Recents results of the Borexino Experiment

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on behalf of the Borexino Collaboration

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The Borexino experiment

- **Main goal**: the detection of low energies solar neutrinos, in particular ^7Be 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.

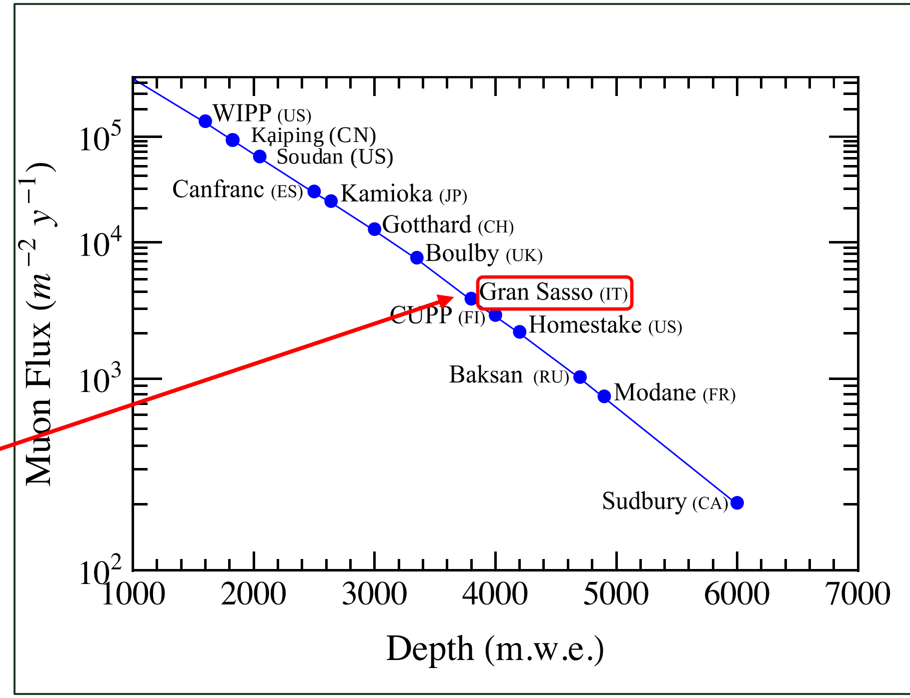
The expected rate of ^7Be solar neutrinos in 100 ton of Borexino scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/kg.

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

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;

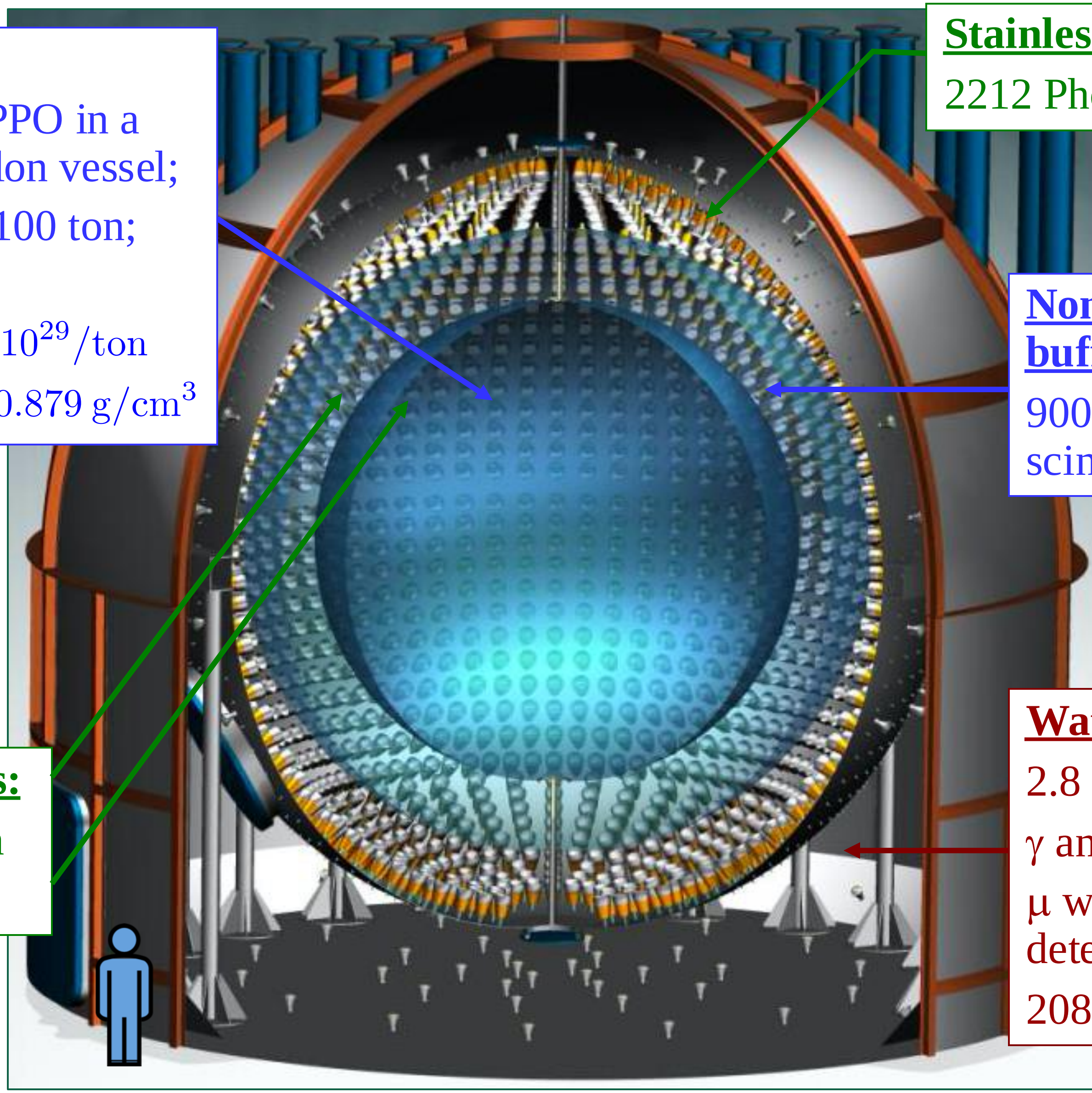
Fiducial mass ~ 100 ton;

