Luca Pelicci[1,2]

(for the Borexino collaboration)

lucapelicci@gmail.com

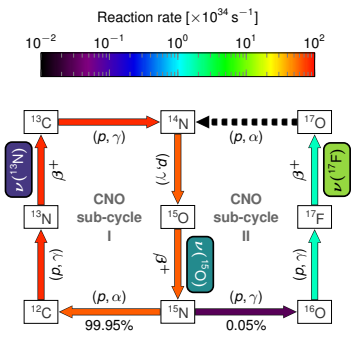
[1]Institut für Kernphysik, Forschungszentrum Jülich, Germany

[2]RWTH Aachen University - Physics Institute III B, Aachen, Germany

Current institution: Università degli studi di Milano

Final CNO solar neutrino measurement with Borexino: directionality measurement and spectral analysis

The importance of CNO neutrinos



- Hydrogen to Helium fusion sequences in the Sun:
  - *pp*-chain ($\sim 0.99 \cdot L_{\odot}$);
  - CNO cycle ($\sim 0.01 \cdot L_{\odot}$).
- Proof of existance of Carbon - Nitrogen - Oxygen (CNO) cycle in nature.
- Dominant process for stars with $M \geq 1.5\ M_{\odot}$.

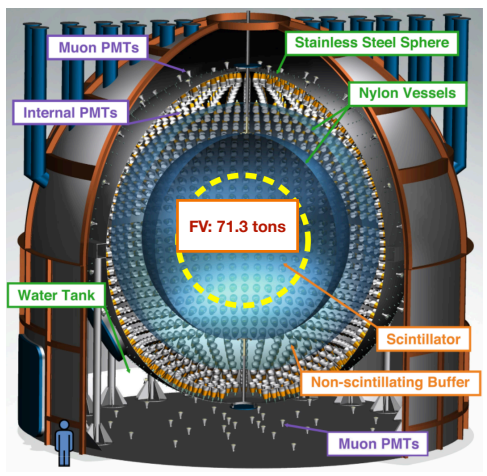
Solution for the ***metallicity problem***?

- The **Standard Solar Model (SSM)** describes the evolution of the Sun with input parameters (e.g. initial metal abundances) calibrated with observables (e.g. current surface metal abundaces) [1]
- Different photospheric measurements give different surface metal abundances (*High-Z* vs *Low-Z*) → **Metallicity problem:** only SSMs based on LZ assumptions align with helioseismology [2]

$\Phi(\nu_s)$ offer a separate observable to test the metallicity of the Sun:

Φ(CNO) is the perfect probe (~28% difference between HZ and LZ)

Borexino detector [3]



- Location: Laboratori Nazionali del Gran Sasso (LNGS), Italy
- Detection channel: neutrino-electron elastic scattering
- 2212 nominal PMTs to detect light
- Unprecedented level of radiopurity
- High effective light yield (~500 p.e./MeV for 2000 PMTs)
- Low energy threshold (~0.12 MeV)
- Good energy (~5% at 1 MeV) and position resolution (~10 cm at 1 MeV)

LS purification (2007) — **LS purification** (2011) — **Thermal insulation** (2016)

Phase-I (2007 - 2010) | Phase-II (2011 - 2016) | Phase-III (2017 - 2021)

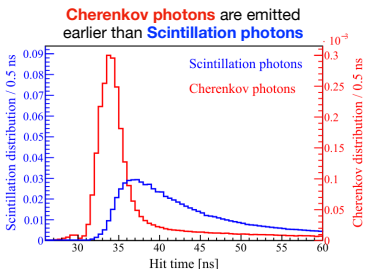
- ^{7}Be-ν, *pep*-ν and ^{8}B-ν 1st observation
- Directional measurement of ^{7}Be-ν
- Comprehensive measurement of pp-chain (**Nature 2018**) [4]
- CNO measurement (2020 [5] and 2022 [6])
- New! **Directional measurement of CNO solar neutrinos [7]**

