Success and Legacy of Borexino

R. Biondi on behalf of BOREXINO Collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

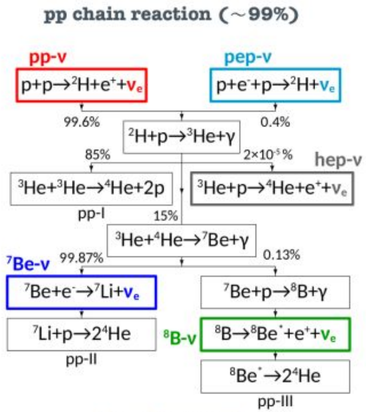
BOREXINO GRAN SASSO

SNvD 2023- 1st June 2023

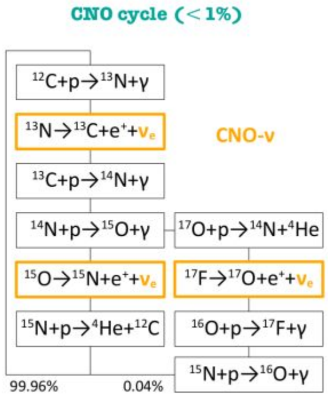
Solar Neutrinos

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

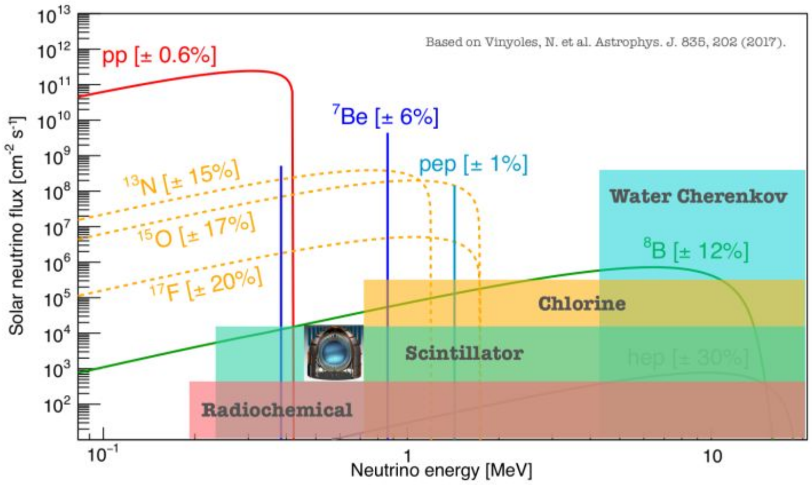
$$4\,p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e \quad (\Delta E \simeq 26 MeV)$$



Bethe&Critchfield (1938)



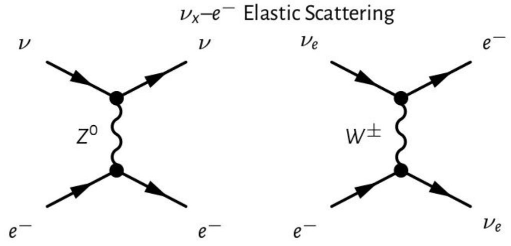
Weizsäcker (1937, 1938), Bethe (1939)



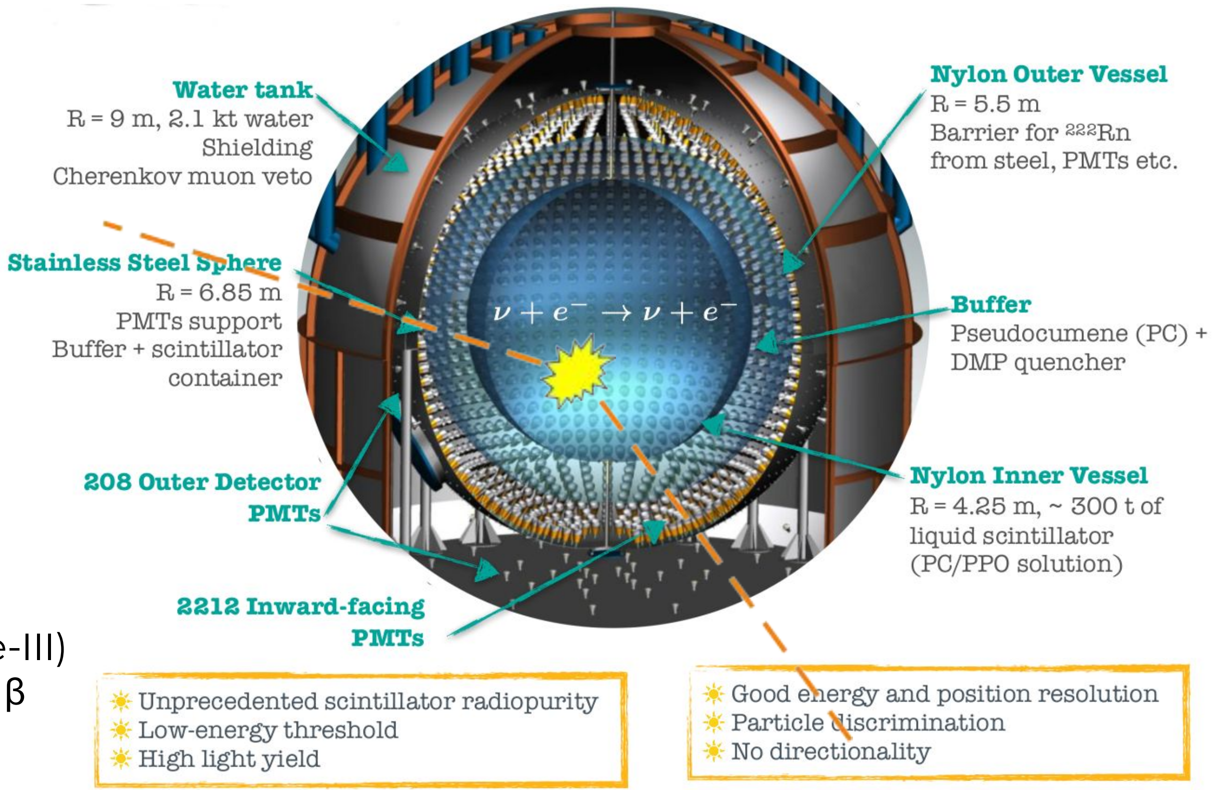
Total neutrino flux at Earth of: **~ 10 ^{11} cm $^{-2}$ s $^{-1}$** .

