First Experimental Evidence of CNO Cycle Solar Neutrinos by Borexino

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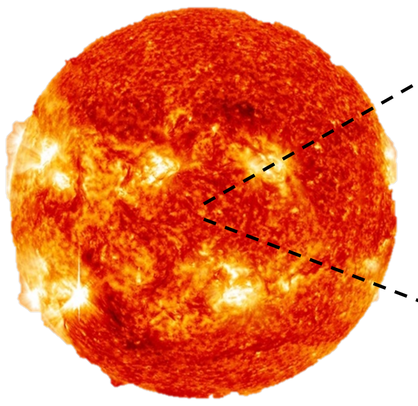
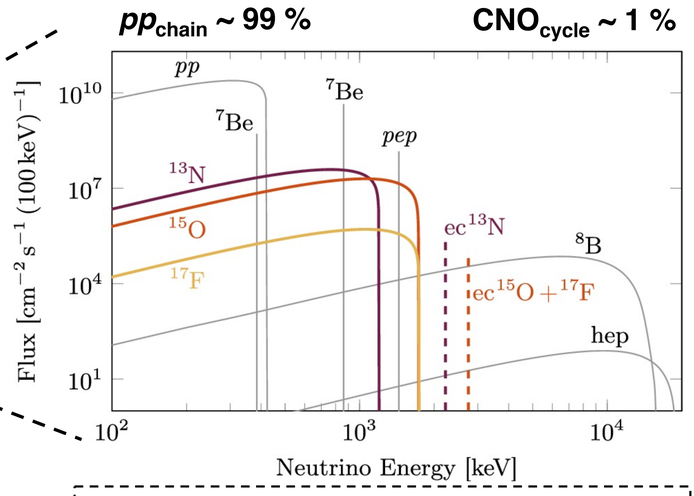
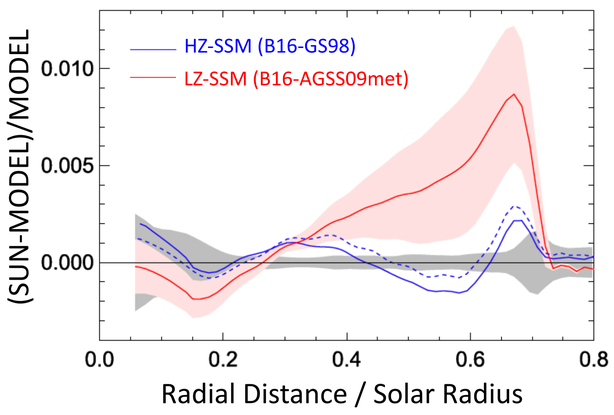
The Sun & the Metallicity Problem



pp_{chain} ~ 99 % CNO_{cycle} ~ 1 %



Sound Speed Profiles Data vs. SSM Prediction

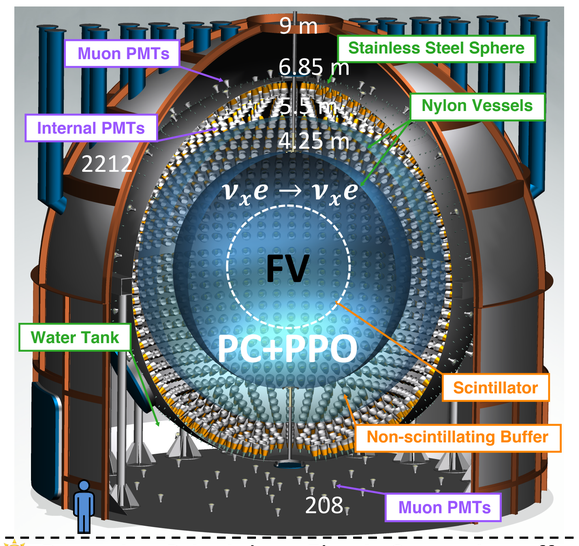


Solar Metallicity =
Input to the Standard Solar Model (B16-SSM)
(Z/X) = Surface-Metal-to-Hydrogen Ratio
High-Metallicity HZ-SSM ⇔ $(Z/X) = 0.0229$
Low-Metallicity LZ-SSM ⇔ $(Z/X) = 0.0178$

***Solar Metallicity Problem*:**
Helioseismology consistent with older HZ (B16-GS98) but in tension with newer LZ (B16-AGSS09met) description

CNO-ν can unravel metallicity problem !

