Prospectives of solar neutrino studies at ESSnuSB Far Detector

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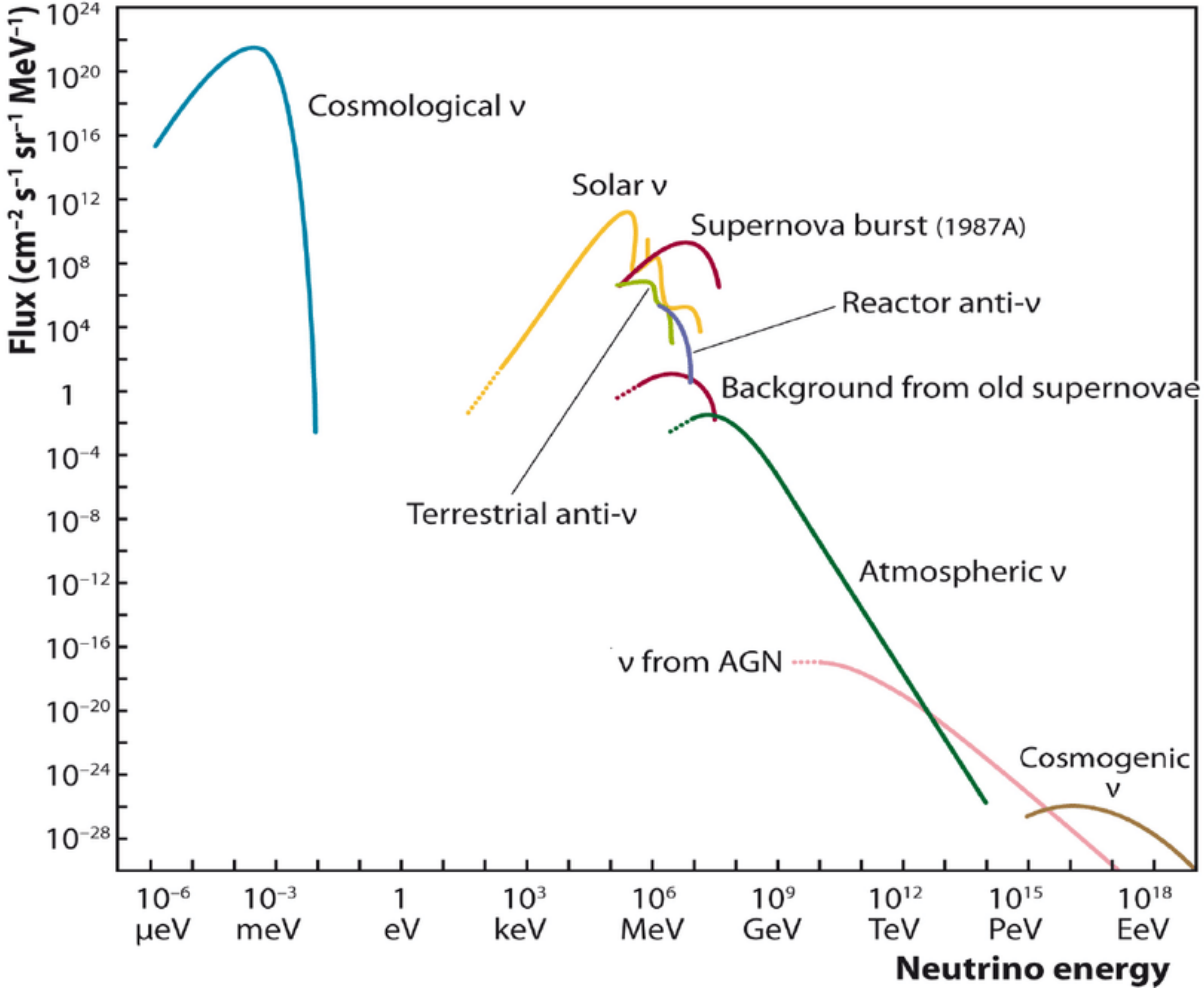
ESS neutrino Super Beam plus

ROMA TRE UNIVERSITÀ DEGLI STUDI

2nd ESSnuSB+ annual meeting, Hamburg, 25/09/2024

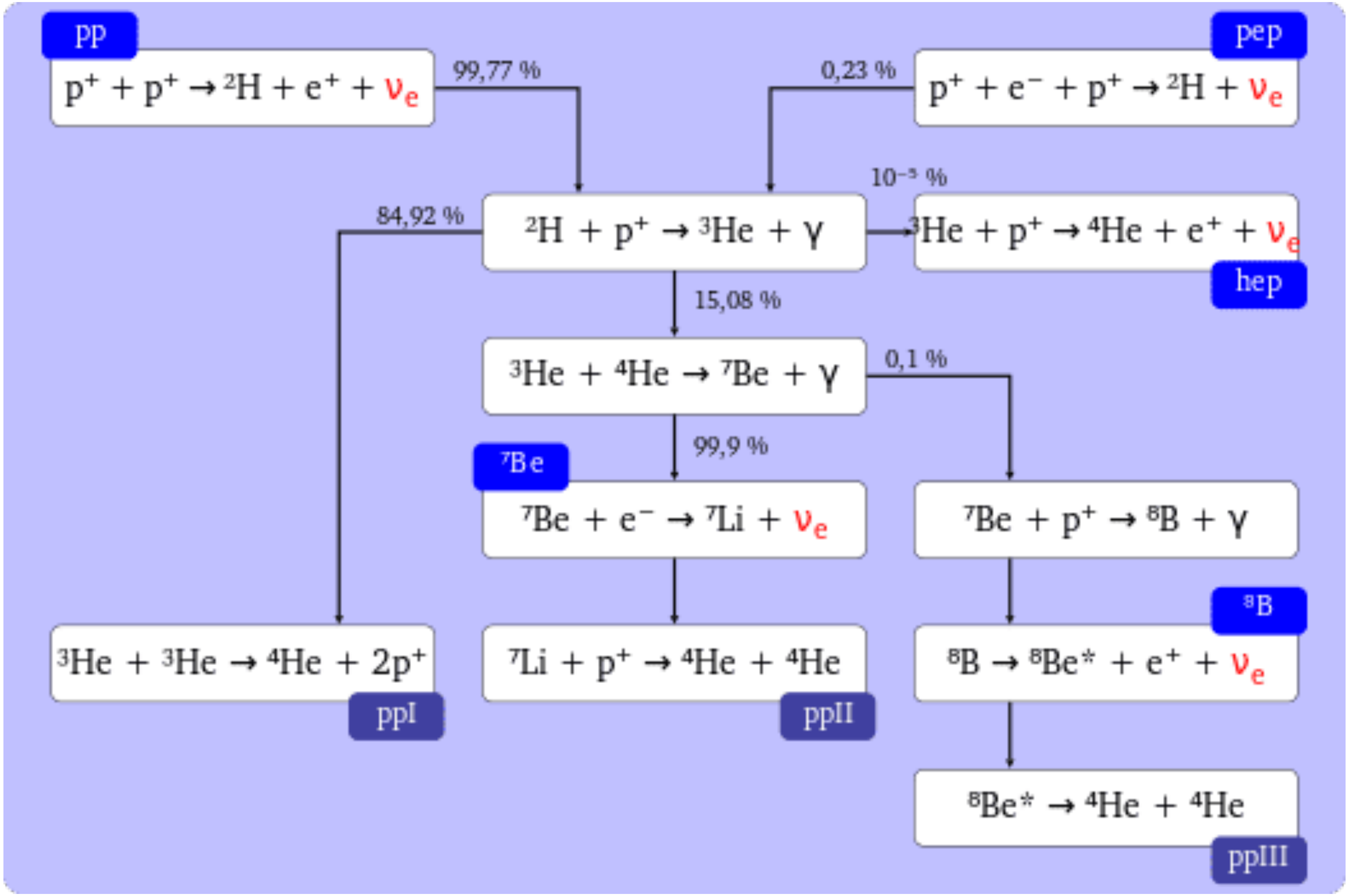


Solar neutrinos:

