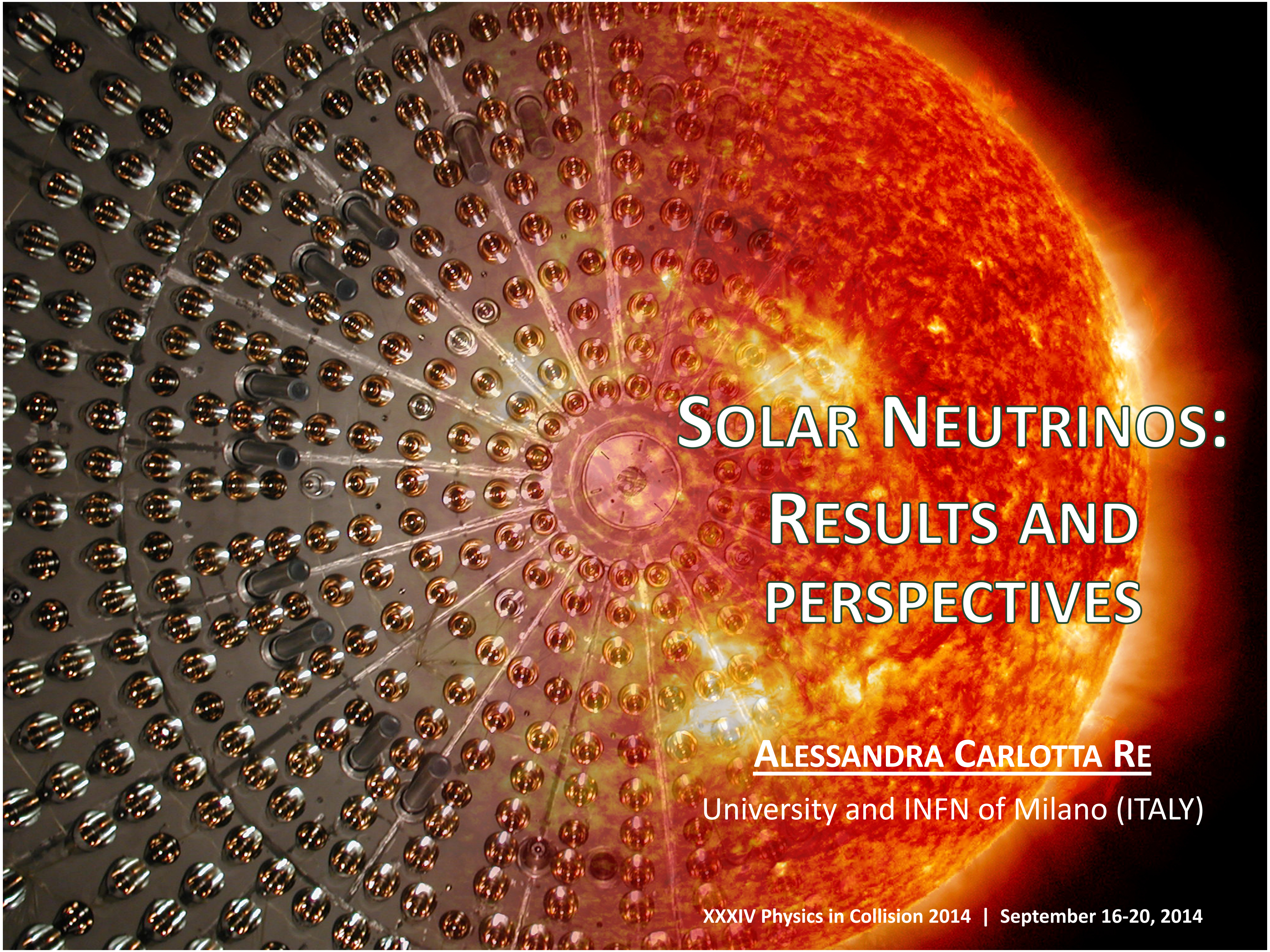

SOLAR NEUTRINOS: RESULTS AND PERSPECTIVES

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NEUTRINOS IN THE STANDARD MODEL

Neutrinos are…

- ⌘ Elementary particles: three bricks of the Standard Model (SM) wall;
- ⌘ Fermions;
- ⌘ Electrically neutral leptons
  → Weak interactions;
- ⌘ Arranged in three familes according to their flavour;

and moreover… Neutrinos OSCILLATE!!

NEUTRINO OSCILLATIONS

As soon as the first solar neutrino experiments started taking data, the so-called Solar Neutrino Problem arose: the measured event rate was significantly lower than expected.

However, these experimental results could be easily explained assuming neutrino flavor oscillations which, as pointed out by Pontecorvo in 1968, can occur only if neutrinos are massive and mixed.

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} \mathrm{U}_{\alpha i}|\nu_i\rangle, \qquad \alpha{=}\mathrm{e}, \mu, \tau$$

where U is the Pontecorvo-Maki-Nagakawa-Sakata mixing matrix:

$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \begin{matrix} c_{ij} = \cos\theta_{ij}\,, \\ s_{ij} = \sin\theta_{ij}\,. \end{matrix}$$

If we assume the normal hierarchy ($\Delta\mathrm{m}^2_{31} \gg \Delta\mathrm{m}^2_{21}$), an expression of the survival probability of an electron neutrino is derived by using the mixing matrix U:

$$\mathrm{P_{ee}} = \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta\mathrm{m}^2_{21}}{4\,\mathrm{E}}\mathrm{L}\right)\right] + \sin^4\theta_{13}$$

THE STANDARD SOLAR MODEL

Every second the Sun produces 10^5 times more energy than mankind has produced over all its history….

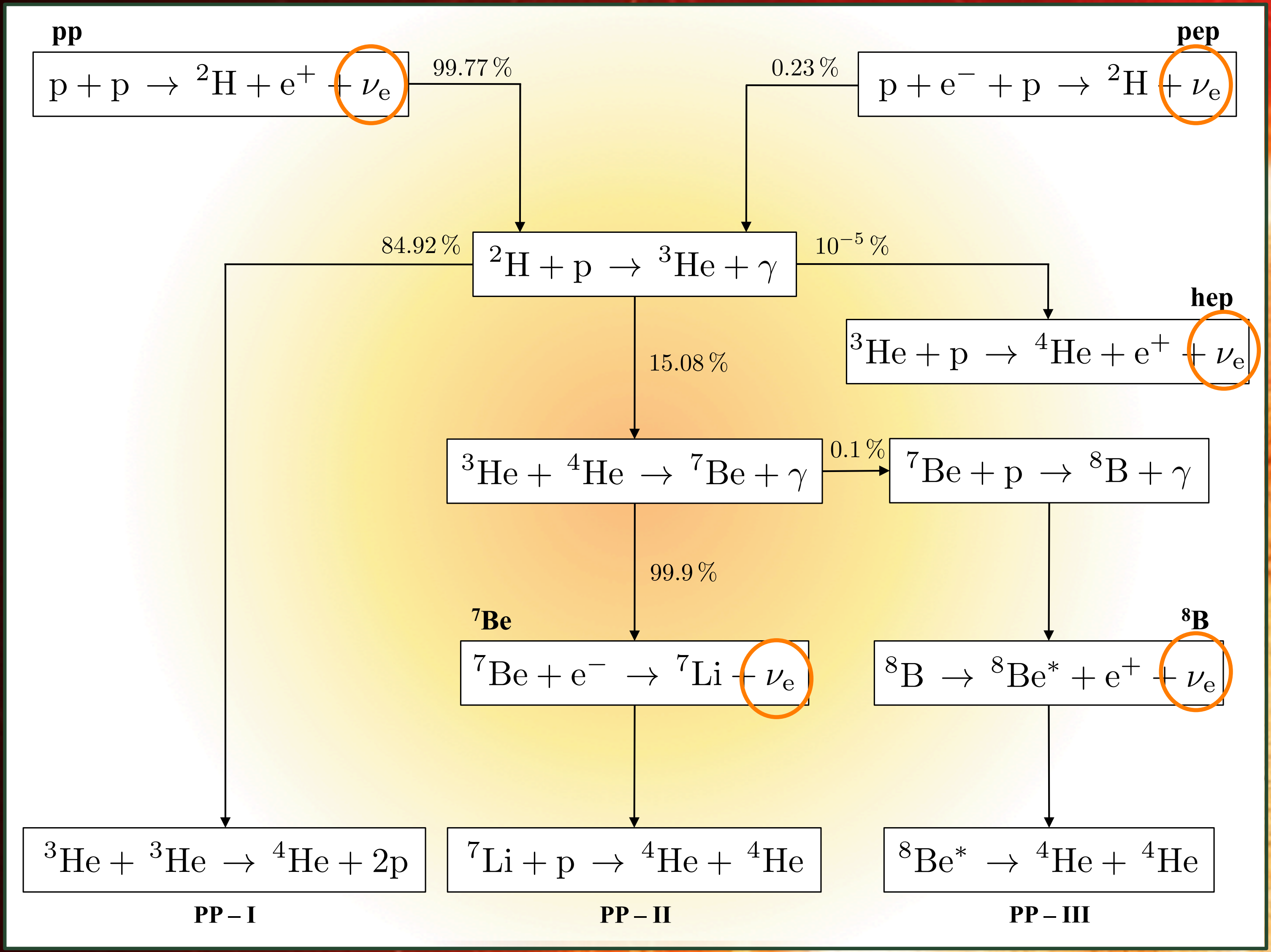
Starting from the energy-conservation laws and energy-transport equations applied to a spherically symmetric gas sphere, the Standard Solar Model (SSM) is “tailored” for our Sun by constraining:

- Nuclear parameters;
- Luminosity;
- Age;
- Mass;
- Radius;
- Equations of state;
- Chemical elements abundance;
- Radiation opacity;

One of the main SSM outputs are <u>Neutrino Fluxes</u>.

To study them is the only way to check the understanding of nuclear processes at the center of the Sun.

THE STANDARD SOLAR MODEL:
THE PP CHAIN



pp

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

99.77 %

pep

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

0.23 %

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

84.92 %

10^{-5} %

hep

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

15.08 %

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

0.1 %

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

99.9 %

^{7}Be

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

^{8}B

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

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

PP – I

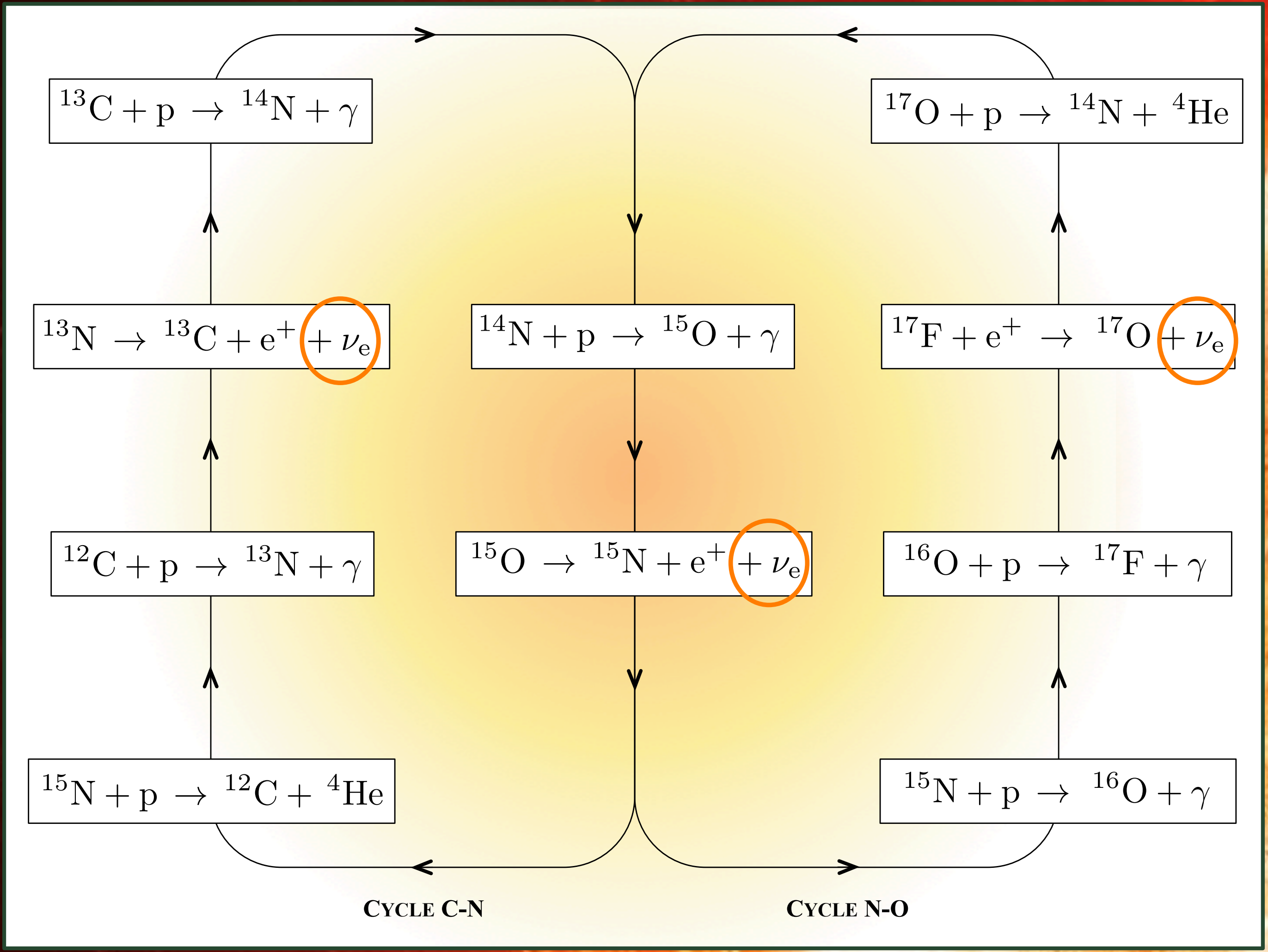
$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

PP – II

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

PP – III

THE STANDARD SOLAR MODEL:
THE CNO CYCLE



$^{13}\mathrm{C} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + \gamma$

$^{17}\mathrm{O} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$

$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$

$^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{O} + \gamma$

$^{17}\mathrm{F} + \mathrm{e}^{+} \rightarrow {}^{17}\mathrm{O} + \nu_{\mathrm{e}}$

