FAREWELL BOREXINO! LESSONS FROM A GREAT STORY

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On behalf of the Borexino Collaboration

Borexino legacy:

- **TECHNIQUE** Borexino is the first experiment that has systematically codified techniques needed for studying neutrino physics with a **threshold down to about 100 keV,** reaching unprecedented levels of radiopurity. Currently, today's rare events and low energy neutrinos experiments (as e.g. Juno, searches for dark matter and 0nbb decay) all have a program to obtain good radiopurity, which largely derives from Borexino.

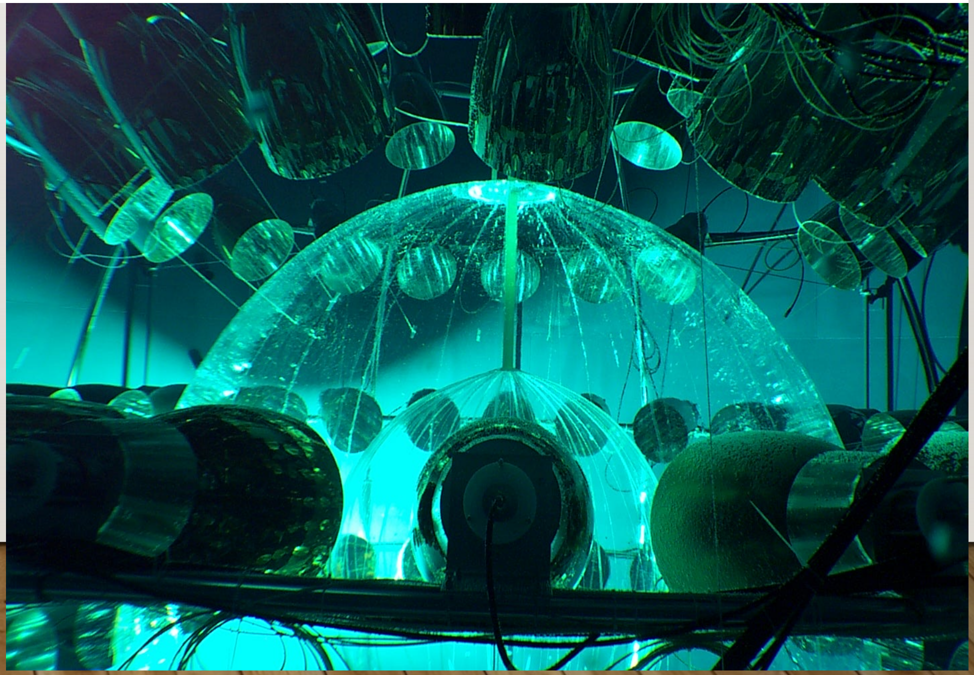
- **SCIENCE**. Borexino has closed a great circle of sky knowledge, opened in 1938 by Bethe and von Weiszackers' hypothesis on **the pp chain and CNO cycle as engines that power Sun and stars**, by means of a multitude of measurements that give **the entire spectrum of solar neutrinos** and reveal how **the Sun and main sequence stars work.**

Note: Since its conception, Borexino has been surrounded by skepticism from a large part of the physics community, who was convinced that the experiment was too difficult and that the needed radiopurity was unattainable. This skepticism also accompanied us during the experiment, when we faced the measurement of the pp reaction and above all the measurement of the CNO. This has not discouraged us from continuing and this stands as an example providing encouragement, especially to young scientists, not to fear embracing even those experiments that appear the most difficult, as those might be yielding the most important result

A bit of Hystory

- 1988-1989 Discussions and design of an experiment capable of studying the **entire spectrum of solar neutrinos.** It was the time of the solar neutrino problem, which has been fixed later by the SNO experiment measuring the higher energy part of the solar neutrino spectrum ($\geq$ 4.5-5 MeV)

- 1990-1995 R&D for tools and methods to obtain radiopurity at ultra-trace level (design level $\leq 10^{-16}$ g/g for Th/U progeny) to be sensitive to sub-MeV solar neutrinos. At that time the best sensitivity instrument on the market was the mass spectrometer with a plasma source (sensitivity $\sim 10^{-12}$ g/g). Then we built the counting test facility (CTF) (4 tons of scintillator seen from 100 PMT and shielded with 1000 tons of highly purified water), a benchmark for Borexino, to measure the radiopurities we needed to achieve. CTF sensitivity: ^{38}U, ^{232}Th. $\sim$5 x10^{-16} g/g / ^{14}C/^{12}C. $\sim$ 2x10^{-18}



A bit of hystory 2

1995-2007 Construction, installation and tuning of the detector (2.5 years of stop from the Teramo court)- Nothing is standard in Borexino regarding components, construction and installation methods. Filling with scintillator purified in batch mode

2007-2010 1st phase of data taking

11 months of scintillator purification in continuous closed loop

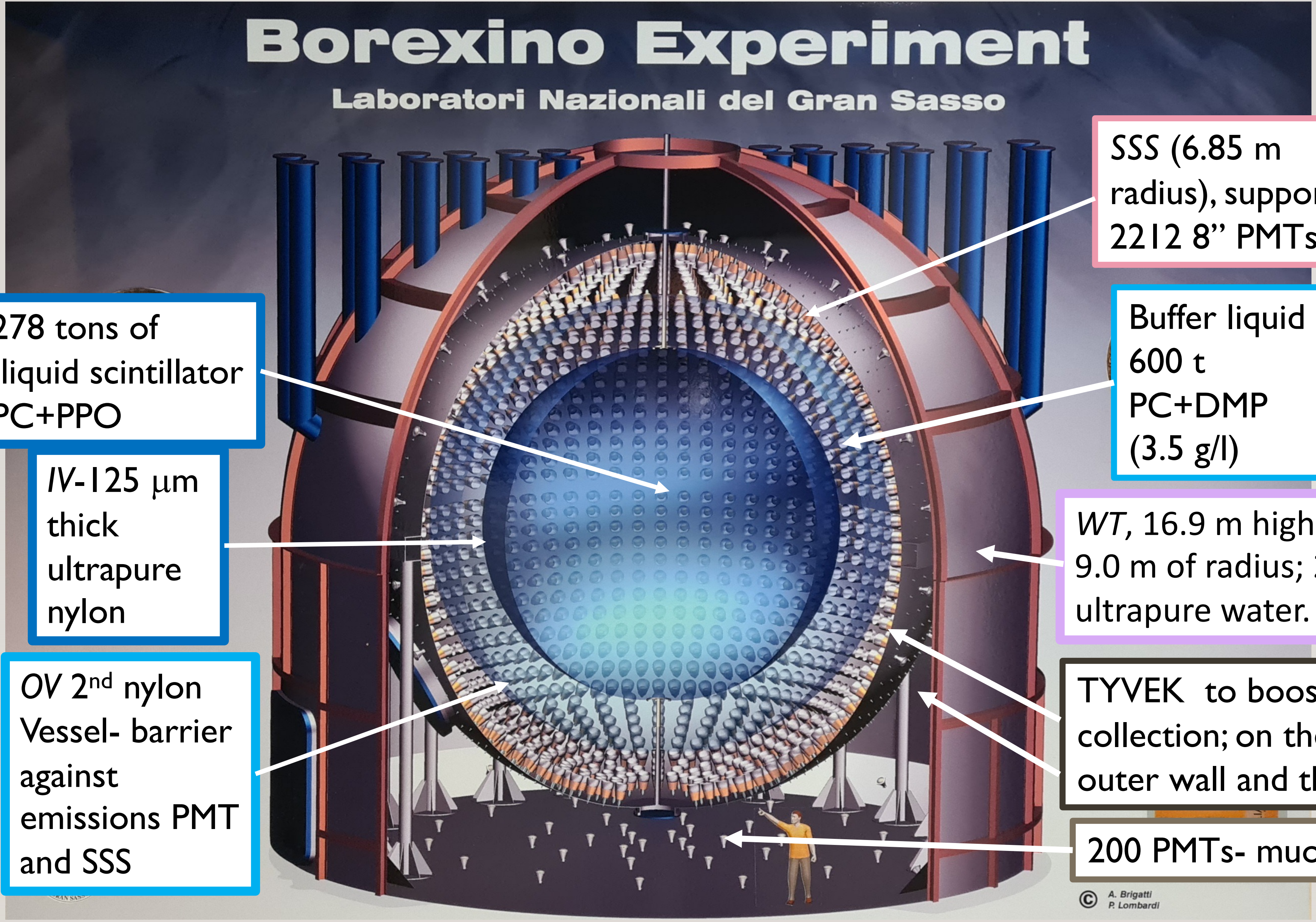
early 2011-mid 2016. 2nd phase of data taking

