Daniele Guffanti
University & INFN Milano-Bicocca
on behalf of the **Borexino Collaboration**

Recent results from Borexino

56th Rencontres de Moriond, March 17th 2022

Outline

2007-2021: 14 years of Solar neutrinos

- **Phase I**
  First high-precision measurement of ^{7}Be, measurement of *pep* and ^{8}B ν's
- **Phase II**
  Comprehensive measurement of the *pp*-chain
- **Phase III**
  First evidence of neutrinos from CNO-cycle

First directional measurement of sub-MeV solar neutrinos

- **CID**
  Correlated and Integrated Directionality
- Application to ^{7}Be

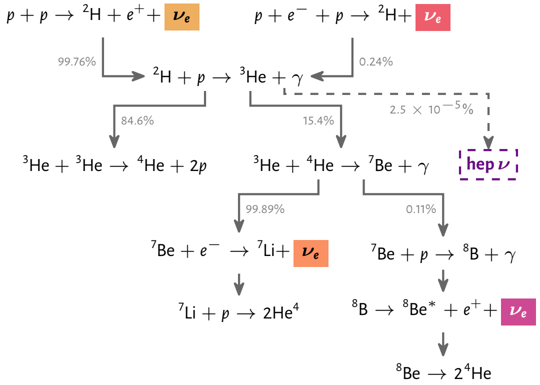
Neutrinos from the Sun

Sun is powered by nuclear fusion reactions: $4\,{}^{1}\text{H} \rightarrow {}^{4}\text{He} + \ldots$

A.S. Eddington Observatory 43 (1920), Nature (1920)

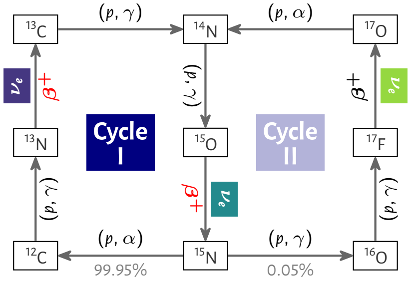
The *pp* chain

Bethe & Critchfield (1938)

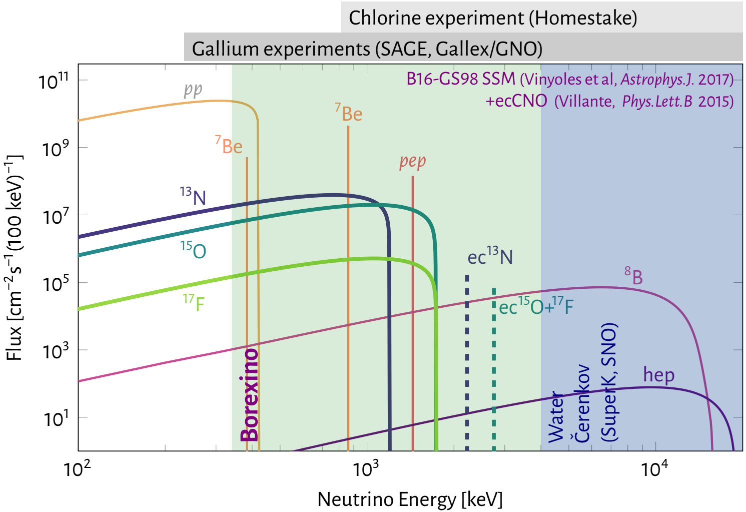


The CNO cycle

Weizsäcker (1937, 1938), Bethe (1939)



The Solar Neutrino Spectrum



Radiochemical experiments

Measurement of the **integrated spectrum** above threshold

Water Čerenkov

- Large mass
- High energy threshold

High precision measurement of ^{8}B

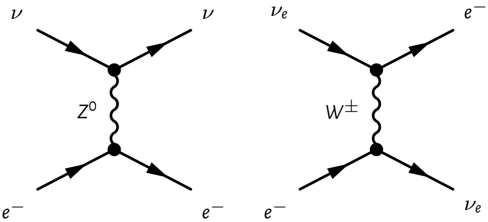
Liquid Scintillator

- Low energy threshold
  ↪ complete coverage of the spectrum
- Spectral separation of solar-ν components

Detection method

e^-–neutrino elastic scattering

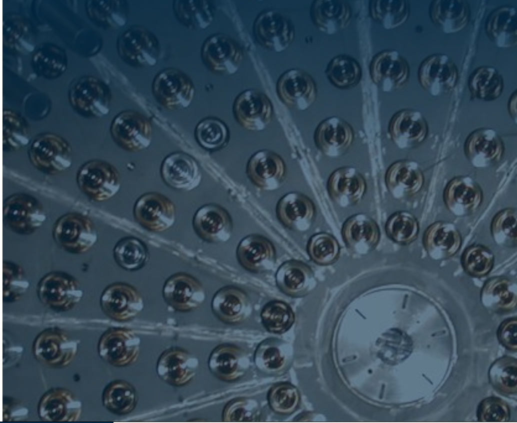
ν_x–e^- Elastic Scattering



Expected rate of ^{7}Be-ν is $\approx$ 50 cpd/100 t (10^{-9}Bq/kg)
Typical activity of tap water $\approx$ 1 Bq/kg

