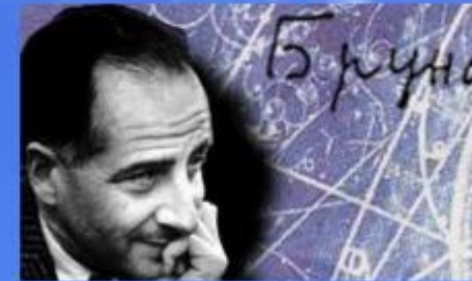
VIII International Pontecorvo Neutrino Physics School



ν_3

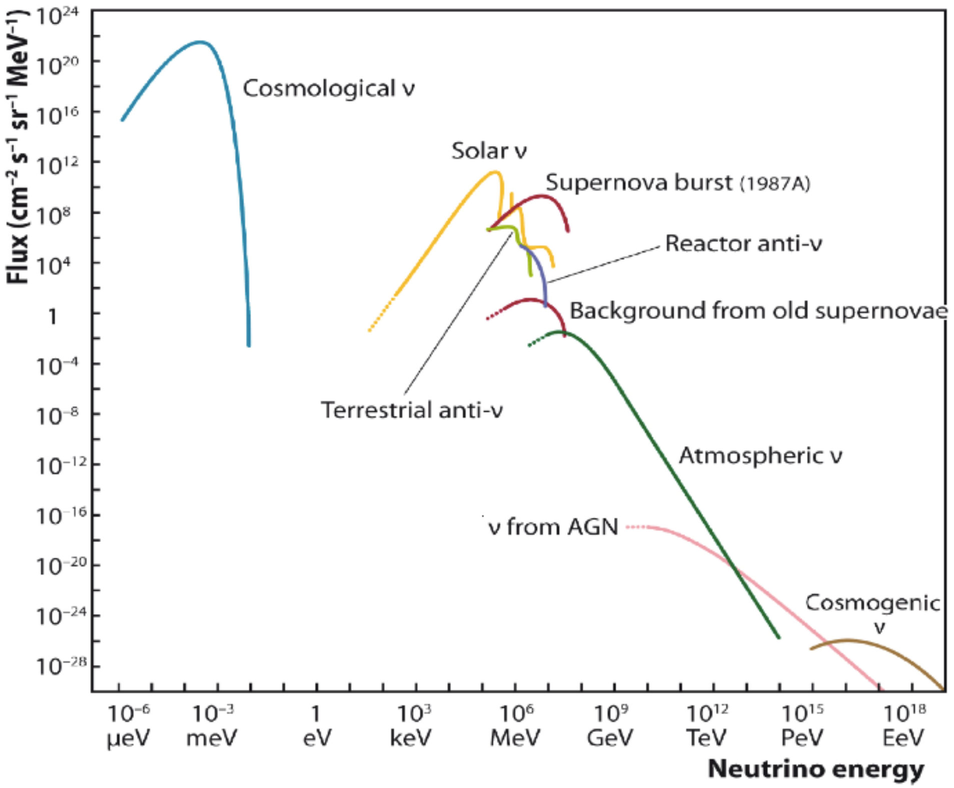
http://theor.jinr.ru/~neutrino

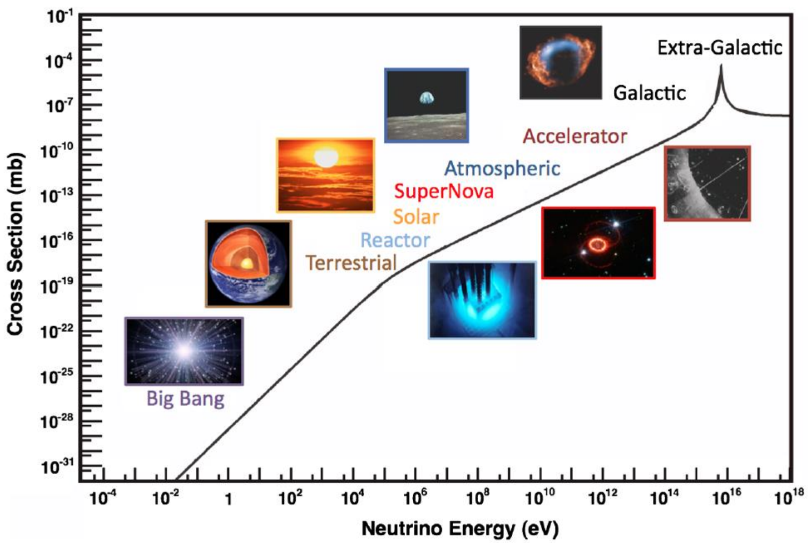
ν_2

Solar neutrino experiments

Oleg Smirnov,
JINR (DLNP), Dubna

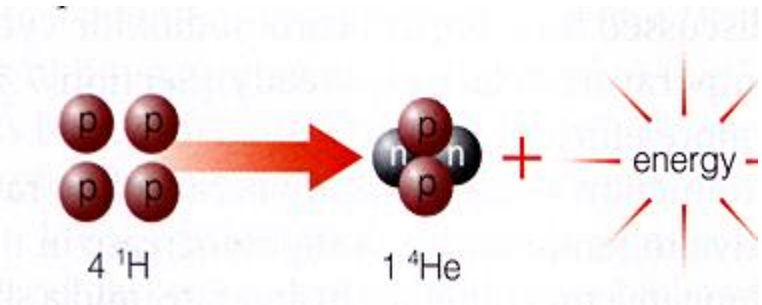
Neutrino fluxes in nature



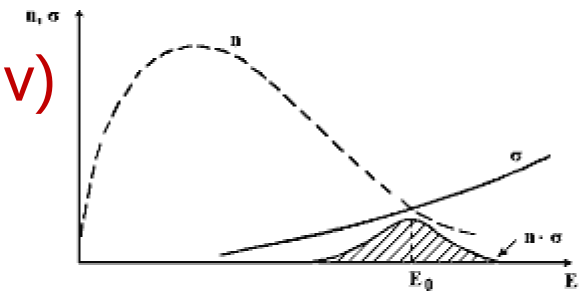


How the Sun shines

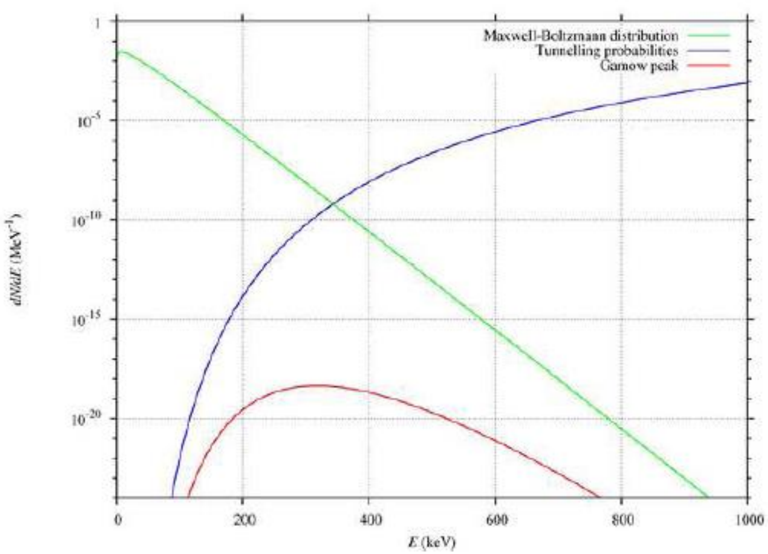
Core temperature~ 10^7 K (~1 keV).



(26.7MeV) (+2v)

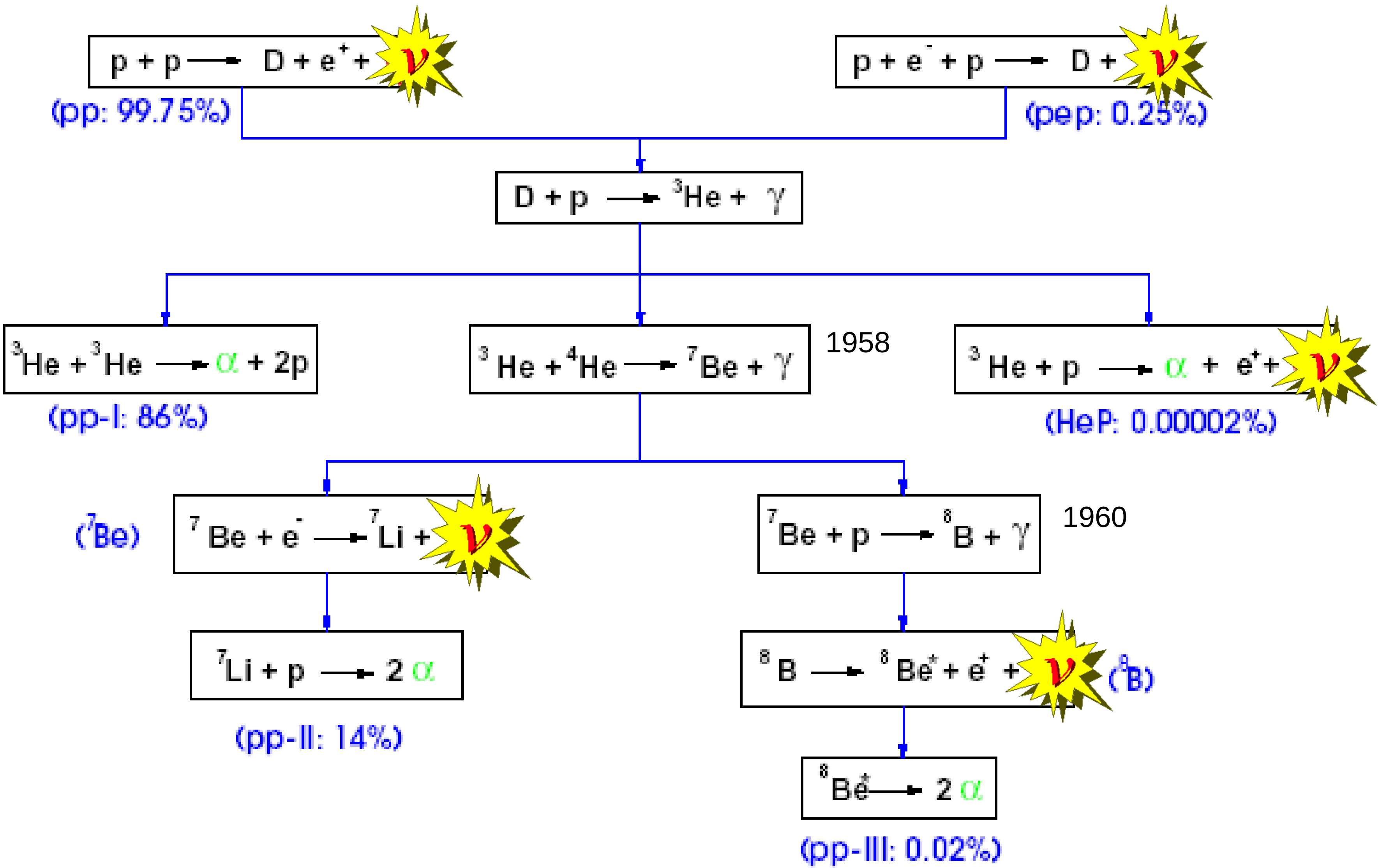


Helium is lighter comparing to 4 protons(0,7%)- this energy is feeding the Sun.
pp-cycle is very slow reaction (time scale $7{,}9\cdot10^9$ y). Energy release = 26,7 MeV, 2 neutrinos are emitted.
Sun power is $L_{Sun}=3.8\cdot10^{26}$ W (380 YW) ➔ $6.5\cdot10^{10}$ neutrino/s/cm².



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

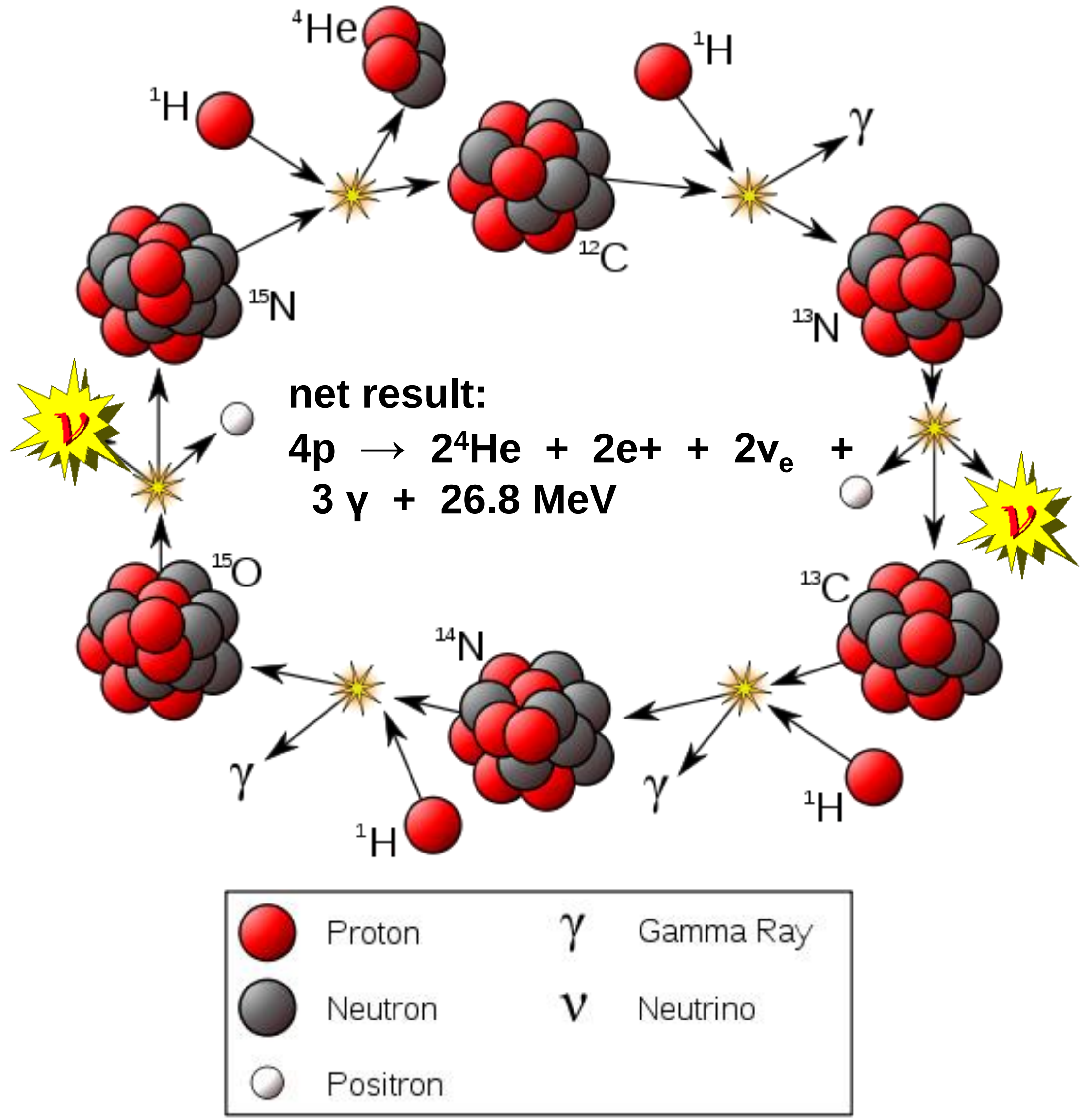


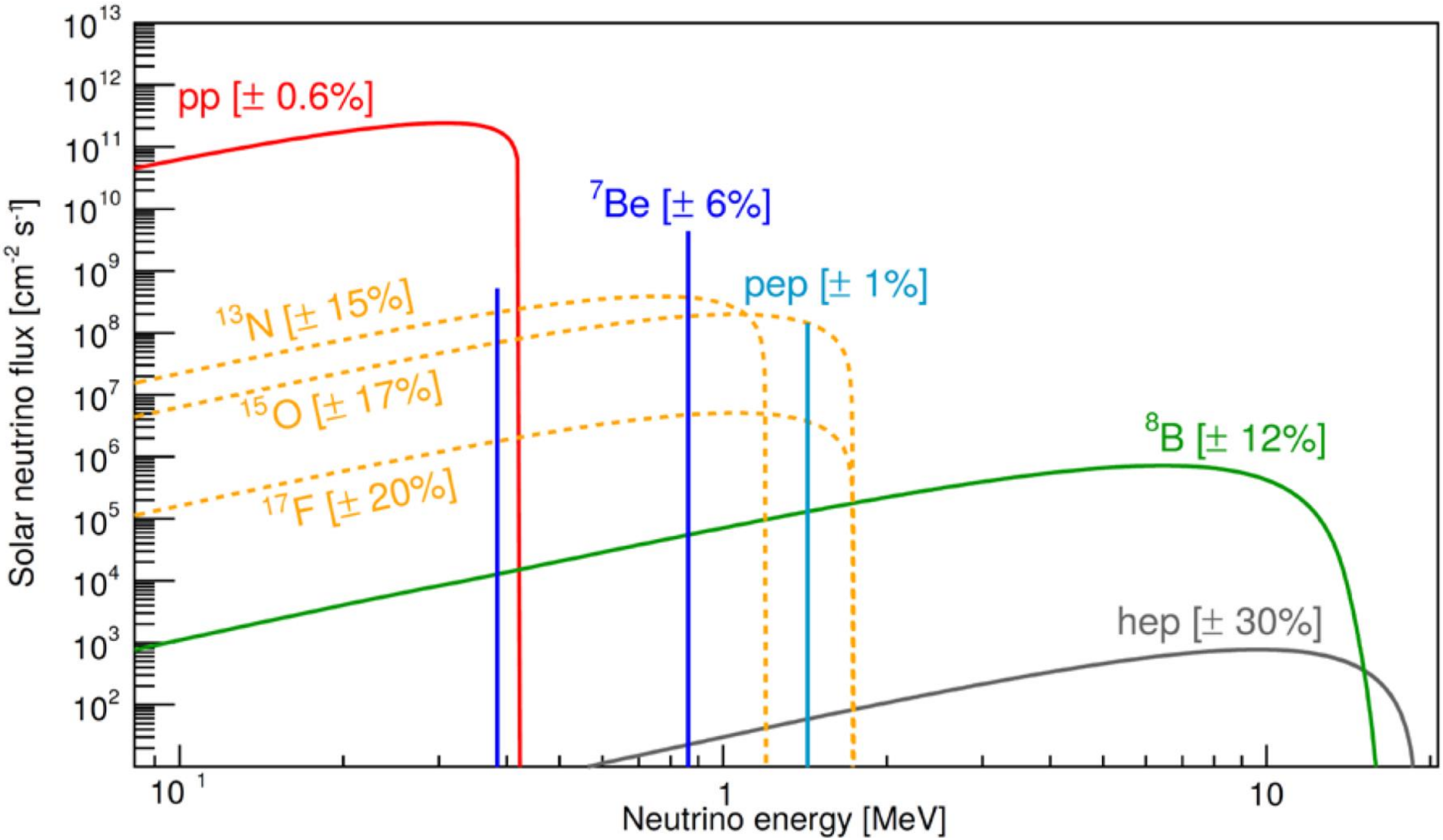
p + p → D + e+ + ν
(pp: 99.75%)
p + e- + p → D + ν
(pep: 0.25%)
D + p → 3He + γ
3He + 3He → α + 2p
(pp-I: 86%)
3 He + 4He → 7Be + γ
1958
3 He + p → α + e+ + ν
(HeP: 0.00002%)
(7Be)
7 Be + e- → 7Li + ν
7Be + p → 8B + γ
1960
7Li + p → 2 α
(pp-II: 14%)
8 B → 8 Be* + e+ + ν
(8B)
8Be* → 2 α
(pp-III: 0.02%)

CNO-cycle

The CNO cycle (carbon-nitrogen-oxygen) is a catalytic cycle. CNO 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 $\sim15\times10^6$ K, but its energy output rises much more rapidly with increasing temperatures and at $\sim 17\times10^6$ 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.

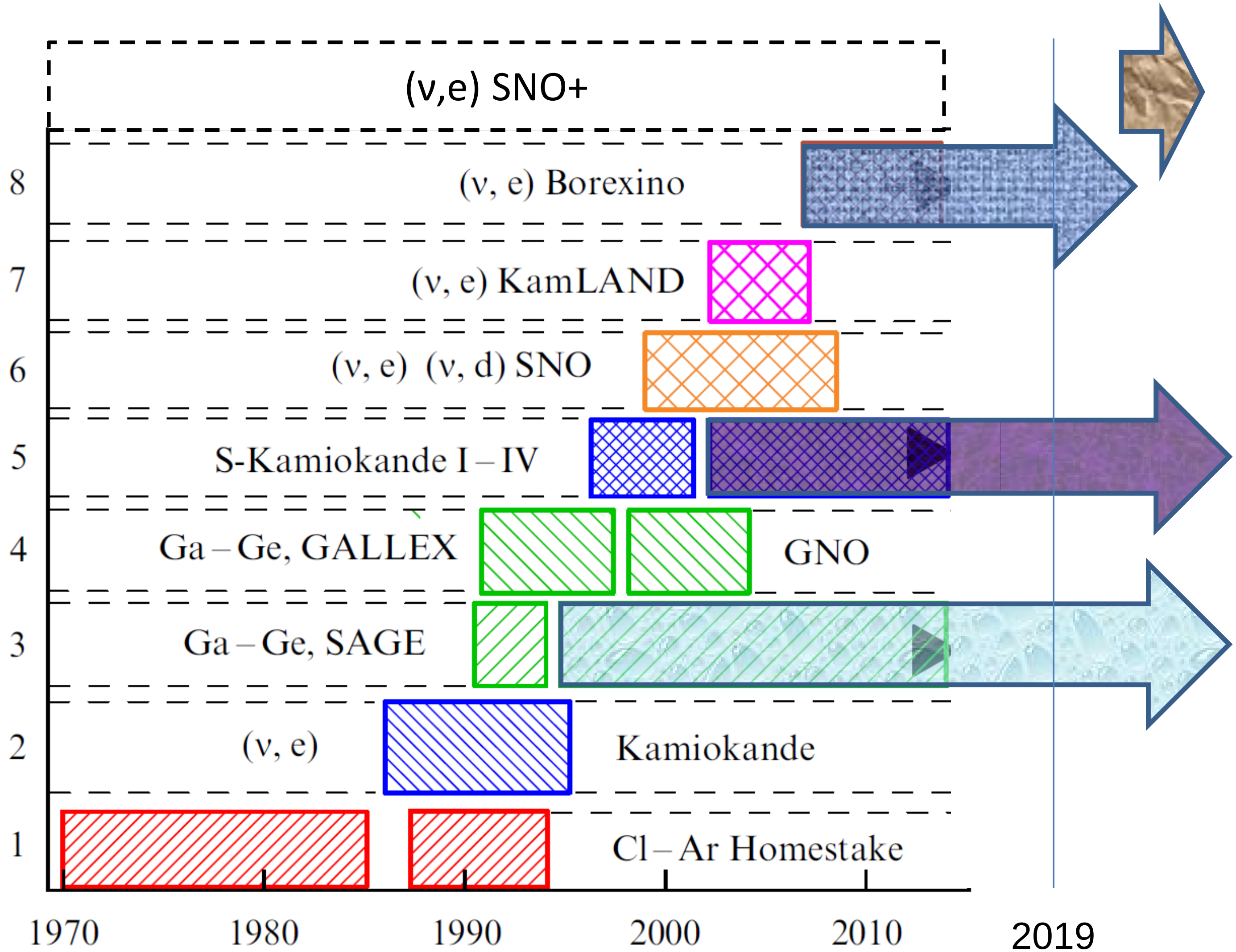
The simplest CN-cycle (CNO-I, or Bethe cycle or carbon cycle) was proposed by Hans Bethe in 1938 and, independently, in 1939 by Carl Friedrich von Weizsäcker).

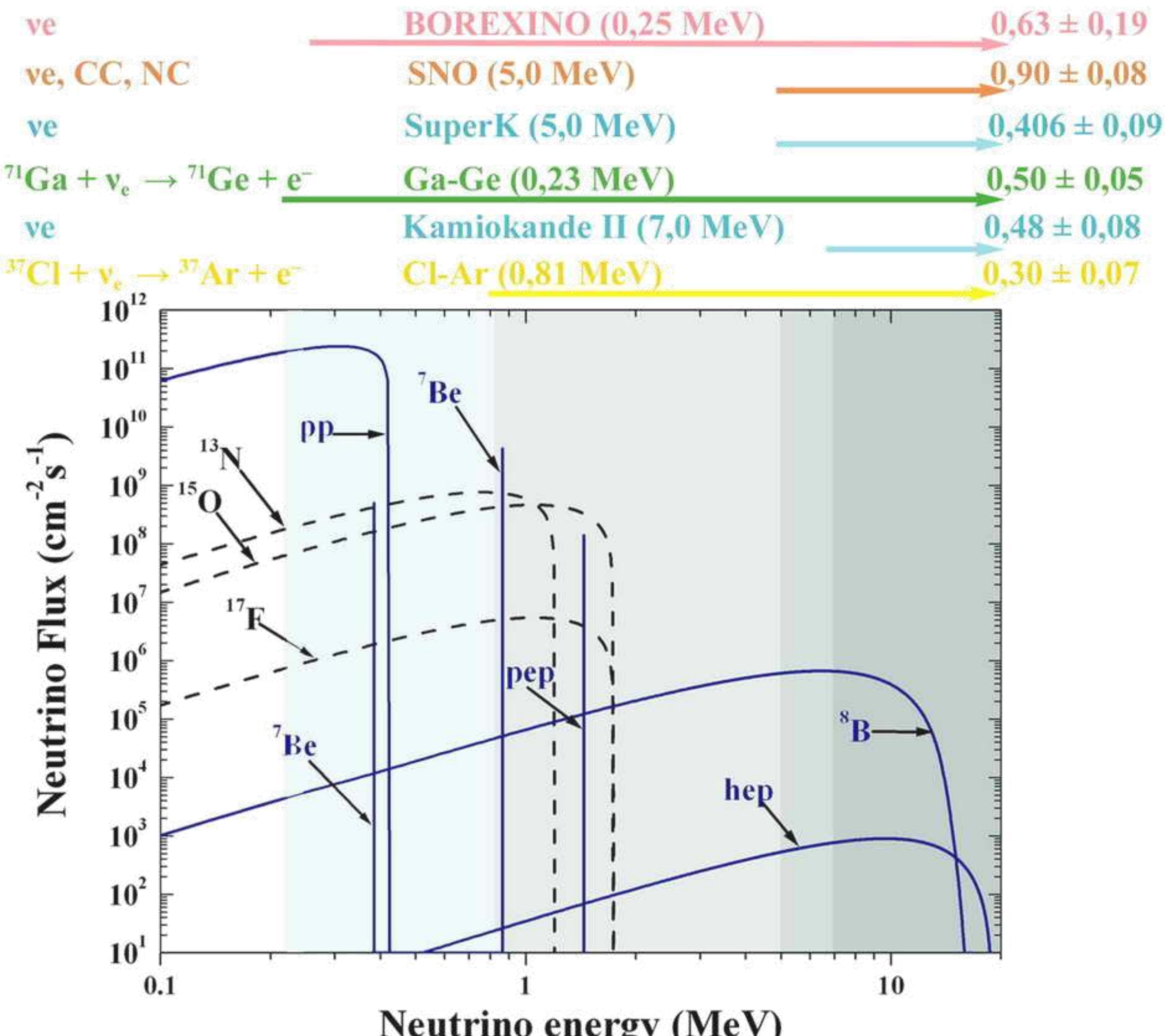




pp [± 0.6%]
7Be [± 6%]
pep [± 1%]
13N [± 15%]
15O [± 17%]
17F [± 20%]
8B [± 12%]
hep [± 30%]
Solar neutrino flux [cm-2 s-1]
Neutrino energy [MeV]
10-1
1
10

Solar neutrino experiments





ve
BOREXINO (0,25 MeV)
0,63 ± 0,19
ve, CC, NC
SNO (5,0 MeV)
0,90 ± 0,08
ve
SuperK (5,0 MeV)
0,406 ± 0,09
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
Ga-Ge (0,23 MeV)
0,50 ± 0,05
ve
Kamiokande II (7,0 MeV)
0,48 ± 0,08
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
Cl-Ar (0,81 MeV)
0,30 ± 0,07
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
pp
^{7}Be
^{13}N
^{15}O
^{17}F
pep
^{7}Be
^{8}B
hep
0.1
1
10
Neutrino Flux ($cm^{-2}s^{-1}$)
Neutrino energy (MeV)

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 $T_{1/2}$.

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

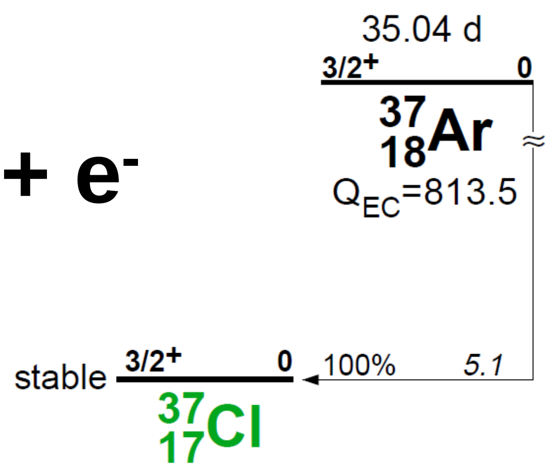
* counting techique: no neutrino direction or energy information is available
*the targets must be huge, containing many tons of material.
*requires sensitive radiochemical methods to separate few atoms of product element (Z+1) from the target Z.
*the experiments are done deep underground to minimize cosmic-ray interactions in the target that can produce protons, (p,n) reactions mimic neutrino capture.
*runs are done 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%.

Radiochemical detection of Solar neutrinos.

Bruno Pontecorvo, 1946:

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

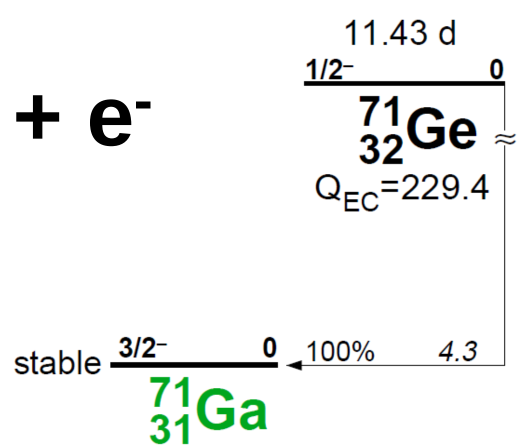
Q=813.5 keV

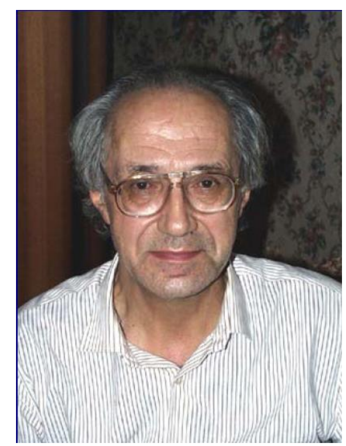


V.Kuz'min, 1965

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

Q=229.4 keV





Radiochemical experiments: proposals

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

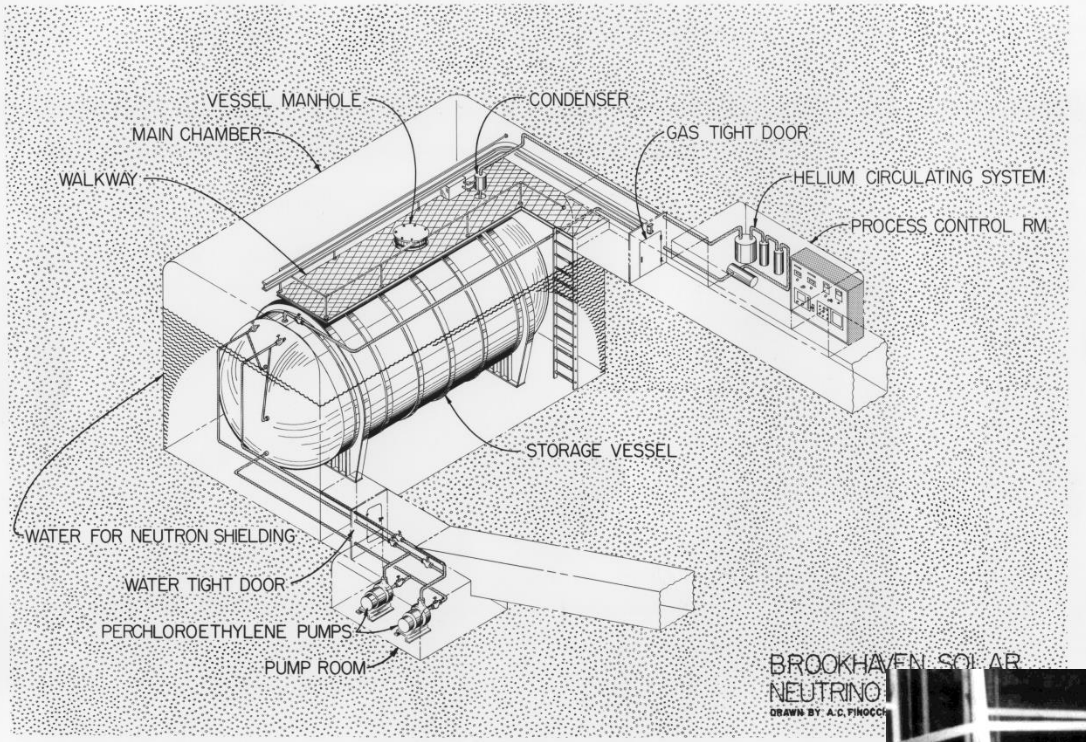
Homestake.