-Only electron neutrinos

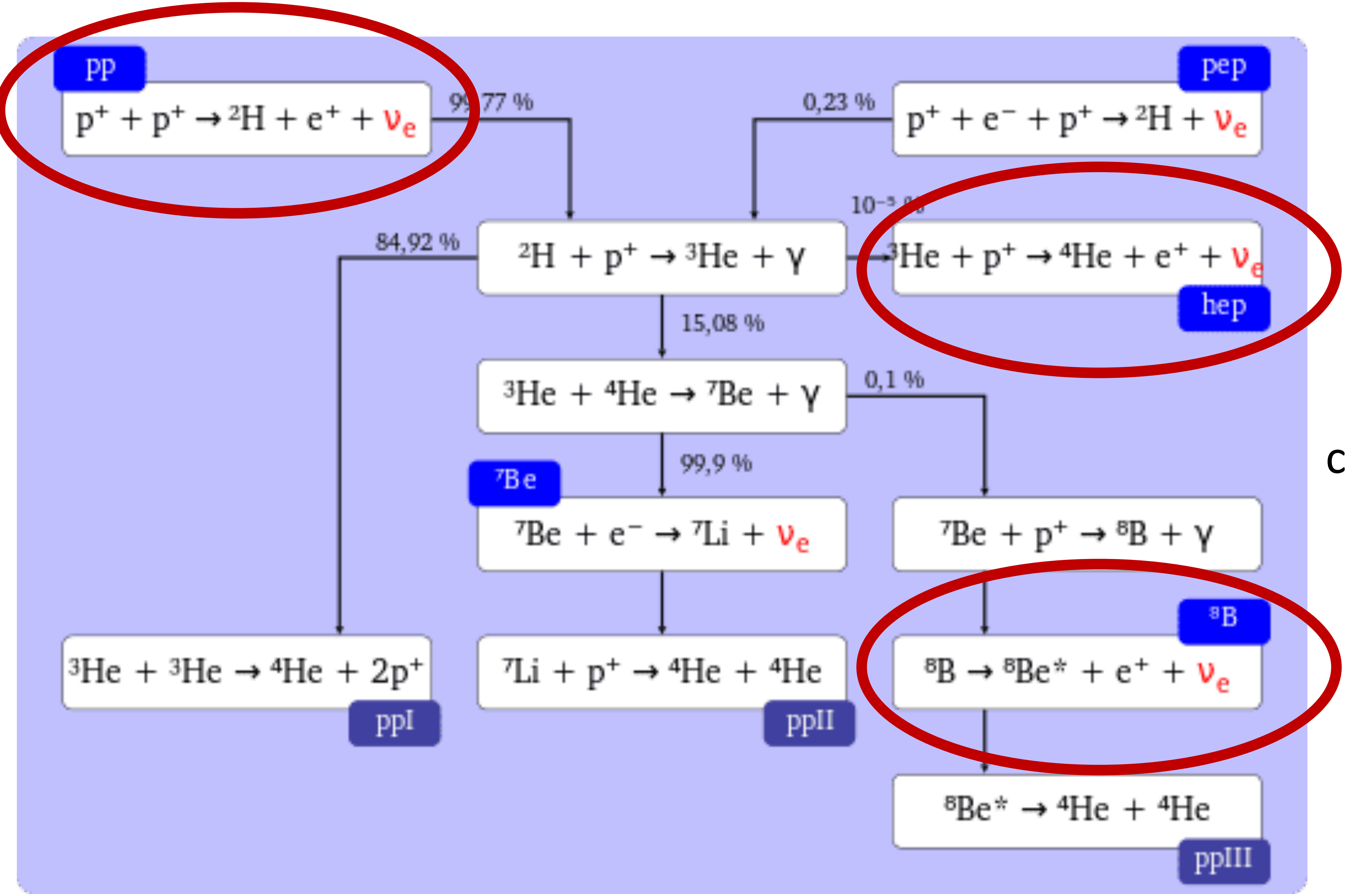
-From hounders of keV to a few MeV

-Highest obserable neutrino flux at the Earth



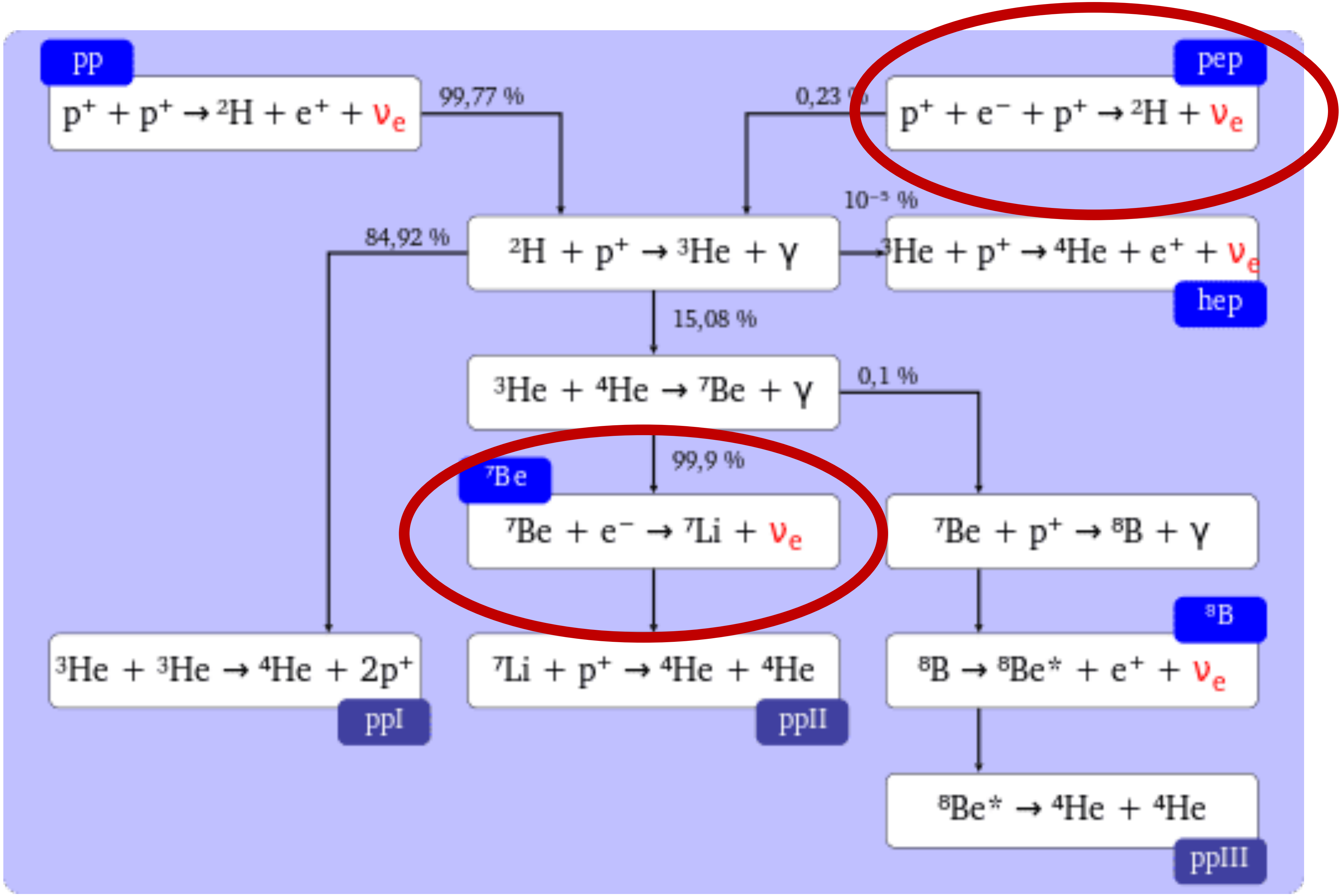
pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
0,23 %
10^{-5} %
84,92 %
${}^2H + p^+ \rightarrow {}^3He + \gamma$
${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
0,1 %
99,9 %
${}^7Be$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p^+ \rightarrow {}^8B + \gamma$
${}^8B$
${}^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI
${}^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
${}^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

+ CNO cycle



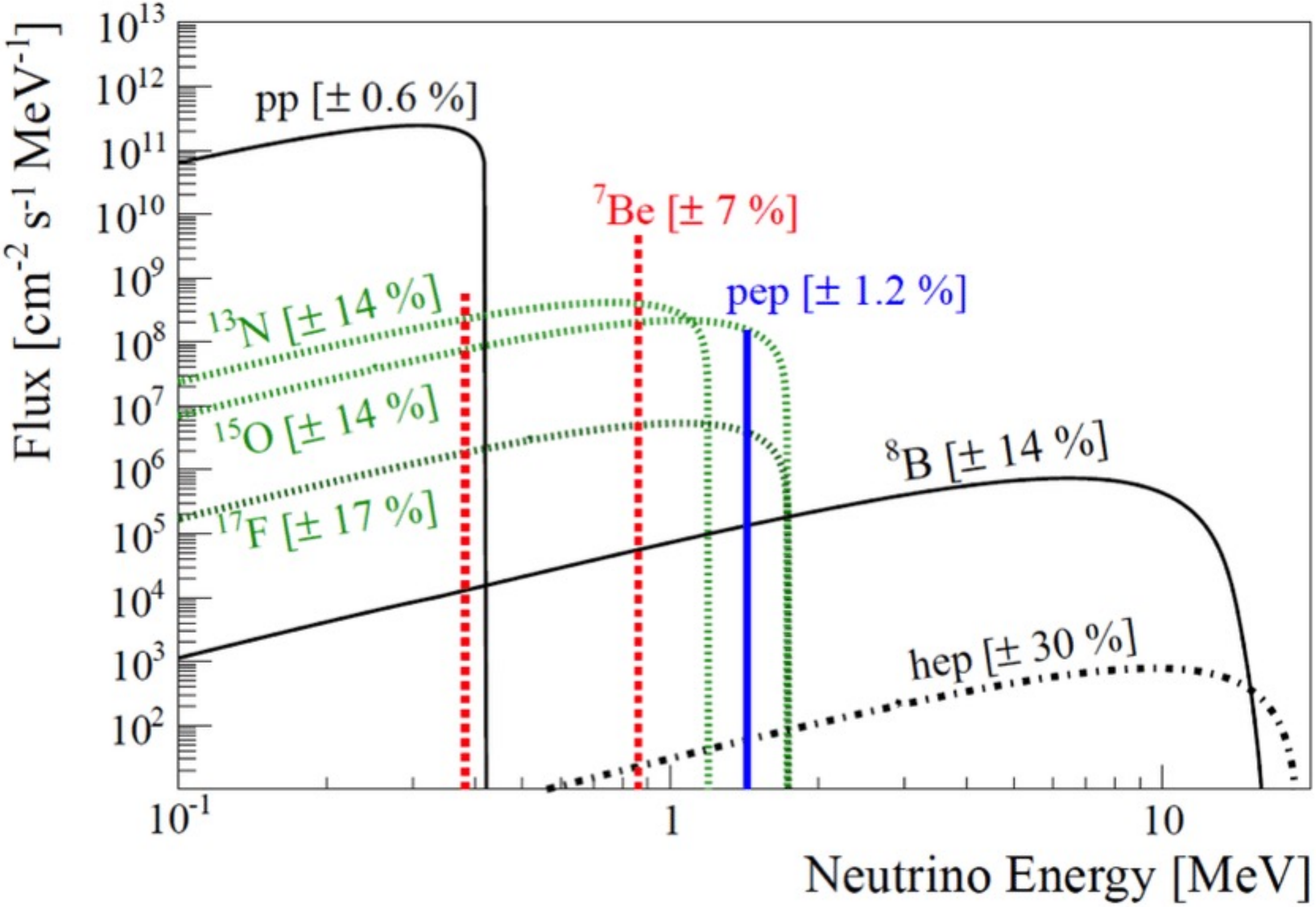
3 bodies: continous spectra

+ CNO cycle



2 bodies: lines

+ CNO cycle



Low energy:

