Experimental detection of the CNO cycle

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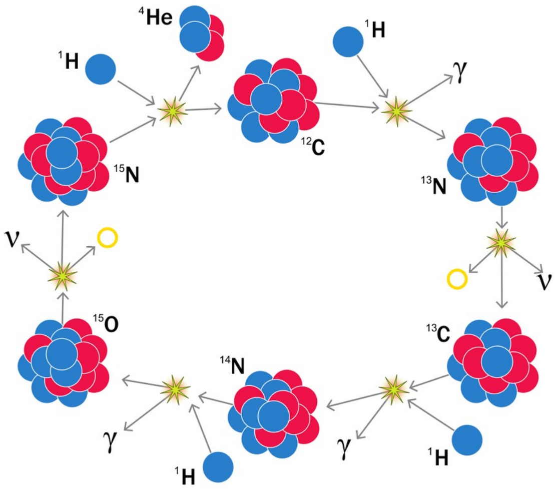
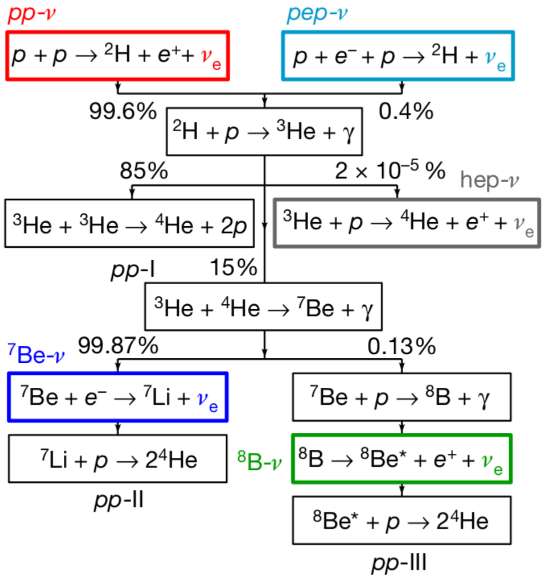


BOREXINO GRAN SASSO

MG16 5-10 JULY 2021
SIXTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

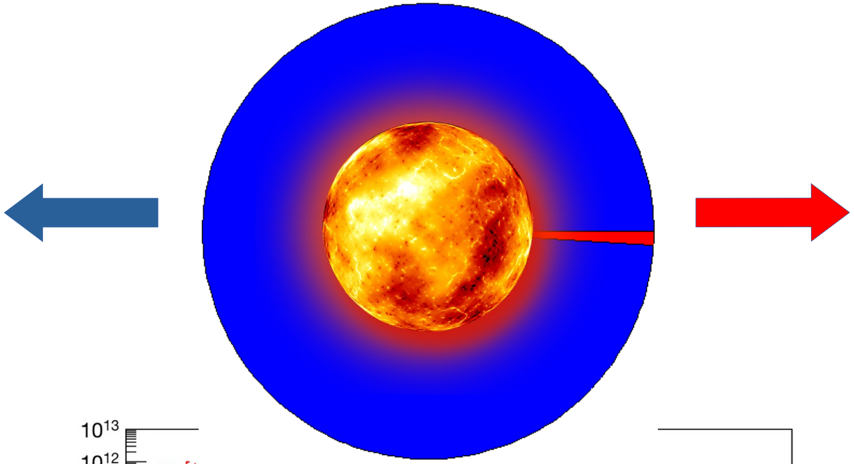
pp vs CNO Competition

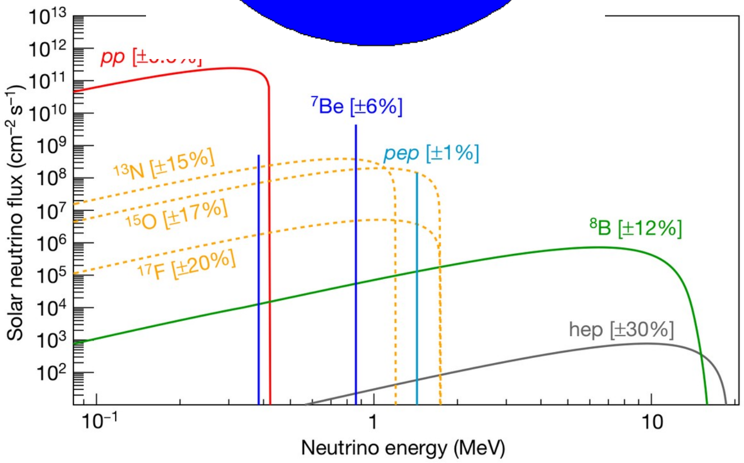
pp chain
(99%)



Dominant in the sun

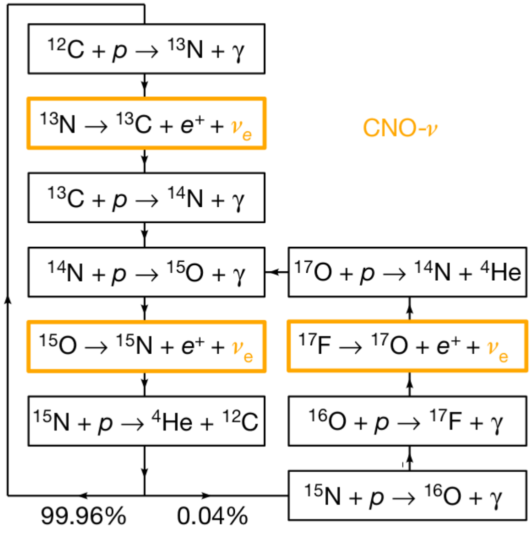
T_{core} ~ 15 x 10^6 K





Solar neutrinos: astro & particle physics

CNO cycle
(1%)



- dominant in stars 1.3 heavier than sun
- crucial for the solar *metallicity problem*

Neutrinos from the sun

Solar luminosity

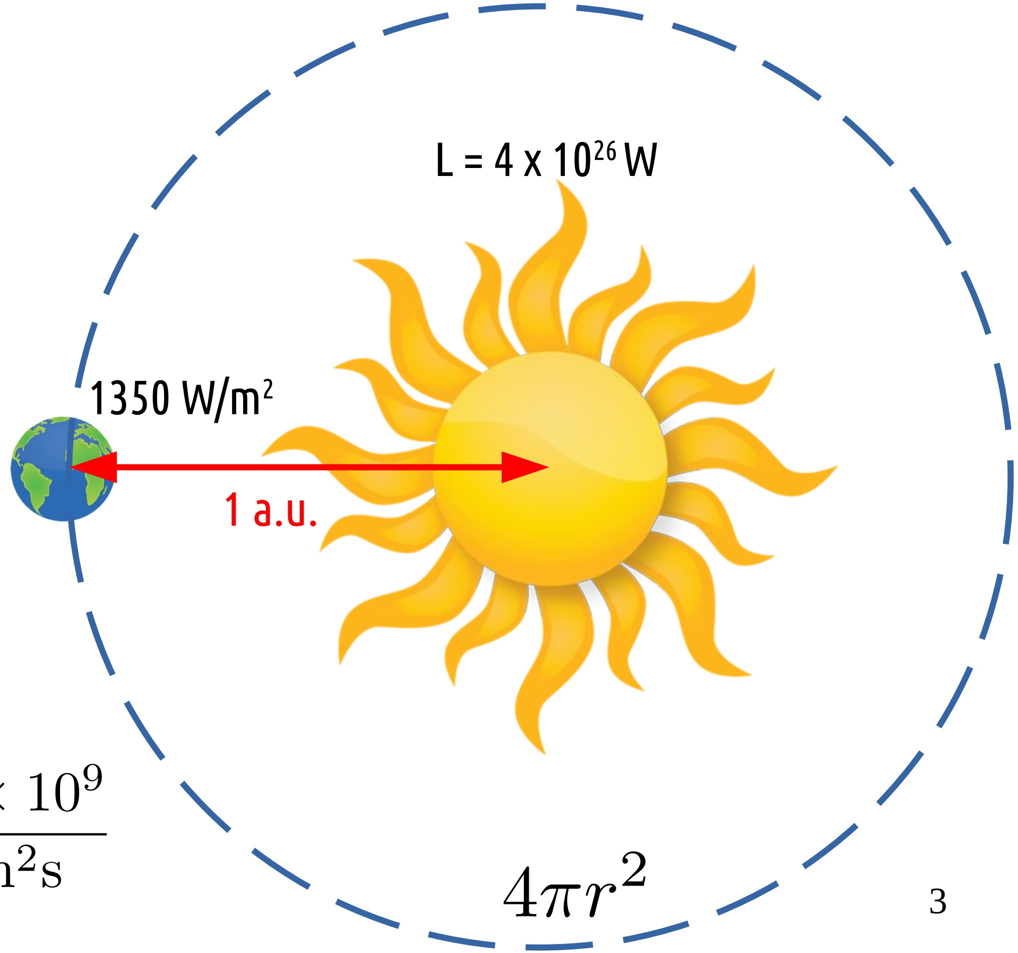
$$L_\odot \approx 4 \times 10^{26}\mathrm{W}$$

