Detection of solar neutrinos from the pp-chain and CNO cycle in Borexino

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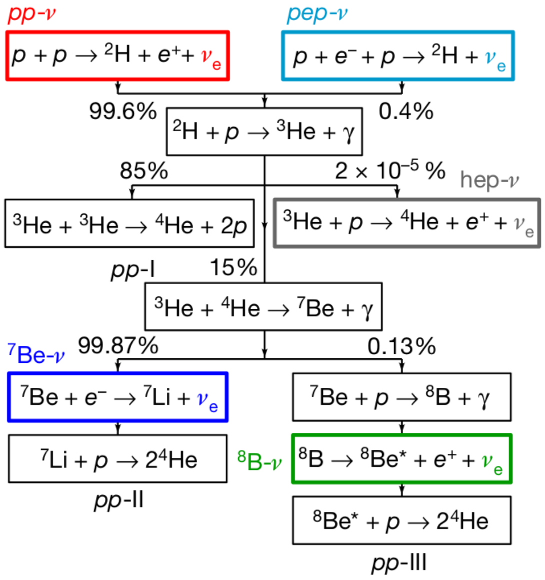
QUINTO INCONTRO NAZIONALE DI FISICA NUCLARE INFN 2022

2022, May 11th

Solar Neutrinos

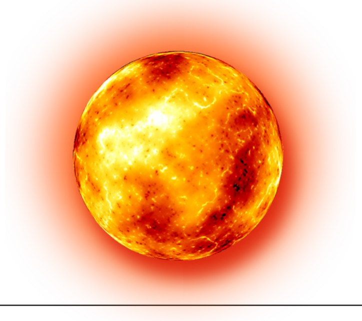
astro & particle physics

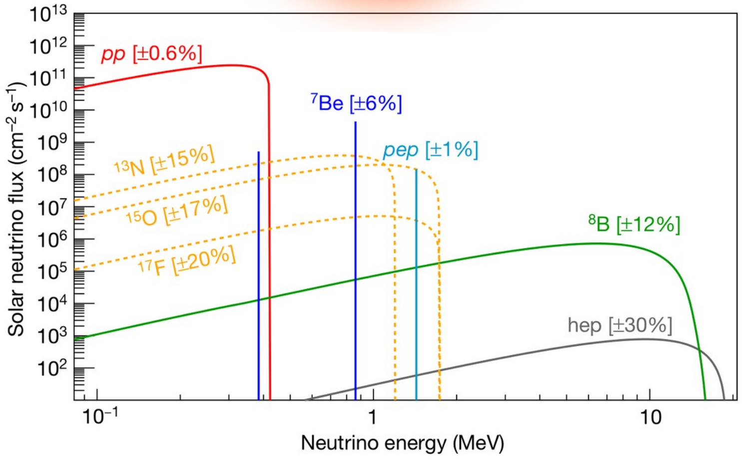
pp chain (99%)



Dominant in the sun

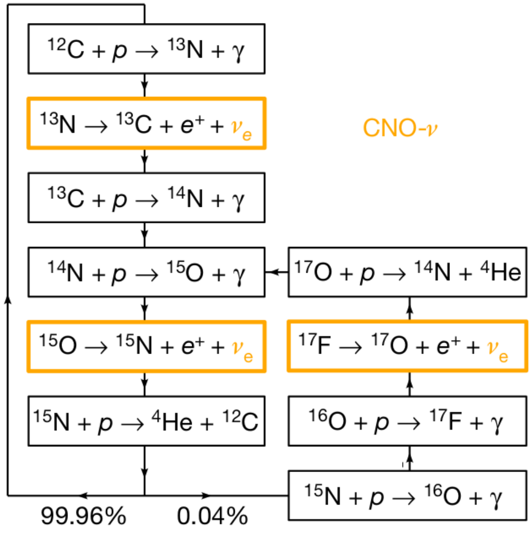
$T_{core} \sim 15 \times 10^6$ K





$$4p \rightarrow {}^4He + 2e^- + 2\nu_e + 26 MeV$$

CNO cycle (1%)



- Dominant in stars 1.3 heavier than sun
- Crucial for the solar *metallicity problem*

Neutrinos from the Sun

Solar luminosity

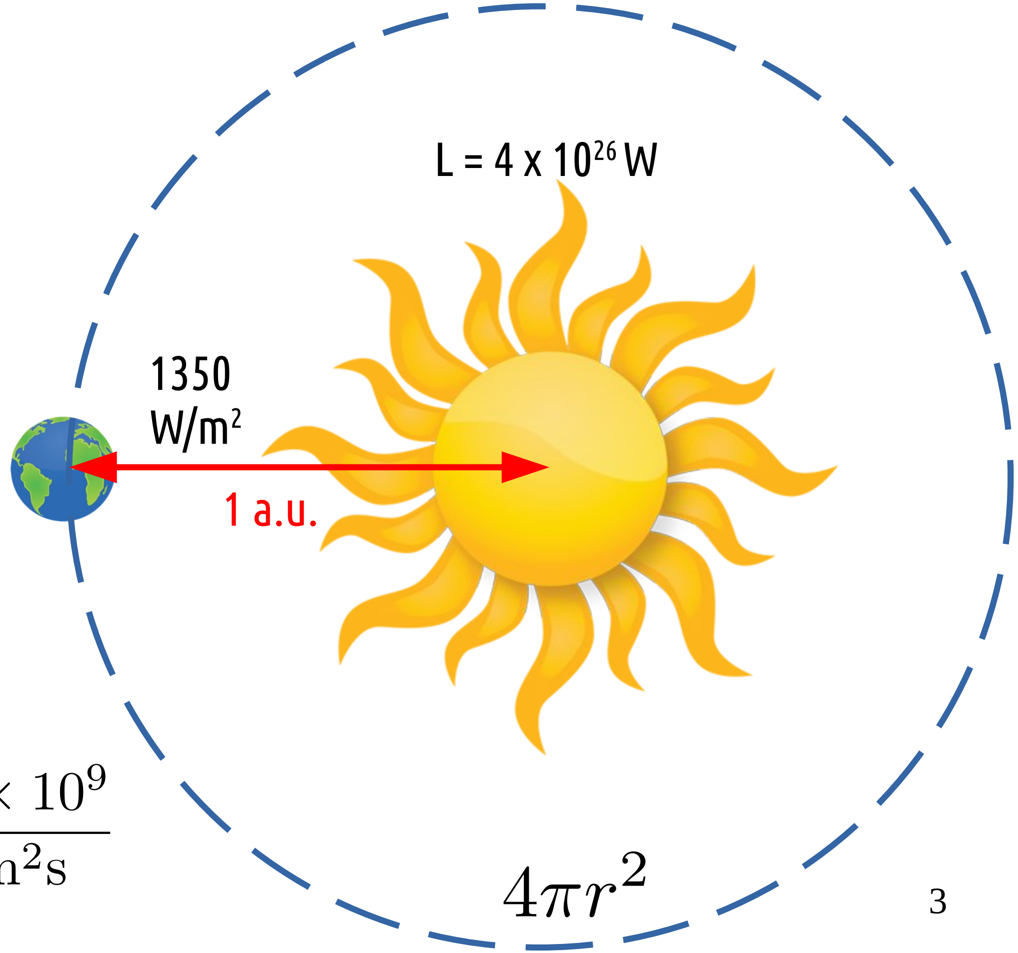
$$L_\odot \approx 4 \times 10^{26}\mathrm{W}$$

Reaction rate

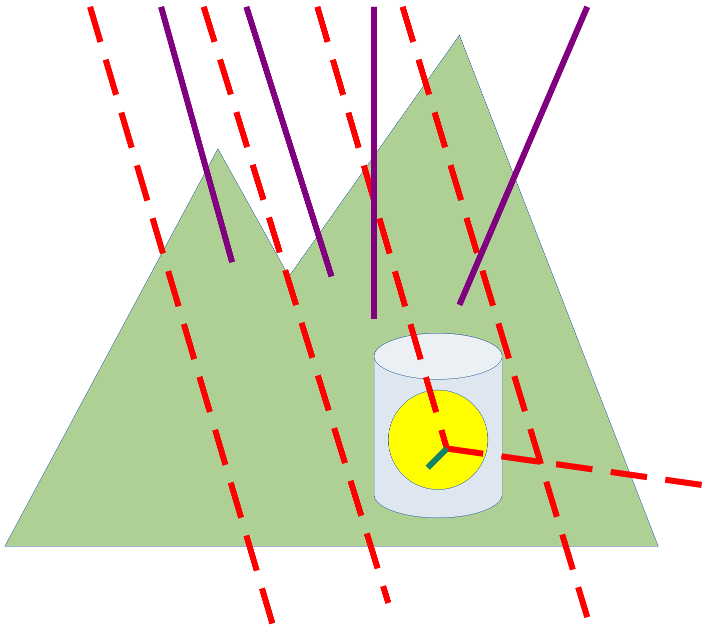
$$R = \frac{L_\odot}{\Delta M c^2} \approx \frac{2.4 \times 10^{39}\,\mathrm{MeV/s}}{26\,\mathrm{MeV}} \approx \frac{10^{38}}{s}$$

Neutrino flux on the earth

$$\Phi_\nu(\mathrm{Earth}) = 2\frac{R}{4\pi d^2} \approx 2\frac{10^{38}}{4\pi(1\mathrm{a.u.})^2} \approx \frac{65 \times 10^9}{\mathrm{cm^2 s}}$$



Building a solar neutrino detector



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

Ingredients:

- Underground
- High radio-purity
- Large mass

An example

$$\Phi_\nu(^7\text{Be}) \approx 5 \times 10^9 \text{cm}^{-2}\text{s}^{-1}$$

Targets in 100 ton of C_9H_{12}

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

Average cross section

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

Interaction rate

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

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

The Borexino saga

1988: S. Raghavan and S. Pakvasa, *Phys. Rev. D 37, 849-857 (1988)*

1990: idea of a sub-Mev solar neutrin detector. A real time neutrino detection

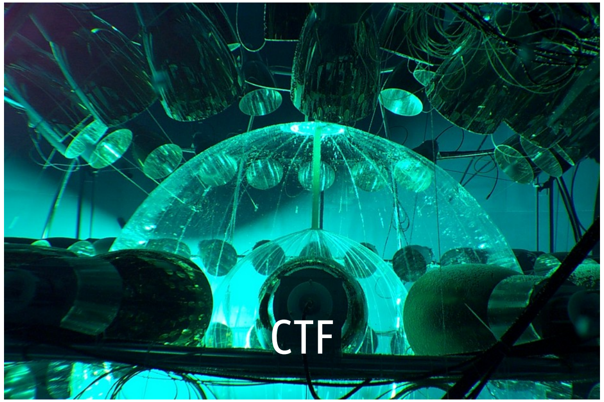
1995: CTF testing the record radiopurity

