Latest results on solar CNO neutrinos from Borexino

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on behalf of the Borexino Collaboration

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photo: BOREXINO calibration

THE BOREXINO EXPERIMENT

- **Main goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.
- **Detection method**: elastic scattering of neutrinos on electrons.
  $\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$
- **Location**: LNGS (Laboratori Nazionali del Gran Sasso), Italy
- **Detection medium**: large mass of organic liquid scintillator.

The expected rate of ^{7}Be solar neutrinos in 100 ton of Borexino scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/kg.

Just for comparison, natural water is about 10 Bq/kg in ^{238}U, ^{232}Th and ^{40}K.
Huge effort to achieve extreme high radiopurity levels

- **Timeline**:

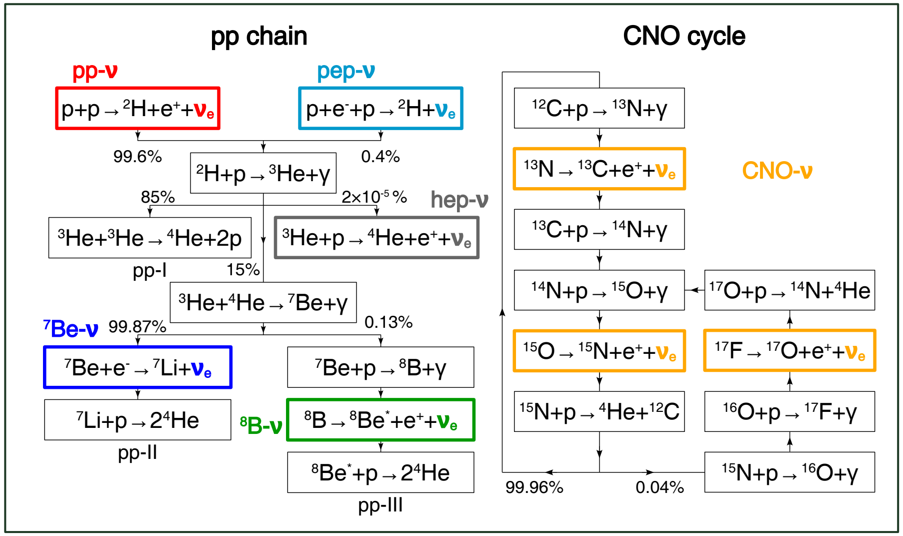
1988-1990 First discussion and design
1990-1995: R&D for radiopurity levels, CTF prototype
1996-2007: construction, filling, commissioning
2007-2021: data taking

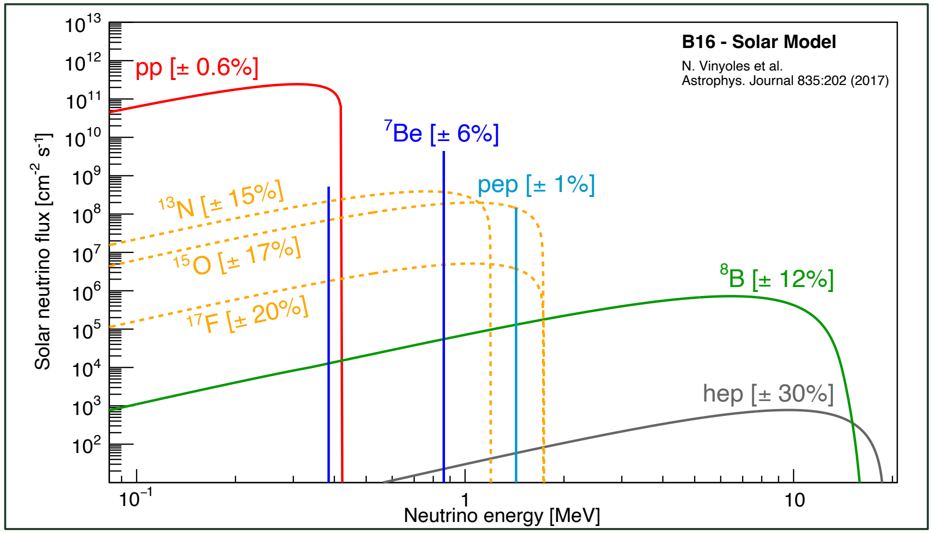
STUDYING THE SUN WITH NEUTRINOS…

$$4\,\mathrm{p} \rightarrow \alpha + 2\,\mathrm{e}^{+} + 2\,\nu_{\mathrm{e}} \qquad \mathrm{E_{released}} \sim 26\,\mathrm{MeV}$$

