Misura dei parametri orbitali della Terra con i neutrini in Borexino

R. Biondi on behalf of BOREXINO Collaboration

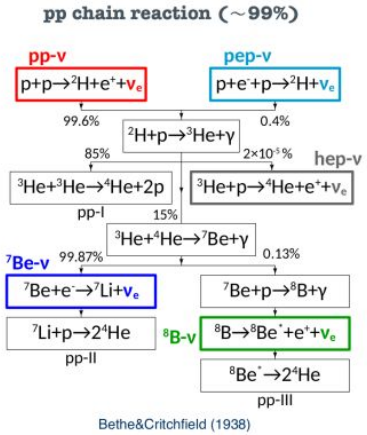
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

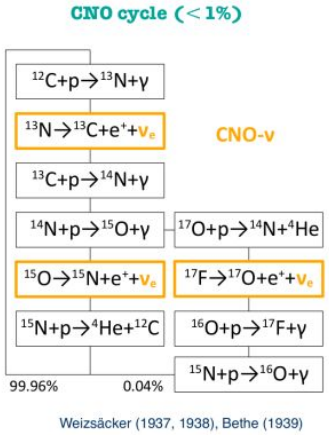
Neutrini Solari e Massimi Sistemi - 22th February 2023

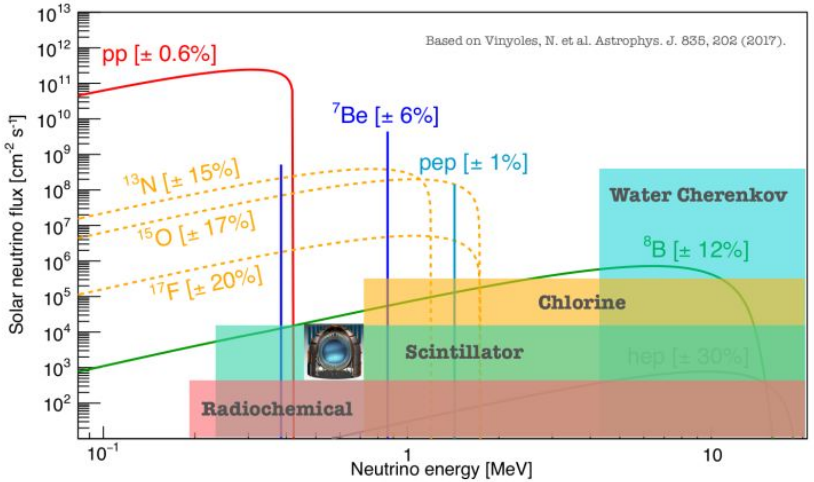
Solar Neutrinos

As we already know, the Sun is powered by **Nuclear Fusion**:

$$4\,p \rightarrow {}^{4}He + 2\,e^{+} + 2\,\nu_e \quad (\Delta E \simeq 26 MeV)$$



