WHY AND HOW THE SUN AND THE STARS SHINE

Since the early days of humanity, man, when looking at the Sun or contemplating the starry sky at night, has been wondering what those light were and how they were able to shine. Now, finally, an experiment, Borexino, provided the definitive answer to this millennial question of mankind

G.Bellini, *Why and how the Sun and the stars shine*, *Nuovo Saggiatore* Vol. 36, anno 2020, no. 5-6

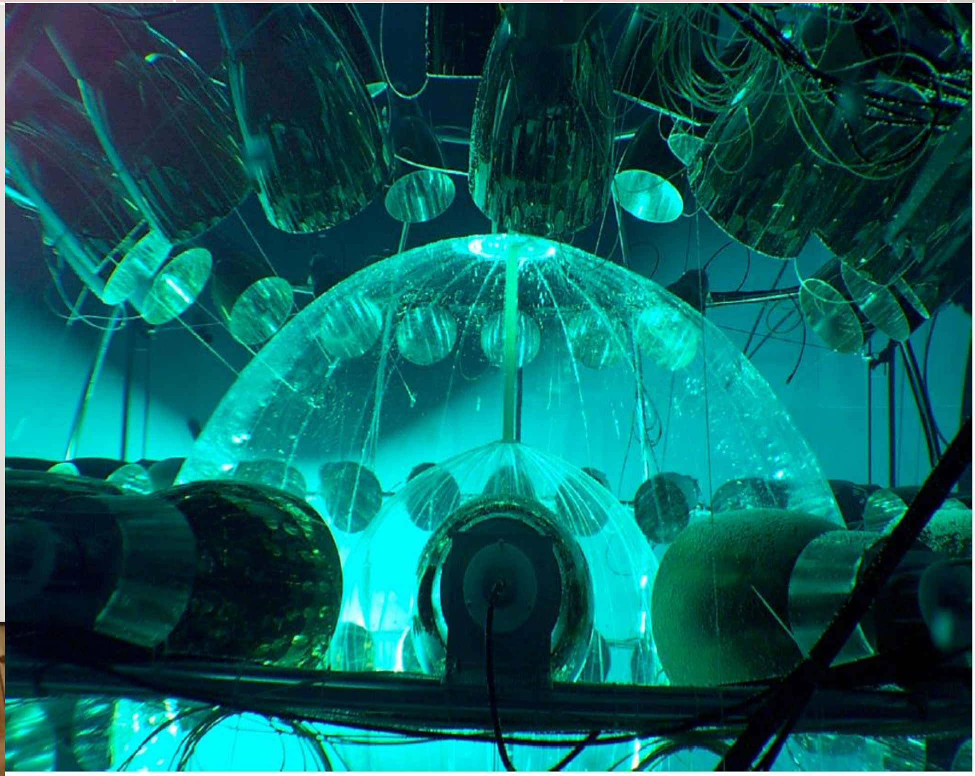
Borexino time table

A challenge which lasted 33 years

1988-1990	1990-1995	1995-2007	2007-2010	2011-2016	2016-2021
Design of the experiment	**R&D of innovative radio-purification methods- C.T.F.**	**Detector construction**	**Phase I and further radio-purification**	**Phase 2**	**Phase 3**

The counting test facility- CTF

A bench mark for Borexino –its aim was to measure the reached radiopurity and then be able to decide if Borexino was an impossible challenge or a challenge can be dealt with,



In Borexino we applied the principle of graded shielding:it is implemented deploying the inner scintillating core at the centre of a set of concentric shells of increasing radiopurity

Preliminary shielding: the overburden of the Gran Sasso Lab,- 4000 m water equivalent

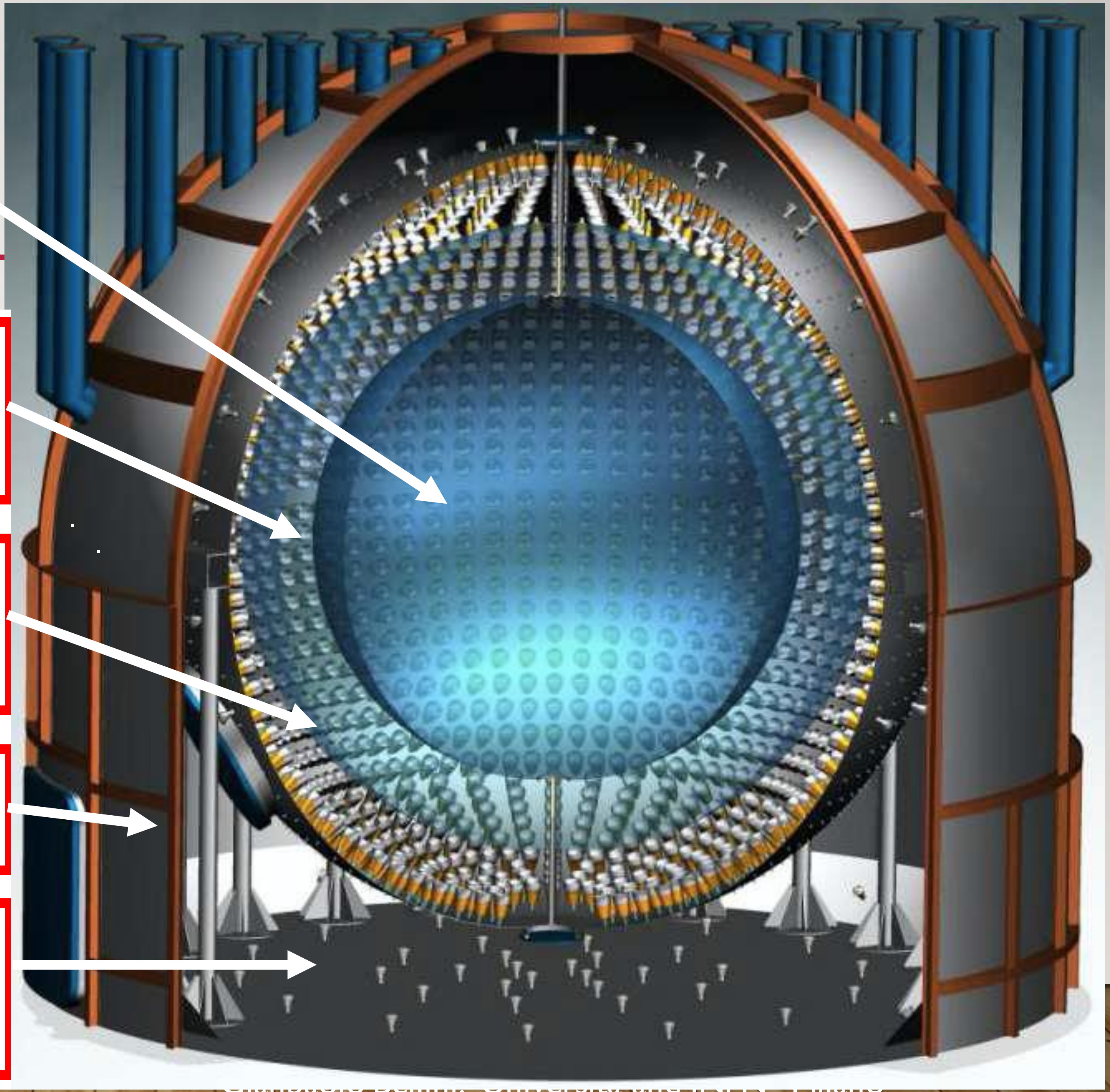
Core of the detector: 300 tons of liquid scintillator (PC+PPO) contained in a nylon vessel of 4.25 m radius;

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;

200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;



