Solar neutrinos from the CNO cycle: Borexino results and solar physics implications

Davide Basilico on behalf of the Borexino collaboration

International Workshop on Weak Interactions and Neutrinos
2025 June 11, Brighton, UK

University of Milan and INFN Milano

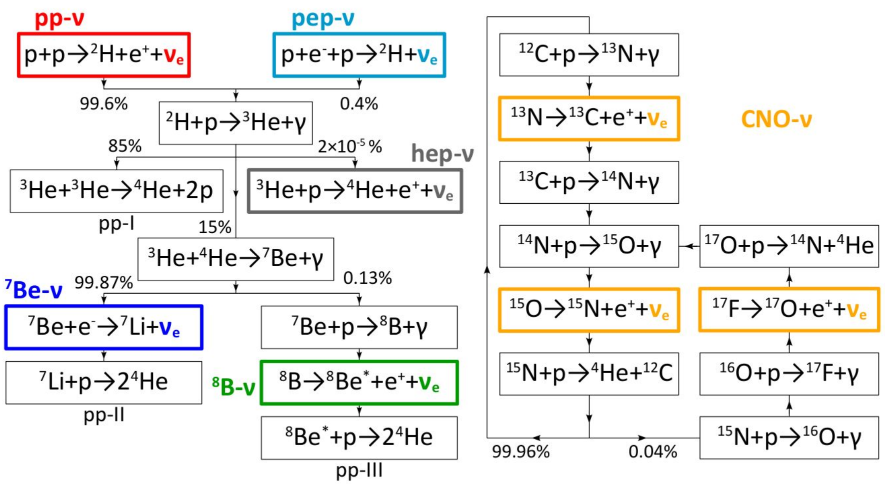
UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

Solar neutrinos

- Sun is powered by nuclear fusion reactions → neutrino emission
- Two sequences: pp-chain (primary in the Sun, ~99% lum.) and the secondary CNO cycle (~1%)

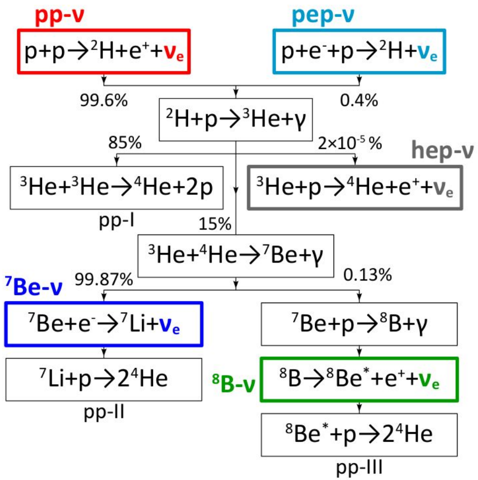
pp chain **CNO cycle**



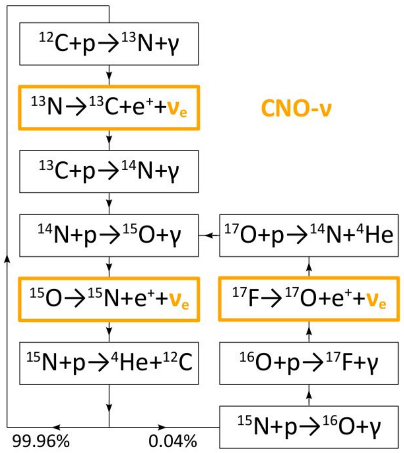
Solar neutrinos

- Sun is powered by nuclear fusion reactions → neutrino emission
- Two sequences: pp-chain (primary in the Sun, ~99% lum.) and the secondary CNO cycle (~1%)
  - **CNO neutrinos → primary mechanism in massive and older stars**
    → Test stellar models, solar metallicity problem

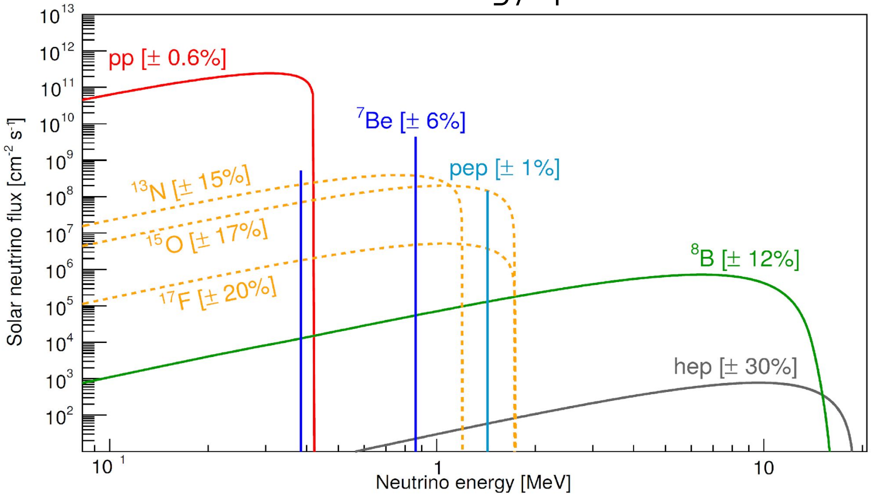
pp chain



CNO cycle



Solar ν energy spectrum



the Solar Metallicity Problem

Metallicity : abundance of elements heavier than He, key input for the Standard Solar Model (SSM) →

SSM: describing the Sun evolution from a protostar to the current star → physical description of the global properties of the Sun including solar ν fluxes

the Solar Metallicity Problem

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SSM: describing the Sun evolution from a protostar to the current star → physical description of the global properties of the Sun including solar ν fluxes

Solar ν	HZ-LZ flux differ.
pp	~0.8%
^{7}Be	~8%
pep	1.4%
^{8}B	~17%
CNO	~28%

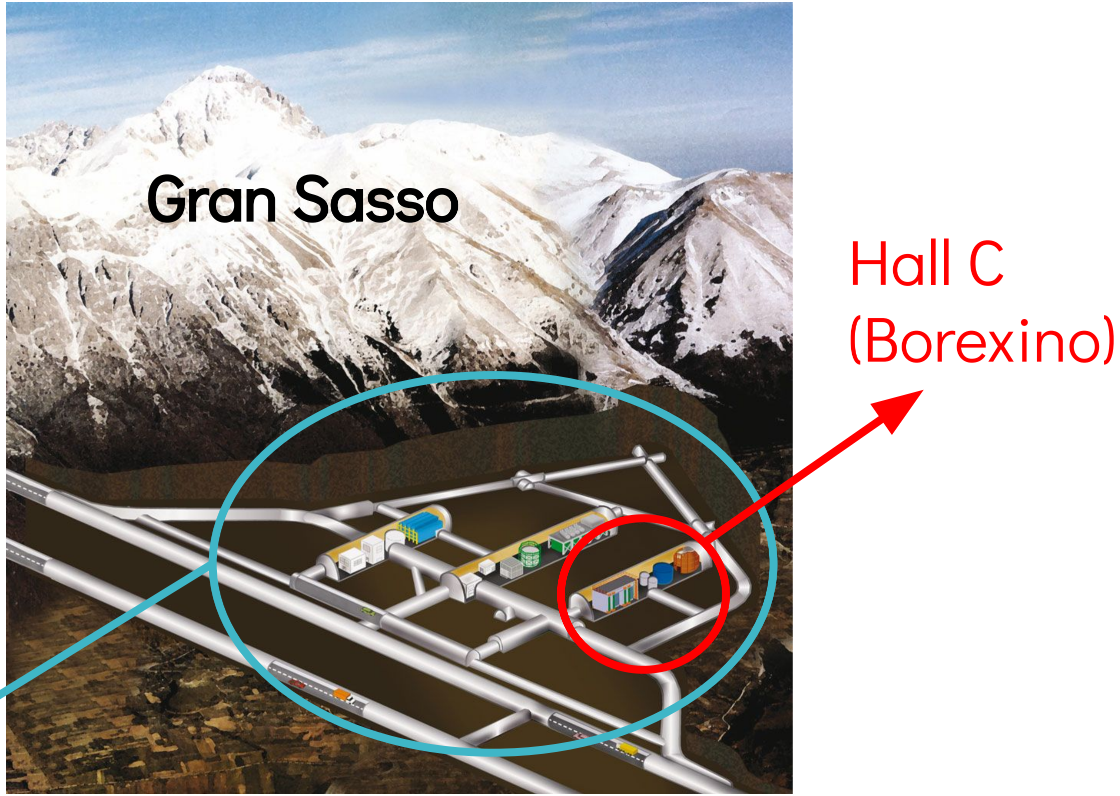
Two scenarios:

high metallicity (HZ) → agreement with helioseismology

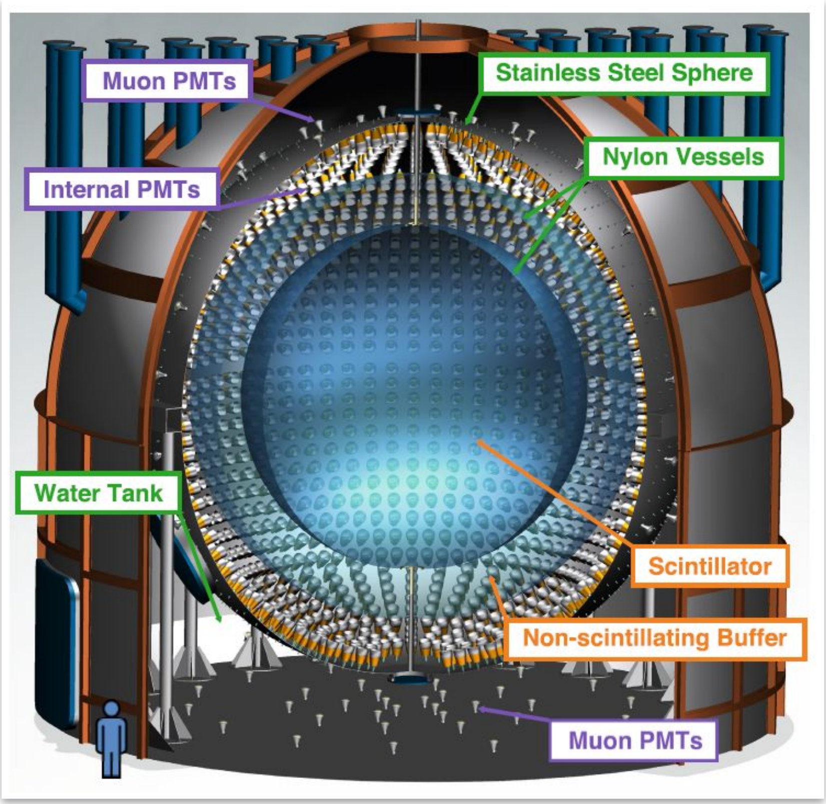
low metallicity (LZ) → observed from solar photosphere

