Solar neutrinos:
Borexino and beyond

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XX International Workshop on Neutrino Telescopes- 23-27 October 2023 - Istituto Veneto di Scienze, Lettere e Arti

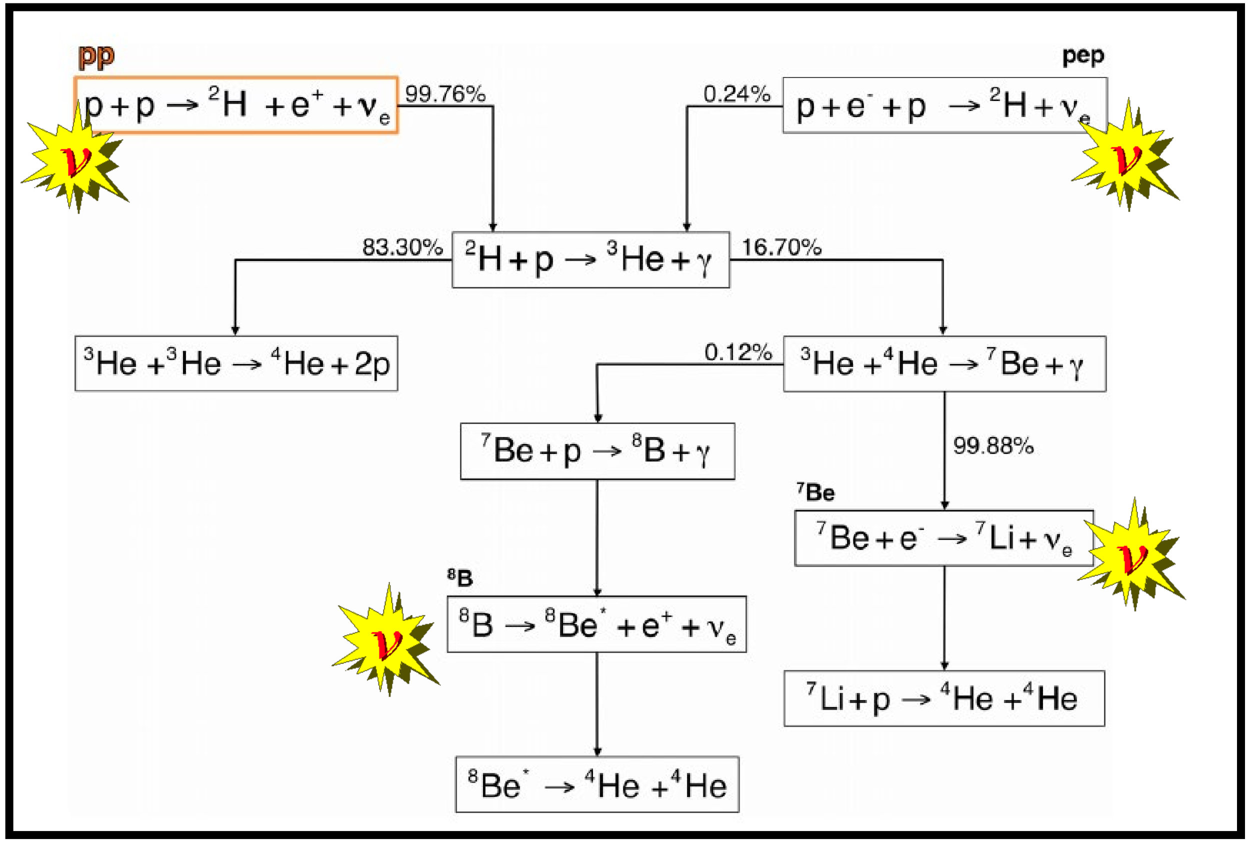
Studying Solar Neutrinos

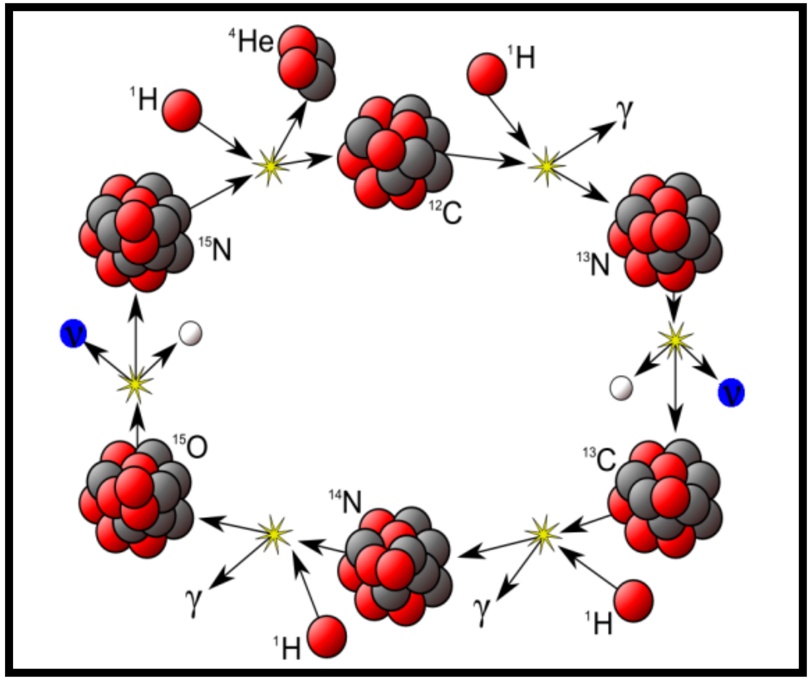
Neutrinos are emitted by fusion reactions occurring in the Sun

$4\,p \rightarrow \alpha + 2\,e^{+} + 2\nu$ (E released ~ 26 MeV)

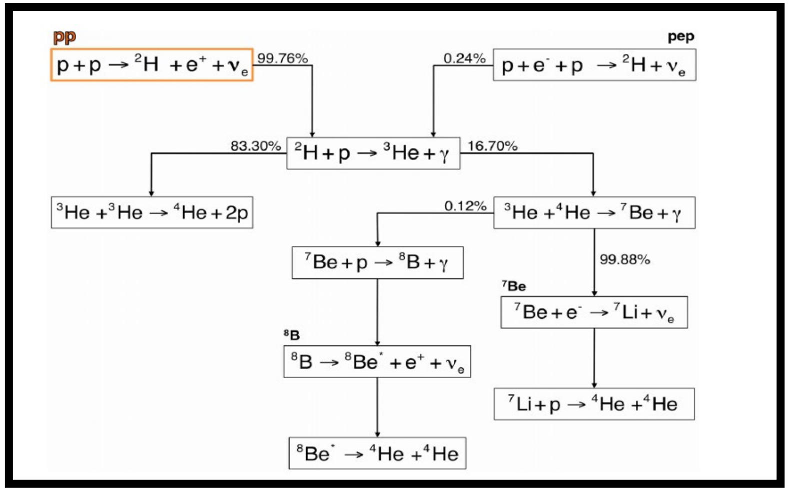
pp CHAIN: ~99% of the Sun energy

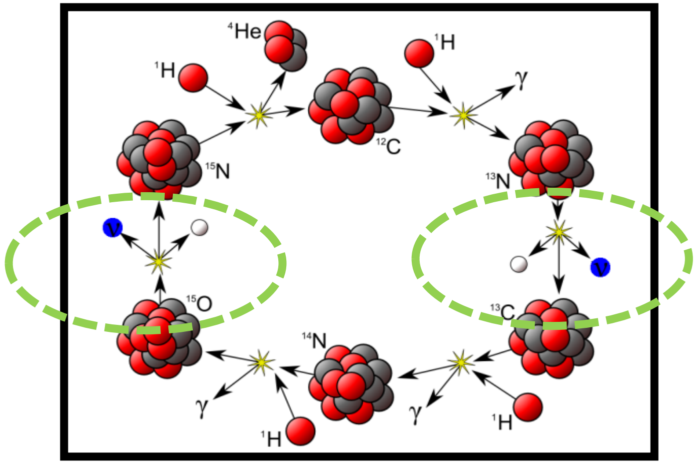
CNO cycle: ~1% of the Sun energy



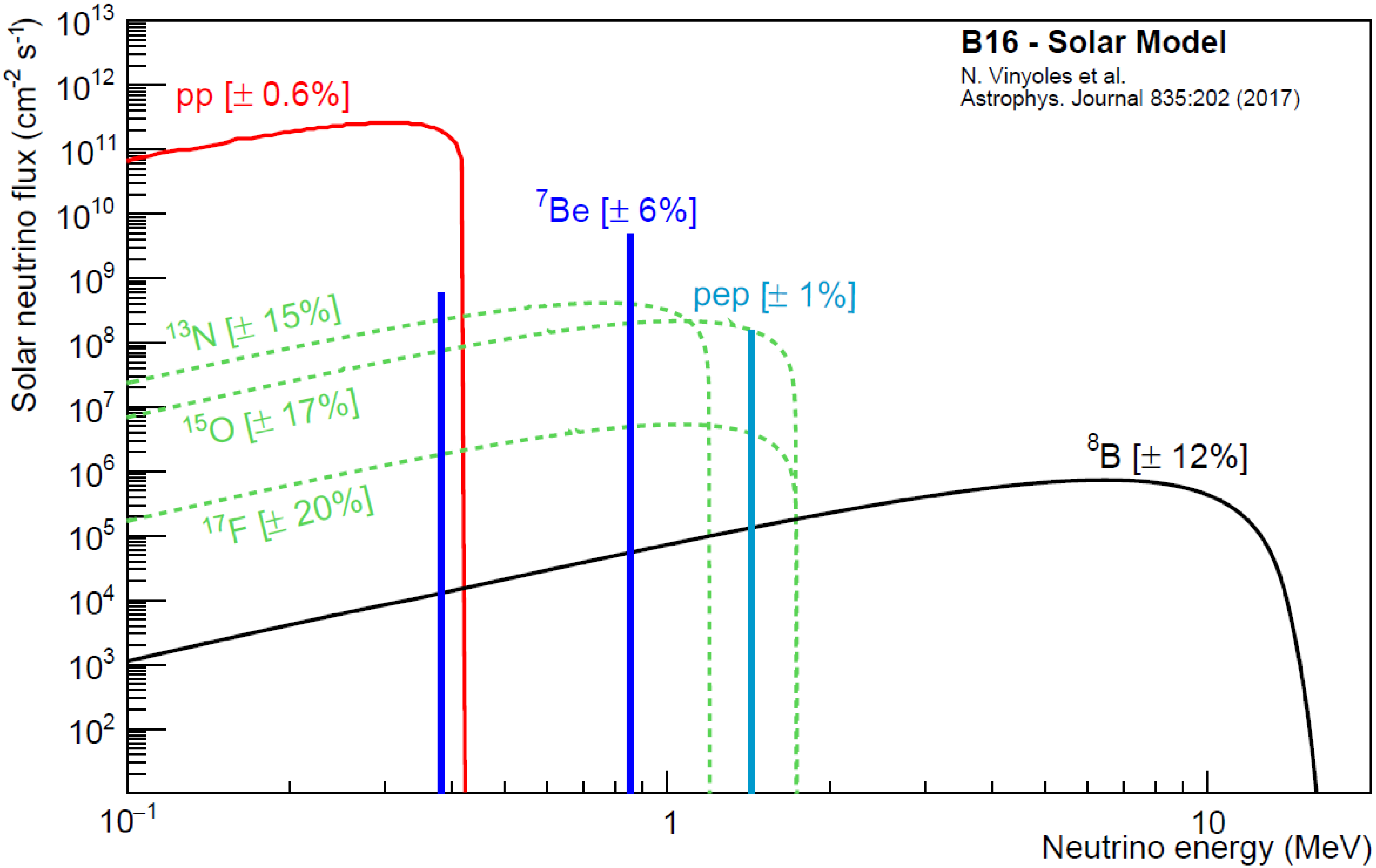


Studying Solar Neutrinos





Tot flux on Earth: 6 x 10^{10} neutrinos/sec/cm^2



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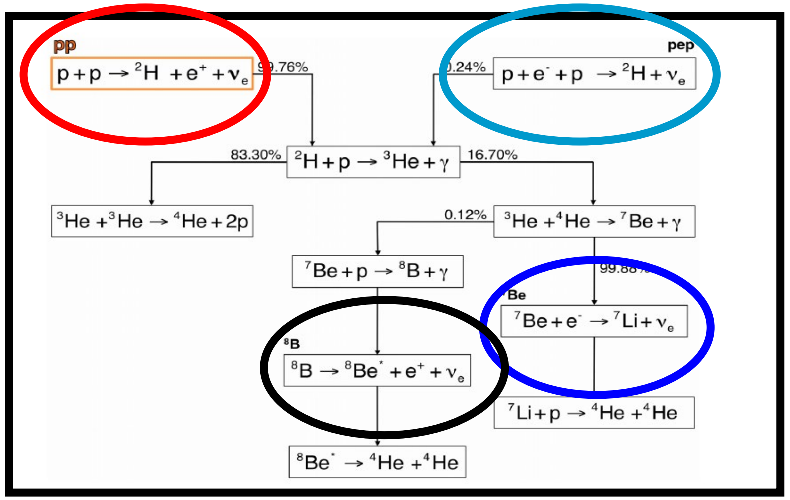

