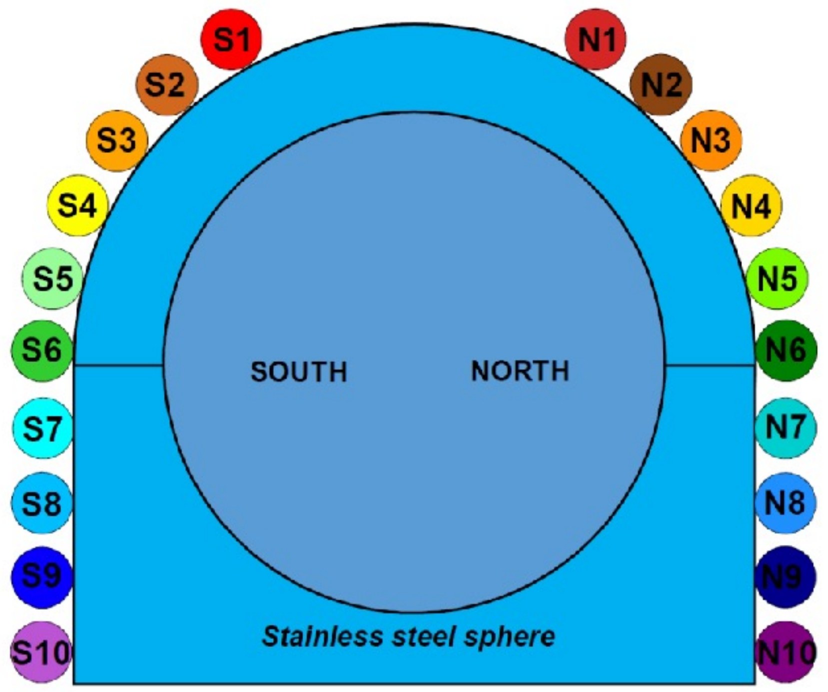
R(^{210}Bi) < R(^{210}Po) + migrated ^{210}Po

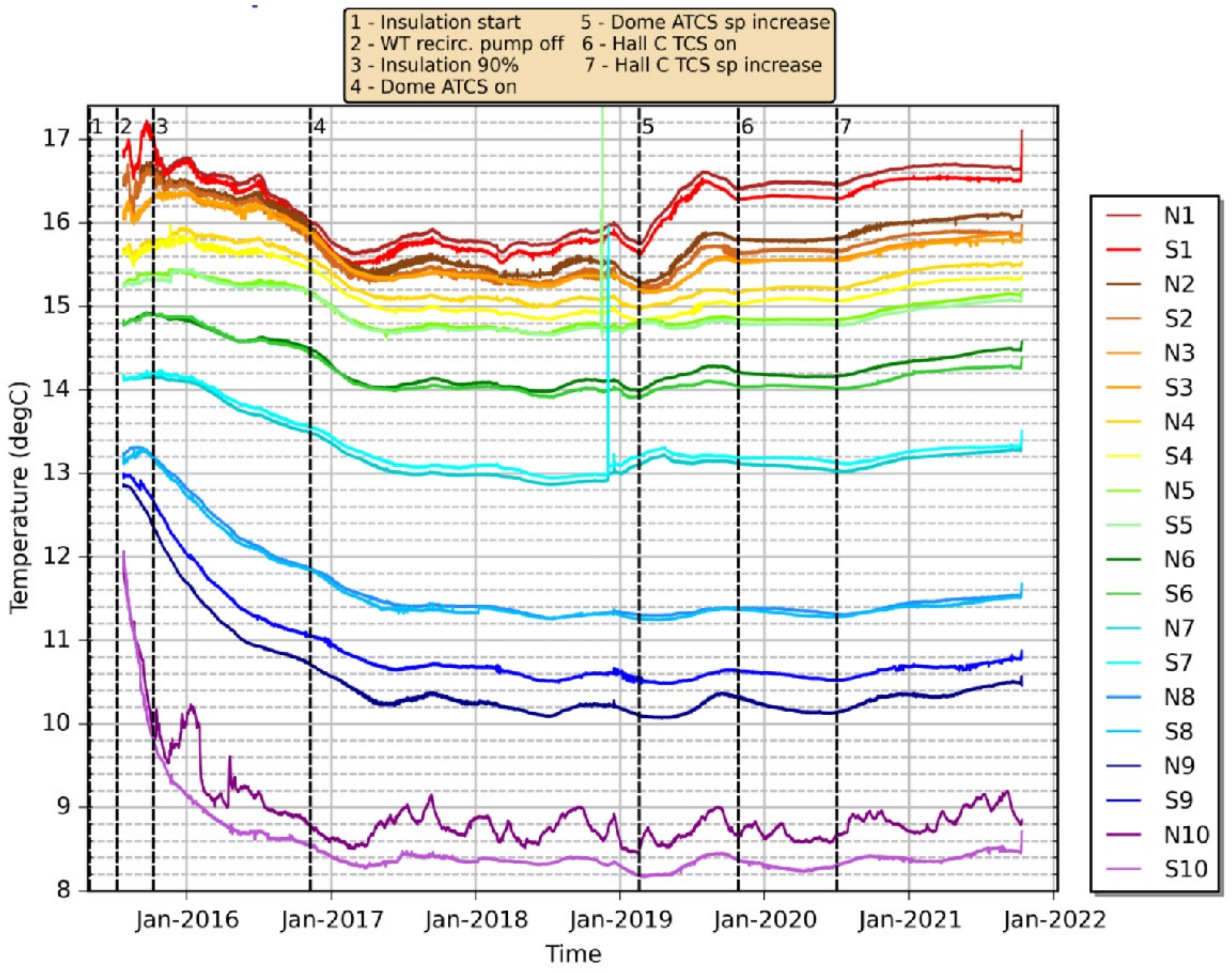
Efforts to suppress the convection motion.

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 964, 1 June 2020, 163801

Fluid-dynamics and transport of ^{210}Po in the scintillator Borexino detector: A numerical analysis

V. Di Marcello [a], D. Bravo-Berguño [b, 1], R. Mereu [c], F. Calaprice [d], A. Di Giacinto [a], A. Di Ludovico [d], Aldo Ianni [a], Andrea Ianni [d], N. Rossi [a], L. Pietrofaccia [d]



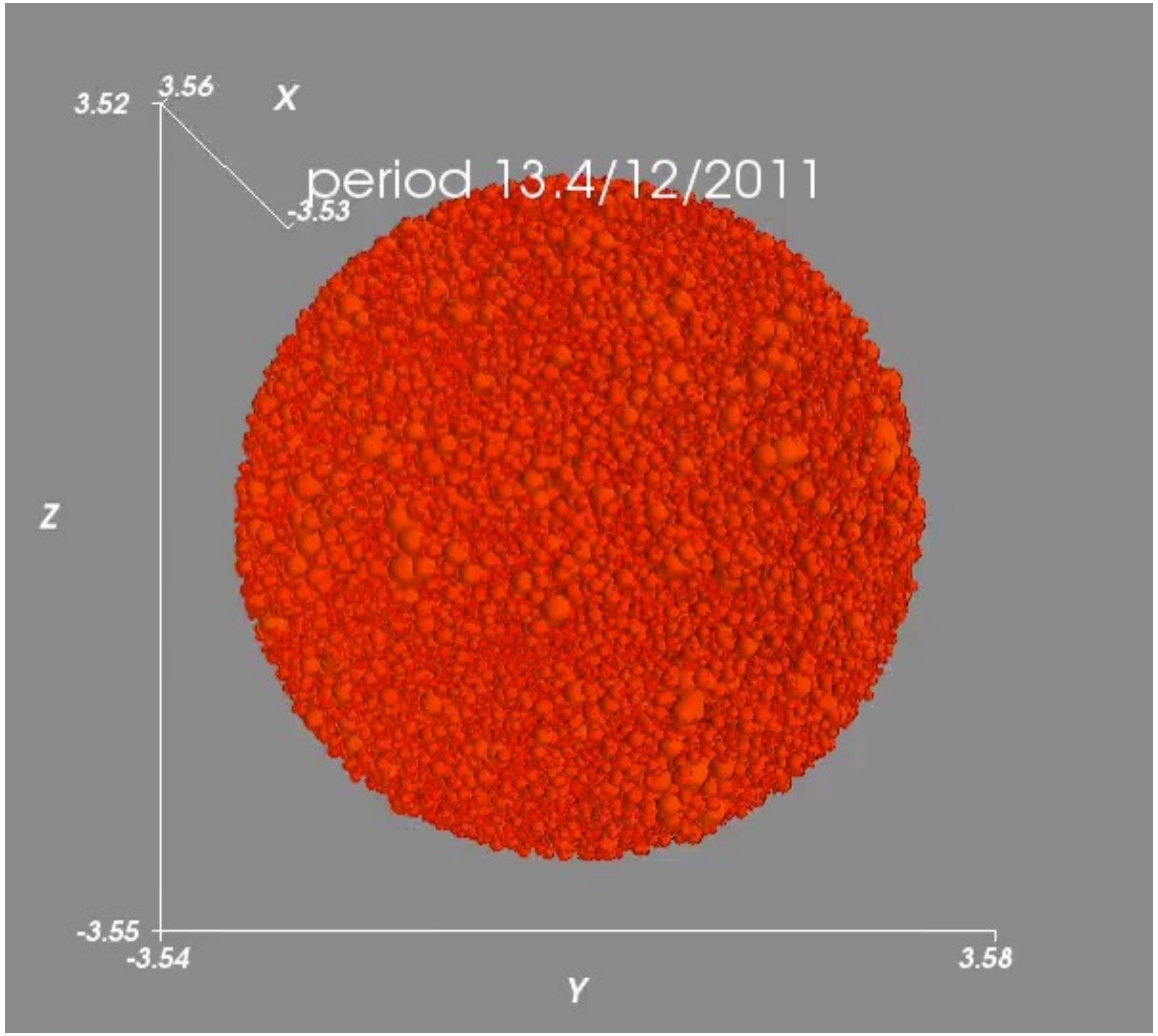


/2006.15115

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

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

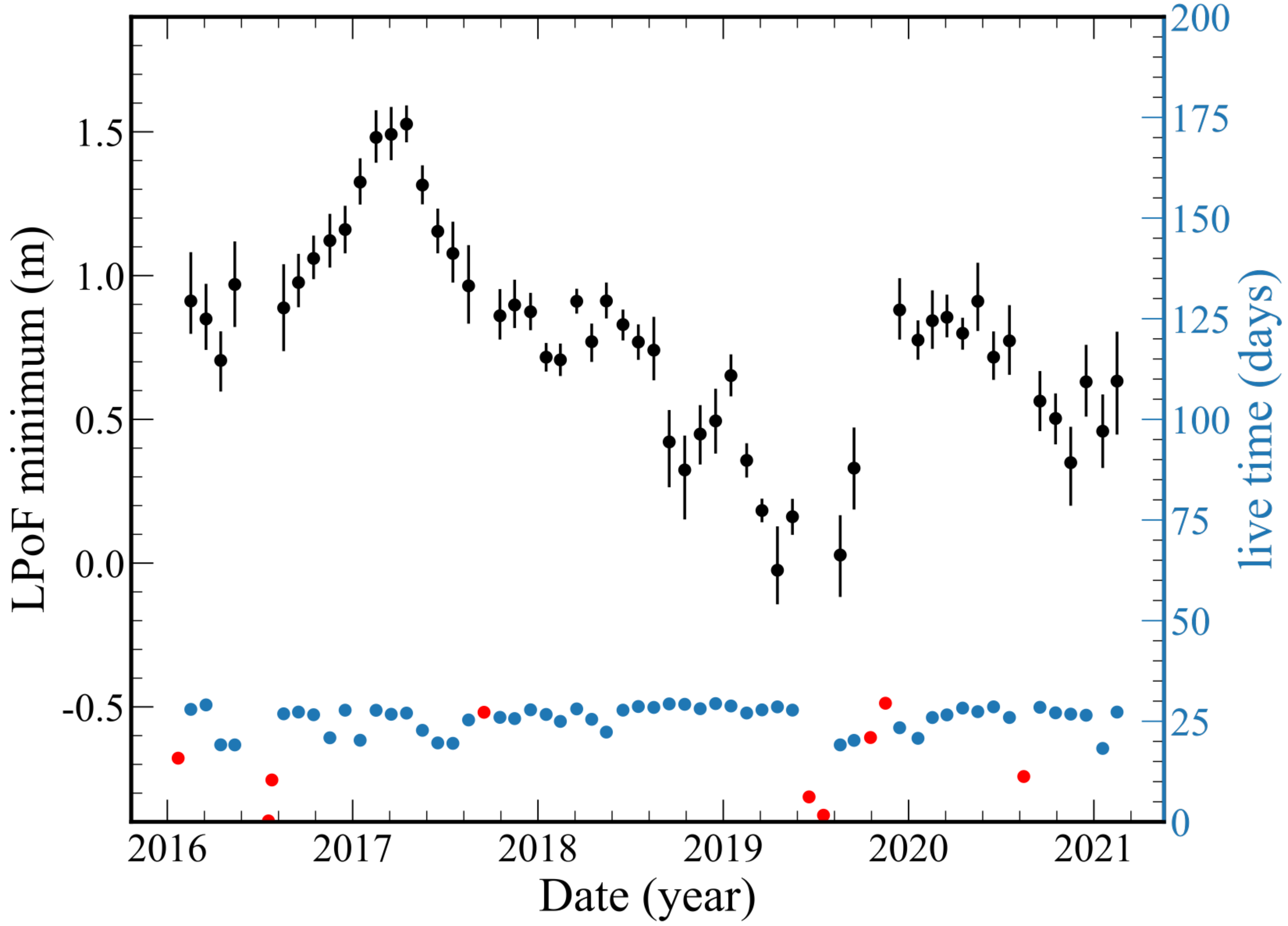
Formation of Low Polonium Field (LPoF)



