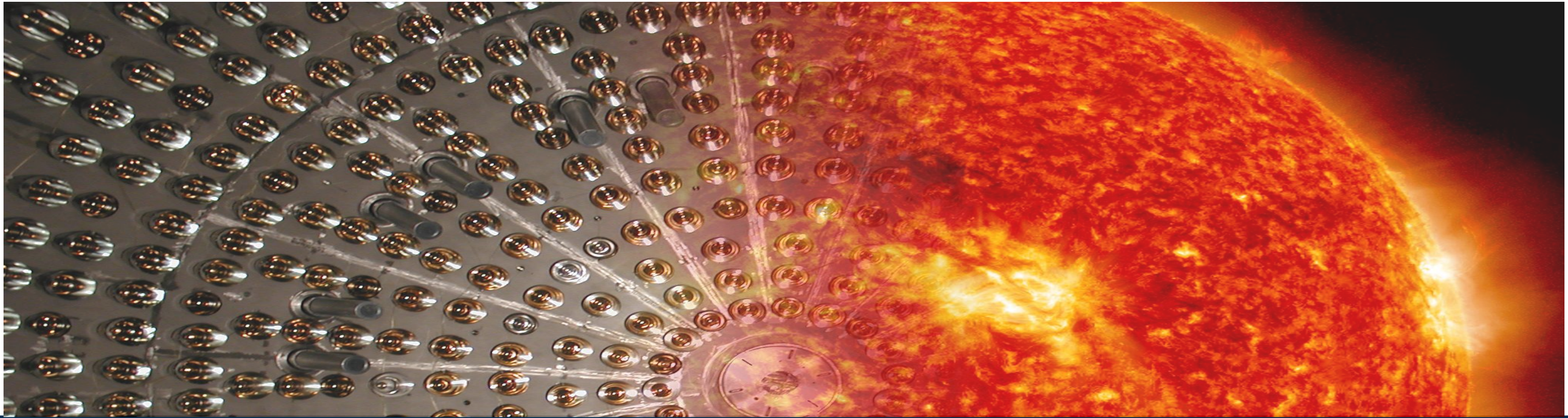


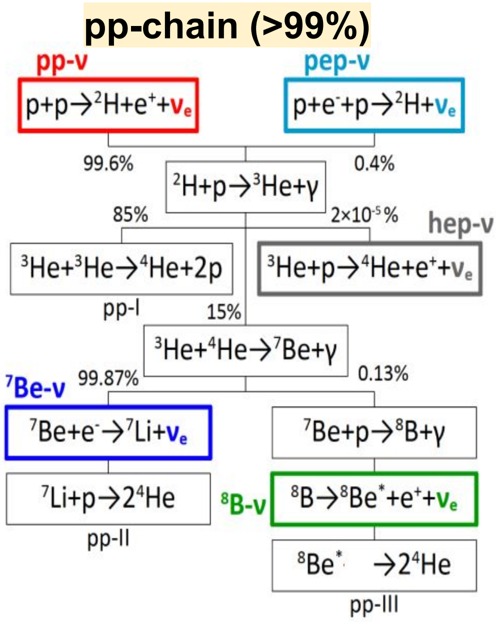
Recent Results from Borexino: Measurement of CNO solar neutrinos and Directionality of sub-MeV solar neutrinos

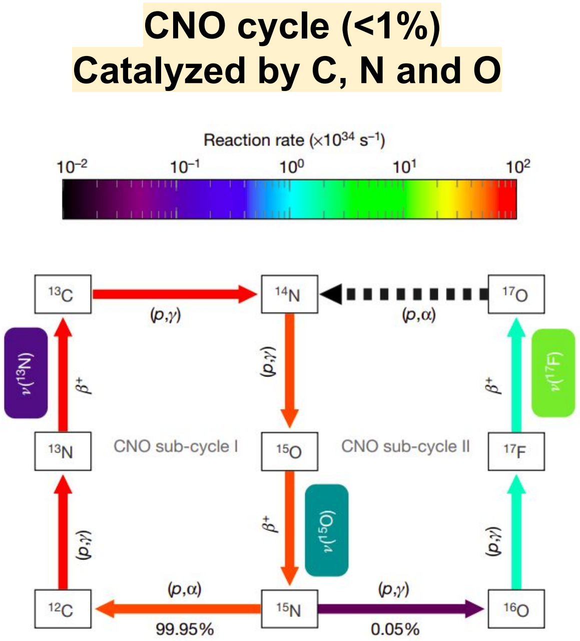
21.10.2022 I Apeksha Singhal [1,2], for the Borexino Collaboration