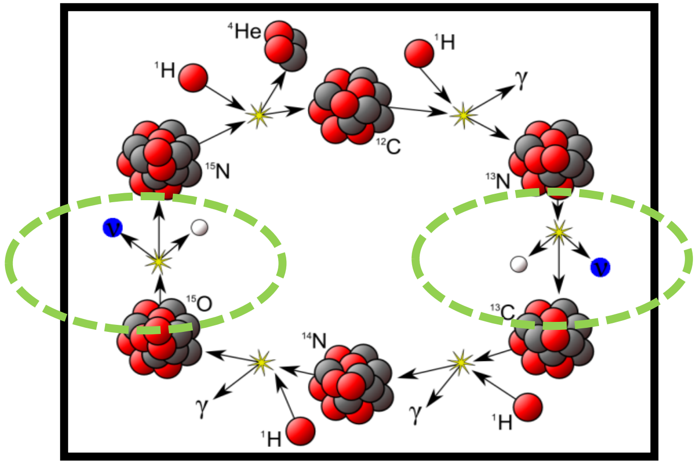

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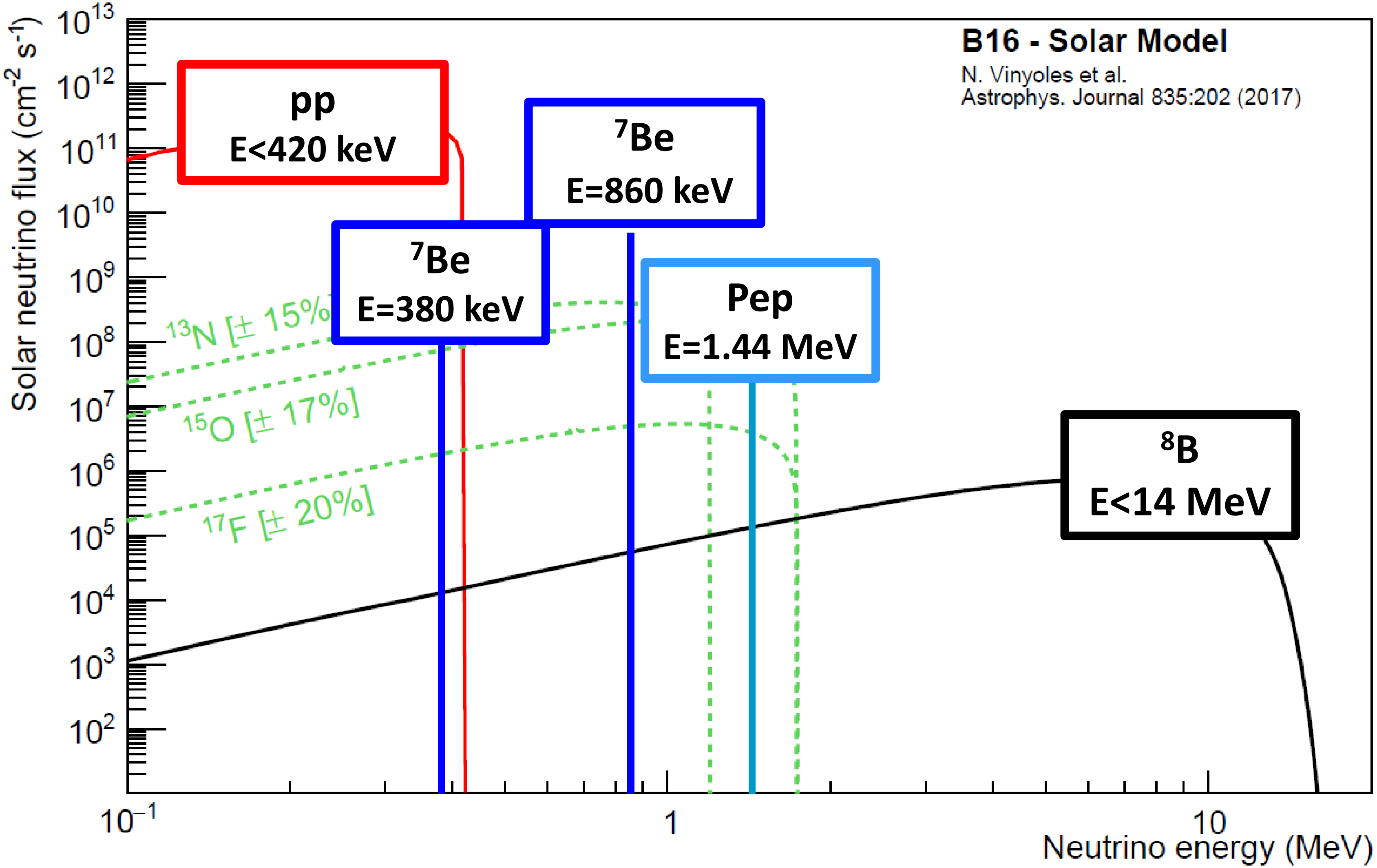


Studying Solar Neutrinos

- Thanks to their elusive nature, solar neutrinos are ideal probes of the Sun interior;
- The history of solar neutrino experiments as proved their importance

The glorious past (1968-2007)
Homestake, Gallex, GNO, SAGE, SNO, Kamiokande,Superk

→

The formidable present (2007-2023)
Borexino, Superk

→

The exciting future
SNO+, Sk-Gd, JUNO,HyperK, DUNE,THEIA, JNE

The glorious past

Homestake, Gallex/GNO, SAGE, Kamiokande, SupeK, SNO

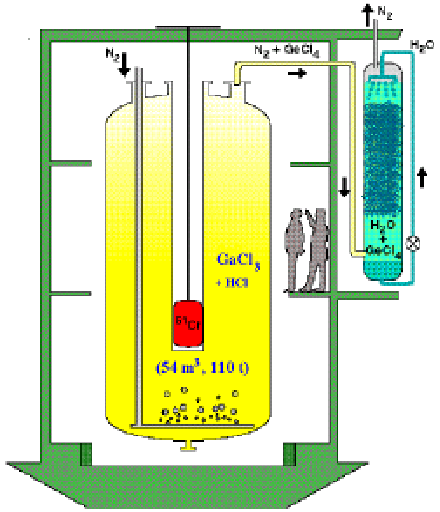
The giants of the (under the) mountain

- **Huge** amounts of material to increase the probability of interaction
- **Underground** to shield from cosmic rays

Homestake
600 t percloroetilene

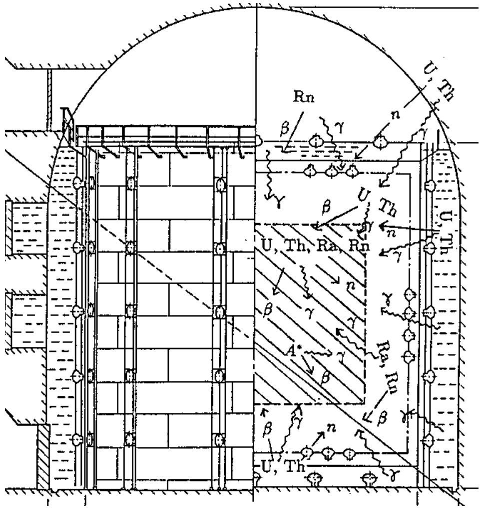
1968-1994

GALLEX/GNO
100 t di $GaCl_3$-HCl



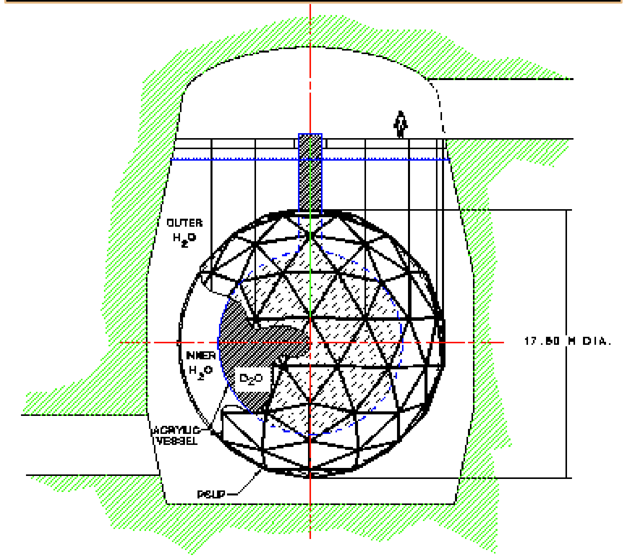
1991-2003

Kamiokande
3000 t of water



1983-1995

SNO
1000 t of heavy water



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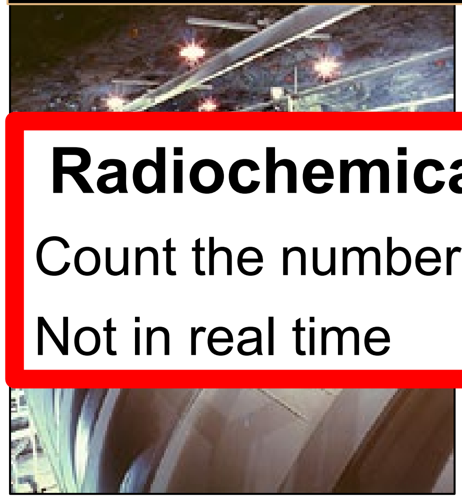

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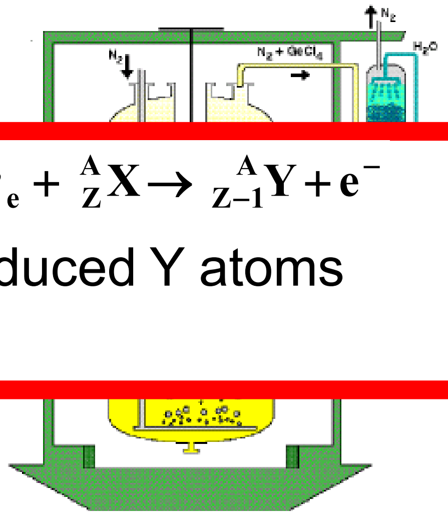

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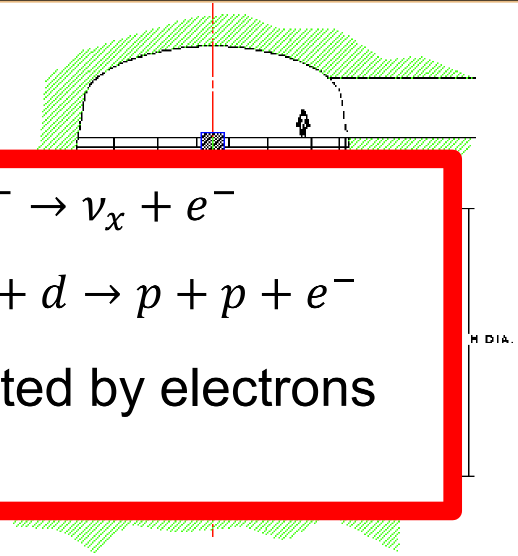


1999-2006

Radiochemical $\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^-$

Count the number of produced Y atoms

Not in real time

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

$\nu_x + d \rightarrow n + p + \nu_x$ $\quad \nu_e + d \rightarrow p + p + e^-$

See Cherenkov light emitted by electrons

Real time

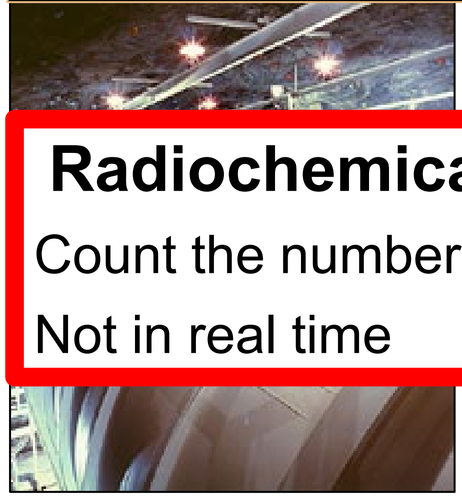
The glorious past

Homestake, Gallex/GNO, SAGE, Kamiokande, SupeK, SNO

The giants of the (under the) mountain

- All experiments observed less neutrinos than predicted by the SSM;
- ➢ **The dawn of the solar neutrino problem**

Homestake
600 t percloroetilene



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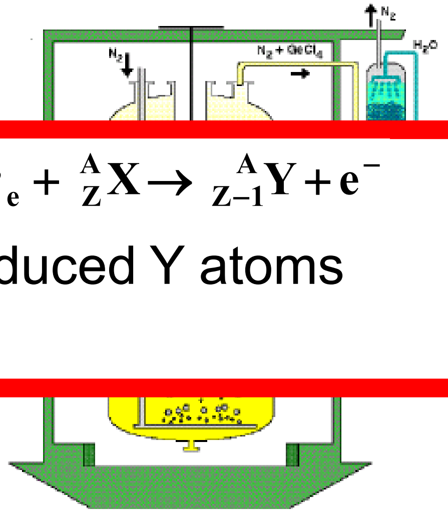

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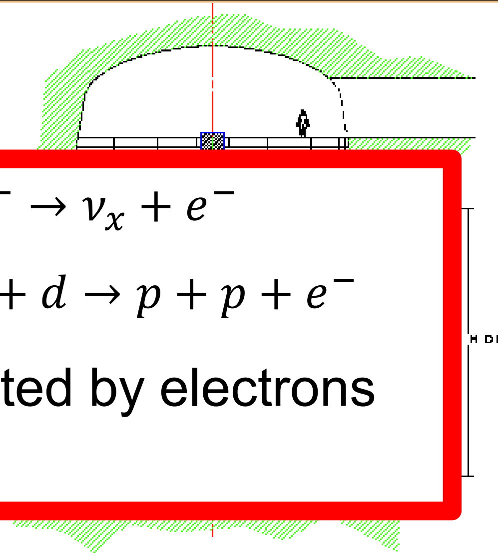

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The glorious past

Homestake, Gallex/GNO, SAGE, Kamiokande, SupeK, SNO

Discovery of neutrino oscillations

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

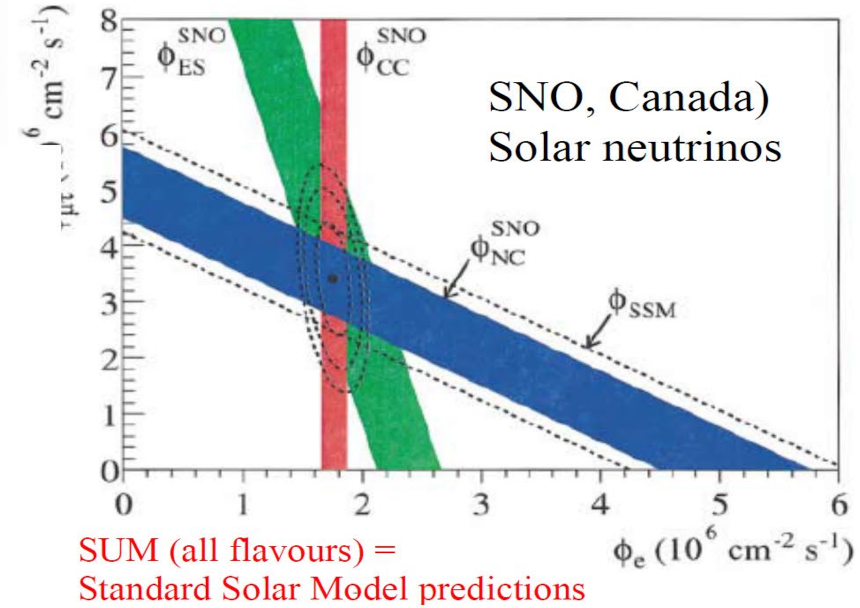
Prize share: 1/2

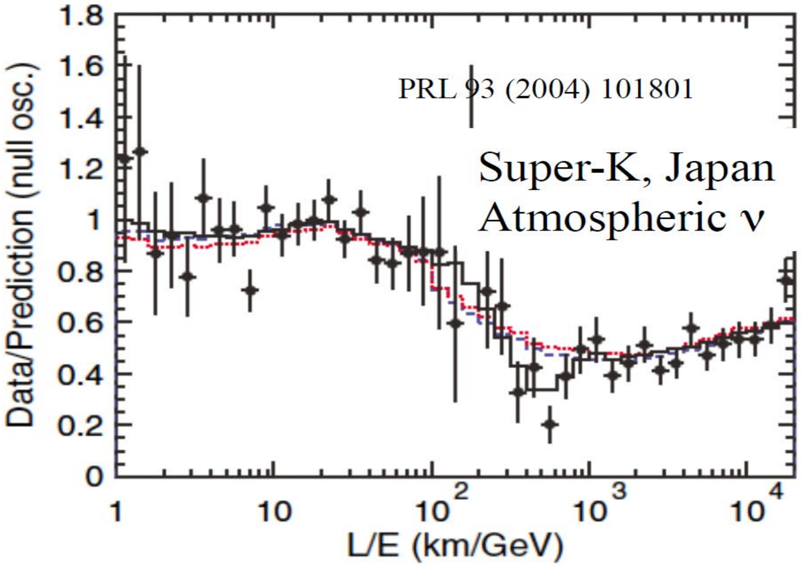
Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaa Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