Measurements of the single fluxes of the pp chain nuclear reactions emitting neutrinos

Detector thermal insulation

mid 2016-end of 2021 3rd phase of data taking

Detection and measurement of the CNO cycle



SSS (6.85 m radius), supports 2212 8” PMTs

278 tons of liquid scintillator PC+PPO

Buffer liquid 600 t PC+DMP (3.5 g/l)

PC=pseudocumene--1,2,4, trimethylbenzene. PPO=2,5, diphenyloxazole

IV-125 μm thick ultrapure nylon

WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

OV 2nd nylon Vessel- barrier against emissions PMT and SSS

TYVEK to boost light collection; on the SSS outer wall and the WT

200 PMTs- muon veto

built like an onion, with a graded shielding: the closer the layer is to the center, the greater its radio-purity

Radiopurity*-1

Scintillator- Ultrafiltration-0.05 μm for particulate; **Distillation**: at 80°C- avoid extraction contaminants from the distillation column- ^{238}**U** and ^{232}**Th** and their progeny; **Water extraction :** water soluble contaminants as ^{40}K and ^{210}Pb; **Gas stripping** with ultraclean nitrogen- Ar, Kr, Xe , ^{222}Rn, oxygen, which spoils light yield; **Advanced cleaning** submicron sized dust particles containing K, Th, and U oxides

Methods not effective for ^{14}C (2678 years lifetime) –raw material oil from very old and deep underground layers

Dedicated pipeline and loading station built on the production site- dedicated isotanks- all treated as the detector components

Detector-The entire detector must be built to maintain the radiopurity record achieved for the scintillator by means of appropriate techniques and methods- **all components have been custom designed; prototyped; built; tested following, in most cases, unconventional approaches; treated and assembled with methods developed in-house.**

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Radiopurity-2

A few examples

- **PMTs** developed with external company with special low radioactivity glass, ceramics, dynode cascade components. **All materials** severely selected for lowest natural radioactivity

- **Scintillator containment nylon vessel:** extrusion in control air; assembled in clean room class 100, equipped with a radon scrubbing device: wrapped in a shroud with high purity N_2 in between; installation within the detector in a synthetic air atmosphere

- **All vessels, pipes, detector surfaces** treated with pickling, passivation, electropolishing, sometimes chelation and mirrored with roughness< 0.8 **μm**, class <50 cleaning operation, to extract embedded impurities and facilitate precision cleaning for dust and particulates (Th, U, and their progeny)

- **Pumps** components, in contact with the scintillator, and **gaskets** replaced with Teflon. **All flanges, valves, fittings, pumps,** surrounded by high purity nitrogen purged boxes. **S**ubmarine connectors manufactured, at our request, with special high radio-purity material.

- Stripping and dynamic blanquets on scintillator and buffer liquids with high purity N_2 via activated cooled carbon traps in liquid phase : ^{222}Rn:<1 μBq/m^3 Low Argon and Krypton N_2

- **Entire inner detector** equipped as a clean room of class 1000; other 5 c.r.

Radio isotope	Source	Software reduction	Achieved Phase1	Achieved Phase2
^{14}C	Intrinsic PC	Threshold Fit on the shape	$\approx 2\ 10^{-18}\ {}^{14}C/{}^{12}C$	
^{238}U ^{235}Th	Dust, particulate all materials	α/β tagging fit	$(1.67\pm0.06)\ 10^{-17}$ $(4.6\pm0.8)\ 10^{-18}$ g/g	$<9.5\ 10^{-20}$ $<7.2\ 10^{-19}$ g/g
^{85}Kr	Air, nuclear weapons		30 ± 5 cpd/100t	6.8 ± 0.8 cpd/100t
^{39}Ar	Air, cosmogenic	fit	<< 1 cpd/100t	
^{210}Po	Embedded on surfaces Vessel emanation	fit	500-100 cpd/100t	Natural decay
^{222}Rn and its progeny	In the underground air and water	α/β tagging, delayed coincidences	< 1 cpd/100t	

These achievements were what was needed to allow the Borexino results displayed below:

- Simultaneous measurement of the individual fluxes of neutrino-emitting reactions: pp, pep, ^{7}Be; ^{8}B measurement,; from the pp chain fusion reactions [Nature, 512 (2014) 383; Nature, 562 (2018) 505]

- Observation of neutrino oscillation in vacuum and measurement of the ratio Pee-vacuum/Pee-matter [Nature, 562 (2018) 505]

- First experimental evidence of the existence of the CNO cycle [*Nature,* 587 (2020) 577; *Phys. Rev. D* 108 (2023) 102005].

- Addressing the HZ vs LZ puzzle with a good hint in favor of high metallicity [*Phys. Rev. Lett.* 129 (2022) 252701]

- Study of geoneutrinos and observation of mantle signal * [*Phys. Rev. D* 101(2020)012009,, *La Rivista del Nuovo Cimento* 45 (2022)]

- Upper limits of rare events such as Pauli principle violation events, neutrino magnetic moment, electron decay and nucleon decay