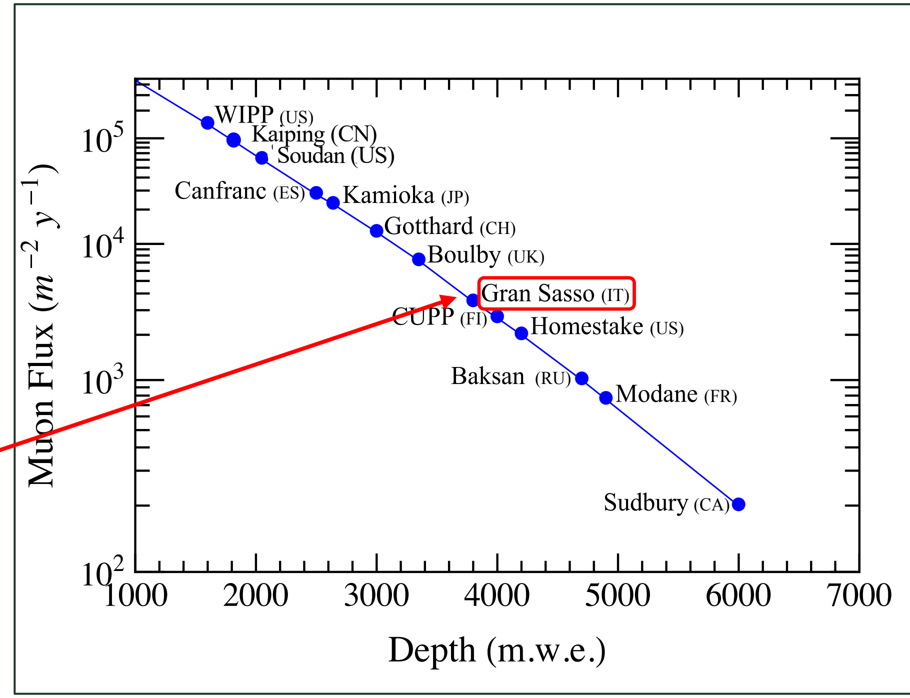
-While γ massively interact with the solar plasma and take about 10^5 years to reach our star surface, neutrinos stream out the Sun and take just 8 minutes to reach the Earth

-Performing solar neutrino spectroscopy is the only way to get a real-time snap-shot of the nuclear processes inside the Sun





LABORATORI NAZIONALI GRAN SASSO (ITALY)



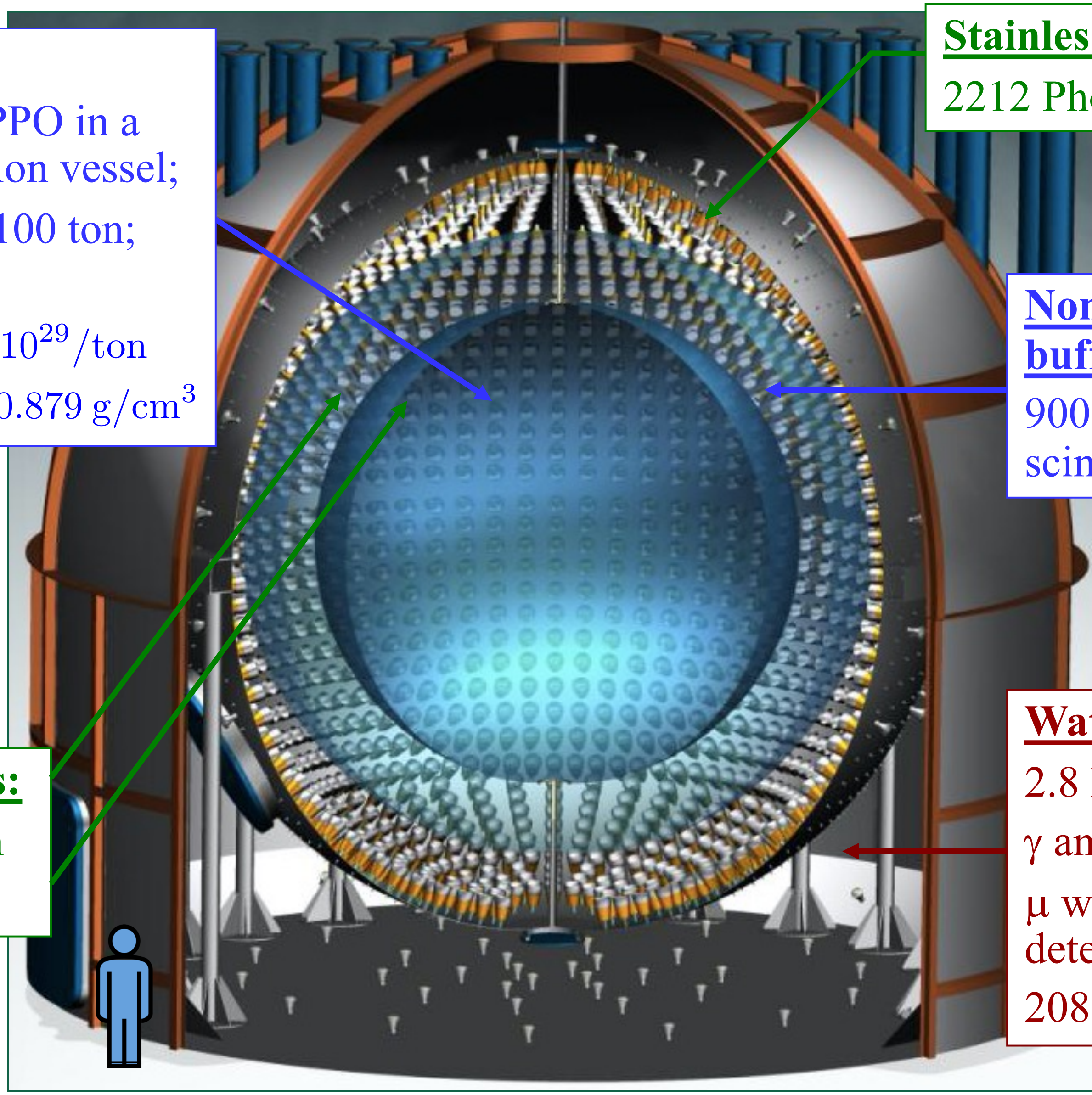
The **LNGS** altitude is 963 m and the average rock cover is about 1400 m.