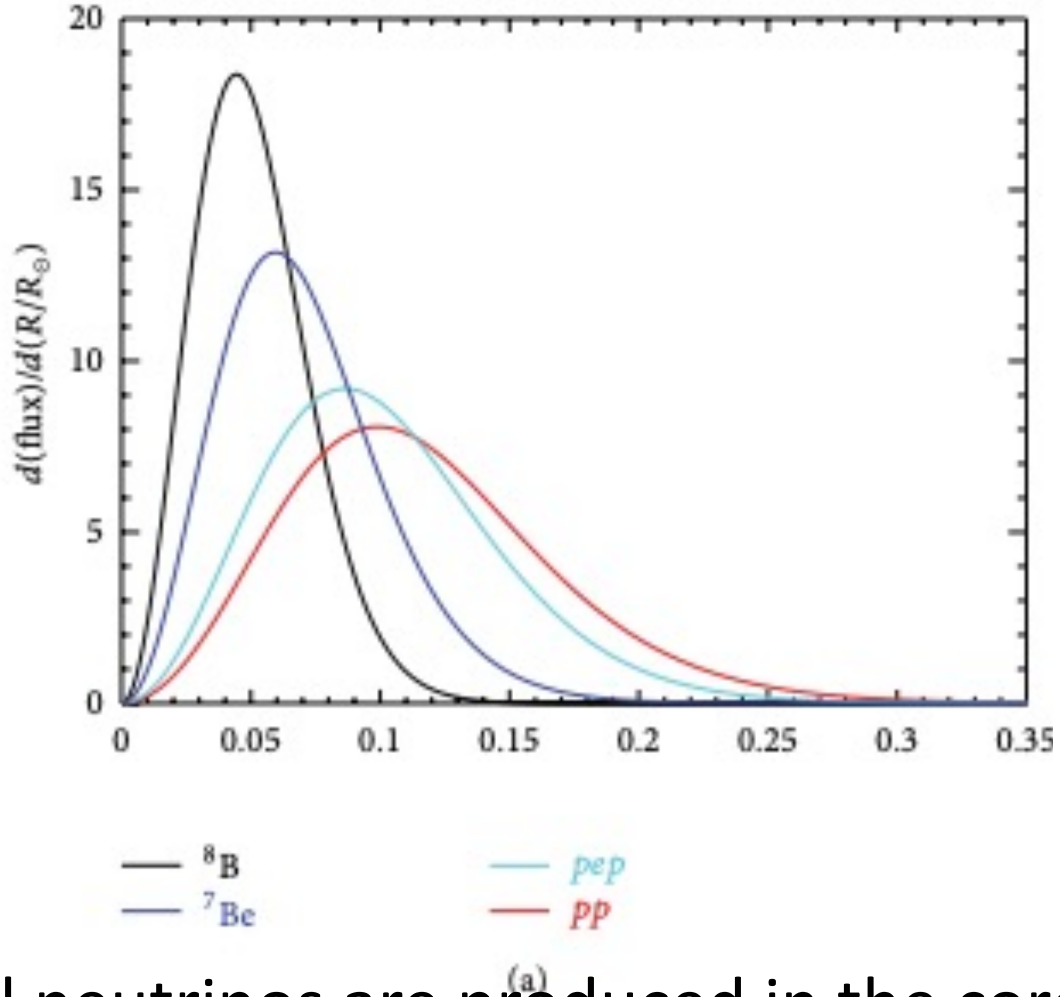
- High pp flux

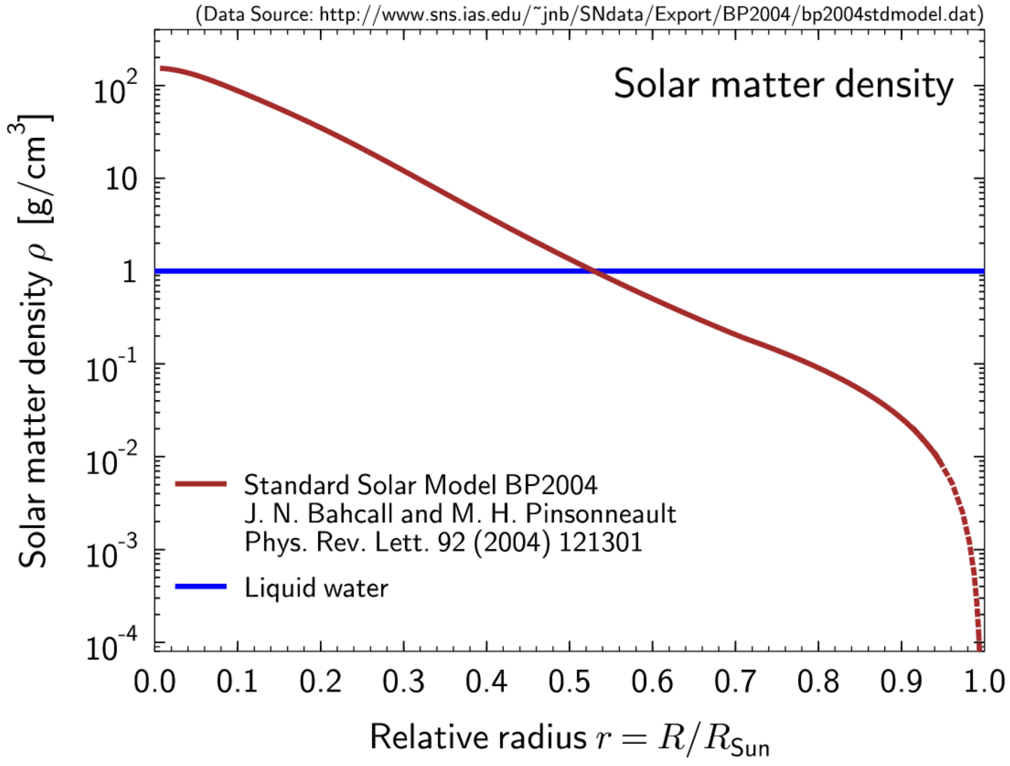
Middle region:

- Be and pep lines

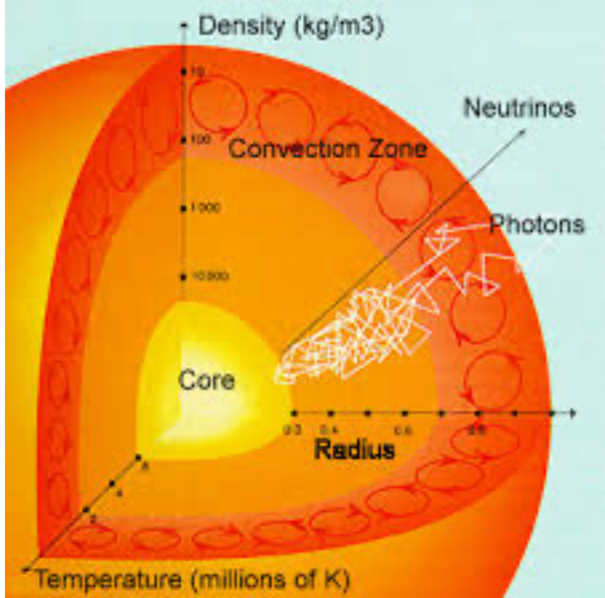
High energy:

- Only B neutrinos and a small hep flux





All neutrinos are produced in the core, where the matter density is of about 100 g/cm^3. While pp are produced in all the core, high energetic neutrinos (B8) need higher temperature and are produced in the inner part of the core.



The journey to the Earth of Solar neutrinos

Let's assume 2 neutrino flavors. Without any effect of the Sun matter

$$\nu_e = cos\theta\ \nu_1 + sin\theta\ \nu_2$$

To the Earth, it's a long travel! Much longer than oscillation lenghts! All oscillations are averaged out and we get

$$\boxed{P_{ee} = 1 - \frac{1}{2} sin^2 2\theta}$$

! Important: the small neutrino energy will not allow to have CC interactions of muon or tau neutrino type. We will there focus only on P_{ee}.

The journey to the Earth of Solar neutrinos

But, exiting the Sun, neutrinos encounter a very high electron density! The matter potential may become important (MSW effect).

$$\cos 2\theta \rightarrow \frac{\cos 2\theta - A}{\sqrt{(\cos 2\theta - A)^2 + sin^2 2\theta}}$$

Where $A = \frac{2\,E\,V}{\Delta m^2}$ and V is matter potential proportional to matter density

If $A \gg \cos 2\theta$, then we obtain that in matter $\cos 2\theta \rightarrow -1$!!!!!