An accurate CNO measurements would help to settle down the Solar Metallicity Problem

Borexino detector

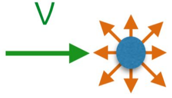


Borexino design



Main goal: solar ν spectroscopy

- Data-taking: 2007-2021 @ LNGS
- 300t of ultrapure liquid scintillator
- **Elastic scattering** channel



$$\nu_x + e^- \rightarrow \nu_x + e^-$$
$$x = e, \mu, \tau$$

- **2000 PMTs to detect produced light**
- **Unprecedented radioactivity levels**: ~10^{-19} g/g ^{238}U, ~$6{\cdot}10^{-19}$ g/g ^{232}Th

Borexino timeline

Purification campaigns to reduce 238U and 232Th contamination

Phase-I
2007-2011

Solar ν:

- 7Be and *pep* first observation
- 8B with low threshold;

Borexino timeline

Purification campaigns to reduce 238U and 232Th contamination

Phase-I
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Phase-II
2012-2016

Solar ν:
- 7Be and *pep* first observation
- 8B with low threshold;

Solar ν:
- Comprehensive measurement of pp-chain neutrinos (Nature 2014 and 2018)

Borexino timeline

Purification campaigns to reduce 238U and 232Th contamination

Thermal insulation

Phase-I
2007-2011

Phase-II
2012-2016

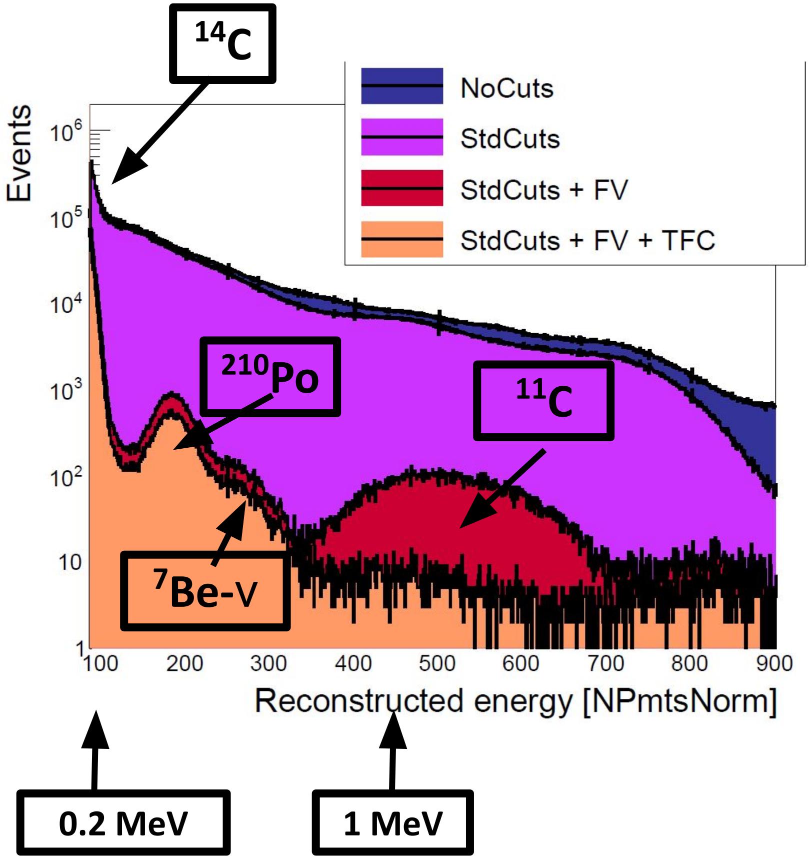
Phase-III
2016-2021

Solar ν:
- 7Be and *pep* first observation
- 8B with low threshold;

Solar ν:
- Comprehensive measurement of *pp*-chain neutrinos (Nature 2014 and 2018)

Solar ν:
- First direct experimental evidence of CNO ν (Nature 2020)
- Final results of Borexino on CNO solar neutrinos (PRD 2023)

Borexino energy spectrum



Raw spectrum

Standard cuts

- μ, cosmogenic, noise, delayed coincidences…

+ FV cut

- Volume fiducialization

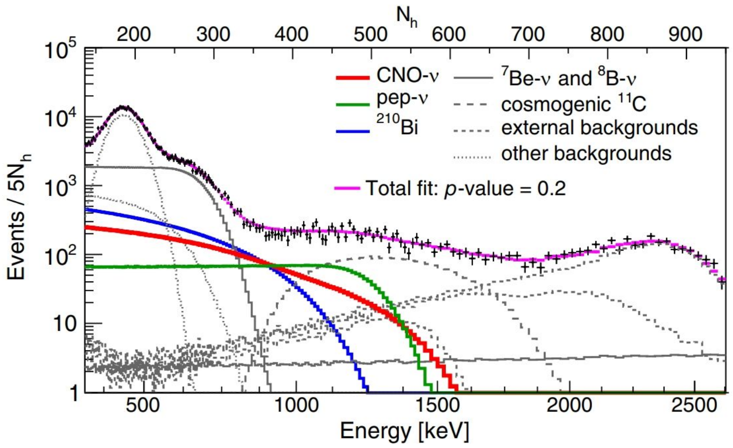
+ Cosmogenic 11C cut

- μ+n coincidence

Still background (β,γ) is present, indistinguishable from ν signal on an event-by-event basis
→ **multivariate fit**

Combined analysis, Phase-III dataset

2D multivariate analysis (energy and radial position) + **directionality** information



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

2D multivariate fit (**energy** + radius)

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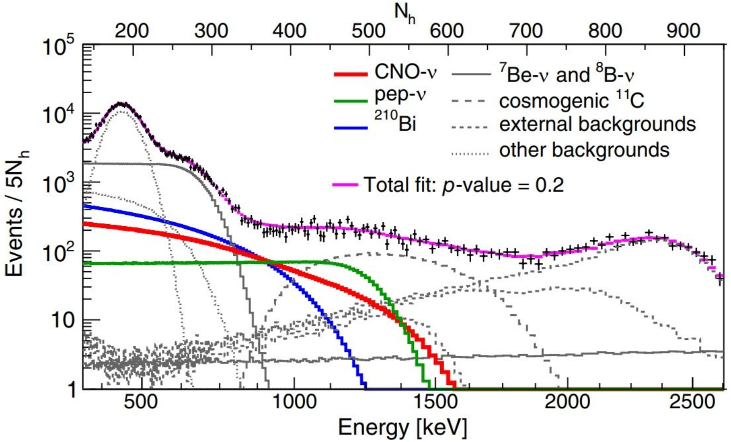

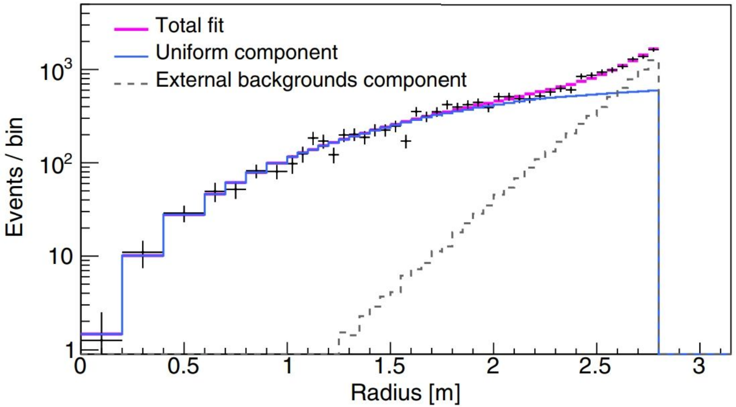

$$\mathcal{L}_{MV+CID} = \underbrace{\mathcal{L}_{MV}} \cdot \mathcal{L}_{pep} \cdot \mathcal{L}_{^{210}Bi} \cdot \mathcal{L}_{CID}^{P-I} \cdot \mathcal{L}_{CID}^{P-II+III}$$

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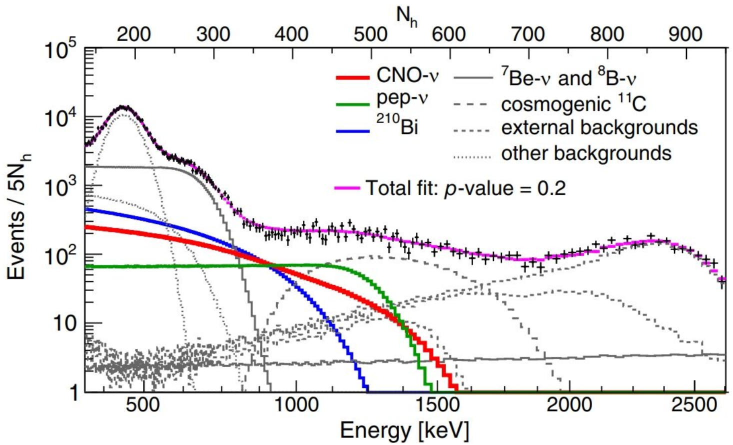