Reaction rate

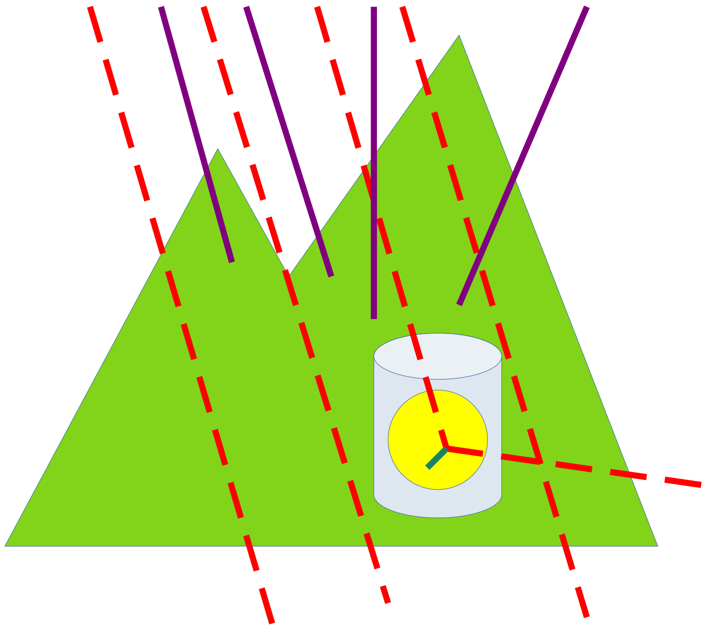
$$R = \frac{L_\odot}{\Delta M c^2} \approx \frac{2.4 \times 10^{39}\ \mathrm{MeV/s}}{26\ \mathrm{MeV}} \approx \frac{10^{38}}{s}$$

Neutrino flux on the earth

$$\Phi_\nu(\mathrm{Earth}) = 2\frac{R}{4\pi d^2} \approx 2\frac{10^{38}}{4\pi(\mathrm{a.u.})^2} \approx \frac{65 \times 10^9}{\mathrm{cm}^2\mathrm{s}}$$



Building a solar neutrino detector



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

Ingredients:

- Underground
- High radio-purity
- Large mass

An example

$$\Phi_\nu(^7\mathrm{Be}) \approx 0.5 \times 10^9 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Targets in 100 ton of C_9H_{12}

$$\mathcal{N}_e \approx 3.3 \times 10^{31}$$

Average cross section

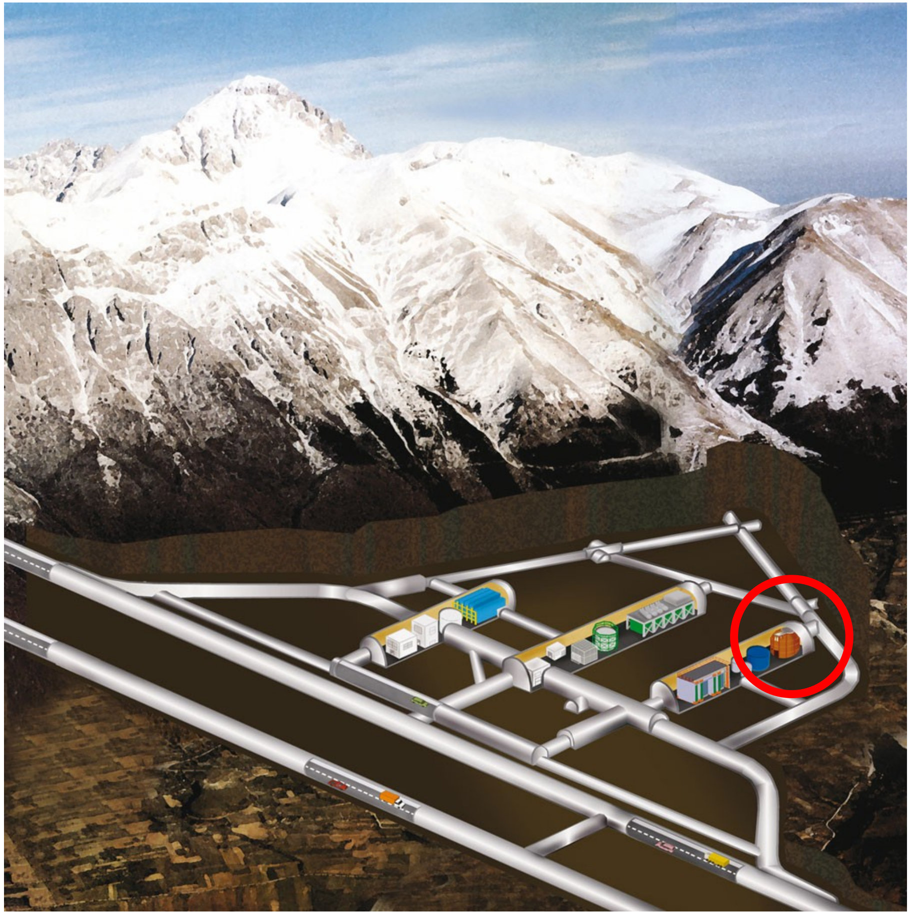
$$\langle \sigma_{\nu e} \rangle \approx 3.4 \times 10^{-45} \mathrm{cm}^2$$

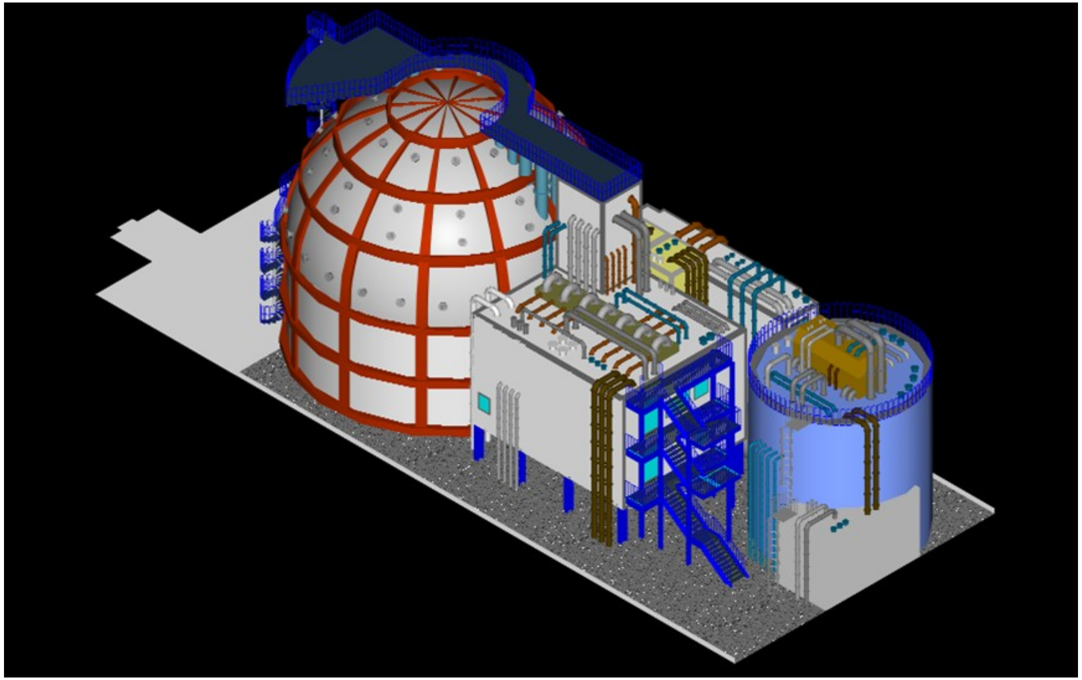
Interaction rate

$$\mathcal{R} = \mathcal{N}_e \Phi_\nu \langle \sigma_{\nu e} \rangle \approx 48 \ \mathrm{cpd}/100\mathrm{t}$$

1 cpd/100t ~ 0.1 nBq/kg !!!