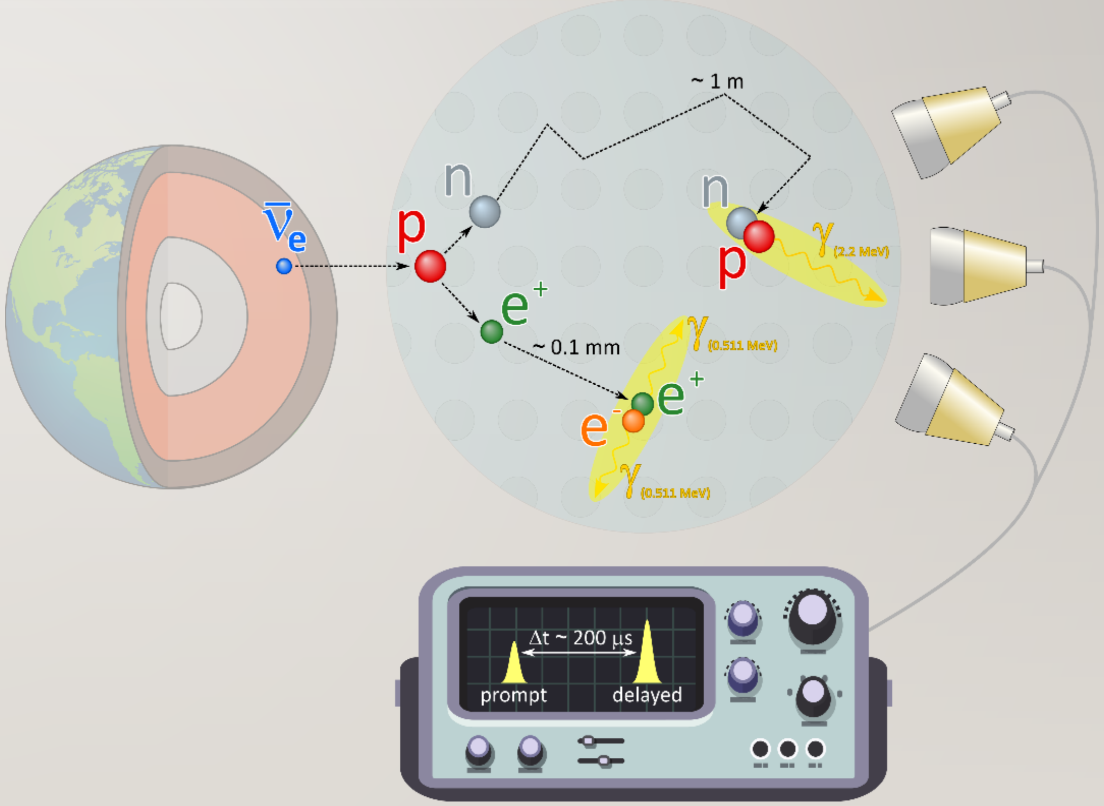
Neutrino and antineutrino detection

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

e⁻ track length negligible

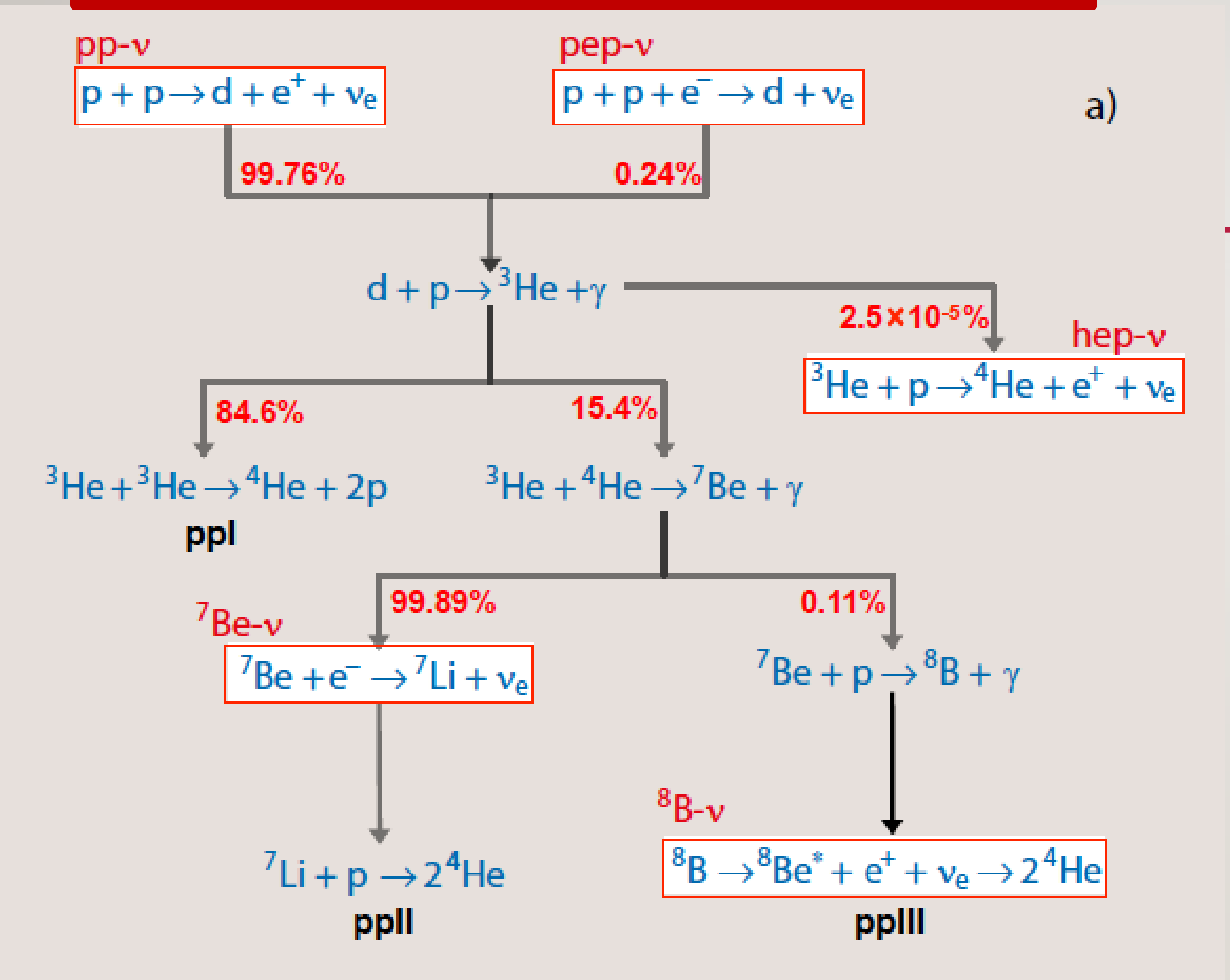
$$\bar{\nu} + p \rightarrow e^+ + n - 1.806\ MeV$$

The outgoing positron promptly annihilates producing two 511 keV gammas: ***prompt signal.***
The outgoing neutron takes a mean time of ~256 µs in Borexino to thermalize and then to be captured by a proton, producing a deuteron with the emission of 2.2 MeV gamma: ***delayed signal***

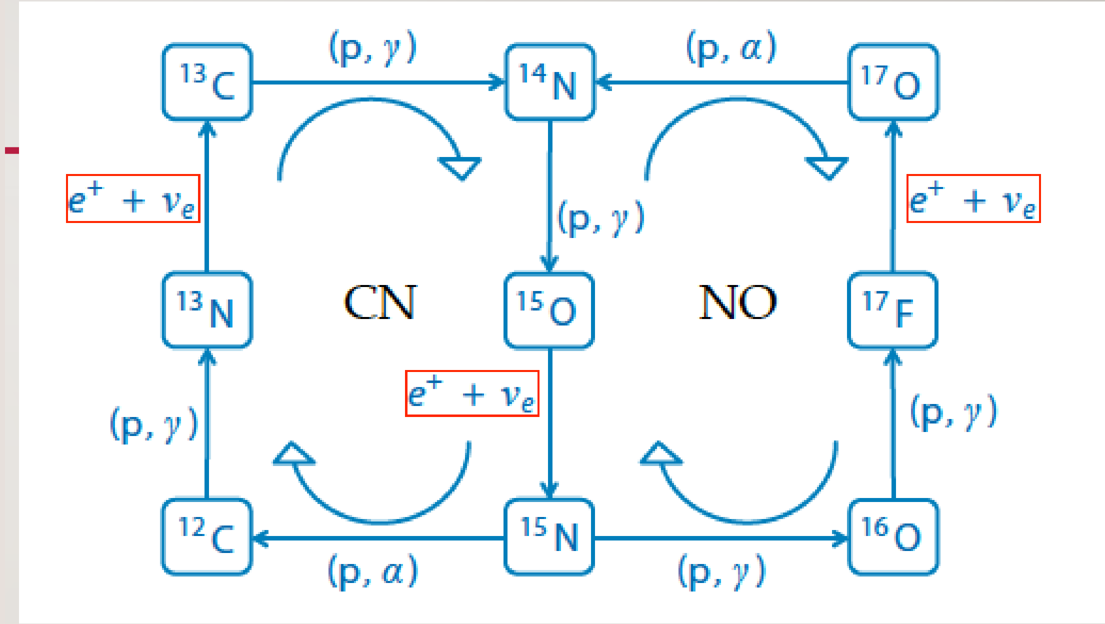


Threshold at 100 keV; previous experiment showed with a threshod at 5 Mev, later reduced to 4 MeV.