Adiabatic assumption: the Sun matter density decreases smoothly from the inner part to the outer part

High density (Sun) **Vacuum (Earth)**

$$P_{ee} = \frac{1}{2}\left(1 + \frac{1}{2}[cos2\theta]^{production}[cos2\theta]^{detection}\right) \longrightarrow \boxed{P_{ee} = sin^2\theta}$$

The journey to the Earth of Solar neutrinos

In Sun conditions, we will have three regimes:

- Low energy: A is smaller, we have vacuum-like behaviour
- Middle energy: transition region (P complicated to write, not to compute)
- High energy: MSW-dominated regime

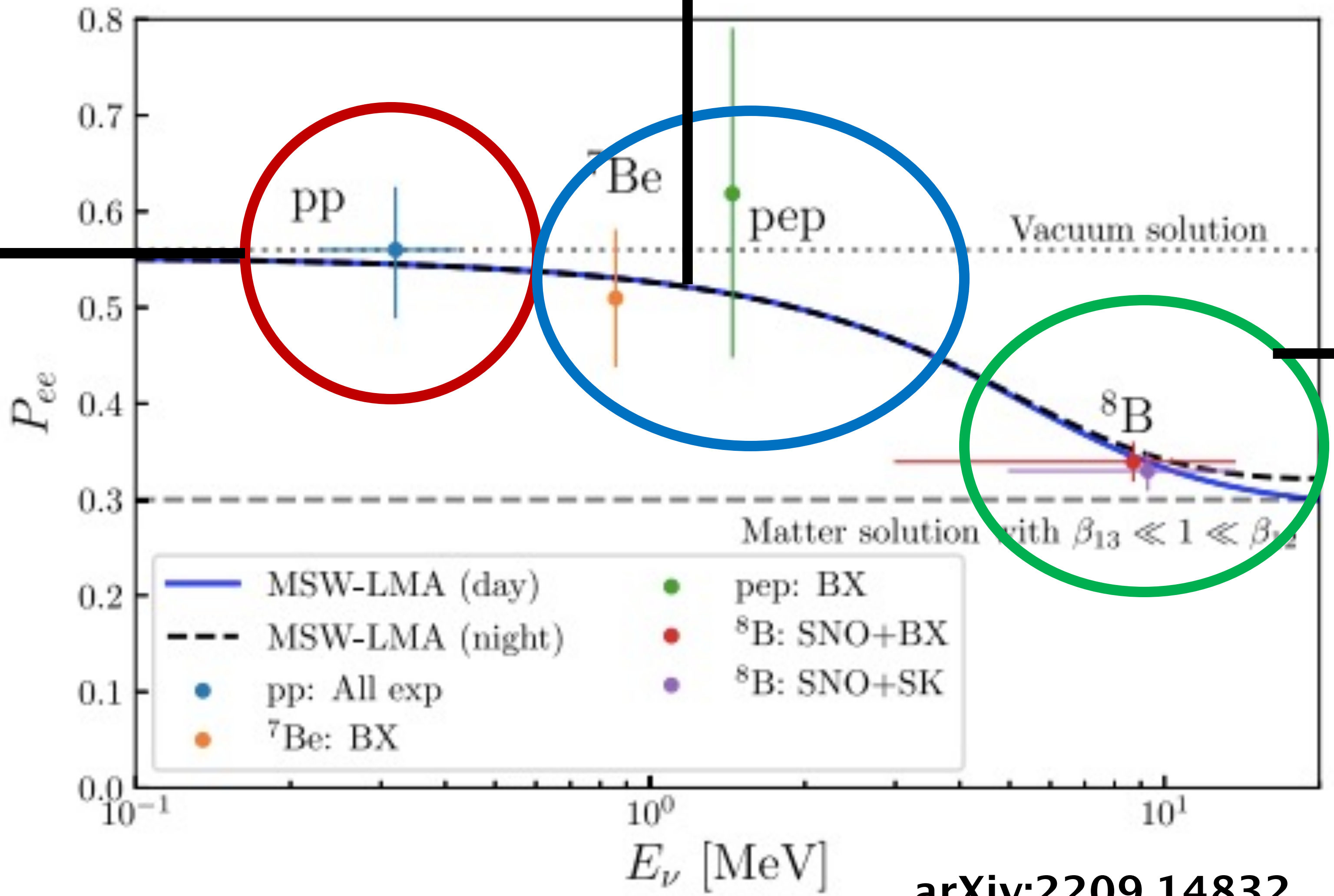
! Important: 3 flavors corrections are small due to the smallness of the reactor mixing angle. They can be obtained with the substitutions: $\Delta m^2 \rightarrow \Delta m^2_{21}, \quad \theta \rightarrow \theta_{12}, \quad A \rightarrow \cos^2\theta_{13}\ A, \quad P^{3f}_{ee} = \cos^4\theta_{13} P^{2f}_{ee} + \sin^4\theta_{13}$

Middle energy region:

Position: approx. value of mass splitting

Existance: $\Delta m_{21}^2 > 0$

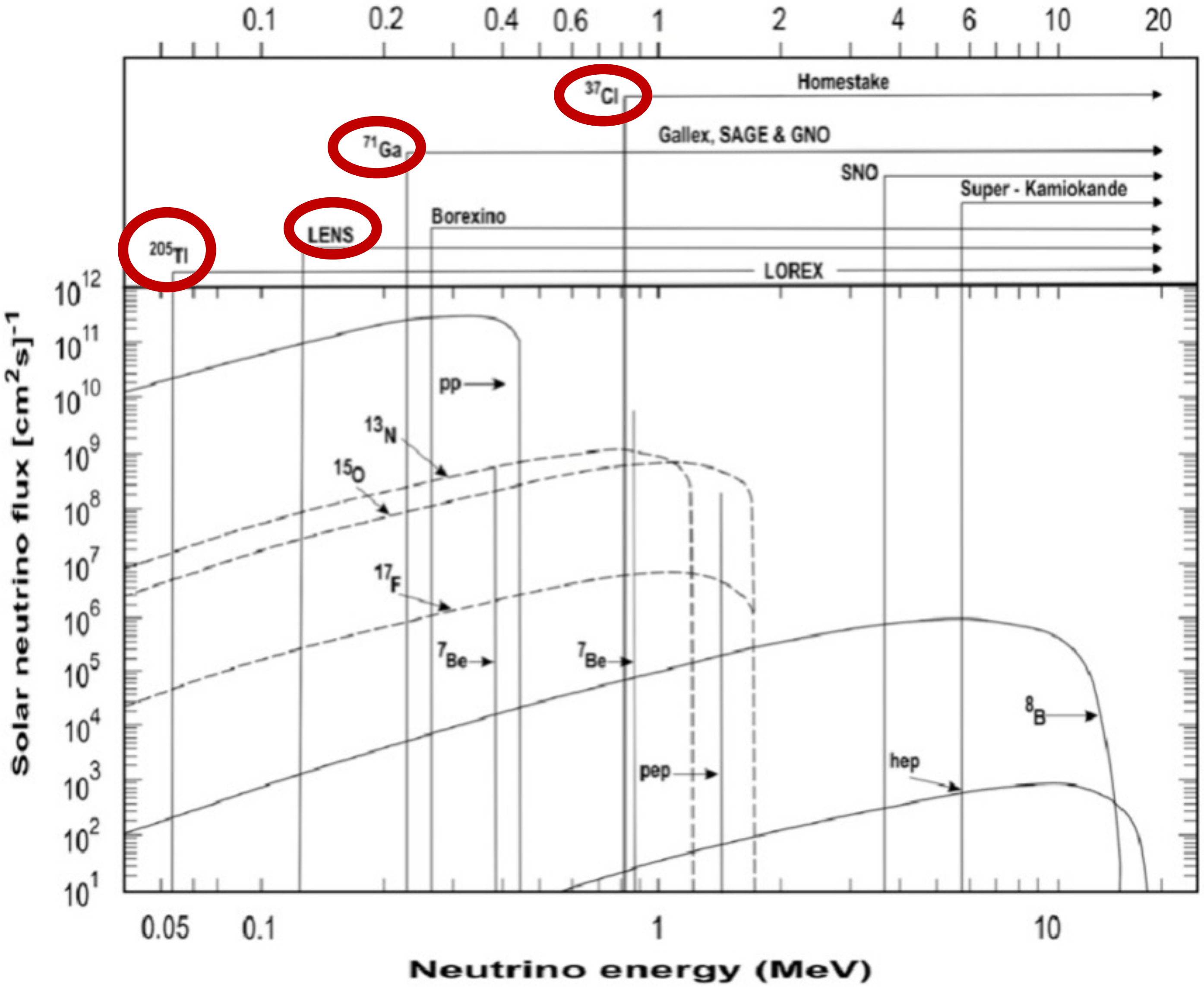
Low energy region:
- Measure of mixing angle