Electron density: $(3.307 \pm 0.003) \times 10^{29}/\text{ton}$

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

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

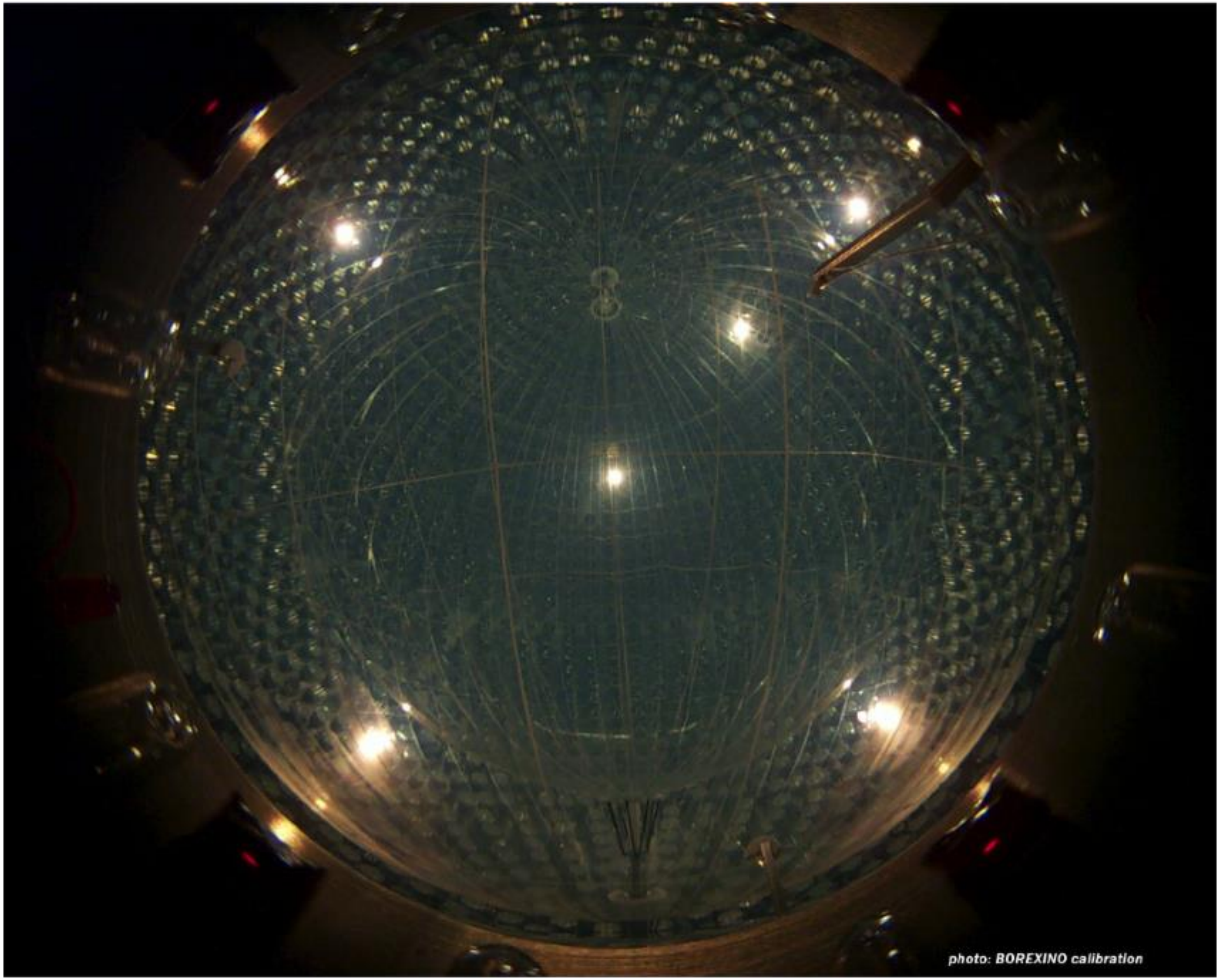
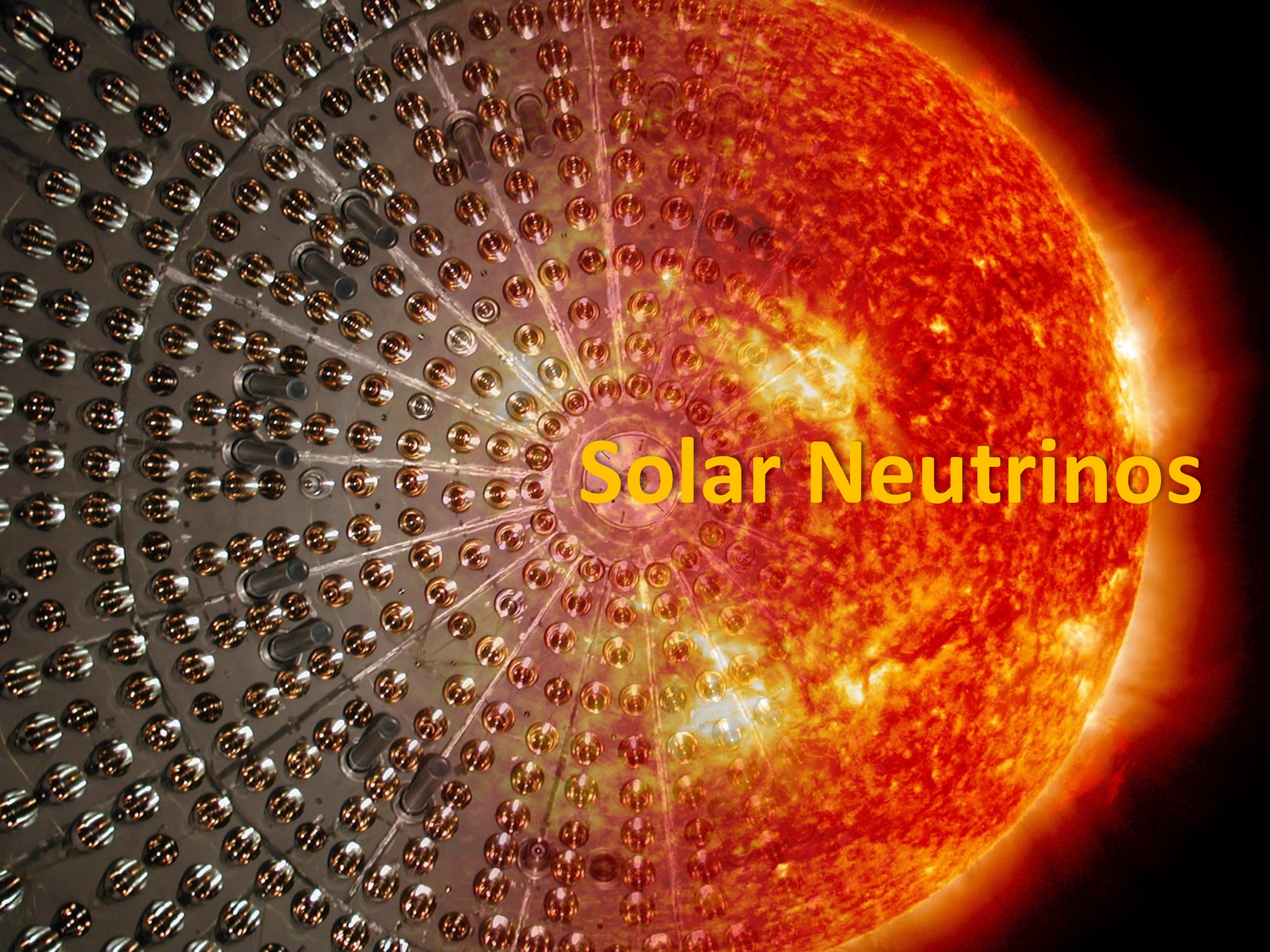


