
# Update of the results on solar neutrino physics exploiting the most recent Borexino data

INFN LNGS
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BOREXINO GRAN SASSO


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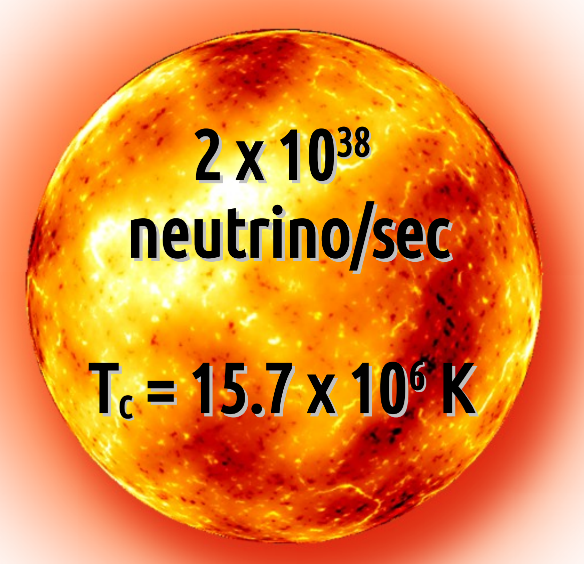
**NOW 2022**

2022, Sep 4 - 11

# Solar Neutrinos: what & why




Main sequence
Star modeling

Byproducts of nuclear fusion in the Sun

$$4\ {}^1\text{H} \rightarrow\ {}^4\text{He} + 2\ \nu_e + 26.7\ \text{MeV}$$

**Neutrino fluxes observable on Earth**

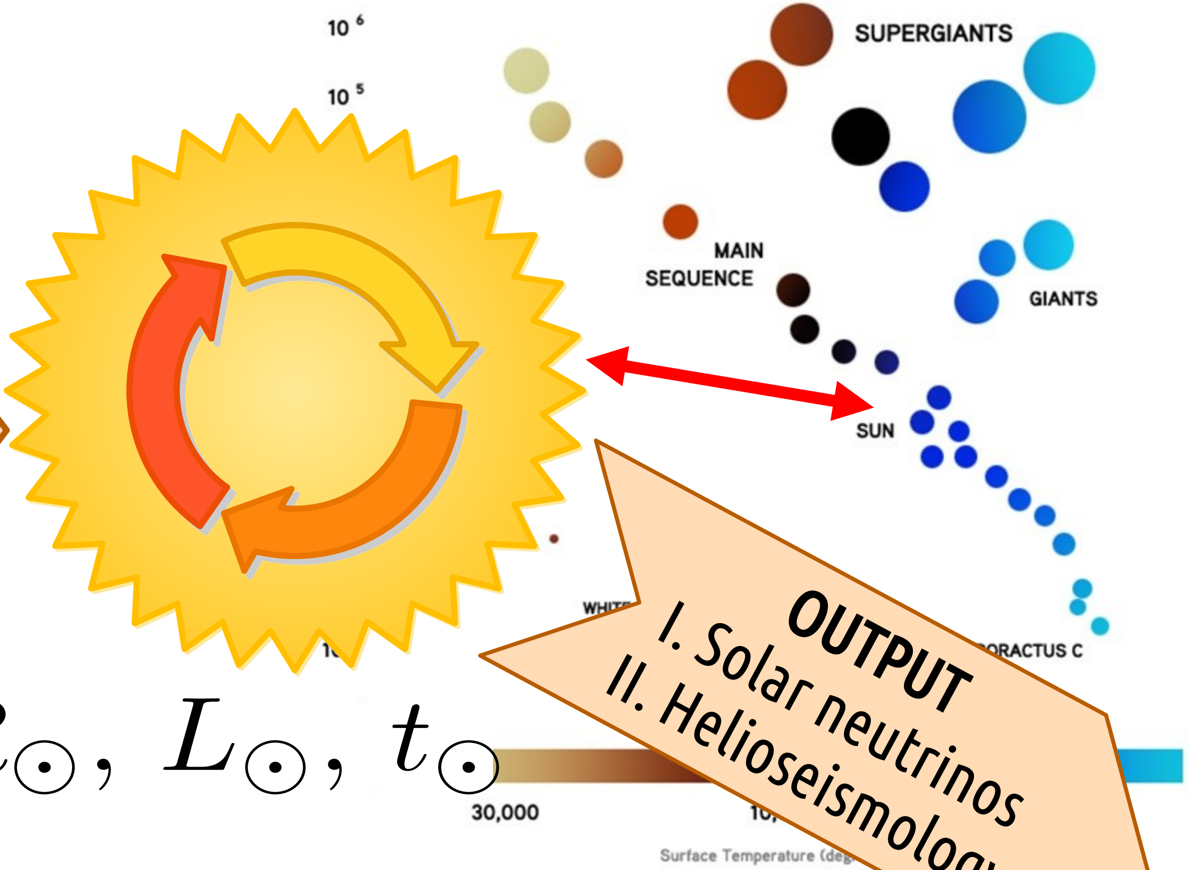
$$\Phi_\nu \approx 60 \times 10^9\ \text{cm}^{-2}\text{s}^{-1}$$

ASTRO & PARTICLE physics

| Conditions of the Sun's core | Properties of propagation in (solar) matter |
|---|---|
| Test of the Solar Standard Model (SSM) | Neutrino flavor conversion |

# Standard Solar Model

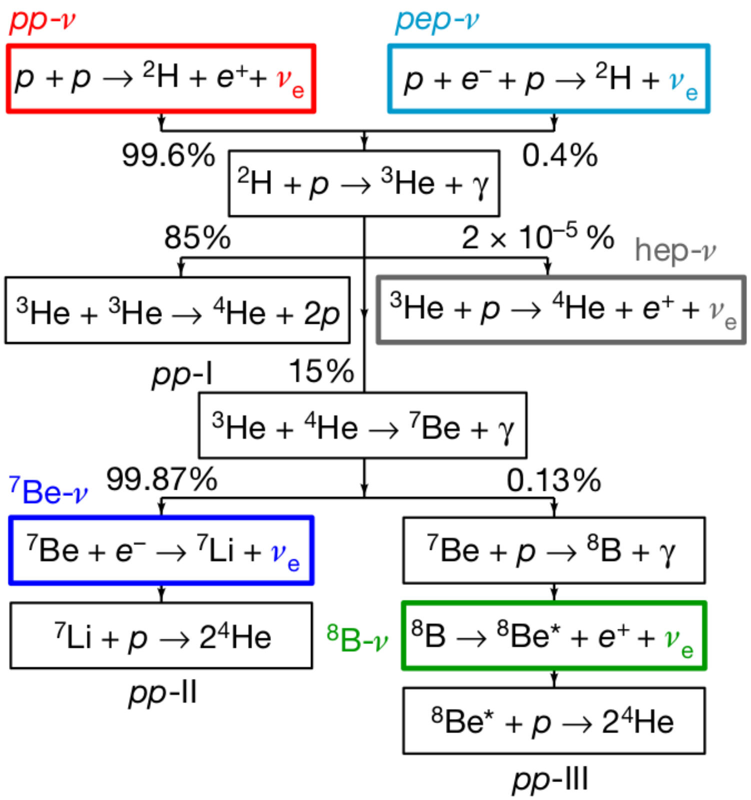
**INPUT**
- Initial chemical composition, $X_i$
- EoS, continuity, transport
- Radiative opacity, $\kappa$
- energy production (nuclear physics)

