# First significant measurement of the Earth's orbital parameters with solar neutrinos in Borexino

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INFN LNGS

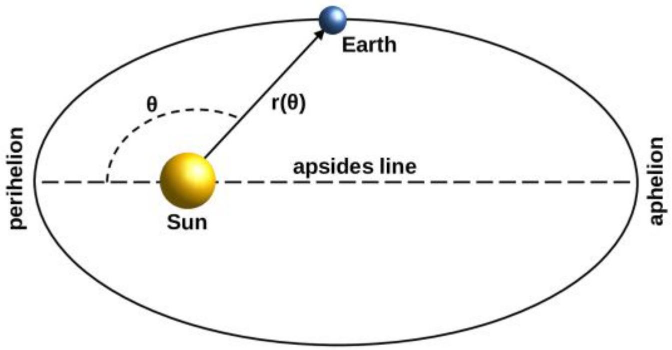
BOREXINO GRAN SASSO

**ICHEP 2022 - 9th July 2021**

# Seasonal Modulation

Solar neutrinos interaction rate time series exhibits an annual periodical modulation due to the **eccentricity $\varepsilon$** of Earth's orbit.

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




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

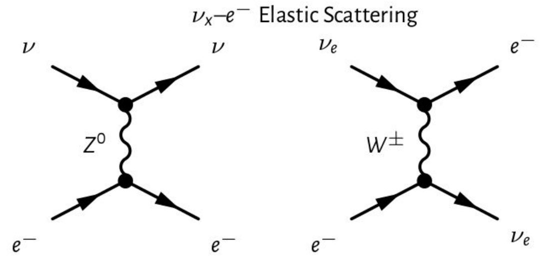
Since $\varepsilon \approx 0.0167 << 1$ the solar neutrino flux hitting the Earth is:

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

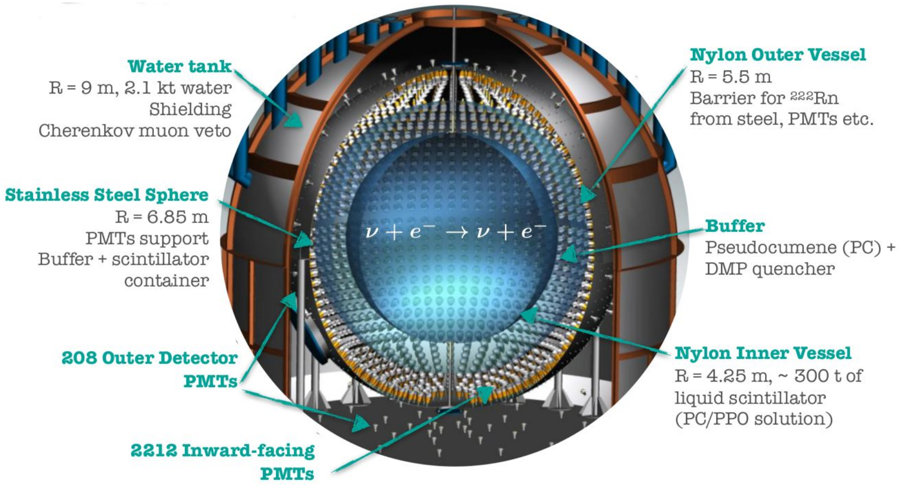
**3.34% Modulation** of Solar neutrinos rate Expected

# Borexino Detector

**Ultrapure liquid scintillator experiment** able to detect light emitted in elastic scattering between solar neutrinos and the electrons of the scintillating material.