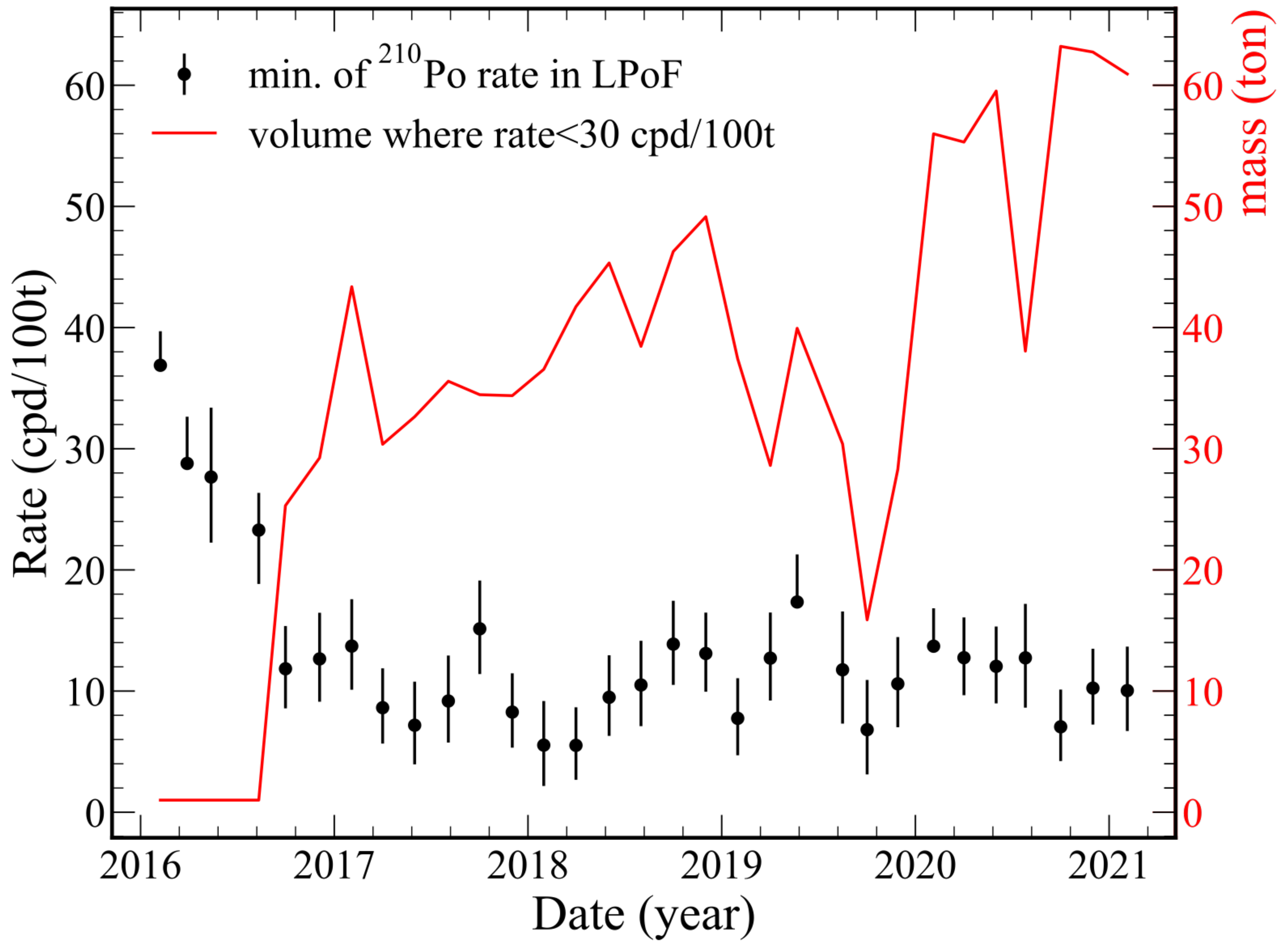
- Large cold dot: low rate;
  Small hot dot: high rate
- 2011-2013: high rate of ^{210}Po left after purification
- 2014-2016: seasonal up and down of low Polonium region (LPoF)
- After 2016: **LPoF relatively stable**

Behavior of Low Polonium Field

Position



Rate



- Relatively stable, but still moving
- Rate @ minimum stable, maybe convection free

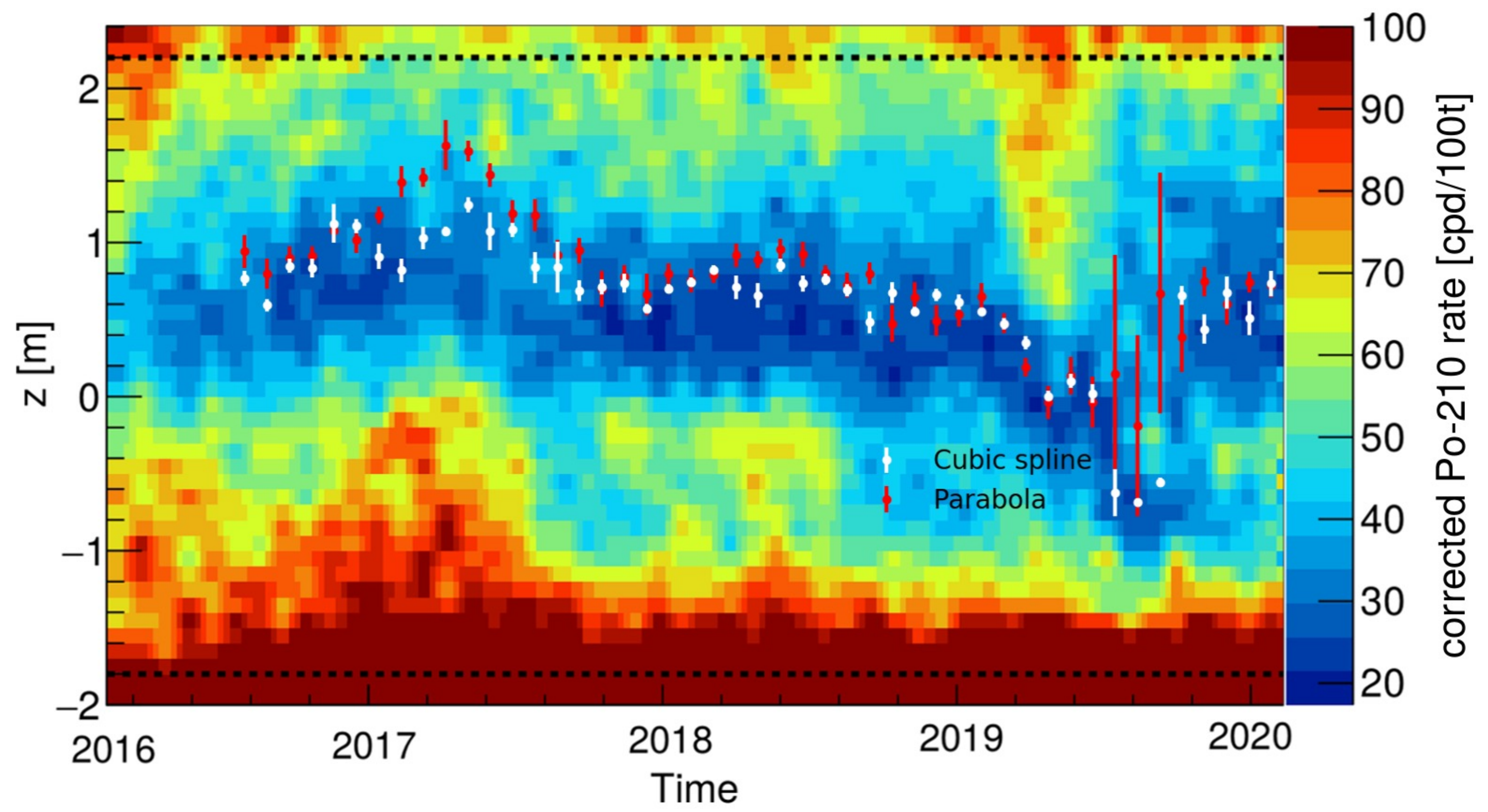
https://characters.fandom.com/wiki/Bambi

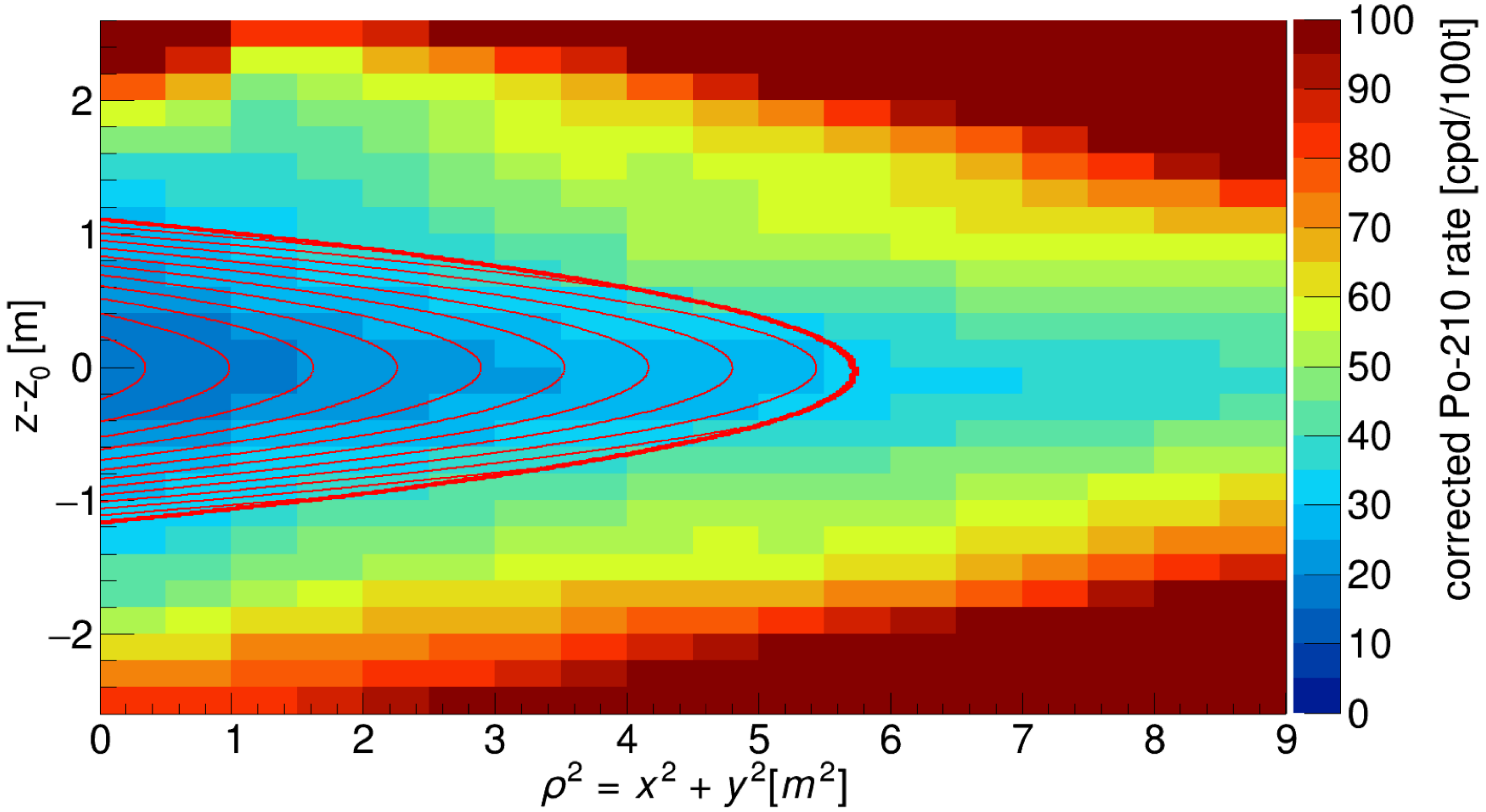
Blind Aligned Merged

parabolic Bubble fIt

(BAMBI)