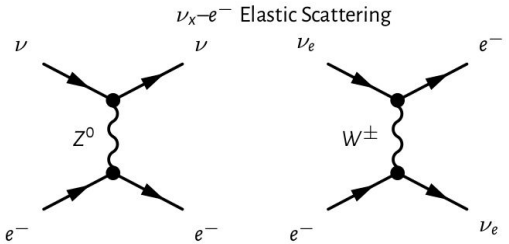


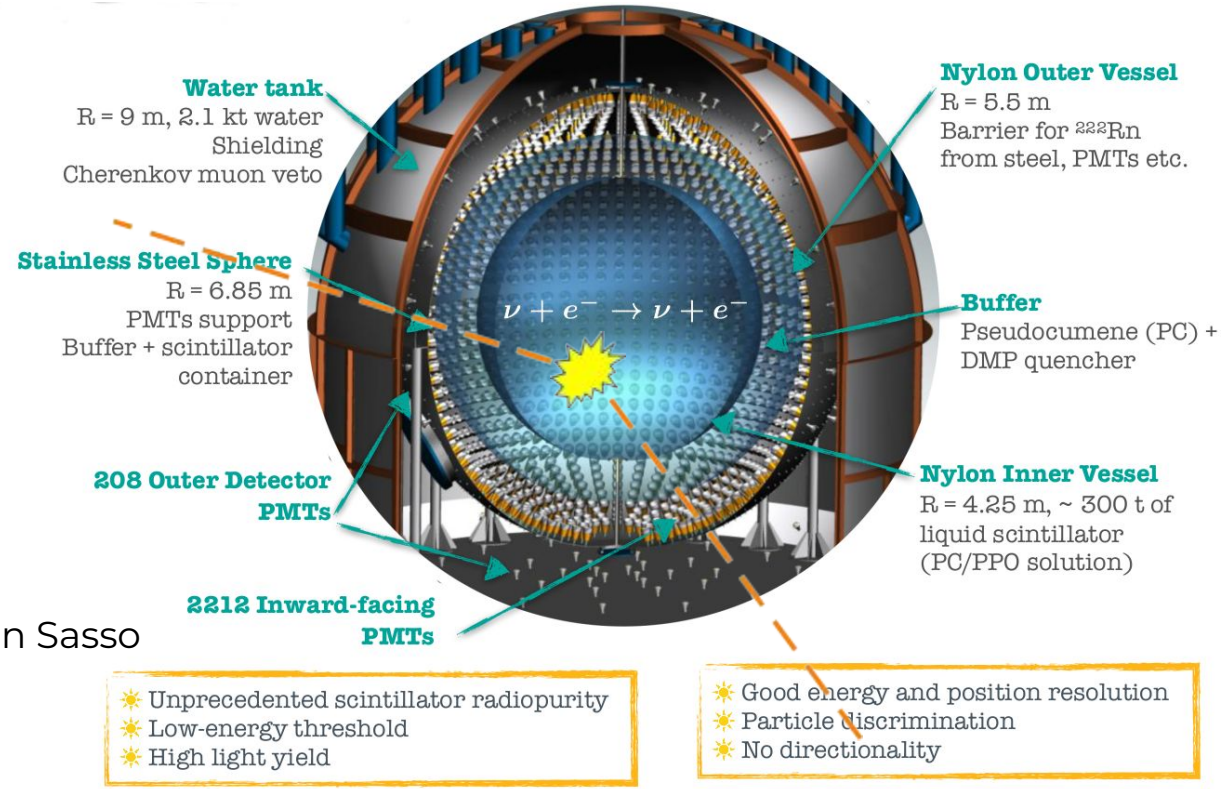


Total neutrino flux at Earth of: **~ 10^{11} cm $^{-2}$ s $^{-1}$** .

Borexino Detector

Ultrapure liquid scintillator experiment



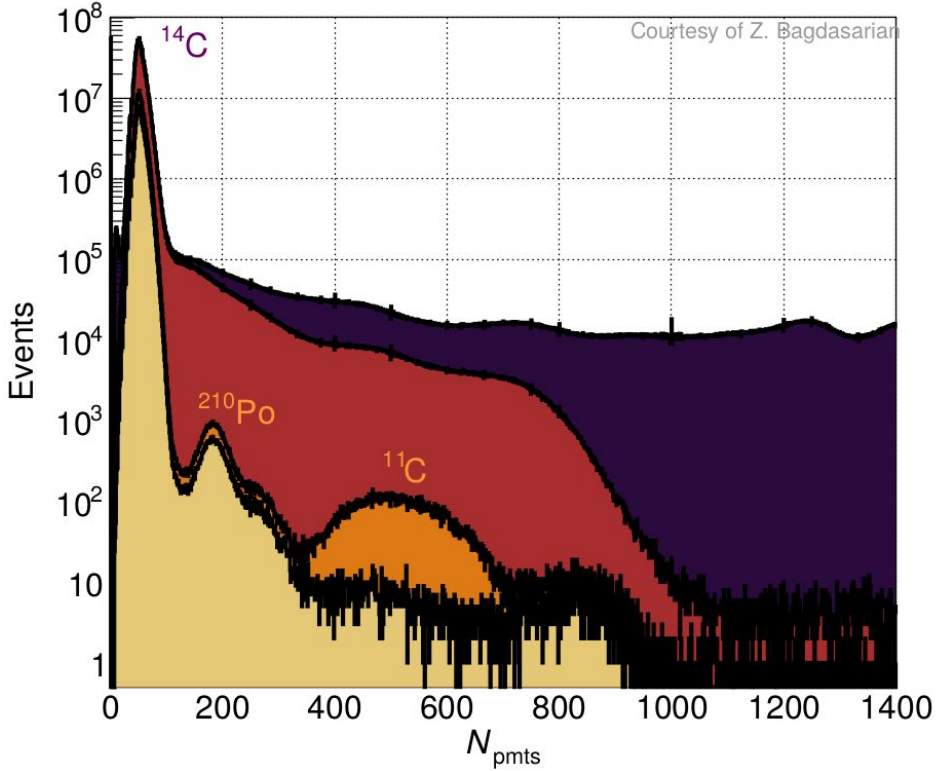


At Laboratori Nazionali del Gran Sasso

1400 mt of rock: 3.800 m.w.e.

