Discovery of solar neutrinos from the CNO fusion cycle within the Sun by the Borexino experiment

PANIC

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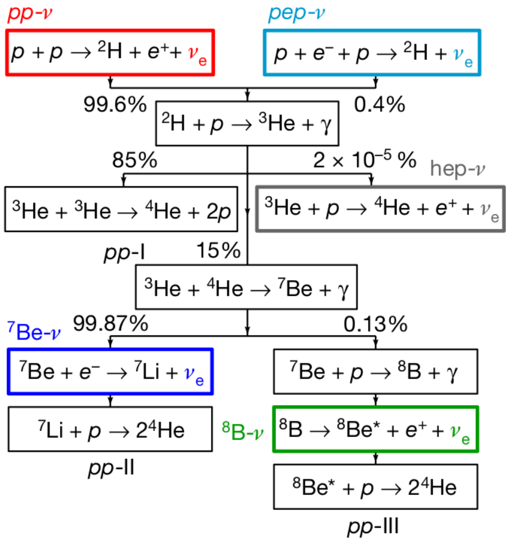
Solar neutrino producion

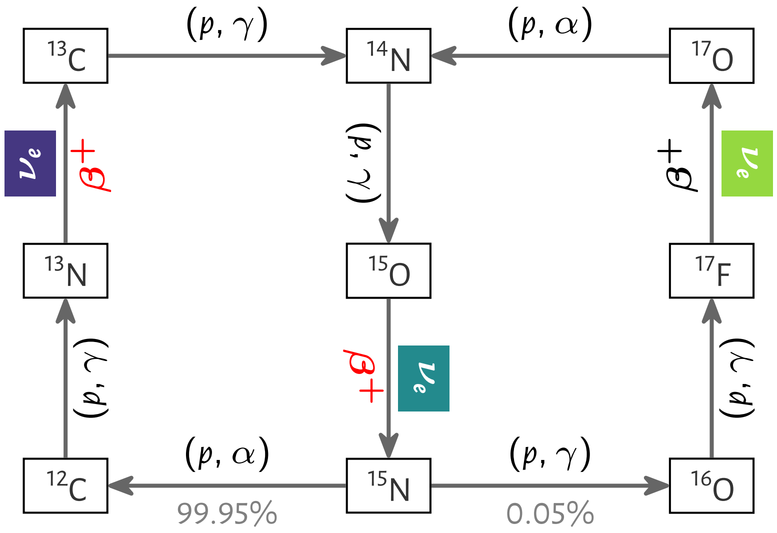
- Nuclear fusion net reaction: $4H \rightarrow He + 2e^- + 2\nu$

pp – chain



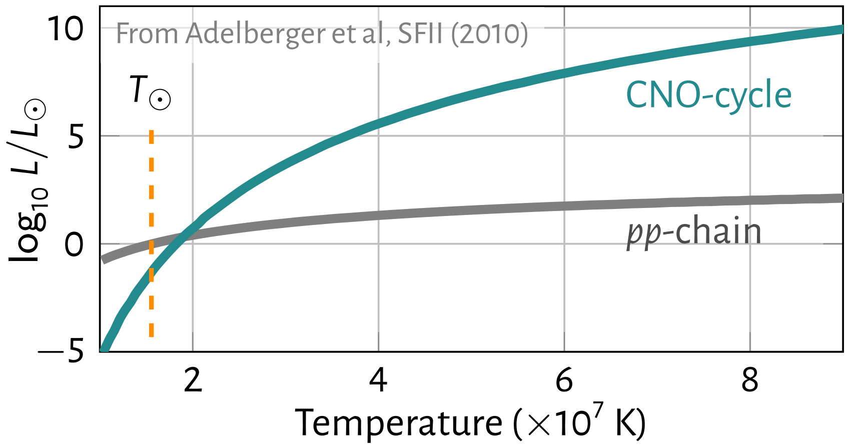
vs.

CNO cycle



Who wins this competition?

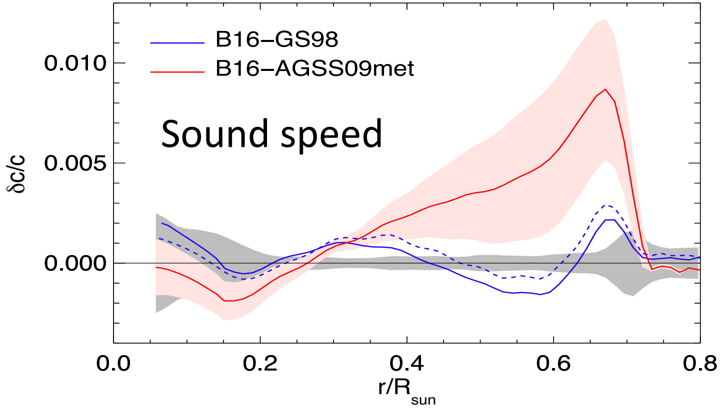
- It depends on the temperature and elemental abundance of the star
- In the Sun, the *pp*-chain does 99% of the job
  - CNO solar neutrinos are hard to spot and so far undetected
- The CNO cycle becomes dominat above ~ 1.3 $M_\odot$