Comprehensive spectroscopy of solar-ν from *pp*-chain and CNO cycle

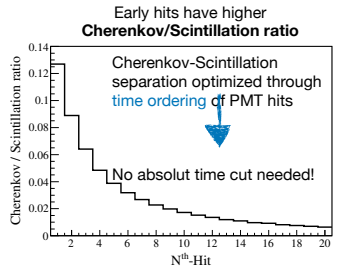
Correlated and Integrated Directionality (CID)

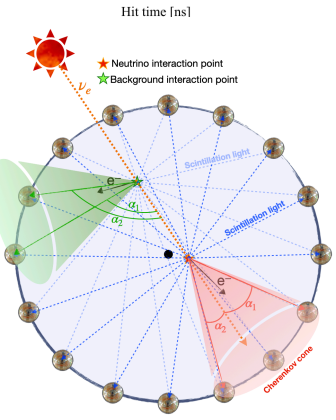
Solar neutrino identification via **sub-dominant but fast Cherenkov light**

Cherenkov photons are emitted earlier than **Scintillation photons**



Early hits have higher **Cherenkov/Scintillation ratio**



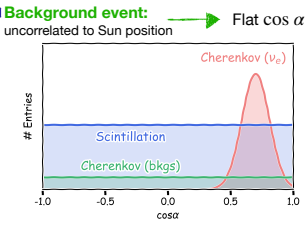


$$\cos\alpha = \vec{d}_{\gamma} \cdot \vec{d}_{\nu}$$

Scintillation light: → Flat $\cos\alpha$

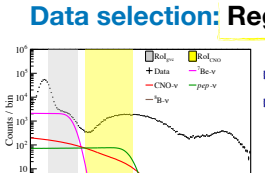
Cherenkov light:

- **ν_e event:** correlated to Sun position → Peak at $\cos\alpha \sim 0.7$
- **Background event:** uncorrelated to Sun position → Flat $\cos\alpha$



- $\cos\alpha$ distributions are produced for each N^{th}-Hit with G4-based Borexino MC [8]
- Number of solar neutrnios (N_{ν}) extracted via simultaneous fit of all $\cos\alpha$ spectra with N^{th}-hit $\in [1-15]$ in Phase-I and $\in [1-17]$ in Phase-II+III

Data selection: Region of Interest for CNO analysis



- Signal: N_{ν} = *pep*-ν (~64%) + CNO-ν (~33%) + ^{8}B-ν (~3%)
- Background: N_{Bkg} = ^{210}Bi + ^{11}C + External γ (No preliminar information on backgrounds is needed)

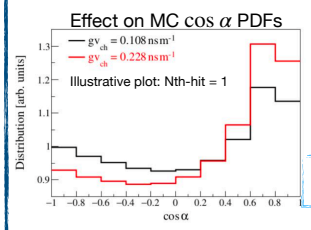
Whole Borexino DAQ: Phase-I and Phase-II+III

Main systematic effects

1. Effective group velocity correction for Cherenkov photons (gv_{ch}^{corr})

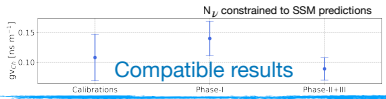
Sc/Ch relative time difference needs calibration in MC: $t_{new}^{ToF} = t_{MC}^{ToF} - gv_{Ch}^{corr} \cdot L_{MC}$

Effect on MC $\cos\alpha$ PDFs



Calibrated on ^{7}Be shoulder: RoI$_{gvc}$

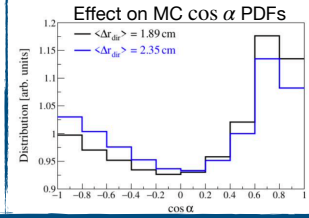
Previously: gv_{Ch} calibrated on γ calibrations in Phase-I