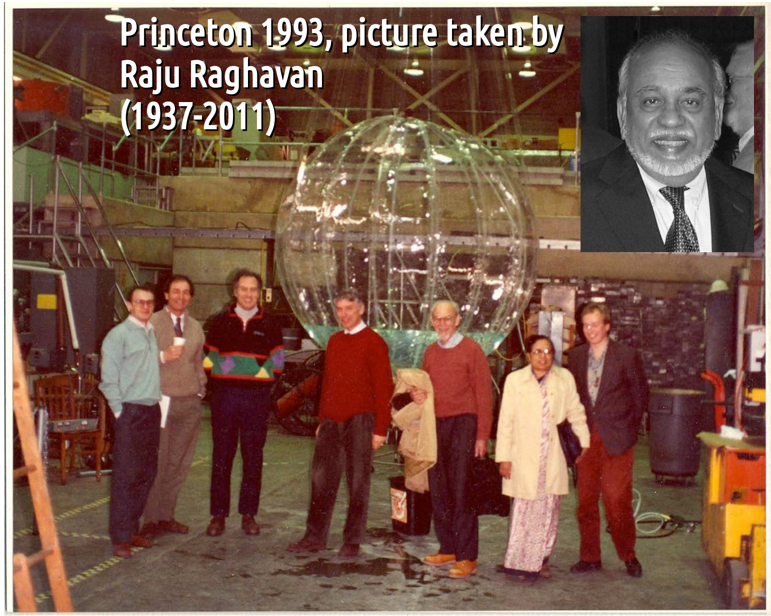
^{238}U, $^{232}Th < 10^{-16}$ g/g

$^{14}C/^{12}C < 10^{-18}$

1996-1997: Approval of the experiment

2007-2021: data taking

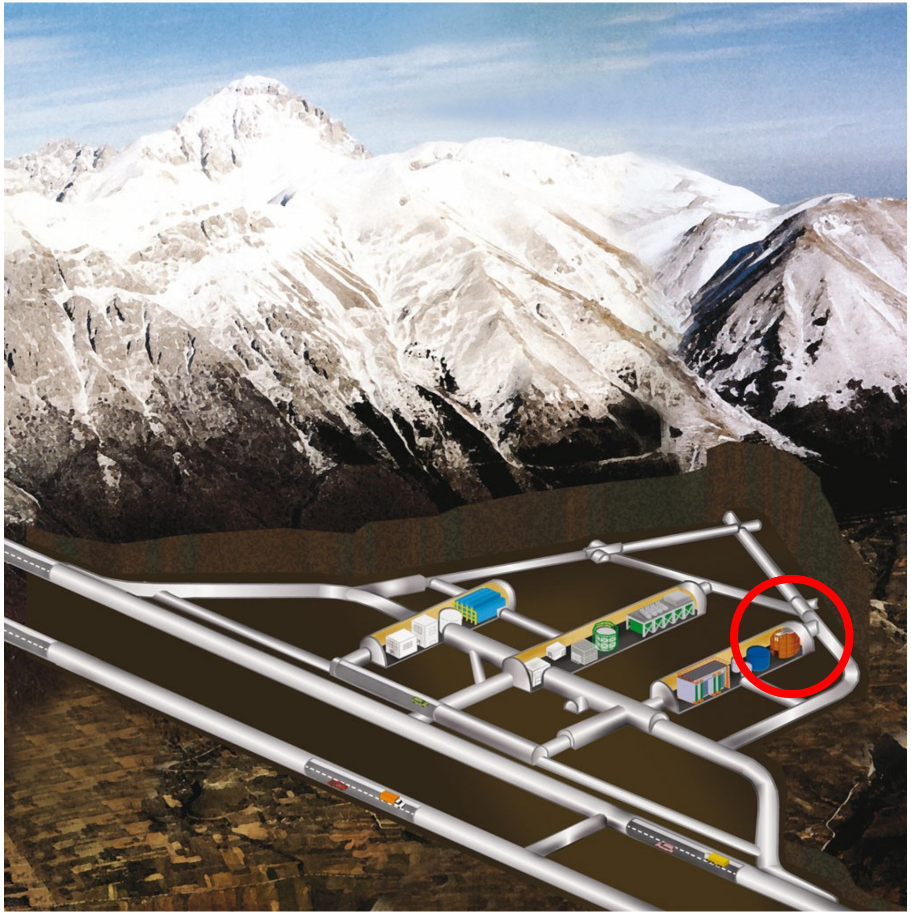


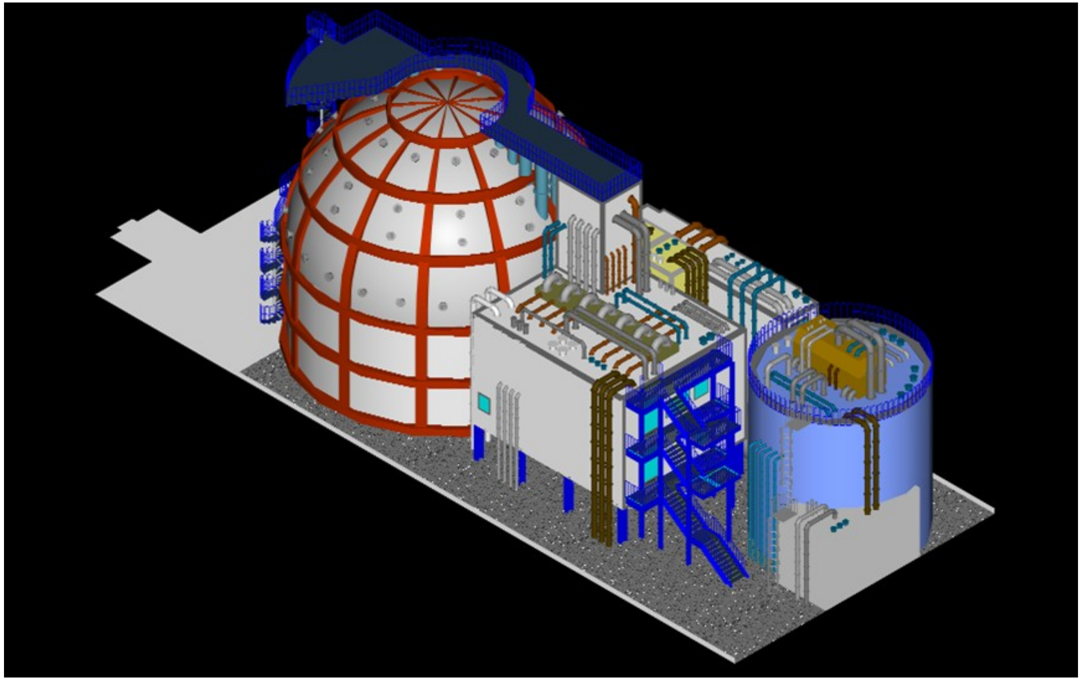


Three Borexino strategies:

- clean materials
- purification
- analysis methods

The BOREXINO detector





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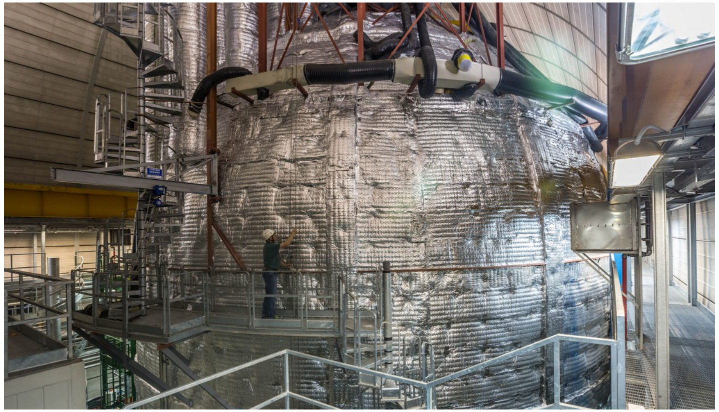
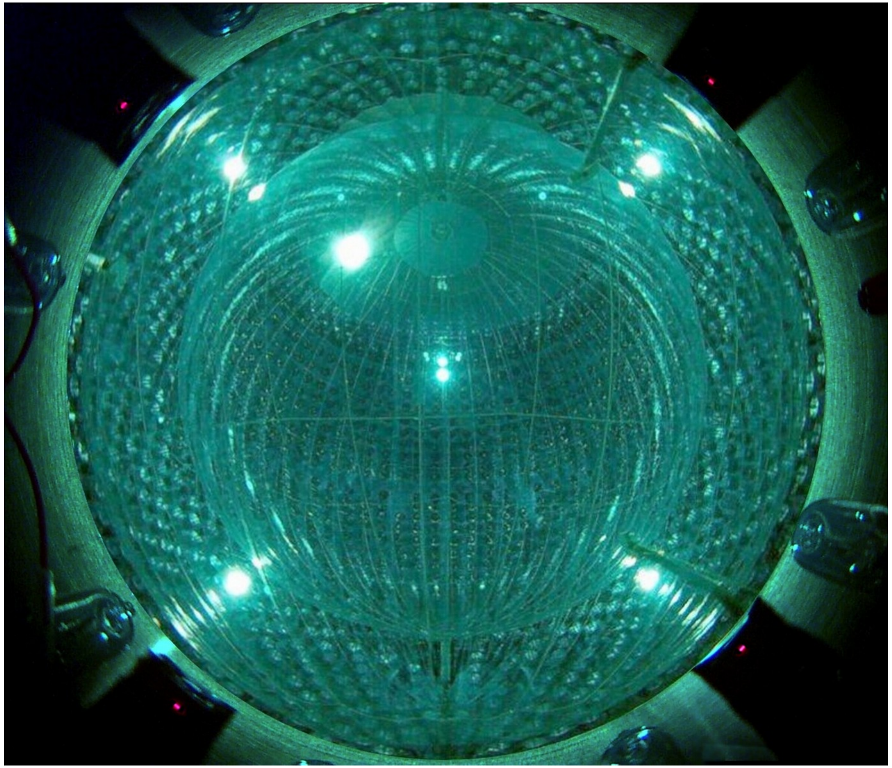
Rock: 3.800 m w.e. – muon flux ~ 1 $m^{-2}h^{-1}$