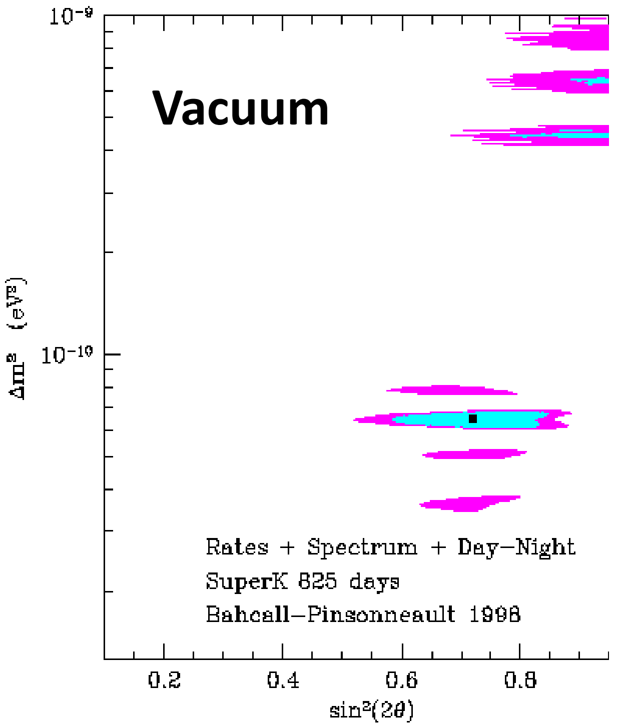


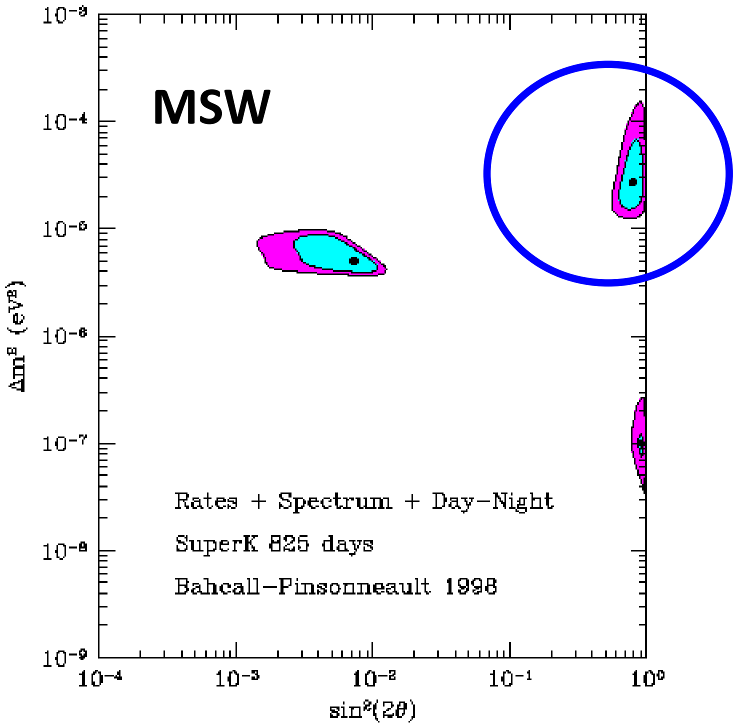
Homestake, Gallex/GNO, SAGE, Kamiokande, SupeK, SNO

The glorious past

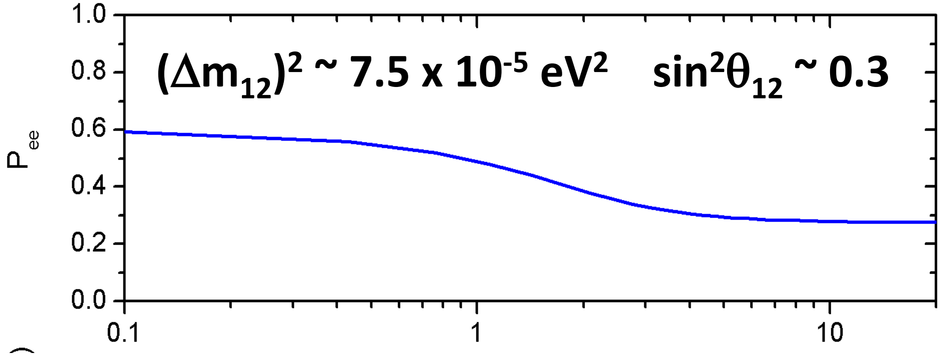
Homestake, Gallex/GNO, SAGE, Kamiokande, SupeK, SNO

- Solar neutrinos undergo flavor conversion during their trip from Sun to Earth;
- The flavor conversion is enhanced in the solar matter by the MSW effect;
- The best fit to all solar nu experiments (+ KamLAND) selects the so-called LMA-MSW;





Survival probability for LMA solution



The formidable present

Borexino
Superkamiokande

After the discovery of neutrino oscillations ...

Astrophysics

Understanding our Sun

- **Study details of the pp chain;**
- **CNO cycle**
- **Metallicity problem**

- **Measuring θ_{12} and Δm_{12}^2**
- **Non Standard Interactions of neutrinos**

Particle physics

open issues on neutrino oscillations;

Next generation experiments Superkamiokande and Borexino have greatly contributed to these aspects;

Borexino
Superkamiokande

The formidable present

Borexino
Superkamiokande

Astrophysics with solar neutrinos: the solar metallicity puzzle

- Metallicity of the Sun: abundance of elements with Z>2 (C, N, O, Ne, Mg, Si, S,Ar, Fe…);
- Obtained from spectroscopic measurement of the photosphere and from studies of meteorites;
- **Different analysis of the spectroscopic data provide different results on metallicity (HZ, LZ);**
- Metallicity is an input of the Standard Solar Models (SSMs are calibrated on it);

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

Measuring individually the fluxes of ^{7}Be, ^{8}B and especially CNO neutrinos can provide a crucial input to solve the puzzle;

Superkamiokande

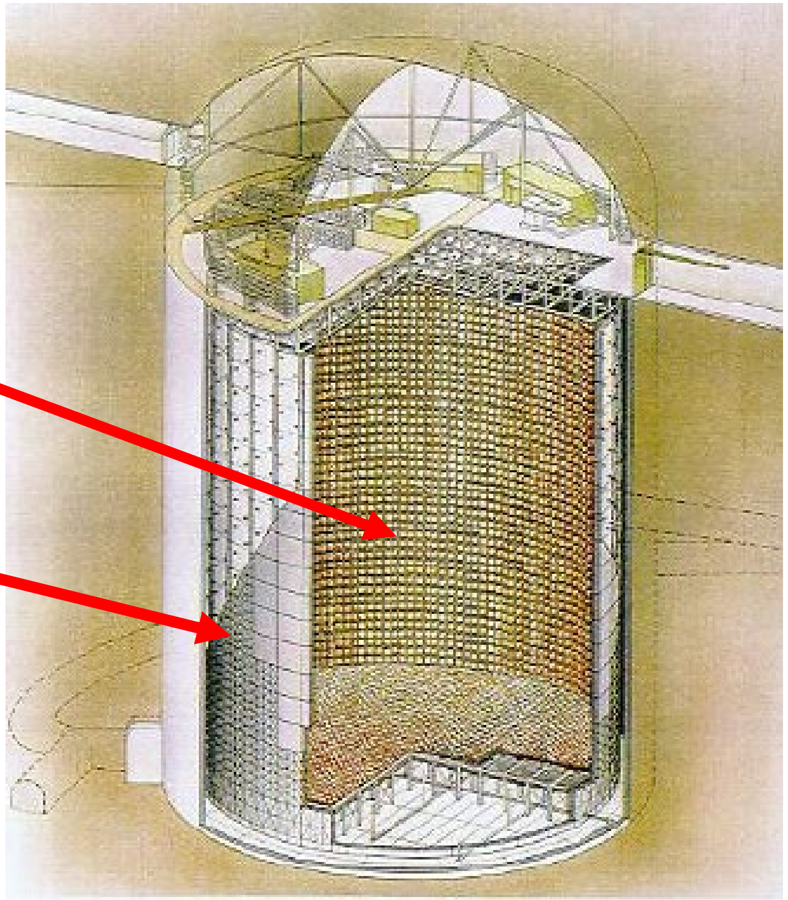
Superkamiokande: essential ingredients (1)

It is a water Cherenkov detector

Core of the detector: 50ktons of water contained in a cylindrical tank d~40m, h ~40m

11129 photomultiplier tubes pointing towards the center to view the Cherenkov light;

Since 1996-2020: four Phases SK-I to SK-IV



@ Kamioka Mine, Hida City, (Japan)

(See plenary talk on SuperK by Magdalena Posiadala-Zezula on October 24)

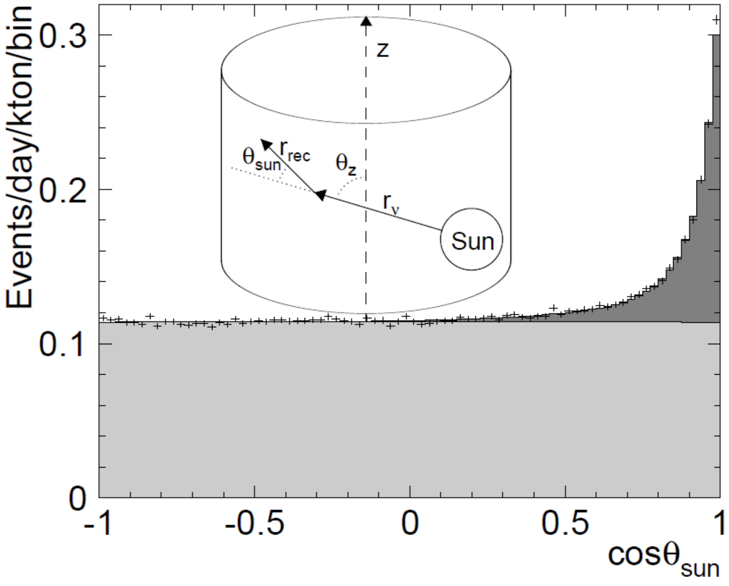
Superkamiokande: essential ingredients (2)

Superkamiokande detects solar neutrinos through scattering on electrons

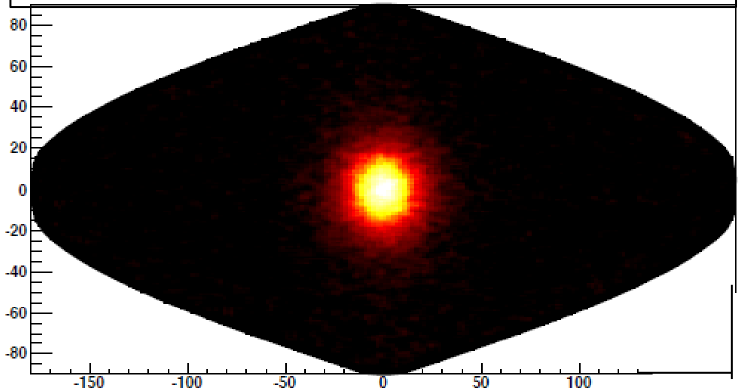
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- If above threshold (T_e ~ 250 keV) the scattered electrons produces Cherenkov light;

For each event

- Number of photons → Energy (Energy resolution of 20% @4 MeV)
- Cherenkov light is directional → direction of electron (angular resolution of 40^0 @ 4 MeV)



Seeing the Sun from underground
The Eye of Sauron



Energy threshold ranging from 4.5 MeV to 3.5 MeV due to radioactivity;

SK is sensitive only to 8B neutrinos

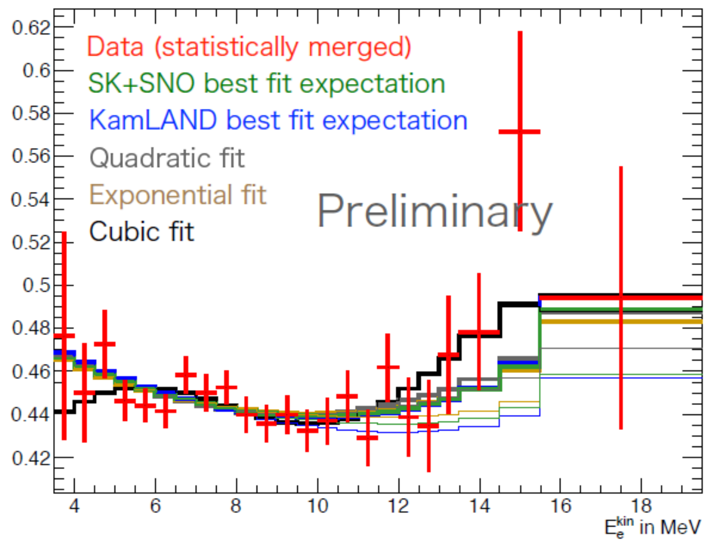
Superkamiokande: results on ^{8}B neutrinos

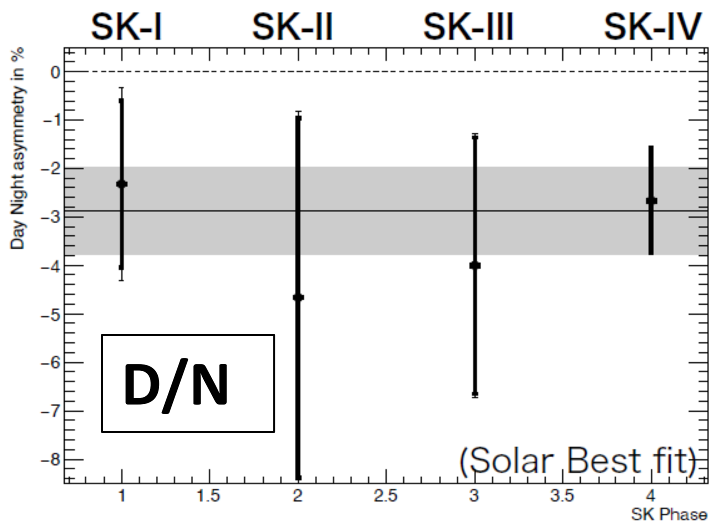
Most precise measurement of the ^{8}B flux with an uncertainty of 1,7%

- 5805 live days collected between SK-I, SK-IV
- Over 100k events of ^{8}B neutrinos

Phase	Livetime [days]	Energy [MeV]	DATA/MC	Flux w/ systematic error [*10^6 /cm^2/sec]	Extracted Signal (Statistical only)
SK-I	1496	4.5-19.5	$0.453 \pm 0.005 ^{+0.016}_{-0.014}$	$2.38 \pm 0.02 \pm 0.08$	$22443 ^{+227}_{-225}$
SK-II	791	6.5-19.5	$0.459 \pm 0.010 \pm 0.030$	$2.41 \pm 0.05 ^{+0.16}_{-0.15}$	$7210 ^{+153}_{-151}$
SK-III	548	4.0-19.5	$0.459 \pm 0.010 \pm 0.030$	$2.40 \pm 0.04 \pm 0.05$	$8148 ^{+133}_{-133}$
SK-IV (Updated)	2970.08	3.5-19.5	$0.443 \pm 0.003 \pm 0.006$	$2.33 \pm 0.01 \pm 0.03$	63890^{+381}_{-379}
Combined	5805	–	$0.447 \pm 0.002 \pm 0.008$	$2.35 \pm 0.01 \pm 0.04$	More than 100k events