The Solar metallicity puzzle

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

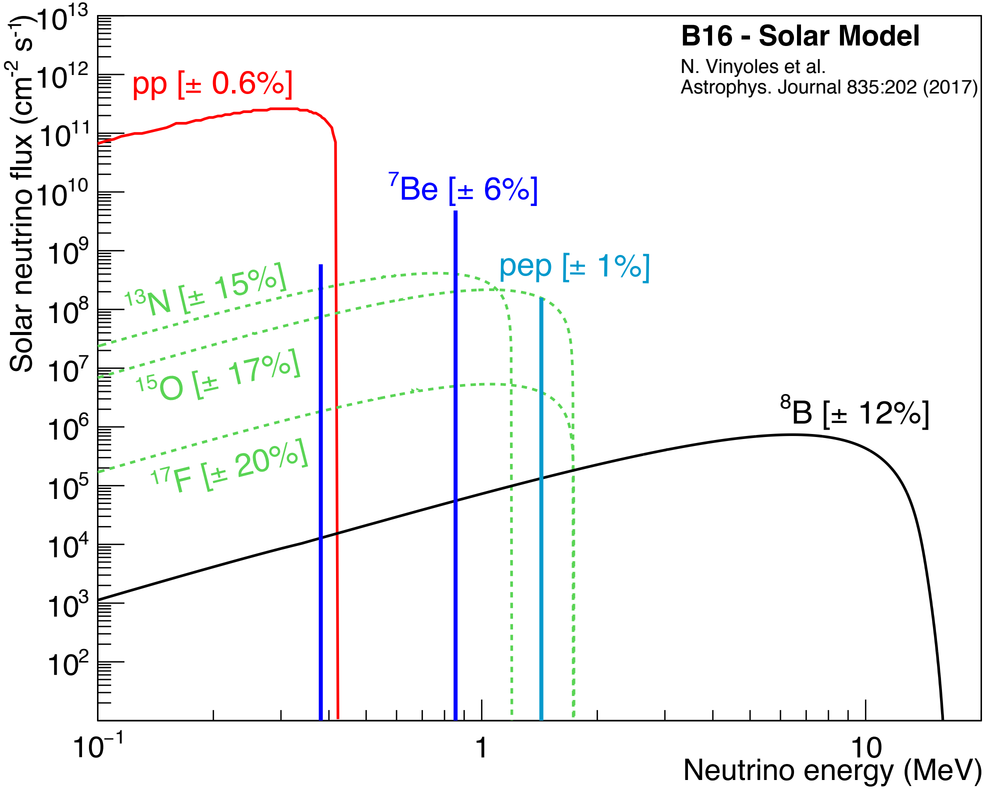
- Helioseismology is a great tool to prove solar models.
- Since 2005: a new 3D analysis of spectroscopic data from photosphere indicates lower values of solar metallicity (LZ) by ~20%.
- But solar models reproducing these new LZ values **disagree with helioseismology data.**



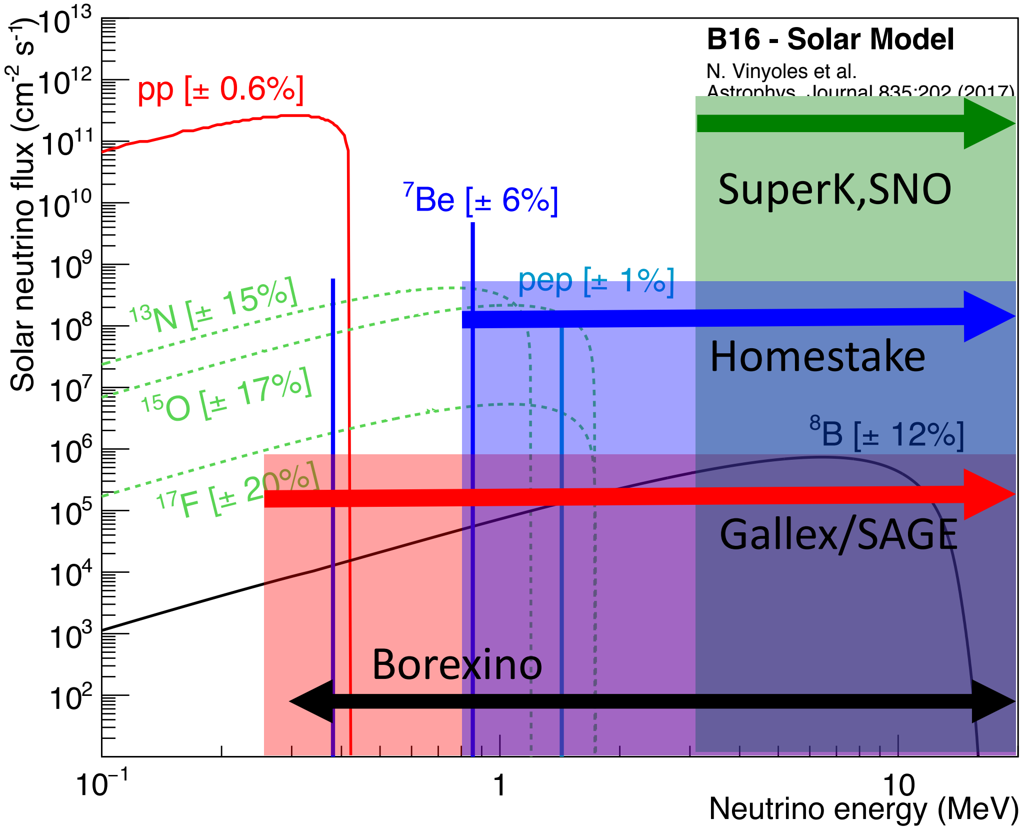
ν flux	GS98 (HZ)	AGSS09met (LZ)	$cm^{-2}\ s^{-1}$	Δ
pp	5.98 (1±0.006)	6.03 (1±0.005)	x 10^{10}	+0.8%
pep	1.44 (1±0.01)	1.46(1±0.009)	x 10^{8}	+1.4%
^{7}Be	4.93 (1±0.06)	4.50 (1±0.06)	x 10^{9}	-8.7%
^{8}B	5.46 (1±0.12)	4.50 (1±0.12)	x 10^{6}	-18%
^{13}N	2.78 (1±0.15)	2.04 (1±0.14)	x 10^{8}	-27%
^{15}O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