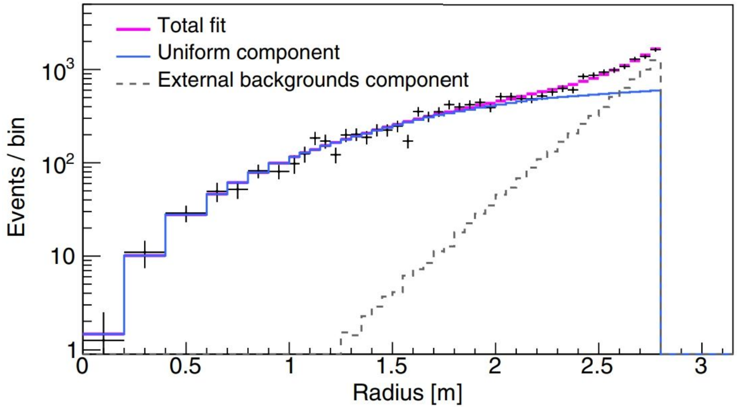

independent constraints

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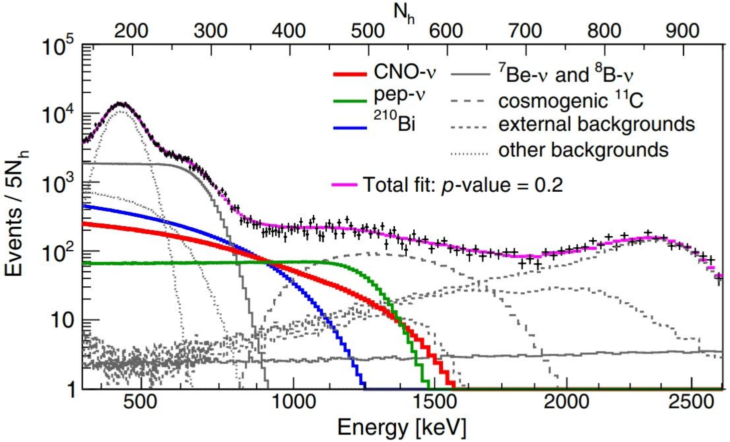

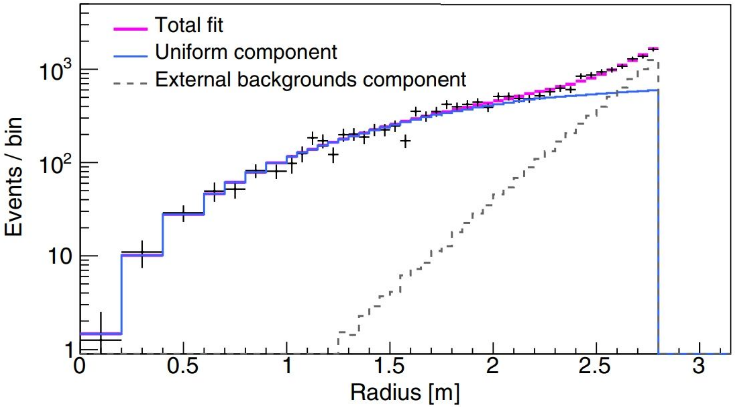

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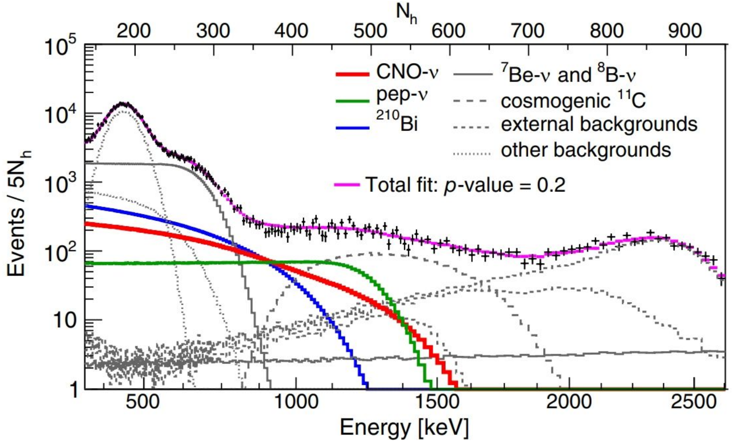
2D multivariate fit (energy + radius)

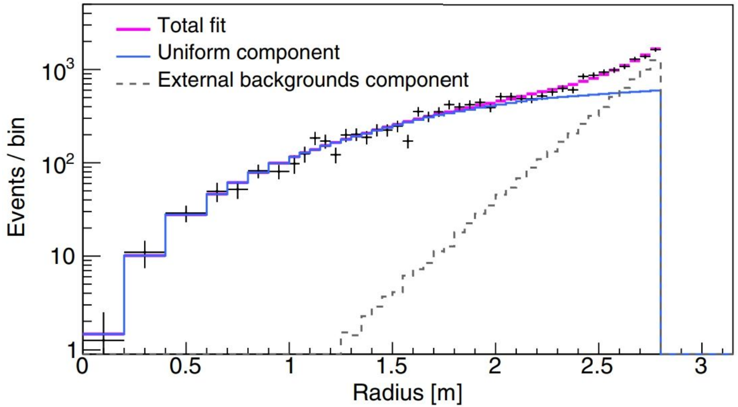
pep ν 1.4% rate constraint (solar physics + flavor oscill.)

210Bi rate 10%. constraint (thermal insulation)

Combined analysis, Phase-III dataset

2D multivariate analysis (energy and radial position) + **directionality** information





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independent constraints

2D multivariate fit (energy + radius)

pep ν 1.4% rate constraint (solar physics + flavor oscill.)

210Bi rate 10%. constraint (thermal insulation)

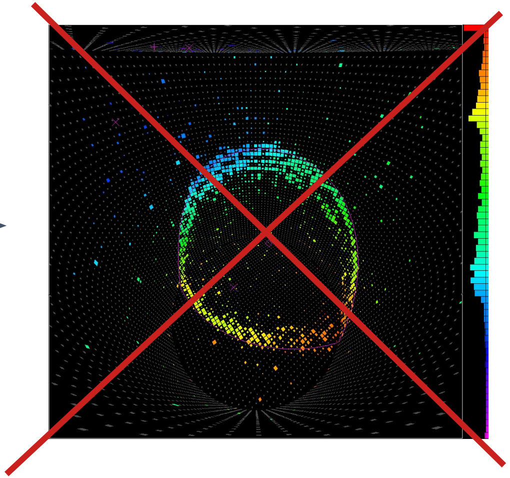
directionality constraints (new)

Directionality in liquid scintillators?

Spectroscopy of solar ν: **reconstructed energy** (high light yield, good energy resolution, low threshold...)

No directional information? scintillation light dominant (~99%) wrt Cherenkov and isotropic, uncorrelated to Sun direction

Clear direction reconstruction on event-by-event basis based on "Cherenkov rings", as in Super Kamiokande, **is not possible**



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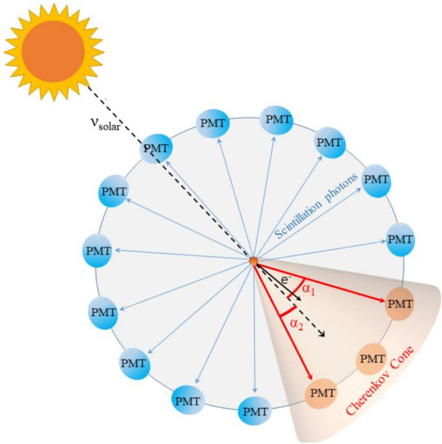
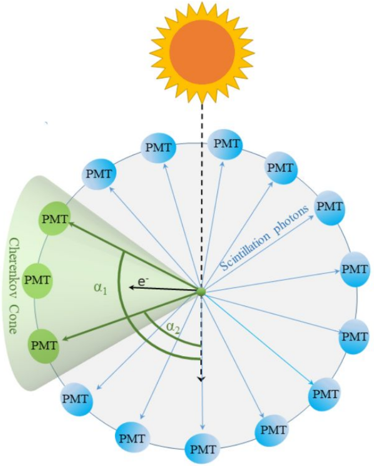




The first detected photons for each event retain a residual directional information

More details in:
Agostini M et al (Borexino Collaboration), *Phys.Rev.Lett.* 128 (2022) 9, 091803

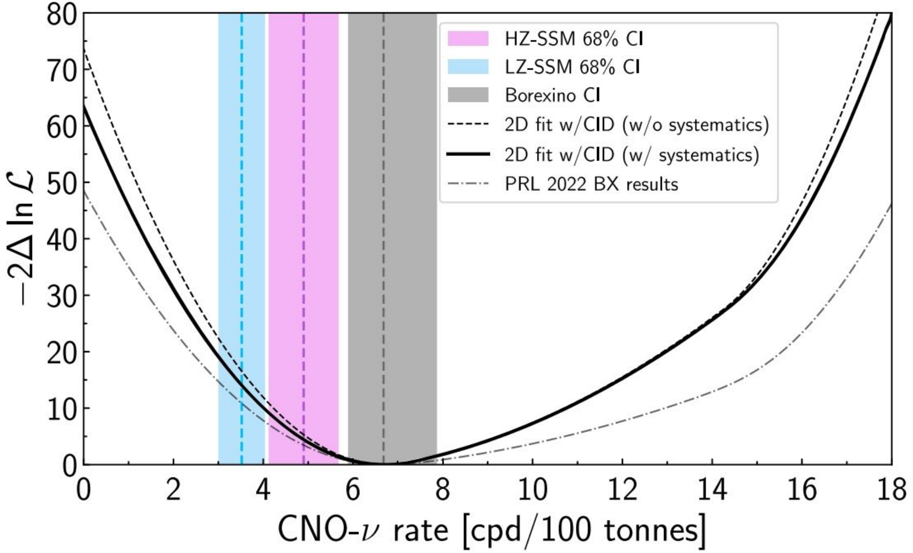
Cherenkov light correlated to Sun position → non-flat angular distribution