Borexino's pictures

During the construction



Now, after the thermal insulation



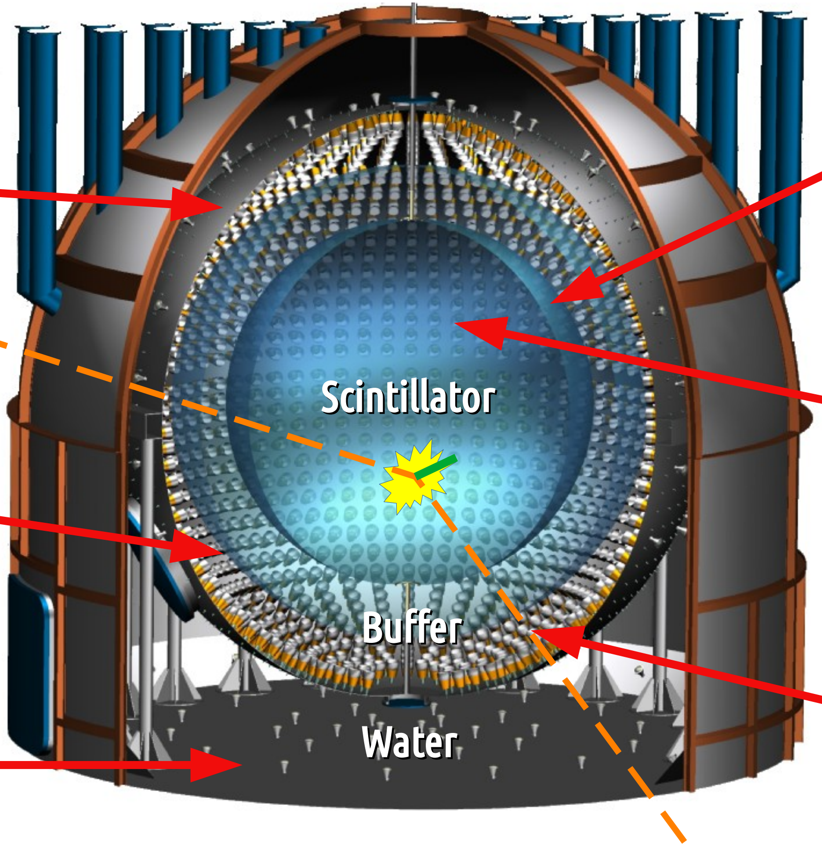
From monitoring camera

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



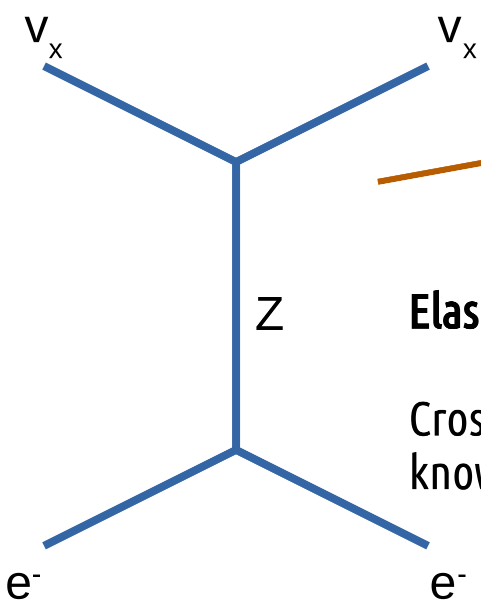
Nylon vessel
125 µm of radioupure nylon

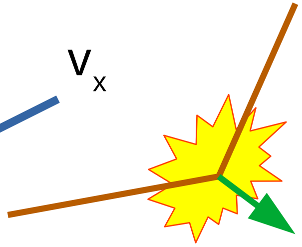
Inner vessel
target: 280 ton of scintillator PC+PPO

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

Detection principle: $\nu_x + e^- \to \nu_x + e^-$

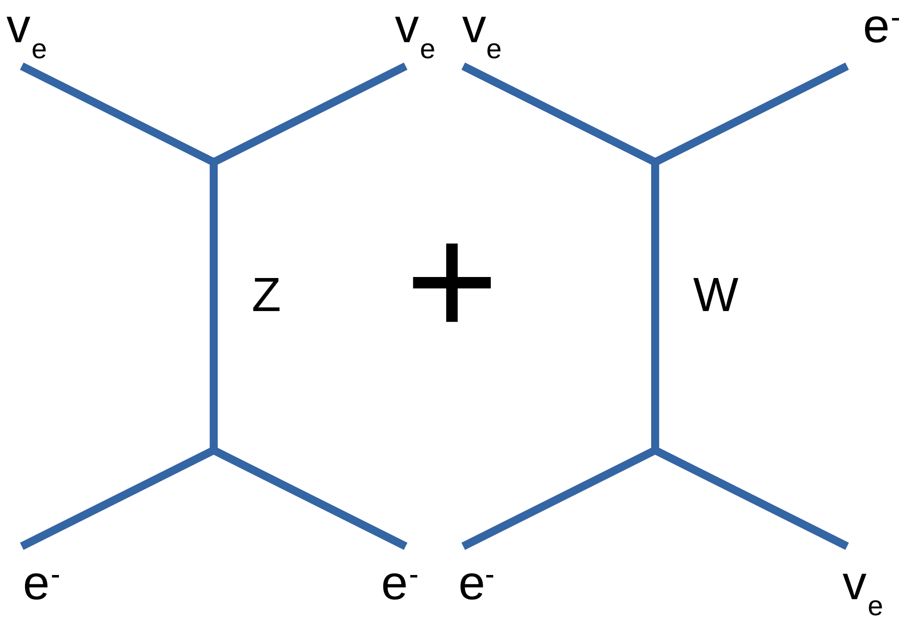
Detection Principle





Elastic Scattering

Cross sections
known from theory



All types (NC)

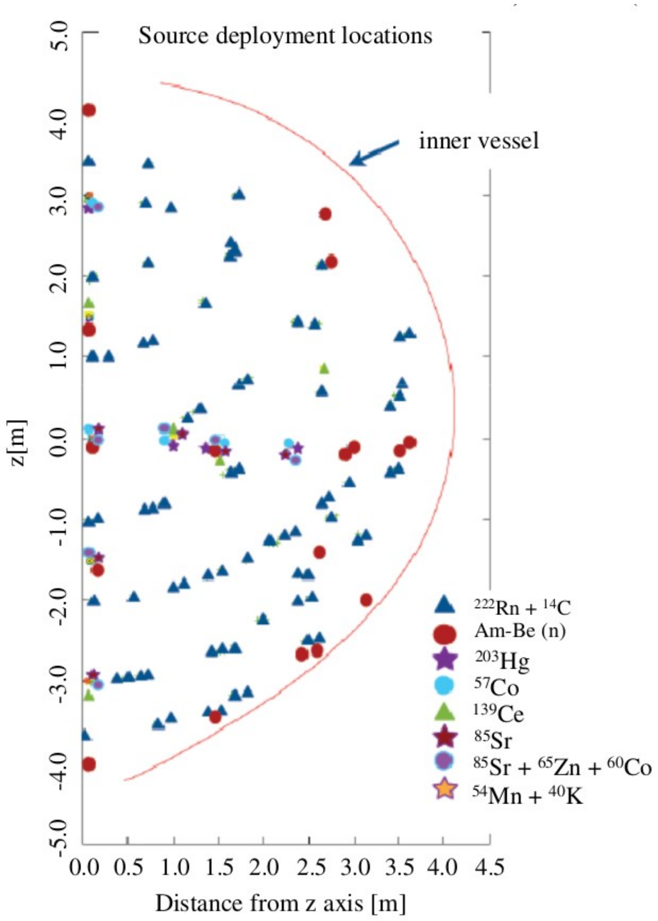
$\nu_x + e^- \rightarrow \nu_x + e^-$

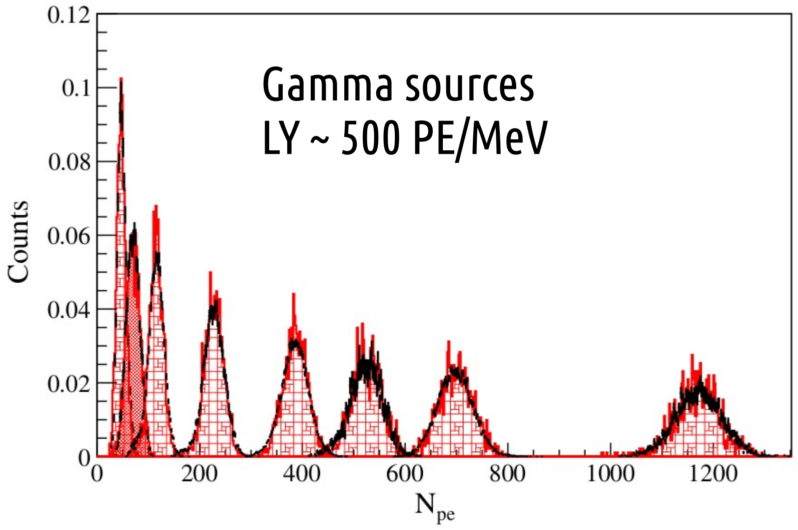
Electron neutrinos (NC, CC)