$^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} + \gamma$

$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$

$^{16}\mathrm{O} + \mathrm{p} \rightarrow {}^{17}\mathrm{F} + \gamma$

$^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$

$^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{16}\mathrm{O} + \gamma$

CYCLE C-N

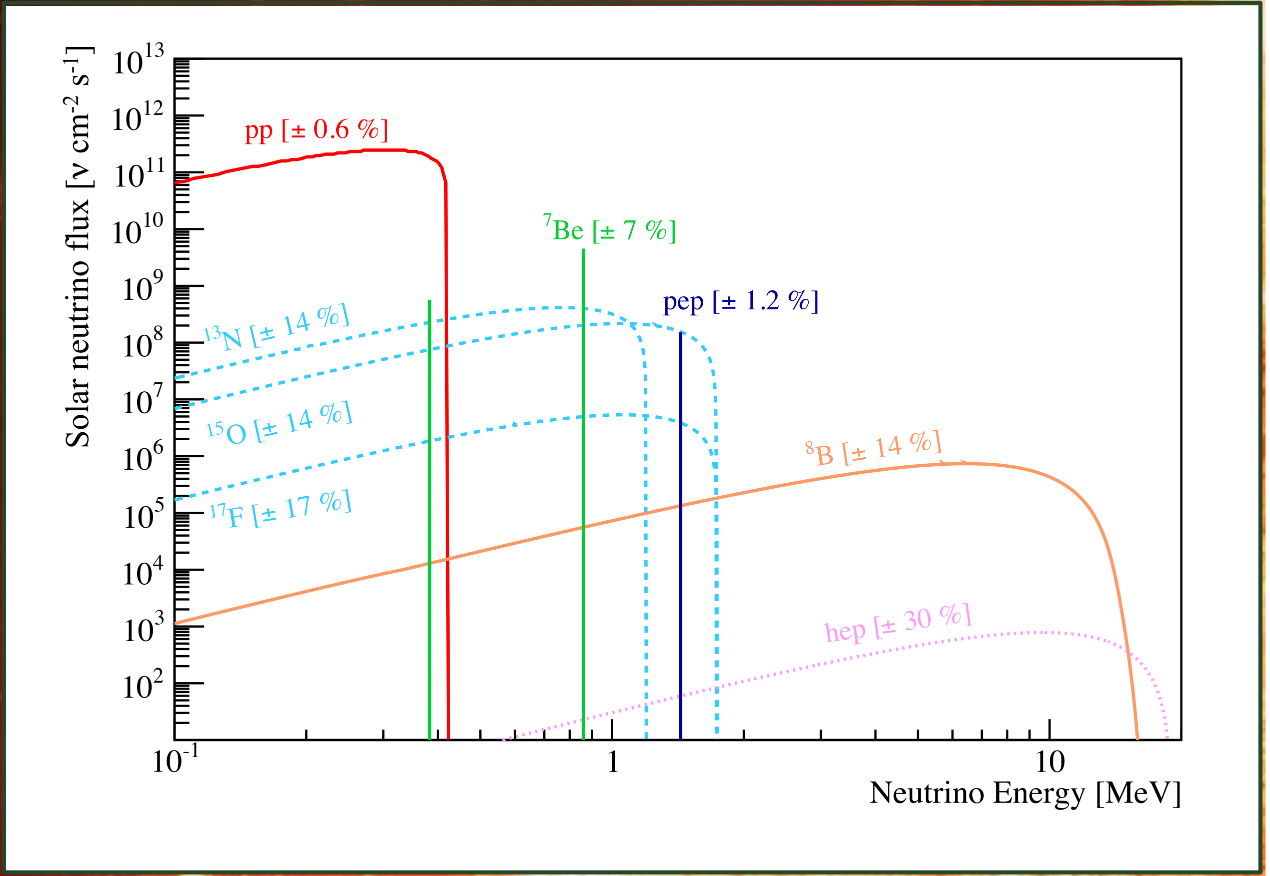
CYCLE N-O

SOLAR ν AND THE STANDARD SOLAR MODEL

The solar neutrino fluxes and spectra are defined by the Standar Solar Model (SSM).

The SSM main assumptions are:

- Sun in hydrostatic equilibrium;
- Primary energy generation by nuclear reactions;
- Elemental abundances determined by fusion reactions only;



SOLAR ν AND THE STANDARD SOLAR MODEL

The “last version” of the standard solar model was published by A. Serenelli, W. Haxton and C. Peña Garay (SHP11)[1] .

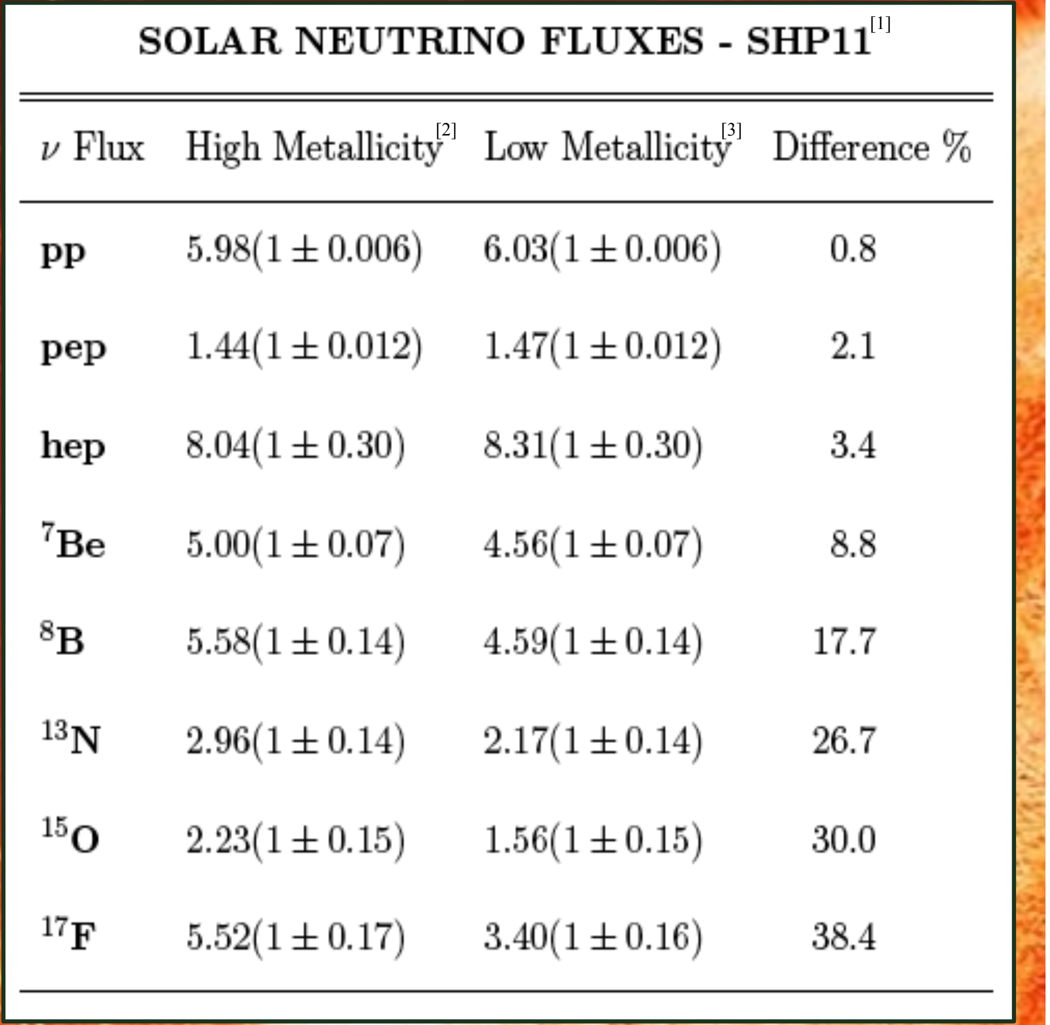
This solar model uses “newly” analyzed nuclear fusion cross sections and, according to the high (GS98[2]) or low (AGSS09[3]) metallicity hypothesis, predicts the different solar neutrinos fluxes.

The metallicity of an object is the fraction of chemical elements other than hydrogen and helium.

[1] ApJ 743 pp. 24, 2011

[3] ApJ 705 L123, 2009

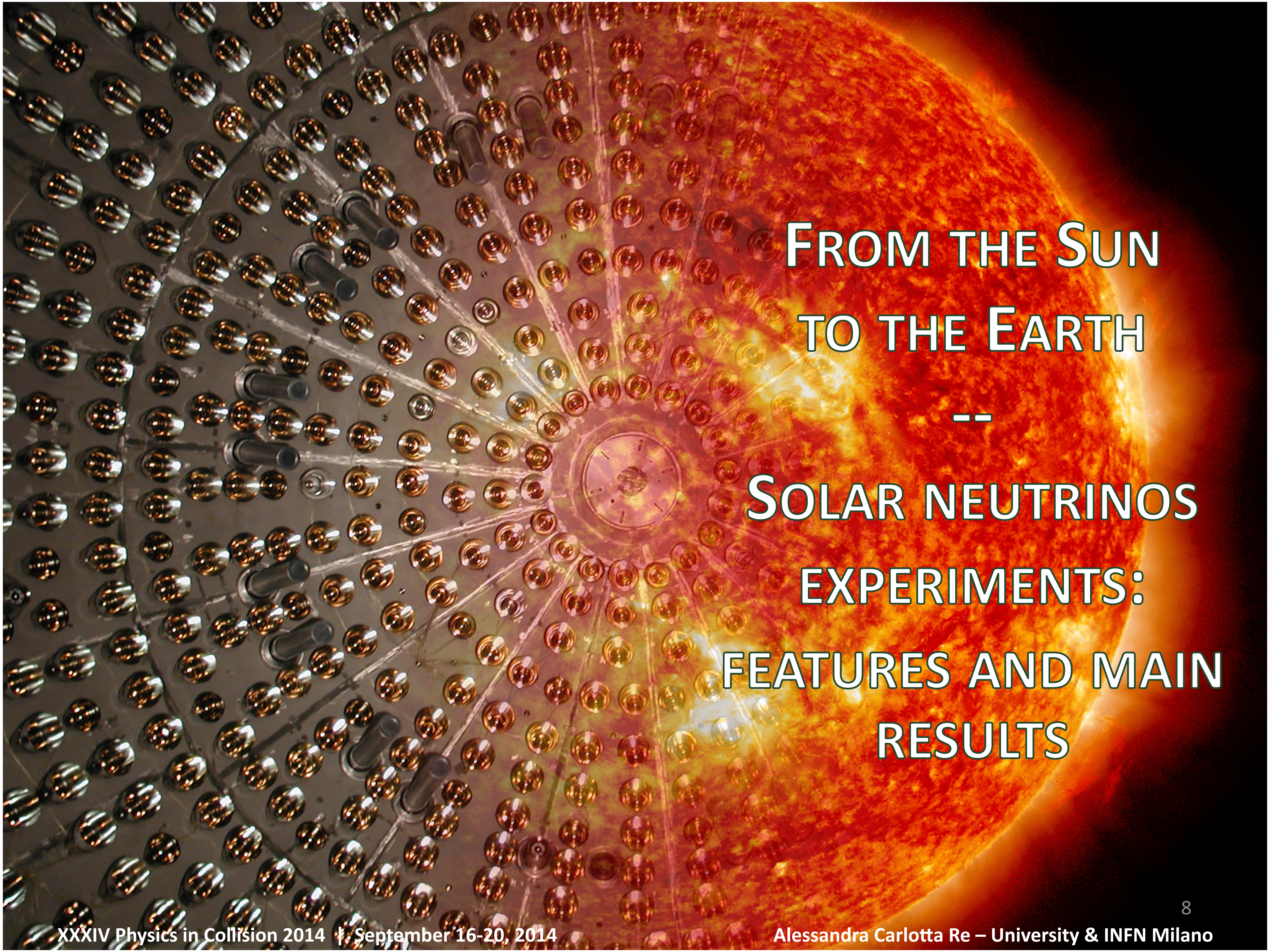
[2] Space Sciences Reviews 85-161, 1998



SOLAR NEUTRINO FLUXES - SHP11[1]

ν Flux	High Metallicity[2]	Low Metallicity[3]	Difference %
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	0.8
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	2.1
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	3.4
^{7}**Be**	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	8.8
^{8}**B**	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	17.7
^{13}**N**	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	26.7
^{15}**O**	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	30.0
^{17}**F**	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	38.4

The fluxes are given in units of 10^{10} (pp), 10^{9} (^{7}Be), 10^{8} (pep, ^{13}N, ^{15}O), 10^{6} (^{8}B, ^{17}F) and 10^{3} (hep) ν cm^{-2} s^{-1}.



FROM THE SUN TO THE EARTH

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SOLAR NEUTRINOS EXPERIMENTS: FEATURES AND MAIN RESULTS

SOLAR-ν EXPERIMENTS: A SHORT HISTORY

Experiments starting during….

1970s - 1980s:

- The **HOMESTAKE** experiment
  Target: all solar neutrinos above $E_\nu > 814$ keV.
  Radiochemical experiment.
  Observed a deficit in solar neutrinos flux.
  An initial skepticism… was followed by triumph and Nobel prize in 2002 (R. Davies).

1980s - 1990s:

- The **(SUPER)KAMIOKANDE** experiment(s)
  Main target: ^{8}B solar neutrino.
  Real-time techniques for a direct detection of ^{8}B solar-ν ($E_\nu \geq 5$ MeV).
  Confirmation of the deficit in solar-ν fluxes.
  First neutrino picture of the Sun (directionality).
  Detection of neutrinos from star other than the Sun (i.e. supernova SN1987-A).

SOLAR-ν EXPERIMENTS: A SHORT HISTORY(2)

1990s - 2000s:

❖ The **GALLEX** (**GNO**) and **SAGE** experiments:

Target: all solar neutrinos above $E_\nu > 233$ keV.

Radiochemical experiment.

Observed a deficit in solar neutrinos flux event at very low energy.

2000s - 2010s:

❖ The **SNO** experiment:

Main target: ^{8}B solar neutrino.

Real-time technique.