Random direction
→ Cherenkov light uncorrelated to Sun
→ isotropic photons angular distribution

Final Borexino results

"Final results of Borexino on CNO solar neutrinos", Borexino Collaboration, Phys.Rev.D 108 (2023) 10, 102005

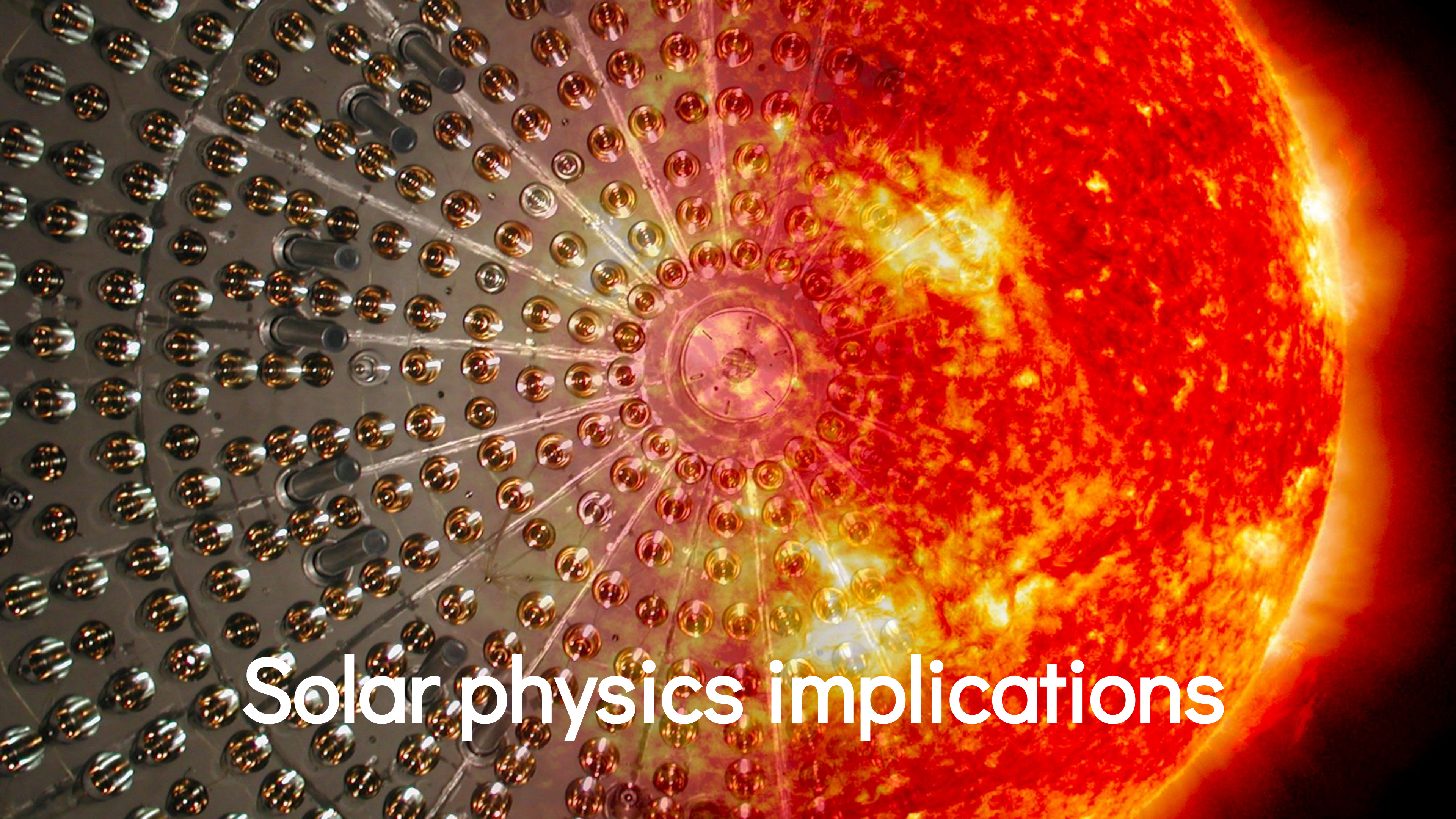
$\Delta\chi^2$ profiles



- Most precise CNO result ever obtained: $\Phi_{CNO} = 6.7^{+1.2}_{-0.8} \times 10^8\ cm^{-2}s^{-1}$
- No CNO hypothesis excluded at about **8σ**

General agreement with SSM-HZ scenario

Binary hypothesis test: HZ vs LZ
→ Assuming SSM-HZ, Borexino results (^{7}Be-ν + ^{8}B-ν + CNO-ν), **SSM-LZ is disfavored at ~3.2σ level**


Solar physics implications

Global determination of solar ν fluxes after Borexino

- *Gonzalez-Garcia, Maltoni, Serenelli, JHEP 02 (2024) 064*: determination of all solar ν fluxes using all available experimental data: (Chlorine, GALLEX, SAGE, SK, SNO, BX)
- Comparison of fluxes with SSM calculations (Herrera and Serenelli, 2023):
  - HZ SSMs are in better agreement with solar neutrino fluxes than the LZ SSMs
  - C+N solar core abundance consistent with HZ abundances.
- Discrimination between solar compositions is at most ~2σ

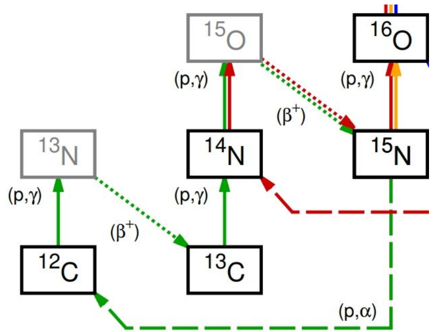
	FIT	B23-SSM	FULL			Be+B+CNO			CNO		
	CNO-Rfixed		n=6			n=3			n=1		
			$\Delta\chi^2$	p_{GF}	CL [σ]	$\Delta\chi^2$	p_{GF}	CL [σ]	$\Delta\chi^2$	p_{GF}	CL [σ]
LZ		AGSS09-met	14.5	0.024	2.3	9.8	0.020	2.3	7.2	0.0073	2.7
HZ		GS98	8.1	0.24	1.2	3.0	0.39	0.86	2.4	0.12	1.5
LZ		AAG21	12.5	0.052	1.9	7.8	0.05	2.0	6.2	0.013	2.5
HZ		MB22-met/phot	7.1	0.31	1.0	2.2	0.53	0.62	2.0	0.16	1.4

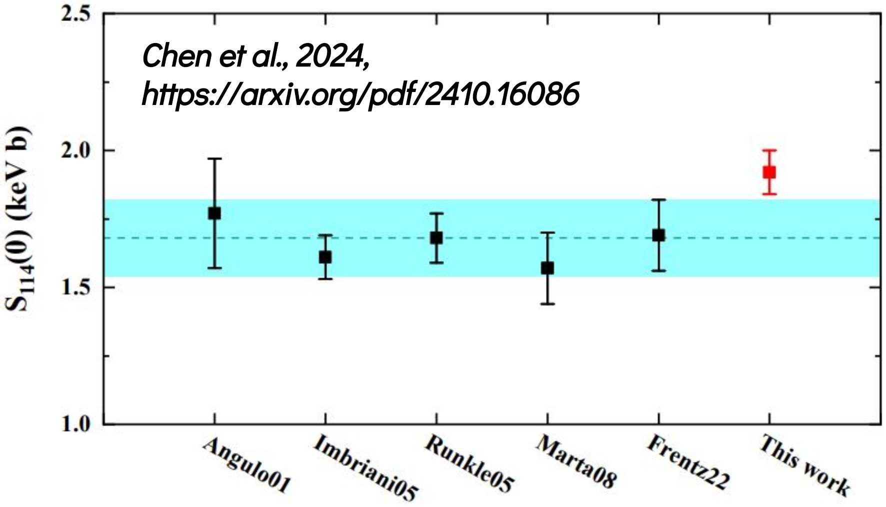
constraints on all the fluxes / 7Be+8B+CNO fluxes / CNO fluxes only

Solar composition: impact of $^{14}N(p,\gamma)^{15}O$ reaction

$^{14}N(p,\gamma)^{15}O$ is the slowest reaction in the CNO cycle
→ crucial role in the SSM calculations of CNO neutrino fluxes
→ measurement of astrophysical S-factor

- Hefei 350 kV accelerator facility, γ spectra measured at 110–260 keV
- S-factors for all transitions simultaneously determined for the first time





higher S-factor → quicker reaction → less metals available → lower metallicity!

Re-evaluation of C+N content in the Sun is also consistent with the LZ composition within 1σ C.L.

→ **solar composition problem still an open question**, need more precise observational data on solar CNO ν!