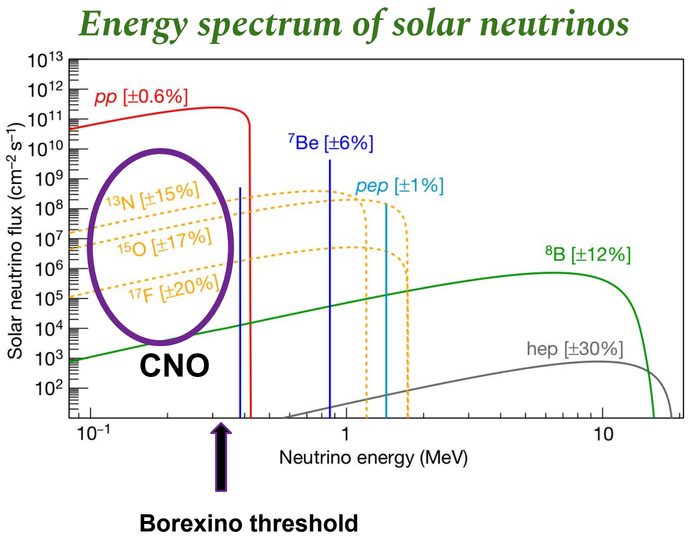
[1] *Forschungszentrum Jülich - Institute for Nuclear Physics, IKP-2, Jülich, Germany*
[2] *RWTH Aachen University - Physics Institute III B, Aachen, Germany*

Solar Neutrinos

According to the Standard Solar Model (SSM), the Sun is powered by two sequences of Hydrogen to Helium conversion reactions :







CNO cycle is dominant in massive stars (>1.3M☉)

CNO solar neutrinos and Solar Metallicity Problem

Metallicity (**Z**/**X**): abundance of elements with Z>2 in the Sun. Can be inferred from spectroscopic measurement of the photosphere.

Evolution of metallicity:

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

Grevesse et al.,Space Sci.Rev. (1998)85

⇒

(2009) Z/X(AGS98) = 0.018
- LZ-Scenario
- Helioseismology ✗

A. Serenelli er al., Astr J. 743,(2011)24

⇒ ● ⇒

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

Asplund et al .Rev.Astr.Astr A&A (2021) 653

⇒

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

Magg et al., arXiV:2203.02255

<u>Solar neutrino fluxes depends on the metallicity input in SSM</u>:

Species	HZ-Flux ($cm^{-2}s^{-1}$)*	LZ-Flux ($cm^{-2}s^{-1}$)**	Relative difference(%)
pp	$5.98(1 \pm 0.006)\times10^{10}$	$6.03(1 \pm 0.005)\times10^{10}$	-0.8
pep	$1.44(1 \pm 0.01)\times10^{8}$	$1.46(1 \pm 0.009)\times10^{8}$	-1.4
^{7}Be	$4.93(1 \pm 0.06)\times10^{9}$	$4.50(1 \pm 0.06)\times10^{9}$	8.9
^{8}B	$5.46(1 \pm 0.12)\times10^{6}$	$4.50(1 \pm 0.12)\times10^{6}$	17.6
^{13}N	$2.78(1 \pm 0.15)\times10^{8}$	$2.04(1 \pm 0.14)\times10^{8}$	26.6
^{15}O	$2.05(1 \pm 0.17)\times10^{8}$	$1.44(1 \pm 0.16)\times10^{8}$	29.7
^{17}F	$5.29(1 \pm 0.20)\times10^{6}$	$3.26(1 \pm 0.18)\times10^{6}$	38.3

