Solar neutrino: Experiments

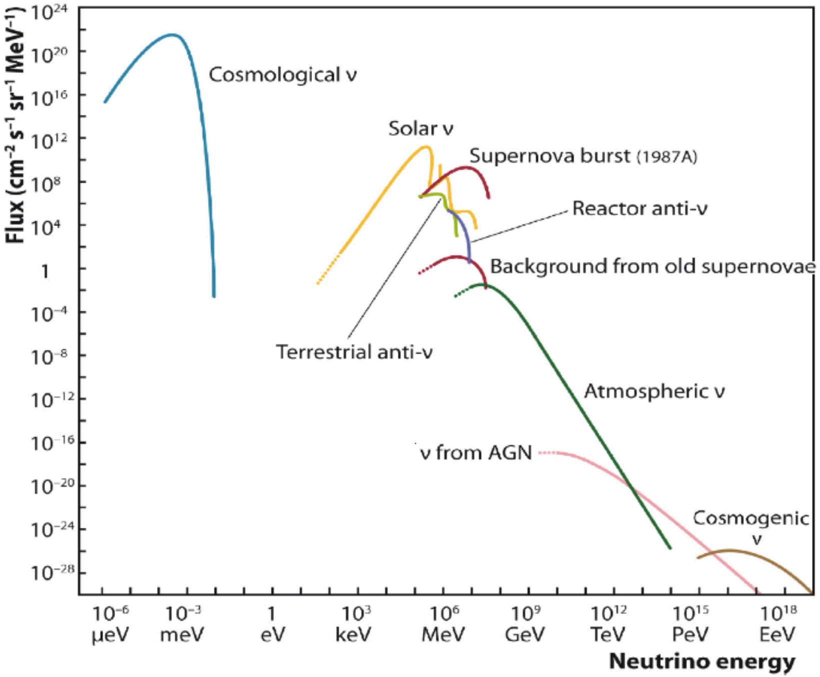
…Пусть не поймаешь нейтрино за бороду
И не посадишь в пробирку,
— Было бы здорово, чтоб Понтекорво
Взял его крепче за шкирку…
Владимир Высоцкий 1964 г.

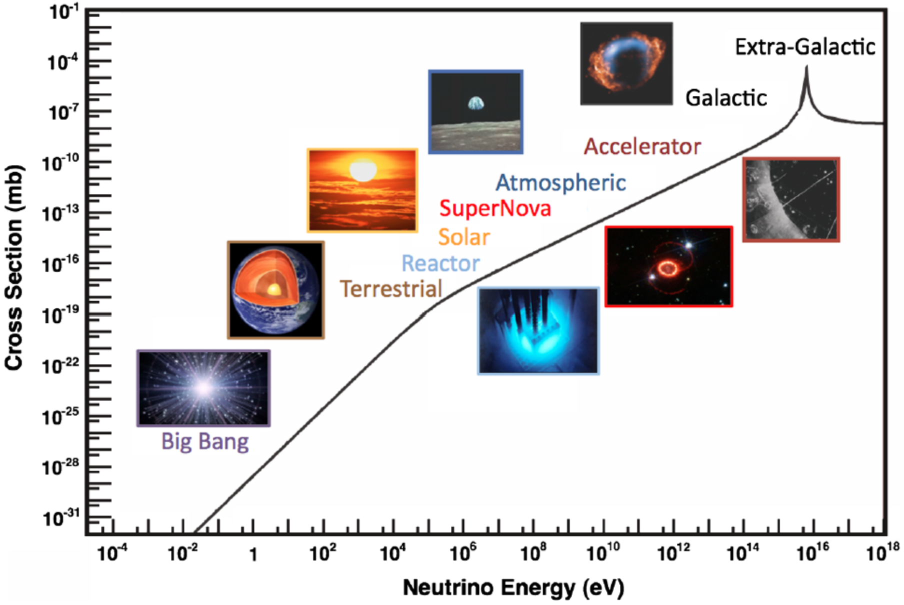
...Even if you don't catch a neutrino by the beard
And put it in a test tube,
It would be great if Pontecorvo
took it tighter by the scruff of the neck…
V.Vysotsky, 1964

Oleg Smirnov
Joint Institute for Nuclear Research, Dubna
November 1, 2023

The XXVII International Scientific Conference of Young Scientists and Specialists

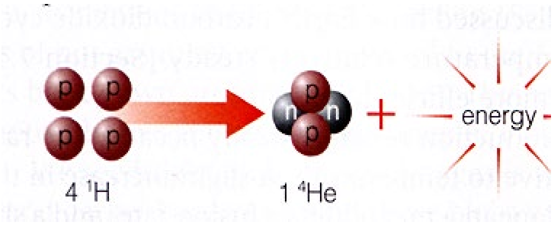
Neutrino fluxes in nature



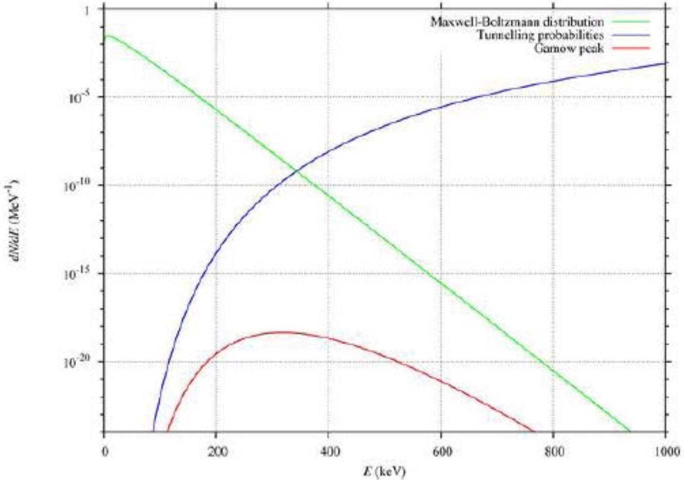


How the Sun shines

Core temperature~ 10^7 K (~1 keV).



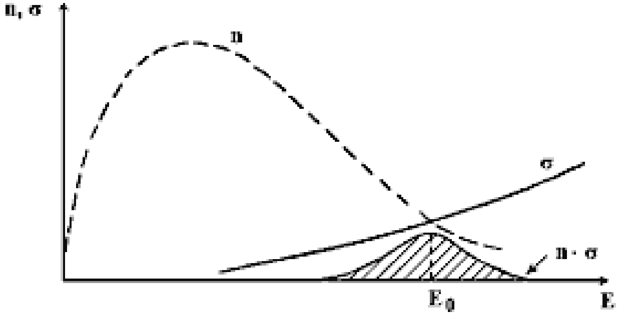
(26.7MeV) (+2ν)



Helium is lighter comparing to 4 protons(0,7%)- this energy is feeding the Sun.

pp-cycle is very slow reaction (time scale 7,9·10^9 y). Energy release = 26,7 MeV, 2 neutrinos are emitted.

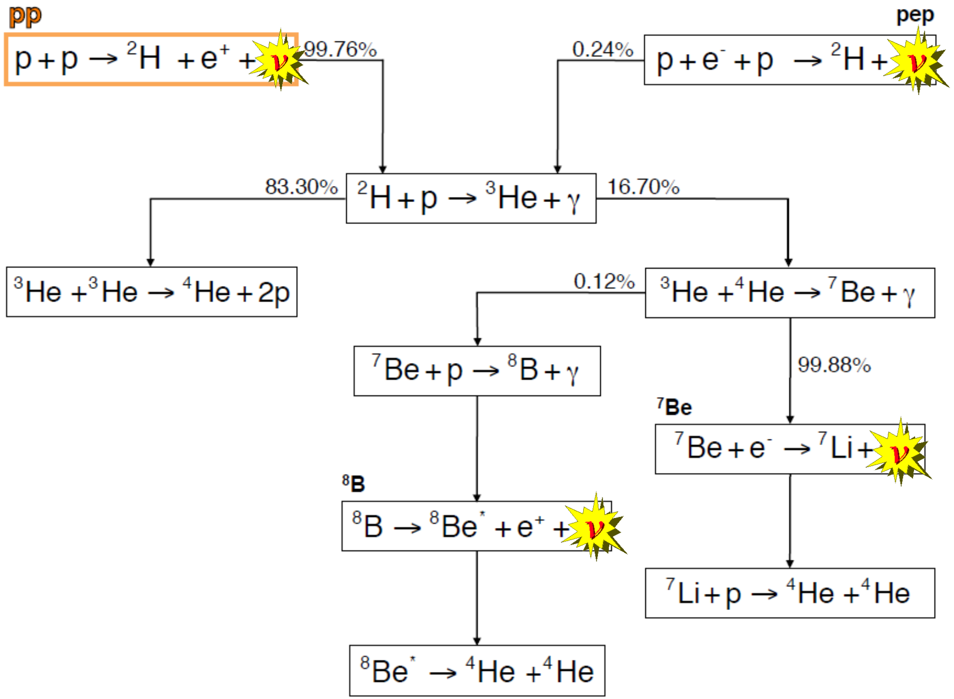
Sun power is L_{Sun}=$3.8 \cdot 10^{26}$ W (380 YW) ➔ $6.5 \cdot 10^{10}$ neutrino/s/cm^2.



Stellar Nuclear reactions occurs in the narrow energy range below 100 keV, the so called Gamow peak.
Reaction cross sectons are very low: pico and femto barns

pp-chain (99%)

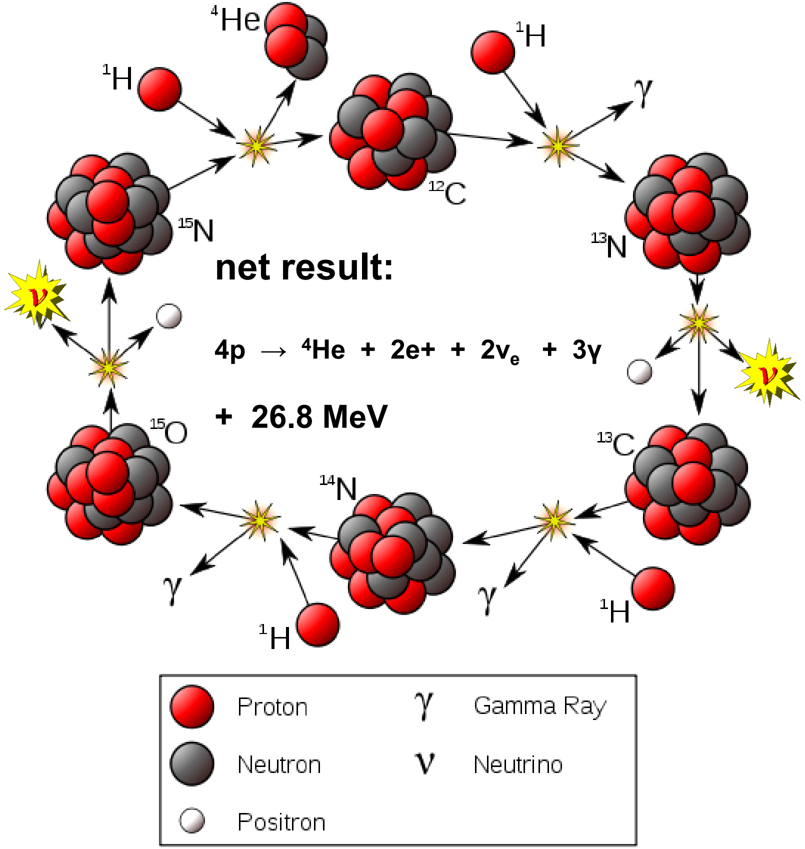
pep – alternative start



neutrino fluxes brings snap-shot of the nuclear reactions in the Sun.

CNO-cycle (carbon-nitrogen-oxygen)

- **a catalytic cycle.**
- **dominates in stars more massive than about 1.3 times the mass of the Sun.**
- **pp-chain reactions start occurring at temperatures around 4×10^6K. A self-maintaining CNO chain starts at ~15×10^6 K, but its energy output rises much more rapidly with increasing temperatures and at ~ 17×10^6 K, the CNO cycle becomes dominant.**
- **The Sun has a core temperature of around 15.7×10^6 K and only 1.7% of He-4 nuclei being produced in the Sun are born in the CNO cycle.**
- **The simplest CN-cycle (CNO-I, or Bethe cycle or carbon cycle) was proposed by Hans Bethe in 1938 and, independently, in 1939 by Carl Friedrich von Weizsäcker).**



net result:

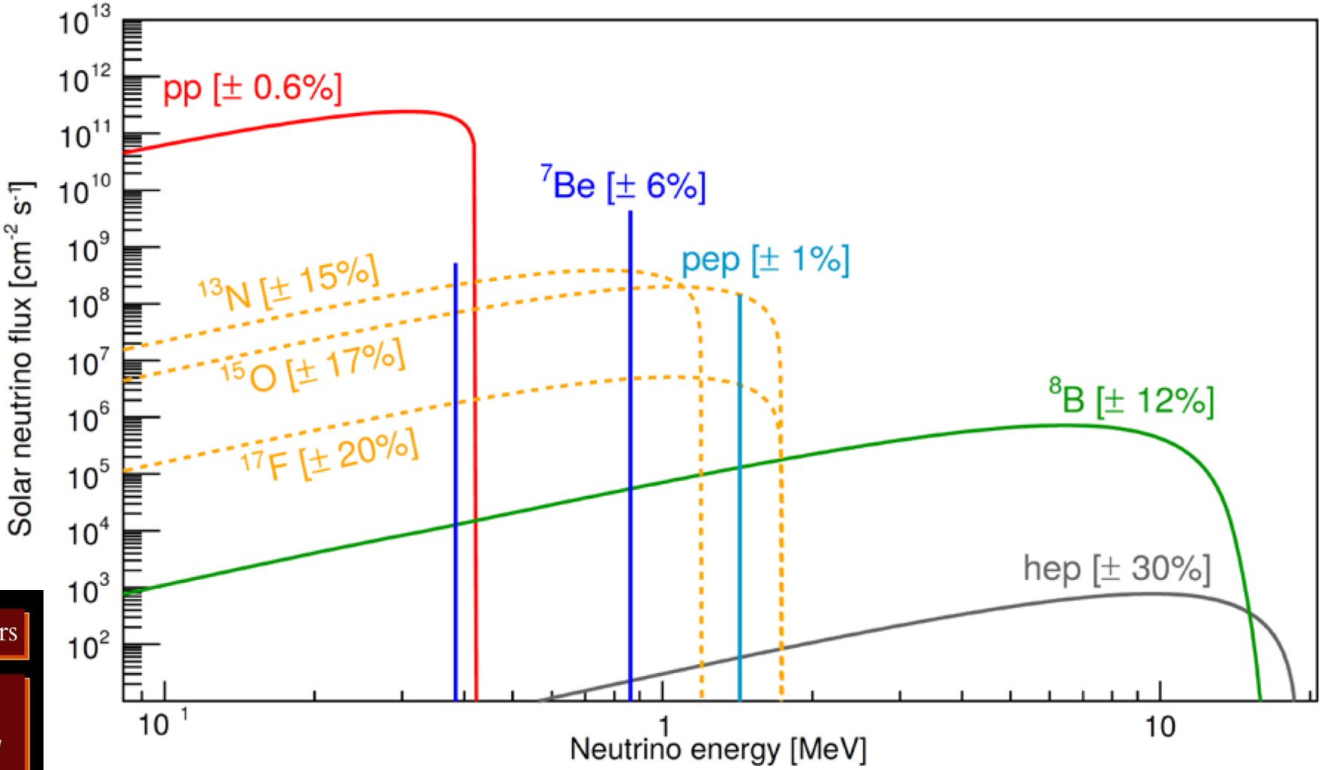
$4p \rightarrow {}^4He + 2e+ + 2\nu_e + 3\gamma$

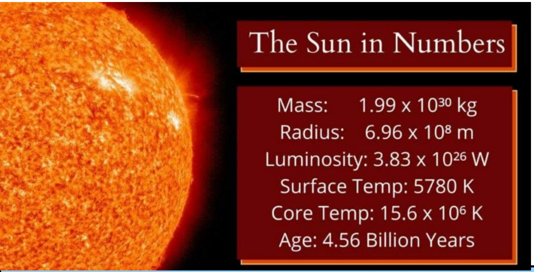
$+\ 26.8$ MeV

Solar Neutrino : spectra

pp & pep : constrains from the Sun luminosity

Uncertainties in the theoretical predictions accumulates along the chain branches




The Sun in Numbers

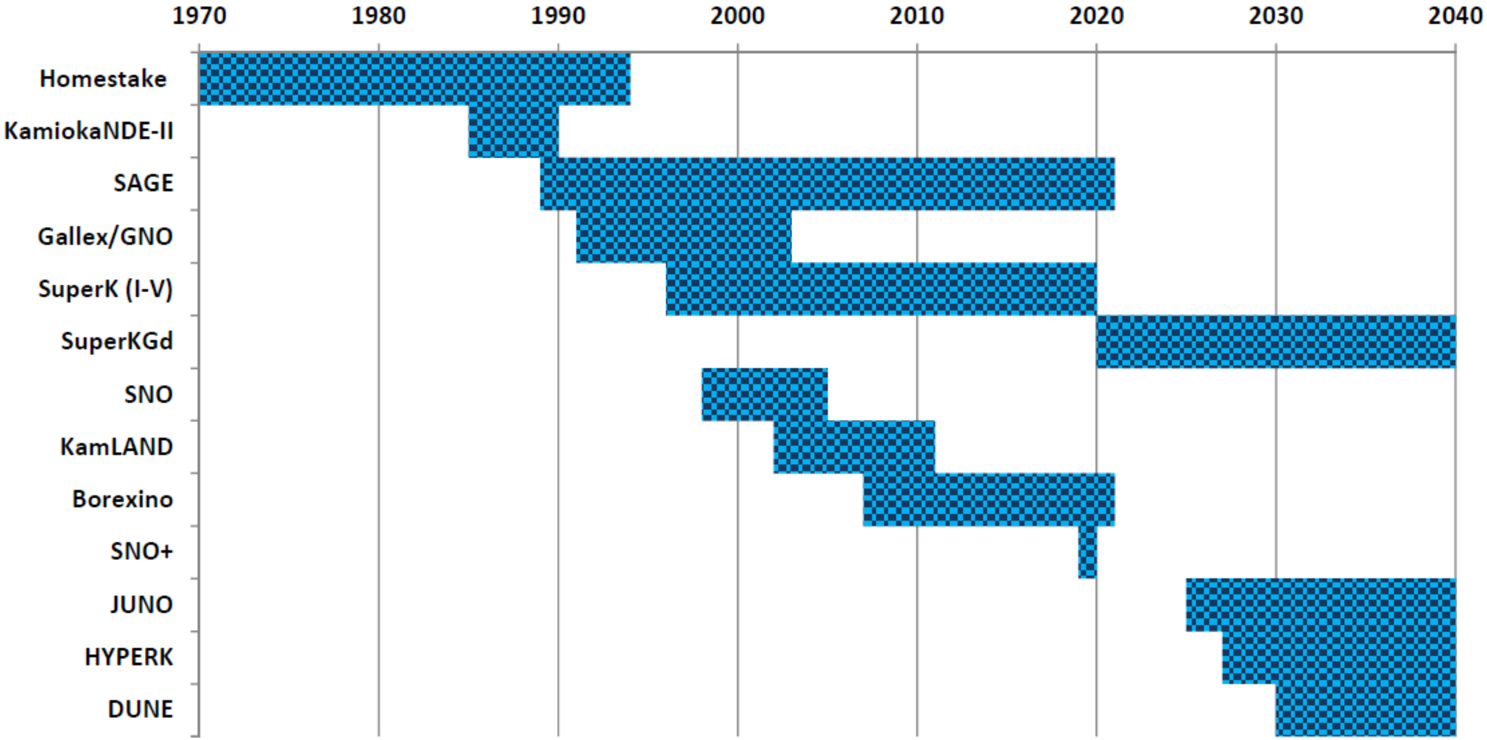
Mass: 1.99 x 10^{30} kg
Radius: 6.96 x 10^8 m
Luminosity: 3.83 x 10^{26} W
Surface Temp: 5780 K
Core Temp: 15.6 x 10^6 K
Age: 4.56 Billion Years

Solar Neutrino spectra – a clue to the Solar physics

The study of neutrino spectra is the only available way to test ideas about the mechanisms of nuclear processes in the center of the Sun.