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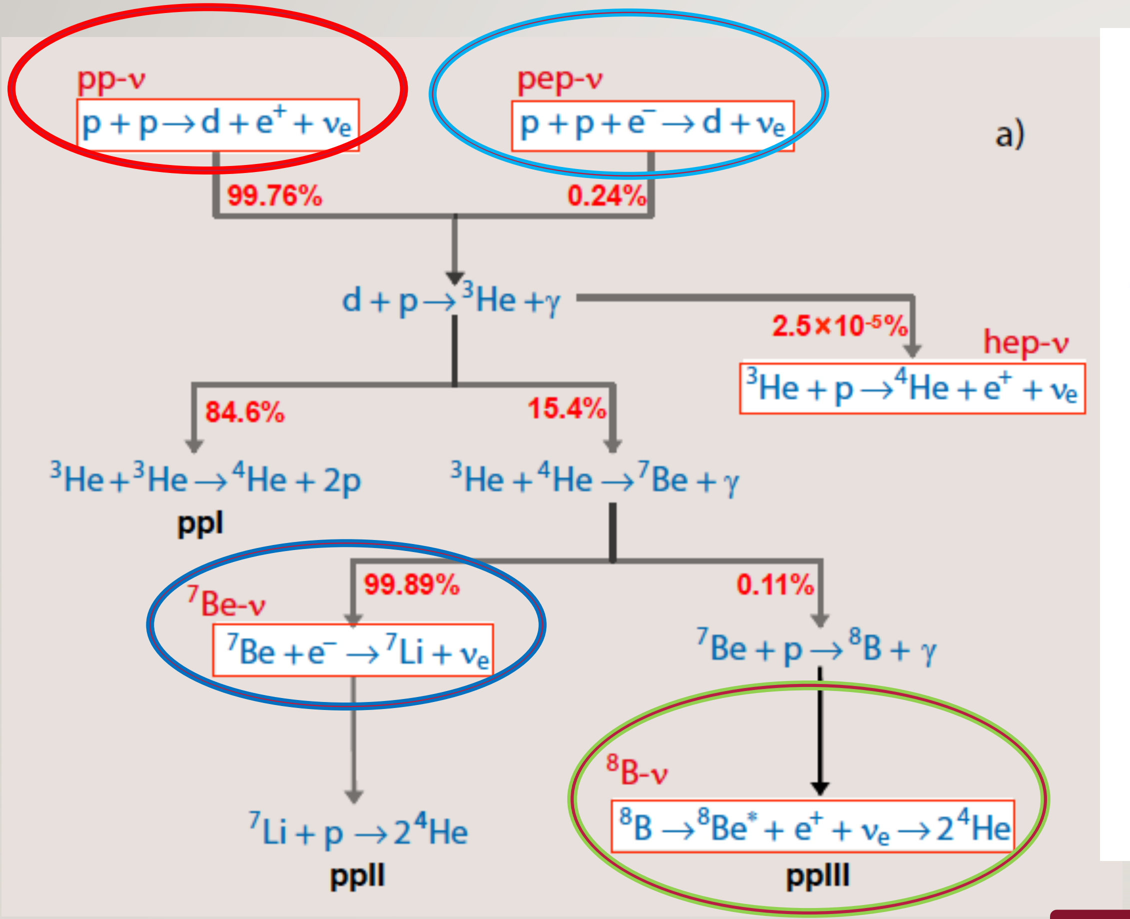
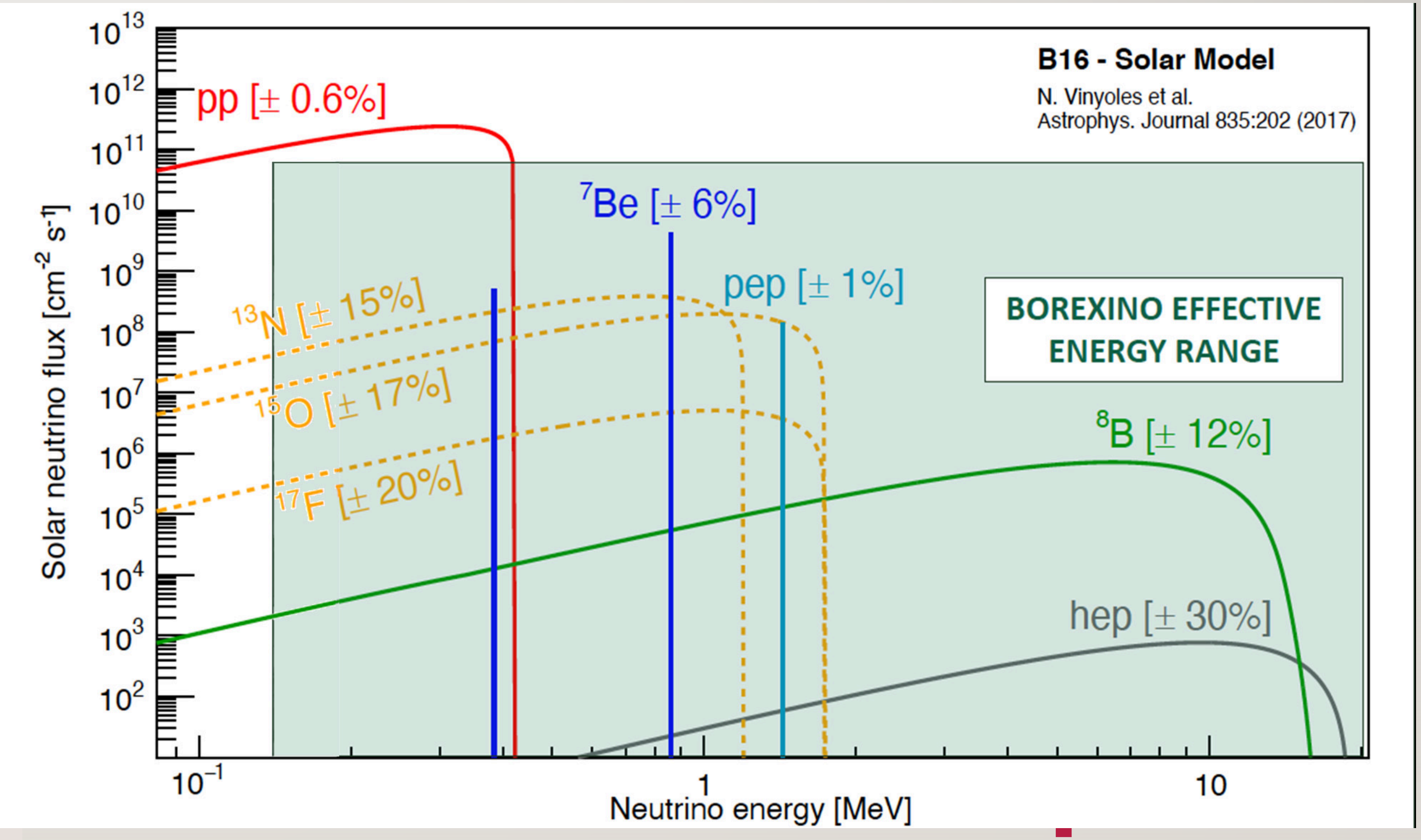
* This argument is included in the Livia Ludhova talk