Metallicity is an input to the SSM, that influences the neutrino flux prediction.
Metallicity-> opacity -> temperature -> cross sections
CNO -> direct influence through C, N, O

Measuring the flux of CNO neutrinos could provide a crucial input to solve the puzzle

** SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (2017) 202 + Grevesse et al.,Space Sci.Rev. (1998)85 12*
*** SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (2017) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

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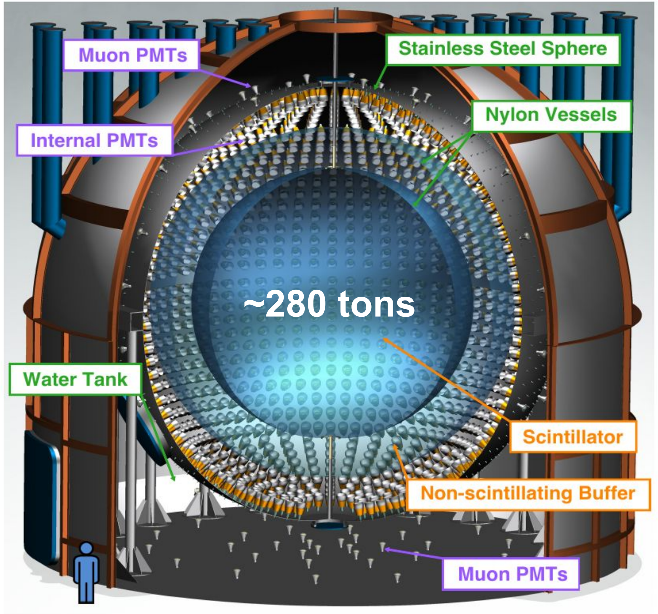
The Borexino Detector

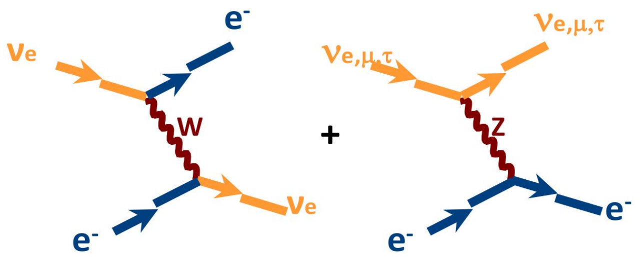


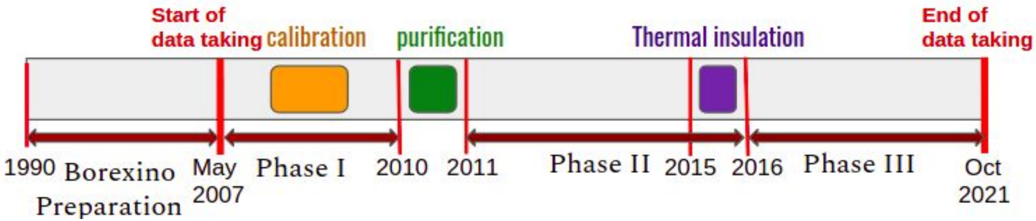
- Located in Laboratori Nazionali del Gran Sasso (LNGS), Italy.
- **The radio-purest** liquid scintillator detector in the world.

^{238}U-chain <9.4x10^{-20} g/g (95% C.L.) and ^{232}Th-chain <5.7x×10^{-19} g/g (95% C.L.)