Borexino Detector

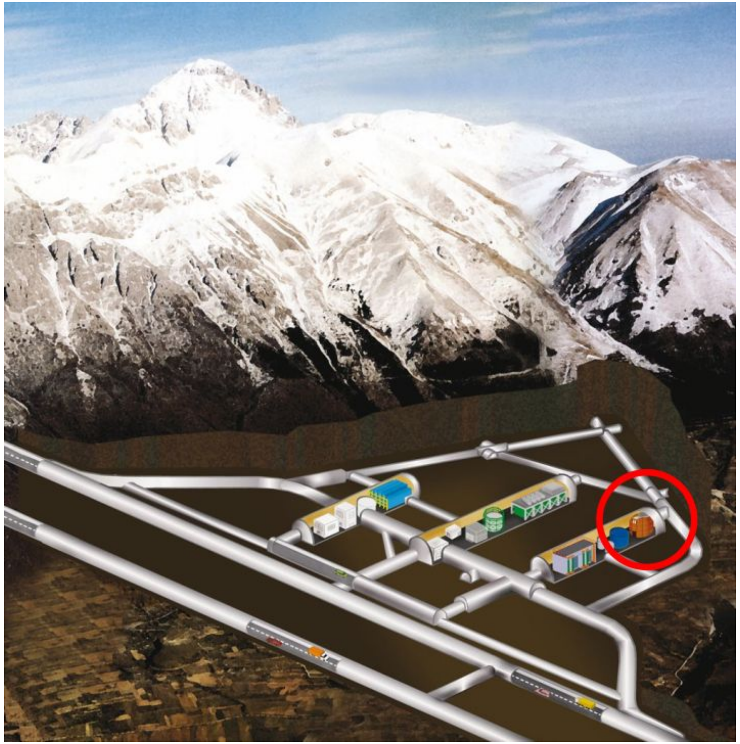
Ultrapure liquid scintillator experiment



- Light Yield ~550 p.e./MeV
- $\Delta E/E$ ~ 6%/(E[MeV])$^{1/2}$
- ΔX ~11 cm @ 1 MeV(Phase-III)
- ν-induced ER identical to β and γ background



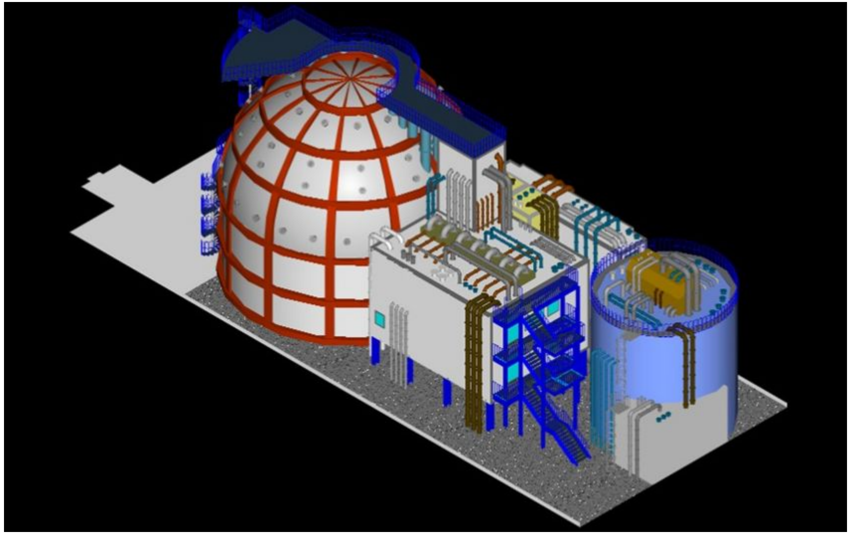
Borexino Location



Laboratori Nazionali del Gran Sasso – INFN (Hall C)

Rock: 3.800 m.w.e.

Muon flux ~ 1 m^{-2} h^{-1} (Suppression factor 10^6)



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

Purification I — **2007**

2010 — **Purification II** — **2012**

Thermal insulation — **2016**

2021 — **Decommissioning**

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**

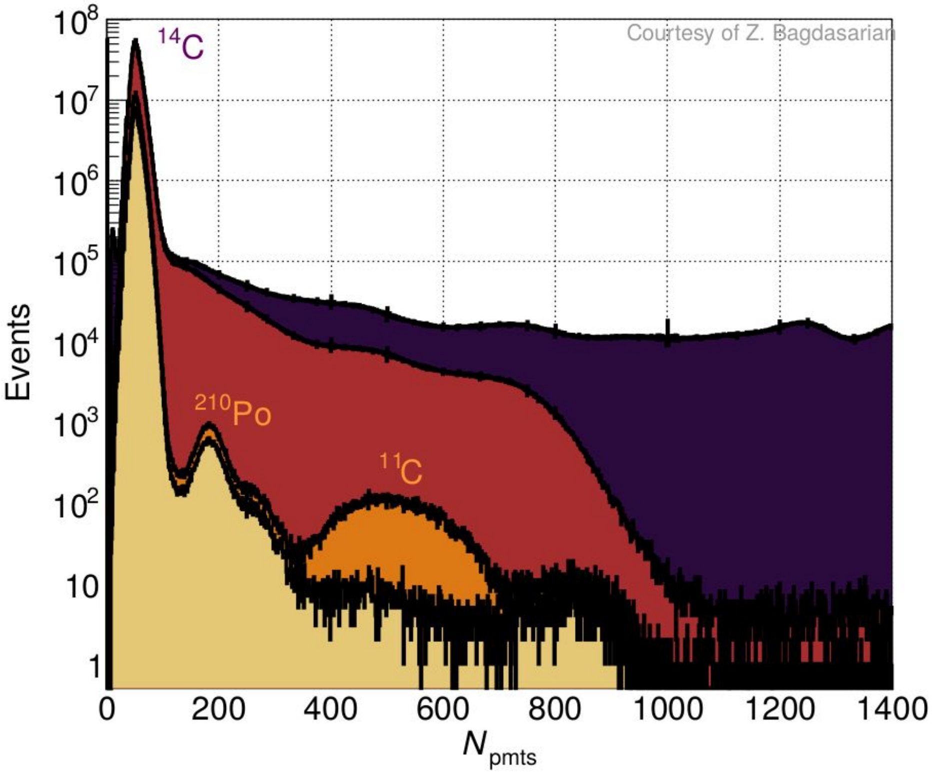
- **Geoneutrinos latest update**

- **CNO detection***

***Nature 587 (2020) 577**

	Requirement	Result Phase-II
^{238}U	1×10^{-16} g/g	$< 9.5 \times 10^{-20}$ g/g
^{232}Th	1×10^{-16} g/g	$< 5.7 \times 10^{-19}$ g/g

The Spectra 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.