High energy region:
- Measure of mixing angle

arXiv:2209.14832

The journey to the solar neutrinos detection



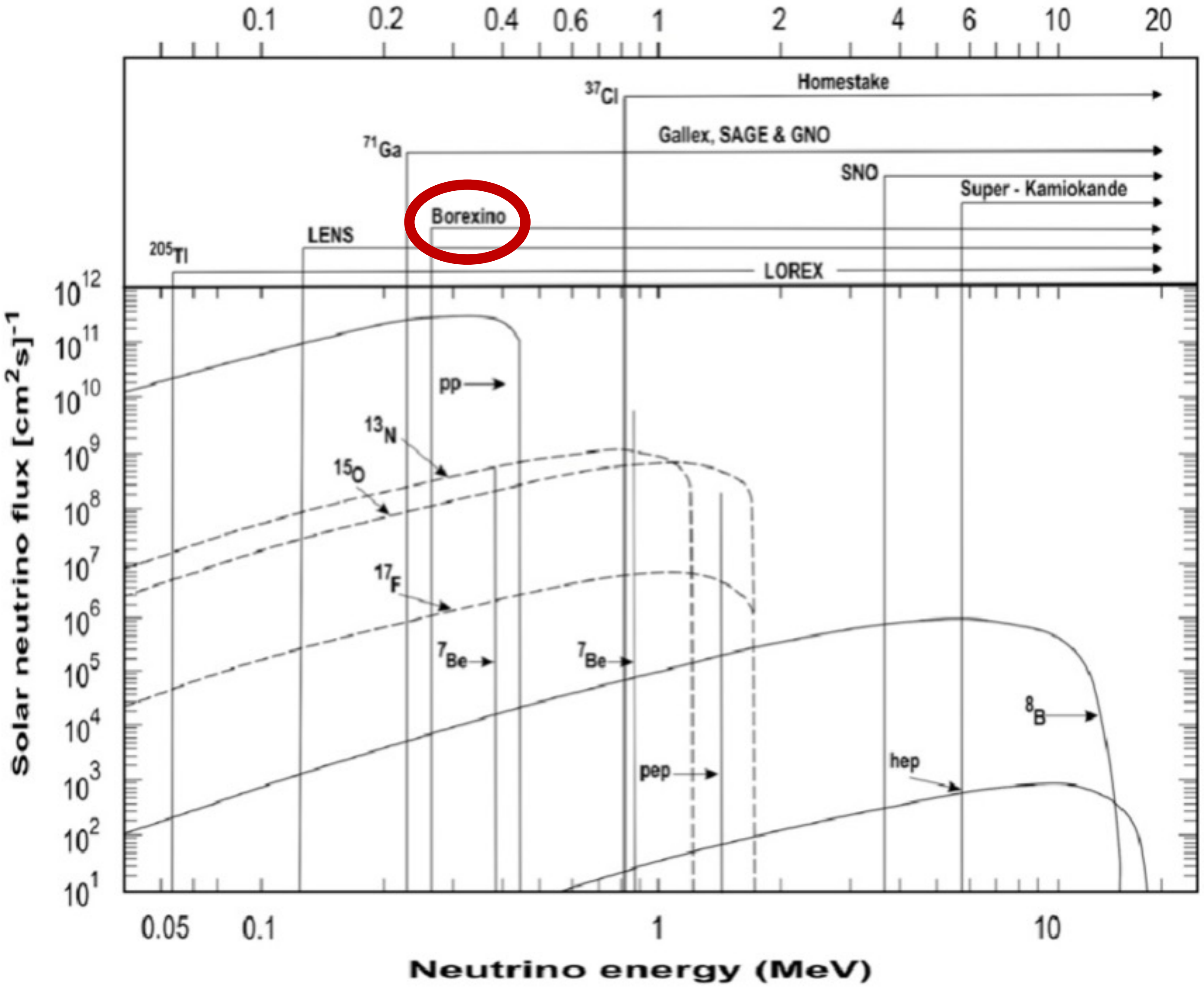
Radiochemical experiments

Electron capture of various elements with different energy threshold

Past:
- Chlorine (E>0.8 MeV)
- Gallium (E>0.2 MeV)

Future (proposed)
- Indium (E>0.15 MeV)
- Tellurium (E>0.05 MeV)

The journey to the solar neutrinos detection



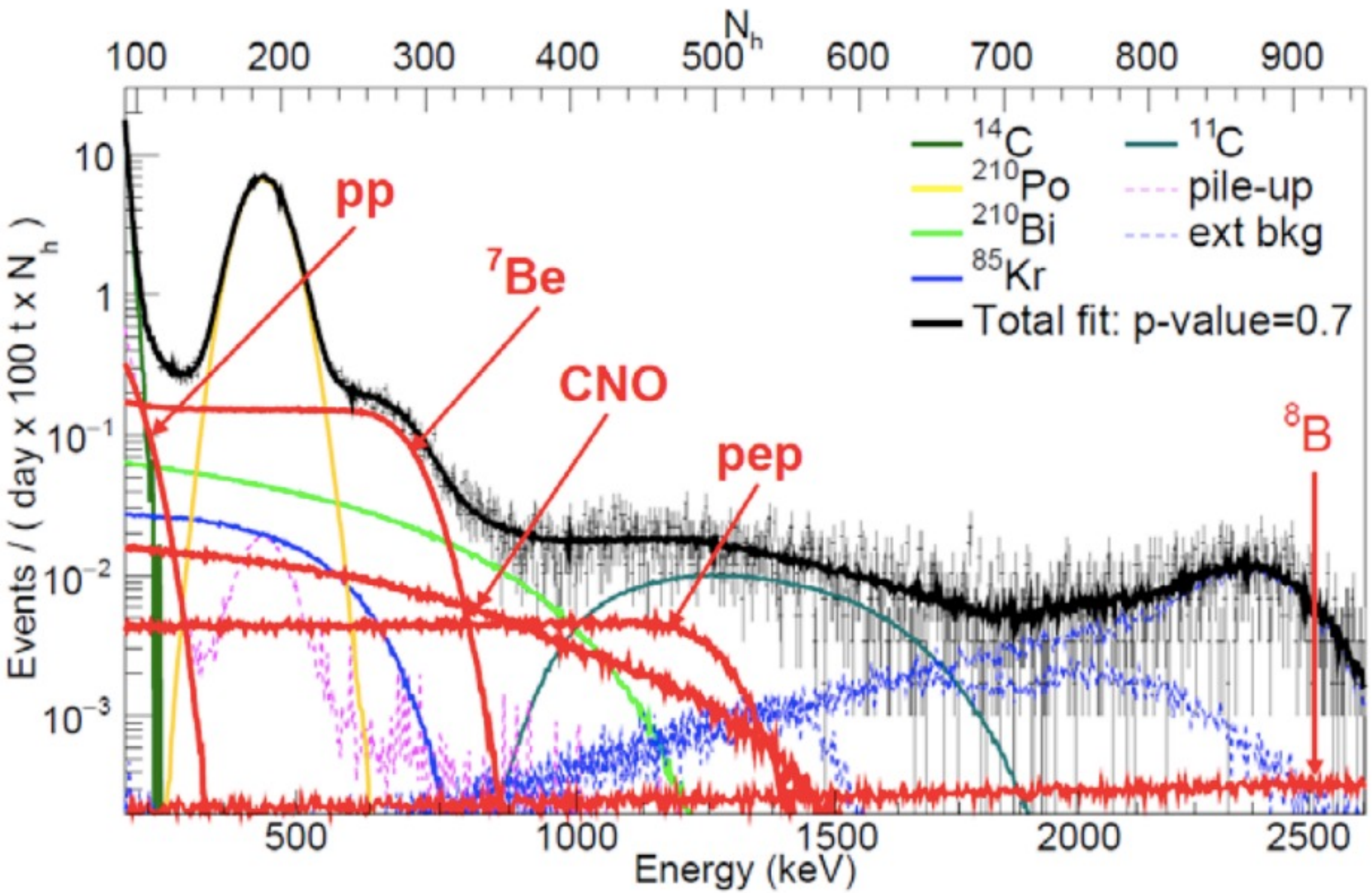
Scintillators

Neutrino-electron elastic scattering. No energy threshold but experimental cuts.

Borexino

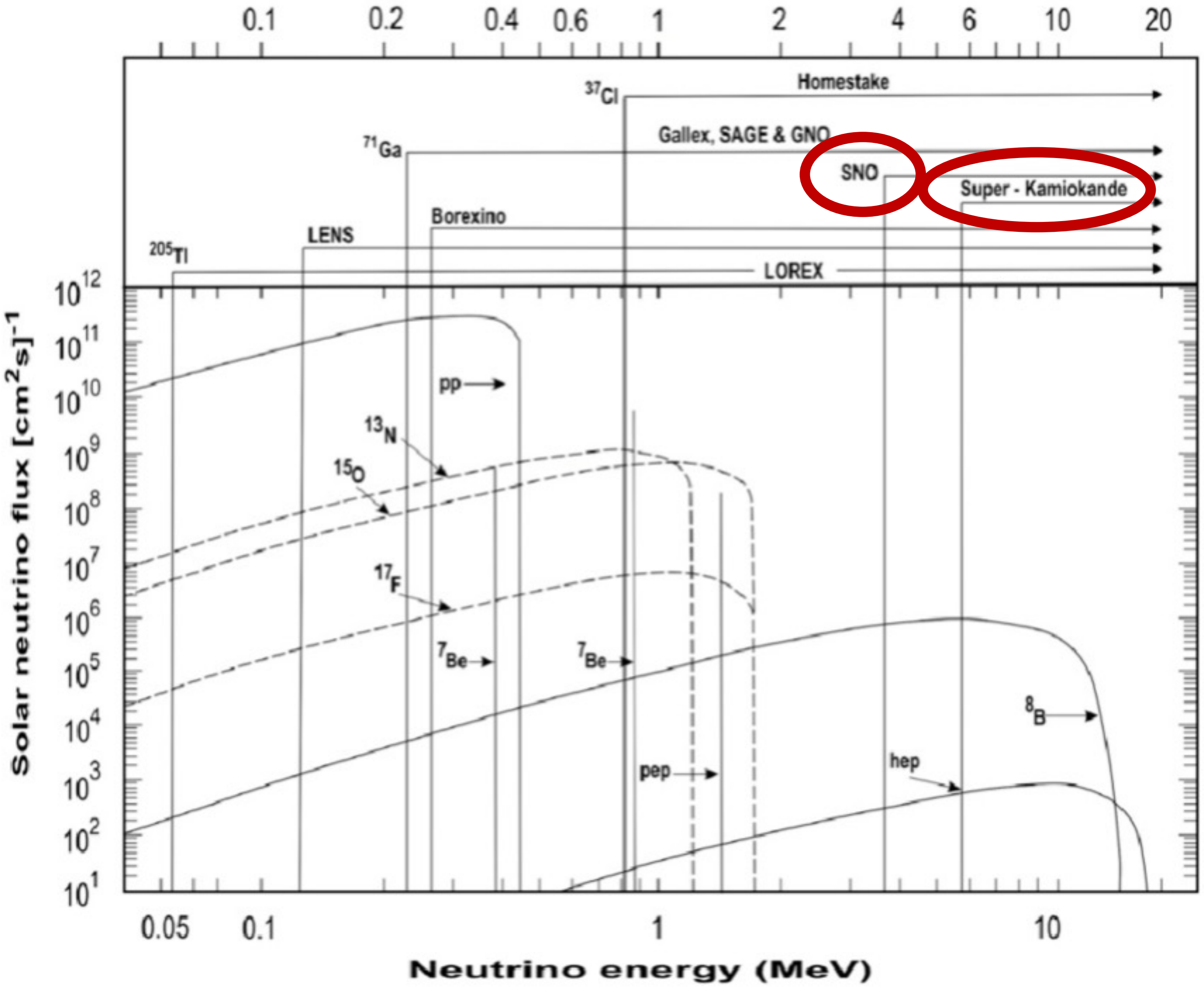
The journey to the solar neutrinos detection

Borexino results!