<u>CNO ν fluxes are the most sensitive to the Sun metallicity</u>

Solar neutrino spectrum



Solar neutrino spectrum

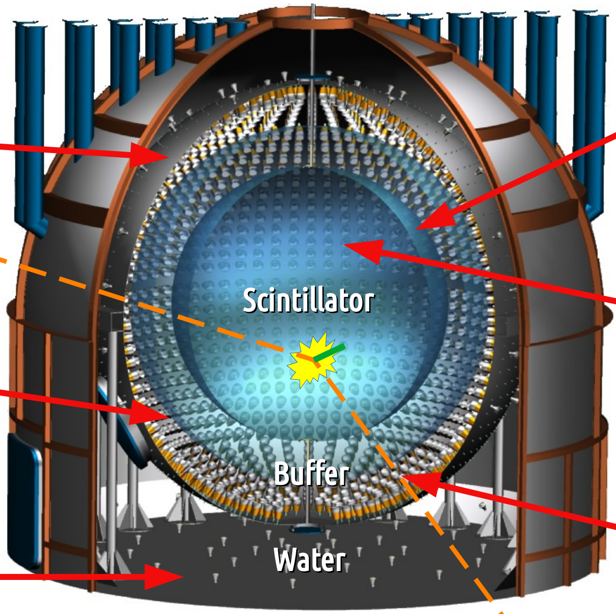


The Borexino detector

Stainless steal sphere
13.7 m of diameter, 1300 m^3 of pseudocumene

Nylon outer vessel
PC+DMP

Water Cherenkov veto
208 PMTs, diameter 18m, 2000 m^3 of water



Nylon vessell
125 µm of radioupure nylon

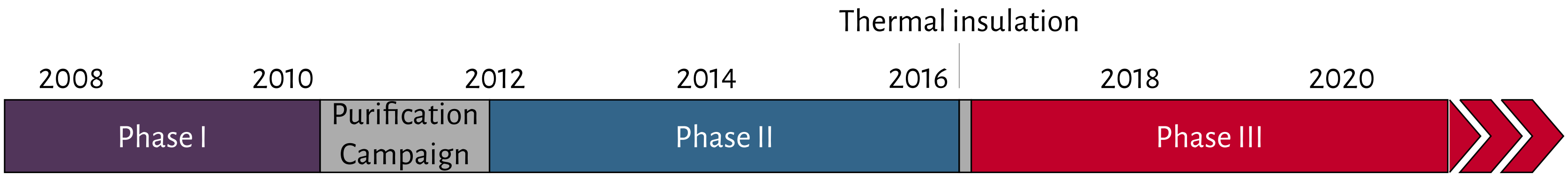
Inner vessel
target: 300 ton of scintillator PC+PPO

Internal PMTs
2212 (nominal), 8”, 35% optical coverage

Detection principle :

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Borexino data taking campaign