The shielding capacity against cosmic rays is about 3800 m.w.e.:

→ in Borexino the muon flux is reduced by a factor 10^6 with respect to the surface.

$$\Phi(\mu) \sim 1\ \mu/\mathrm{m}^2/\mathrm{h}$$

DETECTOR DESIGN



Scintillator:

280 ton of PC+PPO in a 125 μm thick nylon vessel;

Fiducial mass ~ 100 ton;

Electron density:

$(3.307 \pm 0.003) \times 10^{29}/\mathrm{ton}$

Mass density: $\simeq 0.879\ \mathrm{g/cm^3}$

Stainless Steel Sphere:

2212 Photomultipliers

Non-scintillating buffer:

900 ton of quenched scintillator

Nylon vessels:

Outer: 5.50 m

Inner: 4.25 m

Water Tank:

2.8 kton of pure H_2O

γ and n shield

μ water Čerenkov detector

208 PMTs in water

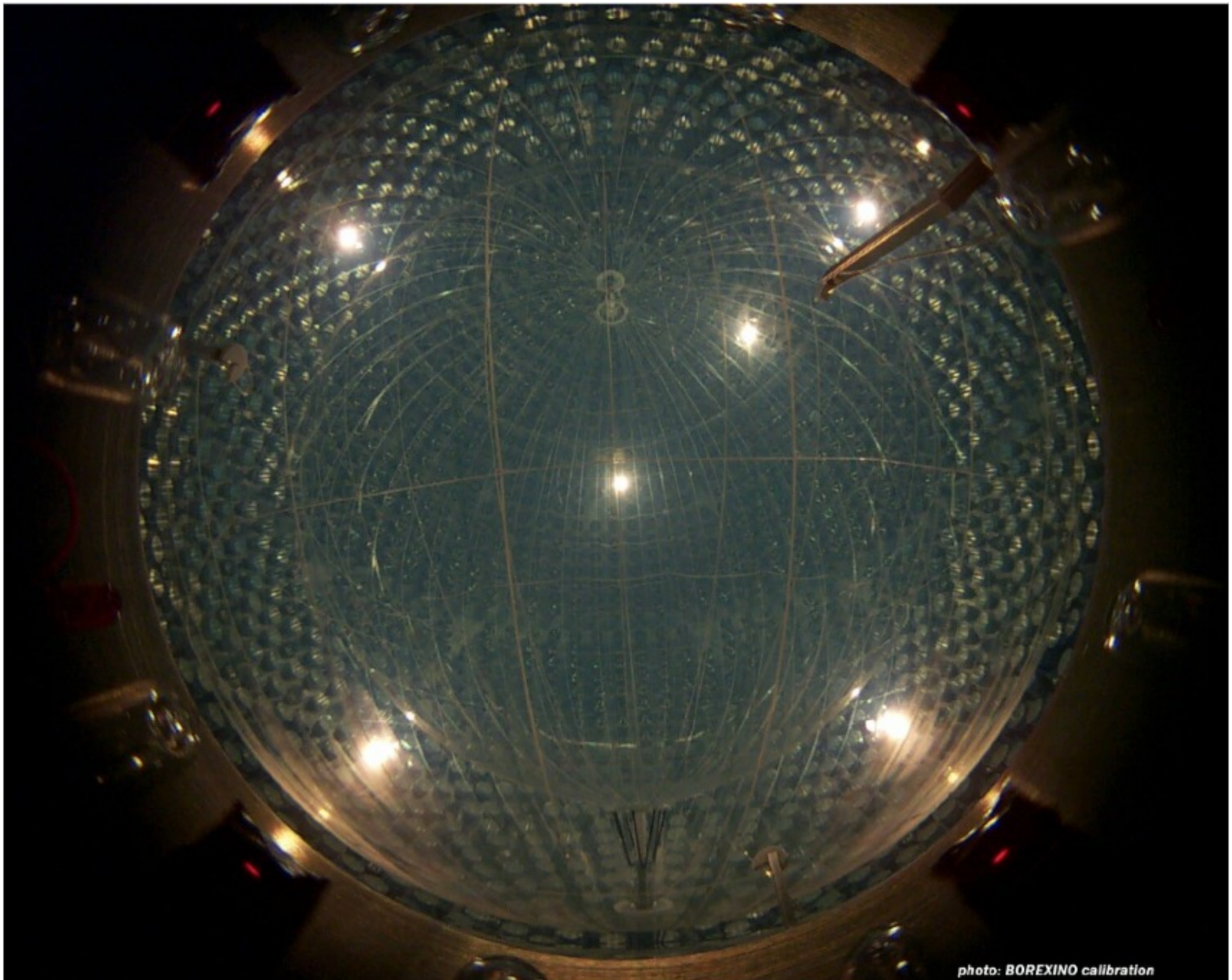


photo: BOREXINO calibration

DATA-TAKING TIMELINE

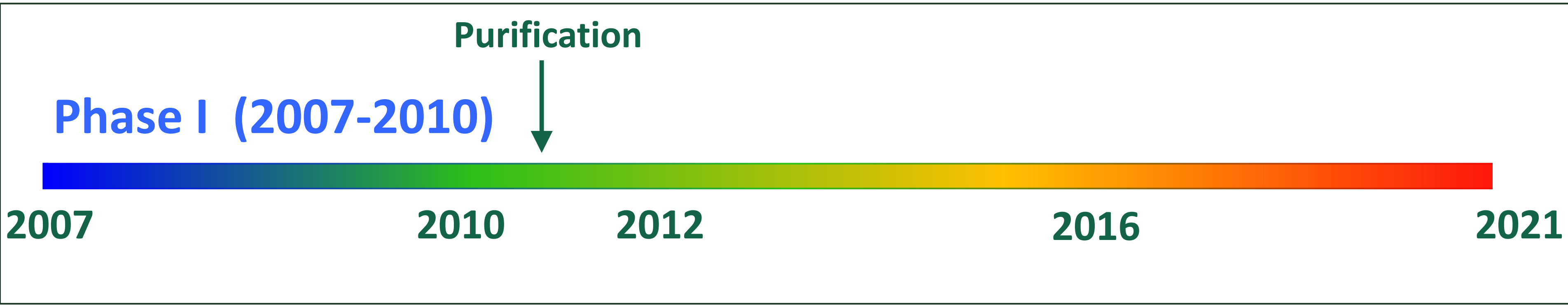
Phase I (2007-2010)

2007 **2010** **2012** **2016** **2021**

Direct measurements of

- ^{7}Be flux: 1st observation + precise measurement (5%);
- Absence of day/night asymmetry for ^{7}Be signal
  => MSW-LMA singled out (> 8.5σ);
- ^{8}B flux with low E threshold;
- pep flux: 1st observation;
- CNO upper limit (best to that date).

DATA-TAKING TIMELINE



2011 – 2nd Purification (6 cycles)
