FIRST DIRECT EVIDENCE OF THE CNO FUSION CYCLE IN THE SUN WITH BOREXINO

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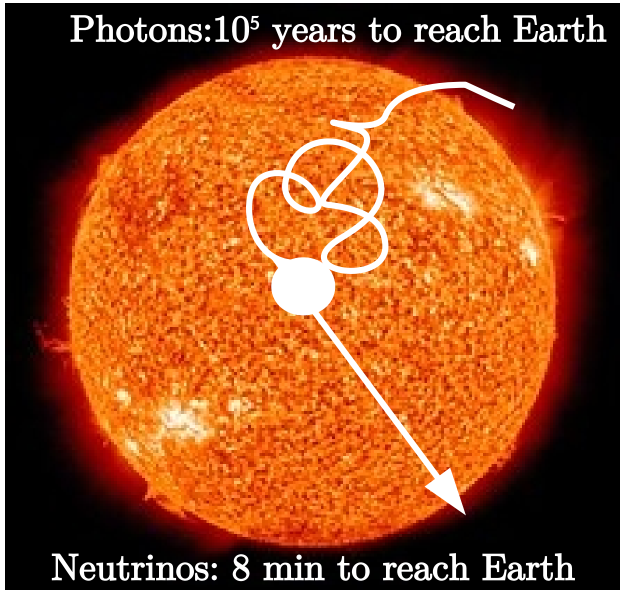
Solar neutrinos

Study the Sun with neutrinos ↔ Study neutrinos with the Sun

Flux on Earth ~10^{11} cm^{-2} s^{-1}
Interaction cross section ~10^{-44} cm^2 @ 1 MeV



- ✔ Produced in the nuclear fusion reactions in the Sun's core
- ✔ Direct information without any loss in energy or direction

Homestake experiment 1960s:
First detection of solar neutrinos

Trending: The metallicity puzzle

Low metallicity (LZ) — High metallicity (HZ)

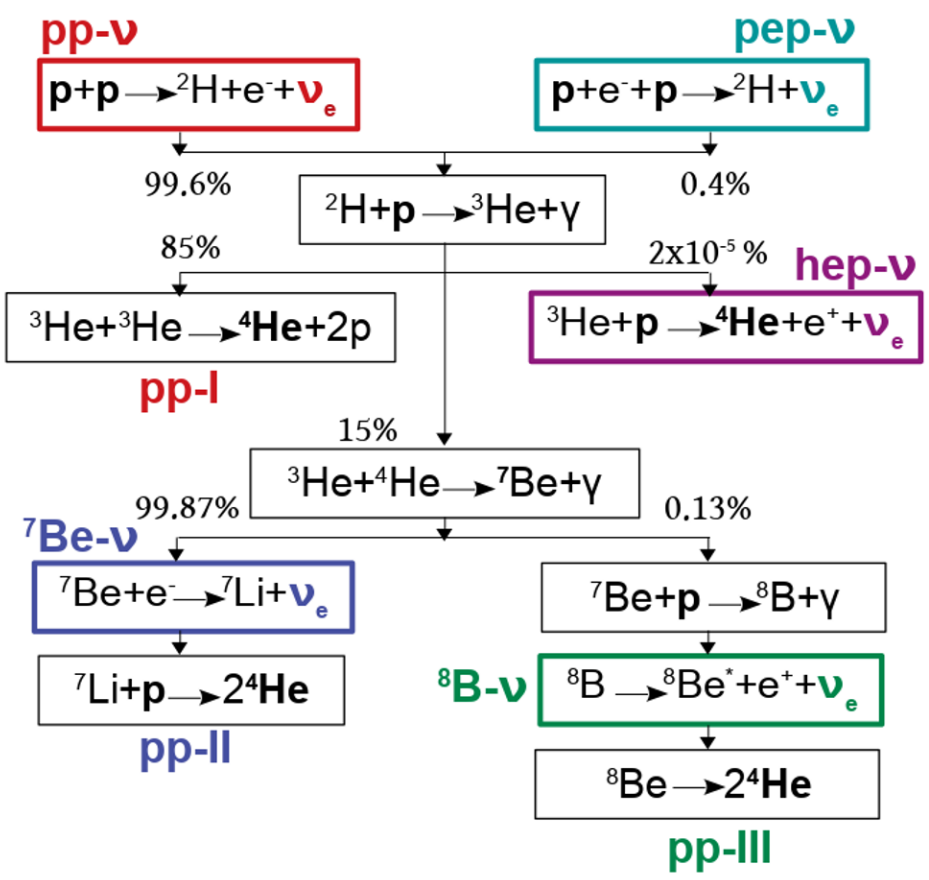
- ✔ Fraction of elements heavier than ^{4}He in the Sun
- ✔ New sound wave profiles:
  → consistent with old HZ (1D) model
  → 1% discrepancy with new LZ (3D) model
- ✔ Can be inferred through direct measurement of solar neutrinos

Solar neutrinos

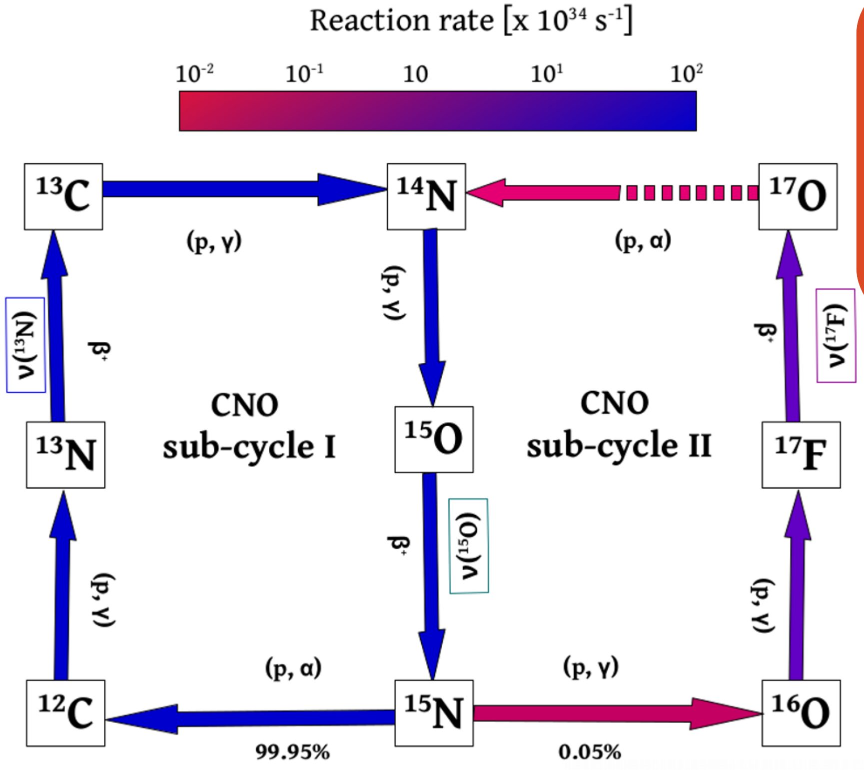
N. Vinyoles, et. al. Astrophys. J., vol. 835, no. 2, p. 202, 2017