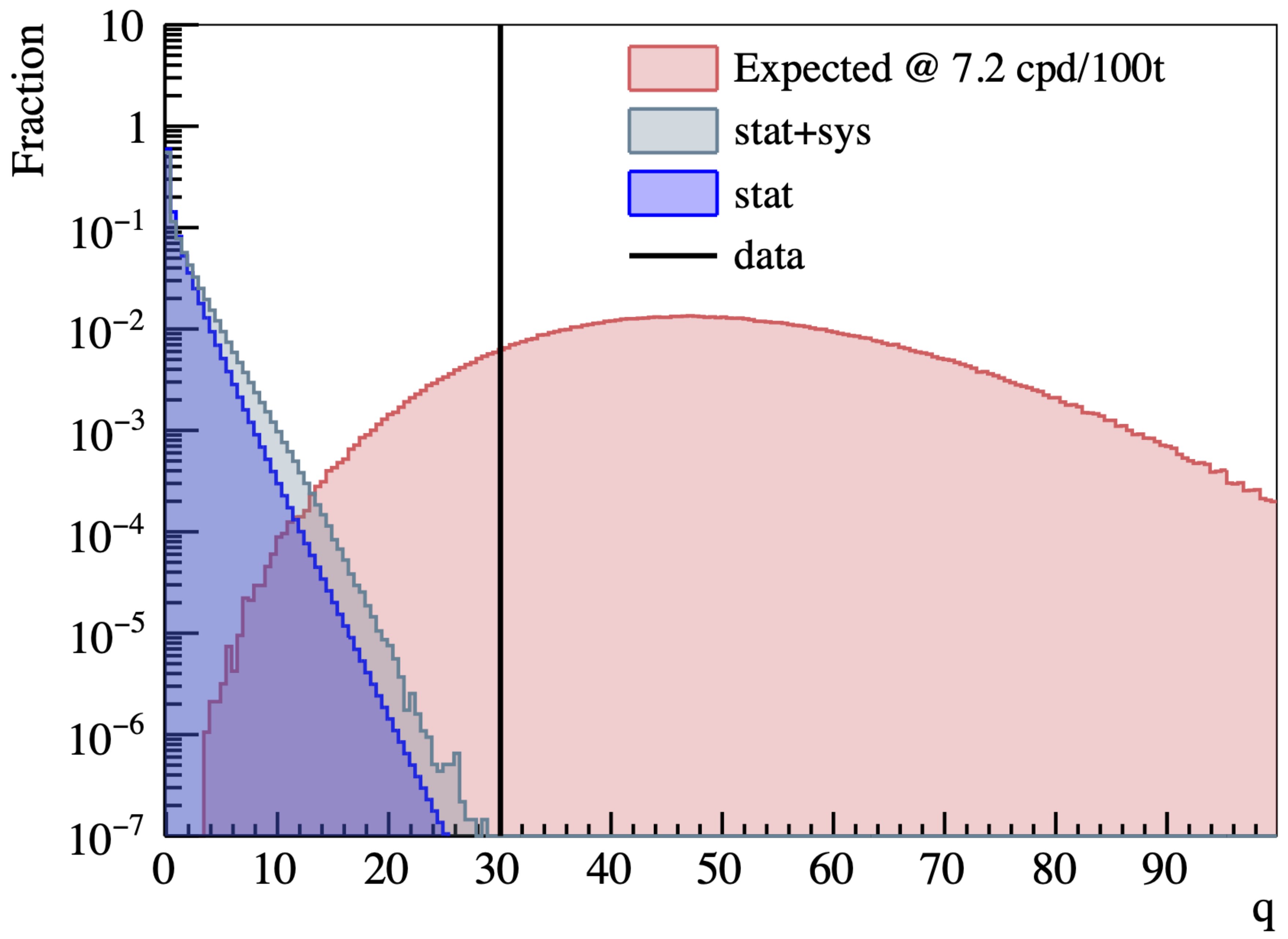
Low Polonium Field (LPoF) analysis

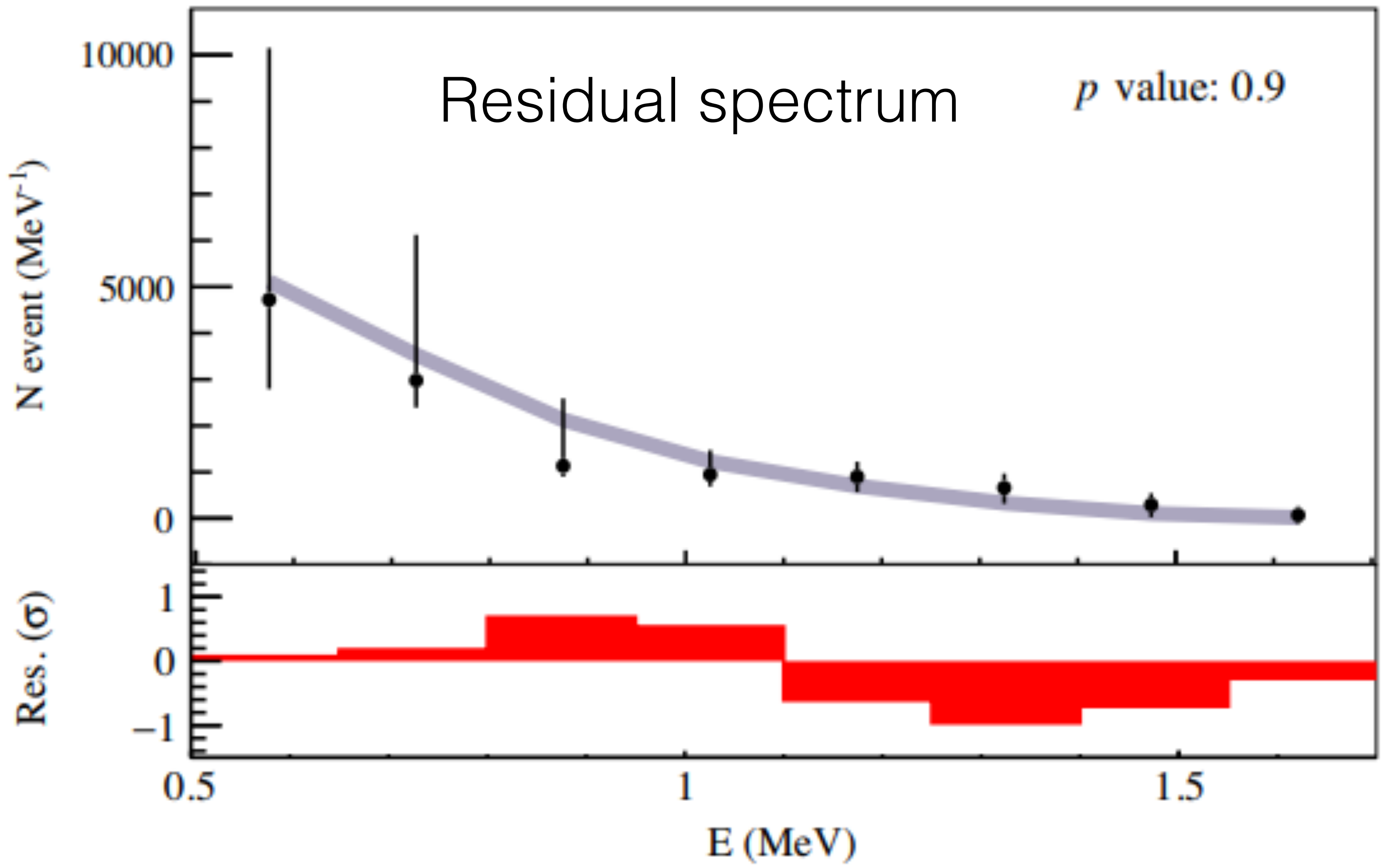




- Residual convection remains
- Low Polonium Field formed at center
- Correct movement of LPoF (Blind alignment)
- Fit event distribution in a bubble shape region in 2D with parabolic functions (bubble fit)
- Previous analyses: no correction, 1D fit; (2σ =>5σ)