- Cosmic Muon flux suppression by ~10^{6}
- Effective Light Yield: ~500 photoelectrons/MeV with ~2000 PMTs
- Energy resolution: 5% @ 1 MeV
- Position resolution: 10cm @ 1 MeV
- Pulse shape discrimination methods available (α/β, e-/e+)

Neutrinos detected via elastic scattering off electrons





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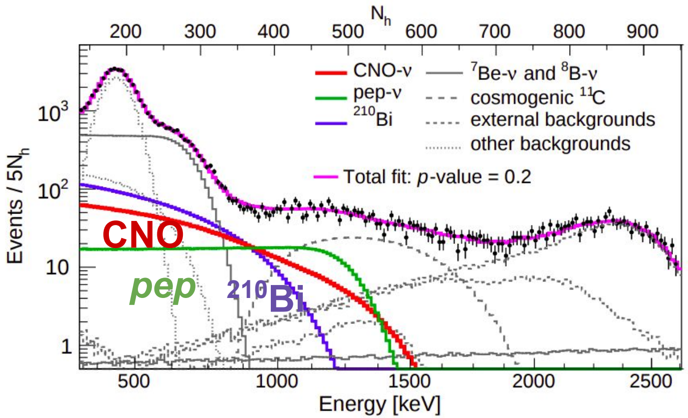
Measurement of CNO solar neutrinos

Borexino Data : Phase-3 (Jan 2017-Oct 2021)

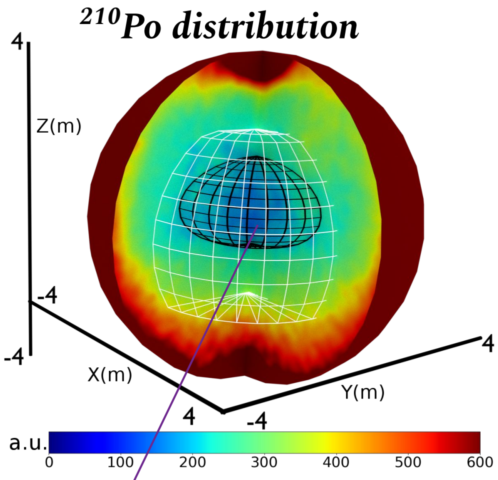


Likelihood fit using cosmogenic ^{11}C-depleted, ^{11}C-enriched energy distributions and radial distributions of data using constraints on

pep-ν rate = 2.74± 0.04 cpd/100 t
(from theory + global analysis fit of solar data without Bx Phase III and the most recent oscillation parameters)*

^{210}Bi rate ≤ 10.8 ± 1.0 cpd/100 t (from ^{210}Po)

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{yr}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,\mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}$$



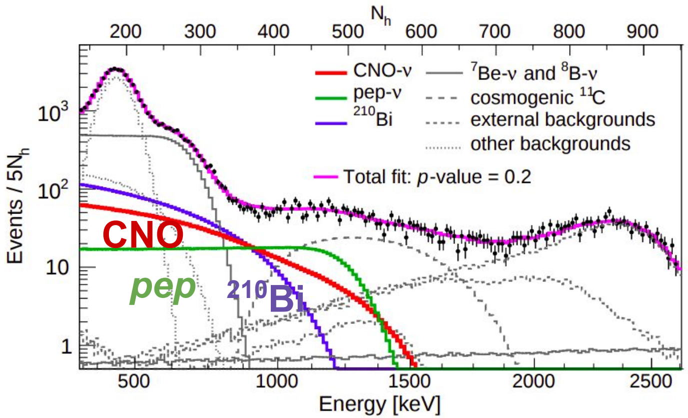
Low Polonium Field (LPoF) ~ 20 tons as the result of "Thermal Insulation" campaign

