Vulcano Workshop 2022

FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

The *not-so-final* results of Borexino

Vulcano Workshop 2022

Frontier Objects in Astrophysics and Particle Physics

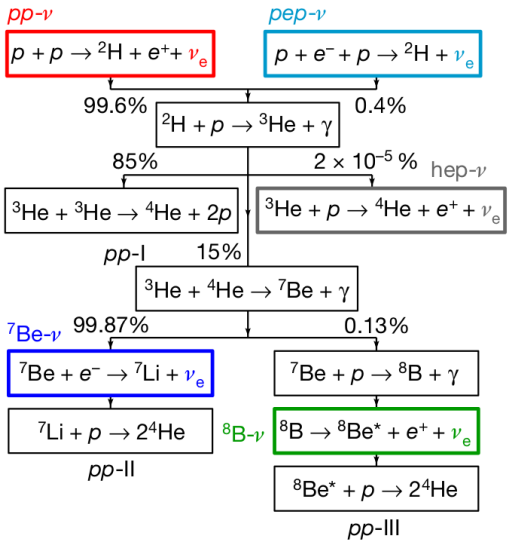
Elba Island – 25 Sept. – 1 Oct. 2022

Davide D'Angelo
for the Borexino collaboration
Università degli Studi di Milano
Istituto Nazionale di Fisica Nucleare

Solar neutrino production

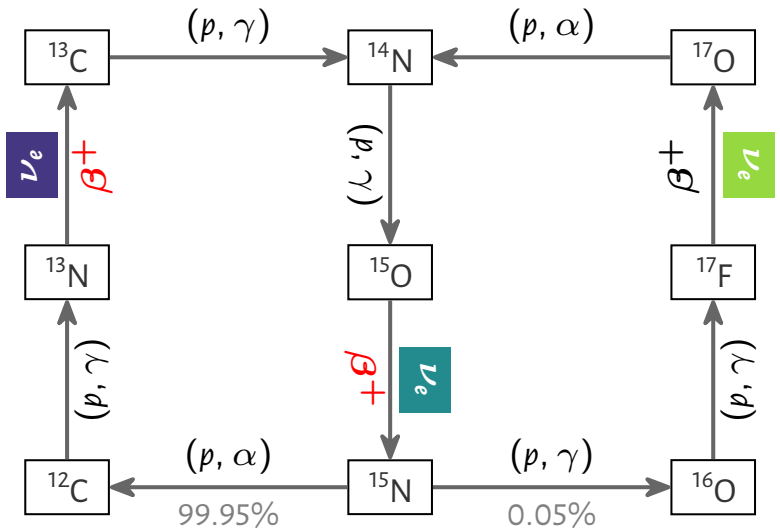
Nuclear fusion net reaction: $4H \rightarrow He + 2e^- + 2\nu_e$

pp – chain



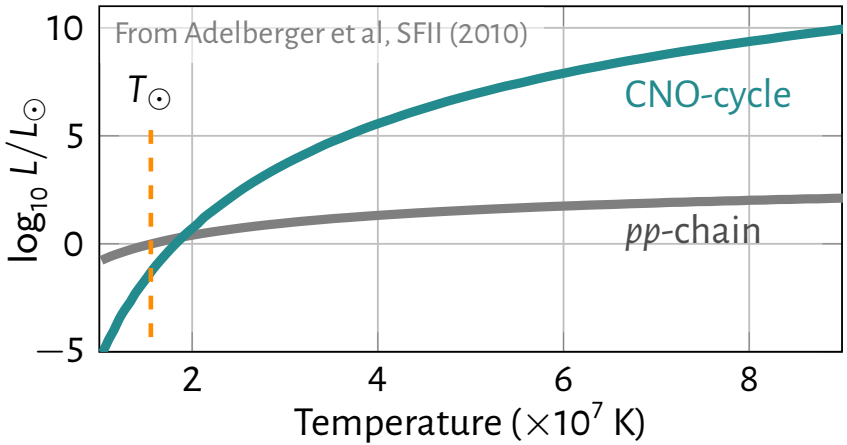
vs.

CNO cycle



Who wins this competition?

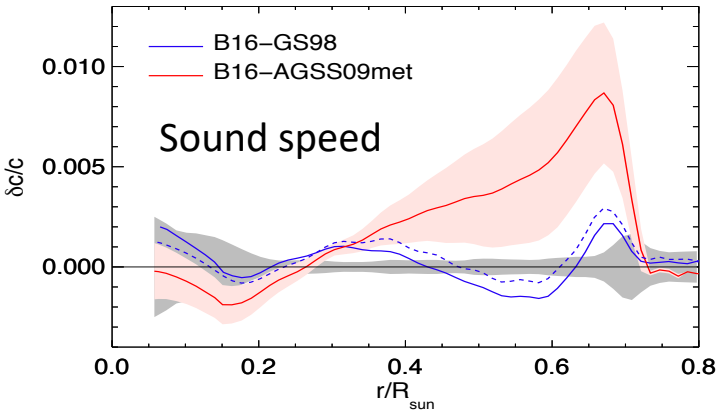
- It depends on the temperature and elemental abundance of the star
- In the Sun, the *pp*-chain does 99% of the job
  - CNO solar neutrinos are hard to spot and undetected (before Borexino)
- The CNO cycle becomes dominant above ~ 1.3 $M_\odot$



The Solar metallicity puzzle

Metallicity (Z): abundance of elements other than H, He

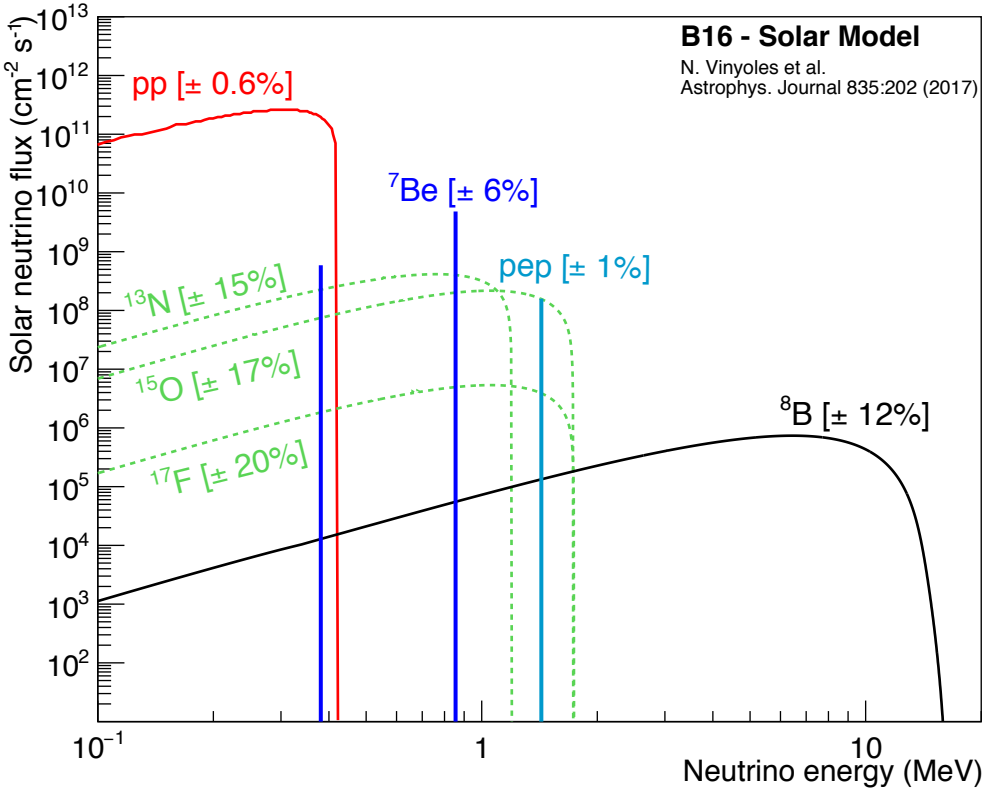
- Helioseismology is a great tool to prove solar models.
- Since 2005: a new 3D analysis of spectroscopic data from photosphere indicates lower values of solar metallicity (LZ) by ~20%.
- But solar models reproducing these new LZ values **disagree with helioseismology data.**