Test against no-CNO hypothesis

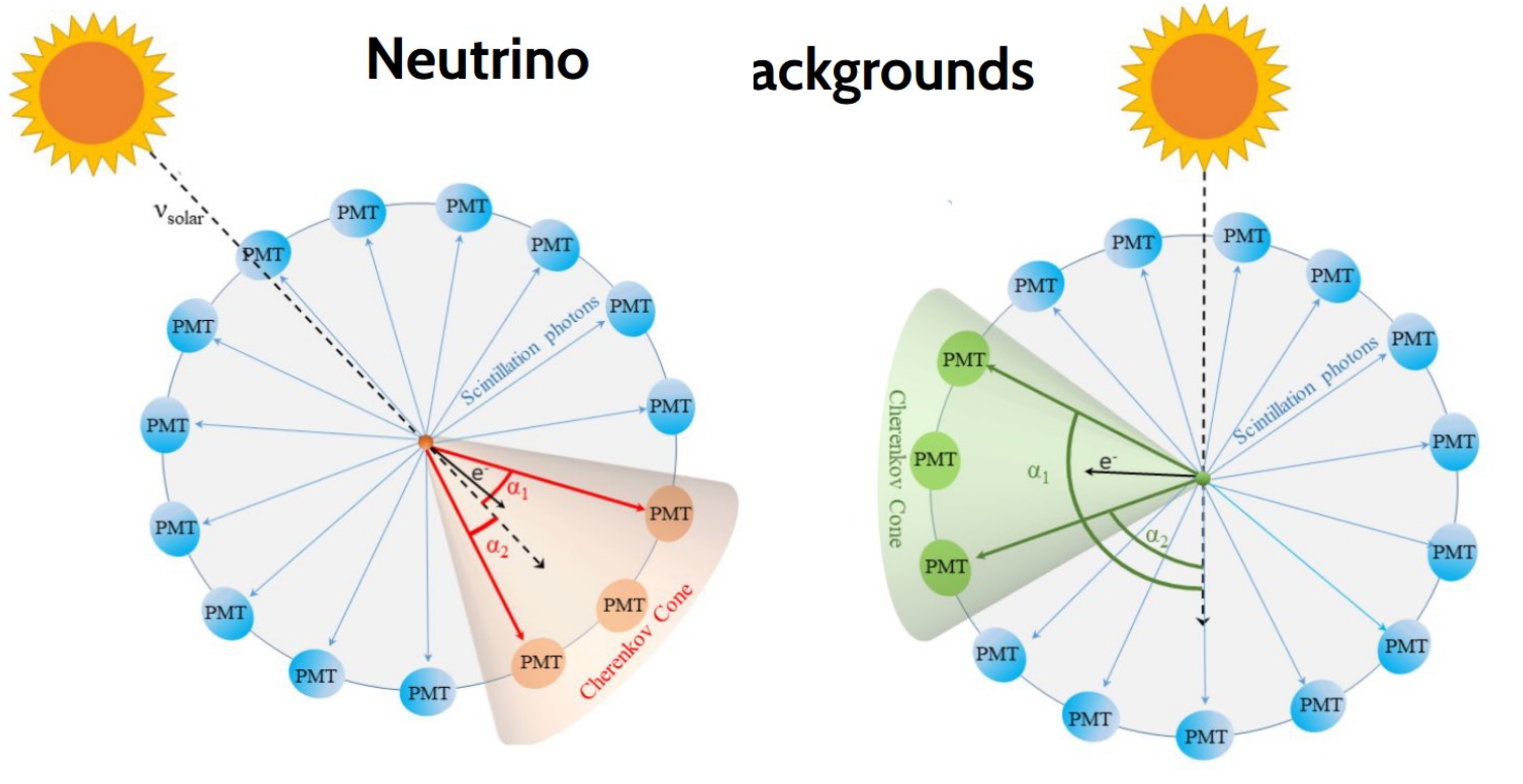


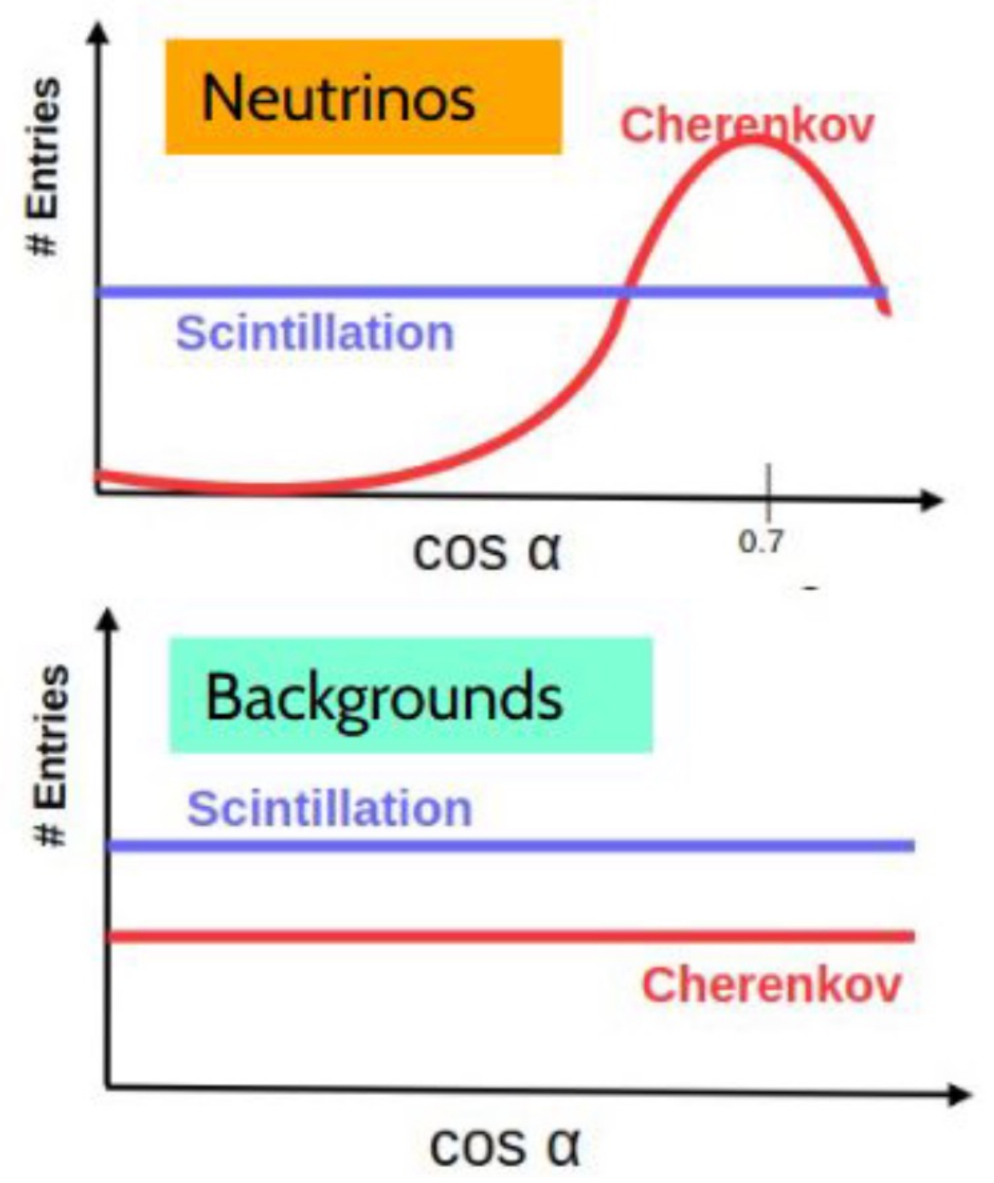


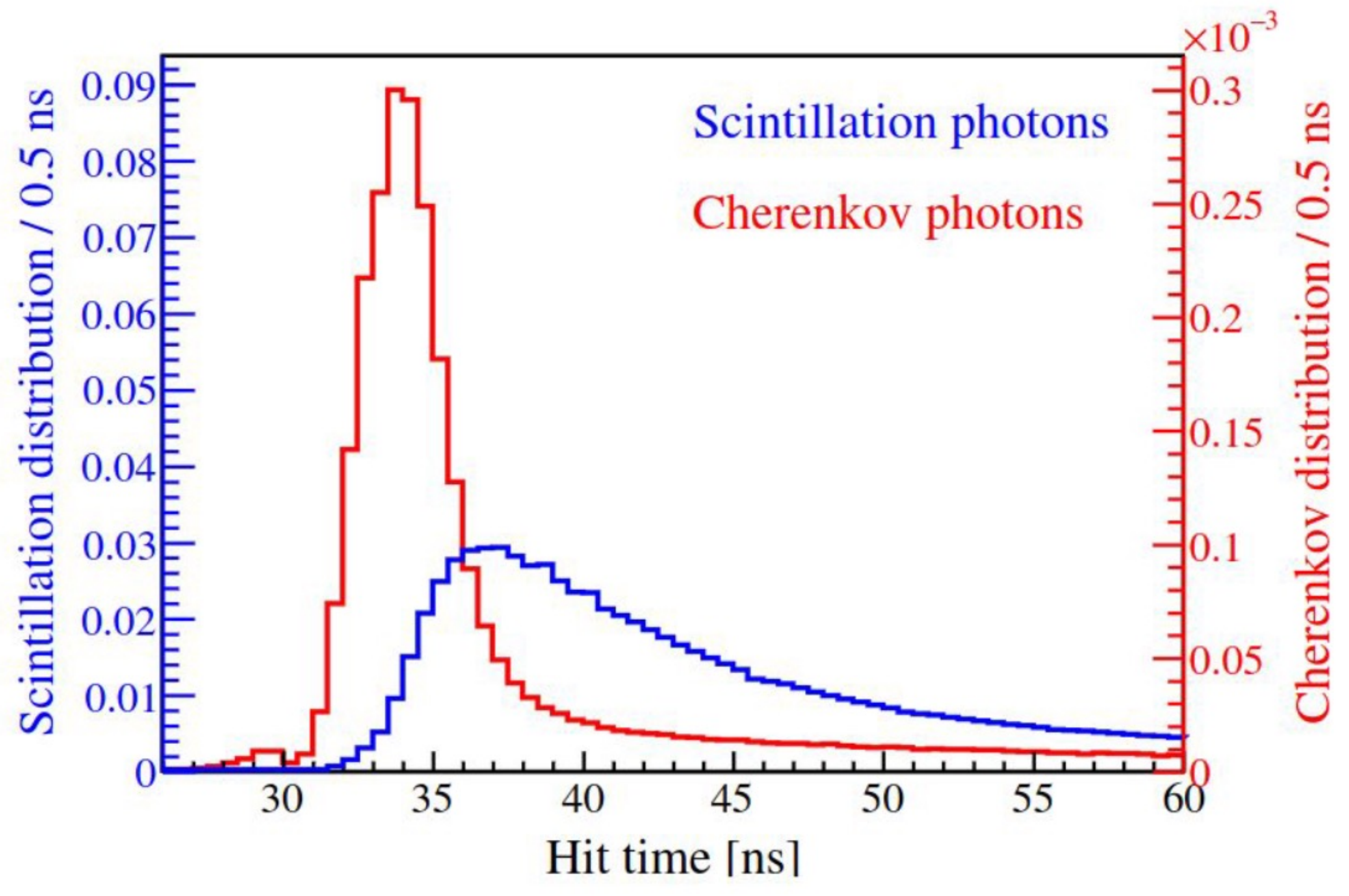
- Profile likelihood as the test statistic
- Use toy-MC method to get the distribution of test statistic. Evaluated p-value has statistical uncertainty.
- Simulated & Fitted 14million dataset
- **5 σ* rejection of no-CNO hypothesis**

*Evaluated with toyMC method and it's >5σ at 99% C.L.

Technology of Correlated and Integrated Directionality (CID)