2001 - Oscillation of solar neutrinos is proved by separately measuring CC (electron flavor) interactions and NC (all flavors) interactions in D_2O

→ total flux agrees with Standard Solar Model!!

SOLAR-ν EXPERIMENTS: A SHORT HISTORY(3)

2000s - 2010s:

- The **KAMLAND** experiment:
  - Original Target: neutrinos from reactors.
  - Measured also ^{8}B and ^{7}Be solar neutrino fluxes.
  - Real-time experiment.
  - Observed and measured oscillations of electron anti-neutrinos from reactors.

- The **BOREXINO** experiment:
  - Original target: ^{7}Be solar neutrino.
  - Real-time experiment.
  - First direct real time observation of ^{7}Be and pep neutrinos.
  - Measurement of low energy ^{8}B neutrino.
  - Best limit on CNO neutrinos.
  - NEW!! FIRST DIRECT REAL-TIME MEASUREMENT OF PP NEUTRINOS (PUBLISHED 3 WEEKS AGO ON NATURE)

SAME SCOPE… DIFFERENT EXPERIMENTS, DIFFERENT STRATEGIES!

What is a **DIRECT** (**INDIRECT**) measurement of an X solar neutrino?

DIRECT: detection of electron recoils triggered by that precise X solar neutrino.

INDIRECT: measure other solar neutrinos and then, assuming the Standard Solar Model is valid, inferring the X neutrino flux (i.e. via the luminosity constraint).

What is a **REAL-TIME** measurement of an X solar neutrino?

In **REAL-TIME** measurements, the X neutrinos are detected one-by-one, via their interactions with electrons, and their energies can be inferred.

The Super Kamiokande, the SNO and the Borexino experiments belong to this category.

Other experiments are not able to count individual events and to tag solar neutrinos so they integrate over a range of energies.

The Homestake, the SAGE and the GALLEX-GNO experiments belong to this category.

REAL-TIME DETECTION OF SOLAR-ν

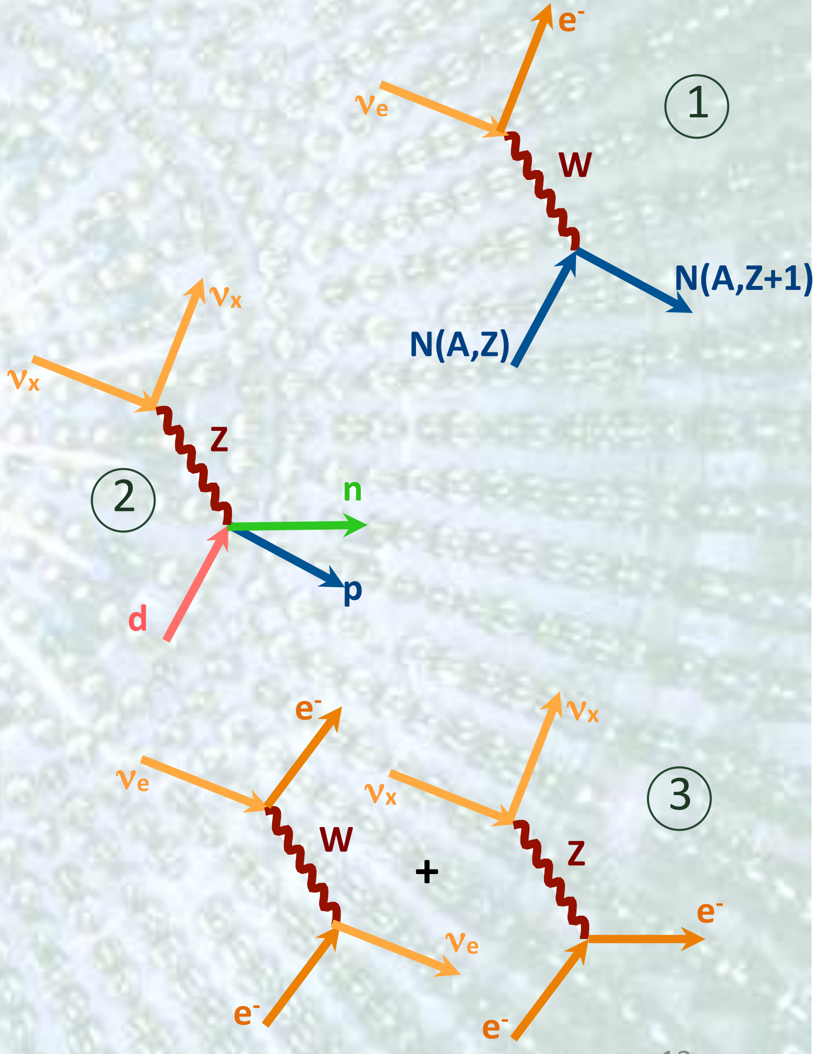
We know that the solar neutrinos are produced in the inner part of the Sun via β^+ decay or electron capture processes.

Their detection can happen via 3 different fundamental reactions:

① **Charged current (CC) interaction**
Inverse β decay on a proton or a nucleus
ν_e only at MeV energies.

② **Neutral current (NC) interaction**
Elastic scattering on a nucleus either with the emission of a recoil neutron. All neutrino flavors have the same cross-section.

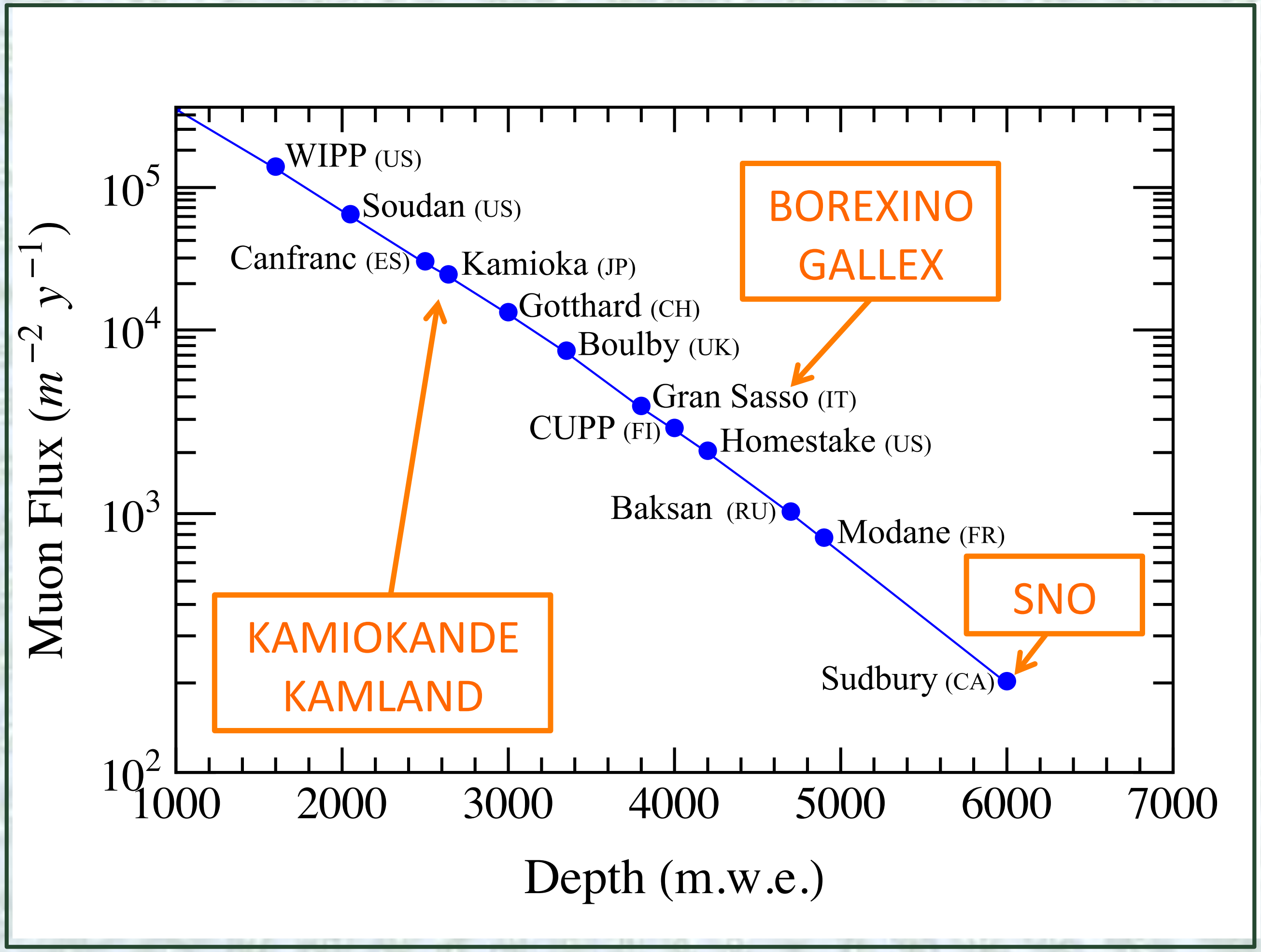
③ **Elastic scattering of an electron**
CC + NC interactions.



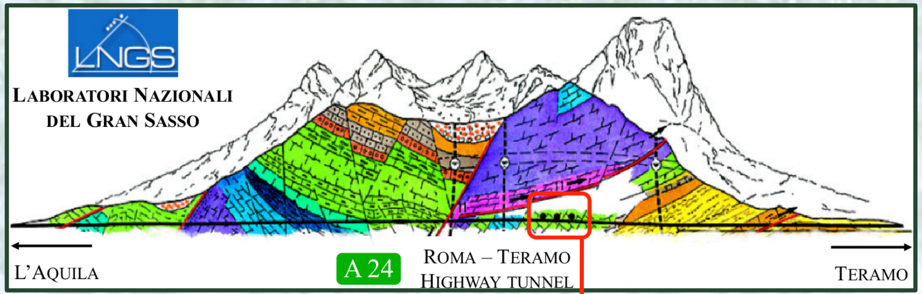
SOLAR-ν EXPERIMENTS: WHERE?

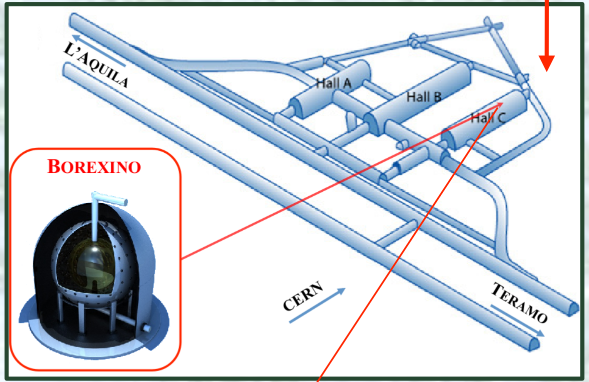
Due to the very small neutrino interaction rates, the shielding against cosmic rays is mandatory.

→ Solar neutrinos experiments can be carried out in underground laboratories only.



LABORATORI NAZIONALI GRAN SASSO
LNGS (ITALY)





The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

$$\Phi(\mu) \sim 1\,\mu/\mathrm{m}^2/\mathrm{h}$$

SOLAR-ν EXPERIMENTS: RADIOPURITY

Radio-Isotope		Concentration or Flux		Strategy for Reduction	
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**
μ	Cosmic	~ 200 s^{-1} m^{-2} @ sea level	< 10^{-10} s^{-1} m^{-2}	Underground exp, water Cerenkov detector	Pulse shape analysis
γ	Rock	---	---	Water	F.V.
γ	PMTs	---	---	Buffer	F. V.
^{14}C	Intrinsic in LS	~10^{-12} g/g	~10^{-18} g/g	Selection	Threshold
^{238}U **^{232}Th**	Dust, metallic	10^{-5}-10^{-6} g/g	< 10^{-16} g/g	Distillation, W.E., filtration, mat. selection, cleanliness	Tagging α/β
^{7}Be	Cosmogenic	~3 10^{-2} Bq/t	< 10^{-6} Bq/t	Distillation	---
^{40}K	Dust, PPO	~2. 10^{-6} g/g (dust)	< 10^{-18} g/g	Distillation,W.E.	---
^{210}Po	Surface contamination from ^{222}Rn	---	< 1 c/d/t	Distillation, W.E., filtration, cleanliness	Fit
^{222}Rn	Emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	< 10 cpd 100 t	N_2 stripping cleanliness	Tagging α/β
^{39}Ar	Air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	Fit
^{85}Kr	Air, nuclear weapons	~ 1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	Fit

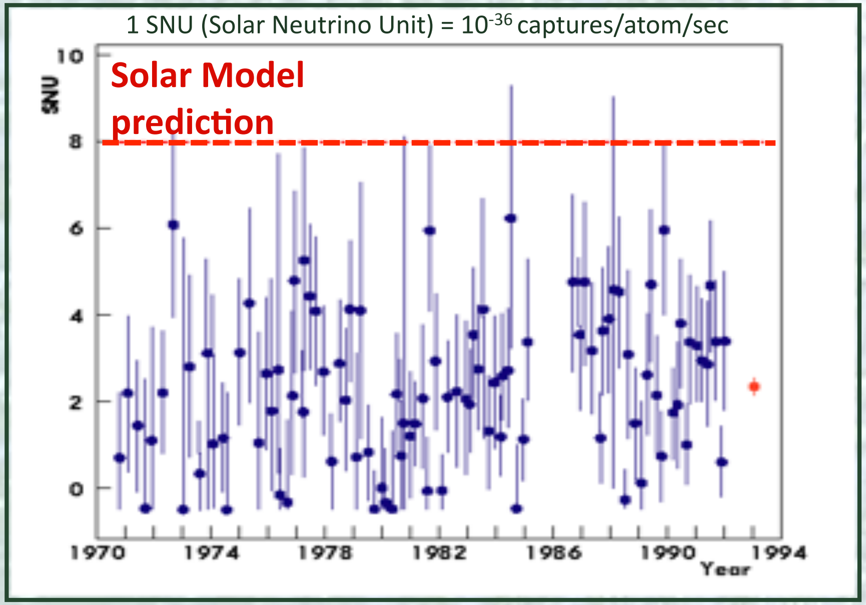
THE HOMESTAKE EXPERIMENT

The Homestake experiment, located in an old gold mine in South Dakota, was the first to observe a deficit in solar neutrinos flux arising the so-called "Solar Neutrino Problem".