solar ν	HZ SSM	LZ SSM	difference HZ-LZ (%)
pp	$5.98\ (1 \pm 0.006) \cdot 10^{10}$	$6.03\ (1 \pm 0.005) \cdot 10^{10}$	-0.84
pep	$1.44\ (1 \pm 0.01) \cdot 10^{8}$	$1.46\ (1 \pm 0.009) \cdot 10^{8}$	-1.39
hep	$7.98\ (1 \pm 0.030) \cdot 10^{3}$	$8.25\ (1 \pm 0.30) \cdot 10^{3}$	-3.38
^{7}Be	$4.93\ (1 \pm 0.06) \cdot 10^{9}$	$4.50\ (1 \pm 0.06) \cdot 10^{9}$	+8.72
^{8}B	$5.46\ (1 \pm 0.12) \cdot 10^{6}$	$4.50\ (1 \pm 0.12) \cdot 10^{6}$	+17.58
CNO	$4.88\ (1 \pm 0.11) \cdot 10^{8}$	$3.51\ (1 \pm 0.11) \cdot 10^{8}$	+28.07

pp chain ~99%



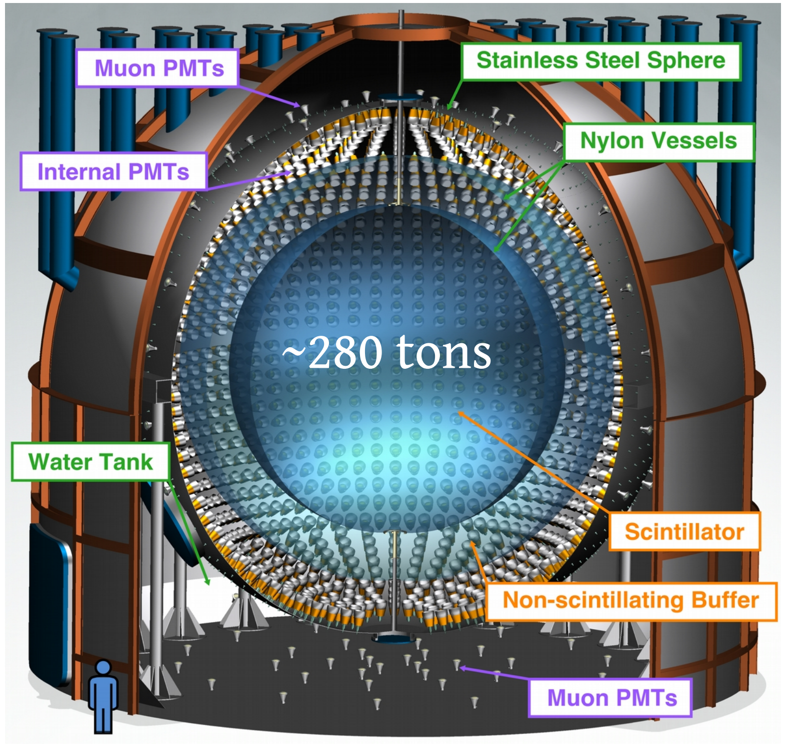
CNO-cycle ~1%



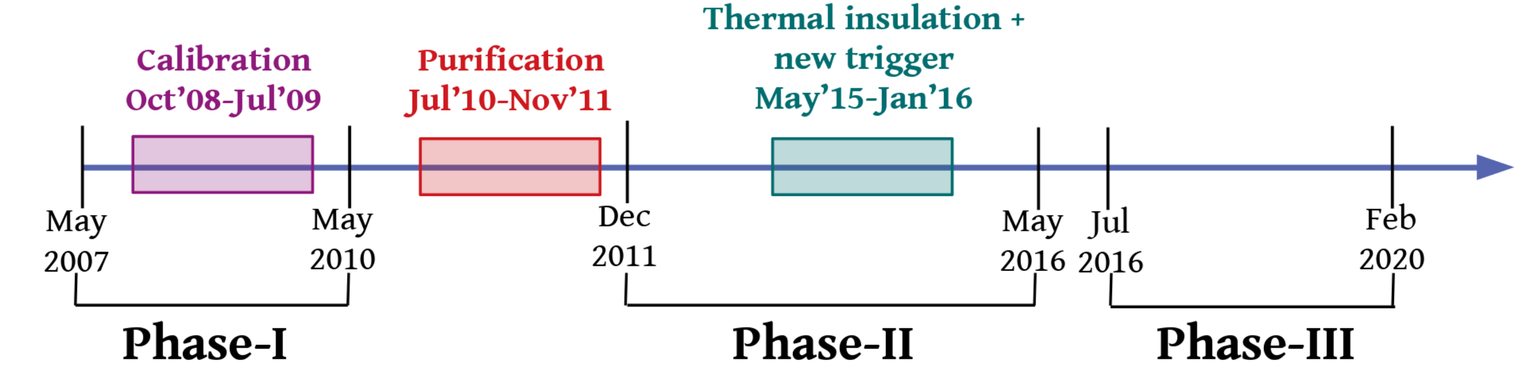
- ✔ Proposed by C. F. Weizsäcker and H. Bethe, 1938-39
- ✔ Main energy production mechanism in heavier stars ($T \gtrsim 2\times10^{7}$ K)
- ✔ Most sensitive to solar metallicity (28%)

The Borexino experiment

@ Laboratori Nazionali del Gran Sasso (LNGS), Italy



- ✔ 3800 m w.e. depth
  muon flux = $(3.432 \pm 0.003) \cdot 10^{-4} m^{-2} s^{-1}$
- ✔ Most radio-pure liquid in the world
  $^{238}U < 9.5 \cdot 10^{-20}$ g/g (95% C.L.)
  $^{232}Th < 7.2 \cdot 10^{-19}$ g/g (95% C.L.)
- ✔ Energy resolution: $6\%/\sqrt{E(MeV)}$
- ✔ Position resolution: ~11 cm@1 MeV