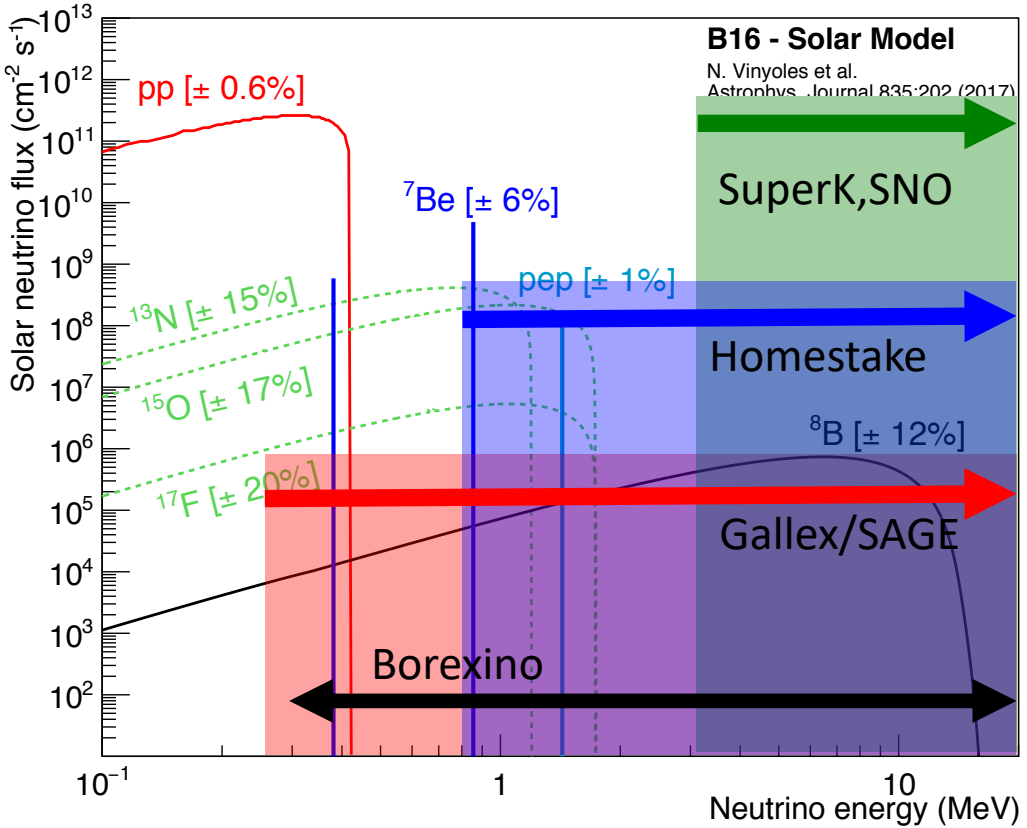
ν flux	GS98 (HZ)	AGSS09met (LZ)	$cm^{-2}\ s^{-1}$	Δ
pp	5.98 (1±0.006)	6.03 (1±0.005)	x 10^{10}	+0.8%
pep	1.44 (1±0.01)	1.46(1±0.009)	x 10^{8}	+1.4%
^{7}Be	4.93 (1±0.06)	4.50 (1±0.06)	x 10^{9}	-8.7%
^{8}B	5.46 (1±0.12)	4.50 (1±0.12)	x 10^{6}	-18%
^{13}N	2.78 (1±0.15)	2.04 (1±0.14)	x 10^{8}	-27%
^{15}O	2.05 (1±0.17)	1.44 (1±0.16)	x 10^{8}	-30%

CNO ν fluxes are the most sensitive to the Sun metallicity

Solar neutrino spectrum



Solar neutrino spectrum

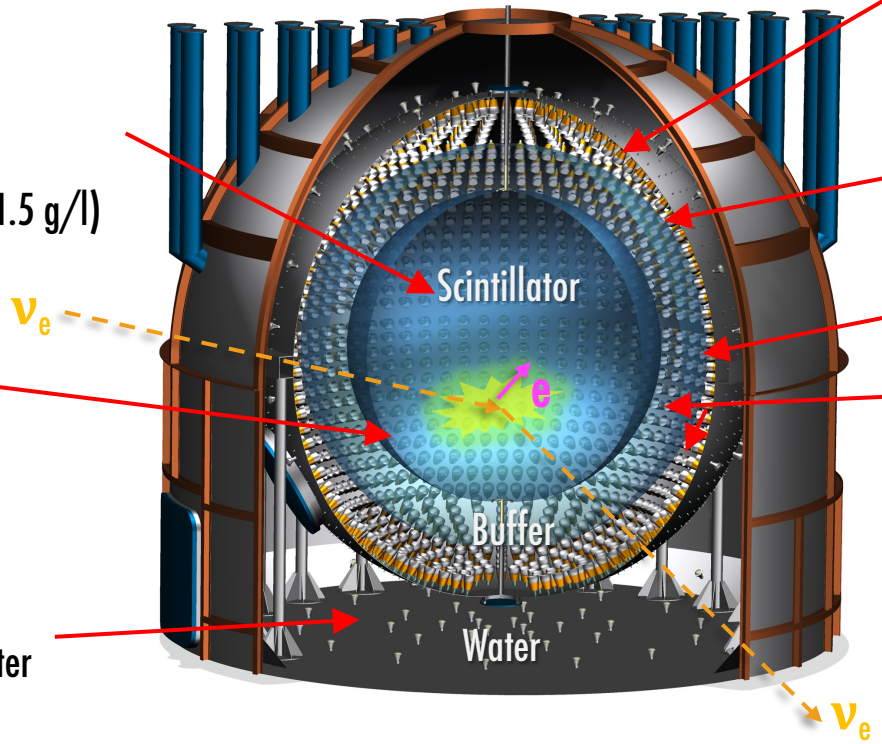


The Borexino detector

Target
300 ton liquid scintillator
Pseudocumene (PC)
+ wavelength shifter (PPO, 1.5 g/l)

Inner Vessel
Diameter: 8.5 m
125 μm thick nylon

Cherenkov muon veto
Diameter: 18 m
2000 ton ultra-pure water
208 PMTs



Stainless Steel Sphere
Diameter: 13.7 m
1300 m^3

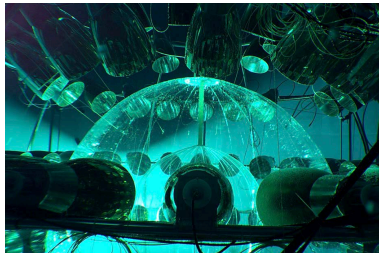
PMTs
2212 (nominal) x 8″
35% optical coverage

Radon barrier

Buffer fluid
PC + DMP (light quencher)

Unmatched radiopurity
< 9 x 10^{-19} g(Th)/g
<8 x 10^{-20} g(U)/g
(largely above design)

A success built over time



1988: First idea (Borex)

1991: Proposal

1994-2001: Counting Test Facility (CTF)

1996-97: approval

1999-2007: construction& commissioning

BOREXINO

at Gran Sasso

Proposal for a real time detector for low energy solar neutrinos

BOREXINO
GRAN SASSO
Volume 1
August 1991

P. Trincherini
C.C.R. Euratom, ISPRA, (VA) - Italy.

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S. Brambilla, M. Campanella, W. Cavalletti., P. D'Angelo,
M. di Corato, M. Giammarchi, D. Giove, D. Giugni, P. Inzani,
I. Iori, S. Malvezzi, L. Manduci, I. Manno, E. Meroni,
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Borexino data taking campaign (2007-2021)

Solar neutrinos

- ^{7}Be: 1st observation + Precise measurement ($\pm$5%)
- *pep*: 1st observation
- ^{8}B: low-threshold measurement
- CNO: best upper limit

+ Other studies …

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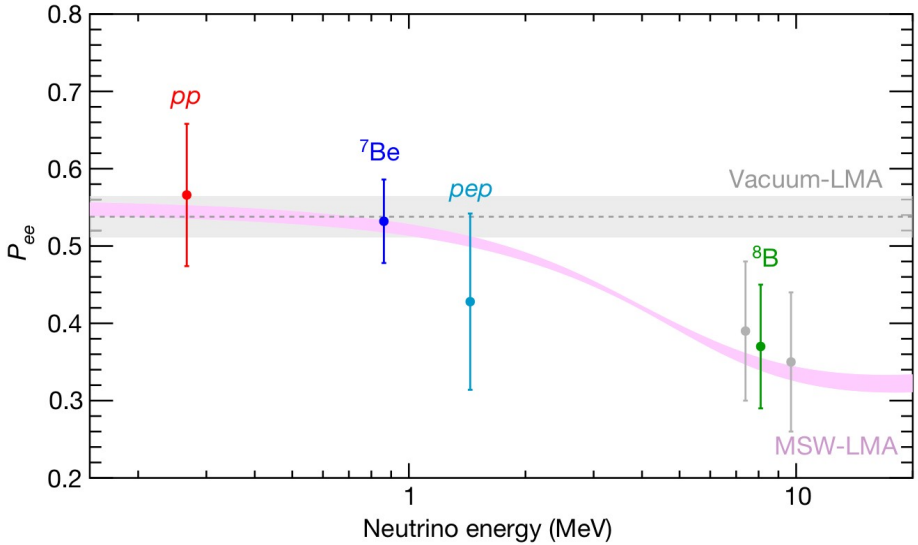
Solar neutrinos

- *pp*: 1st measurement
- ^{7}Be: Seasonal modulation
- Simultaneous meas. of low-*E* solar-ν (*pp*, *pep*, ^{7}Be, CNO limit)
- ^{8}B: improved low-thrs meas.