The Borexino Detector @ LNGS, Italy



- *Detection Principle:* ν Elastic Scattering off e^-
- *Eff. Light Yield:* 500 p.e./MeV in 2000 PMTs
- *Energy Resolution:* 6% @ 1 MeV
- *Position Resolution:* 11 cm @ 1 MeV
- *Threshold:* 50 keV (Hardware)
- *Fiducial Vol. (FV):* R[m]<2.8, -1.8<z[m]<2.2
- *FV mass:* 71.3 ton from 280 ton (total)
- *Radiopurity Levels:* ^{238}U chain ($\tau = 6\times$Gy) < 9.5x10^{-20} g/g (95% C.L.), ^{232}Th chain ($\tau = 20\times$Gy) < 5.7x10^{-19} g/g (95% C.L.)
  → Ultra Radiopure Detector

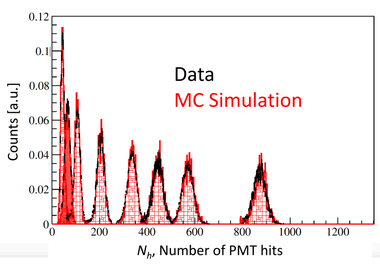
Calibrations and Monte Carlo Simulations

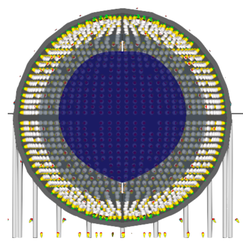
Calibration Campaign ~2009

Isotope	Type	Energy (keV)
^{57}Co	γ	122
^{139}Ce	γ	165
^{203}Hg	γ	279
^{85}Sr	γ	514
^{54}Mn	γ	834
^{65}Zn	γ	1115
^{60}Co	γ	1173 - 1332
^{40}K	γ	1460
^{222}Rn	α/β	0 ÷ 3200
^{14}C	β	0 ÷ 156
^{241}Am-^{9}Be	n	~0 ÷ 10000
Ext. ^{228}Th	γ	2615

- *Placement of sources inside the detector*
- *Energy + Position Reconstruction*
- *Detector Response*
- *Energy Scale*

Monte Carlo Simulations



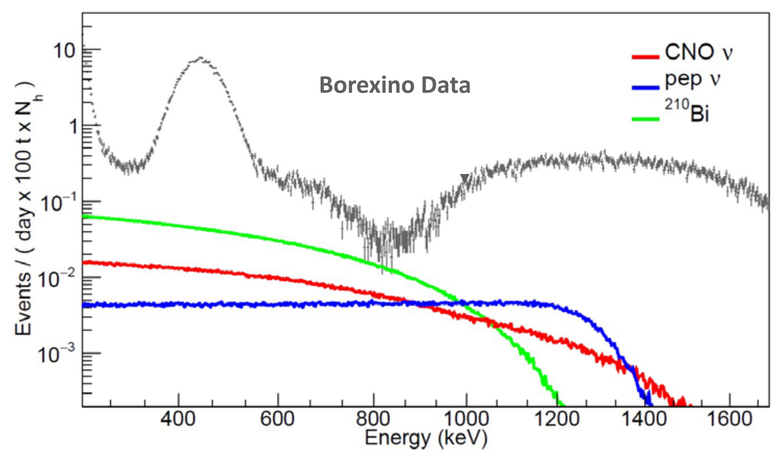


- *Geant4 simulation of the detector, electronics, and physics processes tuned on calibration data*