Nature 512 (2014) 383-386

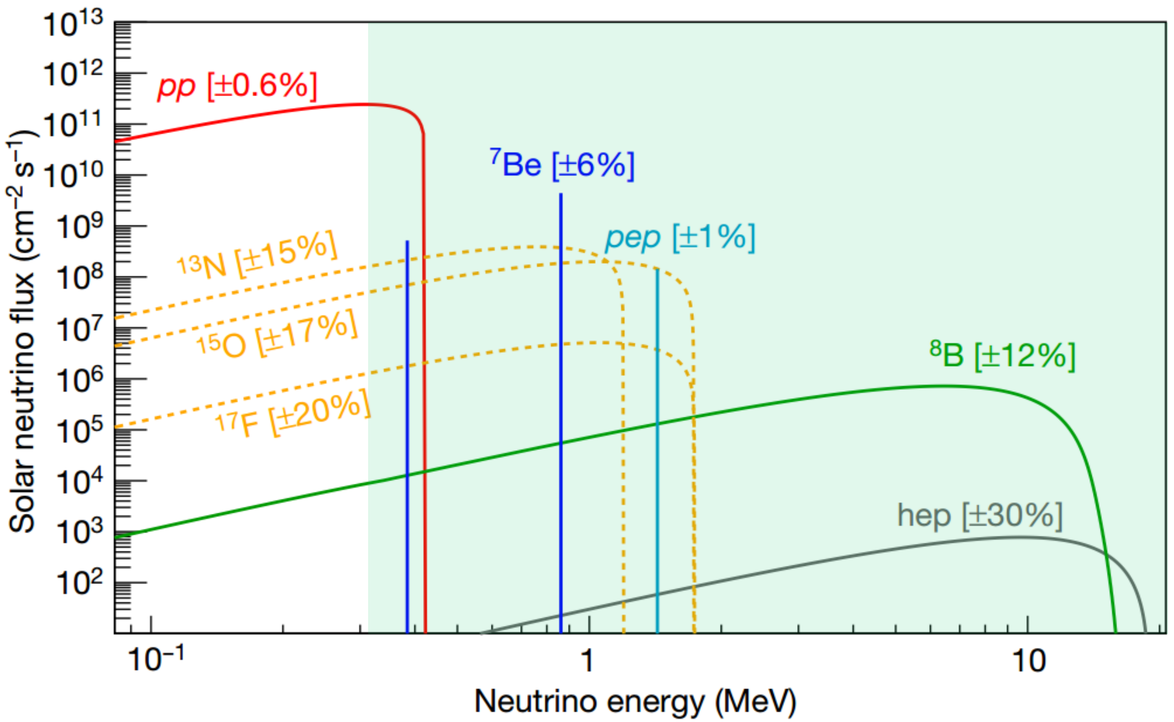
Nature 562 (2018) 505-510

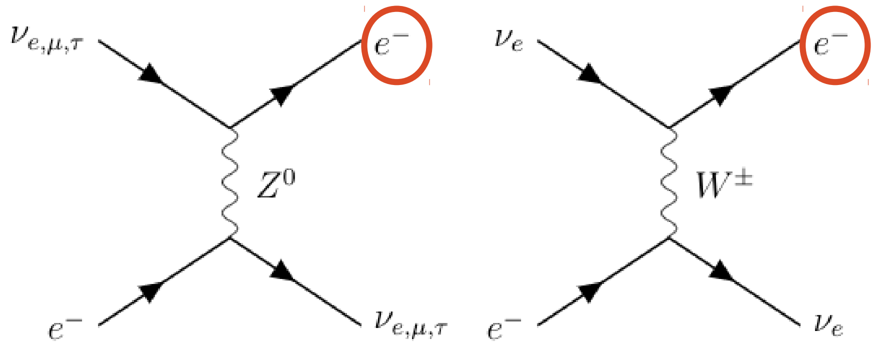
Nature 587 (2020) 577-582
CNO detection

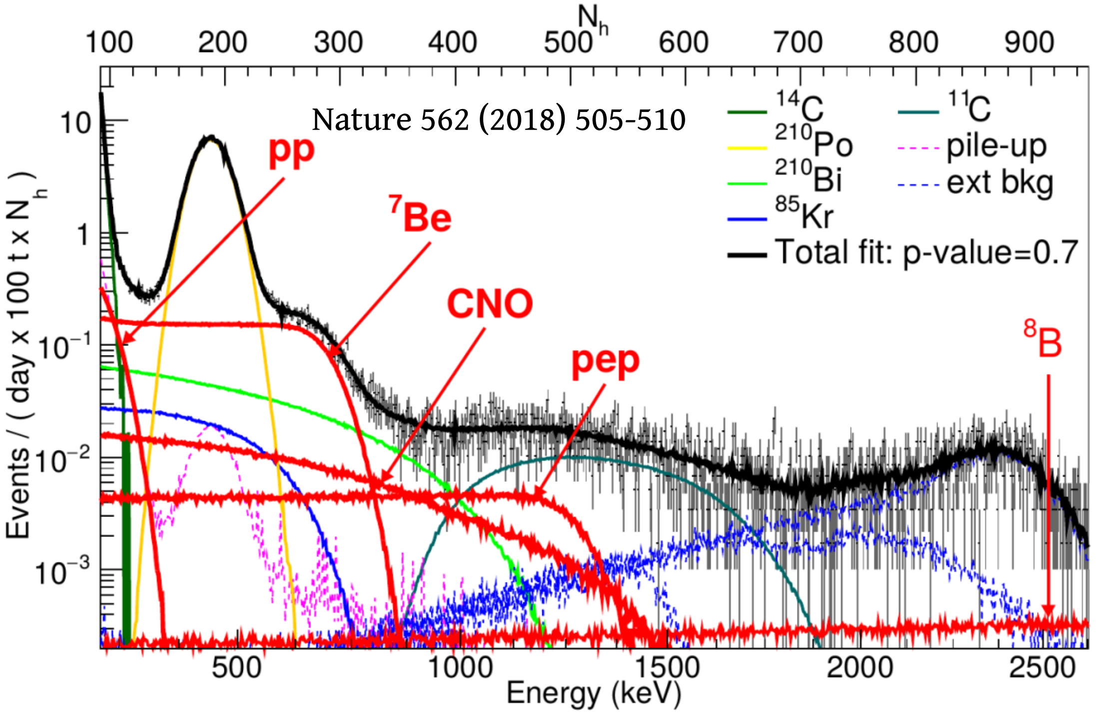
Physics milestones

- ✔ First evidence of CNO solar neutrinos
- ✔ Complete spectroscopy of pp-chain solar neutrinos
- ✔ > 5σ evidence of geoneutrinos, first 99% C.L. rejection of no mantle signal
- ✔ Stringent limits on non-standard interactions and neutrino magnetic moment
- ✔ Evidence for seasonal and long-term modulation of muons, measurement of atmospheric kaon/pion ratio

