First detection of solar neutrinos from the CNO cycle with Borexino

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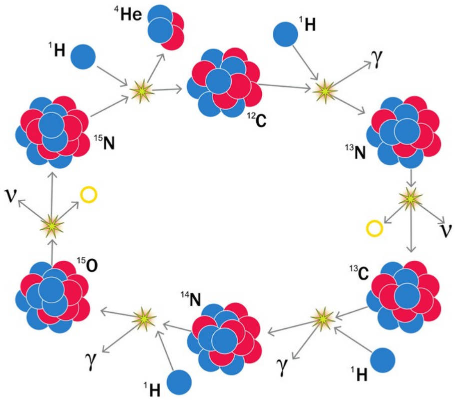


BOREXINO
GRAN SASSO

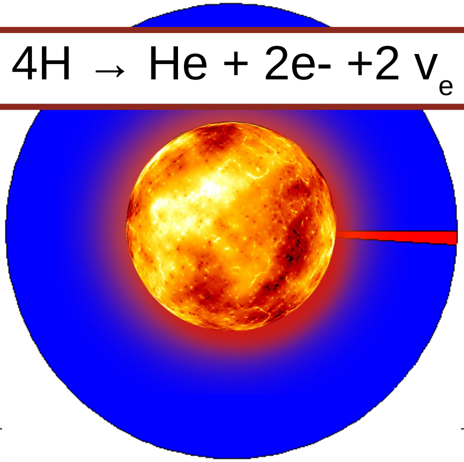
TWENTIETH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

August, 19-25, 2021

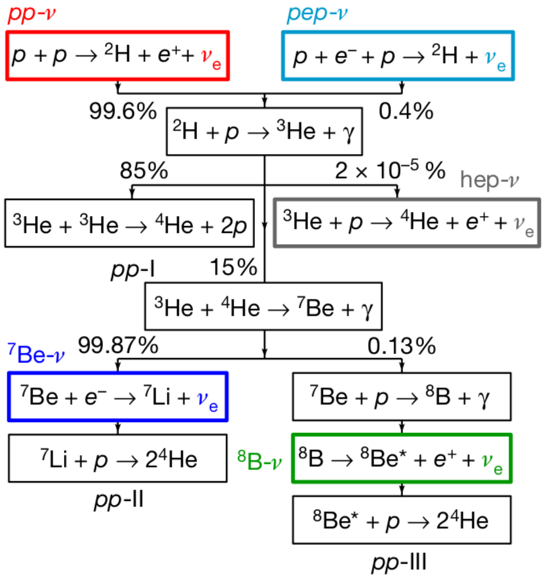
MOSCOW STATE UNIVERSITY

pp vs CNO Competition

$4H \rightarrow He + 2e^- + 2\nu_e$

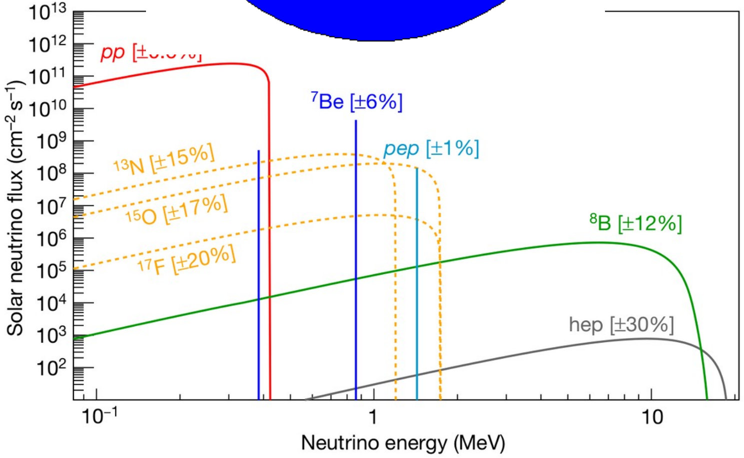


pp chain (99%)