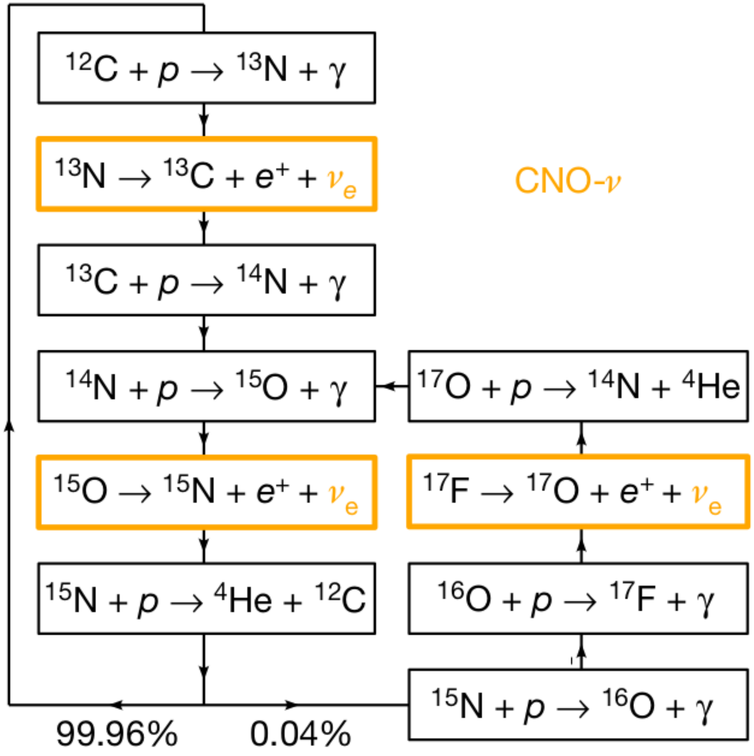



$$R_\odot,\ L_\odot,\ t_\odot$$

**OUTPUT**
I. Solar neutrinos
II. Helioseismology

# Hydrogen burning in the Sun



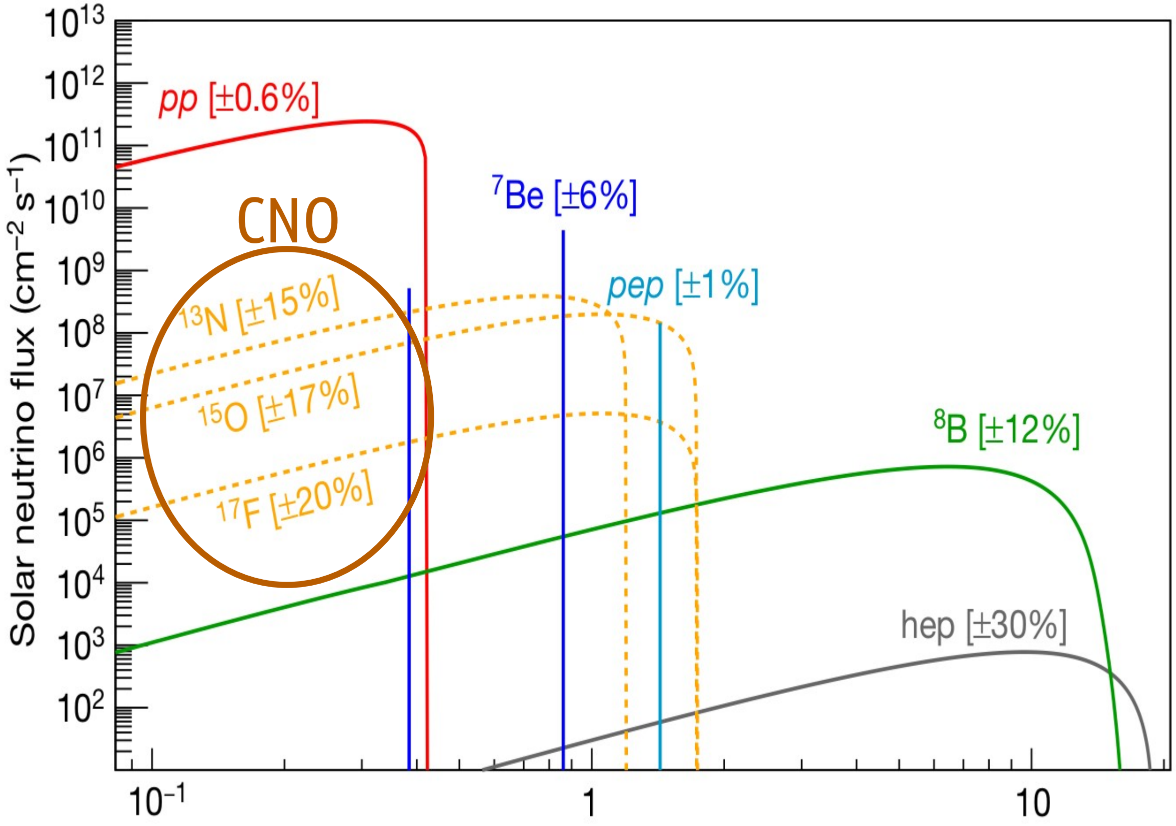




**I. pp chain (99:100)**

**II. CNO cycle (1:100)**

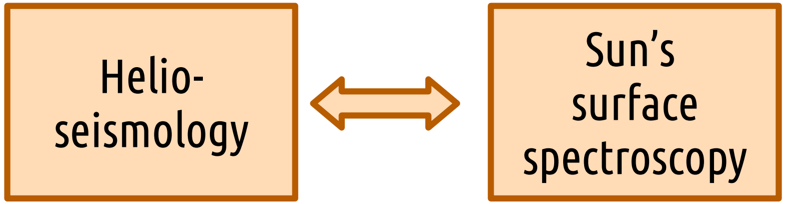
**Dominant in stars > 1.3 $M_\odot$**

# Solar neutrino fluxes




**Solar metallicity problem**

Abundance of elements heavier than He

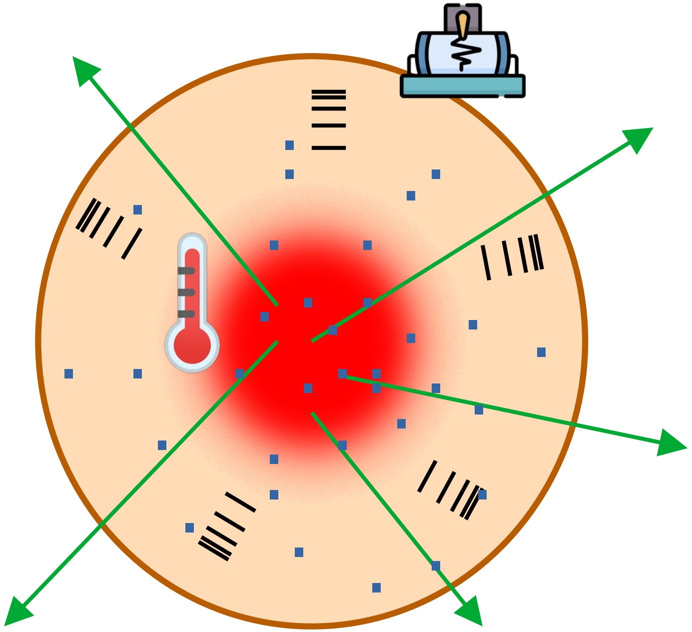


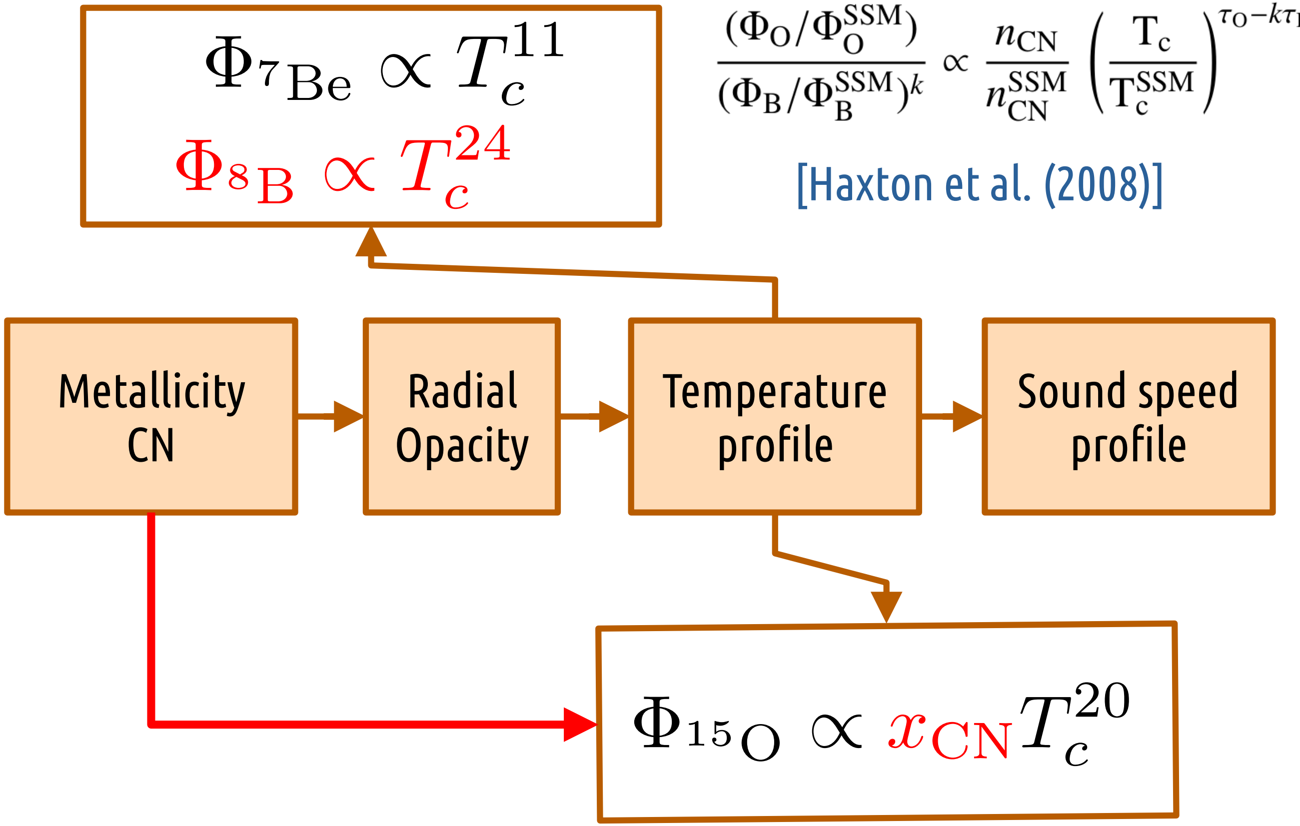

**High:**
SSM B16 – GS98 (1D)
(agreement)

**Low:**
SSM B16 – AGSS09 (3D)
(disagreement)

# CNO and metallicity

CNO neutrino flux retains a direct dependence the CN abundance






$$\frac{(\Phi_{\mathrm{O}}/\Phi_{\mathrm{O}}^{\mathrm{SSM}})}{(\Phi_{\mathrm{B}}/\Phi_{\mathrm{B}}^{\mathrm{SSM}})^k} \propto \frac{n_{\mathrm{CN}}}{n_{\mathrm{CN}}^{\mathrm{SSM}}} \left(\frac{\mathrm{T_c}}{\mathrm{T_c^{SSM}}}\right)^{\tau_{\mathrm{O}} - k\tau_{\mathrm{B}}}$$

[Haxton et al. (2008)]

# Solar neutrino detection (Borexino)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ All types (CC + NC)

Interaction $$\mathcal{R} = \mathcal{N}_e \Phi_\nu \langle \sigma_{\nu e} \rangle$$ Rate

KEY

1. Large mass Target
&
2. Extremely Low background
----
Liquid scintillator

=

~100 events per 100 ton day

divided by

$\Phi = 10^{10}\, cm^{-2} s^{-1}$ × $\langle\sigma\rangle = 10^{-45} cm^2$

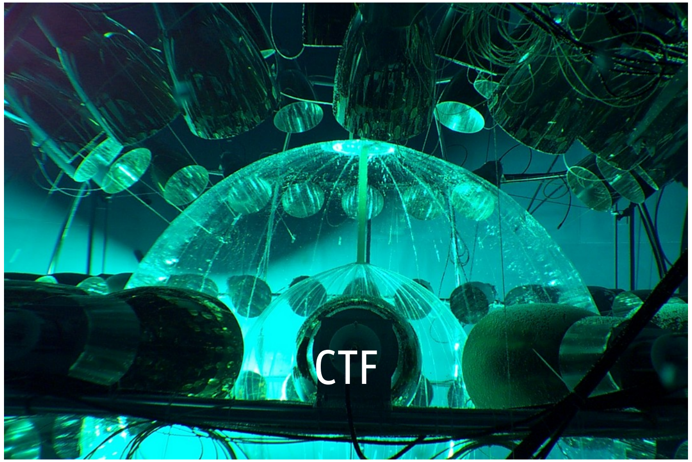
# The Borexino saga

**1990:** idea of a sub-Mev solar neutrino detector.
A real time neutrino detection
(**G. Bellini**, F. Calaprice, R. Raghavan, F. von Feilitzsch)