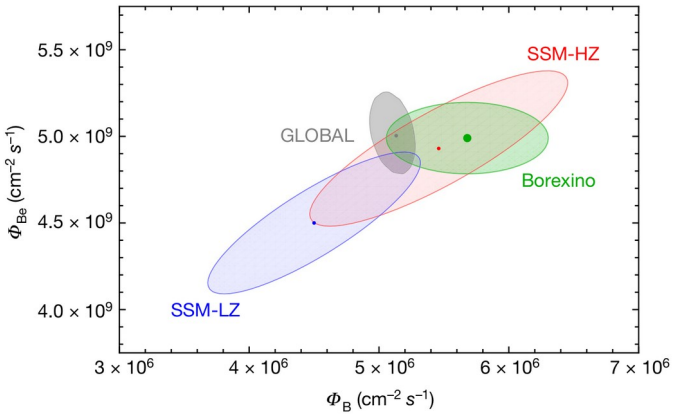
+ Other studies…

Phase-I and II results

Complete spectroscopy of the pp-chain



Still limited sensitivity to the Sun's metallicity



Fundamental test of the LMA-MSW oscillation mechanism

Borexino data taking campaign (2007-2021)

Solar neutrinos

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+ Other studies …

Solar neutrinos

- *pp*: 1st measurement
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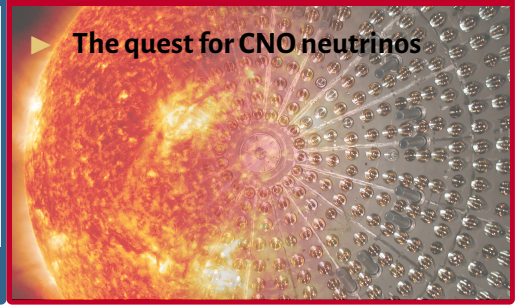
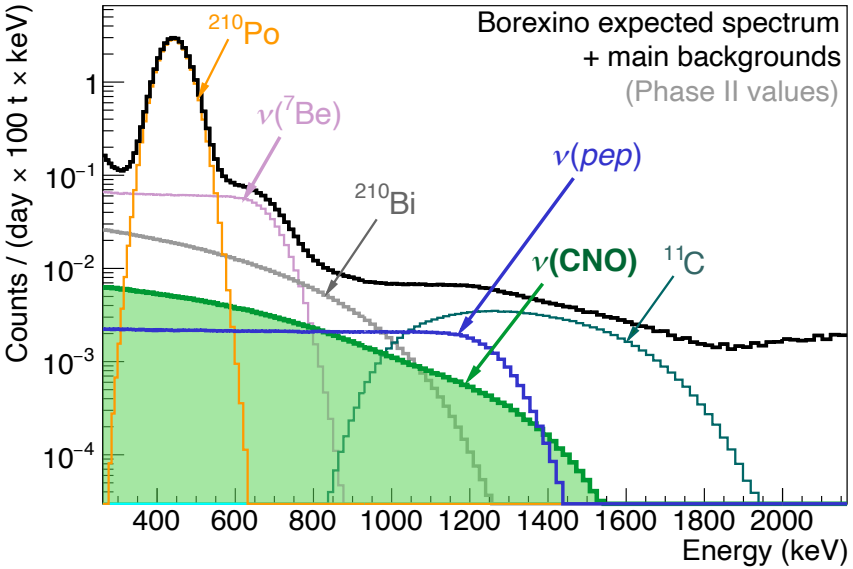
+ Other studies…

Solar neutrinos

- **The quest for CNO neutrinos**

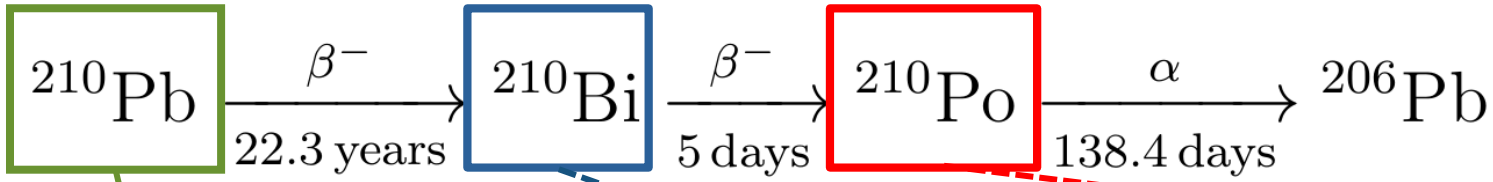


Challenges for the CNO-ν detection



- Borexino spectrum past data selection criteria
  - Including removal of ^{11}C cosmogenic background by Three-Fold Coincidence: EPJ C81 (2021) 1075
- Neutrino signals extracted by multivariate fit
- CNO rate only **3-5 ev/day/100t**
- CNO spectral shape almost degenerate with *pep* and ^{210}Bi decays:
  1. *pep* rate can be constrained to SSM predictions within 1.4%
  2. But what about ^{210}Bi?

Strategy for ^{210}Bi constraint



- 63 keV β^-: below analysis threshold
- Long-term supplier of ^{210}Bi

1160 keV β^- our big enemy!

Easily identified with PSD

Measuring ^{210}Po could allow to constraint ^{210}Bi

…

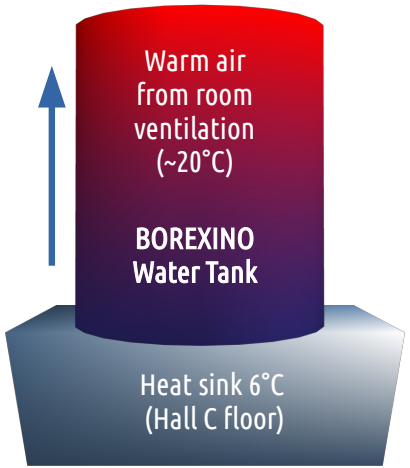
If only we had secular equilibrium!

Strategy for ^{210}Bi constraint

$$^{210}\mathrm{Pb} \xrightarrow[22.3\ \mathrm{years}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\ \mathrm{days}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\ \mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

- ^{210}Po contamination on the inner vessel
- Diffusion is very slow: ~ 10^{-9} m^2/s
- But we observed seasonal convective currents bringing ^{210}Po into the FV

How to prevent convection?