Constrained nuisance parameter in the fit

2. Event position reconstruction bias (Δr_{dir}) towards direction of Cherenkov cone

Effect on MC $\cos\alpha$ PDFs

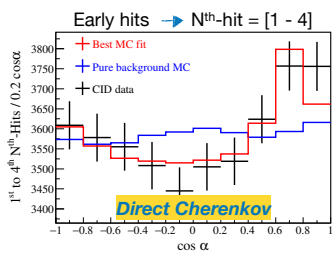


- $\Delta r_{dir} \sim 2$ cm in MC (unknown in data)
- Additional *indirect information* in $\cos\alpha$ distributions of solar neutrinos
- Cannot be calibrated (no Cherenkov calibration source)

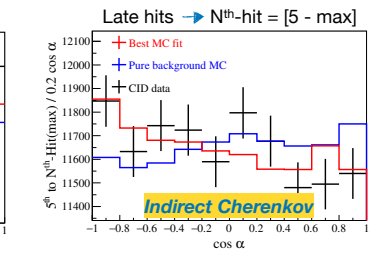
Free nuisance parameter in the fit

CID fit in RoI$_{CNO}$: $\chi^2(N_{\nu}, gv_{Ch}, \Delta r_{dir})$ — Nuisance parameters

Early hits → N^{th}-hit = [1 - 4]



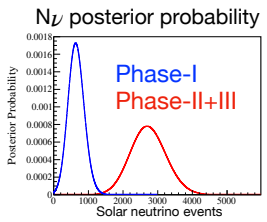
Late hits → N^{th}-hit = [5 - max]



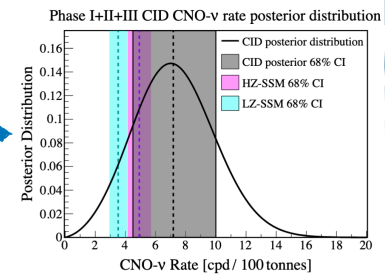
CNO results with CID:

R(CNO) distribution is derived from combined N_{ν} posterior probability (Phase-I+II+III) constraining non-CNO contributions to SSM predictions

N_{ν} posterior probability



Phase I+II+III CID CNO-ν rate posterior distribution



R(CNO) = $7\ .\ 2^{+2.8}_{-2.7}$ cpd/100t

- No assumption on backgrounds (^{210}Bi)
- No-CNO hypothesis disfavoured at $\sim 5.3\sigma$

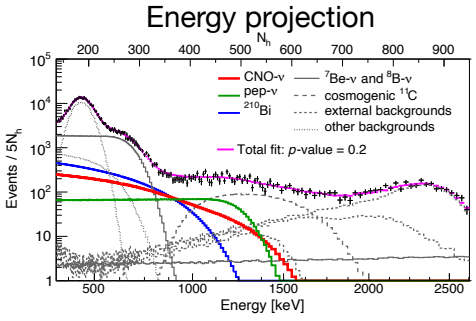
Alternative method for independent determination of Φ(CNO) (at 5.3σ) without ^{210}Bi constraint [7]

The spectral fit

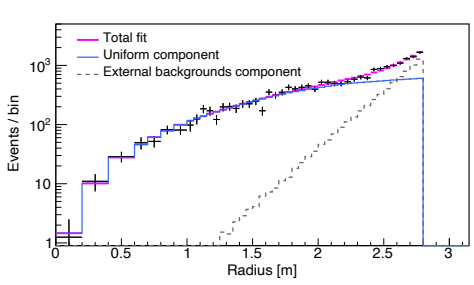
Minimization of a full 2D likelihood function with non-equidistant binning:

$$\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}^{2D}_{E-Sub}(\vec{\theta}, E, R) \cdot \mathcal{L}_{E-Tag}(\vec{\theta}, E) \cdot \mathcal{L}_{pep}(\vec{\theta}) \cdot \mathcal{L}_{^{210}Bi}(\vec{\theta})$$