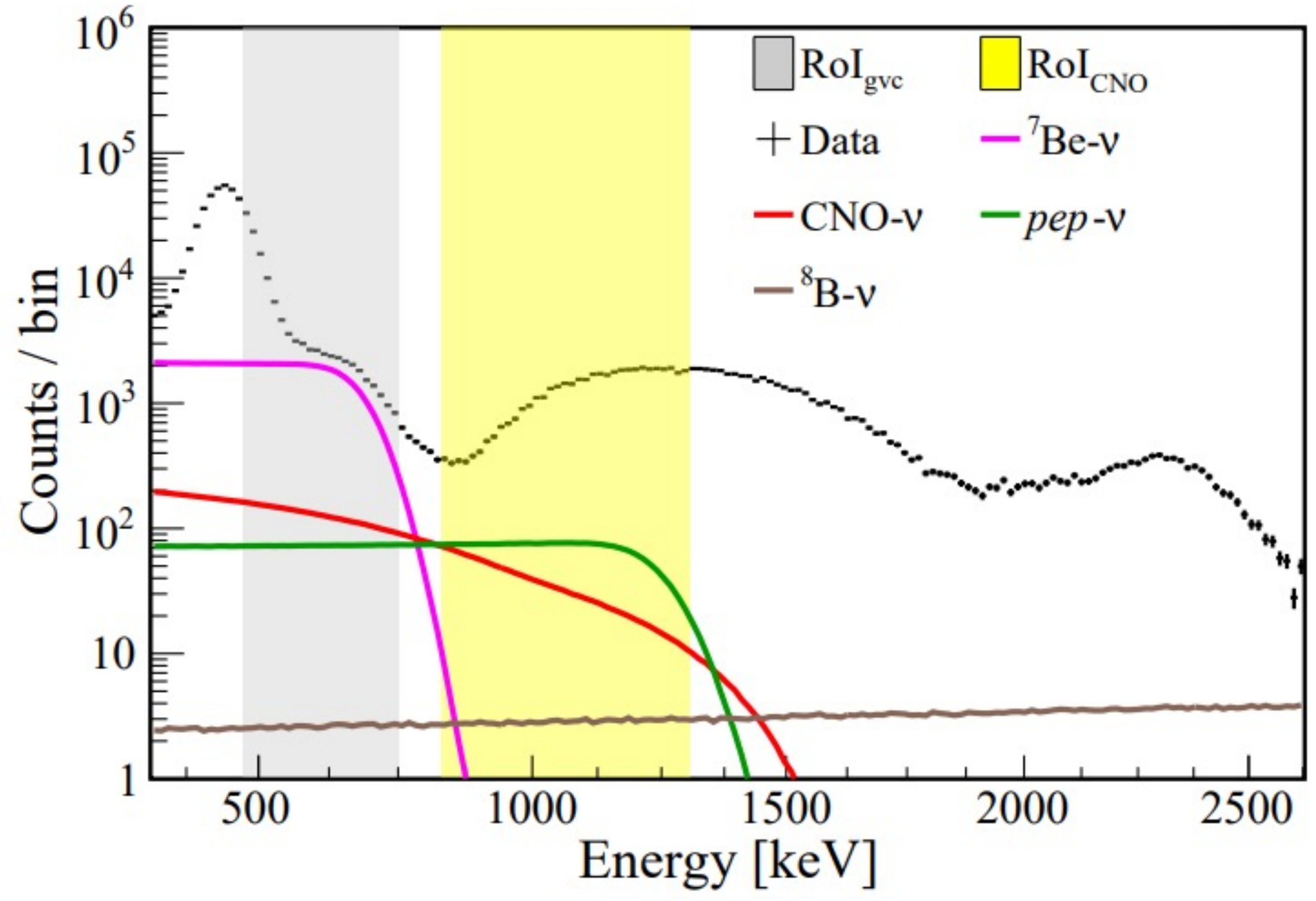


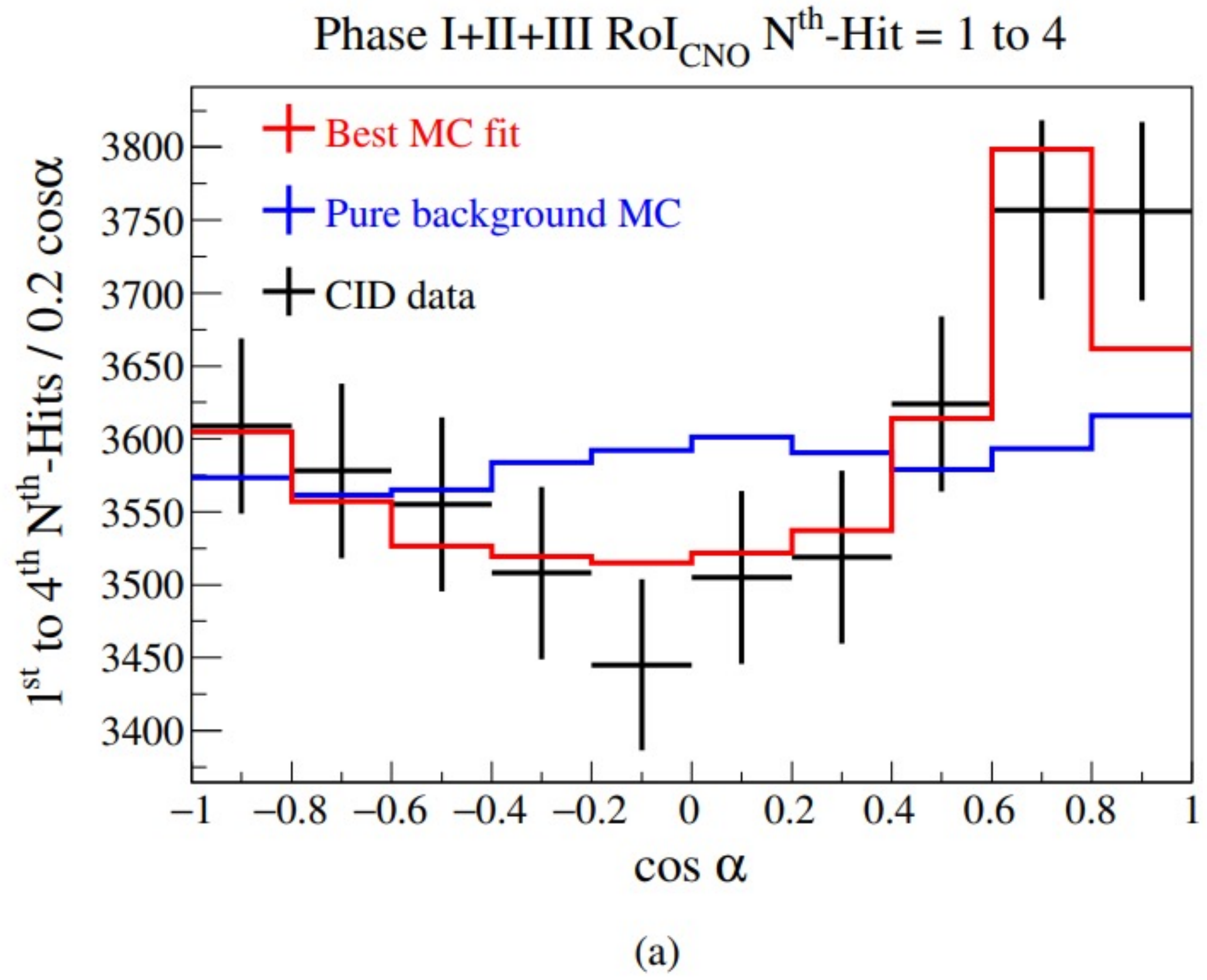


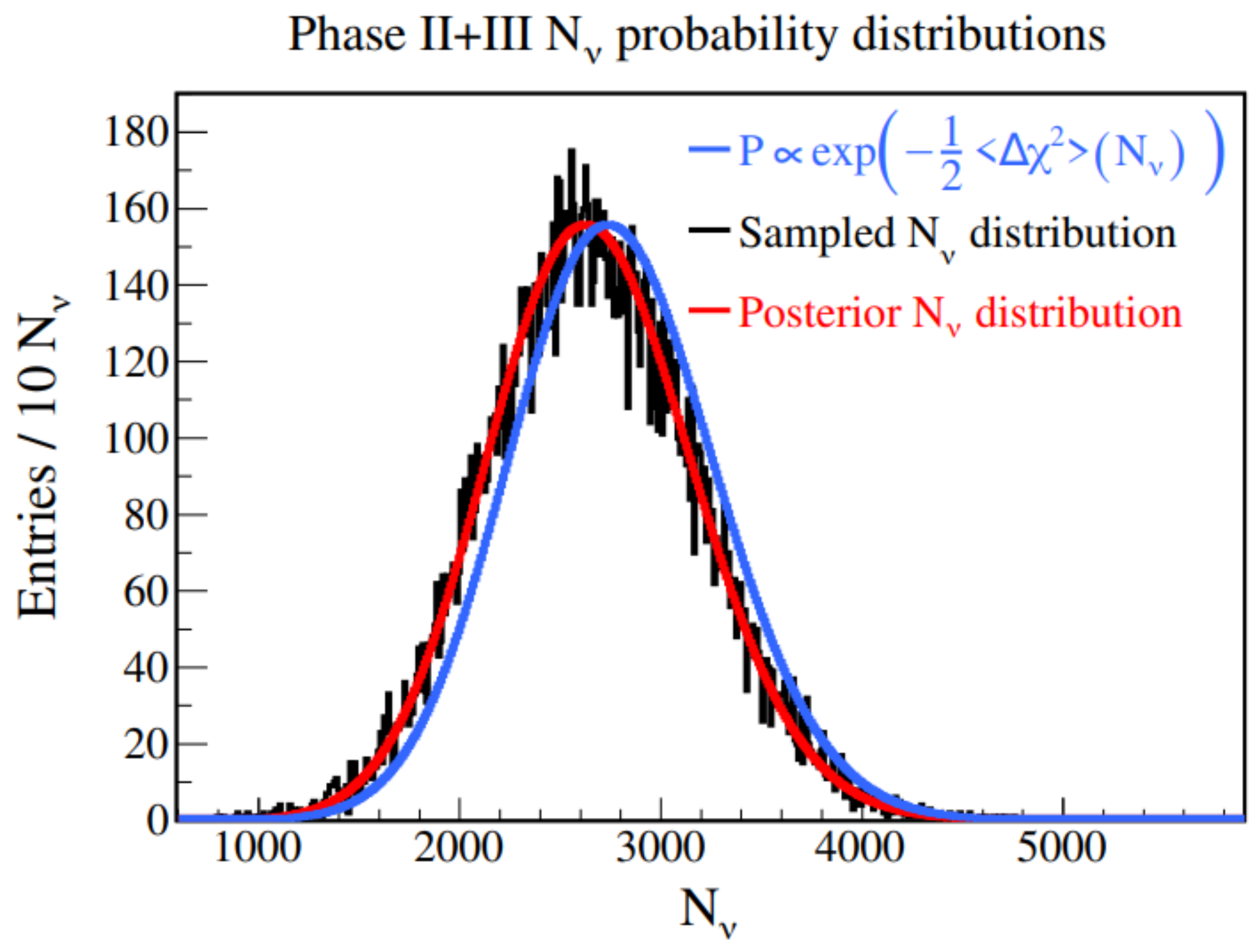


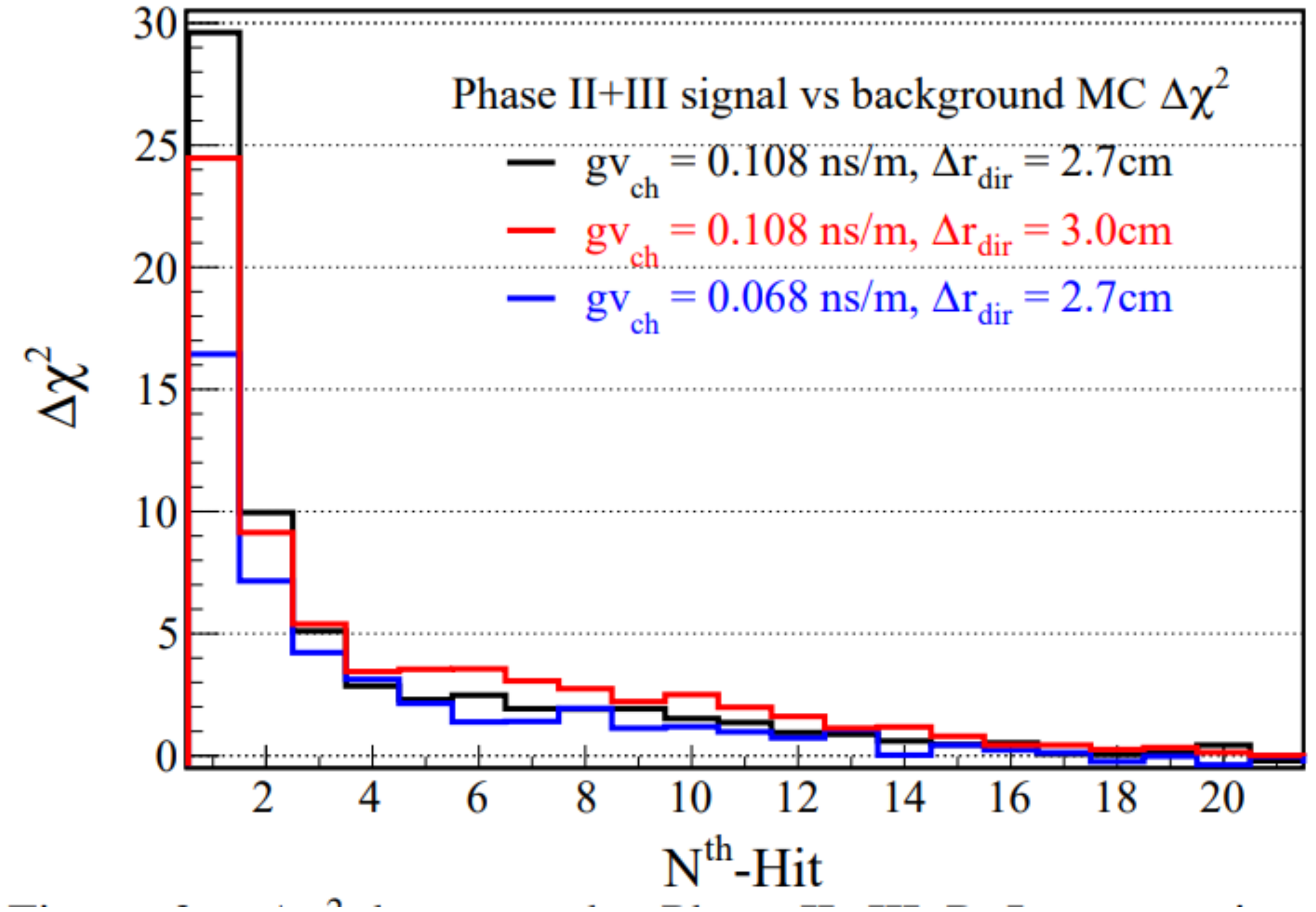
- Use integrated hit-level directional distribution to distinguish between solar events and uniform backgrounds.
- Discriminate Cherenkov photons and Scintillation photons with hit order.