photo: BOREXINO calibration

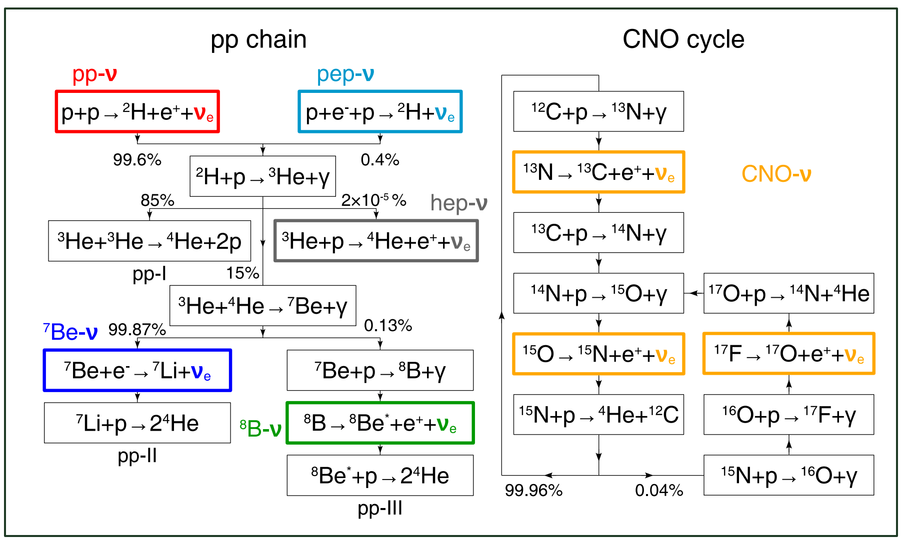

Solar Neutrinos

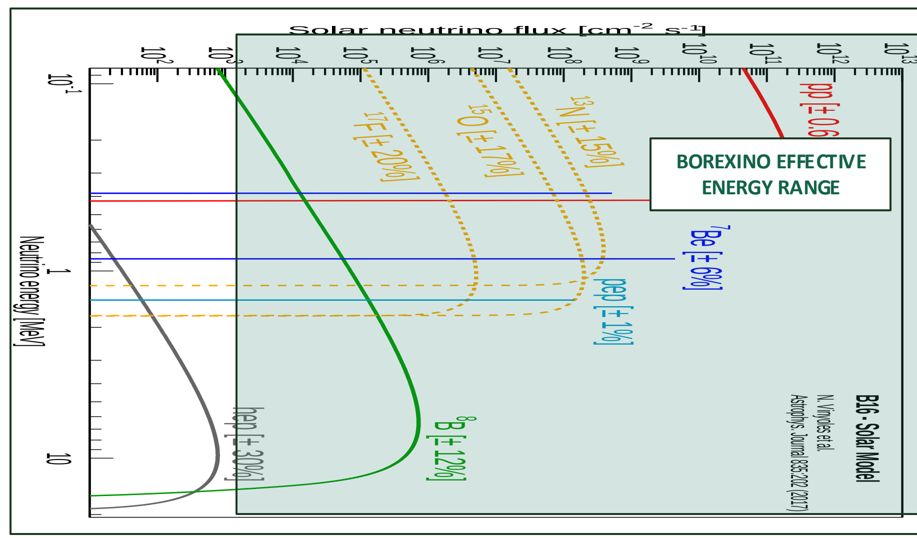
STUDYING THE SUN WITH NEUTRINOS…

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

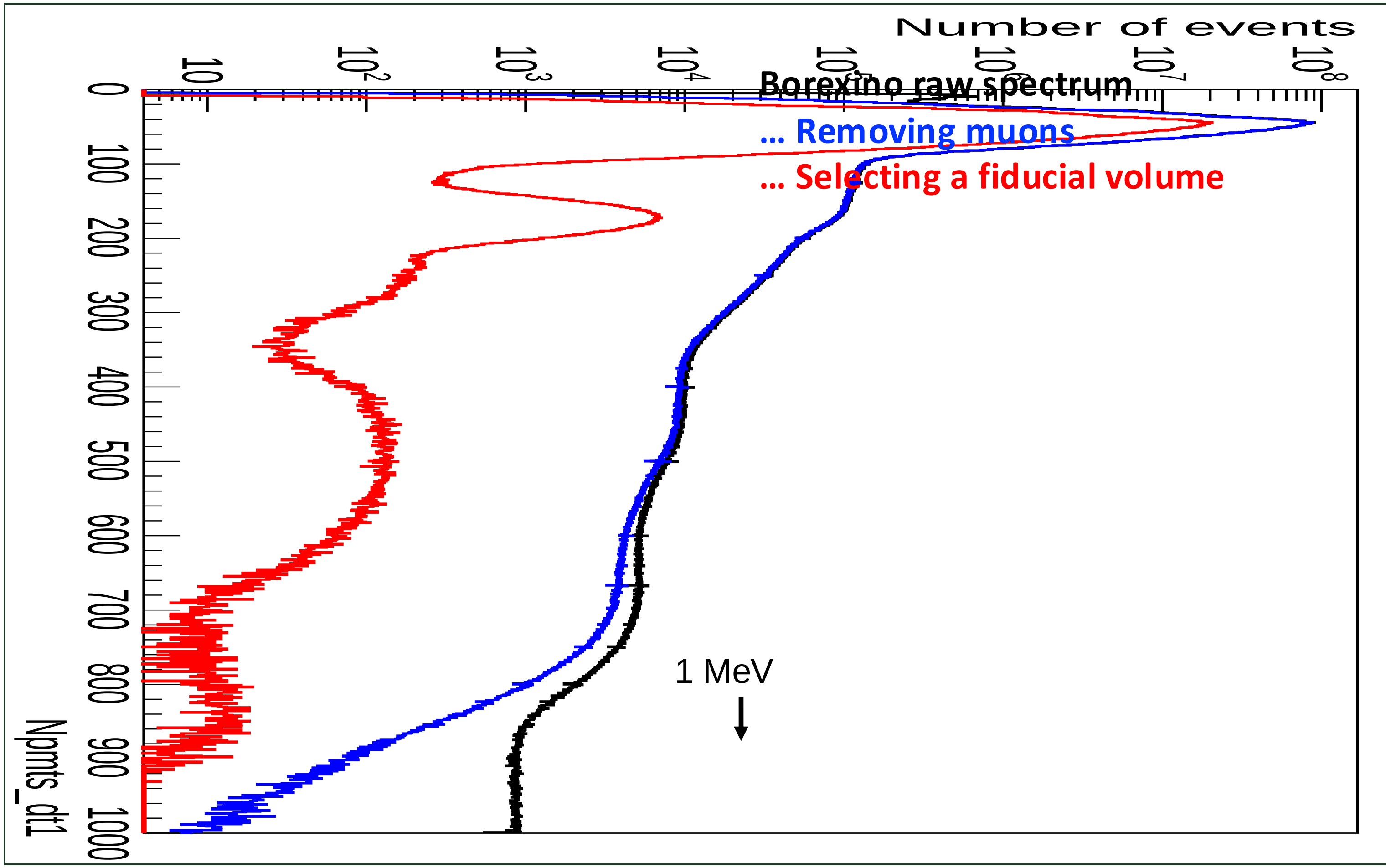
-While γ massively interact with the solar plasma and take about 10^5 years to reach our star surface, neutrinos stream out the Sun and take just 8 minutes to reach the Earth

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





HOW TO EXTRACT A NEUTRINO SIGNAL



We need to develop powerful tools to separate the signal from the residual background components

DATA-TAKING TIMELINE

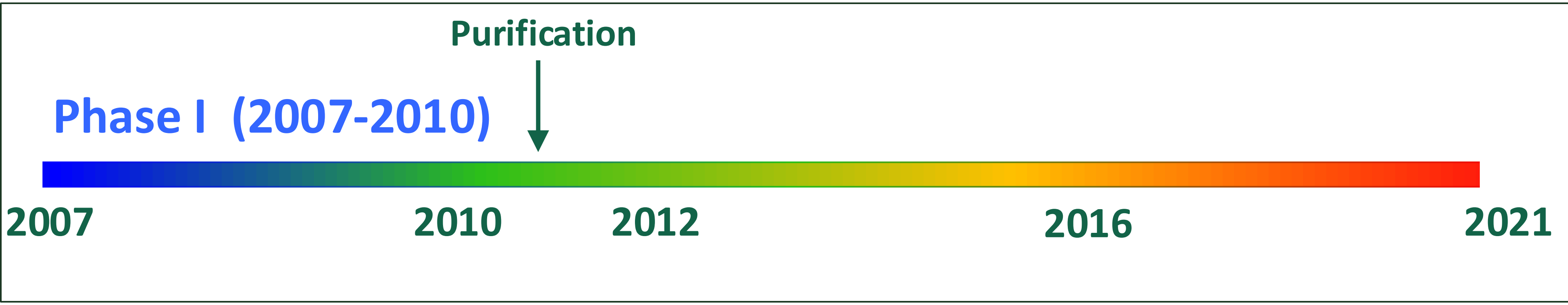
Phase I (2007-2010)

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: < 9.4×10^{-20} g/g (95% C.L.)

^{232}Th: < 5.7×10^{-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

<u>Direct measurements of</u>

- 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)

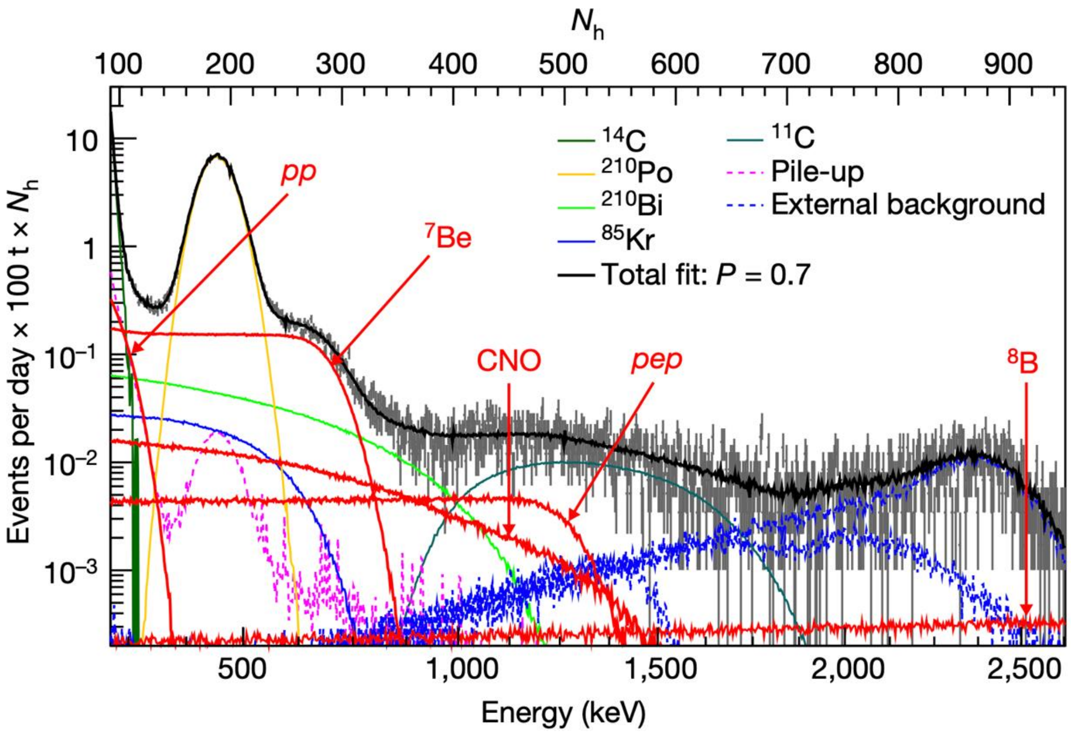
2007 2010 2012 2016 2021

Phase III:

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

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature 562 (2018) 505*



Main background sources:

- **^{14}C**: irreducible background in any organic scintillator;
- **^{210}Bi**: comes from ^{210}Pb, is not in equilibrium with the ^{238}U chain;
- **^{210}Po**: comes from ^{210}Bi, is not in equilibrium with the ^{238}U chain;
- **^{85}Kr**: present in air;
- **^{11}C**: produced by μ;
- **pile-up** of events (mainly ^{14}C).