> Nowhere is the connection between the microcosm and the cosmos more clearly manifested than in neutrino physics.
>
> Bruno Pontecorvo

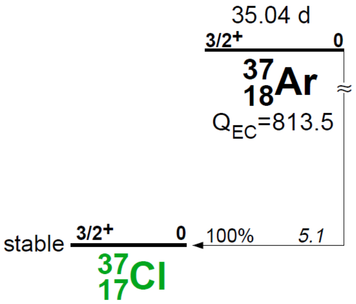
Solar Neutrino Experiments



Radiochemical detection of Solar neutrinos

Bruno Pontecorvo, 1946, proposed chlor-argon method for neutrino detection
"Inverse β^--process", Chalk River Laboratory report PD-205 (1946): .`

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$



Бруно Понтекорво

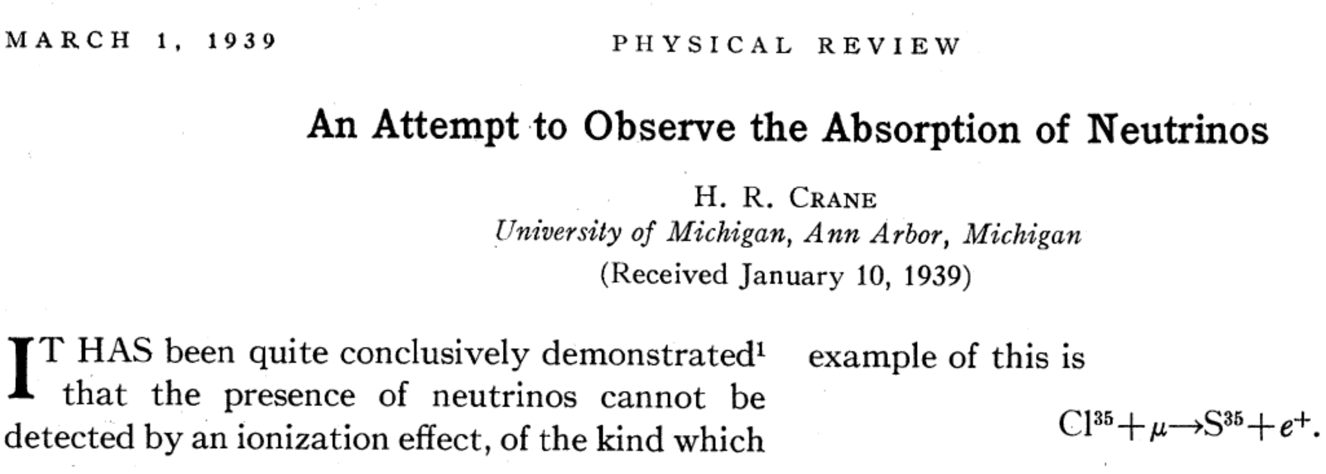
"Confesso di essere piuttosto fiero del mio contributo personale alla nascita dell'astronomia solare neutrinica"
Note Autobiografiche (1988-1989)

^{37}Ar – noble gas. ^{37}Ar atoms are extracted from liquid with He flux. Efficiency of ^{37}Ar of extraction is about 90%. Then ^{37}Ar is absorbed by coal filters, cooled to the liquid nitrogen temperature, and is separated from He.
^{37}Ar - radioactive, captures electron with half-life of 35 d converting back to Cl. Conversion is accompanied by gamma or Auger-electron.
At the beginning of 60s the problem of detecting of such a rare events was successfully solved in USSR and USA. Low background facilities on the base of proportional counters were developed for ^{37}A detection.

A touch of history

- Pontecorvo’s inverse β-process ^{37}Cl-^{37}Ar was described in 1946, in a lecture at a Nuclear Physics Conference organized for students by the National Research Council of Canada at McGill University.
- The lecture, issued as **Report P.D.-205 of the National Research Council of Canada, Division of Atomic Energy, Chalk River, Ontario, 20 Nov.1946**, was immediately classified by the U.S. Atomic Energy Commission. It was declassified on Oct.8, 1949. (in fact no Proceedings were published, only a few lectures).
- Pontecorvo’s first idea was a ^{35}Cl-^{35}S process (Report P.D.-141 dated May21, 1945, classified, apparently unknown to the physics community).
- The neutrino cross-section was extremely small, and neutrino was considered as undetectable at the time being. Purpose of P.D.-141 note was to show that the experimental observation of neutrino “**is not out of question**”, and to suggest a method which might make an experimental observation feasible.
- In P.D.-141 the neutrinos are Majorana neutrinos.
- The ^{37}Cl-^{37}Ar method only acquired full shape in 1948, after Pontecorvo fully clarified the ^{37}Ar decay mode by recording the β-spectrum of ^{37}Ar gas introduced in a high-gain proportional counter, and measured the energy of the Auger electron

Probably, the first radiochemical experiment



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

An Attempt to Observe the Absorption of Neutrinos

H. R. Crane
University of Michigan, Ann Arbor, Michigan

(Received January 10, 1939)

IT HAS been quite conclusively demonstrated[1] that the presence of neutrinos cannot be detected by an ionization effect, of the kind which

example of this is

$$Cl^{35}+\mu\rightarrow S^{35}+e^{+}.$$

3 pounds of NaCl irradiated 90 days by 1 mCi source, study of extracted sulphur with ionization chamber with 10 decay/s sensitivity. No events found.

Small target, low intensity source, low sensitivity

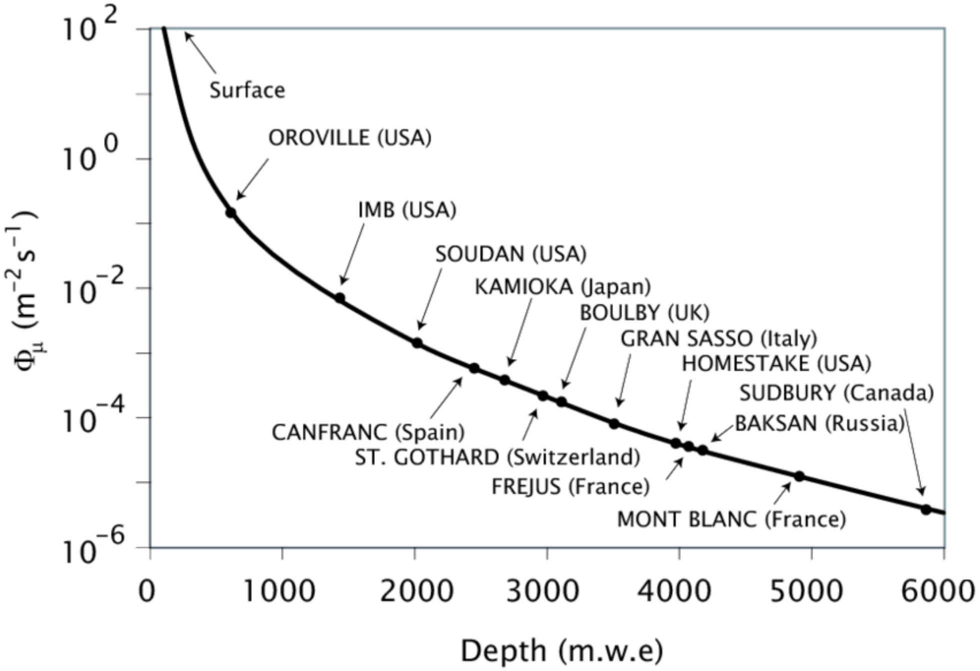
Radiochemical detection of neutrinos

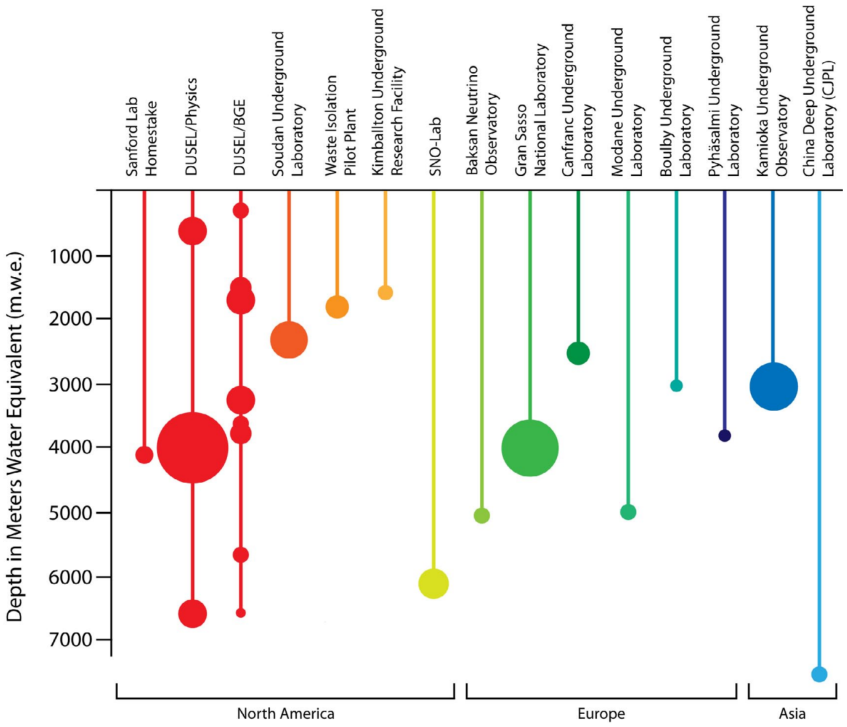
neutrino capture via Inverse Beta Decay (IBD) in a target chemical element with (A, Z). The product element (A,Z+1) is unstable with half-life $T_{1/2}$.

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$$

Typical radiochemical experiment:
*operates in a batch mode, with exposure times on the order of $2T_{1/2}$.
*typically ~10 product atoms are separated from ~10^{30} target atoms with efficiency ≥90%.
*counting techique: no neutrino direction or energy information is available
*the targets must be huge, containing many tons of material.
*requires sensitive radiochemical methods to separate few atoms of product element (Z+1) from the target Z.
*placed deep underground to minimize cosmic-ray interactions in the target that can produce protons, (p,n) reactions mimic neutrino capture.

One should go deep underground to reduce the background





Radiochemical experiments: proposals

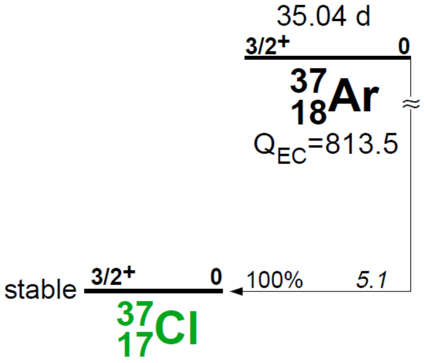
Target	Reaction	$T_{1/2}$	Threshold MeV	Status
Chlorine	$^{37}Cl \rightarrow {}^{37}Ar$	35.0 d	0.814	closed
Gallium	$^{71}Ga \rightarrow {}^{71}Ge$	11.4 d	0.233	Running (SAGE)
Iodine	$^{127}I \rightarrow {}^{127}Xe$	36 d	0.789	Prototype (Lande at al.) at Homestake; abondoned
Molybdenum	$^{98}Mo \rightarrow {}^{98}Tc$	$4 \cdot 10^6$ yr	>1.74	(Wolfsberg et al.) failed, no funding to repeat
Lithium	$^{7}Li \rightarrow {}^{7}Be$	53 d	0.862	[R&D]
Bromine	$^{81}Br \rightarrow {}^{81}Xe$	$2 \cdot 10^5$ yr	0.470	[R&D]
Tantalum	$^{205}Tl \rightarrow {}^{205}Pb$	$14 \cdot 10^6$ yr	0.054	[R&D]
Ytterbium	$^{176}Yb \rightarrow {}^{176}Lu^*$		0.301	[R&D (exLENS)]
Indium	$^{115}In \rightarrow {}^{115}Sn^*$		0.114	[R&D (LENS)]

Radiochemical detection of Solar neutrinos.

Bruno Pontecorvo, 1946:

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Q_{th}=813.5 keV

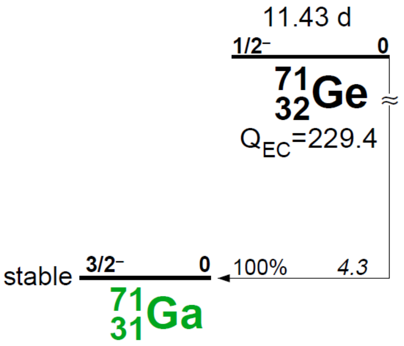


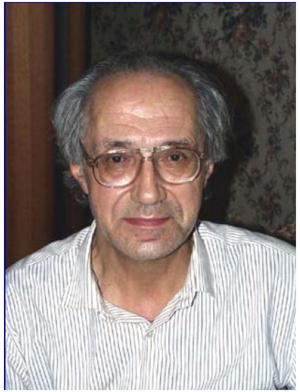
Бруно Понтекорво

V.Kuz'min, 1965

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Q_{th} =229.4 keV



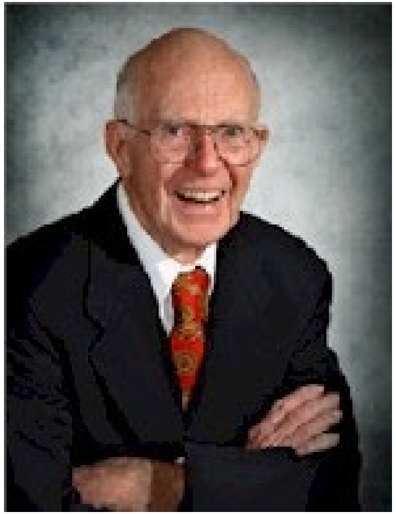


Homestake

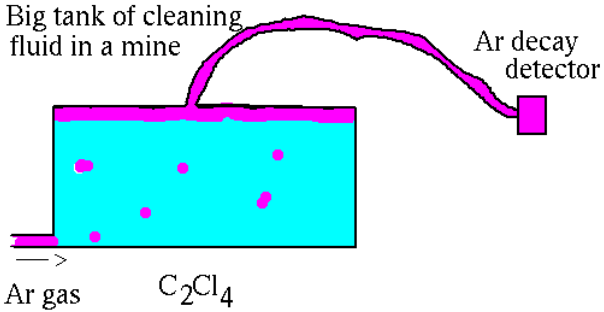
Homestake Mine: mine in South Dacota.

Tank filled with 600 tones of perchloroethylene (C_2Cl_4) at the depth of 1.5 km underground.

Detector was taking data from 1970 to 1994



Raymod Davis Jr. (1914-2006). Nobel prize in 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Pontecorvo met Davis at the first neutrino conference in Moscow in 1968 and expressed the opinion that measuring the form of the counter pulse, in addition to the amplitude, should result in a considerable decrease of the effective background in his solar experiment. The suggestion proved correct as Pontecorvo found out from Davis at the ν-72 conference in Hungary.

Homestake (aka Chlorine experiment)

2.56 ± 0.23 SNU

1/3 of the predicted by SSM → SNP

(0.336 ± 0.090) SSM

SNU=Solar Neutrino Unit, SNU= 1 event per 10^{36} target atoms in 1 second

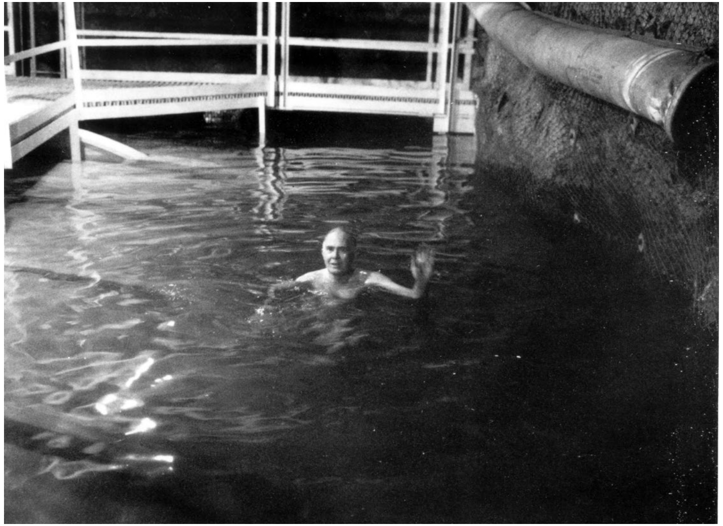
SSM – Standard Solar Model

SNP – Solar Neutrino Problem

John Norris Bahcall (1934 – 2005)

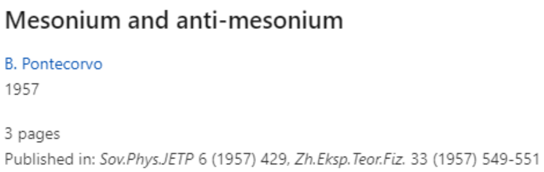
What was wrong? Was our understanding of how the sun shines incorrect? Had I made an error in calculating the rate at which solar neutrinos would be captured in Davis's tank? Was the experiment wrong? Or, did something happen to the neutrinos after they were created in the sun? Over the next twenty years, many different possibilities were examined by hundreds, and perhaps thousands, of physicists, chemists, and astronomers. Both the experiment and the theoretical calculation appeared to be correct.

John N. Bahcall



In 1971 Raymond Davis Jr. takes a dip in the water surrounding the perchloroethylene tank deep within the Homestake Mine.

One of the first ideas to explain the SNP: neutrino oscillates!



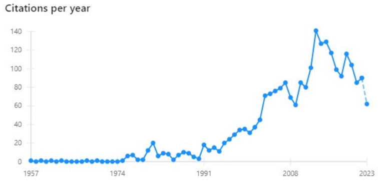
Mesonium and anti-mesonium

B. Pontecorvo

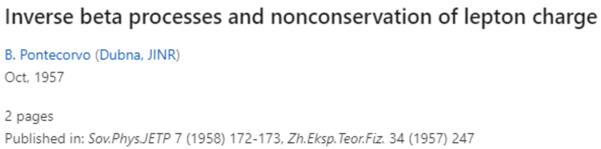
1957

3 pages

Published in: *Sov.Phys.JETP* 6 (1957) 429, *Zh.Eksp.Teor.Fiz.* 33 (1957) 549-551



muonium (μ+e−) to antimuonium (μ −e+) transitions considered. A possibility of the neutrino oscillations is mentioned.



Inverse beta processes and nonconservation of lepton charge

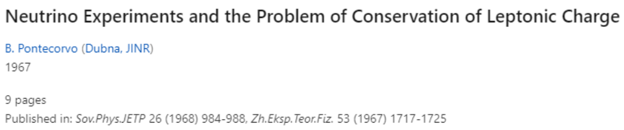
B. Pontecorvo (Dubna, JINR)

Oct, 1957

2 pages

Published in: *Sov.Phys.JETP* 7 (1958) 172-173, *Zh.Eksp.Teor.Fiz.* 34 (1957) 247

paper dedicated to neutrino oscillations



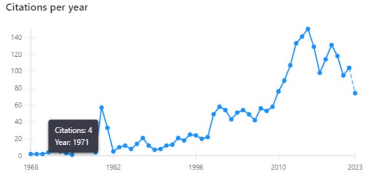
Neutrino Experiments and the Problem of Conservation of Leptonic Charge

B. Pontecorvo (Dubna, JINR)

1967

9 pages

Published in: *Sov.Phys.JETP* 26 (1968) 984-988, *Zh.Eksp.Teor.Fiz.* 53 (1967) 1717-1725



the second paper on neutrino oscillations. Flavor neutrino oscillations ($\nu_e \leftrightarrows \nu_\mu$) and also oscillations between flavor and sterile neutrinos ($\nu_{eL} \leftrightarrows \overline{\nu_{eL}}$, etc.) were considered. Solar neutrino oscillations were considered before the first results of the Davis solar neutrino experiment appeared, B. Pontecorvo anticipated “the solar neutrino problem”.

Neutrino astronomy and lepton charge

V.N. Gribov (Ioffe Phys. Tech. Inst.), B. Pontecorvo (Dubna, JINR)

Dec, 1968

4 pages

Published in: *Phys.Lett.B* 28 (1969) 493

Published: 1969

Suggested that only active left-handed neutrinos ν_e and ν_μ and and right-handed antineutrinos exist in nature (no sterile neutrinos). It was assumed that exist an interaction which does not conserve lepton numbers. The oscillations of solar neutrinos were discussed.

Gallium Experiments

A new experiment was needed to clarify the SNP. A feasible proposal was Ga-Ge experiment, also due to a lower threshold.

The main problem – the quantity of Gallium necessary to provide reasonable neutrino count was comparable with its yearly world production. In 1981 and 1985 the Gallium project was rejected in USA, NSF recommended to collaborate with Europe and USSR (SAGE = Soviet-Amercian Gallium Experiment)

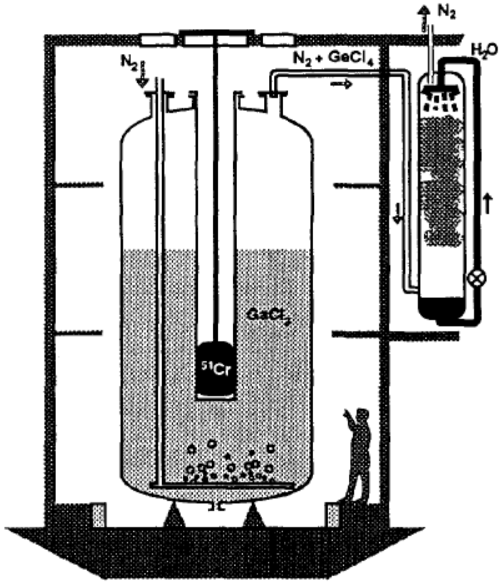
In 1984 group headed by Till Kirsten from Max Plank Institute presented a project of gallium experiment and started to form GALLEX collaboration

Till Kirsten

In USSR works were started as early as in 1975, collaboration SAGE was formed in the end of 80

Vladimir Gavrin

GALLEX (GNO) and SAGE



Liquid metallic Ga in the window of chemical reactor of SAGE experiment

Experimental hall with (chemical) reactors

SAGE at Baksan laboratory (BNO)

GaCl (metal) : 50-57 t

(an unknown fraction of metallic Gallium was stolen in “saint 90s” – quoted as systematic error on the mass in later publications.)

Gallex/GNO at LNGS

$GaCl_4$: 30 t

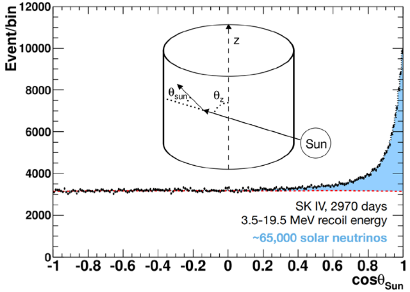
BNO

KamiokaNDE and SuperKamiokaNDE

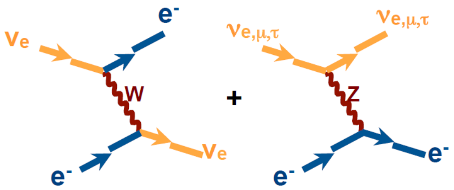
Water Cherenkov detector.