**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

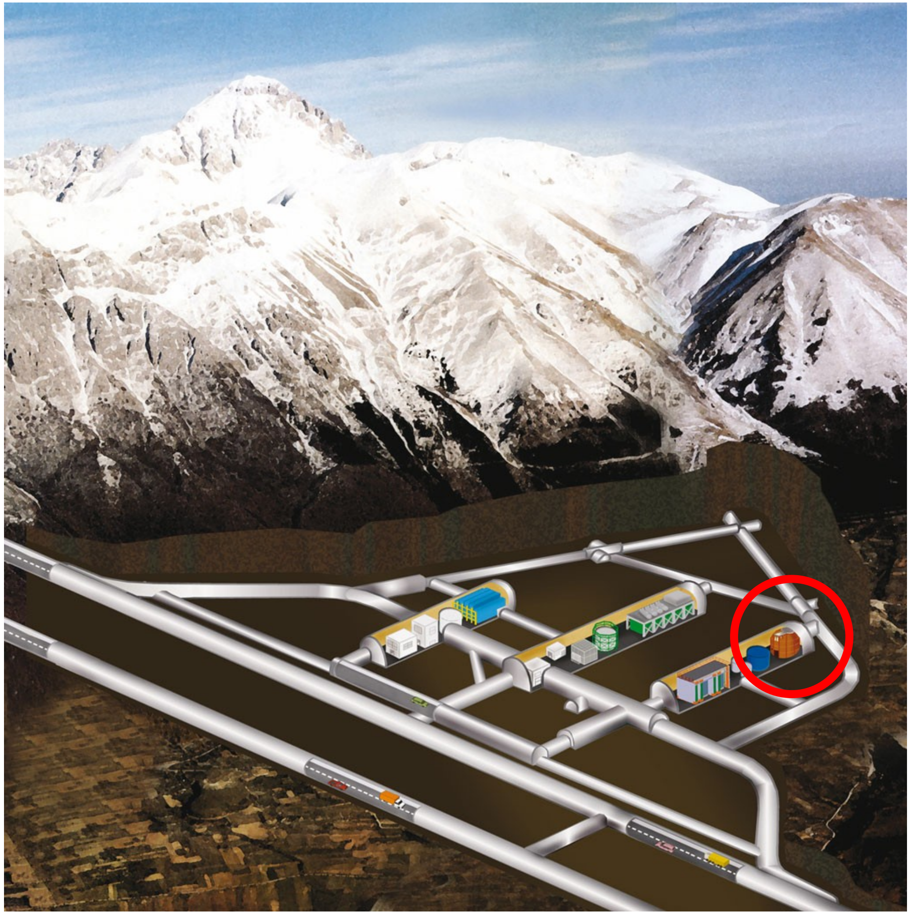
**2007-2021:** data taking

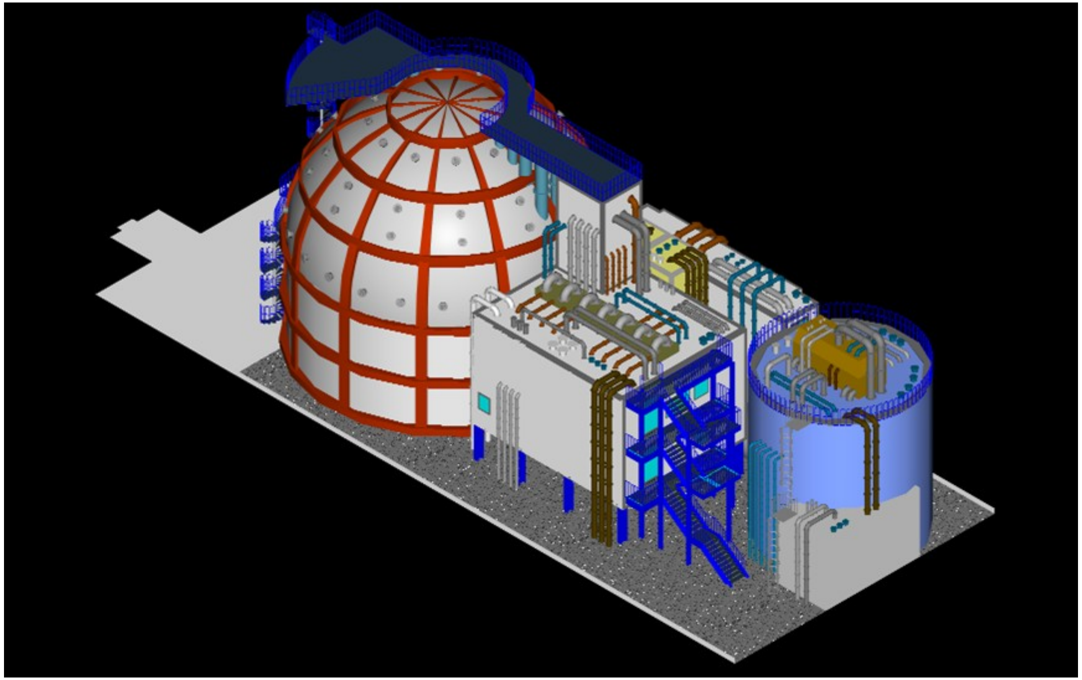




**Three Borexino strategies:**

- clean materials
- purification
- analysis methods

# The BOREXINO detector



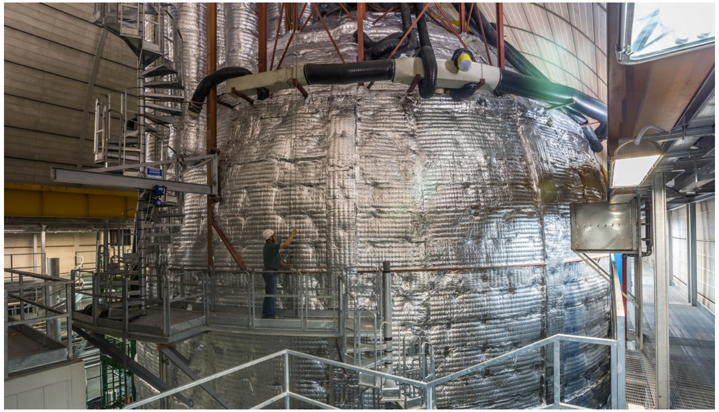


**Laboratori Nazionali del Gran Sasso – INFN** (Hall C)

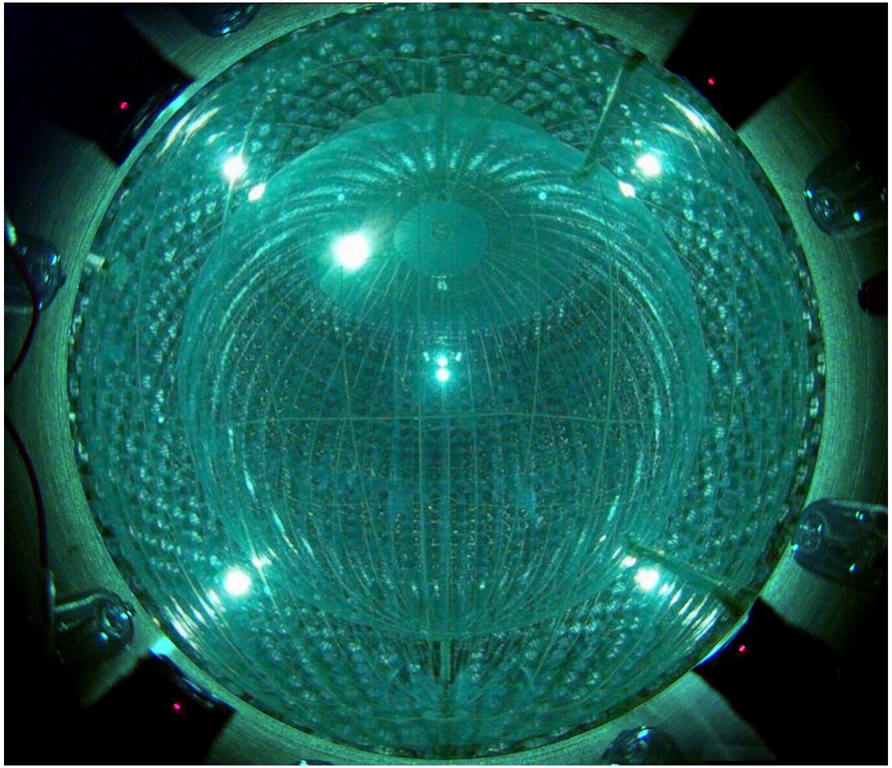
Rock: 3.800 m w.e. – muon flux ~ 1 $m^{-2}h^{-1}$