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature 562 (2018) 505*
LER analysis *Physical Review D 100, 082004 (2019)*
HER analysis *Phys. Rev. D 101, 062001 (2020)*

Solar ν	BOREXINO	B16(GS98) – HZ	B16(AGSS09) - LZ
pp	$6.1(1 \pm 11.6\%) \times 10^{10}$	$5.98(1 \pm 0.6\%) \times 10^{10}$	$6.03(1 \pm 0.5\%) \times 10^{10}$
^{7}Be	$4.99(1 \pm 3.3\%) \times 10^{9}$	$4.93(1 \pm 6\%) \times 10^{9}$	$4.50(1 \pm 6\%) \times 10^{9}$
pep (HZ)	$1.27(1 \pm 17.7\%) \times 10^{8}$	$1.44(1 \pm 0.9\%) \times 10^{8}$	$---$
pep (LZ)	$1.39(1 \pm 16.6\%) \times 10^{8}$	$---$	$1.46(1 \pm 0.9\%) \times 10^{8}$
CNO	$< 7.9 \times 10^{8}$ (95% C.L.)	$4.88(1 \pm 11\%) \times 10^{8}$	$3.51(1 \pm 10\%) \times 10^{8}$
^{8}B	$5.68(1 \pm 8\%) \times 10^{6}$	$5.46(1 \pm 12\%) \times 10^{6}$	$4.50(1 \pm 12\%) \times 10^{6}$

All fluxes results are given in $cm^{-2}\ s^{-1}$.
B16 Neutrino theoretical fluxes from: *N. Vinyoles et al., Astrophys. Journal 835:202 (2017)*
Neutrino oscillation parameters from: *I. Esteban et al., JHEP 01 (2017)*

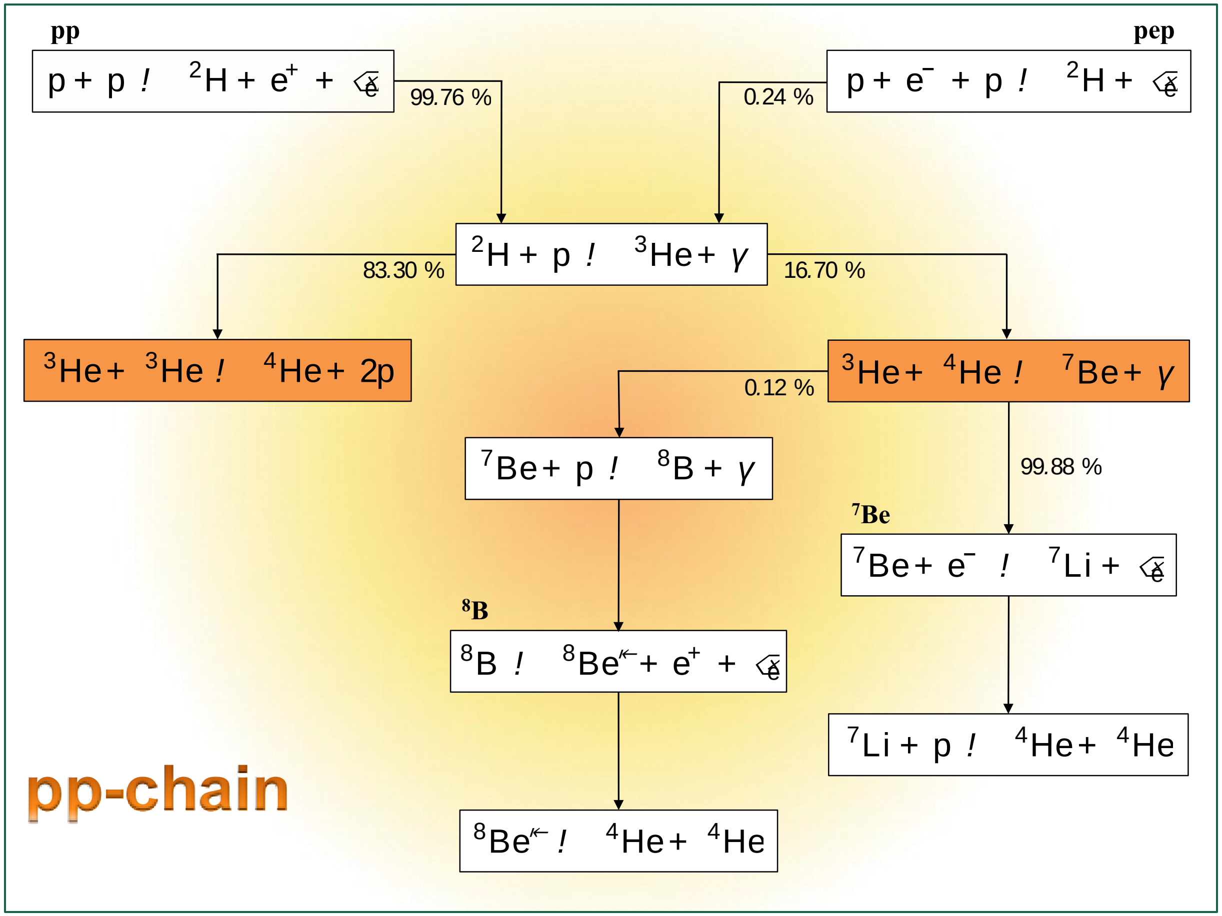
All rates and fluxes improve the uncertainty of the previously published Borexino results.

Solar ν	Uncertainty reduction (err_{new}/err_{old})
pp	0.78
^{7}Be (862 keV)	0.57
pep	0.61
^{8}B	0.48

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature 562 (2018) 505*

Astrophysical implications of the pp-chain flux measurement: probing solar fusion



Probing solar fusion by studying the two primary modes of terminating the pp-chain.

$$\mathcal{R} = \frac{2\Phi(^7\mathrm{Be})}{[\Phi(pp) - \Phi(^7\mathrm{Be})]}$$

B16-SSM expected values:

$\mathcal{R} = 0.180 \pm 0.011$ (HZ)

$\mathcal{R} = 0.161 \pm 0.010$ (LZ)

<u>Borexino result</u>:

$\mathcal{R} = 0.178^{+0.027}_{-0.023}$

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature 562 (2018) 505*

Astrophysical implications of the results: solar luminosity

Using Borexino results only we can calculate the neutrino solar luminosity:

$$\mathbf{L}_\nu = (3.89\,^{+0.35}_{-0.42}) \times 10^{33}\ \mathrm{erg\,s^{-1}}$$

which agrees with the well measured photon value:

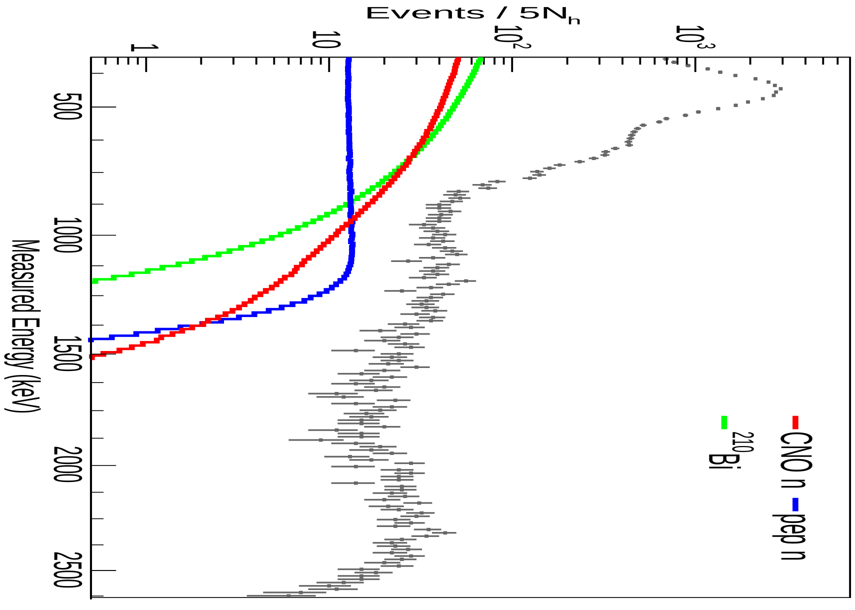
$$\mathbf{L_{ph}} = (3.846 \pm 0.015) \times 10^{33}\ \mathrm{erg\,s^{-1}}$$

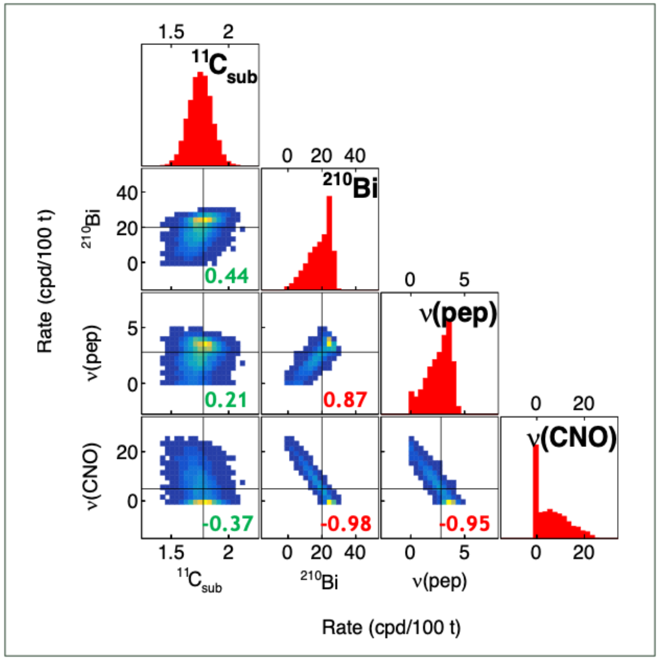
→ This confirms the nuclear origin of the solar power!

→ It proves that the Sun has been in thermodynamic equilibrium over the last 10^5 years

TOWARDS THE CNO-ν MEASUREMENT

The similarity between the CNO, pep and ^{210}Bi spectral shapes limits the sensitivity of Borexino.