Background suppression and high radiopurity are essential for Borexino success

The radiopurity challenge

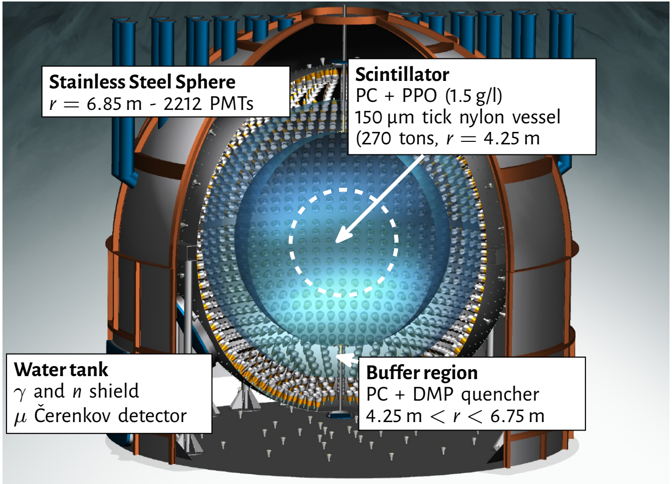


The Borexino Experiment @ LNGS

Borexino is an **ultrapure liquid scintillator** experiment installed at the Gran Sasso National Laboratories of the Italian National Institute of Nuclear Physics

- Light Yield 550 p.e./MeV
  $\hookrightarrow \Delta E/E \sim 6\%/\sqrt{E[\text{MeV}]}$
- Position reconstruction based on time of flight
  ($\approx$ 11 cm resolution at 1 MeV)

↑ 1400 m of rock ↑
(3800 m.w.e.)



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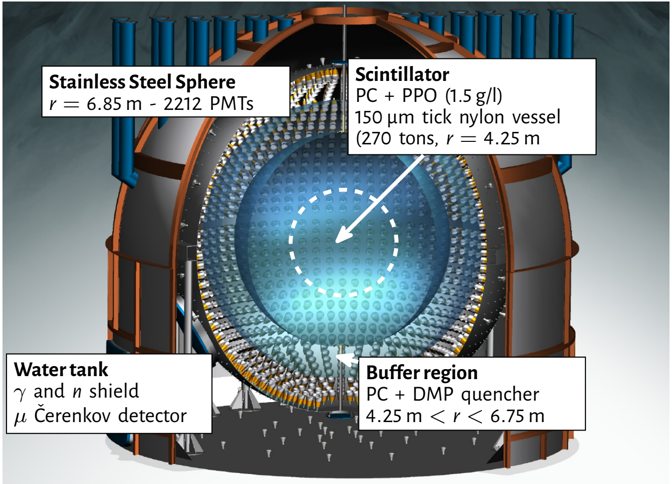
Solar-ν highlights

- 2007-2010 **Phase-I** ^{7}Be, ^{8}B, *pep*
- 2010-2011 **Purification Camp.**
- 2012-2016 **Phase-II** precision *pp*-chain
- 2016-… **Phase-III: The Quest for CNO**

↑ **1400 m of rock** ↑
(3800 m.w.e.)

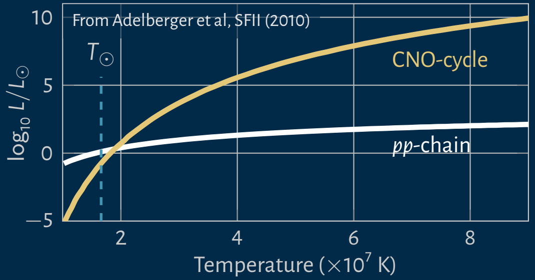


Astrophysics

Relative efficiency of ***pp*-chain** and **CNO-cycle** depends on

- Local temperature
- Element local density

In the Sun $L(pp)/L_\odot \approx 99\%$ vs $L(\text{CNO})/L_\odot \approx 1\%$



Detection of CNO-ν

$\hookrightarrow$ **direct evidence of CNO-cycle**

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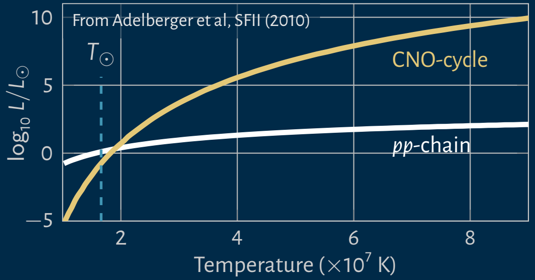