The BOREXINO detector

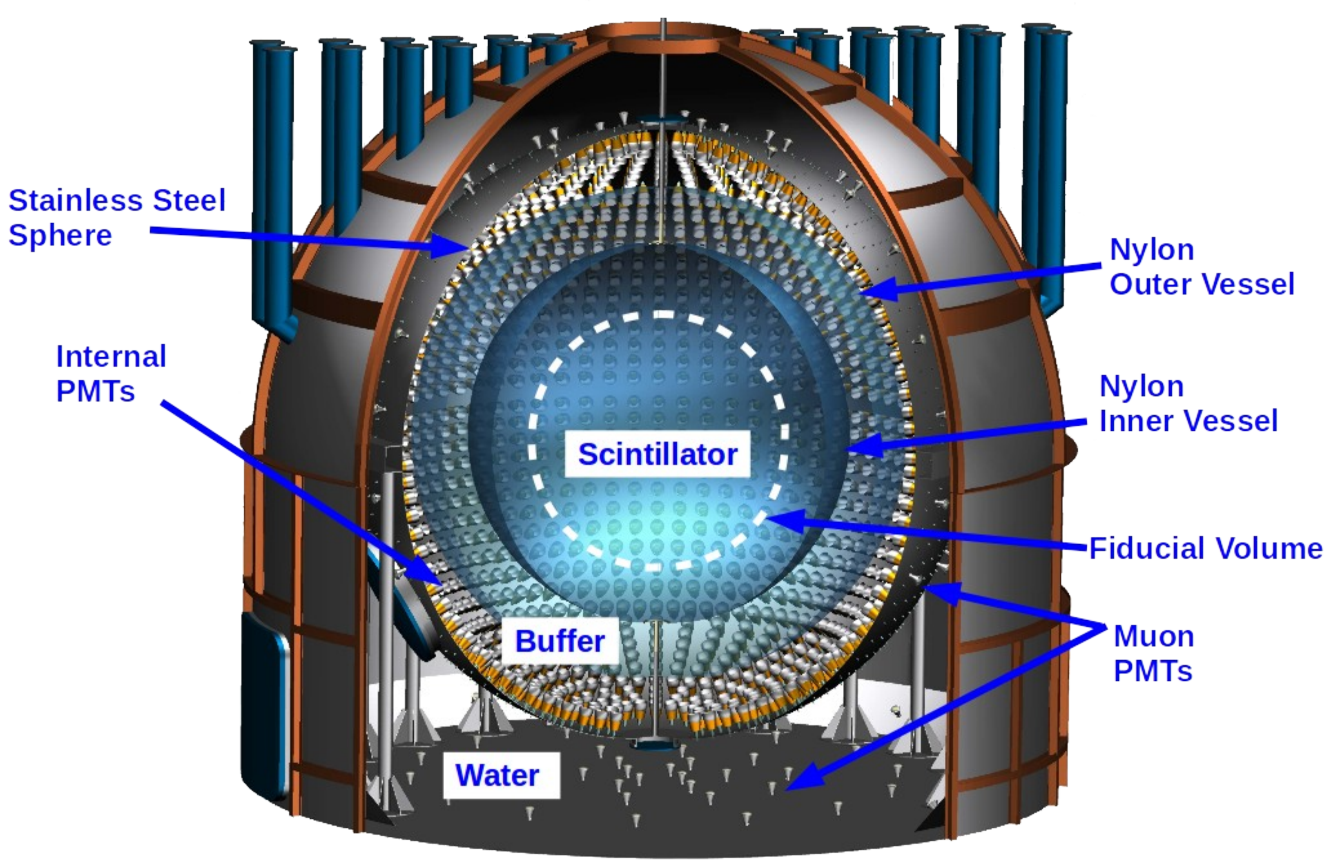




Laboratori Nazionali del Gran Sasso – INFN (Hall C)

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

The Borexino detector



Sphere of diameter
13.7 m (~1300 m^3)

Target (Inner vessel): ~300 ton of liquid scintillator

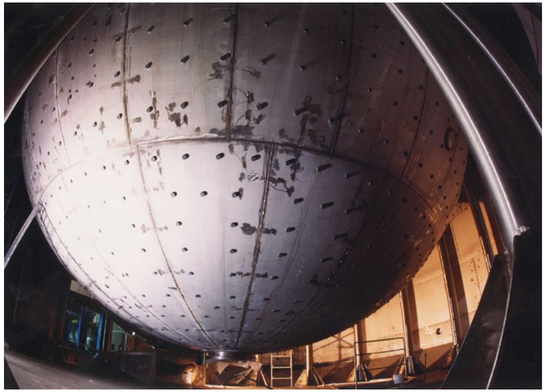
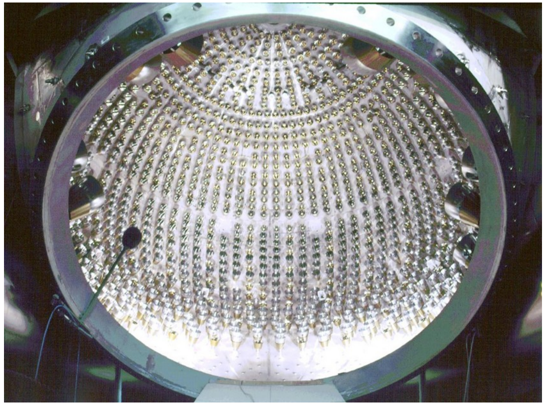
Nylon balloon 125 μm

2212 PMTs (nominal)

~35% optical coverage

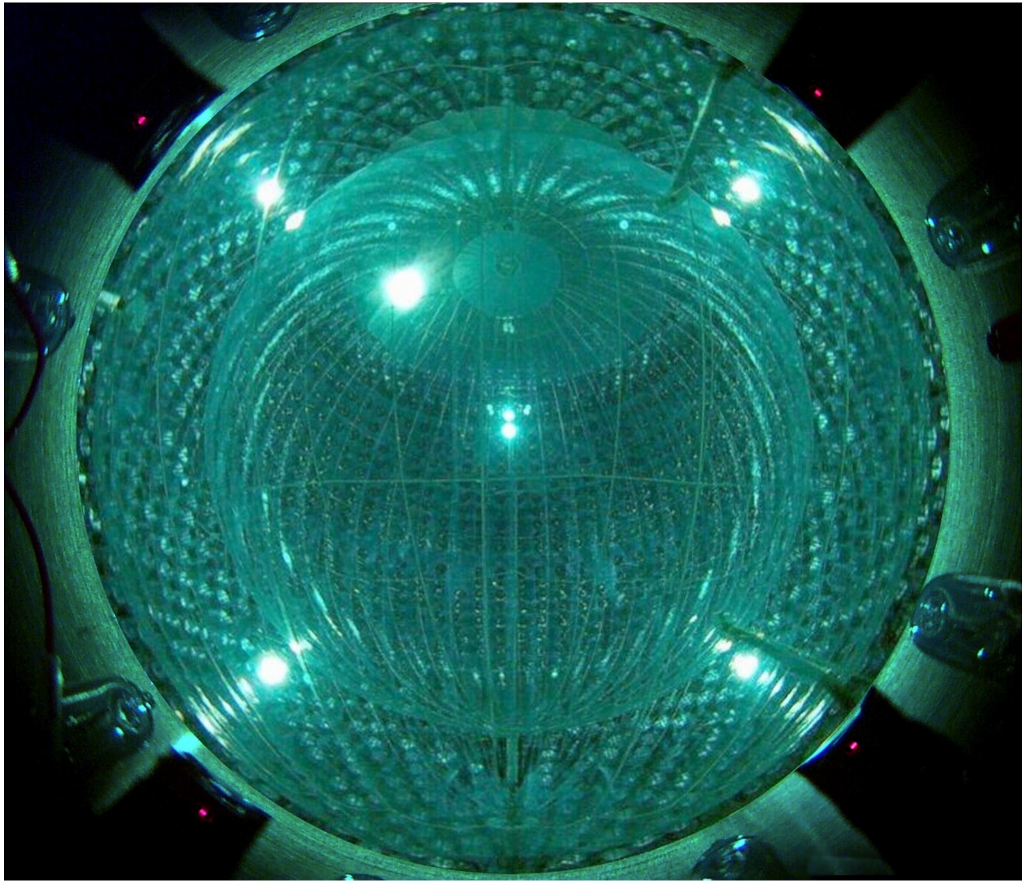
Water Cherenkov Veto
(d = 18 m) 2000 m^3 (208 PMT)

Borexino's pictures


Under construction, before the filling

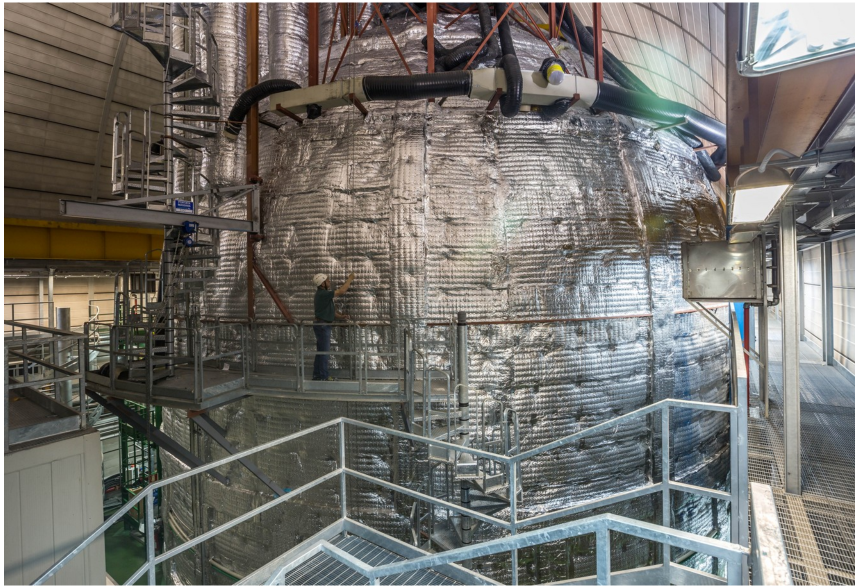
Borexino today



From monitoring camera

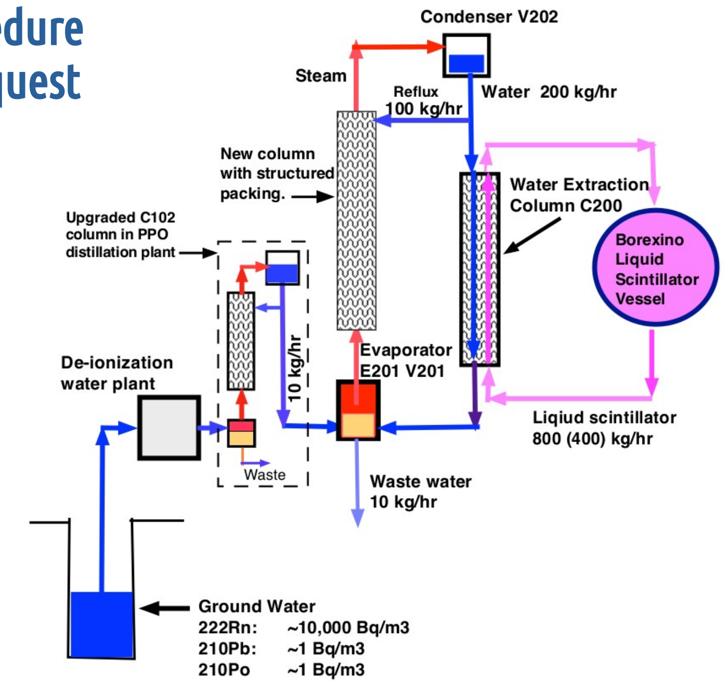
Software reconstruction of the inner vessel