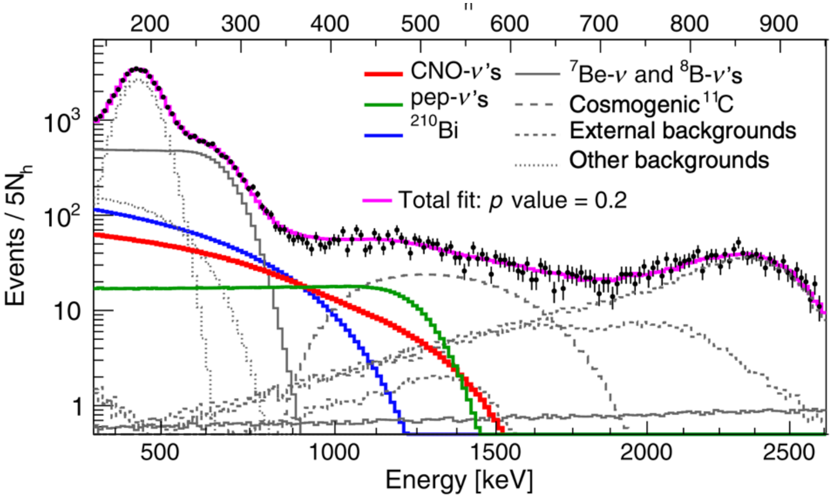




Expected rates:

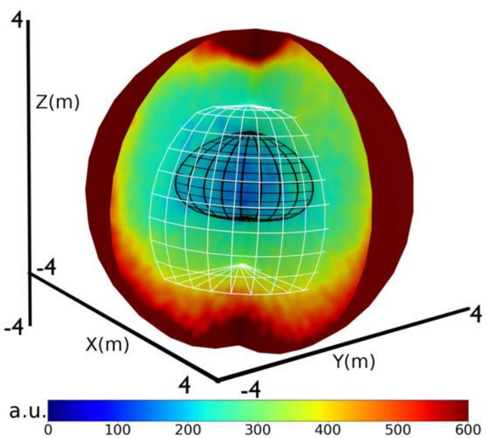
- CNO ν ~ 4-5 cpd/100 ton
- pep ν ~ 3 cpd/100 ton
- ^{210}Bi ~ 15-20 cpd/100 ton

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
  - ^{210}Bi rate <= 10.8±1.0 cpd/100t

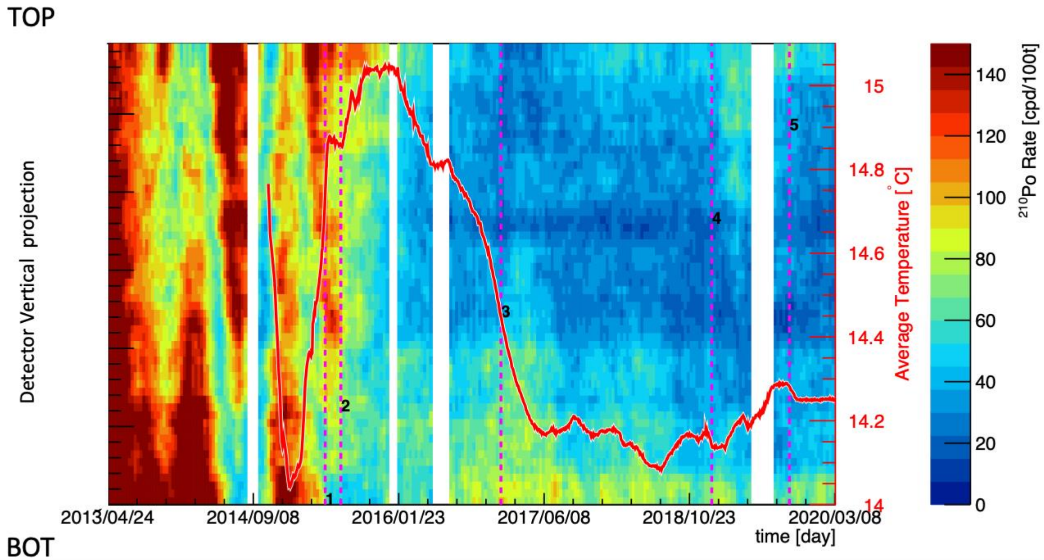


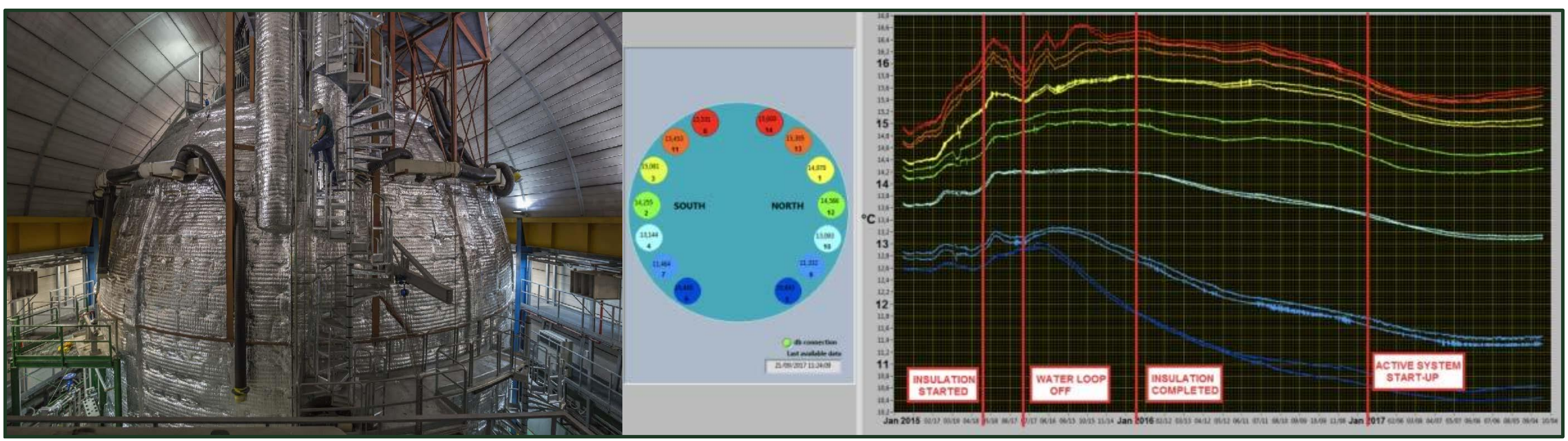
Phys. Rev. Lett. 129, 252701 (2022)

- 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

TOWARDS THE CNO MEASUREMENT

^{210}Po counting rate inside the Inner Vessel scintillator volume



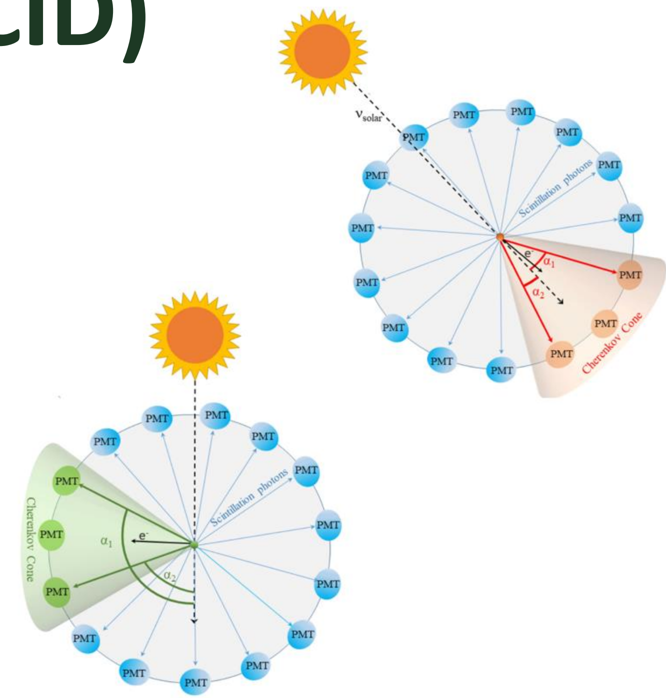


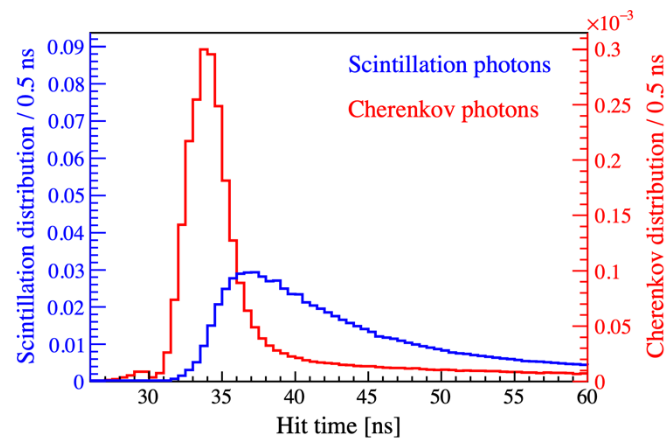
Correlated and Integrated Directionality (CID)