Muon flux ~ 1 m^{-2} h^{-1} - **Suppression factor: 10^6**

The Spectrum of Borexino



Full Spectrum

Muon cut

$\approx$ 4300 μ/day crossing ID

Removes μ, μ-induced n and cosmogenics

Fiducial Volume cut

Reduction of external and surface background

^{11}C suppression (TFC cut)

μ–n pairs coincidences

+ space-time correlation with β-like ev.

$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

n capture ~ 260μs

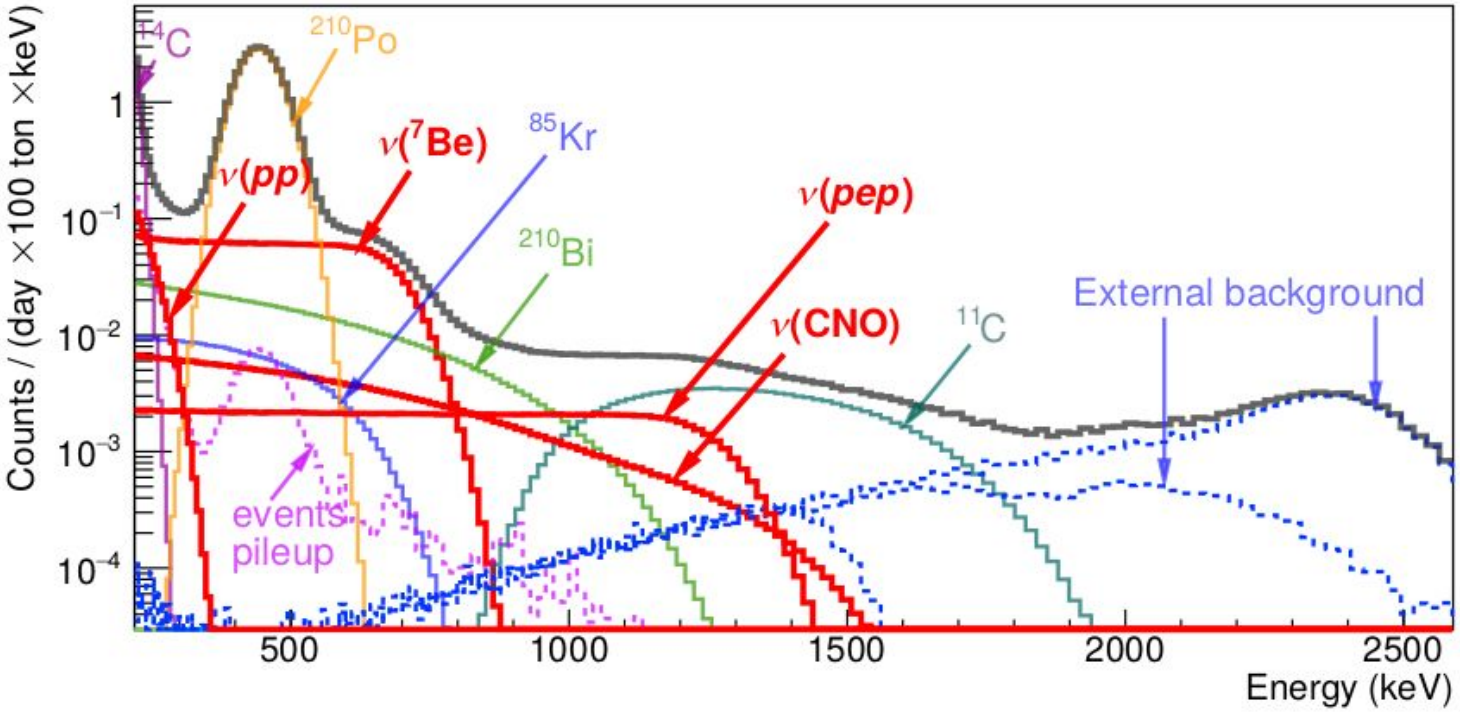
n+p → d+γ (2.2 MeV)

β^+ decay ~ 30 min

${}^{11}C \rightarrow {}^{11}C + e^+ + \nu_e$

Understanding the spectrum

Multi-Variate Spectral Fit to extract Rate of the Solar Neutrinos and Backgrounds.