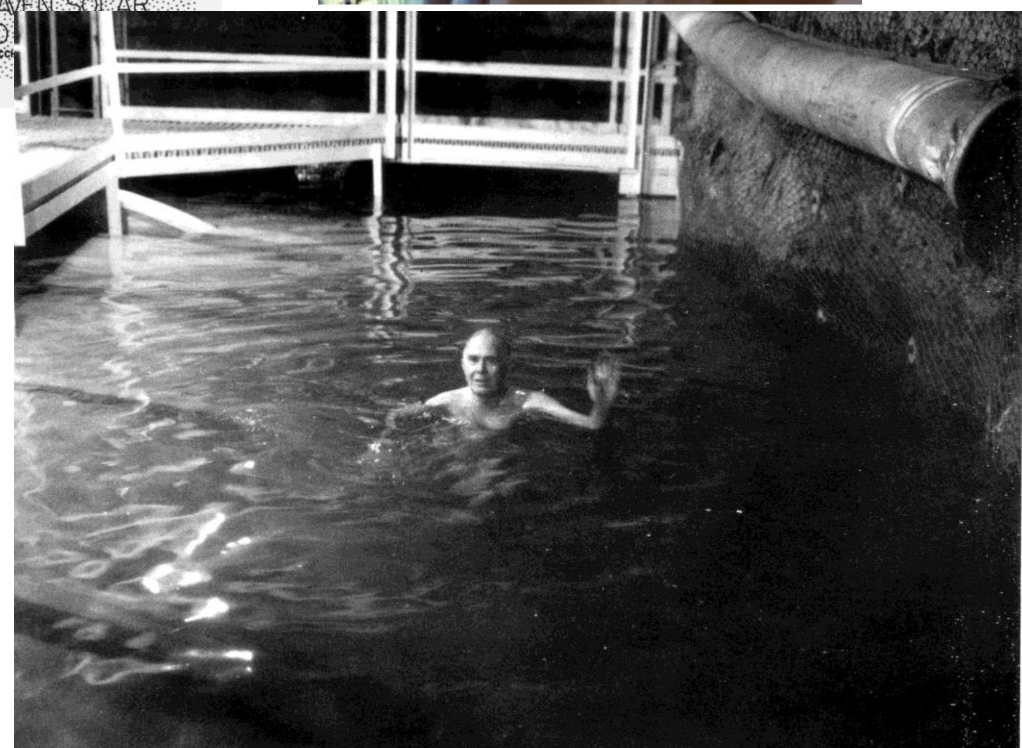
Homestake Mine- mine in South Dacota.

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"





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

Solar Neutrino Problem

John Norris Bahcall (1934 – 2005)

"We argued that, if our understanding of nuclear processes in the interior of the sun was correct, then solar neutrinos would be captured at a rate Davis could measure with a large tank filled with cleaning fluid…

Our sole motivation for urging this experiment was to use neutrinos to enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. As we shall see, Davis and I did not anticipate some of the most interesting aspects of this proposal.

Davis performed the experiment and in 1968 announced the first results. He measured fewer neutrinos than I predicted. As the experiment and the theory were refined, the disagreement appeared more robust. Scientists rejoiced that solar neutrinos were detected but worried why there were fewer neutrinos than predicted.

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

SAGE, GALLEX - GNO

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

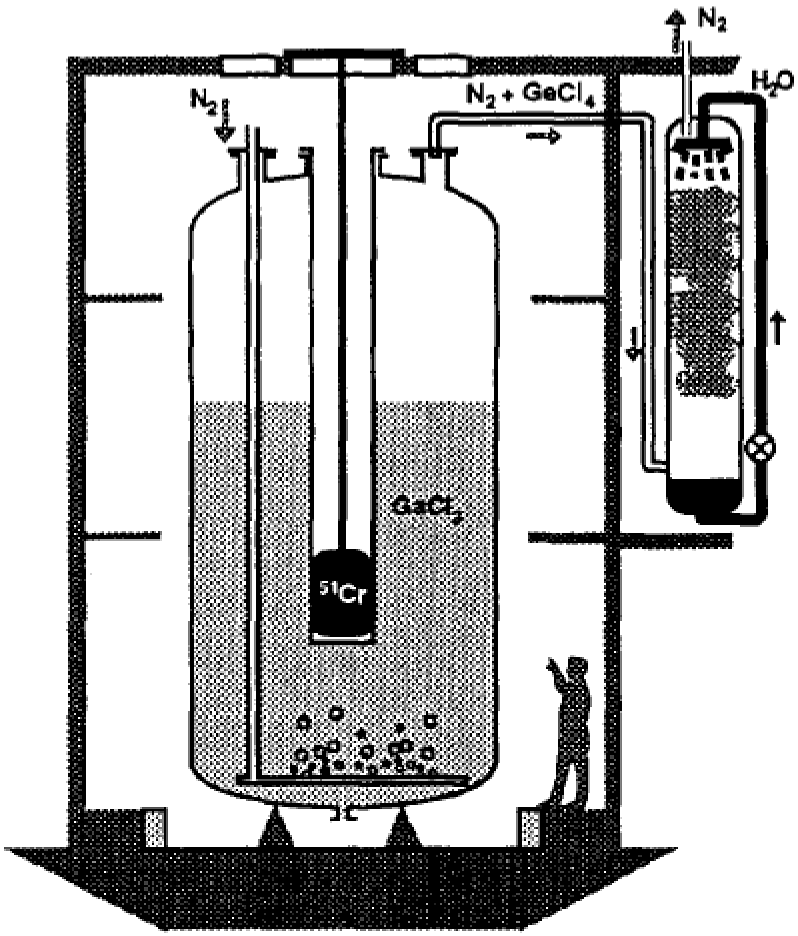
1984 group headed by Till Kirsten from Max Plank Institute presented a project of gallium experiment and started to form GALLEX collaboration

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

Till Kirsten

Vladimir Gavrin

GALLEX and SAGE



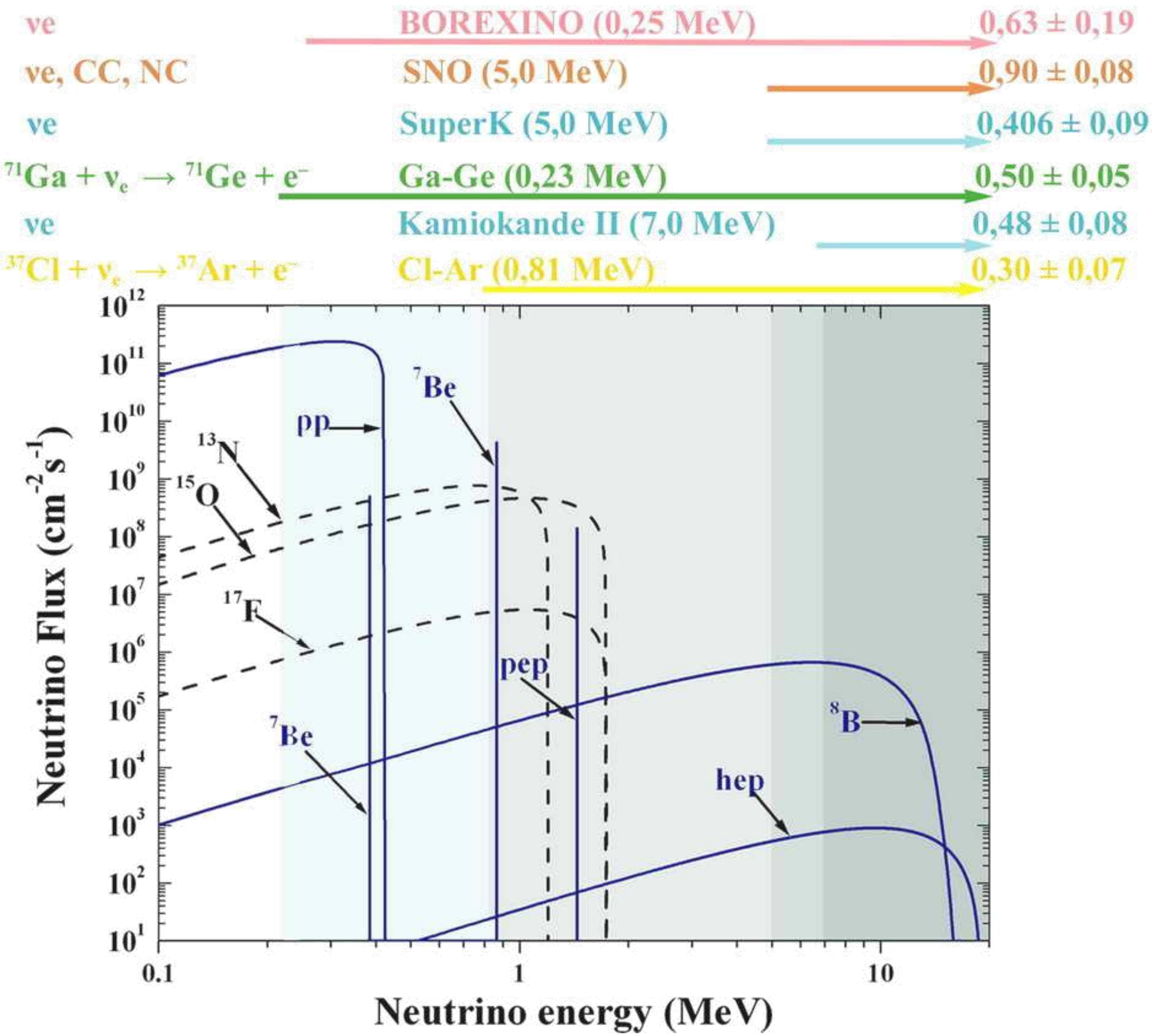
Gallex/GNO

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

Solar neutrino with Radiochemical detectors : results

Experiment	Years	Target mass	Reaction	Threshold keV	Result in SNU [or as a fraction of SSM prediction]
Homestake	1967-1995 1970-1994 108 cycles	C_2Cl_4; 615 t	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	814	[2.55 ± 0.25 SNU] 0.336 ± 0.090
SAGE (operating)	1990-2011: 211 cycles	Met.Ga ; 50-57 t	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	233	[65.1 +3.7-3.8 SNU]
Gallex	1991-1997 67 cycles	$GaCl_3$; 30.3 t			0.605 ± 0.103
GNO-30	1998-2003 58 cycles				0.491 ± 0.081
Gallex+GNO					0.541 ± 0.081 [67.6± 5.1 SNU]
Gallex+GNO+SAGE					[66.1 ± 3.1 SNU]

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

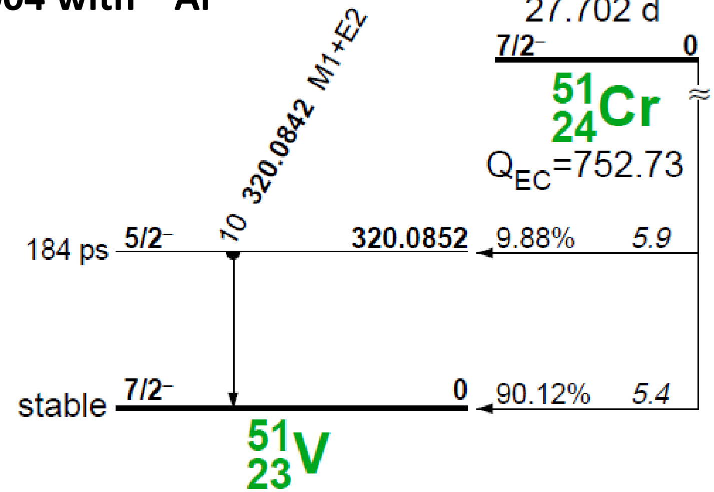


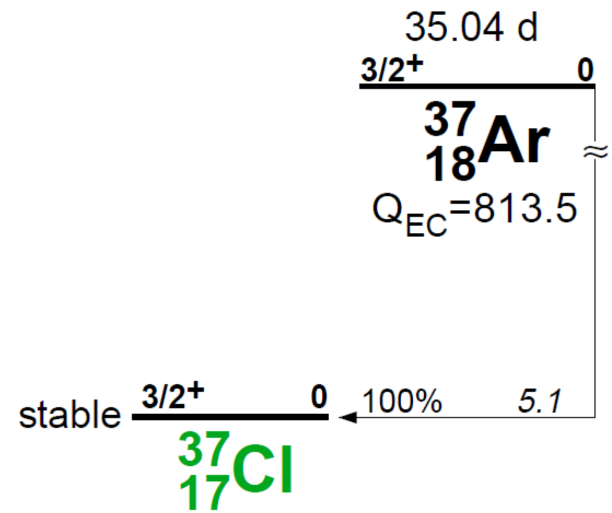
Cl : pp(0%) + ^{7}Be(13%) + pep(2.7%) + CNO(2.4%) + ^{8}B(82%)
Ga: pp(55%) + ^{7}Be(28%) + pep(2.3%) + CNO(3.4%) + ^{8}B(11%)

Calibration with artificial neutrino sources

SAGE and Gallex were calibrated using neutrino source ^{51}Cr

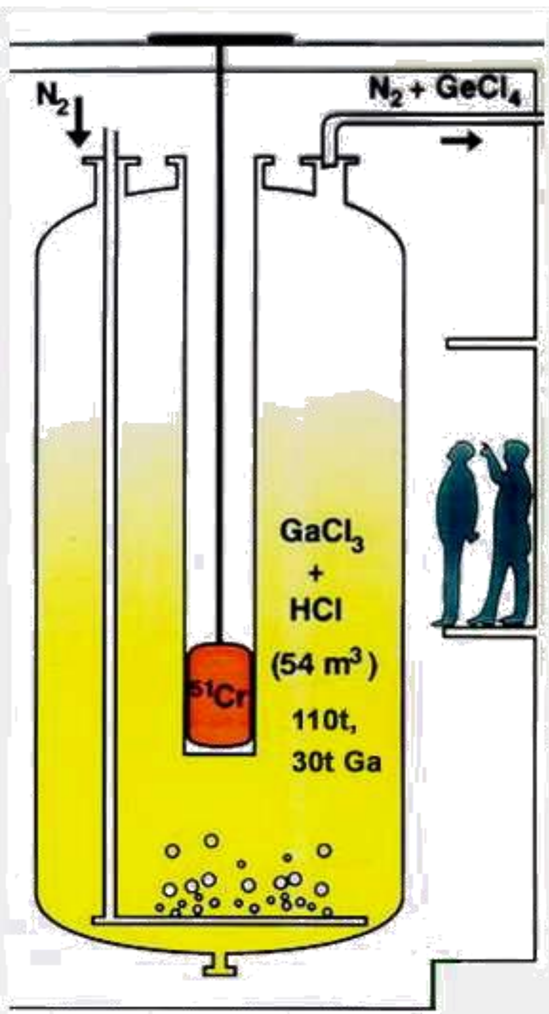
SAGE - in 2004 with ^{37}Ar

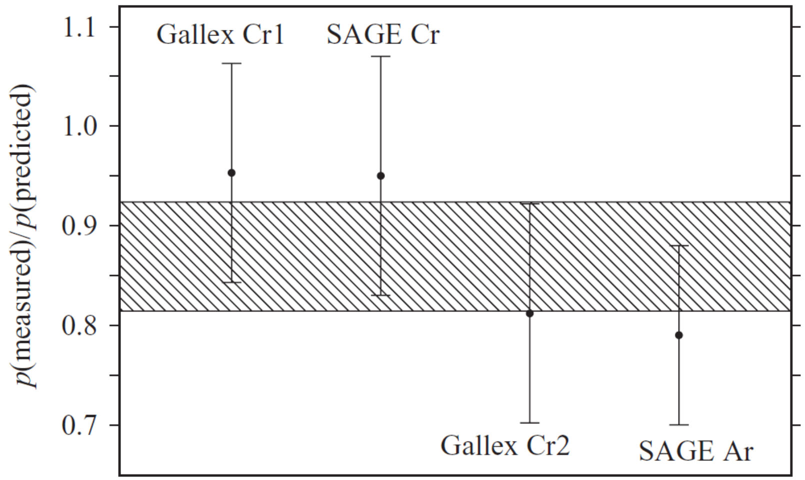




	GALLEX		SAGE	
	m(Ga)=30 t		m(Ga)=13 t	
Source	^{51}Cr -1	^{51}Cr -2	^{51}Cr	^{37}Ar
Activity, MCi	1.714	1.868	0.517	0.409
Measured production rate ρ (^{71}Ge/d)	11.9 ±1.1 ±0.7	10.7 ±1.2 ±0.7	14.0 ±1.5 ±0.8	$11.0^{+1.0}_{-0.9} \pm 0.6$
R = (p_{meas}/p_{pred})	0.95±0.11	0.81±0.11	0.95±0.12	0.79±0.10
R_{comb}	0.88 ± 0.08		0.86 ± 0.08	

Calibration with artificial neutrino sources

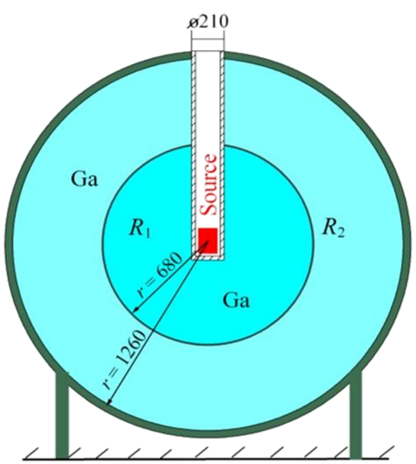


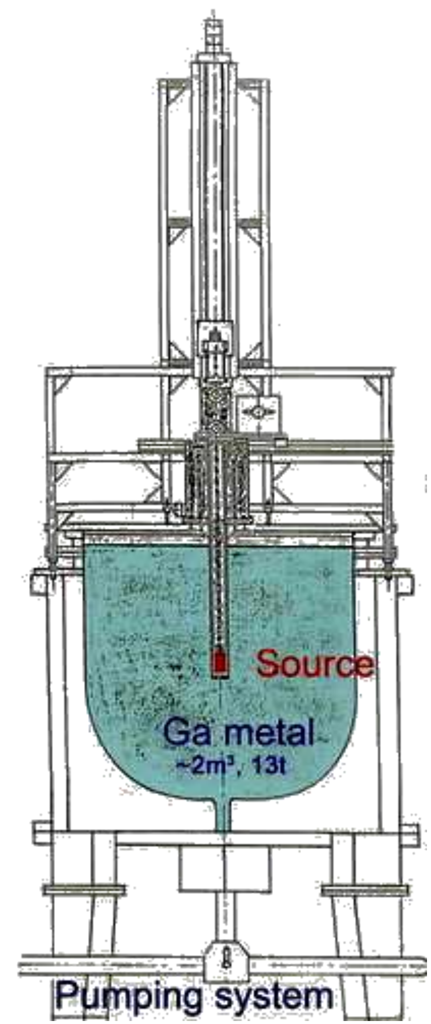


- The weighted average for the four experiments *$R = 0.87 \pm 0.05$*
- $\chi^2/DOF=1.9/3$

Overestimated cross sections?

Sterile neutrino?
BEST





Best status

proposal: 1006.2103, 1204.5379, ...

artificial source: ^{51}Cr of 3 MCi

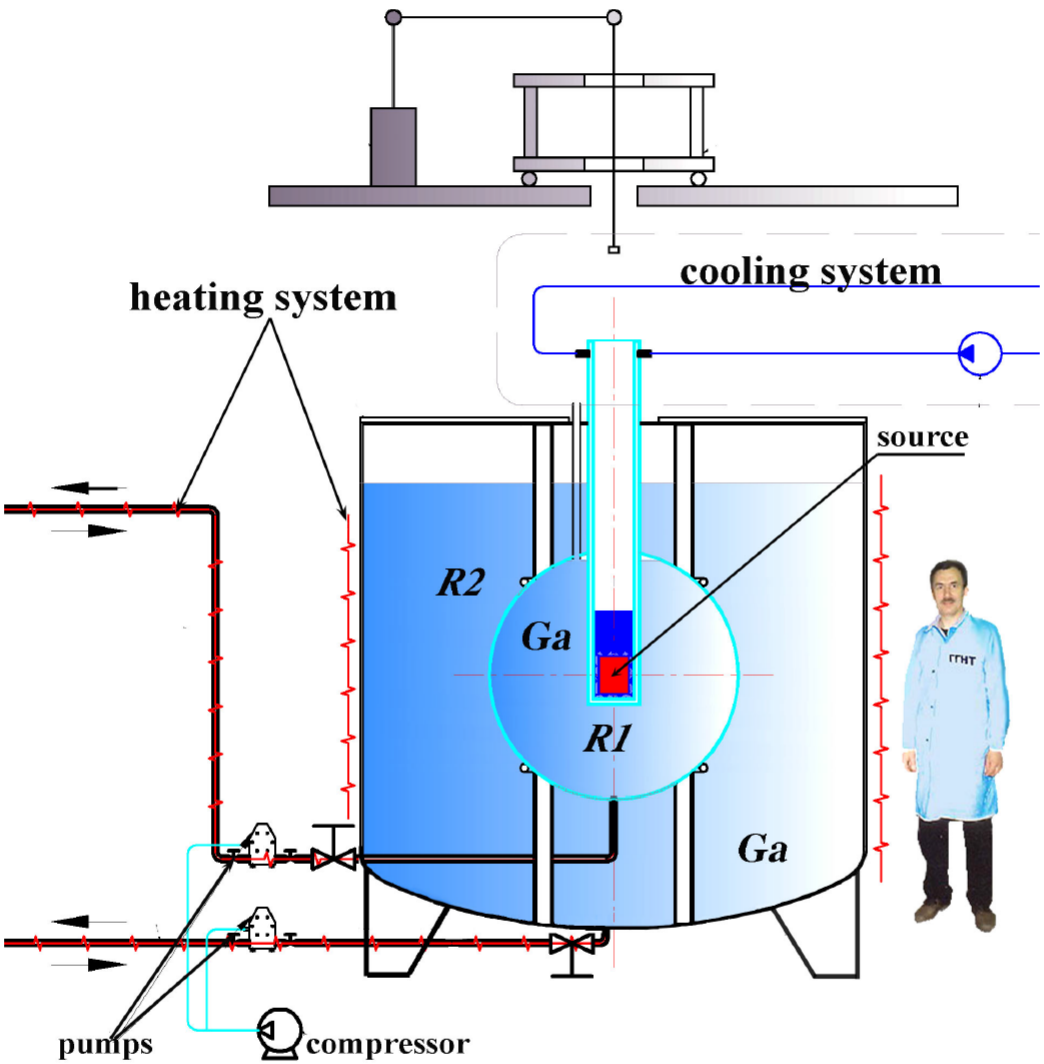
neutrino flux measurment:
$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$

2 detector volumes:
for the flux cross check

geometry is chosen:
to search for $\simeq 1$ eV neutrino
must be sterile...

data taking:
July–September 2019

$\tau_{^{51}\mathrm{Cr}} = 27.7\mathrm{d}$



REAL TIME DETECTORS

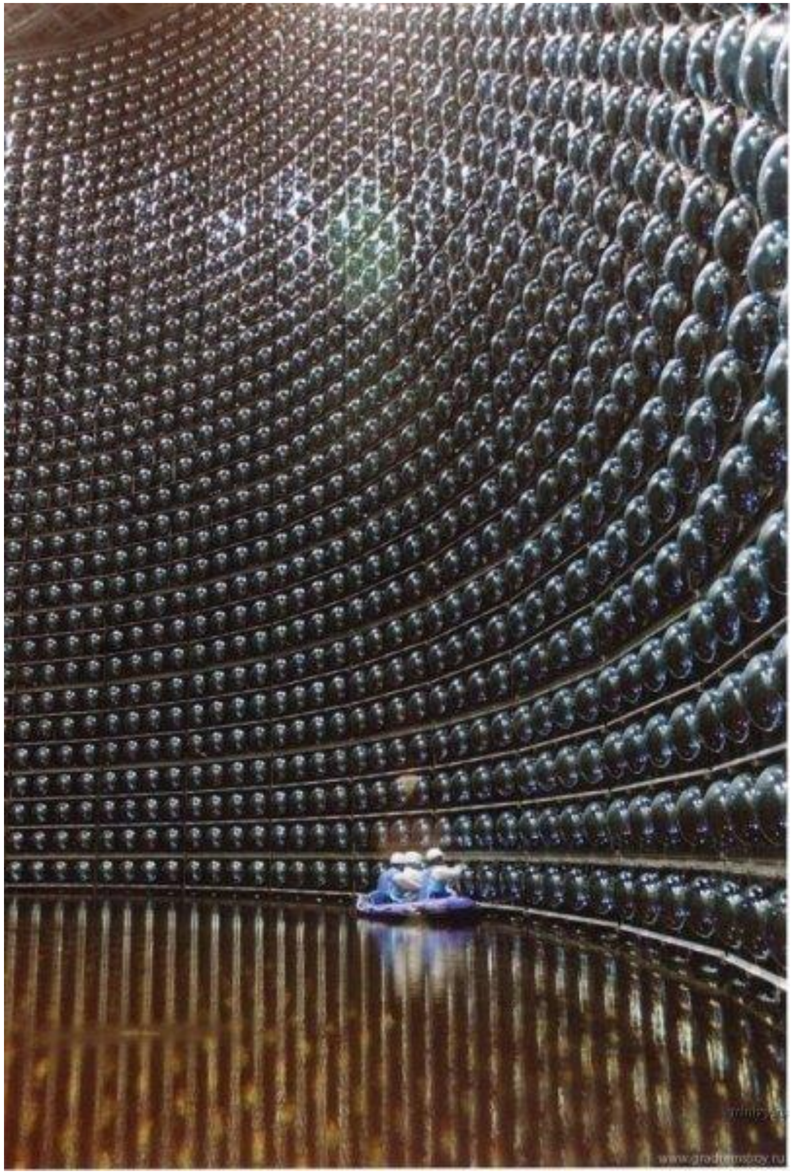
KamiokaNDE and SuperKamiokaNDE

The first one, KamiokaNDE-II, started in 1988 in Japan (at the 1000 m depth in the Kamioka mine). Water Cherenkov detector

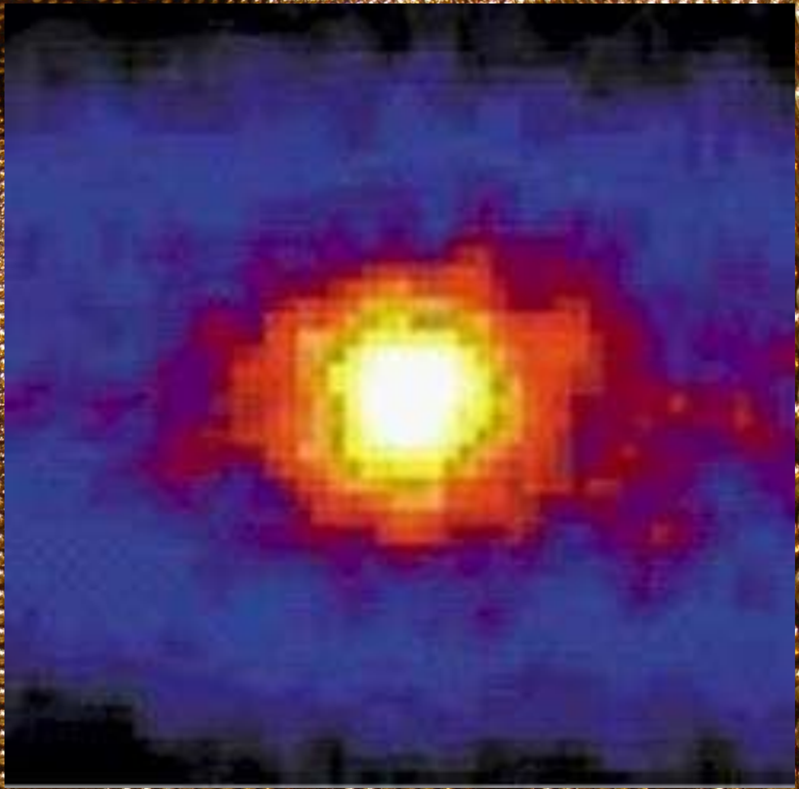
$$\nu + e^- \rightarrow \nu + e^-$$

- **SuperKamiokande** (or Super-K) — 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

Some pictures



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



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.