Detection of CNO-ν

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Solar Physics

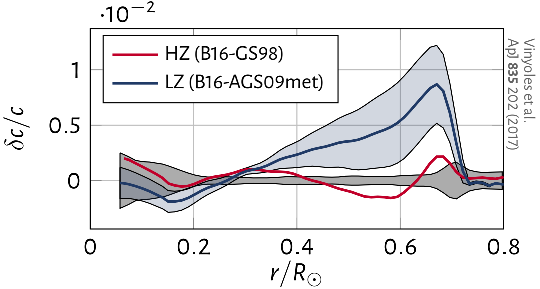
Measurement of $\Phi(\mathrm{CNO})$

$\hookrightarrow$ indication of C+N abundance in the Sun

$\hookrightarrow$ **Hint for solar metallicity**

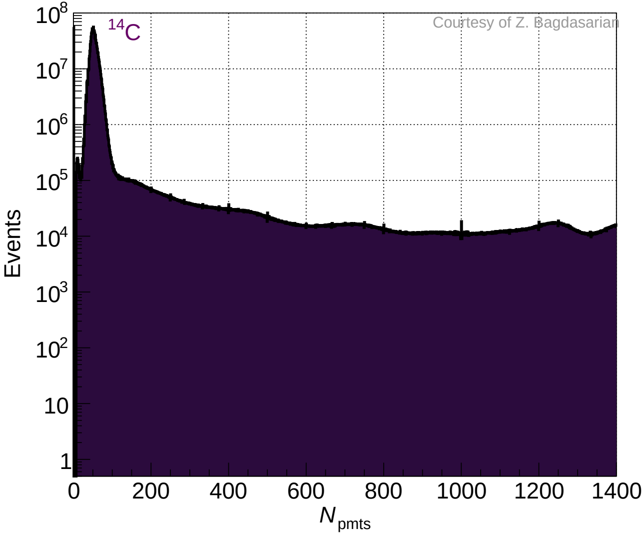
Re-evaluation of photospheric composition

$\hookrightarrow \approx 20\%$ reduction of solar metallicity



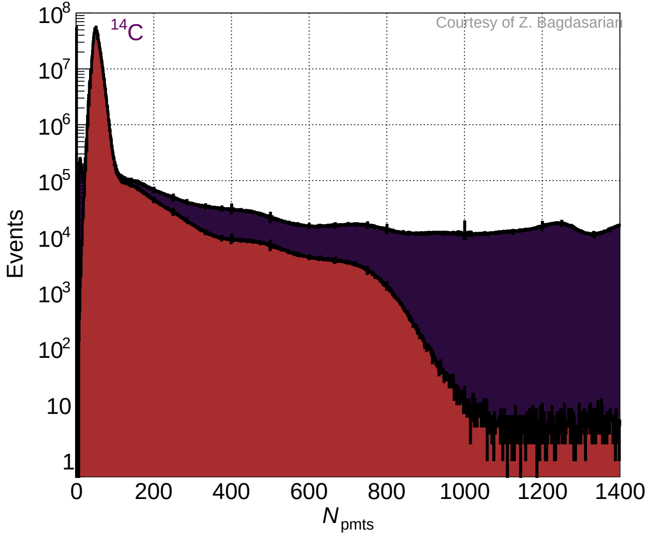
- Strong **tension** with **helioseismology** data
- **Solar-ν also influenced by composition**

Data collected between July 2016 and February 2020 - Exposure 1070 days $\times$ 71.3 ton (FV)



Full Spectrum

Data collected between July 2016 and February 2020 - Exposure 1070 days $\times$ 71.3 ton (FV)



Full Spectrum

Muon cut

$\approx$ 4300 μ/day crossing ID

Removes μ, μ-induced n and cosmogenics

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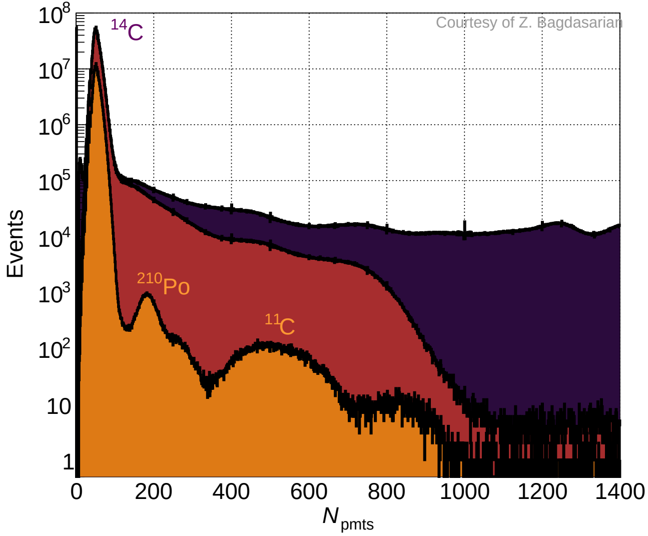

Full Spectrum

Muon cut

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Fiducial Volume cut

Reduction of external and surface background

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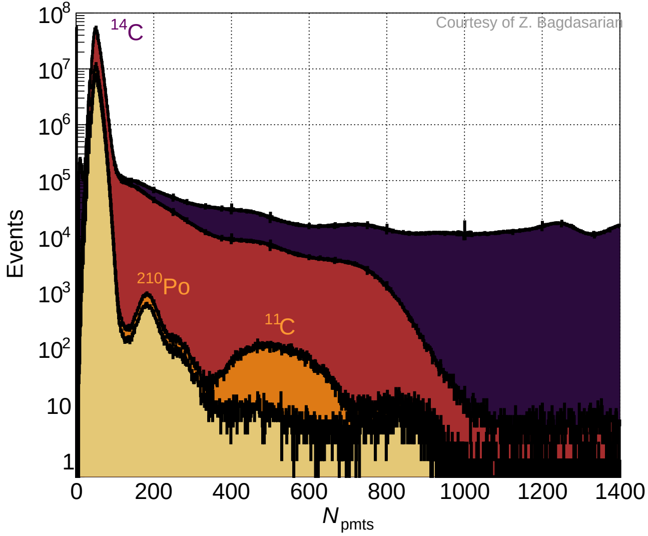