Observation of CNO Cycle Solar Neutrinos in Borexino

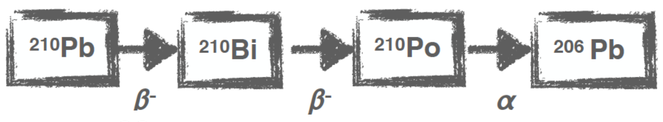
Challenges

Spectral Correlations between CNO, *pep*, ^{210}Bi



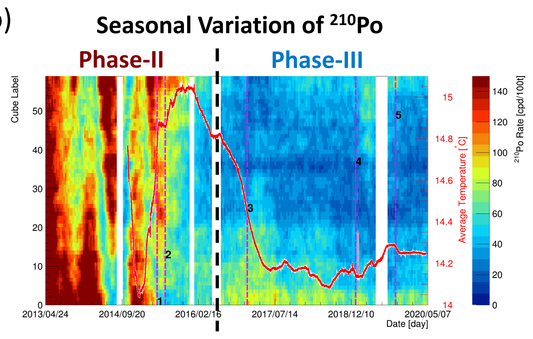
***pep*-ν rate can be constrained with ~1.4% precision ⇔ Global Analysis of Solar Neutrino Data + Luminosity constraint** (Bergström et al., JHEP, 2016:132, 2016)
Result: (2.74±0.04) counts/day/100t (HZ-SSM ≈ LZ-SSM)

^{210}Bi(β^-) from ^{210}Po(α)



Secular Equlibrium: Rate(^{210}Bi) = Rate(^{210}Po)
Alpha Selection in Borexino: possible on Event-by-Event Basis (Multilayer Perceptron Variable = MLP)
Borexino Situation:
Additional Source of ^{210}Po from Inner Vessel + Temperature Gradients
→ Convective Currents
→ Rate(^{210}Bi) ≠ Rate(^{210}Po)

Seasonal Variation of ^{210}Po

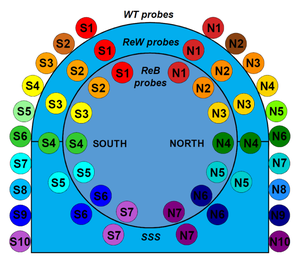


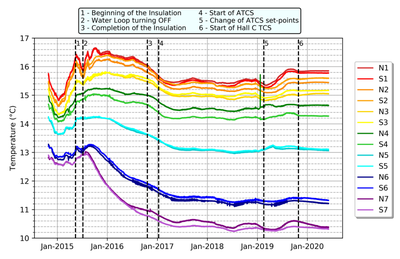
Thermal Stabilization

Towards stopping the Convective Currents

1) Thermal Insulation
Double Layer of Mineral Wool installed around ~2015

2) Active Temperature Control System
66 Temperature probes
(buffer, external tank, different levels)
→ Resolution 0.07 °C

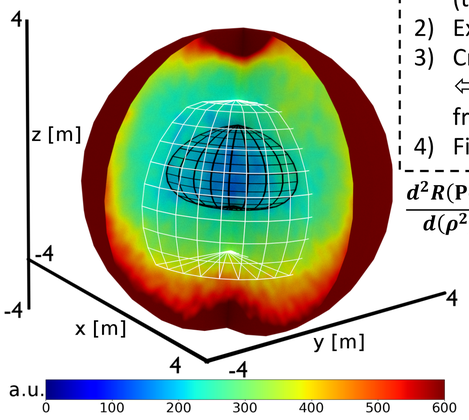




Achieved: excellent temperature stability with the establishment of a stable positive vertical gradient

Low ^{210}Po Field + ^{210}Bi Constraint

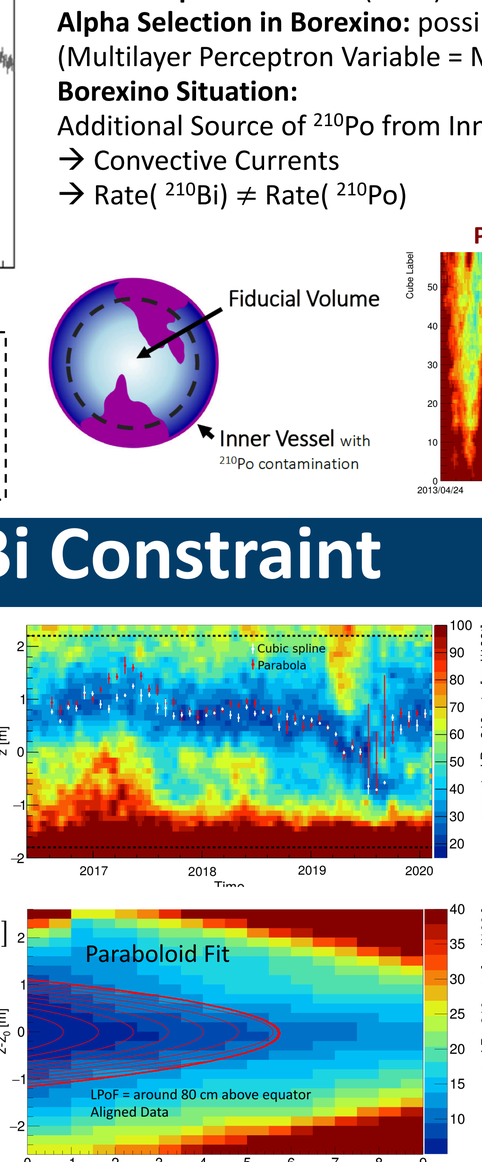
Low Polonium Field (LPoF)
⇔ 20 ton in Bx-Phase-III