$\nu_e + e^- \rightarrow \nu_e + e^-$

Calibrations and features

Source deployment



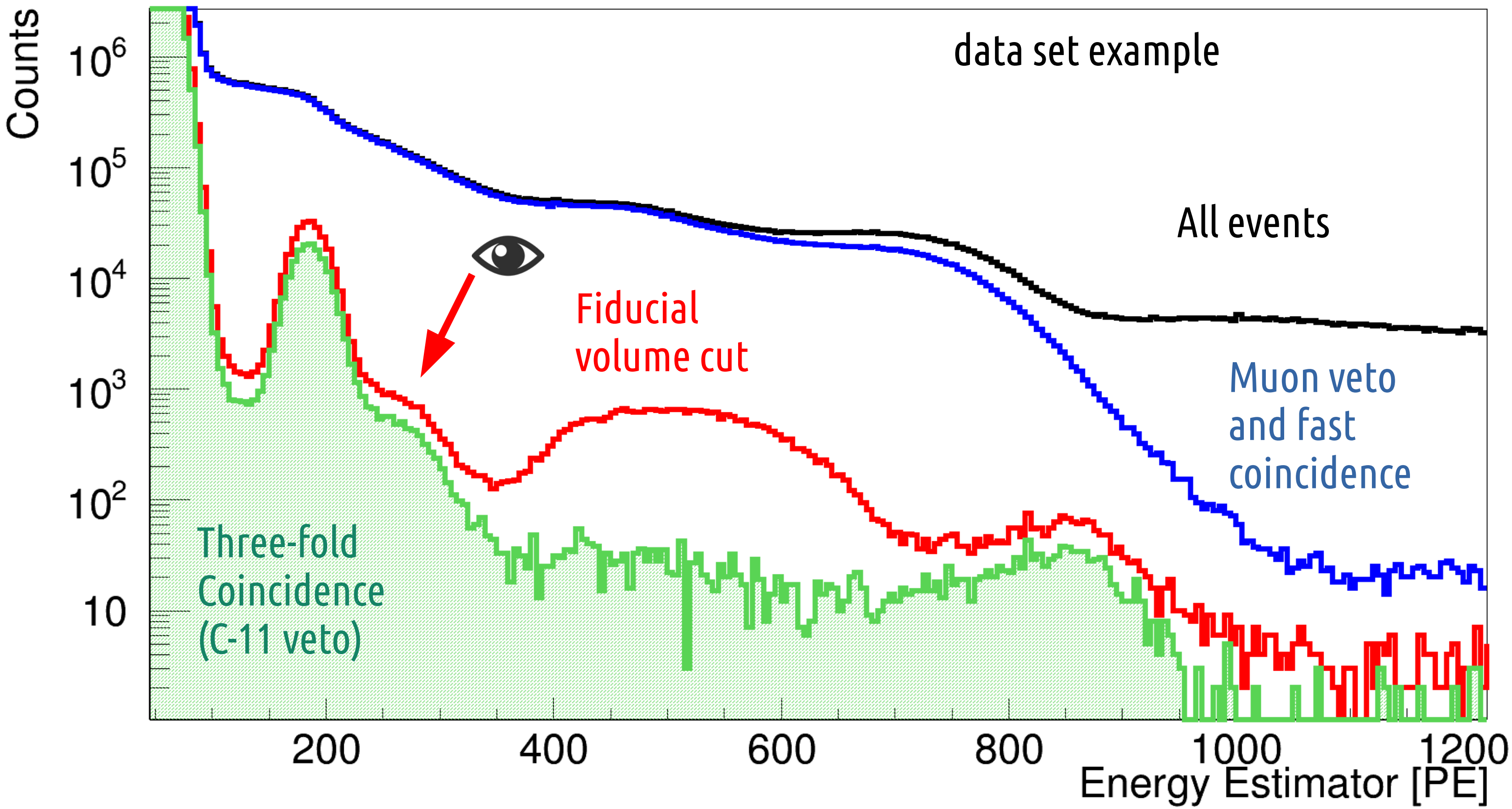


(Considering dying PMTs…)

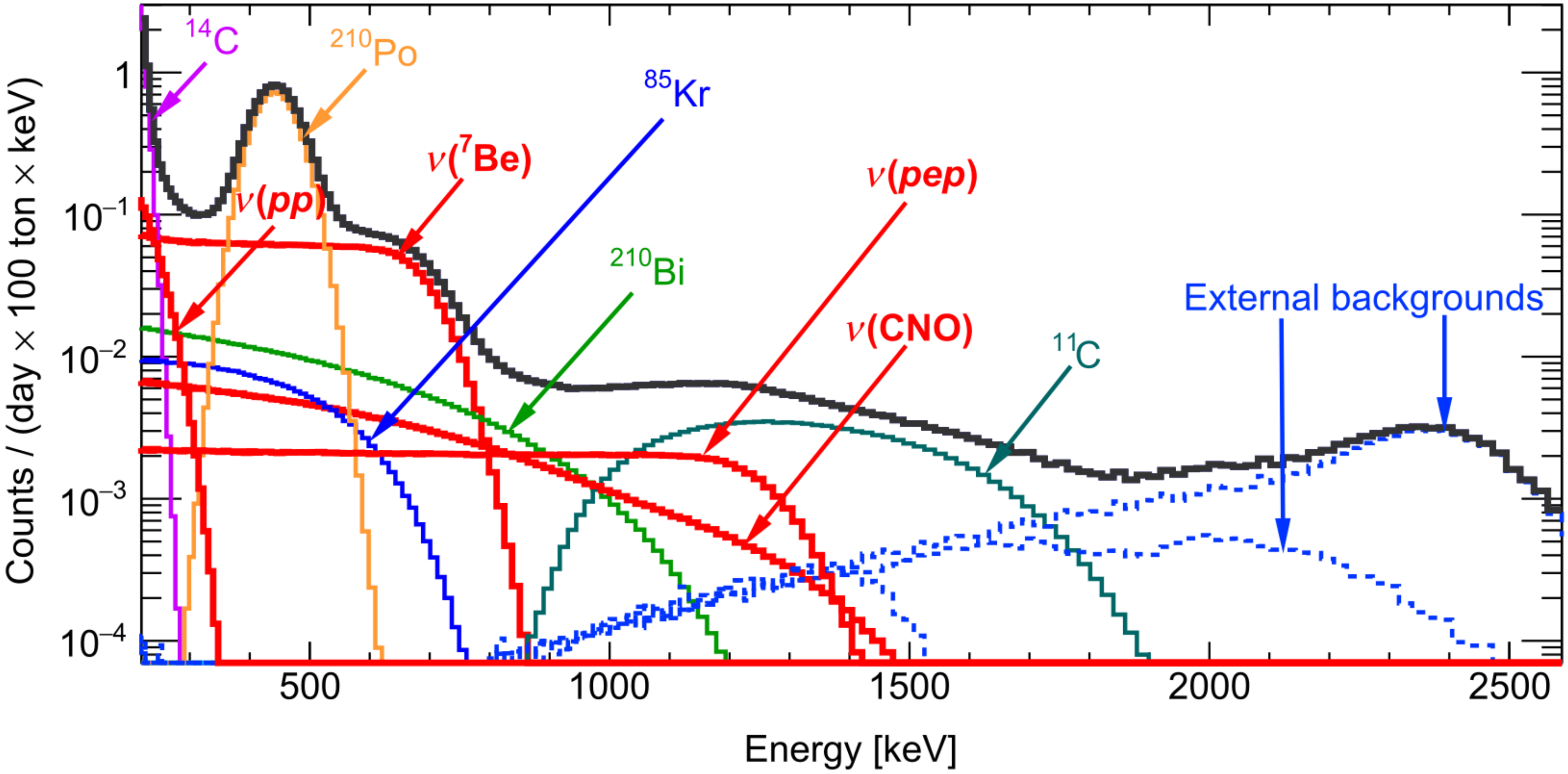
– **Energy Resolution** ~ 5-6% [@1 MeV]
– **Position uncertainty** (ToF) ~ 11 cm

– Pulse shape discrimination: α/β, e+/e-
– Three-fold coincidence:
(1) $\mu + {}^{12}C \rightarrow {}^{11}C + n$; (2) $n + H \rightarrow D$; (3) ${}^{11}C(\beta^+)$

The Borexino energy spectrum

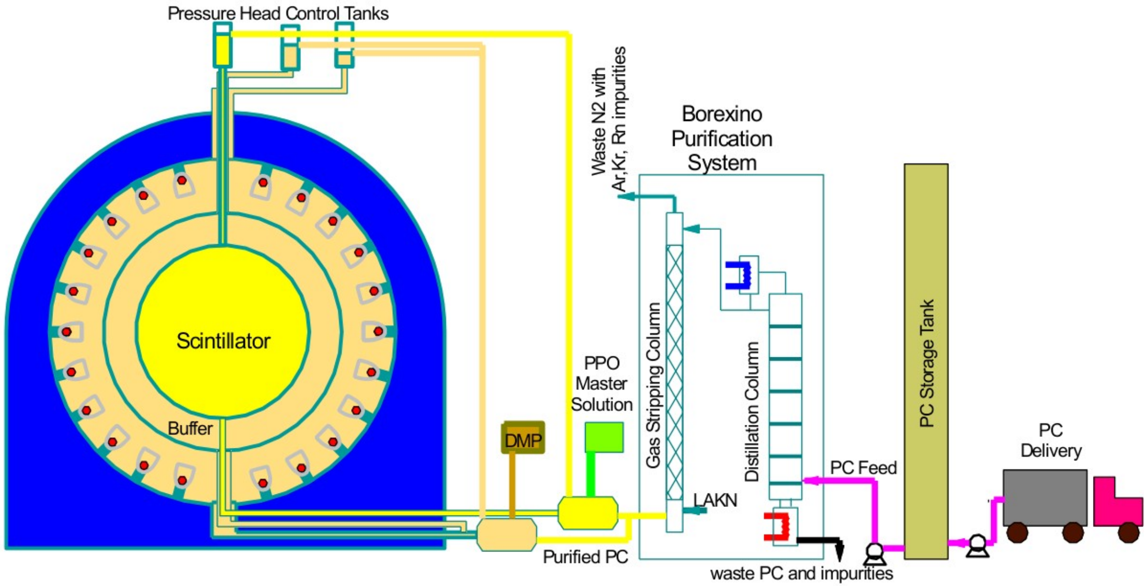


Understanding the spectrum

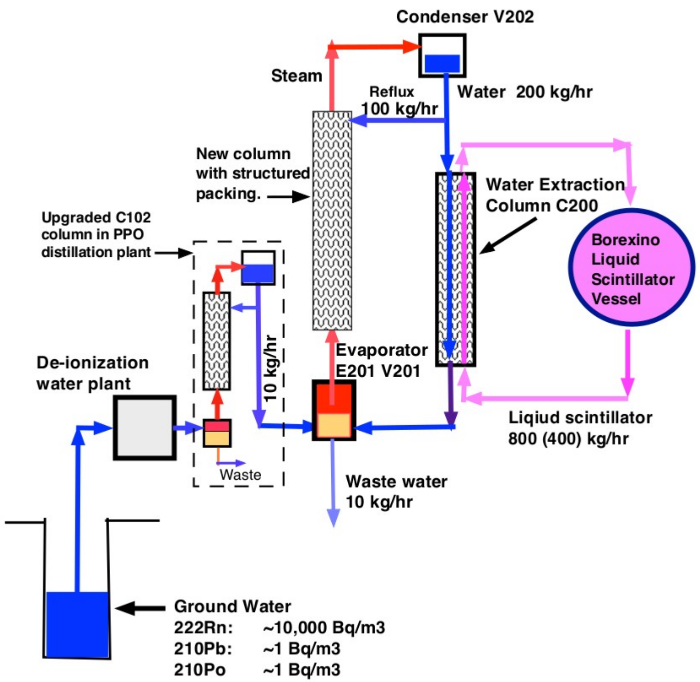


Purification procedures

- Advanced cleaning
- Filtration
- Water extraction
- Distillation
- Nitrogen stripping
- PPO (distillation and water extraction)