It's a radiochemical experiment based on the reaction:

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

The energy threshold of this reaction is 0.814 MeV, so the relevant fluxes are those of ^{7}Be and ^{8}B neutrinos.


1 SNU (Solar Neutrino Unit) = 10^{-36} captures/atom/sec

- Target: a tank with 614 tons of liquid soap (C_2Cl_4);
- Data taking: 1970 – 1994;
- Method: Extraction with filters and counting of ^{37}Ar decays (32 d)

It studied charged interactions without direct detection of the electron.

Only 2200 atoms of ^{37}Ar counted in 25 years!

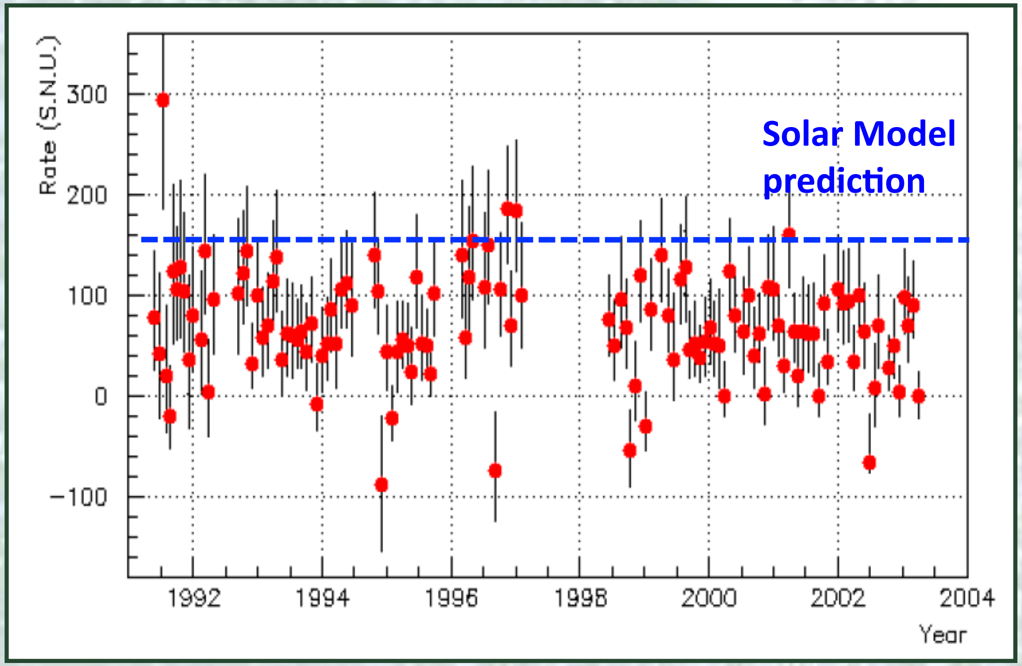
FINAL RESULT: $$\frac{R_{EXP}}{R_{THEO}^{SSM}} = 0.30 \pm 0.03$$

THE GALLIUM EXPERIMENTS

In the early 1990's two radiochemical experiments started taking data:

- ❖ SAGE (Soviet-American Gallium Experiment) in Baksan, Russia.
- ❖ GALLEX (GALLium Experiment) and its direct successor, the GNO experiment (Gallium Neutrino Observatory) in LNGS, Italy.

They both used ^{71}Ga as target for the reaction: $\mathbf{^{71}Ga + \nu_e \rightarrow \, ^{71}Ge + e^-}$



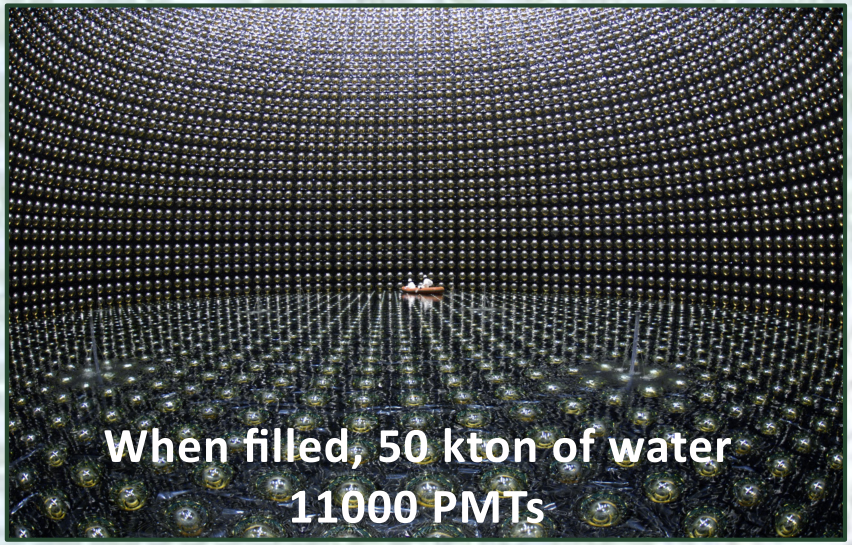
Two special properties of ^{71}Ga target consist in a low energy threshold (0.233 MeV) and a large cross section for the lowest energy solar neutrinos.

Both experiments measured deficit also for low energies:

$$\frac{\mathbf{R_{EXP}}}{\mathbf{R^{SSM}_{THEO}}} = \mathbf{0.52 \pm 0.03}$$

averaged event rate measured by SAGE and GALLEX/GNO.

THE (SUPER) KAMIOKANDE EXPERIMENT



When filled, 50 kton of water
11000 PMTs

The Super Kamiokande experiment is set in Kamioka (Japan) and it is a water Čerenkov detector.

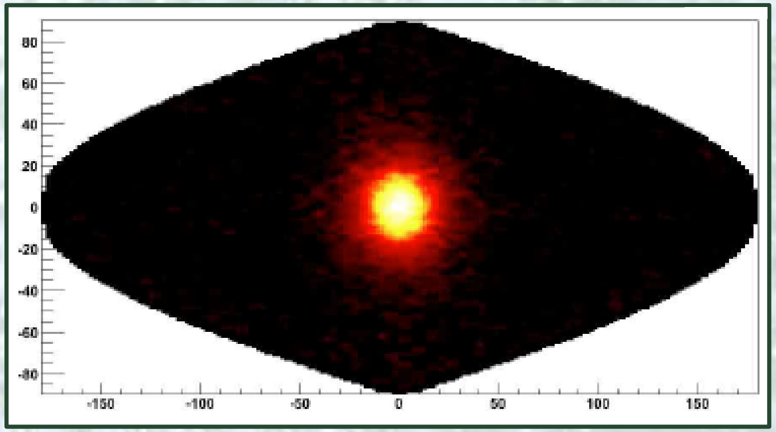
It was the first experiment able to detect real-time solar neutrinos interactions via the elastic scattering process:

$$\nu_{\mathbf{x}} + \mathbf{e}^- \rightarrow \nu_{\mathbf{x}} + \mathbf{e}^-$$

The diffused electron emits Čerenkov light that is detected by a large set of PMTs
The amount of light is proportional to energy and its space-time distribution yields the neutrino incoming direction.

SuperK phase IV is still on-going today!
Main goals:

- Real-time measurements of solar-ν with $E_\nu > 3.5$ MeV;
- Day-night ^{8}B flux differences;
- ^{8}B signal seasonal variation.

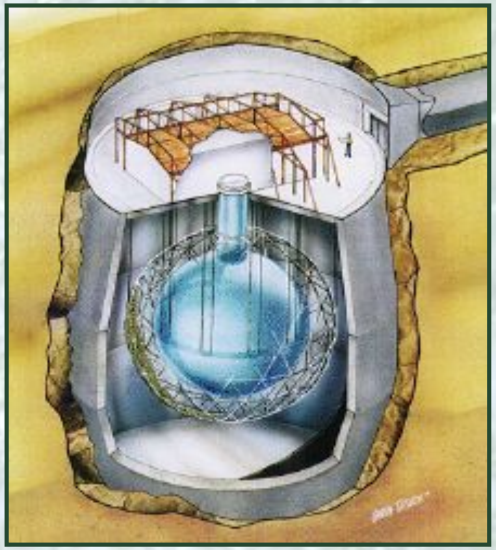


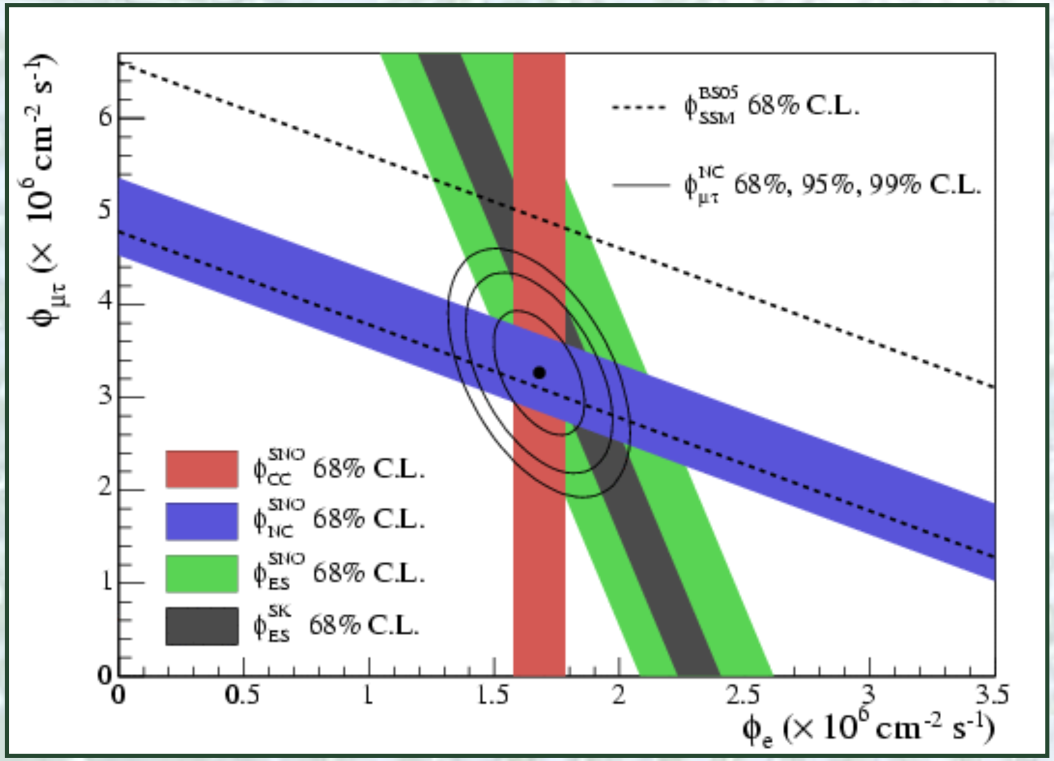
THE SNO EXPERIMENT

The SNO (Sudbury Neutrino Observatory) detector is located in a mine, near Sudbury (Canada) and it is an ultrapure, heavy water detector enclosed in a 12m acrilyc vessel.

SNO reveals the Čerenkov light with about 9500 PMTs.

It was designed in order to give possible explanations of the observed deficit in the solar neutrino flux.



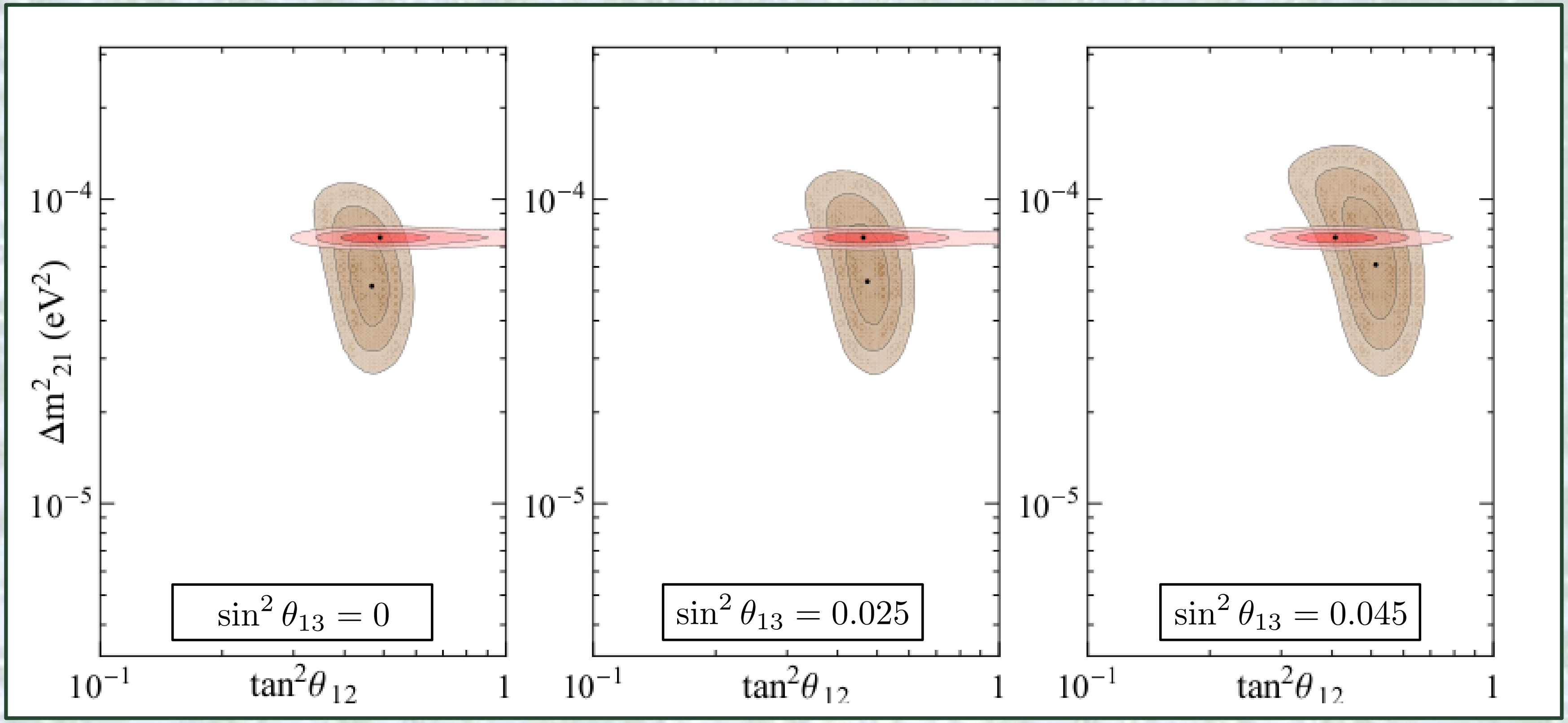


SNO is sensitive to all neutrino flavours.