Further radiopurity improvement

^{85}Kr: reduced by ∼4.6 factor

^{210}Bi: reduced by ∼2.3 factor

^{238}U: $< 9.4 \times 10^{-20}$ g/g (95% C.L.)

^{232}Th: $< 5.7 \times 10^{-19}$ g/g (95% C.L.)

^{210}Po: reduced by > 10 factor due to natural decay

➡ **The scintillator has never been so clean!**

DATA-TAKING TIMELINE

Purification

Phase I (2007-2010) Phase II (2012-2016)

2007 2010 2012 2016 2021

Direct measurements of

- pp flux: 1st direct measurement ;
- Geoneutrinos (> 5σ);
- Electric charge conservation (best limit to date);
- Gamma-ray burst corr.
- ^{7}Be flux seasonal modulation;
- New limit on neutrino magnetic moments;
- Comprehensive measurement of pp-chain solar neutrinos (pep signal > 5σ).

DATA-TAKING TIMELINE

Purification — Thermal Insulation

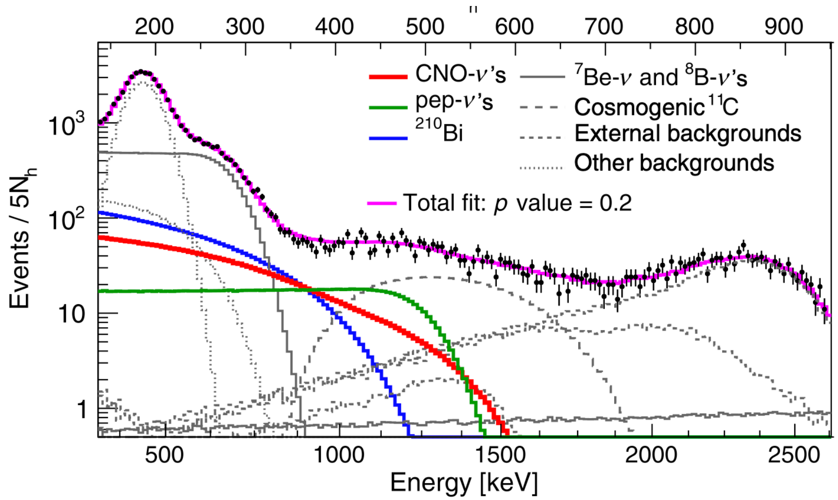
Phase I (2007-2010) — Phase II (2012-2016) — Phase III (2016-2021)

2007 2010 2012 2016 2021

Phase III:

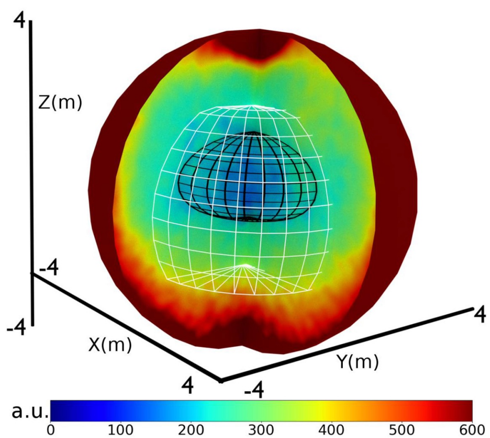
- First direct experimental evidence of CNO ν (2020)
- Improved CNO measurement (2022)
- First direct measurement of sub-MeV solar ν with Borexino
- Directional analysis (CID) of CNO solar neutrinos
- Spectral analysis of CNO ν solar with CID