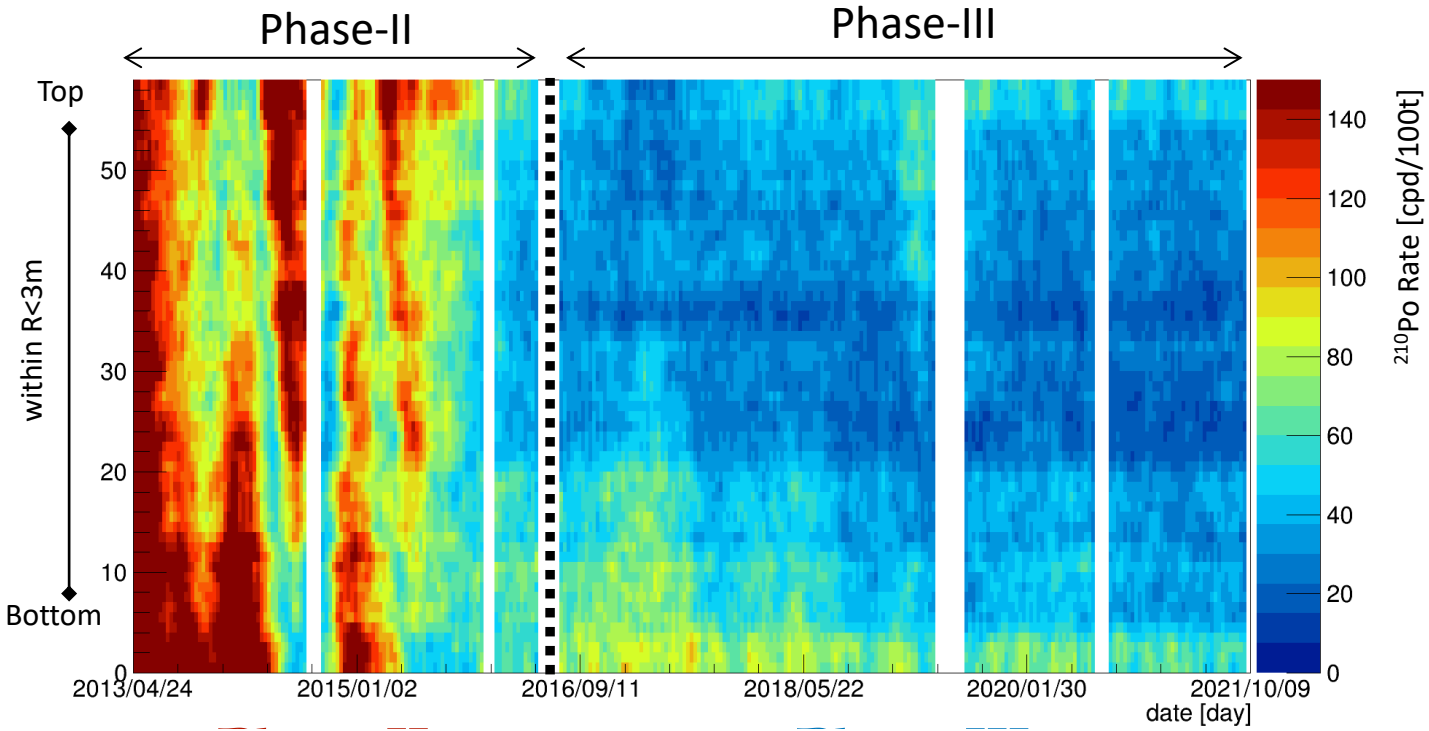


stable vertical temperature gradient

fluid stratification

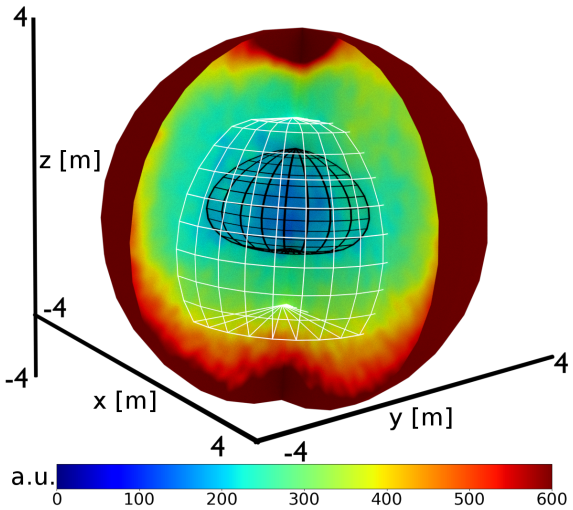
1. Insulation of the water tank (2015-16)
2. Active temperature control of the upper dome (2017)
3. Active temperature control of the Hall ventilation inlet (2019)

Effects of temperature control on ^{210}Po



Verified by a complete fluido-dynamics modelling. V. di Marcello et al., NIM A 964 (2020)

^{210}Bi constraints from *Low Polonium Field*



~ 20t "bubble" of scintillator, located ~80 cm above the center

We measure the ^{210}Po rate in the "bubble":

1. is this all supported by ^{210}Bi?
2. or is it partly due to residual convection?

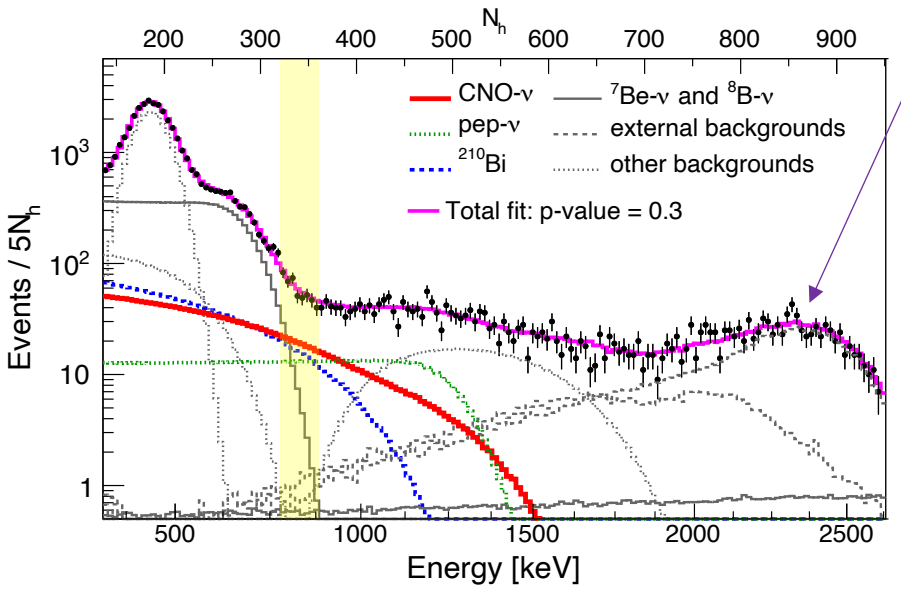
Therefore we set *only* an upper limit on ^{210}Bi

$$R(^{210}Bi) \leq R(^{210}Po)$$

Good! It implies a lower limit on CNO

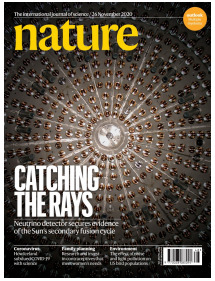
Nature 587, 577–582 (2020)

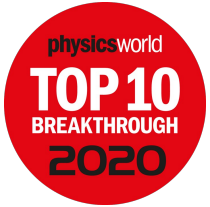
CNO fit results (2020)



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

- Multivariate Monte Carlo fit:
  - ^{11}C-subtracted energy spectrum
  - ^{11}C-enhanced energy spectrum
  - Radial profile
- *pep* rate: gaussian penalty at SSM prediction
- ^{210}Bi rate: semi-gaussian penalty at our upper limit (11.5 ± 1.3) cpd/100t
- Systematics from:
  - Fit configuration (binning, range)
  - Spectral shapes (^{11}C, ^{210}Bi)
  - Detector response (energy scale, non-uniformity, non-linearity)