- Proved that $\Phi(\nu_e)$ is DIFFERENT from $\Phi(\nu_{\mu,}\ \nu_\tau)$;
- Prove that the TOTAL neutrino flux is consistent with the Standard Solar Model predictions.

Today, the SNO collaboration has decided to prioritize neutrino-less 2β decay studies.

THE KAMLAND EXPERIMENT



KamLAND is a 1000 ton liquid scintillator detector currently operating in Kamioka mine (Japan). This underground site is located at an average distance (about 150-210 km) from the several Japanese nuclear plants in fact Kamland mainly studies anti-neutrinos from reactors.

Kamland provided a precise measurement of Δm^2_{21} and the final proof of oscillations. Moreover, well before the Daya Bay measurements, the comparison between Kamland and solar data showed hints for $\theta_{13} \neq 0$.

THE BOREXINO EXPERIMENT

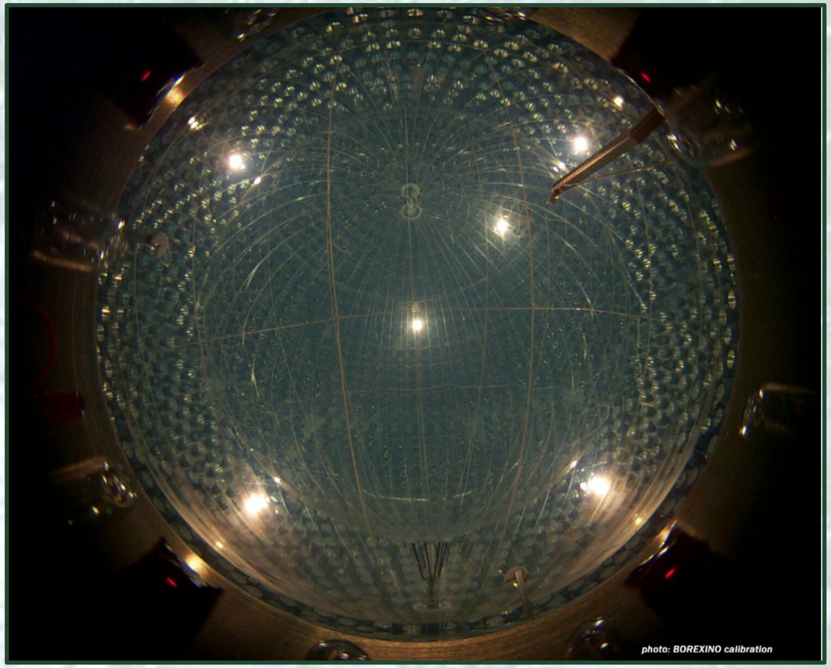
- **Main goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.

- **Detection method**: elastic scattering of neutrinos on electrons.

  $$\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$$

- **Detection medium**: large mass of organic liquid scintillator.
  - Advantages: large light-yield;
  - Disadvantages: no directional information.

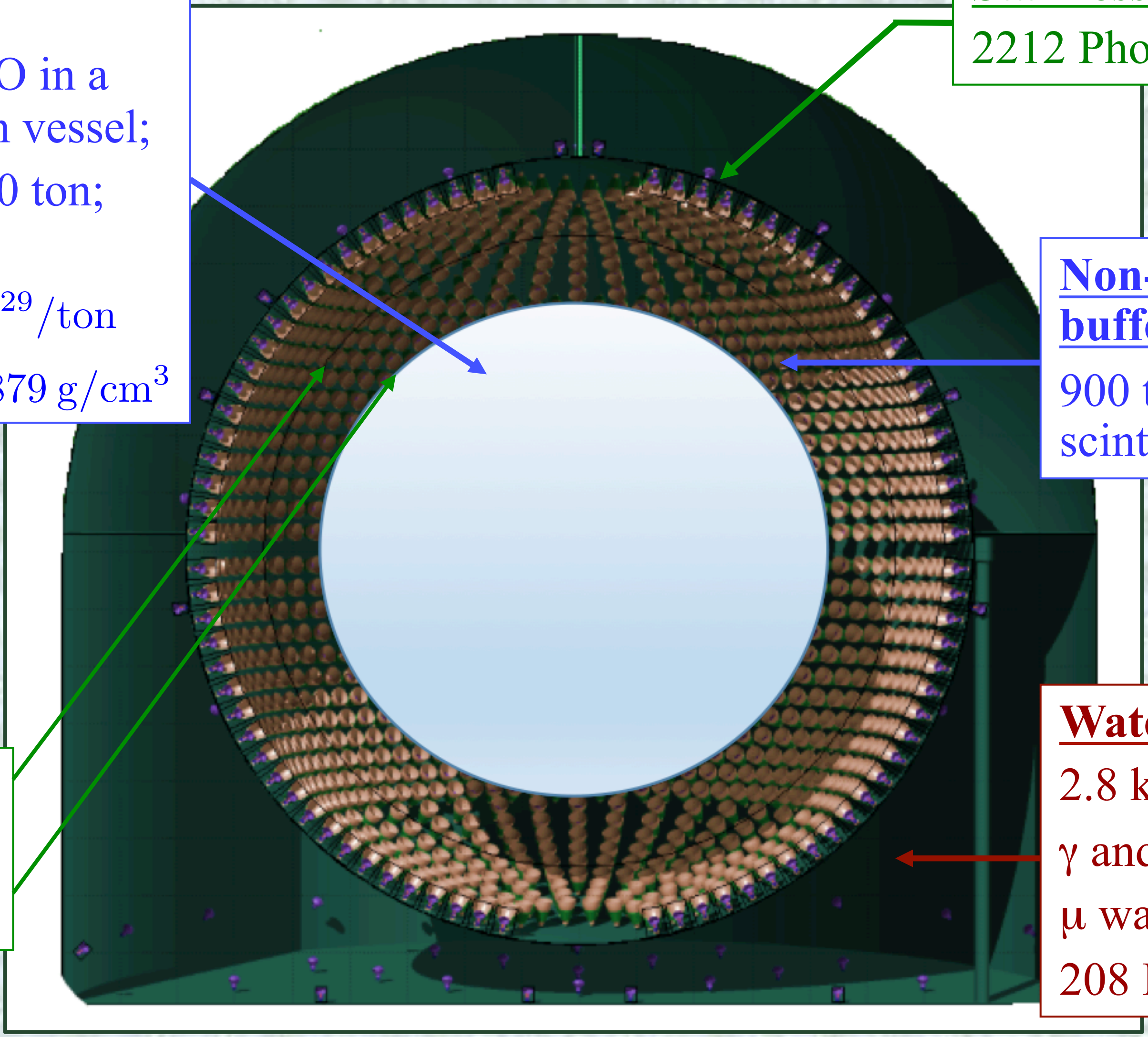
Signal is indistinguishable from background: high radiopurity is a MUST!



The expected rate of ^{7}Be solar neutrinos in 100 ton of BX scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/Kg.

Just for comparison, natural water is about 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K.

THE BOREXINO EXPERIMENT(2)



Scintillator:

280 ton of PC+PPO in a 125 μm thick nylon vessel;

Fiducial mass ~ 100 ton;

Electron density:

$(3.307 \pm 0.003) \times 10^{29}/\mathrm{ton}$

Mass density: $\simeq 0.879\ \mathrm{g/cm^3}$

Stainless Steel Sphere:

2212 PhotoMultipliers

Non-scintillating buffer:

900 ton of quenched scintillator

Water Tank:

2.8 kton of pure H_2O

γ and n shield

μ water Č detector

208 PMTs in water

Nylon vessels:

Outer: 5.50 m

Inner: 4.25 m

SOLAR NEUTRINOS: THE BOREXINO RESULTS

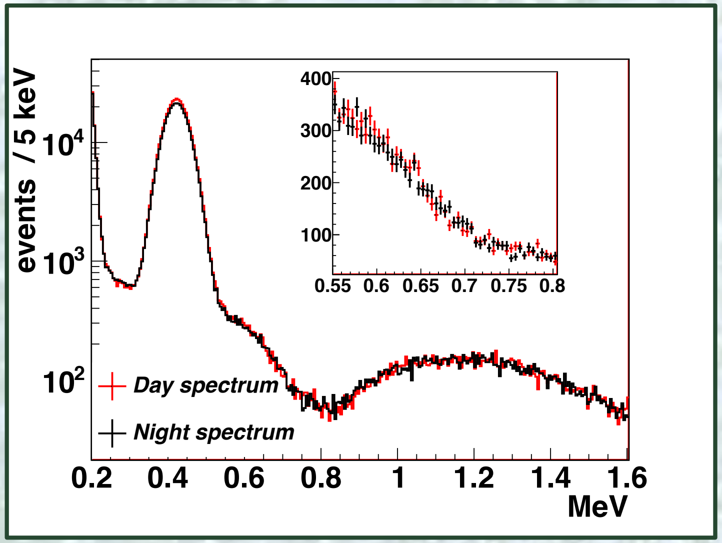
^{7}Be solar neutrino:

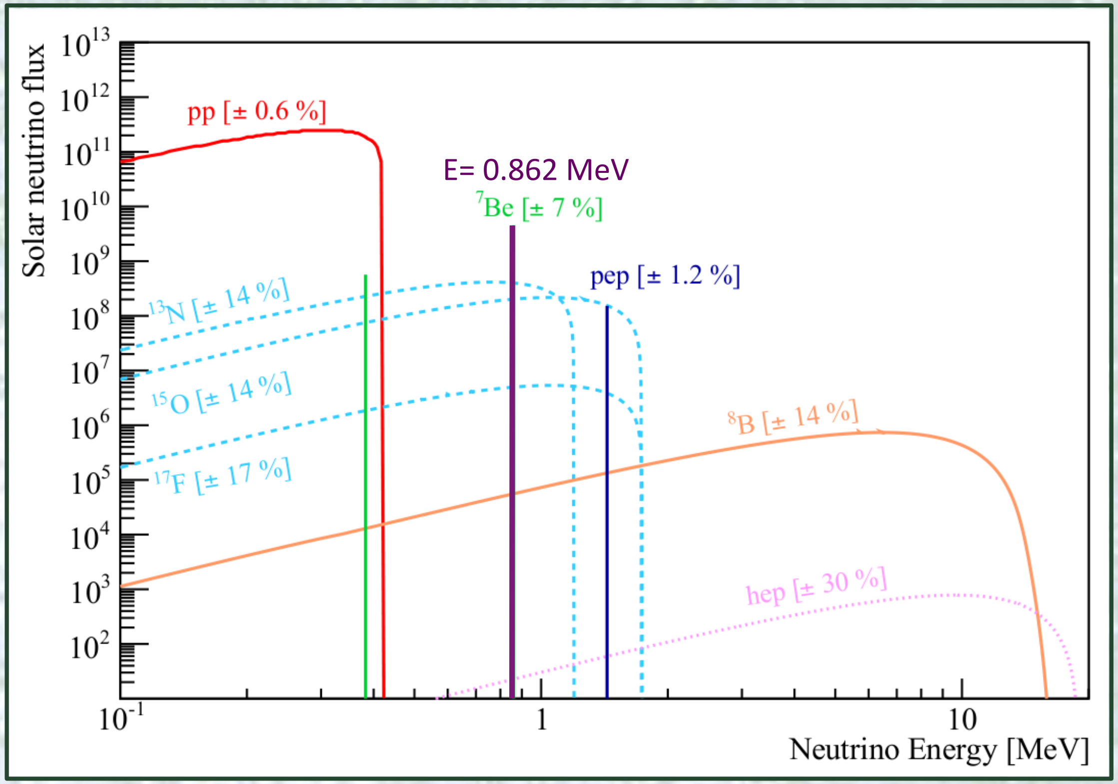
- The ^{7}Be solar neutrino flux: accuracy below 5%.