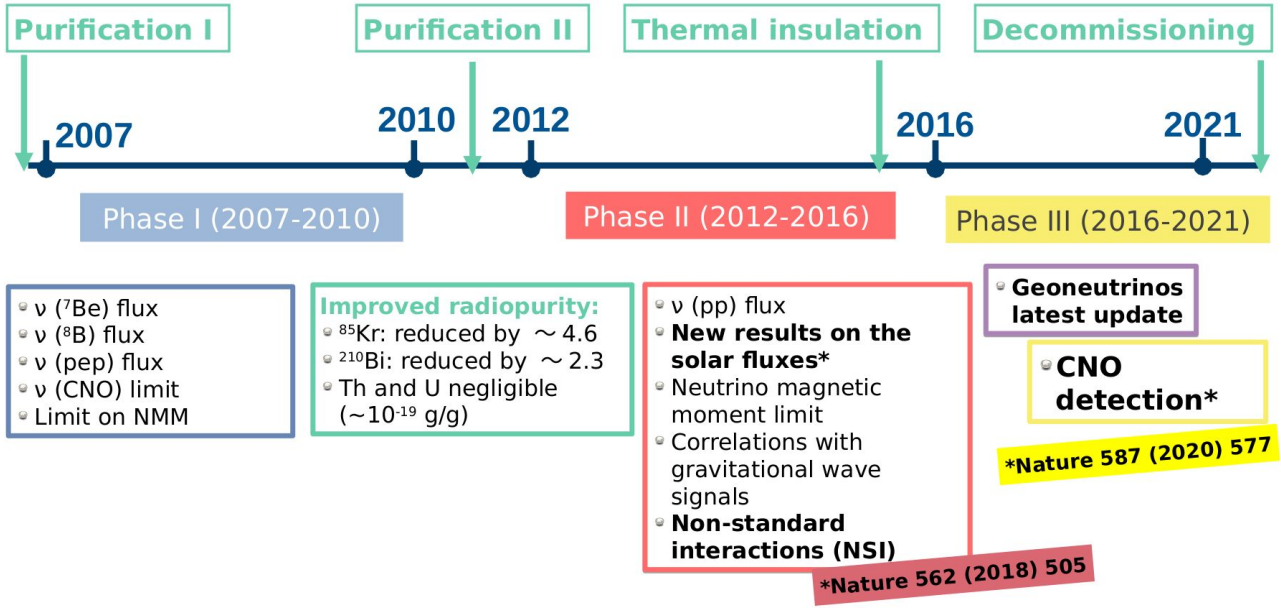


The Long History of Borexino

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



pp - Chain and CNO Cycle Results

- Precision measurement of pp chain solar neutrino fluxes
- First detection of the CNO neutrinos at 7σ
- First hint on **solar metallicity** (2σ tension between LZ metallicity and data)

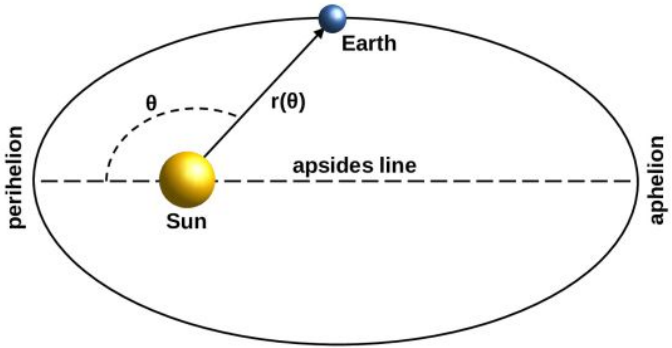
Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)_{-10}^{+6}$	$(6.1\pm0.5)_{-0.5}^{+0.3}\times10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)_{0.7}^{+0.4}$	$(4.99\pm0.11)_{-0.08}^{+0.06}\times10^{9}$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ]	$(1.27\pm0.19)_{-0.12}^{+0.08}\times10^{8}$[HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}\times10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8\times10^{5}$ (90% CL)
CNO	Phys.Rev.Lett. 2022	$6.7_{-0.8}^{+2.0}$	$6.6_{-0.9}^{+2.0}\times10^{8}$