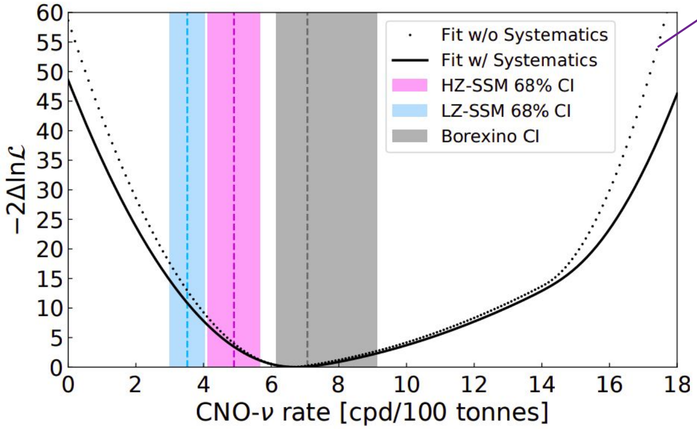
Almost free of convective ^{210}Po from nylon vessel

*Bergström et al https://doi.org/10.1007/JHEP03(2016)132)

Measurement of CNO solar neutrinos

Borexino Data : Phase-3 (Jan 2017-Oct 2021)





Likelihood fit using cosmogenic ^{11}C-depleted,

arXiV:2205.15975,
Accepted for publication in PRL

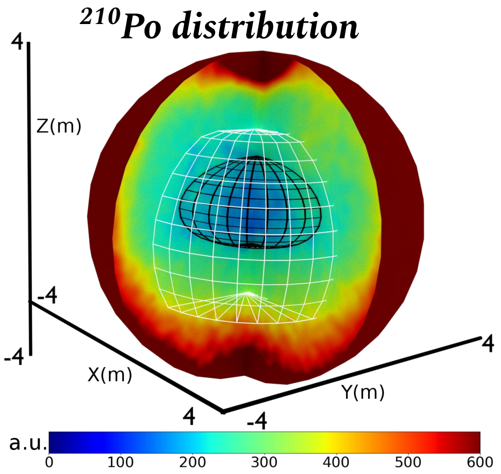
Excluding no-CNO signal hypothesis at ~7σ C.L

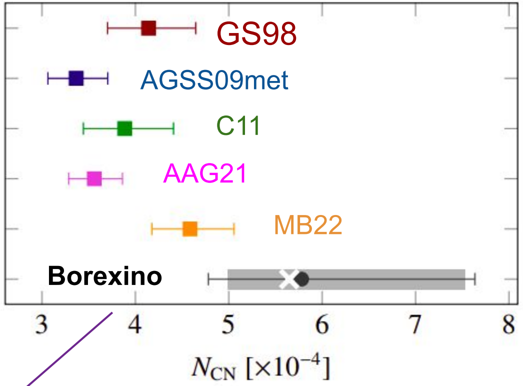
R(CNO)= $6.7^{+2.0}_{-0.8}$ cpd/100 t

Φ(CNO) = $6.6^{+2.0}_{-0.9}$ x 10^8 cm^{-2} s^{-1}

First direct measurement of the C and N abundance from solar-ν

Good agreement with HZ (GS98, MB22), while ~2σ tension with LZ (AGSS09met, C11 , AAG21).





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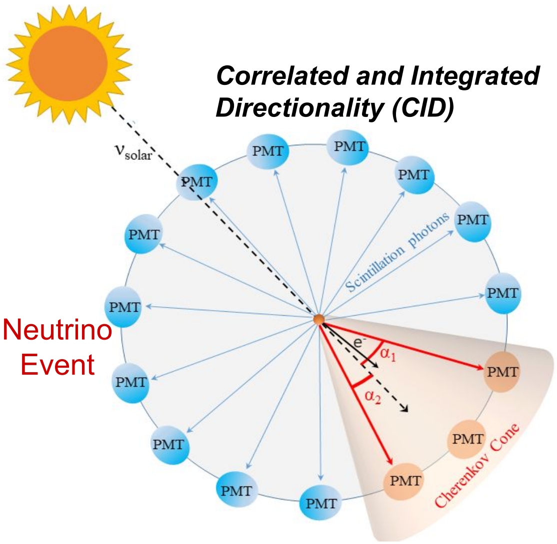
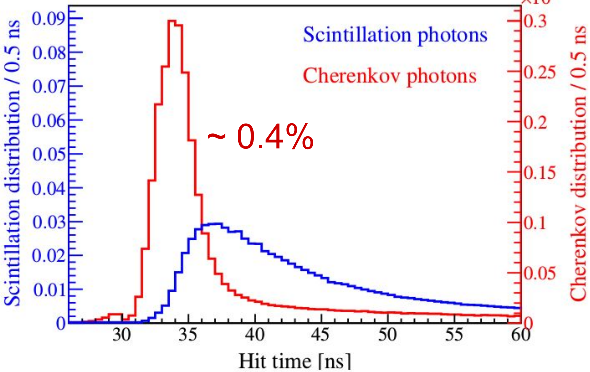
Directionality of sub-MeV solar neutrinos