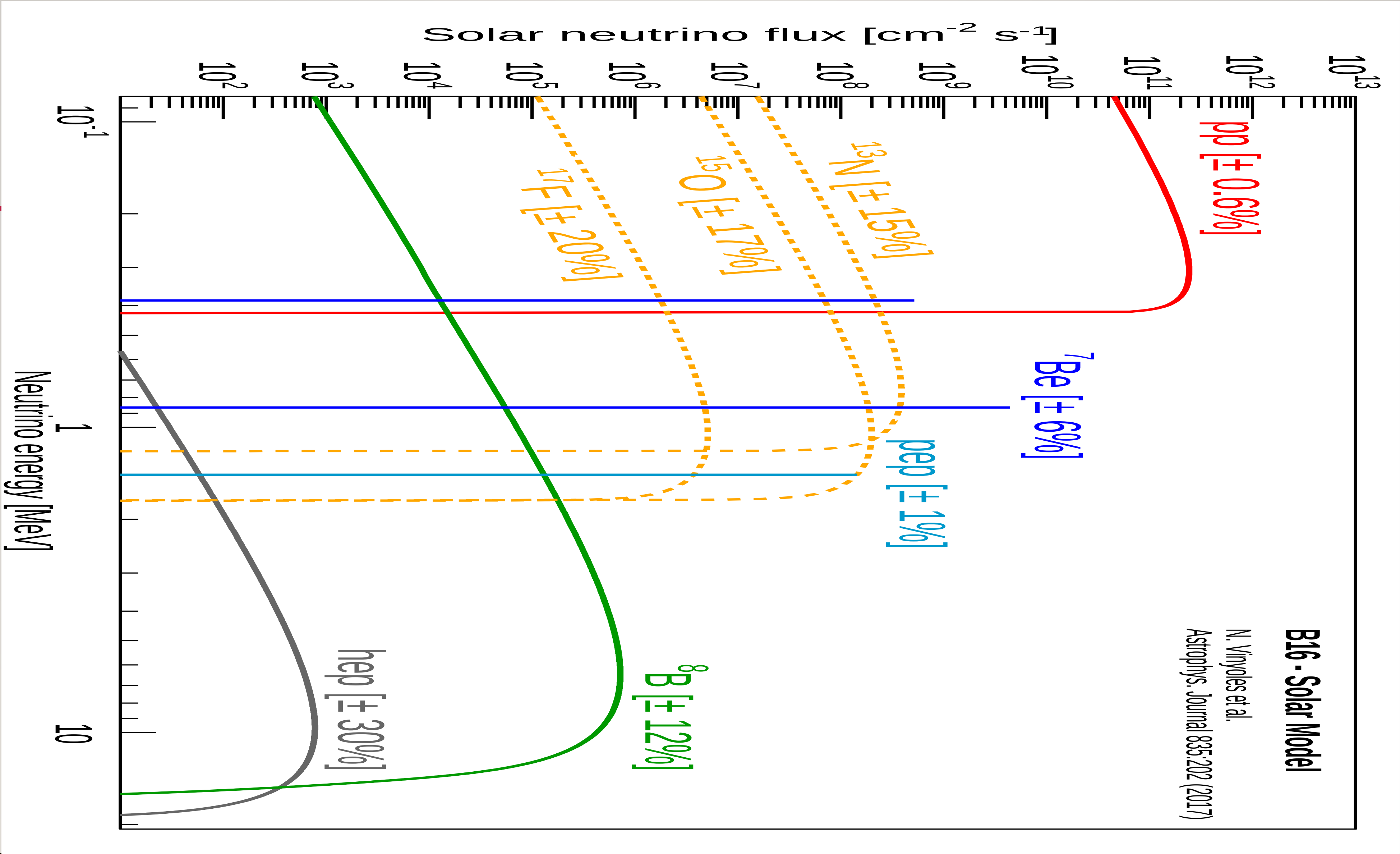
pp cycle- 99% of the Sun energy



CNO cycle. 1% of the Sun energy

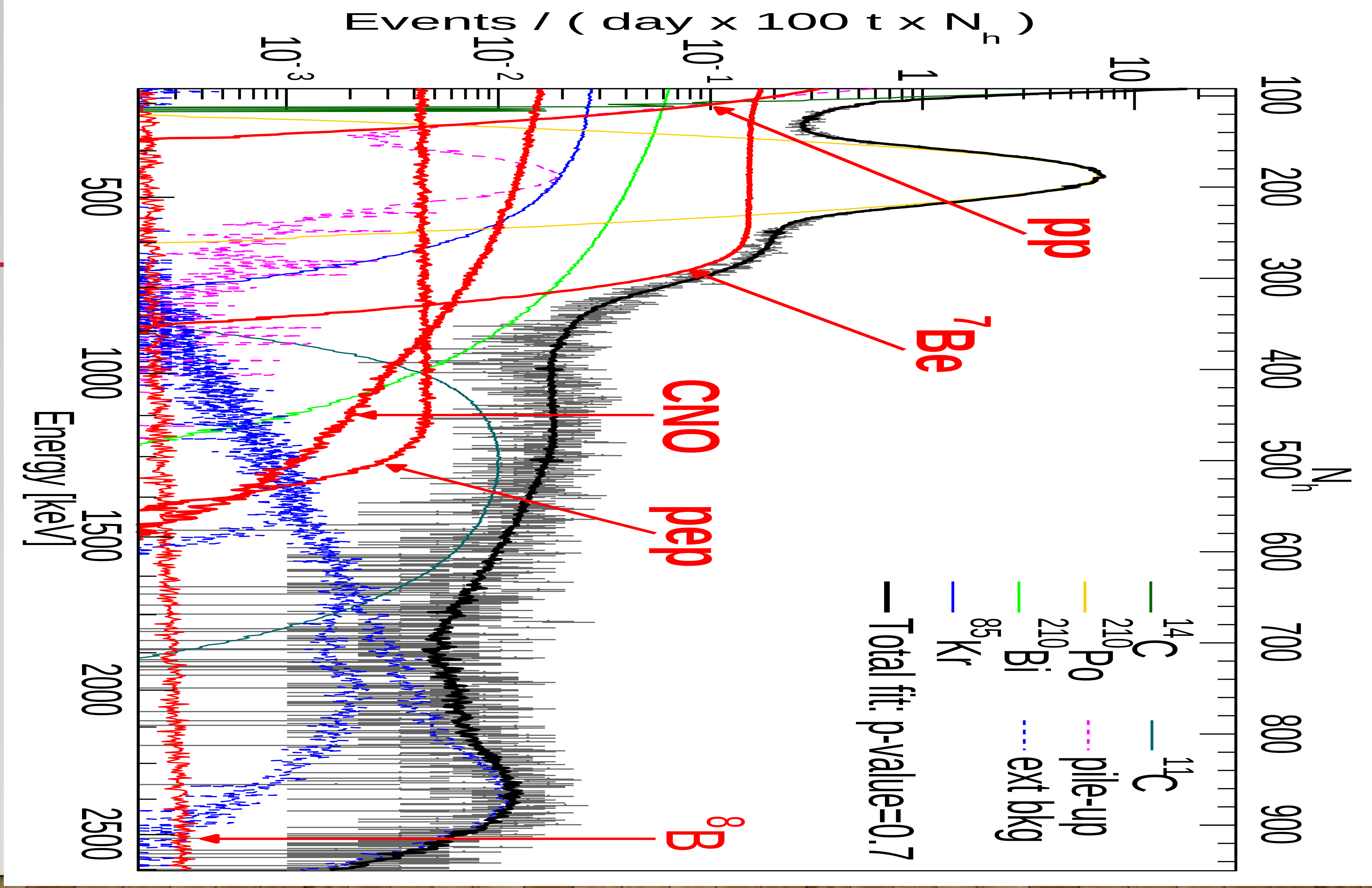


Solar neutrinos energy spectrum



Radio isotope	Source	Software reduction	Achieved Phase1	Achieved Phase2
^{14}C	Intrinsic PC	Threshold Fit on the shape	$\approx 2\ 10^{-18}\ ^{14}C/^{12}C$	
^{238}U ^{235}Th	Dust, particulate all materials	α/β tagging fit	$1.67\pm0.06)\ 10^{-17}$ $(4.6\pm0.8)\ 10^{-18}$ g/g	$<9.5\ 10^{-20}$ $<7.2\ 10^{-19}$ g/g
^{85}Kr	Air, weapons		30 ± 5 cpd/100t	6.8 ± 0.8 cpd/100t
^{85}Ar	Air, cosmogenic	fit	<< 1 cpd/100t	
^{210}Po	Embedded on surfaces	fit	500-100 cpd/100t	Natural decay
^{222}Rn and its progeny	In the underground air and water	α/β tagging, delayed coincidences	< 1 cpd/100t	

Solar pp cycle


Events / (day x 100 t x N_h)
Energy [keV]
N_h
14C
210Po
210Bi
85Kr
11C
pile-up
ext bkg
Total fit: p-value=0.7
pp
7Be
CNO
pep
8B

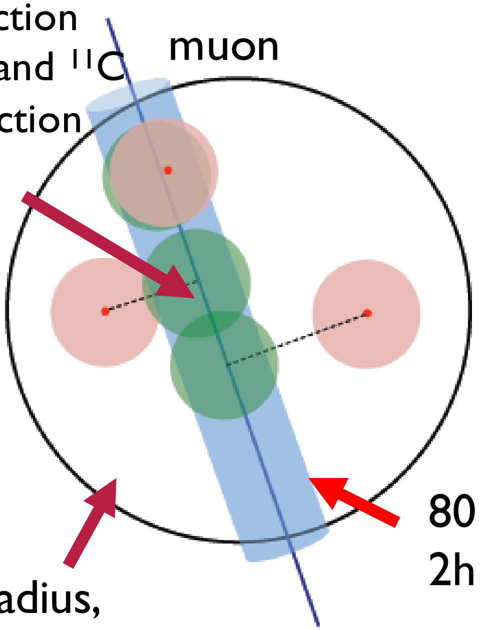
^{11}C reduction

Cosmogenic muons (1.2 μ $m^{-2} h^{-1}$)
Constant rate

1. TFC prompt and delayed signal. Reduction to 10%
2. Pulse shape discrimination. Reduction to 5%

Residual exposure 48.5%

1.TFC- three fold concidence



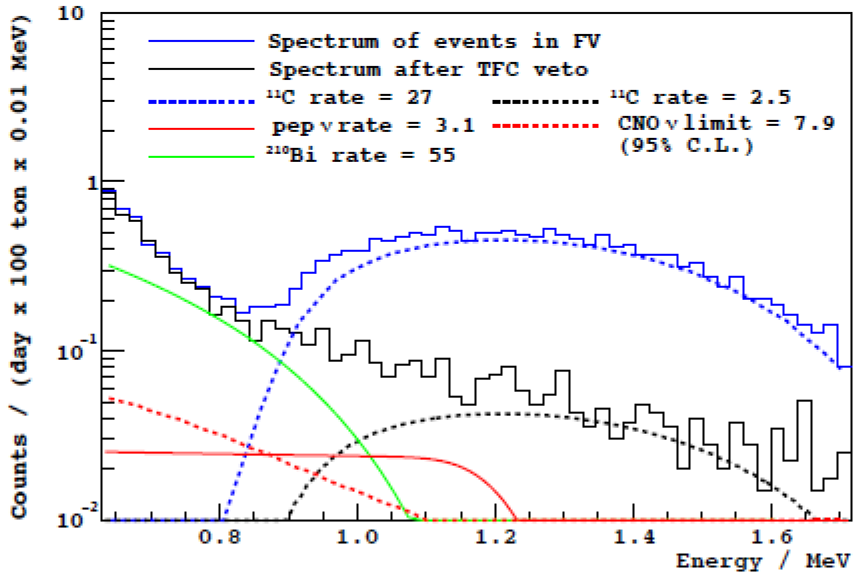
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
t~30min

$n + p \rightarrow d + \gamma$
τ~260μs

n capture on H: γ 2.2 MeV
Space and time Veto

- Annihilation of the positron
- n thermalization



2. Pulse shape discrimination

-ortho-positronium with 140 ns lifetime, reduced to about 3 ns in the l.s.
-2 γs produced in the positron annihilation ➔ distributed topology

Solar physics- pp cycle

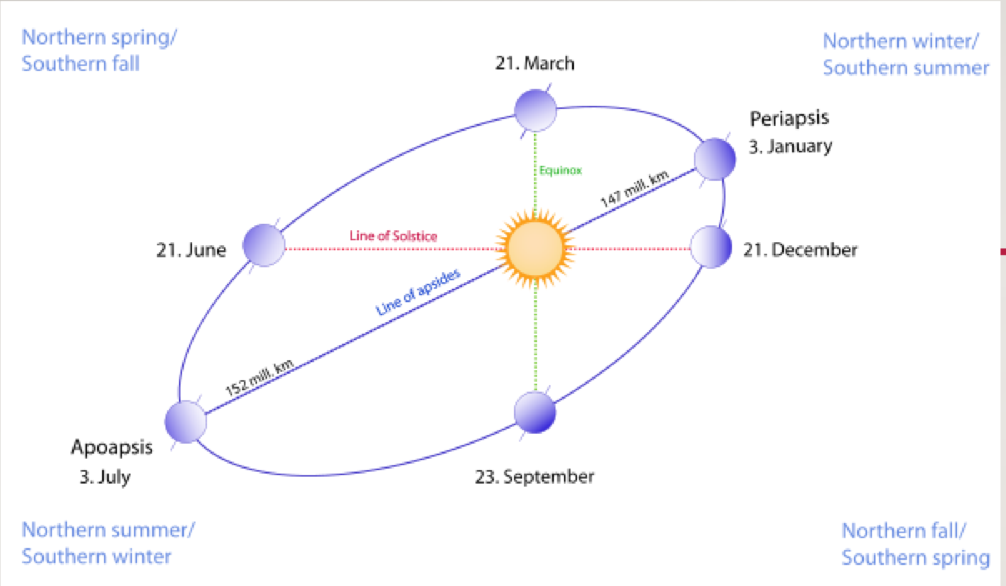
reaction	Borexino rates (cpd/100t)	Borexino fluxes ($cm^{-2}s^{-1}$)	SSM HZ Fluxes ($cm^{-2}s^{-1}$)	SSM LZ Fluxes ($cm^{-2}s^{1}$)	Global fit Fluxes (*) ($cm^{-2}s^{1}$)
pp	$134\pm10^{+6}_{-10}$	$(6.1\pm0.5^{+0.3}_{-0.5})$ x10^{10}	5.98(1$\pm$ 0.006) x 10^{10}	6.03(1$\pm$0.005) x 10^{10}	$5.97^{+0.037}_{-0.033}$ x 10^{10}
^{7}Be	48.3 $\pm 1.1^{+0.4}_{-0.7}$	$(4.99\pm0.11^{+0.06}_{-0.12})$ x10^9	4.93 (1$\pm$ 0.06) x 10^9	4.50(1$\pm$0.06) x 10^9	$4.80^{+0.24}_{-0.22}$ x 10^9
pep§ (HZ)	2.43 $\pm 0.36^{+0.15}_{-0.22}$	$(1.27\pm0.19^{+0.08}_{-0.12})$ x 10^8	1.44 (1$\pm$ 0.009) x 10^8	1.46 (1$\pm$ 0.009) x 10^8	1.448$\pm$0.08 x 10^8
pep§ (LZ)	2.65 $\pm 0.36^{+0.15}_{-0.24}$	$(1.39\pm0.19^{+0.08}_{-0.13})$ x 10^8	1.44 (1$\pm$ 0.009) x 10^8	1.46 (1$\pm$ 0.009) x 10^8	
^{8}B	$0.220^{+0.015+}_{-0.016-}$	$5.68^{+0.39+0.03}_{-0.41-0.03}$	5.46 (1$\pm$0.12) x 10^6	4.50(1$\pm$0.12) x 10^6	$5.16^{+0.13}_{-0.09}$ x 10^6
hep	<0.002 (90% C.L.)	< 1.6 x 10^5 (90% C.L.)	7.98 (1$\pm$0.30) x10^3	8.25(1$\pm$0.12) x 10^3	

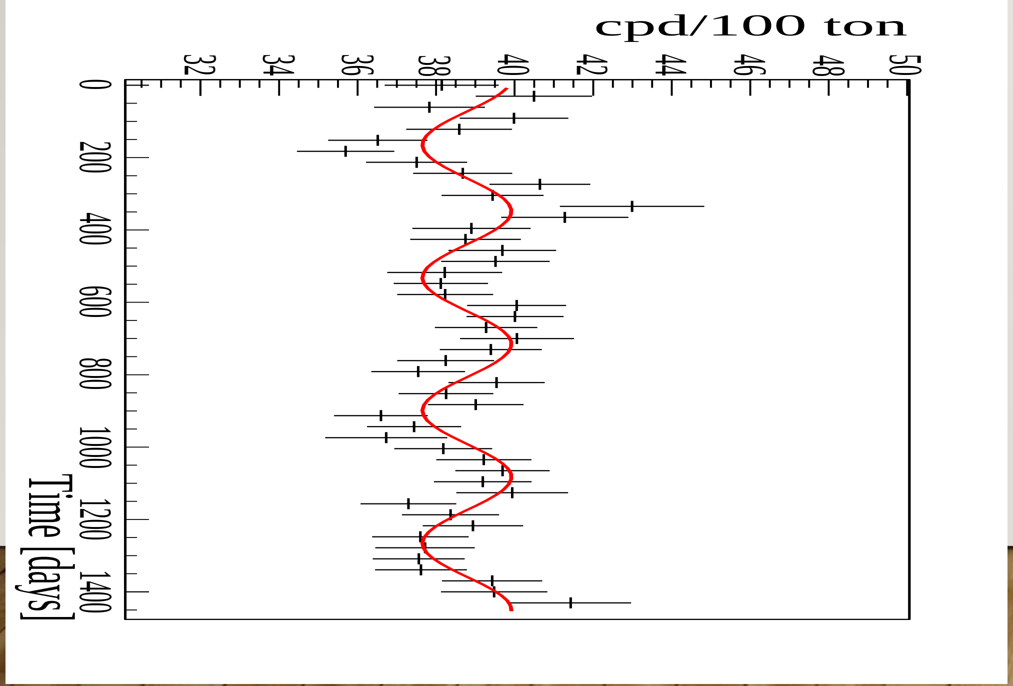
Z=metallicity

from A. Serenelli , F.Villante et al.