- 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

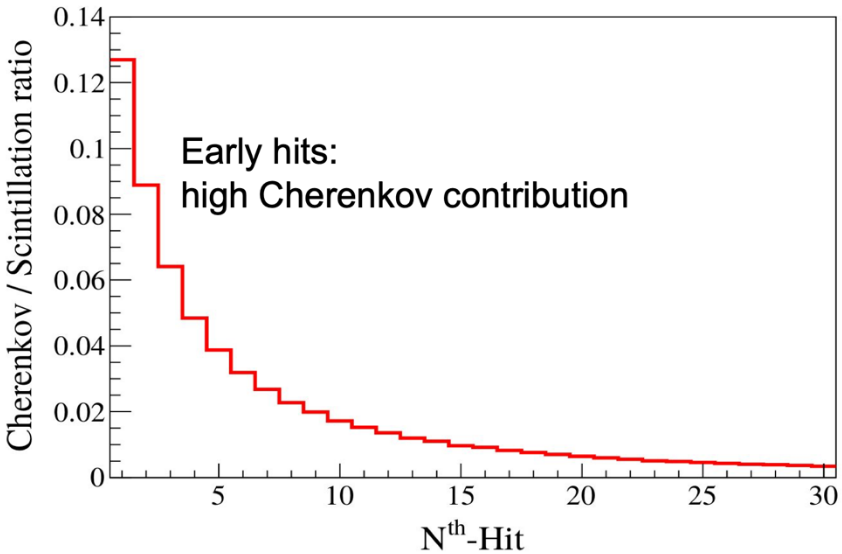
Cherenkov photons are sub-dominant (<1%) but faster than scintillation light

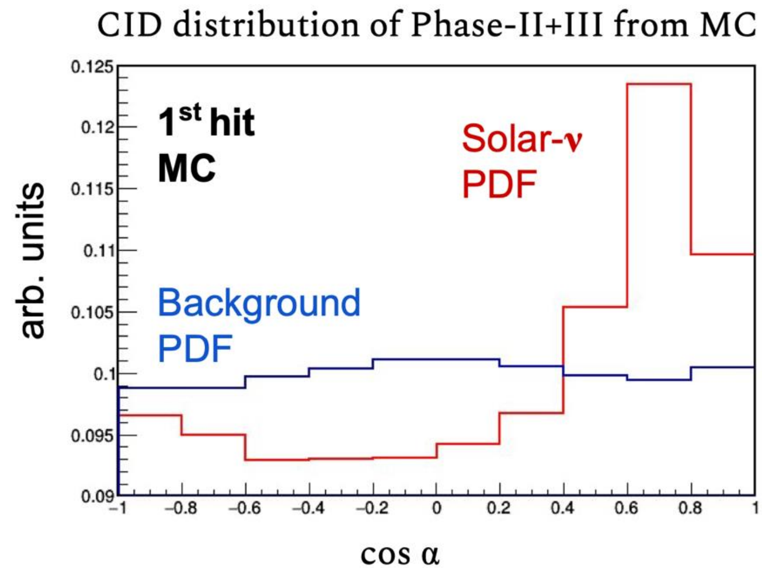
Event by event directional reconstruction not possible
Statistical separation of neutrinos and background with measured cos(α) distribution





CID DISTRIBUTIONS

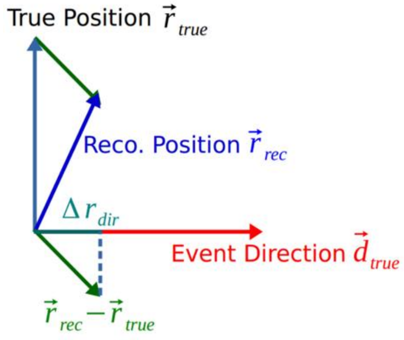


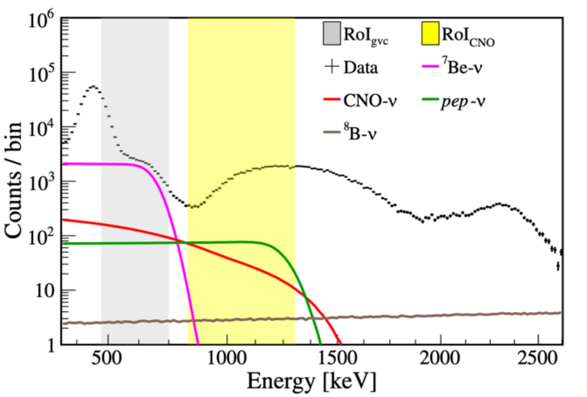


- **PDF production using Geant4-based simulations:**
  - Neutrino interaction, recoil e^- energy deposition, multiple scattering in LS
  - Production of scintillation and Cherenkov light, photon propagation
  - Full electronics simulation
  - Provides N_h as an energy estimator, same as data

Systematics of CID

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





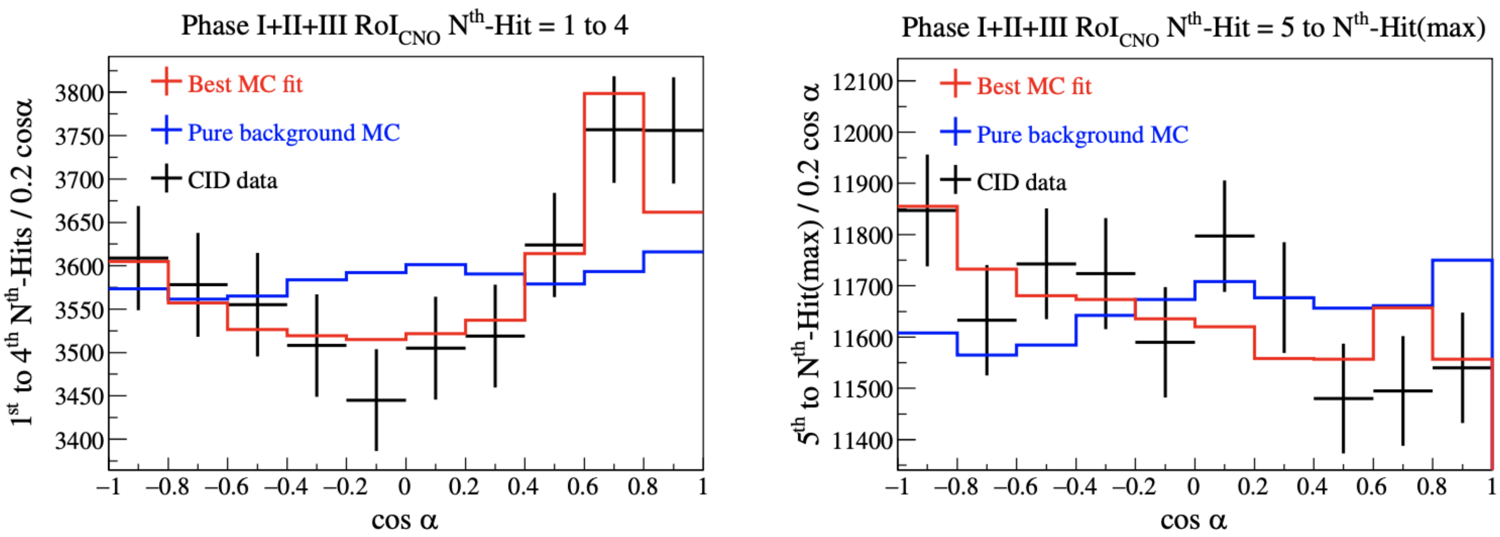
- Group velocity correction for Cherenkov photons

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

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

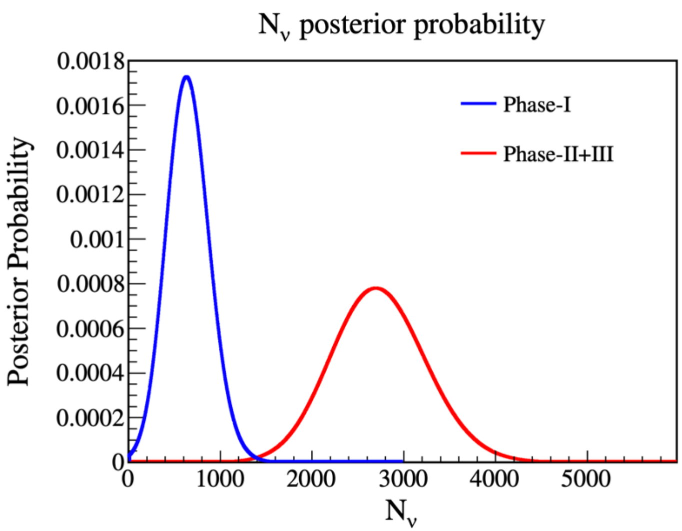
Phase	gv_{ch}^{corr} (ns/m) (stat. + syst.)
Phase-I	0.140 ± 0.029
Phase-II+III	0.089 ± 0.019

Fit to extract the number of ν

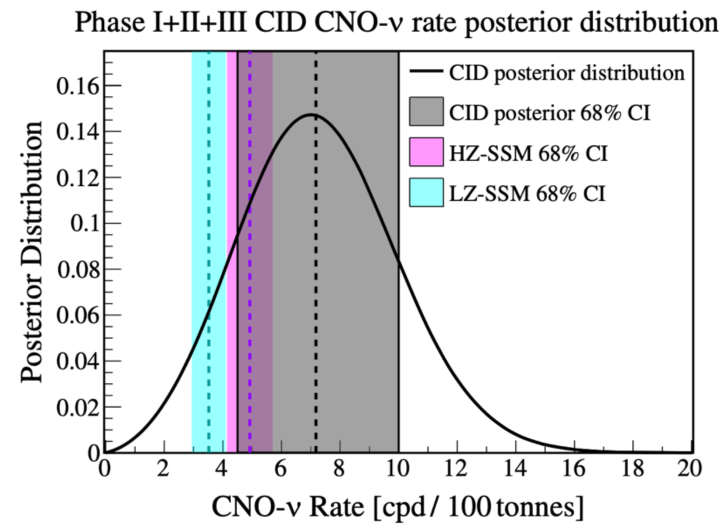


- χ^2 fit to extract the total number of neutrinos in the ROI
- Early hits: direct cherenkov information
- Later hits: indirect information from effect of cherenkov light on position reconstruction