~3% Precision measurement on the ν(^{7}Be) Rate

Seasonal Modulation

Solar neutrinos interaction rate exhibits an annual periodical modulation due to the **eccentricity ε** of Earth's orbit:

$$\epsilon = \frac{r(\pi) - r(0)}{r(\pi) + r(0)}$$



The Earth-Sun distance: $$r(\theta) = \frac{\bar{r}(1-\epsilon^2)}{1+\epsilon\cos(\theta)}$$

Since $\varepsilon \simeq 0.0167 << 1$ the solar neutrino flux hitting the Earth is:

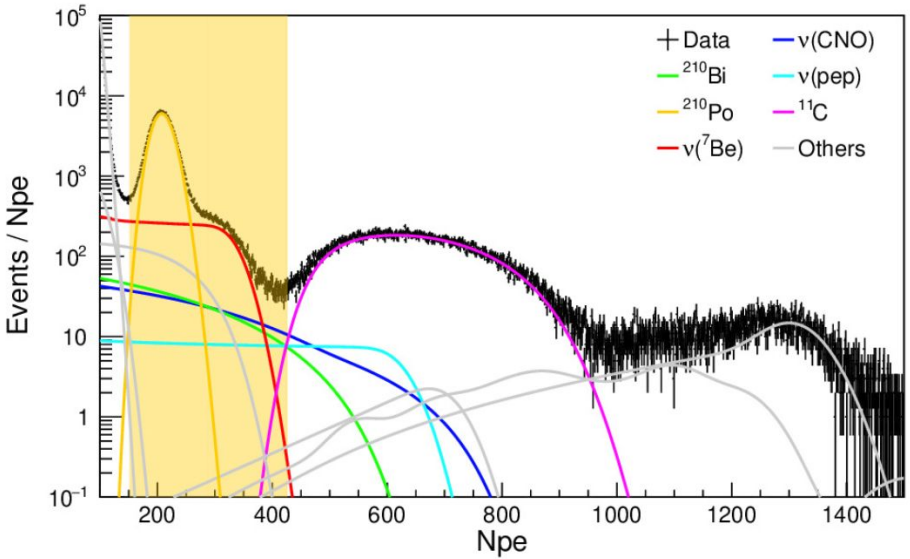
$$\Phi(t) \approx \frac{\Phi_0}{\bar{r}^2}\left[1 + 2\epsilon\cos(\omega_y(t-t_0))\right] + \mathcal{O}(\epsilon^2)$$

3.34% Modulation of Solar neutrinos rate Expected

Data Selection

- Phase-II + Phase-III (December 11th 2011 - October 3rd 2021)
- Spherical fiducial volume of 3 m radius (~100 tonnes)

Background from ^{210}Po α decay events reduced via pulse shape discrimination (efficiency > 99%)



Chosen Region: 150-428 Npe (300-827 keV)

Main contribution from **^{7}Be Neutrinos** (CNO and pep Neutrinos also present)

Analysis Method

Analyzed with a **Likelihood generalized** version of the standard **Lomb-Scargle** (GLS).

S = − ln(GLR) exponentially distributed under the null hypothesis.

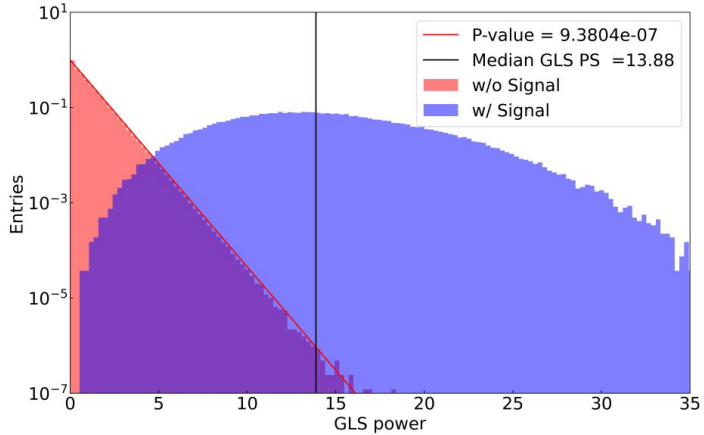
$$GLR(\nu) = \frac{\prod_i^N \frac{\mu_{trend}^{n_i} e^{-\mu_{trend}}}{n_i!}}{\max_{A,\phi} \prod_i^N \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}}$$

It is the **likelihood spectrum** of the signal, sharing the same properties of the LS periodogram

Detrending procedure is carried out by subtracting an empirical combination of exponential trends:

$$R(t) = R_A e^{-t/\tau_A} + R_B e^{-t/\tau_B} \approx R_A e^{-t/\tau_A} + R_B \left(1 - \frac{t}{\tau_B}\right)$$