from J. Bergstroem et al.,

Seasonal modulation





eccentricity of the Earth orbit: 6.7% of total rate difference

- 1456 astronomical days of data
- energy range: 215-715 keV (^{7}Be region)

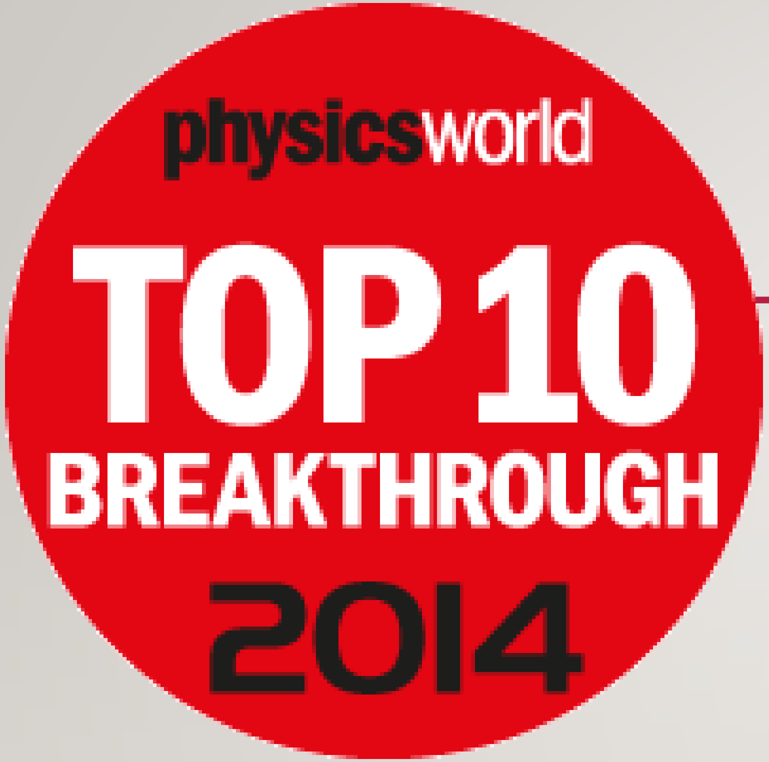
Modulation analysis

- *sinusoidal fit*
- *Lomb-Scargle method*- an extension of the Fourier Transform approach- can treat data sets not evenly distributed in time

- null hypothesis rejected at 3.9σ (99.99% C.L.)
- modulation amplitude (7.1±1.9)%
- best-t period is **T = 367.0 ±10 days**.

pp cycle- conclusions

1. experimental evidence of the **individual nuclear reactions producing neutrinos in the pp solar cycle,** which is the source of **99% of the Sun's energy**.
2. a good **agreement between the experimental data and the model**, obviously within the experimental errors and the uncertainties of the model predictions
3. good agreement between the solar luminosities measured through photons and through neutrinos : L = ($3.89^{+0.35}_{-0.42}$) x 10^{33} erg s^{-1} for neutrinos and L = (3.846 $\pm$ 0.015) x 10^{33} erg s^{-1}) for photons (random track) ➡ the Sun is in **thermodynamic equilibrium over 10^5 years time scale**
4. ratio between the **two pp chain branches**,: RI/II = 2Φ (^{7}Be) / [Φ (pp) - Φ (·Be)] = $0.178^{+0.027}_{-0.023}$, in **accordance with the expectations of the solar model** that give 0.180 $\pm$ 0.011 for the high metallicity and 0.161 $\pm$ 0.010 for the low metallicity



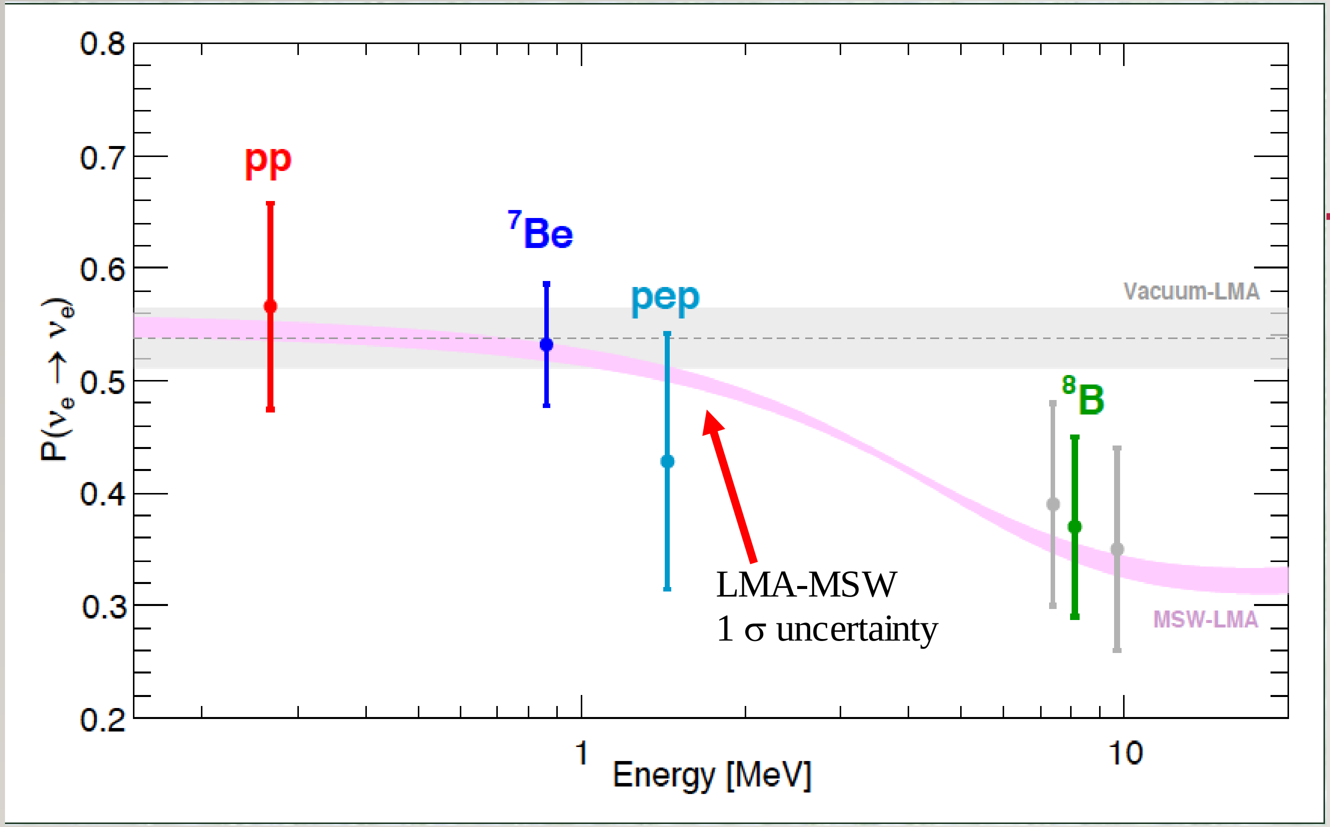
From the British IOP

Celebratory stamp of the Italian Post Office

NEUTRINO PHYSICS

Gianpaolo Bellini. Università and INFN- Milano

Neutrino Physics



electron neutrino survival probability: from 60 keV to >10 MeV.

1. Borexino has measured the electron neutrino Pee in the *vacuum regime*, where, according to the MSW model, the vacuum dominates
2. The Borexino data allowed to probe the vacuum–matter transition from a single experiment.
3. Despite the uncertainty of the various points, that incorporate both the experimental errors and the SSM uncertainties, the experimental results seem in agreement with the predictions of the MSW-LMA model.

Not Standard neutrino Interaction (NSI)

exposure of 1271 days x 71.3 tons

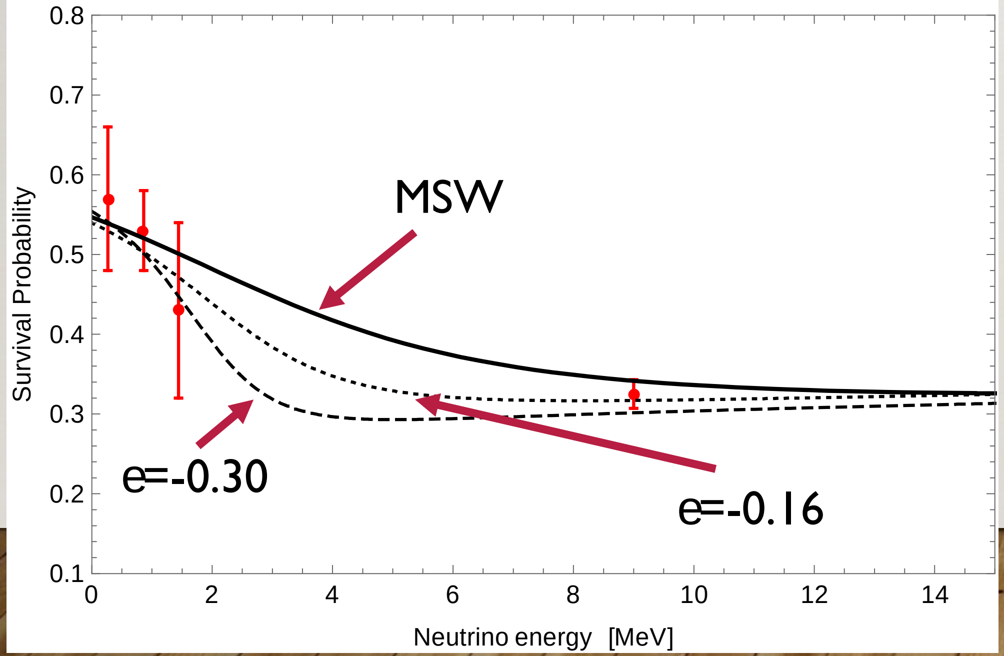
Theories beyond the Standard Model postulate the existence of Non-Standard Interactions (NSI), where flavor-changing NC is possible

The NSI Lagrangian : $-\mathcal{L}_{NC\text{-}NSI} = \sum_{\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{ff'C}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_C f')$, where ∈$ * " " +% parametrizes the NSI strength

nomalized to ! " , f and f' are leptons or quarks, a,b=e,∝,t and C is the chirality of ff' current (L or R). In this analysis only flavor-diagonal case f=f'=e and a=b is considered, with #$% = #$ $' ' (.

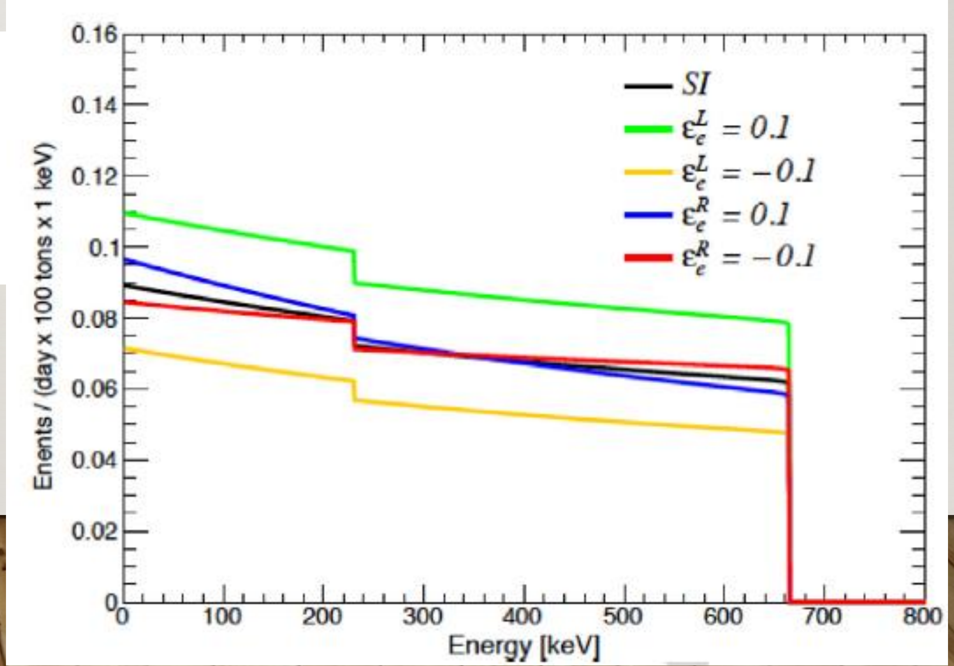
The NSI affects the neutrino propagation in matter and in particular **the vacuum-matter intermediate region**.