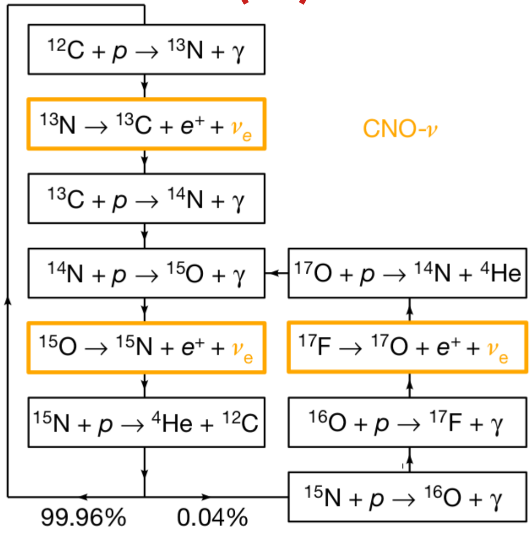
Dominant in the sun

$T_{core} \sim 15 \times 10^6$ K



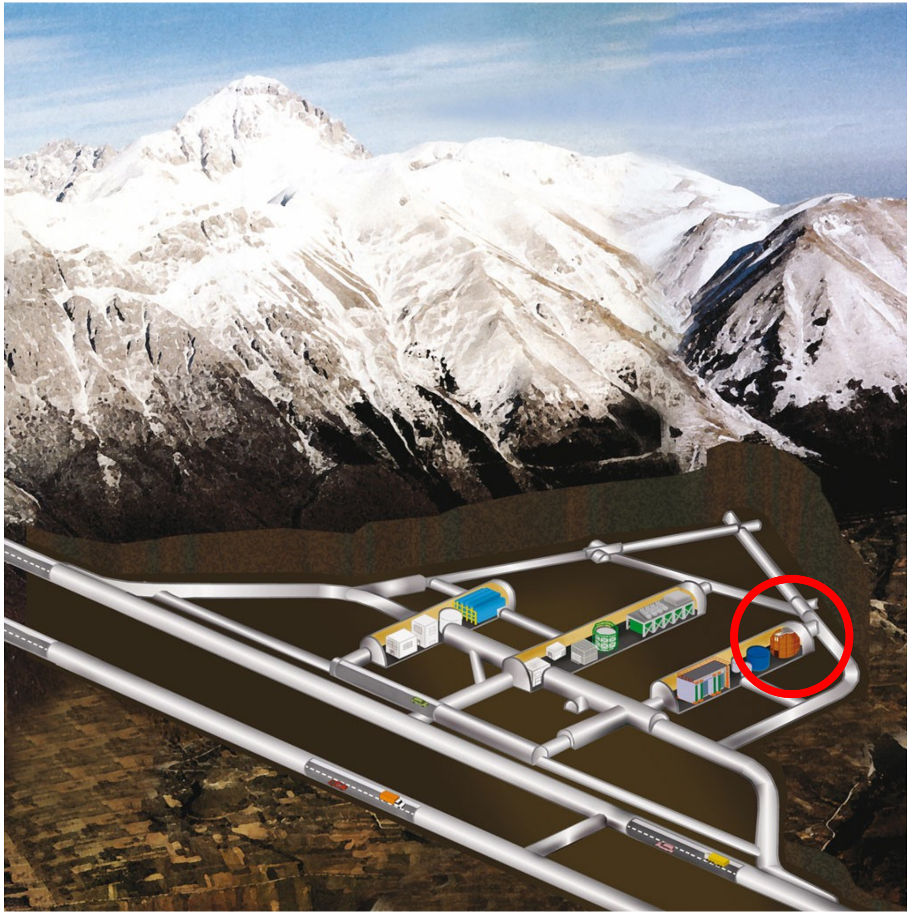
Solar neutrinos: astro & particle physics

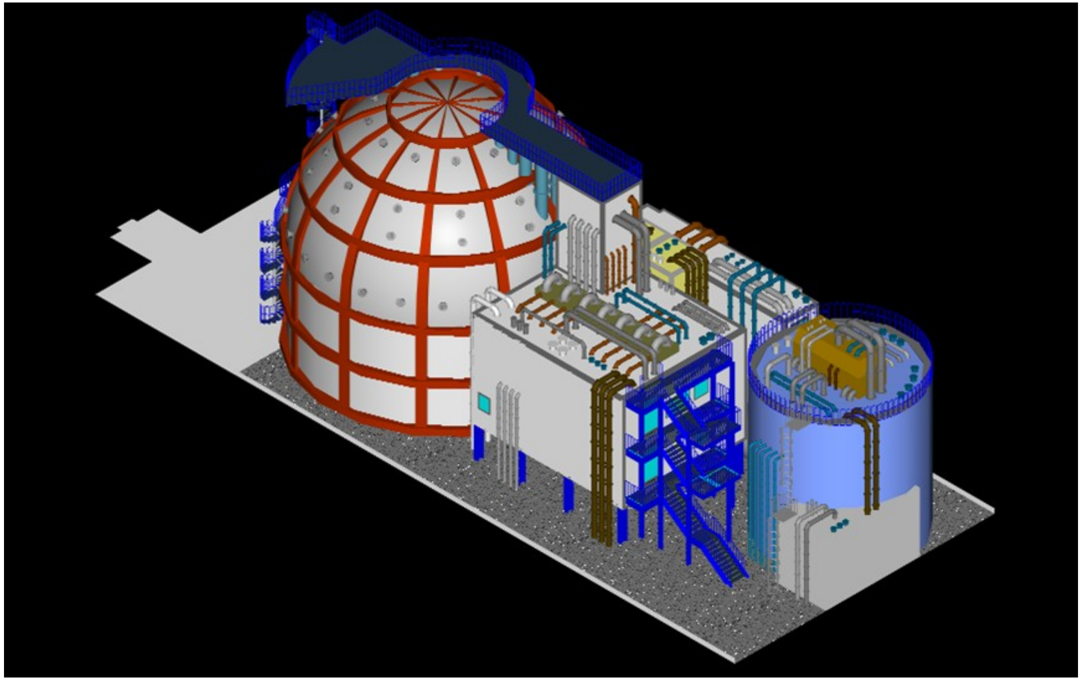
CNO cycle (1%)



- dominant in stars 1.3 heavier than Sun
- crucial for the solar *metallicity problem (Z>He) :* High (HZ) vs Low (LZ)

The BOREXINO detector





Laboratori Nazionali del Gran Sasso – INFN (Hall C)

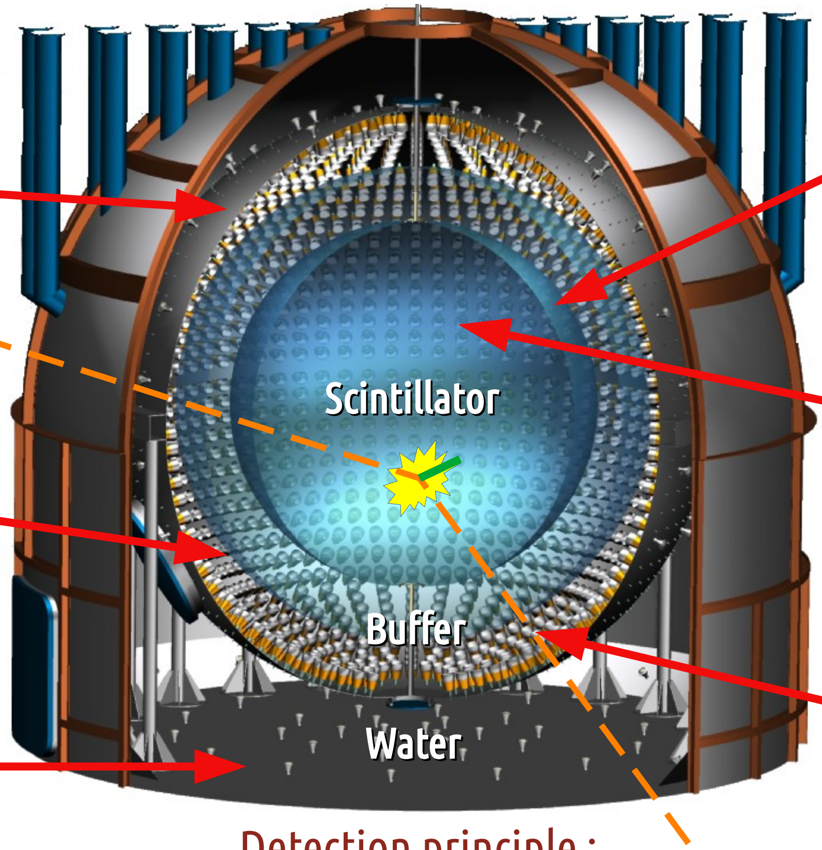
Rock: 3.800 m w.e. – muon flux ~ 1 $m^{-2}h^{-1}$