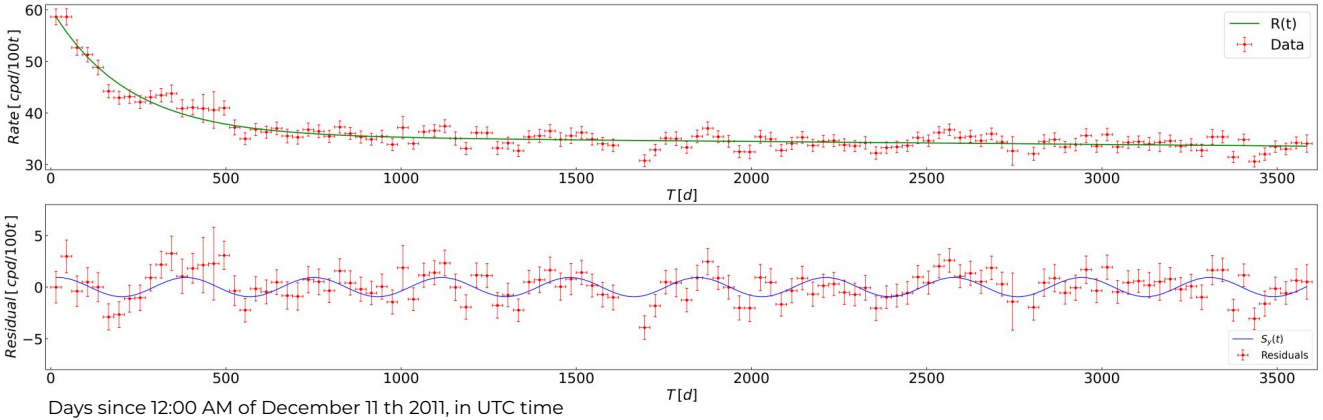
Median sensitivity: for 1 cycle/year obtained from toy Monte Carlo pseudo-experiments

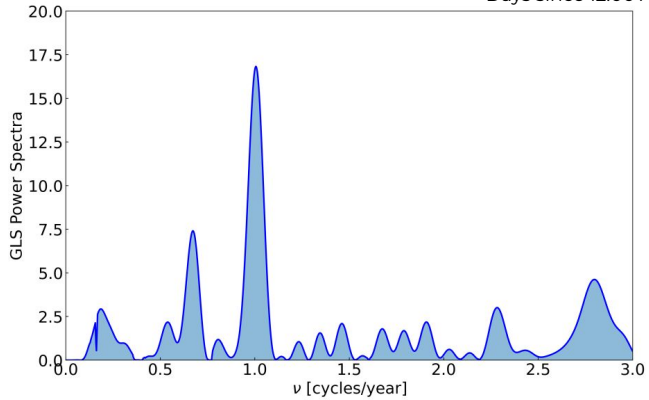


Frequency analysis

Borexino time series binned in intervals of 30 days

Residuals w.r.t. the trend model R(t)





GLS periodogram show a **significant peak** with **S = 16.4** at **1 cycle/year**

5.3 σ significance

Earth's Orbit Parameters

Residuals fitted: $S_y(t) = A_y \cos(\omega_y(t - t_0))$

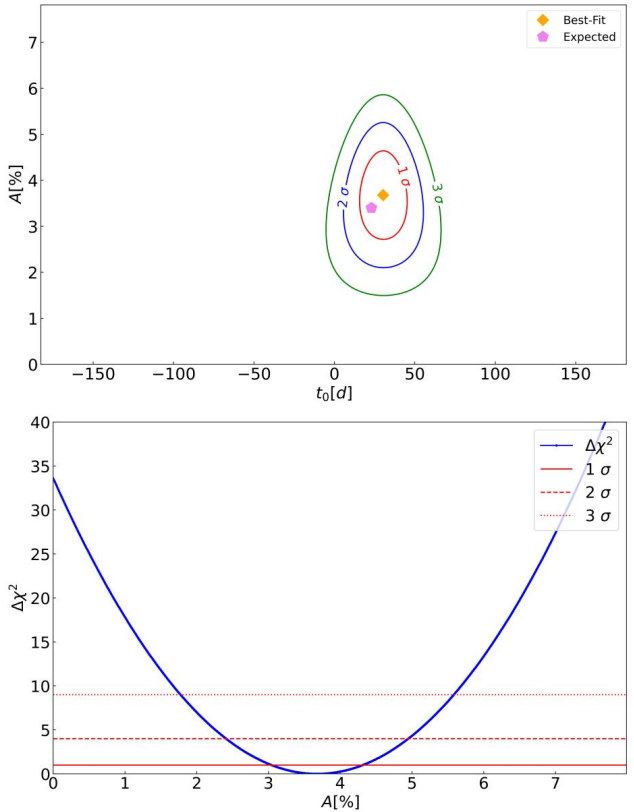
- A_y = (0.94 ± 0.16) cpd/100t
- **T_y = (363.1 ± 3.6)days**
- t_0 = (30 ± 20) days