$$\mu + {}^{12}C \longrightarrow \mu + \boxed{{}^{11}C} + \boxed{n}$$

β^+ decay ~ 30 min

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

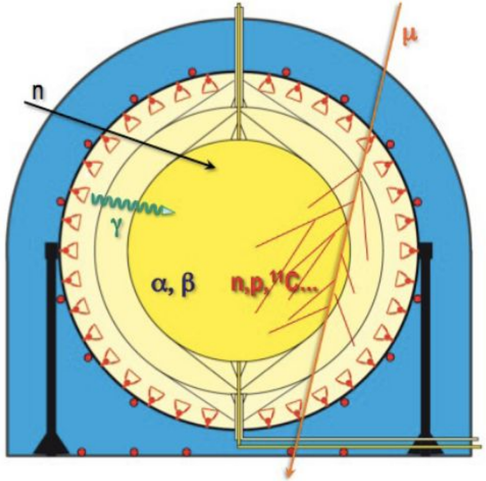
n capture ~ 260μs

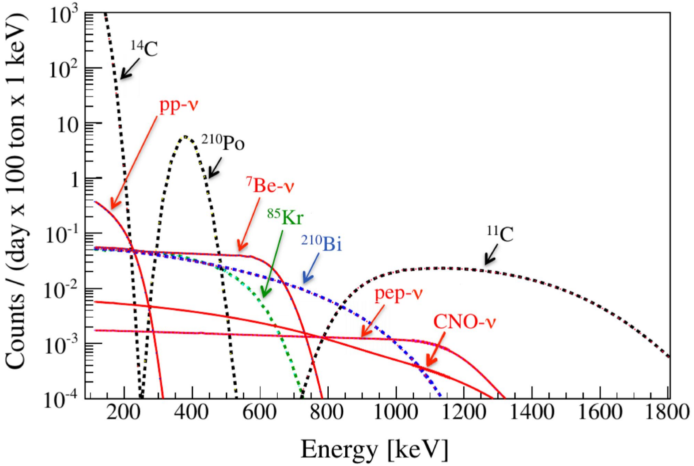
n+p $\longrightarrow$ d+γ (2.2 MeV)

Residual Background

Detection of solar neutrinos is possible only in **extreme low background** conditions

- **External:** γs and n from environment and detector materials (PMTs and SSS, mostly)
- **Internal:** α and β emitters dissolved in the scintillator ^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, ^{85}Kr, ^{210}Pb, ^{210}Po
- **Cosmogenic:** muon–induced long living isotopes (^{11}C, ^{8}He, ^{9}C, ^{9}Li)



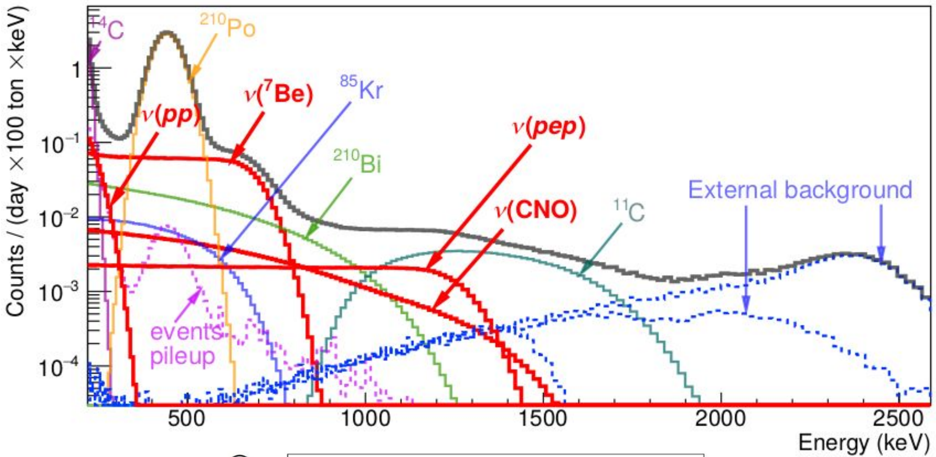


Migrating Contaminants: Internal background components can detach from Nylon Vessel and transported by convection reach the Fiducial Volume ^{210}Po, ^{222}Rn.

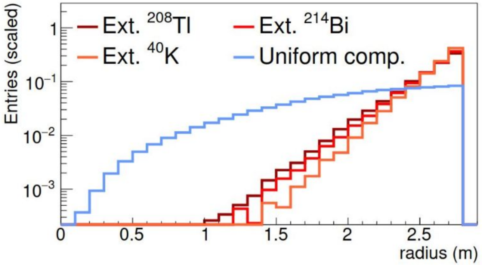
Residual Spectra

Rate of Solar Neutrinos and Backgrounds can be extracted via a **Multi-Variate Spectral Fit**

- Simultaneous fit of **Energy**, **Radial Position** and **Pulse Shape**
- TFC enhanced and subtracted spectra fitted simultaneously
- Reference distributions based on MC simulations (~1% precision)
- Fit parameters: **Interaction Rates** (also Response Function parameters)



$$\mathcal{L}_{\rm MV}(\vec{\theta}) = \mathcal{L}_{\text{TFC-tag}}(\vec{\theta}) \cdot \mathcal{L}_{\text{TFC-sub}}(\vec{\theta}) \cdot \mathcal{L}_{\rm PS}(\vec{\theta}) \cdot \mathcal{L}_{\rm RD}(\vec{\theta}).$$



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

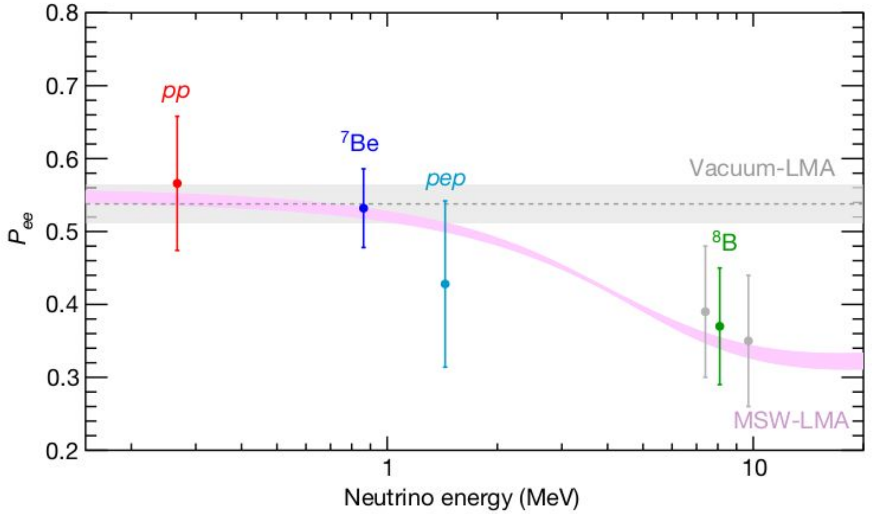
~3% Precision measurement on the ν(^{7}Be) Rate

ν_e Survival probability

Assuming the HZ-SSM fluxes and standard ν_e cross-sections

Measured rates of pp, ^{7}Be, pep and ^{8}B neutrinos can be used to infer the ν_e survival probability at different energies.

Quoted errors include the uncertainties on the SSM solar-neutrino flux predictions.