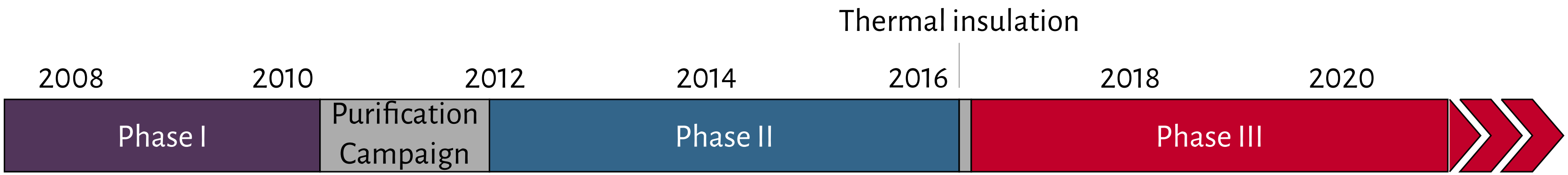


Solar neutrinos

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

+ Other studies …

Borexino data taking campaign



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Solar neutrinos

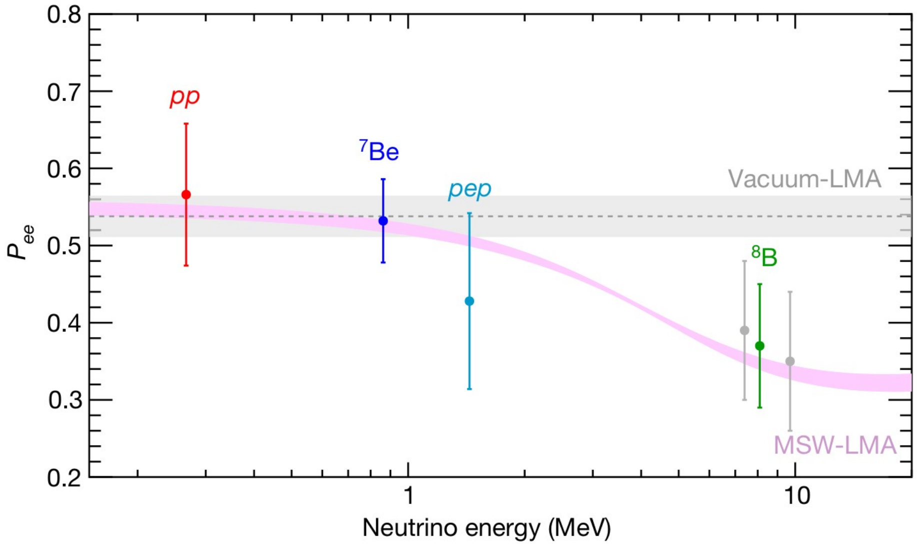
- *pp*: 1st measurement
- ^{7}Be: Seasonal modulation
- Simultaneous meas. of low-E solar-ν (*pp*, *pep*, ^{7}Be, CNO limit)
- ^{8}B: improved low-thrs meas.

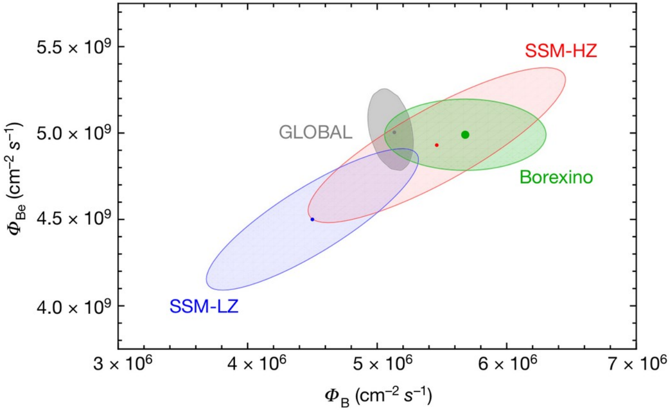
\+ Other studies...

Phase-I and II results

Borexino has slight preference for HZ model, but global analyis much less

Complete spectroscopy of the pp-chain





Fundamental test of the LMA-MSW oscillation mechanism
(e.g. see S.K. Agarwalla et al., JHEP 38, 2020 for limits on NSI)

Limited sensitivity to the Sun's metallicity

Borexino data taking campaign

Thermal insulation

2008	2010	2012	2014	2016	2018	2020

Phase I | Purification Campaign | Phase II | Phase III

Solar neutrinos (Phase I)

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

+ Other studies . . .

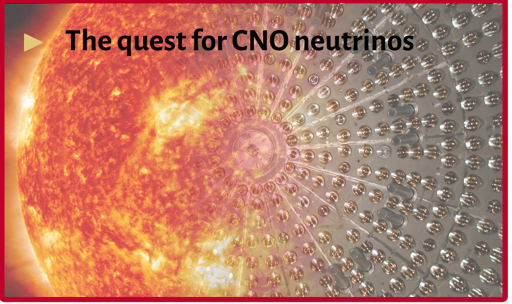
Solar neutrinos (Phase II)

- *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.