The Borexino detector

Stainless steal sphere
13.7 m of diameter,
1300 m³ of
pseudocumene

Nylon outer vessel
PC+DMP

Water Cherenkov veto
208 PMTs, diameter
18m, 2000 m³ of water



Nylon vessell
125 μm of radioupure
nylon

Inner vessel
target: 300 ton of
scintillator PC+PPO

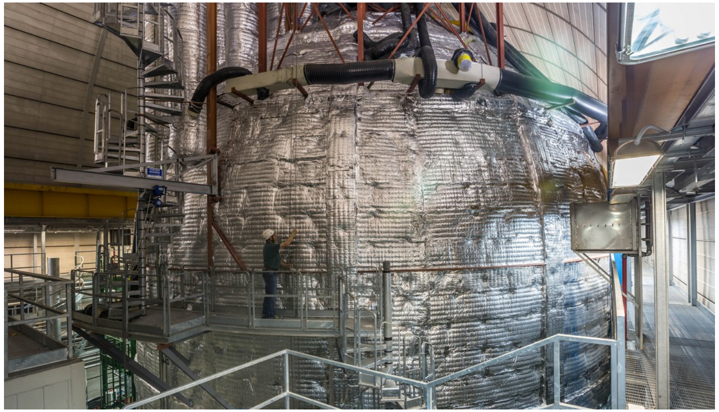
Internal PMTs
2212 (nominal), 8",
35% optical coverage

Detection principle :

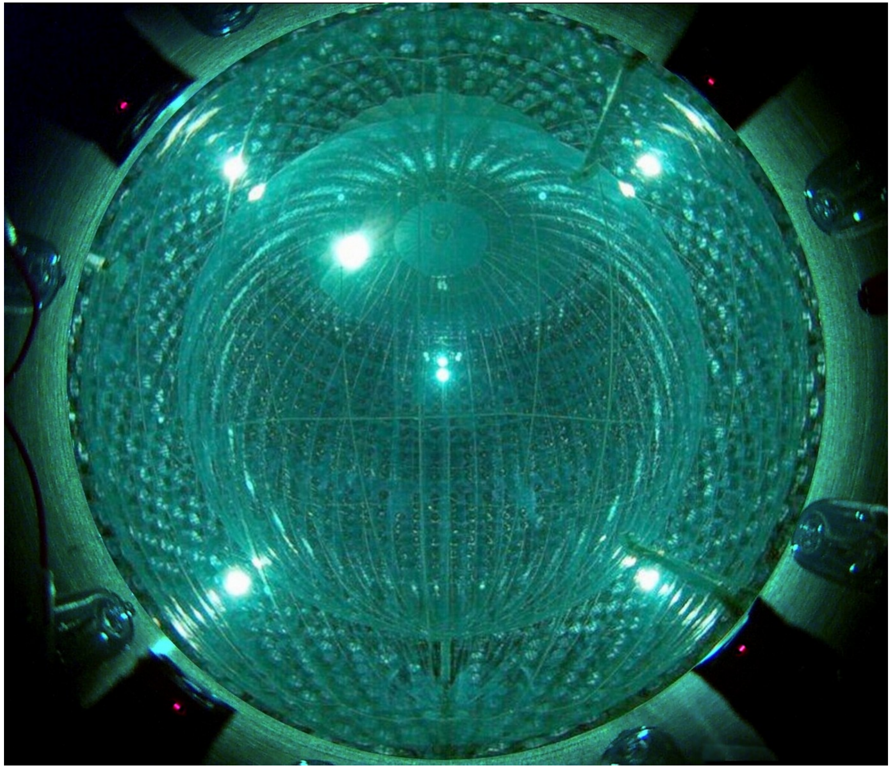
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Borexino's pictures

During the construction



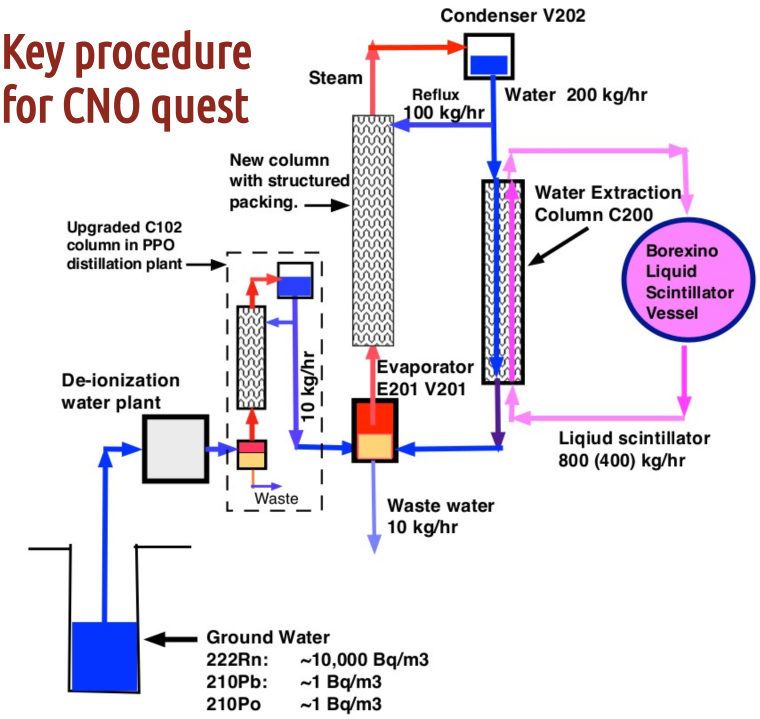
Now, after the thermal insulation



From monitoring camera

Water Extraction and Borexino radiopurity

Key procedure for CNO quest



Six cycles of water extraction from mid-2010 to mid-2011

[1 cpd/100t ~ 0.1 nBq/kg]