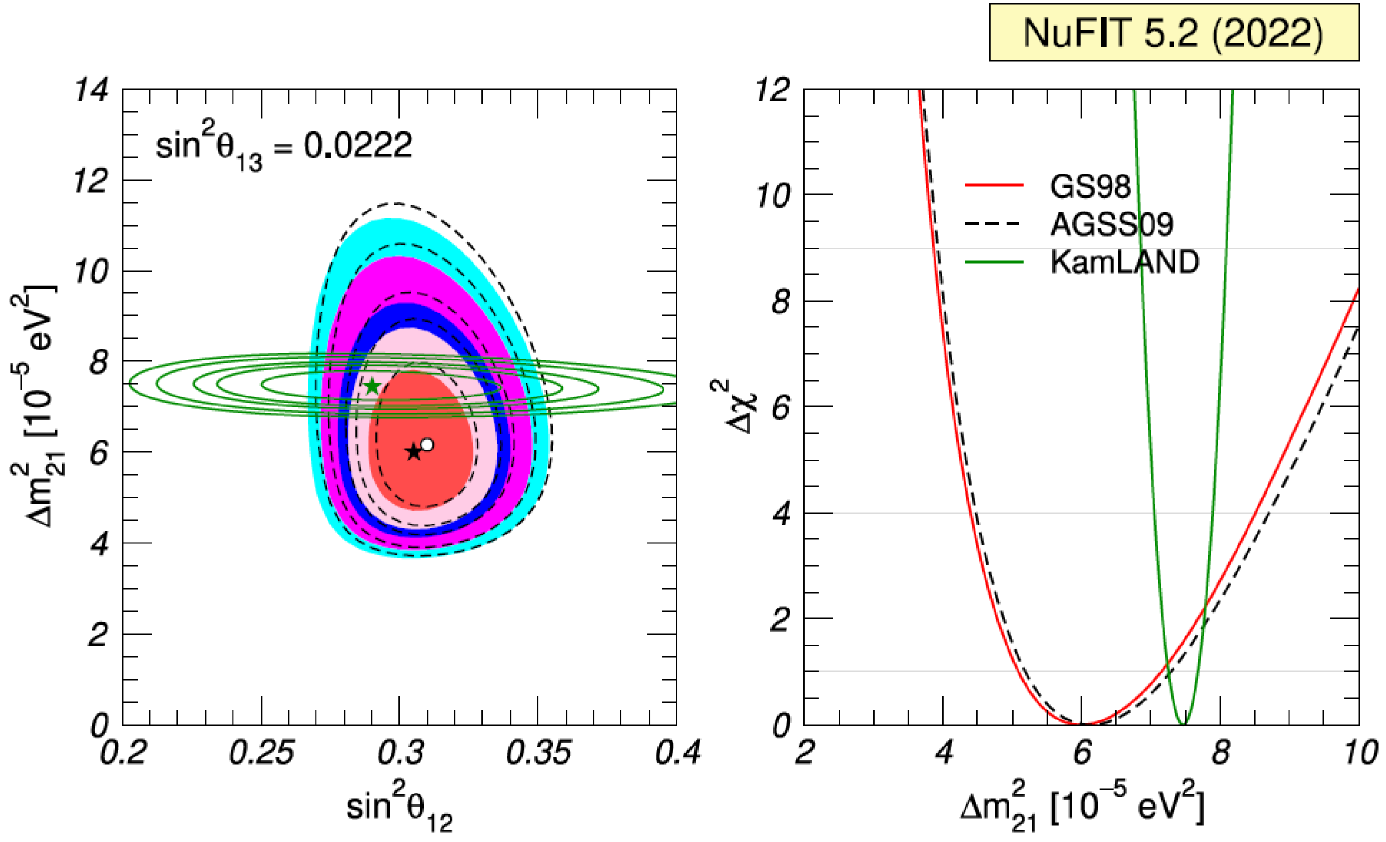
Recoil energy spectrum





Implications of Superkamiokande results

Implications on particle physics: oscillation analysis



Note that the ~ 2σ tension between solar and KamLAND data has significantly reduced

From 2σ → 1σ

Since 2020, SuperK is working with the addition of Gd to improve the neutron tagging efficiency (SK-Gd);

- **Better discrimination of cosmogenic background!**

Borexino

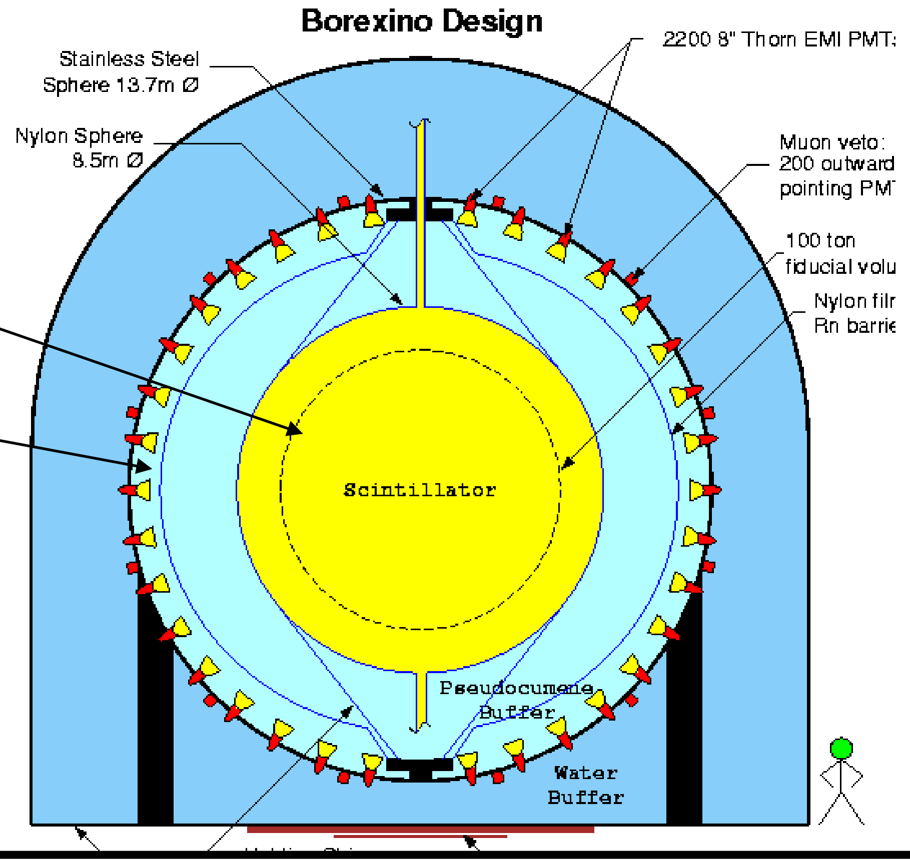
Borexino: essential ingredients (1)

It is a liquid scintillator detector

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

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

Borexino detects neutrinos through scattering on electrons $\nu_x + e^- \rightarrow \nu_x + e^-$



Main goal: study solar neutrinos below 1 MeV

@ Laboratori Nazionali del Gran Sasso (Italy)

Borexino: essential ingredients (2)

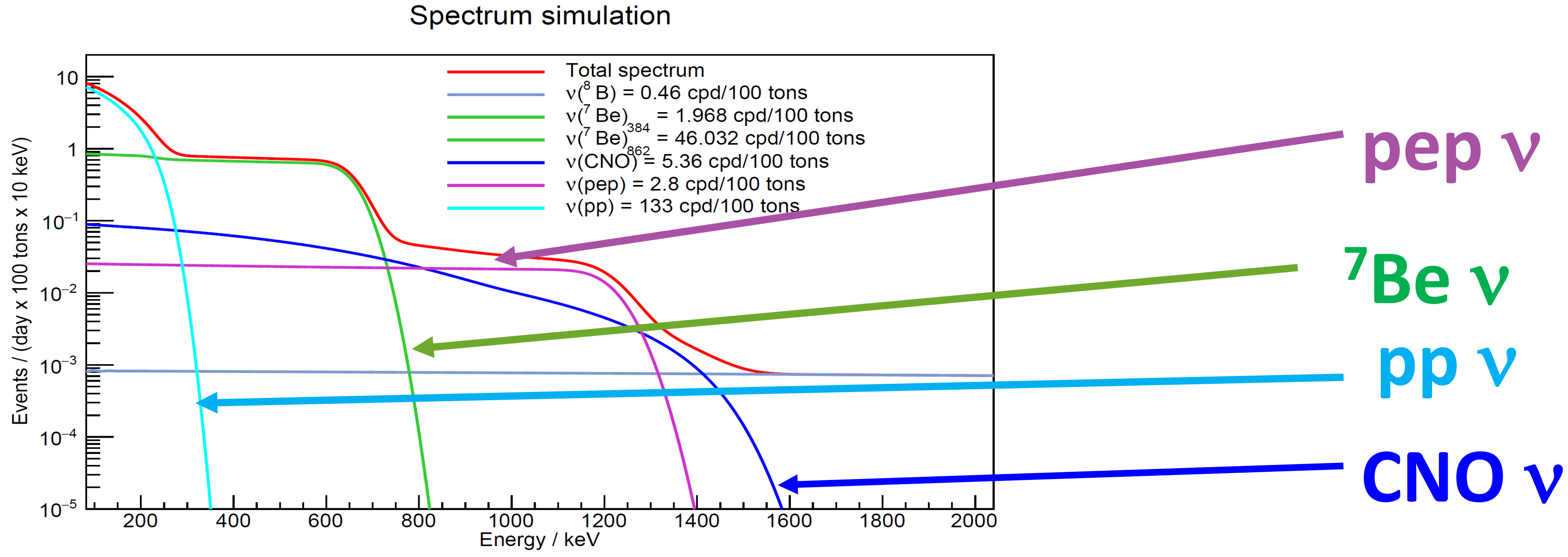
Relatively high light yield (with respect to Cerenkov detectors)

Number of photons larger than random instrumental noise

- Low energy threshold is possible

Relatively good $\sigma(E)/E \sim 5\%/\mathrm{sqrt}(E)$

- Possibility to distinguish contributions from different signal/background in the energy spectrum;



Simulated spectrum of electrons scattered by solar neutrinos

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However, in order to go below 1 MeV

Extreme radiopurity is needed!

Borexino: the quest for the radiopurity Grail

15 years of work

- Purification of the scintillation (distillation, vacuum stripping with low Ar/Kr N2);
- Detector design: concentric shells to shield the inner scintillator from external background
- Material selection and surface treatment, clean construction and handling;

Achievements

- Radiopurity even exceed design goals in some cases ^{238}U chain <9.4x10^{-20} g/g and ^{232}Th chain <5.7x×10^{-19} g/g**;**
- Some background out of specifications (^{210}Po, ^{85}Kr, ^{210}Bi)

Borexino: the long story..

2007	PHASE-I	2009	2012	PHASE-II	2015	2017	PHASE-III	2021

PHASE-I (2007-2010)

Solar neutrinos

- ^{7}Be ν : 1st observation+ precise measurement (5%); Day/Night asymmetry;
- pep ν: 1st observation;
- ^{8}B ν with low treshold;
- CNO ν: best limit;

Other

- geo-ν Evidence > 4.5σ
- Limit on rare processes
- Study on cosmogenics

Purifications

6 cycles of water extraction

Calibrations

PHASE-II (2012-2016)

Solar neutrinos

- pp neutrinos (Nature 2014)
- seasonal modulations (2017)
- *Final results on pp, 7Be and pep and 8B solar ν*

Thermal insulation

PHASE-III (2017-2021)

Solar neutrinos

- 2020: First detection of CNO neutrinos;
- 2022: final result on CNO neutrinos using CID

October 2021: End of Borexino data-taking

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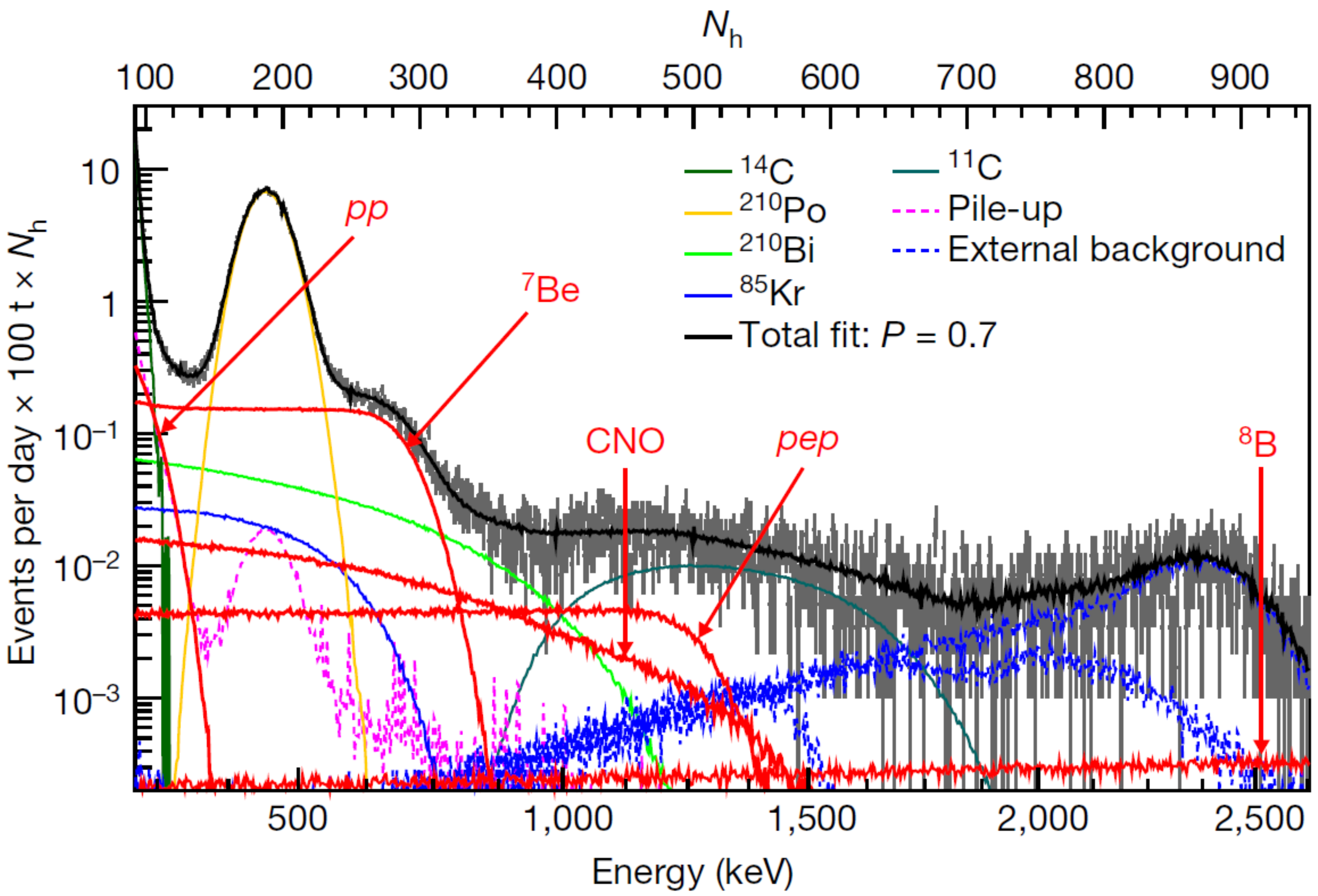
Borexino final results on the p-p chain

Comprehensive results on proton-proton chain solar neutrinos *(Nature, 496 (2018) 505))*



The rates of signal and background are extracted with a fit to the energy distribution of events;

This requires:

- Good energy resolution
- Good knowledge of the detector energy response

Borexino final results on the p-p chain

Solar neutrinos	Rate (Counts/day/100t)	Uncertainty	Flux* (neutrinos/cm²/sec)	SSM predictions** (neutrinos/cm²/sec)
pp	$134 \pm 10^{+6}_{-10}$	9.5%	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1 \pm 0.006) \times 10^{10}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	17%	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1 \pm 0.01) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	17%	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1 \pm 0.01) \times 10^{8}$ (LZ)
7Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	2.7%	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1 \pm 0.06) \times 10^{9}$ (LZ)
8B	$0.223^{+0.015+0.006}_{-0.016-0.006}$	7.6%	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1 \pm 0.12) \times 10^{6}$ (LZ)

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

**neutrino fluxes from: *N.Vinyole,A.Serenelli, F.Villante, S.Basu, J.Bergstrom,M.C.Gonzalez-Garcia, M.Maltoni, C.Pena-Garay, N.Song, Astr.Jour. 835,202 (2017)*

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7Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	2.7%	$(4.99 \pm 0.11^{+0.06}_{-0.08})\text{x}10^{9}$	$4.93(1 \pm 0.06)\ \text{x}10^{9}$ (HZ) $4.50(1 \pm 0.06)\ \text{x}10^{9}$ (LZ)
8B	$0.223^{+0.015+0.006}_{-0.016-0.006}$	7.6%	$(5.68^{+0.39+0.03}_{-0.41-0.03})\text{x}10^{6}$	$5.46(1 \pm 0.12)\ \text{x}10^{6}$ (HZ) $4.50(1 \pm 0.12)\ \text{x}10^{6}$ (LZ)

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*
**neutrino fluxes from: *N.Vinyole,A.Serenelli, F.Villante, S.Basu, J.Bergstrom,M.C.Gonzalez-Garcia, M.Maltoni, C.Pena-Garay, N.Song, Astr.Jour. 835,202 (2017)*

Borexino final results on the p-p chain

Solar neutrinos	Rate (Counts/day/100t)	Uncertainty	Flux* (neutrinos/cm²/sec)	SSM predictions** (neutrinos/cm²/sec)
pp	$134 \pm 10^{+6}_{-10}$	9.5%	$(6.1 \pm 0.5^{+0.3}_{-0.5})\text{x}10^{10}$	$5.98(1 \pm 0.006$[illegible] (HZ) [illegible] (LZ)
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This results are obtained fixing the CNO to the SSM value. What about CNO?