Detection reaction $\nu + e^- \rightarrow \nu + e^-$

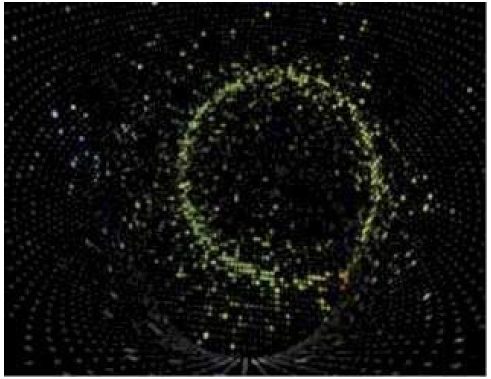
KamiokaNDE-II, 1988, Japan (1000 m depth in the Kamioka mine)



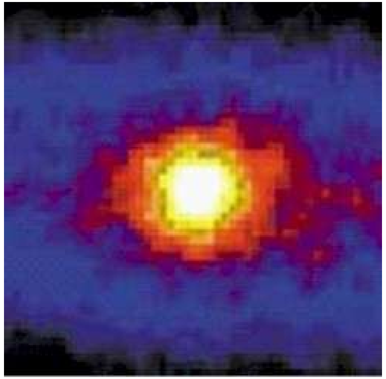
Neutrino detection:
elastic scattering off electrons



SuperKamiokande (or SuperK) — updated (scaled) version of Kamiokande-II, located 180 miles to the north from Tokyo. Japan-USA collaboration.
Construction ended in 1996.
50 ktones of higly purified water.
Equipped with 11146 PMTs



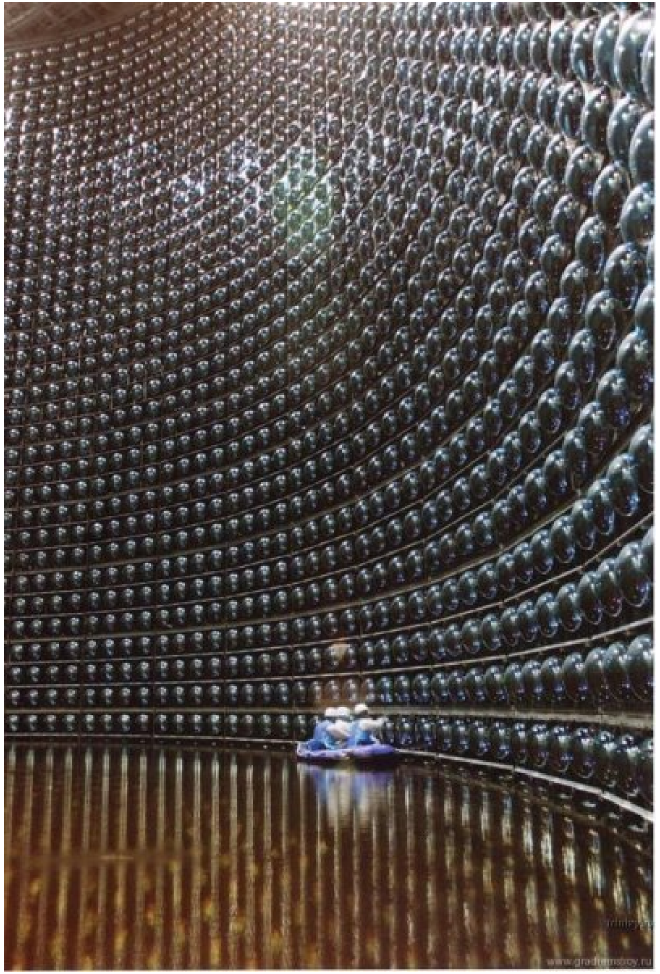
Neutrino detection in SuperKamiokande. Points – PMTs, light ring – Cherenkov light from relativistic recoil electrons.



Neutrinogram of the Sun (angle coordinates), obtained during first 500 days of the data taking by SuperK. Intensity of color corresponds to the number of detected neutrinos in corresponding direction.

Large PMTs – the eyes of the detector

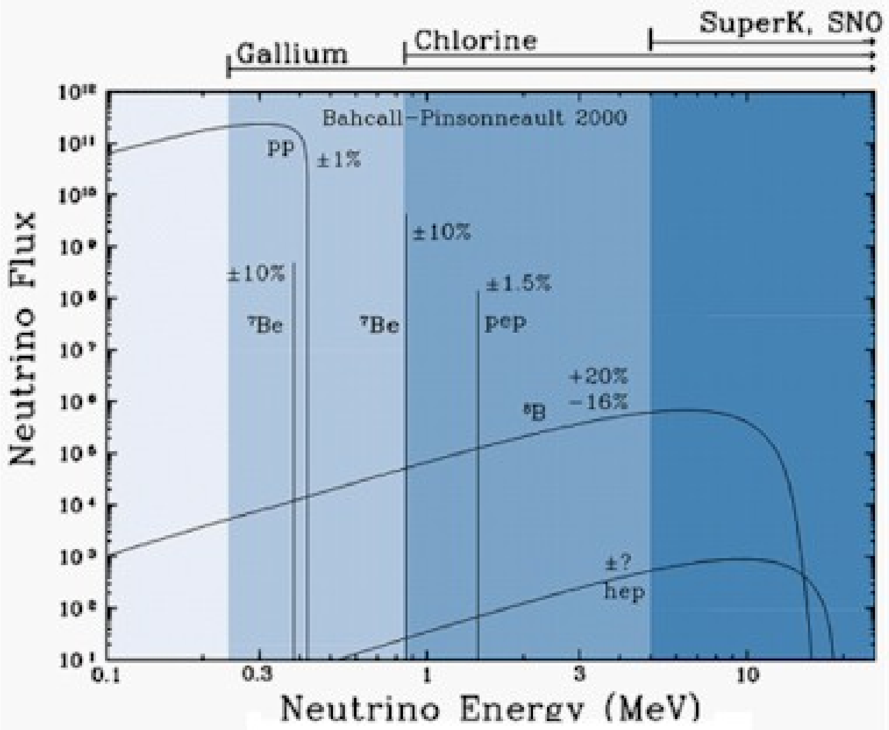
Masatoshi Koshiba (future Nobel prize winner, 2002) is happy to see new PMT with large area photocathode, specially designed by Hamamatsu photonics



KamiokaNDE and SuperKamiokaNDE

Detector		Years, exposure	FV mass	Coverage	E_{Thr} MeV	Result $[\times 10^6\ cm^{-2}s^{-1}]$
KamiokaNDE-II +III		87-90 90-95 2079 d	H_20 3 kt	20% 25%	7.0	$2.82^{+0.25}_{-0.24}\pm0.27$
SuperK (50 kt)	I	96-01 1496 d	H_20 22.5 kt	40%	5.5	$2.380\pm0.024^{+0.064}_{-0.076}$
	II	02-05 791 d		19%	7.0	$2.41\pm0.05^{+0.16}_{-0.15}$
	III	06-08 548 d	22.5 (>5.5MeV) 13.3 (<5.5MeV)	40%	4.5	2.404±0.039±0.053
	IV (T2K phase)	08-18 1664 d (2014)	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)	40%	3.5	2.308±0.020±0.04 (2016)
		2970 d				2.33±0.01±0.03
	I+II+III+IV	5805 d				2.35±0.01±0.04
	V (Gd)	2019		40%	3.5	
HyperK (0.26 Mt)		2027	0.19 Mt	40%	4.5	Project

Was the SNP solved by Ga and Water Cherenkov experiments?



Cl : pp(0%) + ^{7}Be(13%) + pep(2.7%) + CNO(2.4%) + ^{8}B(82%)
Ga: pp(55%) + ^{7}Be(28%) + pep(2.3%) + CNO(3.4%) + ^{8}B(11%)

Gallex+GNO+SAGE: 66.1 ± 3.1 SNU

½ of the expected in SSM

WCh detectors confirmed the Homestake results:
~1/3 of the expected in SSM

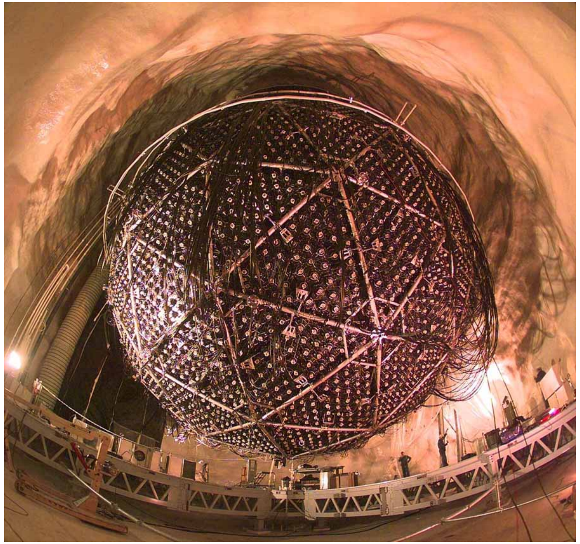
The Solar neutrino flux is suppressed (SNP-1) and deformed (SNP-2)

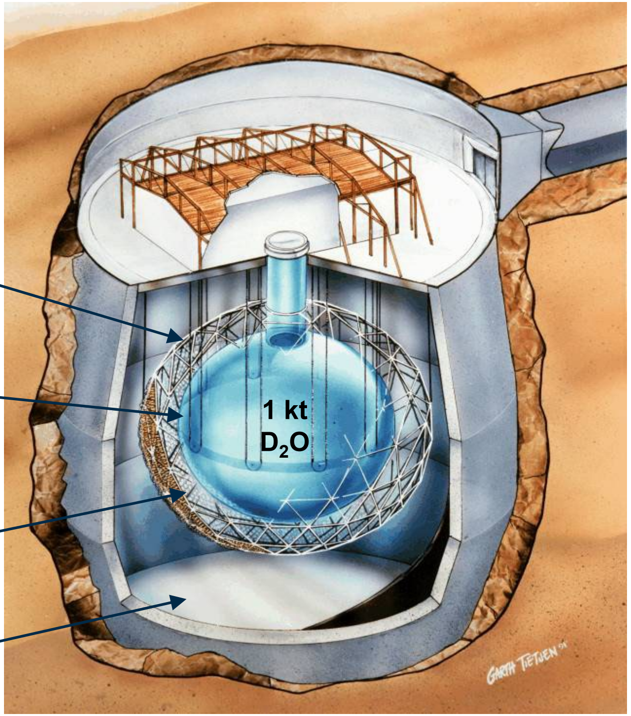
^{8}B neutrinos measured by WCh detectors

SNO (Sudbury Neutrino Observatory)

Heavy water Cherenkov detector

10 neutrino events/day





17.8m dia. PMT Support Structure
9456 20-cm PMTs
56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

2 km to surface

Physics of detection in heavy water

CC $\nu_e + d \rightarrow p + p + e^-$

- measurement of ν_e energy
- Weak directionality: $1 - 0.340 \cos\theta$

NC $\nu_x + d \rightarrow p + n + \nu_x$

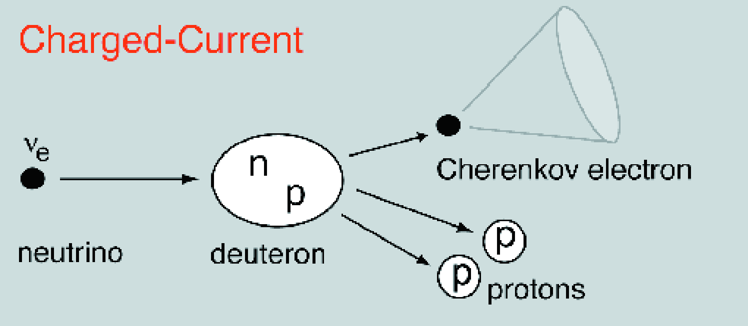
- Measurement of the total ^8B ν flux
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

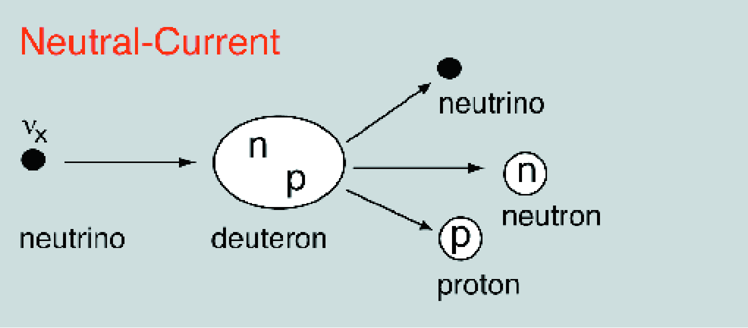
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

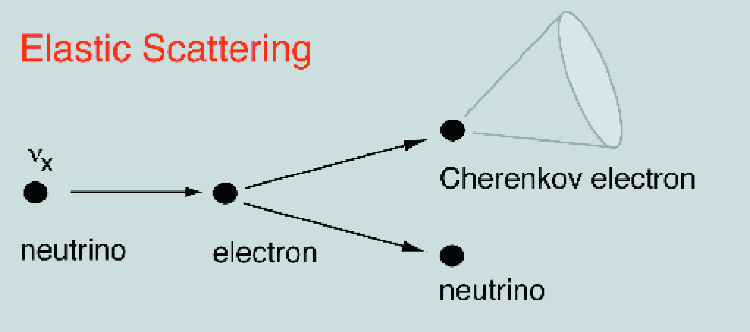
- Low statistics.

$\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$

- Strong directionality: $\theta_e \leq 18^\circ$ (T_e = 10 MeV)





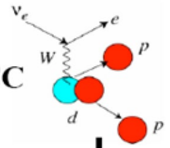


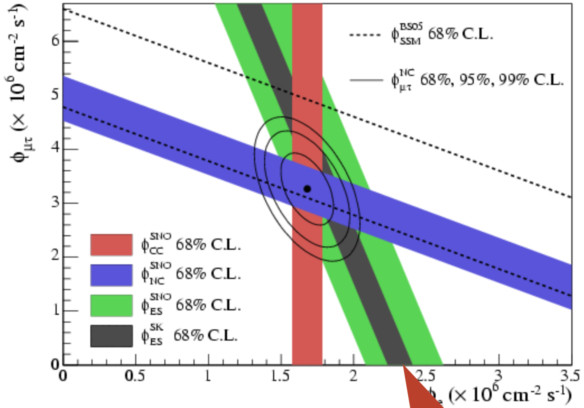
Neutrons detection in 3 phases of the SNO experiment

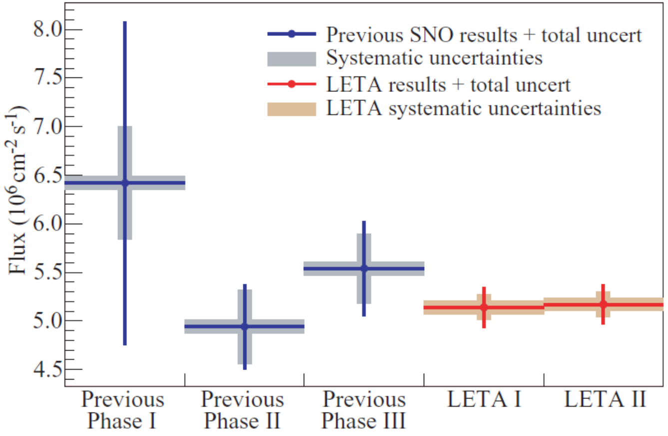
Phase	Method
I	n+d: γ(single;6.25 MeV)
II (NaCl)	n+^{35}Cl: γ(multiple;8.6 MeV)
III	800 meters of ^{3}He counters

SNO: missing neutrinos found!

CC

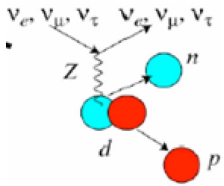




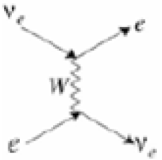


Y: Non-electron neutrino

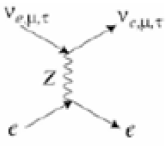
NC



X: Electron neutruno



ES



SNO: results

Phase		Target, mass	Method	Threshold [MeV]	Result [x10^6 $cm^{-2}s^{-1}$]
I	99-01 306.4 d	D_20 1006 t	$\nu_e + d \rightarrow p + p + e^-$ (CC)-1.4 MeV	5.0	$1.76\pm0.05\pm0.09$ (CC) $2.39^{+0.24}_{-0.23}$ (ES) $5.09^{+0.44}_{-0.43}$ (NC)
			$\nu_x + d \rightarrow p + n + \nu_x$ (NC)-2.22 MeV		
			$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)		
II	01-04 391d	+NaCl 2t	$^{35}Cl + n \rightarrow {}^{36}Cl$+8.6 MeV (2-4 γ)	5.5	$1.72\pm0.05\pm0.11$ (CC) $2.34\pm0.23^{+0.15}_{-0.14}$ (ES) $4.81\pm0.19^{+0.28}_{-0.27}$ (NC)
I+II	Low energy threshold analysis (LETA: 3.5 MeV)			3.5	$5.046^{+0.159}_{-0.152}{}^{+0.107}_{-0.123}$ (NC)
III	04-06	$+^3He$ counters	$^3He + n \rightarrow p + {}^3H$ + 0.76 MeV	6.0	$1.67^{+0.05}_{-0.04}{}^{+0.07}_{-0.08}$ (CC) $1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$ (ES) $5.54^{+0.33}_{-0.31}{}^{+0.36}_{-0.34}$ (NC)

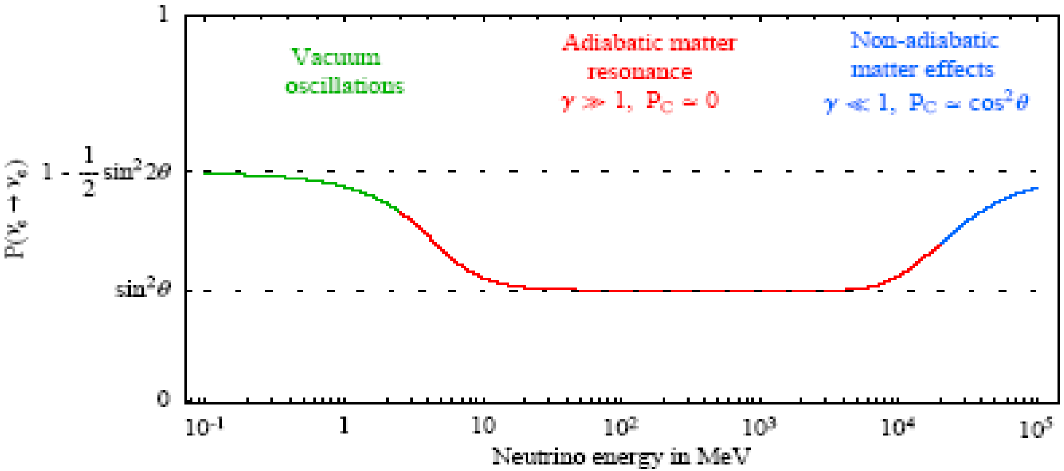
^8B flux (5.25±3.7%)x10^6 $cm^{-2}s^{-1}$

Solar Neutrino Problem: solution

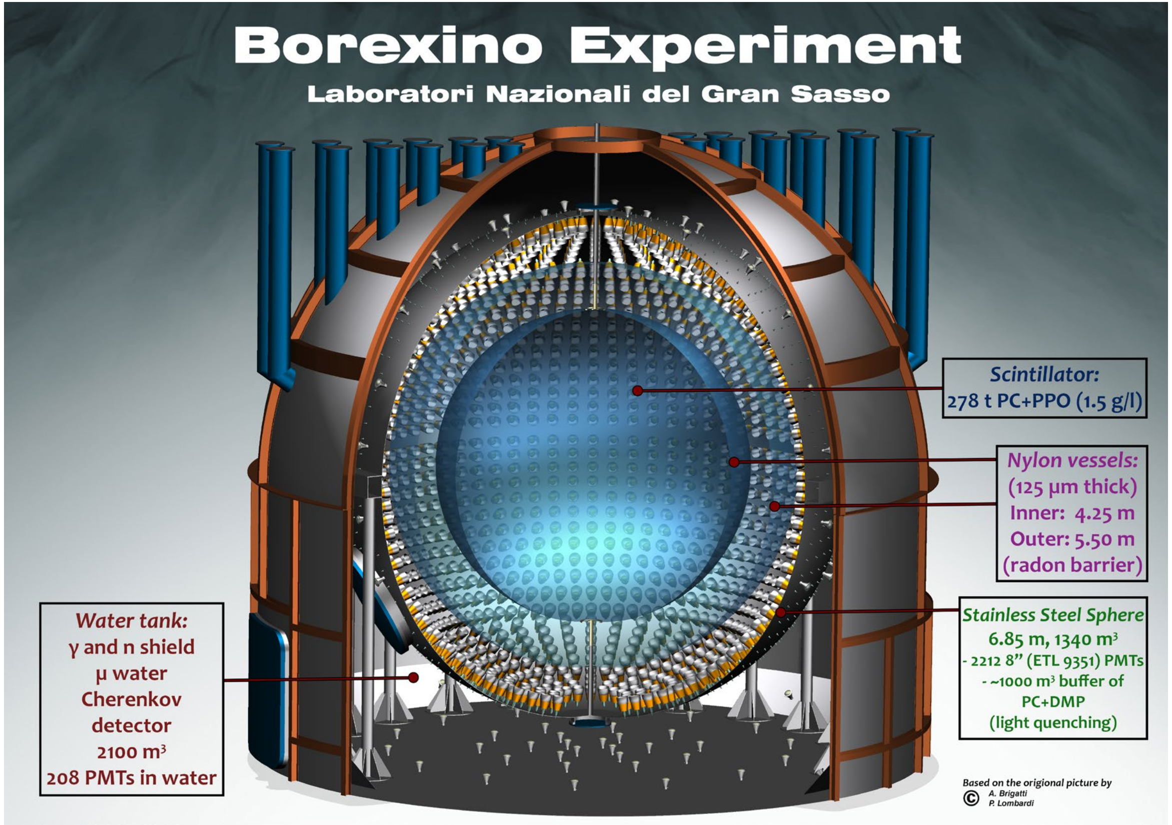
- **a large discrepancy between the predicted and measured fluxes of solar neutrinos:**
  - **Cl & KamiokaNDE ≈ 1/3 of predicted**
  - **Ga: ≈1/2 of predicted**

A lot of solutions have been proposed, now mainly of historical interest.