$$A = 2\epsilon = \frac{A_y}{R_\odot} = (3.68 \pm 0.65)\%$$

First **1%-level** measurement of the orbital period obtained with solar neutrinos only

No other significant minimum of the χ^2 profile is found

The null hypothesis is rejected at 5.9 σ

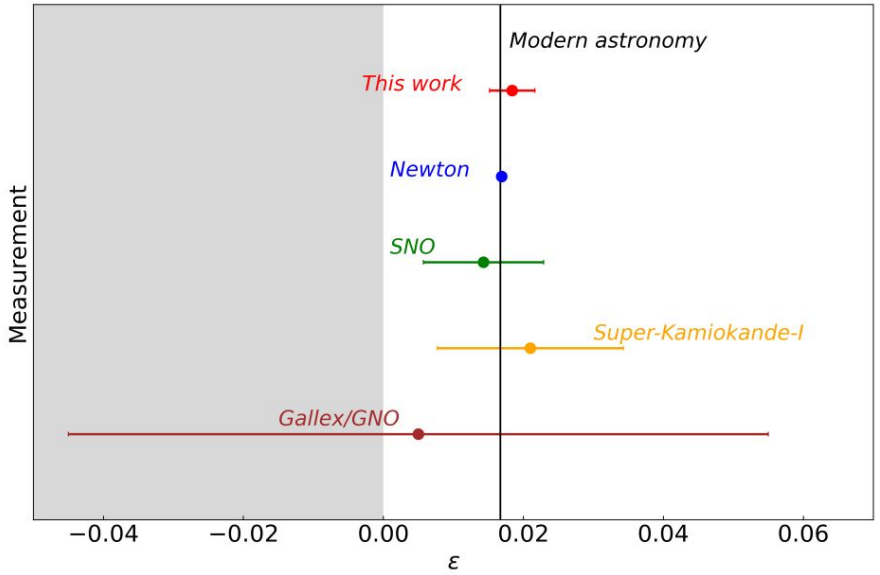


Eccentricity and Solar Neutrinos

$$\epsilon = 0.0184 \pm 0.0032$$

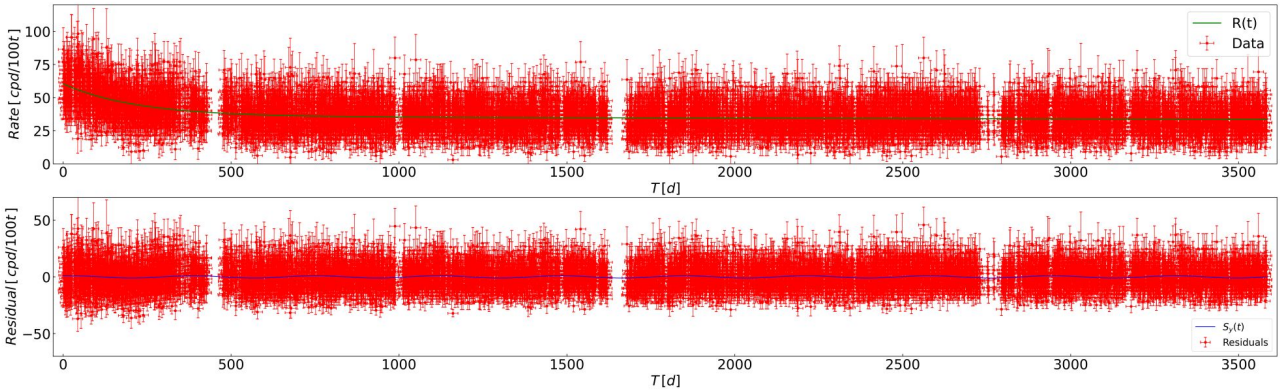
SNO and Super-Kamiokande searched for the annual modulation of **^{8}B neutrinos**