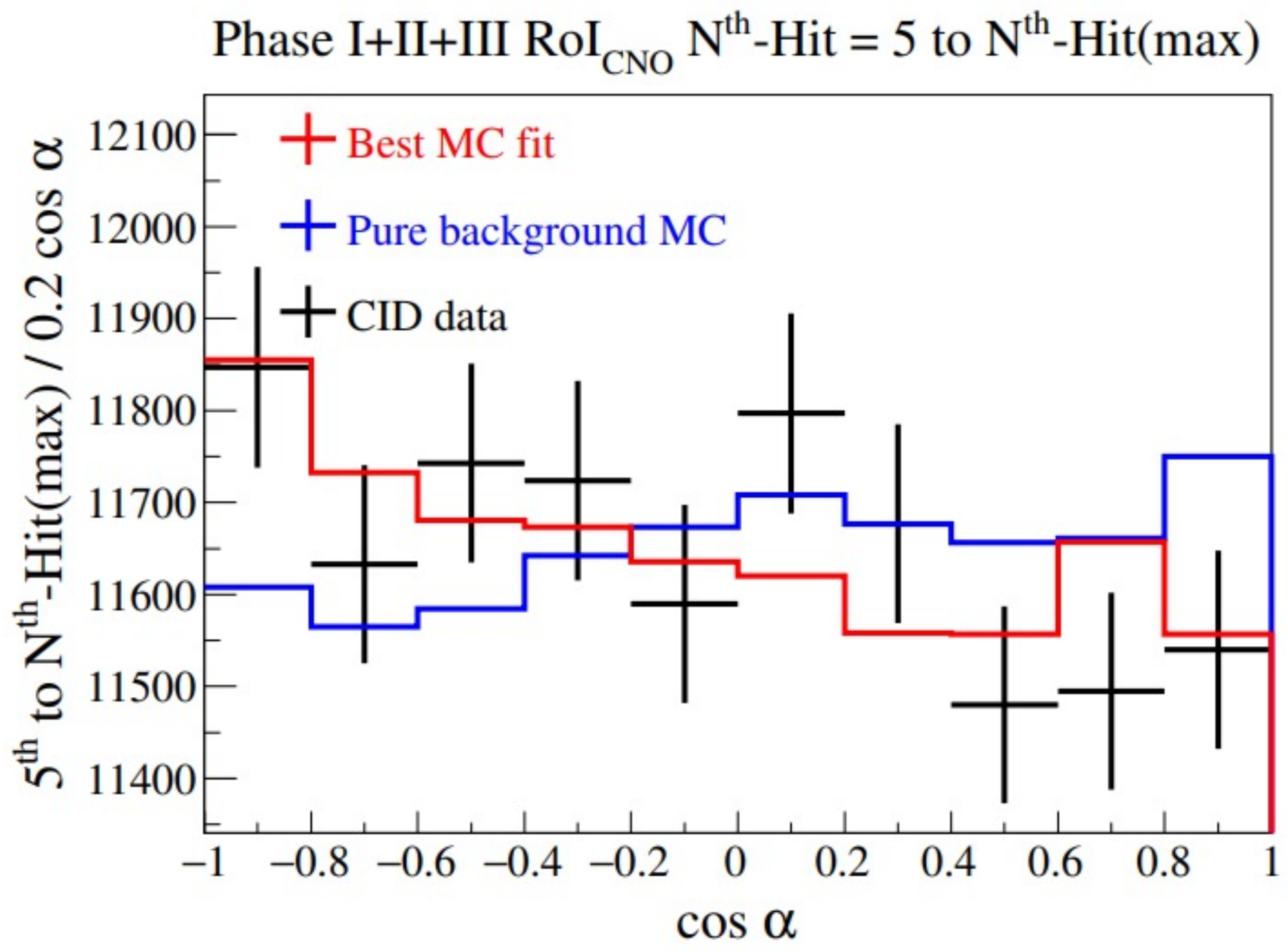
Borexino CNO with CID only







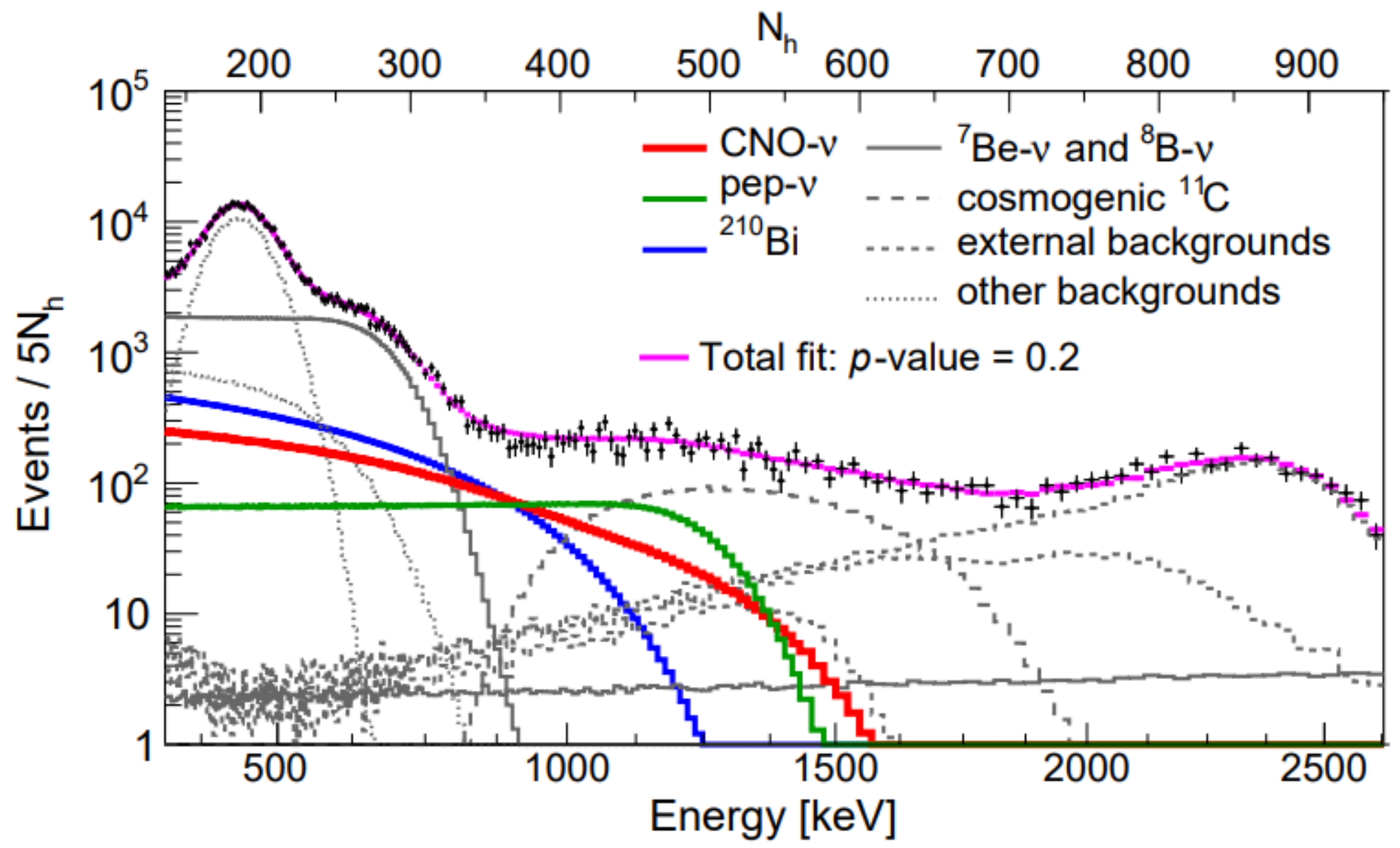


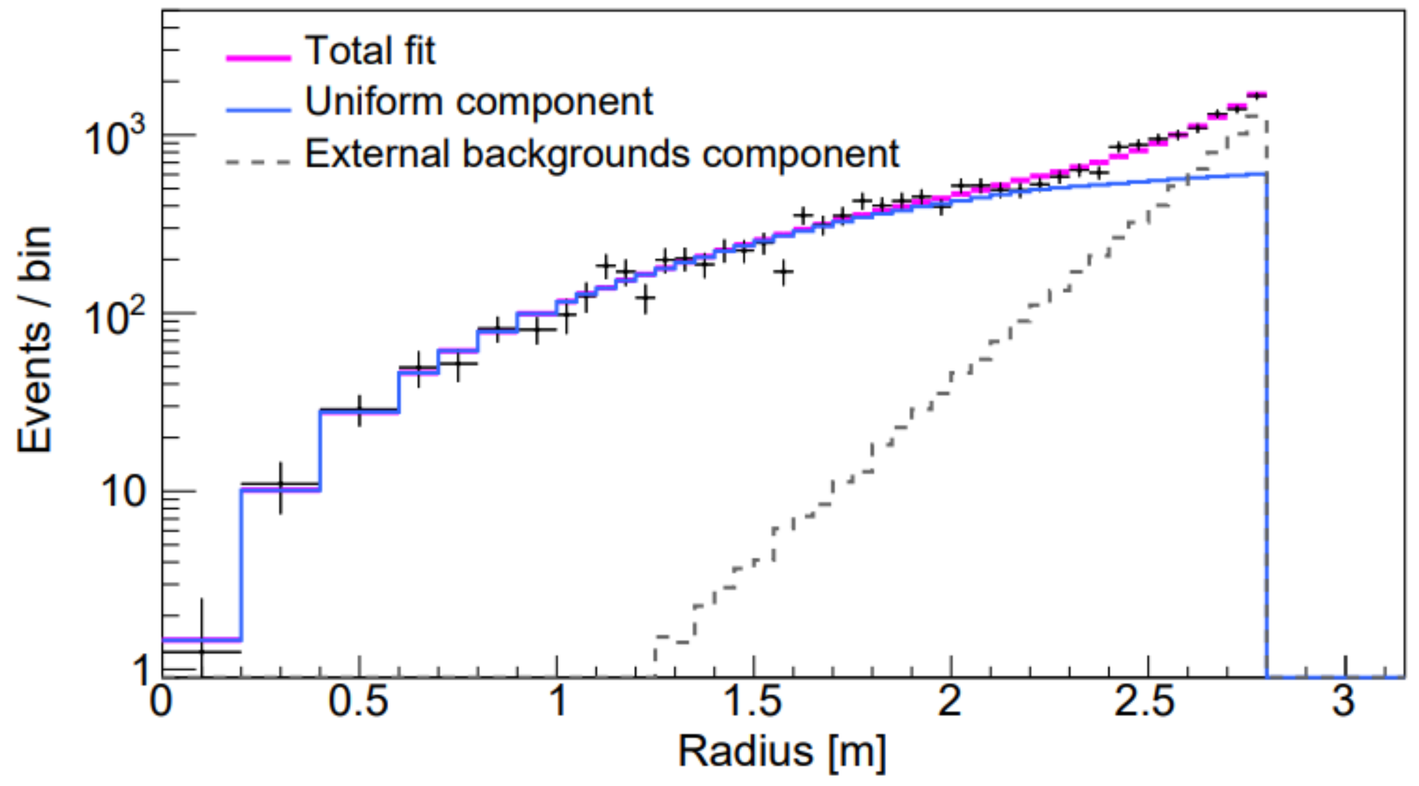


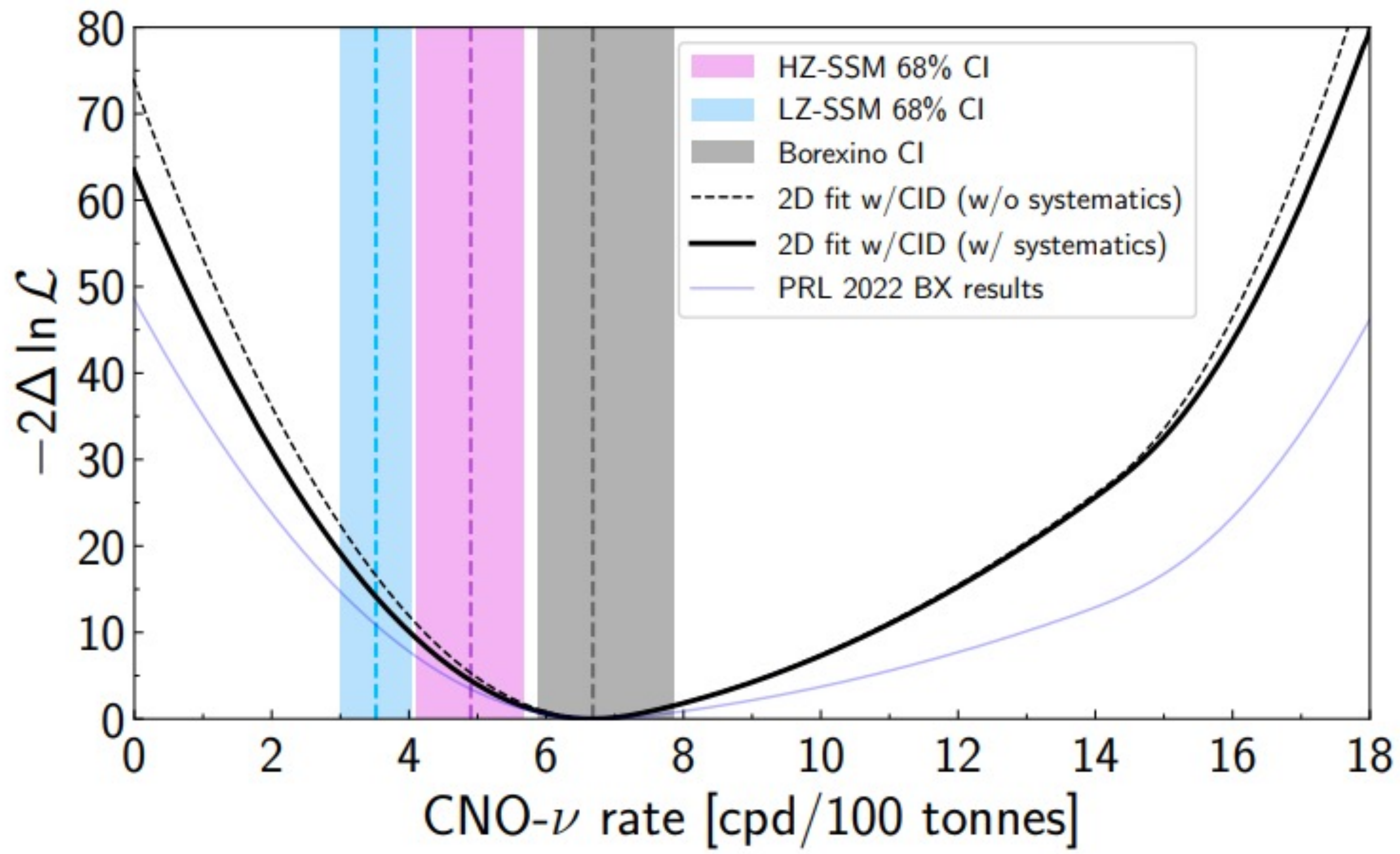
- CID with events in the CNO region of interest, $7.2^{+2.8}_{-2.7}$ cpd/100t
- 5.3σ rejection of no-CNO hypothesis
- Consistent with fit results.

Borexino CID + MV fit

$$\mathcal{L}_{\mathrm{MV+CID}} = \mathcal{L}_{\mathrm{MV}} \cdot \mathcal{L}_{\mathrm{pep}} \cdot \mathcal{L}_{^{210}\mathrm{Bi}} \cdot \mathcal{L}_{\mathrm{CID}}^{\mathrm{P-I}} \cdot \mathcal{L}_{\mathrm{CID}}^{\mathrm{P-II+III}} \quad (4)$$