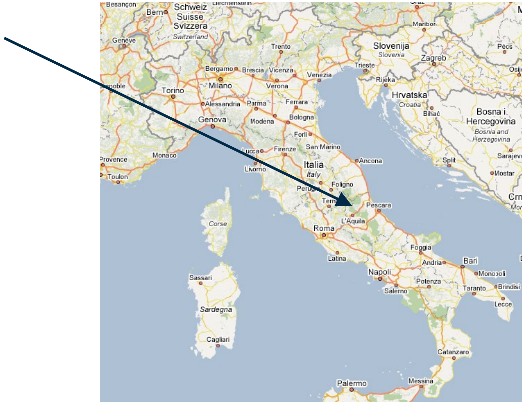
MSW/LMA has been established as the true solution of the SNP



Borexino



- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with low threshold (~200 keV)
- Outer muon detector



Why the name?

The original BOREX proposal was based on B-loaded scintillator

Boron Experiment

R.S.Raghavan, S.Pakvasa, Phys. Rev. D 37, 849 - 857 (1988)

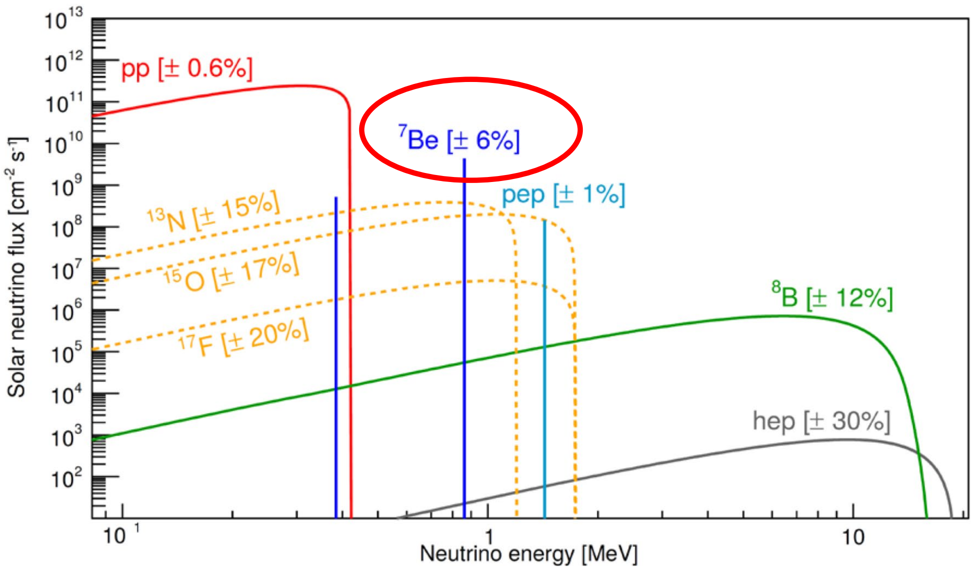
"Probing the nature of the neutrino: The boron solar-neutrino experiment"

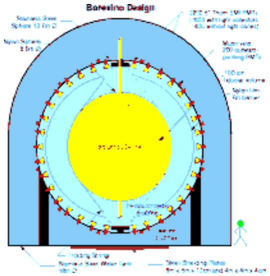
With a welter of neutrino scenarios and uncertain solar models to be unraveled, can solar-neutrino experiments really break new ground in neutrino physics? A new solar-neutrino detector BOREX, based on the nuclide ^{11}B, promises the tools for a definitive exploration of the nature of the neutrino and the structure of the Sun. Using double-mode detection by neutrino excitation of ^{11}B via the neutral-weak-current- and the charged-current-mediated inverse β decay in the same target, independent measurements of the total neutrino flux regardless of flavor and the survival of electron neutrinos in solar matter and a vacuum can be made. Standard models of the Sun, and almost every proposed nonstandard model of the neutrino, can be subjected to sharp and direct tests. The development of BOREX, based on B-loaded liquid-scintillation techniques, is currently in progress.

$\nu_x + e \longrightarrow \nu_x + e$	E>0.25 MeV
$\nu_e + {}^{11}B \longrightarrow e^- + {}^{11}C(\longrightarrow e^+ + {}^{11}B)$	E>4 MeV
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha(2.3\quad MeV) + \gamma(0.48\quad MeV)$	E>1.8 MeV
$n + {}^{1}H \rightarrow {}^{2}H + \gamma(2.2\quad MeV)$	94%
$\overline{\nu}_e + {}^{1}H \longrightarrow e^+ + n$	6%

Ramaswami (Raju) S. Raghavan

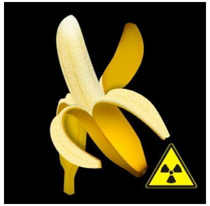
The challenge





~1 Bq

5·10^{-9}
Bq/kg



~19 Bq

banana (150 g) :
19 Bq in ^{40}K

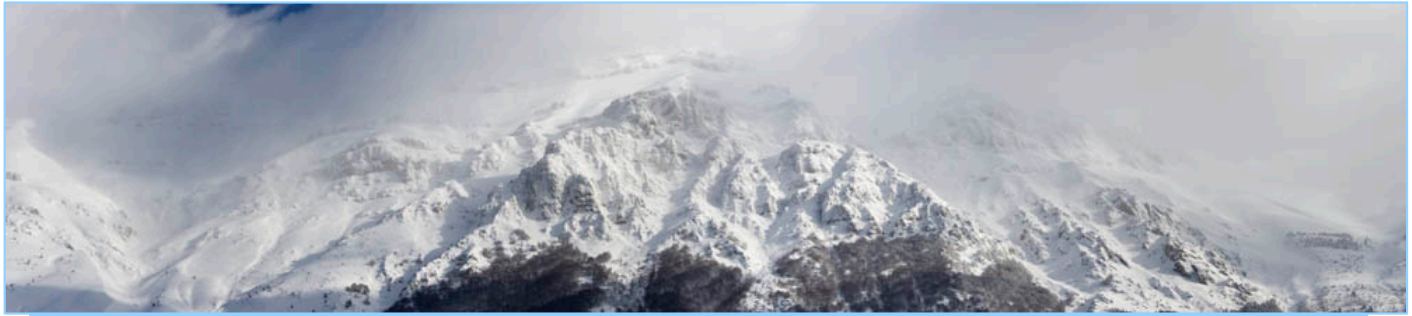
^{40}K in Borexino
<2.4x10^{-7} banana
equivalent (95% C.L.)
(36 μg)

50 events/d/100t expected (ν_e + $\nu_{\mu,\tau}$ elastic scattering on e$^-$) or 5·10^{-9} Bq/kg
(typically: drinking water ~1 Bq/kg; human body in ^{40}K: 5 kBq)

Low energy->no Cherenkov light->No directionality, no other tags-> extremely pure scintillator is needed

Concept of the graded shielding

Increasing radiopurity of materials



Neutrons and external gammas
(ultrapure water layer, 2.15 m, 2400 tones)

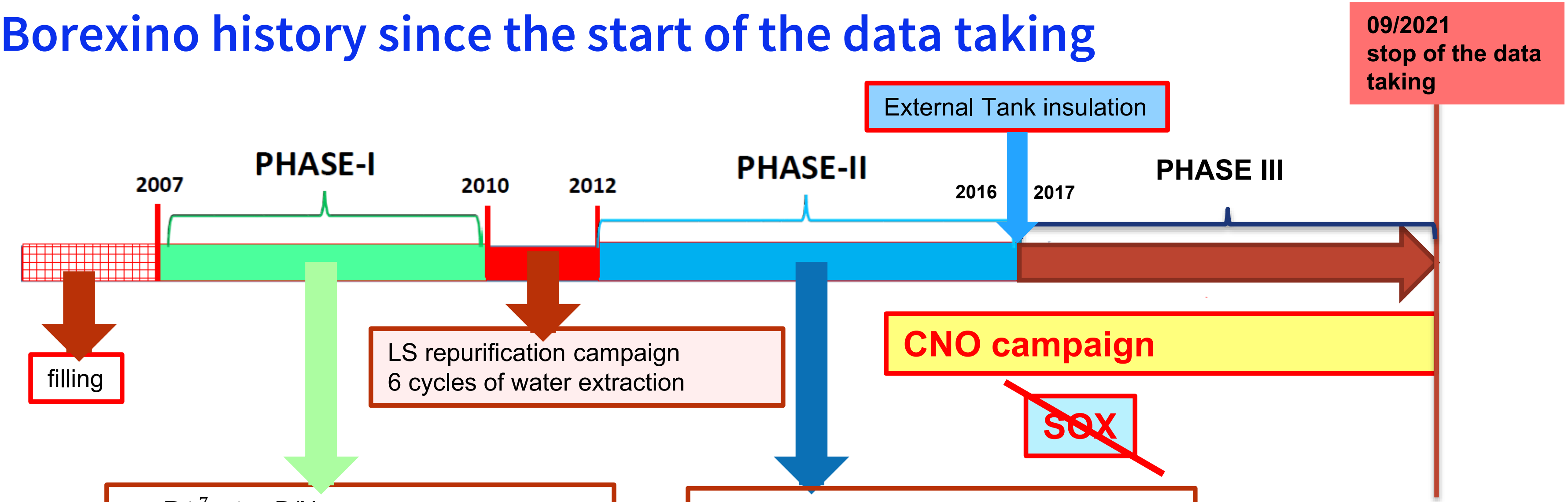
γ-s from construction materials
(PC buffer, 700 tones, 2.5 m)

γ-s from construction materials
(outer layer of scintillator, 1.25 m or 200 tones)

Software-defined active volume of scintillator
(fiducial volume, 3m, 100 tones)

Position reconstruction needed.
Possible source of systematics

Borexino history since the start of the data taking



09/2021 stop of the data taking

External Tank insulation

filling

LS repurification campaign
6 cycles of water extraction

CNO campaign

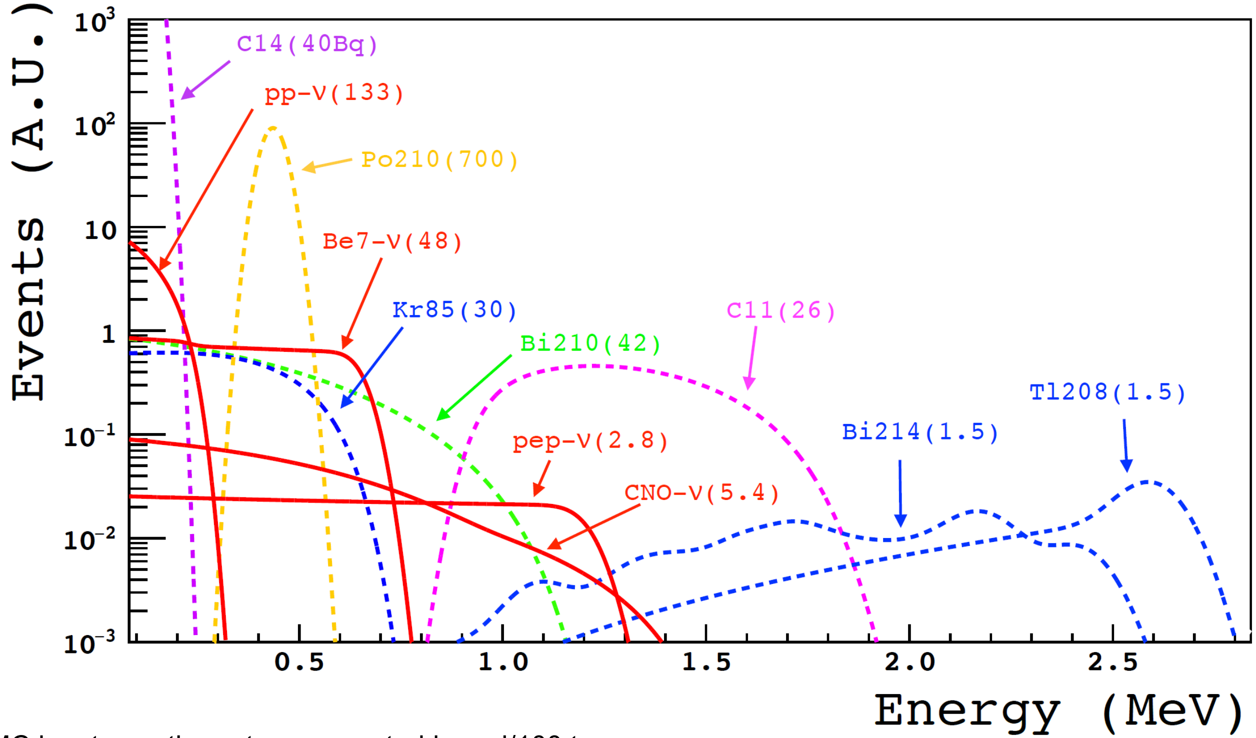
~~SOX~~

- R(^7Be) + D/N
- R(pep) – first observation
- R(^8B)– first with LS
- R(CNO) – limit

geo- ν – first robust observation
cosmic muons flux studies
rare processes

- R(pp)
- Seasonal variations of R(^{7}Be)
- Simultaneous spectroscopy of pp, ^{7}Be and pep ν
- R(^8B)–improved
- geo- ν
- ν magnetic moment
- NSI
- rare processes

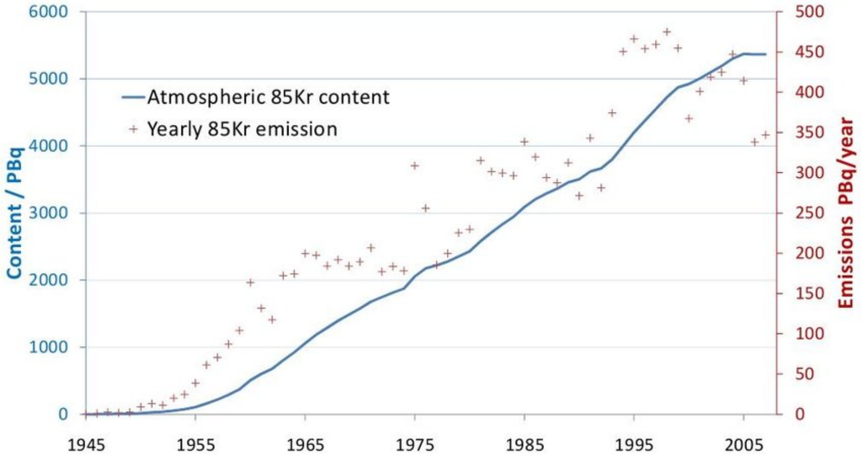
(Expected) contributions to the observed spectrum (MC)



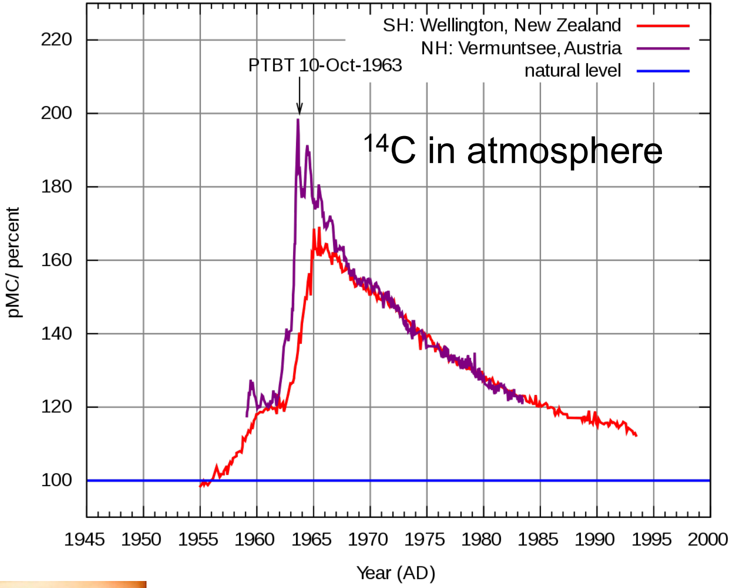
MC input counting rates are quoted in cpd/100 t

- ➢ Solar neutrino → electron recoil spectra
- ➢ Irreducible ^{14}C and other internal radioactive contaminants : α's from ^{210}Po,^{210}Bi (β) both not in secular equilibrium, ^{85}Kr (β), ^{11}C ($β^+$)
- ➢ External γ (high energy)

^{14}C and ^{85}Kr



Atmospheric 85Kr content
Yearly 85Kr emission
Content / PBq
Emissions PBq/year
6000
5000
4000
3000
2000
1000
0
500
450
400
350
300
250
200
150
100
50
0
1945
1955
1965
1975
1985
1995
2005

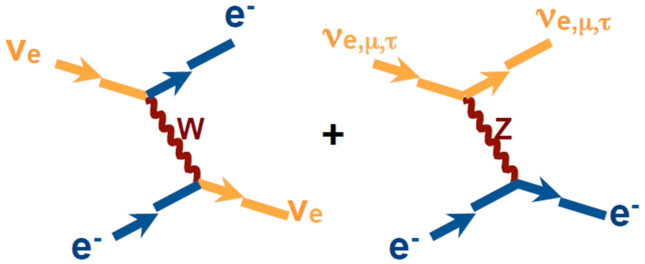


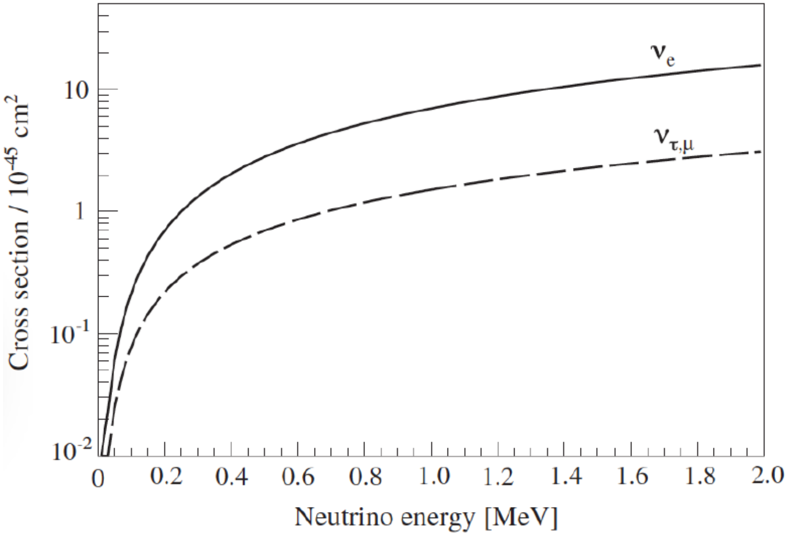
SH: Wellington, New Zealand
NH: Vermuntsee, Austria
natural level
PTBT 10-Oct-1963
14C in atmosphere
pMC/ percent
220
200
180
160
140
120
100
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year (AD)

Detection reactions

Both electron and non-electron flavours are detected, $\sigma(\upsilon_e) \approx 6\ \sigma(\upsilon_{\mu,\tau})$.