The water extraction campaign



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

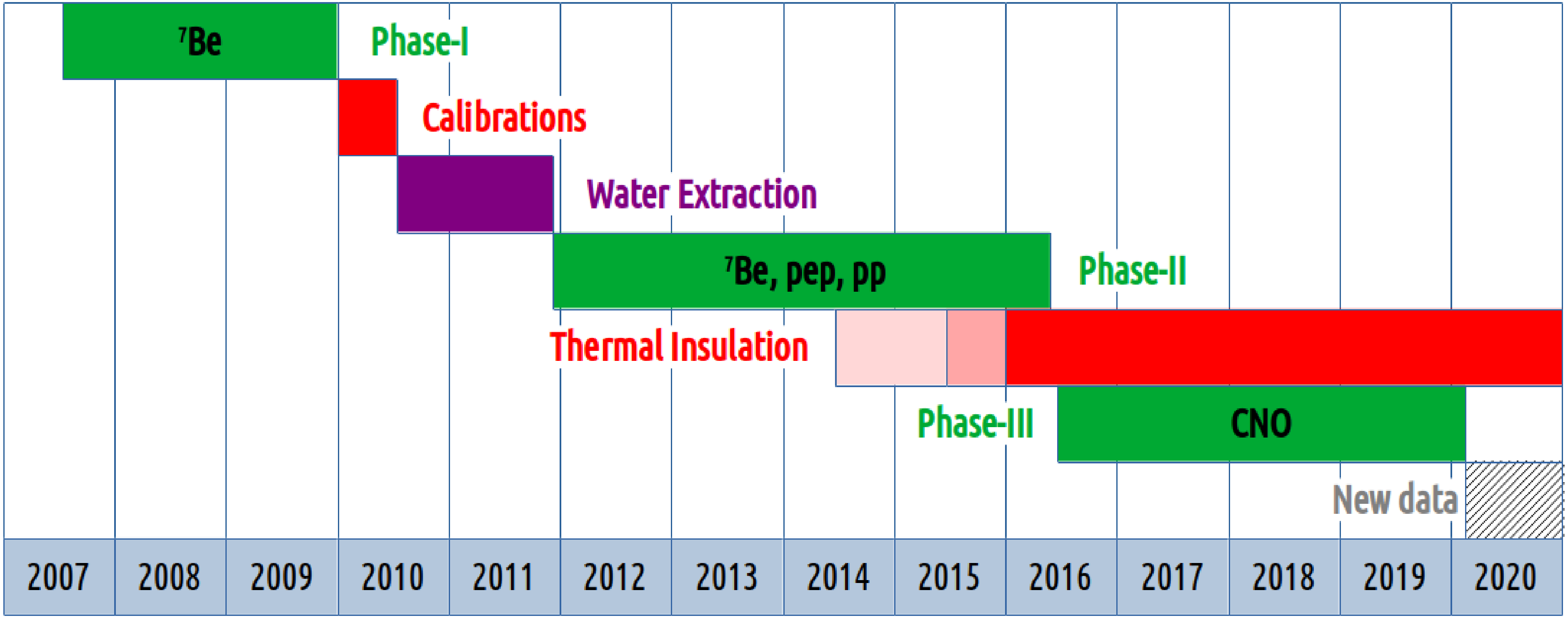
[1 cpd/100t ~ 0.1 nBq/kg]

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

^{238}U < 10^{-19} g/g, ^{232}Th< 10^{-20} g/g
^{39}Ar, ^{40}K << 1 cpd/100t

Borexino Phases

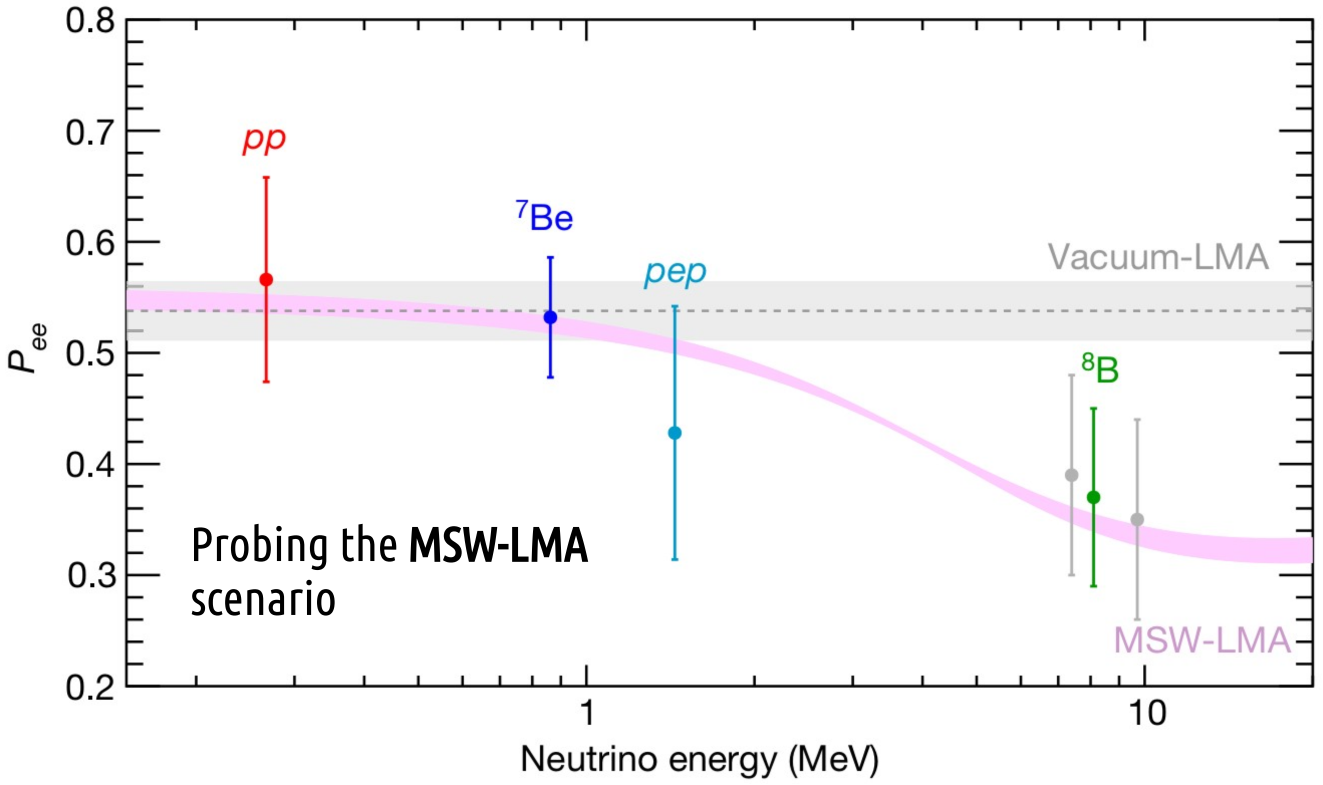
From May 15th 2007 to October 3rd 2021



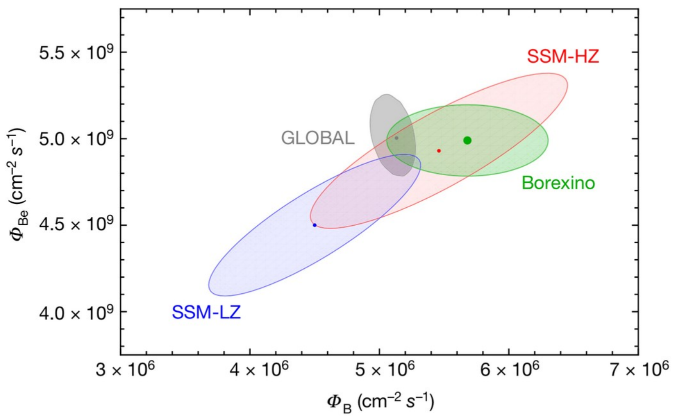
Solar neutrino results

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	$(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ]	$(1.27\pm0.19)_{-0.12}^{+0.08}x10^{8}$[HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}x10^{6}$
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}

Implications of Borexino results



Probing the **MSW-LMA** scenario



Precise measurement of the pp-chain flux. **First CNO detection.**

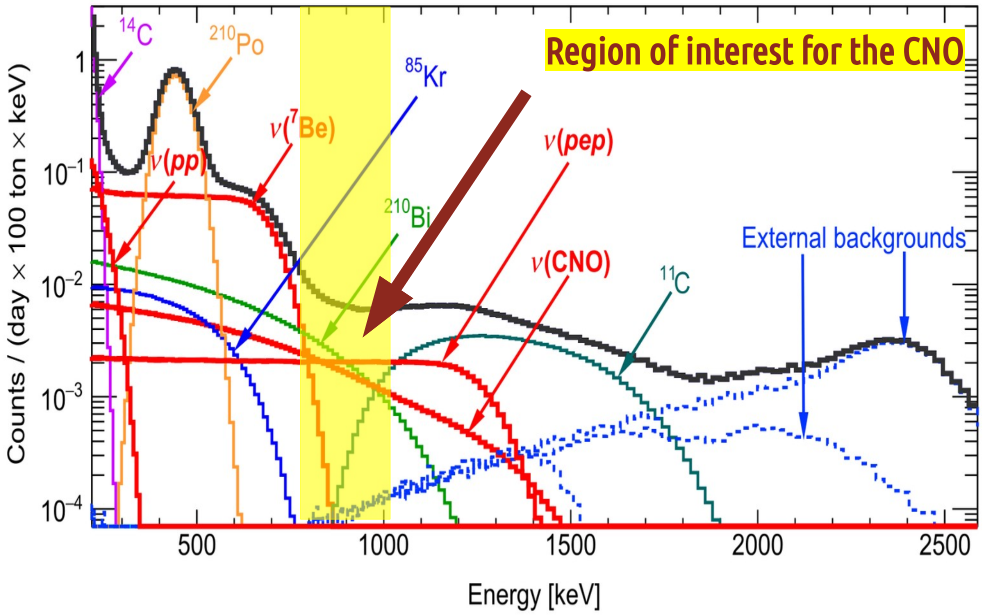
Solar Standard Model

Low metallicity **disfavored at 2.1 σ**

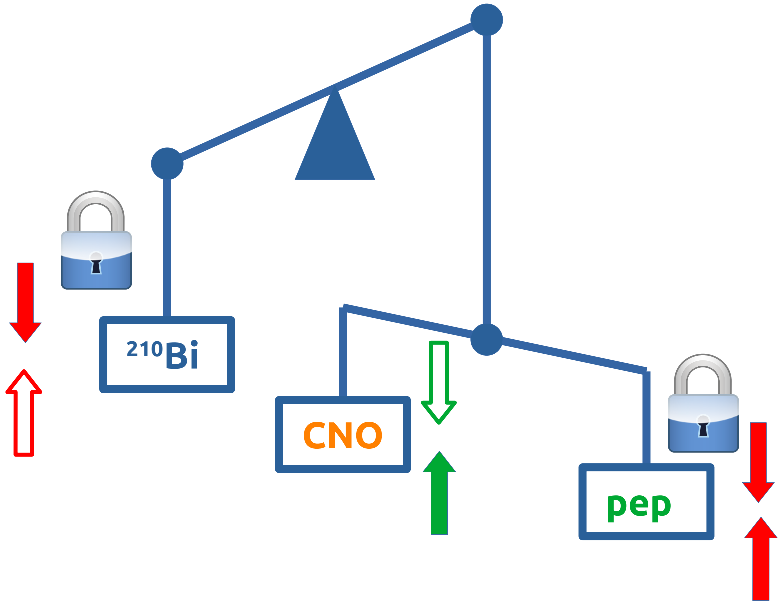
P_{ee} survival probability with Borexino data only!