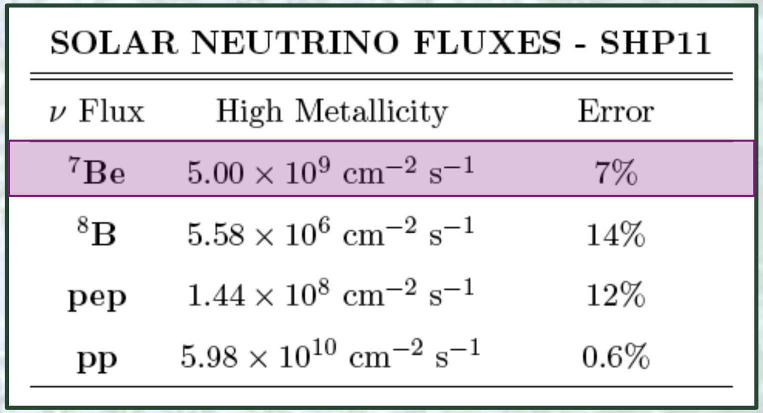
$$46.0 \pm 1.5\,(\mathrm{stat})\,^{+1.5}_{-1.6}\,(\mathrm{syst})\ \mathrm{cpd/100\ ton}$$
$$\Phi(^7\mathrm{Be}) = (2.78 \pm 0.13) \times 10^9\ \mathrm{cm^{-2}\,s^{-1}}$$

- The day-night asymmetry (A_{DN}) measurement (E=862 keV).

$$\mathrm{A_{DN}} = 0.001 \pm 0.012\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})$$







SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
^{7}Be	$5.00 \times 10^9\ \mathrm{cm^{-2}\,s^{-1}}$	7%
^{8}B	$5.58 \times 10^6\ \mathrm{cm^{-2}\,s^{-1}}$	14%
pep	$1.44 \times 10^8\ \mathrm{cm^{-2}\,s^{-1}}$	12%
pp	$5.98 \times 10^{10}\ \mathrm{cm^{-2}\,s^{-1}}$	0.6%

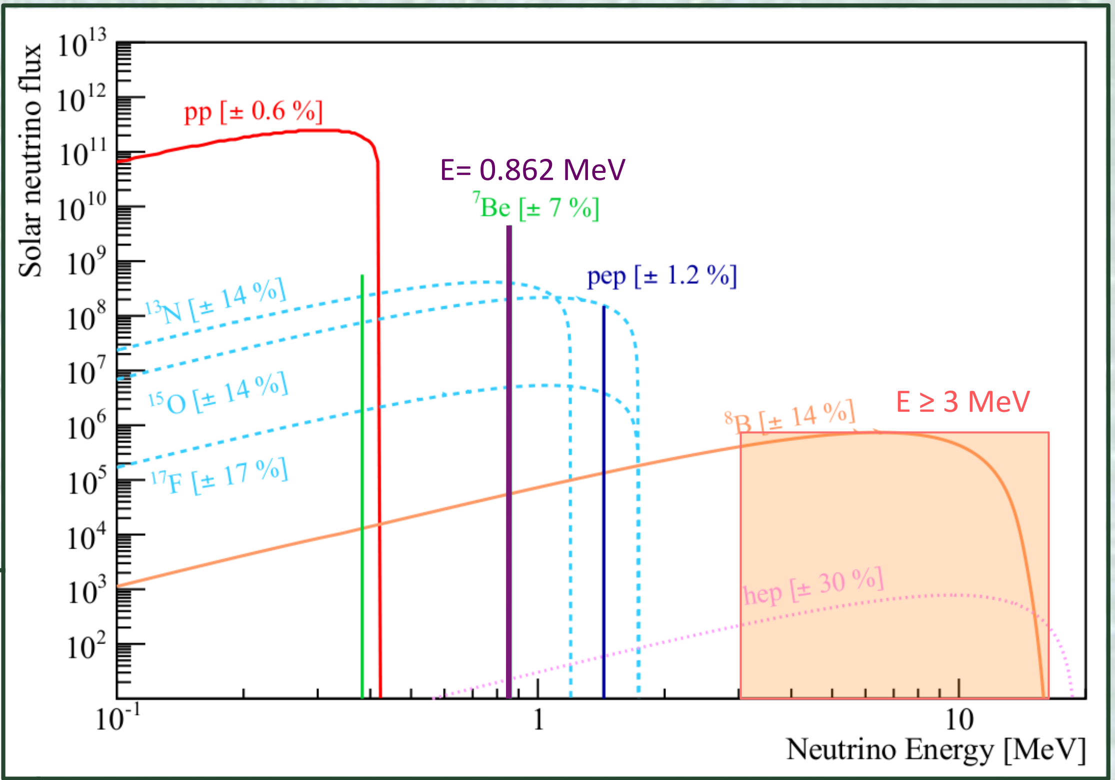
SOLAR NEUTRINOS: THE BOREXINO RESULTS(2)

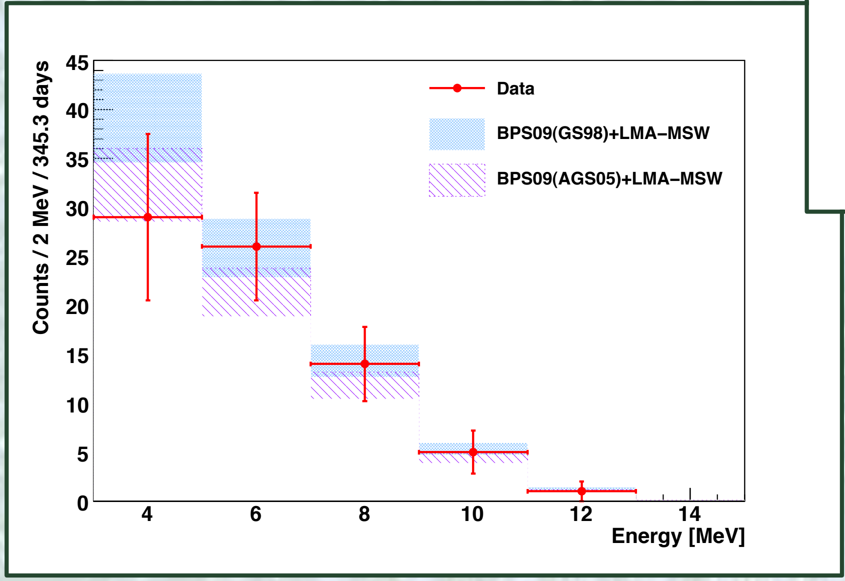
^{8}B solar neutrino:

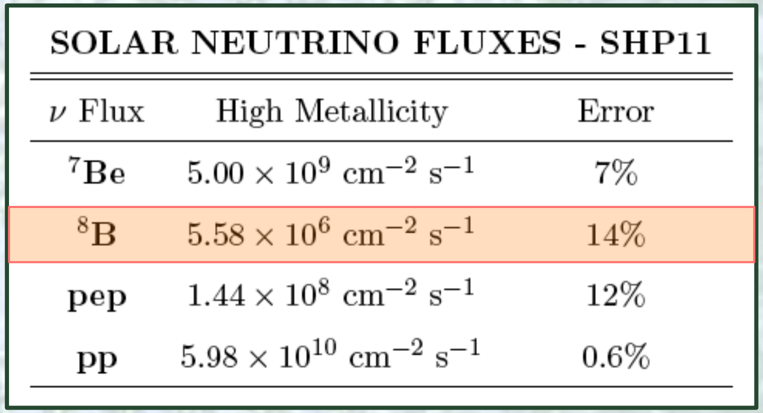
- The ^{8}B neutrino total rate (E$_{th}$= 3 MeV), accuracy about 18%.

$$0.217 \pm 0.038(\mathrm{stat}) \pm 0.008(\mathrm{syst})\ \mathrm{cpd}/100\,\mathrm{ton},$$
$$\Phi(^8\mathrm{B}) = (2.40 \pm 0.41) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,.$$

- The ^{8}B neutrino spectral shape.







SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
^{7}Be	$5.00 \times 10^9\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	7%
^{8}B	$5.58 \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	14%
pep	$1.44 \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	12%
pp	$5.98 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.6%

SOLAR NEUTRINOS: THE BOREXINO RESULTS(3)

pep solar neutrino:

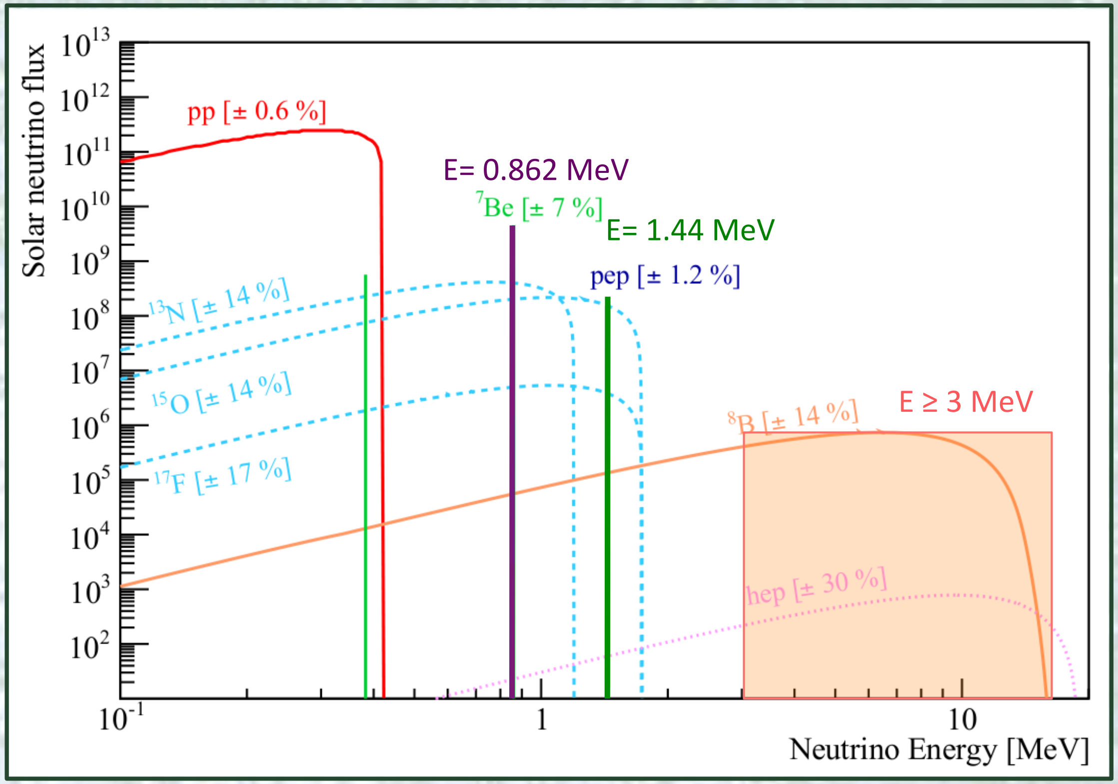
-the pep total ν-rate:

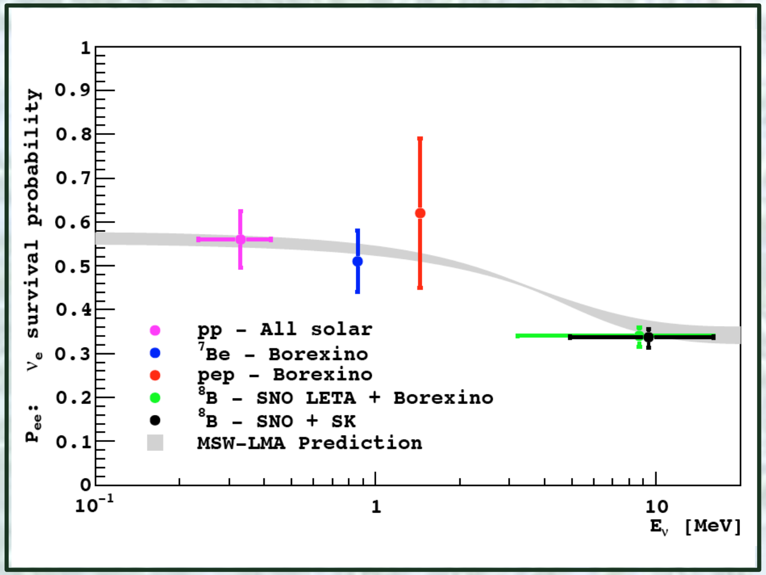
$$\boxed{\begin{array}{c}3.1 \pm 0.6\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{cpd}/100\ \text{ton}\\ \Phi(\text{pep}) = (1.6 \pm 0.3) \times 10^8\ \text{cm}^{-2}\,\text{s}^{-1}\end{array}}$$

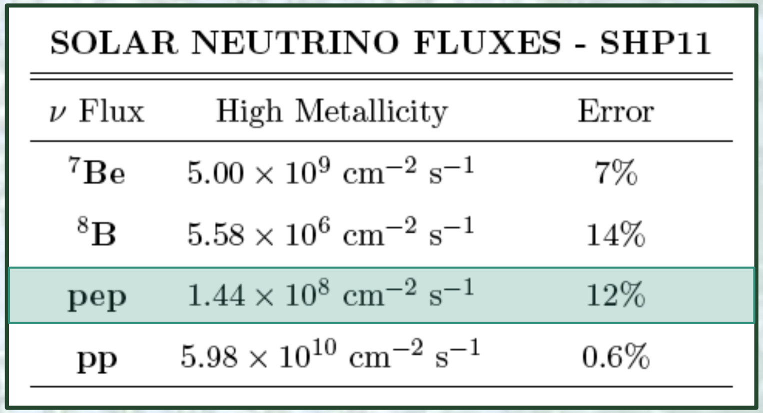
accuracy about 20%

- the (best to date) limit on CNO:

$$\boxed{< 7.9\ \text{cpd}/100\ \text{ton}\quad (95\%\ \text{C.L.})}$$






SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
^{7}Be	$5.00 \times 10^9\ \text{cm}^{-2}\ \text{s}^{-1}$	7%
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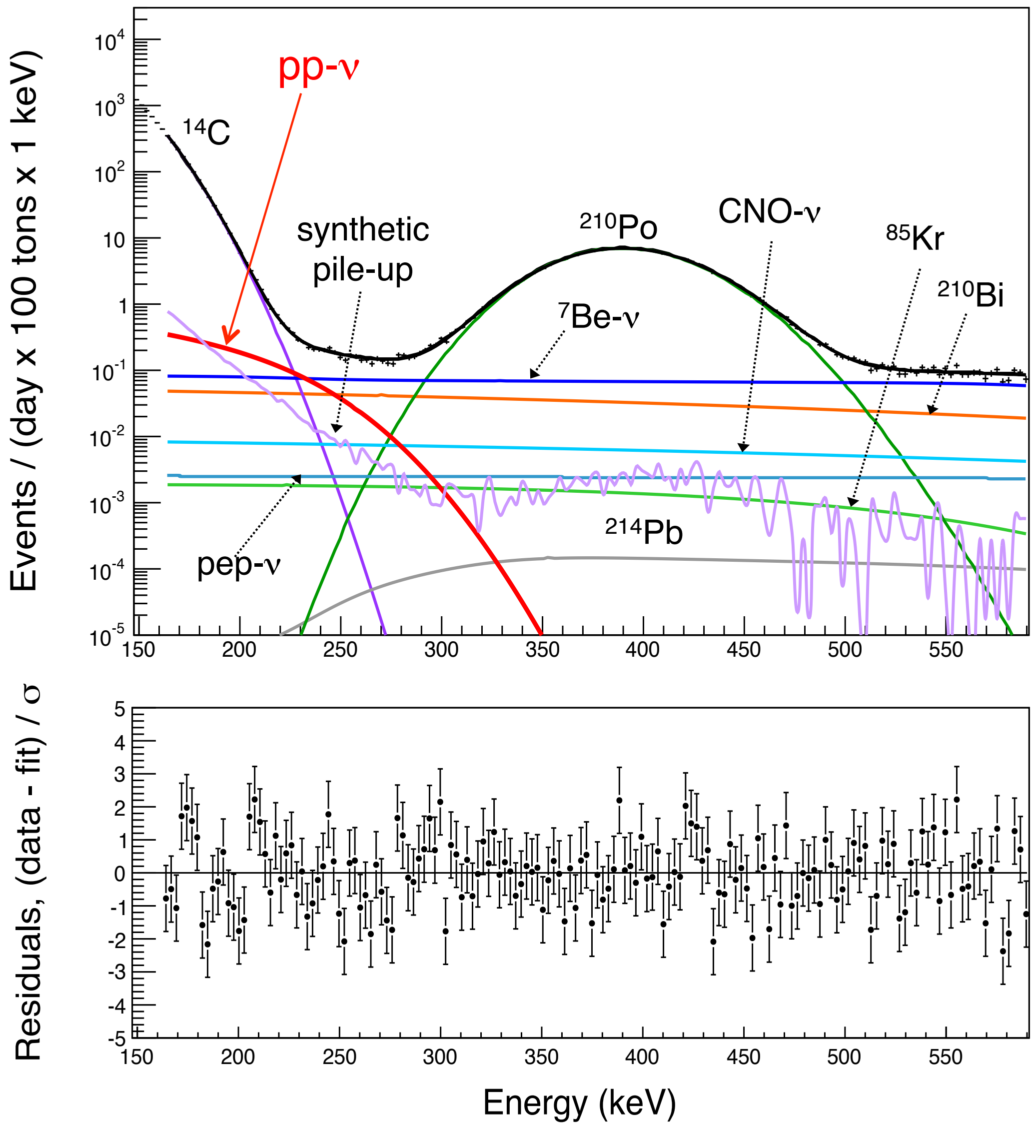
pep	$1.44 \times 10^8\ \text{cm}^{-2}\ \text{s}^{-1}$	12%
pp	$5.98 \times 10^{10}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.6%