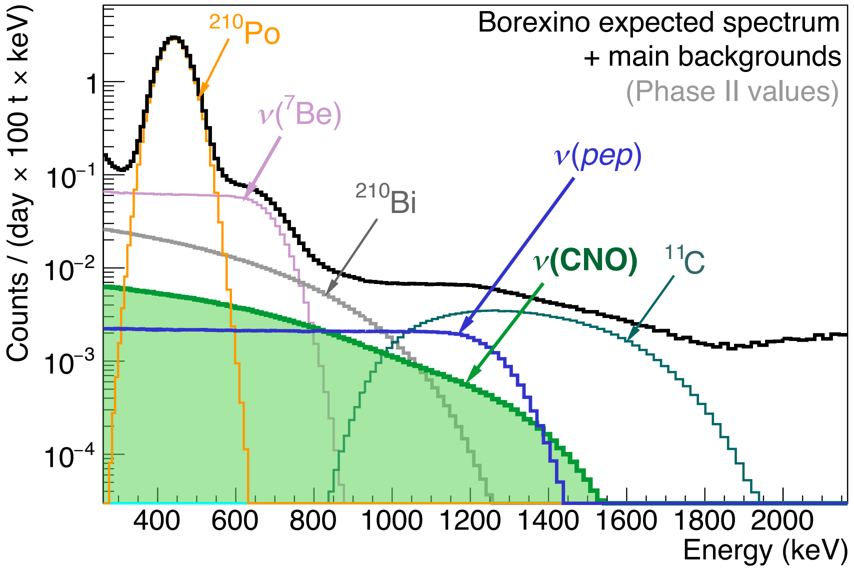
+ Other studies. . .

Solar neutrinos (Phase III)

- **The quest for CNO neutrinos**

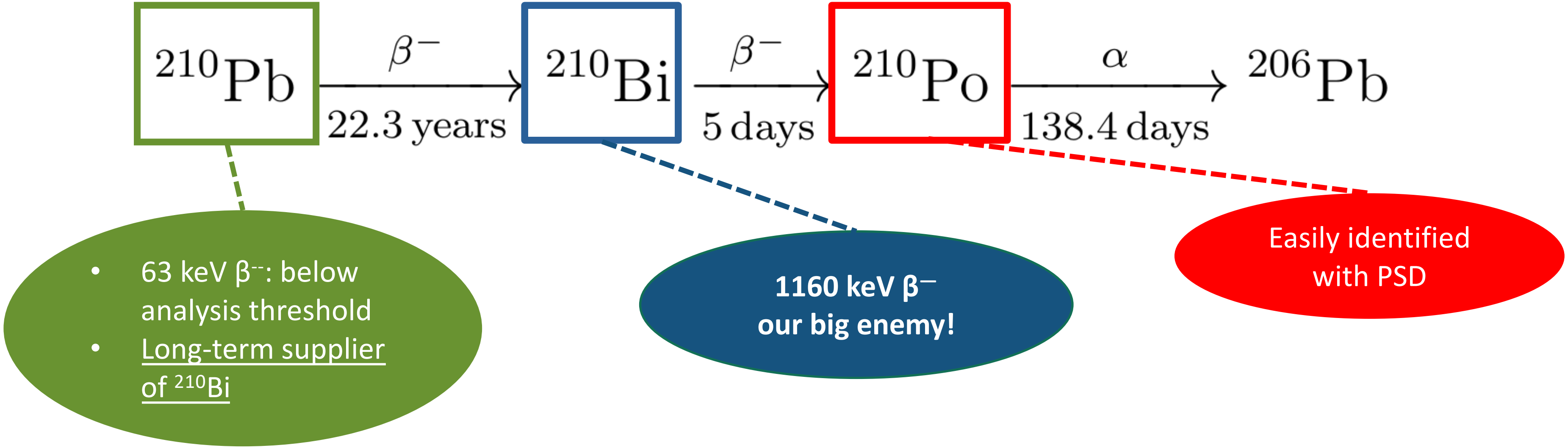


Challenges for the CNO-ν detection



- Borexino spectrum past data selection criteria
  - Including removal of ^{11}C cosmogenic background by Three-Fold Coincidence (arXiv:2106.10973)
- 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* flux can be constrained to SSM predictions witin 1.4%
  2. But what about ^{210}Bi?

Strategy for ^{210}Bi constraint



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

…

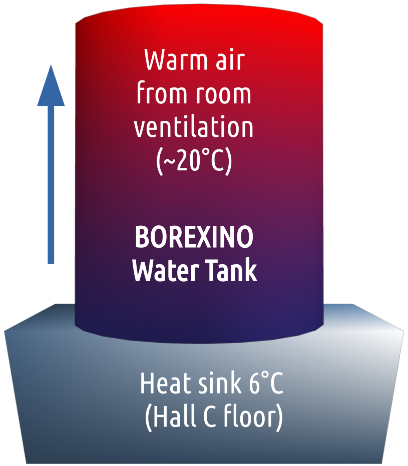
If only we had secular exquilibrium!