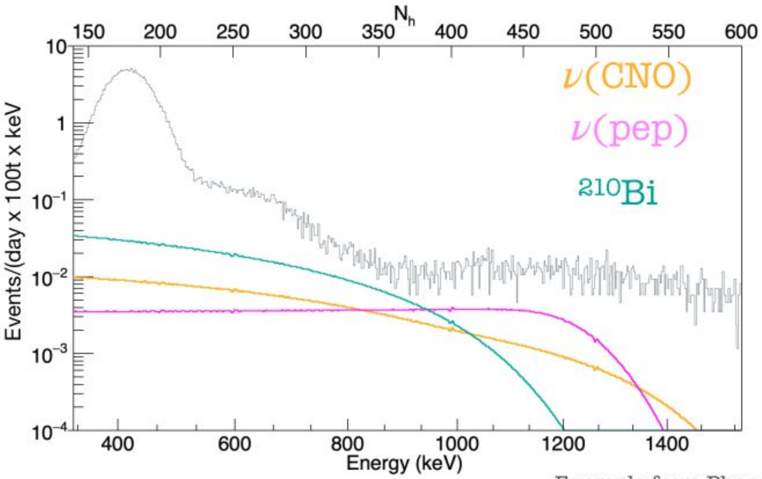
Most precise measurement of the P_{ee} in the LER and is the only experiment that can **simultaneously test neutrino flavour conversion both in the vacuum and in the matter dominated regime**.

Disfavour the vacuum-LMA hypothesis at 98.2% C.L. (Likelihood ratio) and are in excellent agreement with the expectations from the MSW-LMA paradigm

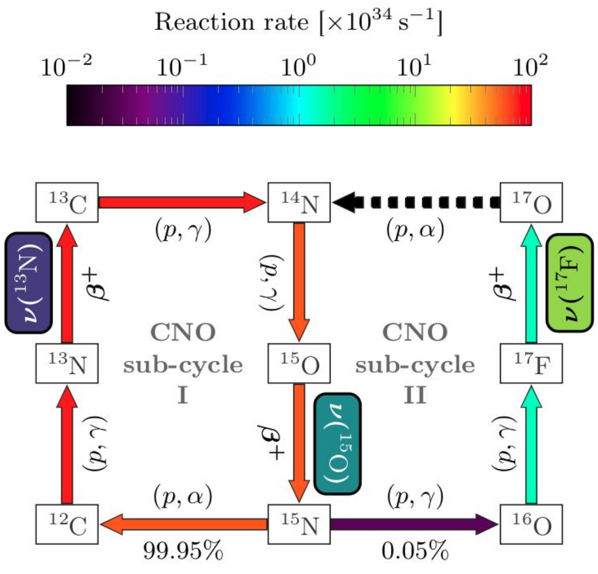
Phase III Challenge: CNO Neutrinos

Why CNO neutrino detection is so important?

- Proof energy production in stars via CNO cycle.
- Expected to be dominant in stars heavier than the sun.
- Sensitive to Sun metallicity (HZ/LZ discrimination)



Example from Phase II



The challenge:

- Low rate of CNO neutrinos
- Shape similar to ^{210}Bi and ν(pep).

Constraint on ^{210}Bi and ν(pep)

ν(pep) rate constraint: from pp/pep ratio (2.74 ± 0.04)cpd/100t

^{210}Bi rate in FV: $R(^{210}Po) = R(^{210}Bi) + R(^{210}Po)_{surface}$

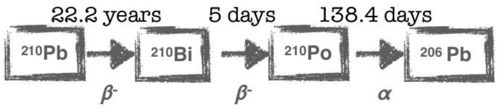
^{210}Po events can be easily selected: monoenergetic α peak

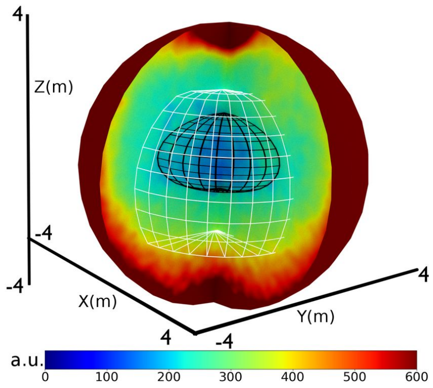
Stability challenges: Minimize convective motions, that contaminate the FV with ^{210}Po from the Vessel, we needed to stabilize experimental hall temperature, insulate the detector, and find the region in the FV where the **$R(^{210}Po)$ is minimal.** Here $R(^{210}Po)_{surface}$ is negligible and we can infer intrinsic $R(^{210}Po)$

The quest for CNO became a quest of ^{210}Bi through ^{210}Po

Considering systematic on the ^{210}Bi uniformity in the FV we can set the upper limit:

$$\mathbf{R(^{210}Bi) \leq R(^{210}Po) = (10.8 \pm 1.0)\,cpd/100t}$$





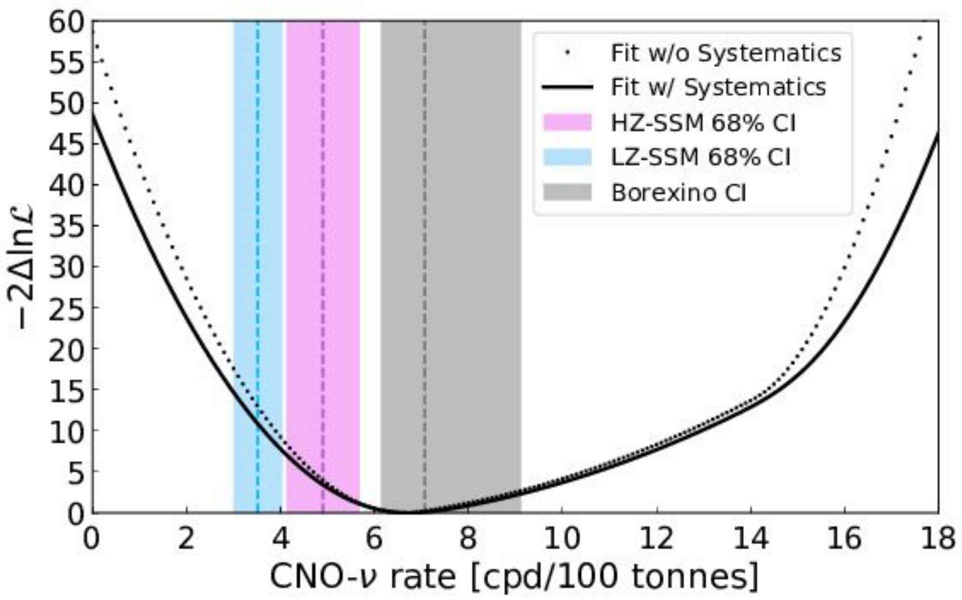
Results

Dataset: Jan. 2017 - Oct. 2021
Exposure: 431.6 days × 71.3 tons.