Solar neutrinos with Borexino



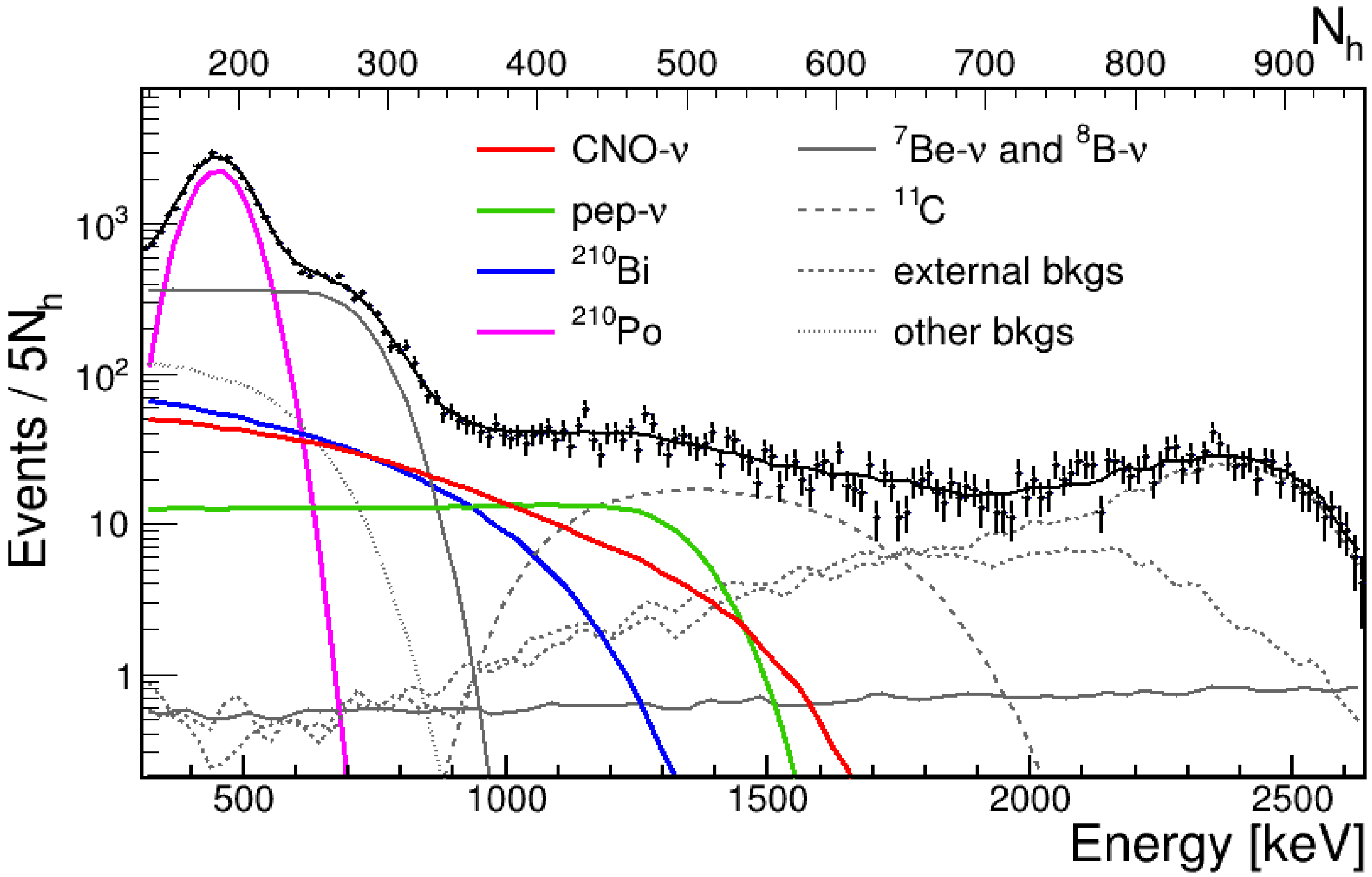




Main backgrounds for low energy

- ✔ ^{14}C (β^-): natural component of liquid scintillator
- ✔ ^{85}Kr (β^-): in air, due to nuclear explosions
- ✔ ^{210}Bi (β^-) and ^{210}Po (α): from ^{238}U chain
- ✔ ^{11}C (β^+): cosmogenic
- ✔ External background: γs from ^{214}Bi, ^{208}Tl, ^{40}K
- ✔ Pile-up of multiple events