# Borexino's pictures

During the construction



Now, after the thermal insulation



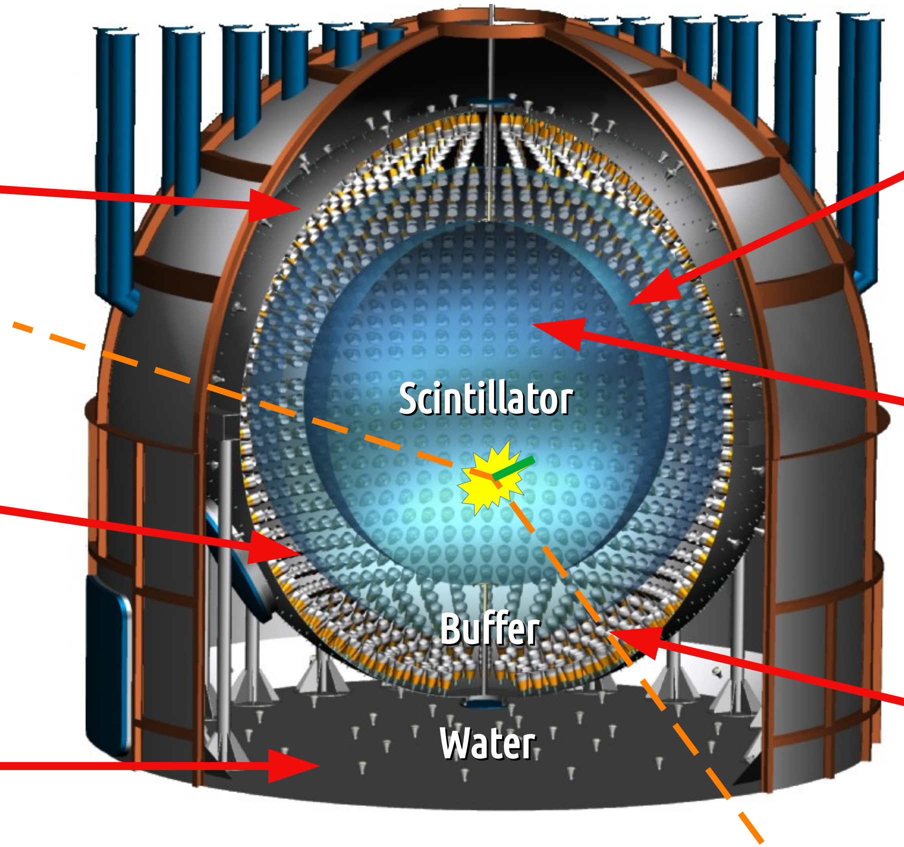
From monitoring camera

# 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

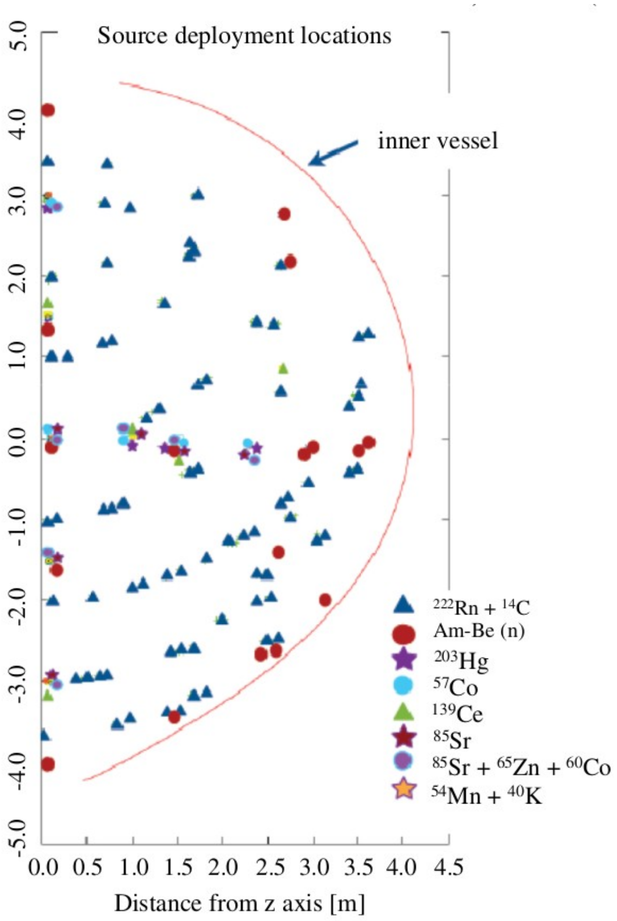
**Inner vessel**
target: 280 ton of scintillator PC+PPO

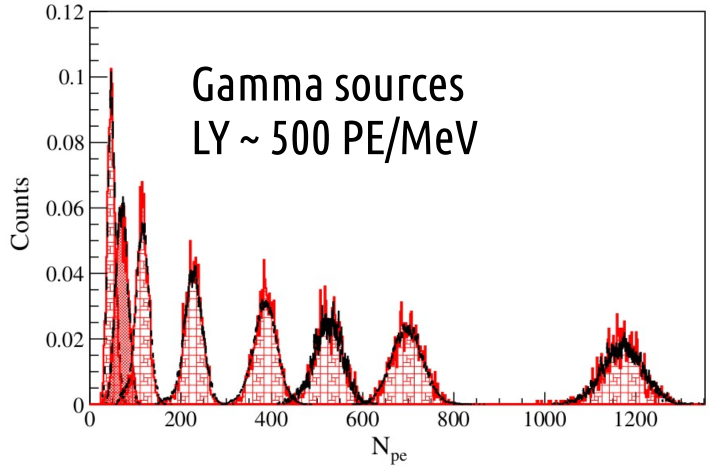
**Internal PMTs**
2212 (nominal), 8”, 35% optical coverage

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

# Calibrations and features

Source deployment



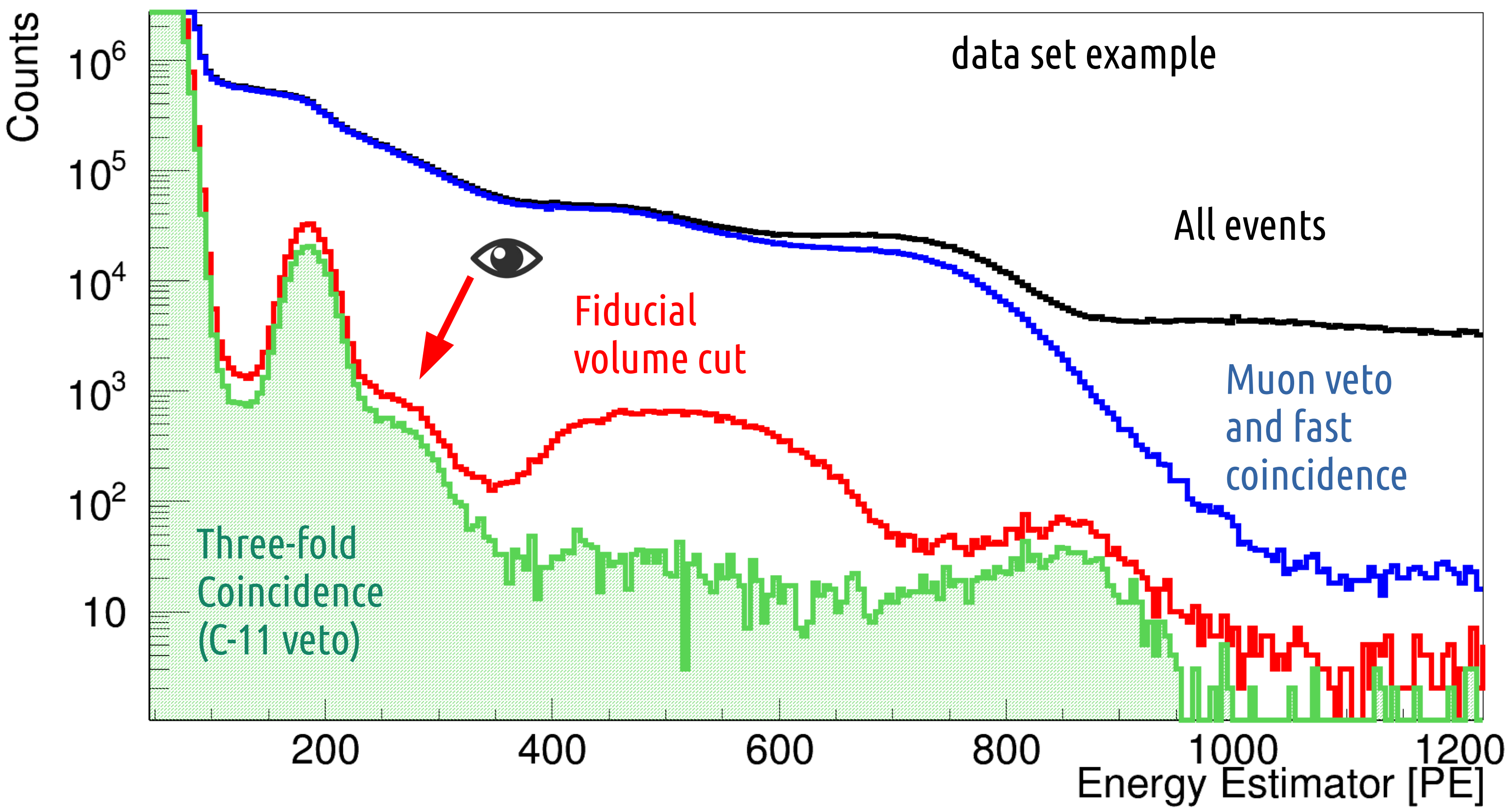




(Considering dying PMTs…)

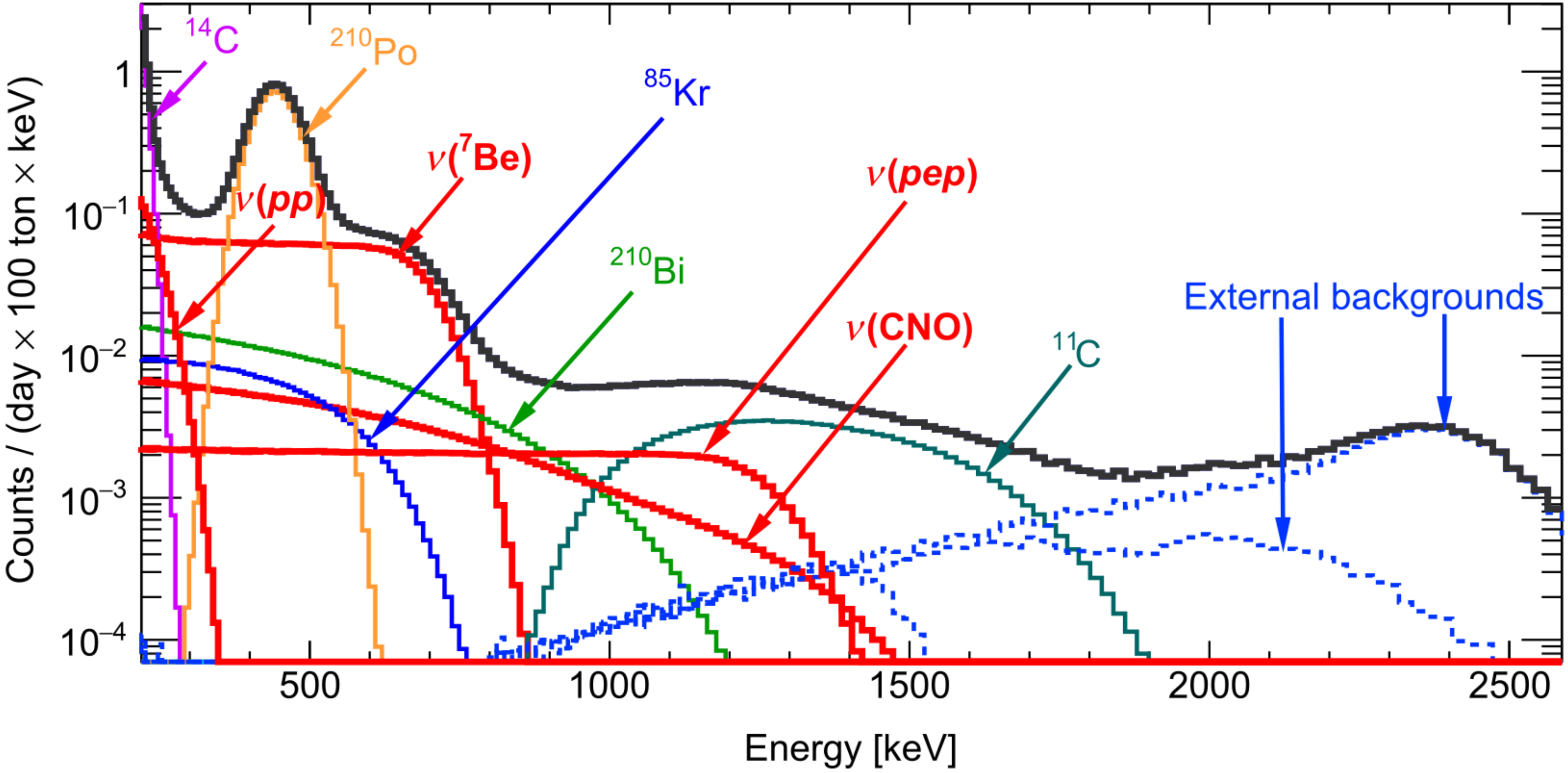
- **Energy resolution** ~ 5-6%   [@1 MeV]
- **Position resolution** (ToF) ~ 11 cm