Model predictions:

HZ-SSM rate: (3.52±0.52) cpd/100 t
LZ-SSM rate: (4.92±0.78) cpd/100 t

Borexino measurement:
ν(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t



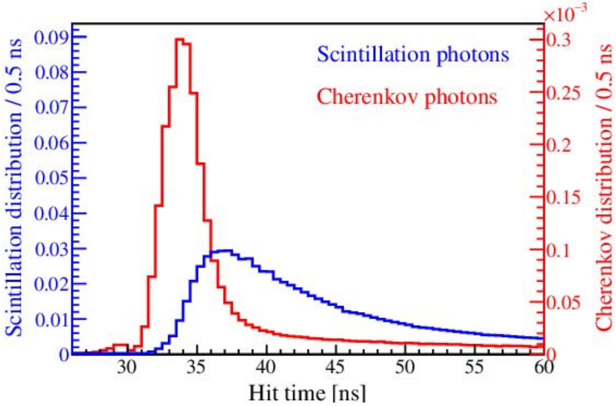
7σ significance of CNO Observation!

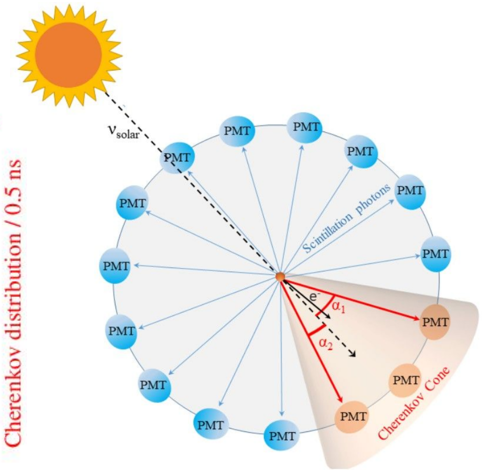
Tension with LZ model ~ 2σ

CNO Flux at Earth: $6.6^{+2.0}_{-0.9}$ x 10^8 cm^{-2} s^{-1}

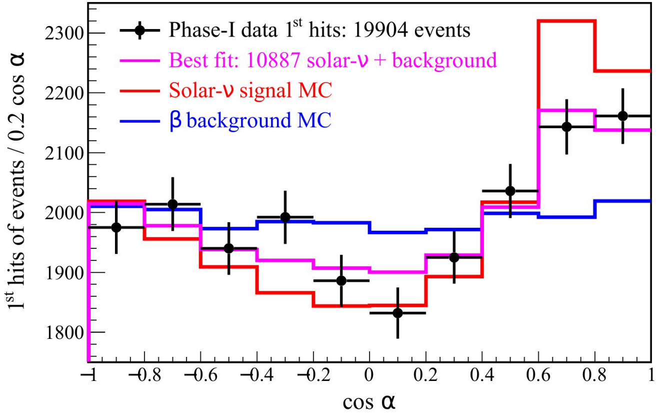
Directionality

Cherenkov light is emitted in Borexino scintillator for T>0.16 MeV
α~16° part of of it is absorbed and re-emitted isotropically





First two PMTs hits of event are considered, events are **correlated the directions of the Sun**
Integrate over selected events



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

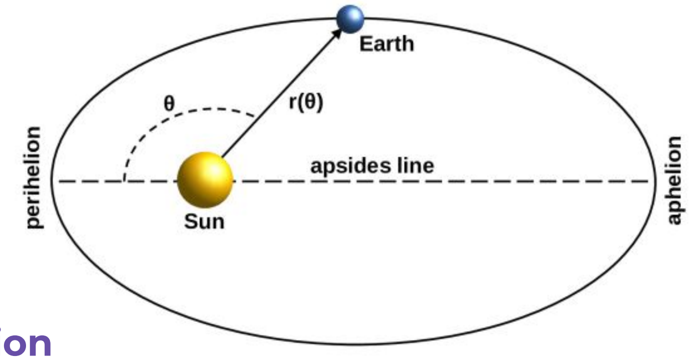
$$\boxed{R(^7\mathrm{Be}) = 51.6^{+13.9}_{-12.5}\,(\mathrm{stat.} + \mathrm{syst.})\,\mathrm{cpd}/100\mathrm{t}}$$

Phys.Rev.D 105 (2022) 5, 052002
Phys.Rev.Lett. 128 (2022) 9, 091803

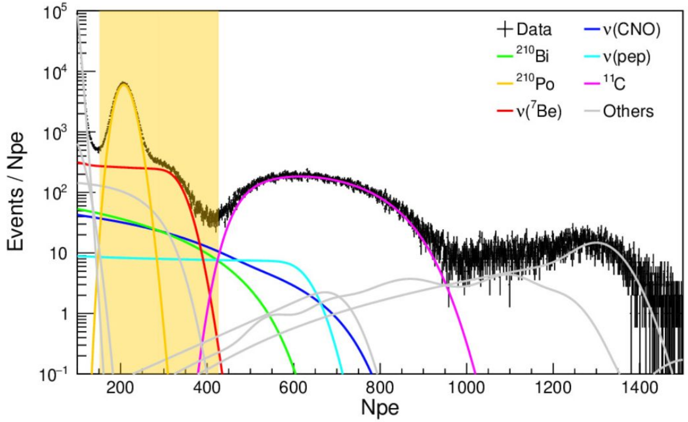
Seasonal Modulation

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

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



3.34% Modulation



- Phase-II + Phase-III (Dec. 11th 2011 - Oct. 3rd 2021)
- Spherical FV of 3 m radius (~100 tonnes)

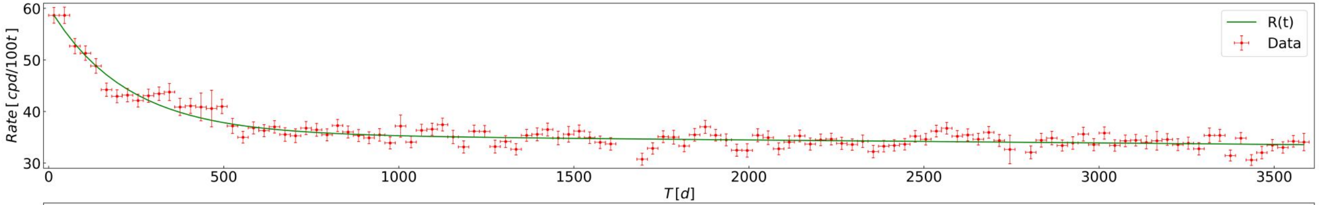
Background from ^{210}**Po** α decay events reduced via pulse shape discrimination (efficiency > 99%)