Data „alignment“
→ Bias Reduction
1) Fit ellipsoid+spline monthly (two methods)
2) Extract z-position vs. time (z_0)
3) Create “aligned“ dataset
   ⇔ shift data according to z_0 from previous month
4) Fit aligned dataset

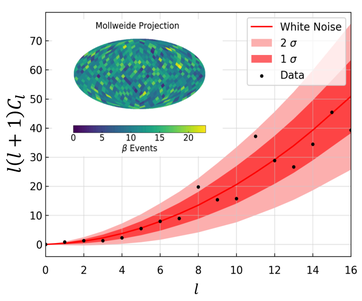
$$\frac{d^2R(\mathrm{Po_{min}})}{d(\rho^2)dz} = \left[R(\mathrm{Po_{min}})\varepsilon_{\mathrm{Ene}}\varepsilon_{\mathrm{MLP}} + R_\beta\right] \times\left(1+\frac{\rho^2}{a^2}+\frac{(z-z_0)^2}{b^2}\right)$$

$\varepsilon_{\mathrm{Ene}}$, $\varepsilon_{\mathrm{MLP}}$ efficiency Energy and MLP (αs)
R_β beta rate after α selection

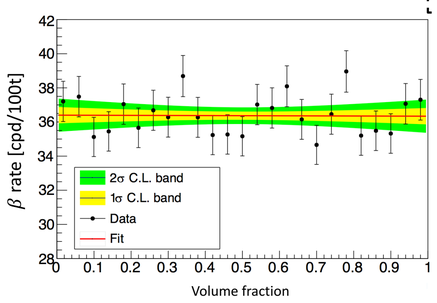


From 20 ton to 71.3 ton (FV Mass)
→ β rate homogeneity + systematics on ^{210}Bi constraint

Angular ±0.59 cpd/100t



Radial ±0.52 cpd/100t



$R(\mathrm{Po_{min}})$	σ_{fit}	σ_{mass}	σ_{bin}	$\sigma^{hom.}_{angular}$	$\sigma^{hom.}_{radial}$	σ^{leak}_{β}	σ_{tot}
11.5	0.88	0.36	0.31	0.59	0.52	0.30	1.30

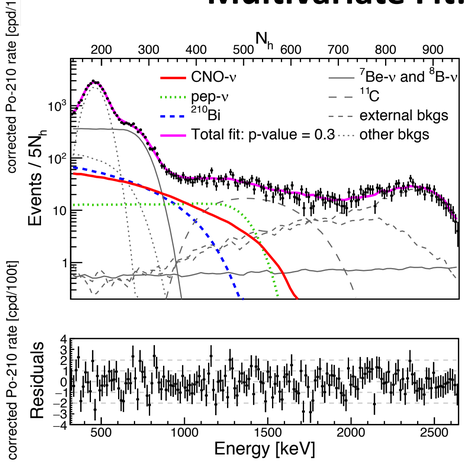
add all systematic uncertainties in quadrature

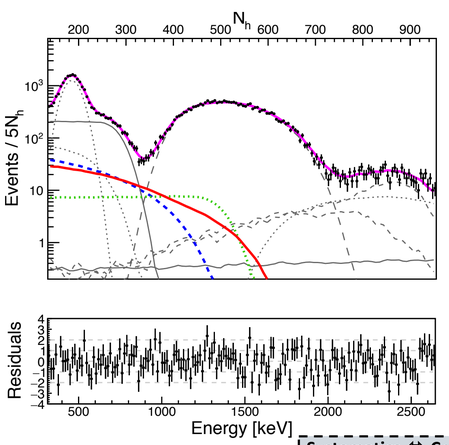
Bismuth-210 Upper Limit Determination
$$R(\mathrm{Po}_{min}) = R(\mathrm{Bi}) + R(\mathrm{Po^{IV}}) \geq R(\mathrm{Bi})$$