CNO measurement using spectral fit



Phase 3 (Jan 2017-Oct 2021):

- Likelihood fit: energy and radial distribution of data
- Fit parameter: rates of each species
- Constraint on:
  - pep-ν rate = 2.74±0.04 cpd/100t
  - 210Bi rate <= 10.8±1.0 cpd/100t

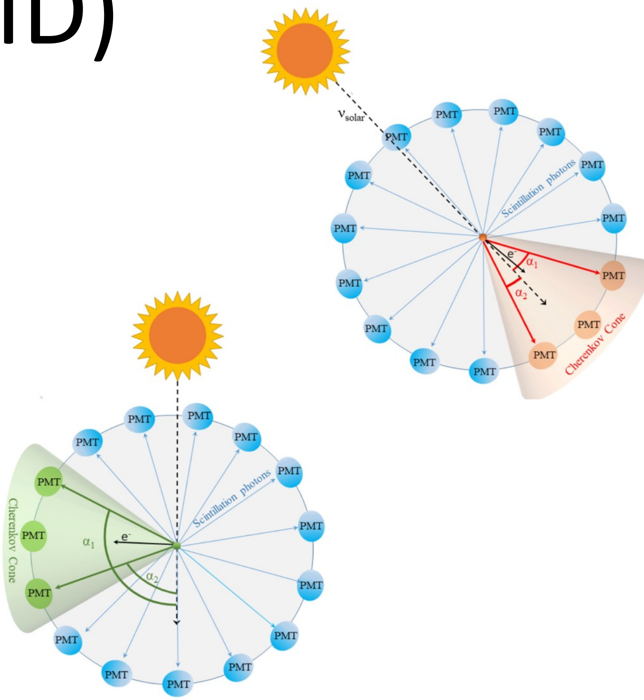


Phys. Rev. Lett. 129, 252701 (2022)

- Theory and global analysis fit on independent solar data: Bergström et al https://doi.org/10.1007/JHEP03(2016)132
- ^{210}Bi rate determined from daughter ^{210}Po rate (α)
- Temperature variation due to seasonal effect causing convective currents
- Brought ^{210}Po from vessel and secular equilibrium is broken
- Thermal insulation of the detector → a low ^{210}Po region is formed

Correlated and Integrated Directionality (CID)

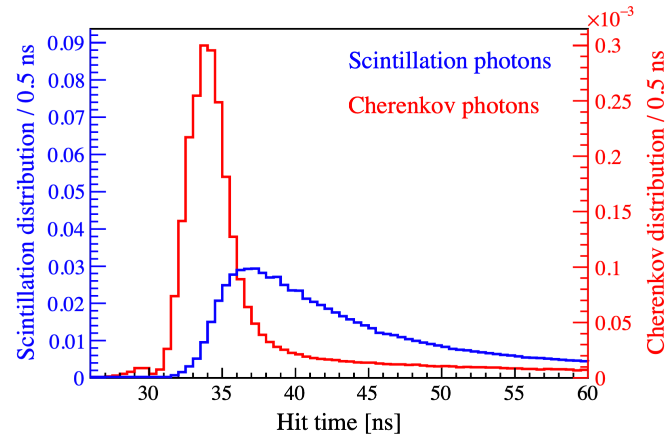
- Scintillation light: flat cos(α) distribution
- Cherenkov light from solar neutrino event: correlated with the Sun's position: not-flat cos(α) distribution
- Cherenkov light from background: uncorrelated with the Sun's position: flat cos(α) distribution



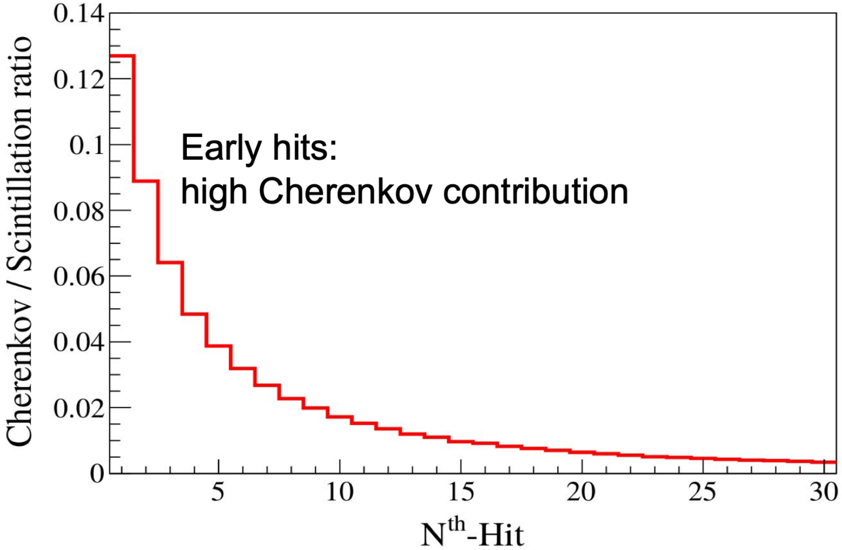
Cherenkov photons are sub-dominant (<1%) but faster than scintillation light