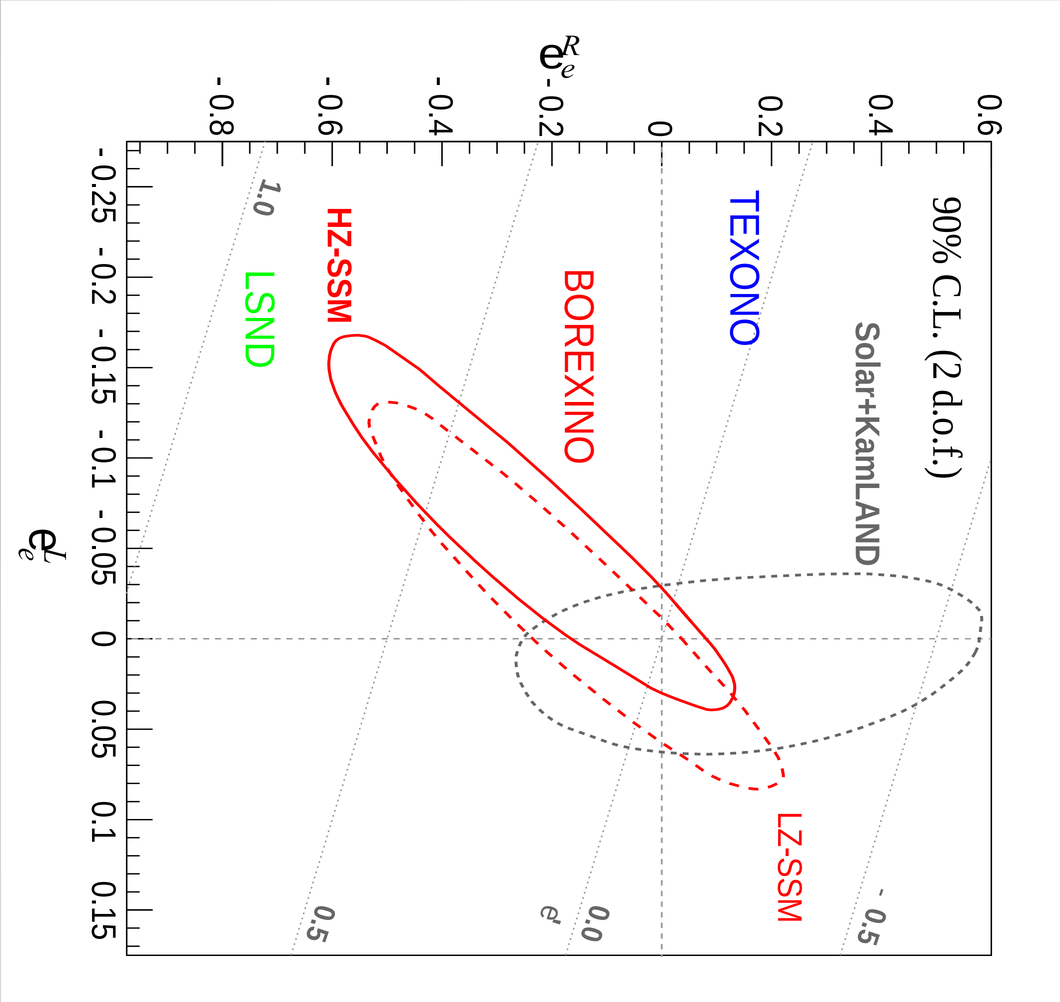
The analysis is carried out on the n-e elastic scattering which is very sensitive to NSI.

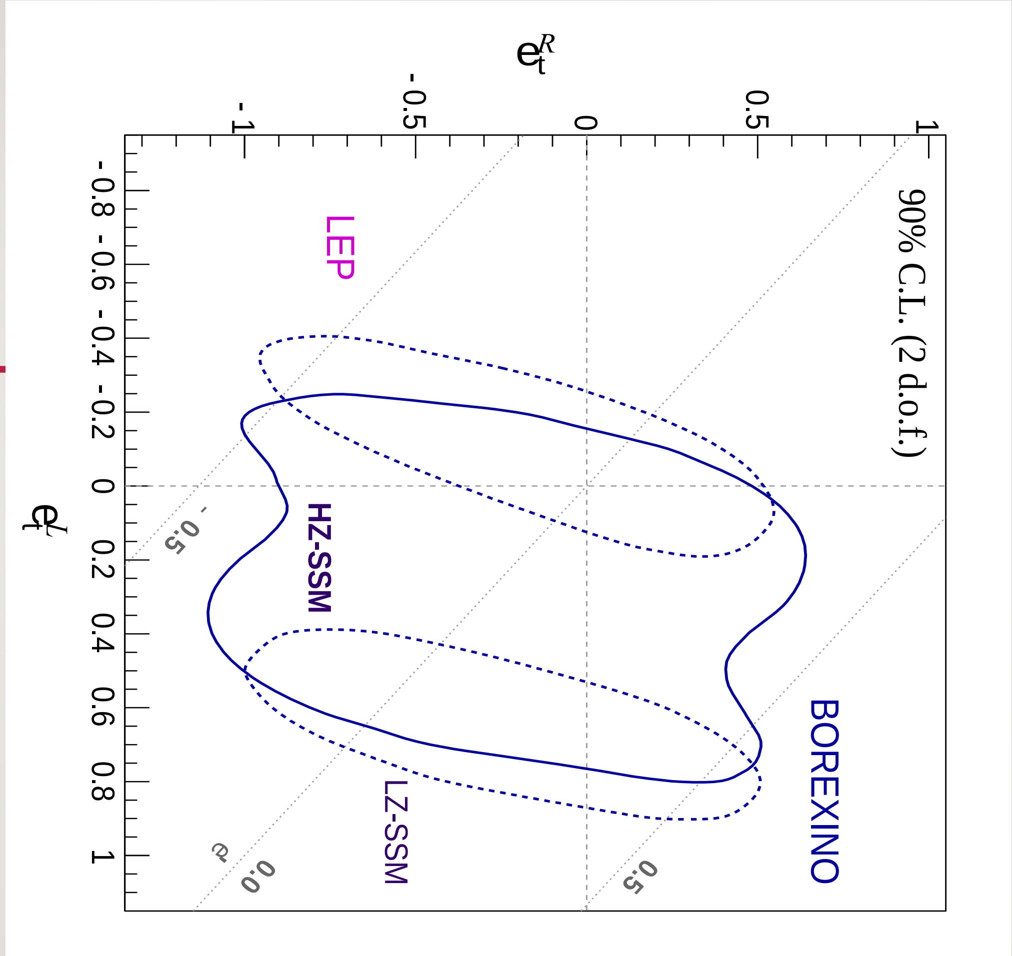


n-e elastic scattering differential rate for ^{7}Be solar neutrinos with and without NSI

pp, ^{7}Be, pep data







allowed region for $\varepsilon_e^{R,L}$ with $\varepsilon_\tau^{R,L}$ fixed at zero

allowed region for $\varepsilon_\tau^{R,L}$ with $\varepsilon_e^{R,L}$ fixed at zero.

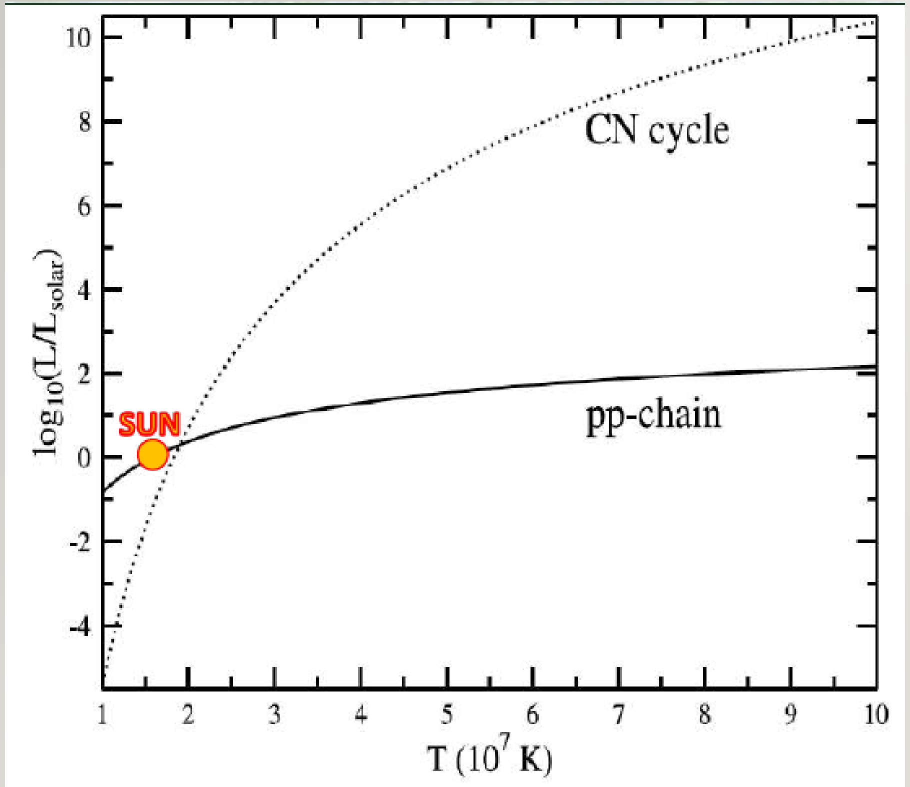
$\epsilon_{\alpha\beta}^{ff'C}$ parametrizes the strength of NSI

THE CNO CYCLE: FROM THE SUN TO THE STARS

Gianpaolo Bellini. Università and INFN- Milano

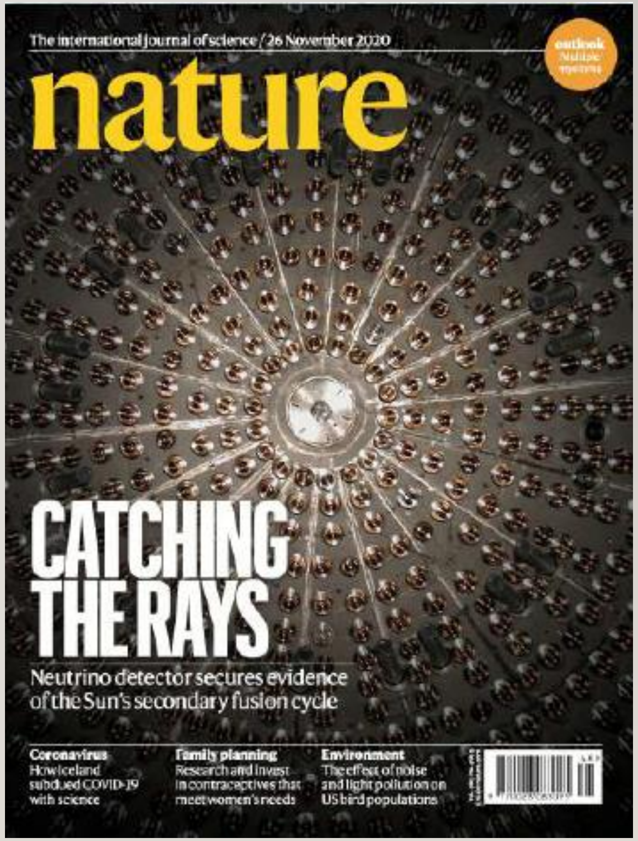
CNO Cycle

- In the Sun the CNO cycle **contributes only for 1%.**
- In the **massive stars is considered dominant** and reaches in their core a temperature of a few x 10^8 K, needed to counterbalance the gravitational force thus preventing their implosion
- But this hypothesis, which dates back to the 1930 (Bethe and Von Weizsäcker), has never been experimentally tried.