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

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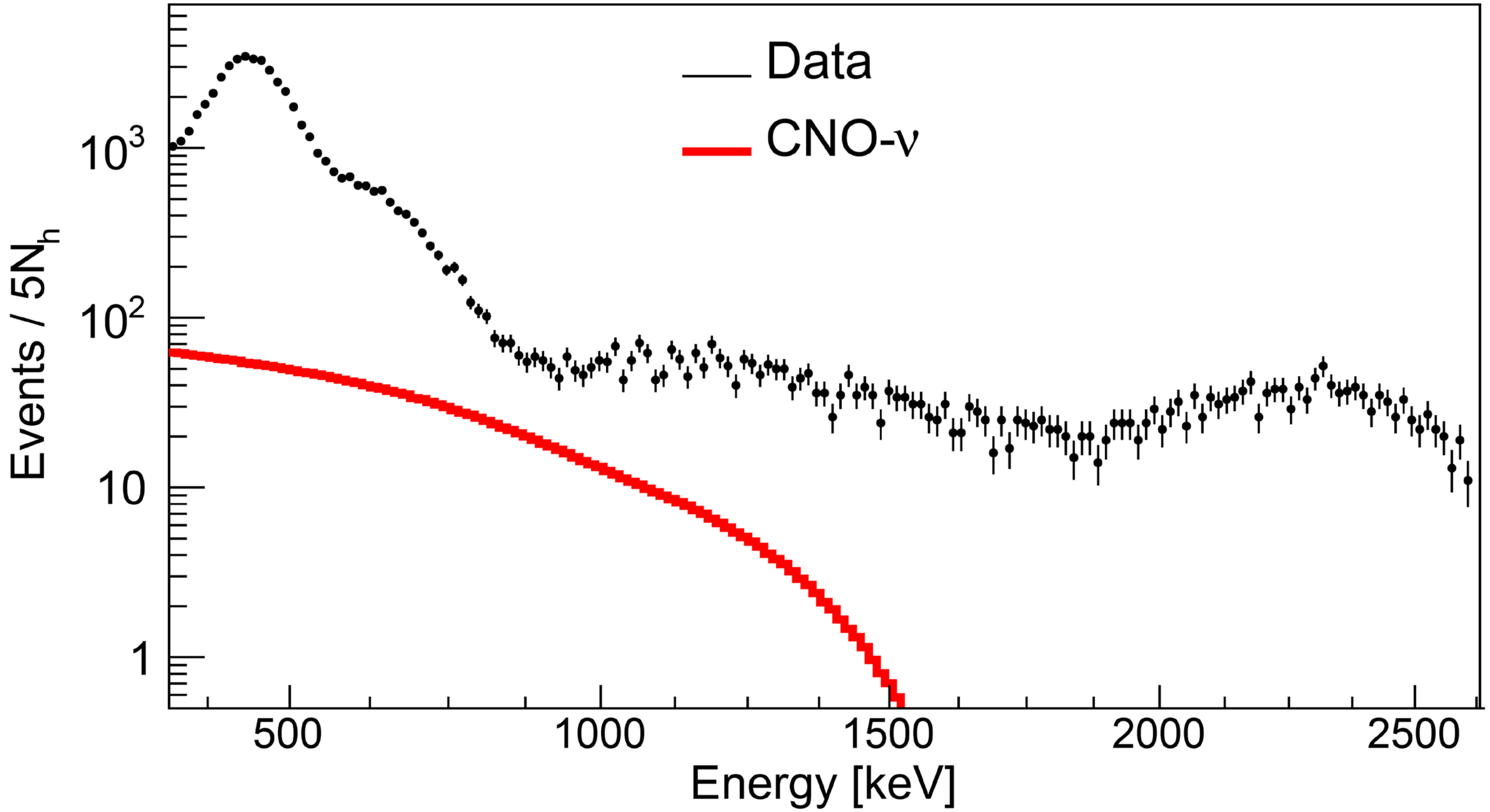
Borexino: the CNO cycle

Looking for a needle in a haystack

The main problem is the ^{210}Bi contamination;



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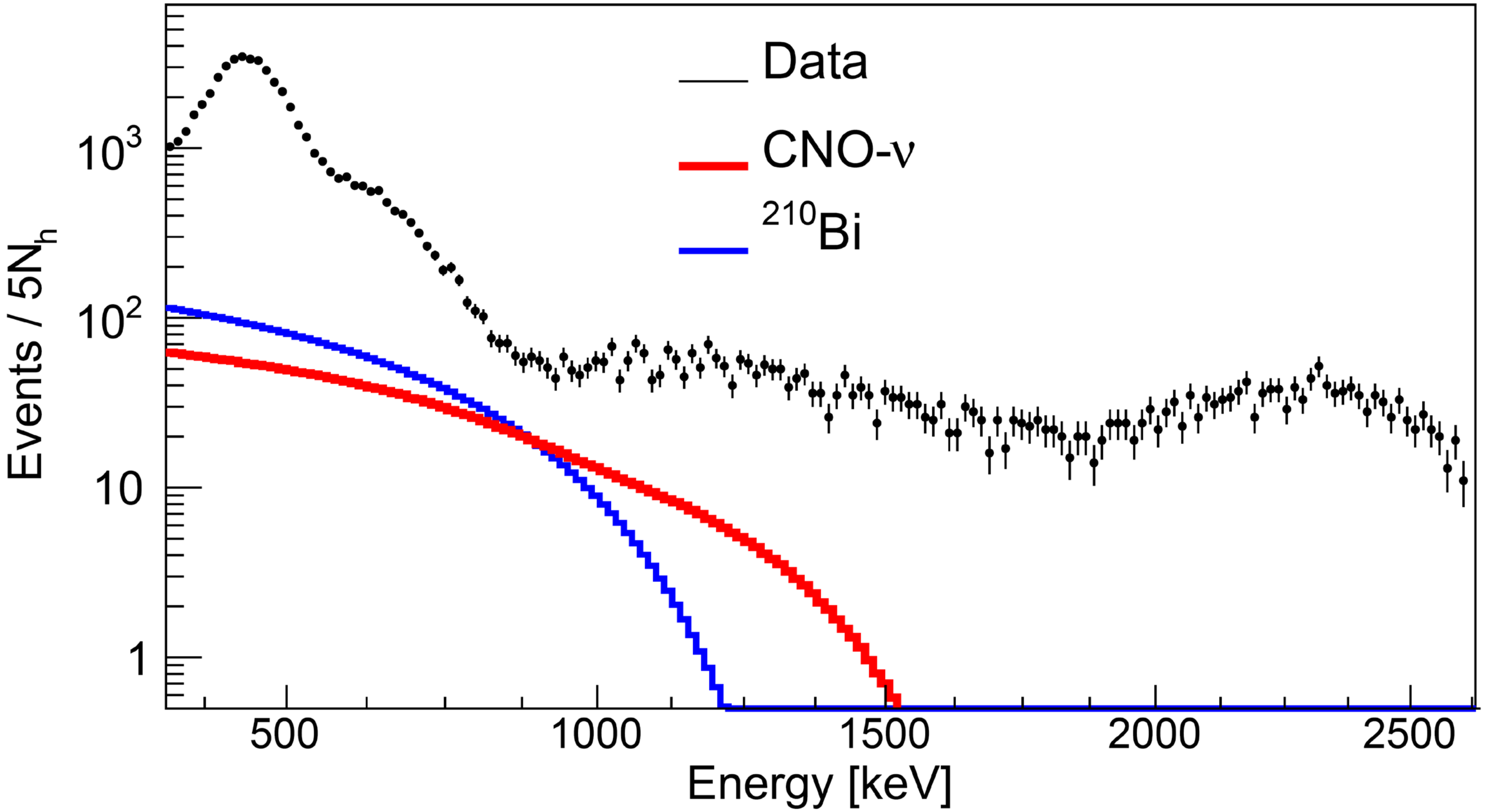

THE PROBLEM

- The rate of CNO and ^{210}Bi is comparable;
- The spectral shape is very similar → the fit cannot disentangle the two contributions easily!

Need an extra help!

Borexino: the CNO cycle

Two additional elements

1) External constraint on ^{210}Bi rate from ^{210}Po;

- Requires secular equilibrium in the $^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po$ chain;
- Can only be applied on Phase-III when the detector was totally insulated to avoid convective currents which bring out-of-equilibrium ^{210}Po from the vessel into the scintillator;

Borexino: the CNO cycle

Two additional elements

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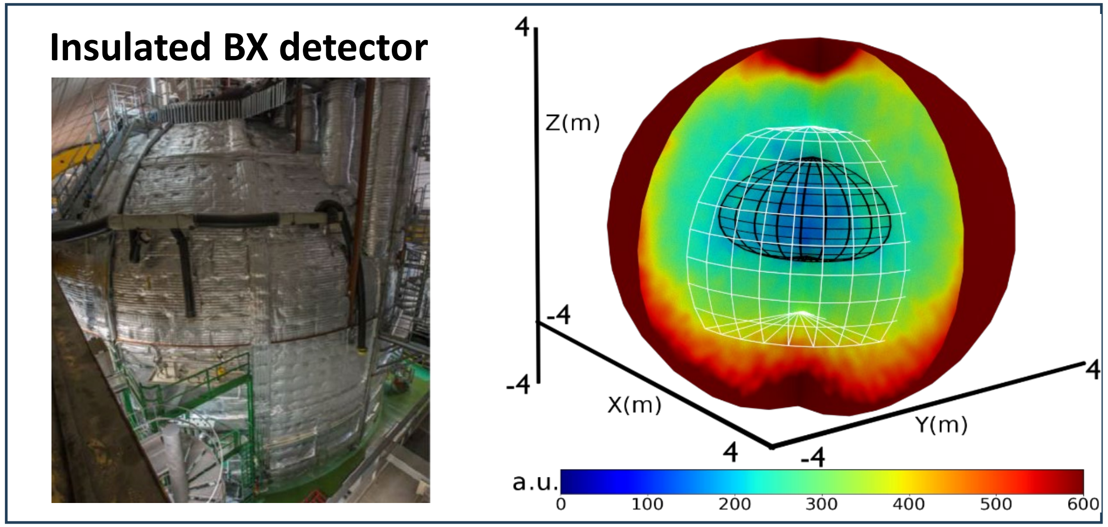

First direct evidence of the existence of CNO neutrinos (~5σ significance)

Nature 587 (2020)578 ; PRL 129 (2022)252701

Borexino: the CNO cycle

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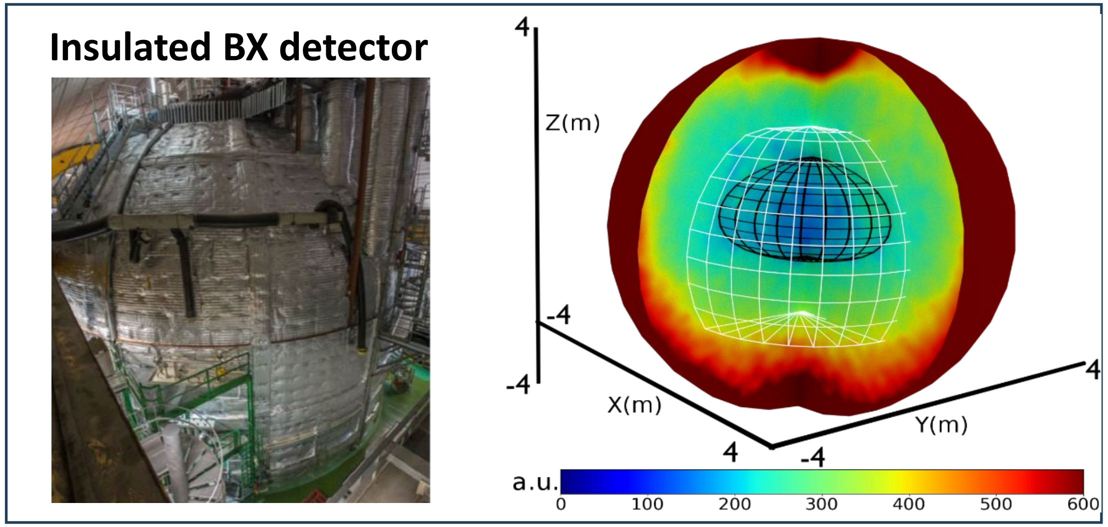


First direct evidence of the existence of CNO neutrinos (~5σ significance)

Nature 587 (2020)578 ; PRL 129 (2022)252701

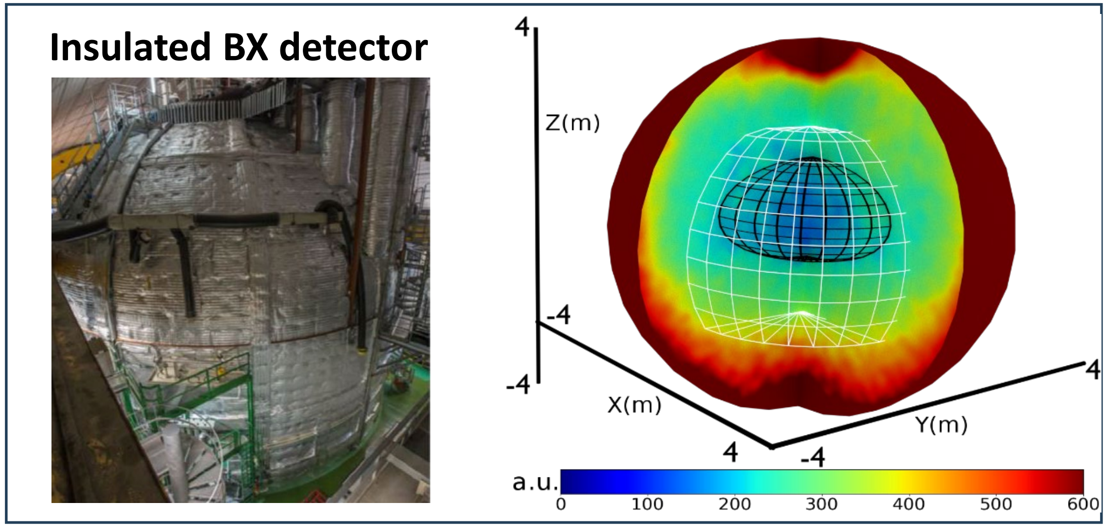
2) Correlation with the Sun direction (CID method)