Neutrino detection:
elastic scattering off electrons





Electron recoil spectra

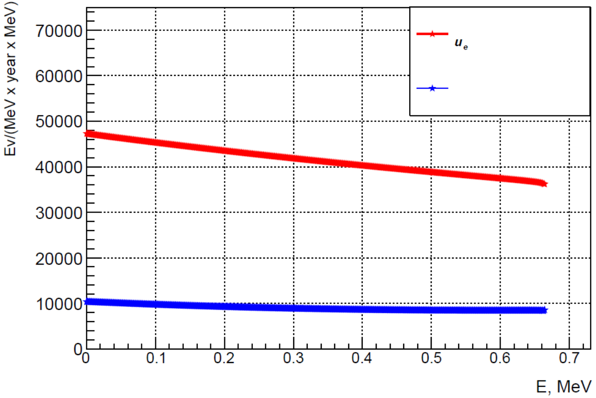
- Detected signal contains a mixure of both contributions :

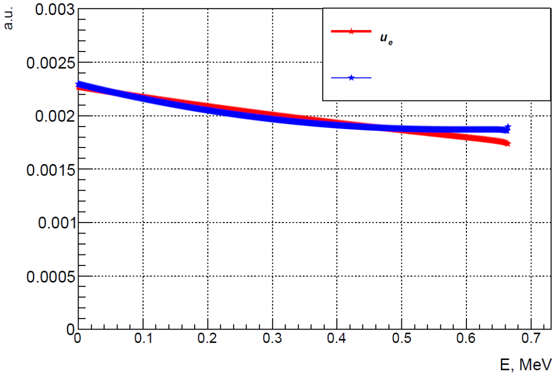
$$\boldsymbol{R(E_\nu,T) = P_{ee}(E_\nu)\varphi_\nu(E_\nu)\frac{d\sigma_e(E_\nu,T)}{dT} + (1 - P_{ee}(E_\nu))\varphi_\nu(E_\nu)\frac{d\sigma_{\mu,\tau}(E_\nu,T)}{dT}}$$

- Elastic scattering cross section for monoenergetic ν has “step-like” form (quasi-Compton) with

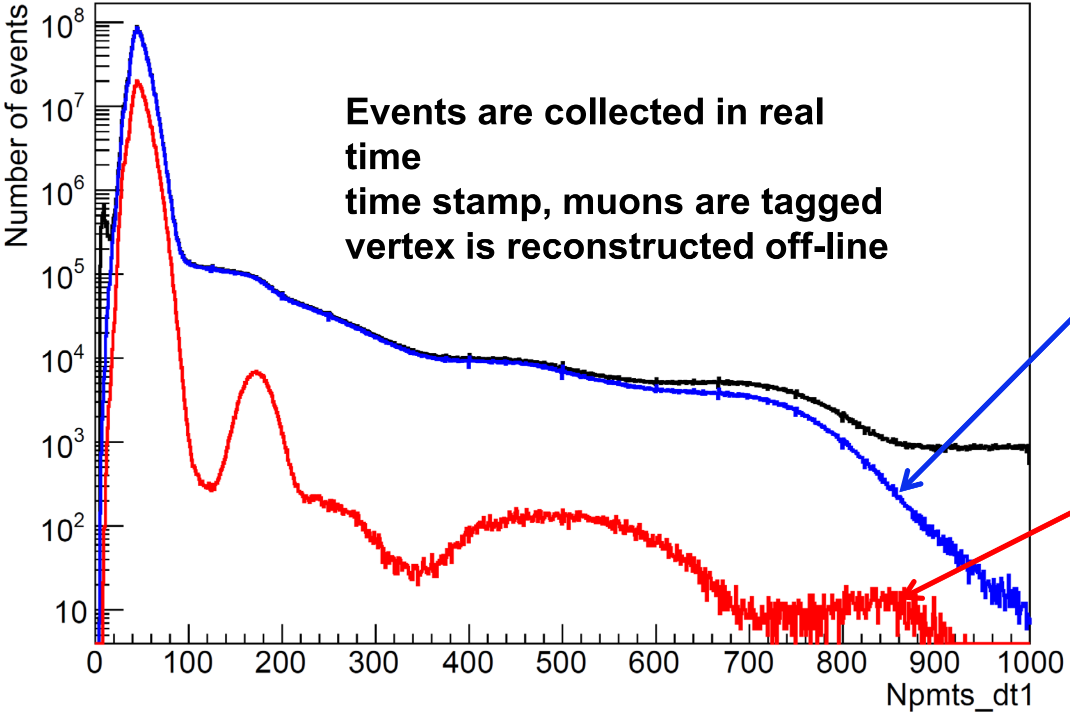
$$T_{max} = \frac{E_\nu}{1+\frac{m_e}{2E_\nu}}$$

Example for ^{7}Be neutrinos (0.862 MeV):





Data selection for spectral aalysis



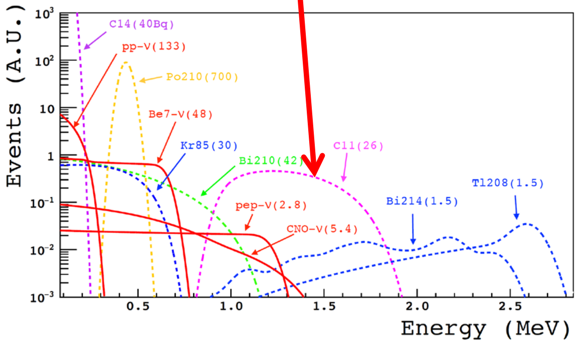
Events are collected in real time
time stamp, muons are tagged
vertex is reconstructed off-line

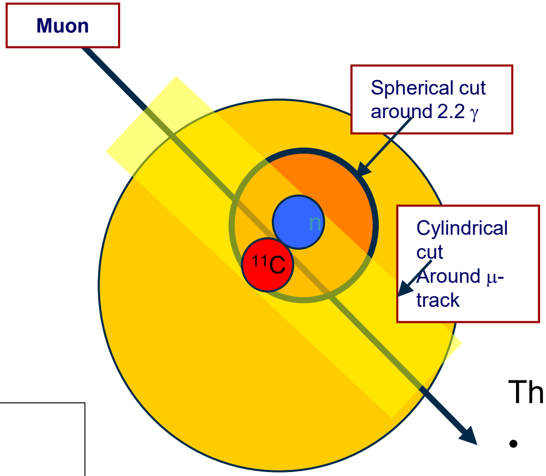
Muon cuts: muon induced events are removed

FV cut: Events in the outermost part of the scintillator volume are removed

Three-fold Coincidence technique (TFC) for ^{11}C tagging

^{11}C is here





^{11}C production in muon interactions is accompanied by neutron:

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

~30 min: $^{11}B + e^+ + \nu_e$

+p, ~250 us: d+γ(2.2 MeV)

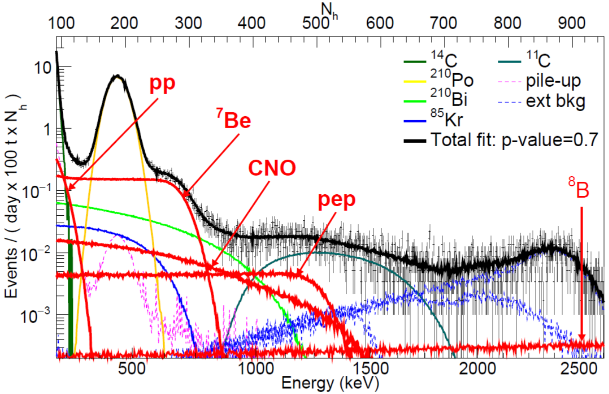
The likelihood for ^{11}C tagging among selected events:

- distance in space and time from the μ-track;
- distance from the neutron;
- neutron multiplicity;
- muon dE/dx and number of muon clusters in an event

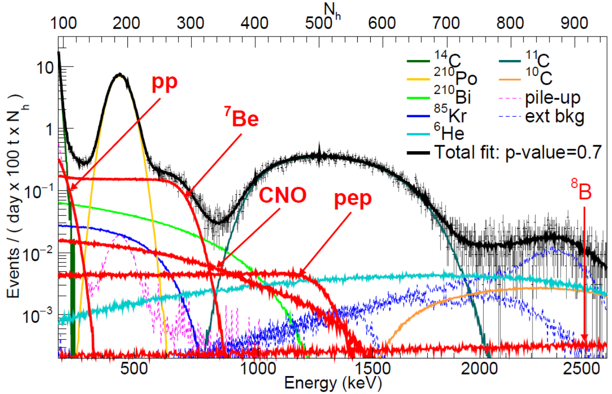
The TFC algorithm has (92±4)% ^{11}C-tagging efficiency, while preserving (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum.

Multivariate fit

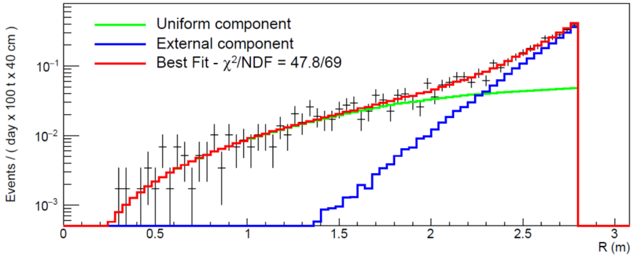
$L(^{11}C_{sub})$ x



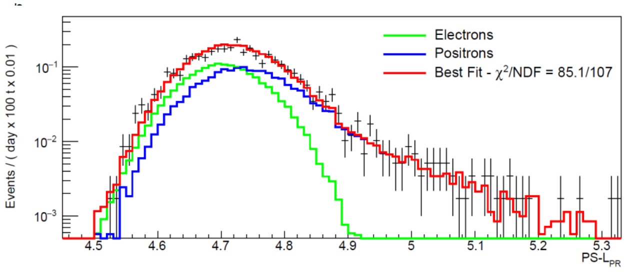
$L(^{11}C_{tag})$ x



Using TFC two complementary spectra are obtained: depleted (left) and enriched (right) in 11C



L(Rad) x

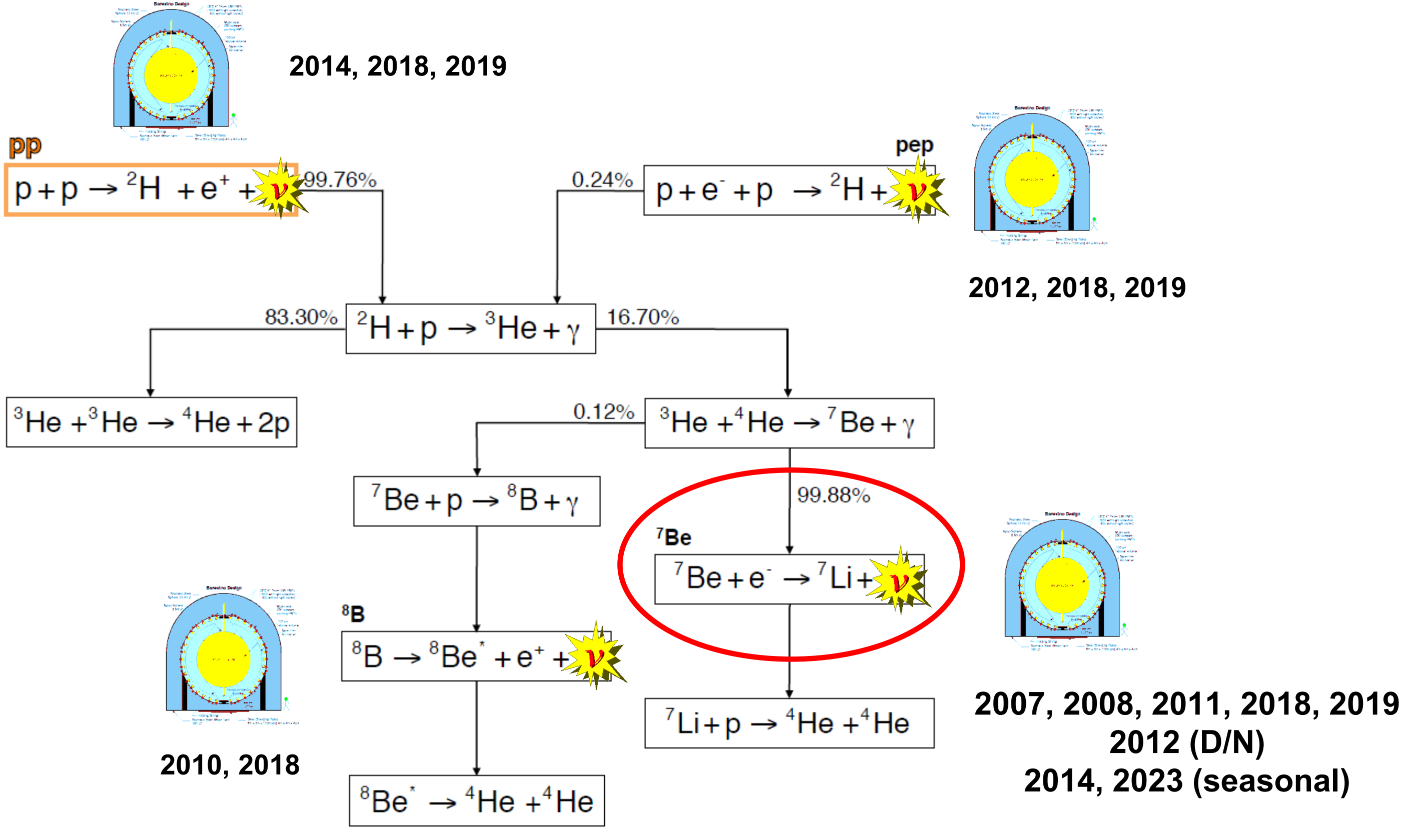


L(PS)

Radial distribution of events (left) and pulse-shape estimator (e-/e+) are fit simultaneously

pp-chain (99%)

neutrino fluxes brings snap-shot of the nuclear reactions in the Sun.



2014, 2018, 2019

pp

$p + p \rightarrow {}^{2}H + e^{+} + \nu$

99.76%

0.24%

pep

$p + e^{-} + p \rightarrow {}^{2}H + \nu$

2012, 2018, 2019

83.30%

$^{2}H + p \rightarrow {}^{3}He + \gamma$

16.70%

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

0.12%

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

99.88%

^{7}Be

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

^{8}B

$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$

$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

$^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$

2010, 2018

2007, 2008, 2011, 2018, 2019
2012 (D/N)
2014, 2023 (seasonal)

2014+ → Phase II data used

pp-chain solar ν : results

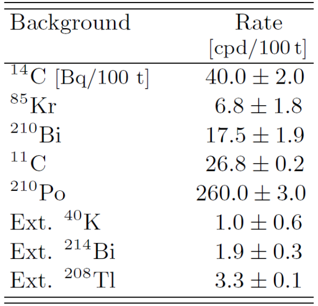
Nature 562 (2018) 505;
Physical Review D 100, 082004 (2019);
Physical Review D 101, 062001 (2020)

flux	**Borexino**	**B16(GS98) : HZ**	**B16(AGSS09) : LZ**
pp	$6.1(1.00\pm0.116)\times10^{10}$	$5.98(1.0\pm0.006)\times10^{10}$	$6.03(1.0\pm0.005)\times10^{10}$
^{7}Be	$4.99(1.00\pm0.033)\times10^{9}$	$4.93(1.00\pm0.06)\times10^{9}$	$4.50(1.00\pm0.06)\times10^{9}$
pep (HZ)	$1.27(1.00\pm0.177)\times10^{8}$	$1.44(1.00\pm0.009)\times10^{8}$	---
pep (LZ)	$1.39(1.00\pm0.166)\times10^{8}$	---	$1.46(1.00\pm0.009)\times10^{8}$
^{8}B	$5.68(1\pm0.08)\times10^{6}$	$5.46(1\pm0.12)\times10^{6}$	$4.50(1\pm0.12)\times10^{6}$

results are quoted in units of cm^{-2}s^{-1}

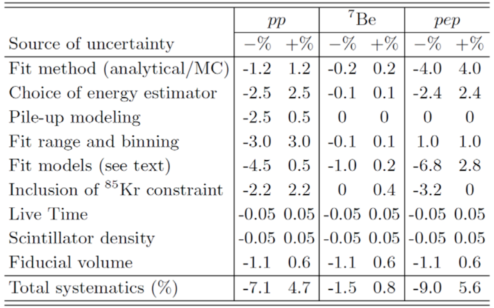
The results are obtained fixing the CNO flux at the SSM values (HM/LM accounted for as systematics)

Backgrounds



Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

Systematics



	pp		^{7}Be		*pep*	
Source of uncertainty	−%	+%	−%	+%	−%	+%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6

The solar metallicity puzzle

- **Solar metallicity = chemical composition of heavy elements. “Metals” in astrophysics are all elements with Z>2**
- **Metallicity :**
    - **1)from spectroscopic measurement of the photosphere;**
    - **2)from studies of meteorites;**
- **Metallicity is an input of the Standard Solar Models**
- **Metallicity influences the outputs of SSM (opacity -> Temperature)**

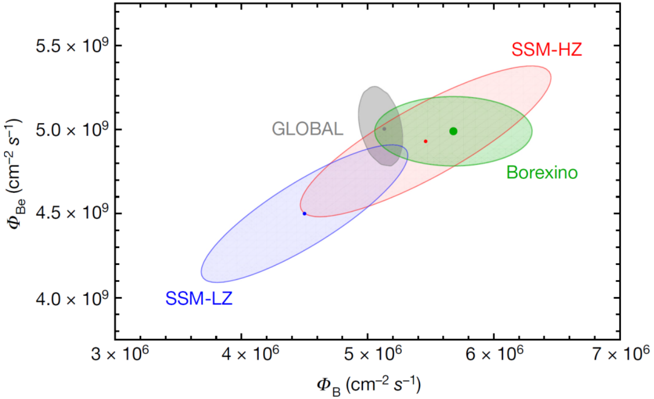
In the early 2000s, the solar composition was revised downwards by about 30%, a result created a problem – solar models constructed with the older metallicities matched the structure of the Sun, the models with the newer metallicities are extremely discrepant.

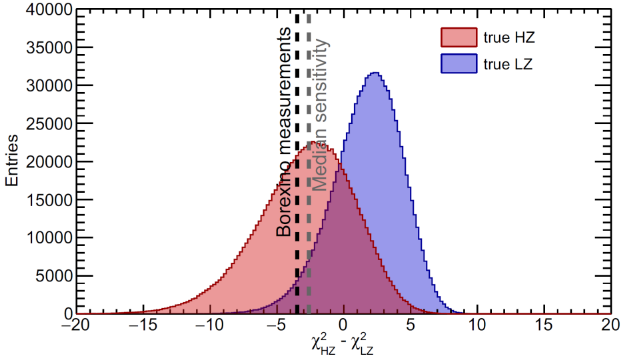
The structure of the Sun can be determined in a model-independent manner by analyzing the frequencies with which the Sun oscillates (helioseismology). All such analyses have shown that the lower abundances produce models that are discrepant.

HZ/LZ SSM predictions

FLUX	Dependence on T: (T^X), X	SSM/HZ	SSM/LZ	(HZ-LZ)/HZ
pp (10^{10} $cm^{-2}s^{-1}$)	-0.9	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} $cm^{-2}s^{-1}$)	-1.4	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} $cm^{-2}s^{-1}$)	11	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} $cm^{-2}s^{-1}$)	24	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} $cm^{-2}s^{-1}$)	18	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} $cm^{-2}s^{-1}$)	20	2.05(1±0.17)	1.44(1±0.16)	29.7%

Solar metallicity puzzle





Global fit to all solar + Kamland data (including the new ⁷Be result from BX)

$$f_{\mathrm{Be}} = \frac{\Phi(\mathrm{Be})}{\Phi(\mathrm{Be})_{\mathrm{HZ}}} = 1.01 \pm 0.03$$

$$f_B = \frac{\Phi(\mathrm{B})}{\Phi(\mathrm{B})_{\mathrm{HZ}}} = 0.93 \pm 0.02$$

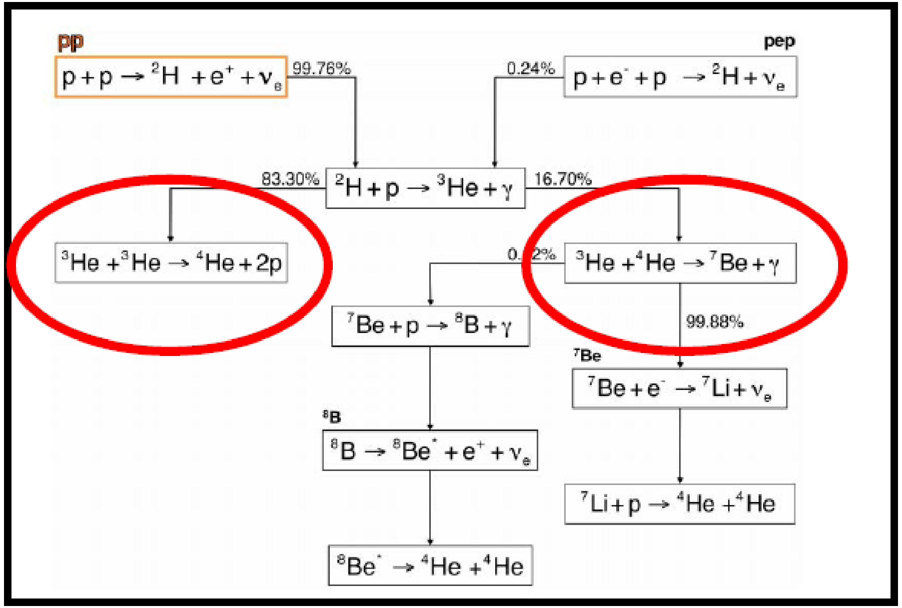
Global analysis performed over BX+SNO+SK+KL data, assuming SSM solar-ν fluxes from N. Vinyoles et al., Astrophys. Journal 835:202 (2017) and neutrino oscillation parameters from I. Esteban et al., JHEP 01 (2017).

- **a hint towards the HZ :**

Assuming HZ to be true, BX data disfavour LZ at 96.6% C.L. (**1.8σ**)
(slightly stronger than the the median sensitivity of 94.2% C.L.).