- 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

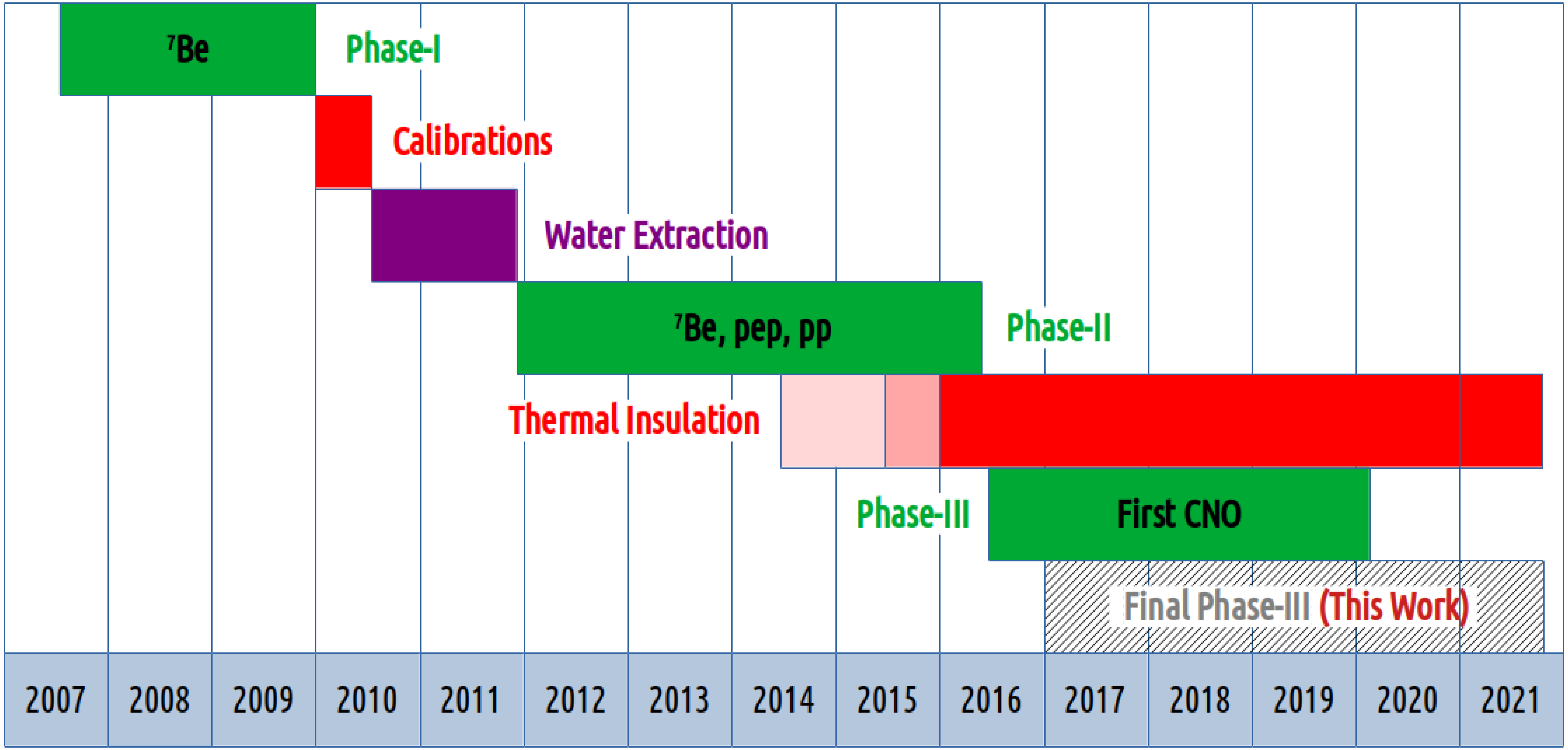


# Understanding the spectrum



# Borexino timeline (data-taking)

From May 15th 2007 to October 3rd 2021




< From May 27th (2007) to October 3rd (2021) >

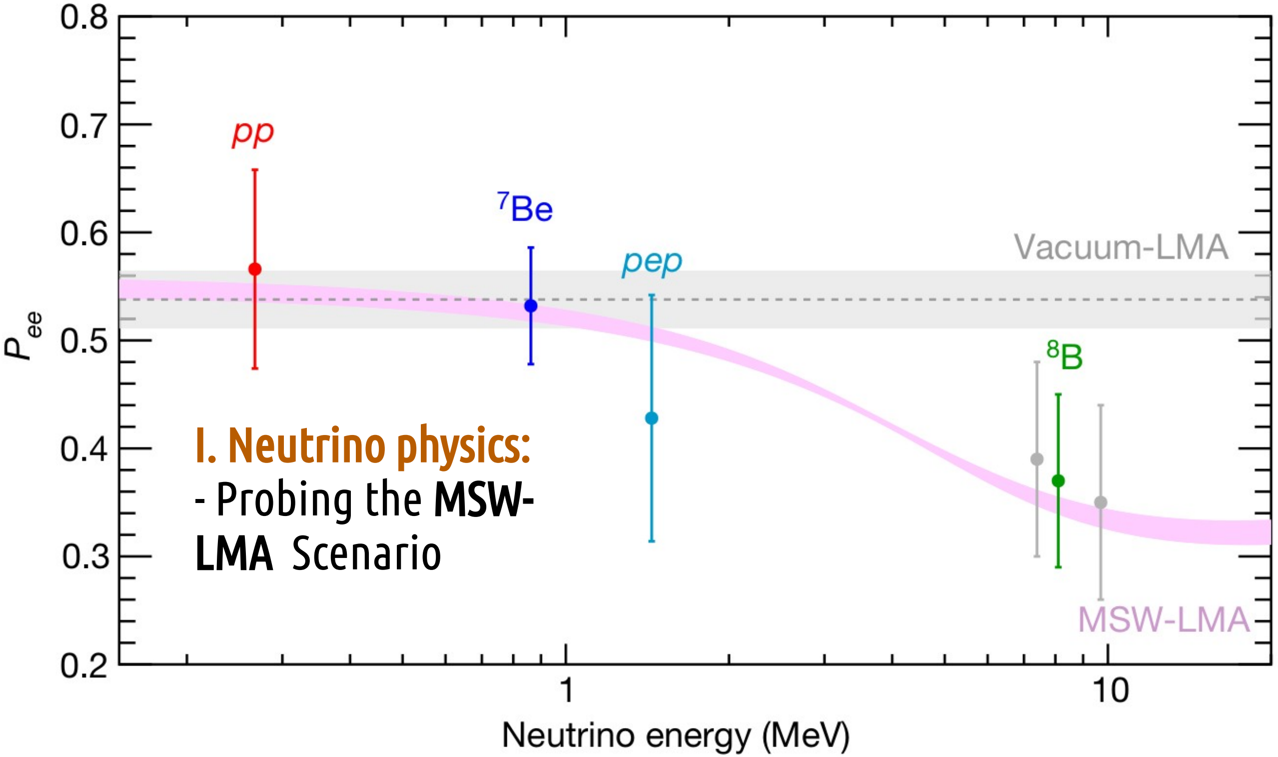
# Solar neutrino results (as of 2020)

| Neutrinos | References | Rate [cpd/100t] | Flux [$cm^{-2}s^{-1}$] |
|---|---|---|---|
| pp | Nature 2014, Nature 2018, PRD 2019 | $(134\pm10)_{-10}^{+6}$ | $(6.1\pm0.5)_{-0.5}^{+0.3}$x$10^{10}$ |
| $^{7}$Be | PLB 2008, PRL 2011, Nature 2018, PRD 2019 | $(48.3\pm1.1)_{0.7}^{+0.4}$ | $(4.99\pm0.11)_{-0.08}^{+0.06}$x$10^{9}$ |
| pep | PRL 2012, Nature 2018 PRD 2019 | $(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ] | $(1.27\pm0.19)_{-0.12}^{+0.08}$x$10^{8}$[HZ] |
| $^{8}$B | PRD 2010, Nature 2018, PRD 2020 | $0.223_{-0.022}^{+0.021}$ | $5.68_{-0.41-0.03}^{+0.39+0.03}$x$10^{6}$ |
| hep | Nature 2018, PRD 2020 | <0.002 (90% CL) | <1.8x$10^{5}$ (90% CL) |
| CNO | Nature 2020 | $7.2_{-1.7}^{+3.0}$ | $7.0_{-2.0}^{+3.0}$x$10^{8}$ |

# Remarks on of the Borexino results

- First direct meausement of the $^{7}$**Be**
- First direct detection of **pp**
- First direct detection of **pep**
- First direct detection of **CNO** neutrino
- Detection of $^{8}$**B** consistent with SuperK+SNO

# Implications of Borexino results




**I. Neutrino physics:**
- Probing the **MSW-LMA** Scenario

$P_{ee}$ survival probability with Borexino data only!