^{210}Bi Upper Limit
$\leq (11.5 \pm 1.3)$ counts/day/100t

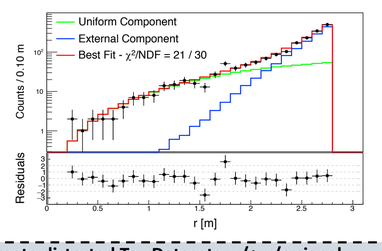
CNO Fit + Significance

Multivariate Fit: $\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}_{^{11}\mathrm{C}-sub}(\vec{\theta})\,\mathcal{L}_{^{11}\mathrm{C}-tag}(\vec{\theta})\,\mathcal{L}_{Radial}(\vec{\theta})$



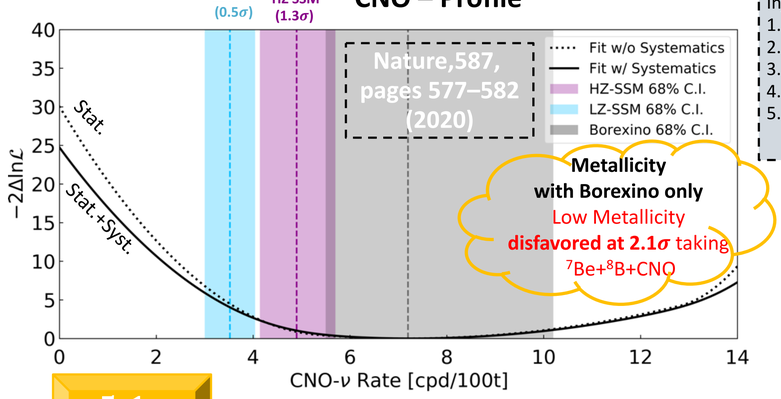


- *pep*-ν constraint = symmetric Gaussian
- ^{210}Bi constraint = semi-symmetric Gaussian (upper limit)



Systematics ⇔ Create distorted Toy Datasets w/+w/o signal
Injected Systematics:
1. non-linearity of the energy scale (0.4%)
2. spatial non-uniformity z-axis (0.28%)
3. light yield (0.32%)
4. ^{11}C peak position
5. other ^{210}Bi spectral shapes (18%) (area of ^{210}Bi is constrained by the upper limit)

CNO – Profile

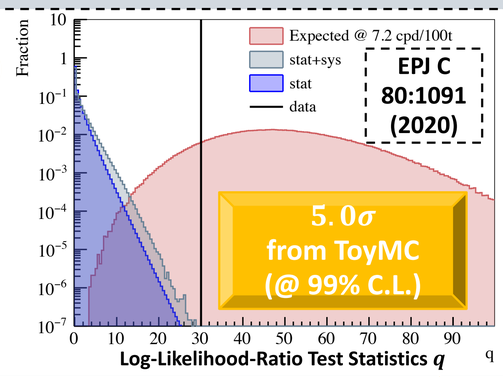


Nature,587, pages 577–582 (2020)

Metallicity with Borexino only
Low Metallicity **disfavored at 2.1σ** taking ^{7}Be+^{8}B+CNO

5.1σ from profiling

Rate: $R(\mathrm{CNO}) = (7.2^{+3.0}_{-1.7})$ cpd/100t
Flux: $\Phi = (7.0^{+3.0}_{-2.0})\times10^{8}$ cm^{-2}s^{-1}



EPJ C 80:1091 (2020)

5.0σ from ToyMC (@ 99% C.L.)

Contact: o.penek@fz-juelich.de

References: 1 M. Agostini et al. (Borexino Collaboration), Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun, Nature, **587**, pages 577–582 (2020), **2** M. Agostini et al. (Borexino Collaboration), Sensitivity to neutrinos from the solar CNO cycle in Borexino, Eur. Phys. J. C 80:1091 (2020)

CNO DISCOVERY