SOLAR NEUTRINOS: THE BOREXINO RESULTS(4)



Rates [cpd/100 ton]

🟥	pp ν:	144 ± 13 (free)
🟦	^{7}Be ν:	46.2 ± 2.1 (constrained)
▬	pep ν:	2.8 (fixed)
▬	CNO ν:	5.36 (fixed)
▬	^{214}Pb:	0.06 (fixed)
🟩	^{210}Po:	583 ± 2 (free)
🟪	^{14}C:	39.8 ± 0.9 (constrained)
▬	Pile-up:	321 ± 7 (constrained)
🟧	^{210}Bi:	27 ± 8 (free)
🟩	^{85}Kr:	1 ± 9 (free)

Fit range: 165-590 keV

χ^2/d.o.f = 172.3/147

G. Bellini et al., Nature, vol. 512, 383-386 (2014).

SOLAR NEUTRINOS: THE BOREXINO RESULTS(4B)

pp solar neutrino rate:

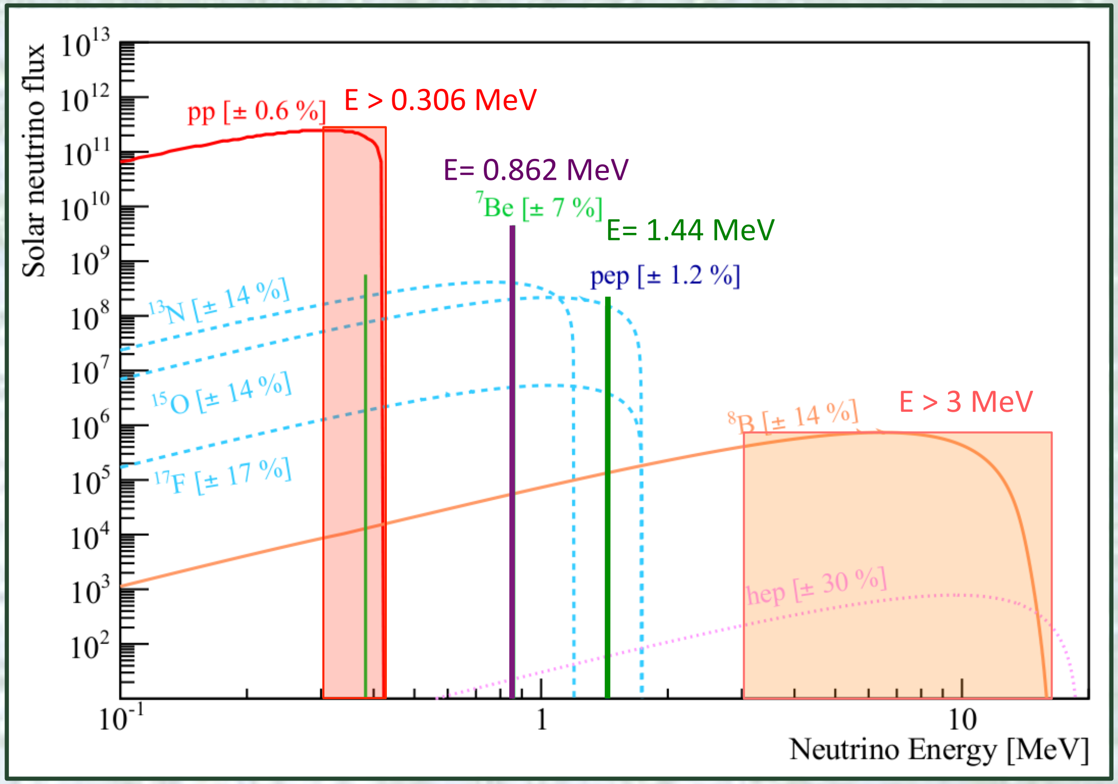
$$\boxed{\begin{array}{c} 144 \pm 10\,(\mathrm{stat}) \pm 13\,(\mathrm{syst})\ \mathrm{cpd}/100\mathrm{ton} \\ \Phi(\mathrm{pp}) = (6.6 \pm 0.7) \times 10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \end{array}}$$

accuracy about 11%.

The pp neutrino rate is extracted by fitting experimental spectrum with the expected spectra of signal and backgrounds.

The observation of pp neutrinos provides us with a direct glimpse at the keystone fusion process that keeps the Sun shining and strongly reinforces our theories on the origin of almost the entirety of the Sun's energy.

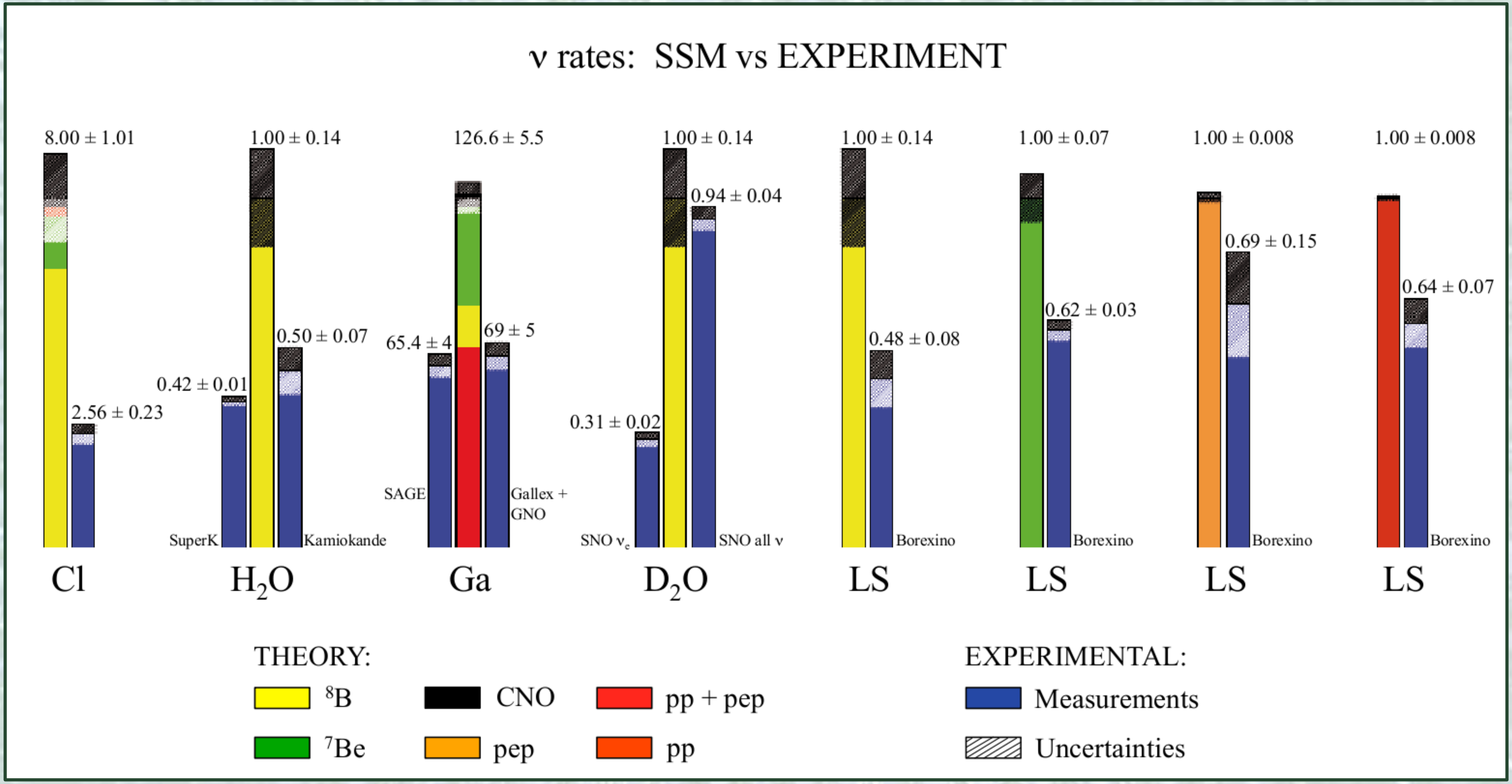
By analyzing pp neutrino emission, Borexino has shown that the energy produced today in the Sun's core is equal to that produced 100.000 years ago.



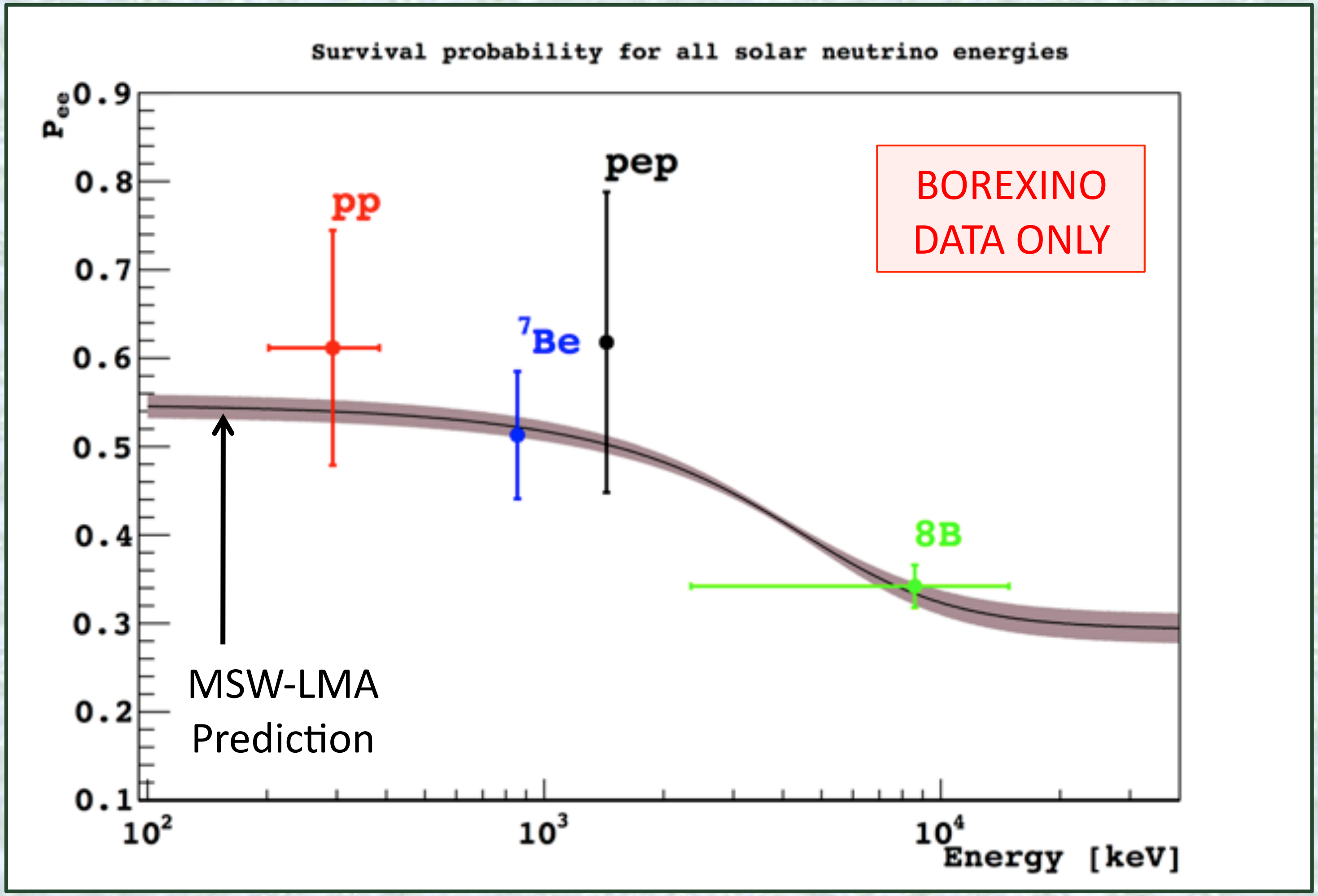
SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
^{7}Be	$5.00 \times 10^9\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	7%
^{8}B	$5.58 \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	14%
pep	$1.44 \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	12%
pp	$5.98 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.6%

SOLAR NEUTRINOS: SUMMARY
OSCILLATIONS



SOLAR NEUTRINOS: SUMMARY OSCILLATIONS(2)