Strategy for ^{210}Bi constraint

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

- ^{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

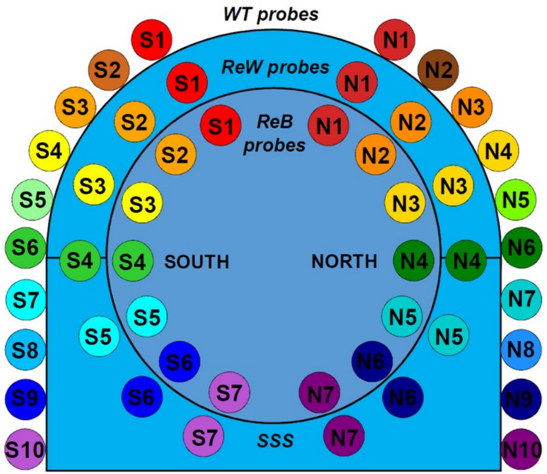
How to prevent convection?

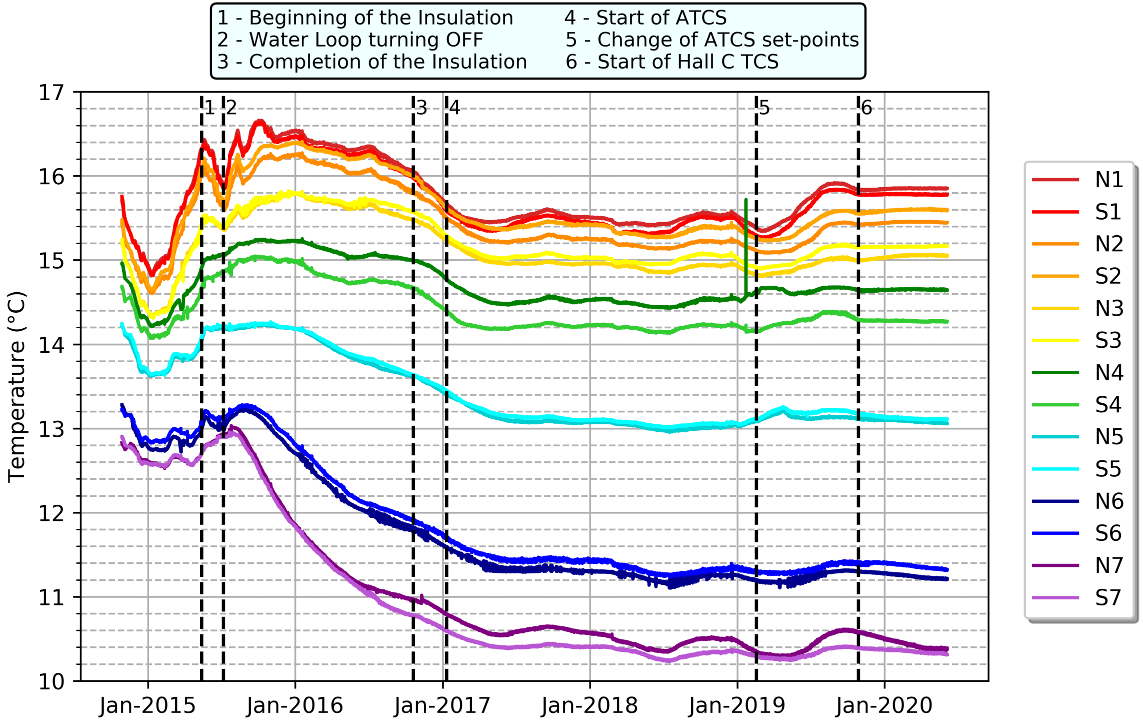


stable vertical temperature gradient → fluid stratification

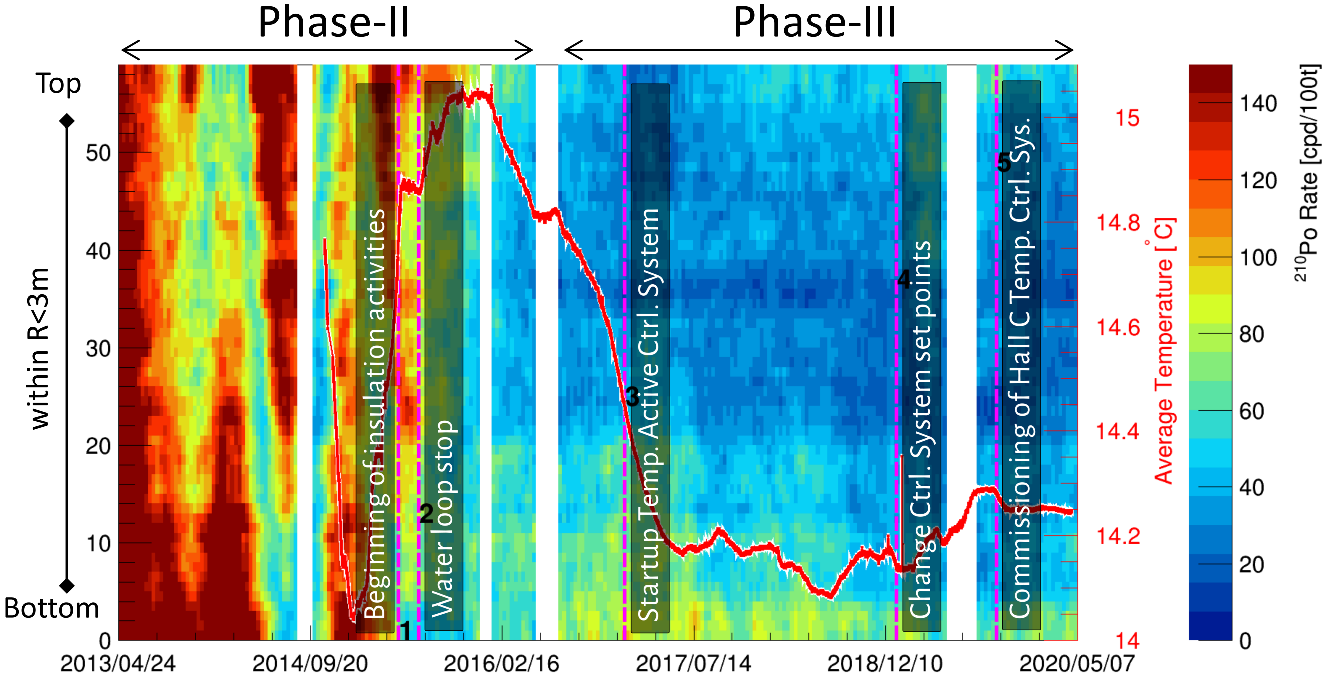
1. Insulation of the water tank (2015-16)
2. Active temperature control of the upper dome (2017)
3. Active temperature control of the Hall ventilation inlet (2019)