KamiokaNDE and SuperKamiokaNDE results

Detector		years	FV mass	PMT Coverage	E_{Thr} MeV	Result [$x10^6$ $sm^{-2}s^{-1}$]
KamiokaNDE-II+ KamiokaNDE-III		87-90 90-95 2079 d	H_20 3 kt	20% 25%	7.0	$2.82^{+0.25}_{-0.24}\pm0.27$
SuperK	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-now 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)
		2860 d				2.29±0.02±0.04 (2018)
HyperKamiokaNDE		?	1 Mt	20%	4.5-7.0	Project

SK in 2018 had in total 5695 days of data

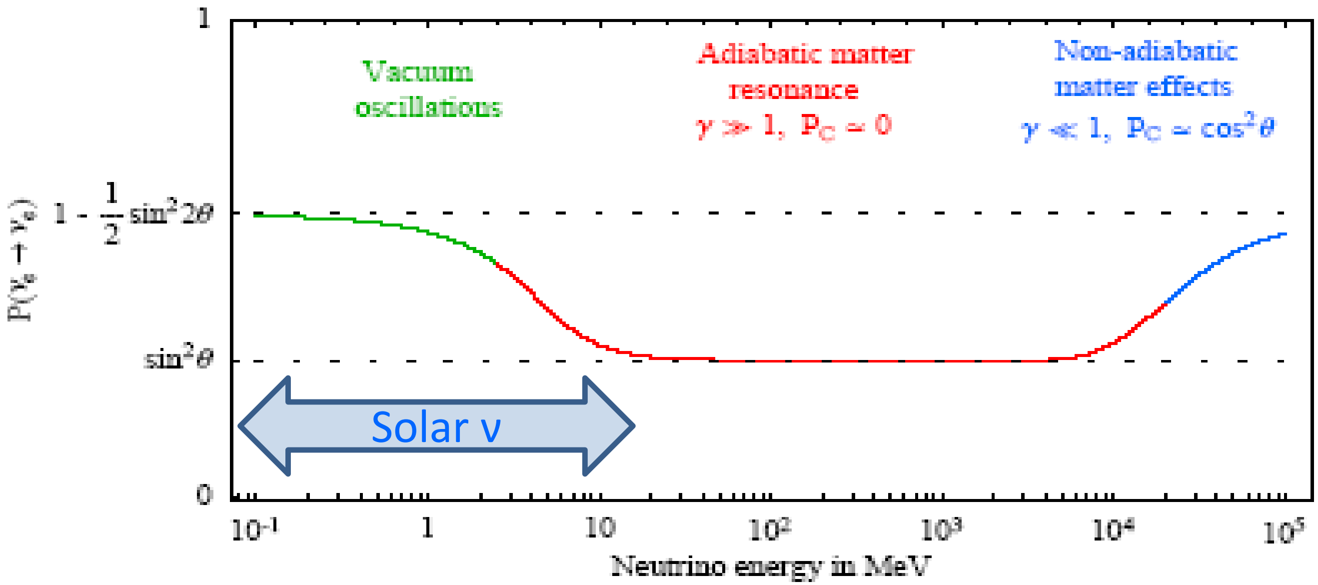
Combined (2016) : 2.345±0.014±0.036 (2016) [1.6%]

Solar Neutrino Problem

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

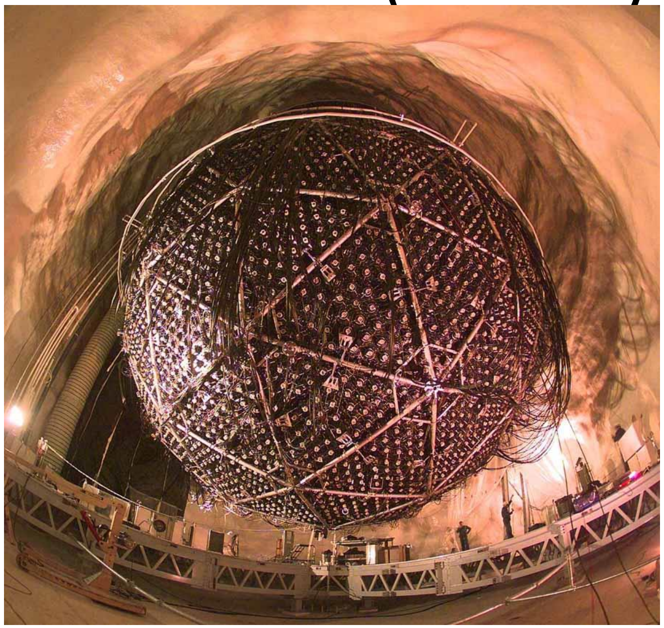
A lot of solutions have been proposed, now mainly of historical interest.

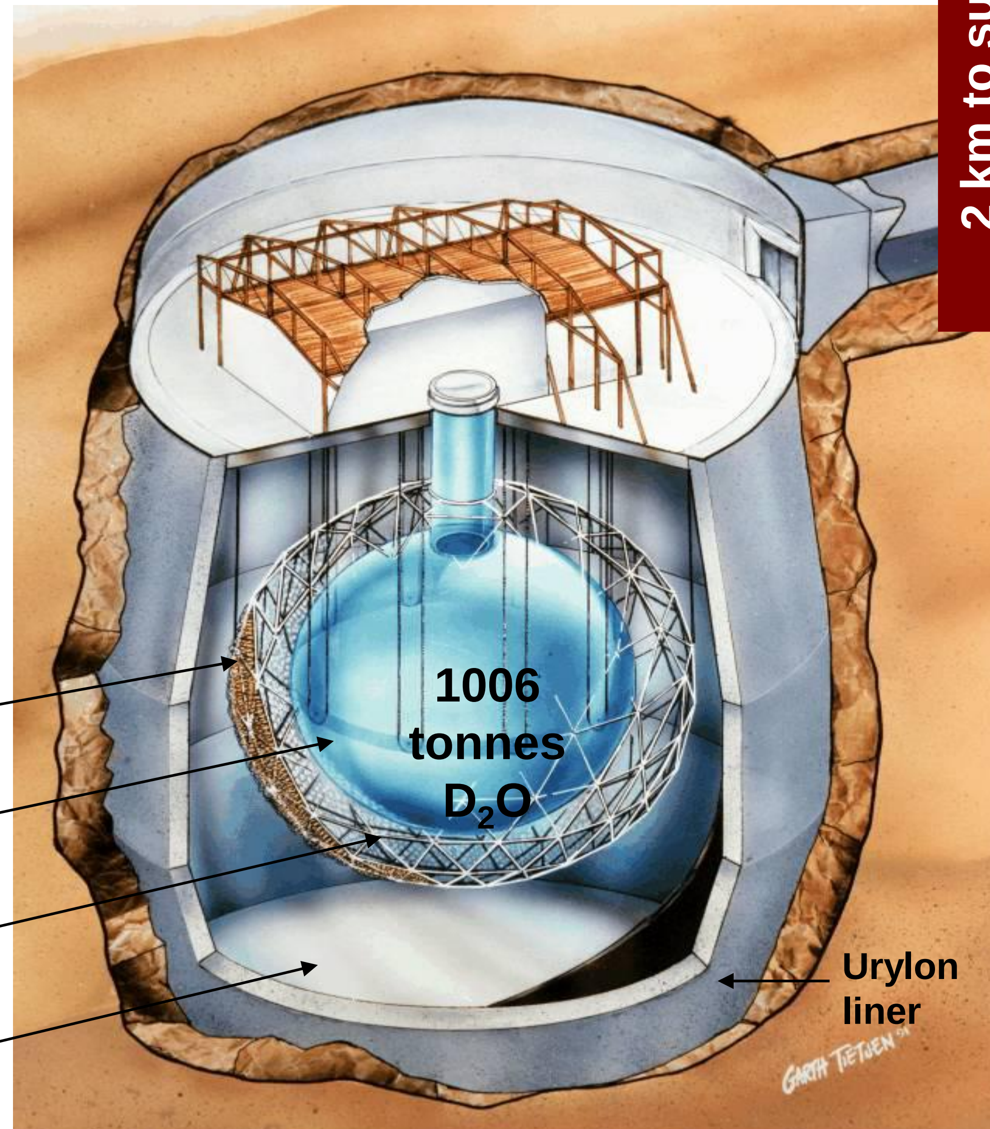
MSW/LMA has been established as the true solution of the SNP (take a chance to hear the details from the author of the theory this night)



Missing neutrino were found by SNO (Sudbury Neutrino Observatory)

2 km to surface





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

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

heavy water Cherenkov detector

10 neutrino events/day

Neutrino detection in heavy water Cherenkov detector

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

- measurement of ν_e energy
- Weak directionality:

$$1 - 0.340\cos\theta$$

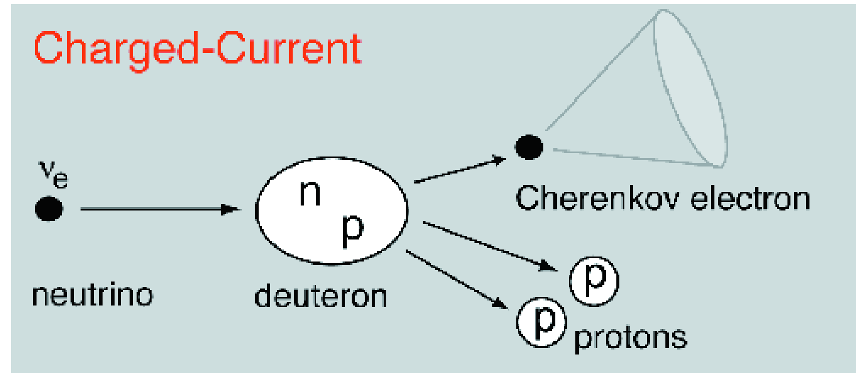
NC $\nu_x + d \rightarrow p + n + \nu_x$

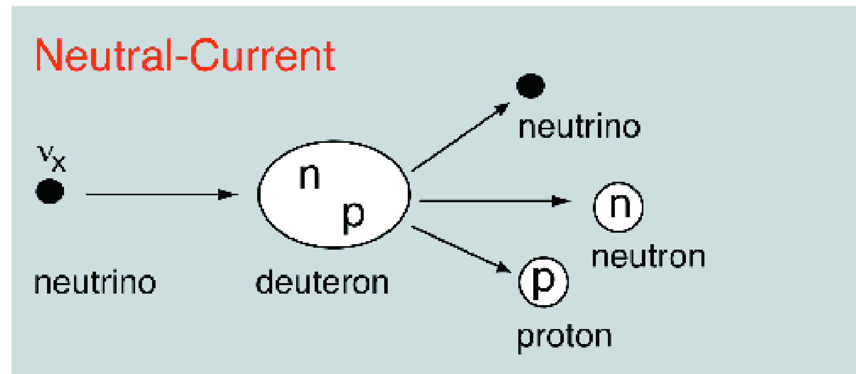
- Measurement of the total ^8B ν flux
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

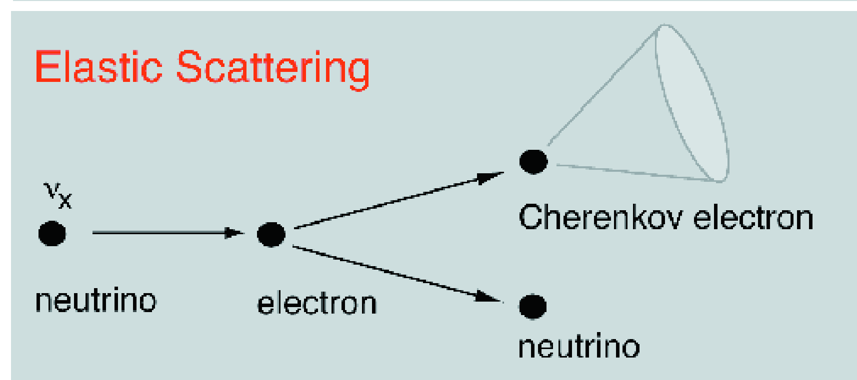
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low statistics
- $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$
- Strong directionality:

$$\theta_e \leq 18^\circ \quad (T_e = 10\text{ MeV})$$

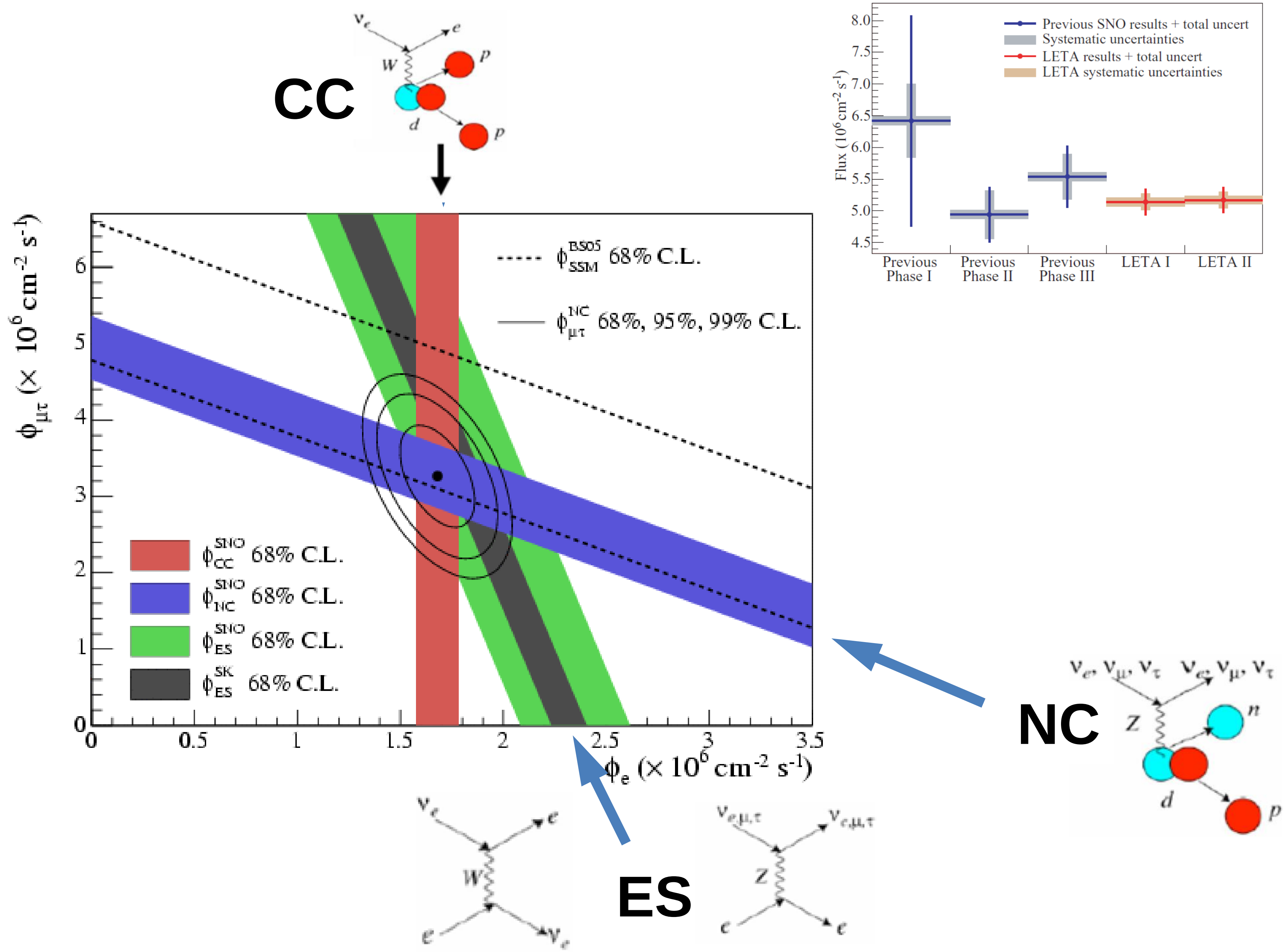






Neutrons detection in different phases of the SNO experiment

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



CC
NC
ES
ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
ϕ^{SNO}_{CC} 68% C.L.
ϕ^{SNO}_{NC} 68% C.L.
ϕ^{SNO}_{ES} 68% C.L.
ϕ^{SK}_{ES} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
Previous SNO results + total uncert
Systematic uncertainties
LETA results + total uncert
LETA systematic uncertainties
Flux (10^6cm^{-2} s^{-1})
Previous Phase I
Previous Phase II
Previous Phase III
LETA I
LETA II

SNO results

Phase		Target, mass	Method	Threshold [MeV]	Result [$\times 10^6$ sm^{-2}s^{-1}]
I	99-01 306.4 d	$D_2 0$ 1006 t	$\nu_e + d \rightarrow p + p + e^-$ (CC)-1.4 MeV $\nu_x + d \rightarrow p + n + \nu_x$ (NC)-2.22 MeV $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)	5.0	$1.76 \pm 0.05 \pm 0.09$ (CC) $2.39^{+0.24}_{-0.23}$ (ES) $5.09^{+0.44}_{-0.43}$ (NC)
II	01-04 391d	+NaCl 2t	$^{35}Cl + n \rightarrow {}^{36}Cl + 8.6$ MeV (2-4 γ)	5.5	$1.72 \pm 0.05 \pm 0.11$ (CC) $2.34 \pm 0.23^{+0.15}_{-0.14}$ (ES) $4.81 \pm 0.19^{+0.28}_{-0.27}$ (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	+^{3}He 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)

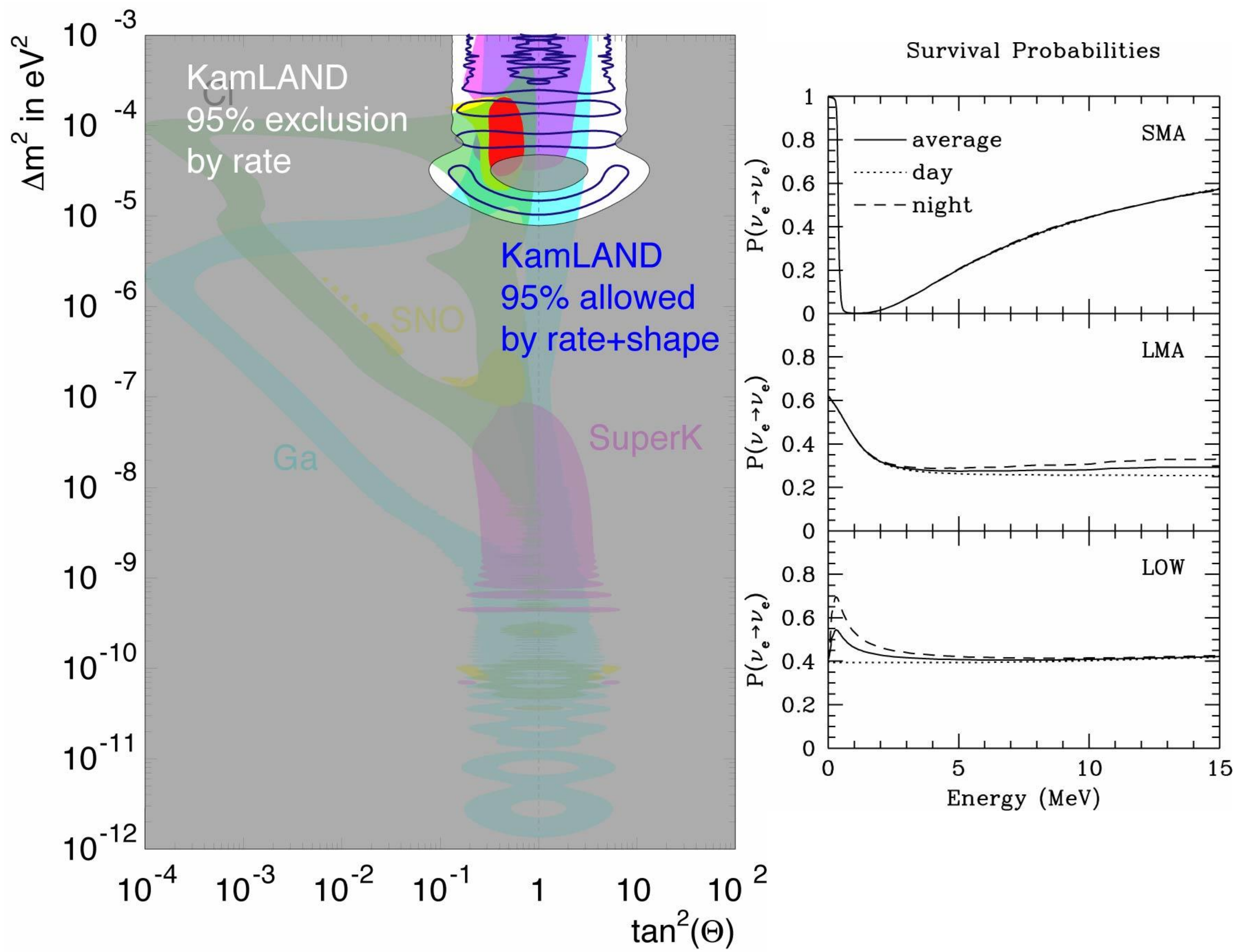
^{8}B flux ($5.25 \pm 3.7\%$)$\times 10^6$ sm^{-2}s^{-1}

Status of MSW solution in 2002

Before SNO

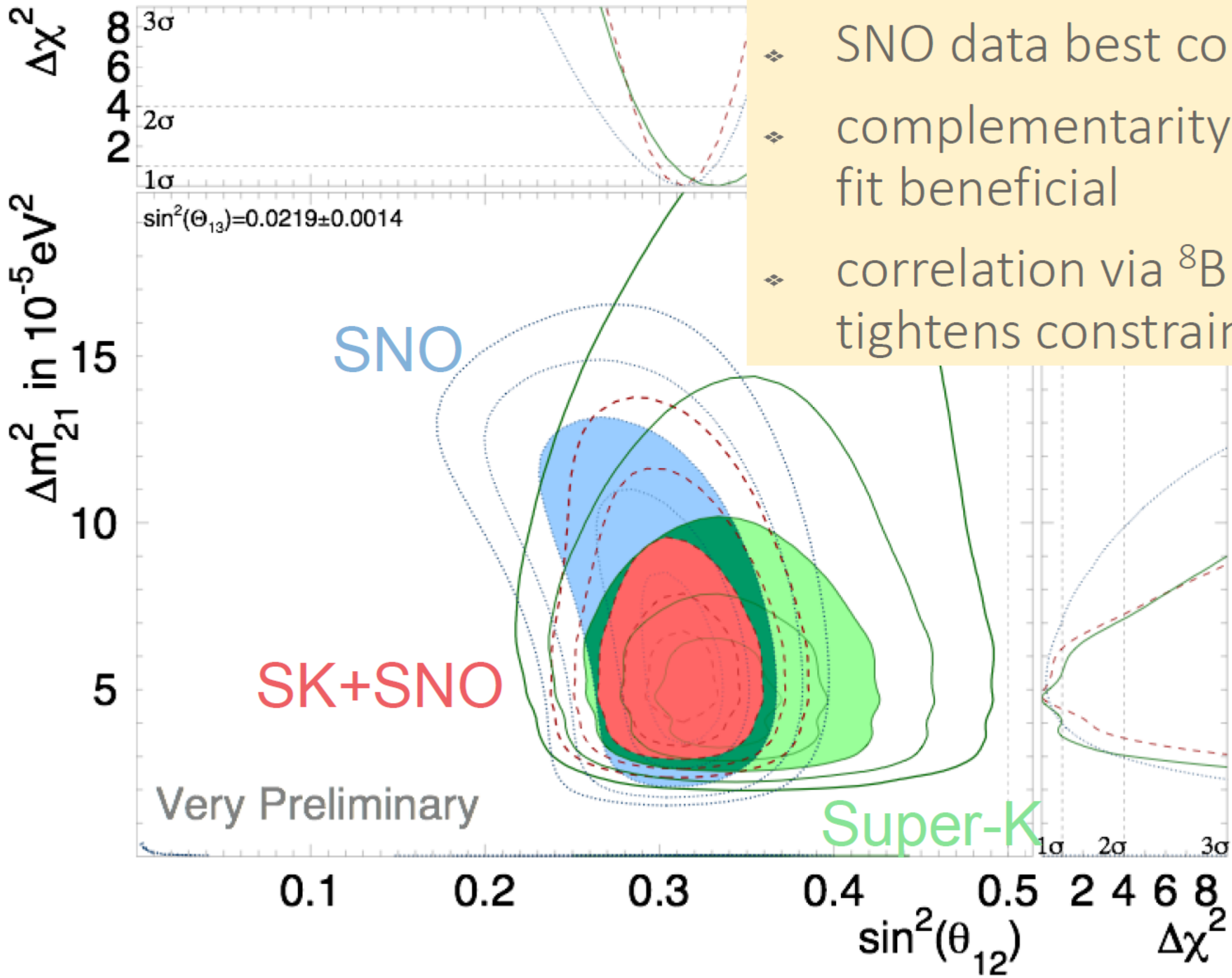
April 2002
SNO

December 2002
KamLAND



Solar ν Angle θ_{12} & Mass^2 Difference

- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- complementarity makes combined fit beneficial
- correlation via ^{8}B flux further tightens constraints

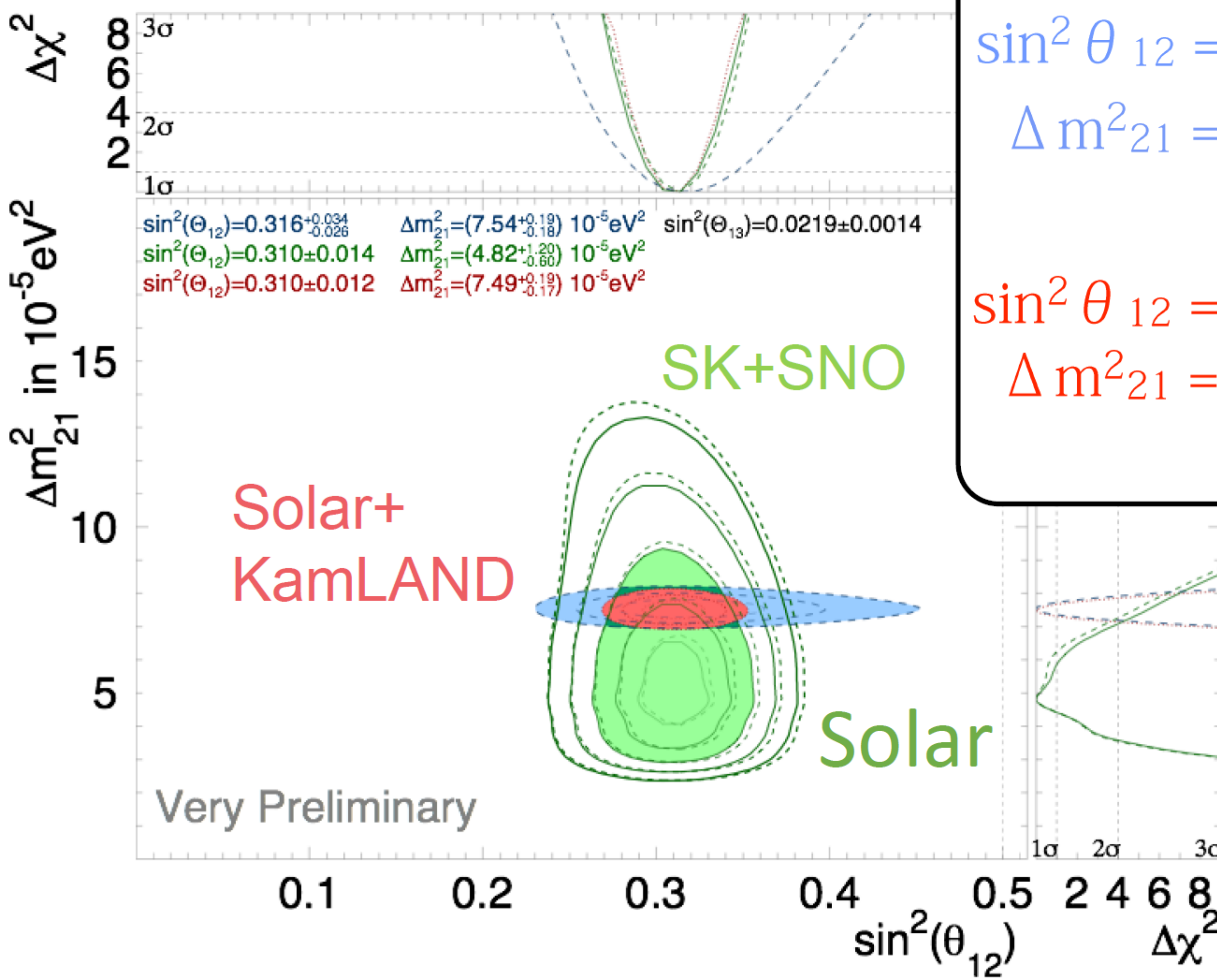


Solar ν Angle θ_{12} & Ma

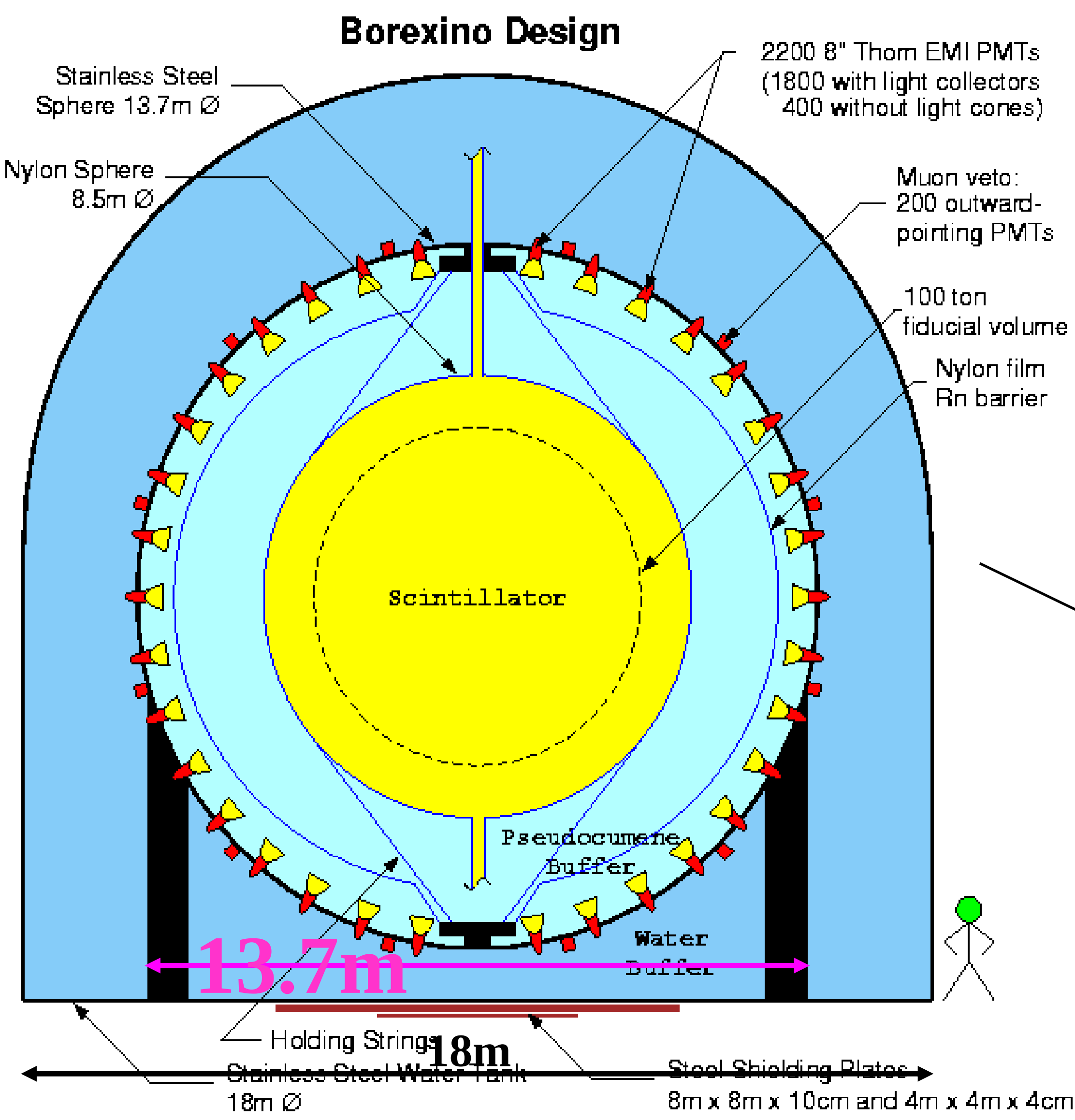
$\sin^2\theta_{12} = 0.310 \pm 0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5}\mathrm{eV}^2$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$

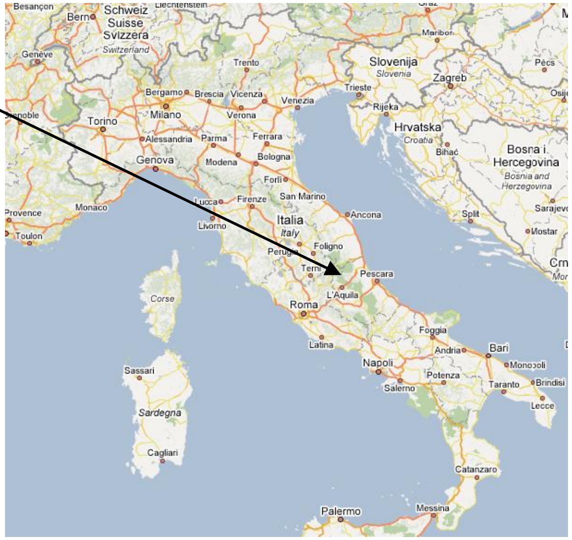
$\sin^2\theta_{12} = 0.310 \pm 0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$



BOREXINO (in operation from May,2007)