Nature **volume 562**, pages505–510 (2018)

The journey to the solar neutrinos detection



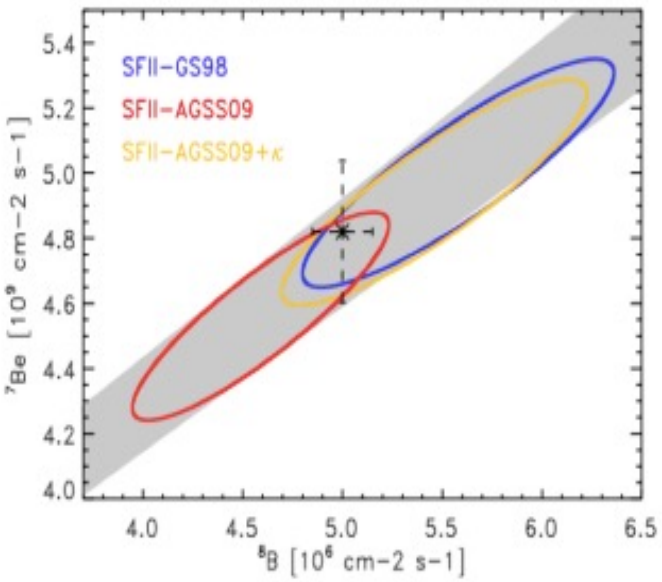
Water Cherenkov

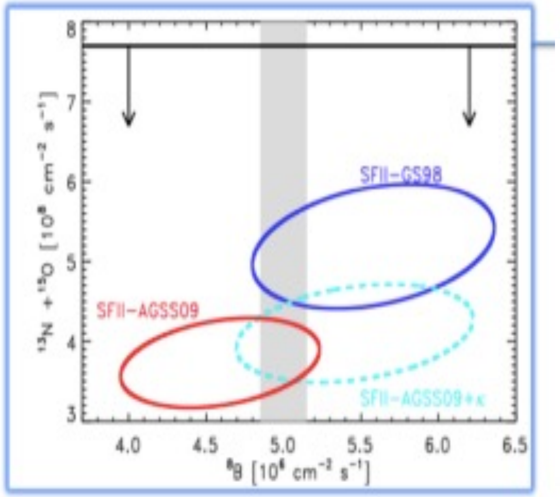
Neutrino-electron elastic scattering. No energy threshold but experimental cuts.

Super-K (E>6 MeV)
SNO (E>4 MeV), deuterium

More than neutrino oscillation

Information about Sun composition! High or low metallicity?
Spectroscopy, Heliosismology and Neutrinos cannot still give a final answer!





Borexino results	LZ disfavoring
^{7}Be-ν + ^{8}B-ν (Phase-II) "Comprehensive measurement of pp-chain solar neutrinos" Borexino Collaboration, Oct 24, 2018. Nature 562 (2018)	1.8σ
CNO-ν + ^{7}Be-ν + ^{8}B-ν (Phase-III and Phase-II) "Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun" Borexino Collaboration, Jun 26, 2020, Nature 587 (2020)	2.1σ

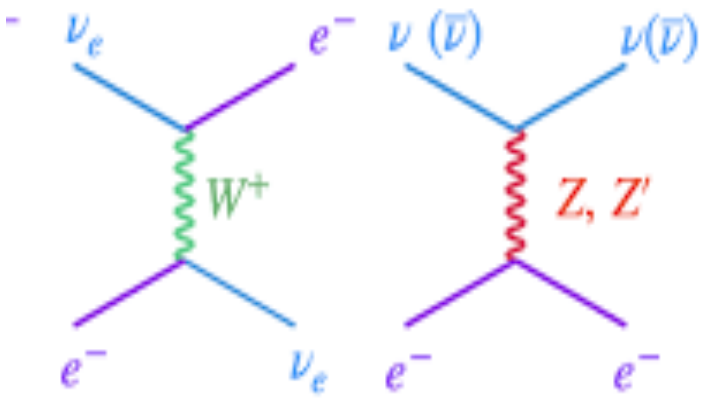
A. M. Serenelli, "A special Borexino event - Borexino Mini-Workshop", Sept. 5 2014

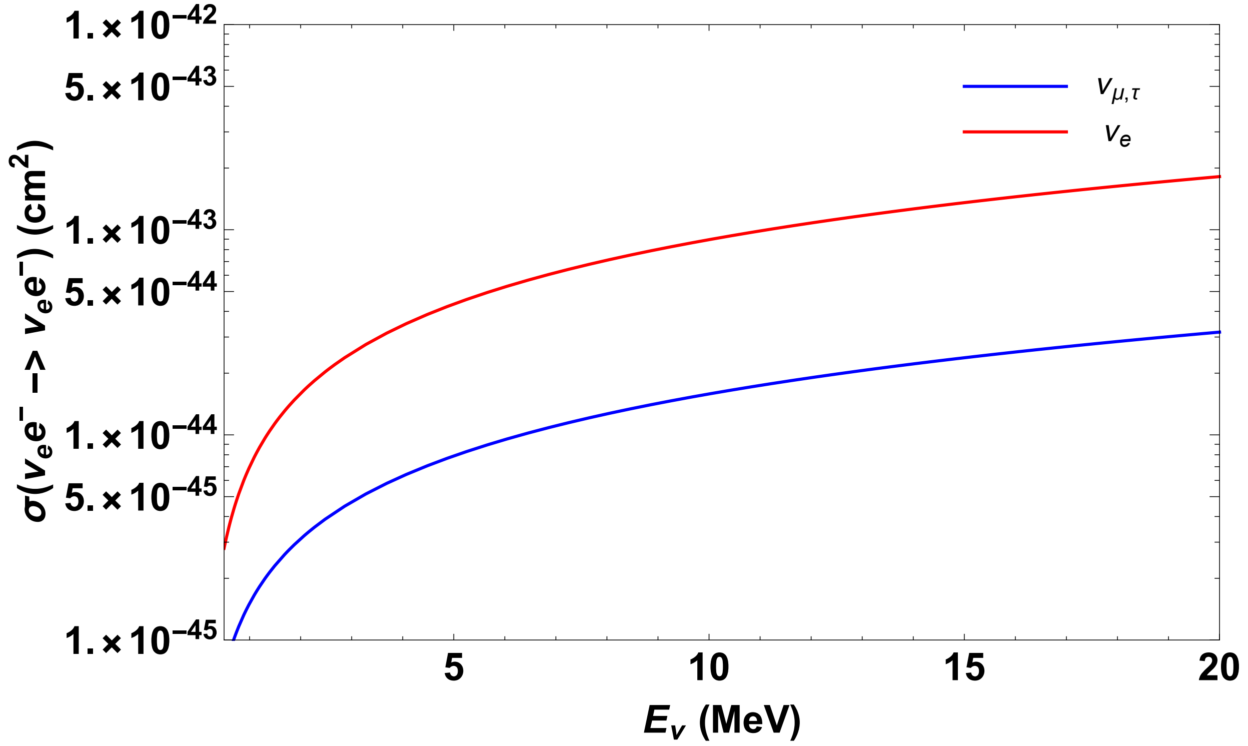
Davide Basilico, How can CNO neutrinos unravel the solar metallicity problem?, NuTel 2021

ESSnuSB and solar neutrinos!

First ingredient: detection channel

Neutrino-electron scattering!





Since NC channel can occur for all flavors, we will observe neutrinos of each flavor with a different probability.

! Important: the energy threshold for the events seems to be of the order of 3-4 MeV of *visible energy* due to the dark hit rate of PMTs (see HK proposal 1805.04163). ***This has to be studied in our case***

Second ingredient: backgrounds

Following the SK and HK analyses, the main backgrounds are:

- Radon-222 contained in the water
- Cosmic muon spallation products
- U, Th in the water and K40 in the PMTs

Second ingredient: backgrounds

Following the SK and HK analyses, the main backgrounds are:

- Radon-222 contained in the water ⟵ <u>High</u>
- Cosmic muon spallation products ⟵ <u>Difficult to control</u>
- U, Th in the water and K40 in the PMTs

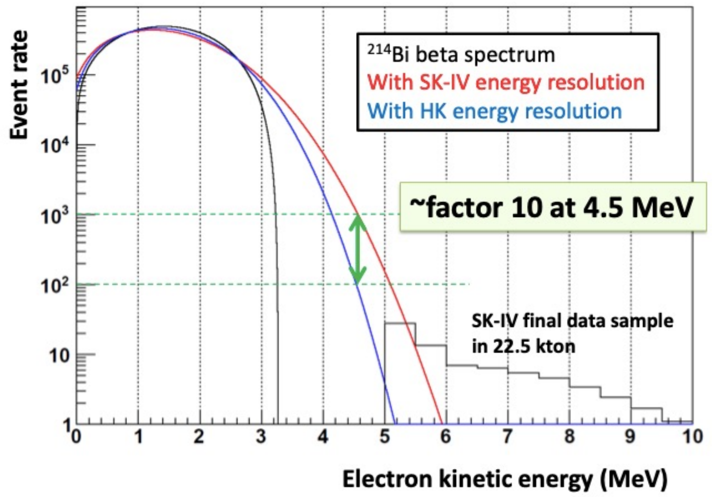
Second ingredient: backgrounds

EXAMPLE:

- Radon-222 contained in the water

Given the threshold for WC detectors (around 4 MeV), the most important contribution comes from the Bi 214 which is present in the Radon 222 decay chain. This has a Q value of 3.2 MeV!

It is important to recognize solar neutrino events close to the energy threshold!