The CNO Strategy

Borexino spectrum after all data selection criteria



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

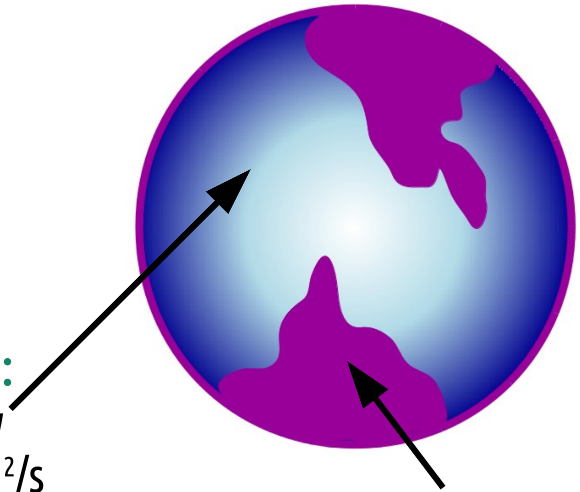


Strategy:

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

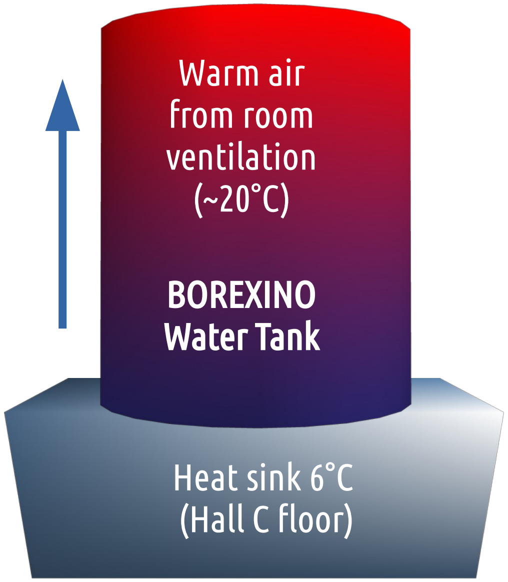
The ^{210}Bi constraint

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



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

Convection:
^{210}Po from the outer regions

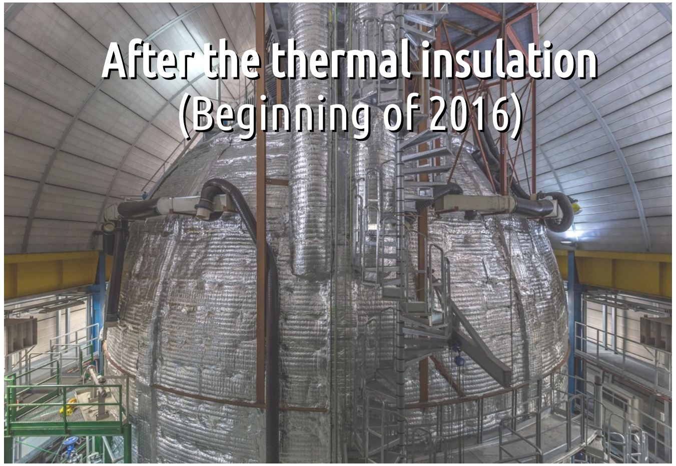


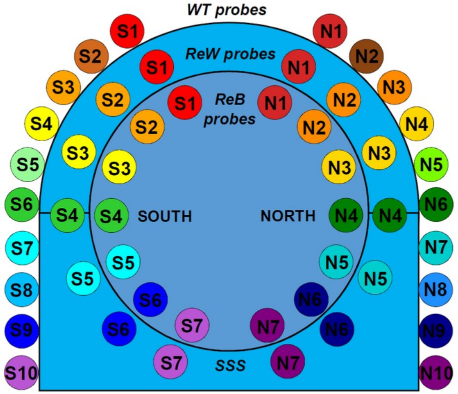
Idea: vertical gradient

THERMAL INSULATION PROGRAM

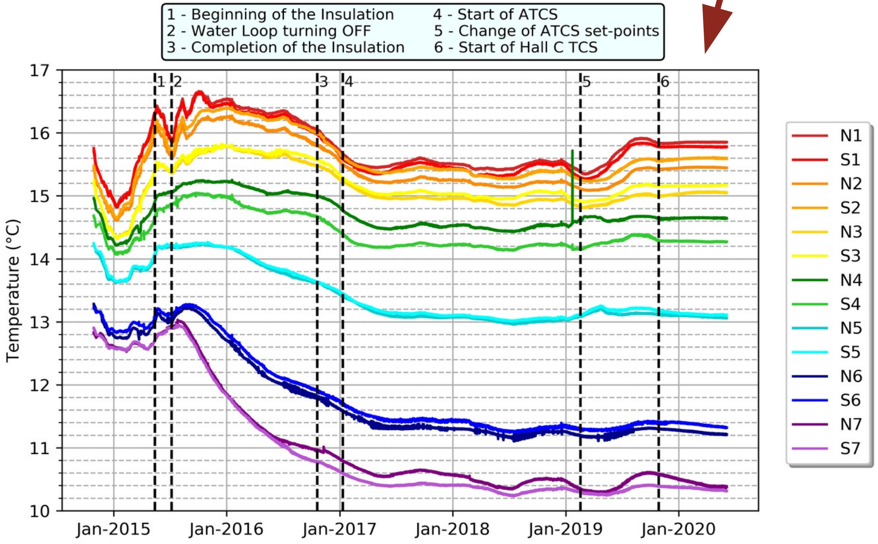
2014: temperature probes
Mid-2015: insulation start
Late 2015: *water recirculation system* shut down
2016: *active temperature control system* (ATCS)
Early 2019: change of the ATCS *set point*
Late 2019: *Hall C - ACTS*

Thermal Insulation



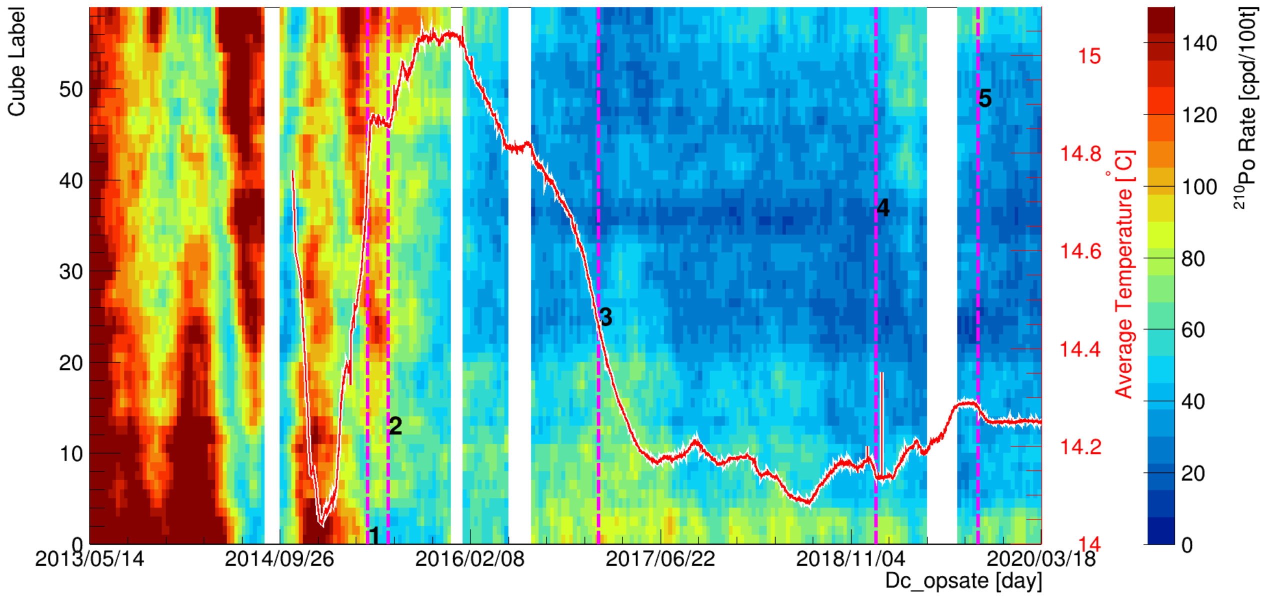


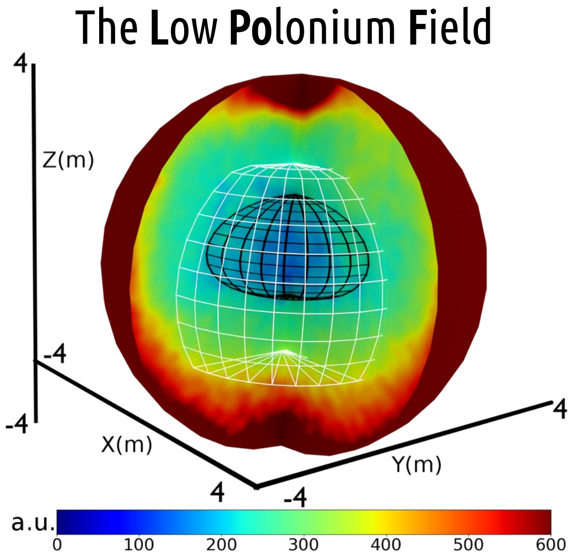
Temperature probes



Temperature evolution during the thermal insulation campaign

Effects on ^{210}Po migration





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

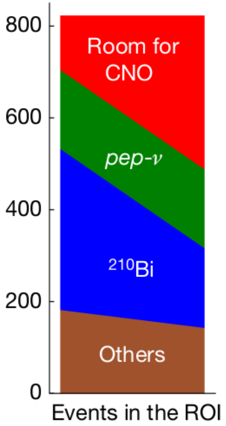
Final constraint: ^{210}Bi < (11.5 ± 1.3) cpd/100t