- p-value (HZ) = 0.87
- p-value (LZ) = 0.11
- **theoretical errors of the SSM are dominating**

pp-chain termination relative intensity



Assuming local equilibrium of ^{2}H and ^{3}He

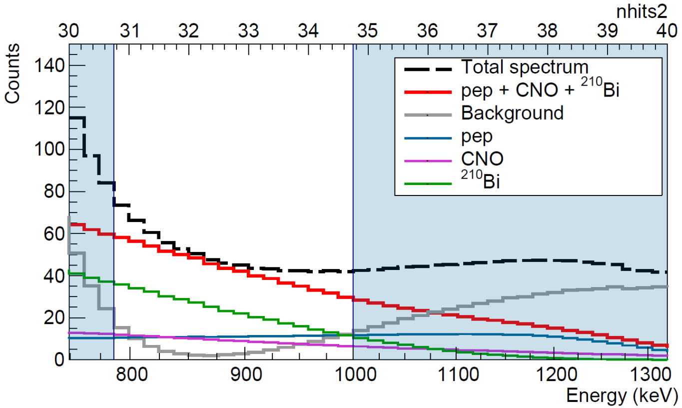
$$R \equiv \frac{<{}^3\mathrm{He} + {}^4\mathrm{He}>}{<{}^3\mathrm{He} + {}^3\mathrm{He}>} = \frac{2\phi({}^7\mathrm{Be})}{\phi(\mathrm{pp}) - \phi({}^7\mathrm{Be})}$$

R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

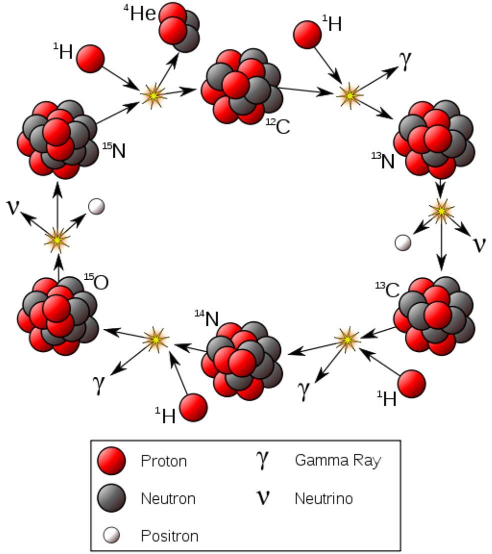
From the pp and ^{7}Be fluxes measurement

$R(BRX)=0.178^{+0.027}_{-0.023}$

Key to the Solar metallicity : CNO flux



Expected spectrum assuming $\nu(CNO)$ HZ flux and other rates from last solar analysis



Predictions: HZ ~5 cpd/100 t
LZ ~3 cpd/100 t

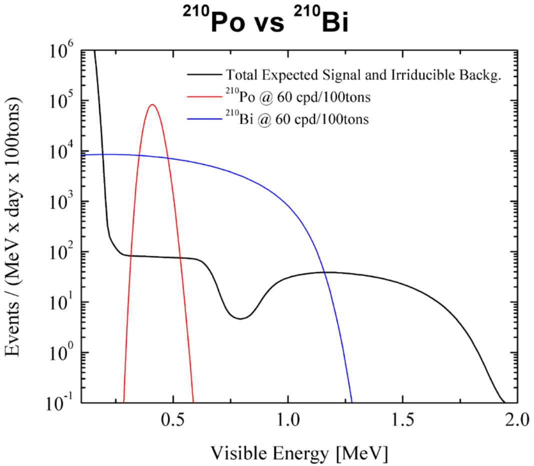
Main background from ^{210}Bi :
~20 cpd/100 t

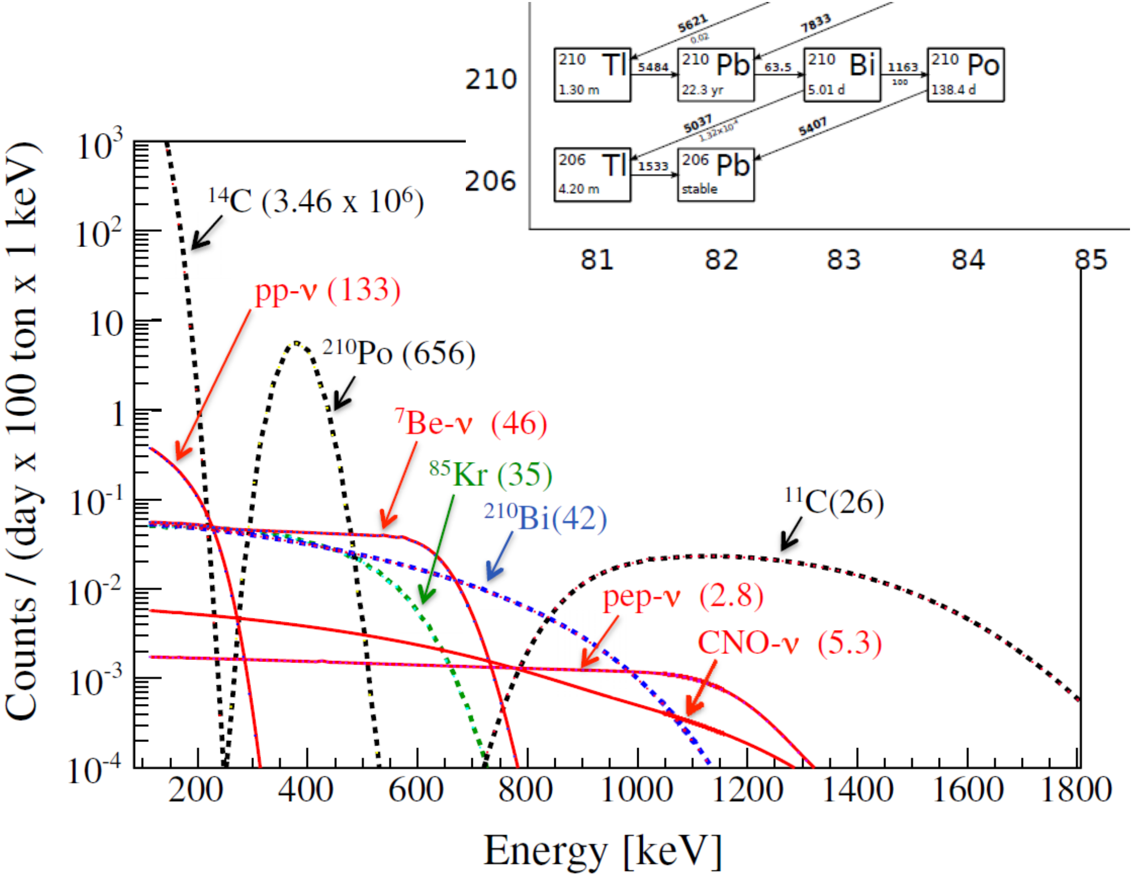
If we will be able to extract ^{210}Bi with few counts precision, we will be able to constraint it in the spectral fit and extract the CNO flux.

Another background in the region of sensitivity is pep-neutrino flux. Can be constrained through pp/pep ratio, using theoretical prediction for pp (luminosity constraint) or pp measured value.

CNO neutrinos

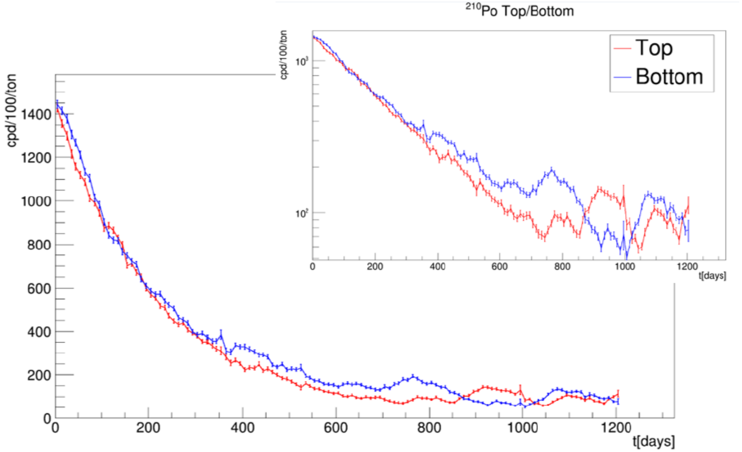
^{210}Bi and CNO:
similar spectral shapes
close rates

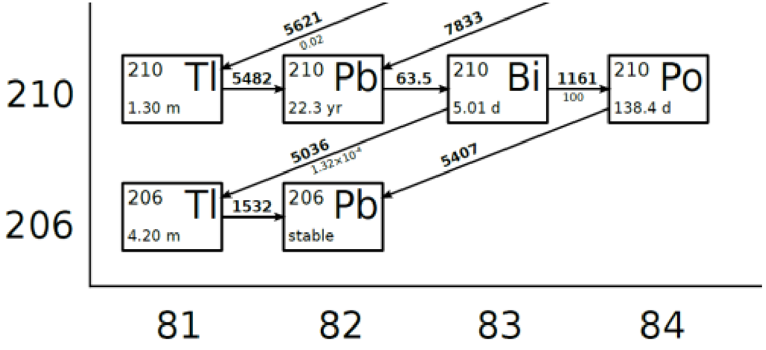




Strategy towards CNO measurement

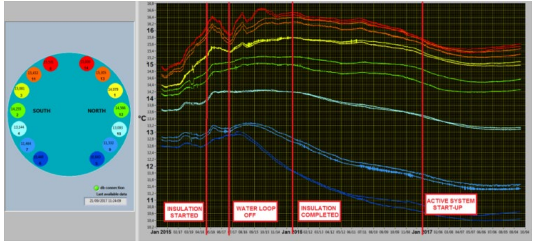
- Main route: using ^{210}Bi-^{210}Po evolution in time to measure “support term” for ^{210}Po (secular equilibrium in ^{210}Pb sub-chain)
- Option: further purification of the LS by water extraction to reduce ^{210}Bi

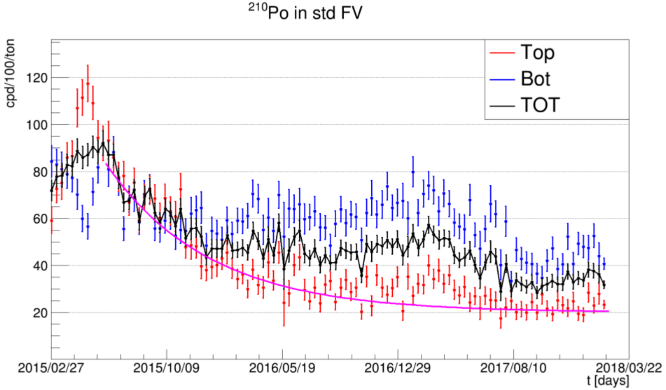


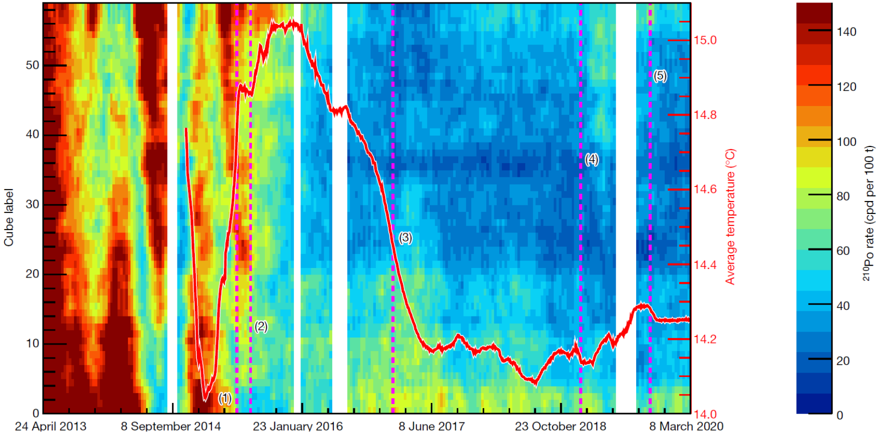


Instabilities observed in the evolution in time of the ^{210}Po (making impossible precision evaluation of the ^{210}Bi) were found to be the result of the temperature instabilities of the surrounding

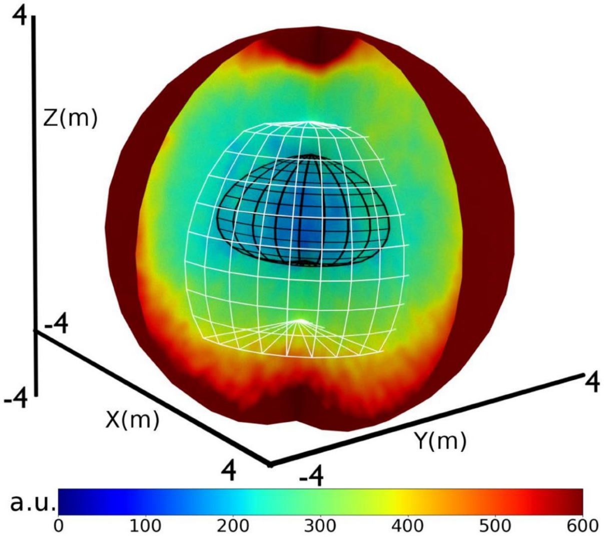
Hardware solution for thermal stabilization : thermal insulation





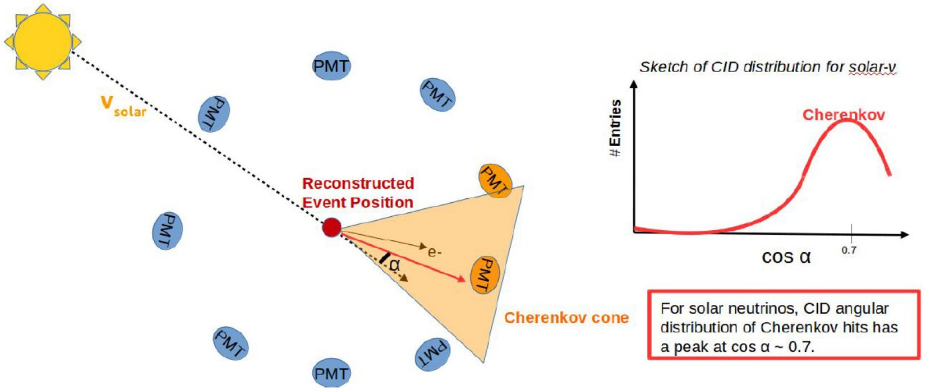


CNO neutrino flux measured



The low Po field was identified and the CNO measurements was performed at 5 σ level
Nature 587 (2020)578 ; PRL 129 (2022)252701

CID angular distribution for solar neutrinos



For solar neutrinos, CID angular distribution of Cherenkov hits has a peak at cos α ~ 0.7.

Correlation with the Sun Direction (CID):

Final Borexino measurement of CNO neutrinos (>7σ):

Accepted for pub on PRD-arXiV 2307.14636

Solar ν : all results by Borexino

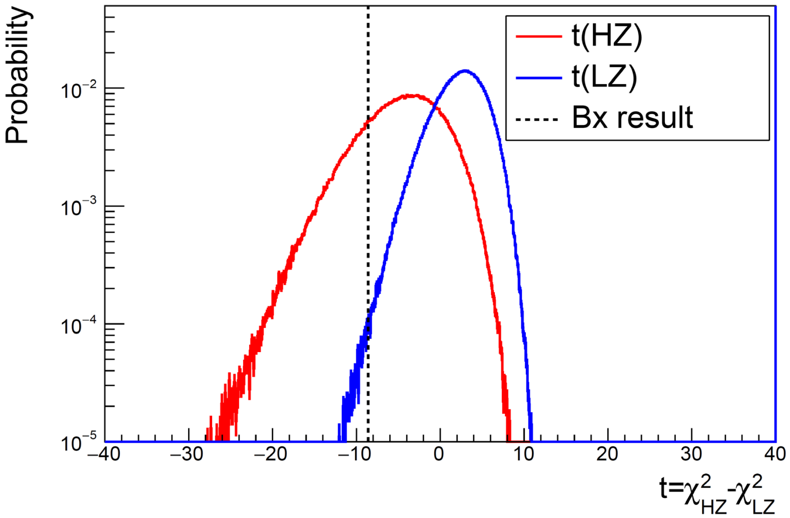
flux	Borexino	B16(GS98) : HZ	B16(AGSS09) : LZ
pp	$6.1(1.00\pm0.116)\times10^{10}$	$5.98(1.0\pm0.006)\times10^{10}$	$6.03(1.0\pm0.005)\times10^{10}$
^{7}Be	$4.99(1.00\pm0.033)\times10^{9}$	$4.93(1.00\pm0.06)\times10^{9}$	$4.50(1.00\pm0.06)\times10^{9}$
pep (HZ)	$1.27(1.00\pm0.177)\times10^{8}$	$1.44(1.00\pm0.009)\times10^{8}$	---
pep (LZ)	$1.39(1.00\pm0.166)\times10^{8}$	---	$1.46(1.00\pm0.009)\times10^{8}$
^{8}B	$5.68(1\pm0.08)\times10^{6}$	$5.46(1\pm0.12)\times10^{6}$	$4.50(1\pm0.12)\times10^{6}$
CNO	$6.7(1.00^{+0.19}_{-0.12})\times10^{8}$	$4.88(1.00\pm0.11)\times10^{8}$	$3.51(1.00\pm0.10)\times10^{8}$

results are quoted in units of $cm^{-2}s^{-1}$

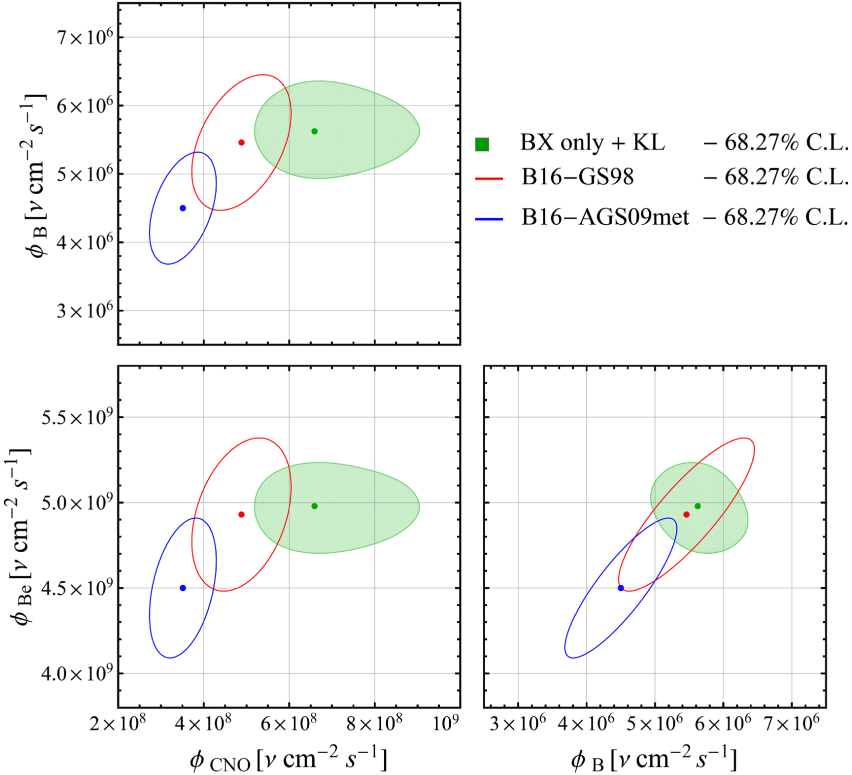
CNO cycle is here !
(C.L. > 7σ)

- CNO is the most important process of energy burning in the universe;
- Its experimental confirmation is a milestone for experimental astrophysics;

Solar metallicity puzzle after the CNO measurement



Assuming SSM-HZ, Borexino results on ^{7}Be, ^{8}B and CNO neutrinos disfavours SSM-LZ with a p-value of 9.1×10^{-4}(~ 3.1σ)



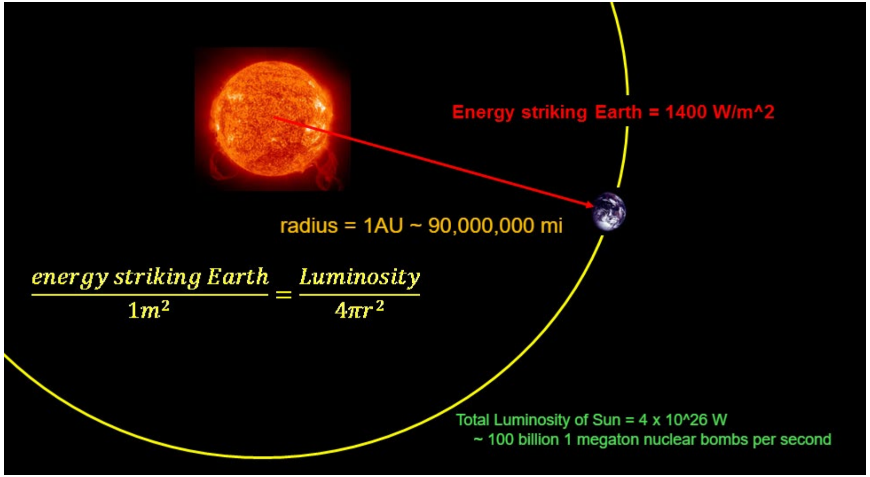
Implications: Solar Luminosity

Borexino data

$$L = (3.89^{+0.35}_{-0.42}) \times 10^{33}\ \mathrm{erg\ s^{-1}}$$

Photon luminosity

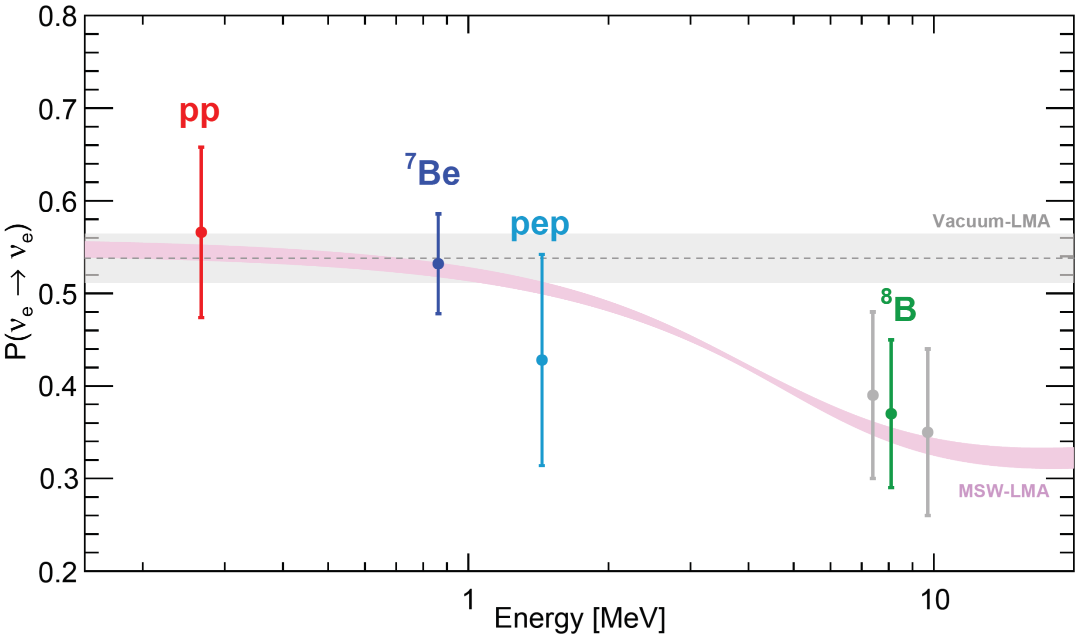
$$L = (3.846 \pm 0.015) \times 10^{33}\ \mathrm{erg\ s^{-1}}$$



This confirms the nuclear origin of the solar power;

•It proves that the Sun has been in thermodynamic equilibrium at least over last 10^5 years (the time required for radiation to diffuse from the center to the surface of the Sun)

Solar Electron Neutrino Survival Probability



MSW errors (1σ) are shown by rose band

Total error on P_{ee}:

- **for pp and pep neutrinos, contribution of experimental errors dominates (easy to predict, difficult to measure)**
- **for ^{7}Be and ^{8}B theoretical predictions of the Solar model are worse than measurements**

Assuming HZ-SSM fluxes we get:

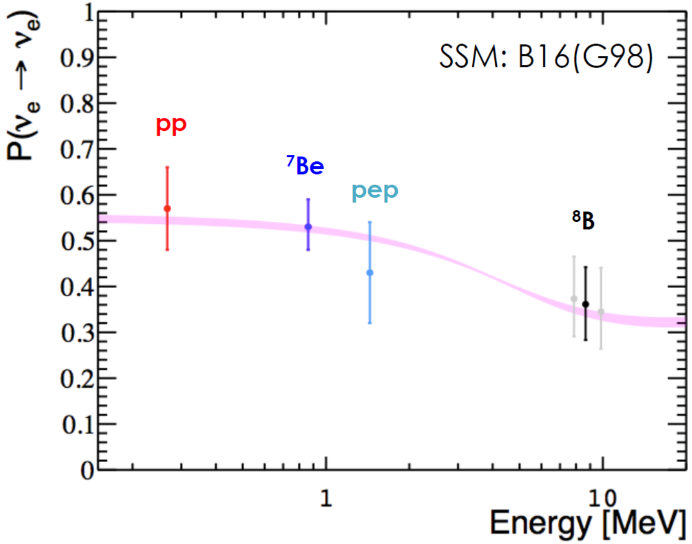
$P_{ee}(pp) = 0.57\pm0.09$
$P_{ee}(^7Be) = 0.53\pm0.05$
$P_{ee}(pep) = 0.43\pm0.11$
$P_{ee}(^8B) = 0.37\pm0.08$

Data disfavour vacuum-LMA hypothesis at 98.2% C.L.