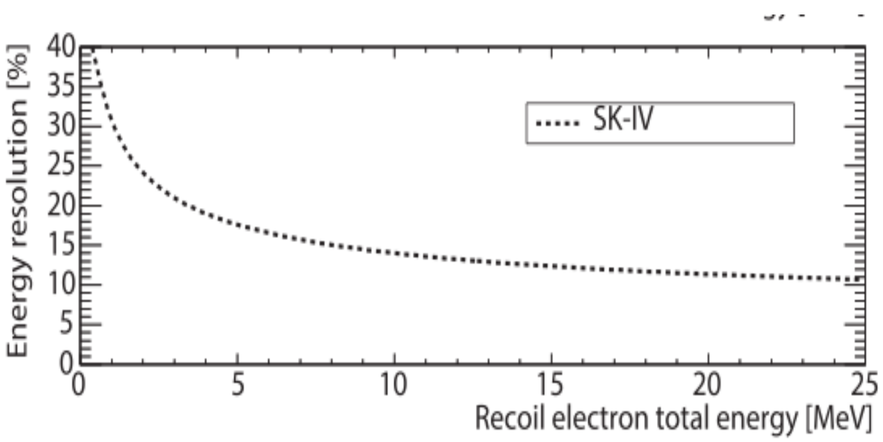


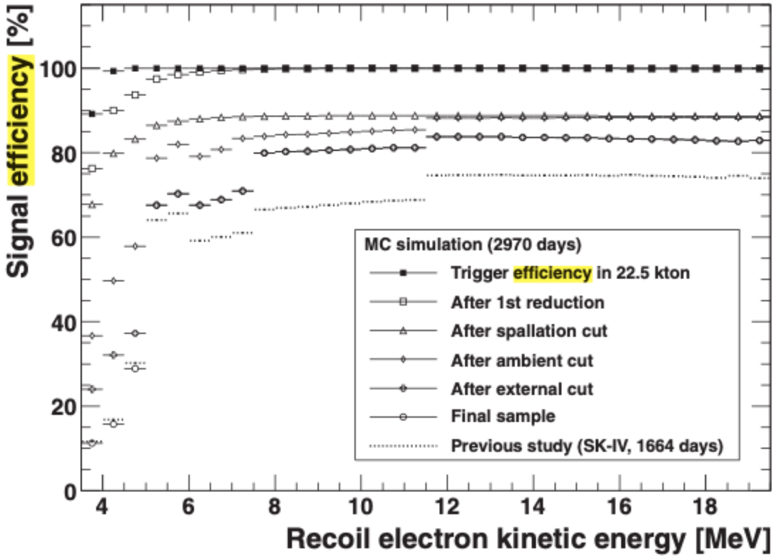
Effect on SK and HK: Improving resolution, results improve!

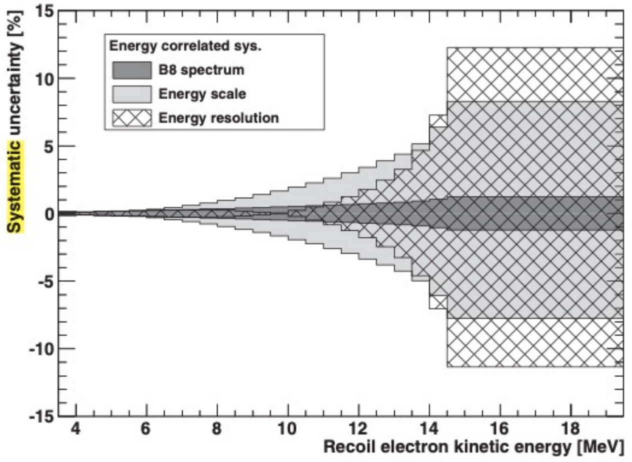
Third ingredient: signal efficiency, energy resolution and systematics

For solar neutrinos, we need to understand the detector response to low energy neutrinos. Physics results are ***very dependent*** on the energy resolution and on the number of events.

Example: SK-IV (2008-2018)







Solar neutrino measurements using the full data period of Super-Kamiokande-IV, 2312.12907

Expected number of events

First of all, given the energy threshold, we can see only B8 neutrinos (and hopefully some hep neutrinos, see later).

-> Rough estimation: HK claims 130 nu-e scattering events per day for 187 kt detector.

[**Solar neutrino physics at Hyper-Kamiokande**, *PoS* ICRC2019 (2020) 1037
Hyper-Kamiokande Design Report, 1805.04163]

In our case, for two tanks of 270kt, we might expect **370 evts per day**

HUGE statistic for a solar neutrino experiment!

Expected number of events

Let’s do a quick calculation on why we expect such a number.

Cross section: $\mathbf{10^{-43}}\boldsymbol{cm^2}$

Total flux of B8 neutrinos: $\mathbf{5\times10^{6}}\boldsymbol{cm^{-2}s^{-1}}$

Number of targets (electrons): $\mathbf{10^{35}}$ [roughly $\mathbf{10^{23}}$ in one gram of water]

$$N_{evts} = \sigma\ \phi\ n = 10^{-2}\ \ per\ second$$

Other cuts to apply:

1) Probability is roughly 1/3 (neglecting other flavors)
2) The kinematic cut only take 60-70% of the B8 spectrum
3) Efficiency 80%

+Energy resolution effects and <u>*latitude effects*</u> *(also important)*

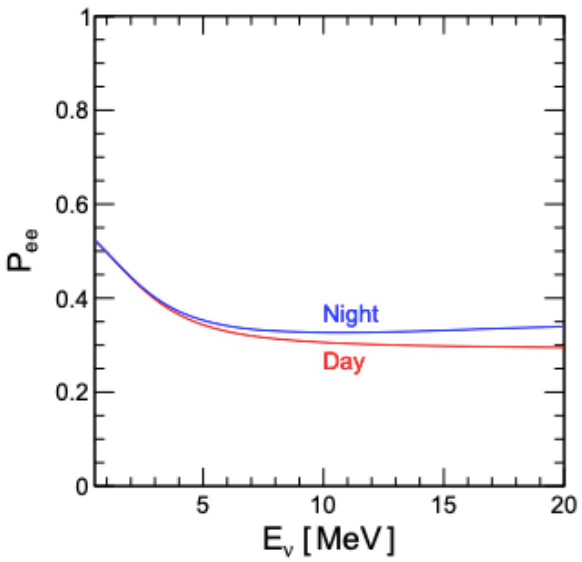
$$N_{evts} \sim 10^{-3}/s$$

$$\boxed{N_{evts} \sim 10^{2}/day}$$

What can we do with these neutrinos?

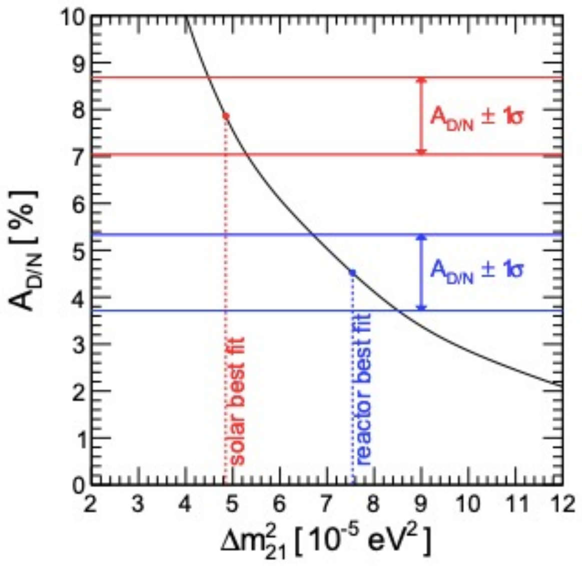
First observable: day-night asymmetry

Matter effects can regenerate electron neutrinos at night, when solar neutrinos pass through the Earth!



1808.08232

D-N asymmetry is sensitive to mass splitting!

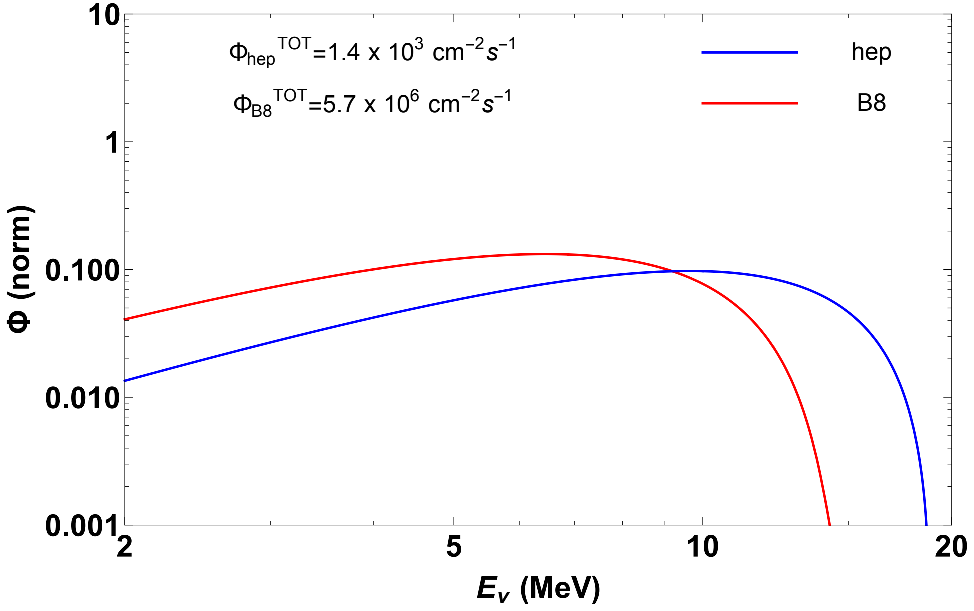


Well estabilished phenomenon, but not observed at 5sigma

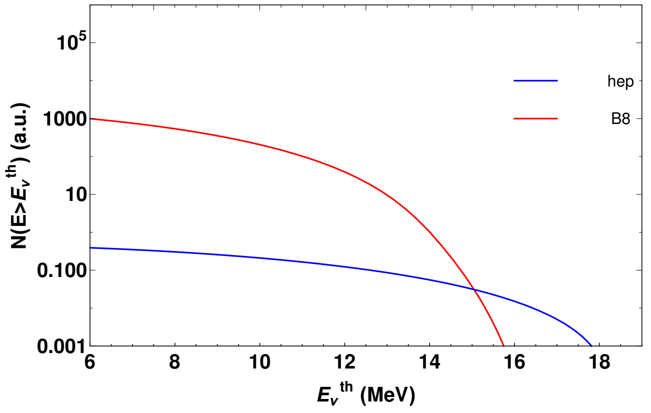
- KamLAND mass splitting (in tension with less precise solar measurements) might be tested with this measurement!
- HK will have a great sensitivity (1805.04163), we could do better!