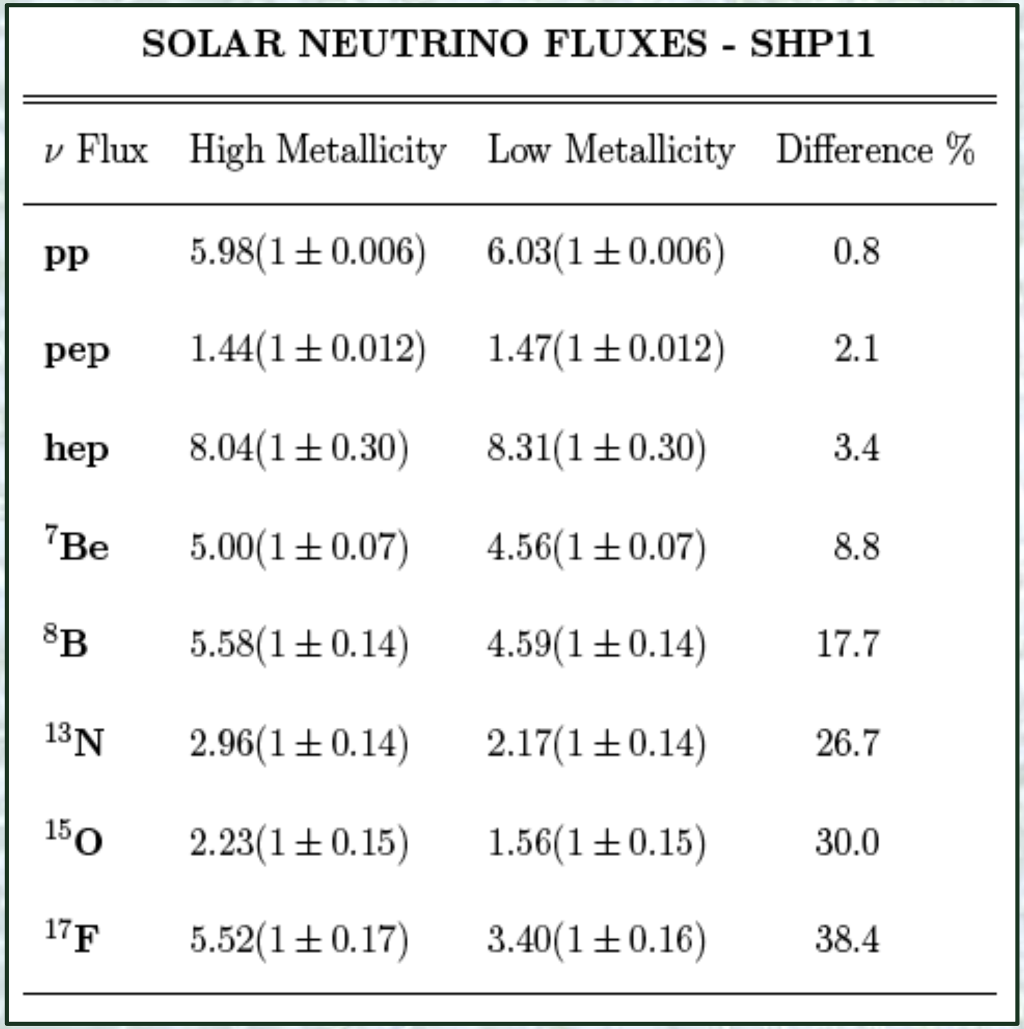
SOLAR NEUTRINOS: SUMMARY

SOLAR PHYSICS

	pp	^{7}Be	pep	CNO	^{8}B
SuperK					± 1.4%, $E_\nu \geq 3.5$ MeV Ref. 1
SNO					± 3.8%, $E_\nu \geq 3.5$ MeV Ref. 2
Kamland		± 15% Ref. 8			± 15%, $E_\nu \geq 5.5$ MeV Ref. 3
Borexino	± 10.6% Ref. 7	± 5% Ref. 6	± 19% Ref. 5	UpperLim. Ref. 5	± 17%, $E_\nu \geq 3$ MeV Ref. 4

1) Y. Koshio (SK Coll.) Neutrino 2014 talk
2) B. Aharmim et al (SNO Coll.) Phys. Rev. C 88 025501 (2013)
3) S. Abe et al (Kamland Collaboration) Phys. Rev. C 84 035804 (2011)
4) G. Bellini et al (Borexino Collaboration) Phys. Rev. D 82, 3 (033006) 2010
5) G. Bellini et al., (Borexino Collaboration) Phys. Rev. Lett. 108 (2012) 051302.
6) G. Bellini et al., (Borexino Collaboration) Phys. Rev. Lett. 107 (2011) 141362.
7) G. Bellini et al. (Borexino Collaboration) Nature 512 383 (2014)
8) A. Gando et al. (Kamland Collaboration) arxiv:1405.6190v1 (May2014)

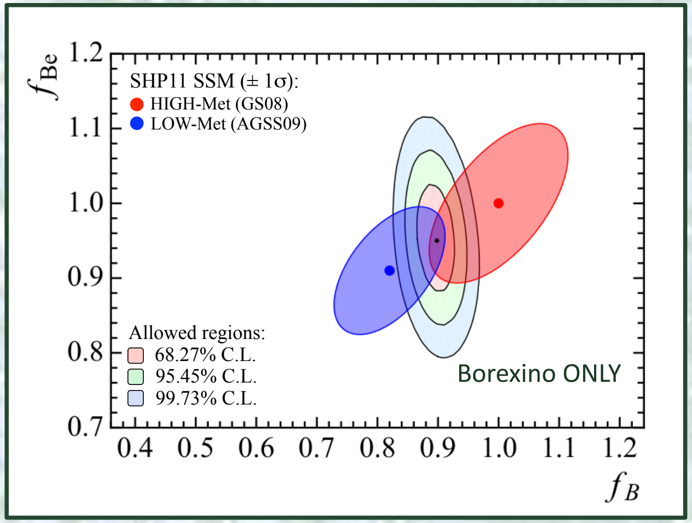
SOLAR NEUTRINOS: SUMMARY
SOLAR PHYSICS(2)



SOLAR NEUTRINO FLUXES - SHP11

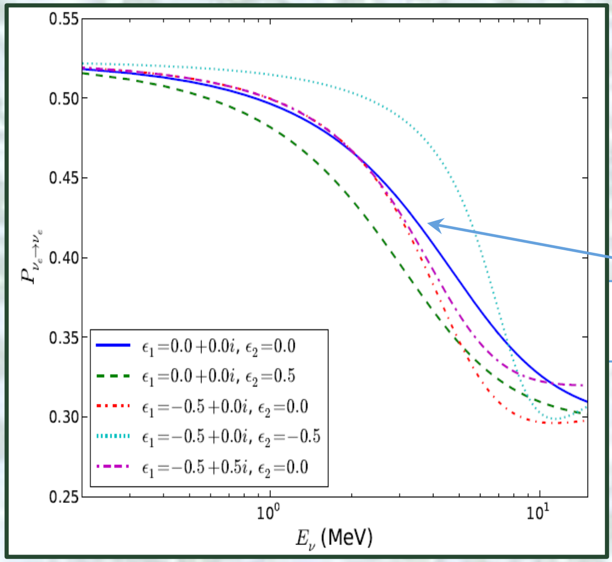
ν Flux	High Metallicity	Low Metallicity	Difference %
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	0.8
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	2.1
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	3.4
^{7}**Be**	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	8.8
^{8}**B**	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	17.7
^{13}**N**	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	26.7
^{15}**O**	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	30.0
^{17}**F**	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	38.4

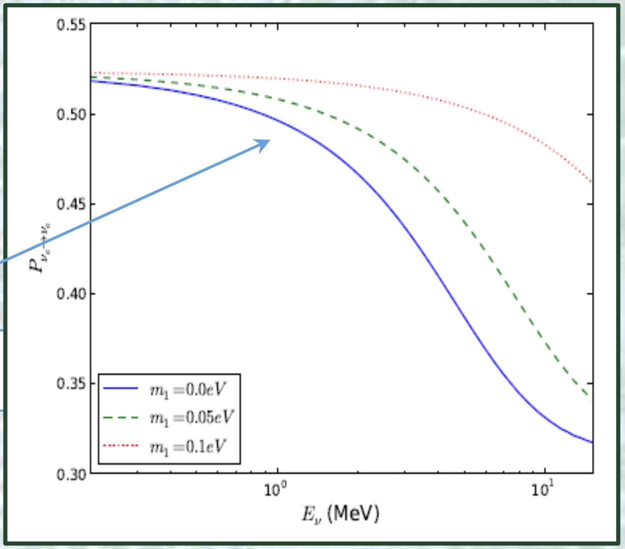
At present, solar neutrino data cannot discriminate between low or high metallicity hypothesis in the SSM: both the 1σ theoretical range of low and high metallicity models lies in the 3σ allowed region by the current neutrino data.



SOLAR NEUTRINOS: SUMMARY
NON STANDARD PHYSICS

Non standard forward scattering

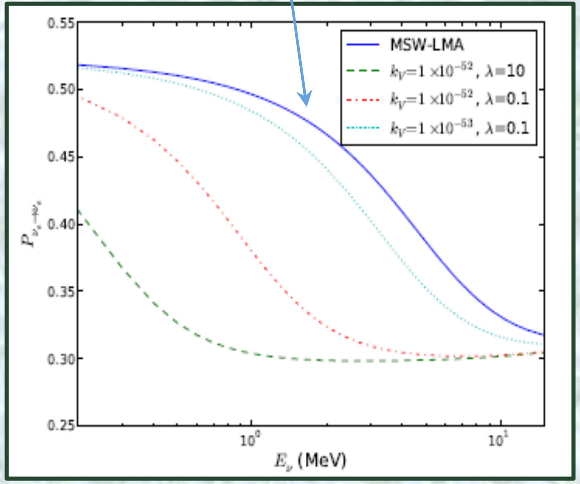




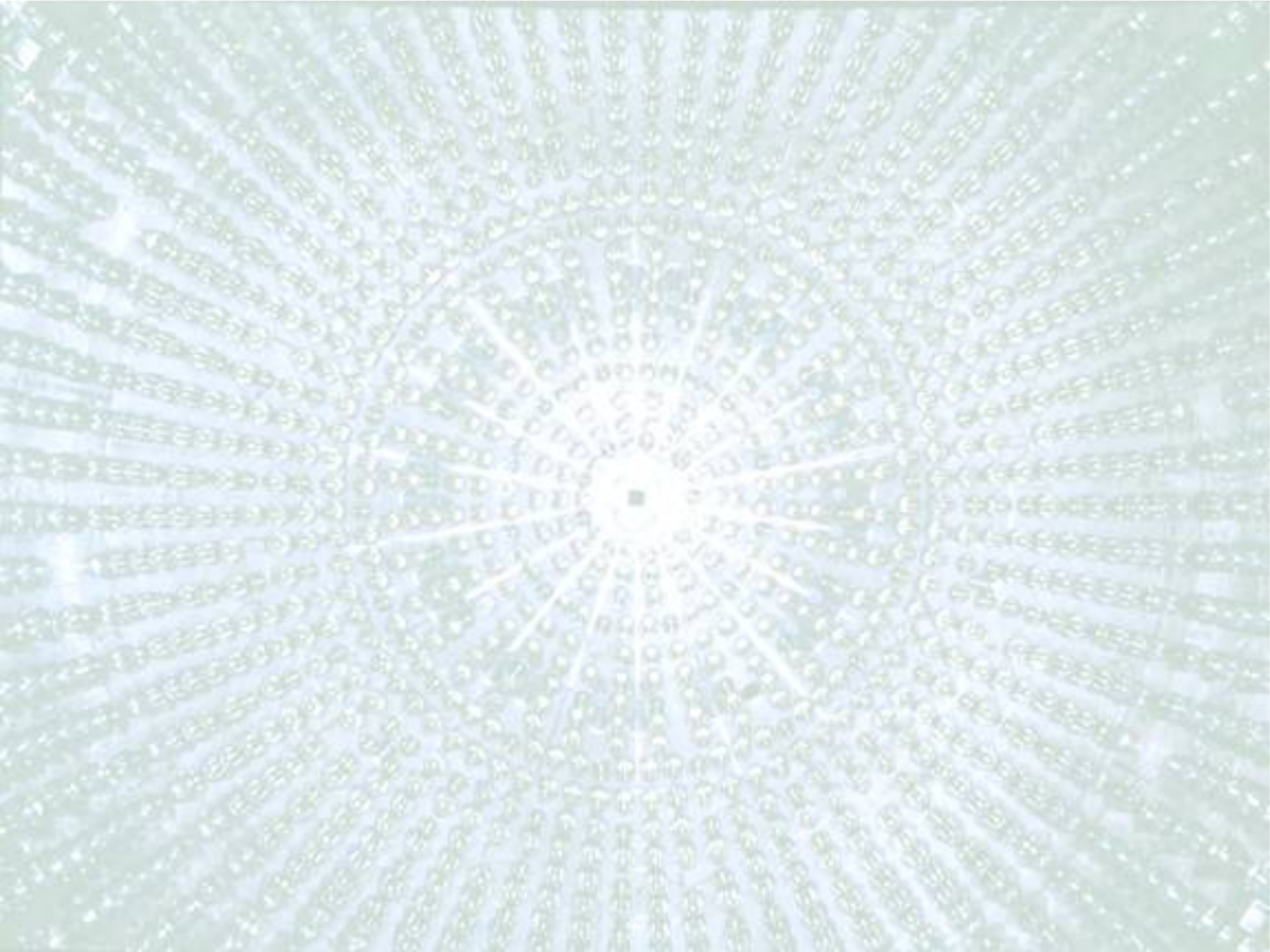
LMA and standard model

MaVan models

NSI between ν and electrons modify P_{ee} vs E (MSW)



Long range interactions



BOREXINO PERSPECTIVES

Since 2007, the Borexino experiment has had a very rich physics program:

- SOLAR NEUTRINOS: ^{7}Be, ^{7}Be DayNight Asymmetry, ^{7}Be seasonal modulations, ^{8}B (above 2.8 MeV), pep, CNO; **pp neutrinos!!!**
- GEONEUTRINOS;
- SUPERNOVÆ (anti)NEUTRINOS;
- EXOTIC PARTICLES SEARCH;
- RARE PROCESSES;
- NEUTRINO PROPERTIES;

In the so-called Borexino-phase II, we have many goals!

Among them….

- SOLAR NEUTRINOS:
  * Improve the limit on CNO and the significance of the pep signal (target: 3σ or more but ^{210}Bi suppression is required);
- STERILE NEUTRINO(s) SEARCH.

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