Full Spectrum

Muon cut

≈ 4300 μ/day crossing ID

Removes μ, μ-induced n and cosmogenics

Fiducial Volume cut

Reduction of external and surface background

^{11}C suppression (TFC cut)

μ–n pairs coincidences

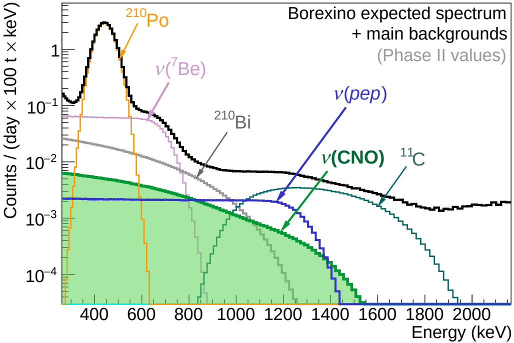
+ space-time correlation with β-like ev.

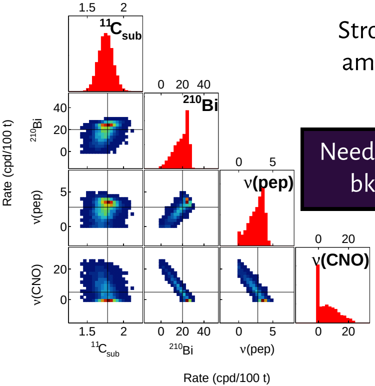
The CNO challenge

Small exp. rate
3–5 cpd/100 t

No prominent spectral feature

Spectral degeneracy with ^{210}Bi and *pep* bkg





↓

Strong correlation among fit results

↓

Need of independent bkg. constraints

Fit best estimates correlations
MC-generated pseudo-exp.
BX coll, Phys.Rev.D 100 (2019) 8

^{210}Bi independent constraint

F. Villante et al, Phys. Lett. B 701(3) (2011)
arXiv:1104.1335 [hep-ph]

^{210}Pb dissolved in the scintillator

$$^{210}\text{Pb} \xrightarrow[22.2\text{ y}]{(\beta)t_{1/2}} {}^{210}\text{Bi} \xrightarrow[5.0\text{ d}]{(\beta)t_{1/2}} {}^{210}\text{Po} \xrightarrow[138.4\text{ d}]{(\alpha)t_{1/2}} {}^{206}\text{Pb (stable)}$$

No source of ^{210}Pb $\rightarrow$ ^{210}Bi in equilibrium
$\hookrightarrow$ ^{210}Po in equilibrium too

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$\hookrightarrow$ ^{210}Po in equilibrium too

⚠ ^{210}Po can detach from nylon vessel!

Convective currents inside the LS carry ^{210}Po inside the FV
Thermal stabilization of the entire detector
(Insulation, TACS, Hall C stabilization, ...)

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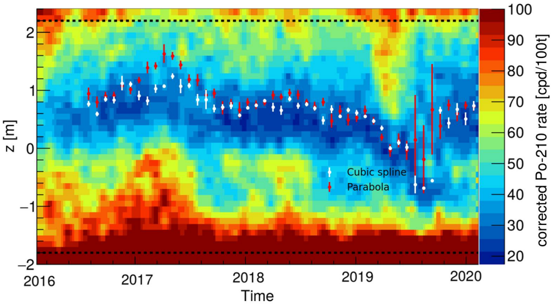


Extraction of ^{210}Bi constraint

BX Coll., Nature 587 (2020)

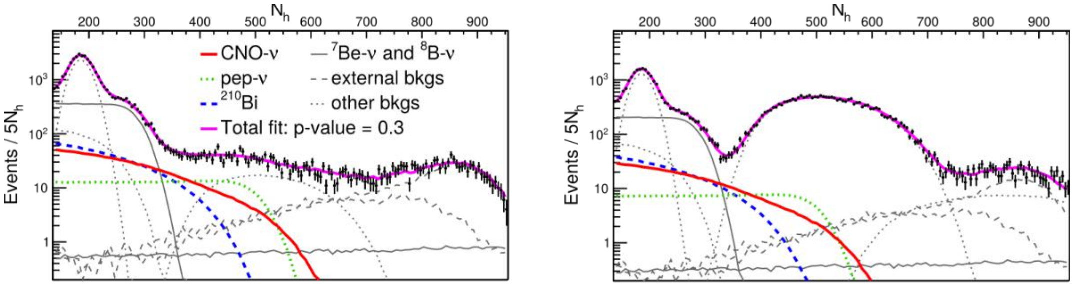
- Trace z position of ^{210}Po minimum over time
- Align data
- $R_{min}(^{210}\mathrm{Po}) = R(^{210}\mathrm{Bi}) +$ residual convection

$\hookrightarrow$ $R(^{210}\mathrm{Bi})$ upper limit $= 11.5 \pm 1.3$ cpd/100 t

CNO result

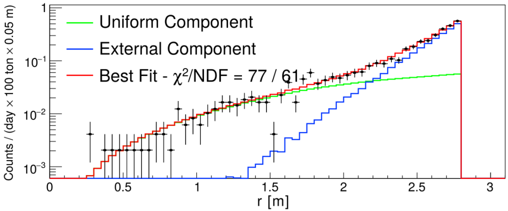
BX Coll, Nature 587 (2020)
`arXiv:2006.15115 [hep-ex]`