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

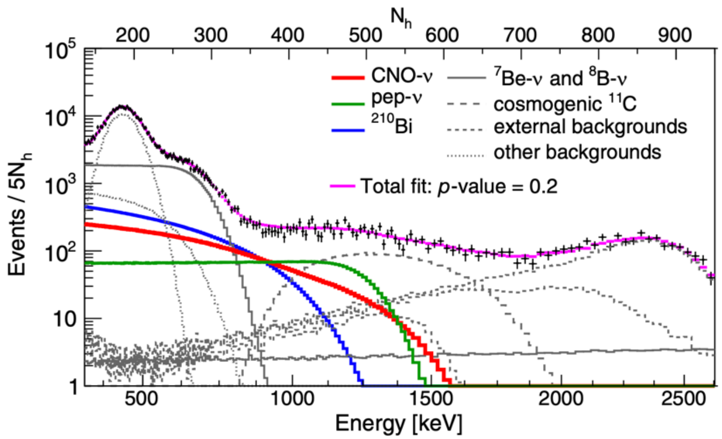
6.5 σ for Phase II+III

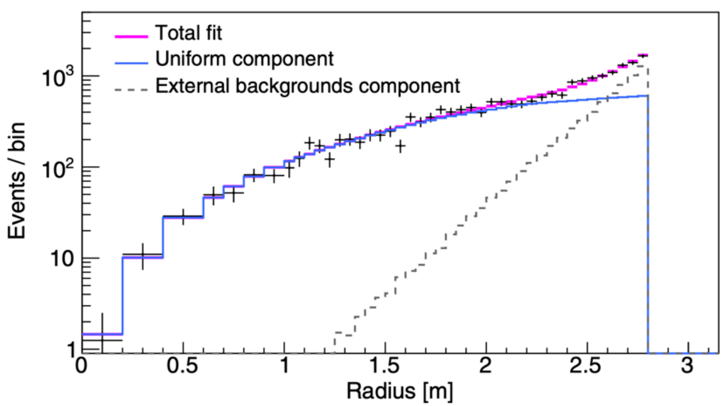
No CNO neutrino hypothesis disfavored at 5.3σ for all phases, no constraint on ^{210}Bi used

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

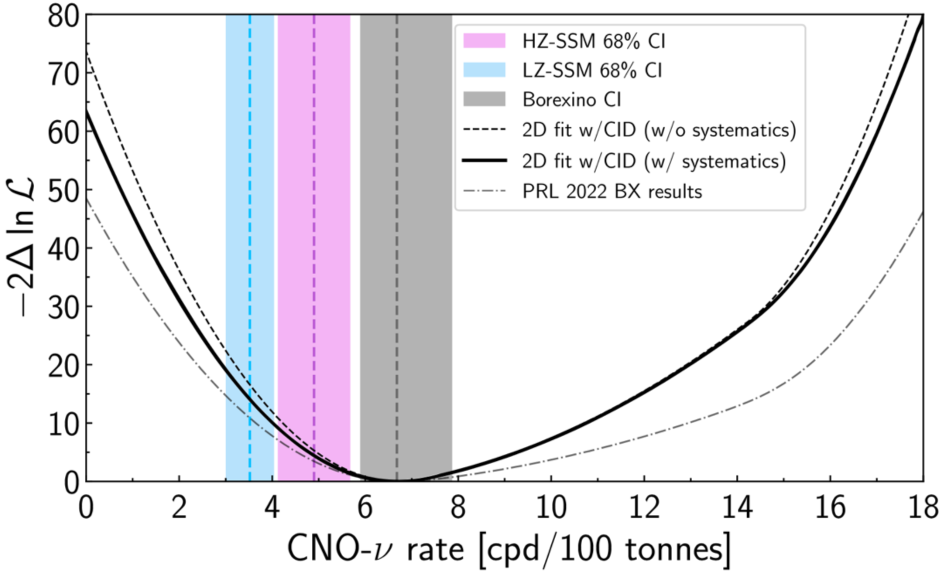
COMBINED ANALYSIS: FINAL BOREXINO RESULTS

Excluding no-CNO signal hypothesis at 8σ CL

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

Φ(CNO)= $6.7^{+1.2}_{-0.8}$ x10^8 cm^{-2} s^{-1}

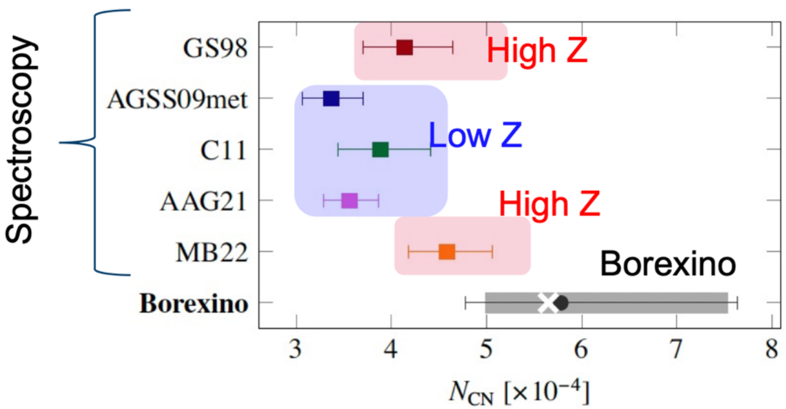
Direct measurement of the neutrino flux is in agreement with HZ solar model



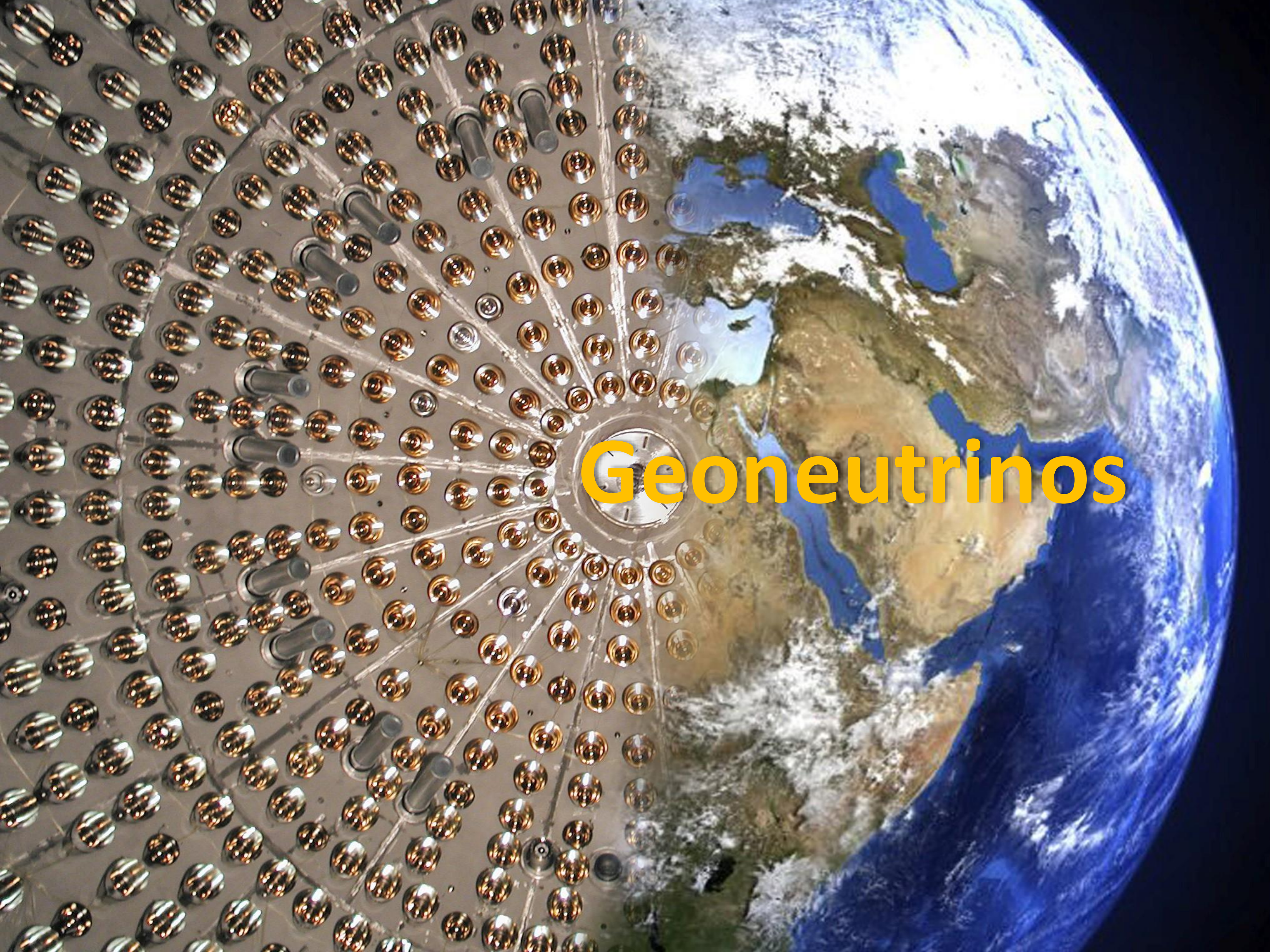
PRD 108, 102005 (2023)

N_{CN} = (C + N)/H in the Sun: 1st value based on neutrinos

Solar metallicity: ~2σ preference for high - Z



$$N_{CN} = (5.78^{+1.86}_{-1.00}) \cdot 10^{-4}$$


Geoneutrinos

WHY TO STUDY GEONEUTRINOS?