Conclusions

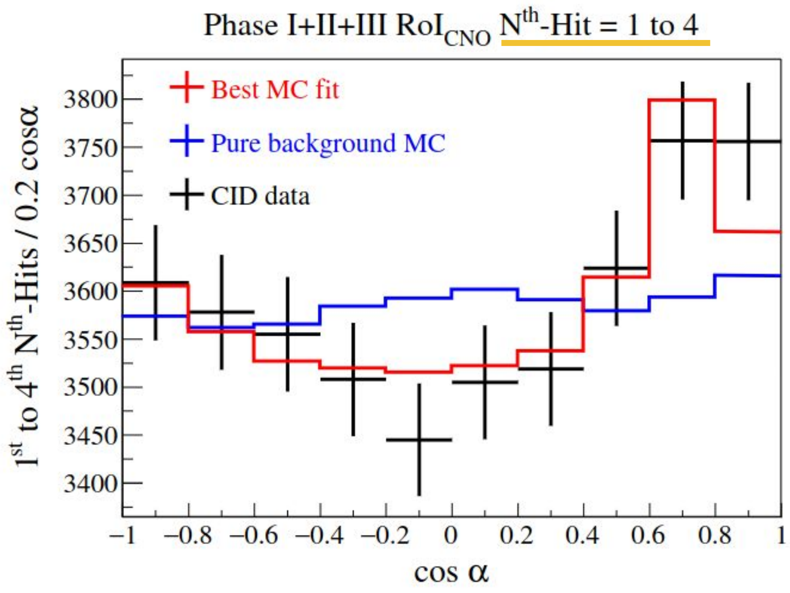
- Borexino has measured **all the solar ν fluxes, and CNO ν flux >5σ significance**
- **Solar astrophysics implications** and SSM:
  - Borexino disfavors LZ scenario at 3.2σ level;
  - global analysis: solar ν provide ~2σ disfavoring of LZ scenario;
- Solar composition problem still an open question
  → role of directionality for solar ν measurements is reinforced
  → new avenues for future LS-based (JUNO) or hybrid neutrino experiments

Thanks!

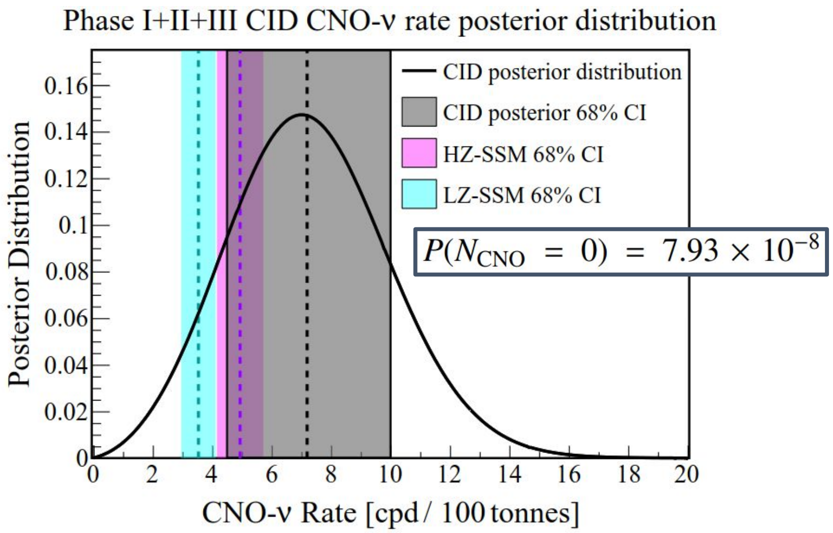
Backup

Angular fit

gv_{ch} calibration **unlocks** the CID analysis on the whole Borexino dataset and without 210Bi constraint
Events cosα distribution in the CNO ROI ➔ **obtain number of ν ($N_\nu = N_{CNO} + N_{pep} + N_{8B}$) and background** events



Earliest 4 hits: direct Cherenkov information (peak for neutrinos at cos α ~ 0.75)



- No-CNO hypothesis, applying also pep ν constraint, rejected at **5.3σ level**
- No assumption on background levels (e.g. 210Bi)

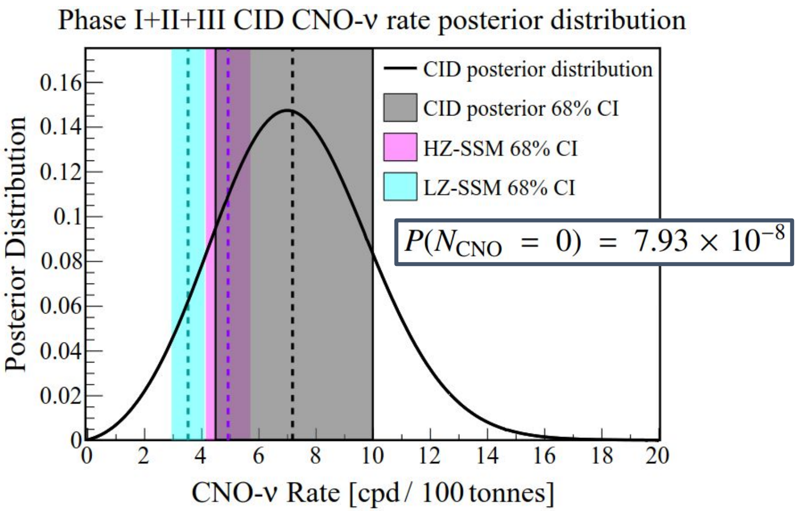
Solar neutrino fluxes

Source	E_ν (MeV)	GS98	AAGS21	MB22p	units ($cm^{-2}s^{-1}$)
pp	$\leq$0.420	5.96 (0.6%)	6.00 (0.6%)	5.95 (0.6%)	10^{10}
pep	1.442	1.43 (1.1%)	1.45 (1.1%)	1.42 (1.3%)	10^{8}
hep	$\leq$18.77	7.95 (31%)	8.16 (31%)	7.93 (30%)	10^{3}
^{7}Be	0.862$^{(a)}$ 0.384$^{(b)}$	4.85 (7.4%)	4.52 (7.3%)	4.88 (8.1%)	10^{9}
^{8}B	$\lesssim$ 15	5.03 (13%)	4.31 (13%)	5.07 (15%)	10^{6}
^{13}N	$\leq$1.198	2.80 (16%)	2.22 (13%)	3.10 (15%)	10^{8}
^{15}O	$\leq$1.732	2.07 (18%)	1.58 (16%)	2.30 (18%)	10^{8}
^{17}F	$\leq$1.738	5.35 (20%)	3.40 (16%)	4.70 (17%)	10^{6}

Notes: (a) 90% and (b) 10% of the ^{7}Be neutrino flux, respectively.

TABLE II Solar neutrino sources, energies, and SSM flux predictions. All β decay sources produce continuous spectra, while the pep and ^{7}Be electron-capture sources produce line spectra. The fluxes are taken from the SSM calculations of Herrera and Serenelli (2023), computed with nuclear reaction rates shown in Table I, for the compositions of GS98 (Grevesse and Sauval, 1998) (high-Z), AAG21 (Asplund *et al.*, 2021) (low-Z), and MB22p (Magg *et al.*, 2022) (high-Z) with associated uncertainties indicated.

CNO ν results, directionality only



Convolving both posteriors
Subtracting pep-ν ^{8}B-ν contrib.
Including systematics

- No-CNO hypothesis, applying also pep ν constraint, rejected at **5.3σ level**
- No assumption on background levels (e.g. 210Bi)
- Solar models prediction agreement: LZ-SSM is 1.7 times less likely to be true than HZ-SSM

$$R^{CID}_{CNO} = 7.2 \pm 2.5\ (\text{stat}) \pm 0.4\ (\text{sys})\ ^{+1.1}_{-0.8}\ (\text{nuisance})\ \frac{\text{cpd}}{100\,\text{tonnes}} = 7.2^{+2.8}_{-2.7}\ \frac{\text{cpd}}{100\,\text{tonnes}}$$

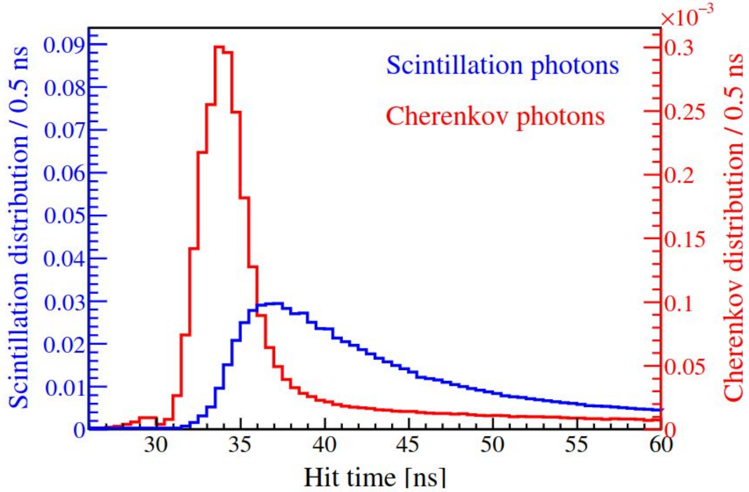
Correlated and **I**ntegrated **D**irectionality (CID)

Scintillation and Cherenkov detected photons (hits) are indistinguishable on an event-by-event basis.

➔ Statistical separation is needed

➔ Cherenkov photons are **faster**: emitted in **ps**, while scintillation in **ns**

➔ Exploit the arrival times of the photons on PMTs



Correlated and Integrated Directionality (CID)

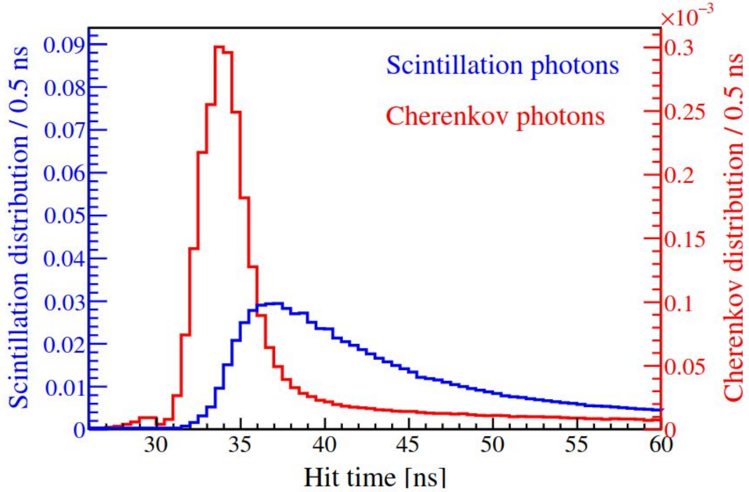
Scintillation and Cherenkov detected photons (hits) are indistinguishable on an event-by-event basis.