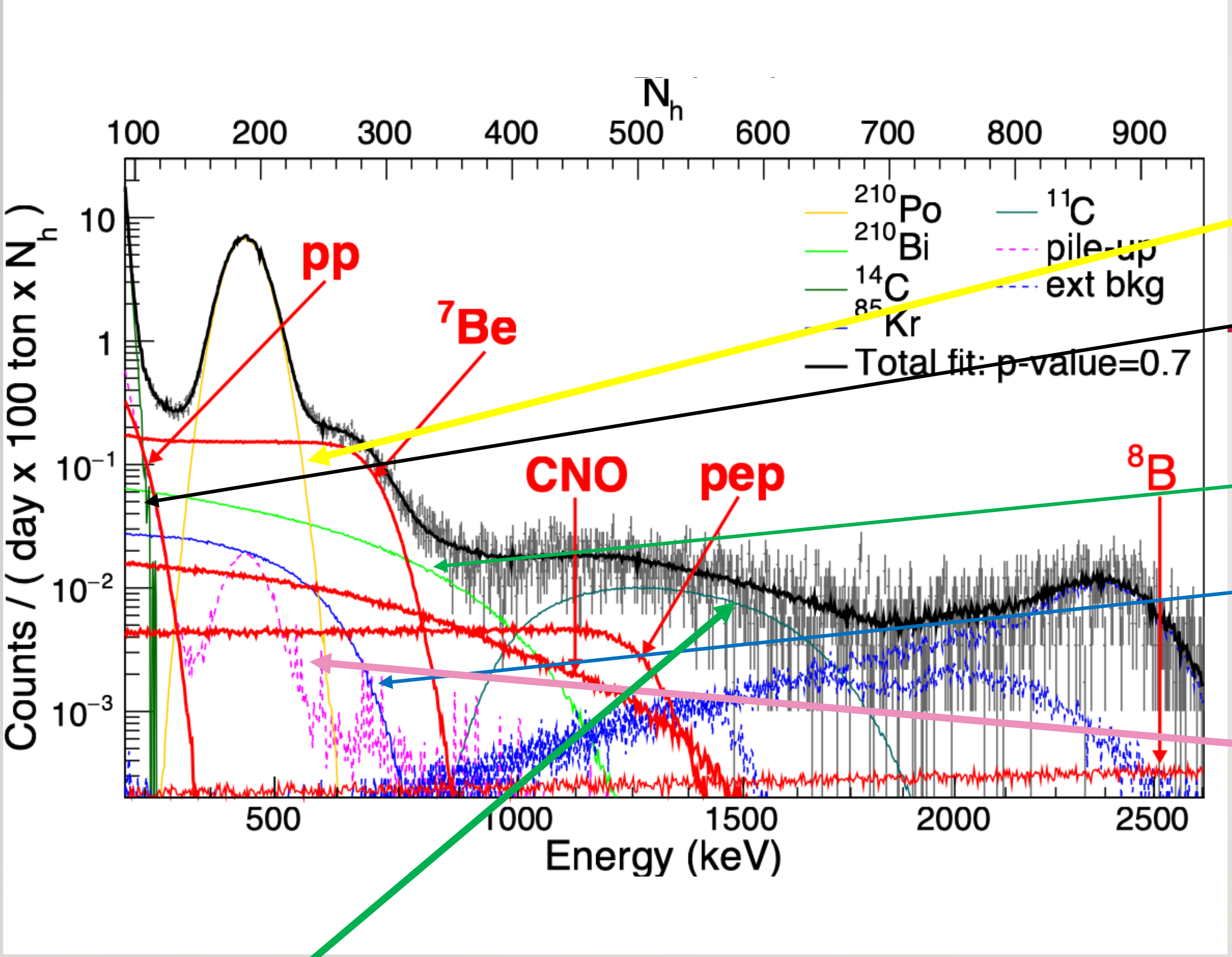
Measurements of the single fluxes from the pp chain nuclear reaction emitting neutrinos





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

First spectroscopy of pp,^{7}Be and pep



^{210} Po

^{14}C

^{210} Bi

^{85}Kr

Residue despite the radiopurity record

Pile-up due to the ^{14}C rate

^{11}C (β+ decay, τ = 29.4 min) continuously produced by muons (1.2 m /m^{2}h survived through the GS overburden) spallation on C; due to the e+-annihilation, the spectrum is shifted above 1 MeV and falls in pep ν's energy window
Three-Fold Coincidence reduces to 10%. (incident muon+muon decay+neutron capture)
Pulse shape discrimination reduces to 5% (ortho-positronium with 140 ns lifetime, reduced to about 3 ns in the l.s.
-2 γs produced in the positron annihilation-distributed topology)

	Borexino rates (cpd/100t)	Borexino fluxes ($cm^{-2}s^{-1}$)	SSM HZ Fluxes ($cm^{-2}s^{-1}$)	SSM LZ Fluxes ($cm^{-2}s^{1}$)	(HZ-LZ)/HZ. Dependence on T
pp	134 $\pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5})$ $\times 10^{10}$	$5.98(1 \pm 0.006)$ $\times 10^{10}$	$6.03(1 \pm 0.005)$ $\times 10^{10}$	-0.8% $T^{-0.9}$
^{7}Be	48.3 $\pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.12})$ $\times 10^{9}$	$4.93\ (1 \pm 0.06)$ $\times 10^{9}$	$4.50(1 \pm 0.06)$ $\times 10^{9}$	8.9% T^{11}
pep	2.43 $\pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12})$ $\times 10^{8}$	$1.44\ (1 \pm 0.009)$ $\times 10^{8}$	$1.46\ (1 \pm 0.009)$ $\times 10^{8}$	-1.4% $T^{1.4}$
^{8}B	$0.220^{+0.015}_{-0.016}$	$5.68^{+0.39+0.03}_{-0.41-0.03}$ $\times 10^{6}$	$5.46\ (1 \pm 0.12)$ $\times 10^{6}$	$4.50(1 \pm 0.12)$ $\times 10^{6}$	**17.6%** T^{24}
^{13}N	$6.7^{+1.2}_{-0.8}$	$6.7^{+1.2}_{-0.8}$ $\times 10^{8}$	$4.89(1 \pm 0.0.16)$ $\times 10^{8}$	$3.51(1 \pm 0.15)$ $\times 10^{8}$	27.9% T^{19}
^{15}O					