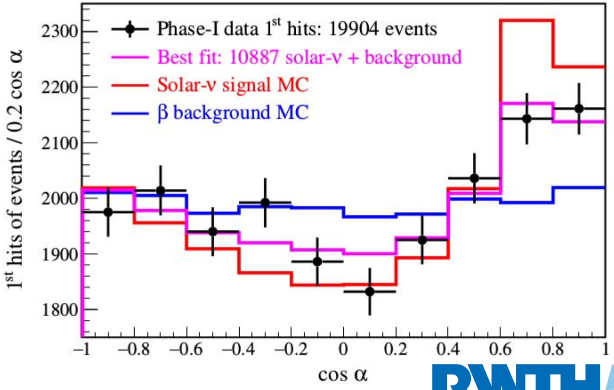
PRL 128 (2022) 091803 + PRD 105(2022) 052002.

- **Motivation:** Next-generation hybrid detectors: efforts to combine advantages of Cherenkov light (directional) and scintillation light (High light yield).
- **CID:** Correlating the first 2 hits of an event (around ^{7}Be edge) with known position of the Sun and integrating over all events.

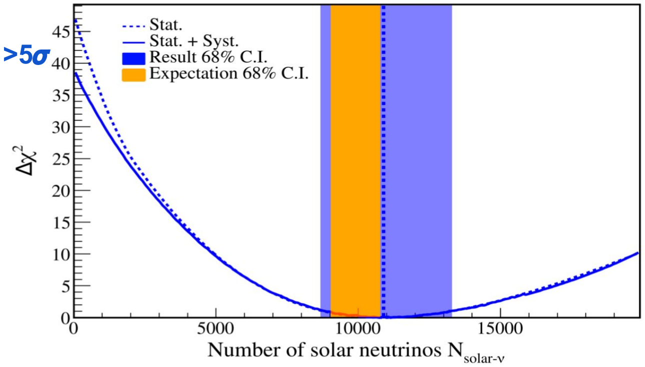
PMT hit time distribution in Borexino MC



Best fit of 1st hit of 19904 events in Phase-I



Δχ2 profile for fit of 1st+2nd hits in Phase-I



$N_{solar-\nu} = 10887^{+2386}_{-2103}$ (stat.) ± 947 (syst.)

$R(^7Be) = 51.6^{+13.9}_{-12.5}$ (stat.+syst.) cpd/ 100t.

- **>5σ detection of sub-MeV solar neutrinos using their directional Cherenkov photons**
- **Proof-of-principle for the next-generation liquid scintillator based detectors.**

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Summary

- Borexino has detected neutrinos from the CNO cycle in the Sun with a significance of ~7σ.

- Abundance of C and N in the Sun, determined for the first time with solar neutrinos, in a good agreement with HZ photospheric measurements; ~2σ tension with the LZ photospheric measurements.

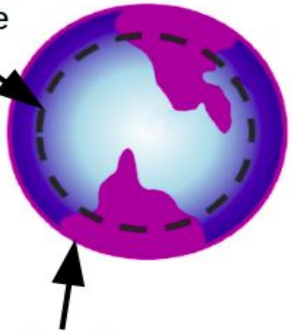
- >5σ detection of sub-MeV solar neutrinos using their directional Cherenkov photons and extracted ^{7}Be neutrinos rate in agreement with Standard Solar Model predictions and Borexino Phase-I spectral fit results.