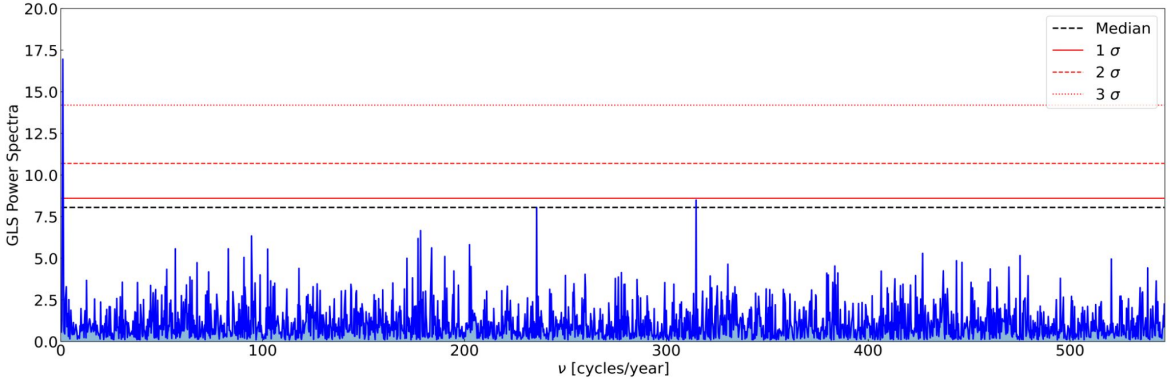
Evidence for annual modulation is also found with **1-2σ significance** by both experiments. Gallex/GNO



Full periodogram

Using smaller time bins, is possible to extend the periodogram analysis to frequencies **above 1 cycles/day**



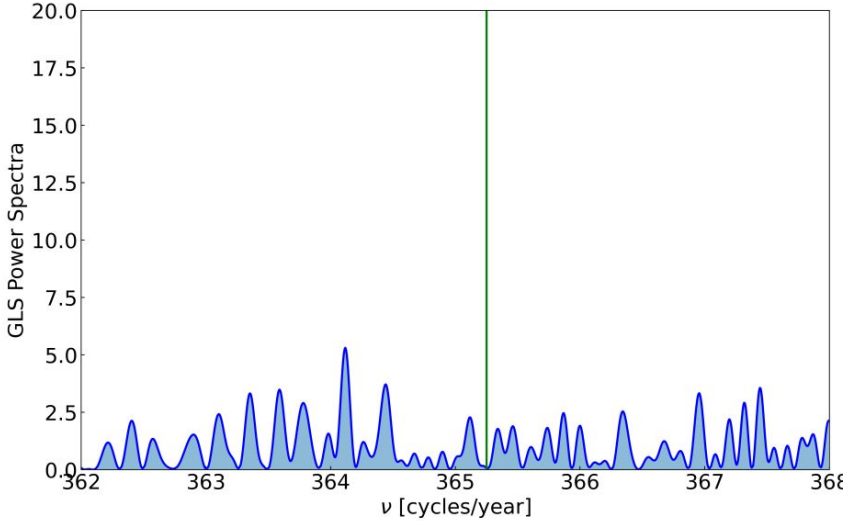


Significance of other peaks is evaluated using **Look-elsewhere effect**

Daily Modulation

Daily effects is interesting for electron neutrino regeneration in the Earth, sterile neutrino phenomenology and new interactions beyond the Standard Model

Borexino Phase-I: $A_{dn} = 2(D - N)/(D + N)$
$= 0.001 \pm 0.012\ (stat) \pm 0.007\ (syst)$



Residual fitted to a sinusoidal function whose amplitude A_d:

Give: **A_{dn} = 0.0030 ± 0.0094(stat) ± 0.0002(sys)** [compatible with 0 at 1σ]

$$A_{dn} = \frac{2A_d}{\sqrt{2}R_\odot}$$

Conclusions

The stability of Borexino's response and energy resolution and the understanding the backgrounds have made possible the search for solar neutrino rate modulations over the last 10 years using the **generalized Lomb-Scargle method:**

- No significant periodic signal other than the **annual modulation**
- Compatible within 1 σ with astronomical measurements
- Absence of modulation excluded is at >5 σ C.L.
- **Most precise measurement of the Earth's orbit eccentricity** using solar neutrinos only.
- **Limits on diurnal modulation** < 1.3% (90% CL)
- Annual modulation in Borexino data confirms the **solar origin** its signal.

Thank you!