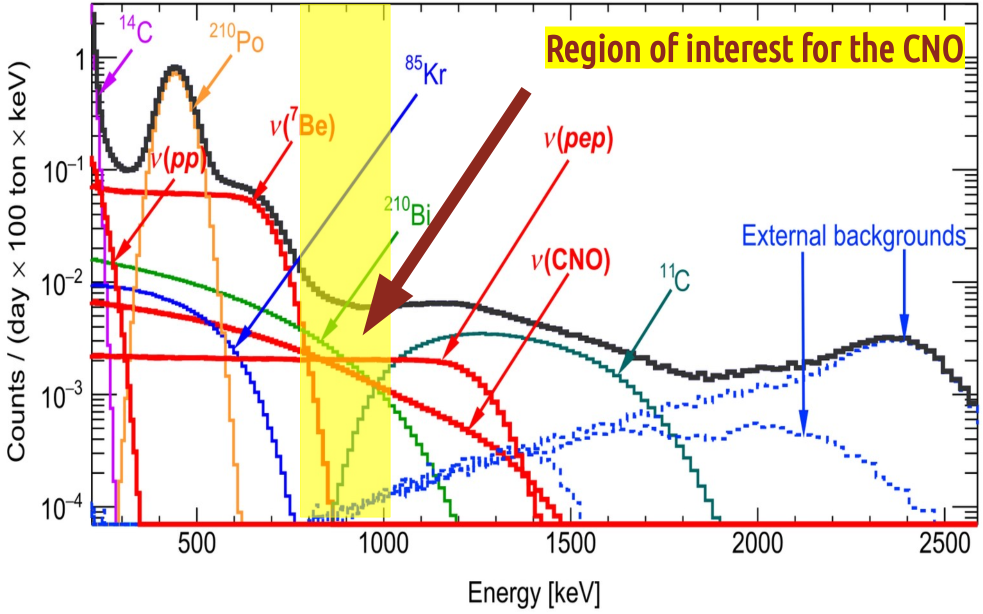
**II. Standard solar model**

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

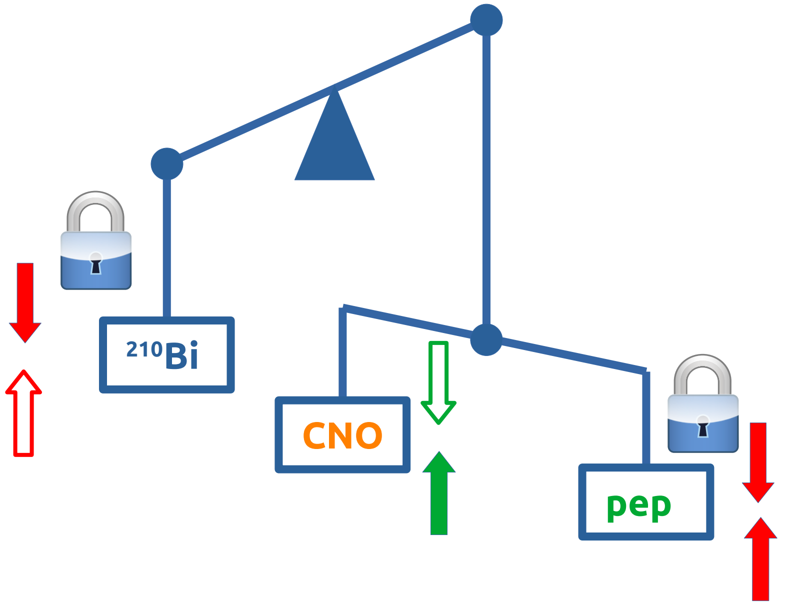
Low metallicity disfavored at
- 1.8σ (pp chain) [Nature 2018]
- 2.1 σ (pp chain + CNO) [Nature 2020]
- and...

# The CNO Strategy

Borexino spectrum after all data selection criteria




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



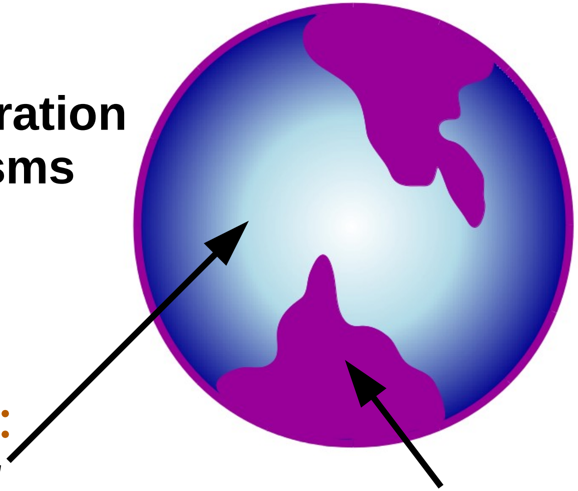

**Strategy:**

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

# The $^{210}$Bi constraint

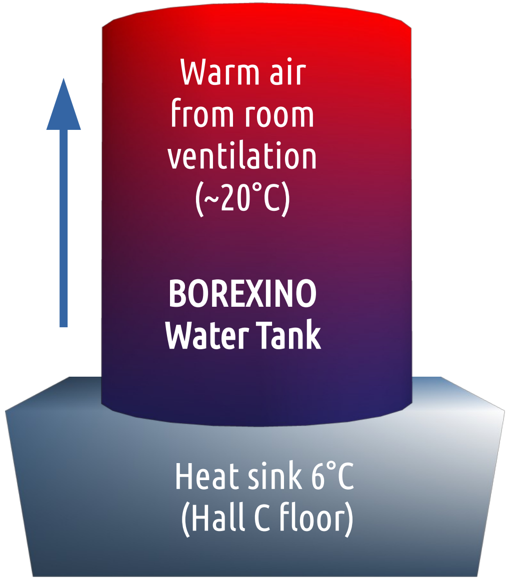
$$^{210}\mathrm{Pb} \xrightarrow[22.3\ \mathrm{years}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\ \mathrm{days}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\ \mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

**$^{210}$Po migration Mechanisms**

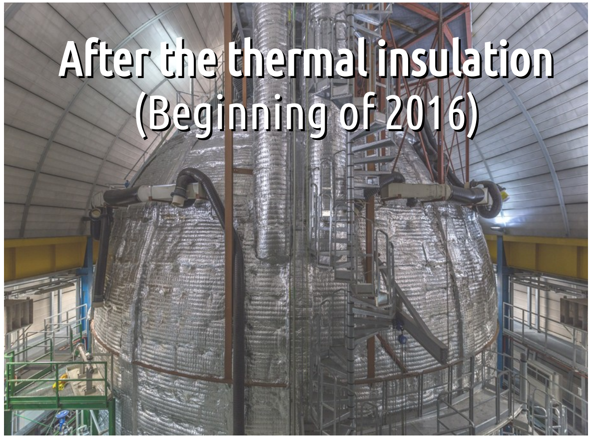


**Diffusion:**
Very slow
D ~ $10^{-9}$ m$^2$/s
(diffusion coefficient)

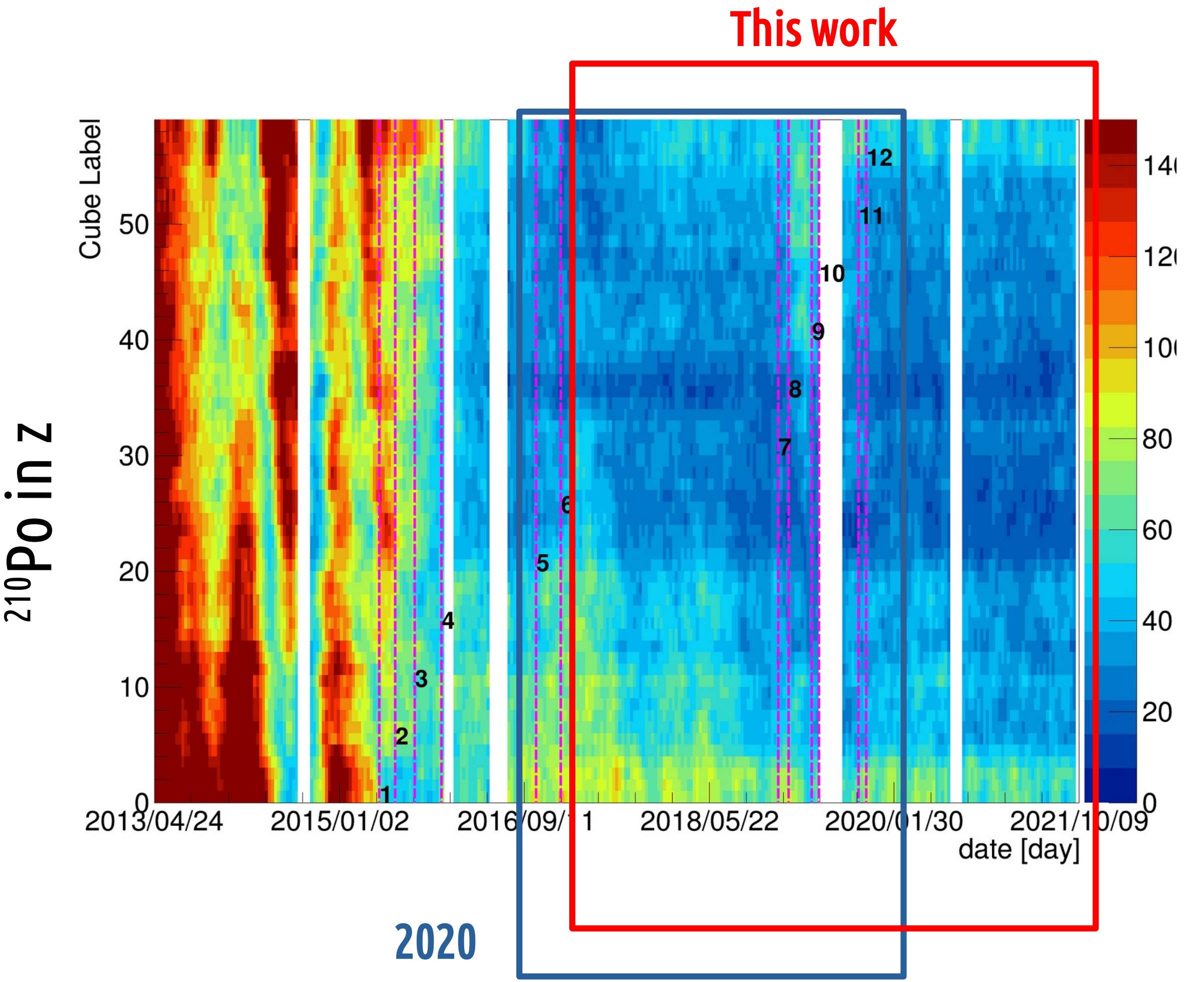
**Convection:**
$^{210}$Po from the outer regions (strongly reduced by insulation)