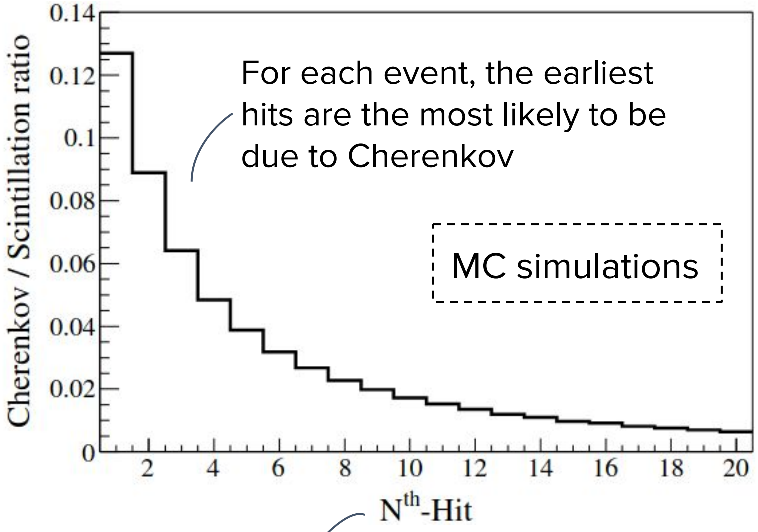
➜ Statistical separation is needed

➜ Cherenkov photons are **faster**: emitted in **ps**, while scintillation in **ns**

➜ Exploit the arrival times of the photons on PMTs

CID: **correlate** first hits of each event in time with Sun position and **integrate** over time



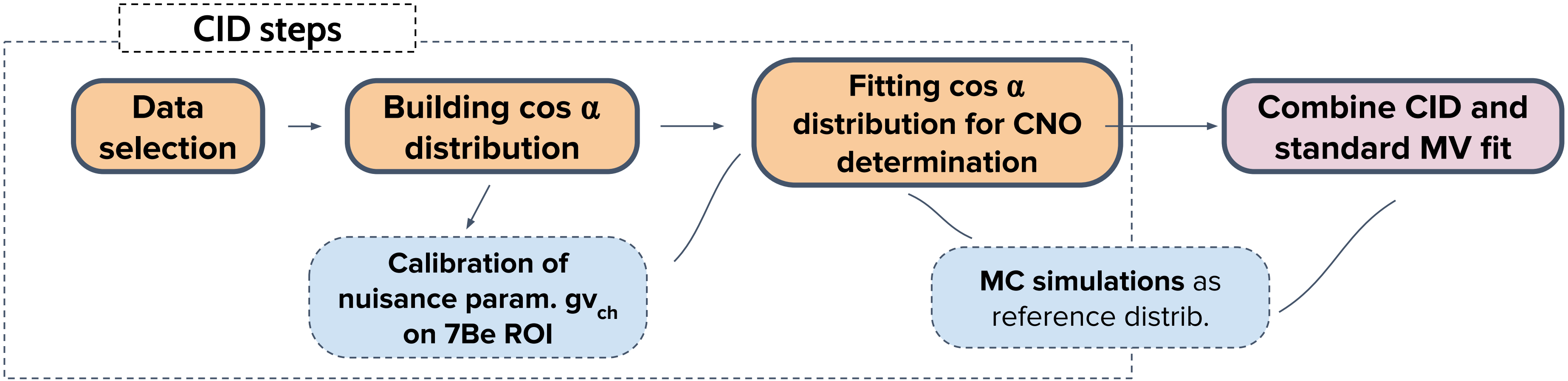


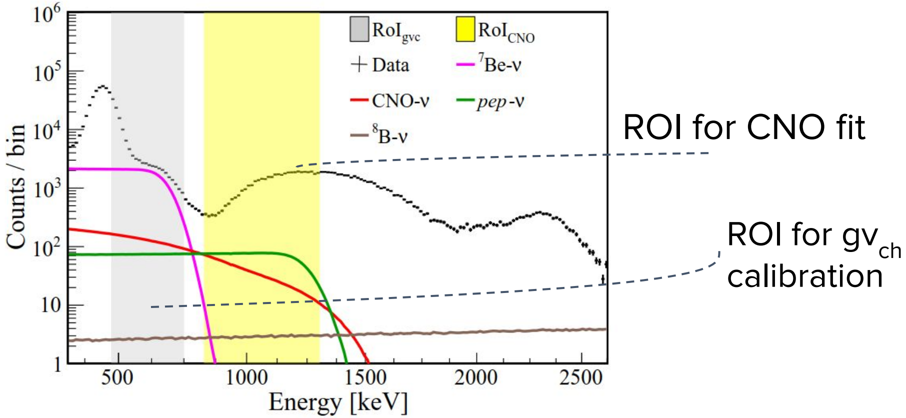
For each event, the earliest hits are the most likely to be due to Cherenkov

MC simulations

For each event: order of photons arrival to the PMTs

Strategy of CID analysis



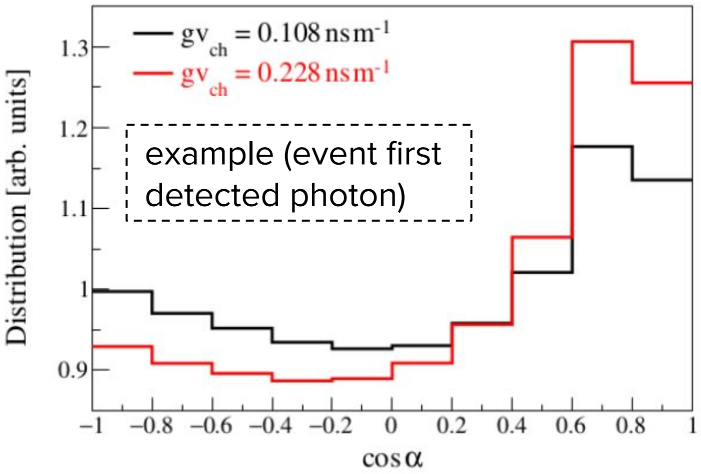


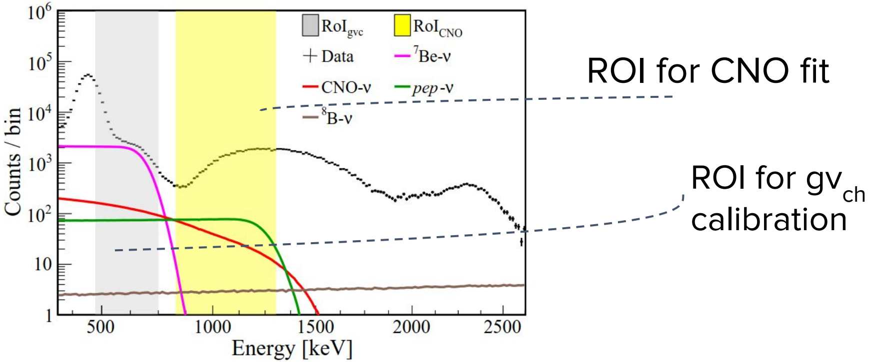
- Full Borexino dataset (2007-2021)
Exposure: 595.85 y x tonnes

- No information on background is needed!

CID method: nuisance parameters

1) **Group velocity of Cherenkov photons**, relative to scintillation, at MC level: $\mathbf{t_{corrected} = t_{MC} - gv_{ch} d_{MC}}$





Can be calibrated: 7Be shoulder ROI

➔ **constrained** nuisance parameter in CNO analysis

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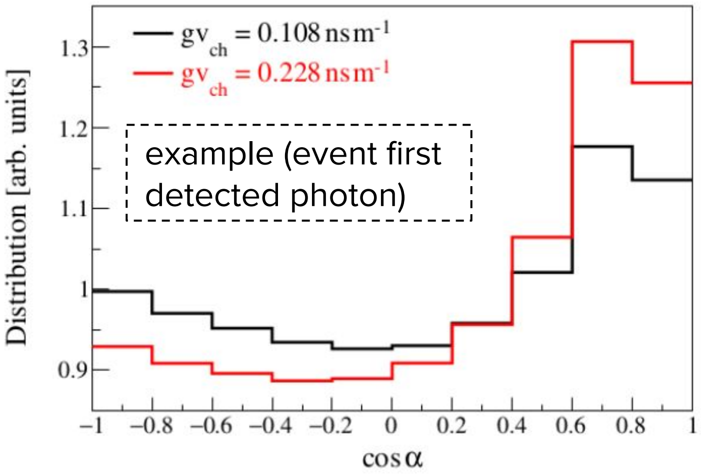
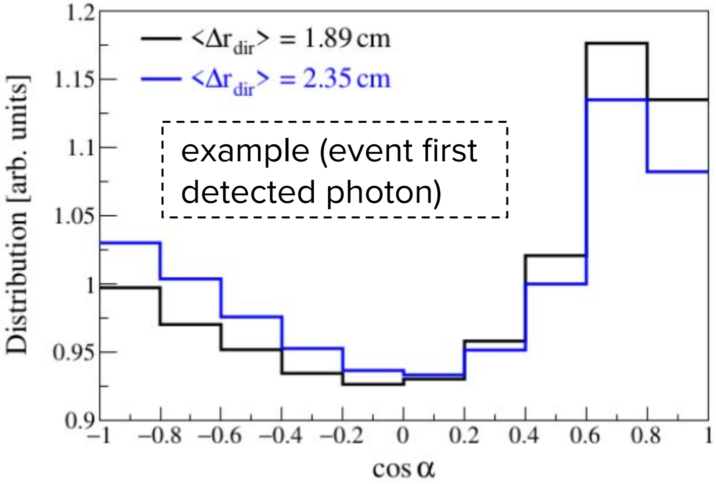