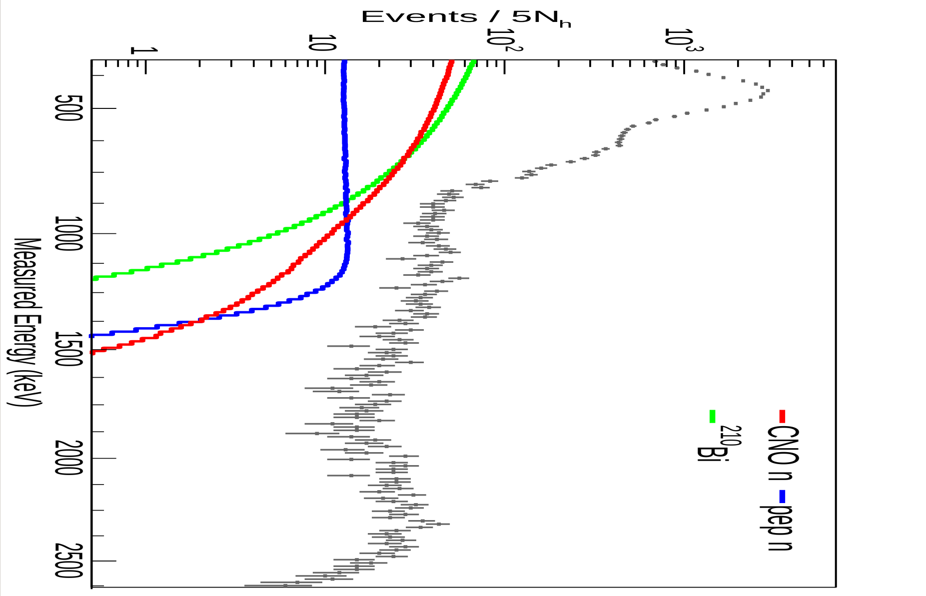
W.C. Haxton, A:M Serenelli (2008)

The experimental demonstration of the existence of the CNO cycle has been the most recent achievement of Borexino



CNO Cycle

difficulties in measuring the CNO because ^{210}Bi, CNO, pep fall in the same energy window and the energy spectrum of CNO has no particular tagging

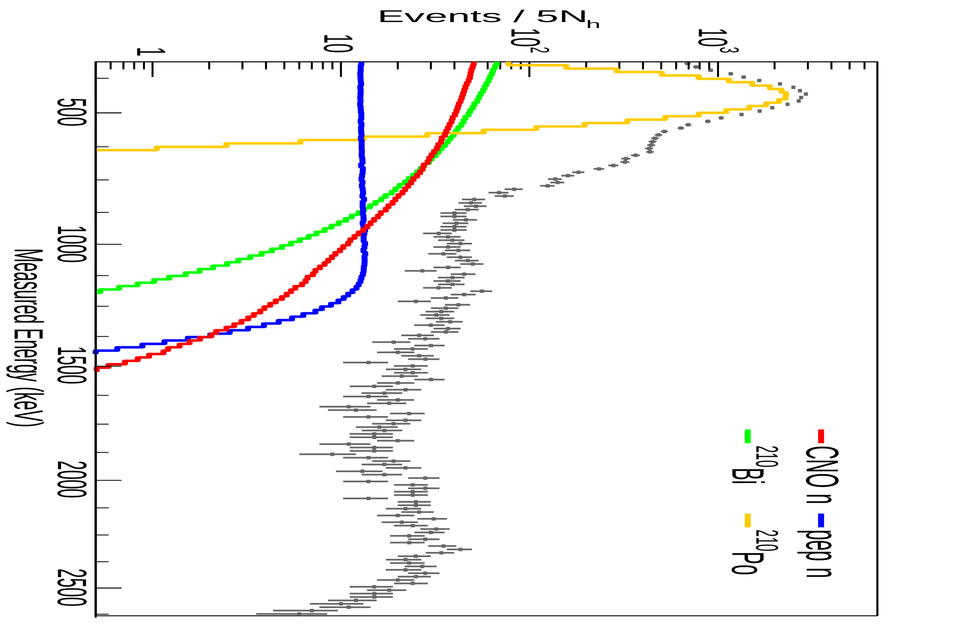


- Borexino data
- CNO ν expected spectrum
- ^{210}Bi spectrum
- pep ν spectrum

The **spectral fit** returns only the sum of **CNO** and **^{210}Bi**, if both are left free

BUT

The pep flux can be constrained at the 1.4 % level through the solar luminosity constraint coupled to SSM predictions on the pp to pep rates ratio and the most recent oscillation parameters - J. Bergström et al., JHEP, 2016:132, 2016



what is needed is **a reliable determination** of ^{210}Bi; a **constraint** on it can be obtained from ^{210}Po

secular equilibrium

$^{210}Pb \xrightarrow{\beta^-} {}^{210}Bi \xrightarrow{\beta^-} {}^{210}Po \xrightarrow{\alpha} {}^{208}Pb$ (stable)

23y 5d 138 d

CNO Cycle

The goal is to extract the ^{210}Bi rate from the ^{210}Po, which decaying has to reach a constant plateau.
^{210}Po can be easily identified via the α/β pulse shape discrimination

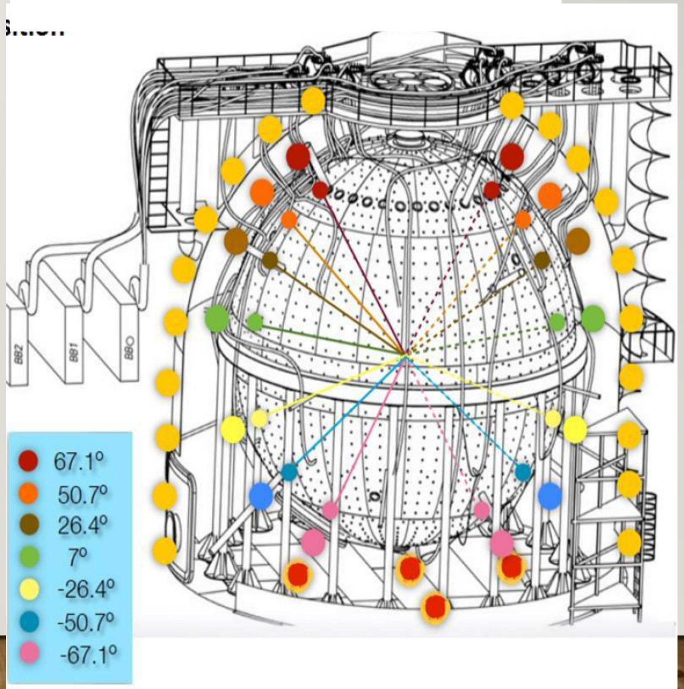
Due to the secular equilibrium an independent measurement of the ^{210}Po decay rate gives the ^{210}Bi decay rate

^{210}Po consists of two components, one **out of equilibrium** which increases during operations as purification or scintillator refilling and a second one **in secular equilibrium.** The component O. of S.E. decays and the rate reaches a constant plateau corresponding to the component in S.E with ^{210}Pb and then with ^{210}Bi.. Fluctuations are observed in this plateau due to convective motions which bring in the F.V. ^{210}Po present on the I.V. walls, produced by the ^{210}Pb

Then we have to avoid the convective motions

a stabilization of the temperature is necessary

temperature probes-



CNO Cycle

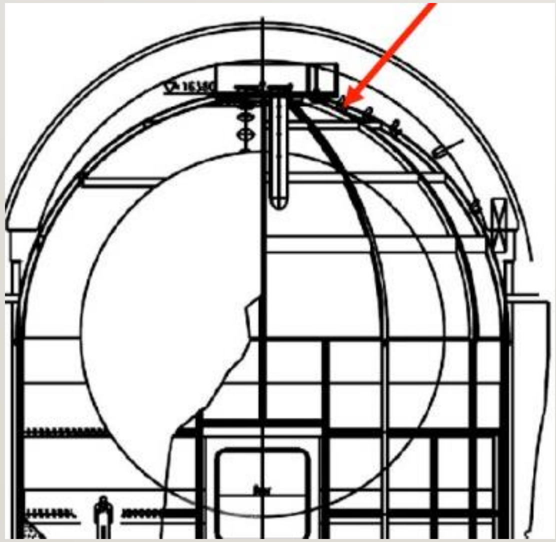
Stabilization system-2014-2016

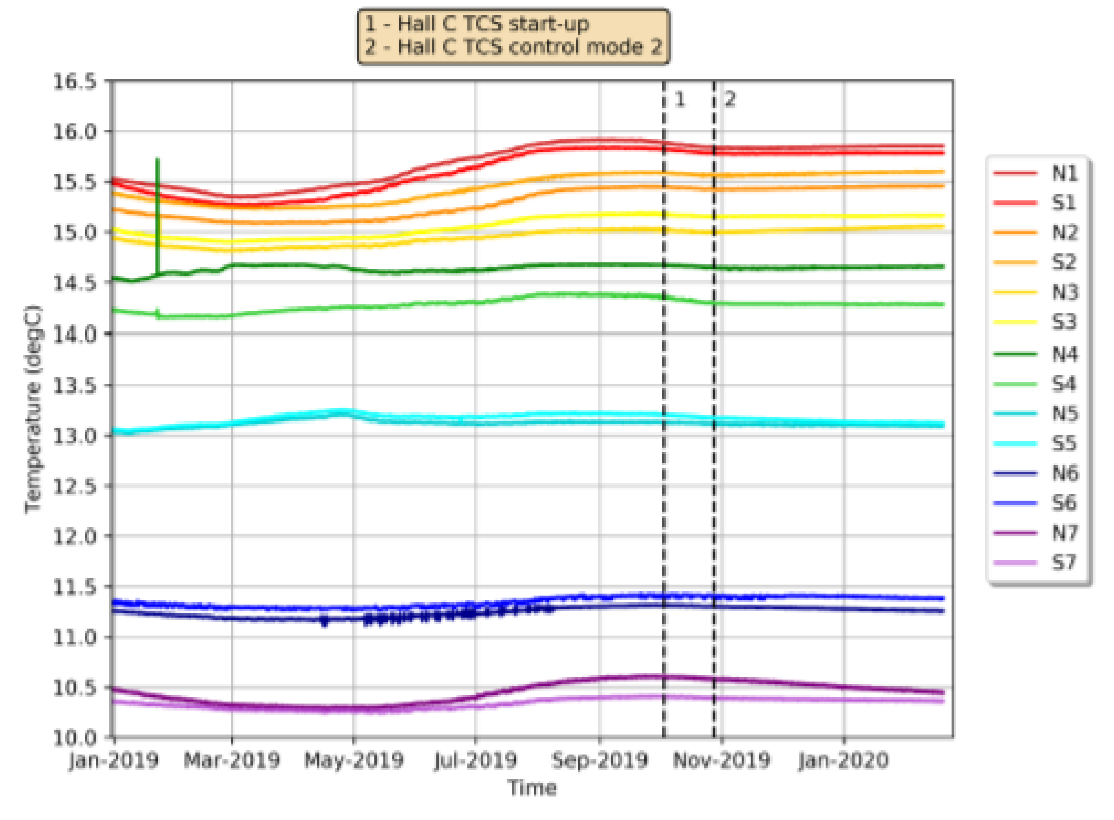
I[st] step: thermal insulation

- Double layer of mineral wool (thermal conductivity down to 0.03 W/m/K)