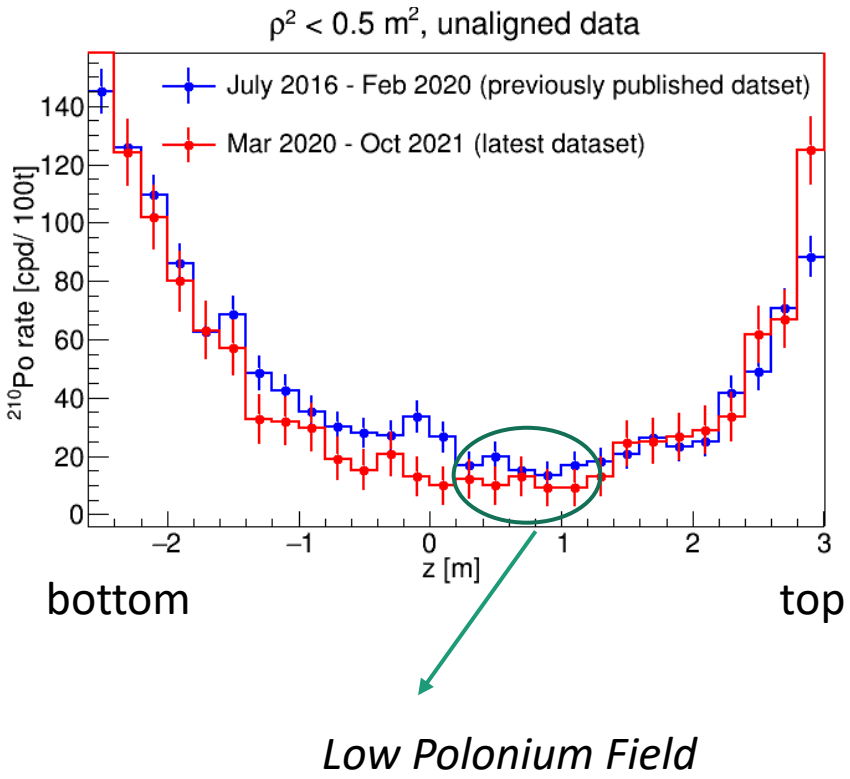




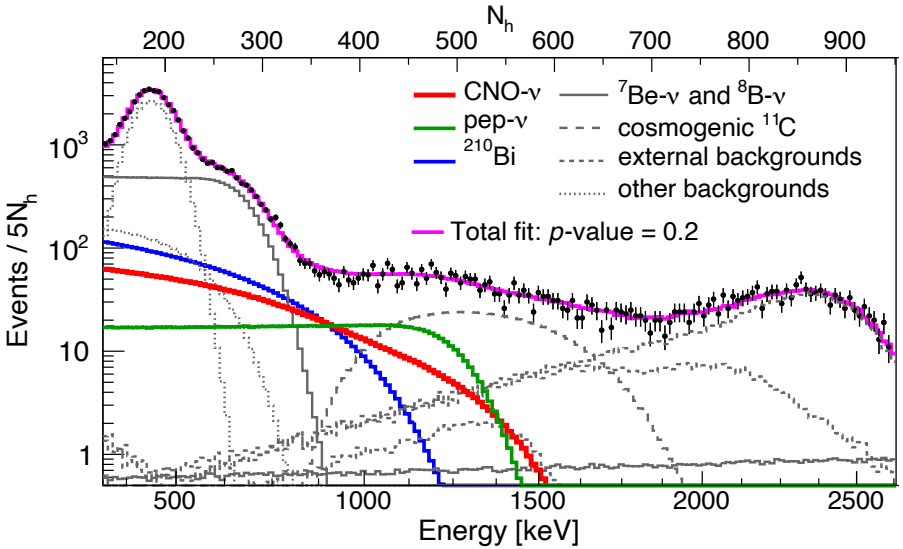
- No CNO hypothesis excluded at 5.0 σ
- Including other pp-chain fluxes from Borexino: LZ disfavoured at 2.1 σ

What's new?

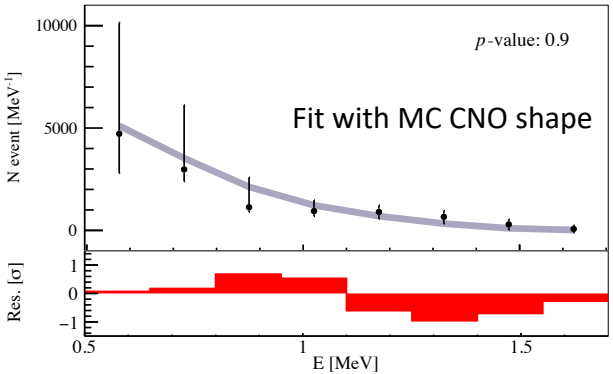
- Dataset:
  - removed ~ 7 month of 2016 (still high ^{210}Po)
  - added ~19 month Mar 2020 -> Oct 2021
  - Total exposure: + 33%
- Larger *Low Polonium Field* with less ^{210}Po
- More strigent upper limit:
  R(^{210}Bi) < (10.8 ± 1.0) cpd/100t



CNO fit results (2022)



Spectrum after subtracting
all non-CNO contributions



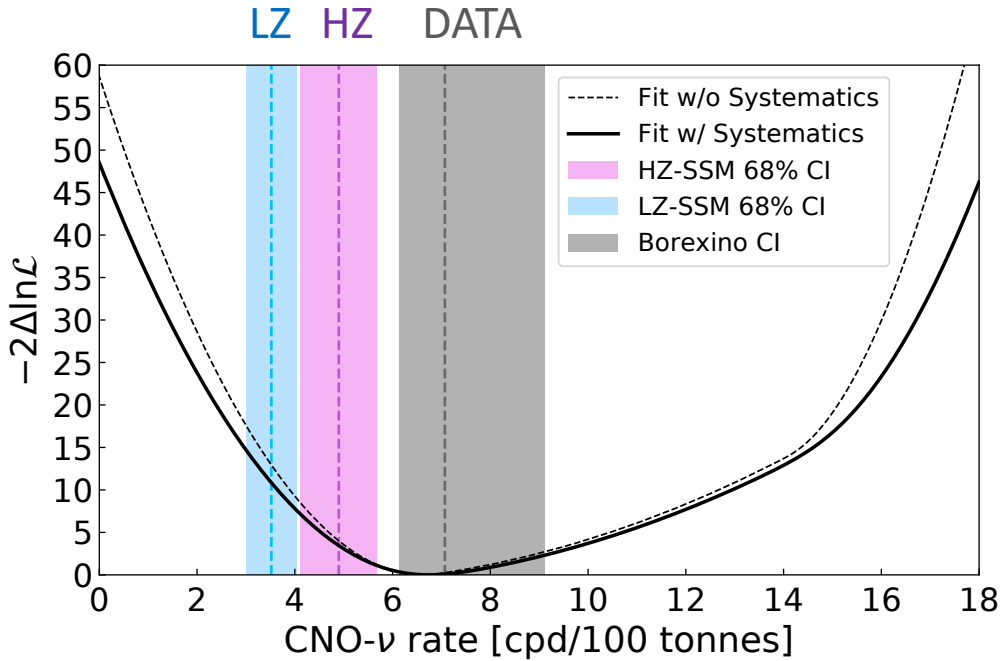
$$R_{CNO} = 6.7^{+2.0}_{-0.8}(stat)^{+0.5}_{-0.4}(sys)\ \text{cpd/100t}$$

arXiv:2205.15975
(subm. for publ. on Phys. Rev Lett.)

CNO fit results (2022)

$R_{CNO} = 6.7^{+2.0}_{-0.8}$ cpd/100 t

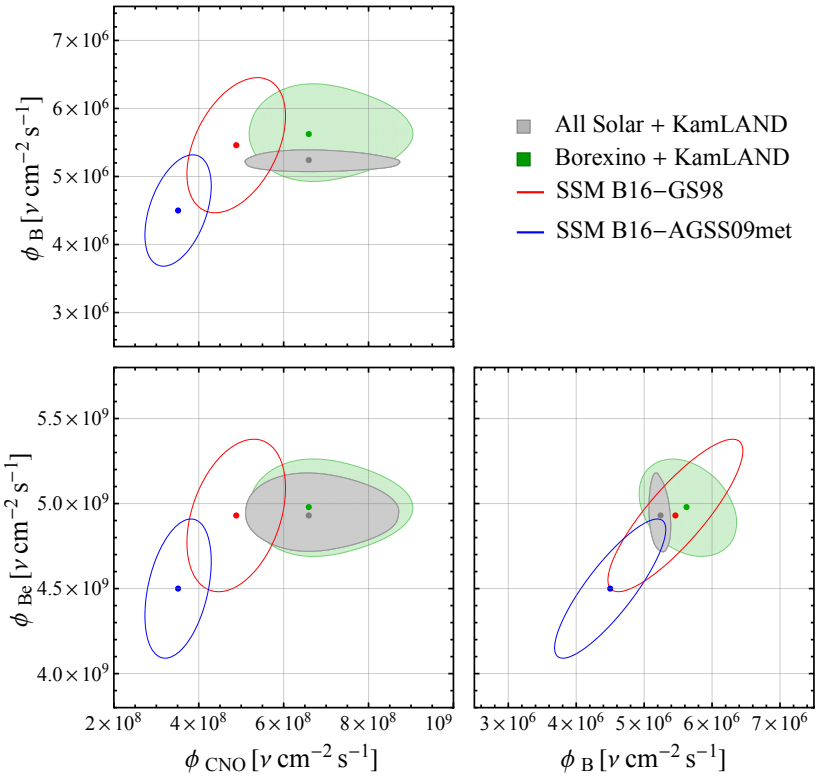
$\Phi_{CNO} = 6.6^{+2.0}_{-0.9} \times 10^{8}$ cm^{-2} s^{-1}



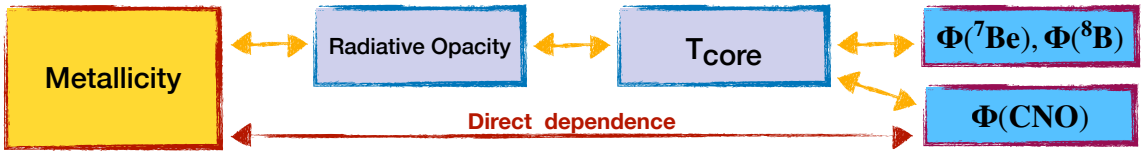
No-CNO hypothesis excluded at 7.0 σ

Implications for solar physics

- Global fit to all Borexino / all solar data (+ KamLAND)
- **Compatibility with the High-Z model**
- Tension with the Low-Z model
  - *Only* when CNO data are included!
  - p-value shifts 0.327 -> 0.028
- Assuming High-HZ, Borexino results (^{7}Be, ^{8}B, CNO) disfavour Low-Z model at ~3.1σ.