- Proof-of-principle for next-generation LS-based detectors. Highly recommended to use dedicated calibration for Cherenkov light.

Outlook: Application of CID in spectral fit to measure CNO neutrinos is under study.

Backup

The ^{210}Bi Constraint Challenge



- Temperature variation due to seasonal effects causing convective currents and brings ^{210}Po from nylon vessel surface to fiducial volume.
- Secular equilibrium is broken.
- Two contributions for ^{210}Po:
  ^{210}Po from ^{210}Bi decay and ^{210}Po from vessel.

Solution: Thermally stabilize the detector

Thermal insulation of detector using mineral wool (Dec 2015)

Achievement of excellent temperature stability due to effort of over 6 years

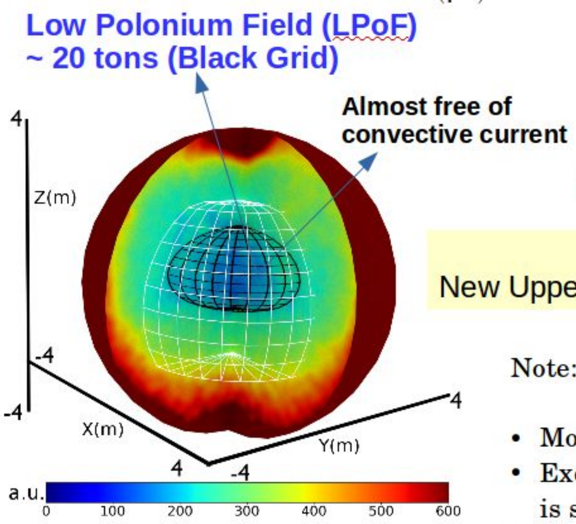
The ^{210}Bi Constraint Challenge

Identifying low ^{210}Po rate region to get the ^{210}Bi constraint,

$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = (R(^{210}Po_{min}) * eff_{\alpha} * eff_{E} + \beta_{leak}) * [1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}]$$

Efficiency due to cuts

Residual β events in α region



$R(^{210}Bi) < R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po_{vessel})$

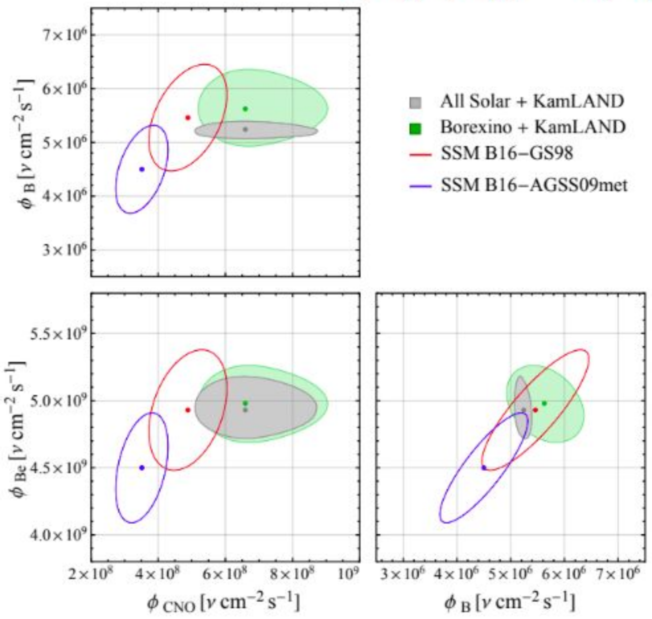
Considering all systematics,
New Upper limit on ^{210}Bi rate: $R(^{210}Bi) <= (10.8 \pm 1.0)$ cpd/100t

Note: With respect to 2020 results:

- More exposure
- Excluded 2016 where unsupported ^{210}Po contribution is still high,
- More stable temperature leads to larger LPoF region