2[nd] step: copper coils under insulation- water in the serpentines controls the top temperature at about 15,5 ^{0}C -the bottom temperature (rock) is ~ 7. ^{0}C

Top-bottom gradient stabilized

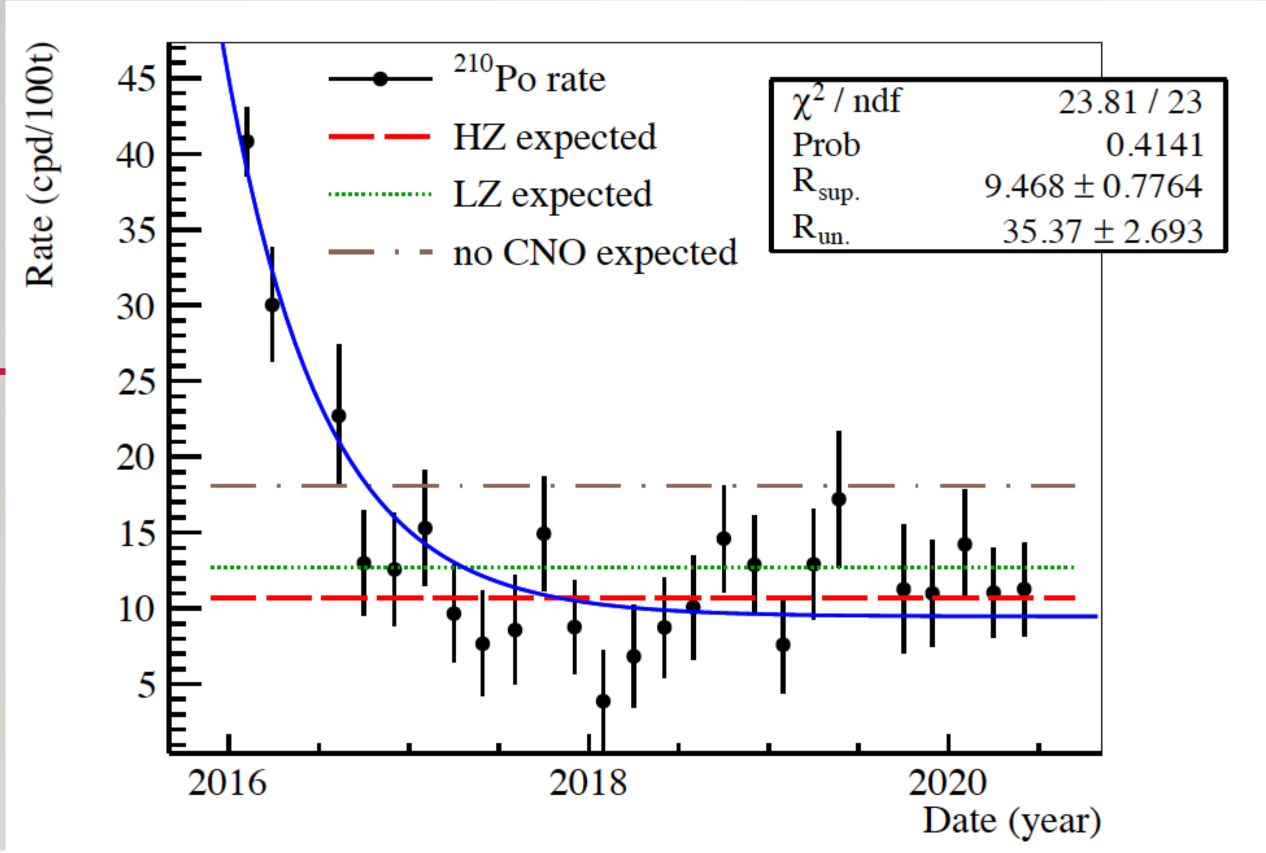




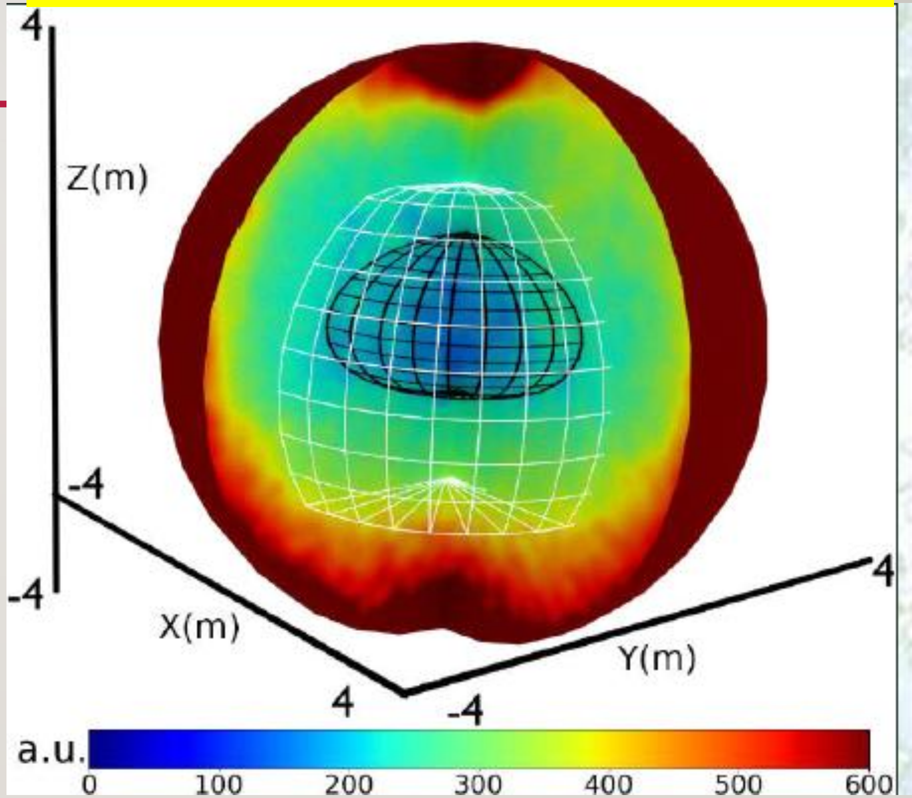
Excellent temperature stability achieved

Probes resolution 0.07 °C

CNO Cycle



Three-dimensional view of the ^{210}Po activity inside the entire Inner Vessel - the innermost **blueish region contains the LPoF (black grid) - the white grid is the software-defined Fiducial Volume**



1. ^{210}Po (alpha) events are fitted to **find the minimum ^{210}Po rate in the sub-region**
2. Low Polonium Field (LPoF) at around 80cm above equator, but it moves over time very slowly

Check the spatial uniformity of ^{210}Bi-
Uniform within about 0.55 cpd/100 tons

The LPoF blueish region corresponds to **about 20 tons** to be compared to about 78 tons of the Fiducial adopted in this analysis

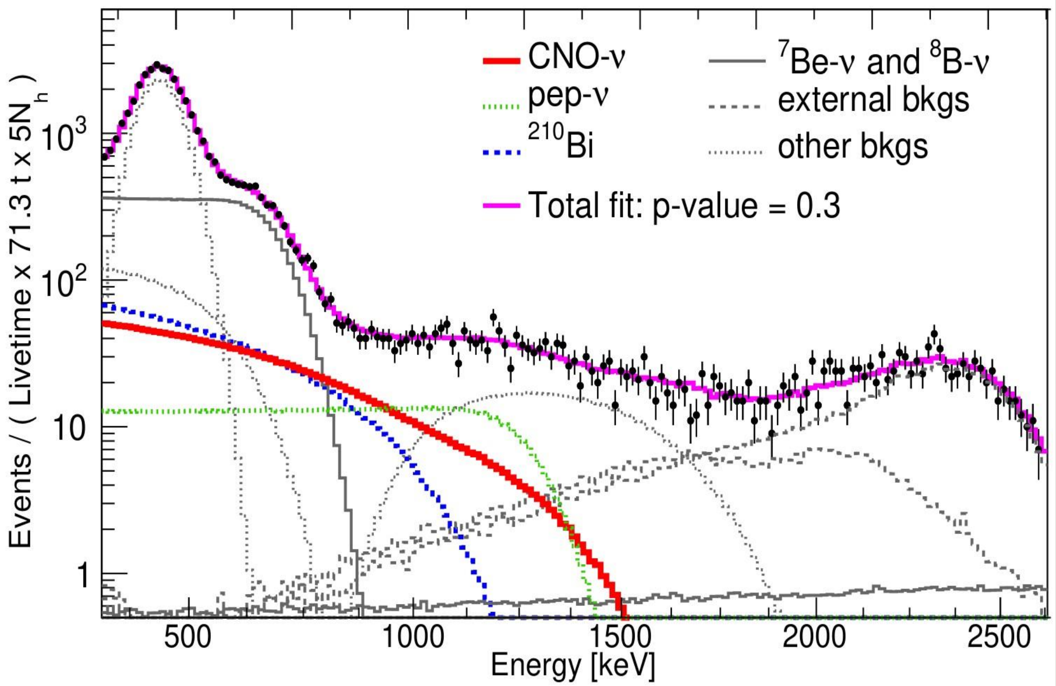
CNO Cycle

^{210}Po rate from the Low Polonium with all errors: $R_{min} = 11.5 \pm 1.3 \frac{cpd}{100\ t}$

The lowest ^{210}Po rate has been conservatively assumed as a upper limit for ^{210}Bi, because we cannot exclude in principle that residual ^{210}Po from the vessel surface would be present

$R(^{210}Bi) \leq 11.5 \pm 1.3$ cpd/100t

Multivariate fit (0.32-2.64 MeV)
July '16 – February '20



Maximization of a binned likelihood: 3 distributions simultaneously:

- **Reconstructed energy for TFC-tagged and TFC-subtracted datasets (^{11}C identification)**
- **Radial position**

pep-ν rate constrained – solar luminosity
^{210}Bi rate constrained -- ^{210}Bi-^{210}Po tagging
CNO rate -left free
Other ν and bkg rates- left free

CNO Cycle

From the multivariate fit

Further systematic: energy response function -from detector calibration

1. energy scale ~0.23%
2. non linearity ~ 0.4%

CNO result: 7.2 (-1.7 +3.0) cpd/100t stat + sys

corresponding to a flux of neutrinos on Earth;
$7.0\ (-1.9\ \ +2.9) \times 10^{8}\ cm^{-2}\ s^{-1}$

Likelihood significance

13.8 millions pseudo-datasets with no CNO

Real dataset

M.L. significance greater than **5 σ** at 99% CL

No CNO hypothesis disfavored at 5 σ

When all solar neutrino fluxes measured by Borexino, including CNO, are combined, the LZ hypothesis is disfavored at a level of 2.1σ.

physicsworld

TOP 10

BREAKTHROUGH

2020

Antineutrinos from the Earth

Gianpaolo Bellini. Università and INFN- Milano

Geoneutrino = antineutrinos from the Earth

naturally present in the Earth, produced by the natural radioactivity: only experiments using liquid scintillator- They are : Borexino and KamLAND ; both detect the antineutrinos **via the Inverse beta decay, with a threshold at $1.806\ MeV$**

Therefore the only natural chains detected are.

$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ MeV$$ 38%

$$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\ MeV$$ 15%

Their spectrum ends at 3.26 MeV due to the ^{214}Bi decay in the ^{238}U chain;. due to the 6371 km of the Earth radius, the oscillation effect is averaged and the Pee is about 0.54.

TNU (Terrestrial Neutrino Unit): number of interactions detected in 1 year on a target of 10^{32} protons, corresponding to ~ 1 kt of Liquid scintillator.