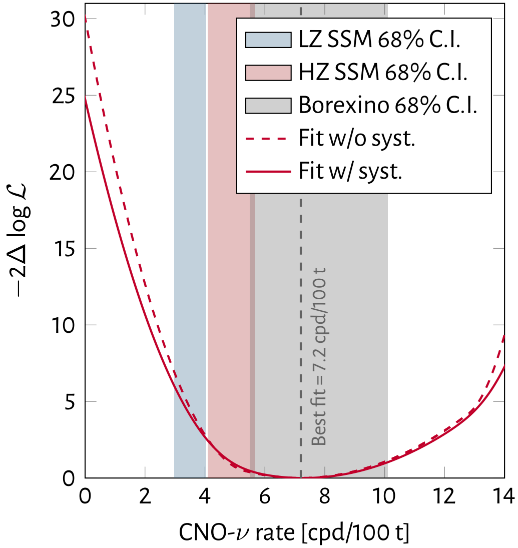
Simultaneous fit of ^{11}C-subtracted and -tagged dataset + radial distribution



Fit Configuration

- *pep* rate: constrained (solar luminosity)
- ^{210}Bi rate: 1-side constraint (^{210}Bi–^{210}Po tag)
- CNO rate: free
- other backgrounds: free





Systematics evaluation

- **Fit configuration** Fit range, binning, ...
- **^{11}C spectrum** Distortions induced by noise cuts
- **^{210}Bi spectrum** Uncertainties on the β spectrum
- **Detector response**
  - Energy scale (0.23%)
  - Non-uniformity (0.28%)
  - Non-linearity (0.40%)

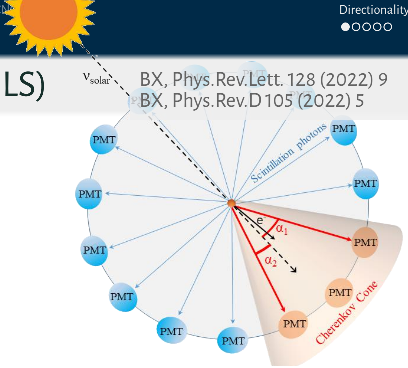
$$R_{\mathrm{CNO}} = 7.2^{+2.9}_{-1.7}\,(\mathrm{stat})^{+0.6}_{-0.5}\,(\mathrm{sys})\ \mathrm{cpd/100\ t}$$

Detection significance estimated with a profiled likelihood test-statistics

No-CNO hp. disfavoured with $> 5\sigma$ significance

Directional measurement of sub-MeV neutrinos (in LS)

BX, Phys.Rev.Lett. 128 (2022) 9
BX, Phys.Rev.D 105 (2022) 5



PMT hits in Borexino:

- $>$ 99.5% Isotropic scintillation photons
- $<$ 0.5% Directional Čerenkov photons

✘ Impossible to reconstruct ν direction for each event

✔ Look for patterns in **individual PMT hits** for many events

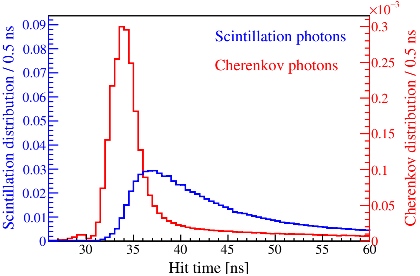
Correlated and Integrated Directionality (CID)

Angle between Sun direction and n-th PMT hit

$$\cos\alpha_i = \hat{\boldsymbol{n}}_{\text{Sun}} \cdot \frac{\boldsymbol{x}_{\text{int}} - \boldsymbol{x}_{\text{PMT } i\text{-hit}}}{|\boldsymbol{x}_{\text{int}} - \boldsymbol{x}_{\text{PMT } i\text{-hit}}|}$$

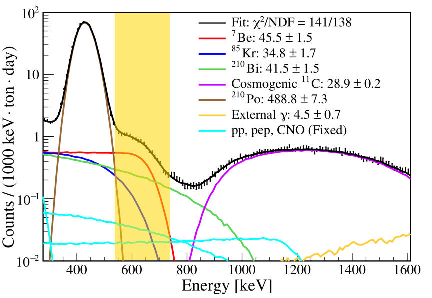
- Scint. light: time profile $\mathcal{O}$(ns)
- Čerenkov light: $\mathcal{O}$(ps)

Select first/second hits to maximise the Čerenkov/Scintillation ratio



Event selection

- Phase I(+ II + III) = 740.7 (+1291.5 + 1072)
- FV: $R < 3.3$ m (< 3.0 m) = 132.1 t (99.3 t)
- ROI: 0.5–0.8 MeV