PP Chain

CNO cycle

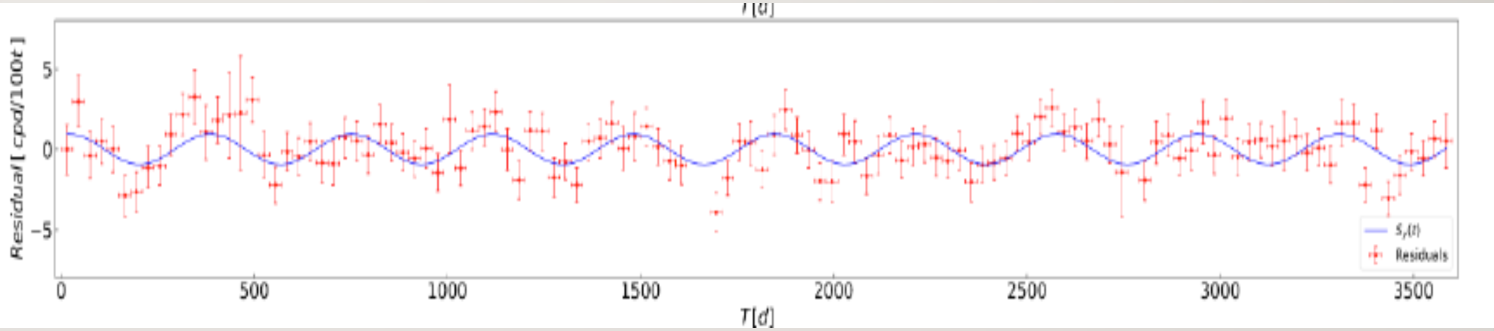
Test on the solar luminosity

Good agreement between luminosities via **photons and via neutrinos-**

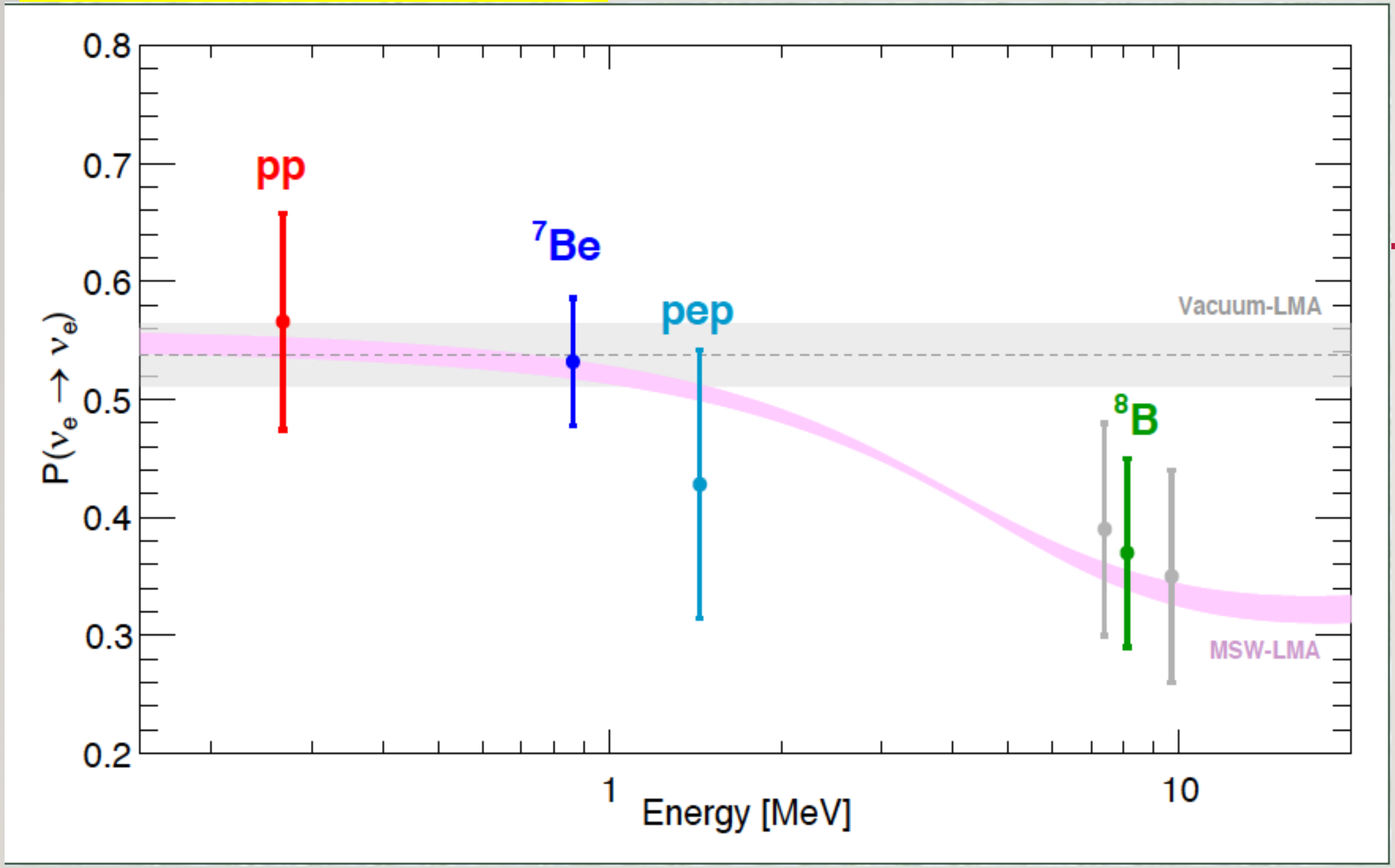
Useful because this is a test **of the fundamental assumptions in the SSM paradigm showing that there are no additional energy losses or production mechanisms besides those normally included in solar model calculations**

Determination of the Earth’s orbit with solar neutrinos

Modulation (6.7% peak-to-peak amplitude measured during 10 years)-
Excellent agreement with the astronomical measurements



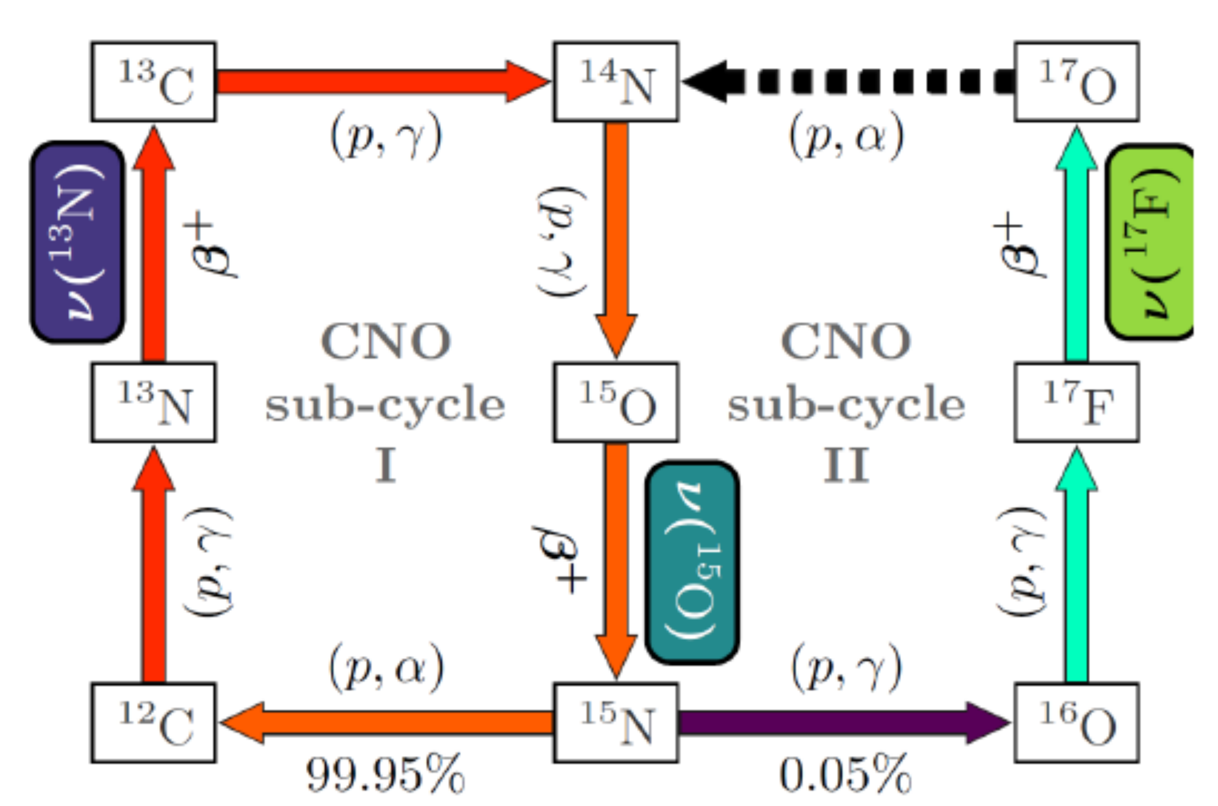
Neutrino oscillation



day/night effect found null by Borexino in the ^{7}Be energy window. This excludes at more than 8.5σ the Δm_{12}^2 energy range 10^{-6}-10^{-7} eV^2 (**low** solution)– **Singles out the LMA solution with solar neutrinos only, without KamLAND antineutrinos, then without CPT assumption**