Determination of C+N abundance



$$\Phi_B/\Phi_B^{SSM} \propto (T_c/T_c^{SSM})^{\tau_B}$$ ← 24

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c^{SSM})^{\tau_O}$$ 20

From Borexino CNO measurement

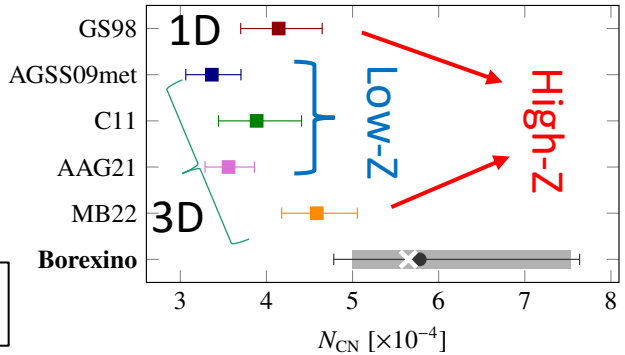
$$\frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{k}} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \left(\frac{T_c}{T_c^{SSM}}\right)^{\tau_O - k\tau_B}$$

from solar global analysis

choosing k appropriately minimizes dep. on T_C

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

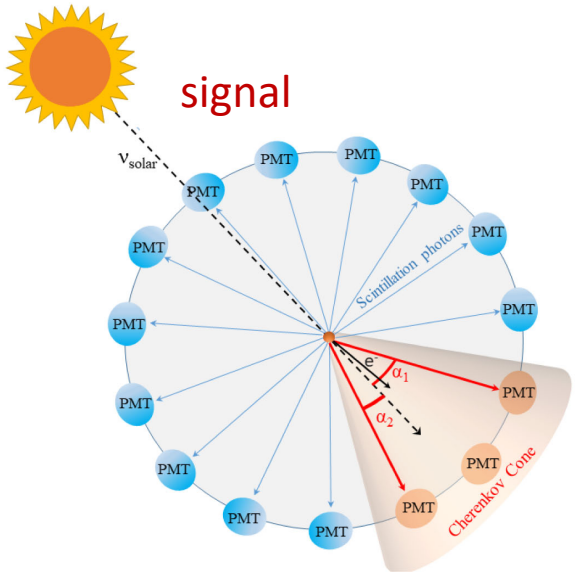
^{8}B flux used as thermometer of the Sun

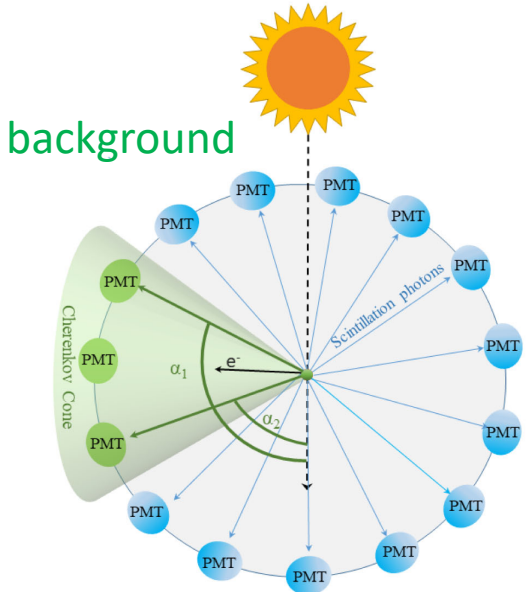


Directional measurement

Phys. Rev. Lett. 128 (2022) 091803
Phys. Rev. D 105 (2022) 052002

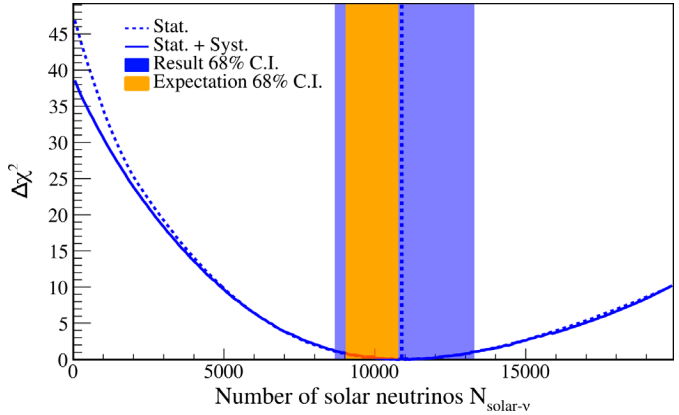
- *First* directional measurement of sub-MeV solar neutrinos in liquid scintillator.
- First two PMT hits in each event have a higher chance of being **Cherenkov** rather than scintillation
- For neutrino events they should correlate with the position of the Sun, unlike for background.





Directional measurement

- Focus on ^{7}Be energy region: [0.54, 074] MeV
- Using Phase-I data and enlarged FV (132t)

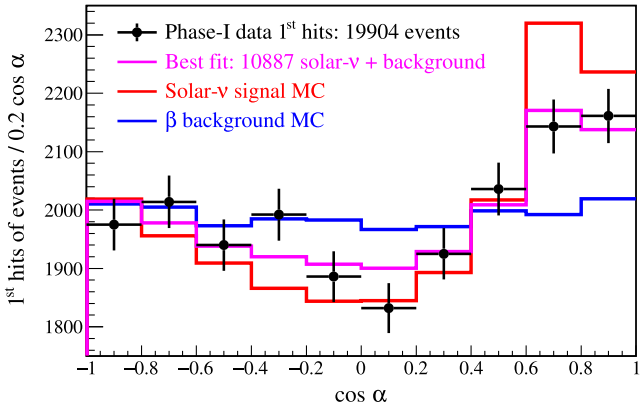


No neutrino hypothesis rejected at > 5σ

$$N_{\text{solar-}\nu} = 10887^{+2386}_{-2103}(\text{stat}) \pm 947(\text{syst})$$

$$R_{^{7}Be} = 51.6^{+13.9}_{-12.5}\text{cpd/100t}$$

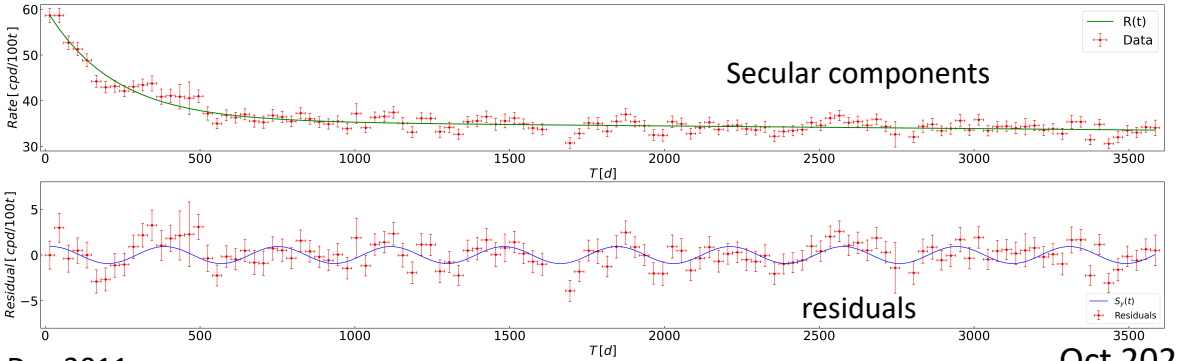
(in agreement with Phase-I measurement)



Peak expected at cos α ~ 0.7
(considering energy and ref. index)