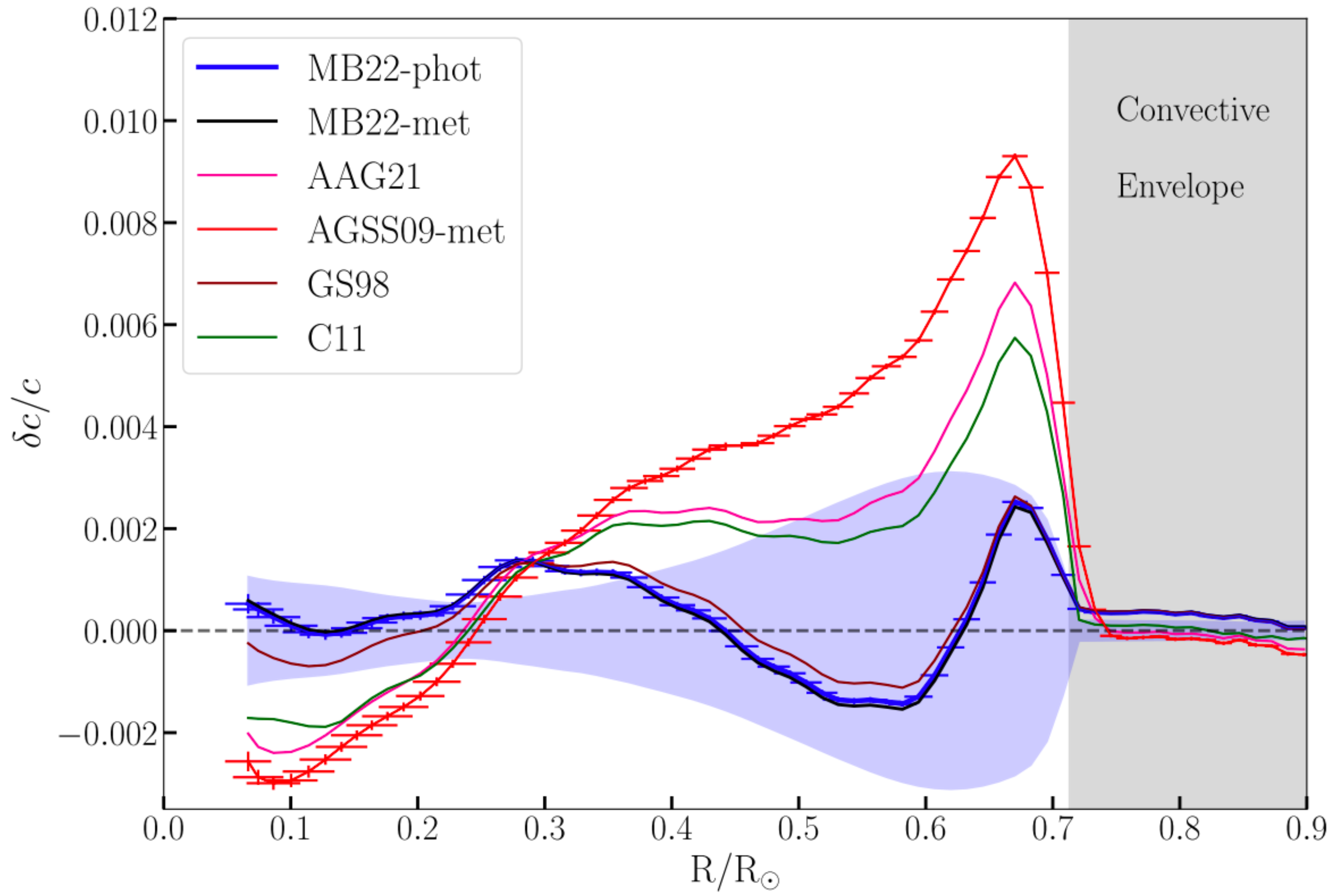




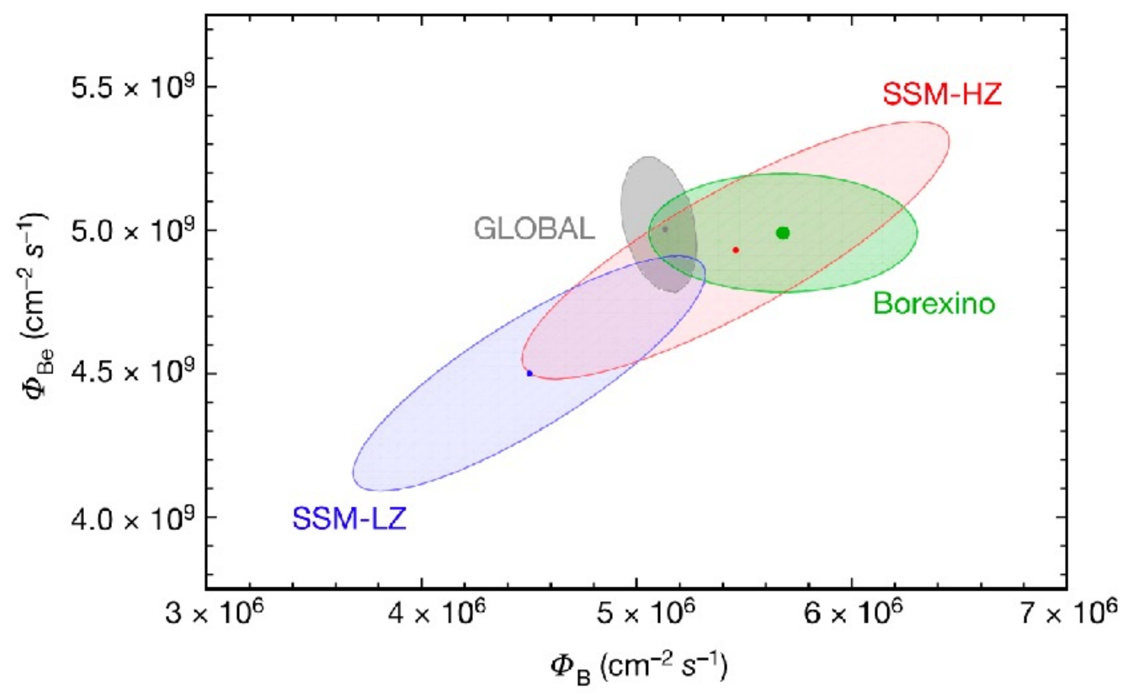
- Combining MV fit, CID analysis, Borexino obtained CNO as $6.7^{+1.2}_{-0.8}$ cpd/100t
- See Final results of Borexino on CNO solar neutrinos, Borexino Collaboration, Phys. Rev. D **108**, 102005

Solar abundance problem and Solar neutrinos

Sound speed profile

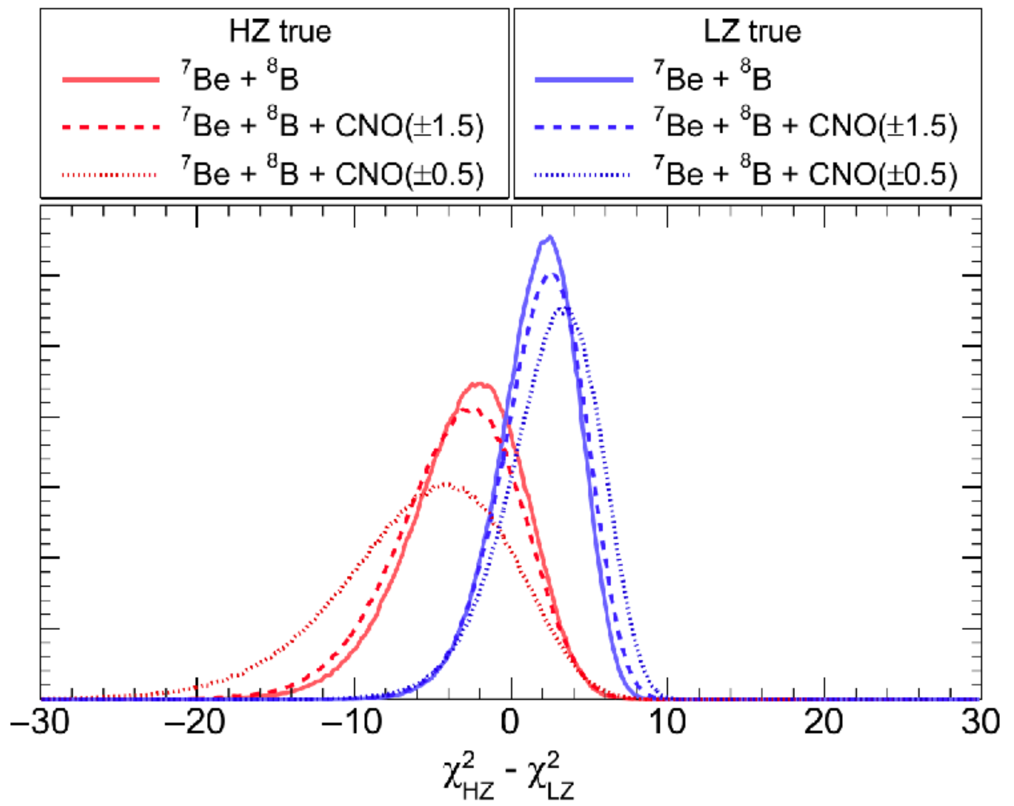


E. Magg et al. v2203.02255



Solar neutrino fluxes

Borexino Collaboration (2018). Comprehensive measurement of pp-chain solar neutrinos. Nature, 562(7728), 505–510.



Hypothesis test against SSM-HZ/LZ

Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. EPJC, 80(11).

- Volatile metal abundances is reconstructed from absorption lines.
- Various (say, HZ vs LZ) models exists. Neutrino fluxes can be used to test them.

pp-chain + CNO-cycle cancellation

- SSM inputs
  - Environmental, impact T_c (core temperature) Solar parameters, Heavy metal abundance;
  - Nuclear, not impacting T_c Nuclear matrix element
- If we modify "env without CN", T_c is modified, **ln Φ(^{8}B) vs ln Φ(^{15}O)** graph fall on the diagonal line
- If we modify also nuclear + CN: Environmental, impact T_c **ln Φ(^{8}B) vs ln Φ(^{15}O)** move away from diagonal
- Jacobian **Φ(^{8}B) vs Φ(^{15}O)** => **ln Φ(^{8}B) vs ln Φ(^{8}B)-κ ln Φ(^{15}O)**
  - **ln Φ(^{8}B)-κ ln Φ(^{15}O)** insensitive to "env without CN";
  - **ln Φ(^{8}B)-κ ln Φ(^{15}O)** (almost) only depend on nuclear + CN

Definitions

$\{Q\}$: SSM outputs $\quad q_i = Q_i/Q_i^{SSM}$

$\{\beta\}$: SSM inputs $\quad x_i = \beta_i/\beta_i^{SSM}$

$\alpha(i,j): \dfrac{\partial \ln q_i}{\partial \ln x_j}$

$$q_i = \prod_j^{sol} (x_j)^{\alpha(i,j)} \cdot \prod_j^{nucl} (x_j)^{\alpha(i,j)} \cdot \prod_j^{met} (x_j)^{\alpha(i,j)}$$