Observation **oscillation in vacuum regime - P_{ee}~0.55** in vacuum regime to be compared with matter regime **P_{ee}~0.32**. The entire plot obtained by the same experiment, then factorizing all the systematics. Constant Pee rejected at **98% C.L**

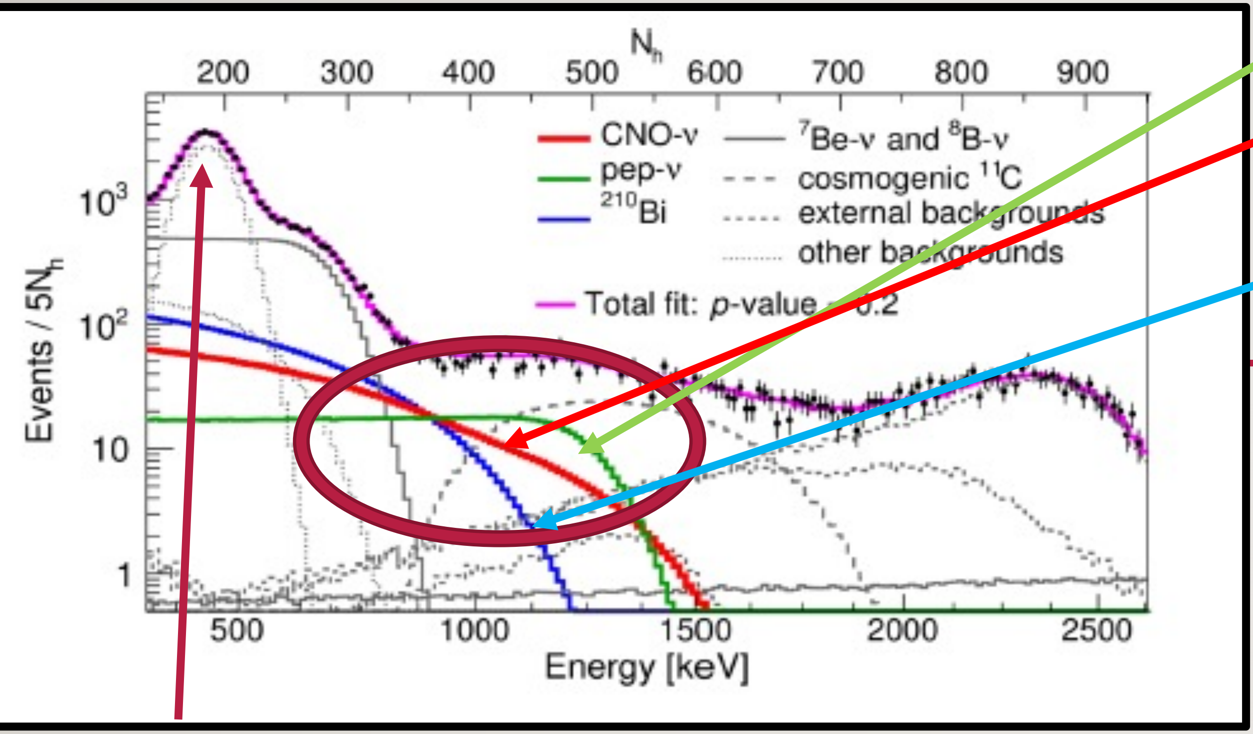
First direct demonstration that the CNO cycle is real



Hypothesized by Bethe and Von Weizsäcker in 1938
- Hydrogen burning is catalyzed by Carbon, Oxygen and Nitrogen at a temperature about one order of magnitude more than pp chain.

Astrophysical theories have identified the CNO cycle as dominant in massive stars, i.e. those with a mass greater than the Sun by at least 30%.

3 methods : ^{210}Bi measurement and spectral fit; directionality; ^{210}Bi measurement + directionality



pep

CNO

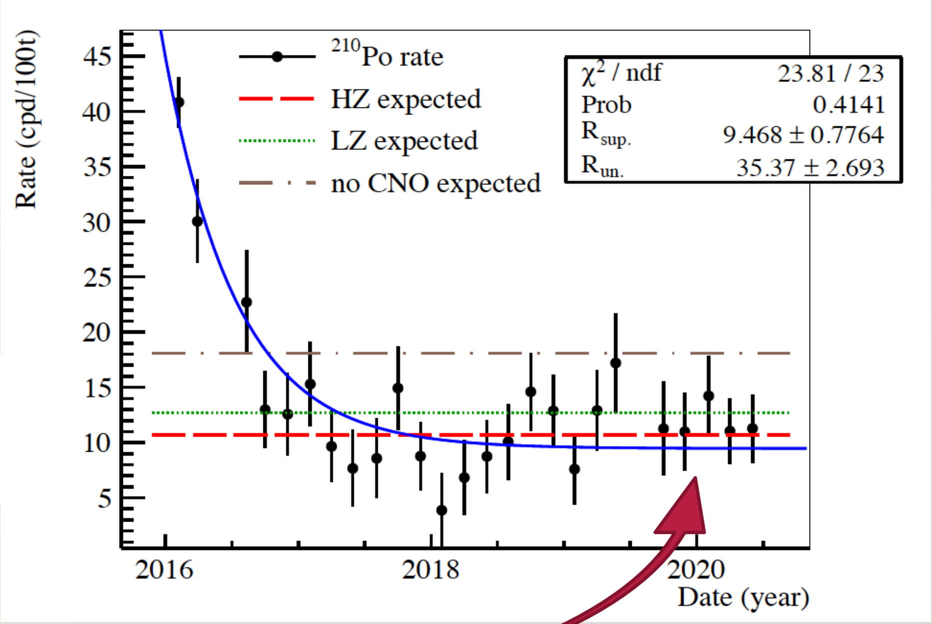
210 BI

$^{210}Pb \xrightarrow{\beta^-} {}^{210}Bi \xrightarrow{\beta^-} {}^{210}Po \xrightarrow{\alpha} {}^{208}Pb$ (stable)