- $E_{th}$ = 150 KeV
- Light Yield: ~550 p.e./MeV
- Energy resolution: ΔE/E ~ 5%/(E[MeV])$^{1/2}$
- Position reconstruction: ~10 cm at 1 MeV
- ν-induced electron recoils indistinguishable from β and γ background

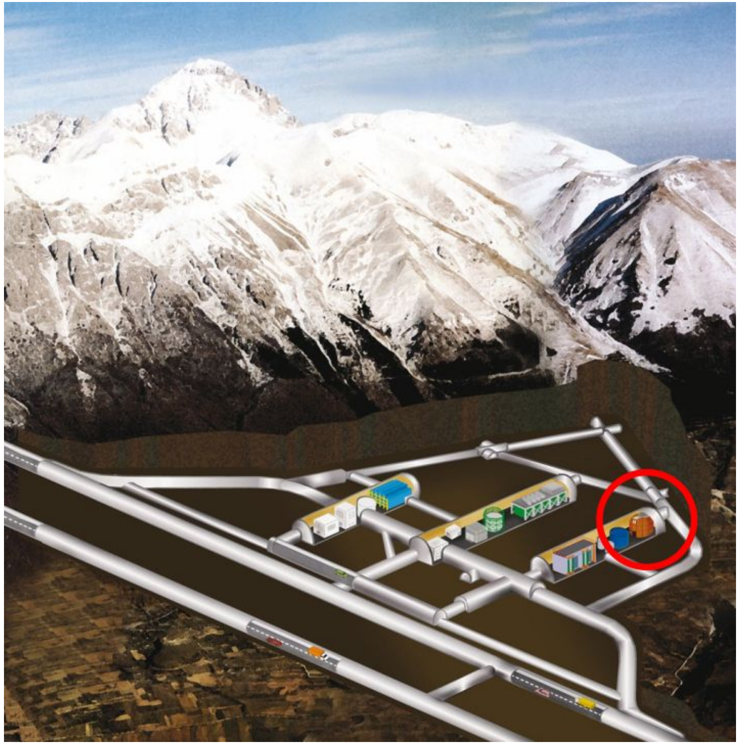



- Unprecedented scintillator radiopurity
- Low-energy threshold
- High light yield

- Good energy and position resolution
- Particle discrimination
- No directionality

| | Requirement | Result Phase-II |
|---|---|---|
| $^{238}$U | $1 \times 10^{-16}$ g/g | $< 9.5 \times 10^{-20}$ g/g |
| $^{232}$Th | $1 \times 10^{-16}$ g/g | $< 5.7 \times 10^{-19}$ g/g |
| $^{210}$Po | $<$ 100 cpd/100ton | $\sim$ 50 cpd/100ton |
| $^{210}$Bi | | $\sim$ 20 cpd/100ton |
| $^{14}$C | $1 \times 10^{-18}$ g/g | $\sim 2 \times 10^{-18}$ g/g |

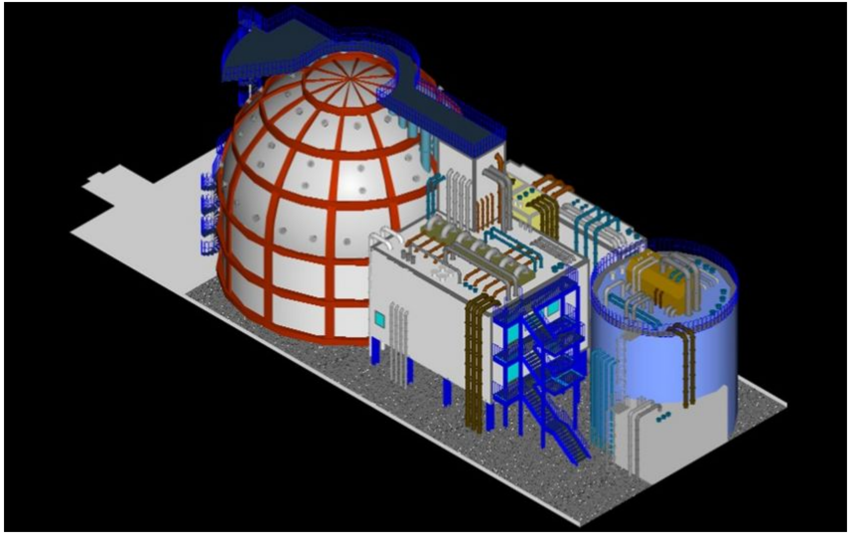
# Borexino Location



Laboratori Nazionali del Gran Sasso – INFN (Hall C)

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

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



# The Long History of Borexino

Purification I — Purification II — Thermal insulation — Decommissioning

2007 — 2010 — 2012 — 2016 — 2021

Phase I (2007-2010)