Comparison with Standard Solar Model prediction

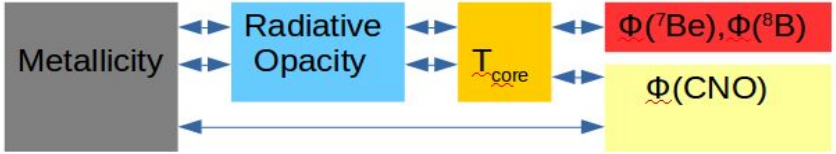
Results of the global analysis in the Φ_B - Φ_{Be}, Φ_B - Φ_{CNO}, and Φ_{Be} - Φ_{CNO} planes.



- Global analysis of all solar neutrino data + KamLAND reactor data (grey regions) and of Borexino data only + KamLAND (green regions) is performed.
- The results are in agreement with SSM-HZ (B16-GS98) predictions, while the comparison feature a small tension with the SSM-LZ (B16-AGSS09met) model (p-value = 0.028 for global analysis and p-value = 0.018 for Bx only)
- The small tension is created by including the CNO results.

All the allowed regions are reported at 68.27% C.L.

Determining C and N abundance from CNO measurement



$$\Phi_B/\Phi_B^{SSM} \propto (T_c/T_c^{SSM})^{\tau_B} \qquad \tau_B \approx 24$$

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c^{SSM})^{\tau_O} \qquad \tau_O \approx 20$$

CN abundance at solar core

Using the ^{8}B neutrino flux measurement as a “thermometer” to constrain the temperature of the solar core.

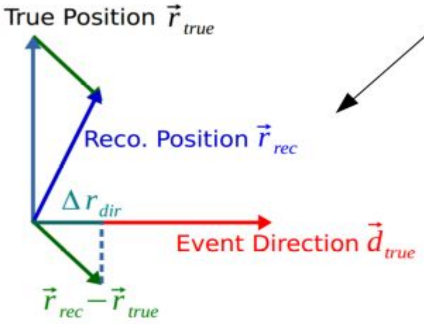
Constructing a ratio between one of the neutrino fluxes generated in the CNO cycle and the ^{8}B neutrinos flux with a proper weighting factor k

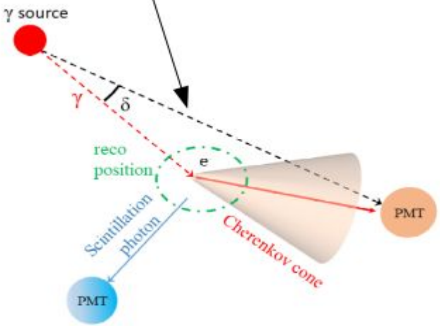
$$\frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \left(\frac{T_c}{T_c^{SSM}}\right)^{\tau_O - k\tau_B}$$

k (=0.83) is chosen to minimize variations due to temperature.

CID : Fit Method with Systematics

$$\chi^2(N_{\text{solar}-\nu}) = \sum_{n=1}^{N}\sum_{i=1}^{I}\left(\frac{\left((\cos\alpha)^D_{n,i} - (\cos\alpha)^M_{n,i}(N_{\text{solar}-\nu}, \Delta r_{\text{dir}}, gv^{\text{corr}}_{\text{ch}})\right)^2}{(\sigma^D_{n,i})^2 + (\sigma^M_{n,i})^2} + \frac{(gv^{\text{corr}}_{\text{ch}} - 0.108\,\text{ns m}^{-1})^2}{(0.039\,\text{ns m}^{-1})^2}\right)$$





- **Δr_{dir}** : bias in position reconstruction of e-.
- It cannot be corrected without a e- Cherenkov calibration.
- Treated as nuisance free parameter

- Calibrate *relative* speed of Cherenkov and scintillation photons in MC.
- Effective correction for the group velocity of Cherenkov photons with γ-sources (Phase I): gv_{Ch} = 0.108 ± 0.039 ns/m (2% correction on refractive index at 400 nm)