Hall C



The water extraction campaign

Key procedure for CNO quest



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

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

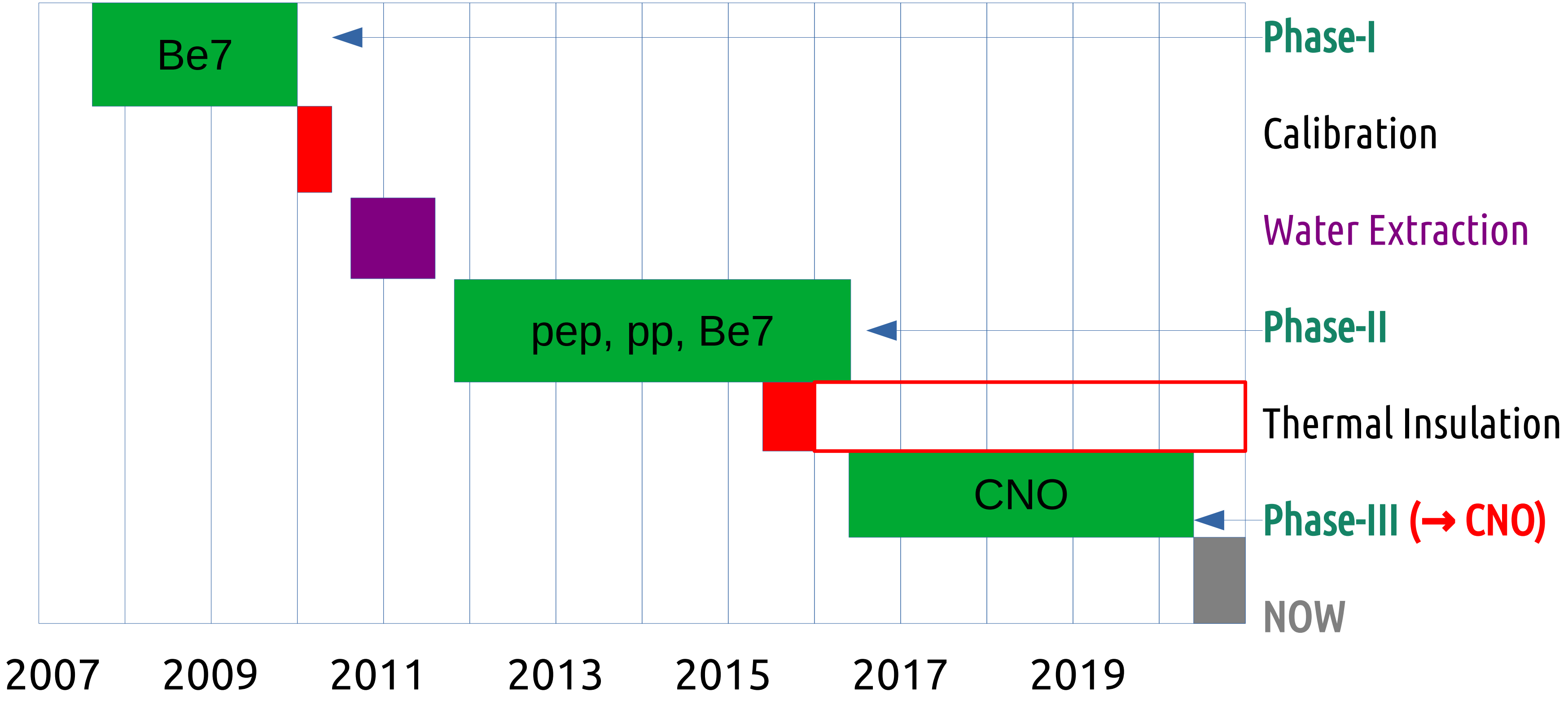
	Before [cpd/100t]	After [cpd/100t]
^{210}Bi	~40	~10
^{85}Kr	~30	~5
^{210}Po	>2000	<30 (decay)

^{238}U, ^{232}Th < 10^{-19} g/g

^{39}Ar, ^{40}K << 1 cpd/100t

Expected CNO ~ 5 cpd/100t

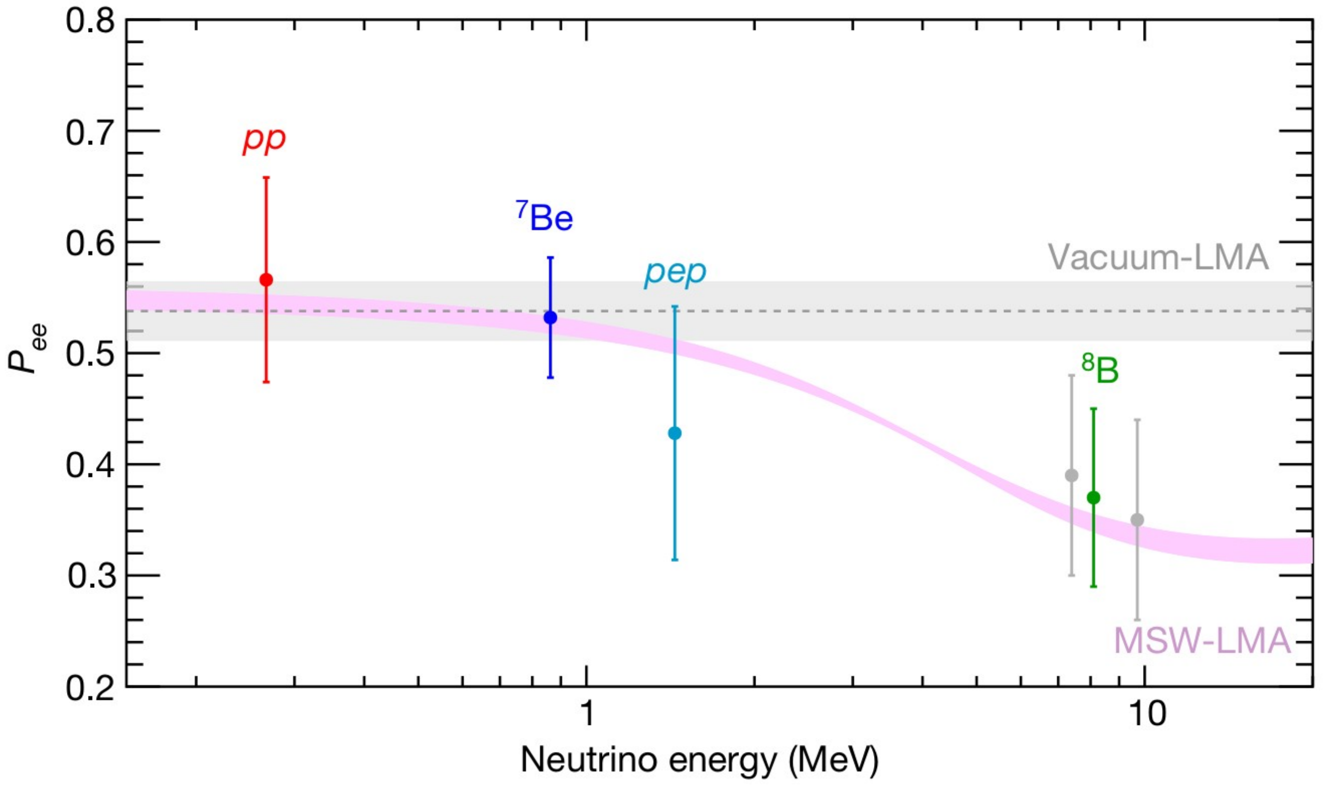
The three phases of Borexino



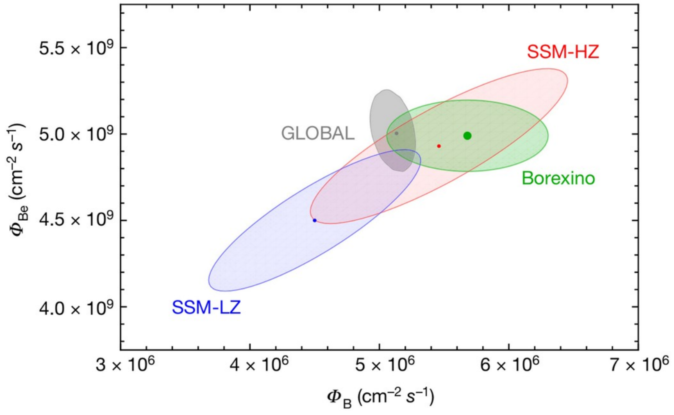
Results from Borexino (2018)

Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)_{-10}^{+6}$	$(6.1\pm0.5)_{-0.5}^{+0.3}x10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)_{-0.7}^{+0.4}$	$(4.99\pm0.11)_{-0.08}^{+0.06}x10^{9}$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.7\pm0.4)_{-0.2}^{+0.1}$	$(1.3\pm0.3)_{-0.1}^{+0.1}x10^{8}$
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}x10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8x10^{5}$ (90% CL)
CNO	PRL 2010, Nature 2018 (upper limit)	<8.1 (95% CL)	$<7.9x10^{8}$ (95%CL)

Implications of Borexino results



P_{ee} survival probability with Borexino data only!