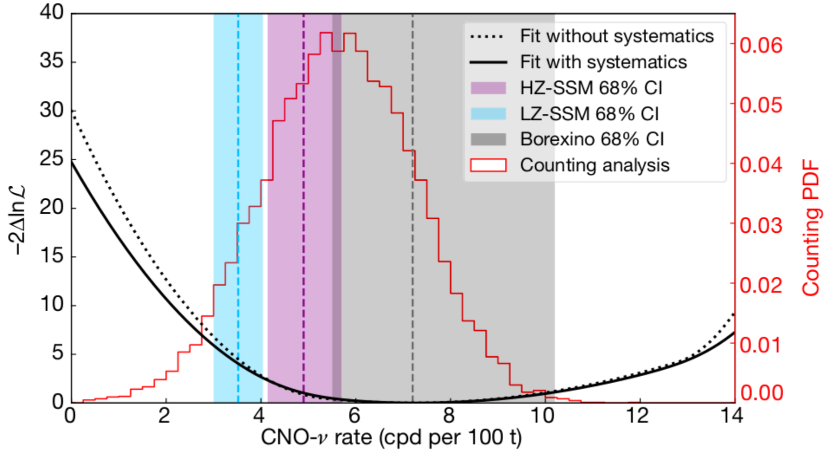
CNO neutrino analysis

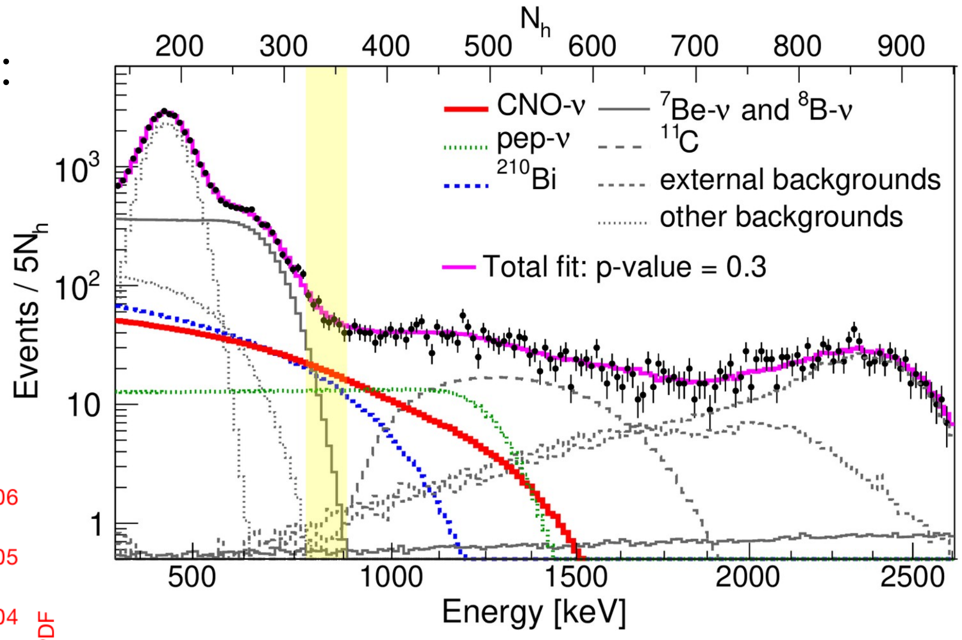
Main ingredients in the multivariate spectral analysis:

A) pep 1.4%
Gaussian penalty

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

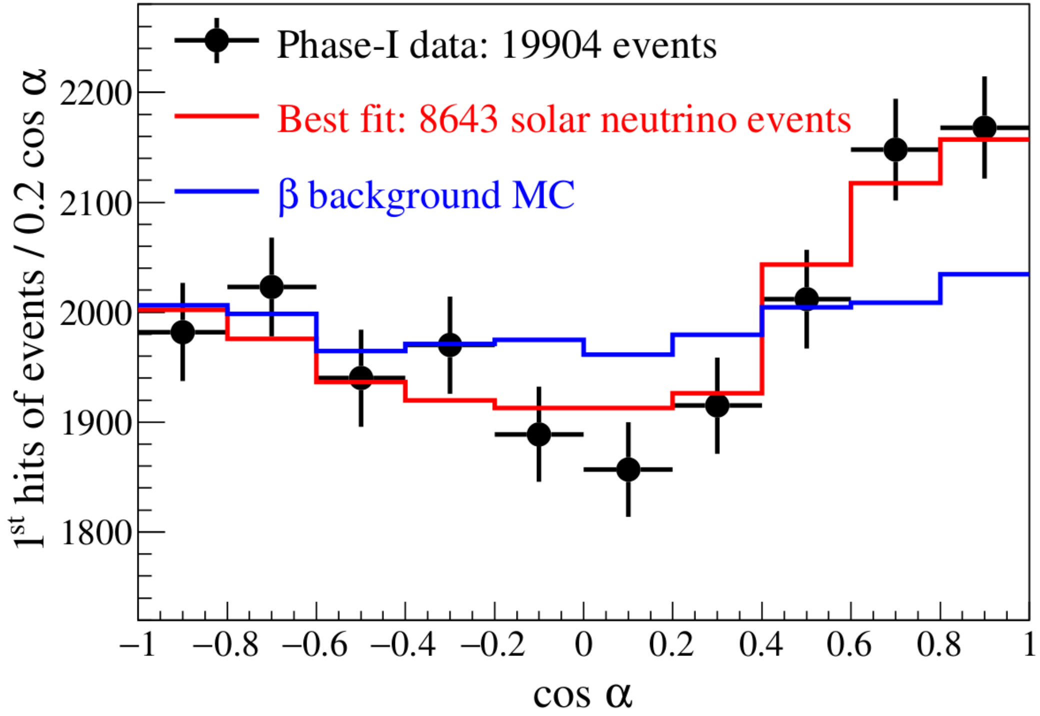




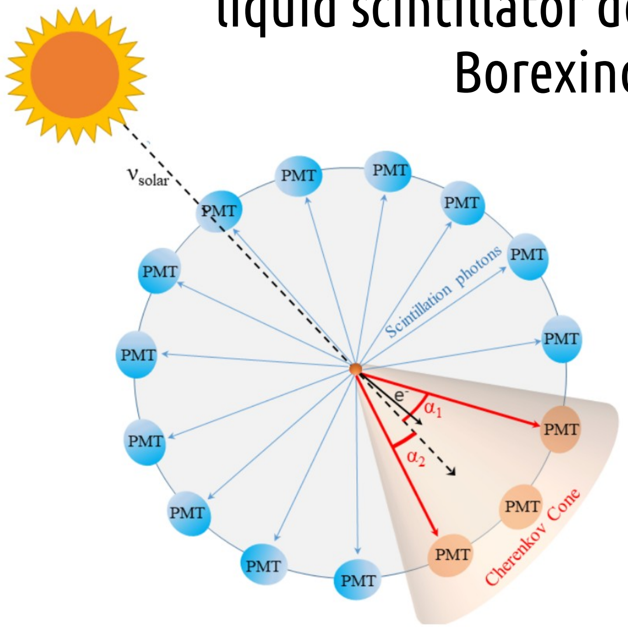


Result (68% CL stat + sys) = $7.2_{-1.7}^{+3.0}$ cpd/100t

Recent results: Directionality

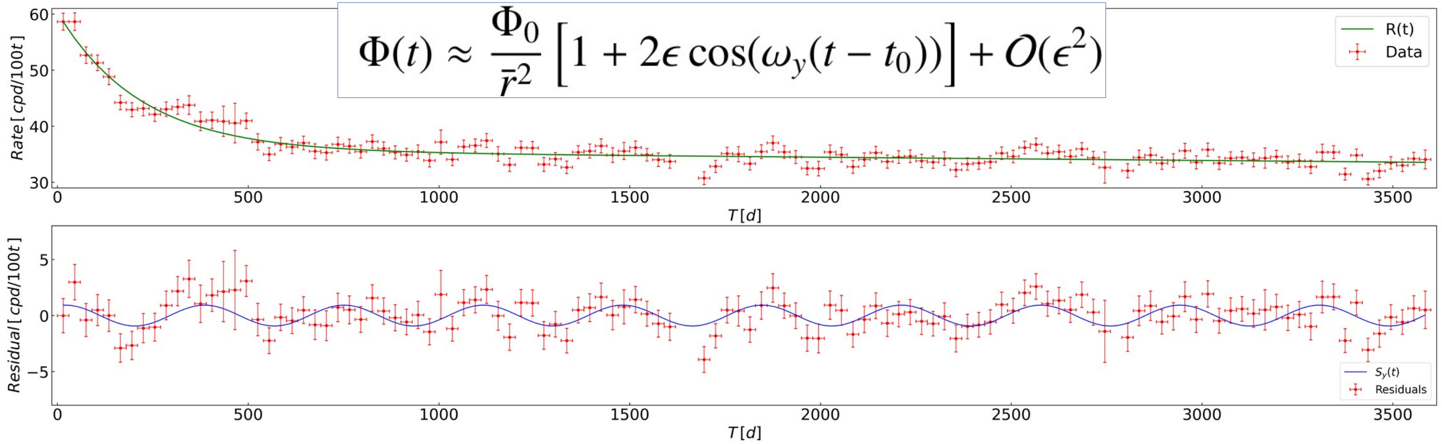


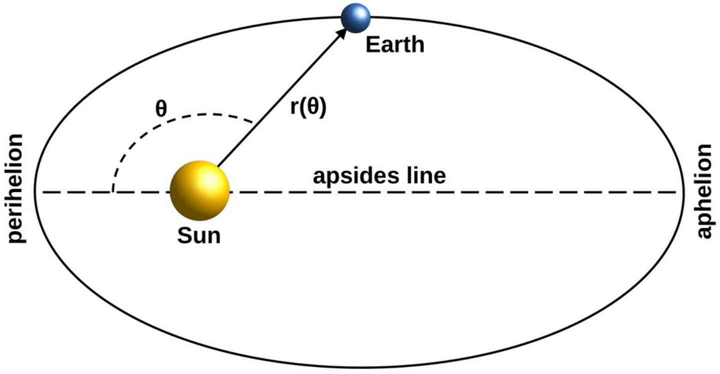
First demonstration of directional measurement of sub-MeV solar neutrinos in a liquid scintillator detector with Borexino