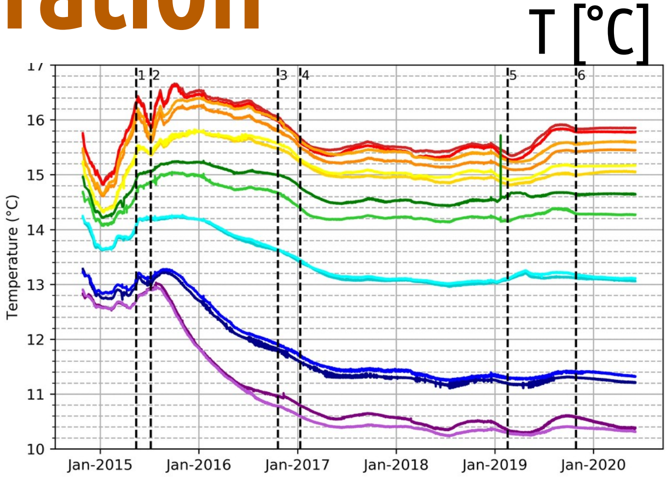


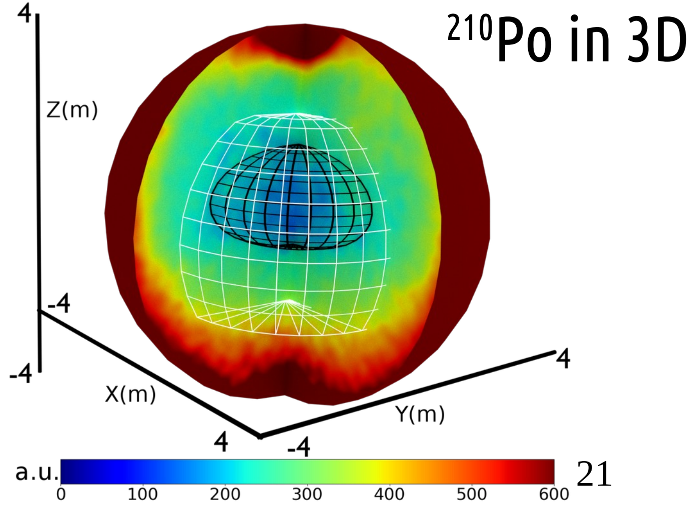

**Idea:** vertical gradient

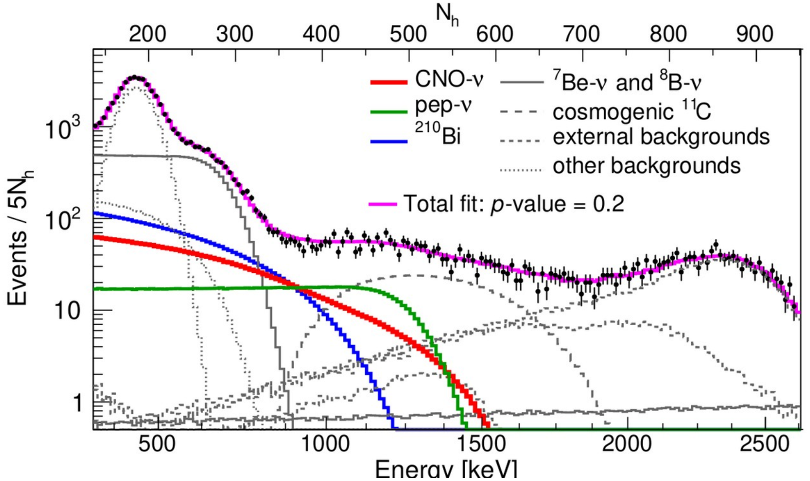
# Effects on $^{210}$Po migration

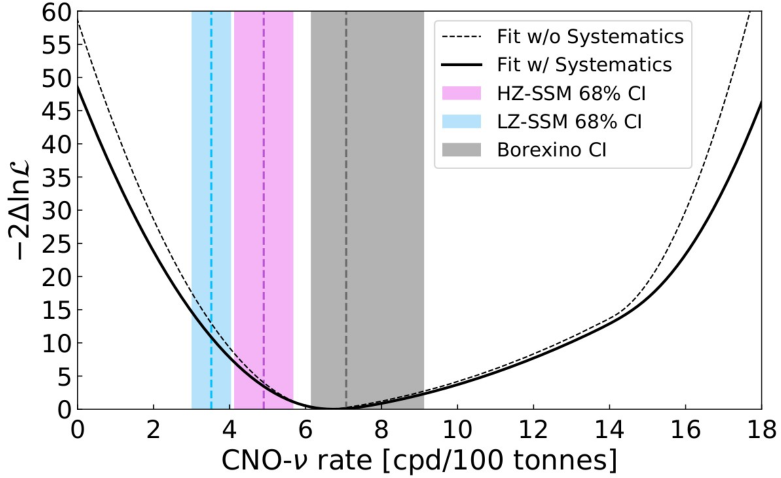


# CNO analysis (New results)




| Analysis | OLD | UPDATE |
| --- | --- | --- |
| $^{210}$Bi rate [cpd/100t] | 11.5 ± 1.3 | 10.8 ± 1.0 |
| CNO rate [cpd/100t] | $7.2^{+3.0}_{-1.7}$ | $6.7^{+2.0}_{-0.8}$ |
| CNO flux [$10^8 cm^{-2}s^{-1}$] | $7.0^{+3.0}_{-2.0}$ | $6.6^{+2.0}_{-0.9}$ |
| Significance | 5 σ | 7 σ |
| LZ rejection Bx only | 2.1 σ | 3.1 σ |

Improved result

# Updating the table (2022)

| Neutrinos | References | Rate [cpd/100t] | Flux [$cm^{-2}s^{-1}$] |
|---|---|---|---|
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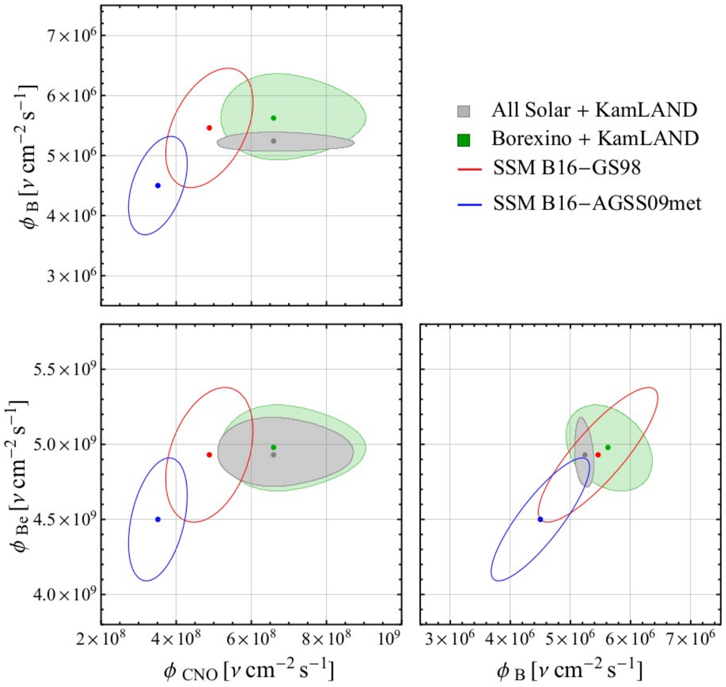
| hep | Nature 2018, PRD 2020 | <0.002 (90% CL) | <1.8x$10^{5}$ (90% CL) |
| **CNO** | **Nature 2020** | $\mathbf{6.7_{-0.8}^{+2.0}}$ | $\mathbf{6.6_{-0.9}^{+2.0}}$**x**$\mathbf{10^{8}}$ |

**Borexino ONLY!**

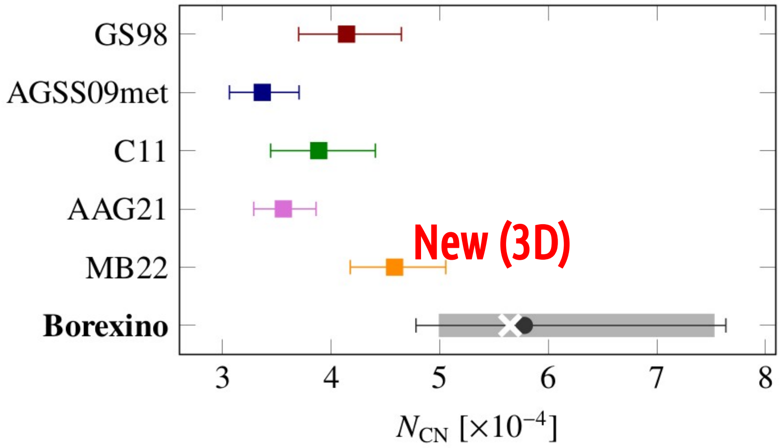
# Implications of the new results

## Global analysis




Tension between LZ and neutrino data

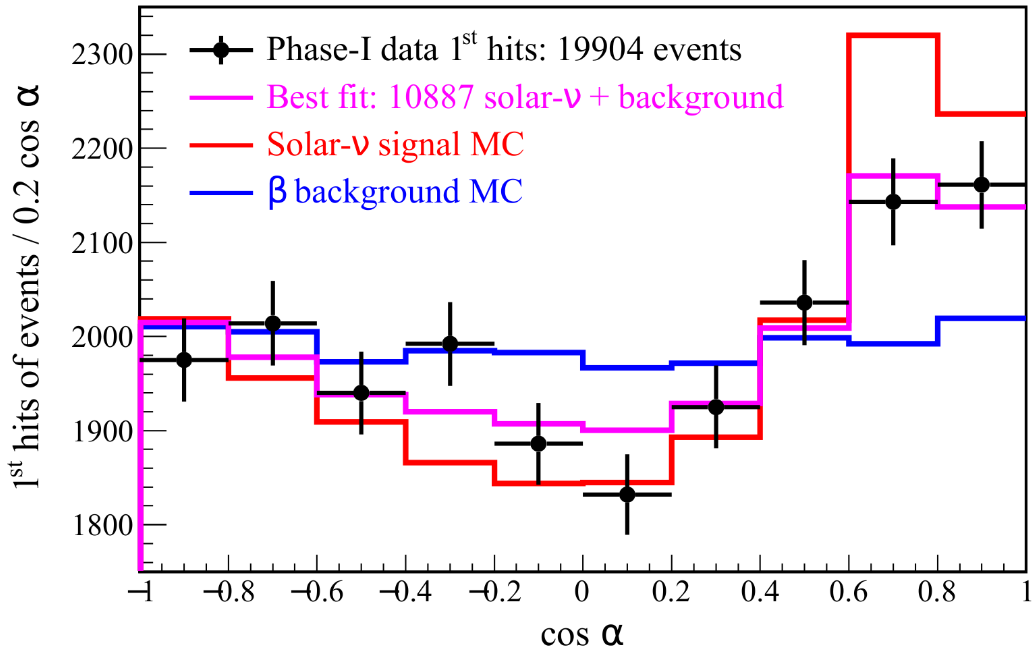
## Metallicity determination




$$\frac{N_{CN}}{N_{CN}^{SSM}} = 1.35 \times (0.96)^{-0.769} \times \times \left[1^{+0.303}_{-0.136}(\mathrm{CNO}) \pm 0.097(\mathrm{nucl}) \pm 0.023(^{8}\mathrm{B}) \pm 0.005(\mathrm{env}) \pm 0.027(\mathrm{diff}) \pm 0.022(^{13}\mathrm{N}/^{15}\mathrm{O})\right]$$