2) Small **bias in position reconstruction** in direction of the solar neutrino **Δr** due to Cherenkov hits



Can be calibrated: 7Be shoulder ROI

➜ **constrained** nuisance parameter in CNO analysis

Cannot be calibrated: no dedicated e- Cherenkov calibration source

➜ **free** nuisance parameter in CNO analysis

Systematic uncertainties

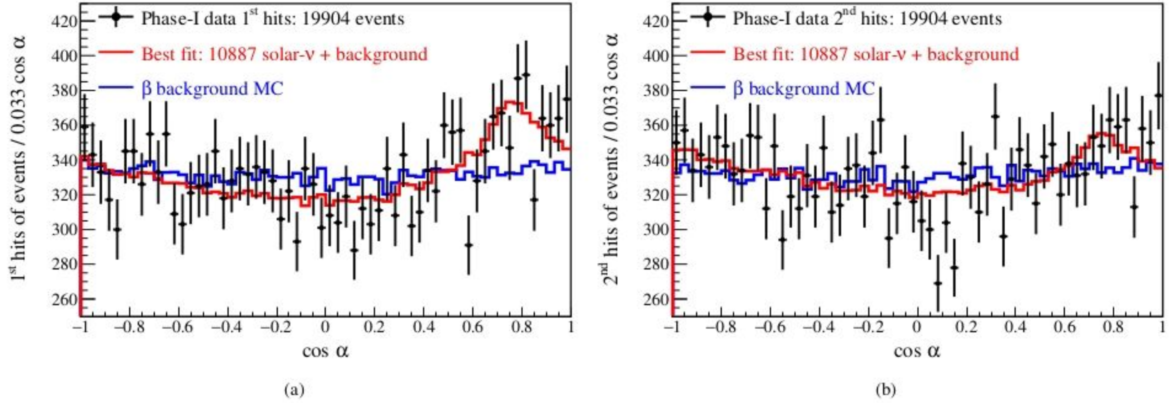
Source of gv_{ch} uncertainty	Phase-I	Phase-II+III
PMT selection	2.1%	1.6%
PMT time corrections	3.7%	2.1%
MLP event selection	1.0%	1.0%
Fiducial mass	$\left(^{+0.2}_{-1.2}\right)$ %	$\left(^{+0.2}_{-1.2}\right)$ %
Fraction of neutrinos in RoI	1.3%	0.9%

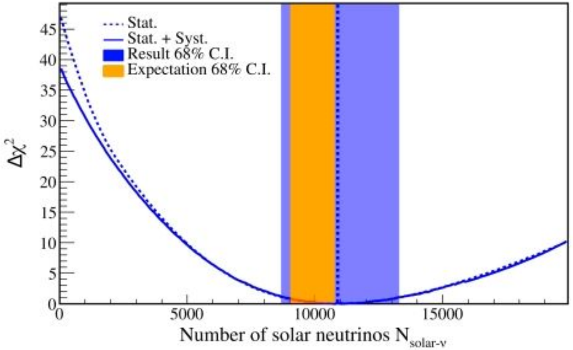
TABLE I. Systematic uncertainties of the gv_{ch} measurement in the RoI_{gvc}, relative to the best fit value.

Source of uncertainty	Phase-I	Phase-II+III
For N_ν		
PMT selection	1.3%	0.6%
PMT time corrections	4.2%	2.4%
Low number of signal events	2.2%	–
CNO-ν vs. pep-ν MC	2.2%	2.0%
For N_{CNO}		
pep+^{8}B-ν constraint	4.6%	1.8%
For R_{CNO}		
Fiducial mass	$\left(^{+0.2}_{-1.2}\right)$ %	$\left(^{+0.2}_{-1.2}\right)$ %
Fraction of CNO-ν in RoI	1.4%	1.4%

TABLE II. Systematic uncertainties on the number of solar neutrino events N_ν in RoI_{CNO}, relative to the best fit value. The uncertainty from pep+^{8}B-ν constraint is relevant only for N_{CNO}. The last two rows are relevant only for the CNO-ν rate (R_{CNO}) calculation.

7Be results with directionality

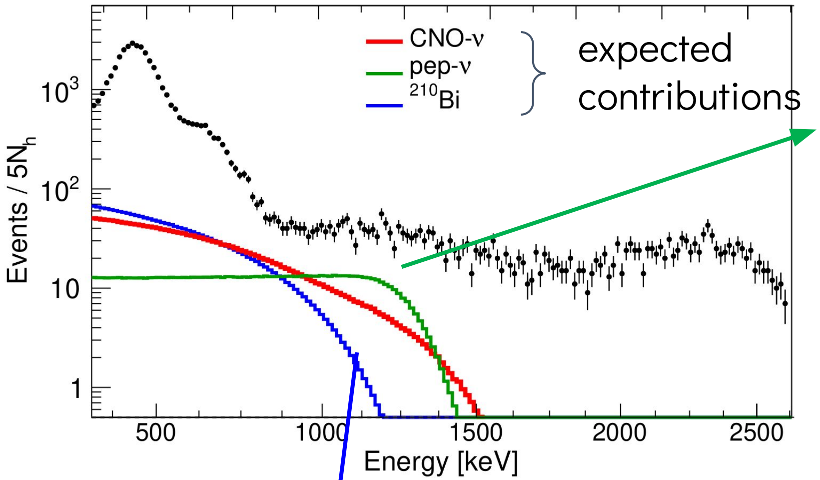




The cos α distributions of the first (a) and second (b) hits of all the selected events (black points) compared with the best fit curve (red) for the resulting number of solar neutrinos $N_{solar-\nu}$ plus background,

Why a CNO- ν measurement is challenging?

→ to extract **CNO-ν** signal, need to constrain **pep-ν**, **^{210}Bi** independently on spectral fit



pep-ν neutrinos signal is constrained according to Standard Solar Model predictions (1.4% precision level)

The annoying **^{210}Bi background** is constrained independently on the spectral fit
→ secular equilibrium with its daughter ^{210}Po

$$^{210}\text{Pb} \xrightarrow[32.2y]{\beta} {}^{210}\text{Bi} \xrightarrow[7.23d]{\beta} {}^{210}\text{Po} \xrightarrow[199.6d]{\alpha} {}^{206}\text{Pb}$$

The ^{210}Bi constraint challenge

^{210}**Bi** rate can be constrained exploiting the equilibrium with its daughter nucleus ^{210}Po

→ Can we easily guarantee **secular equilibrium** between ^{210}Bi and ^{210}Po, such that **R(^{210}Bi)=R(^{210}Po)?**

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supplier of
210Bi

easily identified event-by-event thanks to α discrimination techniques:
→ **R(Po) can be easily determined**

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→ **R(Po) can be easily determined**

Can we easily guarantee secular equilibrium between ^{210}Bi and ^{210}Po, such that R(^{210}Bi)=R(^{210}Po)?

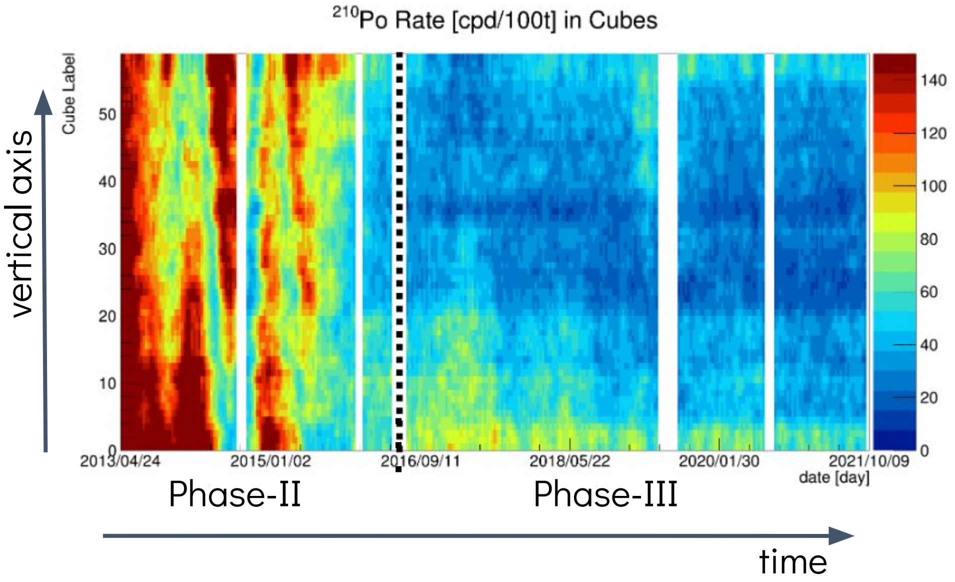
NO: convective motions (temperature gradients) can inject the FV with unknown amount of out-of-equlibrium ^{210}Po present on the nylon inner vessel

linked to R(Bi): our goal!

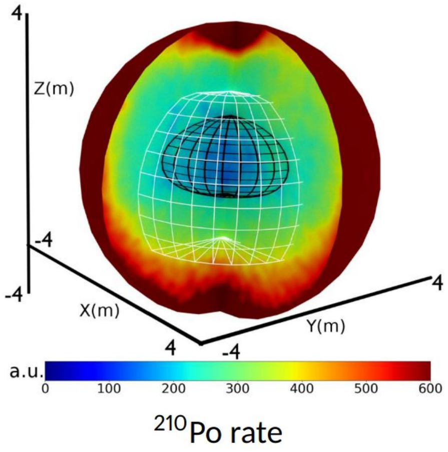
$$R(Po) = R(Po)_{supported} + R(Po)_{out\text{-}of\text{-}equilibrium}$$

The ^{210}Bi constraint challenge

Solution: select a region in which Po convective motions are strongly attenuated
→ thanks to the temperature insulation of the detector, from 2015 on



Low Po Field : ~20 tons above the equator



R(Bi) < R(Po)

(possible residual 210Po convection)

Determine a R(Bi) upper limit → R(CNO) lower limit!