Geo-neutrinos are the anti-neutrinos produced in the decays of the progenies of Uranium, of Thorium, and Potassium inside the Earth.

Geo-neutrinos bring to the surface information from the whole planet:
they are a unique direct probe of our Earth's interior!

Open questions:
- What is the radiogenic contribution to the terrestrial heat?
- What is the distribution of the radiogenic elements within the Earth?

GEONEUTRINOS IN BOREXINO

Physical Review D 101, 012009 (2020)

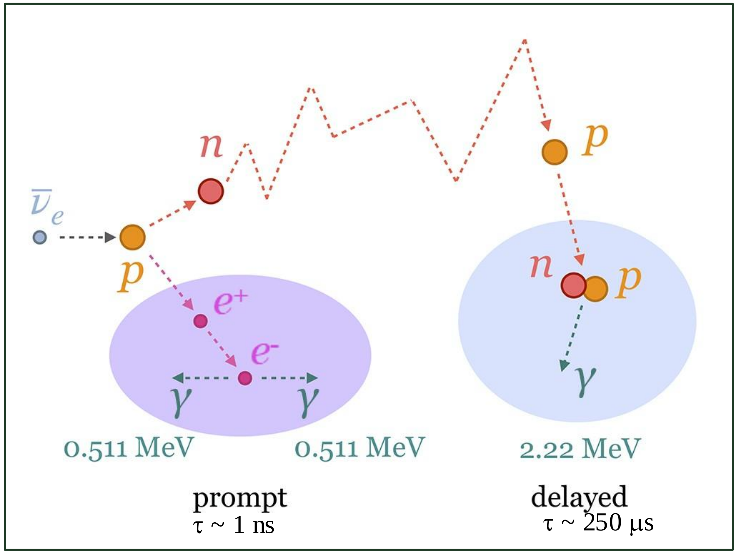
In Borexino, electron anti-ν are detected via the inverse beta decay reaction:

$$\overline{\nu_e} + \mathbf{p} \rightarrow \mathbf{e}^+ + \mathbf{n}$$

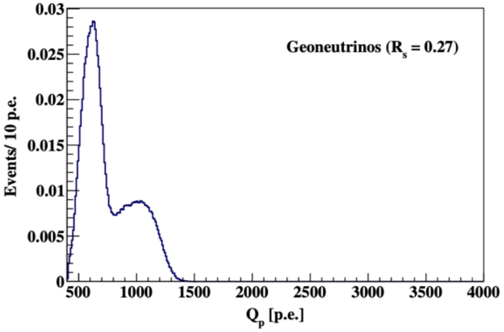
$$\sigma_{\mathrm{IBD}} \approx 10^{-42}\,\mathrm{cm}^2$$

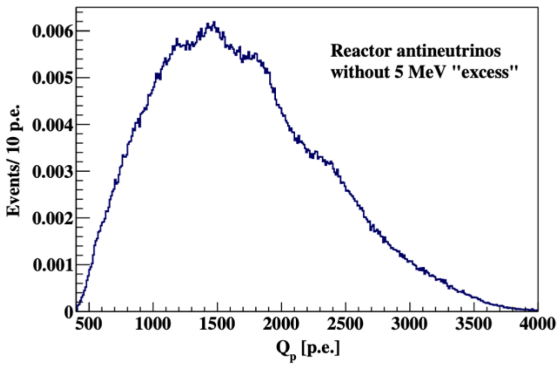
Charge current interaction → detection of $\overline{\nu_e}$ only

Threshold: 1.8 MeV



The main source of background is due to reactor antineutrinos (same interaction channel, different energy range): ~ 90 events





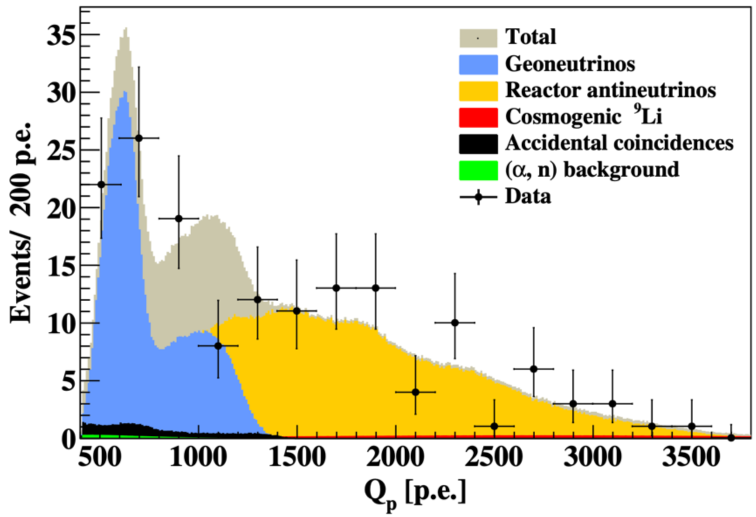
Other backgrounds

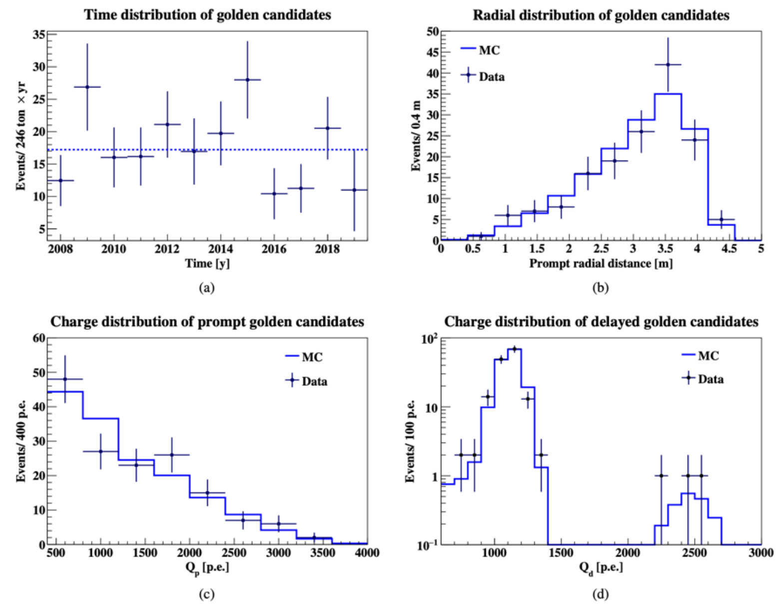
Background type	Events
^{9}Li background	3.6 ± 1.0
Untagged muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi $-$ ^{214}Po	0.003 ± 0.001
Total	8.28 ± 1.01

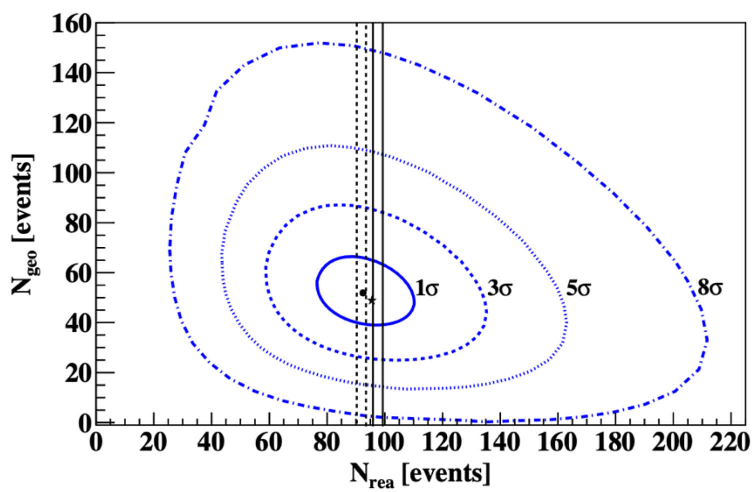
GEONEUTRINOS IN BOREXINO

Physical Review D 101, 012009 (2020)

- 154 events passed the selection cuts







- A **total uncertainty** of around ~18% achieved in the geoneutrino signal.
- **Rejection of the null-hypothesis** of mantle signal at 99% C.L.
- **Radiogenic heat**: 2.4σ tension with models predicting lowest amount of mantle signal.

SUMMARY

- Borexino was able to extensively probe the solar neutrinos flux having measured both the pp-chain solar neutrinos and CNO-cycle neutrinos

- 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


Thank you for your attention!
The Borexino Collaboration