	Before [cpd/100t]	After [cpd/100t]
^{210}Bi	~40	~10
^{85}Kr	~30	~5
^{210}Po	>2000	<30 (decaying)

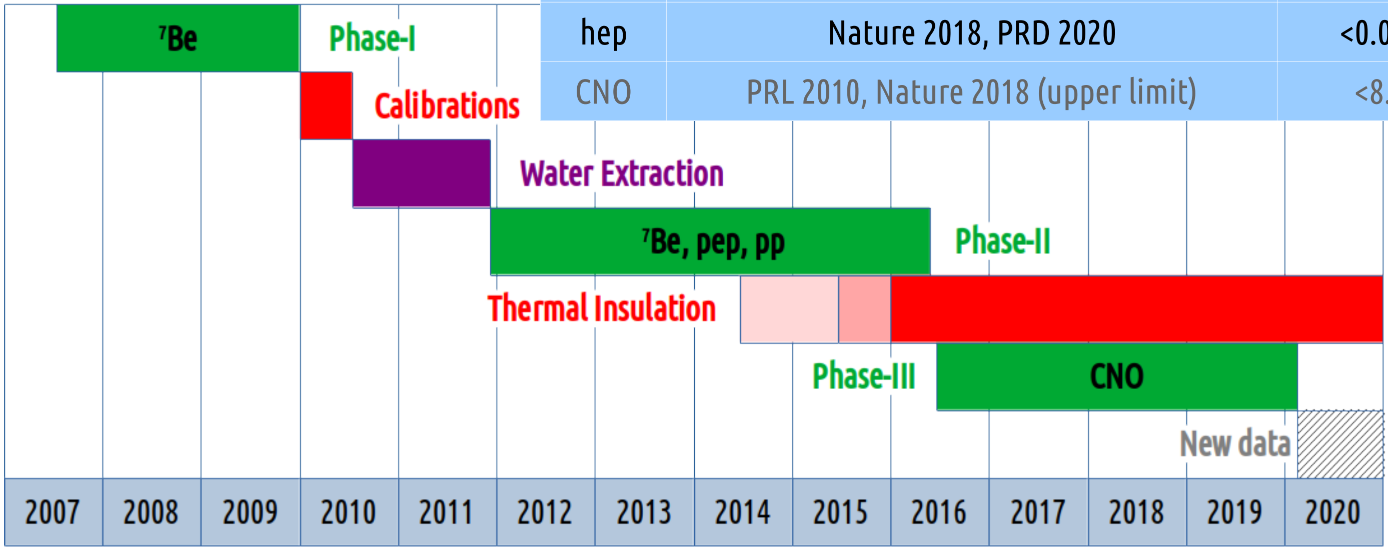
^{238}U<9.5x10^{-20} g/g (95%CL) ,
^{232}Th < 5.7x10^{-19} g/g (95%CL),
^{39}Ar, ^{40}K << 1 cpd/100t

Expected CNO ~ 3-5 cpd/100t

(Solar) results from Borexino (2018)

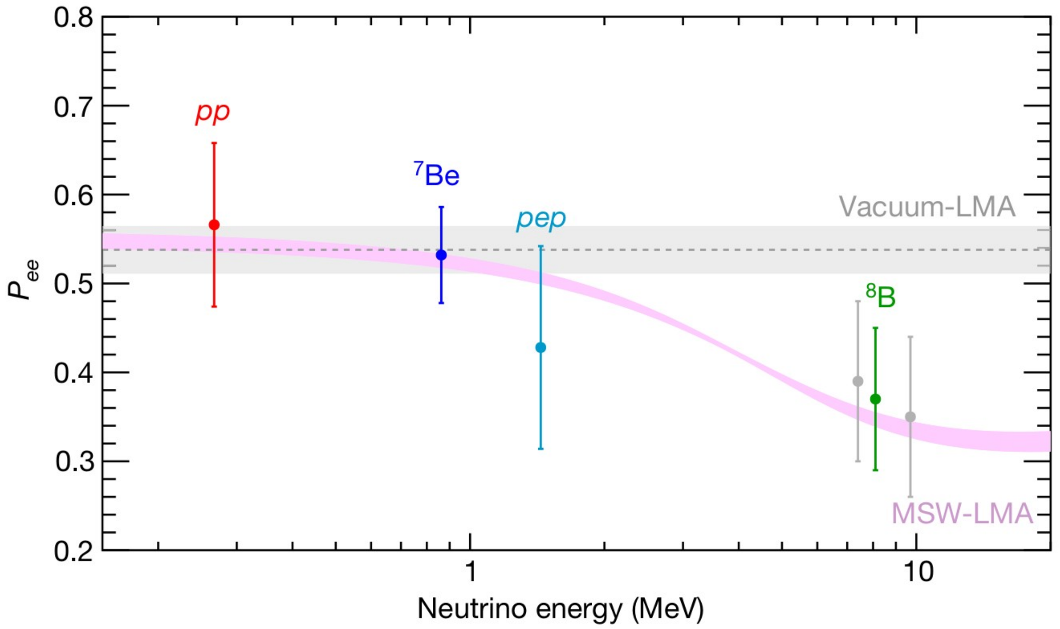
Borexino has produced its results in **three experimental phases**, alternated with hardware improvements

Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)^{+6}_{-10}$	$(6.1\pm0.5)^{+0.3}_{-0.5}\times10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)^{+0.4}_{-0.7}$	$(4.99\pm0.11)^{+0.06}_{-0.08}\times10^{9}$
pep	PRL 2012, Nature 2018, PRD 2019	$(2.43\pm0.36)^{+0.15}_{-0.22}$ [HZ]	$(1.27\pm0.19)^{+0.08}_{-0.12}\times10^{8}$ [HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223^{+0.021}_{-0.022}$	$5.68^{+0.39+0.03}_{-0.41-0.03}\times10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8\times10^5$ (90% CL)
CNO	PRL 2010, Nature 2018 (upper limit)	<8.1 (95% CL)	$<7.9\times10^8$ (95%CL)

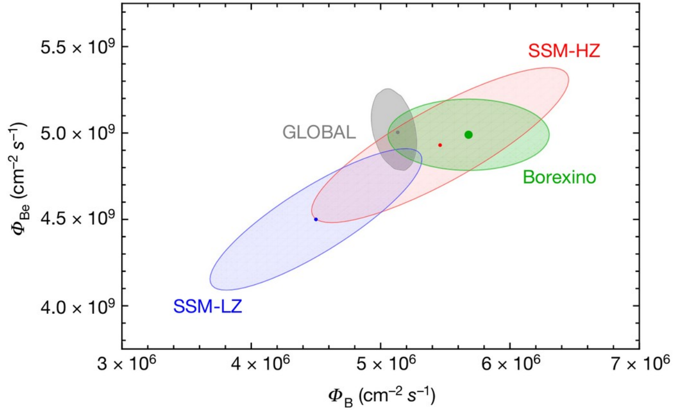


Before 2020:
- Precise measurement of the pp-chain fluxes
- best experimental limit on CNO

Implications of Borexino results



P_{ee} survival probability with Borexino data only!



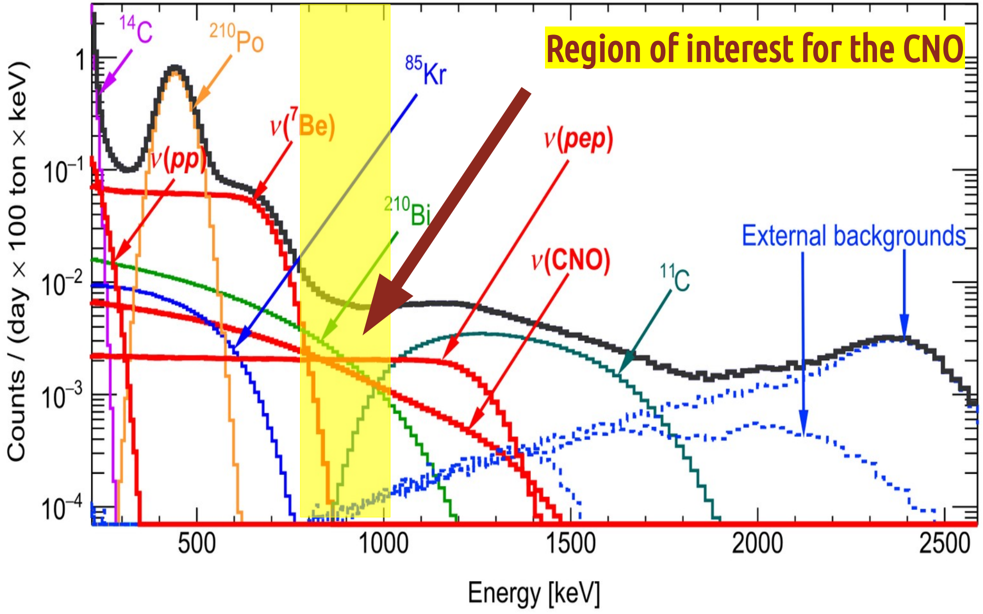
Precise measurements era:

Probing the **MSW-LMA** scenario

Low metallicity **disfavored at 1.8 σ**

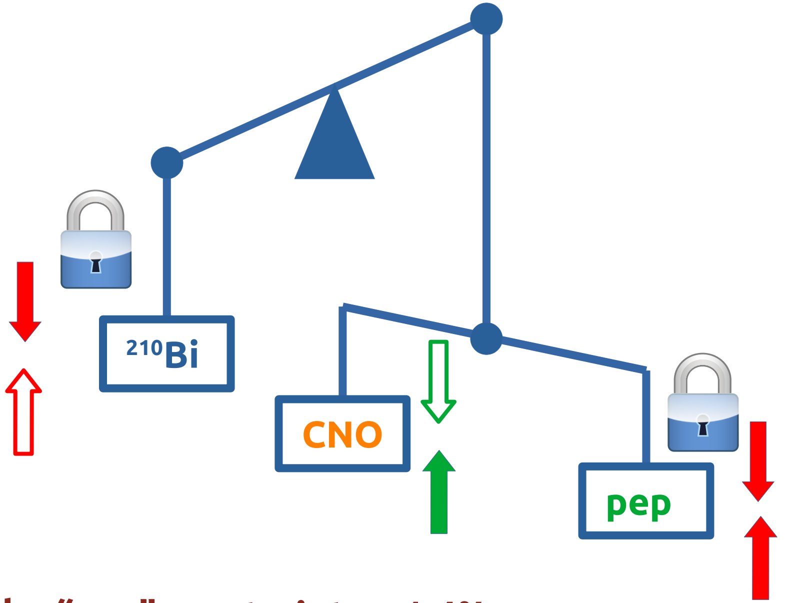
The CNO Strategy

Borexino spectrum after all data selection criteria



Strategy:
1. **independent constraint of pep**
2. **independent constraint and ^{210}Bi (upper limit)**

CNO <> pep <> ^{210}Bi correlation



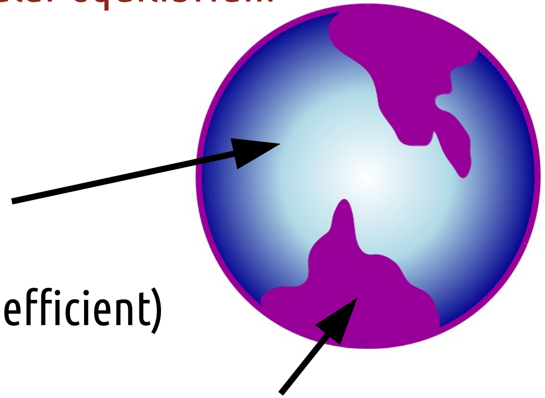
1. the "pep" constraint → 1.4%

Solar solar luminosity, pp/pep ratio, existing solar neutrino, and oscillation parameters