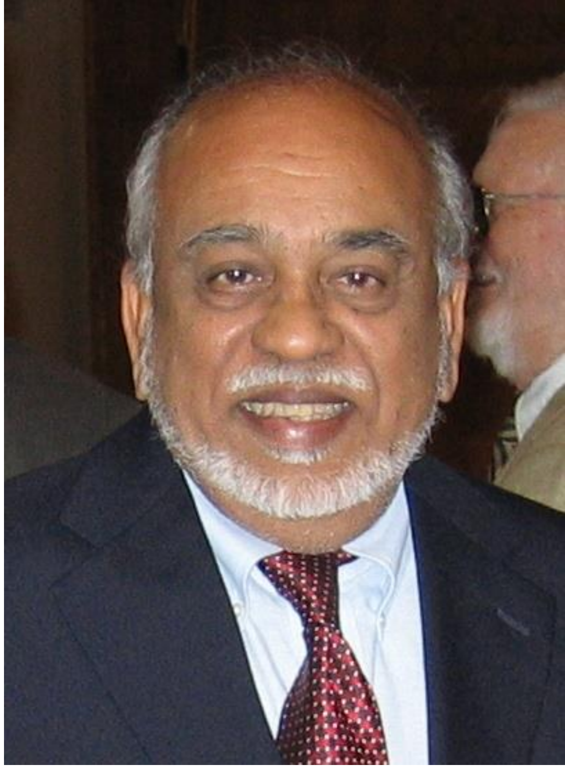
- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with low threshold (~200 keV)
- Outer muon detector



The original BOREX proposal was based on B-loaded scintillator “

R.S.Raghavan, S.Pakvasa, Phys. Rev. D 37, 849 - 857 (1988)
"Probing the nature of the neutrino: The boron solar-neutrino experiment"

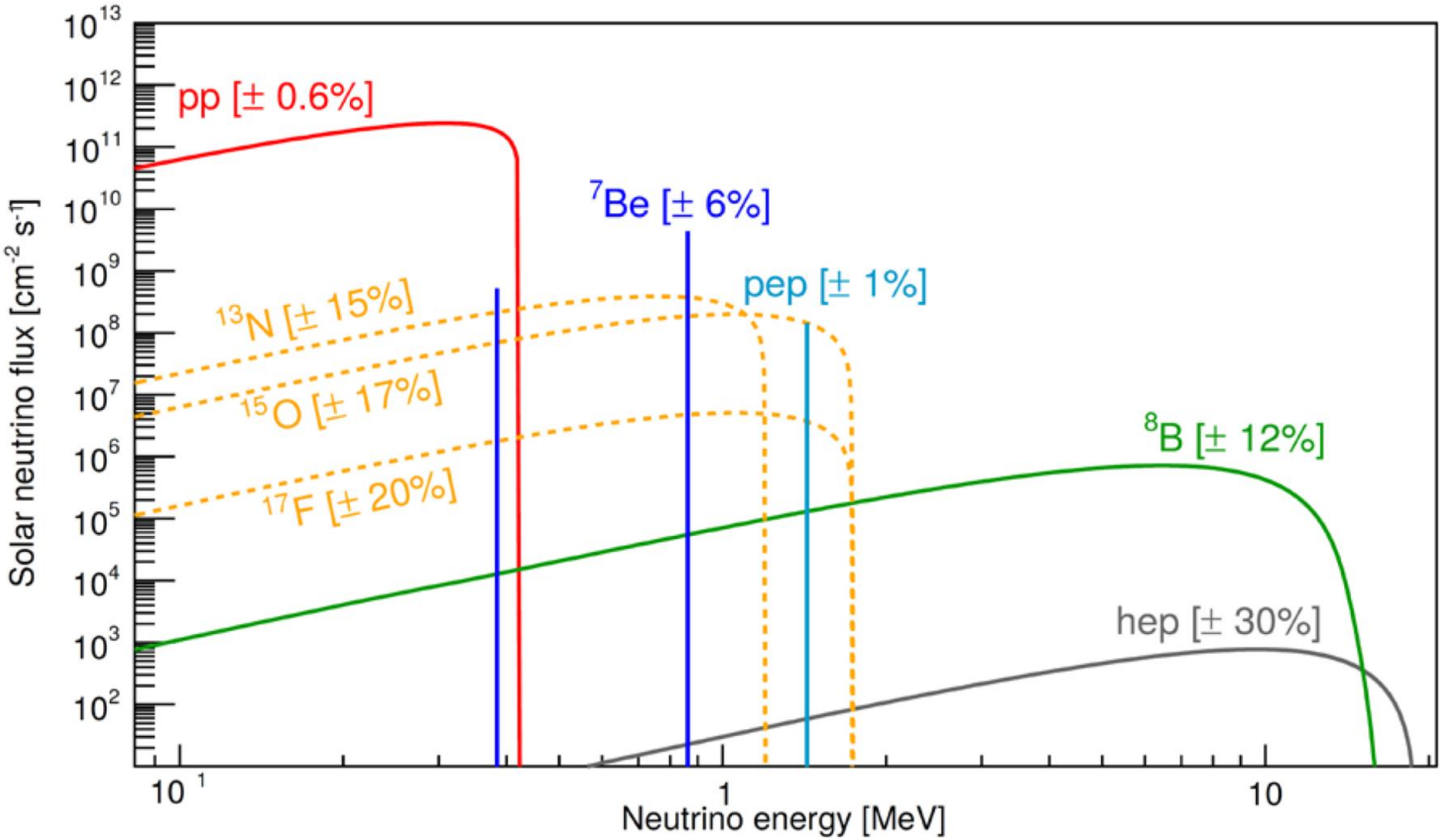
With a welter of neutrino scenarios and uncertain solar models to be unraveled, can solar-neutrino experiments really break new ground in neutrino physics? A new solar-neutrino detector BOREX, based on the nuclide ^{11}B, promises the tools for a definitive exploration of the nature of the neutrino and 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.



Ramaswami (Raju) S. Raghavan

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

Solar neutrino spectra



~1 Bq

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

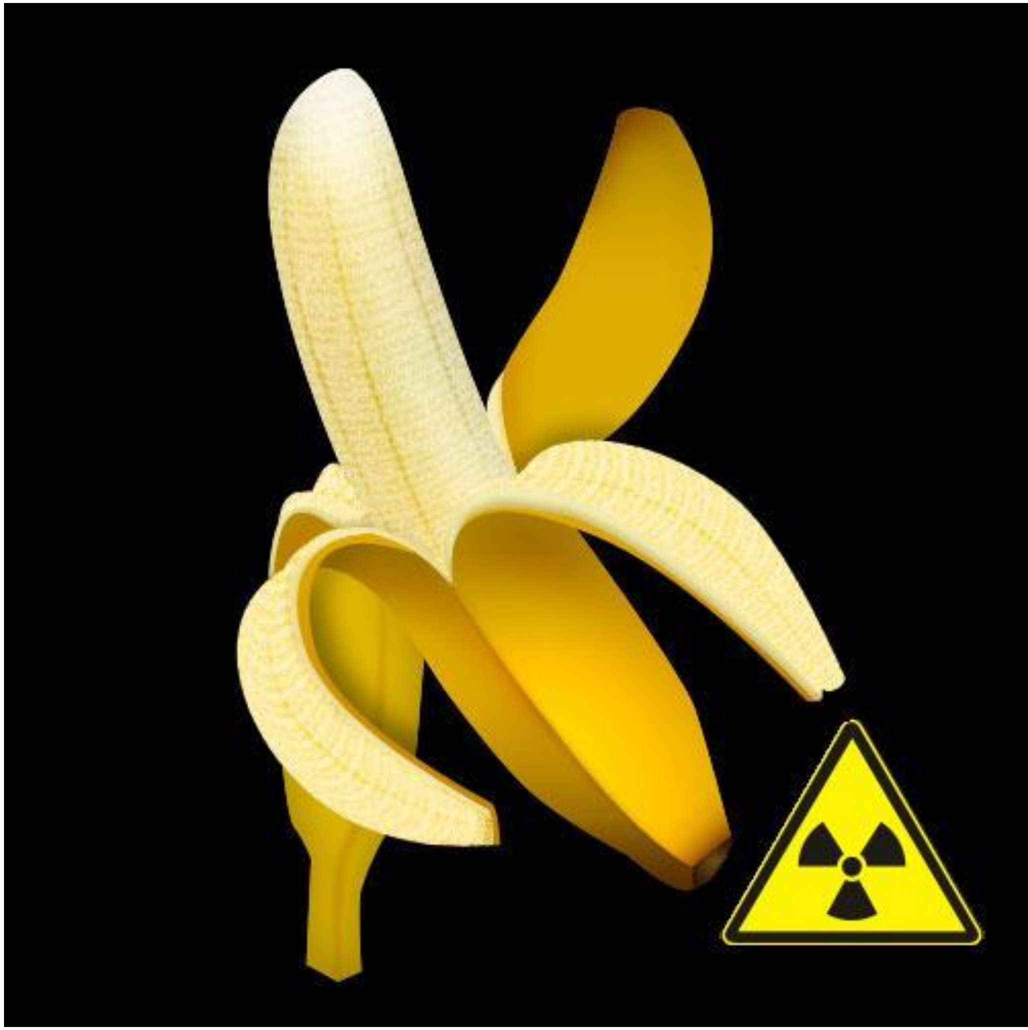
Low energy->no Cherenkov light->No directionality,
no other tags-> extremely pure scintillator is needed

Liquid Scintillator Radiopurity

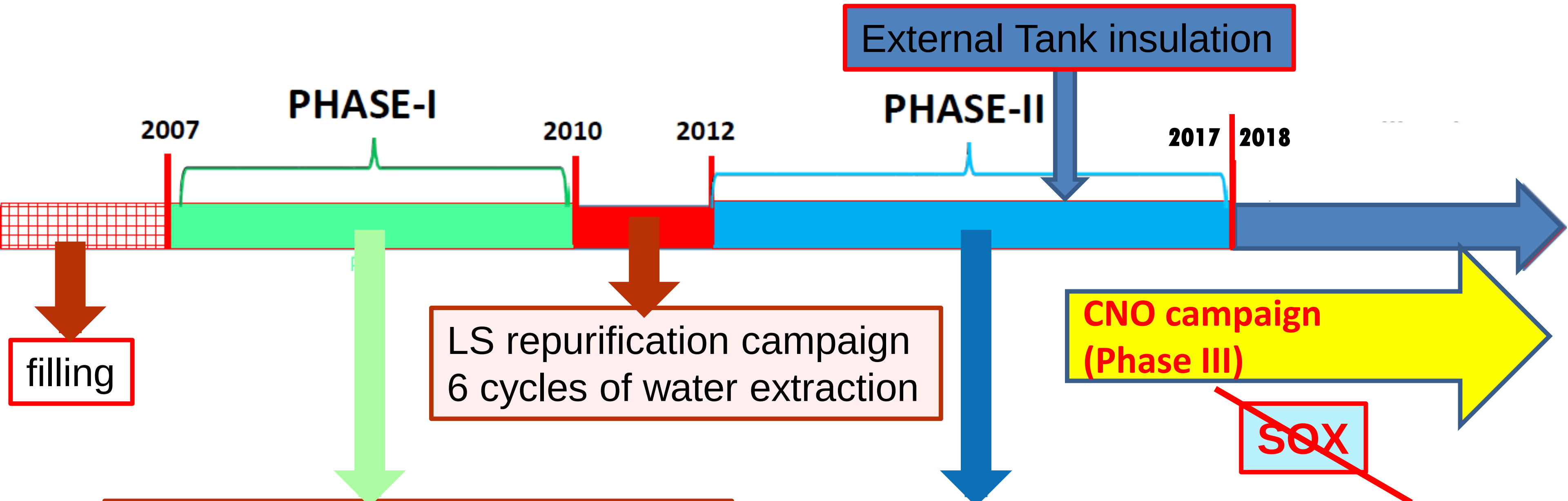
Isotope	Typical abundance (source)	Borexino goals	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	10^{-12} (cosmogenic)	~10^{-18}	$2.7·10^{-18}$	$2.7·10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	10^{-6}-10^{-5} (dust)	~10^{-16} (1 μBq/t)	$(1.6±0.1)·10^{-17}$	<$9.5· 10^{-20}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	10^{-6}-10^{-5} (dust)	~10^{-16}	$(6.8±1.5)· 10^{-18}$	<$7.2· 10^{-19}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	100 atoms/cm^3 (air)	10	1	0.1
^{40}K, g[K_{nat}]/g	$2·10^{-6}$ (dust)	~10^{-15}	<$1.7·10^{-15}$ (95%)	---
^{210}Po, ev/d/t	Surface contamination	~10^{-2}	80 (initial), $T_{1/2}$=134 days;	2 (initial)→0.2
^{210}Bi, ev/d/100 t	Inequilibrium with ^{222}Rn or ^{210}Pb	Not specified	20-70	~20
^{85}Kr ev/d/100 t	1 Bq/m^3 (technogenic, air)	~1	30.4±5 cpd/100t	6.8±1.8
^{39}Ar ev/d/100 t	17 mBq/m^3 (cosmogenic in air)	~1	<<^{85}Kr	

Banana equivalent

- **1 gramm of natural K : 32 Bq ^{40}K**
- **19 Bq in 150 g banana.**
- **^{40}K content in Borexino is <$2.4x10^{-7}$ (95% C.L.) of banana equivalent (or 36 μg)**



Borexino since the start of the data taking

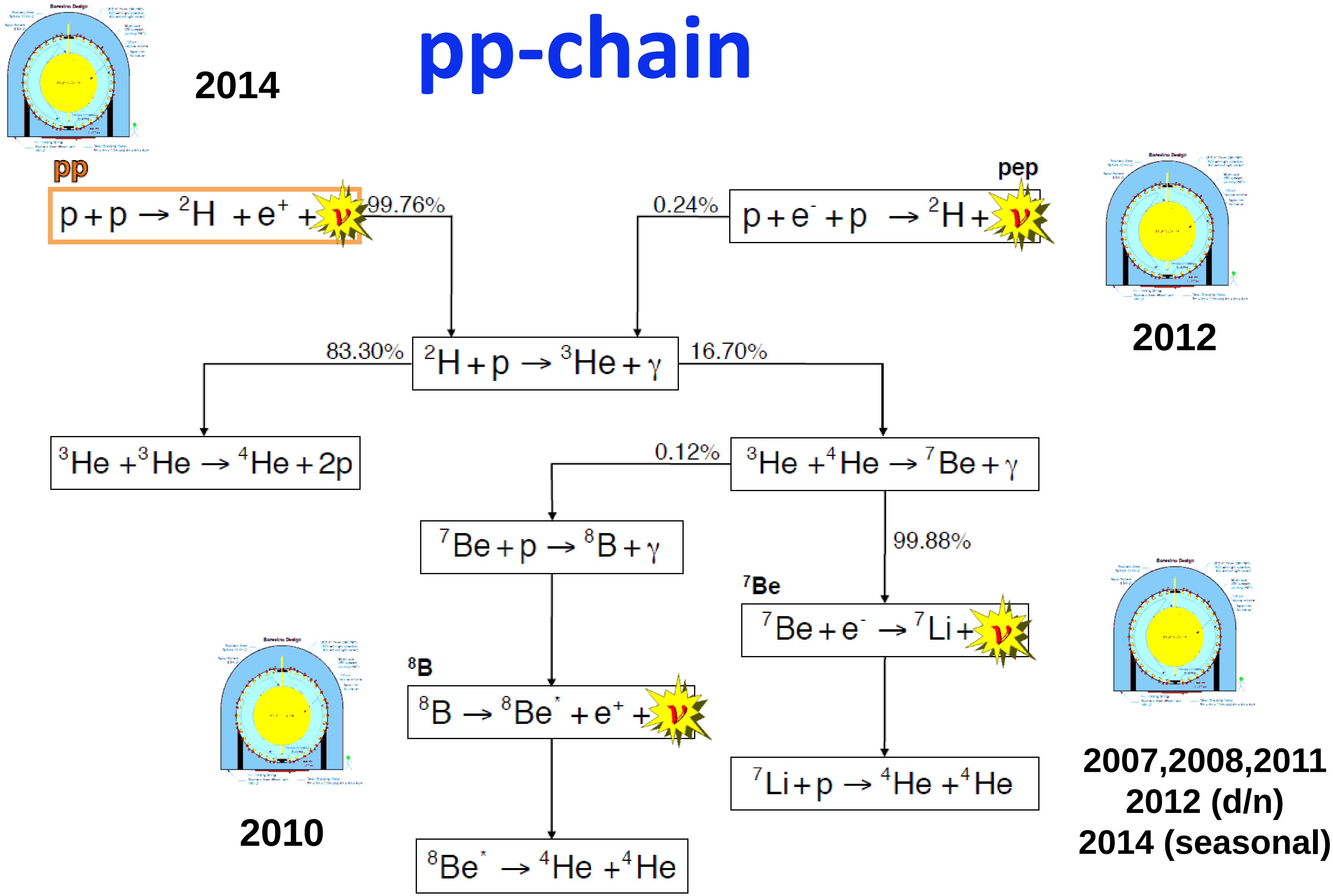


- R(^{7}Be) + D/N
- R(pep) – first observation
- R(^{8}B)– first with LS
- R(CNO) – limit

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(^{8}B)–improved
- geo- ν
- ν magnetic moment
- NSI (under study)
- rare processes

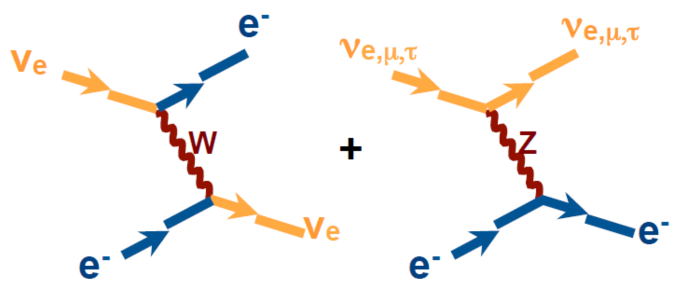
pp-chain



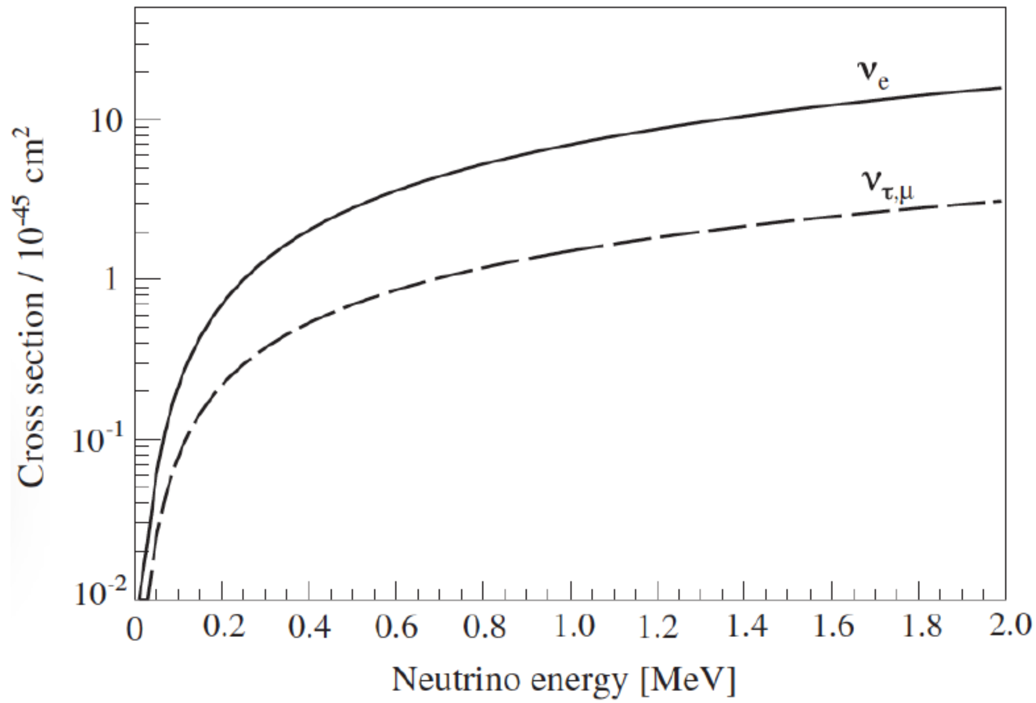
2014+ → Phase II data used; the last update of the results published in 2018

Detection

Neutrino detection:
elastic scattering off electrons



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



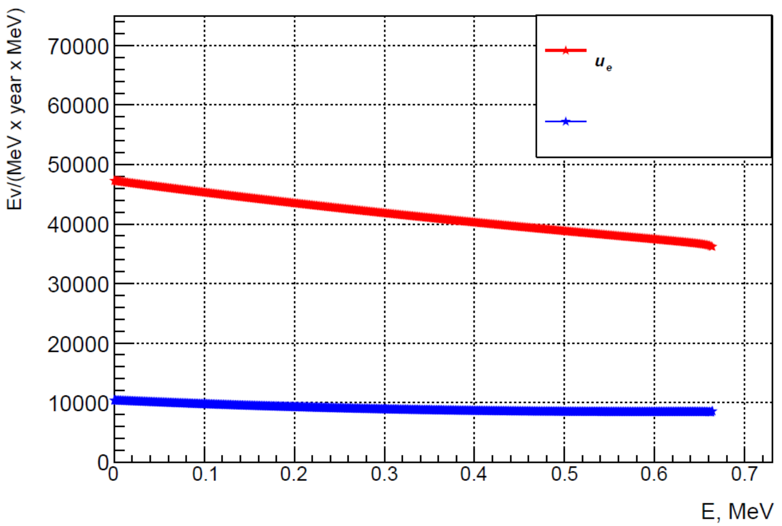
Detection

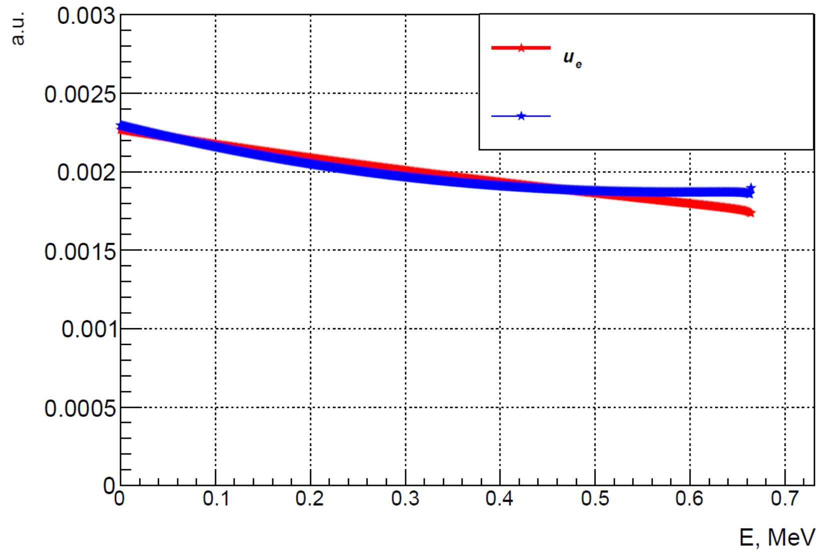
- **Detected signal contains a mixure of both contributions :**

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

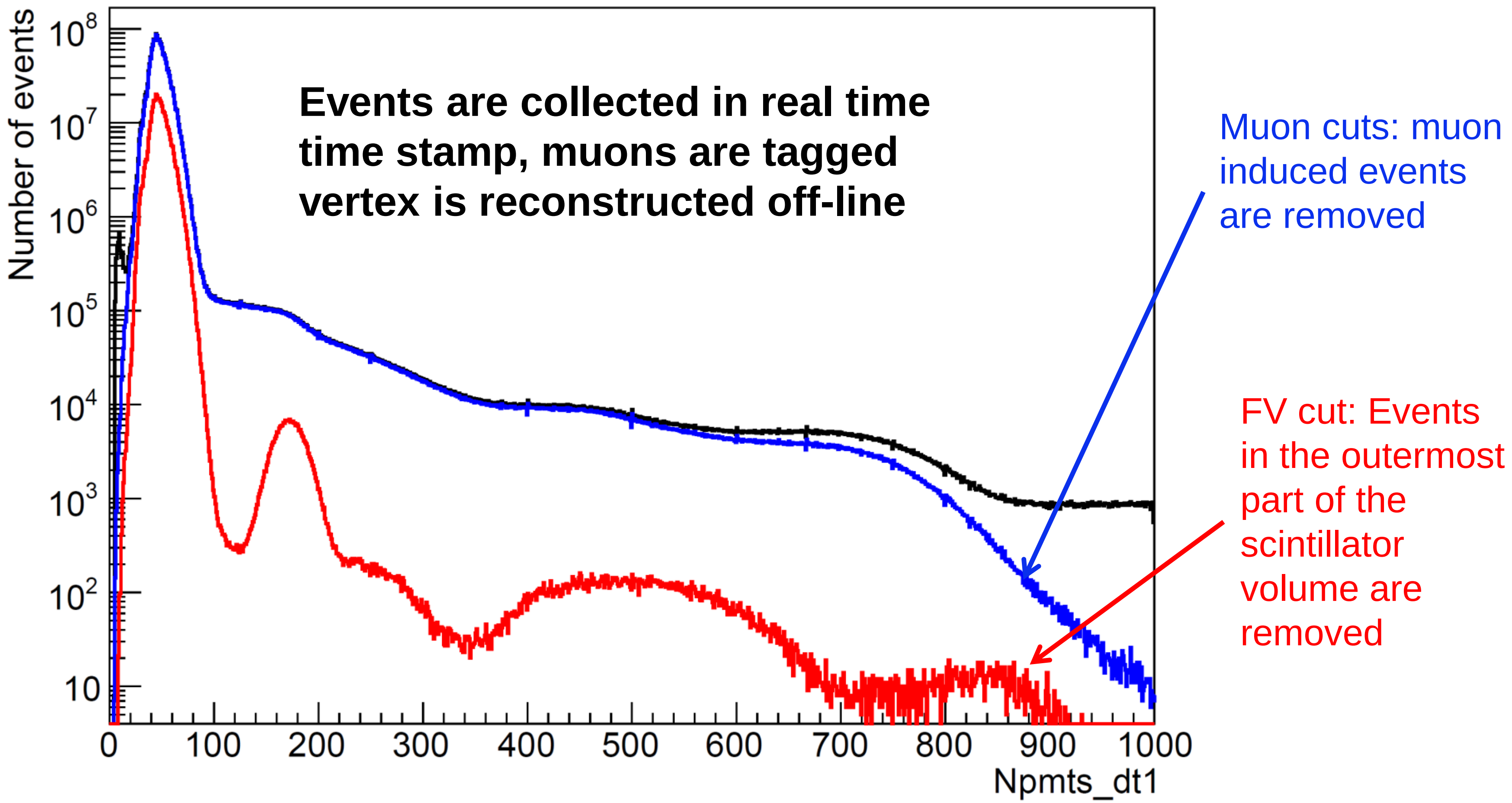
- **Elastic scattering cross section for monoenergetic ν has "step-like" form (quasi-Compton) with** $T_{max} = \frac{E_\nu}{1+\frac{m_e}{2E_\nu}}$

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





Data selection for solar neutrino analysis

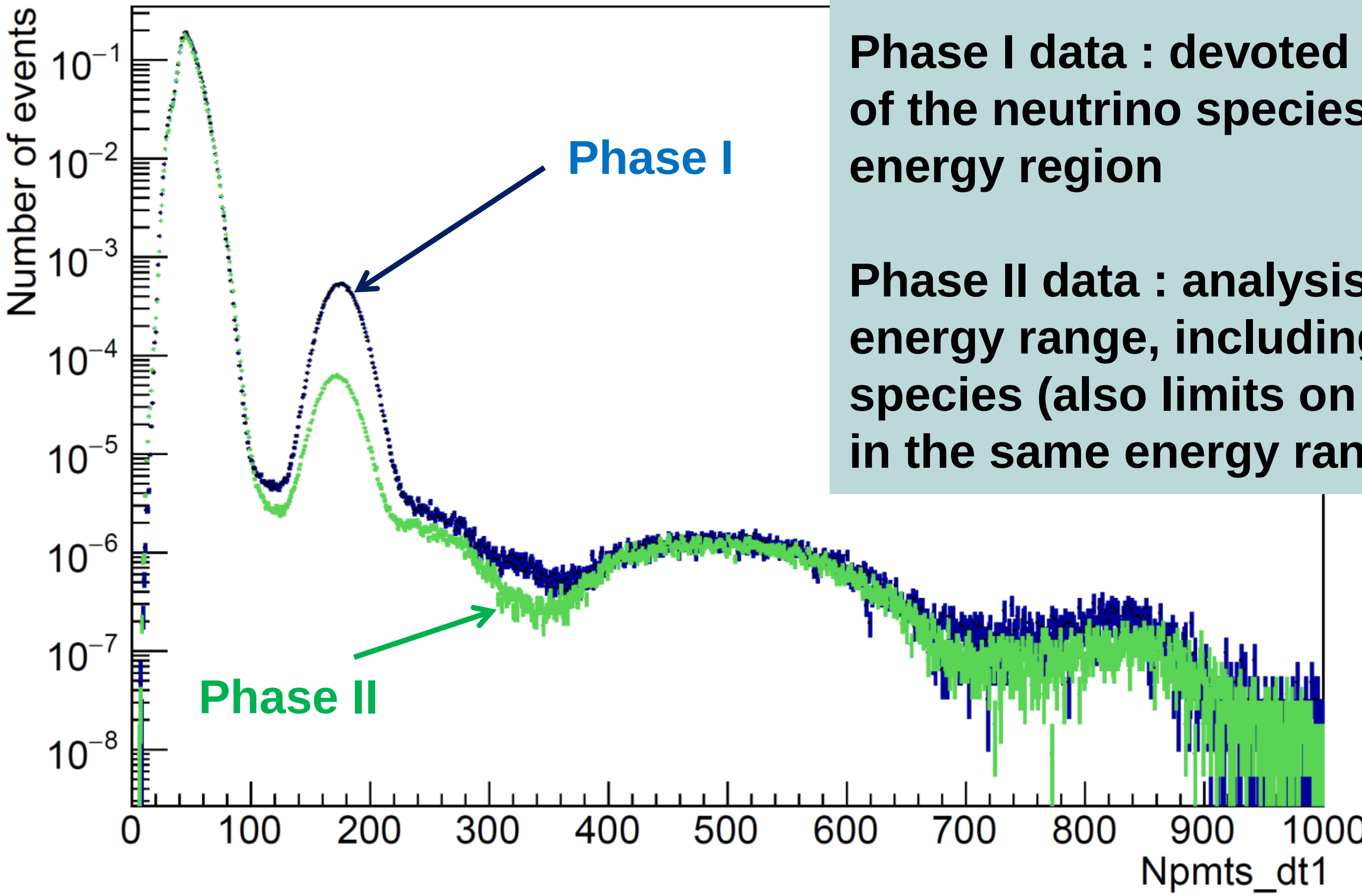


Phase I/Phase II

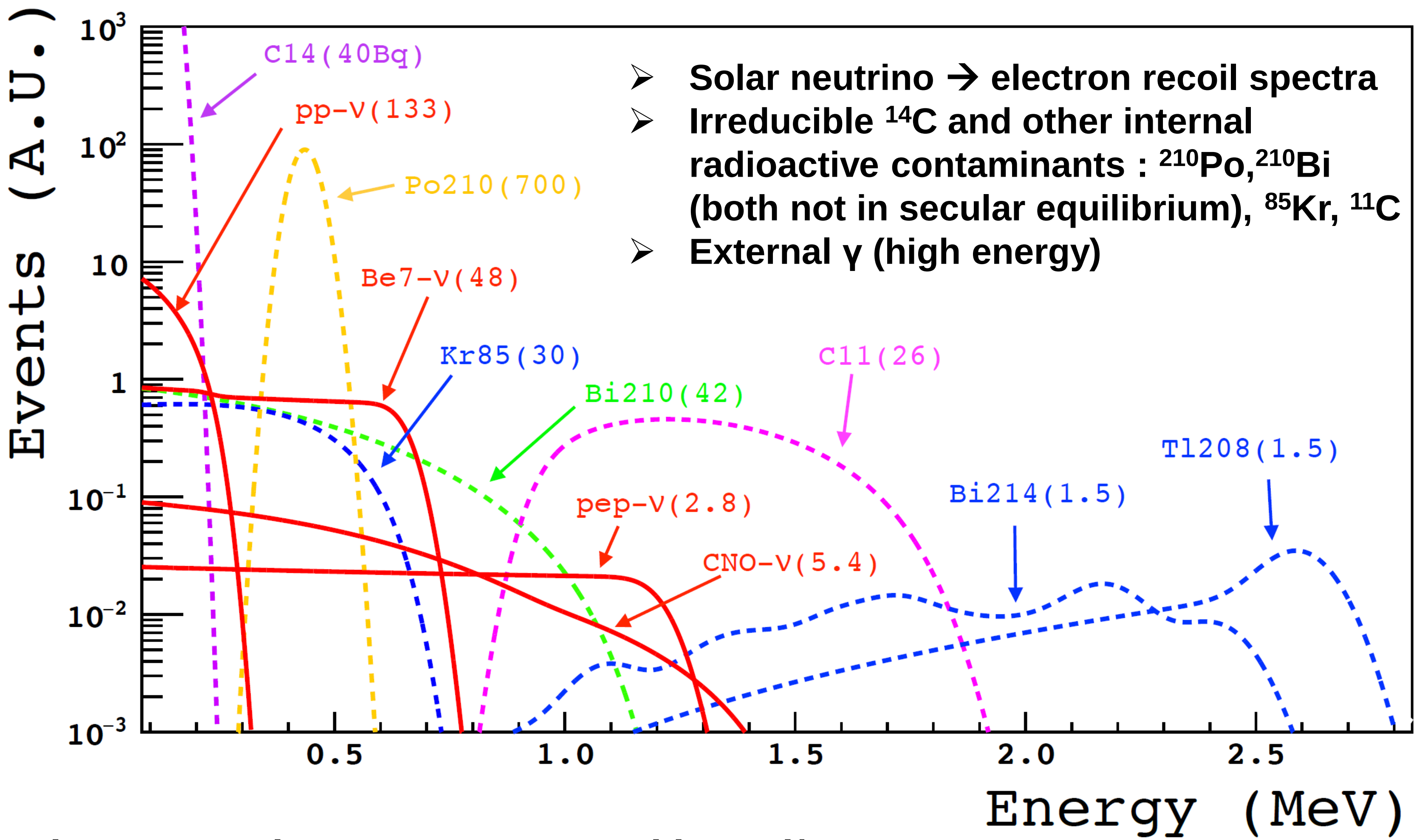
Phase II: lower ^{85}Kr and ^{210}Bi, reduced ^{210}Po