CNO detection: Challenges and strategy



Absolutely necessary to constrain *pep* and ^{210}Bi

The *pep* constraint

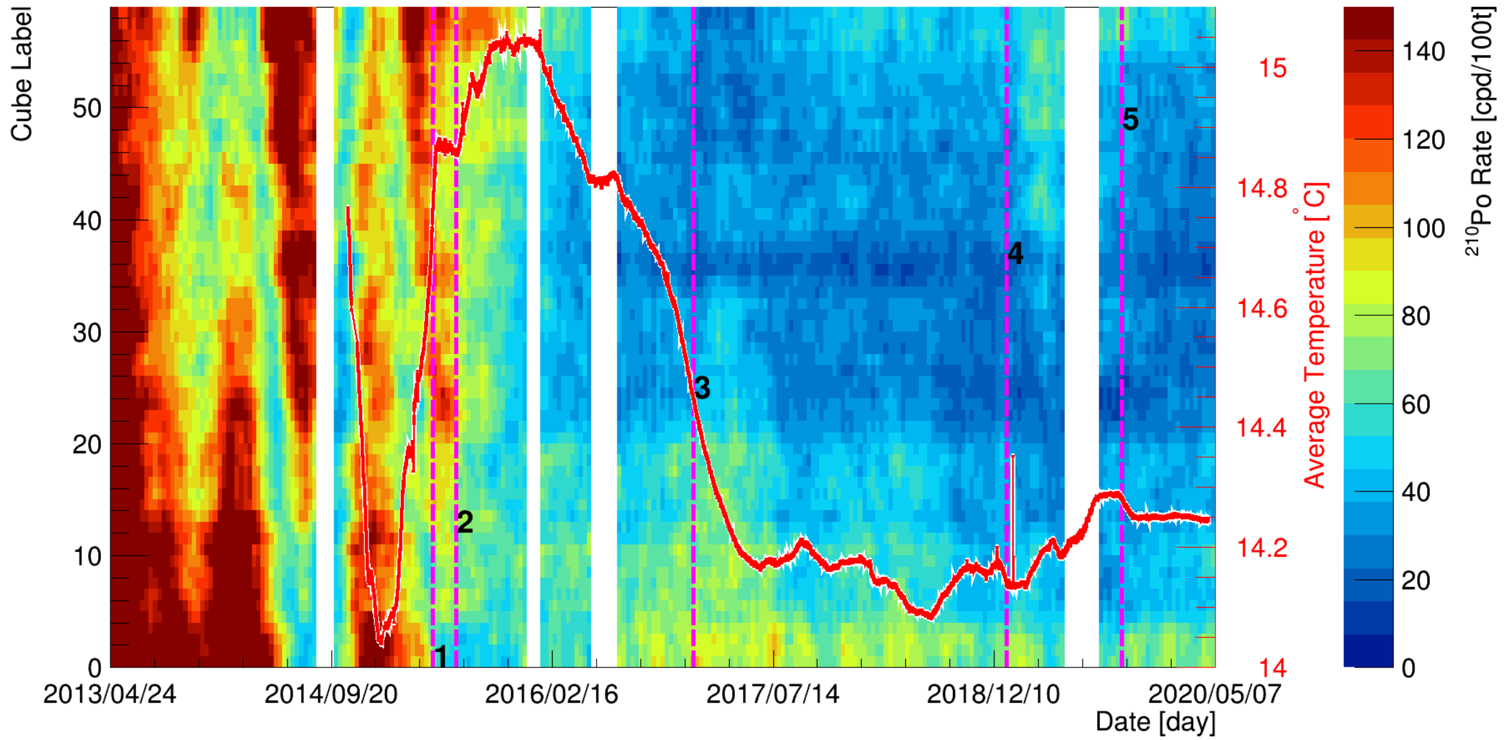
- ✔ *pp/pep* ratio + solar luminosity constraints + solar neutrino experimental data w/o Borexino
- ✔ 2.74 ± 0.04 cpd/100t (1.4% precision)

The ^{210}Bi constraint (next slides)

- ✔ Estimated through ^{210}Po (α-tagging)
- ✔ ^{210}Po in Borexino = supported ^{210}Po + convective ^{210}Po
- ✔ min ^{210}Po → ^{210}Bi upper limit → CNO lower limit

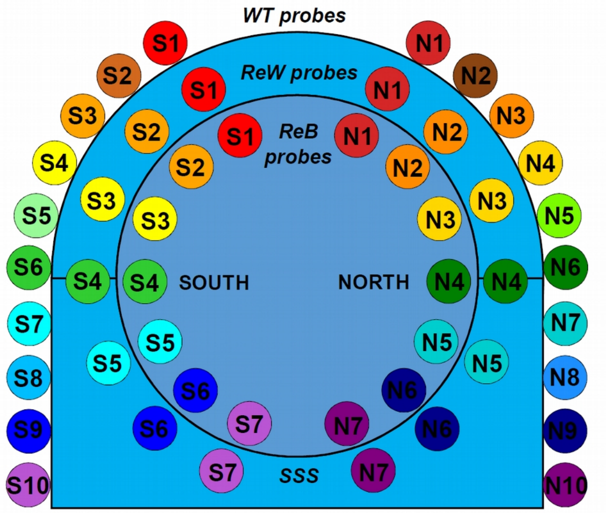
Thermal insulation and stabilisation

Until 2016:
^{210}Po in Borexino: Supported ^{210}Po + Convective ^{210}Po



Thermal insulation

Active temperature control



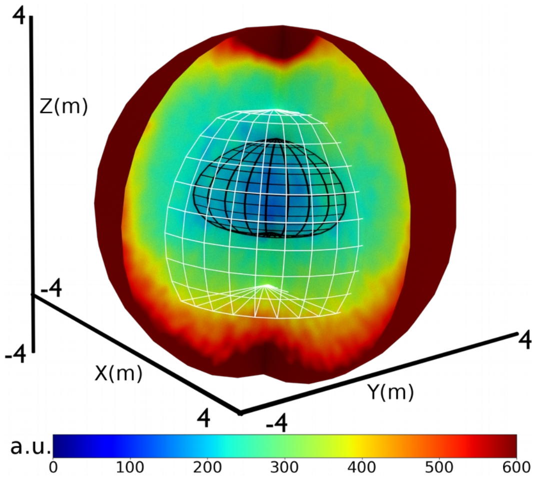
The Low Polonium Field/The ^{210}Bi constraint