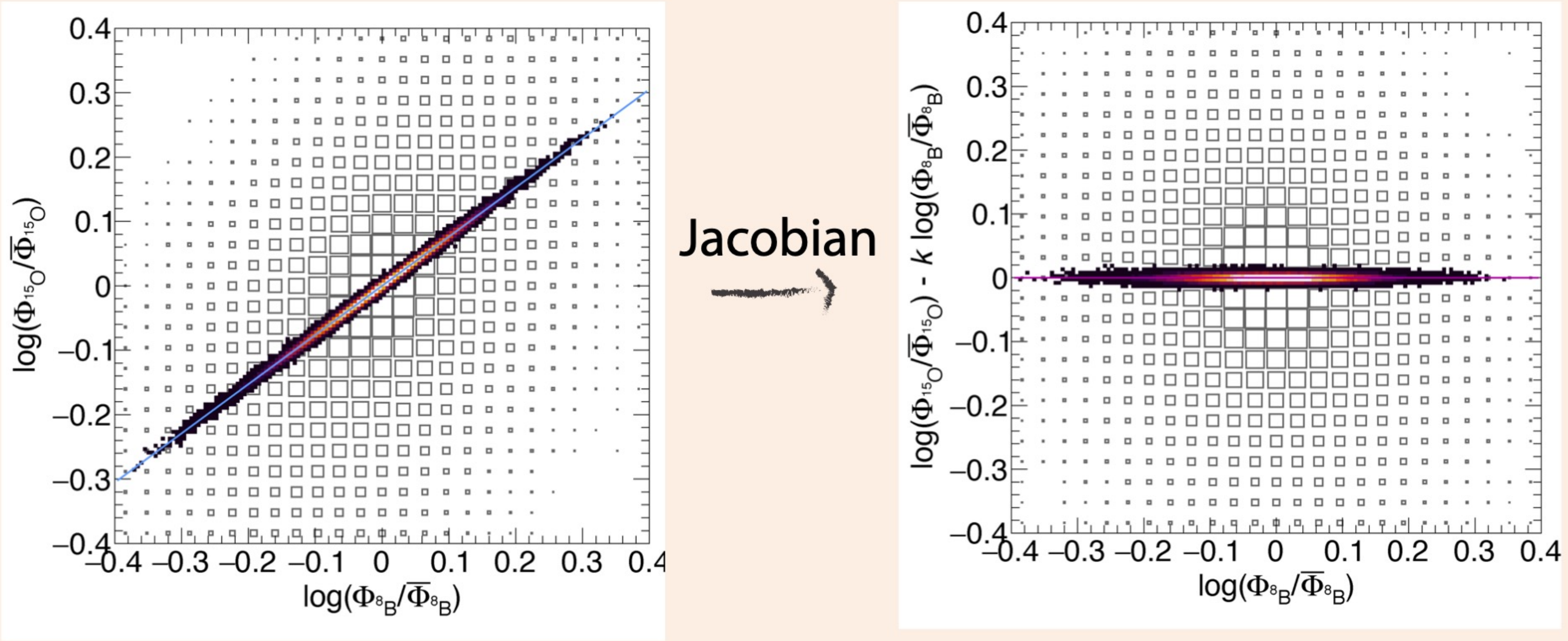
find κ which minimize *Var*

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

Solar: $L_\odot, \tau_\odot, \kappa$, Diffusion

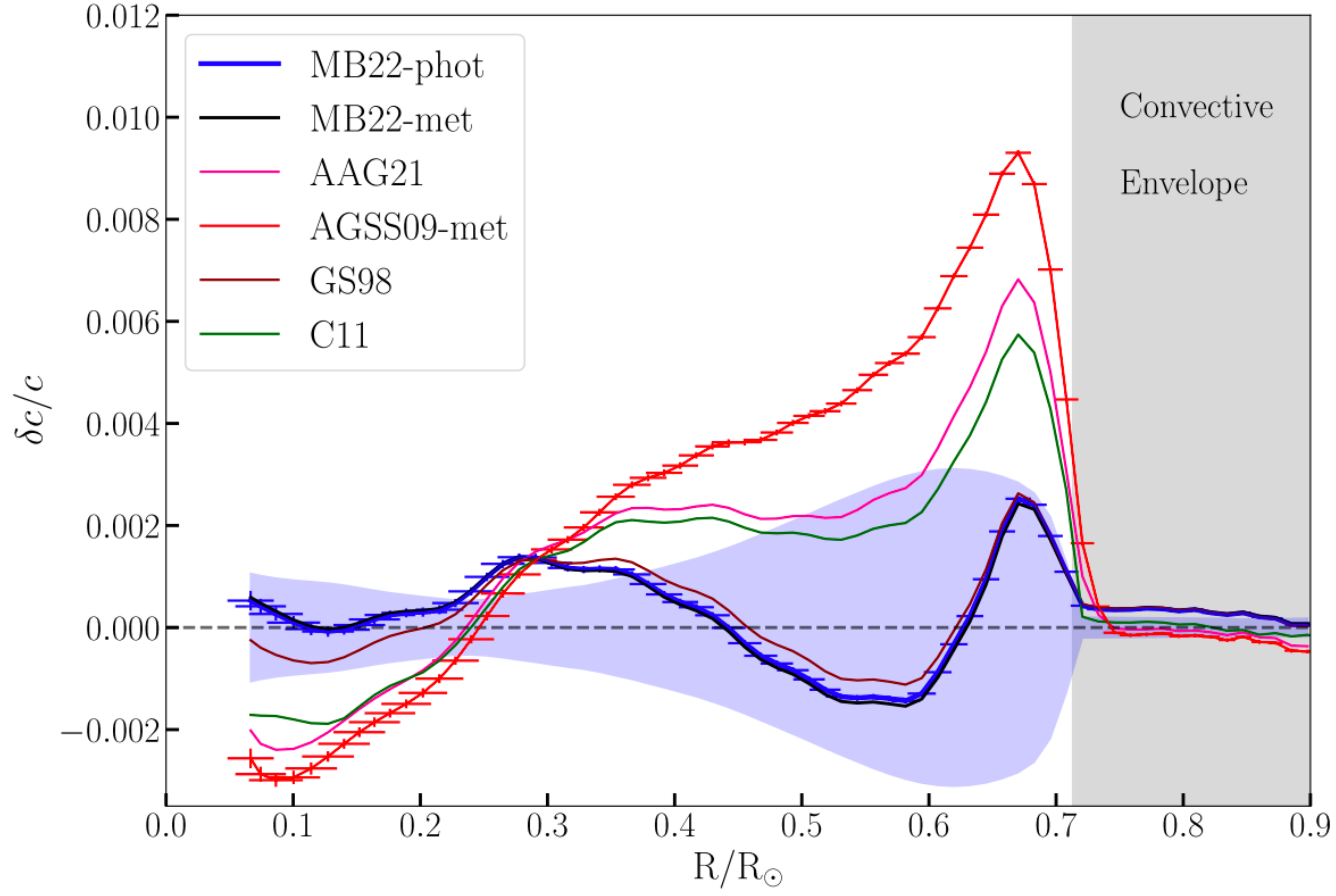
Nuclear: $S_{11}, S_{33}, S_{34}, S_{e7}, S_{17}, S_{hep}, S_{114}, S_{116}$

Heavy elements abundance: C, N, O, Ne, Mg, Si, S, Ar, Fe

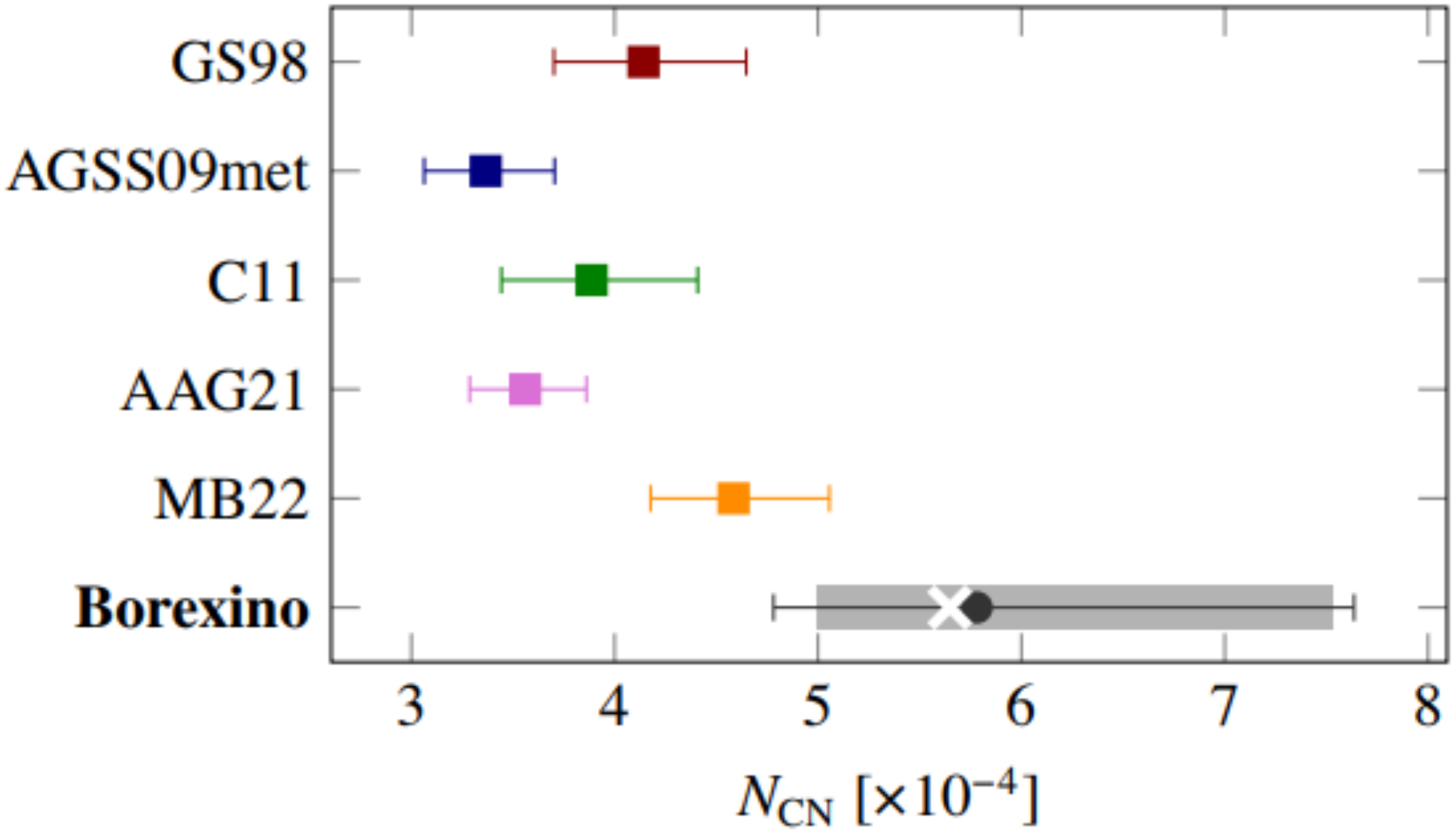


Results: CN abundance from solar neutrinos

Comparison on sound speed
(E. Magg et al. v2203.02255)



Comparison on CN abuandance
(Borexino, PRL 2022)

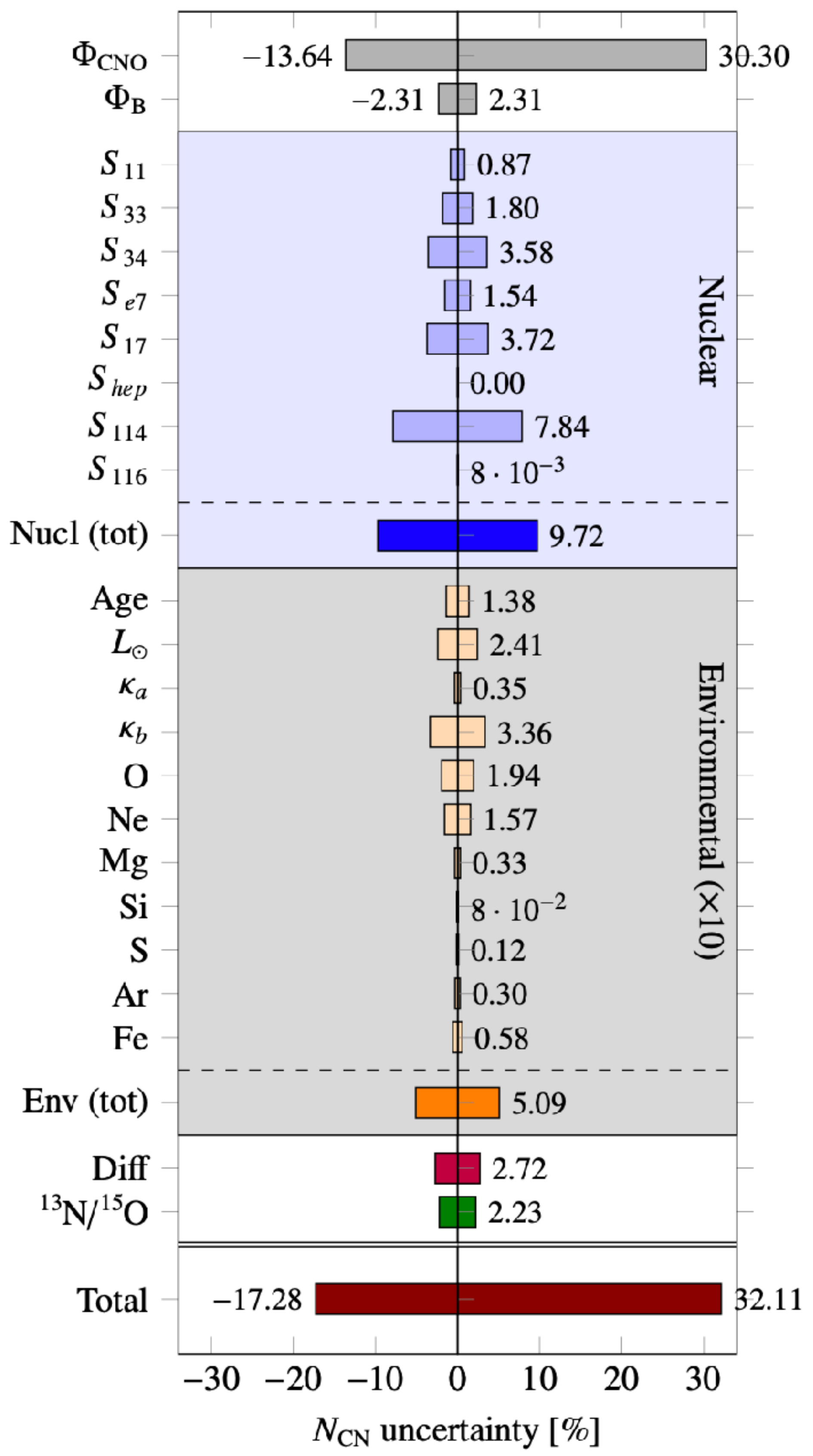


More to expect?

- DARWIN claimed may measure pp neutrinos at 0.15% level with 300ty (DARWIN, EPJC 80, 1133, 2020).
  - May be used together with luminosity to constrain CNO neutrino flux (Francesco Vissani, Solar Neutrinos, 121-141, 2019)
- Metallicity measurement limited by fusion cross-section measurement. To be updated. Wait for LUNA-MV, JUNA, and other underground laboratories for nuclear astrophysics.
- Next generation experiments may establish evidence of solar neutrinos from *hep* branch (DUNE and possible low-energy optimized modules (SoLAr)).

$$0.9800 \times \varphi_{\rm pp} + 0.0939 \times \varphi_{\rm Be} + 0.0092 \times \varphi_{\rm CNO} + \\ +0.0089 \times \varphi_{\rm pep} + \text{small terms} = 6.379 \times (1 \pm 0.4\%)$$

Francesco Vissani, Luminosity constraint and entangled solar neutrino signals , Solar Neutrinos, pp. 121-141 (2019)



systematics in measurement of metallicity using solar neutrinos

(From talk of Borexino on Neutrino 2022)

Conclusions

- Borexino achieved best precision measurement of CNO solar neutrinos $6.7^{+1.2}_{-0.8}$ cpd/100t
- The relative CN abundance w.r.t. H is $5.81^{+1.22}_{-0.84}$ x10^{-4}
- The relative abundance systematic uncertainties are dominated by the nuclear fusion cross-sections, and will be improved in the near future.