Phase II (2012-2016)

Phase III (2016-2021)

- ν ($^{7}$Be) flux
- ν ($^{8}$B) flux
- ν (pep) flux
- ν (CNO) limit
- Limit on NMM

Improved radiopurity:
- $^{85}$Kr: reduced by ~4.6
- $^{210}$Bi: reduced by ~2.3
- Th and U negligible ($\sim 10^{-19}$ g/g)

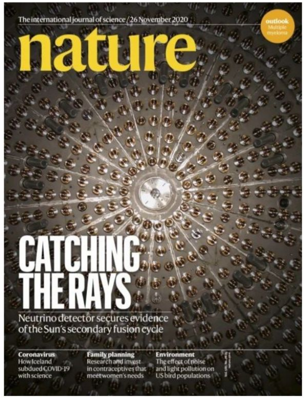
- ν (pp) flux
- **New results on the solar fluxes***
- Neutrino magnetic moment limit
- Correlations with gravitational wave signals
- **Non-standard interactions (NSI)**

***Nature 562 (2018) 505**

- **Geoneutrinos latest update**

- **CNO detection***

***Nature 587 (2020) 577**




**A long and successful journey**


G. & V. Cocconi Prize
2021 - EPS

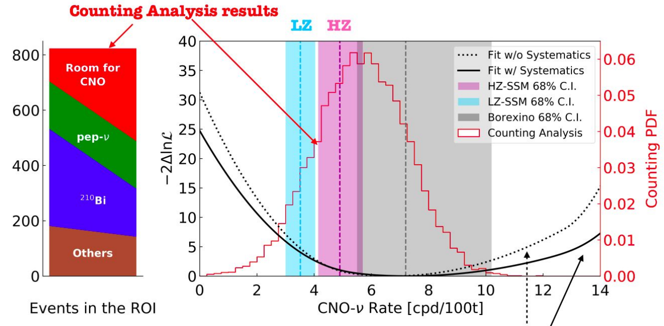
# pp - Chain and CNO Cycle Results

RESEARCH ARTICLE

**Table 2 | Borexino experimental solar-neutrino results**

| Solar neutrino | Rate (counts per day per 100 t) | Flux ($cm^{-2} s^{-1}$) | Flux–SSM predictions ($cm^{-2} s^{-1}$) |
|---|---|---|---|
| *pp* | $134 \pm 10^{+6}_{-10}$ | $(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$ | $5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ)<br>$6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ) |
| $^{7}$Be | $48.3 \pm 1.1^{+0.4}_{-0.7}$ | $(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$ | $4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ)<br>$4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ) |
| *pep* (HZ) | $2.43 \pm 0.36^{+0.15}_{-0.22}$ | $(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$ | $1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ)<br>$1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ) |
| *pep* (LZ) | $2.65 \pm 0.36^{+0.15}_{-0.24}$ | $(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$ | $1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ)<br>$1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ) |
| $^{8}B_{HER-I}$ | $0.136^{+0.013+0.003}_{-0.013-0.003}$ | $(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$ | $5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ)<br>$4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ) |
| $^{8}B_{HER-II}$ | $0.087^{+0.080+0.005}_{-0.010-0.005}$ | $(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$ | $5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ)<br>$4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ) |
| $^{8}B_{HER}$ | $0.223^{+0.015+0.006}_{-0.016-0.006}$ | $(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$ | $5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ)<br>$4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ) |
| CNO | <8.1 (95% C.L.) | $<7.9 \times 10^{8}$ (95% C.L.) | $4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ)<br>$3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ) |
| hep | <0.002 (90% C.L.) | $<2.2 \times 10^{5}$ (90% C.L.) | $7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ)<br>$8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ) |

Measured neutrino rates (second column): for *pp*, $^{7}$Be, *pep* and CNO neutrinos we quote the total counts without any threshold; for $^{8}$B and hep neutrinos we quote the counts above the corresponding analysis threshold. Neutrino fluxes (third column) are obtained from the measured rates assuming the MSW-LMA oscillation parameters[19], standard neutrino–electron cross-sections[27] and a density of electrons in the scintillator of $(3.307 \pm 0.003) \times 10^{31}$ electrons per 100 t. All fluxes are integral values without any threshold. The result for *pep* neutrinos depends on whether we assume HZ or LZ SSM predictions to constrain the CNO neutrino flux. The last column shows the fluxes predicted by the SSM for the HZ or LZ hypotheses[18].