Second observable: hep neutrinos

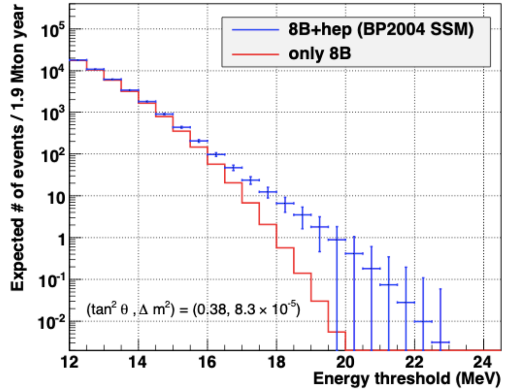
Hep neutrinos have never been observed since their spectrum almost completely overlap with the much bigger B8 spectrum. BUT: hep spectrum endpoint is at larger energies!



With good energy resolution, one can count how many events are above a certain threshold!



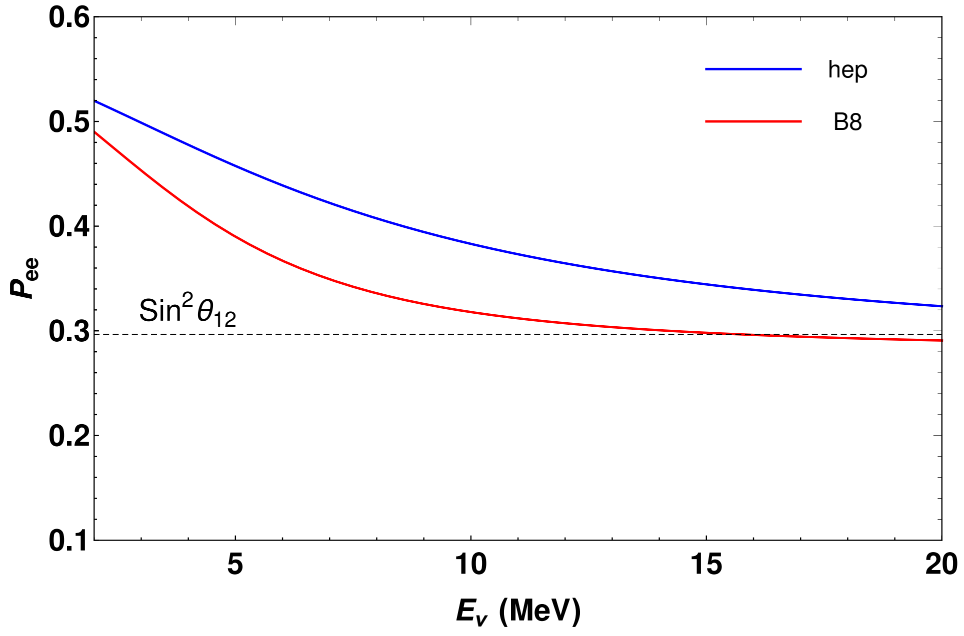
If we collect enough statistic above 16 MeV, we can distinguish the two fluxes!



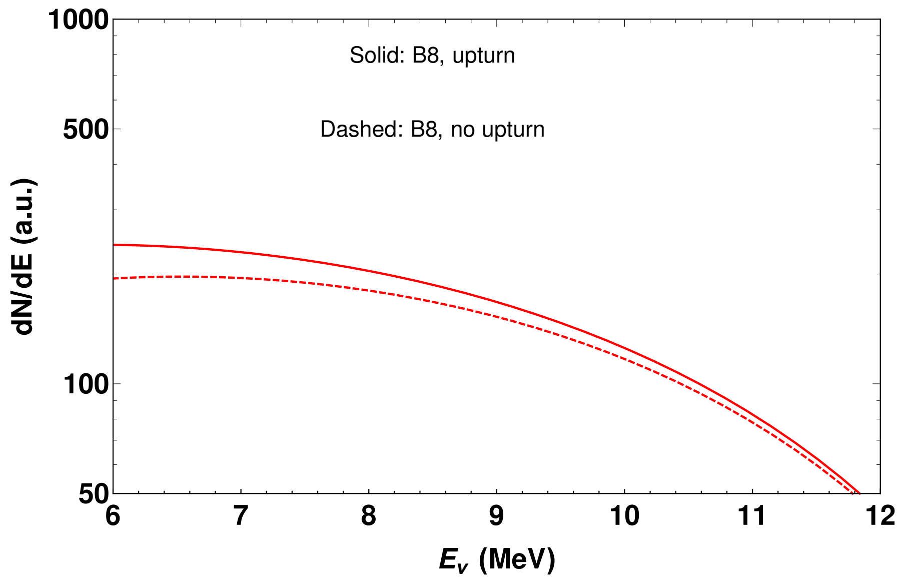
1805.04163 for HK

Third observable: B8 spectrum upturn

Below 10 MeV the probability for B8 neutrino is no longer full MSW dominated. SNO has measured the spectrum but not the upturn with a good statistical significance!

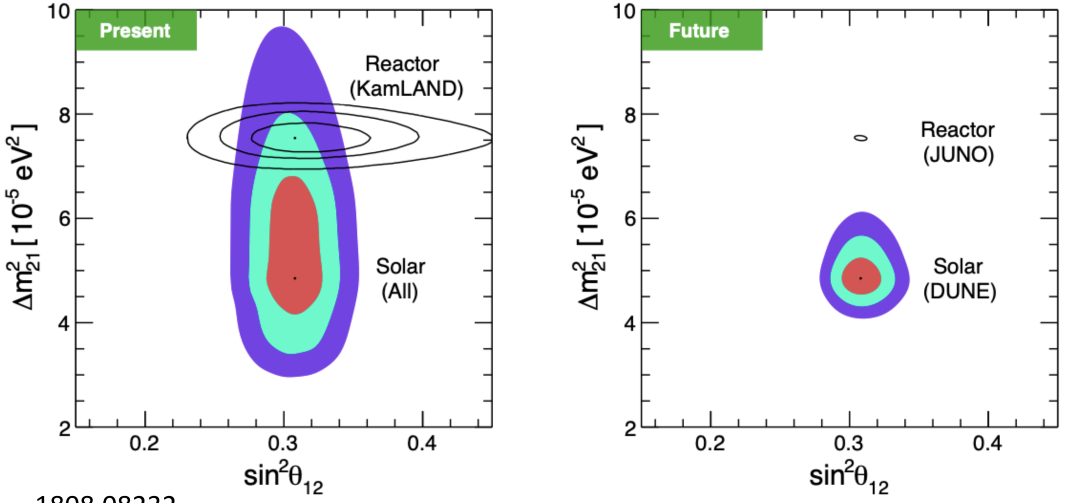


With a good statistic we can distinguish the presence of the upturn



Others: th12 measurement and BSM

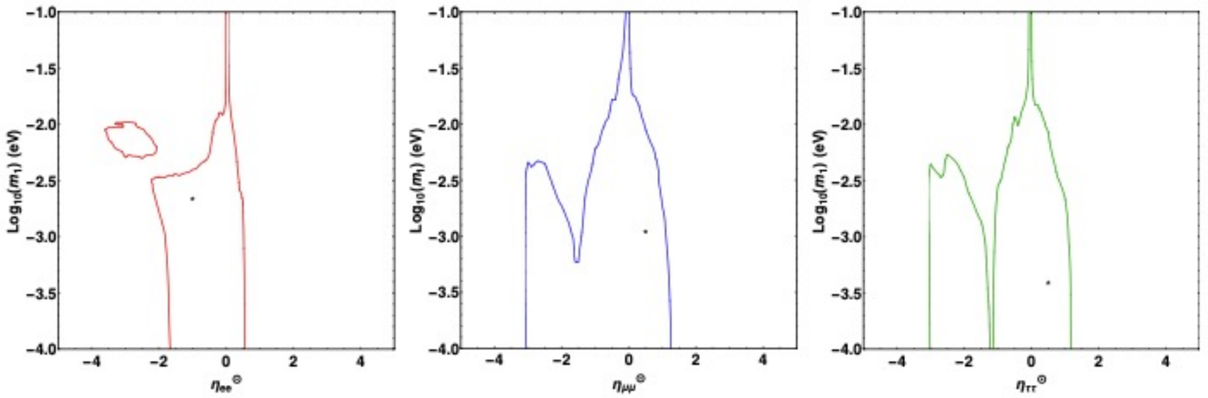
After the flux measurement by other experiments, one can measure the depletion of the flux and constraint the solar mixing angle.



1808.08232

DUNE example, but with no tension JUNO overperform solar experiments

Matter-enhanced BSM effects can be studied with solar neutrinos!



Example: my today's paper on scalar NSI with solar data from Borexino and SNO 2409.15411

Conclusions

- Solar neutrinos are extremely interesting from the point of view of neutrino oscillation and to study the Sun composition

- WC detectors can observe the high energy tail of the solar neutrino spectrum, our huge detector could play a leading role!

- We need to understand the detector response to the low energy neutrino electron elastic scattering events

- Hep neutrinos, B8 spectrum upturn and day-night asymmetry could be discovered