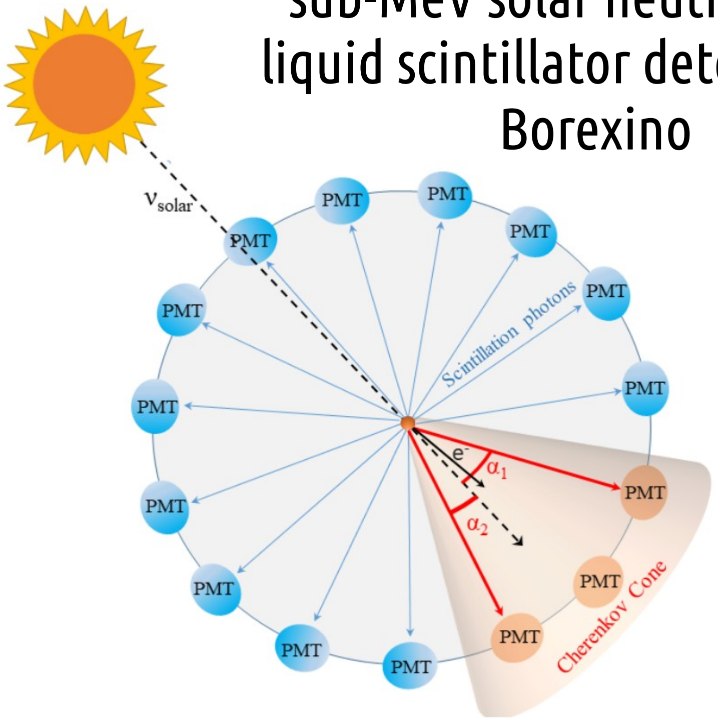
2σ tension between LZ metallicity and data

# Recent results 1/2: directionality



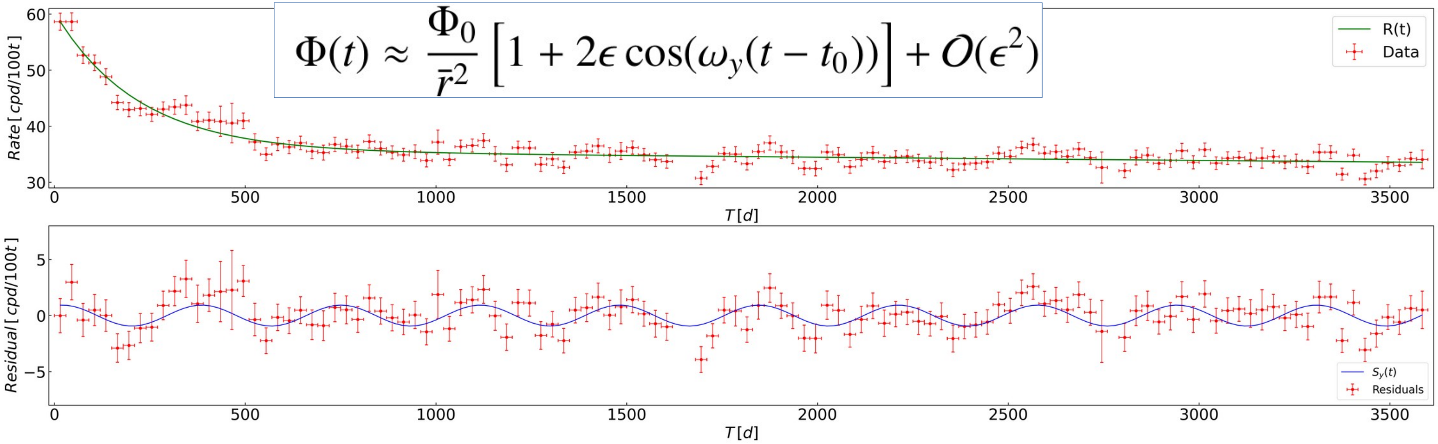

$$\mathcal{R}(^7Be) = 51.6^{+13.9}_{-12.5}\ \text{cpd/100t}$$

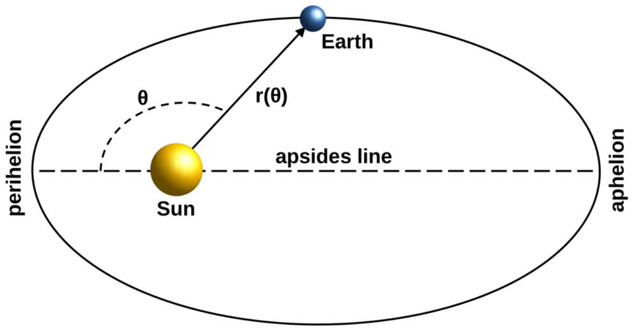
First demonstration of directional measurement of sub-MeV solar neutrinos in a liquid scintillator detector with Borexino



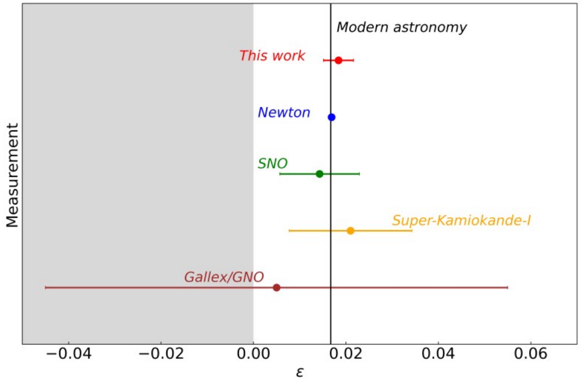
# Recent results 2/2: Eccentricity

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



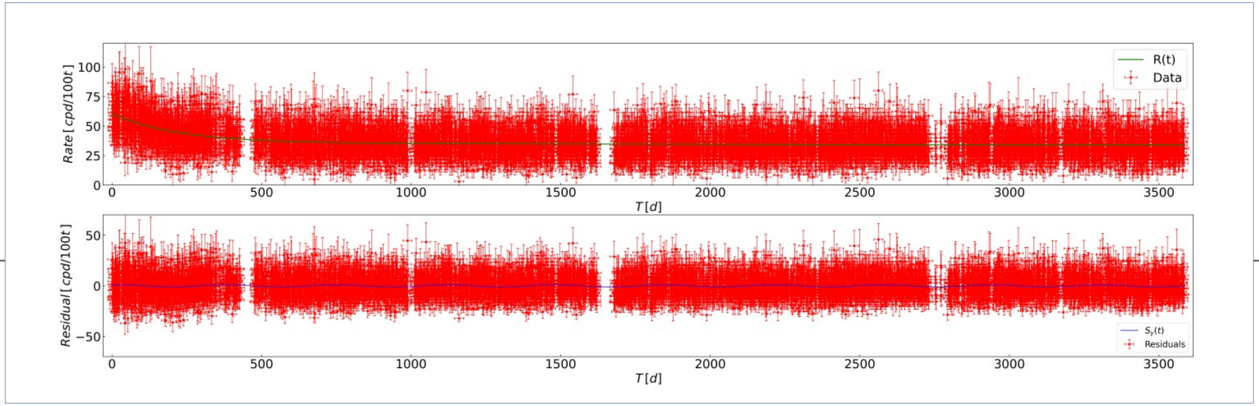

Independent determination of the Earth's orbital parameters with solar neutrinos in Borexino (5σ)

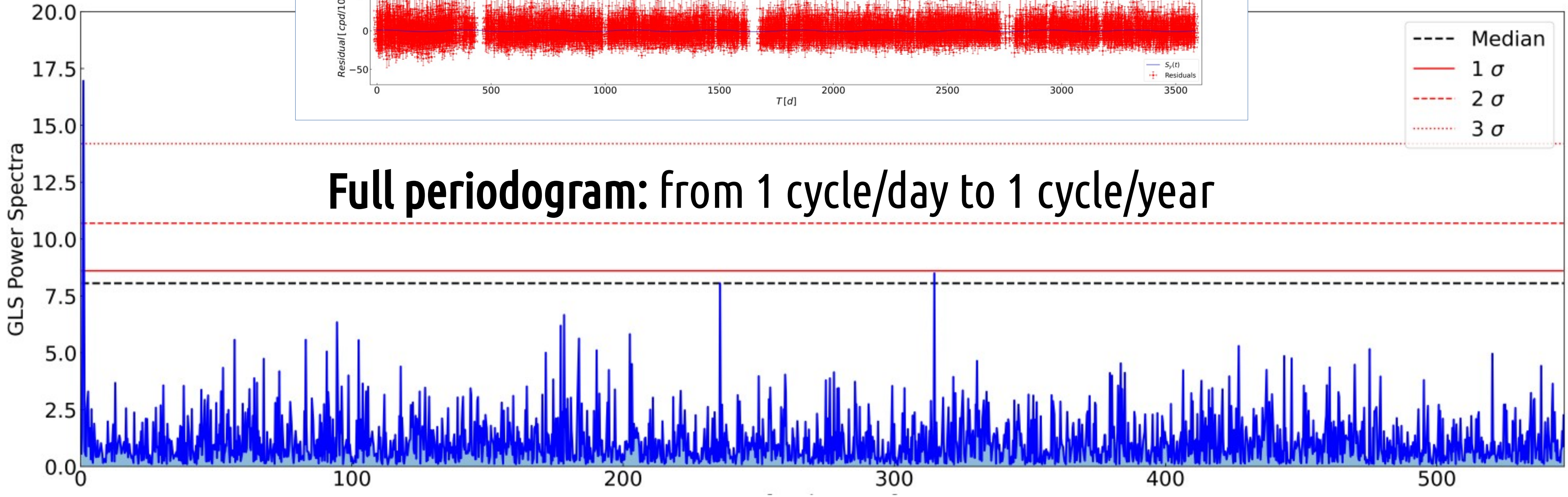



$$\mathcal{R}(^7Be) = 55 \pm 9 \text{ cpd}/100\text{t}$$

$$\varepsilon = 0.0184 \pm 0.0032\ (5.9\sigma)$$

# Full Periodogram




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

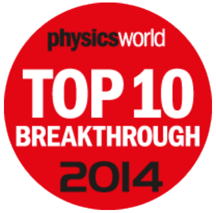
Non other significant modulation (day-night, sun's day, ...)

# Borexino & Sun: remarks

- Precision measurement of **pp chain** solar neutrino fluxes
- First detection of the **CNO neutrinos** (and now at **7σ**)
- New dataset $\mathbf{\Phi_{CNO} = 6.6_{-0.9}^{+2.0} x10^{8}\ cm^{-2}\ s^{-1}}$
- **LZ** (AGSS09) disfavoured at **3.1σ** with respect to HZ (GS98)
- CNO from Borexino → independent determination of the **CN/H abundance** (2 σ tension with LZ)

# Thank you very much!


G. & V. Cocconi Prize
2021 - EPS






Pontecorvo Prize
2015 G. Bellini

Fermi Prize
2017 G. Bellini