Background: the **cosmogenic unstable isotopes,** the **(α,n) reactions** and the **antineutrinos from the nuclear reactors**

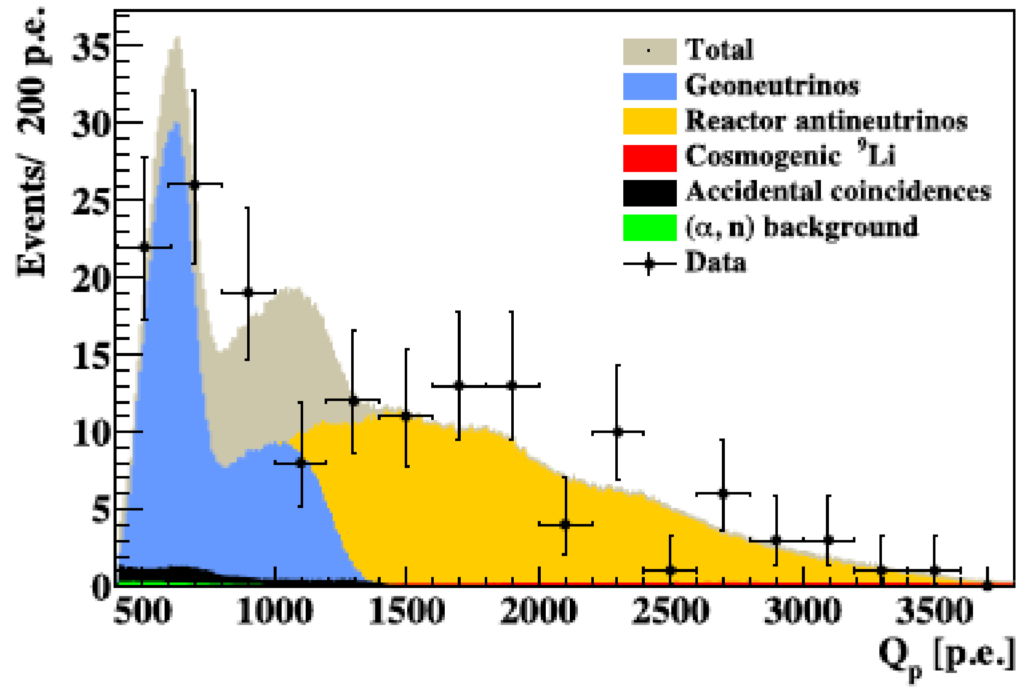
easily rejected by proper energy cuts

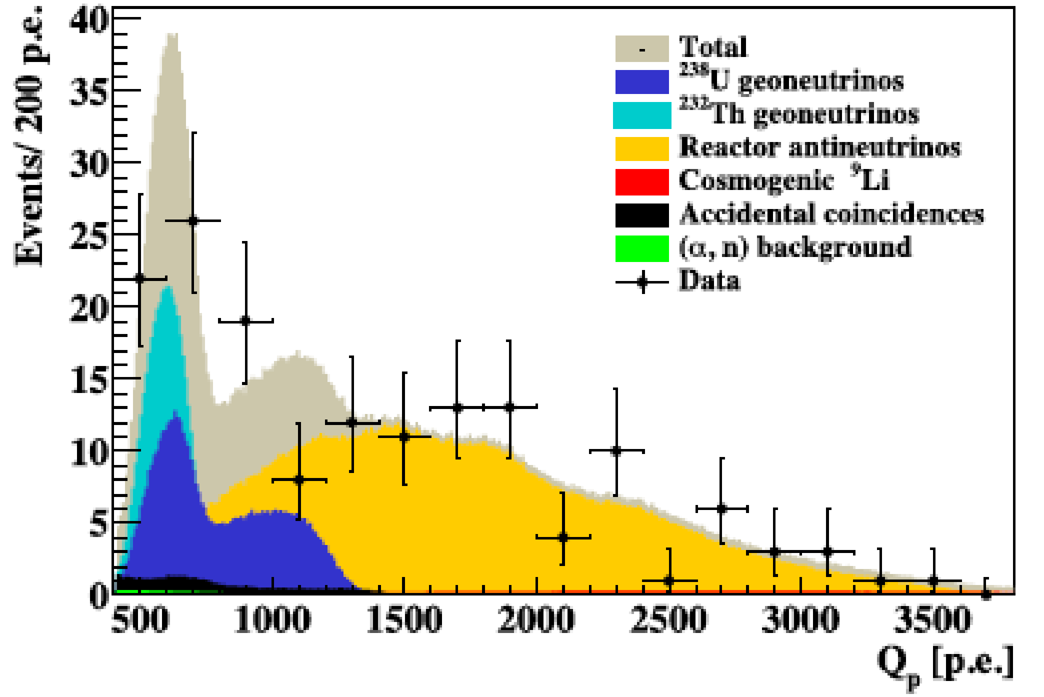
negligible due to the unprecedented low radioactivity achieved in Borexino

Calculated, using the data base of the IAEA, and taking into account all important parameters concerning 194 European plus 246 world power reactors

December 2007–April 2019. 3263.74 days. $(1.29 \pm 0.05) \times 10^{32}$ proton x year

geo-neutrinos flux: about 10^{6} cm^{-2} s^{-1}





chondritic ratio $^{238}U/^{232}Th = 3.9$ assumed

Th and U free parameters

Geo-ν events*	$51.9^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(syst)$
Geo-ν events (TNU)*	$46.3^{+8.4}_{-7.7}(stat)^{+2.4}_{-1.8}(syst)$
Geo-ν events**	$N_{Tot} = 48.9^{+25.1}_{-20.7}$
	$N_U = 27.8^{+15.4}_{-11.8}$
	$N_{Th} = 21.1^{+9.7}_{-8.4}$
Expected reactor antineutrinos	$97.6 \pm 1.7(stat) \pm 5.2(syst)$
Expected reactor antineutrinos (TNU)	$79.7^{+1.4}_{-1.3}$
Observed reactor antineutrinos*	$92.5^{+13.3}_{-10.5}$

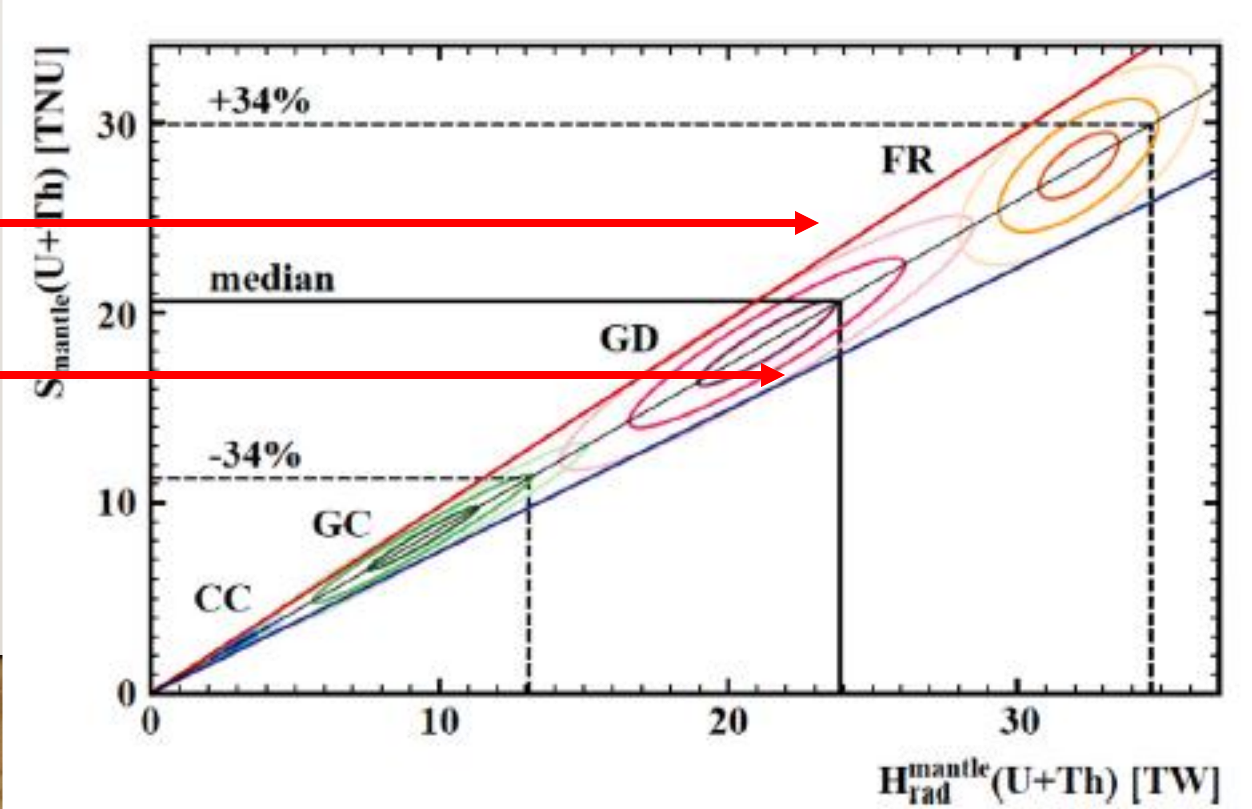
- Extraction of the mantle Signal
- Estimation of the radiogenitc heath
- Comparison of the data with the various Bulk Silicate Earth models: cosmo-chemical, geochemical, geodynamical

Mantle signal- First the contribution of the crust has to be subtracted: two components, crust in the region around the Gran Sasso (LOC) is calculated considering an area of **492 km x 444 km,** and the contribution of the rest of the crust (ROC), using the **1°x1° 3D** model and integrating the contribution on the whole Earth. The two contributions give in total $29.8^{+5.5}_{-4.6}$ events.
The mantle contribution, is obtained by subtracting the crust rate : **Nmantle = 23.1 events**
No signal rejected with 99.0% C.L.. With MC pseudo.experiment: (^{238}U)> 13ppb and ($_{232}$Th)> 48 ppb
:

Radiogenic heath. radiogenic power of the lithosphere, LOC + ROC, can be calculated taking into account the events rate and the heat produced by the single radioactive decay : (U + Th) = $6.9^{+1.6}_{-1.2}$ μW/kg.
But the distribution of radioactive nuclides in the mantle is unknown:; two hypotheses: **distribution homogeneous** and *concentrated around the Core–Mantle boundary-*

maximum

minimum



Adding the 40K (18%) :
H^{mantle}_{rda} **(H+Th+K)=**$8.1^{+1.9}_{-1.4}$ **TW**
Adding the crust contribution
H_{rad} (H+Th+K)=$38.2^{13.6}_{-1.4}$**TW**
About 81% of the total terrestrial heath

Conclusions

1. Borexino has been the first experiment probing **sub-MeV neutrinos in real-time,** and is still now **the unique experiment** able to proceed with these studies.
2. Borexino has measured for **the first time all pp chain nuclear reactions producing neutrinos**, measuring, in particular, simultaneously the pp, ^{7}Be, and pep neutrino flux, ^{8}B neutrinos with a low threshold and probing hep neutrinos.
3. These results paved the way to actual breakthroughs not only on Solar physics, but also on neutrino physics. **The ν_e survival probability in the vacuum regime is measured** for the first time by Borexino and the **vacuum–matter transition** has been probed by a single experiment. In addition, a number of non-standard neutrino interactions has been studied by Borexino with world leading limits.
4. The detection of the CNO cycle closes a long history, which began in the 90s of the last century, when Hans Bethe and Carl Friedrich von Weizsacker, independently, proposed that the fusion of hydrogen in stars could also be catalyzed by nuclei heavier than He. Then the theory of energy generation hypothesizes that the CNO would be the primary channel for hydrogen burning in stars more massive than the Sun , and it is in fact the primary channel for hydrogen burning in the Universe. This hypothesis never received an observational confirmation until now, when Borexino **has observed CNO neutrinos** proving also that its contribution in the Sun is of the order of 1%.
5. The pp and CNO cycles measurements give an hint in favor of the high metallicity inside the Sun.
6. Again thanks to the low intrinsic background, Borexino has **observed geo-neutrinos** with >5σ statistical significance and studied them to obtain Earth geo-physical and geo-chemical information.

The Borexino collaboration

Thank you !!!!