(i.e., neutrino do not oscillate but undergo MSW transition)

MSW/LMA : electron neutrino survival probabilities

High metallicity SSM

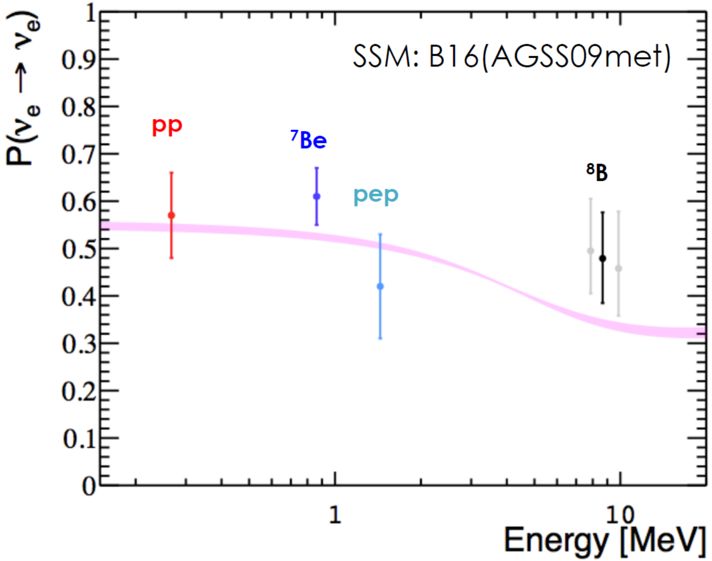


p-values:

Bx only: 0.998

All exp: 0.956

Low metallicity SSM

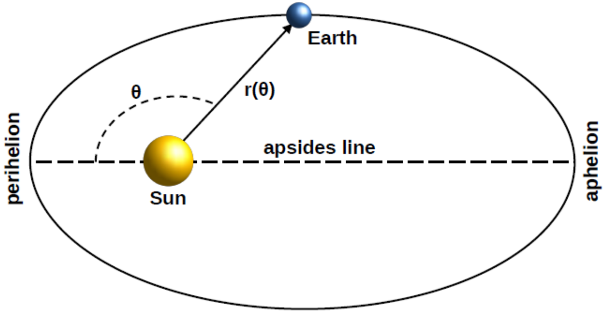


p-values:

Bx only: 0.362

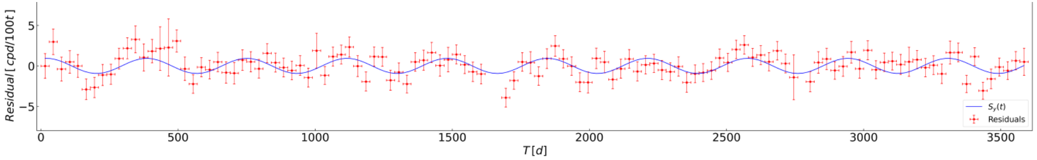
All exp: 0.465

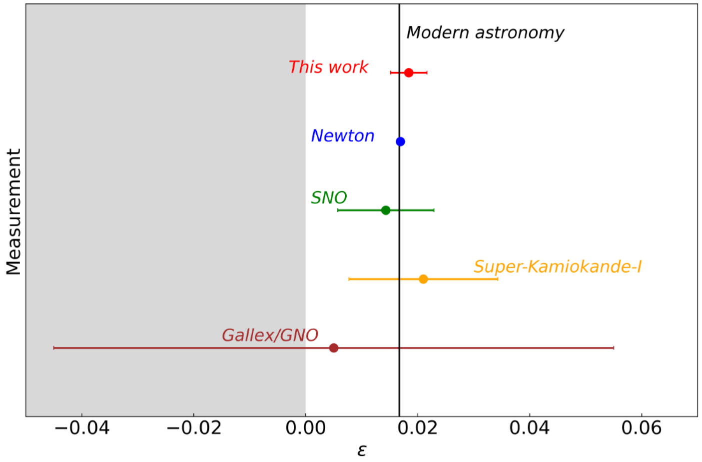
Seasonal modulations of ^{7}Be neutrino flux : confirmation of the Solar origin



"Independent determination of the Earth's orbital parameters with solar neutrinos in Borexino"

Astroparticle Physics 145 (2023) 102788





T=363.1±3.6 the duration of the astronomical year is measured from underground using neutrino!

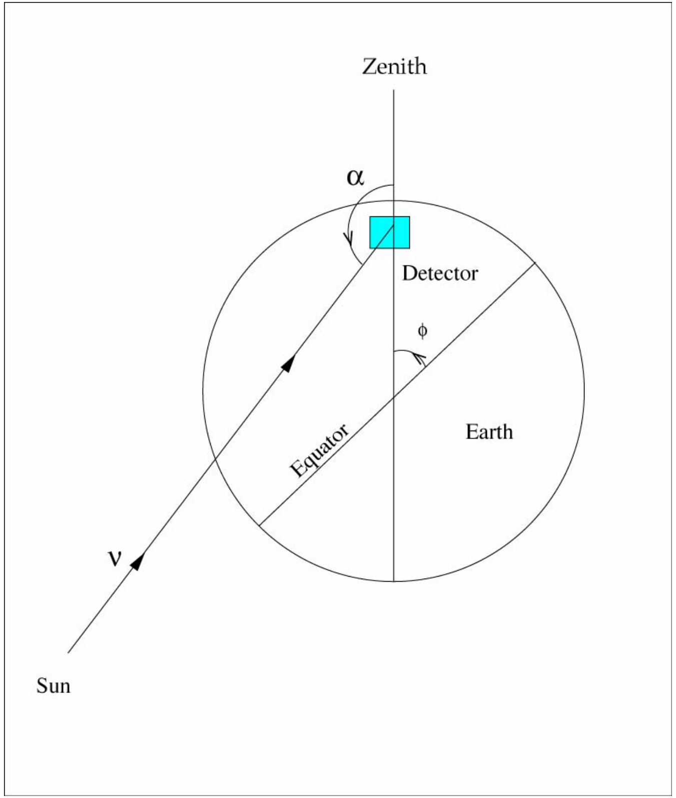
Day/Night neutrino signal asymmetry

Borexino : no diurnal variations of ^{7}Be neutrino flux

“negative” result on day/night assimetry with 3 years statistics (380.63 “nights” + 360.25 “days”) is in agreement with MSW/LMA predictions:

$$ADN = \frac{N - D}{N + D} = 0.001 \pm 0.012(stat) \pm 0.007(syst)$$

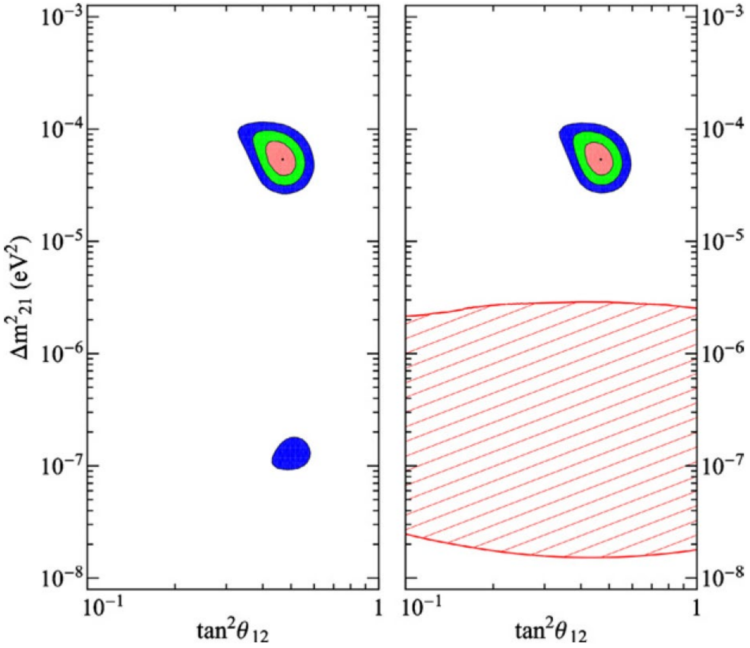
G. Bellini et al., Phys. Lett. B 707 (2012).



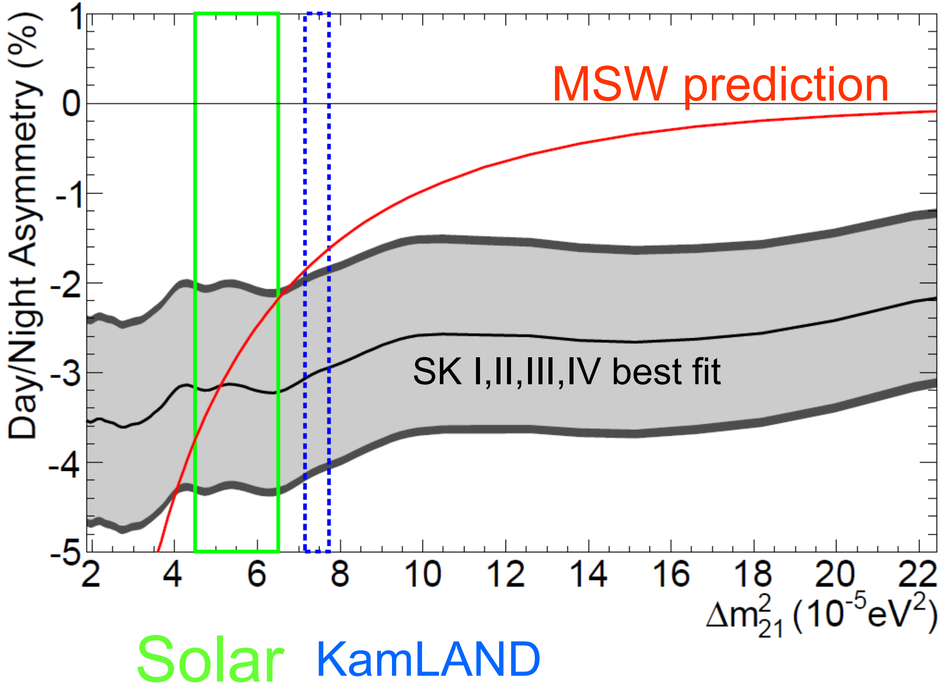
Absence of a day–night asymmetry in the ^{7}Be solar neutrino rate in Borexino

Physics Letters B 707 (2012) 22–26

A_{dn} = 0.001 ± 0.012 (stat) ± 0.007 (syst)



Diurnal variations of ^{8}B signal in SK

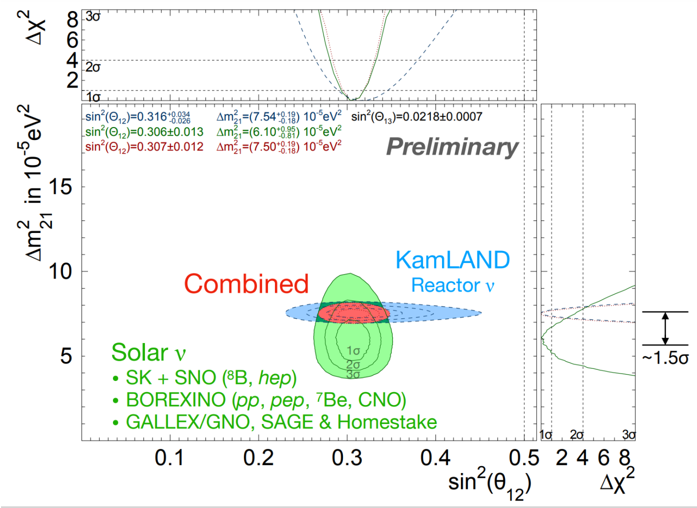


2014:

A_{DN}=-3.2±1.1±0.5 [%] (2.8σ)

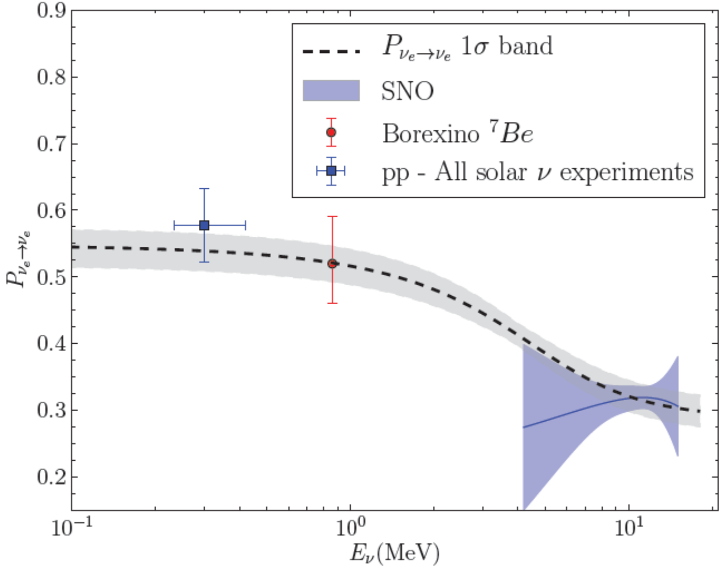
2016:

A_{DN}=-3.2±1.0±0.5 [%] (2.9σ)

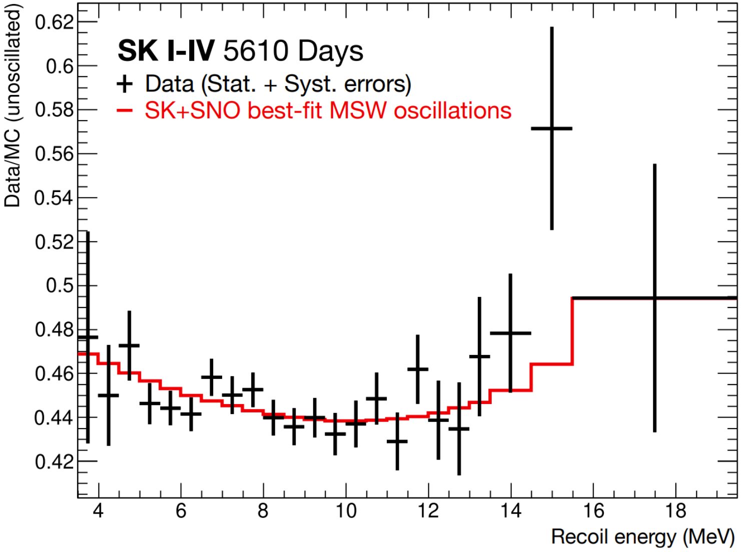


Upturn in ^{8}B spectrum

SNO



SK



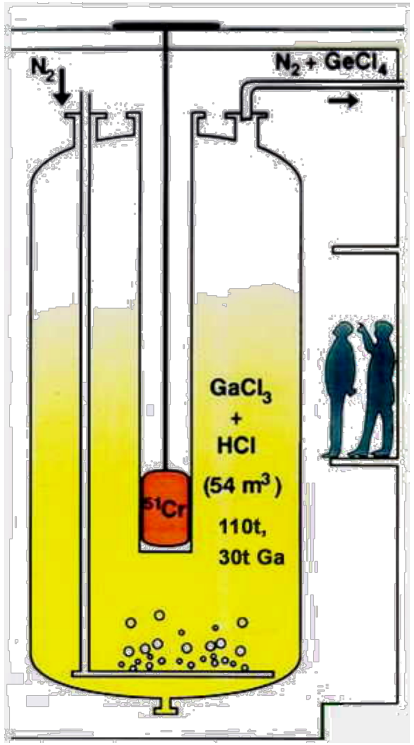
Beyond the Solar neutrinos with Solar neutrino detectors

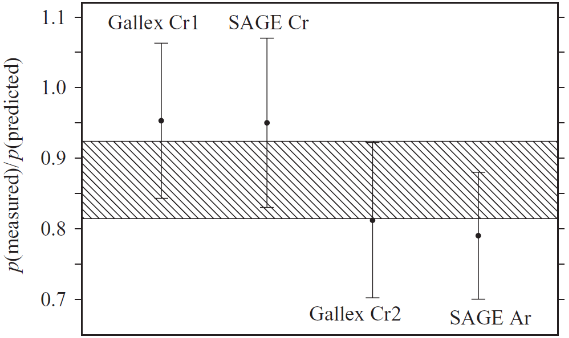
Modern detectors are thought of as multipurpose detectors:
a vast physical program is envisaged beyond the primary goal.

Measurements of geo-neutrino fluxes with the Solar neutrino detector (Borexino) and/or with the reactor antineutrino detector (KamLAND) is a good example. Another example: using GaGe method for the search of the sterile neutrinos (BEST at BNO).

Real-time Solar neutrino experiments are also an important component of Multimessenger Astronomy.

BEST (**B**aksan **E**xperiment on **S**terile **T**ransitions)

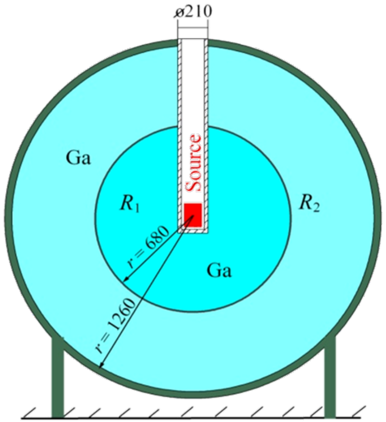


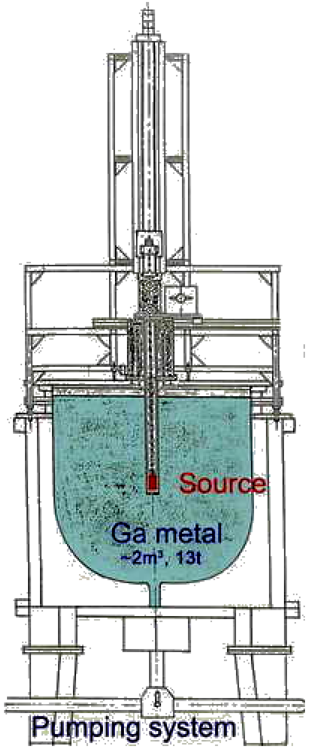


- **The weighted average for the four experiments *R* = *0.87 ± 0.05***
- *χ^2/DOF=1.9/3*

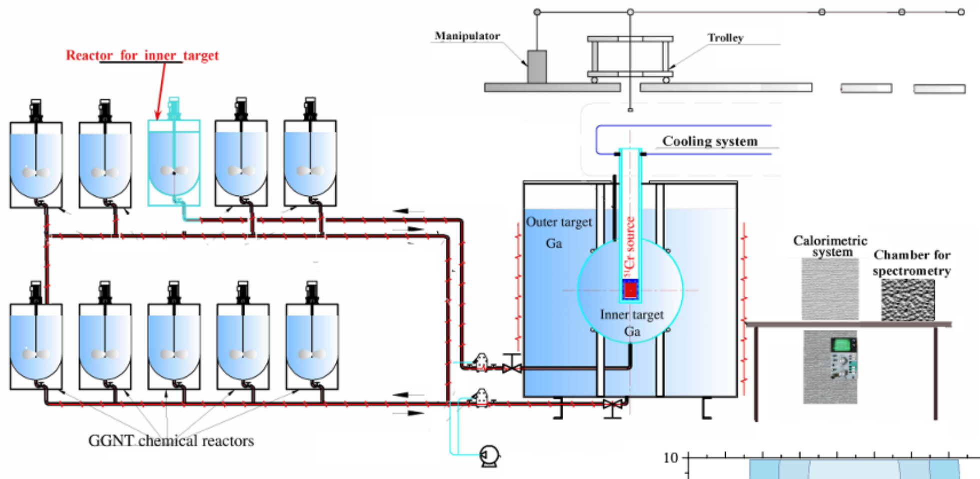
Overestimated cross sections?