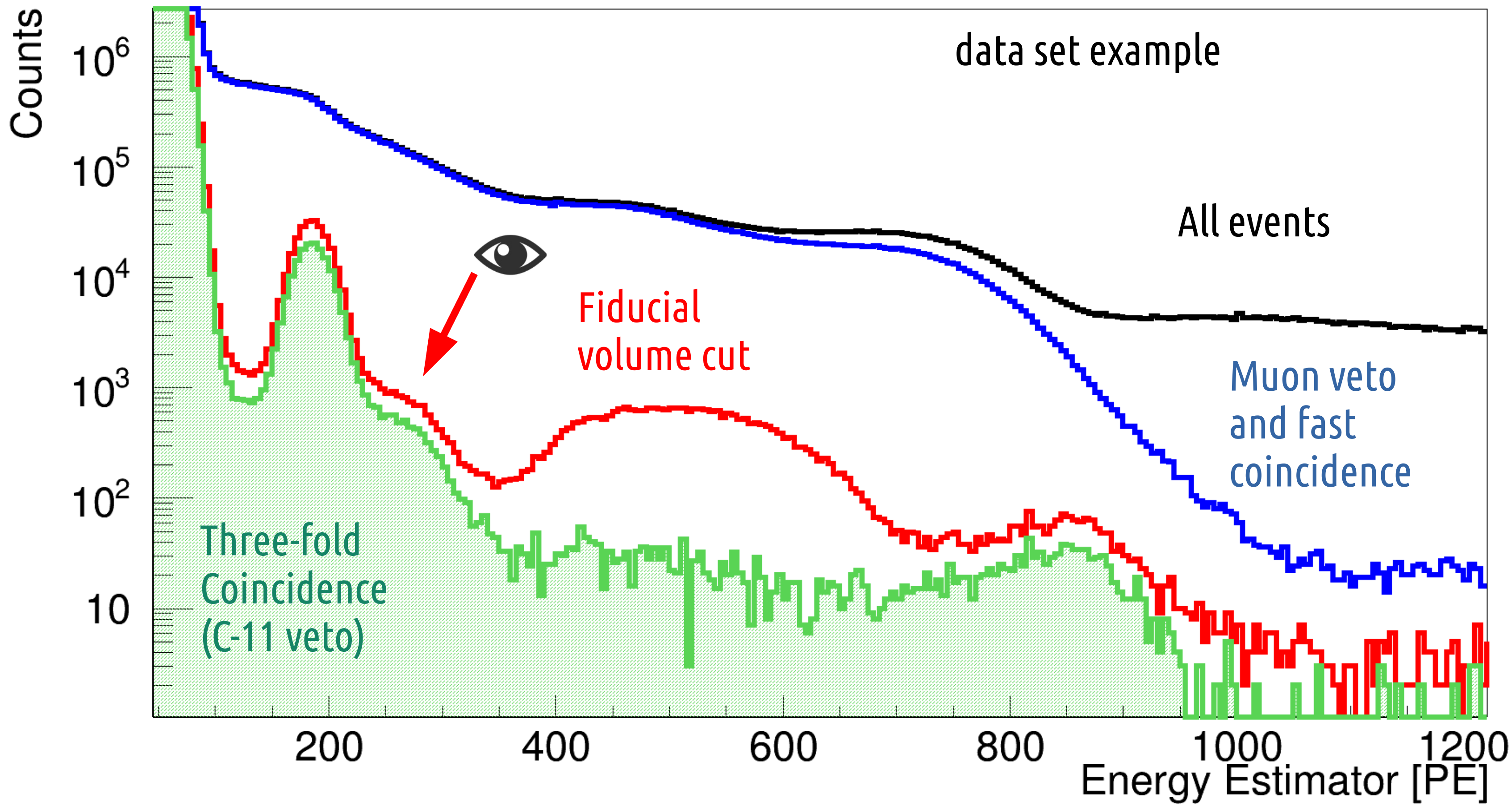


Precise measurements era:

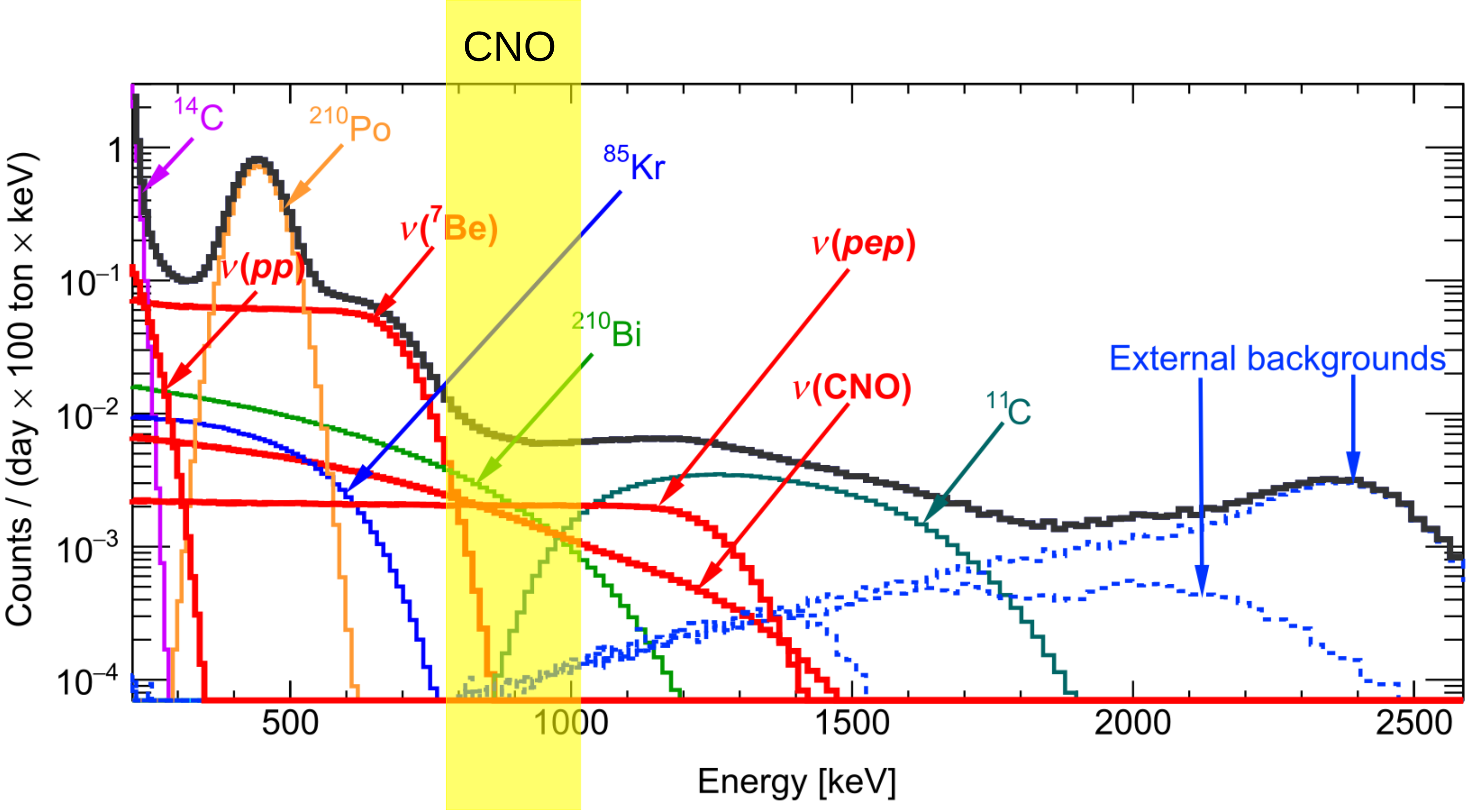
Probing the **MSW-LMA** scenario

Low metallicity **disfavored at 1.8 σ**

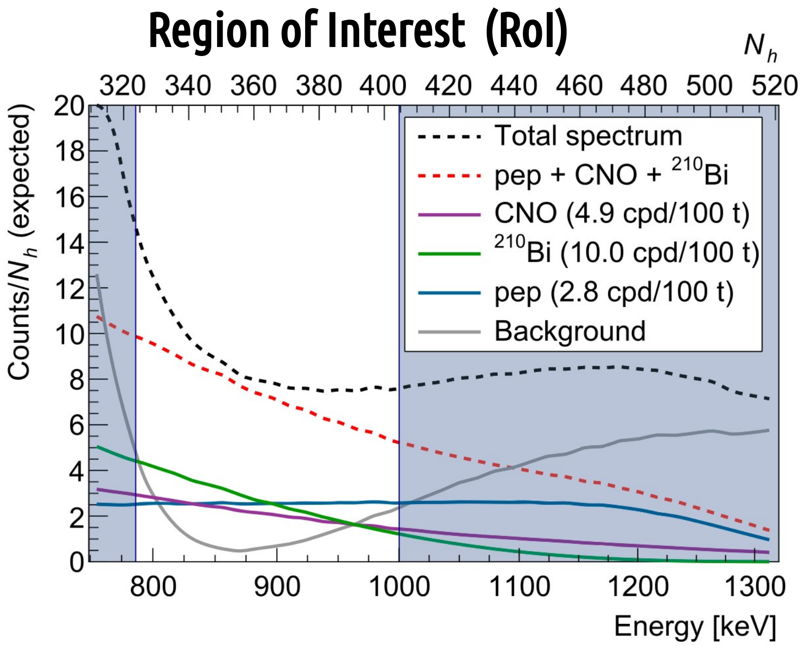
The Borexino energy spectrum

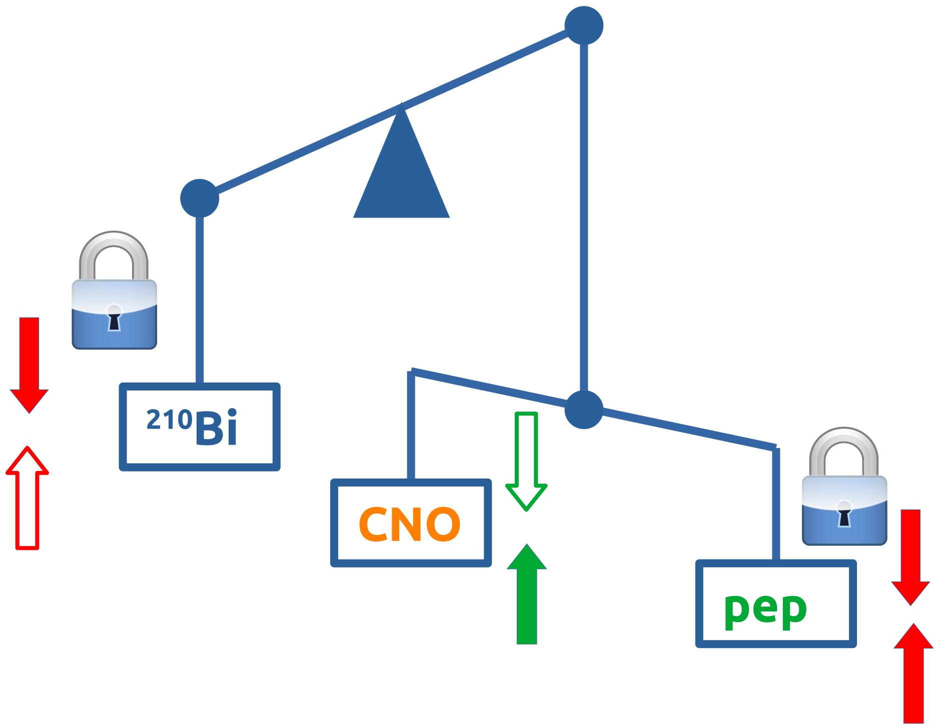


Understanding the spectrum



Sensitivity to CNO neutrinos





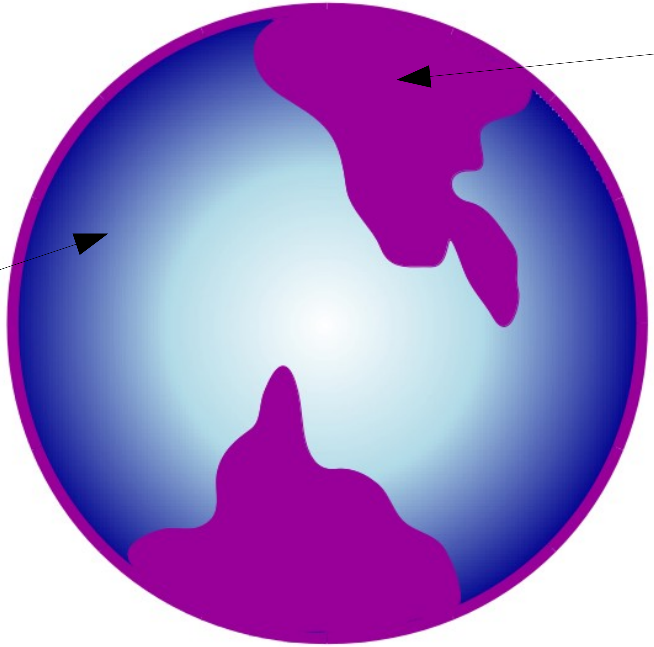
CNO <> pep <> ^{210}Bi correlation
Core of the problem: *counting analysis* in the RoI

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

More about independent ^{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 assuming the secular equilibrium



Convection:
^{210}Po from the outer regions

Thermal Insulation program

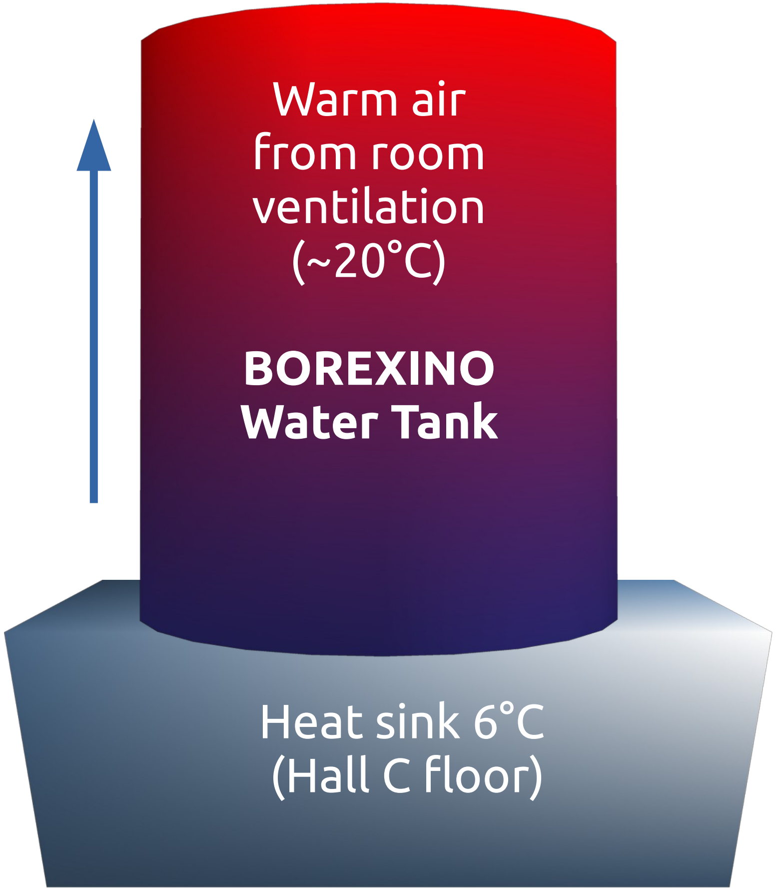
Diffusion:
Very slow
D ~ 10^{-9} m^2/s
(diffusion coefficient)

Scenarios:
1. Plateau → Symmetric Constraint
2. Minimum → Upper Limit

Thermal insulation program

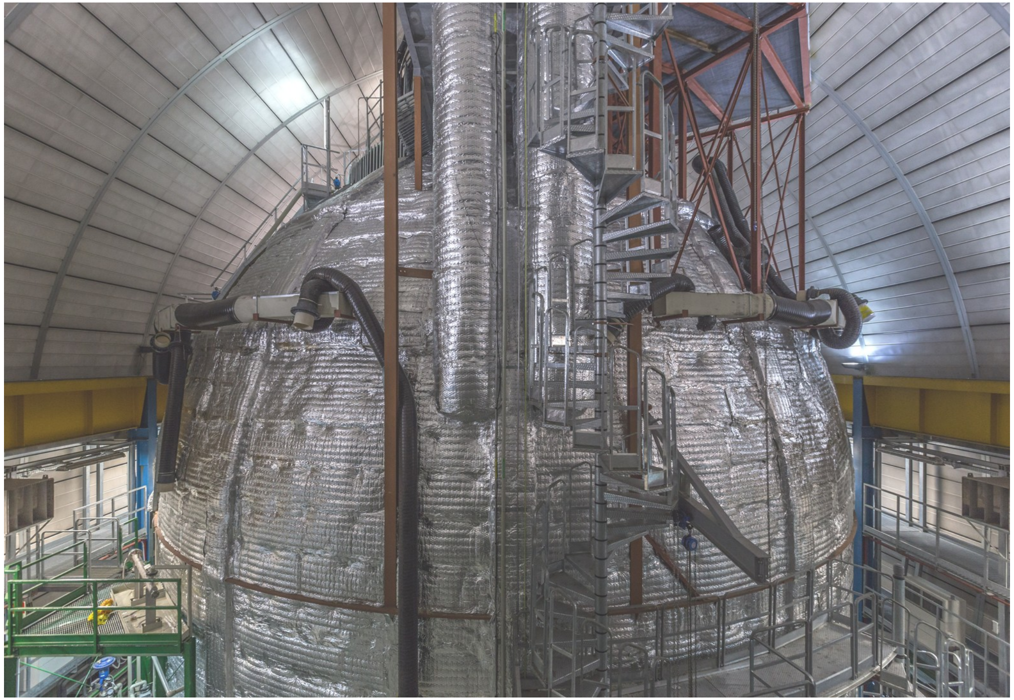
Idea:
Strong and stable temperature **vertical gradient** prevents convective motions