23y 5d 138

^{210}Po in equilibrium + contribution **out of equilibrium**

^{210}Po



Out of equilibrium + convective motions
From IV walls to Fiducial volume

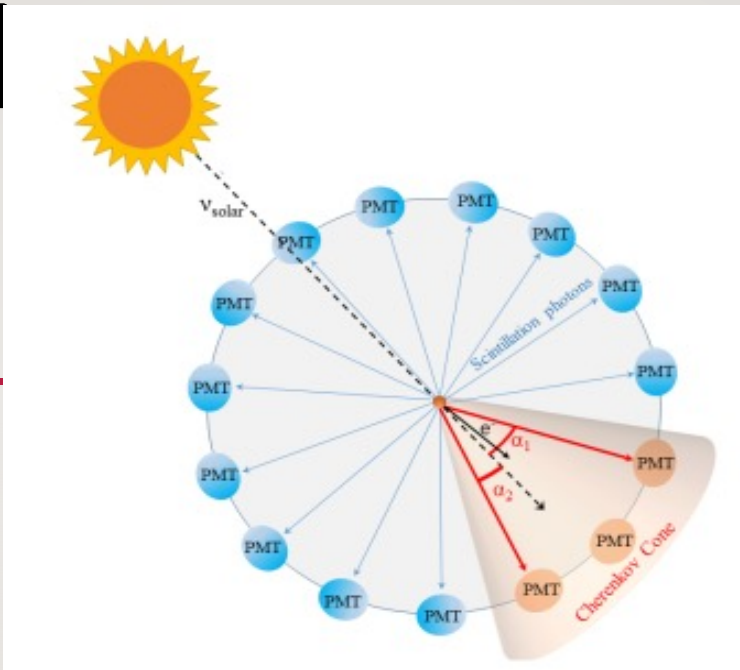
Detector thermal insulation with an active control of the W.T. and of the experimental hall

Temperature stability achieved within 0.07°

^{210}Po rate= ^{210}Bi=11.5 $\pm 1.3\ \frac{cpd}{100\ t}$

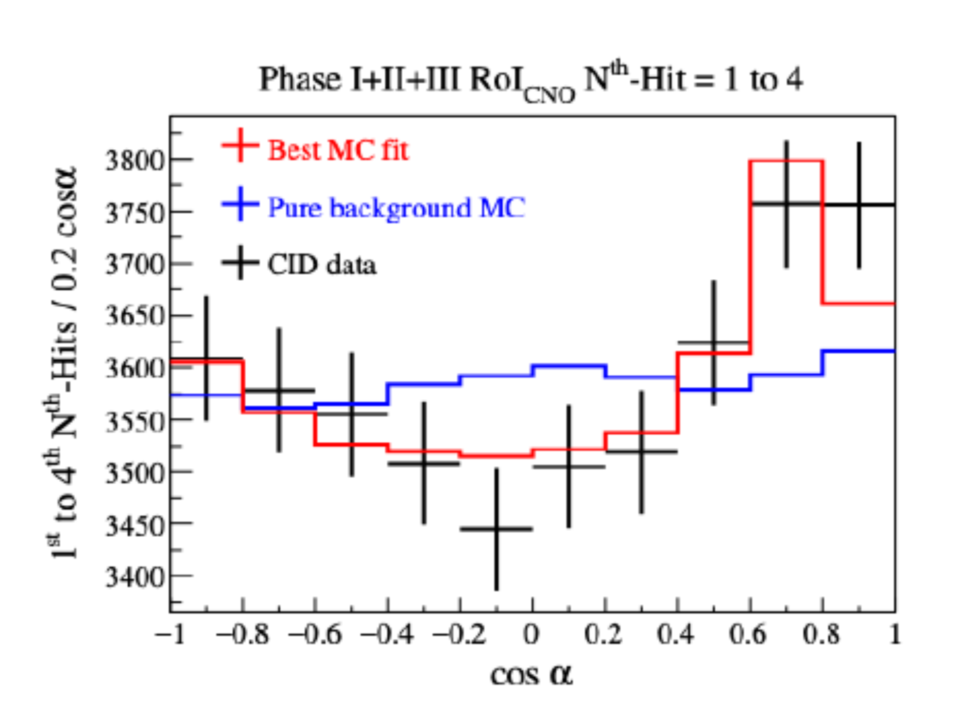
CNO with the directionality

The refractive index of the Borexino scintillator is ~1.55, setting the electron Cherenkov radiation threshold at ~167 keV



- Scintillation hits and background uncorrelated with the Sun direction
- Cherenkov neutrino signals correlated
- The recoil electrons scattered roughly in the direction of solar neutrinos

Detection of the 1-2 **earliest hits which are the most likely be due to Cherenkov** emission because the Cherenkov light is emitted almost instantly, while the scintillation light emission follows a multi-exponential decay time where the fastest component has 1.6 n



CNO rate

Test on 7Be

CNO

^{210}Bi constraint

CNO rate $\mathbf{6.7^{+2.0}_{-0.8}}$ cpd/100t (stat+sys)

Flux: $\mathbf{6.7^{+2.0}_{-0.9}}$ x 10^8 cm^{-2} s^{-1}

No CNO-excluded at 7σ C.L.

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directionality

CNO rate

$\mathbf{7.2^{+2.5+1.2}_{-2.5-0.9}}$ cpd/100t $(\mathbf{stat.+syst})$

No CNO-excluded at 5σ C.L.

Note: **The agreement between the results of these two completely independent analyses demonstrates how robust is the CNO cycle Borexino measurement**

^{210}Bi constraint
plus
directionality

CNO rate $\mathbf{6.7^{+1.2}_{-0.7}}$ cpd/100 tons

Flux: $\mathbf{6.7^{+1.2}_{-0.8}} \times 10^8$ cm^{-2} s^{-1}

No CNO-excluded at 8σ C.L.

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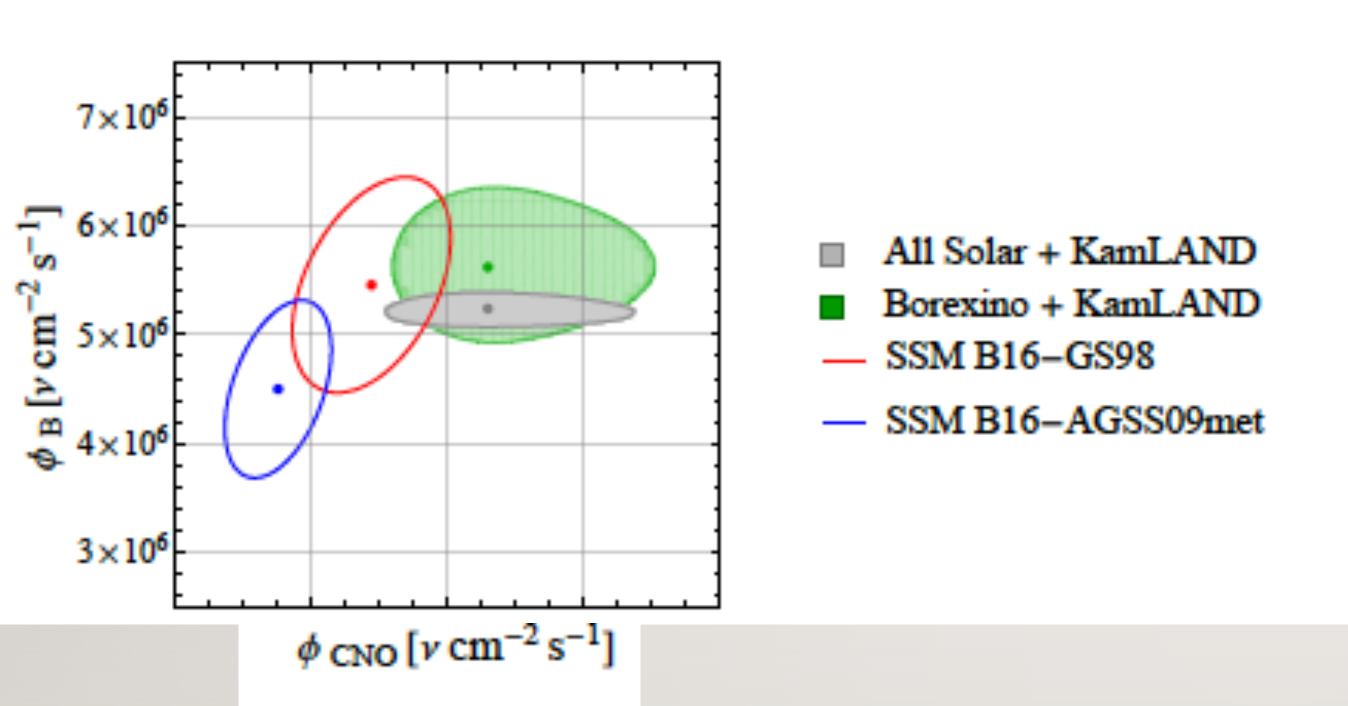
^{15}O					