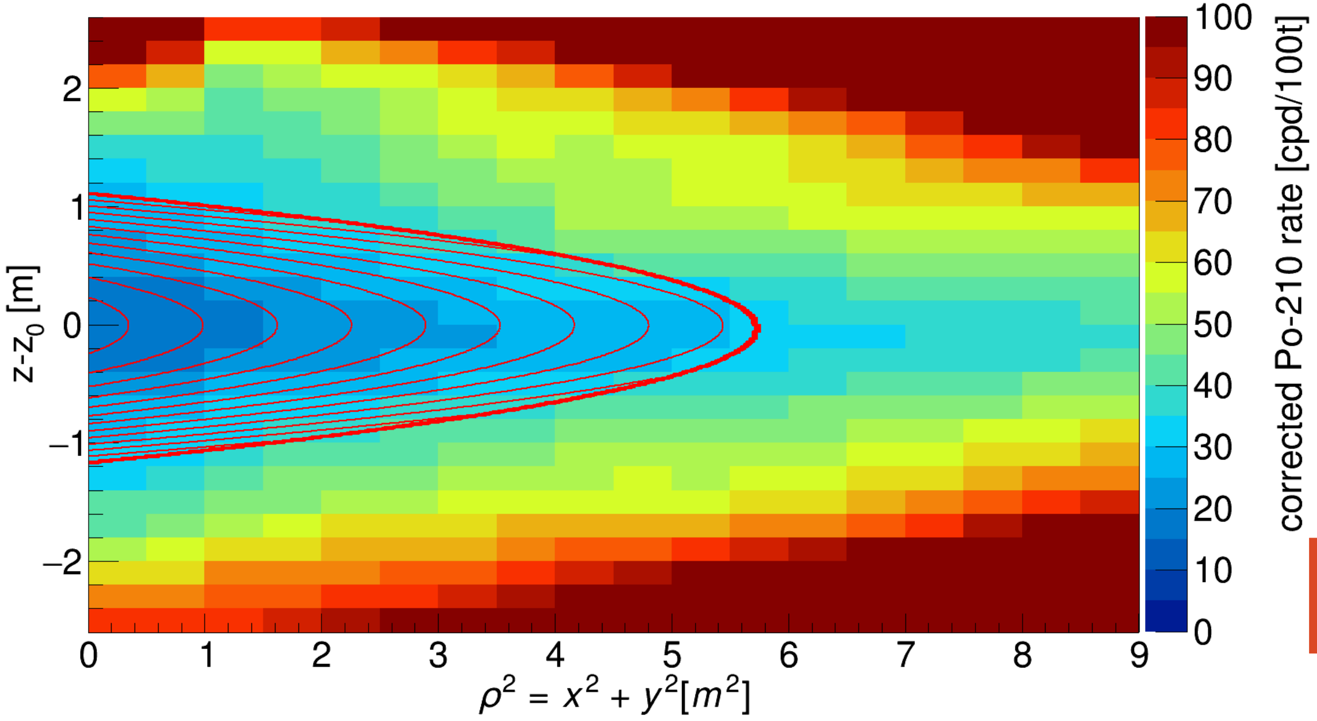
$$\frac{d^2 R_{Po}}{d(\rho^2)dz} = [R(^{210}Po_{min})\epsilon_E \epsilon_{MLP} + R_\beta]\left(1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right)$$

Efficiency due to cuts

Residual β events in the alpha region

(or) cubic spline along z





- ✔ ~20 tons
- ✔ Blind alignment of data:
  fit previous month → get center → align current month
- ✔ ^{210}Po selected using energy and pulse-shape cuts
- ✔ Systematic sources:
  ^{210}Bi homogeneity in whole FV ~70 tons
  Fit: mass and binning
  β-leakage estimation

$R(^{210}Po_{min})$=(or)$R(^{210}Bi) \leq 11.5 \pm 1.3$ cpd/100t

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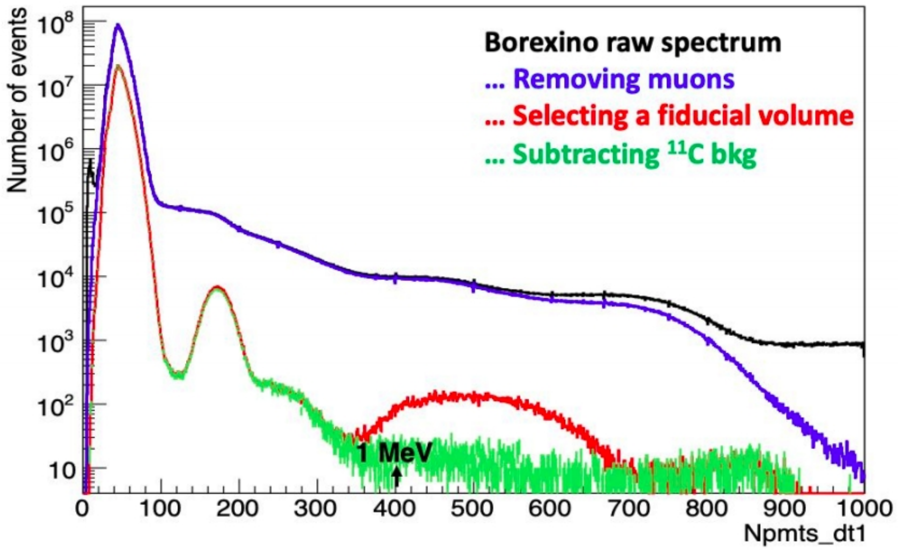
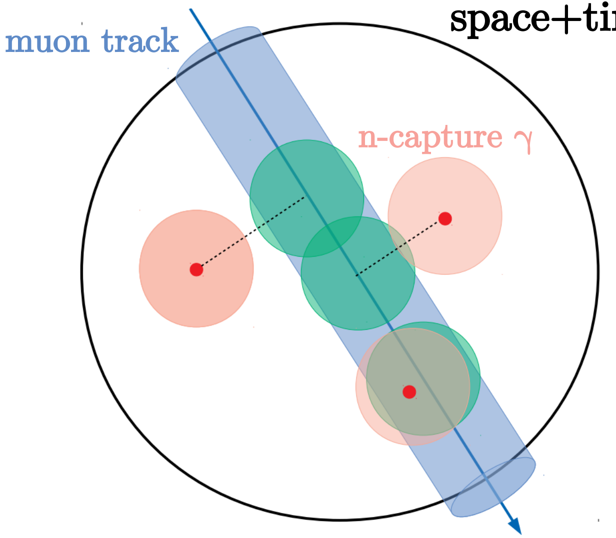
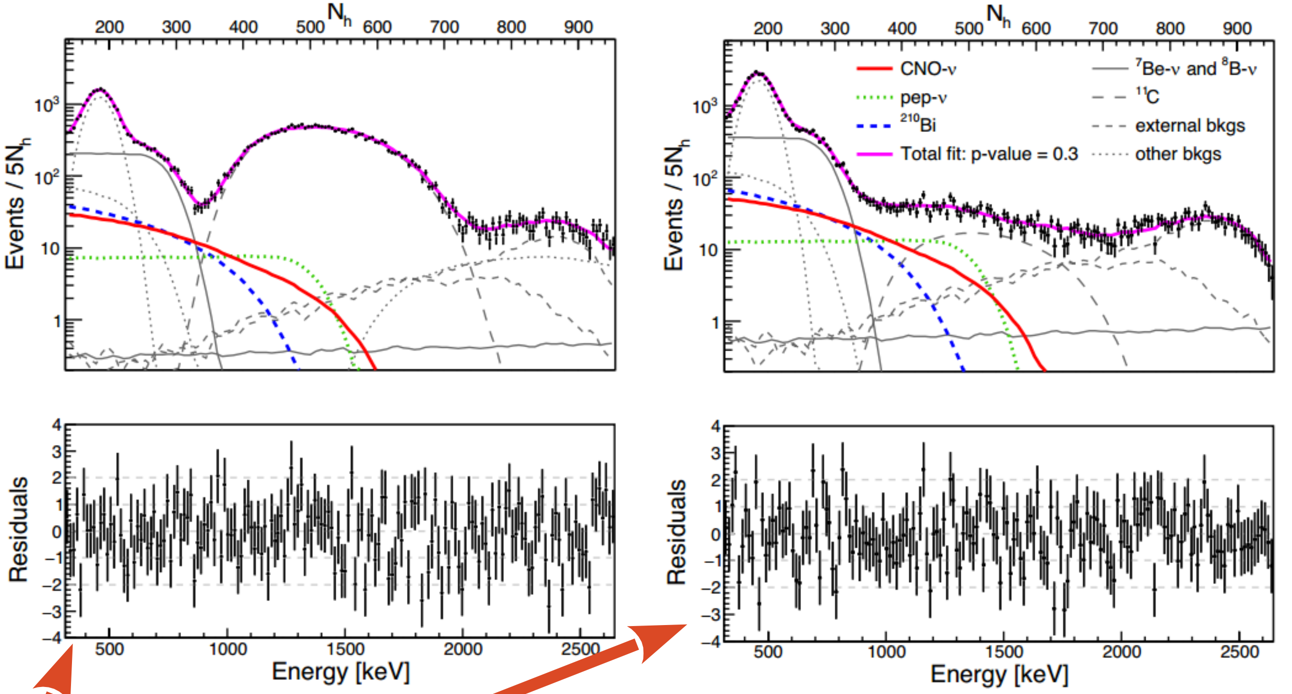
The multivariate spectral fit