Temperature stabilization



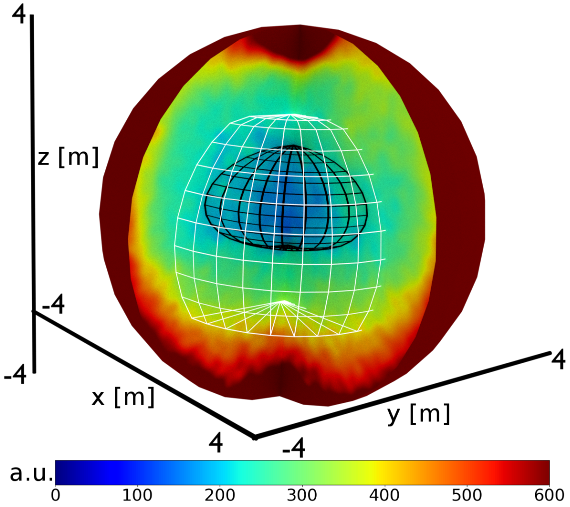


Effects of temperature control on ^{210}Po



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?

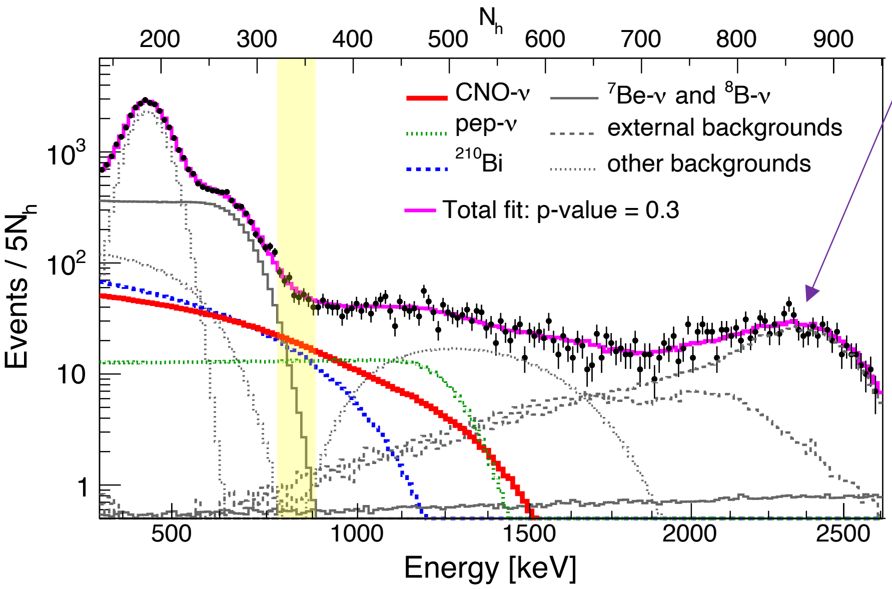
Therefore we set *only* an upper limit on ^{210}Bi

$$R(^{210}\mathrm{Bi}) \leq 11.5 \pm 1.3\ \mathrm{cpd}/100\ \mathrm{t}$$

[Includes systematics from space+time uniformity of ^{210}Bi]

Good! It implies a lower limit on CNO

CNO fit result



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

- 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
- Counting analysis in ROI (yellow band) for consistency check