Long standing puzzle HZ vs LZ



The rate of the CNO reactions features a direct dependence on the abundance of C and N in the solar core. One can then define a weighted ratio of CNO-to-pp neutrino fluxes that is directly proportional to the C+N abundance in the Sun's core (and independent on the core temperature Tc). This ratio calculated with the CNO results from Borexino and compared with expectations obtained with different surface abundances *

LZ disfavored at ≈ 2 σ

LZ disfavored at > 3.1 σ

* F. Villante, A. Serenelli Front. Astron. Space Sci., 7(2020) 62856
A. M. Serenelli, W.C. Haxton, C. Pena-garay, *Astrophys.J.* 743 (2011) 24
W.C. Haxton, A.M. Serenelli, *Astrophys.J.* 687 (2008) 678

BUT, all solar neutrino fluxes (produced in both the pp chain and the CNO-cycle) display an indirect dependence on solar environmental parameters, such as abundance of heavy elements, solar age, luminosity, opacity, diffusion, through the effect on the core temperature, T_c.

Borexino obtained a hint in favours of HZ

BOREXINO COLLABORATORS WHO SUCCEEDED EACH OTHER DURING THE 32 YEARS OF THE EXPERIMENT

(each time the collaboration consisted of no more than 130 members, including technicians)

Agostini M., Alimonti G., Altenmueller K., Appel S., Arpesella C., Atroshchenko V., Bacchiocchi G., Back H., Bagdasarian Z., Balata M., Barone D., Basilico D., Beau T., Bellini G., Benziger J., Bick D., Biondi R., Bonetti S., Bonfini G., Bravo D., Brigatti A., Buck C., Buizza Avanzini M., Caccianiga B., Cadonati L., Calaprice F., Caminata A., Cappelli L., Caprioli S., Carlini M., Carraro C., Cavalcante P., Cavanna F., Cecchet G., Chavarria A., Chen M., Chepurnov A., Choi K., Collica L., Cubaiu A., Dadoun O., Dalnoki-Veress F., D'Angelo D., Darnton N., Davini S., De Bari A., De Bellefon A., De Haas E., De Kerret H., Derbin A., Deutsch M., Di Credico A., Di Giacinto A., Di Ludovico A., Di Marcello V., Ding X., Di Noto L., Di Pietro G., Drachnev I., Eisenstein R., Elisei F., Empl A., Etenko A., Fernholz R., Fiorentini G., Fomenko K., Ford R., Formozov A., Franco D., Freudiger B., Froborg F., Gabriele F., Galbiati C., Gatti F., Gazzana S., Ghiano C., Giammarchi M., Giugni D., Goeger-Neff M., Goettel A., Goldbrunner T., Golubchikov A., Goretti A., Grandi L., Grieb C., Gromov M., Gschwender M., Guardincerri E., Guffanti D., Hagner C., Hagner T., Hampel W., Harding E., Hardy S., Hartmann F., Hertrich T., Heusser G., Houdy T., Hult M., Hungerford E., Ianni A., Ianni A.M., Jany A., Jedrzejczak K., Jeschke D., Jochum J., Johnson M., Joyce M., Kayunov A., Kidner S., Kiko J., Kirsten T., Kobychev V., Korablev D., Korga G., Korschinek G., Koshio Y., Kozlov Y., Kryn D., Kumaran S., Lachenmaier T., Lagomarsino V., La Marche P., Laubenstein M., Lehnert B., Lendvai C., Leung M., Lewke T., Litvinovich E., Loer B., Loeser F., Lombardi F., Lombardi P., Lomskaya I., Ludhova L., Lukyanchenko G., Lukyanchenko L., Machulin I., Magni S., Malvezzi S., Manecki S., Maneira J., Maneschg W., Manno I., Mantovani F., Manuzio D., Manuzio G., Marcocci S., Maricic J., Martemianov A., Martyn J., Masetti F., Mazzucato U., McCarty K., McKinsey D., Meindl Q., Meroni E., Meyer M., Miramonti L., Misiaszek M., Montanari D., Montuschi M., Monzani M.E., Mosteiro P., Muratova V., Musico P., Neder H., Nelson A., Neumair B., Niedermeier L., Nieslony M., Nisi S., Nostro A., Nugmanov R., Oberauer L., Obolensky M., Opitz B., Orekhov V., Orsini M., Ortica F., Otis K., **Pallavicini M.,** Papp L., Parmeggiano S., Pelicci L., Pelliccia N., Peña-Garay C., Penek Ö., Perasso L., Perasso S., Perotti A., Pietrofaccia L., Pilipenko N., Pocar A., Porcelli A., Preda A., Raghavan R., Raikov G., Ranalli M.T., **Ranucci G.,** Rau W., Razeto A., Re A., Redchuk M., Resconi E., Ricci B., Risso P., Romani A., Roncin R., Rossi N., Rottenanger S., Rountree S.D., Ruscitti M., Sabelnikov A., Saggese P., Saldanha R., Salvo C., Scardaoni R., Schimizzi D., Schoenert S., Schuhbeck K., Seitz E., Semenov D., Settanta G., Shutt T., Simgen H., Singhal A., Skorokhvatov M., Smirnov O., Sonnenschein A., Soricelli F., Sotnikov A., Stokes L., Sukhotin S., Suvorov Y., Tarasenkov V., Tartaglia R., Testera G., Thurn J., Toropova M., Ullucci P., Unzhakov E., Vignaud D., Villante F., Vishneva A., Vitale S., Vogelaar B., von Feilitzsch F., von Hentig R., Vyrodov V., Wang H., Weinz S., Williams B., Winter J., Wojcik M., Wright A., Wurm M., Xu J., Yokley Z., Zaimidoroga O., Zavatarelli S., Zuber K., Zuzel G.,

Borexino Collaboration

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UHH Universität Hamburg

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Thank for your attention

physicsworld TOP 10 BREAKTHROUGH 2014

physicsworld TOP 10 BREAKTHROUGH 2020


Giuseppe & Vanna Cocconi Prize HEP 2021


Bruno Pontecorvo International Award 2015


Enrico Fermi Award 2017

Stamp of the Italian Post office 2014

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