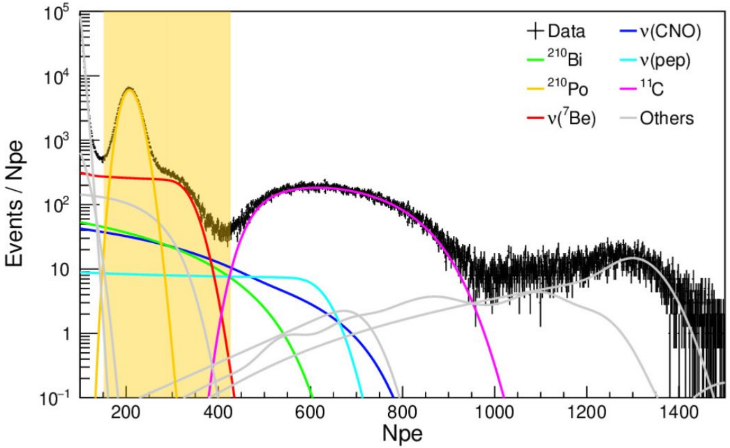

- $^{210}$Bi determination - the biggest systematics for both counting and multivariate fit
- Compatible results

$\nu(CNO) = 7.2^{+2.9}_{-1.7}$ (stat) cpd/100t

**Order ~3% precision measurement on the $\nu(^{7}Be)$ Rate**

# Data Selection

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




Energy window defined to maximize signal to background ratio

$$FoM\,(\Delta E) = \frac{R_S}{\sigma(R_{tot})}$$

$R_S$: $\nu_S$ rate in $\Delta E$

Background from $^{210}$Po $\alpha$ 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)

# Generalized Lomb Scargle Method

Total event rate time series are analyzed with a **Likelihood generalized** version of the standard **Lomb-Scargle** (GLS).

Expected number of events in the i-th bin: $\mu_i = \mu_{trend}(t_i)\,[1 + A\cos(2\pi\nu(t_i + \phi))]$

For Poissonian statistics, the likelihood function is : $L = \prod_i^N \frac{\mu_i^{n_i}\, e^{-\mu_i}}{n_i!}$

$\mu_{trend}(t)$: non constant backgrounds

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

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

And it is the **likelihood spectrum** of the signal, sharing the same properties of the LS periodogram **$S = \Delta\chi^2$**

(Wilks's theorem)

The standard LS is a special case of the Likelihood method in which the errors are not considered

# Detrend Procedure & Sensitivity

To use binned data normalized to different live times, the likelihood function must be rewritten in terms of rate:

$$L = \prod_{i=0}^{N} \frac{y_i^{x_i} e^{-y_i}}{\Gamma(x_i + 1)}$$

$x_i$ ($y_i$): measured (expected) rate

Time series of Borexino rate shows **secular trends** R(t), which could bias the measured amplitude of modulations.

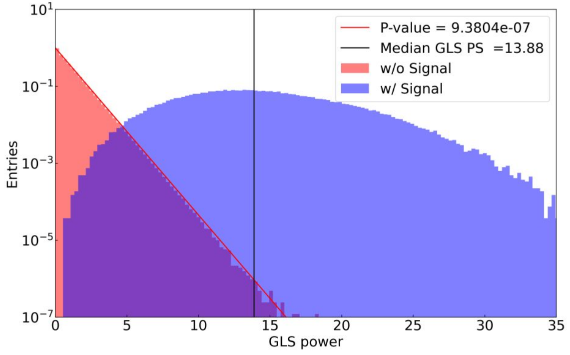
**Detrending procedure** is carried out by subtracting an empirical combination of exponential trends:

($\tau_B$ >> 10 years)

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

$R_A$: leakage of $^{210}$Po $\alpha$ events
$R_B$: slowly varying $^{210}$Bi and $^{85}$Kr backgrounds