2. the "^{210}Bi" constraint

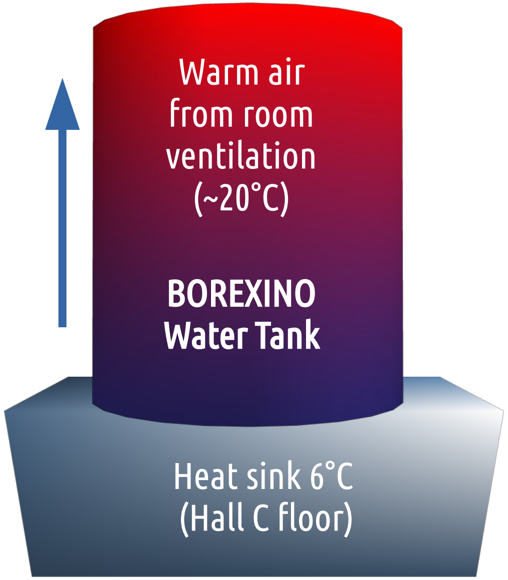
$$^{210}\mathrm{Pb} \xrightarrow[22.3\ \mathrm{years}]{\beta^-} \boxed{^{210}\mathrm{Bi}} \xrightarrow[5\ \mathrm{days}]{\beta^-} \boxed{^{210}\mathrm{Po}} \xrightarrow[138.4\ \mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

Exploiting the A=210 chain through secular equilibrium



Diffusion:
Very slow
D ~ 10^{-9} m^2/s
(diffusion coefficient)

Convection:
^{210}Po from the outer regions

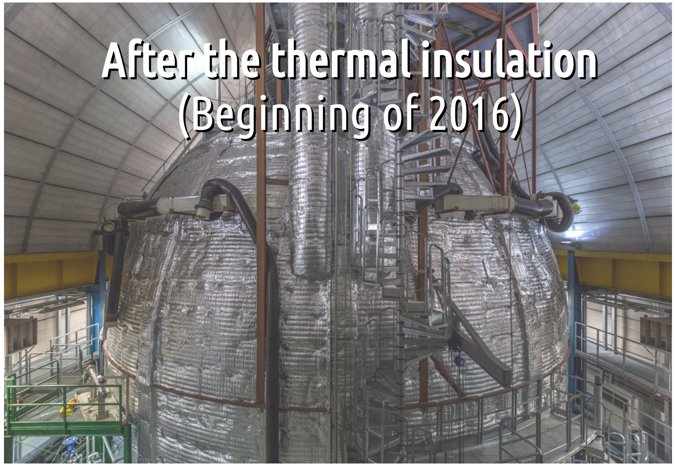


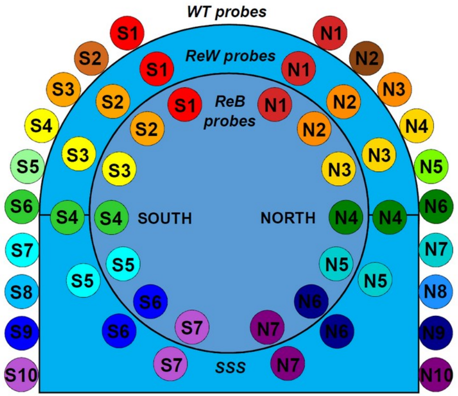
Idea: vertical gradient

THERMAL INSULATION PROGRAM

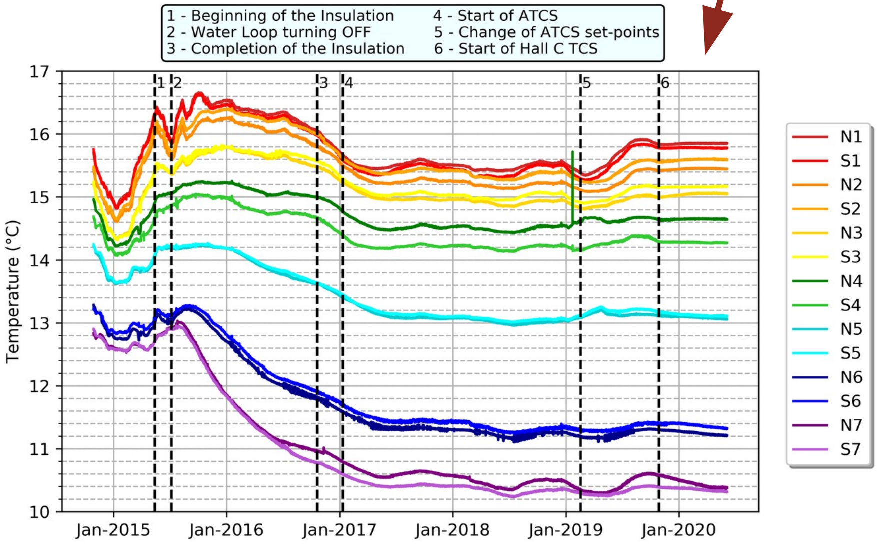
2014: temperature probes
Mid-2015: insulation start
Late 2015: *water recirculation system* shut down
2016: *active temperature control system* (ATCS)
Early 2019: change of the ATCS *set point*
Late 2019: *Hall C - ACTS*