Phase I data : devoted analysis for each of the neutrino species with restricted energy region

Phase II data : analysis in the extended energy range, including pp, ^{7}Be and pep species (also limits on CNO are obtained in the same energy range)



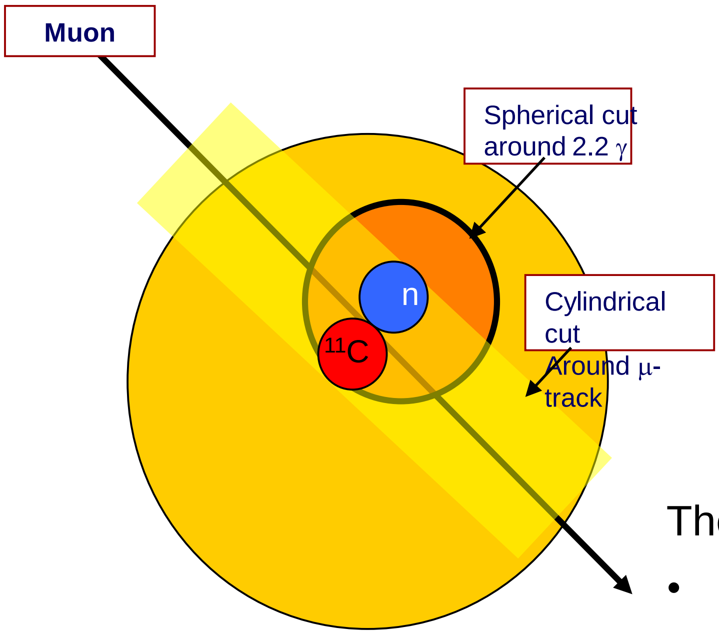
(Expected) contributions to the observed spectrum (MC)



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

MC input counting rates are quoted in cpd/100 t

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



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

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

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

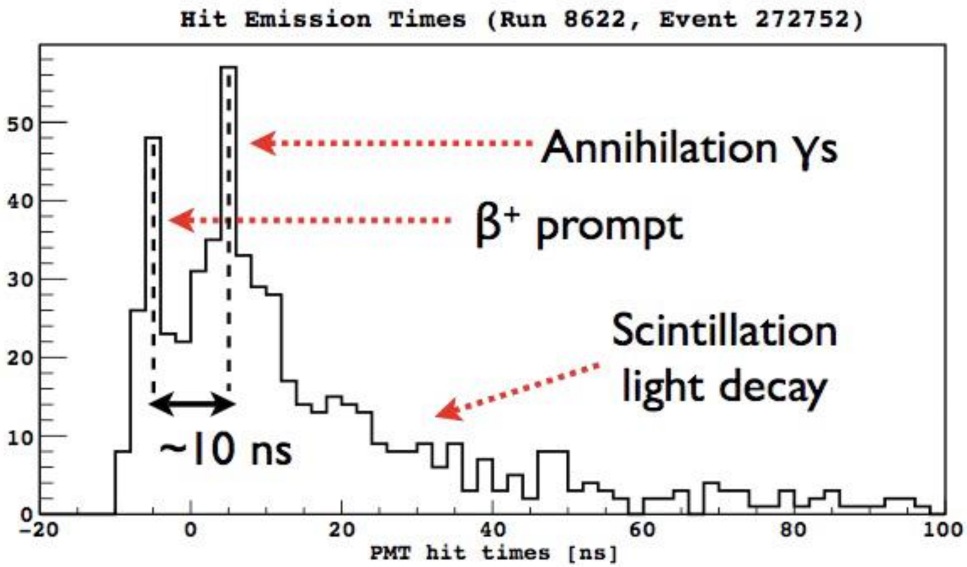
~250 us: $+p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$

The likelihood for ^{11}C tagging is using:

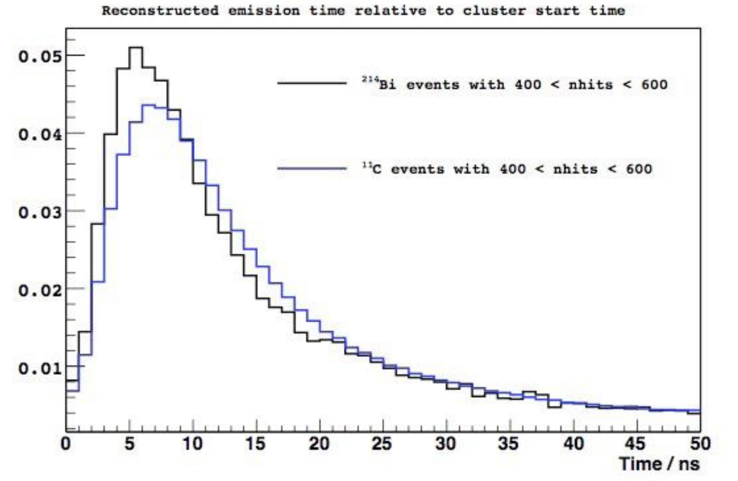
- distance in space and time from the μ-track;
- distance from the neutron;
- neutron multiplicity;
- muon dE/dx and number of muon clusters in an event

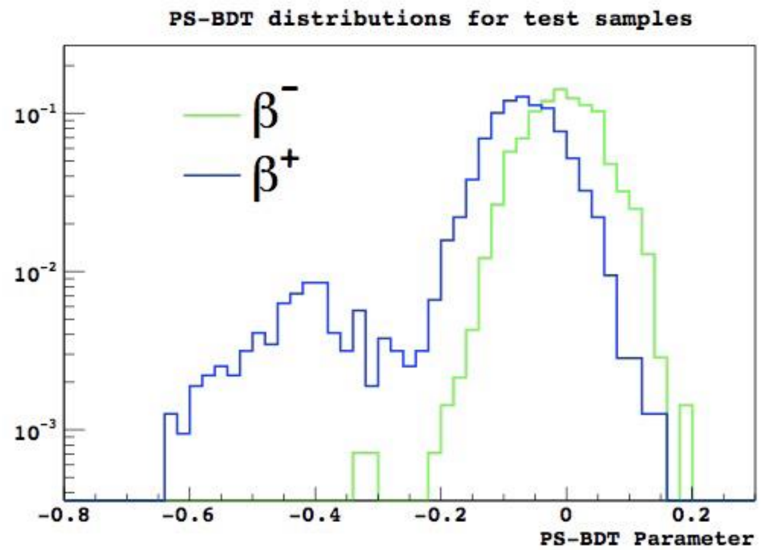
The TFC algorithm has (92±4)% ^{11}C-tagging eciency, while preserving (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum.

e^+/e^- discrimination



50% of β^+ decays give *ortho*-positronium ($t_{1/2} = 3$ ns).





- Use NN (BDT, later MLP) to optimize discrimination.
- Train, test, and build PDF with events cut by TFC.

Multivariate approach

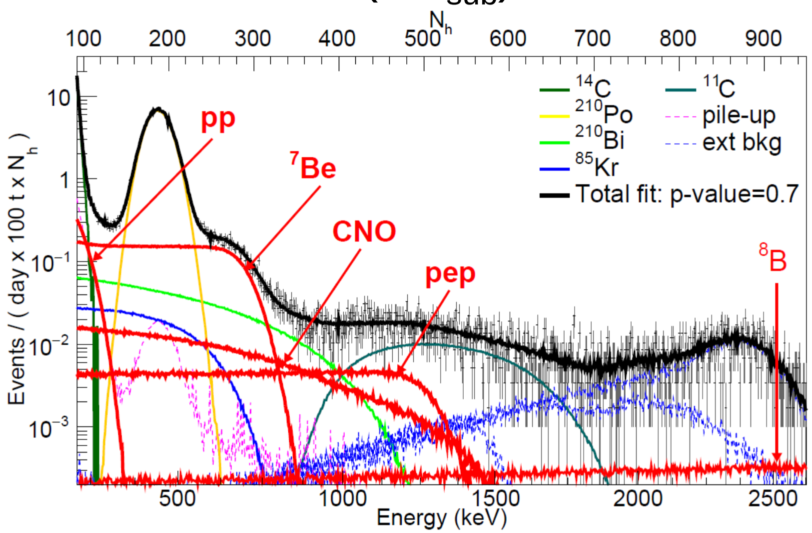
Originally developed for pep-neutrino analysis (2012) to separate electron spectra from overhelming contribution of ^{11}C

Technique consists in including in the likelihood:

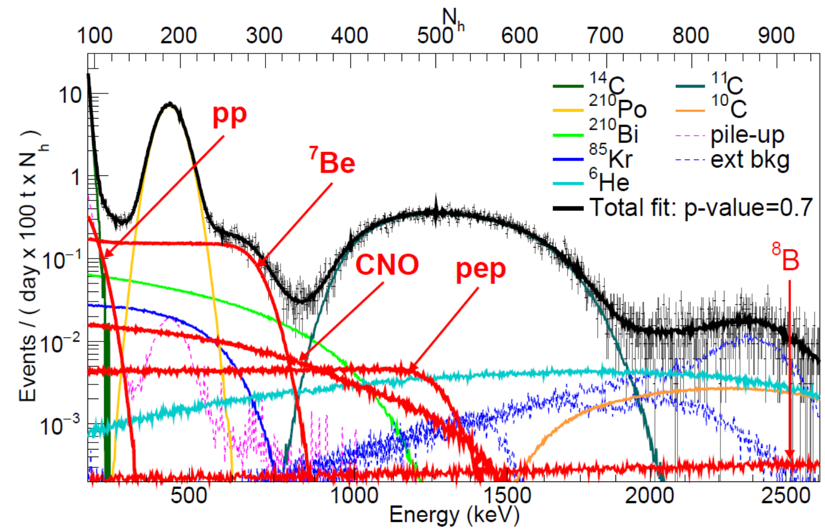
- **Energy spectrum split into complementary TFC-tagged (^{11}C enriched) and TFC-subtracted (^{11}C depleted) spectra →next slide for details.**
- **Pulse-shape discriminator (PS-L_{PR}) of e^+/e^- : (^{11}C decays emiting β^+) based on the difference of the scintillation time profile for e^- and e^+ due to:**
    - **50% of e^+ annihilation is delayed by ortho-positronium formation (τ~3 ns);**
    - **e^+ energy deposit is not point-like because of the two annihilation gammas;**
- **Radial distribution (allows to separate external backgrounds from uniformly distributed signals);**

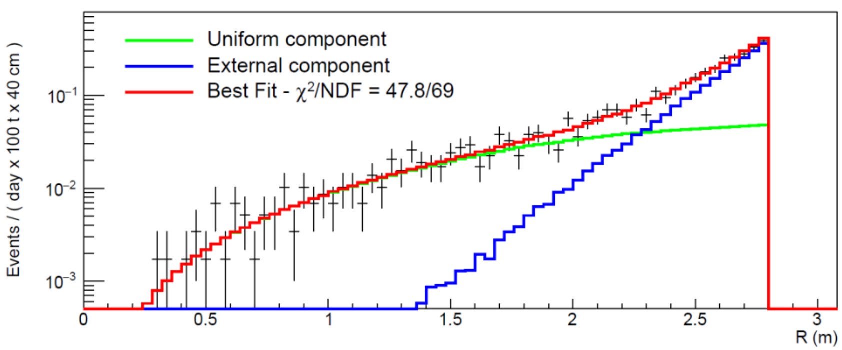
Multivariate fit example

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

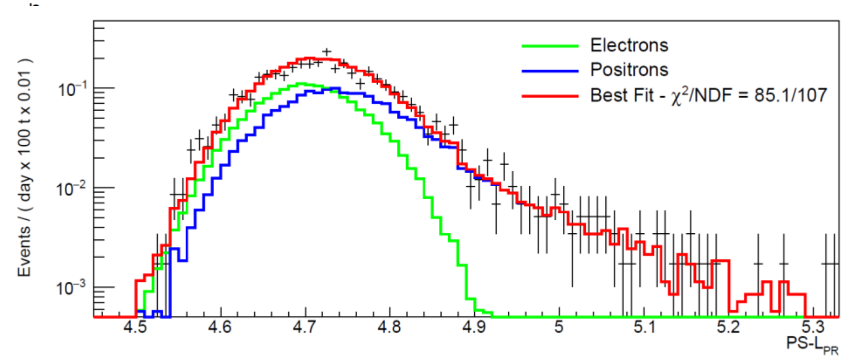


$L(^{11}C_{tag})$ x





L(Rad) x

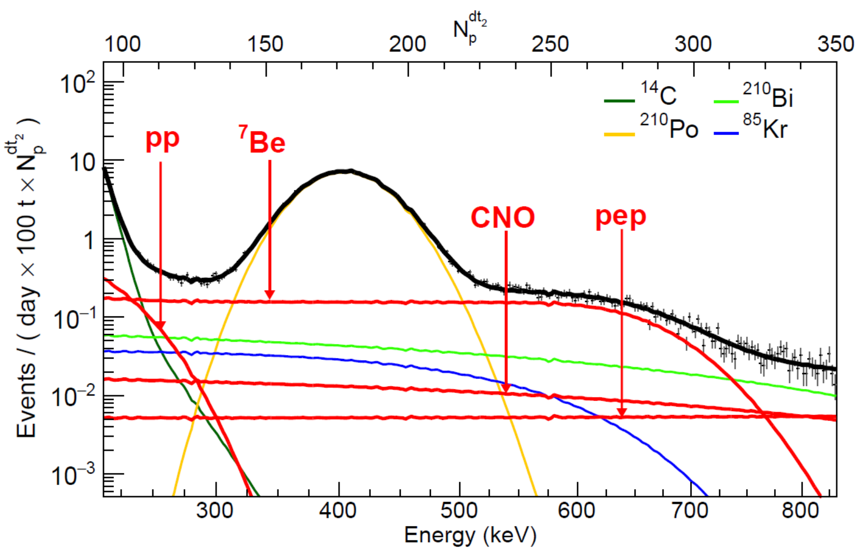


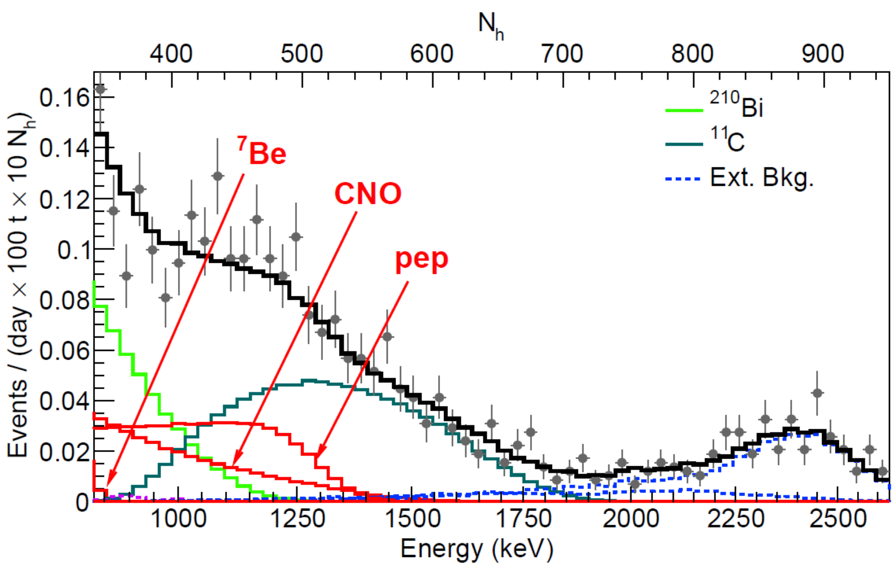
L(PS)

Multivariate fit is sensitive to pp, ^{7}Be and pep contributions.

Note: CNO-neutrino energies are in the ROI and are included in the fit, but the sensitivity is limited because of the similarity to ^{210}Bi spectrum → pp/pep rates ratio constrained in the fit to the predictions of HZ/LZ models

CNO (MSW/LMA):
HZ: (4.91±0.56) cpd/100t
LZ: (3.62±0.37) cpd/100t





Zoom into low-energy part of the spectrum

In this plot pep-neutrino characteristic shoulder is made visible by applying more stringent cuts (R<2.8 m and L_{PS}<4.8)

Results
(2018)

- **Data-set:** Dec 14th 2011- May 21st 2016
- **Total exposure**: 1291.51 days x 71.3 tons
- **Fit range**: (0.19-2.93) MeV

Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	131.0 ± 2.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.1 ± 2.3	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^9$	47.8 ± 2.9	$4.93\,(1 \pm 0.06) \times 10^9$	43.7 ± 2.6	$4.50\,(1 \pm 0.06) \times 10^9$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^8$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^8$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^8$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^8$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^8$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^8$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^8$ (95% C.L.)	4.91 ± 0.56	$4.88\,(1 \pm 0.11) \times 10^8$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^8$

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

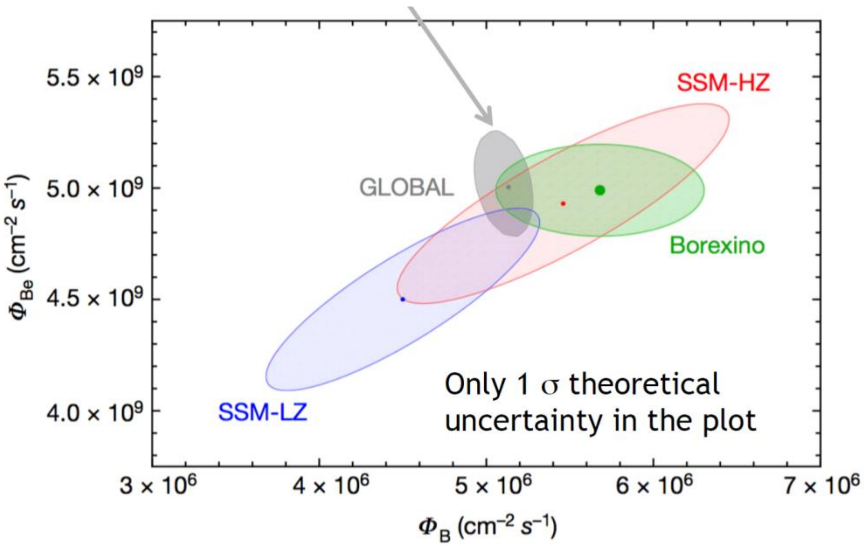
Systematics

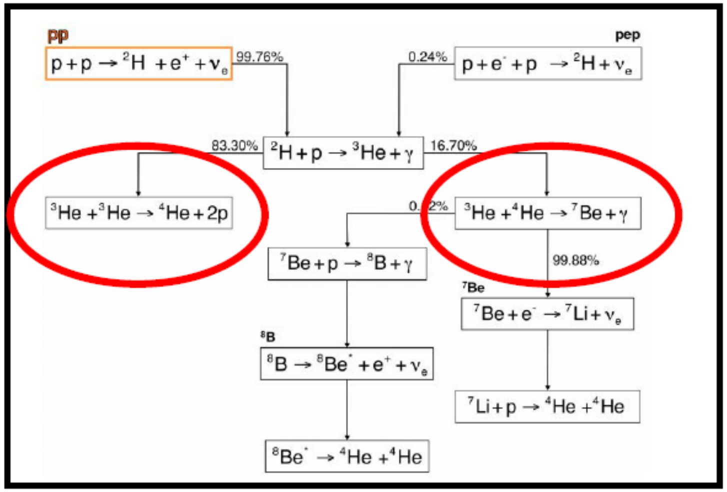
Source of uncertainty	pp −%	pp +%	^{7}Be −%	^{7}Be +%	pep −%	pep +%	
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0	
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4	
Pile-up modeling	-2.5	0.5	0	0	0	0	
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0	
Fit models	-4.5	0.5	-1.0	0.2	-6.8	2.8	^{210}Bi, E-scale, response
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0	**R(^{85}Kr)<7.5 @ 95%**
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	**LS mass**
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	

Borexino results (2018)

Rates	Borexino new results cpd/100t	Uncertainty reduction	Expected HZ cpd/100t	Expected LZ cpd/100t
pp	$134 \pm 10^{+6}_{-10}$	11 -> 9%	131.0 ± 2.4	132.1 ± 2.4
^{7}Be (862+384 keV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	4.7 -> 2.7 %	47.8 ± 2.9	43.7 ± 2.6
Pep (CNO fixed at HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	22 -> 16%	2.74 ± 0.05	2.78 ± 0.05
Pep (CNO fixed at LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	22 -> 16%	2.74 ± 0.05	2.78 ± 0.05
^{8}B (E_{e-}> 3MeV)	$0.223\ ^{+0.015}_{-0016} \pm 0.006$	18 -> 8%	0.211 ± 0.025	0.173 ± 0.021
Hep (E_{e-}> 11MeV)	<0.002 (90% C.L.)		$(8.0 \pm 2.2) \times 10^{-5}$	$(7.5 \pm 0.9) \times 10^{-5}$
CNO	< 8.1 (95% C.L.)		4.91 ± 0.56	3.62 ± 0.37

Solar metallicity problem





- **Global fit to all solar + Kamland data (including the new ^{7}Be result from BX)**

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

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

- **a hint towards the HM :**

LZ is excluded by BX data at 96.6% C.L. (1.8σ) level

- **theoretical errors are dominating**

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

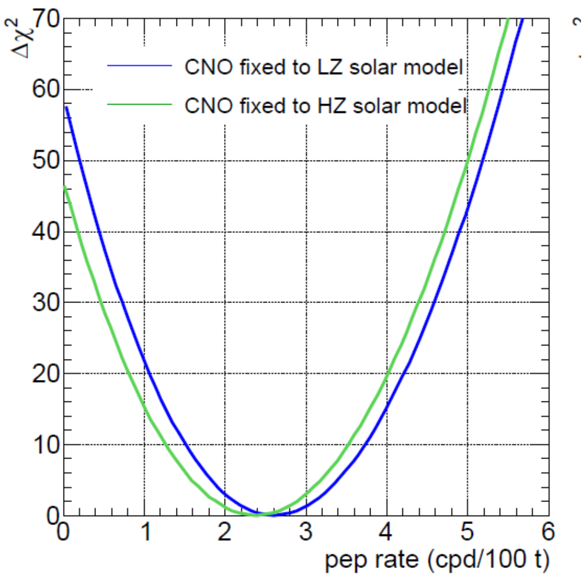
R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

From the pp and ^{7}Be fluxes measurement

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

What is new in Borexino results

>5σ evidence of pep signal (including systematics)



	Earlier result (cpd/100t)	Actual result (cpd/100t)	Precision
pp	144±13±10	$134 \pm 10^{+6}_{-10}$	11%
^{7}Be(*)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	4.7→2.7%
pep	3.1±0.6±0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	22→16%

***Result for ^{7}Be 862 keV line is quoted**
Precision improved by 10,43, and 39% correspondingly in simultaneous fit of all 3 components

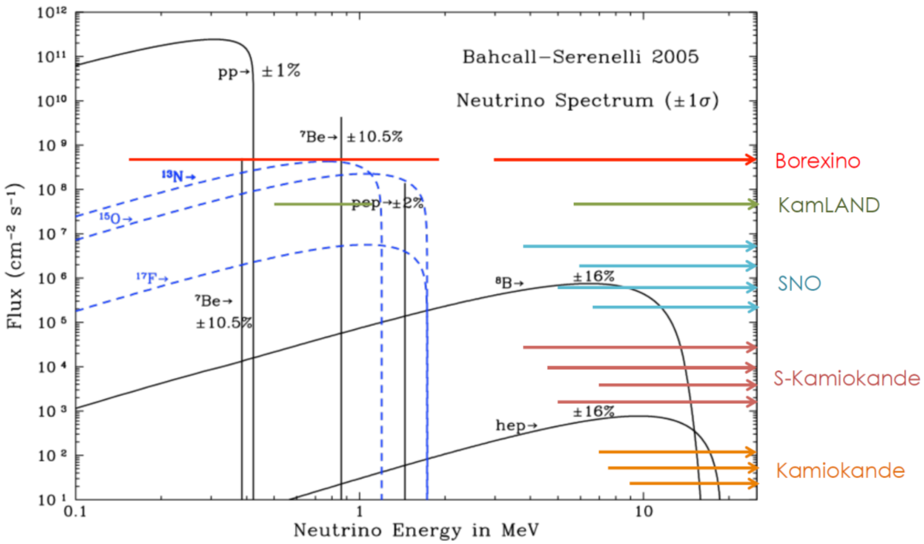
Solar luminosity: $L_\nu^{Borexino} = (3.9 \pm 0.4) \times 10^{33}$ erg/s, is in agreement with measured photon luminosity $L_\gamma = (3.846 \pm 0.015) \times 10^{33}$ erg/s

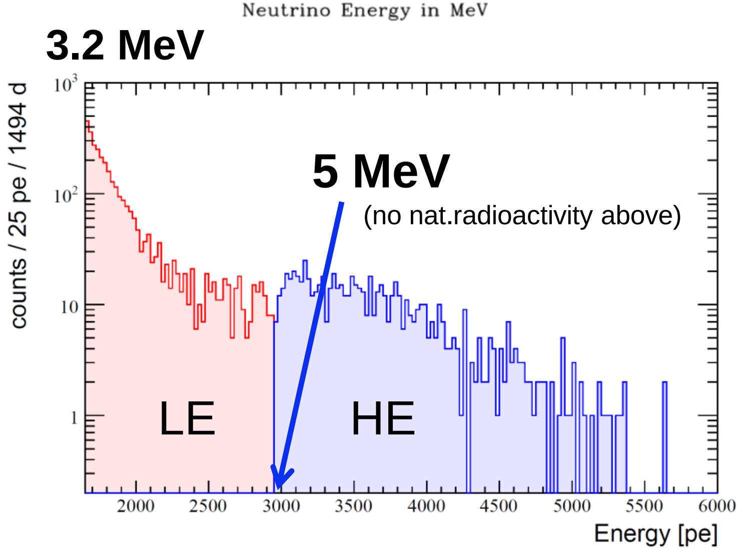
CNO: 95% C.L. limit on CNO rate : R(CNO)<8.1 cpd/100 t
flux : $\varphi(CNO) < 7.9 \cdot 10^8$ cm^{-2}s^{-1}

Less stringent constraints on pep in the CNO contribution analysis compared to Phase I

Expected (HZ) 4.91±0.56 (LZ) 3.62±0.37 cpd/100 t (2σ apart)

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure





What is improved in analysis:

- Better understanding of backgrounds (external γs, cosmogenic)
- No FV cut : 1.5 ktons·yr exposure between 2008 and 2016 (x11.5 of the Phase I analysis)
- Lowest energy threshold among RT detectors
- Identified new source of background due to n capture on C and Fe
- New estimate of the cosmogenic ^{11}Be

$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}.$$

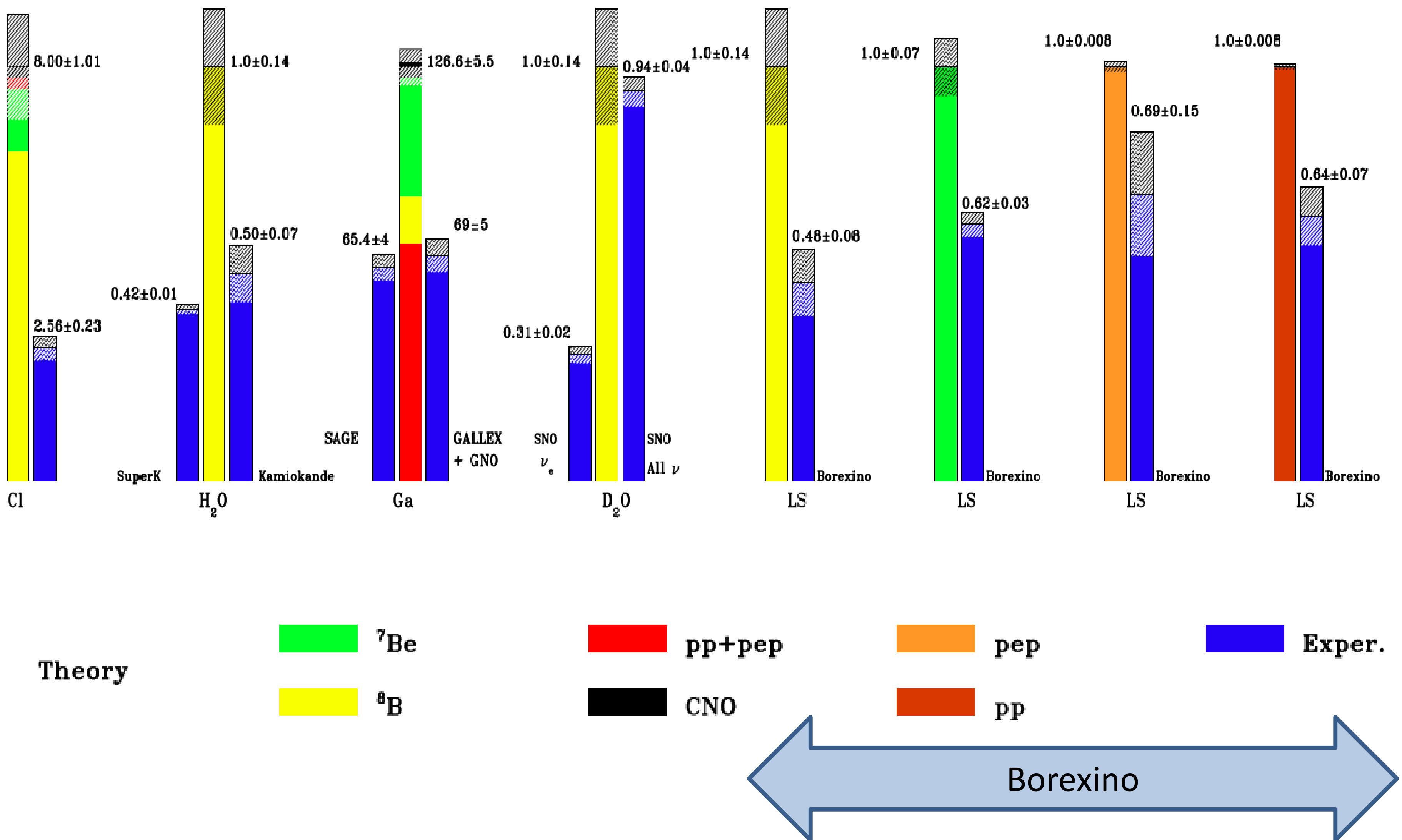
Expected rate in the LE+HE range:

0.211± 0.025 cpd/100 t

Assuming B16(G98) SSM and MSW+LMA

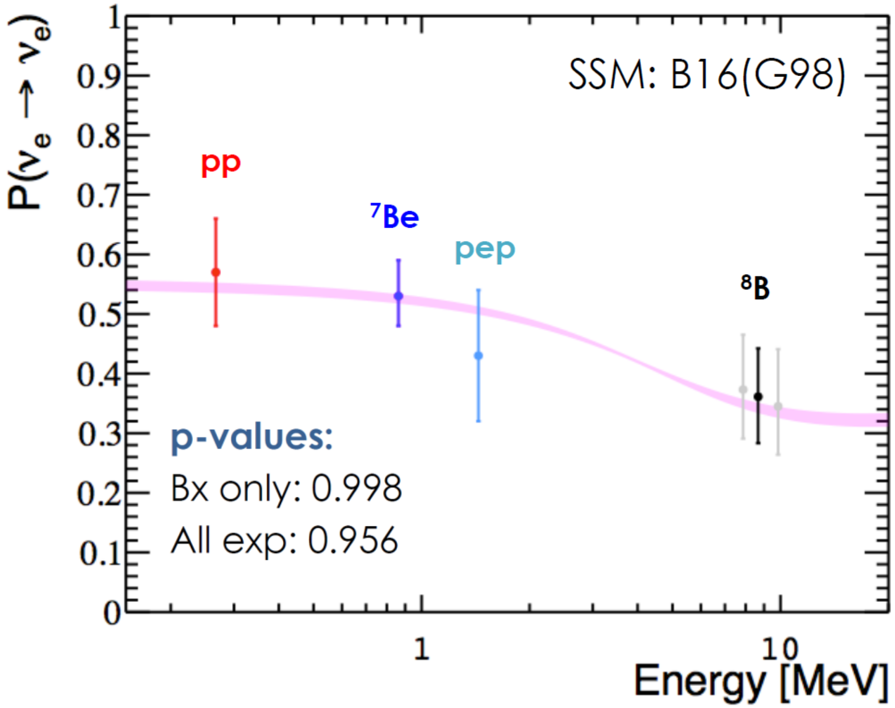
φ(hep)<2.2 × 10^5 cm^{-2} s^{-1} (90% C.L.)
vs 7.98/8.25 × 10^3 in HZ/LZ SSM.