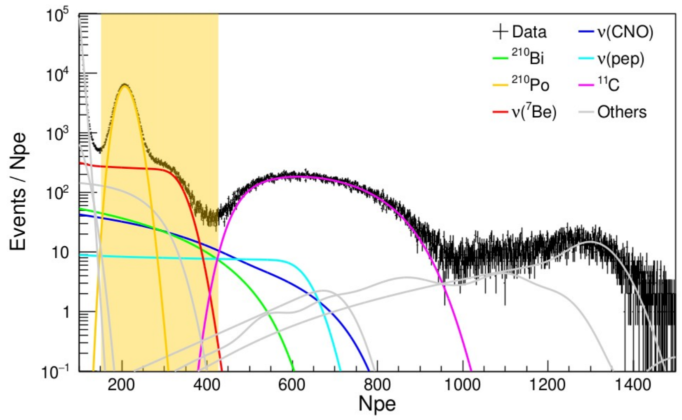
Recent results: Eccentricity

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

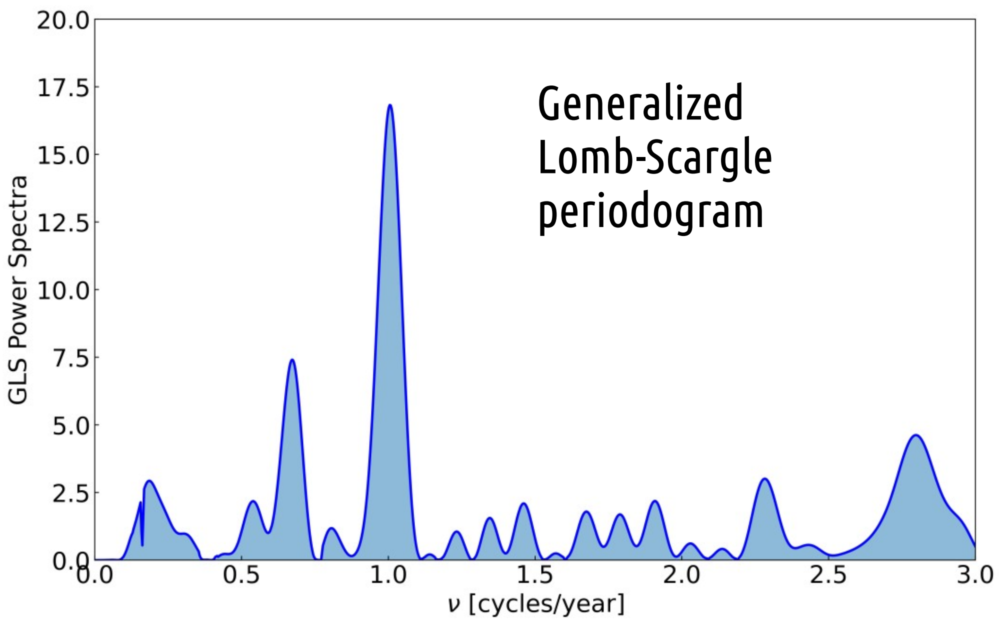


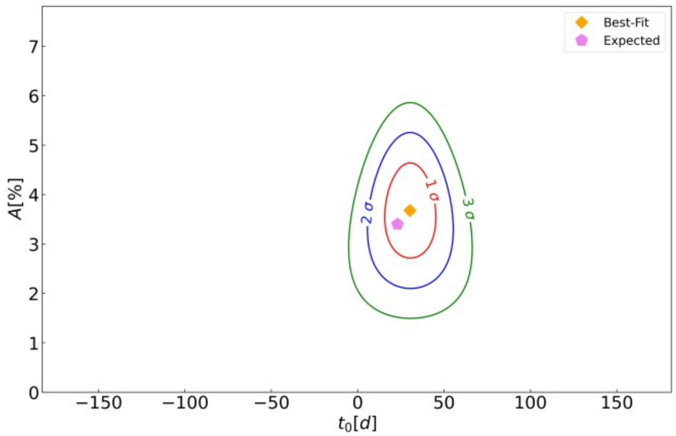


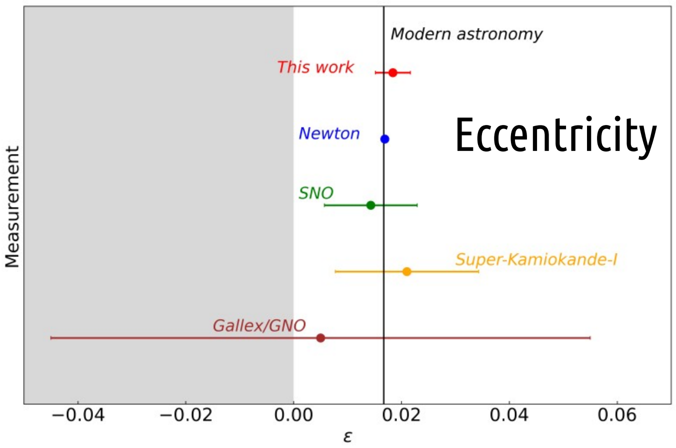
Independent determination of the Earth's orbital parameters with solar neutrinos in Borexino (*preprint*)



Earth's orbit parameters





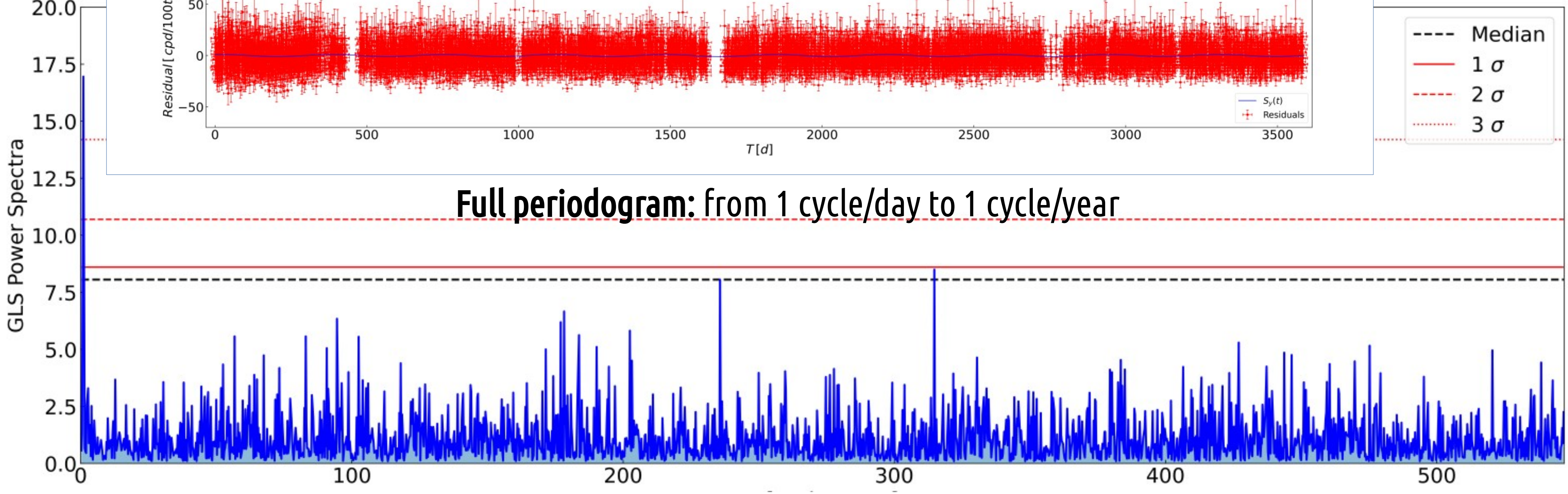


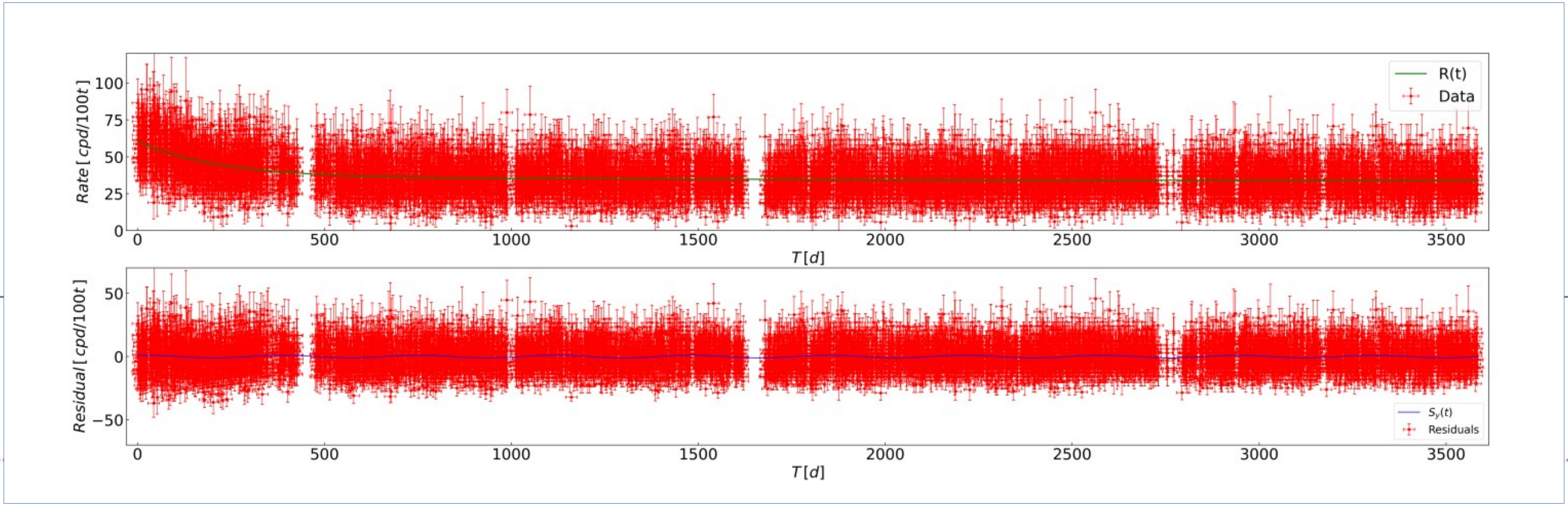
$\varepsilon = 0.0184 \pm 0.0032$

$T = (363.1 \pm 3.6)$

$t_0 = (30 \pm 20)$

All frequencies





Full periodogram: from 1 cycle/day to 1 cycle/year

Thank you very much!

physicsworld TOP 10 BREAKTHROUGH 2014

physicsworld TOP 10 BREAKTHROUGH 2020

G. & V. Cocconi Prize
2021 - EPS

Pontecorvo Prize
2015 G. Bellini

Fermi Prize
2017 G. Bellini