Energy projection



Radial projection

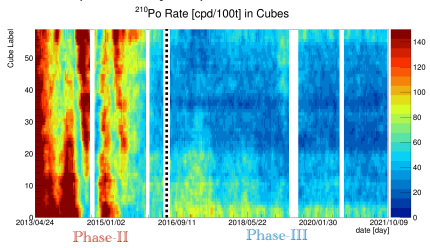


Constraints:

1. **pep−ν constraint:** *pep*-ν = 2.74 ± 0.04 cpd/100 t (solar luminosity constraint + global analysis of solar data)
2. **^{210}Bi constraint** through ^{210}Po:

$$^{210}\mathbf{Pb} \xrightarrow[Q_{\beta}=63.5\ keV]{\beta\ \tau\approx 32\ y} {}^{210}\mathbf{Bi} \xrightarrow[Q_{\beta}=1160\ keV]{\beta\ \tau\approx 7.23\ d} {}^{210}\mathbf{Po} \xrightarrow[Q_{\alpha}=5.3\ MeV]{\alpha\ \tau\approx 199.1\ d} {}^{206}\mathbf{Pb}$$

Convective motions in the LS (caused by ΔT) → Unknown amount of out-of-equilibrium ^{210}Po^V from the vessele in the FV → Thermal insulation of the detector



Minimum ^{210}Po rate ⟷ ^{210}Bi upper limit

$$R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po^{V}) \geq R(^{210}Bi)$$

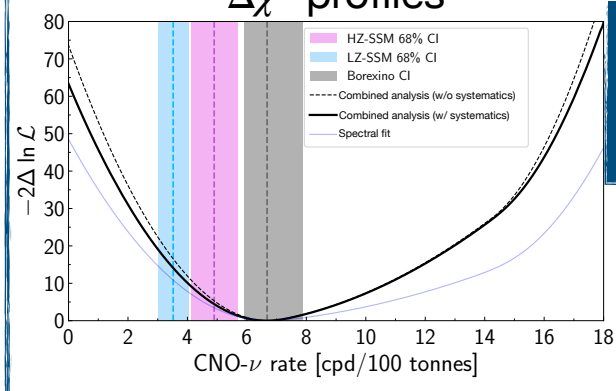
R(^{210}Bi) = 10.8 ± 1.0 cpd/100t

The combined analysis

CID results are included as external pull terms based on N_{ν} posteriors:

$$\mathcal{L}_{Combined}(\vec{\theta}) = \mathcal{L}_{MV}(\vec{\theta}) \cdot \mathcal{L}^{P-I}_{CID}(\vec{\theta}) \cdot \mathcal{L}^{P-II+III}_{CID}(\vec{\theta})$$

$\Delta\chi^2$ profiles



The final and most precise Borexino result on CNO-ν:

$$\Phi(\text{CNO}) = 6.7^{+1.2}_{-0.8} \cdot 10^{8}\ \text{cm}^2\text{s}^{-1}$$

- Signficance to no-CNO hypothesis
- Solar impications:
  - $N_{CN} = 5.81^{+1.22}_{-0.94} \cdot 10^{-4}$ (~2σ tension with LZ)
  - LZ-SSM disfavoured at 3.2σ level (binary hypothesis test)

The Borexino CNO saga

References

[1] Núria Vinyoles et al. "A new Generation of Standard Solar Models". In: Astrophys. J. 835.2 (2017).
[2] N. Grevesse and A. Sauval. "Standard Solar Composition". In: Space Science Reviews 85 (1998)
[3] G. Alimonti et al. "The Borexino detector at the Laboratori Nazionali del Gran Sasso". In: Nucl. Instrum. Meth. A600 (2009).
[4] M. Agostini et al. "Comprehensive measurement of pp-chain solar neutrinos". In: Nature 562.7728 (2018).
[5] M. Agostini et al. "Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun". In: Nature 587 (2020).
[6] 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". In: Physical Review Letters 129.25 (2022)
[7] G. et al. Bellini. "Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy". In: Phys. Rev. D 89 (11 2014)