Solar experiments vs models

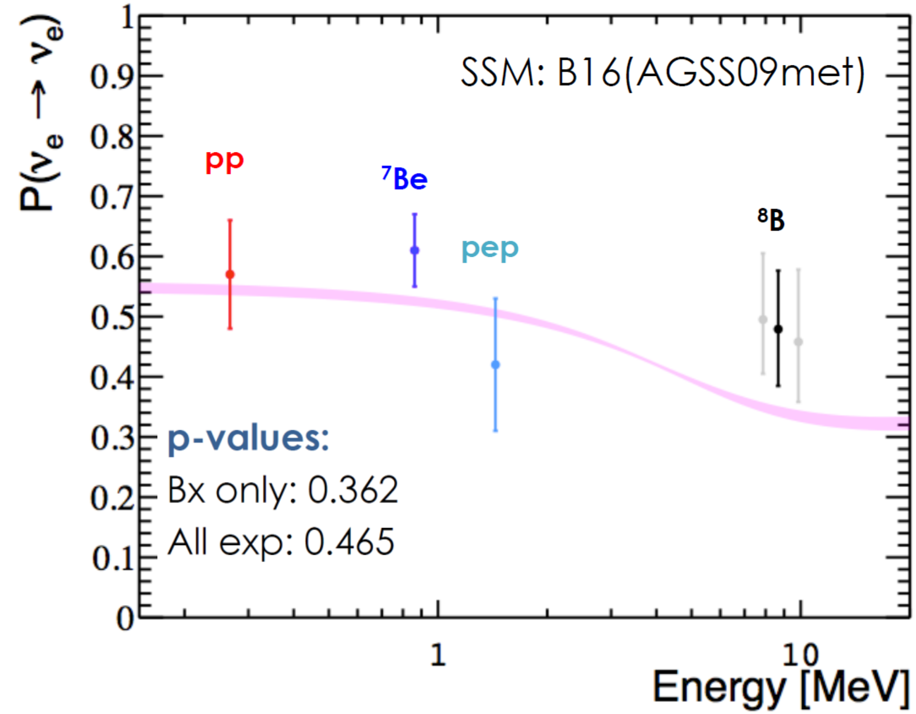


MSW/LMA : electron neutrino survival probabilities

High metallicity SSM

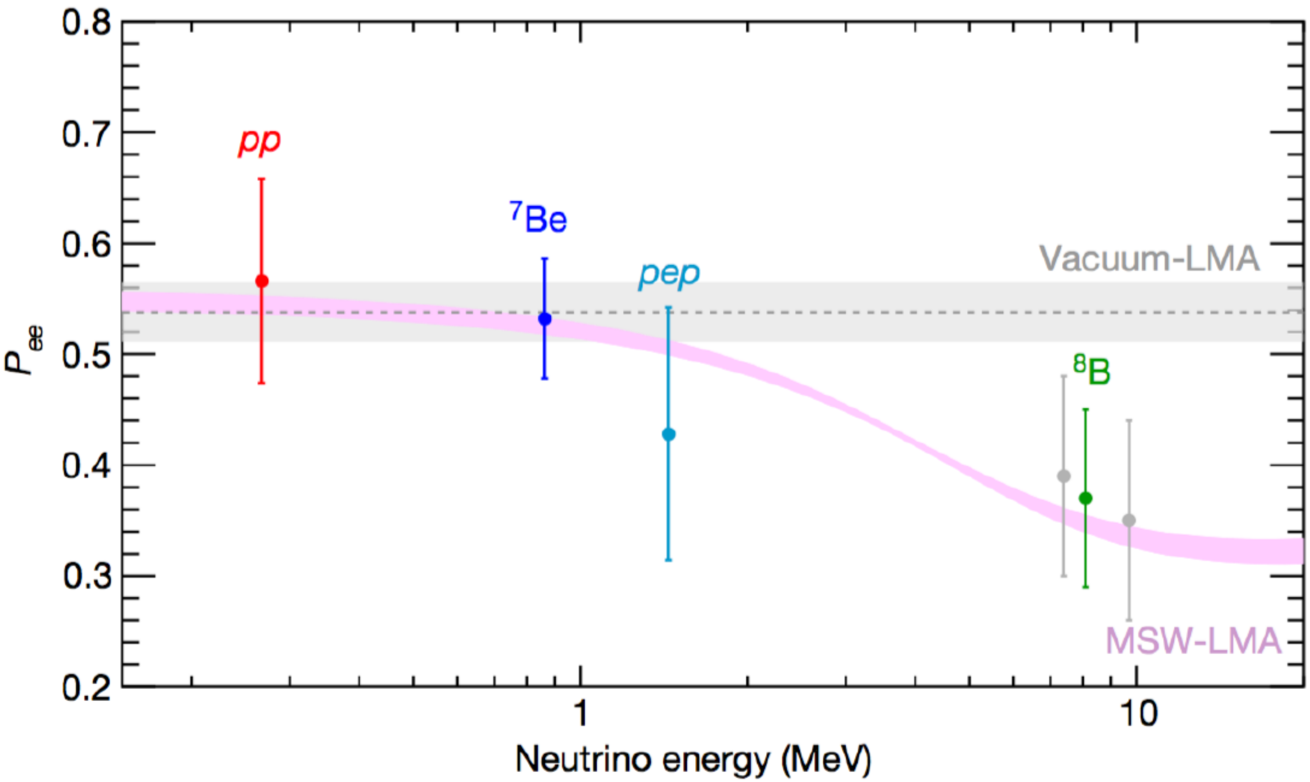


Low metallicity SSM



MSW errors (1σ) are shown by rose band

MSW/LMA for SSM(HZ)



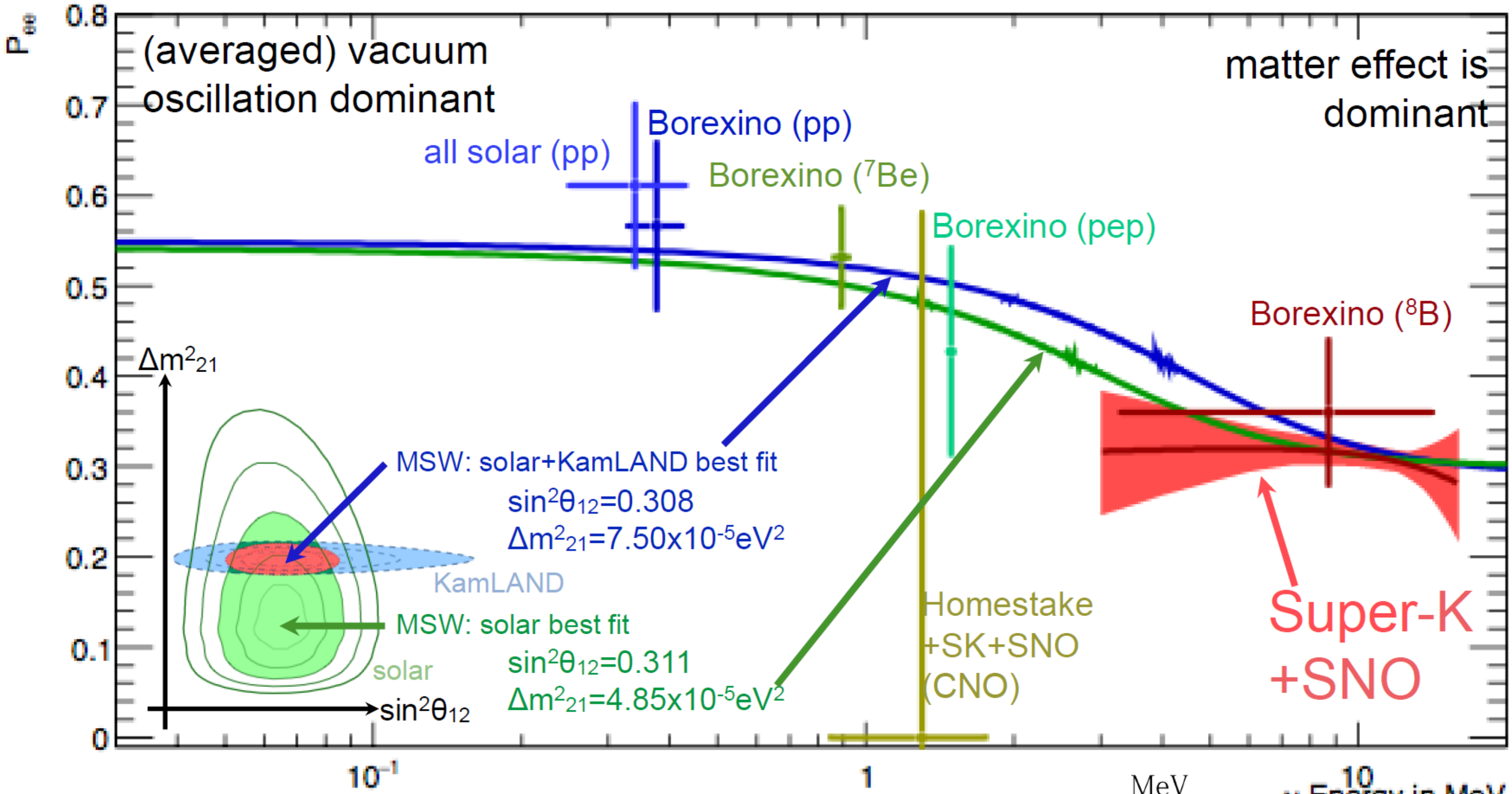
Rejected at 98.2% C.L.

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**

Survival probabilities from all solar ν results

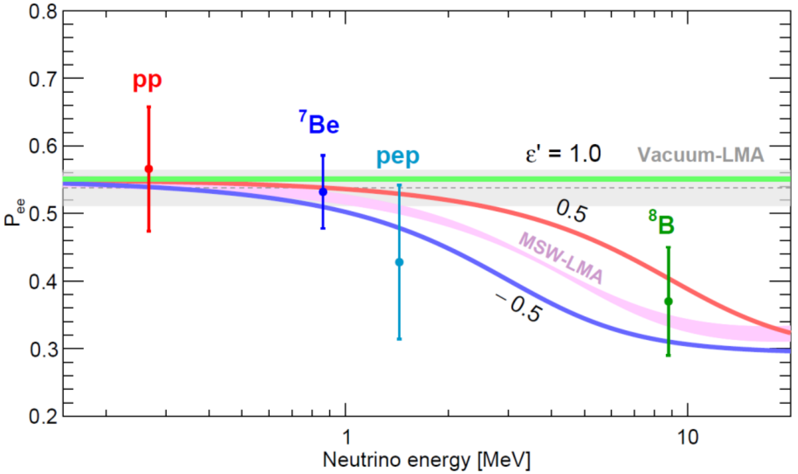
"Upturn" predicted by standard MSW is not seen yet.



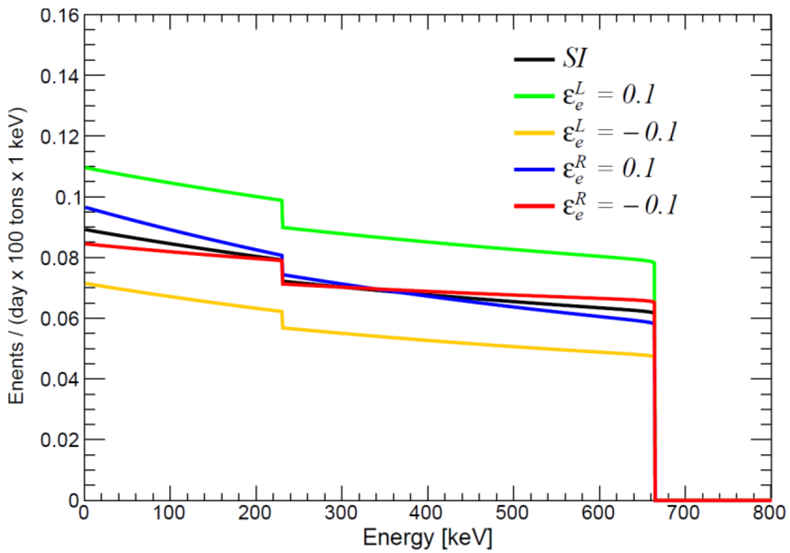
Non-standard interactions

The absence of the visible upturn triggered speculations on NSI

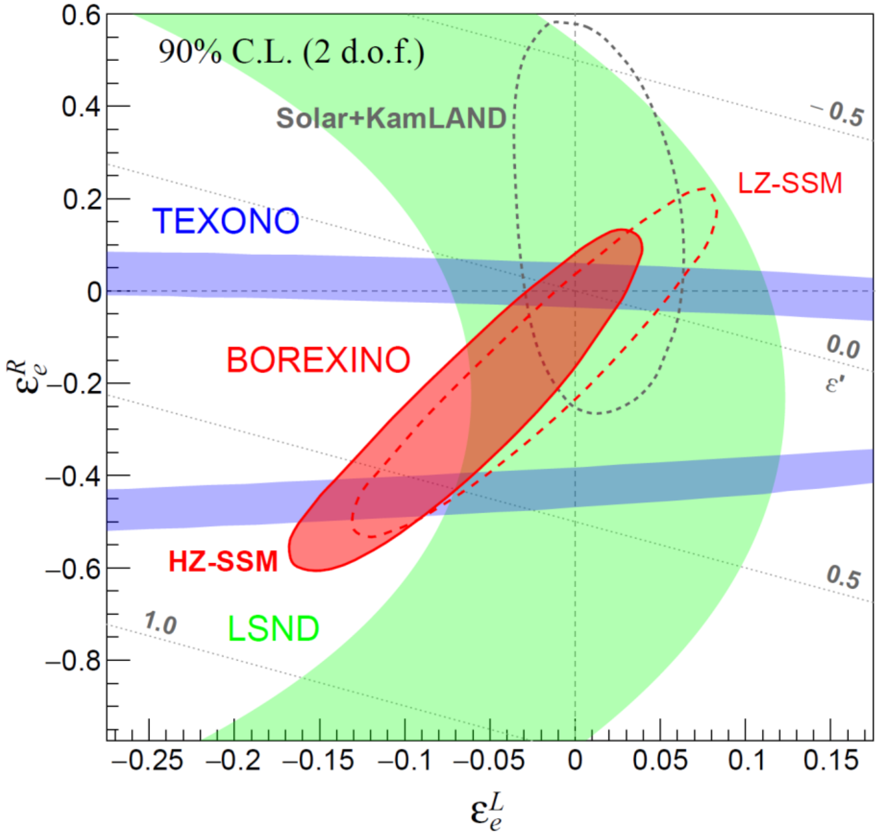
NSIs modifies Pee…

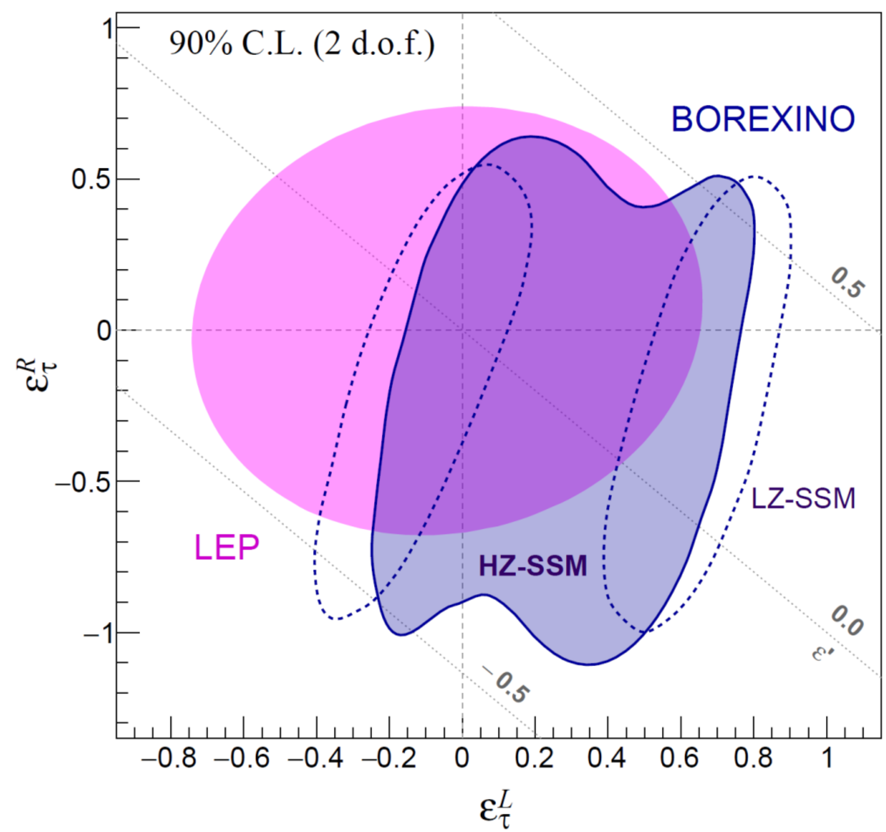


… and cross sections



Constrains on NSI

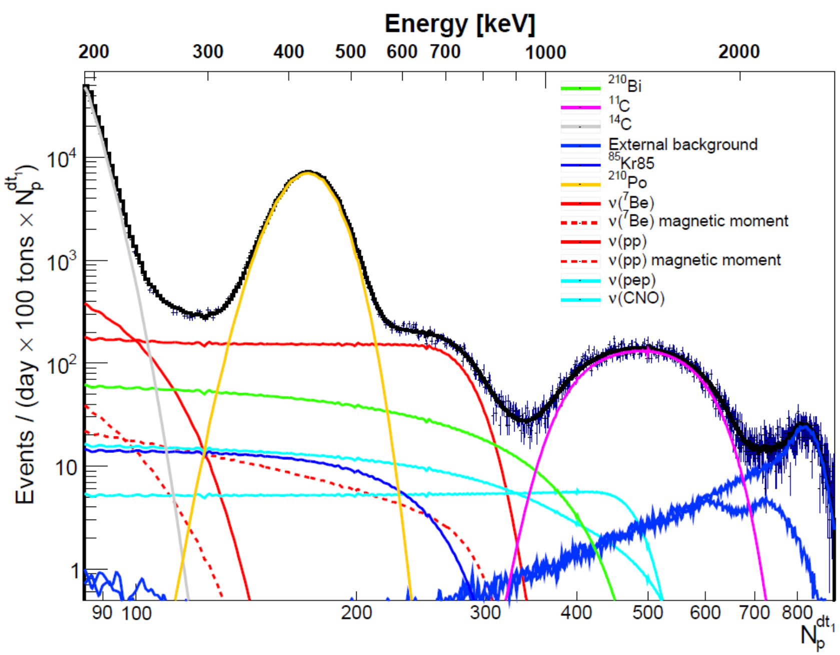




Effective magnetic moment of Solar neutrino

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



$$\boxed{\cancel{\chi^2 = \sum_{i=1}^{N_{bin}} \left(\frac{O_R^i - N_R^i(\mu_R)}{\Delta_i}\right)^2}}$$

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.

Limits on mm of neutrino flavours and mass eigenstates

In Solar neutrino experiments we measure: $(\mu_\nu)_{eff}{}^2 = \sum_\alpha P_{e\alpha}(\mu_\nu)_\alpha{}^2$

In frames of the MSW/LMA solution:

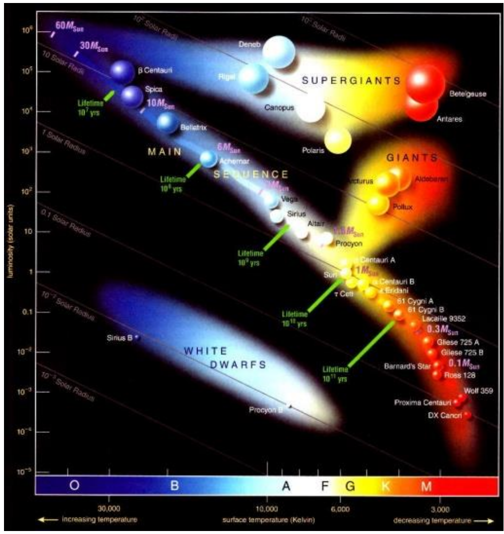
$$\mu^2{}_{eff} = P^{3\nu}\mu^2{}_e + (1 - P^{3\nu})(\cos^2\theta_{23}\,\mu^2{}_\mu + \sin^2\theta_{23}\mu^2{}_\tau)$$

$\boldsymbol{\mu_{\nu_e} < 3.9}$
$\boldsymbol{\mu_{\nu_\mu} < 5.8}$
$\boldsymbol{\mu_{\nu_\tau} < 5.8}$

GEMMA:	$\mu_{\nu_e} < 2.9$
LSND:	$\mu_{\nu_\mu} < 68$
DONUT:	$\mu_{\nu_\tau} < 39000$

All @90% C.L.

units of $\boldsymbol{10^{-11}\mu_B}$



Mass eigenstates basis:

- $|\mu_{11}| \le 3.4 \quad |\mu_{22}| \le 5.1 \quad |\mu_{33}| \le 18.7$

  $|\mu_{12}| \le 2.8 \quad |\mu_{13}| \le 3.4 \quad |\mu_{23}| \le 5.0$

Astropysics: $\mu_\nu{}^2 = \sum_{\alpha,\beta}\left|\mu_\nu{}^{\alpha\beta}\right|^2 < 3 \cdot 10^{-12}$

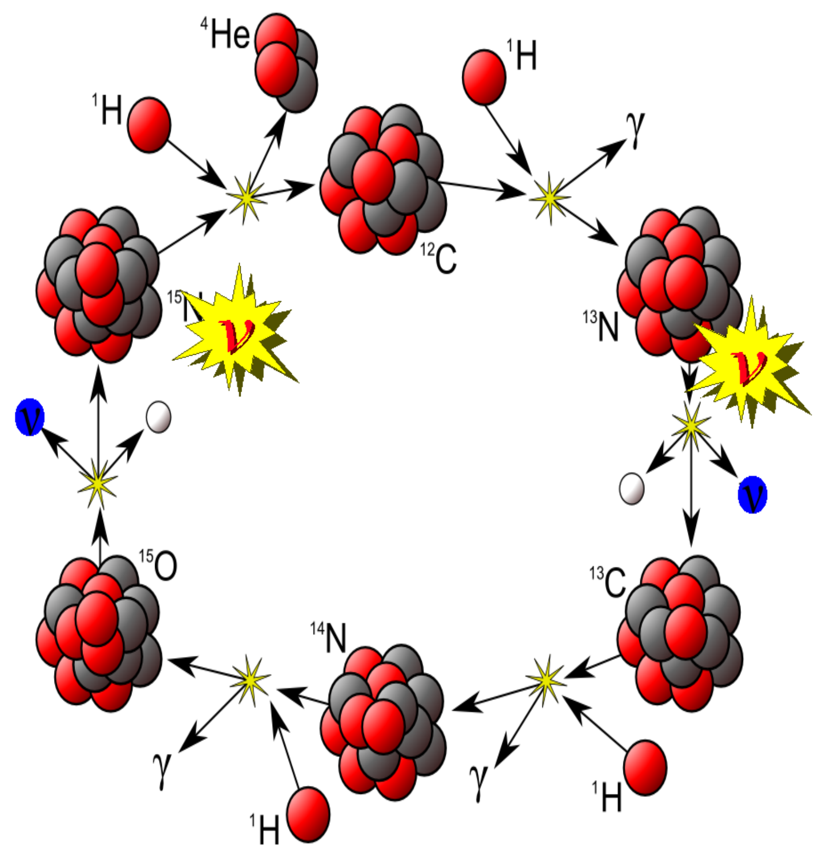
Solar CNO- neutrino cycle:

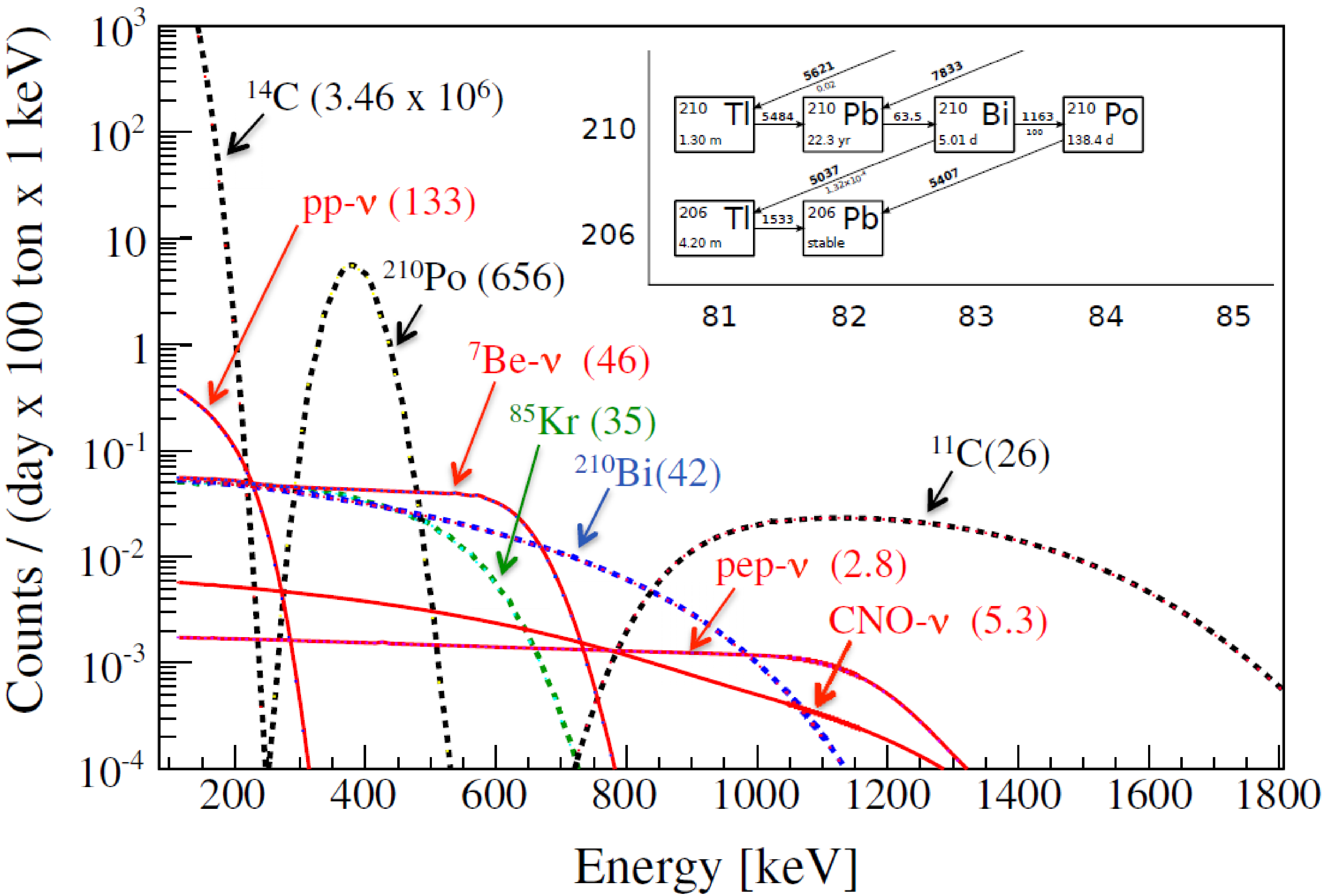
a clue to the chemical composition of the Sun

dominates in massive stars (~1% of solar luminosity*)*

“bottle-neck” N(p,γ) reaction, slower than expected (LUNA result).

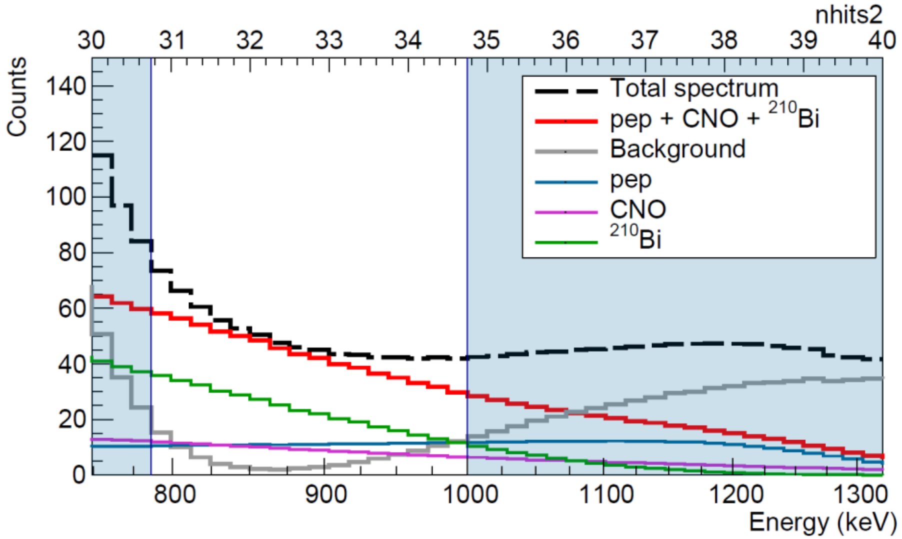
Very sensitive to the solar abundance problem. A direct test of the heavily debated solar C, N and O abundances would come from measuring the CNO neutrinos.