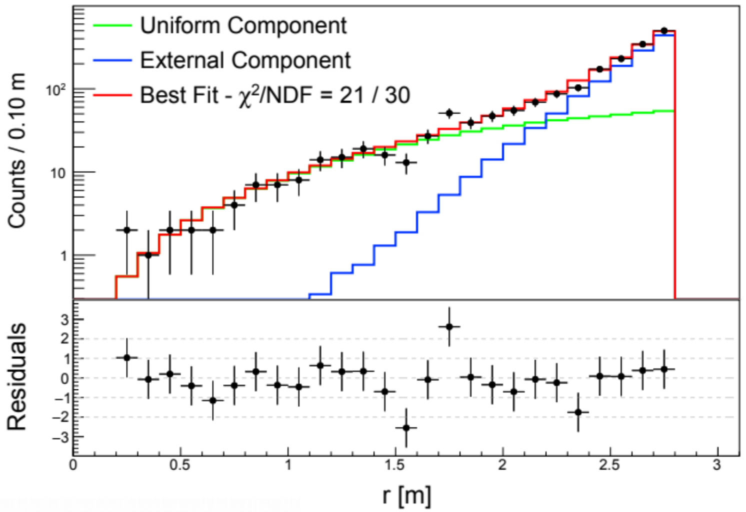


Three-fold coincidence tagging of ^{11}C
space+time veto





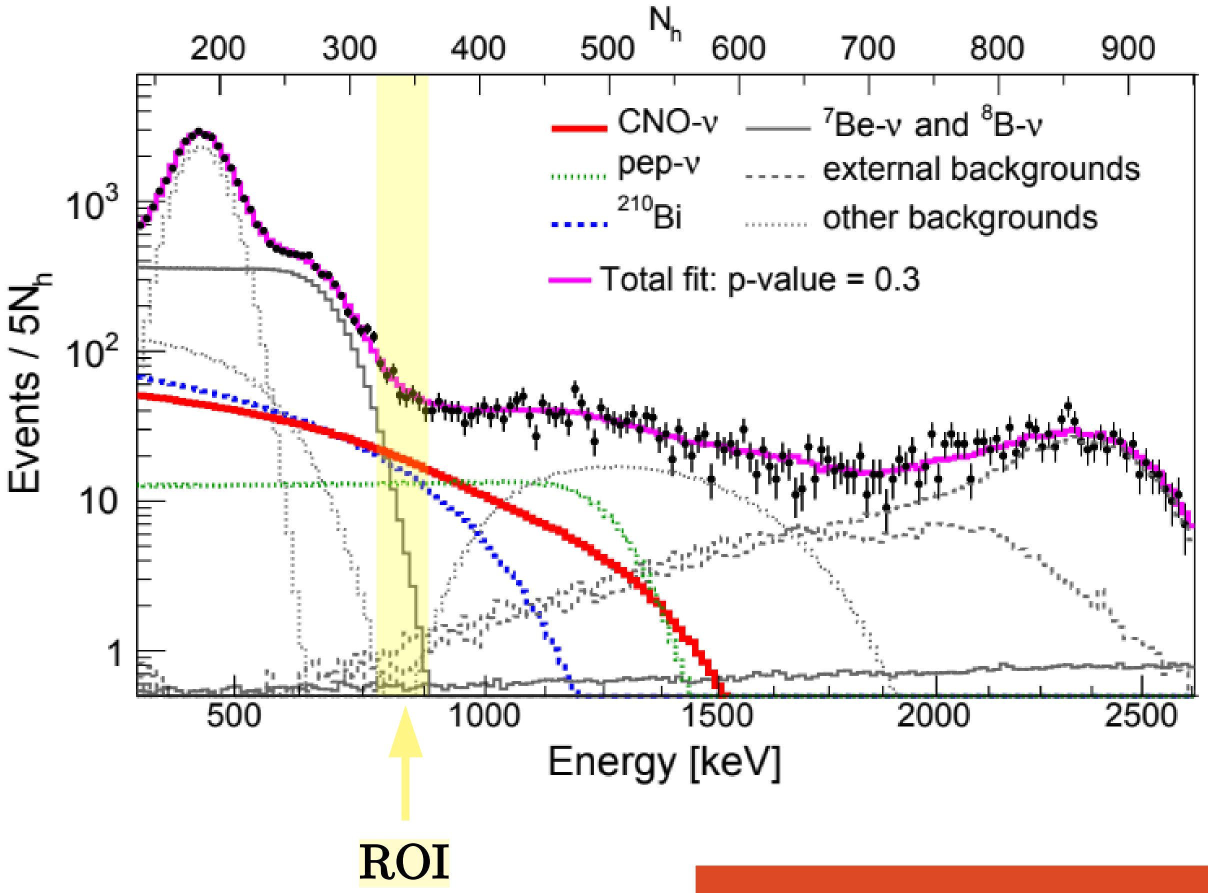
$$\mathcal{L}_{MV} = \mathcal{L}_{C11\text{-}tag} \cdot \mathcal{L}_{C11\text{-}sub} \cdot \mathcal{L}_{radial}$$