CNO-ν results

NEW!

Phase-III

Nature 587 (2020) 577-582

- Dataset: Jul 2016 - Feb 2020
- Data-Monte Carlo agreement stable until 2020
- ^{210}Bi rate constraint:
  - R(^{210}Bi) < 11.5 ± 1.3 cpd/100t

Main result:

First CNO neutrinos detection

(absence hyp. excluded at 5.0σ level)

Phase-III Final

accepted PRL, arXiV:2205.15975 2022

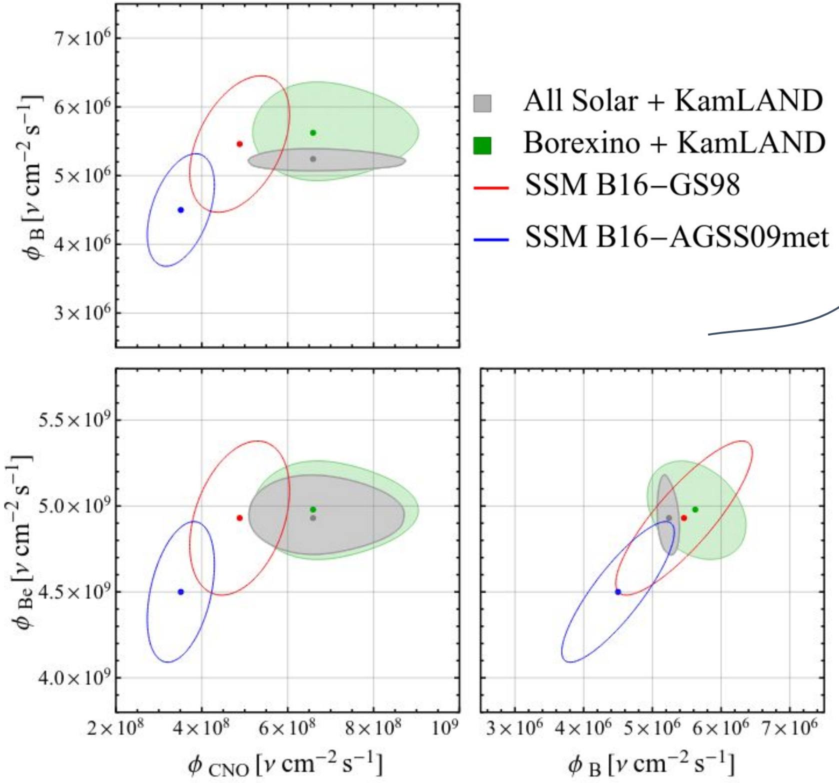
- Dataset: Jan 2017 - Oct 2021
  → +33% exposure
- Data-Monte Carlo agreement improved for recent years (better than 1% level)
- ^{210}Bi rate constraint:
  - R(^{210}Bi) < 10.8 ± 1.0 cpd/100t
    Improved precision

Main result:

Improved CNO detection significance (7.0σ)

→ **relevant solar astrophysical implications**

Global analysis of solar ν fluxes



2-dimensional planes C.I. for ν fluxes: ^{7}Be-ν, ^{8}B-ν, CNO

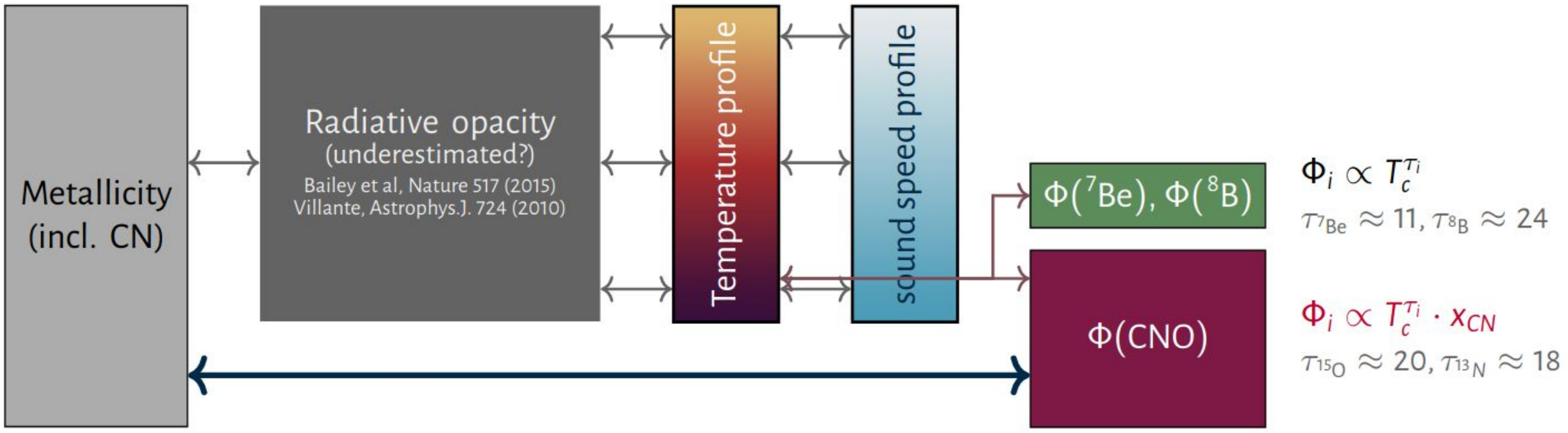
General **agreement with SSM-HZ** scenario

Binary hypothesis test: HZ vs LZ

→ Assuming SSM-HZ, Borexino results (^{7}Be-ν + ^{8}B-ν + CNO-ν), **SSM-LZ is disfavored at ~3.1σ level**

Determination of C+N core abundance

- CNO fluxes directly and indirectly depend on Carbon and Nitrogen content in solar core
  - strongly dependent on metallicity scenario (~28%)
- pp chain fluxes (8B, 7Be) depend only indirectly on metallicity, via solar core temperature **T_c**



Solar-ν fluxes estimations → degeneracy of metallicity + T_c + opacity

Use precision measurem. of ^{8}B-ν to constrain T_c → extract CN abundance in the core

Determination of C+N core abundance

CNO-ν and ^{8}B-ν fluxes depends on T_c by power-laws;

$$\Phi_i \propto T_c^{\tau_i} \cdot x_{CN}$$

$$\tau_{^{15}O} \approx 20, \tau_{^{13}N} \approx 18$$

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$$\tau_{^7Be} \approx 11, \tau_{^8B} \approx 24$$

Key idea: ϕ ratio cancels out dependence on T_c and holds the C+N content dependence

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$$\frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{0.769}} = \frac{N_{CN}}{N_{CN}^{SSM}} \times$$
$$\times\,[1 \pm (0.097(\text{nucl}) \oplus 0.005(\text{env}) \oplus 0.027(\text{diff}))]\,.$$

S-factors, nuclear reactions

Elements abund., solar properties

Diffusion

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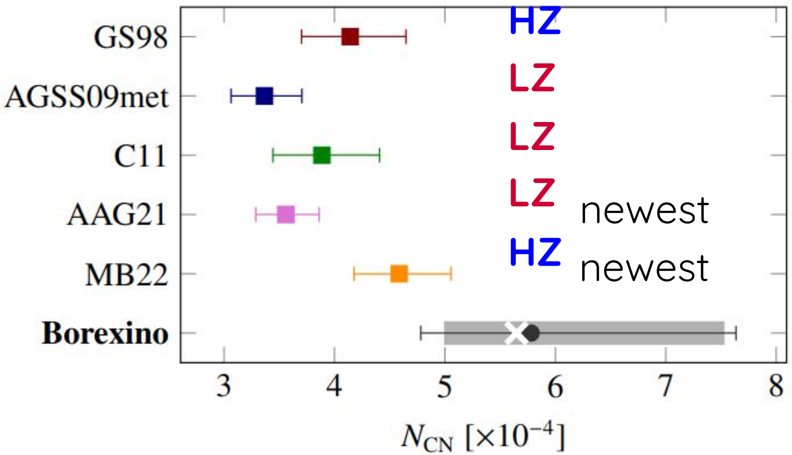

First estimate of solar C+N abundance based on CNO neutrinos

- Agreement with HZ (GS98, MB22), while ~2σ tension with LZ (AGSS09met, C11 , AAG21).
- Error dominated by experimental uncertainty

Latest Borexino solar neutrino results

- Improved Measurement of Solar Neutrinos from the Carbon-Nitrogen-Oxygen Cycle by Borexino and Its Implications for the Standard Solar Model
  Phys.Rev.Lett. 129 (2022) 25, 252701, https://arxiv.org/abs/2205.15975

- Independent determination of the Earth's orbital parameters with solar neutrinos in Borexino,
  Astropart.Phys. 145 (2023) 102778, https://arxiv.org/abs/2204.07029

- First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino
  Phys.Rev.Lett. 128 (2022) 9, 091803, https://arxiv.org/abs/2112.11816

- Correlated and integrated directionality for sub-MeV solar neutrinos in Borexino
  Phys.Rev.D 105 (2022) 5, 052002, https://arxiv.org/abs/2109.04770

- Improved measurement of 8B solar neutrinos with 1.5kt · yof Borexino exposure
  Phys.Rev.D 101 (2020) 6, 062001, https://arxiv.org/abs/1709.00756