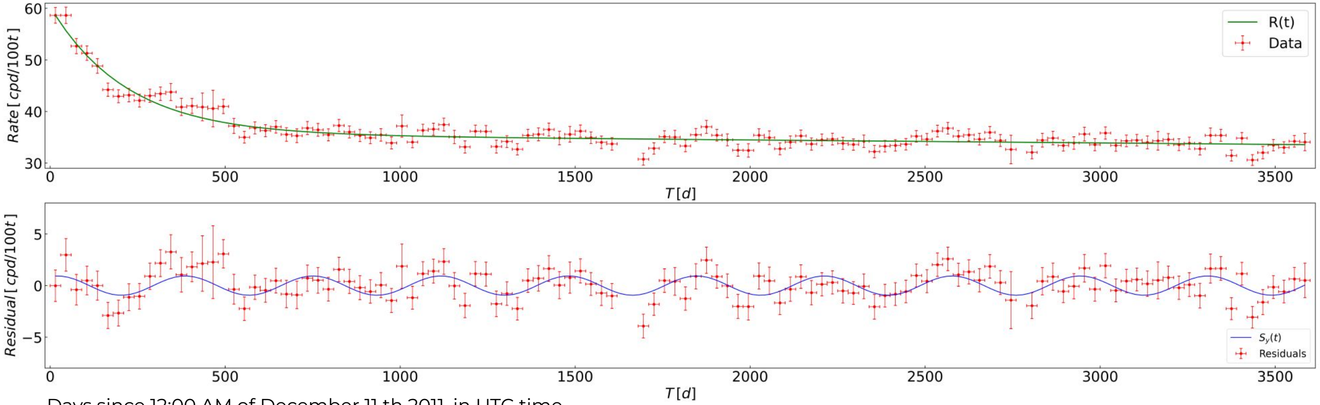
**Median sensitivity** for the expected power spectrum at 1 cycle/year can be obtained from toy Monte Carlo pseudo-experiments generated with and without the expected signal over a Borexino-like time series.



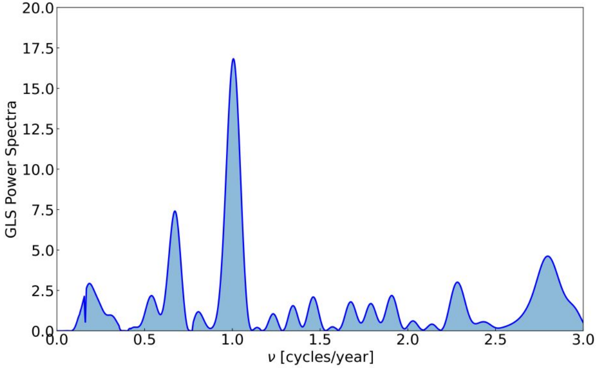
# Frequency analysis

Borexino rate time series binned in intervals of 30 days

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




Days since 12:00 AM of December 11 th 2011, in UTC time




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

**5.3 σ significance**

p-value = $5.9 \times 10^{-8}$ - one sided Gaussian

# 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

$\chi^2$/dof = 0.96.

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

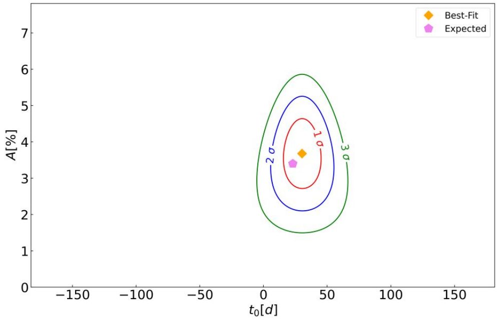
$R_\odot$: average solar neutrino rate from Solar Standard Models

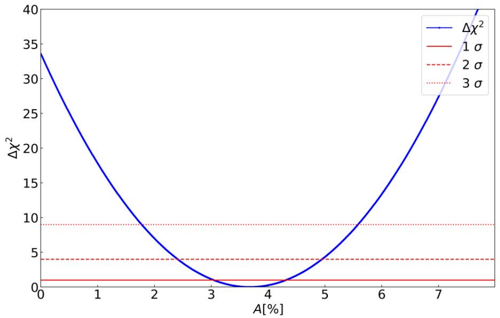
The agreement with expected values supports the Earth's orbital origin of the modulation in the Borexino time series.