Milestones:
2014: installation of temperature probes
Mid-2015: *beginning* of the insulation program
Late 2015: turning off of the *water recirculation system* in the water tank
2016: first operation of the *active temperature control system* (ATCS)
Early 2019: change of the ATCS *set point*
Late 2019: installation and commissioning of the H*all C ACTS*



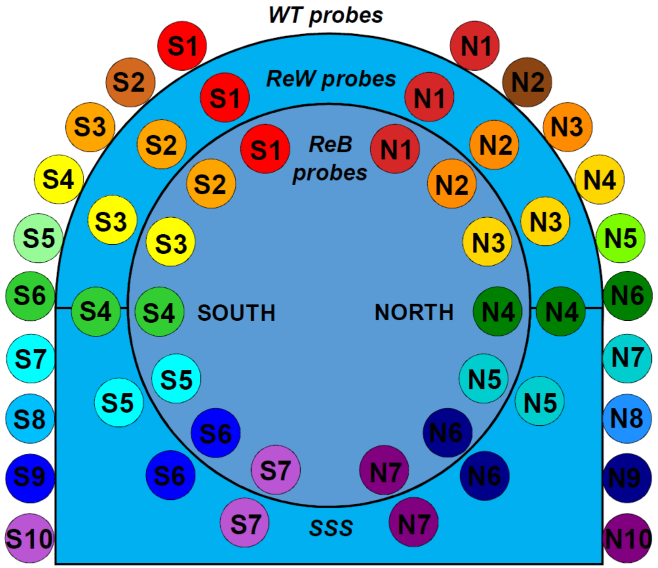
Thermal Insulation

Before the thermal insulation
(Mid-2015)

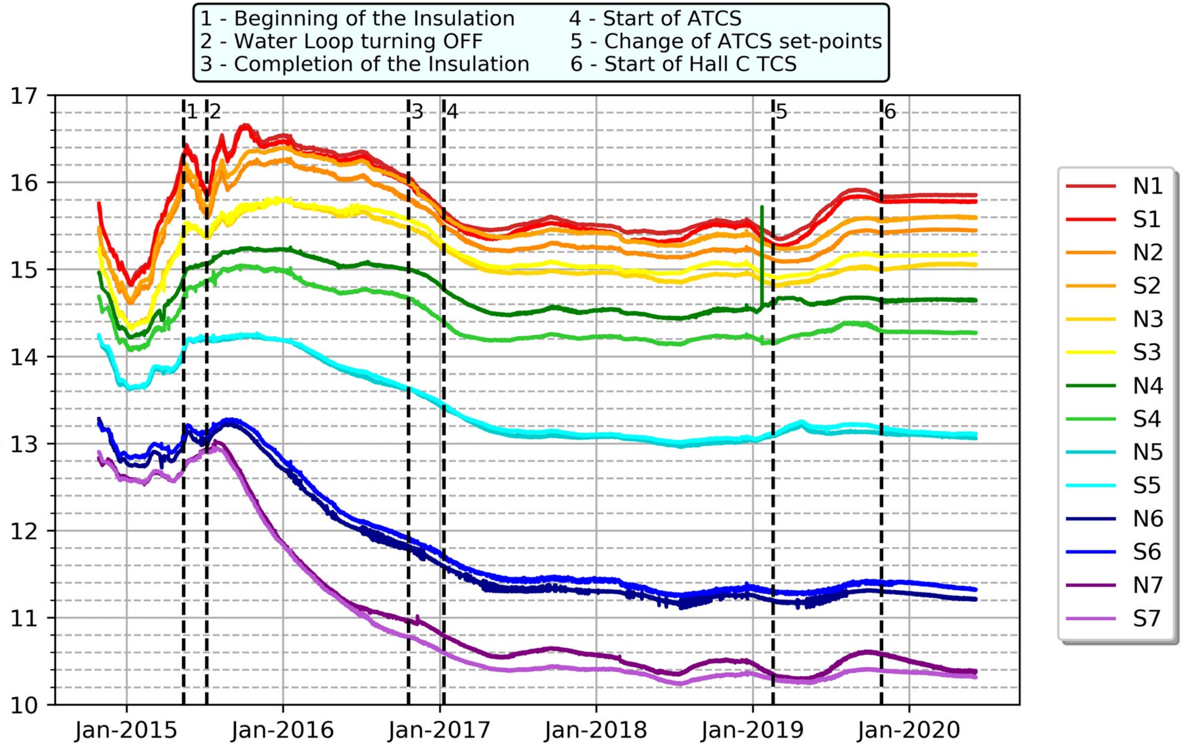


After the thermal insulation
(Beginning of 2016)

Effects on the temperatures

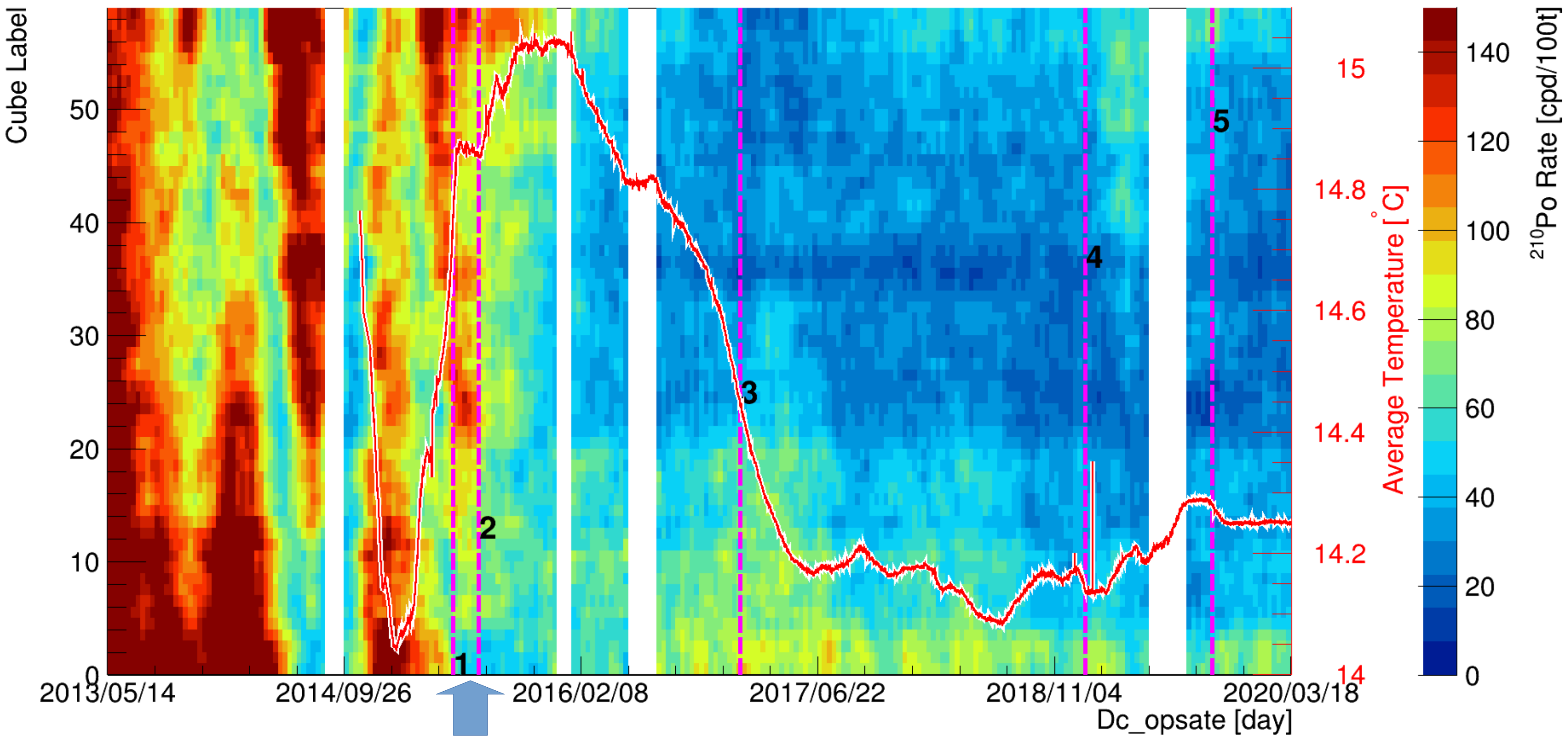


Temperature probes



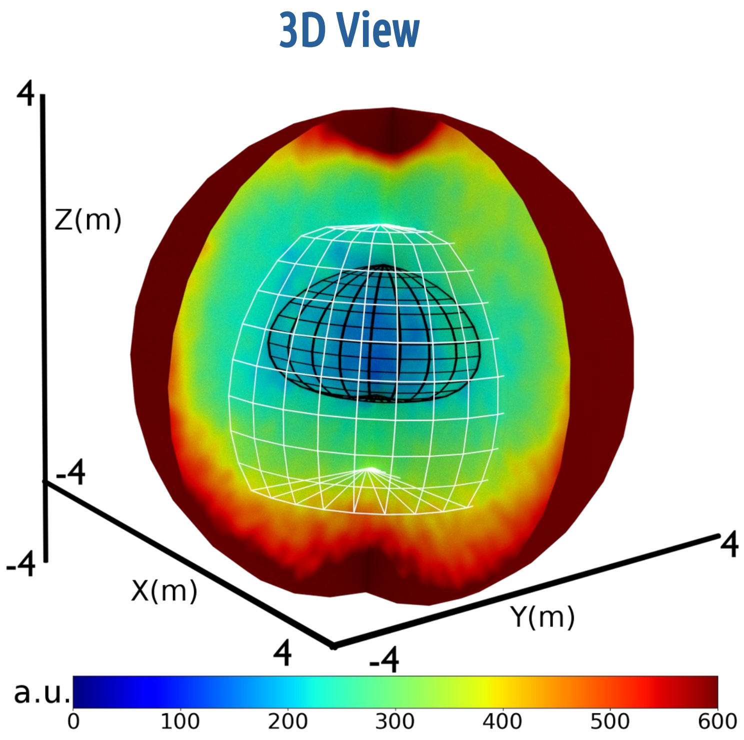
Probes closer to the inner detectors
with thermal program milestones