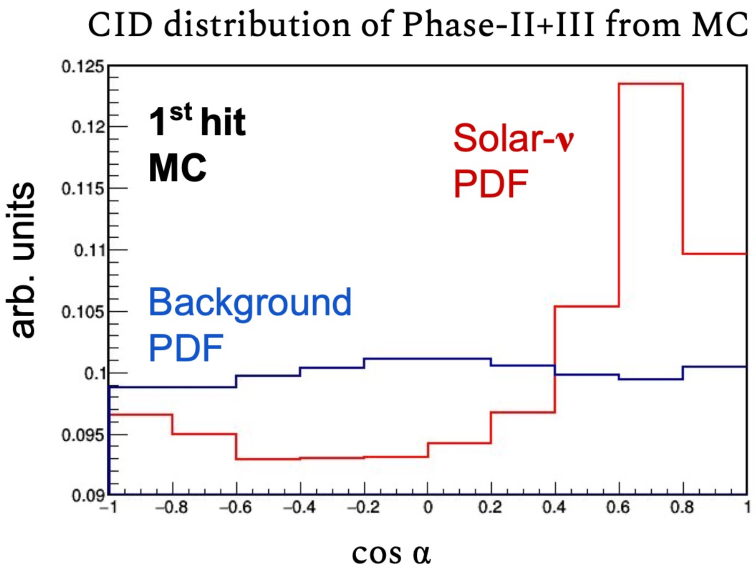
Event by event directional reconstruction not possible

Statistical separation of neutrinos and background with measured cos(α) distribution



CID distributions

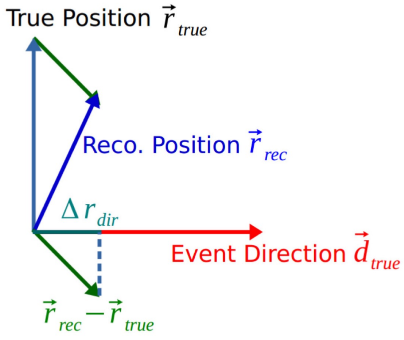


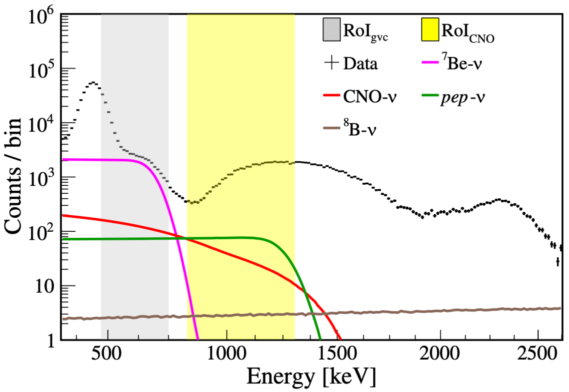


- **PDF production using Geant4-based simulations:**
  - Neutrino interaction, recoil e^- energy deposition, multiple scattering in LS
  - Production of scintillation and Cherenkov light, photon propagation
  - Full electronics simulation
  - Provides N_h as an energy estimator, same as data

Systematics of CID

- Position reconstruction bias towards e$^-$ direction
  - Expected value in MC~2cm, treated as nuisance paramter in the fit





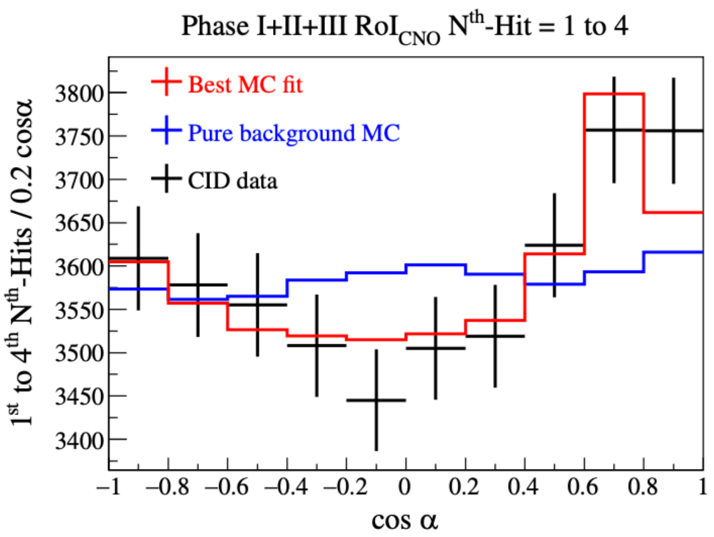
- Group velocity correction for Cherenkov photons