Main contribution from ^{7}**Be Neutrinos**

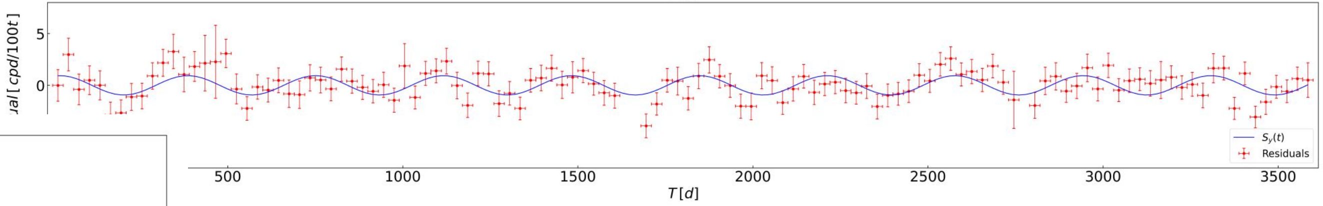
Frequency analysis

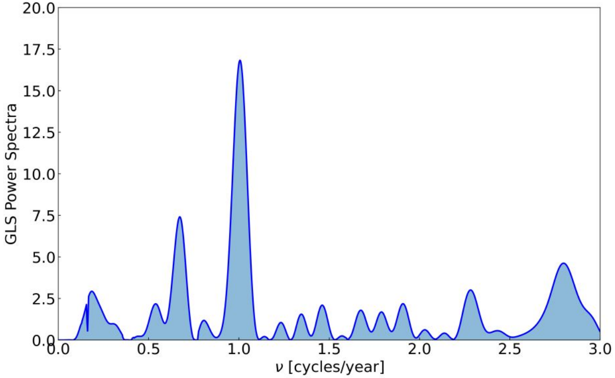
Analyzed with a **Likelihood generalized** version of the standard **Lomb-Scargle** (GLS) and **Detrending procedure** subtracting an empirical combination of exponential trends

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

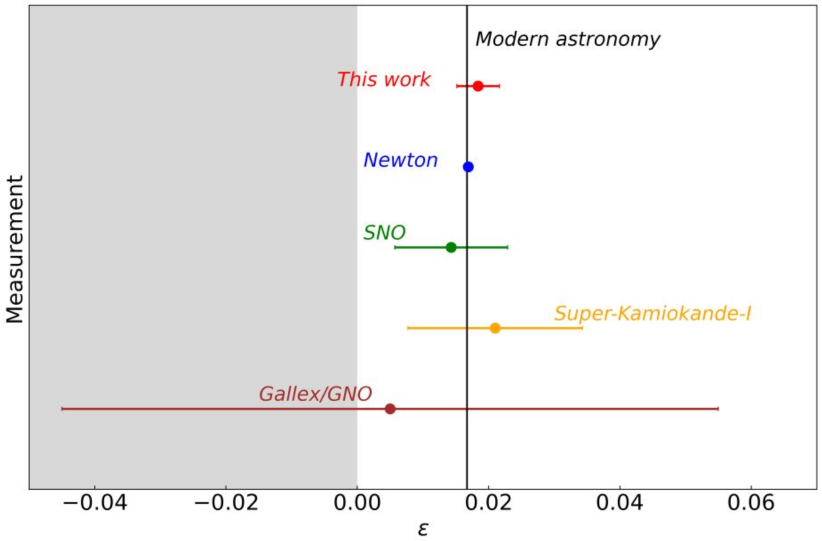
Earth's Orbit Parameters

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

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

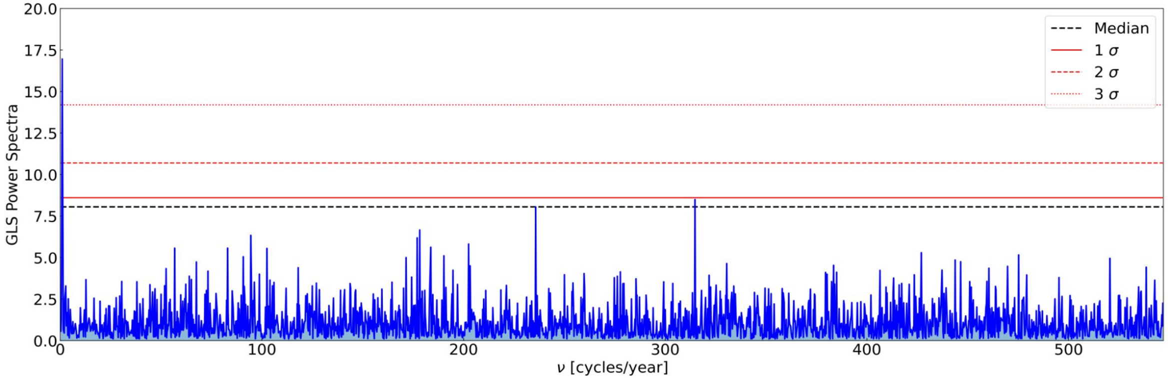
$$\boxed{\epsilon = 0.0184 \pm 0.0032}$$



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

Full periodogram and Daily Modulation

Using smaller time bins, is possible to extend the analysis to frequencies **above 1 cycles/day**, significance of other peaks is evaluated using **Look-elsewhere effect**



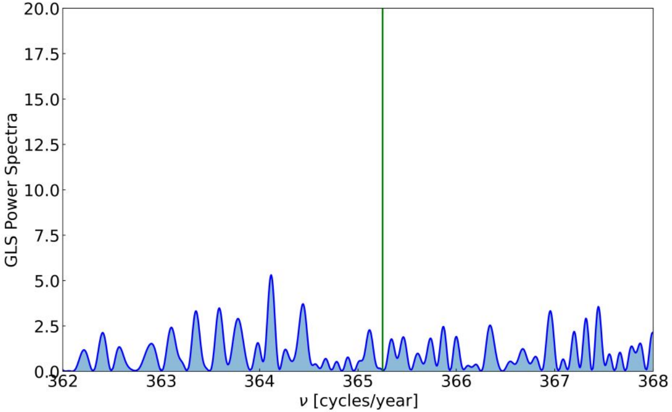
Borexino Phase-I:

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

Residual fitted to a sinusoidal function whose amplitude A_d:

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

Give: $\mathbf{A_{dn} = 0.0030 \pm 0.0094(stat) \pm 0.0002(sys)}$

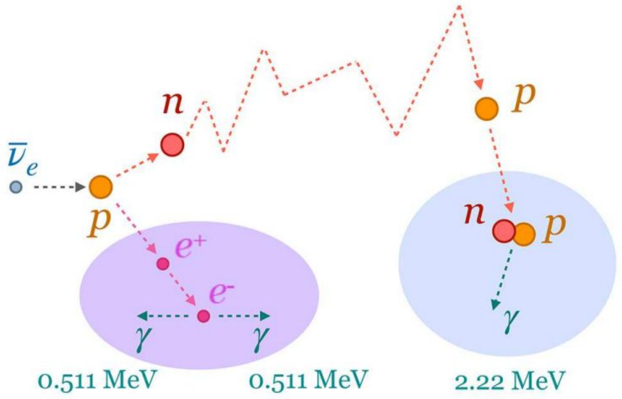


Geoneutrinos

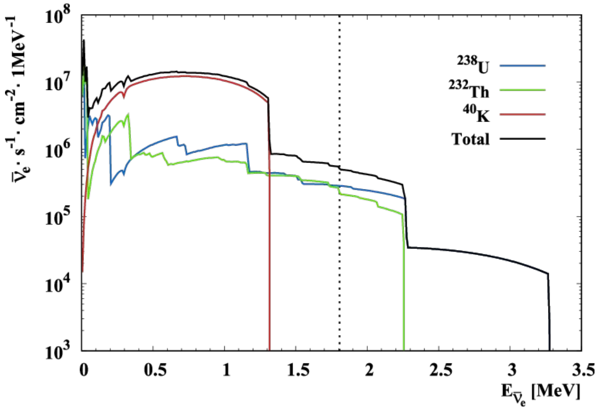
Phys.Rev.D 101 (2020) 1, 012009

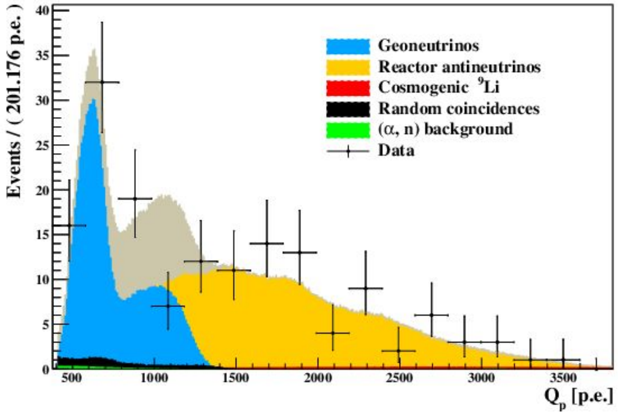
Dataset: Dec 2007 – Apr 2019 (3262.74 days)

Inverse β-decay (IBD): clear signal with prompt (e^+Annihilation) and delayed (n-capture) component a



$$N_{geo} = 52.6^{+9.4}_{-8.6}\,(\mathrm{stat})^{+2.7}_{-2.1}\,(\mathrm{sys})$$



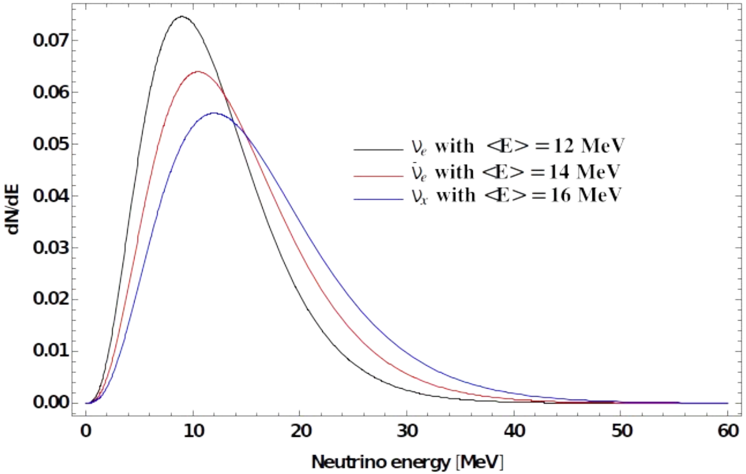


Supernova Neutrinos

Astropart. Phys., 16 (2002) 361.
Nuovo Cim. C 29, 269-280 (2006)

- Type II: Mainly $e^+ + e^- \rightarrow \nu_i + \bar{\nu}_i$
- Distance: D = 10 kpc
- Binding Energy: $L_\nu = 3 \times 10^{53}$ erg

$$\phi(E) = N \frac{L_\nu}{D^2} \frac{(\alpha+1)^{\alpha+1}}{\Gamma(\alpha+1)} \frac{1}{E_0^2} \left(\frac{E}{E_0}\right)^\alpha e^{-(\alpha+1)E/E_0}$$



With:
E_0 : average energy
N = 5.216×10^{12}
α=3

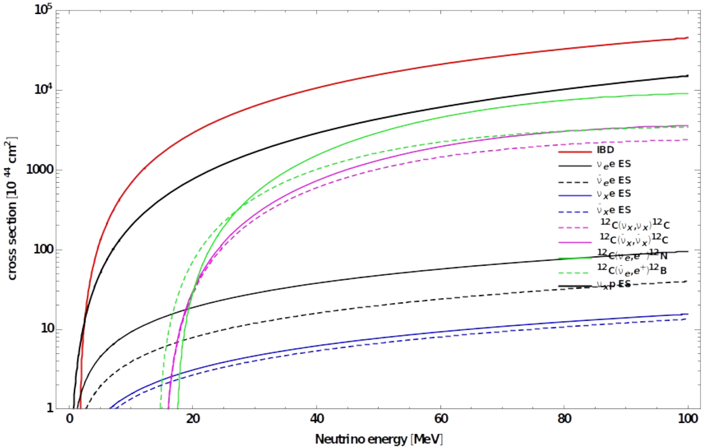
$\nu_x = \nu_\mu$ and ν_τ

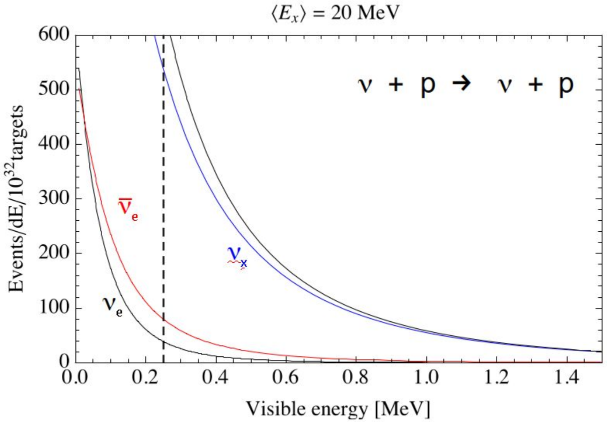
- Total irradiated Energy by ν_e: 5×10^{52} erg
- Total irradiated Energy by $\bar{\nu}_e$: 5×10^{52} erg
- Total irradiated Energy by ν_x : 1×10^{53} erg
- Emitted neutrinos: 1.26×10^{58}

Neutrino flux at 10 kpc: 1.06×10^{12} cm^{-2}

Interaction Channels in Borexino

- Elastic scattering (ES): $\nu + e^- \rightarrow \nu + e^-$,
- Inverse-beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$, $E_{th} = 1.806$ MeV
- $^{12}C(\nu, \nu')^{12}C^*$, $E_{th} = 15.11$ MeV
- $^{12}C(\bar{\nu}_e, e^+)^{12}B$, $E_{th} = 14.39$ MeV
- $^{12}C(\nu_e, e^-)^{12}N$, $E_{th} = 17.34$ MeV
- $\nu + p \rightarrow \nu + p$, affected by quenching (measured in AmBe calibration)