Proof-of-Principle for future hybrid detectors

Earth's eccentricity by solar ν

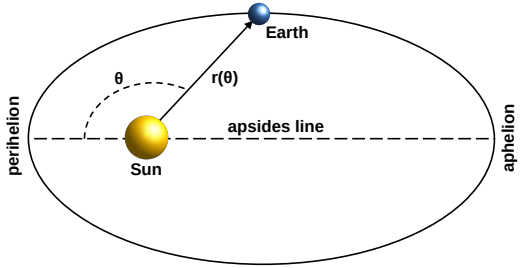


Dec 2011

Phase II + III

30d binning

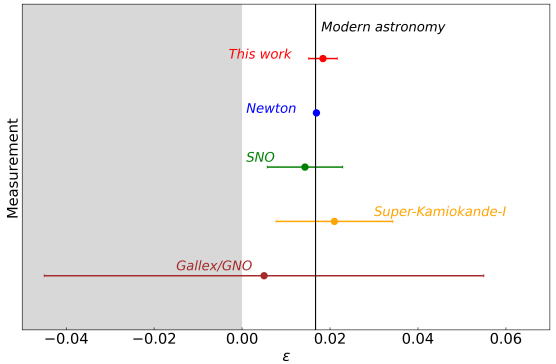
Oct 2021



$$\Phi(t) \approx \frac{\Phi_0}{\bar{r}^2}\left[1 + 2\epsilon\cos(\omega_y(t - t_0))\right] + \mathcal{O}(\epsilon^2)$$

[Lomb-Scargle analysis: no other significant modulation]

$$\varepsilon = 0.0184 \pm 0.0032\ (5.9\sigma)$$



Best result with solar ν

arXiv:2204.07029
accept. for publ. on Astropart. Phys.

Summary

- New 2022 result with full Phase-III data yield a 7 σ evidence of CNO neutrino observation
- Low metallicity models are disfavoured at 3.1 σ
- *First* directional solar neutrino neutrino measurement by Chrenkov radation in a liquid scintillator detector
- Best determination of the Earth's eccentricity by solar neutrinos

All Borexino solar ν results in one table

Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)_{-10}^{+6}$	$(6.1\pm0.5)_{-0.5}^{+0.3}\times10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)_{0.7}^{+0.4}$	$(4.99\pm0.11)_{-0.08}^{+0.06}\times10^{9}$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ]	$(1.27\pm0.19)_{-0.12}^{+0.08}\times10^{8}$[HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}\times10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8\times10^{5}$ (90% CL)
CNO	**arXiv 2022**	$6.7_{-0.8}^{+2.0}$	$6.6_{-0.9}^{+2.0}\times10^{8}$

- Borexino was a unique detector with an unmatched radiopurity
- It has performed the **full solar neutrino spectroscopy** with a single experiment
- Data taking ended in Oct 2021 …
- … but data analysis is still ongoing: Stay tuned!

This has been a wonderful ride

Thank you!

European Physical Society
PRIZE

The 2021 Giuseppe and Vanna Cocconi Prize
for an outstanding contribution to Particle Astrophysics and Cosmology
is awarded to the
Borexino Collaboration
for their ground-breaking observation of solar neutrinos from the pp chain and CNO cycle that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.

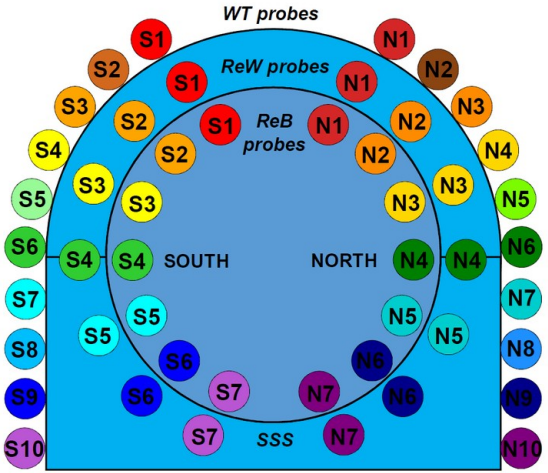
Luc Bergé
President
European Physical Society

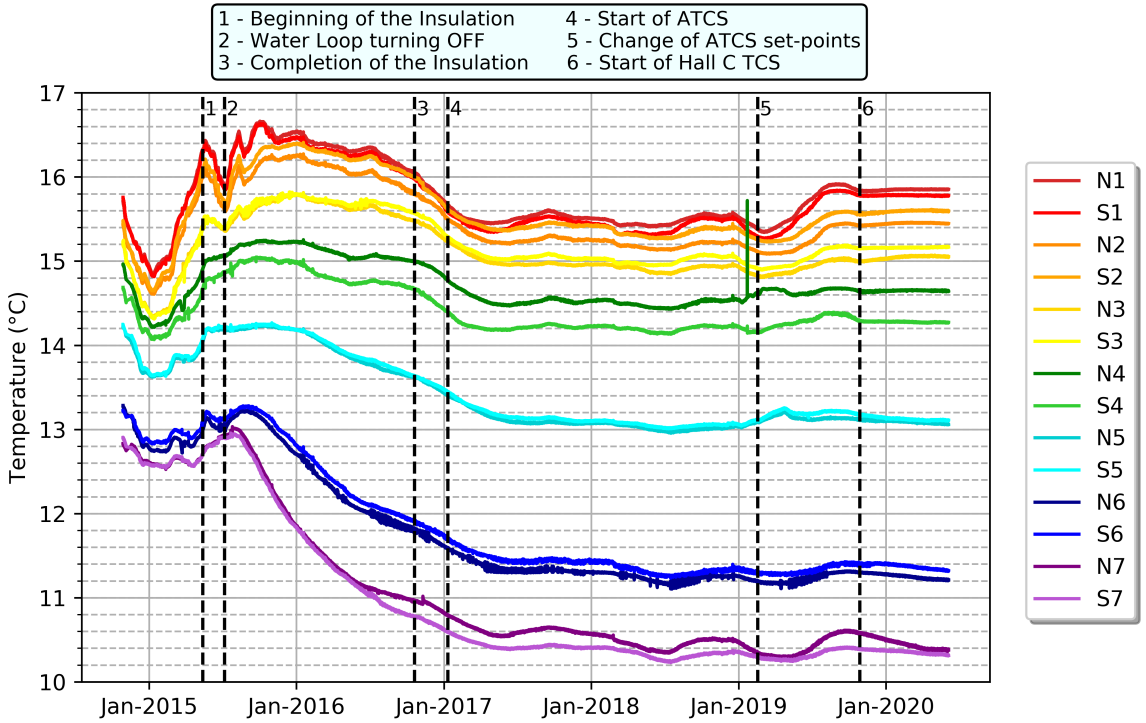
Thomas Gehrmann
Chair
EPS High Energy and Particle Physics Division