- Exploits the few Cherenkov photons of each events to statistically separate solar neutrino signal from backgrounds;
- Exploit the fact that Cherenkov photons are emitted earlier than scintillation photons;

Borexino: the CNO cycle

Two additional elements

1) External constraint on ^{210}Bi rate from ^{210}Po;



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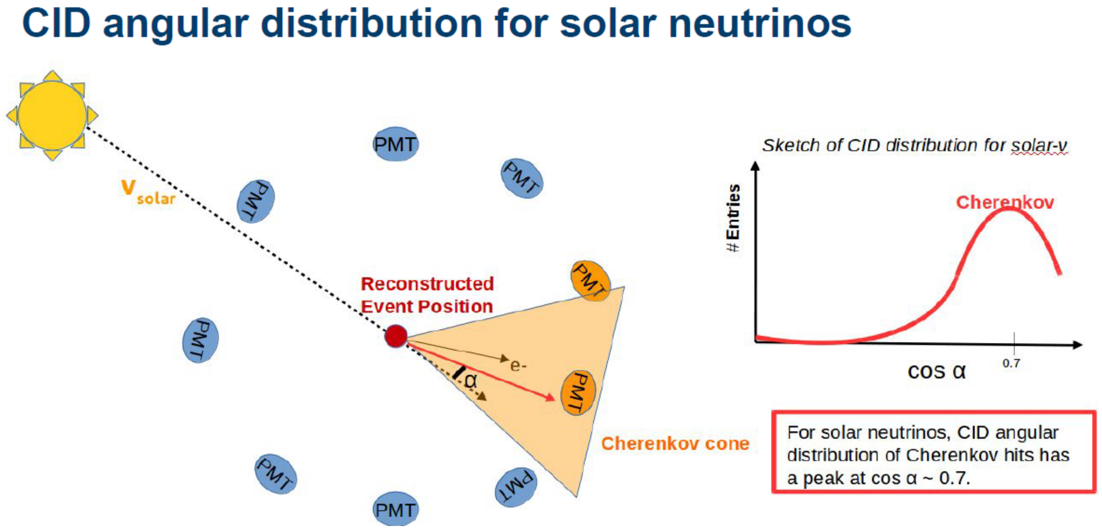

Final Borexino measurement of CNO neutrinos (using only 2 or 1+2) (>7σ)

Accepted for pub on PRD- arXiV 2307.14636

(See parallel talk by Luca Pelicci on October 26)

Borexino final results on the p-p chain and CNO cycle

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CNO	$6.7^{+1.2+0.3}_{-0.7-0.4}$	+30% -12%	$(6.7^{+1.2+0.3}_{-0.8-0.4})x10^{8}$	4.88(1 ± 0.11) x10^{8} (HZ) 3.51(1 ± 0.10) x10^{8} (LZ)

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

**neutrino fluxes from: *N.Vinyole,A.Serenelli, F.Villante, S.Basu, J.Bergstrom,M.C.Gonzalez-Garcia, M.Maltoni, C.Pena-Garay, N.Song, Astr.Jour. 835,202 (2017)*

Implications of the BX results

Implications of the BX results on astrophysics

Implication n.1: solar luminosity

- Neutrinos are detected on Earth only 8 minutes after they have been produced in the core of the Sun → They provide a real-time picture of the core of the Sun;
- The solar luminosity can be calculated using only Borexino results

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

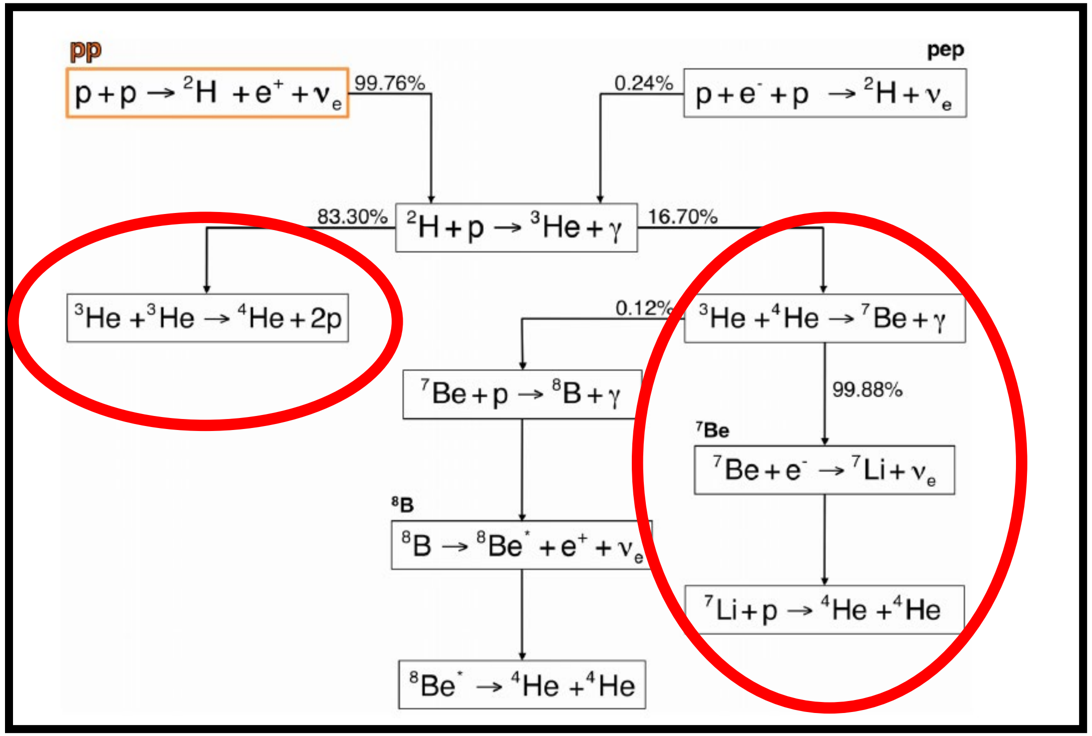
which is found to be in agreement with the well measured photon output

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

- This confirms the nuclear origin of the solar power;
- It proves that the Sun has been in thermodynamic equilibrium over 10^5 years (the time required for radiation to flow from the center to the surface of the Sun)

Implications of the BX results on astrophysics

Implication n.2: probing solar fusion



From the pp and ^{7}Be flux new measurement

$$\boxed{\mathbb{R} = 0.178^{+0.027}_{-0.023}}$$

- From the pp and ^{7}Be flux measurements it is possible to determine the ratio $\mathbb{R}$ between the rate of ^{3}He-^{3}He e ^{4}He-^{3}He;

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

- It is an important experimental test of the solar fusion

- Theoretical predictions

$\mathbb{R}$(HZ)= 0.180 ± 0.011

$\mathbb{R}$(LZ)= 0.161 ± 0.010

Implications of the BX results on astrophysics

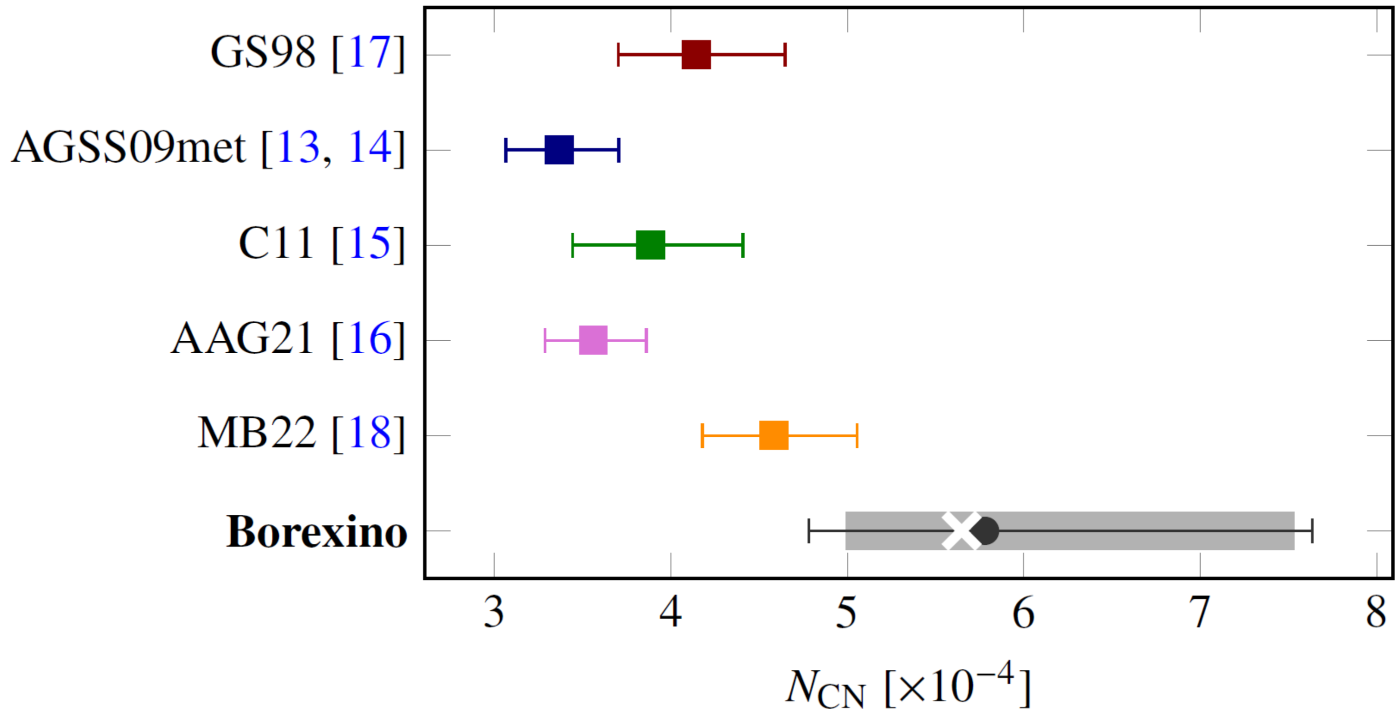
Implication n.3: existence of the CNO cycle

- Borexino has verified for the first time the existence of neutrinos from the CNO cycle (with a significance > 7σ)
- CNO is sub-dominant in the Sun, but it is believed to be one of the most important process of energy burning in the universe;
- **For this reason, its experimental confirmation is a milestone for experimental astrophysics;**

Implications of the BX results on astrophysics

Implication n.4: determining the C and N abundance

- Combining the precise measurement of ^8B from other experiments with the CNO measurement by Borexino it is possible to determine the C and N content (with respect to H) compared directly with the measurements derived from the solar photosphere;



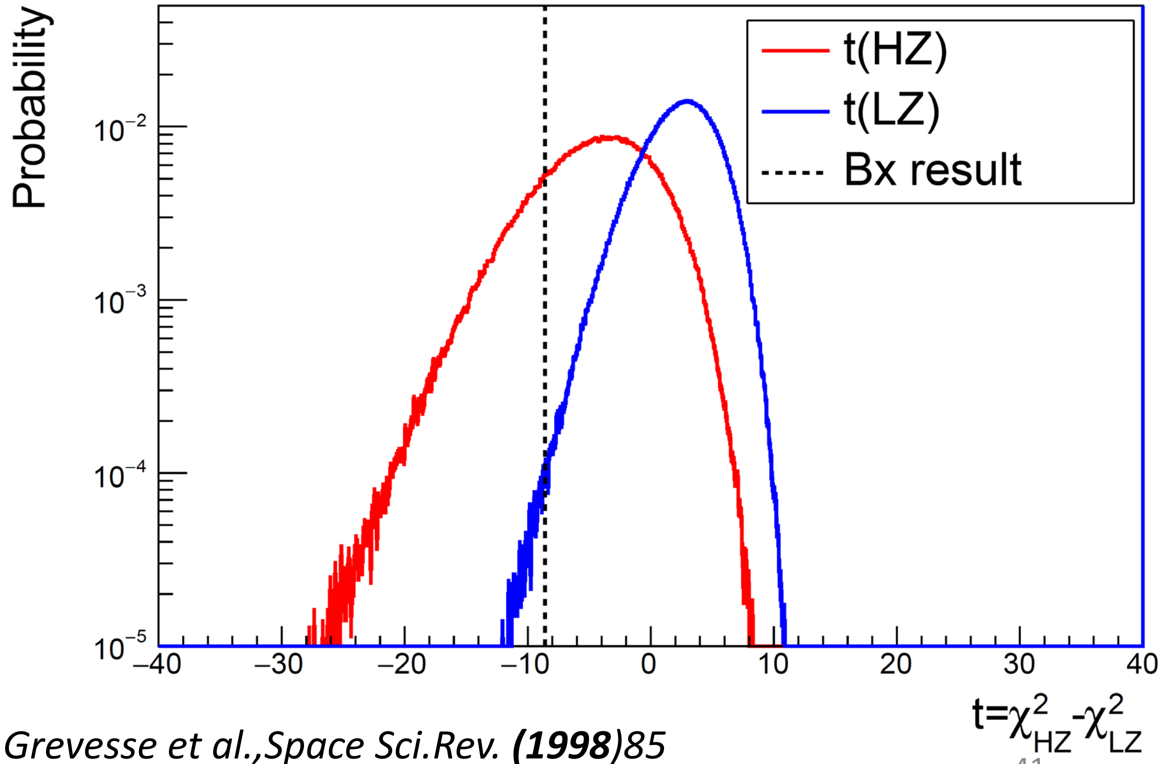
BX measurement agrees nicely with the High Metallicity ones, while features a ~2σ tension with the low metallicity measurements

Implications of the BX results on astrophysics

Implication n.5: the metallicity issue

- Combining the BX measurements on CNO, ^{7}Be and ^{8}B neutrino fluxes;
- We perform a frequentist hypothesis test based on a likelihood-ratio test statistics (SSM-HZ[1] vs SSM-LZ[2]), including ^{7}Be, ^{8}B and CNO flux predictions;

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)