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

No other significant minimum of the $\chi^2$ profile is found

**The null hypothesis is rejected at 5.9 σ**



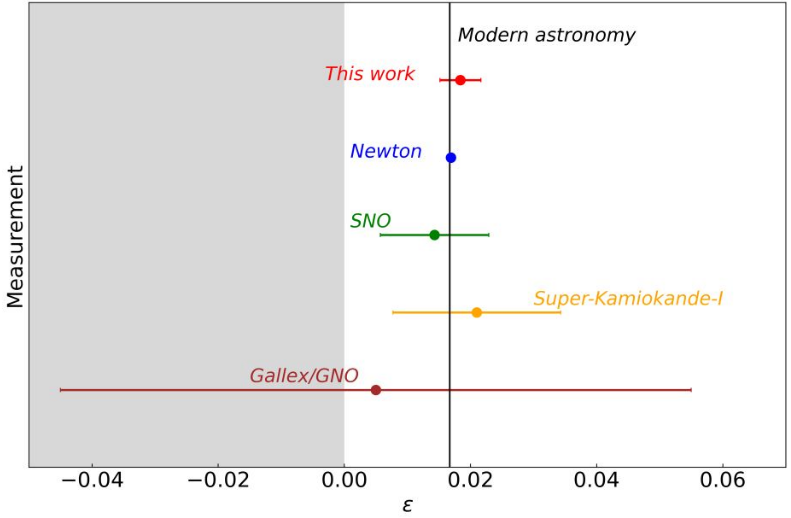
# Eccentricity and Solar Neutrinos

Taking into account **Systematics** due to energy scale stability, detector resolution, $\alpha$ removal efficiency, fiducial volume, selection criteria and detrending model (~ 1%) we obtain:

$$\epsilon = 0.0184 \pm 0.0032$$

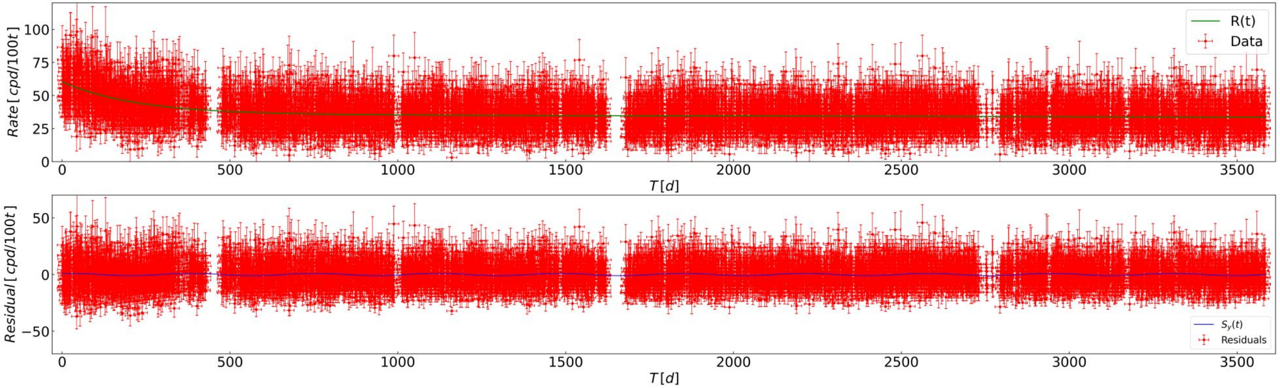
SNO and Super-Kamiokande searched for the annual modulation of **$^{8}$B neutrinos** selected with higher threshold.