For $\nu + p$ ES 80% of the signal above the threshold is due to ν_x and this allow us to **measure the average energy of SN's ν_x**

Given sub-MeV average energy, only a Borexino like detector can be used to detect this channel that gives complementary information with respect to IBD

Predicted neutrino events in Borexino

A burst of around **~100 events** would appear in Borexino within a time interval of about 10 s

Supernova Detection via ν + p → ν + p

TABLE II. – *Detectable protons in Borexino (300 t), produced via ν-p elastic scattering, according to four different experimental thresholds and compared to the expected background from* ^{14}C. *All the thresholds between 150 and 250 keV are suitable for this detection, since they provide a signal to background ratio greater than 10.*

Experimental threshold	Detectable scattered protons	^{14}C events in 10 s
100 keV	135 ± 12	64 ± 8
150 keV	126 ± 11	9 ± 3
200 keV	118 ± 11	4 ± 2
250 keV	111 ± 10	–

Supernova Trigger via Inverse β-decay

Interaction channel	Threshold [MeV]	Expected average energy [MeV]	Events per kton w/o oscillation	Events per kton w/ oscillations
ES	0.2	~7.5	16	16
IDB	1.02	~20	193	202
$^{12}C(\bar{\nu}_e, e^+)^{12}B$	1.02	15	4.5	5.2
$^{12}C(\nu_e, e^-)^{12}N$	0.2	12	2.2	7.3
$^{12}C(\nu, \nu')^{12}C^*$	15.1	15.1	19	19
ν + p → ν + p	0.2	0.4	90	90

- Evaluation of antineutrino background (CTF data): 1.46×10^{-4} events in 10 s.
- $P(\nu \geq 2) = 1.08 \times 10^{-8}$: Rate of accidental coincidences of 0.034 year^{-1} (SNEWS ok)

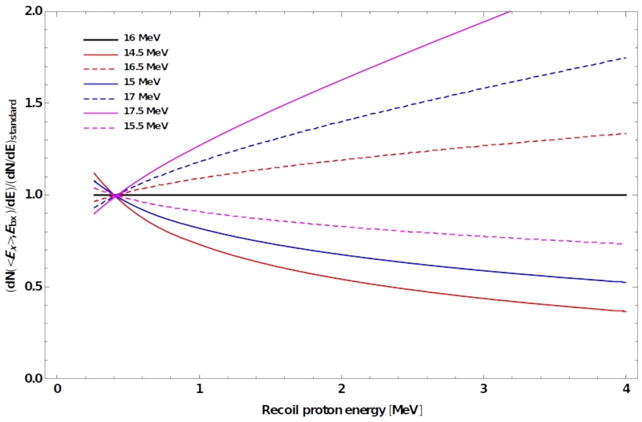
With this conditions Borexino will be able to detect Supernovae from **63 kpc**

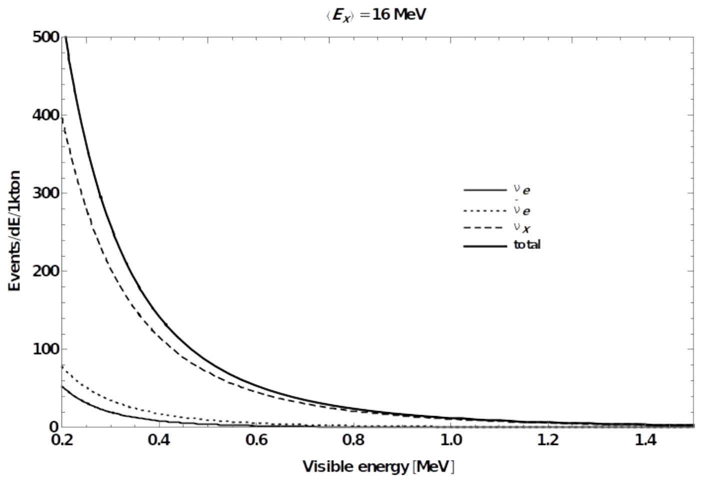
Temperature of SN ν’s

The ν + p → ν + p spectrum is mainly from ν_x above threshold:

Measuring the spectrum we break the degeneracy between average energy and binding energy:

$$N \propto \langle\sigma\rangle \frac{E_{binding_x}}{E_x}$$





Pointed out by J. Beacom et al. for the n-p elastic scattering in organic liquid scintillators in 2002

Non-standard neutrino physics

Borexino elastic-scattering and neutral-current detection capabilities will be a powerful tool in exploring non-standard features of neutrinos

Mass limits from time of flight:

- Massive neutrinos will reach Earth with a delay with respect to the massless species
- IBD events provide the “time stamp” for the massless species
- $\nu - p$ elastic scattering and the neutral-current excitation of ^{12}C are dominated by ν_μ / ν_τ
- Time delay between the neutral-current or scattering events and charged-current events provides a handle on the mass of ν_μ and/or ν_τ

$$\Delta t = \frac{D}{2c}\left(\frac{m_\nu}{E_\nu}\right)^2$$

Oscillations from reactions on ^{12}C: Higher energy ν_μ could oscillate into ν_e, resulting in an increased event rate. A comparison between $^{12}C(\bar{\nu}_e, e^+)^{12}B$, $^{12}C(\nu_e, e^-)^{12}N$ and $^{12}C(\nu, \nu')^{12}C^*$ might, then, give strong constraints on the mixing parameters.

Bad luck: no supernovae during Borexino’s life-time

Conclusions

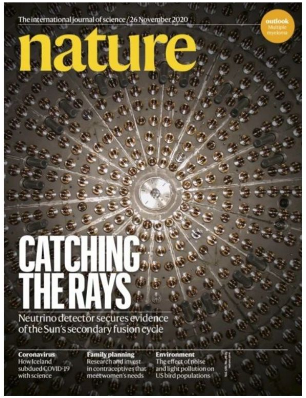
Borexino ended it's successful career in October 2021, during which it was able to achieve a large number of significant results:

- Full spectroscopy of pp-chain neutrinos
- First ever measure of CNO neutrino flux
- Detection of GeoNeutrinos
- Solar neutrinos seasonal modulation
- Directionality measurement
- Limits on new physics

Unfortunately no Supernova explosion during its lifetime.

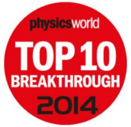
Yet Borexino has shown that with its level of radio-purity some unique detection channel on Supernova Neutrinos can be proved to boost our understanding on this rare but special event in our galaxy

Thank you!



Hans A. Bethe Prize
2023 F. P. Calaprice

G. & V. Cocconi Prize
2021 - EPS



Pontecorvo Prize
2015 G. Bellini

Fermi Prize
2017 G. Bellini