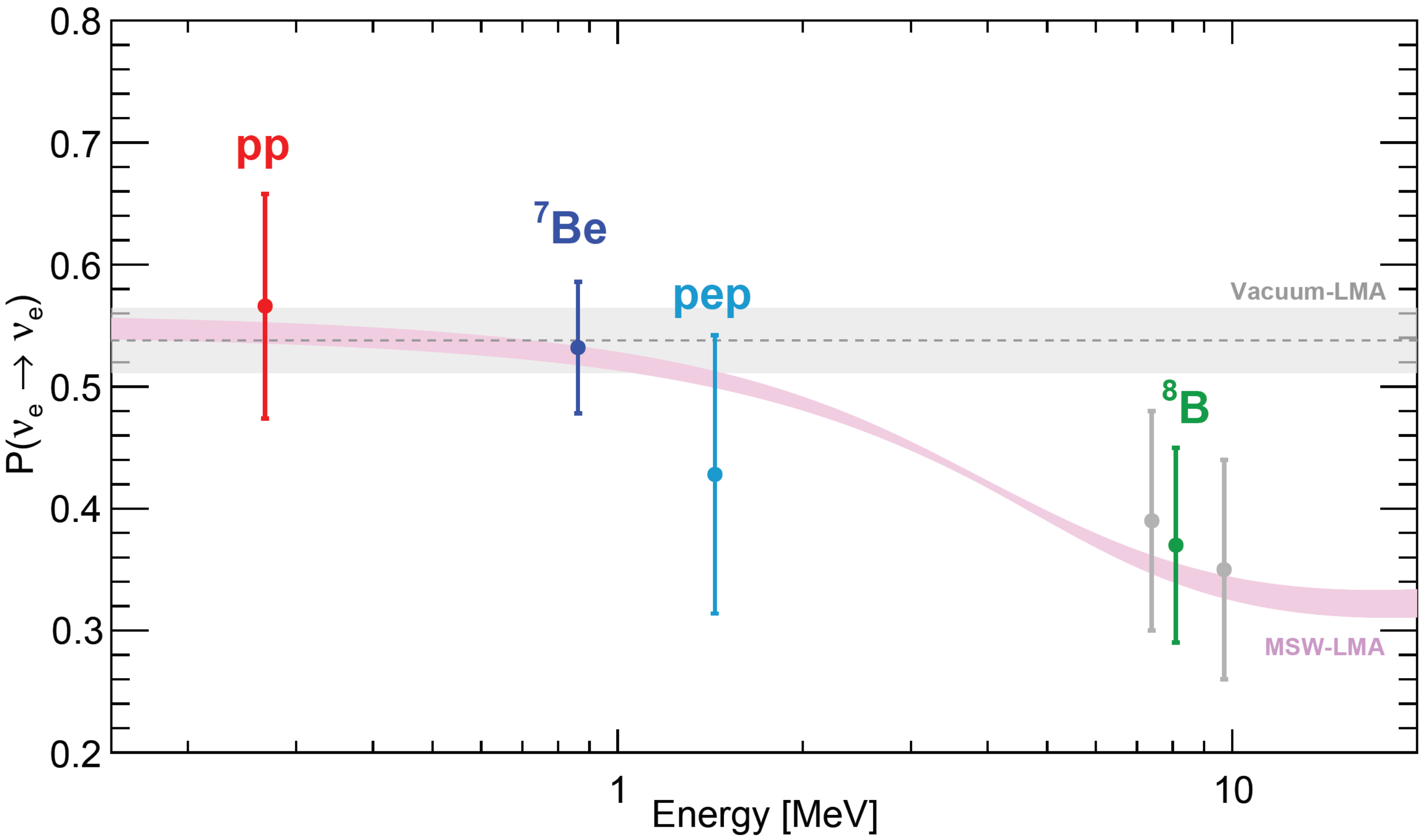


(1) SSM-HZ= B16-GS98: *Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al.,Space Sci.Rev. (**1998**)85*

(2) SSM-LZ= B16-AGSS09met: *Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

Implications of the BX results on particle physics

Implication n.1: survival probability P_{ee}



*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

From the measured interacton rates and 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.

The exciting future

JUNO, HyperK, DUNE, THEIA, JNE

What next on solar neutrinos?

Still several open issues which could be settled with future more precise measurements

Solar physics:

- **Metallicity puzzle**
  - could be definitely settled with more precise measurements of the ^{7}Be, ^{8}B and especially CNO flux;
- **hep neutrinos** still missing
  - $p + {}^{3}He \rightarrow {}^{4}He + e^{+} + \nu_e$
  - Flux very low: $8x10^3$ (ν /cm^2/sec)
  - Highest energy: E_{max} ~ 19 MeV;

The exciting future

JUNO, HyperK, DUNE, THEIA, JNE

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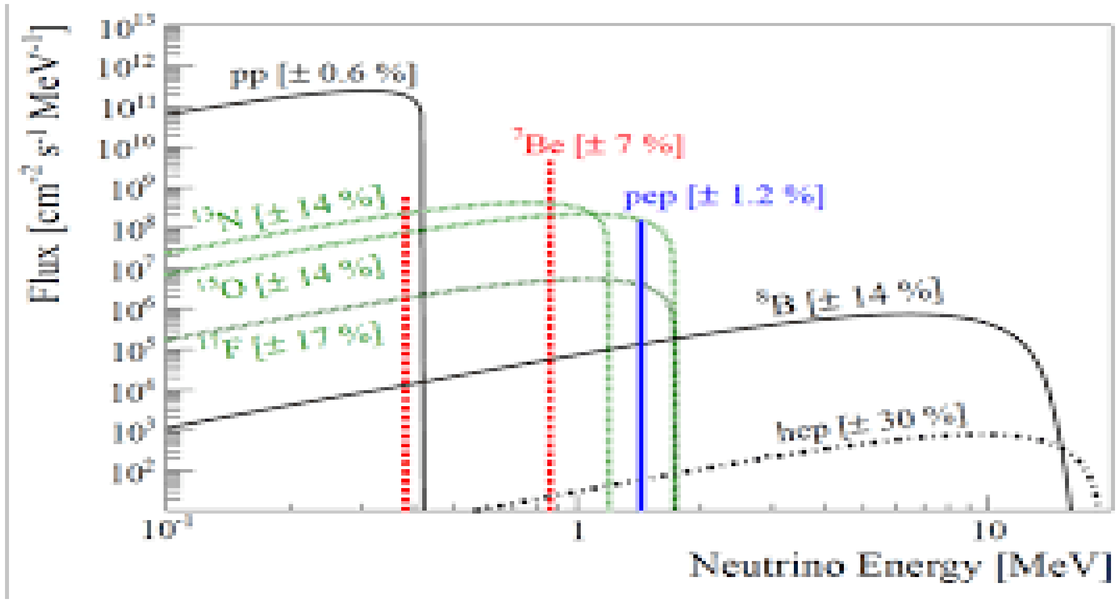
Solar physics:



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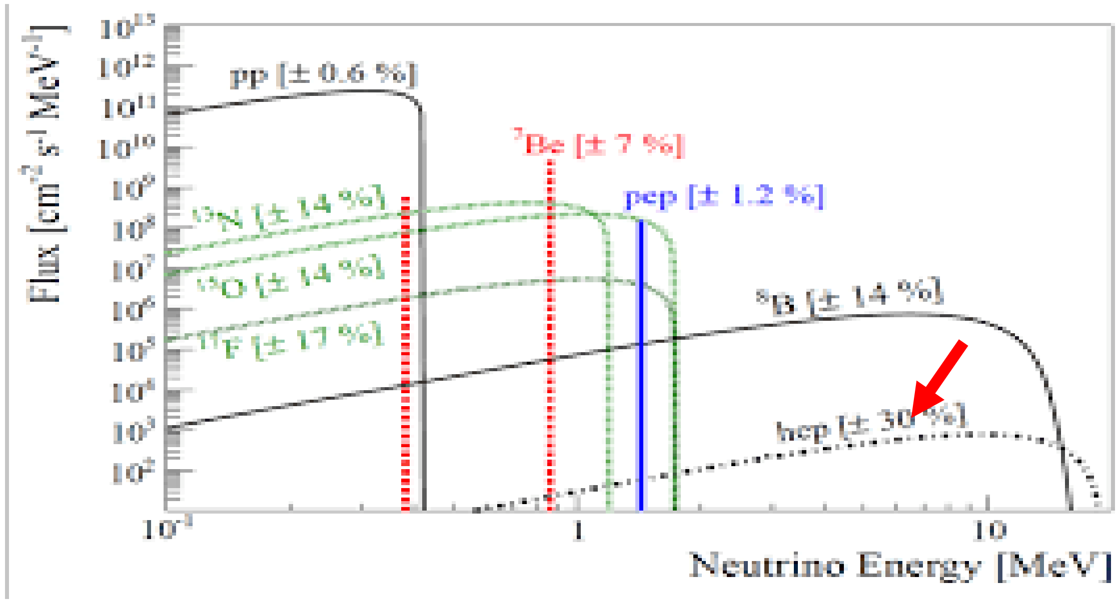

Particle physics:

- Completing the details of the ``standard'' LMA-MSW oscillations (D/N, upturn...)

Investigating non standard physics

- Non Standard Neutrino Interactions (NSI);
- Oscillatons into sterile ν,
- Neutrino magnetic moment μ_ν,
- Neutrino decay;
- Other..

The exciting future

JUNO, HyperK, DUNE, THEIA, JNE

What next on solar neutrinos?

Still several open issues which could be settled with future more precise measurements

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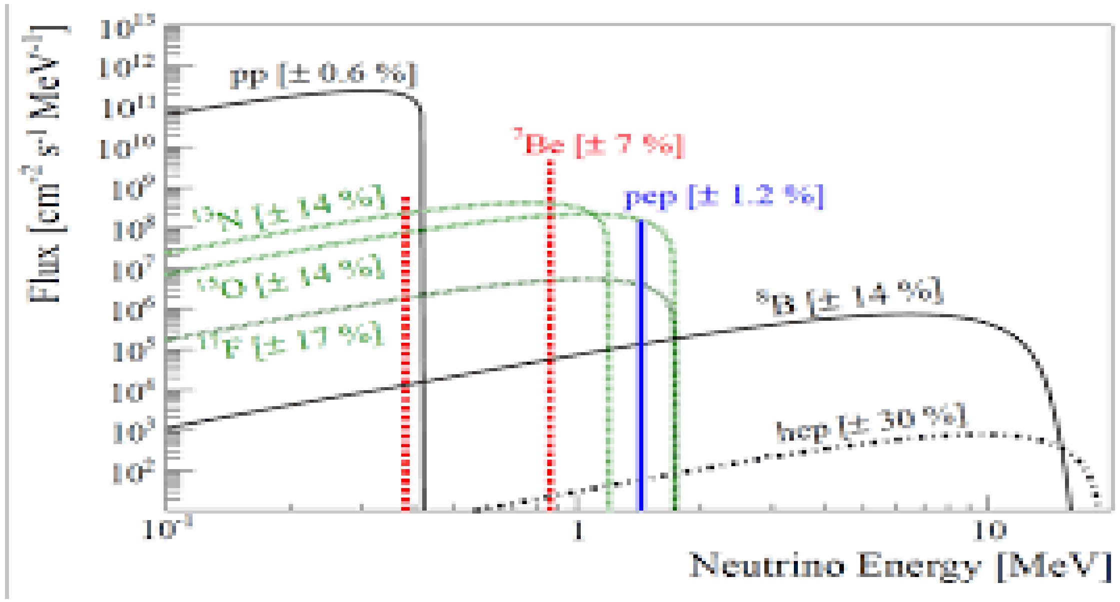

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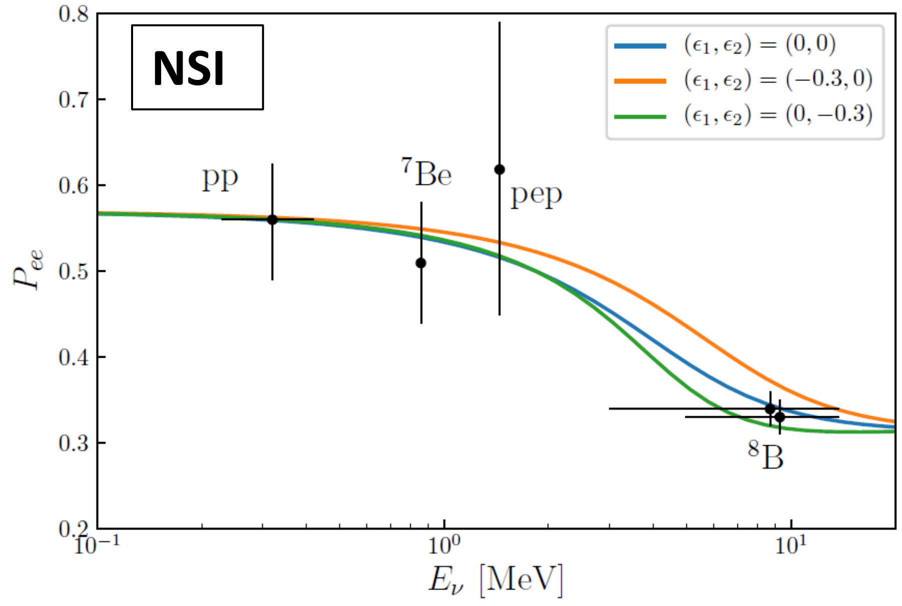


The exciting future

JUNO, HyperK, DUNE, THEIA, JNE

How to further improve the solar neutrino measurement?

1) Using standard techniques (either water Cherenkov or scintillation) and making the detectors bigger and bigger:

- Water Cherenkov: from SuperK (22.5kt)→ HyperK (190kt)
- Scintillators: from Borexino (75t) → SNO+ (800t) →JUNO (10kt)

2) Using new techniques:

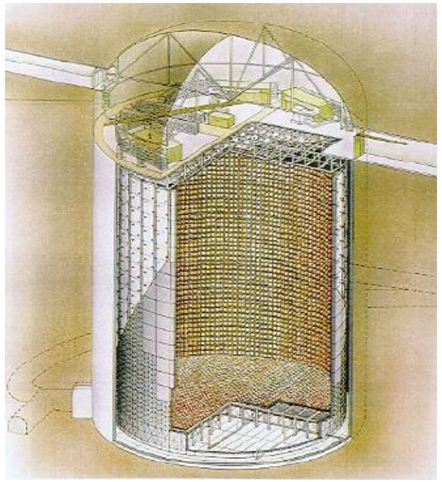
- Hybrid Detectors combining Cherenkov and scintillation (Theia, JNE)
- LAr TPC (DUNE)

N.B.: no future experiment is being designed **exclusively** to study solar neutrinos; they are multi-purpose neutrino detectors;

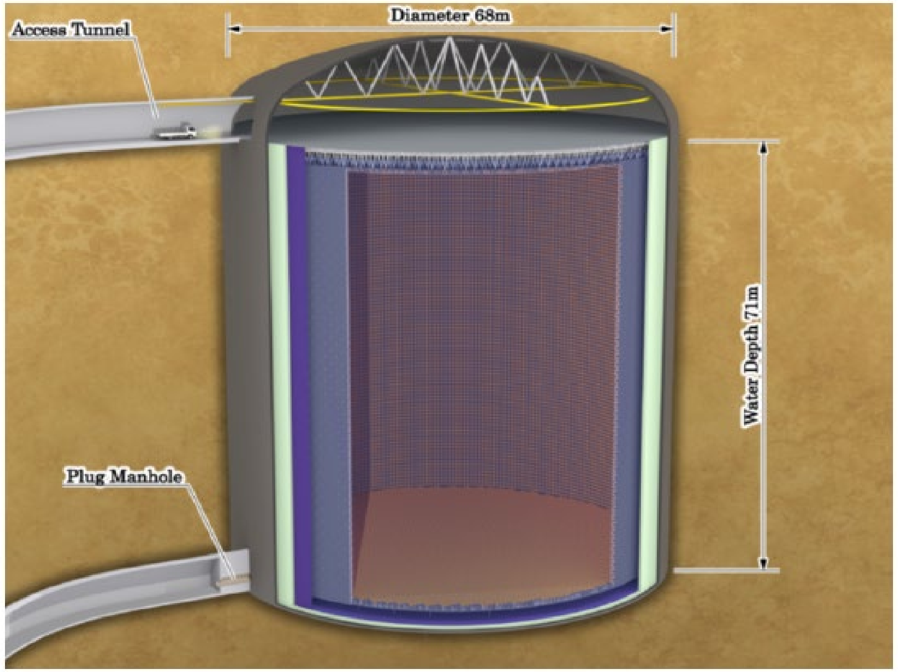
➢ This may be a problem especially for what concerns low-energy solar neutrinos, where low-radioactivity levels are mandatory;

Cherenkov detectors: from Superk to HyperK

SK: Fiducial M=22.5kt



Hyperk: Fiducial Mass=190kt



^{8}B solar neutrinos

In ~ 10 years

- Possibility to detect upturn at 5σ;
- D/N at 4σ-8σ depending on background;
- Possibility to see hep neutrinos at ~3σ;