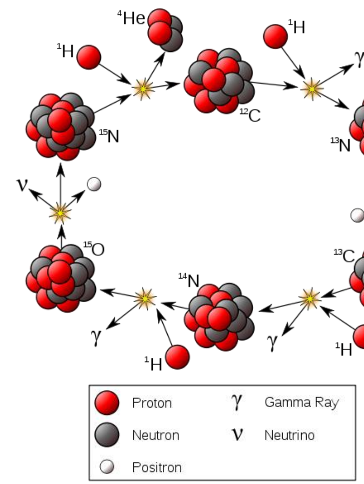


14C (3.46 x 10^6)
pp-ν (133)
210Po (656)
7Be-ν (46)
85Kr (35)
210Bi(42)
11C(26)
pep-ν (2.8)
CNO-ν (5.3)
210 Tl 1.30 m
210 Pb 22.3 yr
210 Bi 5.01 d
210 Po 138.4 d
206 Tl 4.20 m
206 Pb stable
5484
63.5
1163
1533
5621
7833
5037
5407
210
206
81
82
83
84
85
Counts / (day x 100 ton x 1 keV)
Energy [keV]

Key to the Solar metallicity : CNO neutrino flux



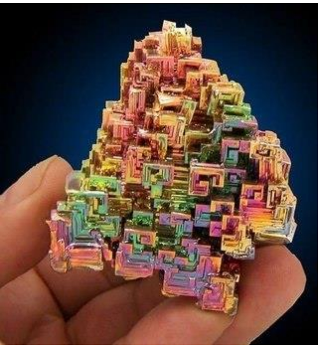
Expected spectrum assuming ν(CNO) HZ flux and other rates from last solar analysis



Predictions:

HZ : 4.91±0.56 cpd/100 t

LZ : 3.62±0.37 cpd/100 t

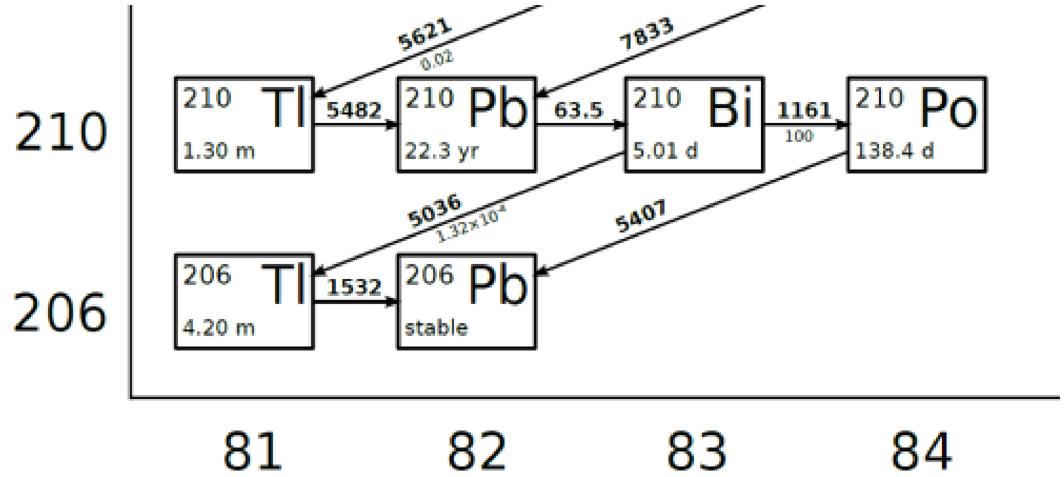


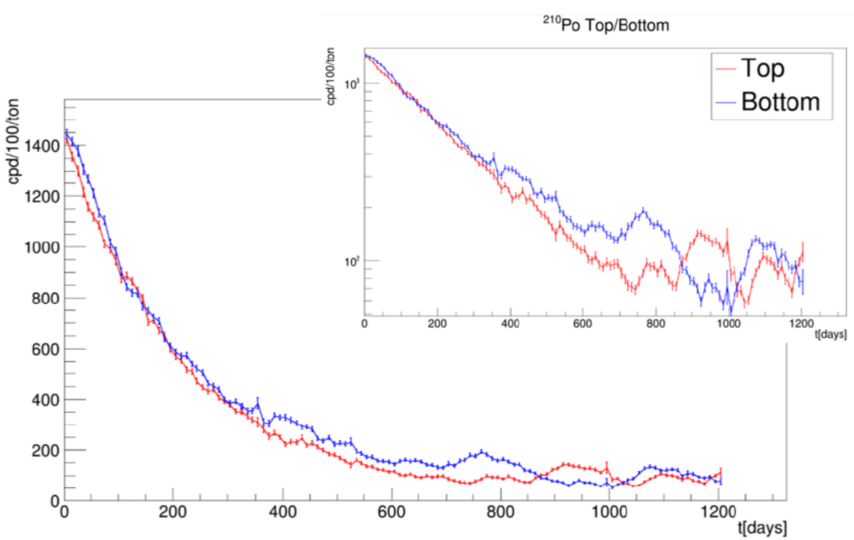
Main background from ^{210}Bi : ~20 cpd/100 t
Measure ^{210}Bi with few counts precision →
constrain it in the spectral fit →
extract the CNO flux.

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.

Strategy towards CNO measurement

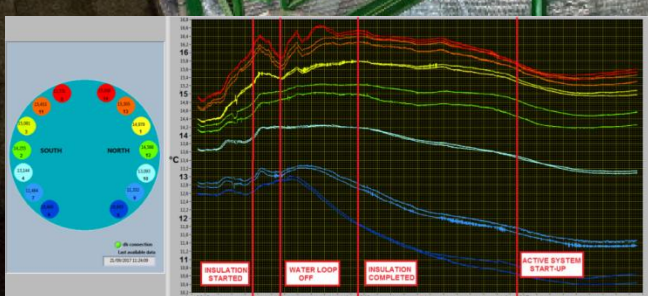
- Main route: using ^{210}Bi-^{210}Po temporal evolution to measure "support term" for ^{210}Po (secular equilibrium in ^{210}Pb sub-chain)
- Option: further purification o the LS by water extraction to reduce ^{210}Bi

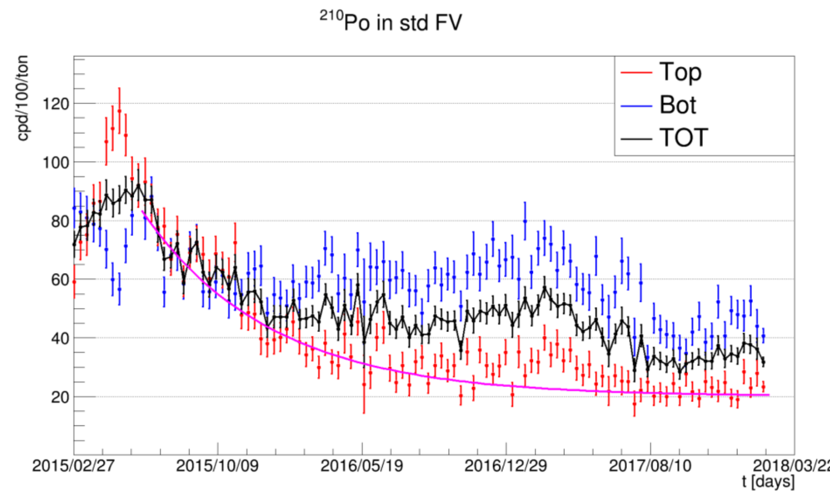


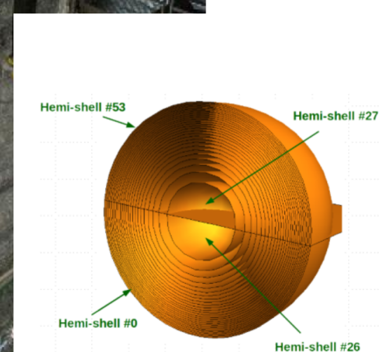


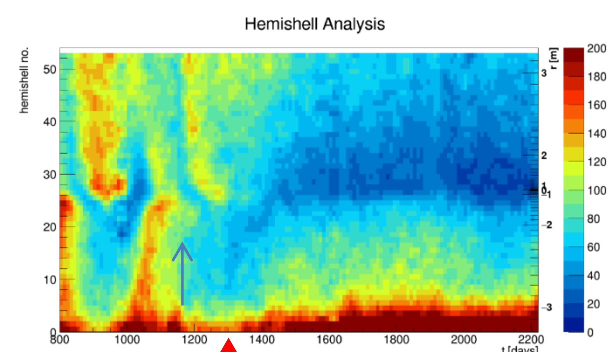
Instabilities observed in the temporal evolution of the ^{210}Po (making impossible precision evaluation of the ^{210}Bi) were found to be the result of the temperature instabilities of the surrounding

Hardware solution for thermal stabilization : thermal insulation of the external tank









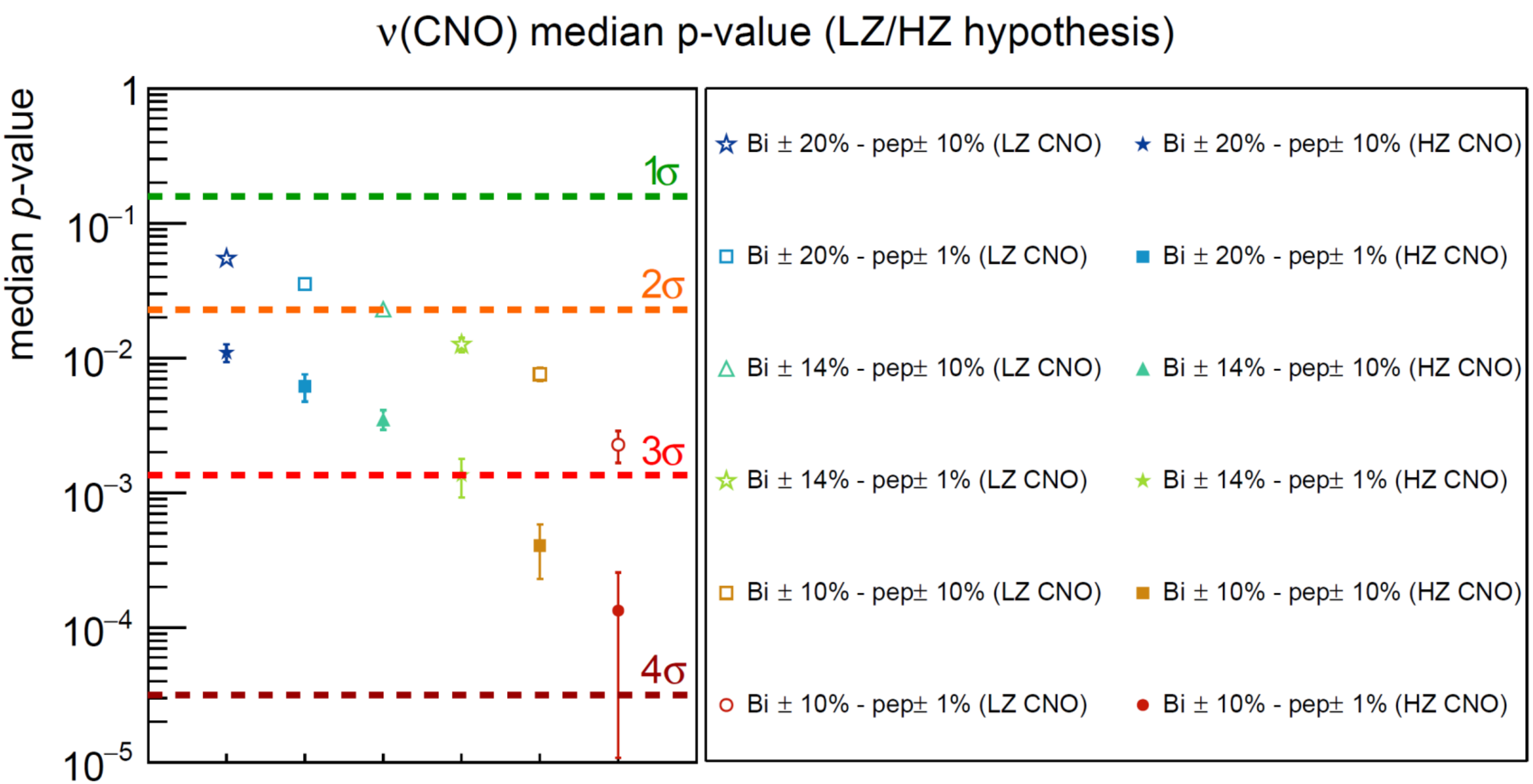
day 1300: insulation (summer 2015)

CNO sensitivity

Depends on both ^{210}Bi and pep-neutrino rates.

Assumed that ^{210}Bi will be measured (10-20%) and

pep-rate can be constrained by constraining pp/pep ratio in the fit.

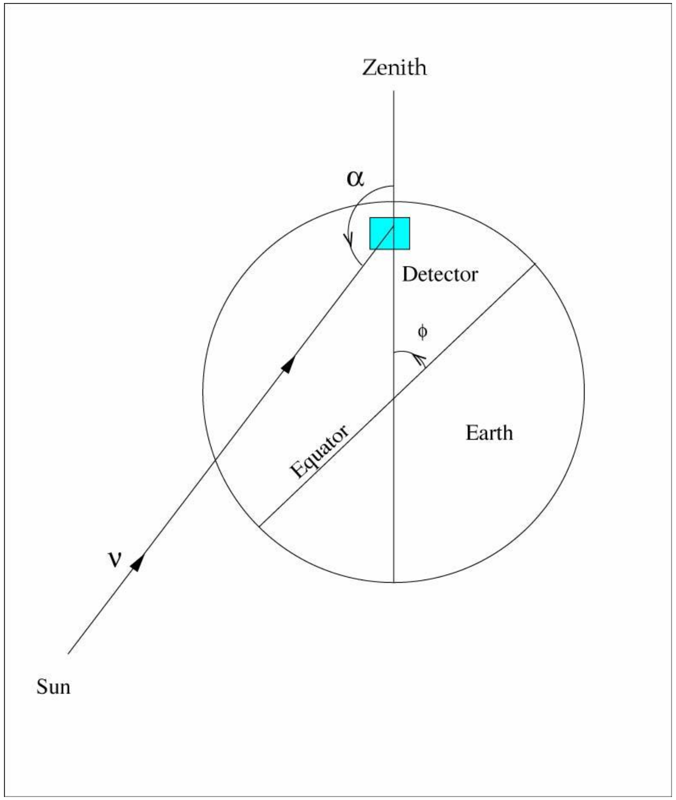


TIME VARIATIONS OF THE SOLAR NEUTRINO SIGNAL

Time variations of the solar neutrino signal

- **seasonal** : elliptic Earth orbit
- **diurnal (day/night)** : regeneration in the Earth. MSW/LMA predicts ~3% day/night asymmetry of ^{8}B count and no asymmetry for ^{7}Be
- **other** time variations?

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

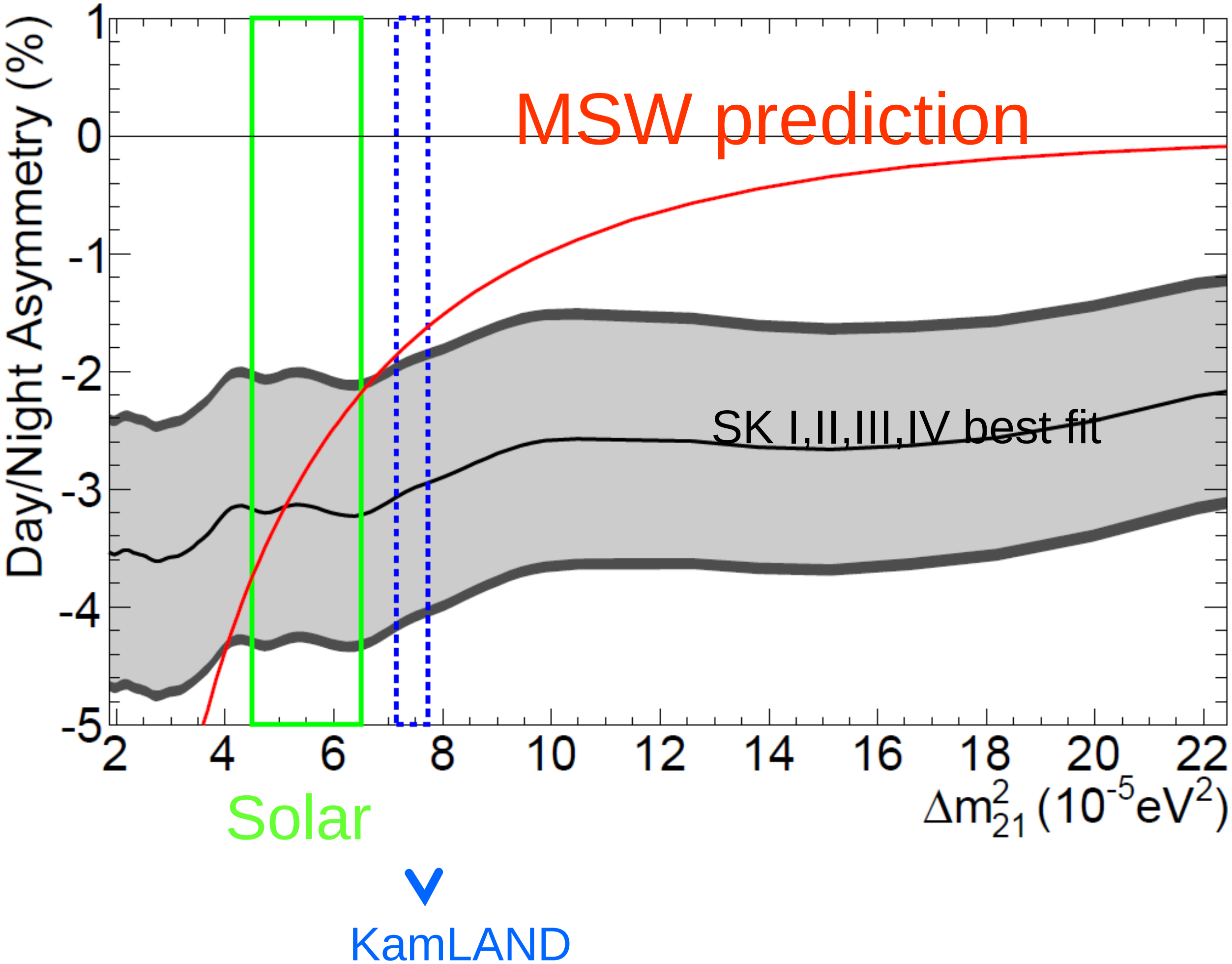


"negative" result on day/night assimetry with 3 years statistics (380.63 "nights" + 360.25 "days") is in agreement with MSW/LMA predictions:

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

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

SuperK : first Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

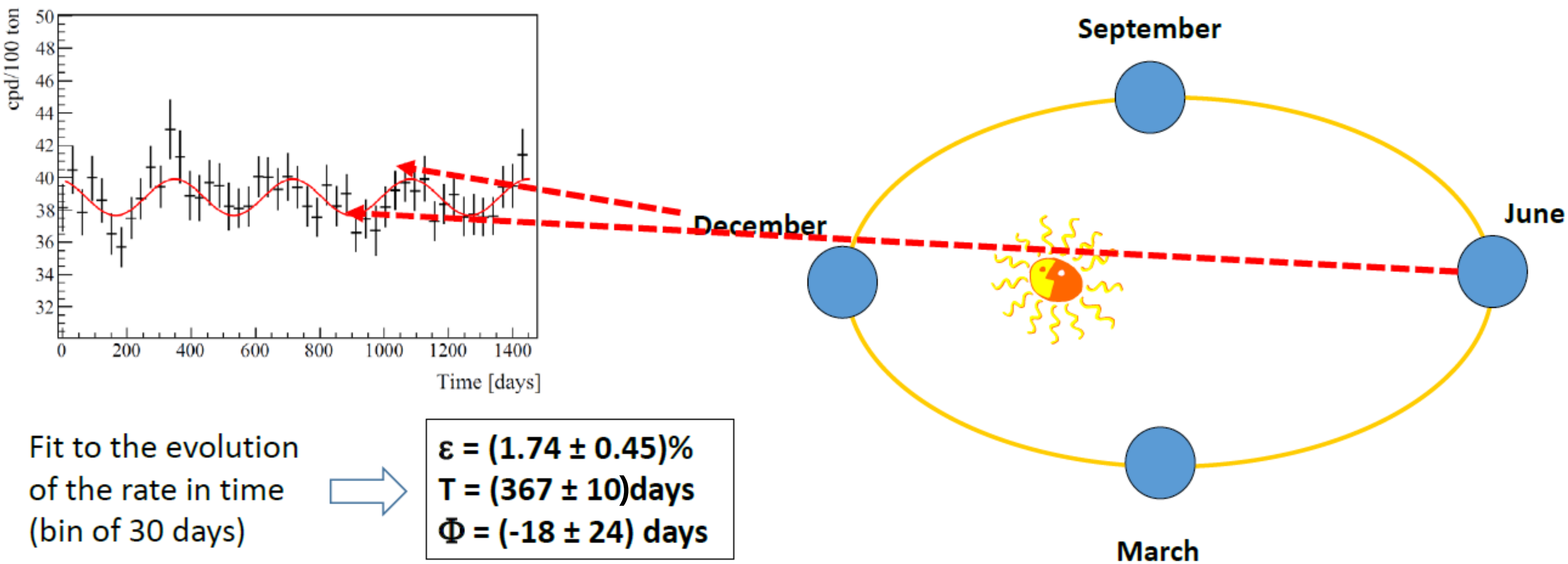


2014:
A_{DN}=-3.2±1.1±0.5 [%]
(2.8σ)

2016:
A_{DN}=-3.2±1.0±0.5 [%]
(2.9σ)

Seasonal modulations of ^{7}Be neutrino flux

M. Agostini et al. / Astroparticle Physics 92 (2017) 21–29



Fit to the evolution of the rate in time (bin of 30 days)

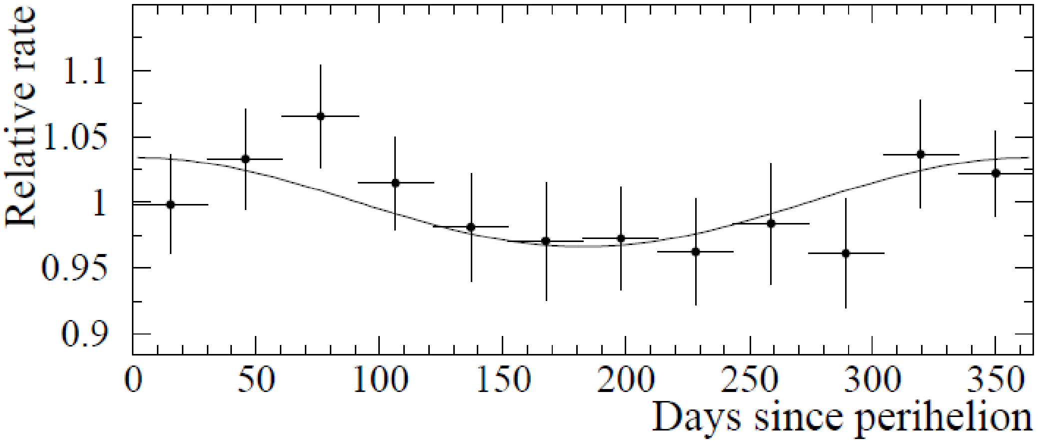
ε = (1.74 ± 0.45)%
T = (367 ± 10)days
Φ = (-18 ± 24) days

The duration of the astronomical year is measured from underground using neutrino!

Time variations of Solar neutrino flux

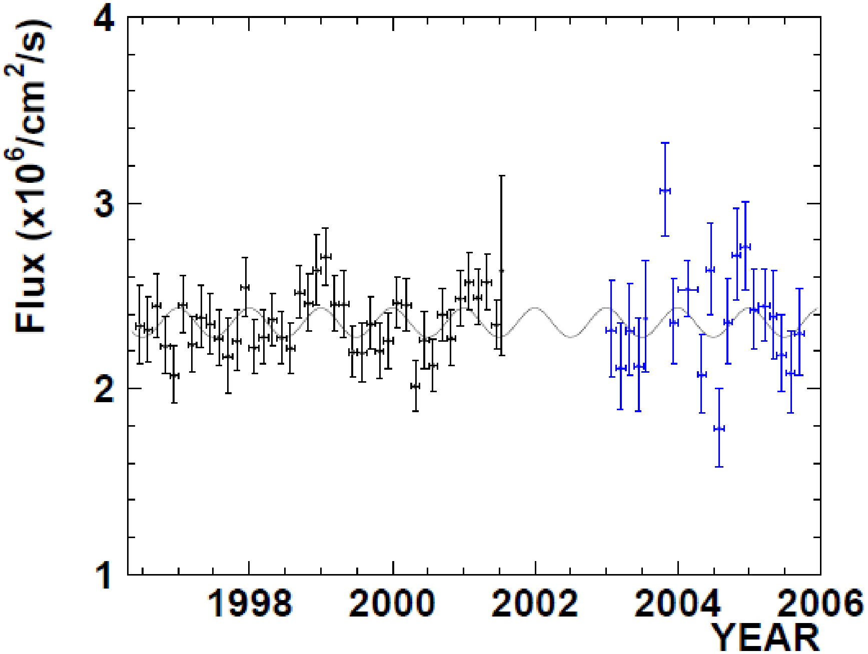
±3.5% variations due to the seasonal variation of Earth-Sun distance

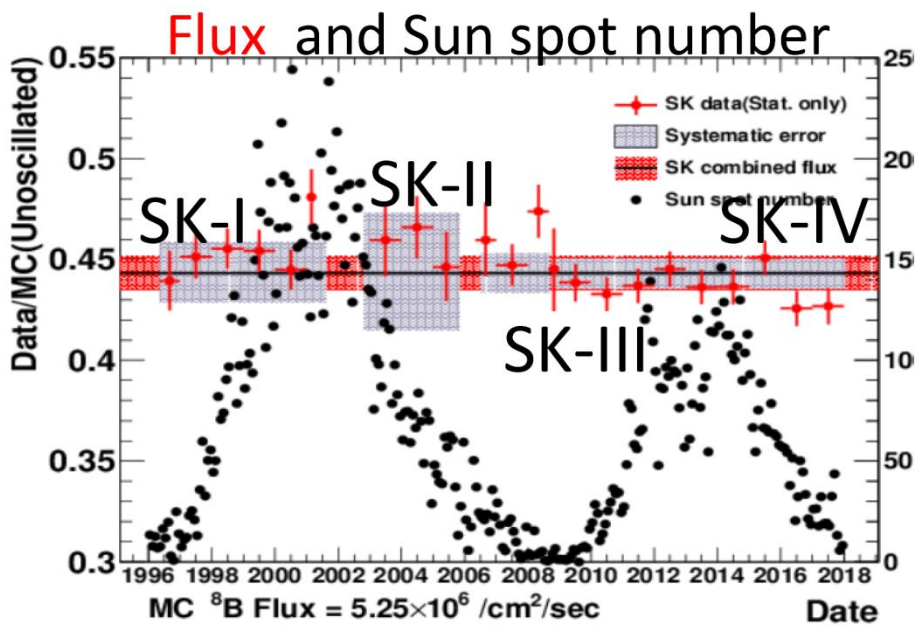
SNO



- **2005: the variation at a period of one year is consistent with modulation of the neutrino flux by the Earth's orbital eccentricity. No significant sinusoidal periodicities between 1 day and 10 years.**
- **2009: 3 additional analyses:**
- **1)frequencies 1/day to 144/day, sensitivity to sinusoidal signals with amplitudes ≥12%**
- **2)regions in which g-mode signals (24 h - 10 min) have been claimed by experiments aboard the SoHO satellite, sensitive to signals with amplitudes of 10% or greater.**
- **3)extra power across the entire frequency band.**
- **No statistically significant signal was detected in any of the three searches.**

SuperK-I+SuperK-II

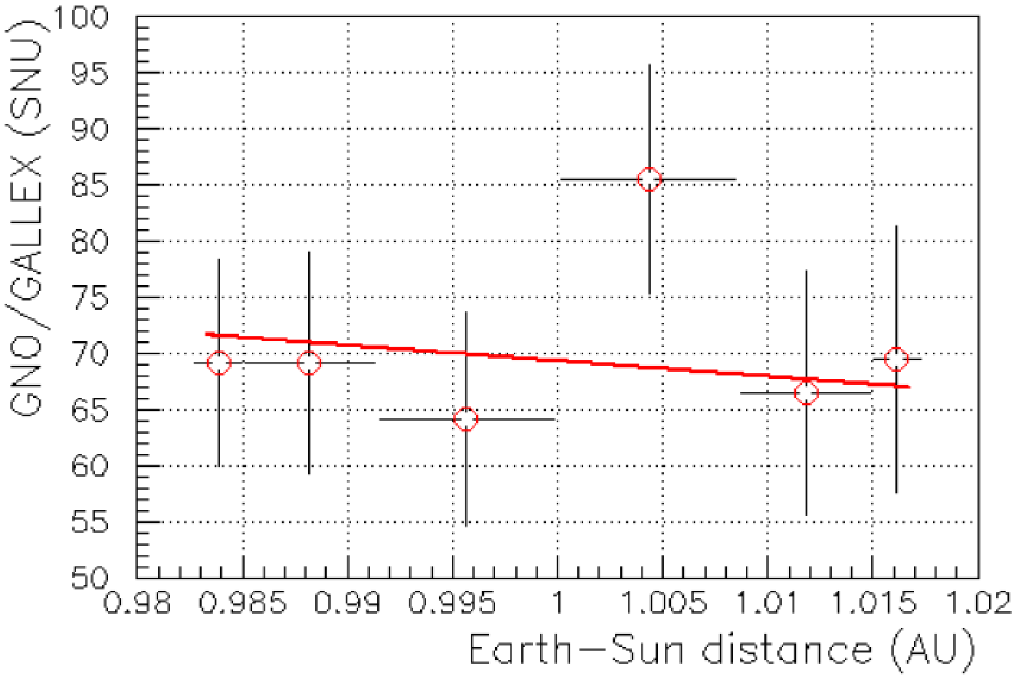




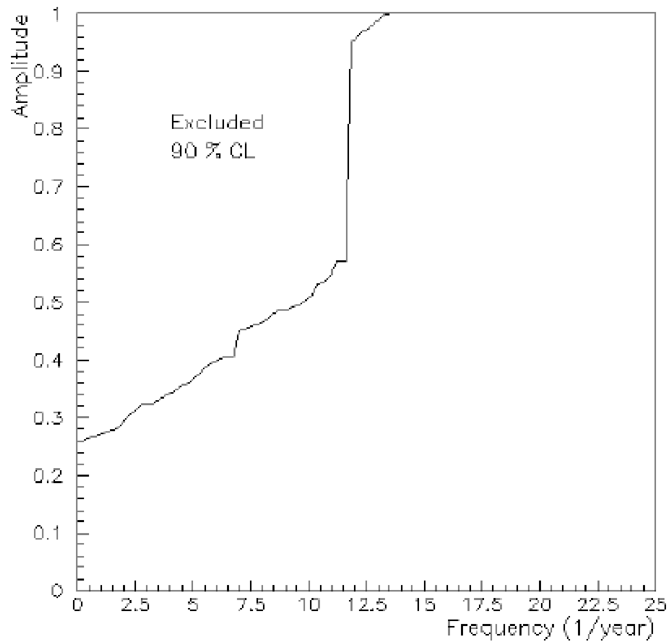
1.5 months bins
Solid line: $1/r^2$

The SK-I and II 1-year binned solar flux data gives an agreement of χ^2/N.D.F. = 6/11 (52% c.l.) when compared to a straight line.