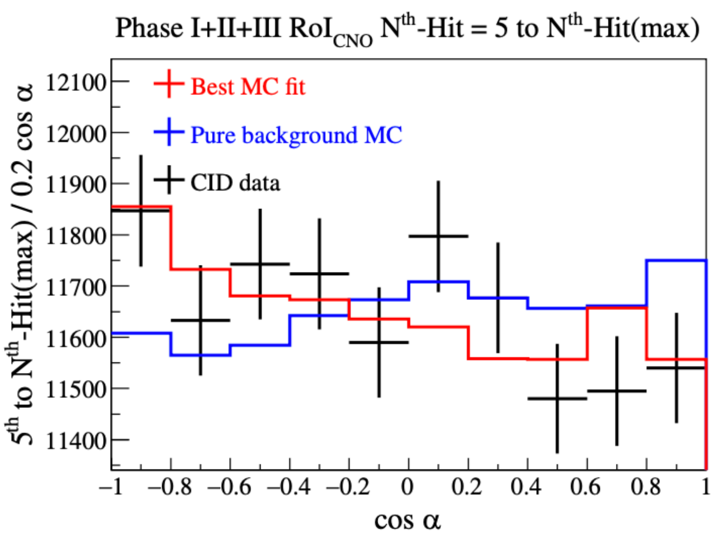
$$t_{\text{new}}^{\text{ToF}} = t_{\text{old}}^{\text{ToF}} - (gv_{\text{ch}}^{\text{corr}} \cdot L_{\text{true}}) = t_{\text{old}}^{\text{ToF}} - \left(\frac{\Delta n_{\text{ch}}}{c} \cdot L_{\text{true}}\right)$$

  - Constrained in the fit, ~2% correction in group velocity

Phase	gv_{ch}^{corr} (ns/m) (stat. + syst.)
Phase-I	0.140 ± 0.029
Phase-II+III	0.089 ± 0.019

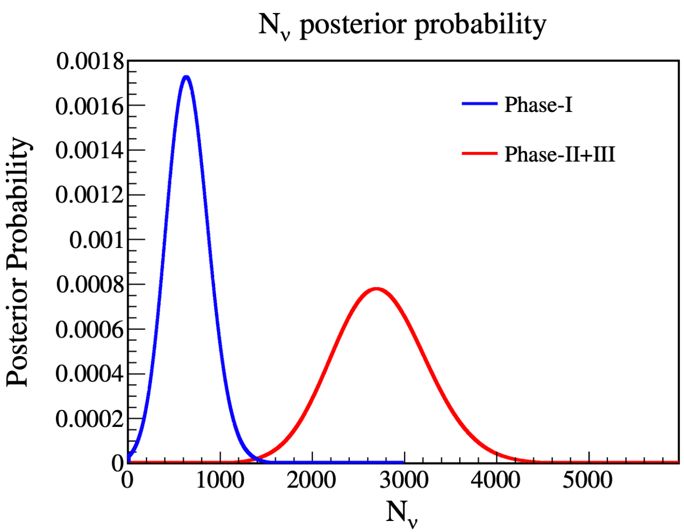
Fit to extract the number of ν



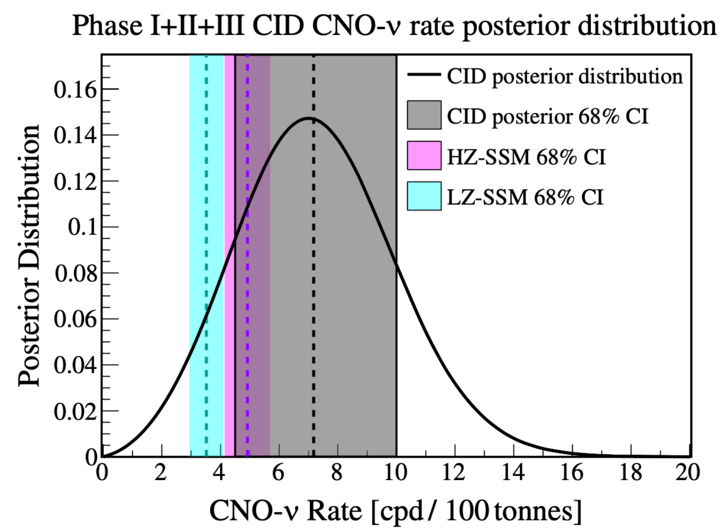


- χ^2 fit to extract the total number of neutrinos in the ROI
- Early hits: direct cherenkov information
- Later hits: indirect information from effect of cherenkov light on position reconstruction

CID-only results on CNO solar neutrinos



Constraint on no-CNO ν rate from SSM, all phases combined



Posterior Bayesian distribution using MC method and including systematics

No-neutrino hypothesis excluded:

4.2 σ for Phase I

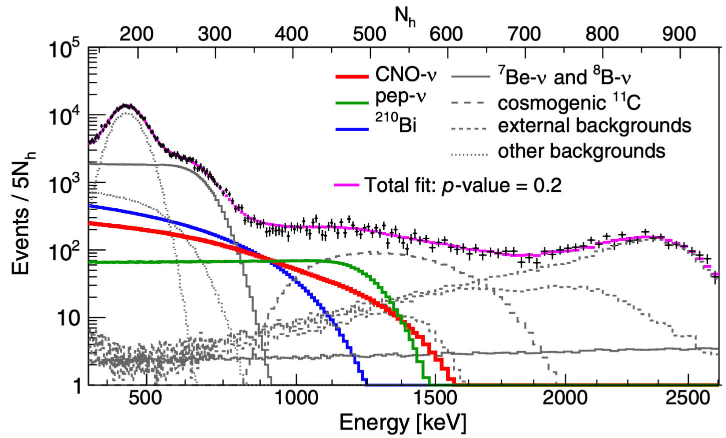
6.5 σ for Phase II+III

No CNO neutrino hypothesis disfavored at 5.3σ for all phases, no constraint on ^{210}Bi used