Thermal Insulation



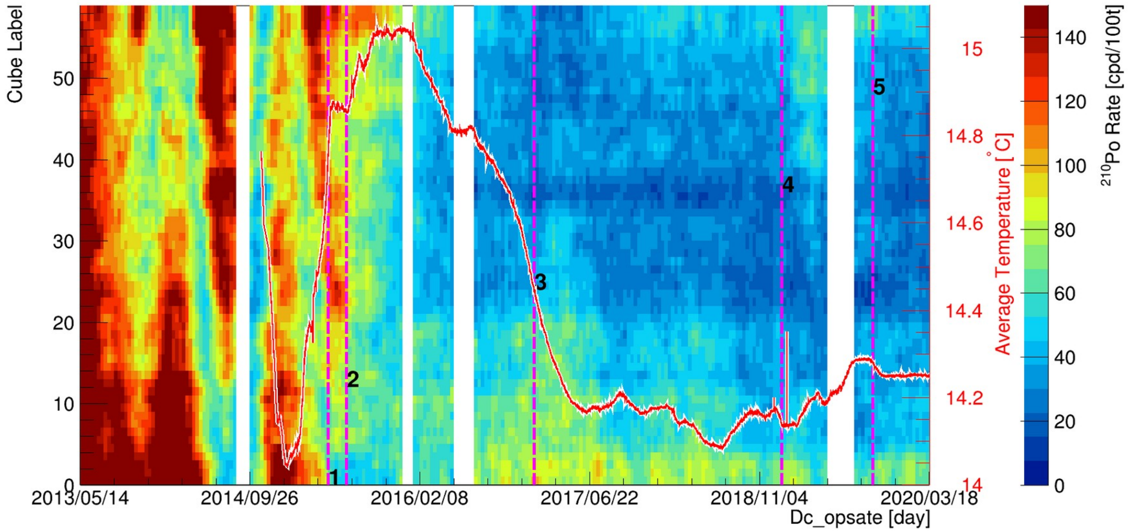


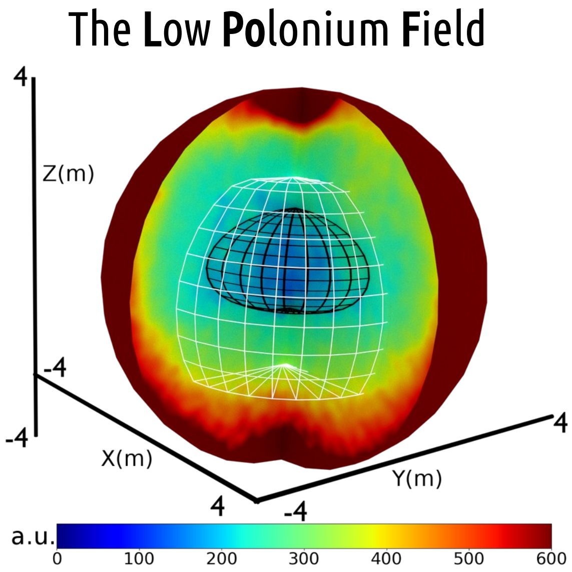
Temperature probes



Temperature evolution during the thermal insulation campaign

Effects on ^{210}Po migration





Minimum at z ~ 80 cm, Compatible with numerical fluid dynamics simulations

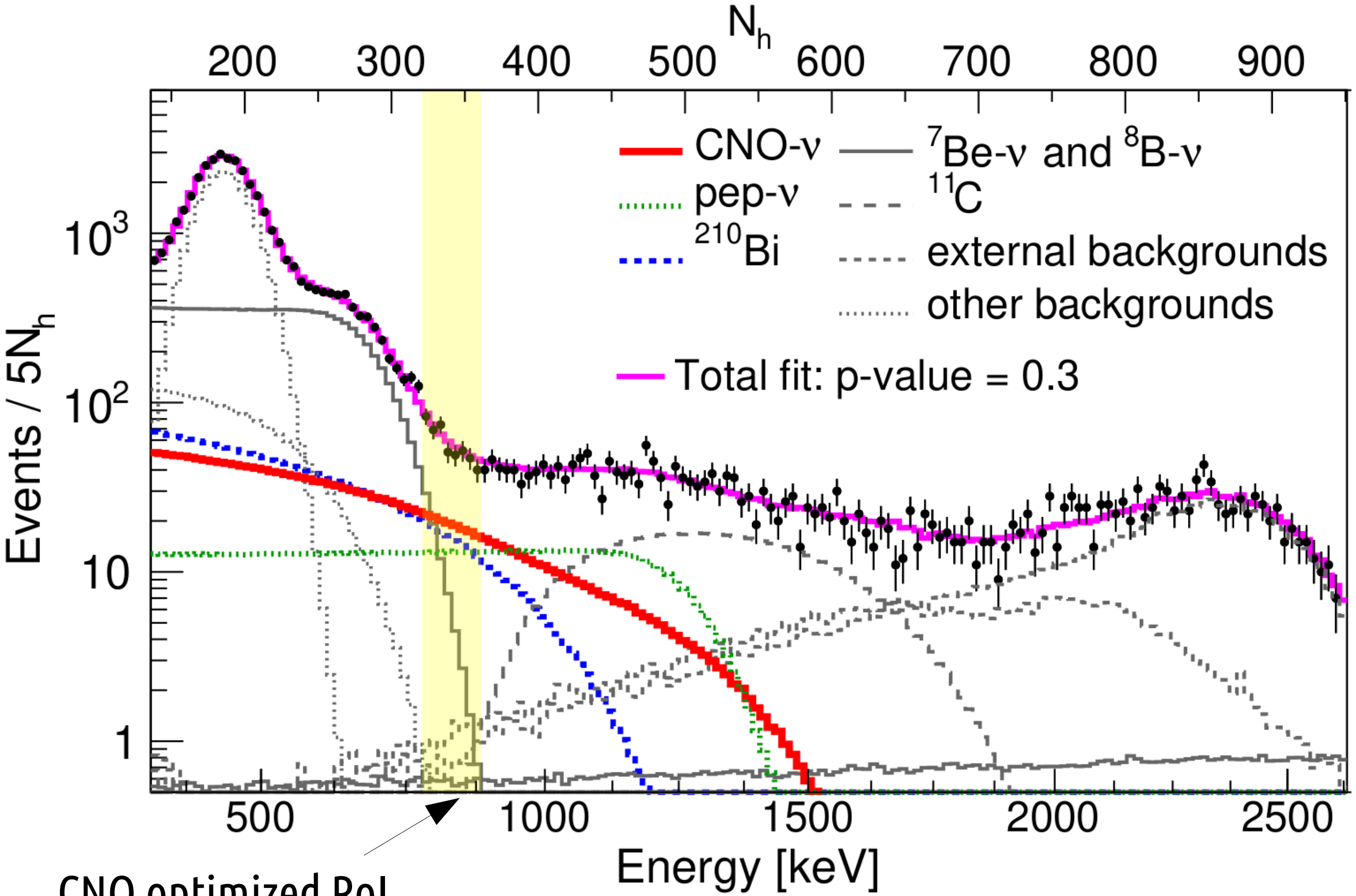
^{210}Po activity: R(minimum) = R(^{210}Bi) + R(Vessel)