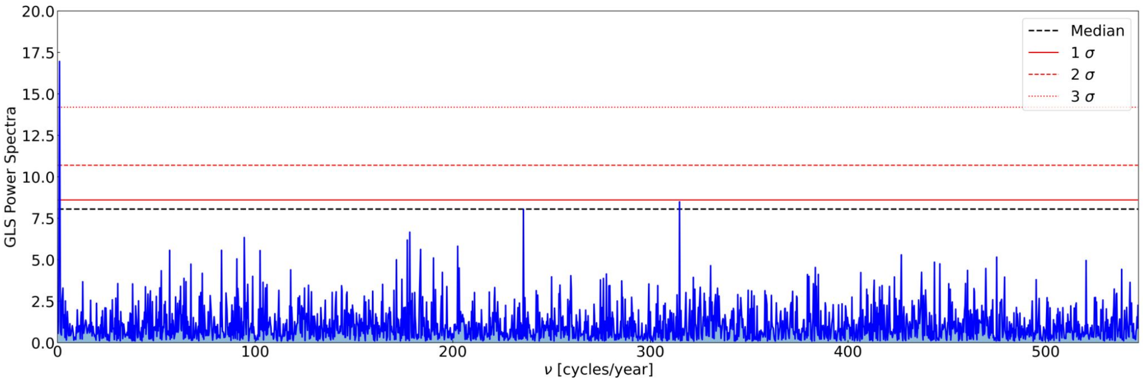
Evidence for annual modulation is also found with **1-2σ significance** by both experiments.
Gallex/GNO



# Full periodogram

Arranging the time series in intervals of 8 hours (Nyquist theorem), is possible to extend the periodogram analysis to frequencies **above 1 cycles/day**



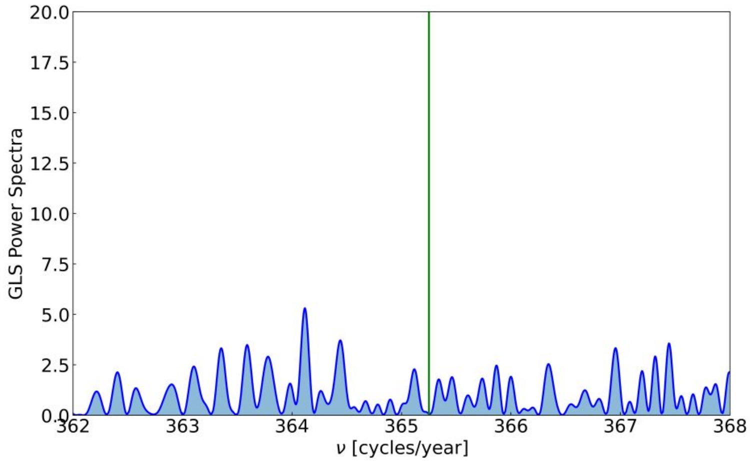




Significance of other peaks is evaluated using **Look-elsewhere effect:** generating Monte Carlo pseudo-experiments of white noise only, whose distribution of GLS spectra maximum defines the median significance threshold.

# Daily Modulation

Presence of **~daily effects** is interesting for electron neutrino regeneration in the Earth, sterile neutrino phenomenology and new interactions beyond the Standard Model

Borexino Phase-I constrained the day-night asymmetry of the solar neutrino interaction rate:
$A_{dn} = 2(D - N)/(D + N) = 0.001 \pm 0.012$ (stat) $\pm 0.007$ (syst)




Time series residual fitted to a sinusoidal function whose amplitude $A_d$ is related to $A_{dn}$

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

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

Not directly comparable with the Borexino Phase-I

# Conclusions

We have searched for solar neutrino rate modulations in time series of the total rate over the last 10 years using the **generalized Lomb-Scargle method**.

- No significant periodic signal other than the **annual modulation** has been identified. The signal is compatible within 1 $\sigma$ with astronomical measurements and the absence of modulation is at >5 $\sigma$ C.L.
- **Most precise measurement of the Earth's orbit eccentricity** obtained using solar neutrinos only.
- We can set **limits on diurnal modulation** $< 1.3\%$ (90% CL)
- The presence of annual modulation in Borexino data confirms the **solar origin** its signal.

This measurement was made possible by the stability of the detector response and energy resolution, as well as by the understanding of the radioactive background contamination in it.

**Thank you!**