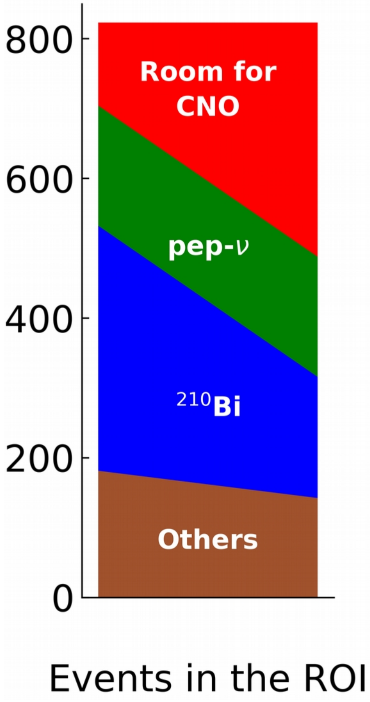
Systematic uncertainties from MC shapes

- ✔ ^{210}Bi reference shape (18%)
- ✔ ^{11}C reference shape (2.3%)
- ✔ Energy response function (0.9%)

Complementary counting analysis

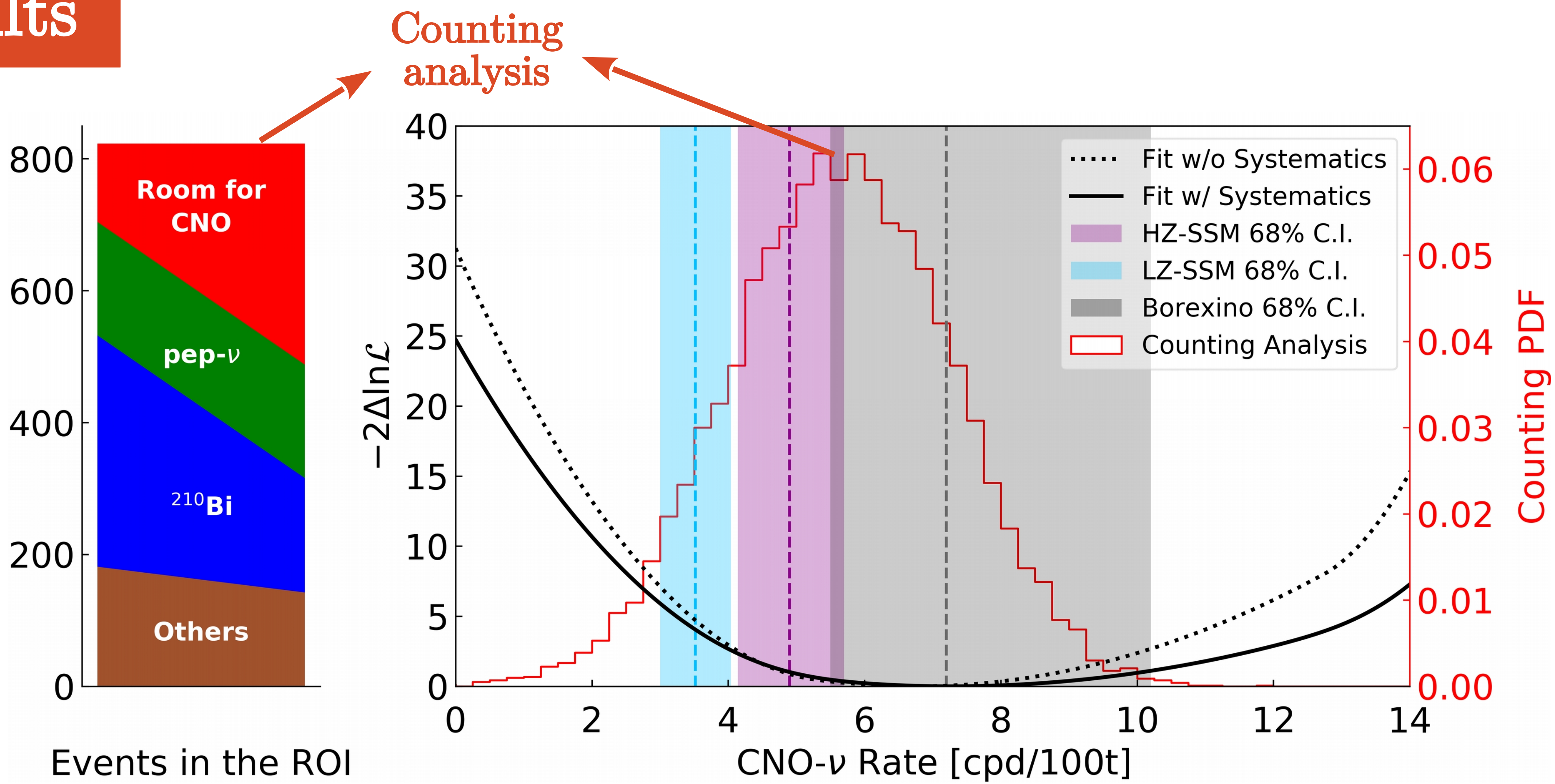


- ✔ Events counted after subtraction of backgrounds
- ✔ ν(CNO) + ν(pep) + ^{210}Bi = 80%
  ν(^{7}Be) + residual ^{11}C = 18%
  Others < 2%
- ✔ Using the same *pep* & ^{210}Bi constraints used for MV fit
- ✔ ν(^{7}Be) varied between HZ and LZ predictions
- ✔ Other backgrounds obtained from charge analytical fit
- ✔ Assuming there are no unknown backgrounds



CNO presence confirmed at 3.5σ level

Results



> 5σ rejection of no-CNO hypothesis at 99% C.L.
$\nu(\mathrm{CNO}) = 7.2^{+3.0}_{-1.7}$ cpd/100t

Conclusions & Outlook

- ✔ Borexino has provided the first direct evidence of the CNO-fusion cycle in the Sun after its first proposal in 1938-39.
- ✔ Utmost significance for Astrophysics in understanding the main energy production in our Universe and the stars.
- ✔ Borexino has fully unraveled the two fusion processes powering the Sun, bringing us a step closer in understanding our star.
- ✔ Previous Borexino results on ^{8}B and ^{7}Be solar neutrinos
  → LZ disfavoured at 96.6% C.L.
  Future CNO measurement can solve the metallicity puzzle!