R(Vessel) > 0 → Upper limit → lower limit for CNO (anti-correlation)

Bi < (11.5 ± 1.0) cpd/100t (stat + sys) Systematic uncertainty (uniformity): 0.8 cpd/100

Final constraint: ^{210}Bi < (11.5 ± 1.3) cpd/100t

CNO neutrino analysis



CNO optimized RoI

Main ingredients in the spectral analysis:

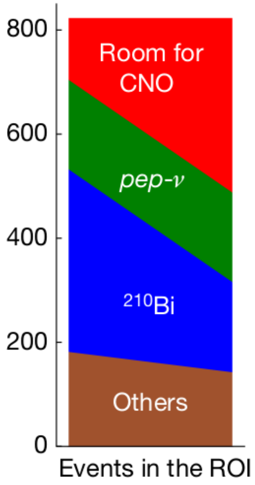
A) pep 1.4%
Gaussian penalty

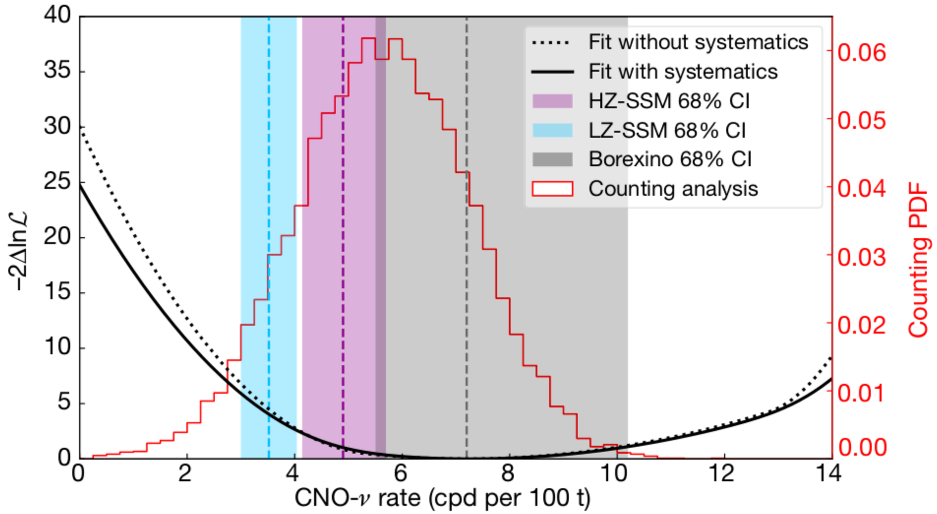
B) ^{210}Bi 11%
Semi-Gaussian penalty

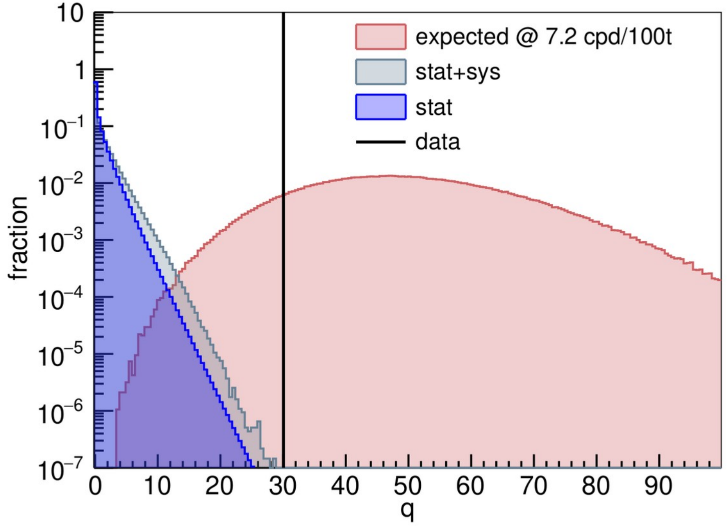
1. Multivariate Montecarlo Fit

2. Counting Analysis (RoI)
Analytical modelling
(consistency check)

Final results about CNO







Systematics: Response, resolution, spectral shapes and LY: **σ_L = -0.5, σ_R= +0.6** (5.1 σ significance)

Hypothesis CNO=0 excluded at 5.0 σ (99%CL) Model compatibility: 0.5σ (HZ), 1.3σ (LZ)

Result (68% CL stat + sys) = 7.2 $_{-1.7}^{+3.0}$ cpd/100t

LZ disfavored at 2.1 σ including other fluxes from pp-chain (Borexino only)

Updating the table with CNO neutrinos

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^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3 \pm 1.1)_{0.7}^{+0.4}$	$(4.99 \pm 0.11_{-0.08}^{+0.06}) x 10^9$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.43 \pm 0.36)_{-0.22}^{+0.15}$ [HZ] $(2.65 \pm 0.36)_{-0.24}^{+0.15}$[LZ]	$(1.27 \pm 0.19_{-0.12}^{+0.08}) x 10^8$ [HZ] $(1.39 \pm 0.19_{-0.12}^{+0.08}) x 10^8$[LZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$(5.68_{-0.41-0.03}^{+0.39+0.03}) x 10^6$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8 x 10^5$ (90% CL)
CNO	**Nature 2020 (THIS WORK)**	$\mathbf{7.2_{-1.7}^{+3.0}}$	$\mathbf{7.0_{-2.0}^{+3.0} x 10^8}$

Thank you very much!

EPS

G. & V. Cocconi Prize
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