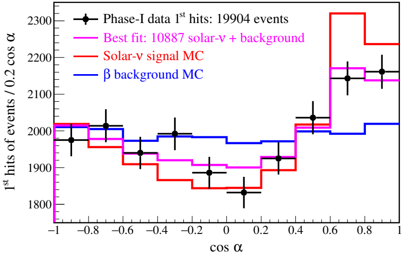
Analysis strategy

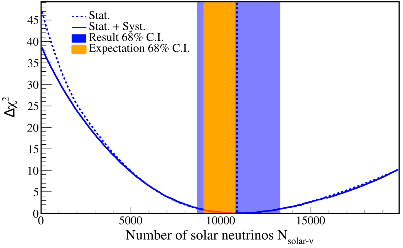
- PDFs produced by MC
- Use 1st and 2nd hits
- Add model nuisance parameters to the fit

Main sources of uncertainties

- Čerenkov light group velocity
  Čerenkov ph. have a different spectrum than Scint.
  No dedicated calibration - γ-sources used
  Penalty term in the fit likelihood
- Position reconstruction bias
  Small bias observed in MC towards true e^- dir.
  (1.89 cm to be compared with 12 cm resolution)
  Free parameter in the fit

Results





Measurement of ν events in the ROI from Phase I data

$R(^7\mathrm{Be})_{\mathrm{CID}} = 51.6^{+13.9}_{-12.5}$ cpd/100 t

$R(^7\mathrm{Be})_{\mathrm{Phase\ II}} = 48.3 \pm 1.1^{+0.4}_{-0.7}$ cpd/100 t

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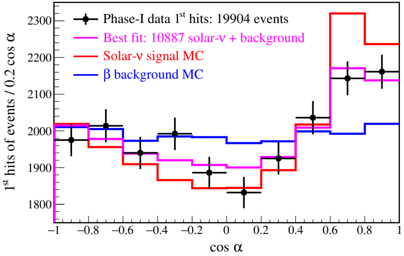

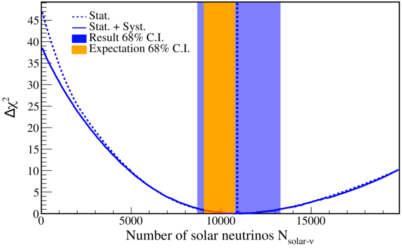

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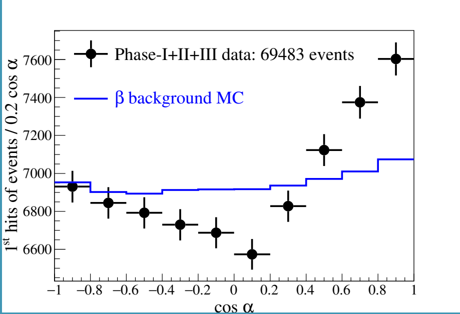
Hard to calibrate Čerenkov group velocity for Phase II and III

Use Phase I+II+III data to exclude the bkg only hypothesis

Significance $> 5\sigma$



Conclusions

Borexino last physics run: 10.07.2021

Complete investigation of the Solar neutrino spectrum

- Complete measurement of *pp*-chain
- **First evidence of CNO-cycle**

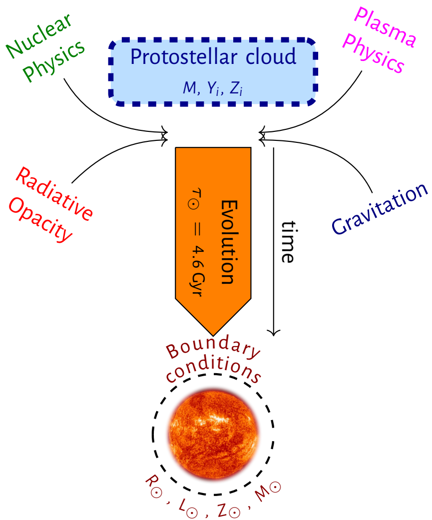
Fundamental results for testing the Standard Solar Model

First directional measurement of sub-MeV $\nu's$

- Proves that directional measurements are possible in LS
- Current LS experiment can readily implement CID
- Exiting prospects for next generation optical "hybrid" neutrino detectors

Thank you
for
your attention

The Standard Solar Model (SSM)



Input parameters

- Mass
- Hydrogen fraction X_i
- Helium fraction Y_i
- Metal fraction Z_i

Physical processes

- Gravitation
- Plasma Physics
- Nuclear Physics
- Radiative Opacity

Assumptions

- Hydrostatic equilibrium
- Energy produced *only* via *pp*-Chain and CNO cycle
- Energy is transported via conduction until $r < 0.71 R_\odot$, after that convection takes place

SSM Predictions

Complete snapshot of the Sun

- Helioseismology (sound speed profile)
- Solar Neutrino Fluxes

Solar neutrino test of the SSM - *pp*-chain

BX, Nature 562 (2018)

Luminosity

$$L_\odot^\nu = 4\pi\, \mathrm{au}^2 \sum_i \alpha_i \Phi_i$$

$$L_\odot^\nu = (3.89^{+0.35}_{-0.42}) \times 10^{33} \mathrm{erg\,s}^{-1}$$
$$L_\odot^\gamma = (3.846 \pm 0.015) \times 10^{33} \mathrm{erg\,s}^{-1}$$