Effects on ^{210}Po



Crucial reduction of the convective motions

The low polonium field



Minimum at z ~ 80 cm

Compatible with numerical fluid dynamics simulations

^{210}Po activity

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

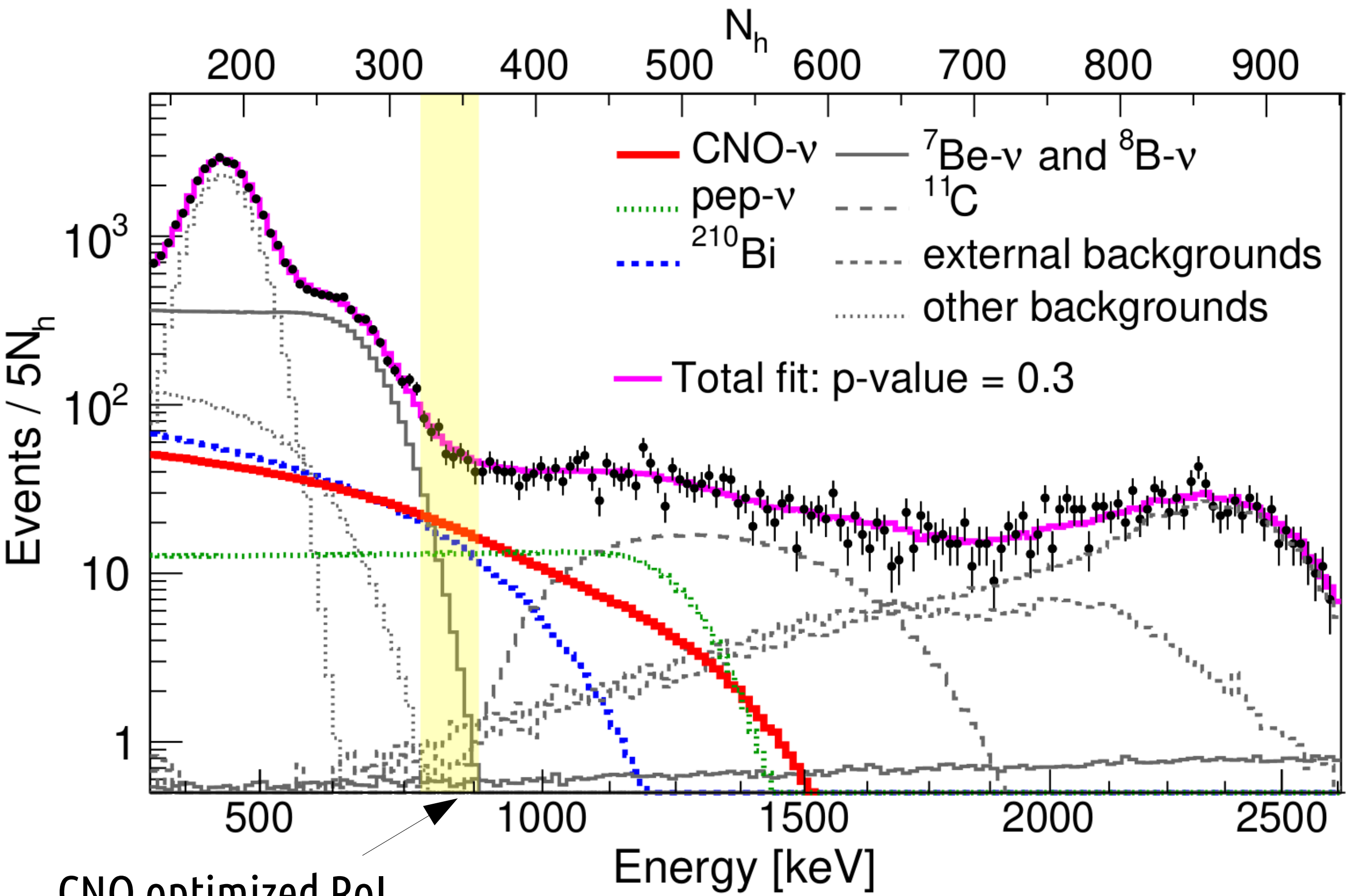
R(Vessel) > 0 → Upper limit → lower limit for CNO (anti-correlation)

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:

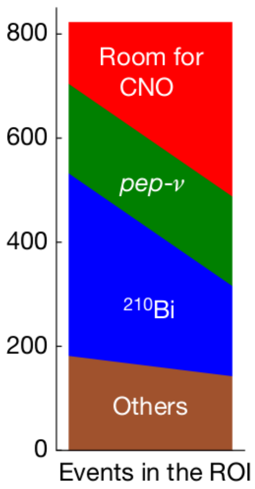
A) pep 1.4%
Simmetric penalty

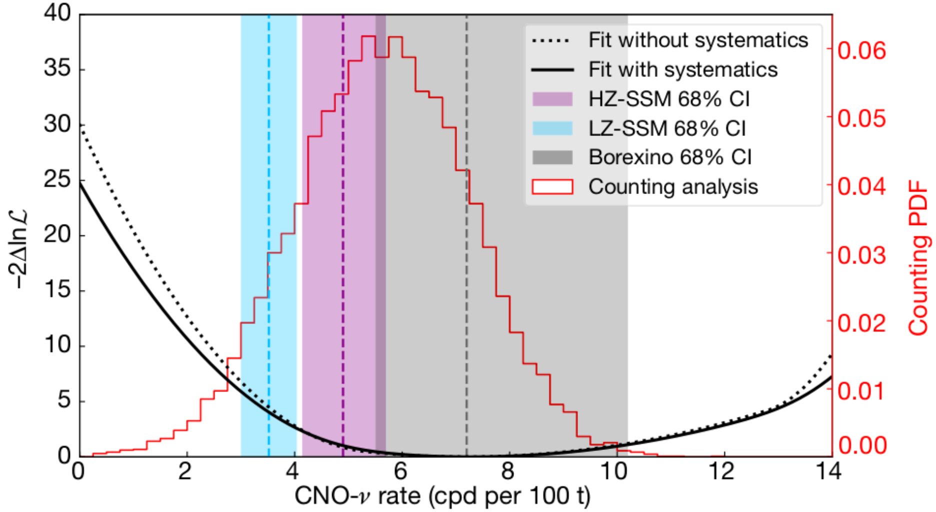
B) ^{210}Bi 11%
Asymmetric penalty

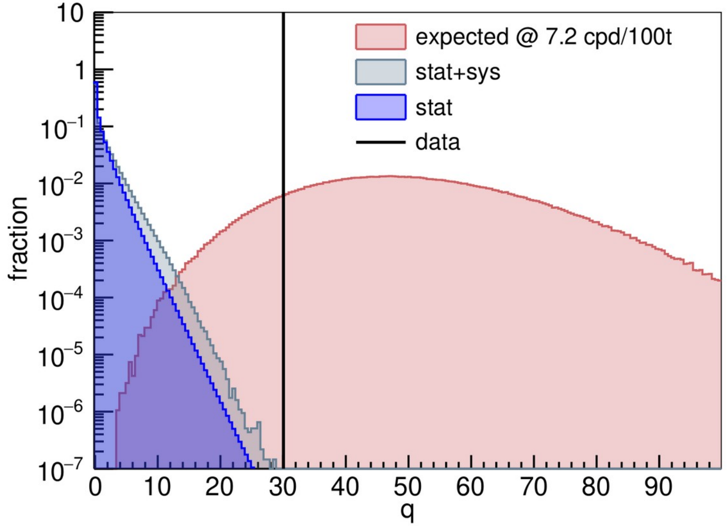
1. Multivariate Montecarlo Fit

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

Final result







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

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hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8x10^{5}$ (90% CL)
CNO	Nature 2020 (THIS WORK)	$7.2_{-1.7}^{+3.0}$	$7.0_{-2.0}^{+3.0}x10^{8}$

Thank you very much!

EPS

G. & V. Cocconi Prize 2021

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