Extracted CNO rate:

$7.2^{+2.8}_{-2.7}$ cpd/100t

Combined analysis: final Borexino results



Phase III: Jan 2017-Oct 2021

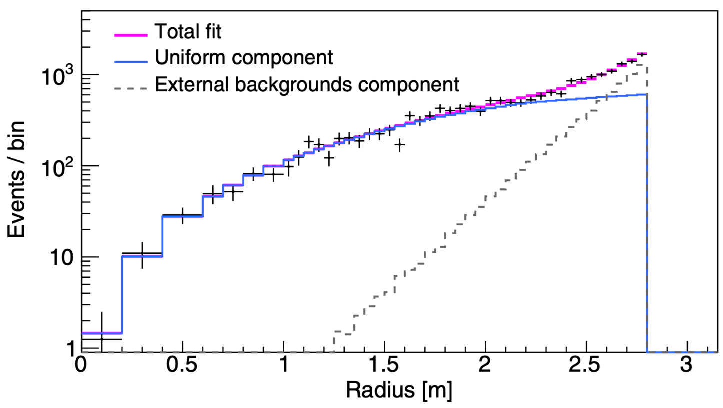
ROI: (0.43-2.64) MeV

Exposure: 1431.6 days x 71.3 t

Performing combined likelihood fit

Phase III only

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



Standard multivariate fit (PRL 2022):

- MV: energy+ radial distributions
- pep ν 1.4% rate constraint (solar physics + oscillations)
- ^{210}Bi rate 10% constraint (thermal insulation)

Pull terms from CID posterior

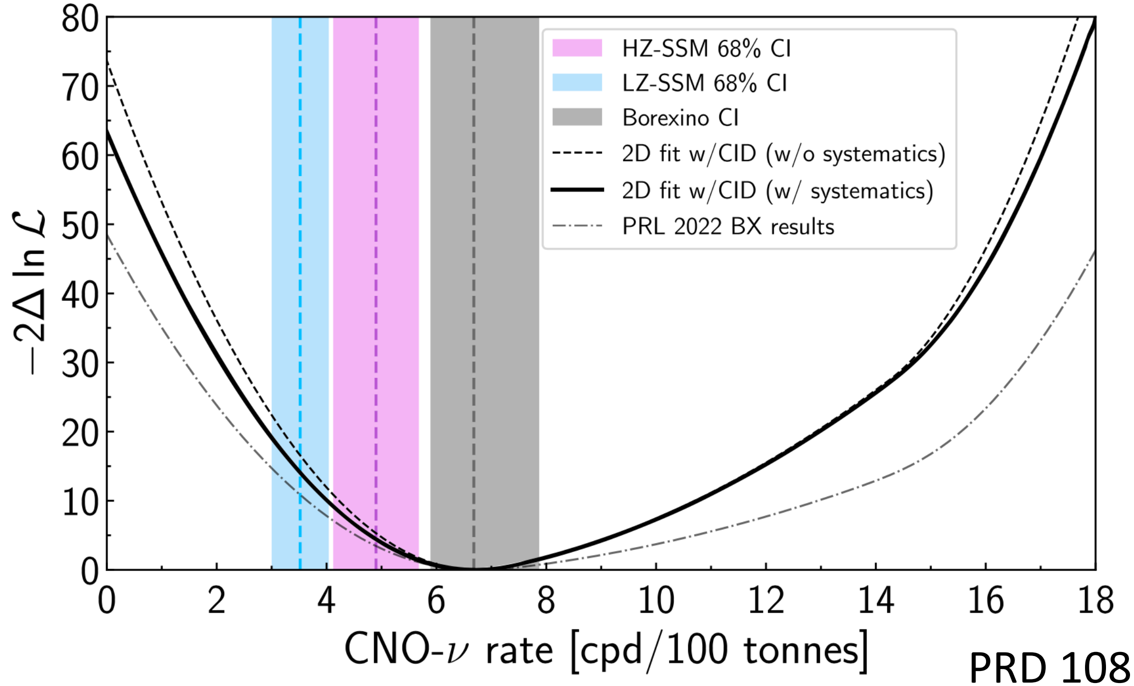
Combined analysis: final Borexino results

Excluding no-CNO signal hypothesis at 8σ CL

$R(CNO) = 6.7^{+1.2}_{-0.8}$ cpd/100t

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

Direct measurement of the neutrino flux is in agreement with HZ solar model, ~2σ tension with LZ model



PRD 108, 102005 (2023)

Summary

- By using a novel technique based on events directionality only, Borexino has measured CNO ν flux at 5σ level
  - The subdominant Cherenkov light plays a role in LS detectors
  - No a-priori knowledge of the background
- Combining multivariate fit and CID
  - Most precise CNO ν flux measurement ever obtained
  - SSM: low metallicity scenario disfavored at 3.2σ level when combining this result with other Borexino results
- The CID techniques open new avenues for future LS based or hybrid neutrino experiments

Summary of Borexino results

- Comprehensive measurement of pp-cycle neutrinos: Nature 562, 505-510, 2018
- Comprehensive geoneutrinos analysis: PRD 101, 012009, 2020
- Final result on CNO solar neutrinos: PRD 108, 102005, 2023

- In case of questions don't hesitate to contact me: caminata@ge.infn.it