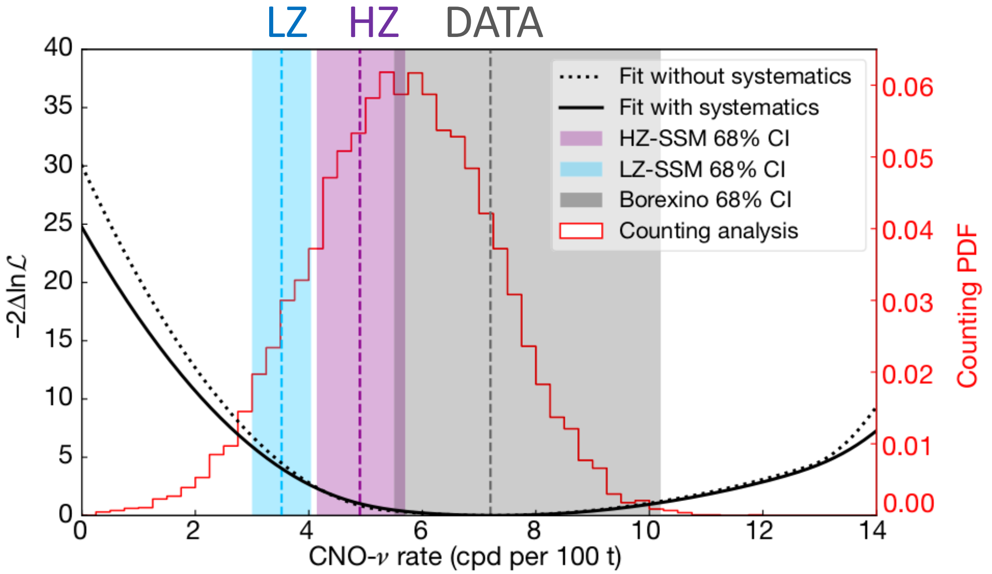
Systematics from:

- Fit configuration (binning, range)
- Spectral shapes (^{11}C, ^{210}Bi)
- Detector response (energy scale, non-uniformity, non-linearity)

Implications

$R_{CNO} = 7.2^{+3.0}_{-1.7}$ cpd/100 t

$\Phi_{CNO} = 7.0^{+3.0}_{-2.0} \times 10^{8}$ cm^{-2} s^{-1}



- No CNO hypothesis excluded at 5.0 σ (99% C.L.)
- HZ (LZ) model compatible at 0.5 (1.3) σ
- Including other pp-chain fluxes from Borexino: LZ disfavoured at 2.1 σ

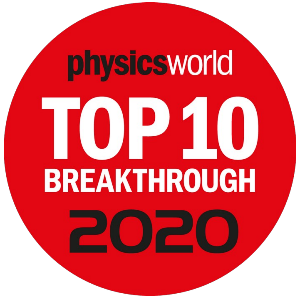
Conclusions

Unmatched radiopurity

Thermal stabilization

Borexino has performed the *first* detection of CNO neutrinos from the Sun with 5.0 σ significance

and the complete solar neutrino spectroscopy with a single experiment




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

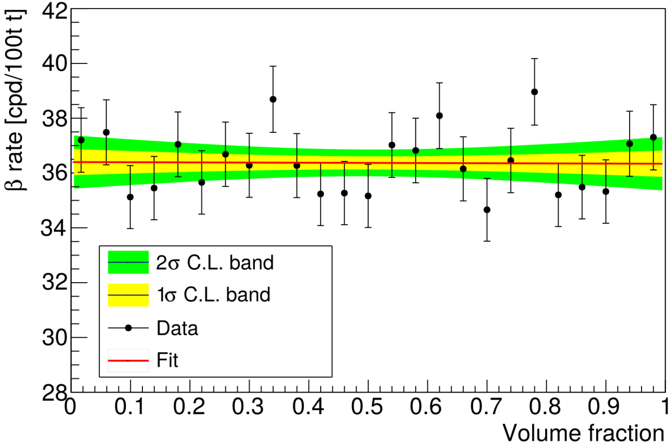
Mulhouse, France, 26 July 2021


Thank you!

Backup

^{210}Bi spatial uniformity

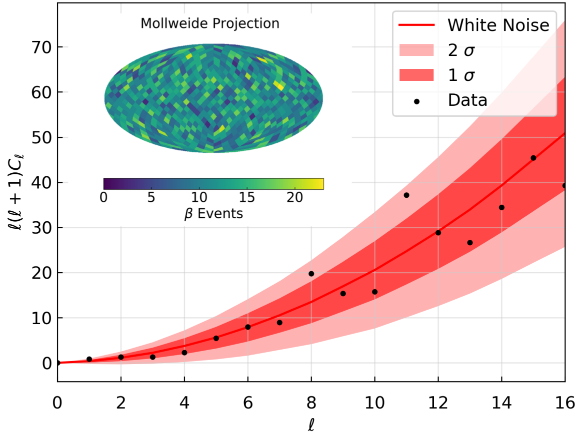
Radial distribution



Radial shell analysis

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

Angular distribution



Spherical Harmonic decomposition

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