- HyperK located in Tochibora Mine~ 8Km far from SK (**overburden= 650 m**, less than SK);
- 40k PMTs with high QE and better time resolution→ **better energy and angular resolution**;
- Main goal: far detector for the JPARC beam → study the δ_{CP}, NMO ...
- Data taking start ~2027

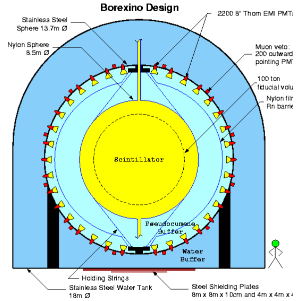
(See plenary talk on HyperK by Nataly Ospina on October 26)

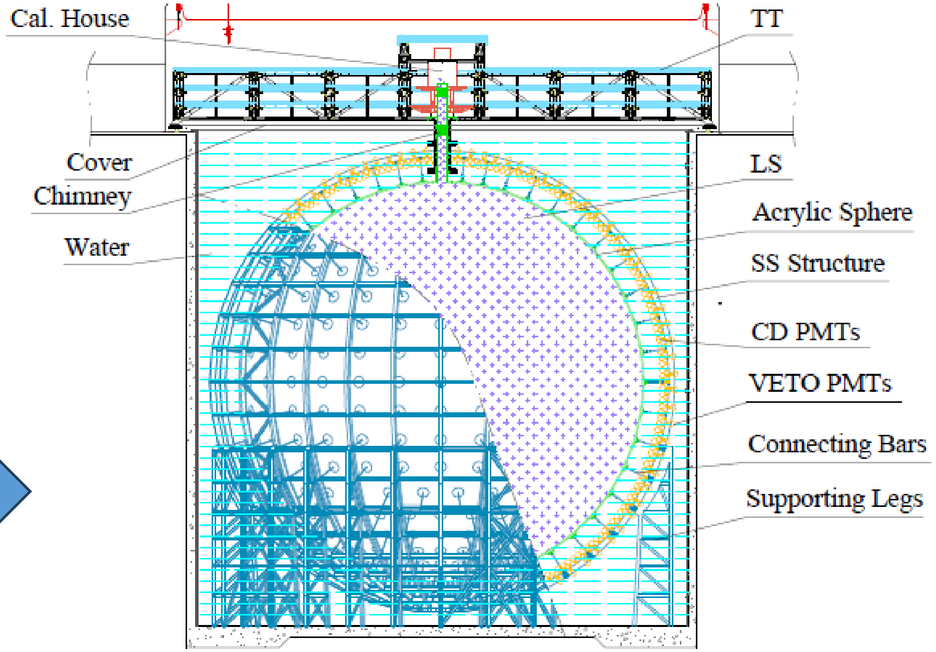
Scintillator detectors: from Borexino to JUNO

- JUNO will be located in Jiangmen (China) (**overburden 700 m, less than Borexino!);**
- 43k PMTs for a total coverage of 77% → **excellent energy resolution of ~ 3%/sqrt(E);**
- **Main goal**: study NMO with reactor neutrinos;
- Data taking start in 2025;

JUNO: Fiducial M=10kt

BX: Fiducial M=75t





^{8}B solar neutrinos

- Collect ~ 60k events (10y) in the $\nu + e \rightarrow \nu + e$ channel
- Also possible to see

CC: $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}N^*$

7Be, pep, CNO solar neutrinos

- Radiopurity is an issue;
- Good perspective even in non-optimal radiopurity conditions thanks to the excellent resolution and large statistics;

(See plenary talk on JUNO by Yuri Malyshkin on October 25)

(Seel talk by Apeksha Singhal on October 26)

Hybrid detectors

Why hybrid detectors?

- Hybrid detectors are designed to exploit simultaneously the advantages of scintillation and Cherenkov light;
  - Advantage of scintillation light: better energy resolution; possibility to go to low threshold;
  - Advantage of Cherenkov light: directionality;
- This is particularly useful to boost the sensitivity to solar neutrinos (as proved by Borexino with the CID method);

Critical issues

- All scintillators also emit Cherenkov light, but it is very little! (<1% of scintillation light)
- Need to optimize the Cherenkov/scintillation ratio in order to profit from the advantage of both techniques;
- How to separate Cherenkov from scintillation light when analyzing data?

Hybrid detectors: Theia

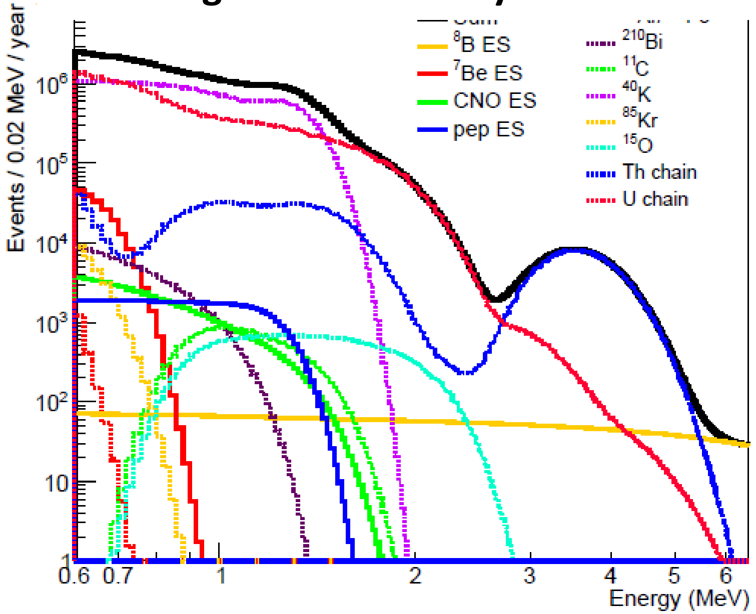
- Theia will be located at SURF (Sanford Underground Research Facility)- South Dakota;
- Mass: 25kt → 100kt;
- **Multi-purpose detector:** far detector for LBNF beam →study δ_{CP}, NMO ...

➢ **Also solar neutrinos (high and low energy)**

Technique: water based Liquid scintillator (WbLS)

- Addition of a small amount of LS to the water (between 1%-10%) (colloidal solution)
- Optimization of LS content: more LS → more photons → less angular resolution;
- Issue: how to separate Cherenkov from scintillation light? (R&D in progress)
  - Timing and angular info;
  - Slowing scintillator down;
  - Dichroic filters;

Simulated spectrum for Theia (LS@ 5%) assuming BX radioactivity



Uncertainty on CNO could be as low as ~ 4%

- 5years;
- 60kt Fiducial M;
- $\sigma(\theta) \sim 25^0$

Also possibility to introduce 7Li for CC (8B neutrinos)

(See parallel talk on THEIA by Hans Steiger on October 24)

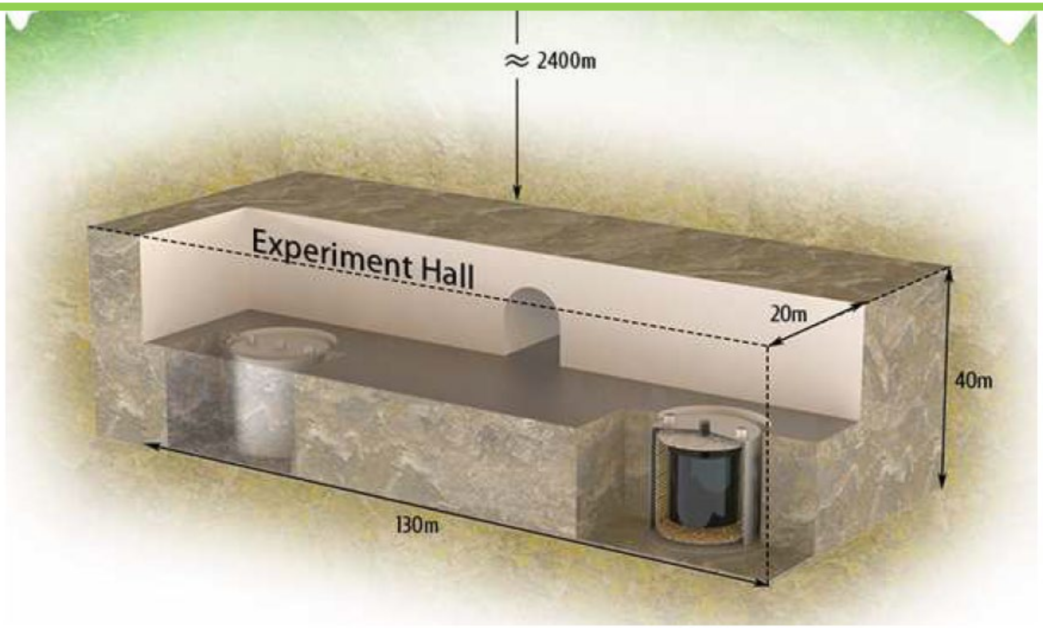
Hybrid detectors: JNE (Jinping Neutrino Experiment)

- JNE will be located at CJPL (China) (**overburden 2400 m**);
- **Mass: 2kt**
- **Multi-purpose detector: solar, SN, geo-neutrinos…**

JPE would be the deepest detector → the least contaminated by cosmogenic background

Both high and low energy solar neutrinos (particularly interesting for CNO neutrinos)

Technique: slow scintillator
- Reduced concentration of primary fluor to slow down the scintillation;
- Fluorescence time distribution stretches to several tens of nanoseconds;
- Enhance capability to separate Cherenkov and scintillation light;



Liquid Ar TPC: DUNE

- DUNE will be located at SURF (Sanford Underground Research Facility)- South Dakota;
- Fiducial Mass: 20kt → 40kt;
- **Main goal:** far detector for LBNF beam →study δ_{CP}, NMO ...

➢ **Also solar neutrinos (mainly high energy)**

Technique: Lar TPC

- Neutrinos can be seen with:

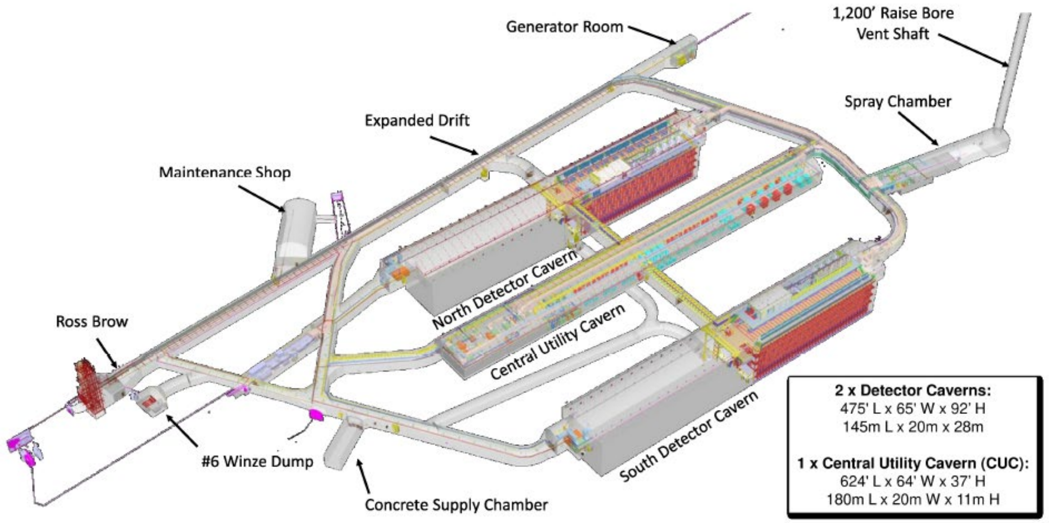
  $\nu_x + e^- \rightarrow \nu_x + e^-$ scattering (ES)

  $\nu_e + {}^{40}Ar \rightarrow e^- \; {}^{40}K^*$ ($E_{th} \sim 4$ MeV) (CC)
- Possibility to exploit the tracking capability of the TPC to point the Sun;

➢ High statistics of 8B neutrino interactions (~2.5 cpd/kt) with ES;

➢ Measure neutrino energy with CC (study upturn);

➢ Possibility to detect hep for the first time;



See plenary talk on DUNE by Christos Touramanis on October 26

(See parallel talk on SoLAr by Anja Gauch on October 24 for a study specifically to optmize TPC to low energies)

Conclusions (1)

Solar neutrinos have proved to be an exceptional tool for both solar and particle physics:

Detailed study of the fusion mechanism in the Sun:

- past and present experiments have detected separately neutrinos from all solar reactions, allowing to study in detail the fusion mechanism which power our star;

First direct detection of CNO:

- Borexino has proved experimentally the existence of this mechanism which is believed to power the most massive stars in the universe;

Solar metallicity:

- The results from 7Be, 8B and CNO show a mild preference (2σ-3σ) for the SSM-HZ scenario → more precision needed!

Conclusions (2)

Solar neutrinos have proved to be an exceptional tool for both solar and particle physics:

Physics of oscillations:

- Past and present experiments (+KamLAND) have been able of determining the solar oscillation parameters $\sin^2\theta_{12}$ and Δm_{12}^2 with precision of the order of 4% and 3% respectively
- SuperK has been able to see a first hint of the upturn → more data needed!
- SuperK and Borexino have studied D/N asymmetry and found it in agreement with LMA-MSW → more data needed!
- Future more precise measurements of D/N or Pee i the transition region may reveal physics beyond the Standard Model;

Exciting future ahead !

Thank you!

Experime nt	Location (Overburden)	Fiducial Mass	Technology	Detection reaction	Solar nu	Start
HYPERK	Tochibora Mine (Japan) 650 m	~190kt	Water Cherenkov	$\nu + e \rightarrow \nu + e$	8B, hep	2027
JUNO	Jiangmen (China) 700 m	~10kt	Scintillator	$\nu + e \rightarrow \nu + e$ $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$ $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}N^*$	8B, 7Be, pep, CNO, pp (?)	2025
THEIA	SURF (S.Dakota)1500 m	~12kt-60kt	WbLS	$\nu + e \rightarrow \nu + e$ possibility to insert Li	8B, 7Be, pep, CNO, pp (?)	Future
JNE	Jinping (China) 2400 m	2kt	Slow scintillator	$\nu + e \rightarrow \nu + e$ possibility to insert Li	8B, 7Be, pep, CNO, pp (?)	Future
DUNE	SURF (S.Dakota)1500 m	20kt-40kt	Lar-TPC	$\nu + e \rightarrow \nu + e$ $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	8B, hep	2030

Requested further details

Solar neutrinos: Borexino and beyond

In this talk, I will discuss the past and present of solar neutrino physics, from the first pioneering experiments which gave rise to the so-called solar neutrino problem to the most recent results by Borexino and Superkamiokande. Studying solar neutrinos has been extraordinarily rewarding, both from a particle physics and an astrophysical point of view: on one side, it has provided the first indication of physics beyond the Standard Model of Particle physics, by showing that neutrinos oscillate and therefore have non-null mass; on the other hand, it has provided important verification of the Standard Solar Model, confirming the mechanism of nuclear reactions that powers our Sun and also demonstrating experimentally for the first time, the existence of the CNO cycle. I will highlight the main difficulties in detecting solar neutrinos and will discuss the state-of-the-art of the most recent results on solar neutrino experiments, in particular the ones from Borexino. Finally, I will give a glimpse on the future of solar neutrino physics, by discussing the main experiments which will have potentially an important role in the field. These experiments could settle in the future some of the currently open issues, like the solar metallicity controversy, by significantly increasing the statistics of data collected (thanks to the increased mass) and/or by exploiting innovative techniques, like the one which combines scintillation and Cherenkov light.

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