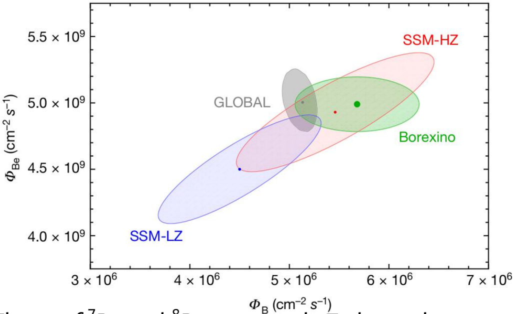
^{3}He-^{3}He / ^{3}He-^{4}He burning rate

Relative intensity of main *pp*-chain terminations

$$R_{I/II} = \frac{2\Phi(^7\mathrm{Be})}{\Phi(pp) - \Phi(^7\mathrm{Be})}$$

$$R_{I/II}^{BX} = 0.178^{+0.027}_{-0.023}$$
$$R_{I/II}^{B16\text{-}GS98} = 0.180 \pm 0.011$$
$$R_{I/II}^{B16\text{-}AGSS09m} = 0.161 \pm 0.010$$

Core temperature

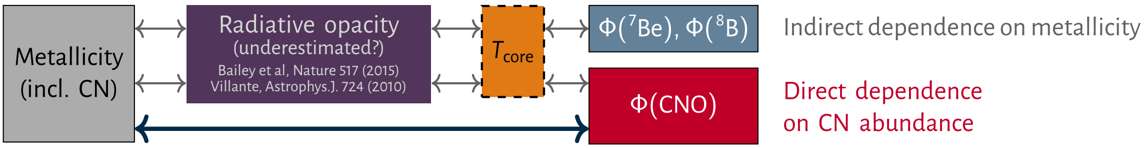


Fluxes of ^{7}Be and ^{8}B are strongly T_c dependent

$$\Phi(^7\mathrm{Be}) \propto S_{34} \cdot (S_{11}/S_{33}) \cdot T_c^{11}$$
$$\Phi(^8\mathrm{B}) \propto (S_{11}/S_{e7}) \cdot S_{34} \cdot (S_{11}/S_{33})^{1/2} \cdot T_c^{24}$$

Villate & Serenelli, Front.Astron.Space Sci. 7 (2021) 112

Solar neutrino test of the SSM - CNO-cycle



Use **^{8}B neutrino** measurement as a **thermometer**
to **fix core temperature** and **cancel** the effect of **temperature** from $\Phi(CNO)$

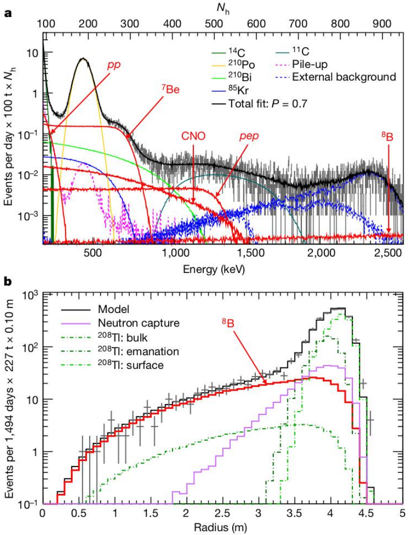
↪ **Access to CN abundance in the Sun core**

Haxton & Serenelli, Astrophys.J. 687.1 (2008)
Serenelli, Peña-Garay, Haxton, Phys.Rev.D 87(4) (2013)

↪ CN do not contribute much to the total opacity but can be used to test **crucial** SSM assumption

Measurement of *pp*-chain solar neutrinos with Borexino

BX Coll, Nature 562 (2018)



Low-Energy Region

[BX, Phys.Rev.D 100 (2019) 8]

Exposure: 1291.51 days $\times$ 71.3 t

Energy range: 0.19–2.93 MeV

Analysis: Simultaneous fit of ^{11}C-sub. and -tag. datasets (N_h, r, PS)

Constraints: ^{14}C, pileup, (CNO)

High-Energy Region

[BX, Phys.Rev.D 101 (2020) 6]

Exposure: 2062.4 days $\times$ 227.8 t

Energy range: HER-I 3.2–5.7 MeV + HER-II 5.7–16 MeV

Analysis: Radial events' distribution

Constraints: ^{208}Tl (internal), ^{214}Bi (internal)

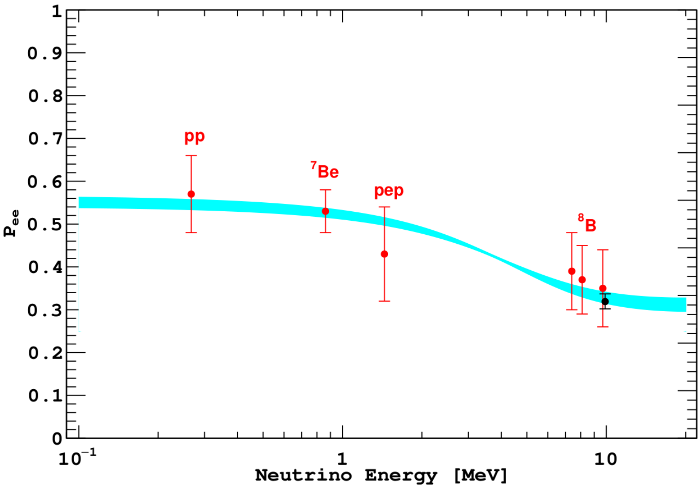
Measurement of *pp*-chain solar neutrinos with Borexino