Mulhouse, France, 26 July 2021

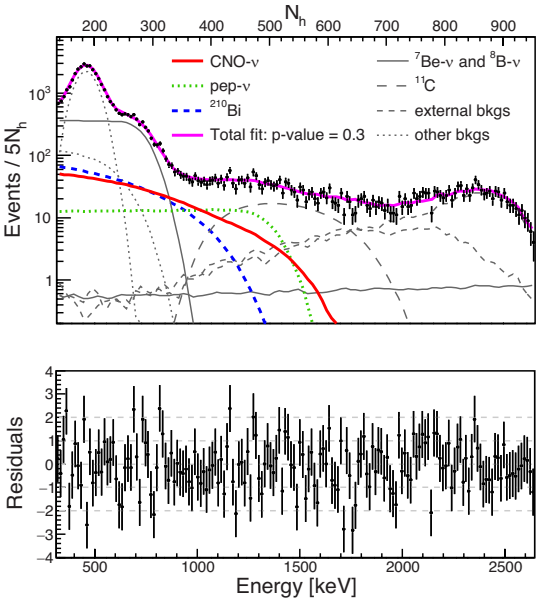
Backup

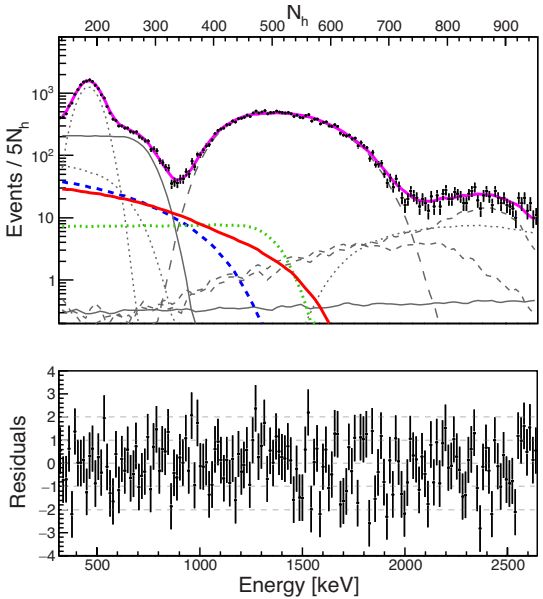
Temperature stabilization

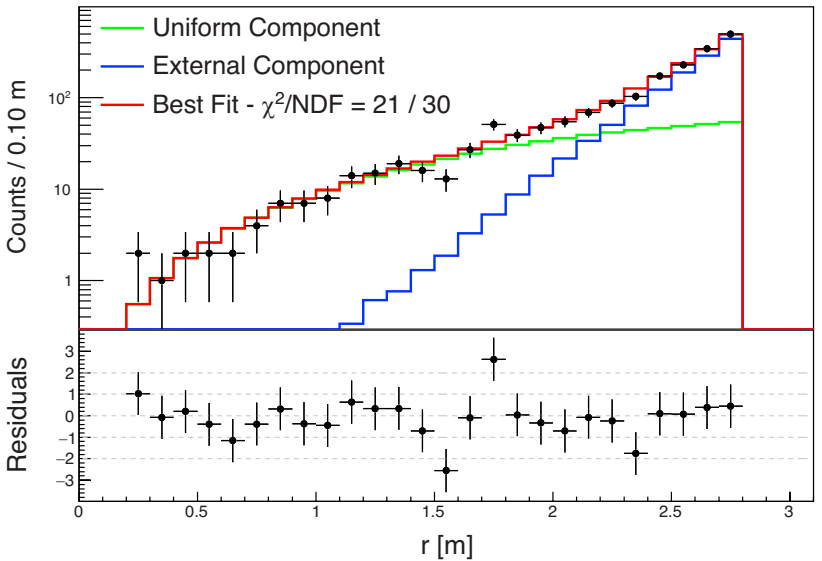




Multivariate fit





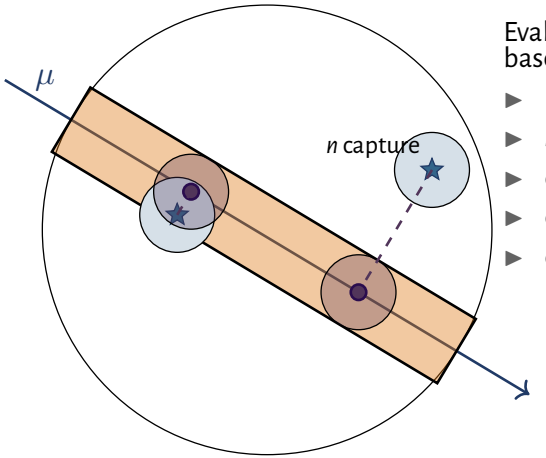


Three-fold Coincidence

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

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

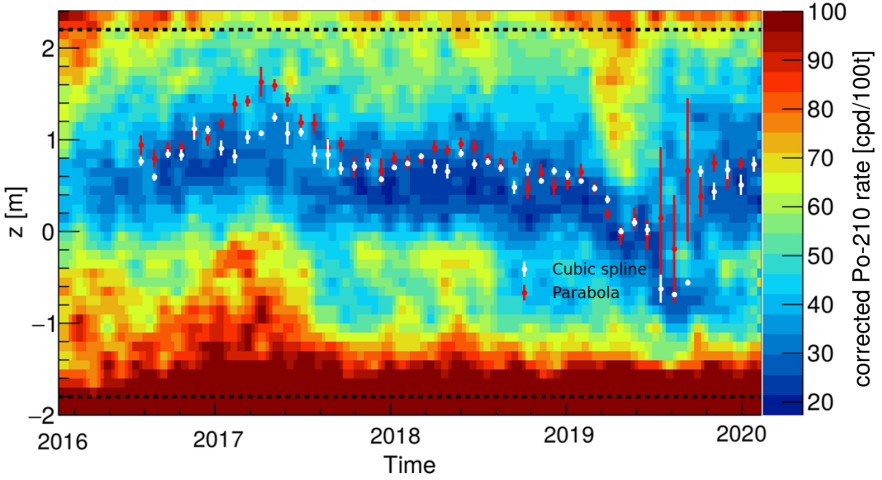
β^+ decay $\tau \approx 30$ min
${}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^+ + \nu_e$



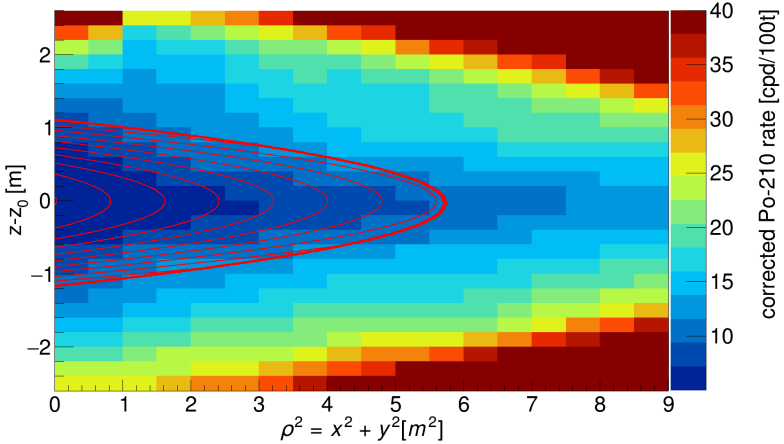
Evaluate ^{11}C likelihood for each candidate based on:

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

Low Polonium Field analysis

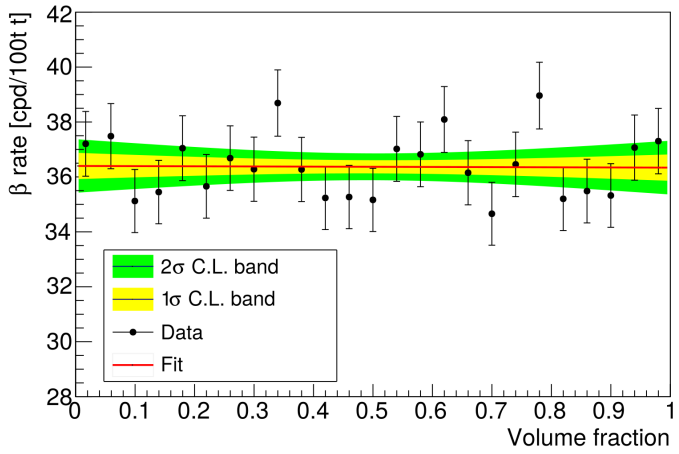


- 3D paraboloidal fit of the “bubble” in 2 months binning
- Alignment of the z position



^{210}Bi spatial uniformity

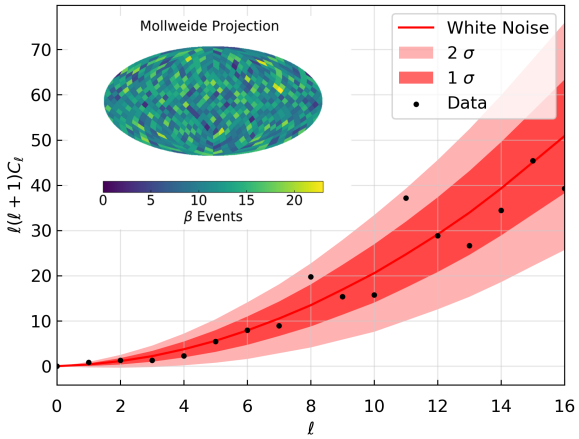
Radial distribution



Radial shell analysis

$\sigma^{sys}(\mathrm{rad}) = 0.51\ \mathrm{cpd/100\ t}$

Angular distribution



Spherical Harmonic decomposition

$\sigma^{sys}(\mathrm{ang}) = 0.59\ \mathrm{cpd/100\ t}$

Systematics

Fit cfg.

Negligible

^{11}C spectrum

Deformation induced by noise cuts

^{210}Bi spectrum

Different references for β-spectrum (diff.$\approx$ 18%)

Detector response

Vary detector response parameters within range allowed by calibration

- Energy scale (0.23%)
- non-uniformity (0.28%)
- non-linearity (0.4%)