Gallex+GNO

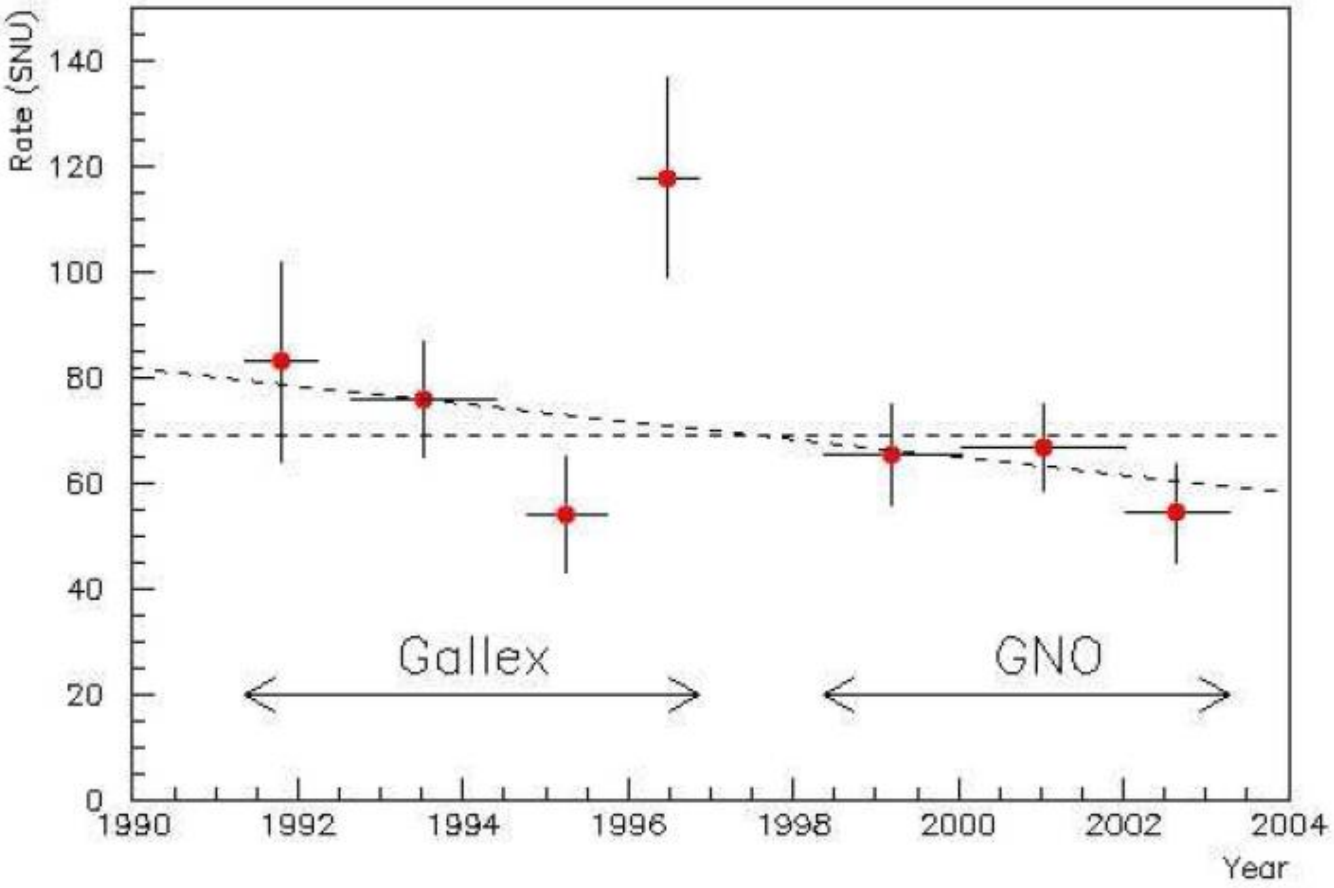


GNO/GALLEX signal vs. heliocentric distance of the Earth. The straight line indicates the expected flux variation due to purely geometrical ($1/d^2$) effect



90 % CL exclusion plot in the frequency/amplitude plane from the analysis of GALLEX and GNO data

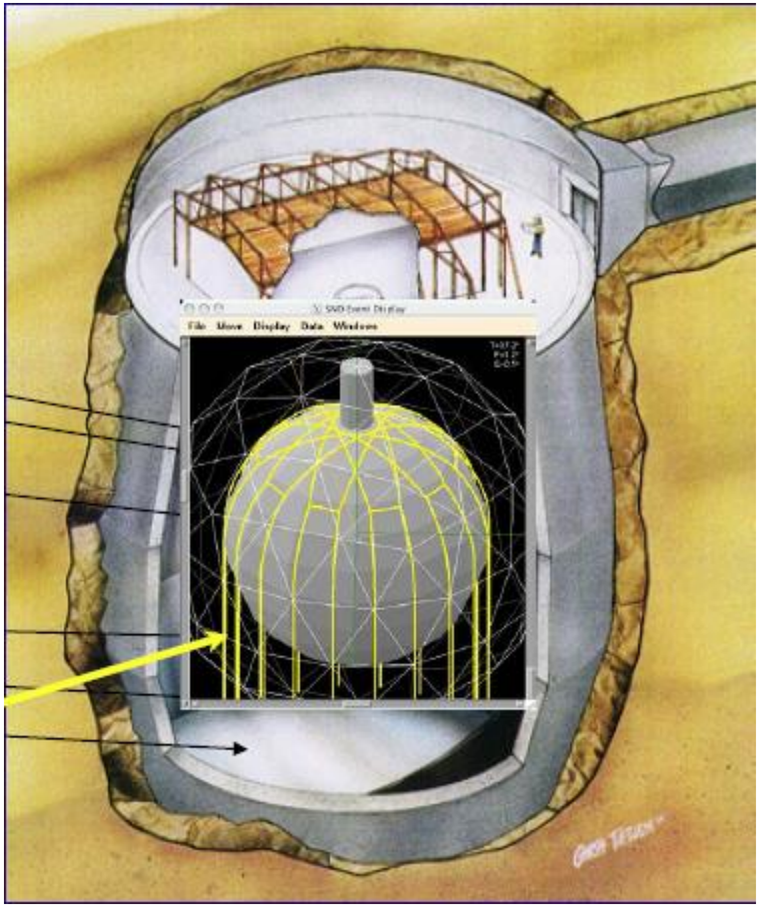
Gallex+GNO (grouped in periods)



results are consistent with a flat behaviour; however a weak time dependency (of unknown origin) is not excluded (13.2/6 vs 10.8/5)

FUTURE EXPERIMENTS

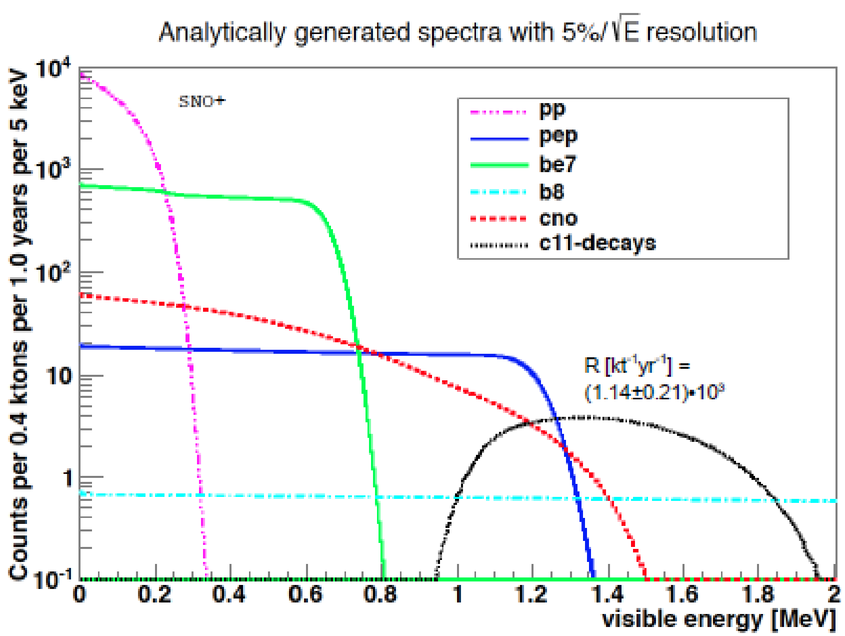
SNO+

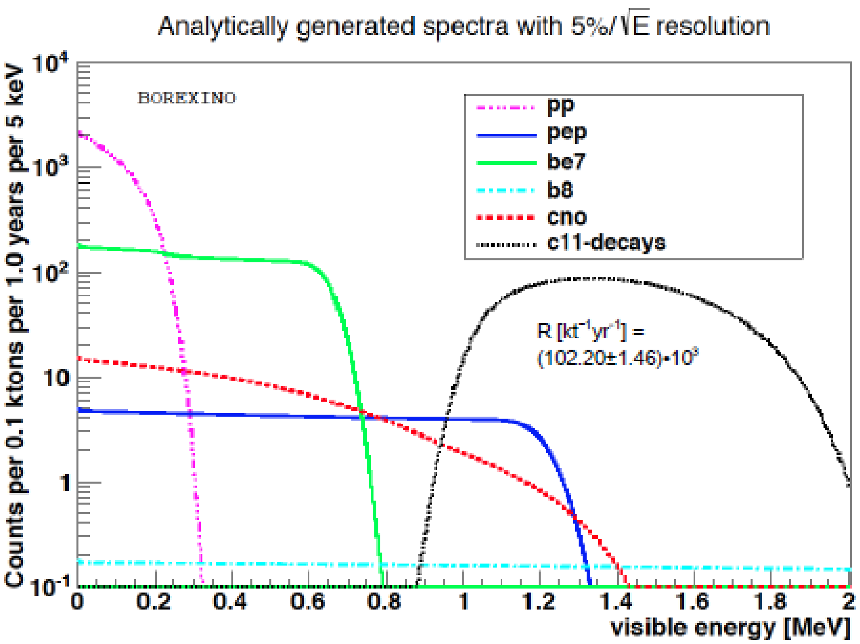


780 tons of Linear Alkyl Benzene (LAB) contained in a spherical acrylic vessel (AV) of 12 m diameter and 5 cm thickness;
9500 PMTs provides coverage of 54%.
The PMTs and the AV are located in a cavity excavated in the rock filled with about 7000 tons of ultrapure water.
A radon seal and Urylon liner provide a second layer of shielding to avoid any contact of the detector with the mine air.
The 6000 m.w.e. rock shielding : 3 μ/hour.

LAB was chosen as scintillator for the SNO+ experiment due to its chemical compatibility with acrylic, its high light yield (50 - 100 times higher than heavy water), the good optical transparency and low scattering. Moreover, high purity levels are easily available and due to the fast decay it is possible to discriminate between beta and alpha particles.

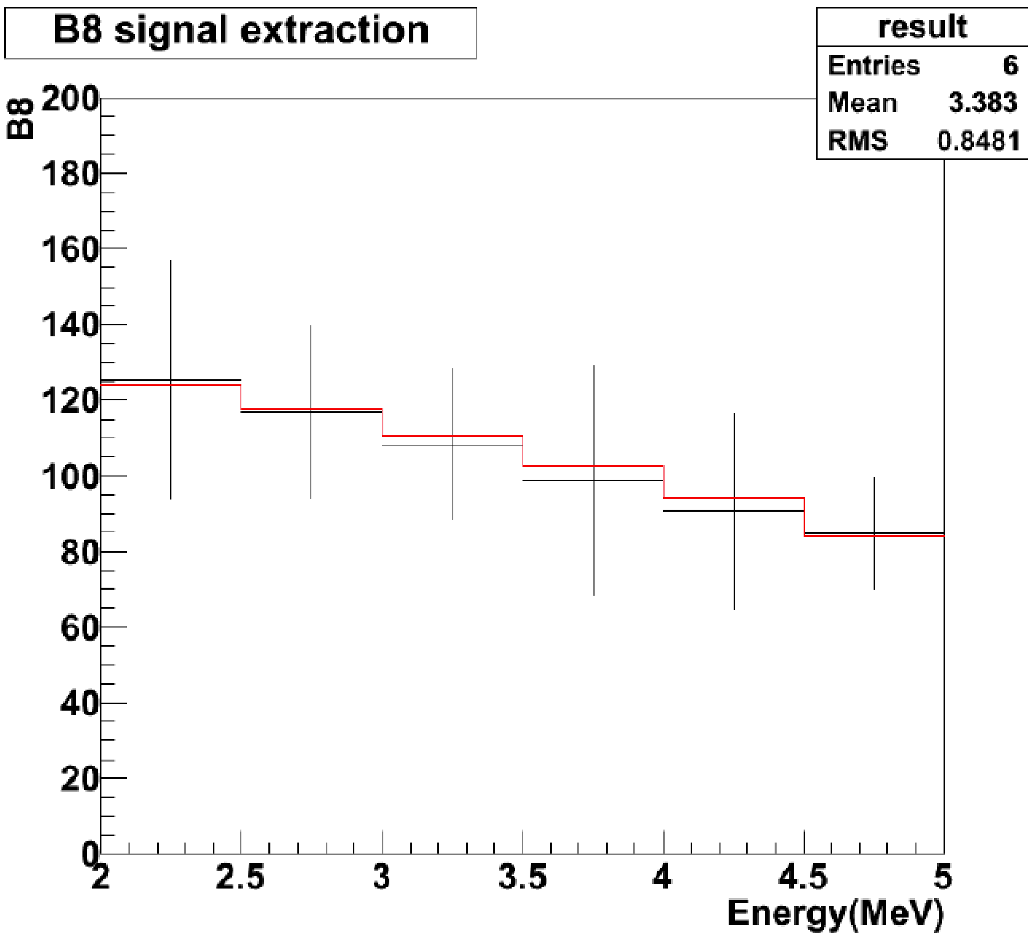
SNO+ Solar neutrino phase





^{7}Be and ^{8}B neutrinos
pep & CNO neutrinos: U and Th < 10^{-17} g/g. Amongst the diffrerent daughters ^{210}Bi is the most important since it partially falls in the region of interest.
3600 pep events/(kton·year), for electron recoils >0.8 MeV
goal: ±5% total uncertainty after 3 years (including systematic and SSM)
CNO measurement goal: ±10% after 3 years.

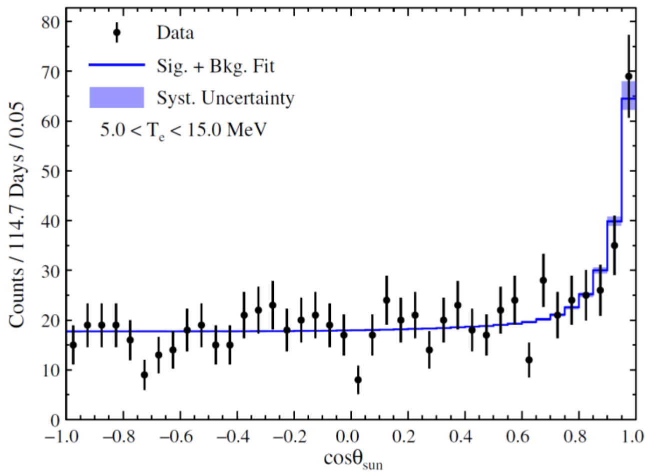
SNO+ ^{8}B neutrino



1 yr of data simulation

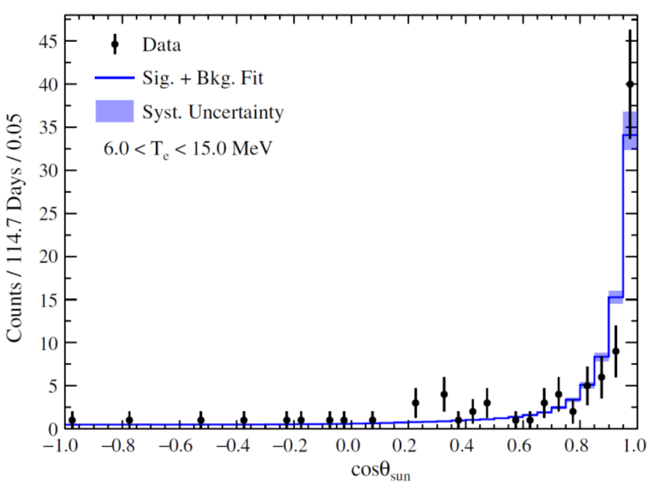
SNO+ water phase; 114.7 days

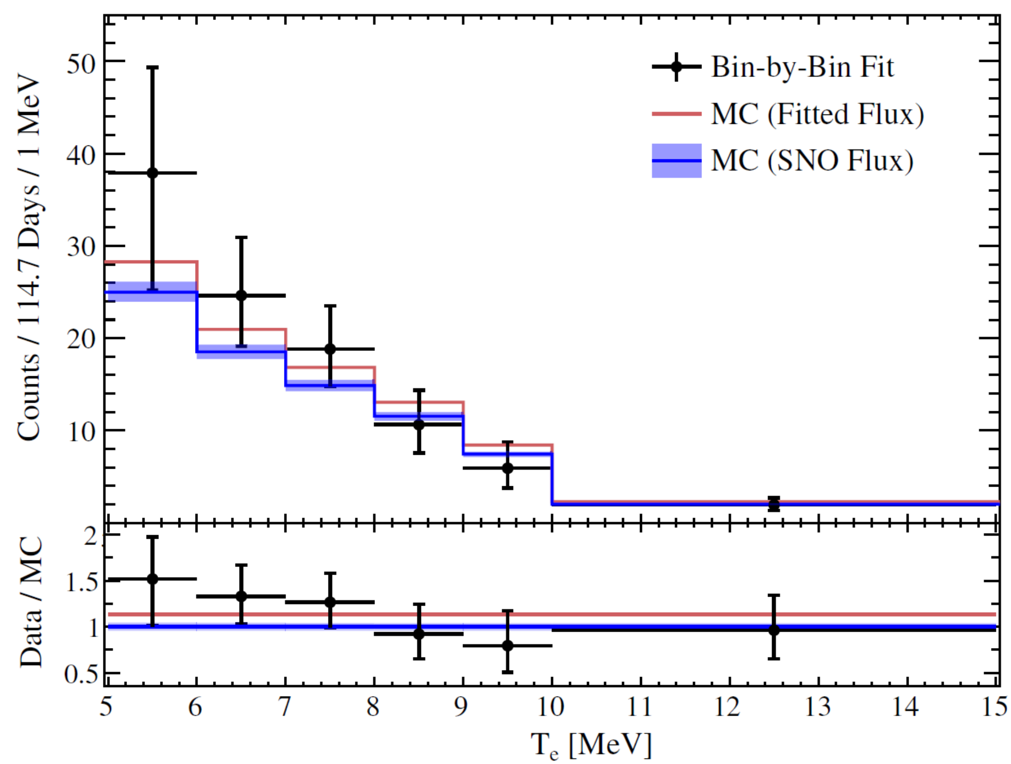
Phys.Rev. D 99, 012012 (2019)



$$\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat})^{+0.28}_{-0.30}(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

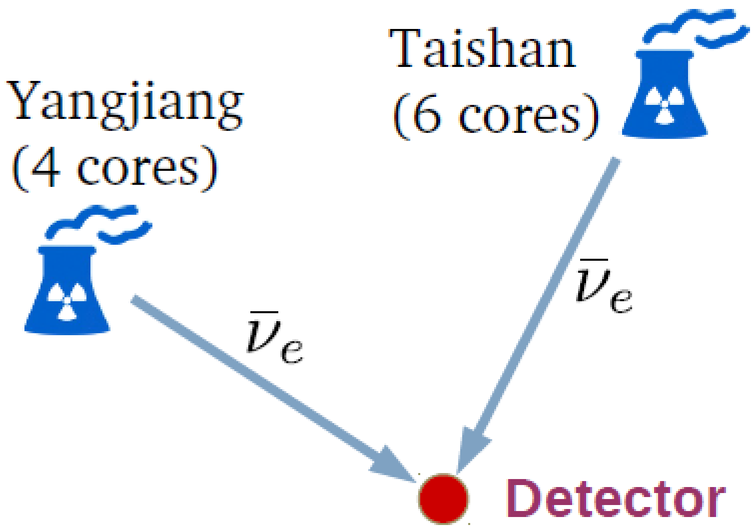
Compatible with SNO measurement





JUNO

Jiangmen Underground Neutrino Observatory



- 20 kt LAB-based LS
- sphere in cylindrical water pool
- 10^5 IBD events/6 yr
- **Res(E)=3% @ 1 MeV**
- 18,000 20” PMTs +
  25,000 3” PMTs
- LY~1200 p.e./MeV
- 75% geometric coverage
- Needs good position reconstruction
- Cosmic muons tracking : water pool (Cherenkov detector) + top tracker

- Baseline 52.5 km
- Overburden 700 m (1900 m.w.e.)

Solar neutrino with JUNO

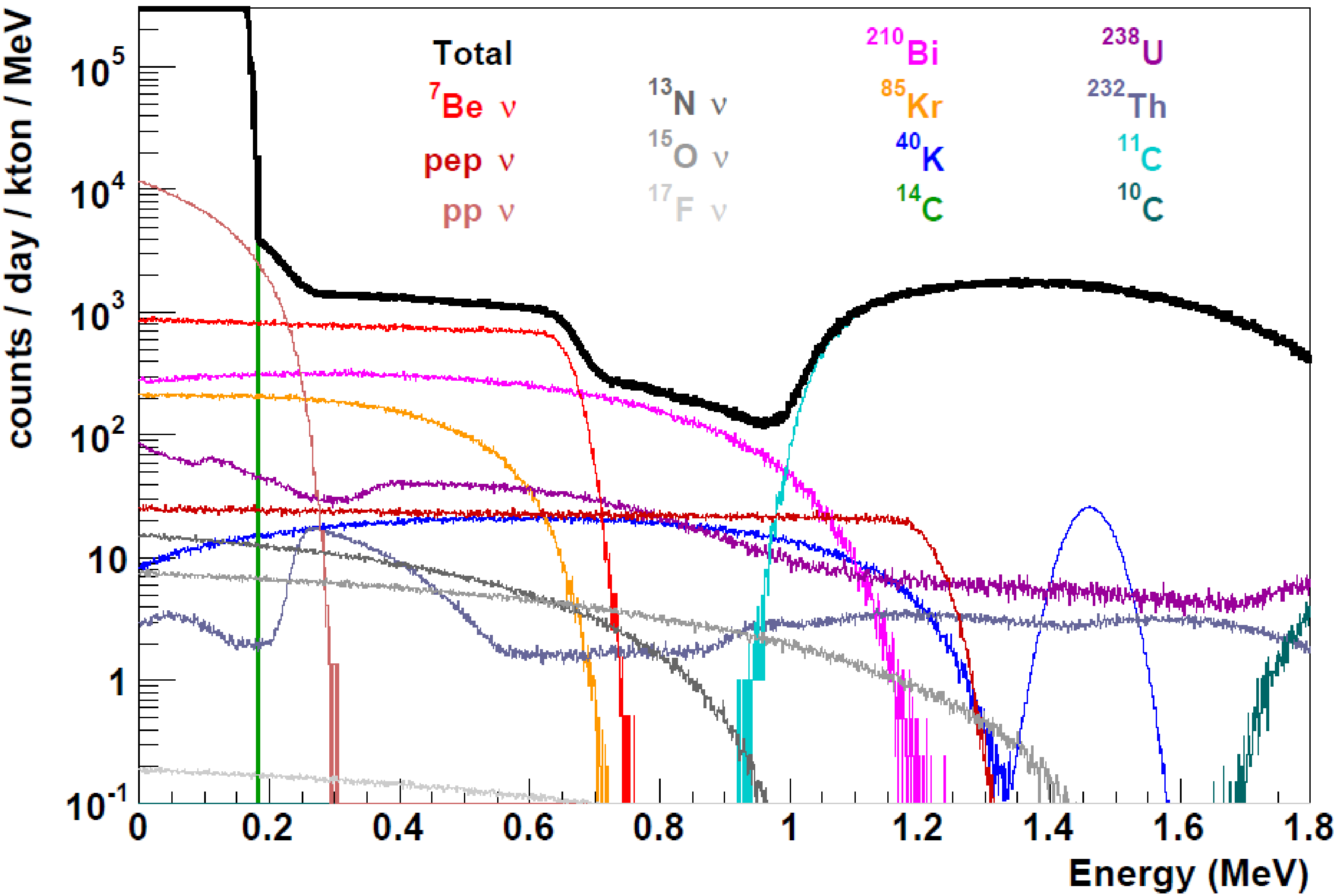
JUNO is large volume LS detector, bigger than successful Borexino with better resolution, but at shallower depth.
Radiopurity?

Internal radiopurity requirements		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]

“single” events (non tagged) from νe elastic scattering

Source	Rate [cpd/1kt]
pp ν	1378
^{7}Be ν	517
pep ν	28
^{8}B ν	4.5
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1

JUNO low-energy “singles” spectrum for “ideal” radiopurity



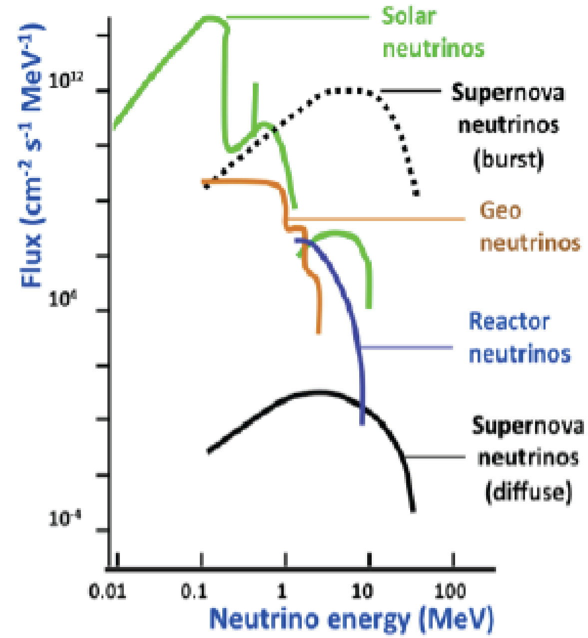
KamLAND. Solar phase

- KamLAND provided ^{7}Be flux measurement (20%) analyzing data from the reactor phase
- Apparently the Solar neutrino program was abondoned, the detector is taking data in the KL-zen phase ($0\nu\beta\beta$ search in ^{136}Xe).

LENA (Low Energy Neutrino Astronomy)

50 kt scale; ~200 p.e./MeV
LS: LAB + PPO and Bis-MSB as solutes is favored

low-energy range with neutrino energies up to a few tens of MeV:
Galactic Supernova neutrinos
Diffuse Supernova neutrinos
Geo/Reactor antineutrino
Solar neutrinos

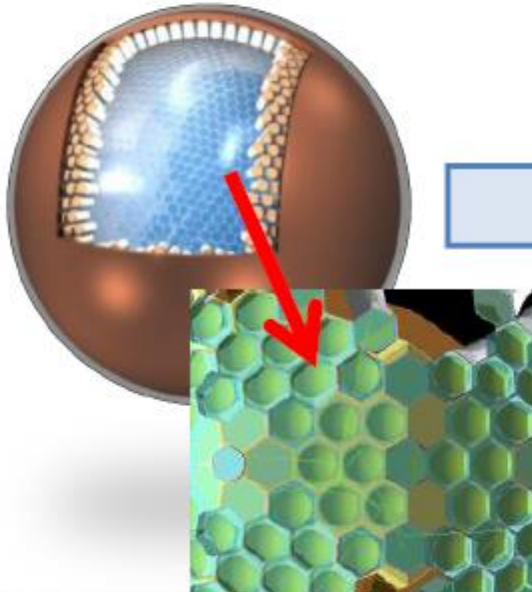


Source	Channel	EW [MeV]	$m_{\rm fid}$ [kt]	Rate [cpd]
pp	$\nu e \to e\nu$	>0.25	30	40
pep		0.8–1.4	30	2.8×10^2
^{7}Be		>0.25	35	1.0×10^4
^{8}B		>2.8	35	79
CNO		0.8–1.4	30	1.9×10^2
^{8}B	^{13}C	>2.2	35	2.4

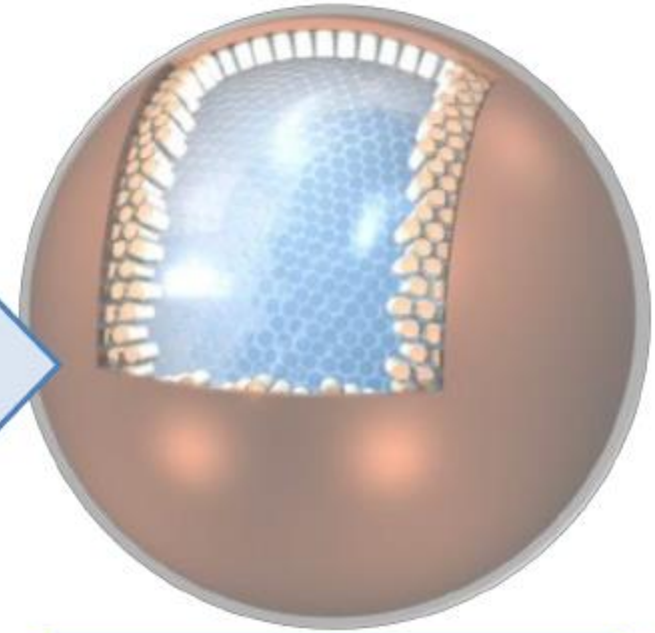
XMASS project

XMASS-I

XMASS-1.5



XMASS-II



Now

835 kg,
100 kg Fiducial volume (FV)
ϕ80 cm, 642 PMTs
Since 2010 Nov.

・ Dark matter search

5 ton,
1 ton FV
(x 10 of XMASS-I)
ϕ1.5 m, ~1000 PMTs

・ Dark matter search

25 ton, **10 ton FV**
ϕ2.5 m

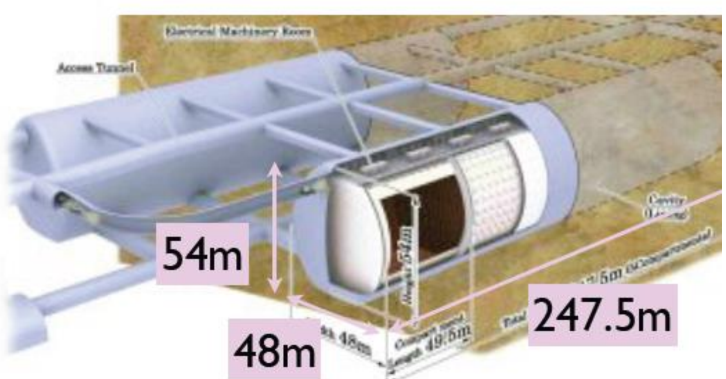
Multi purpose
・ Dark matter
・ pp solar neutrino
・ $0\nu2\beta$ decay

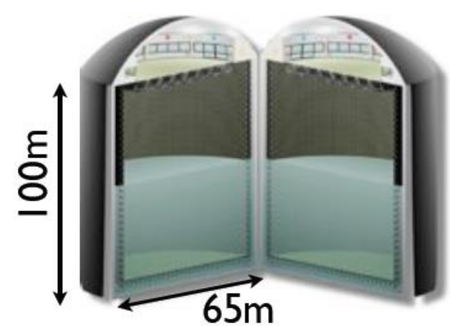
Y. Suzuki, hep-ph/0008296

Megatonne scale WC detectors

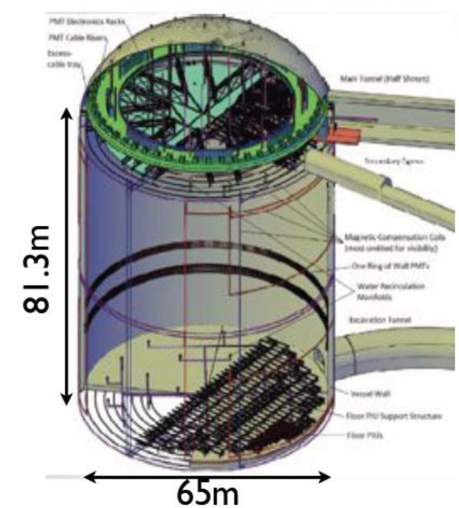
Well-proven technology of water Cherenkov detectors

- HyperK (Japan) (arXiv 1109.3262)
- MEMPHYS (Frejus)
- LBNE-WC (US) (arXiv:1204.2295; 350 pp)





200kton fiducial volume



Remaining ? in Solar neutrino physics

- Solar metallicity problem; will it be solved by Borexino?
- CNO neutrino flux measurement
- “Upturn” in the ^{8}B spectrum. Is it a hint for the NSIs or just a statistical fluctuation?
- The “tension” between SK and KL parameters
- The observation of the D/N variations of the ^{8}B signal still missing

Instead of conclusion

- “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.