BX Coll, Nature 562 (2018)

Solar-ν	Rate [cpd/100 t]	Flux [cm^{-2} s^{-1}]	Flux - SSM [cm^{-2} s^{-1}]
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1 \pm 0.006) \times 10^{10}$ [B16-GS98] $6.03(1 \pm 0.005) \times 10^{10}$ [B16-AGSS09met]
pep [HZ CNO] *pep* [LZ CNO]	$2.43 \pm 0.36^{+0.15}_{-0.22}$ $2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$ $(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ [B16-GS98] $1.46(1 \pm 0.009) \times 10^{8}$ [B16-AGSS09met]
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.0.8}) \times 10^{9}$	$4.93(1 \pm 0.06) \times 10^{9}$ [B16-GS98] $4.50(1 \pm 0.06) \times 10^{10}$ [B16-AGSS09met]
^{8}B	$0.223^{+0.015}_{-0.016}{}^{+0.4}_{-0.7}$	$(5.68^{+0.39}_{-0.41}{}^{+0.06}_{-0.0.8}) \times 10^{6}$	$5.46(1 \pm 0.12) \times 10^{6}$ [B16-GS98] $4.50(1 \pm 0.12) \times 10^{6}$ [B16-AGSS09met]

Solar neutrino survival probability

A. Ianni in PDG 2020
Neutrino masses, mixing, and Oscillation

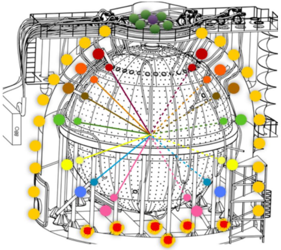


How to stop convective motions

D. Bravo–Berguño et al, NIM A 885 (2018)
arXiv:1712.05709 [physics.ins-det]

Understanding Borexino fluid dynamics

Temperature Monitoring System



Latitudinal Temperature Probe System
54 Temperature probes

Fluid dynamics simulation

Improve understanding of the detector fluid dynamics
V. di Marcello et al., NIM A 964 (2020)

Thermal Stabilization → **Fix temperature gradient**

Detector Insulation

Thermal Insulation System (TIS) Double layer of mineral wool (20 cm)

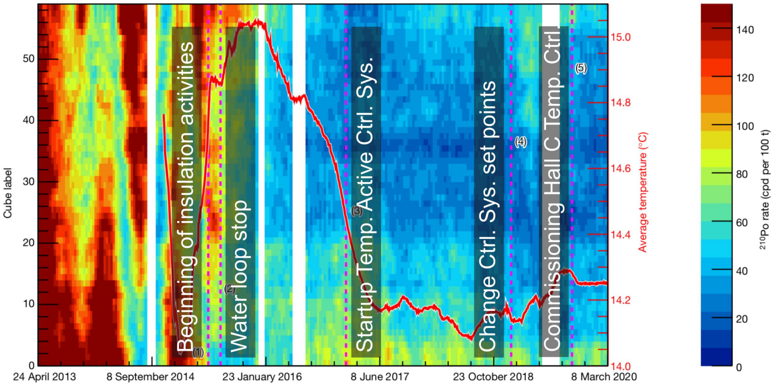
Active Gradient Stabilization System (AGSS)

controlled temperature water loop circuits
(uppermost dome "ring")

Hall C Temperature Stabilization

Effect on ^{210}Po spatial density

BX Coll, Nature 587 (2020)
arXiv:2006.15115 [hep-ex]

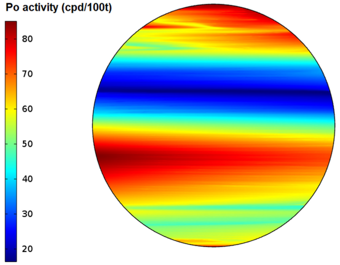


Stabilization measures have been extremely effective in reducing ^{210}Po motions

Low density Polonium Field

observed $\approx$ 80 cm north of equator

Remarkable agreement with Fluid dynamic simulations



V. di Marcello et al., NIM A 964 (2020)

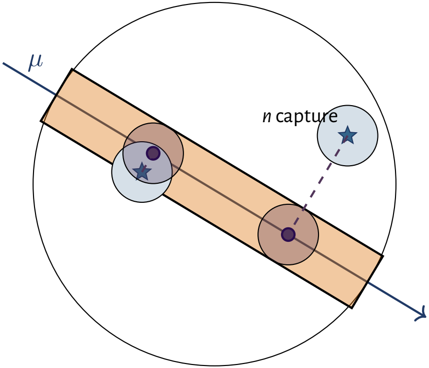
^{11}C suppression

BX Coll, arXiv:2106.10973 [hep-ex]

$$\mu + {}^{12}\mathrm{C} \rightarrow \mu + \boxed{{}^{11}\mathrm{C}} + \boxed{n}$$

n capture $\tau \approx 260\ \mu\mathrm{s}$
$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$

β^+ decay $\tau \approx 30$ min
${}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^+ + \nu_e$



Evaluate ^{11}C likelihood for each candidate based on:

- muon dE/dx
- n multiplicity
- distance from μ track
- distance from n vtx
- distance from n vtx projection on μ track