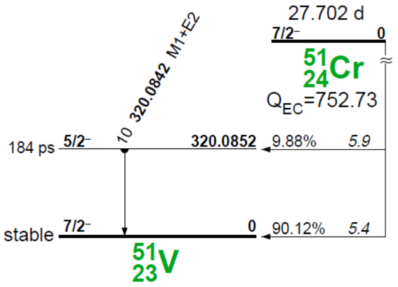
Sterile neutrino?
BEST

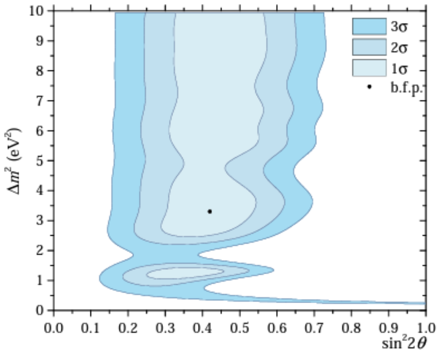


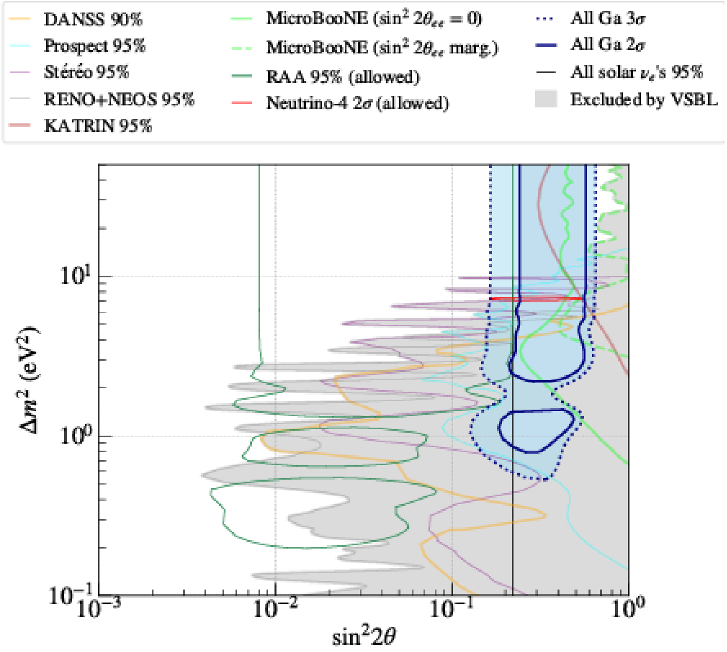


BEST (Baksan Experiment on Sterile Transitions)



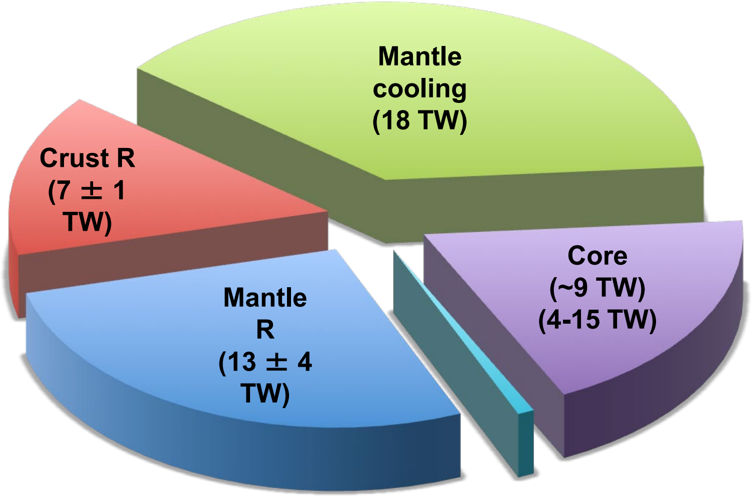


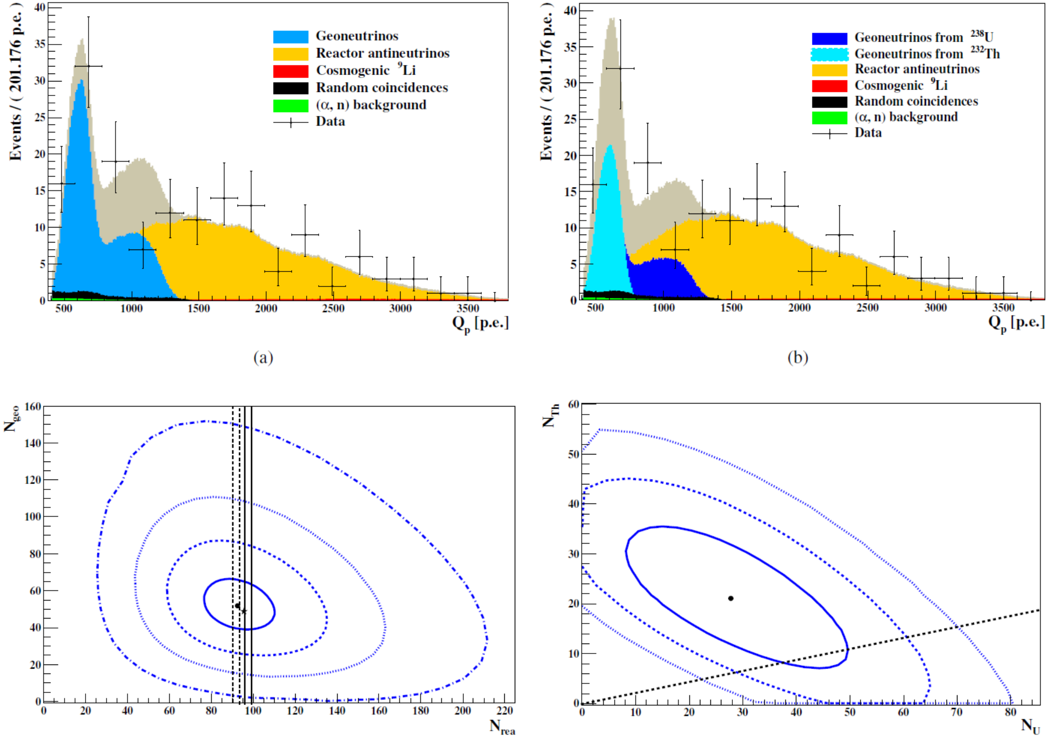




Geo-neutrino (Borexino)

52.6 +9.4/-8.6(stat) +2.7/-2.1(syst) events (Th/U=3.9)
+17/-15 %　　+18.3/-17.2 %





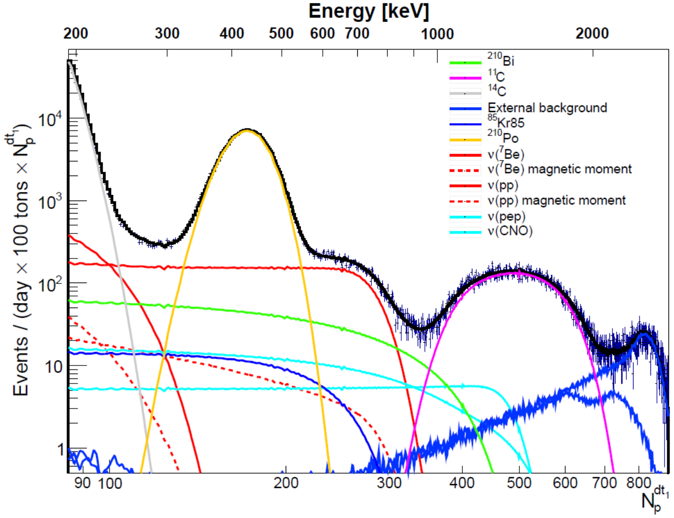
(a)　　(b)

Effective magnetic moment of Solar neutrino

XENON1T (2020) observes excess of events that can be explained by anomalous neutrino MM:
$1.4 < \mu_\nu < 2.9 \times 10{-}11\ \mu_B$ (90% CL)

Phys. Rev D 96, 091103(R) (2017)

Borexino is spectroscopical detector.
Solar neutrino analysis (spectral fit) is performed assuming SM cross sections
The shapes can be adjusted to take into account any non-standard interactions (NSI), including neutrino EM interactions



Radiochemical (Ga) constraints

$$\sum_i \frac{R_i^{Brx}}{R_i^{Expected}} R_i^{Ga} \frac{\langle \sigma^{\odot}{}_i \rangle_{new}}{\langle \sigma^{\odot}{}_i \rangle_{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

Without Ga constraint: $\mu_\nu < 4.0 \cdot 10^{-11}\ \mu_B$, 90% C.L.

With Ga constraint: $\mu_\nu < 2.6 \cdot 10^{-11}\ \mu_B$, 90% C.L.

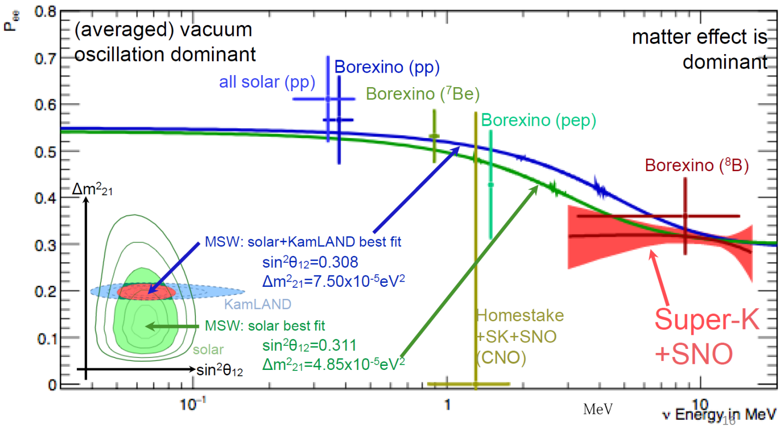
+ systematics: **$\mu_\nu < 2.8 \cdot 10^{-11}\ \mu_B$**, 90% C.L.

Non-standard neutrino interactions

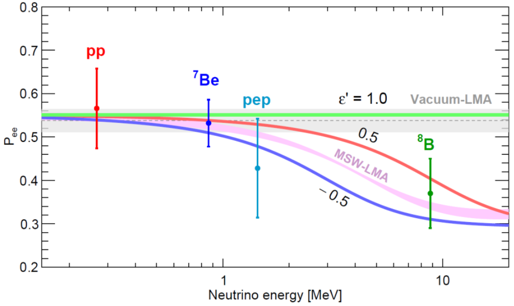
The absence of the visible upturn in the SuperK spectrum triggered speculations on NSI

Survival probabilities from all solar ν results

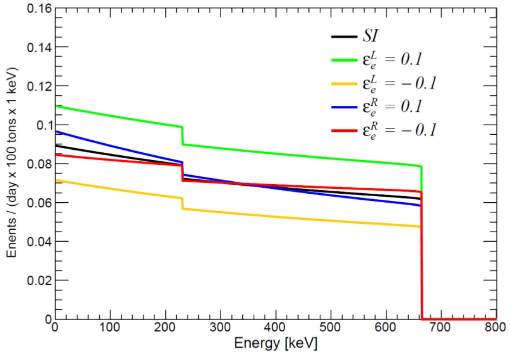
“Upturn” predicted by standard MSW is not seen yet.



NSIs modifies Pee…

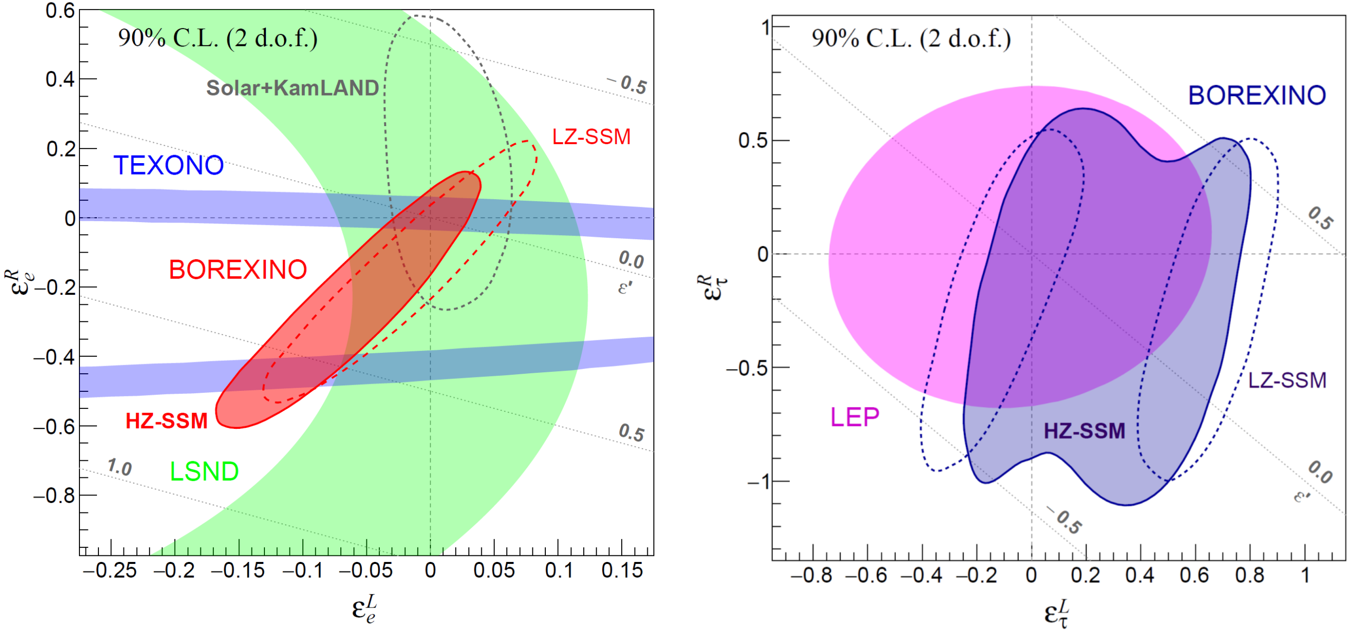


… and cross sections



Constrains on NSI

JHEP02(2020)038



Searches for rare physics

- NN, NNN disappearance (decays into invisible channels)
- Search for Pauli forbidden transitions in nuclei
- e->ν+γ decay (charge conservation; life-time of electron
- Dark Matter
- Sterile neutrino
- Search for axions
- Heavy sterile neutrino mixing in ^{8}B decay
- Antineutrinos from the Sun
- DSNB (Diffuse SN Neutrino Background)
- etc....

Multimessanger Astronomy

- SNEWS
- Search for low-energy neutrinos in coincidence with:
    - GRB
    - GW
    - Fast radiobursts
    - Solar flares
    - ….

Future

- It looks like Borexino was the last detector with a primary goal of detecting Solar neutrino.

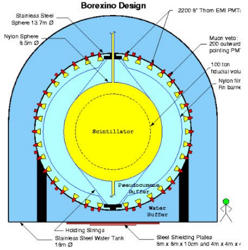
- All future detectors with sensitivity to Solar neutrino have another priority and this complicates the Solar neutrino studies (mainly not deep enough, radiopurity).

- But, in general, larger volumes and better energy resolution offer a good possibility for further studies of the Solar neutrino.

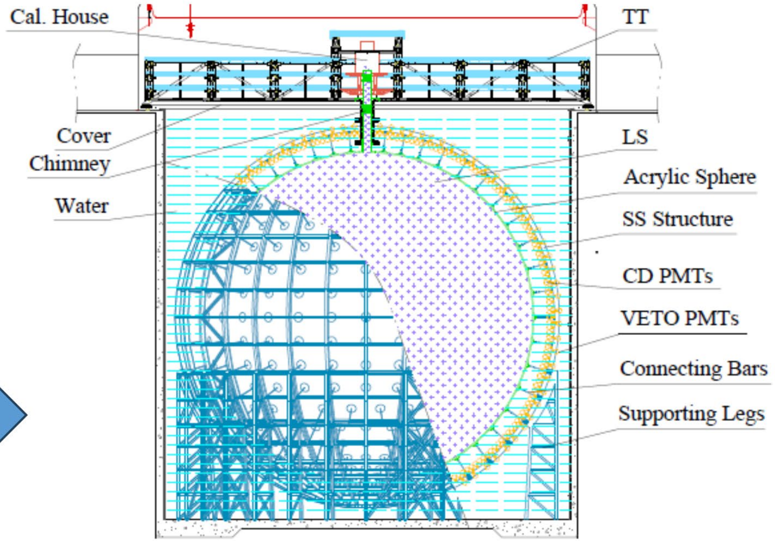
JUNO

Reactor antineutrino detector; primary goal: NMO

BX: Fiducial M=75t



JUNO: Fiducial M=10kt



8B solar neutrinos

- 60k ES events in 10y

- Also possible to see

CC: v_e+ ^{13}C ->e$^-$+ ^{13}N
NC: v_x+ ^{13}C->v_x+ ^{13}N*

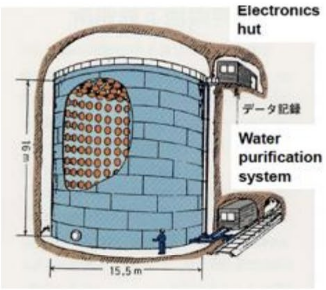
7Be, pep, CNO solar neutrinos

- Radiopurity?

Planned data taking start: 2024

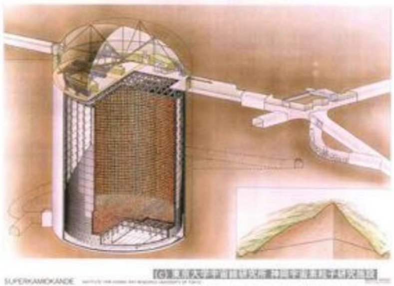
HyperK – the third generation of Kamioka WCh detectors

Kamiokande
(1983 – 1996)



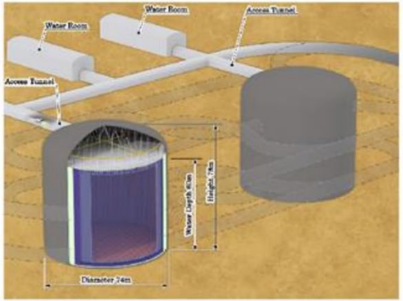
3 kton
20% coverage with 50 cm PMT

Super-Kamiokande
(1996 –)



50 kton
40% coverage with 50 cm PMT

Hyper-Kamiokande
(2027 –)



260 kton
20% coverage with high-QE 50 cm PMT

^{8}B solar neutrinos
In ~ 10 years

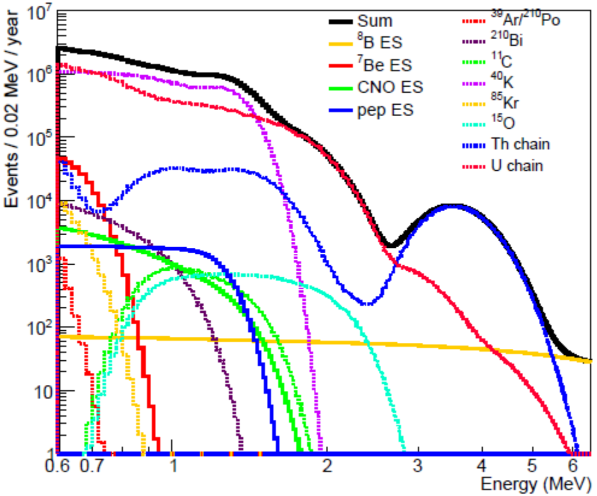
- Upturn at 5σ;
- D/N at 4σ-8σ (depending on background)
- hep neutrinos at ~3σ;

Tochibora Mine ~8 Km far from SuperK (overburden= 650 m, less than SuperK!);
- better energy and angular resolution;
- **Main goal**: far detector for the JPARC beam : study the δ_{CP}, NMO ...
- Data taking start ~2027

THEIA

Multi-purpose detector: far detector for LBNF beam: δ_{CP}, NMO ...

- Theia will be located at SURF (Sanford Underground Research Facility, South Dakota)
- Mass: (25 – 100) kt;
- **water based Liquid scintillator (WbLS)**



Uncertainty on CNO ~ 4%

−5 years;

−60 kt Fiducial M;

$-\sigma(\theta) \sim 25^0$

^{7}Li for CC (8B neutrinos)

Instead of conclusions

- “It is now well realized that the Sun and the Earth were created for neutrino oscillation experiments. The Earth–Sun distance was chosen as the oscillation length, solar matter density was selected specially to include the Mikheev–Smirnov–Wolfenstein effect, and the Sun was prepared in the form of an ideal electron neutrino source.
- When all was done, Bruno Pontecorvo was created to invent the idea of neutrino oscillations, John Bahcall was created to calculate the solar neutrino fluxes, Ray Davis was created to accomplish the first neutrino experiment, and all other individuals in solar neutrino physics were created to finalize this hard job…”

M. Goodman, cited by V. Berezinsky.