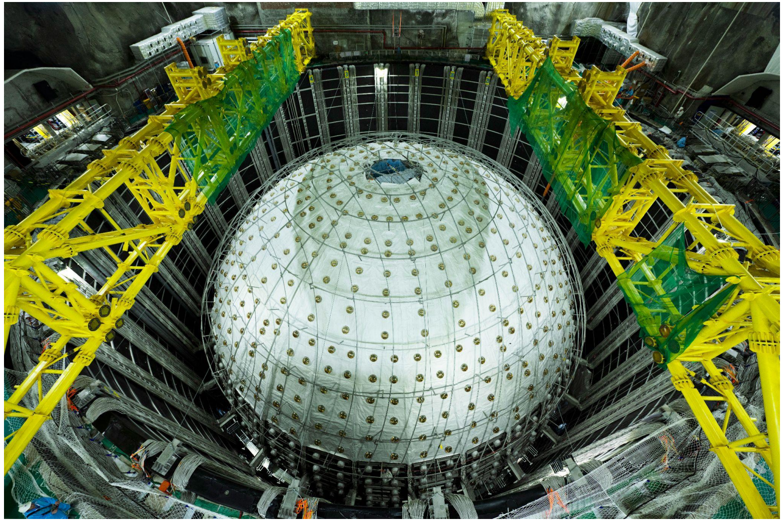
Physics potential of solar neutrino detection with JUNO



Claudio Coletta

on behalf of the JUNO collaboration

September 4th, 2025

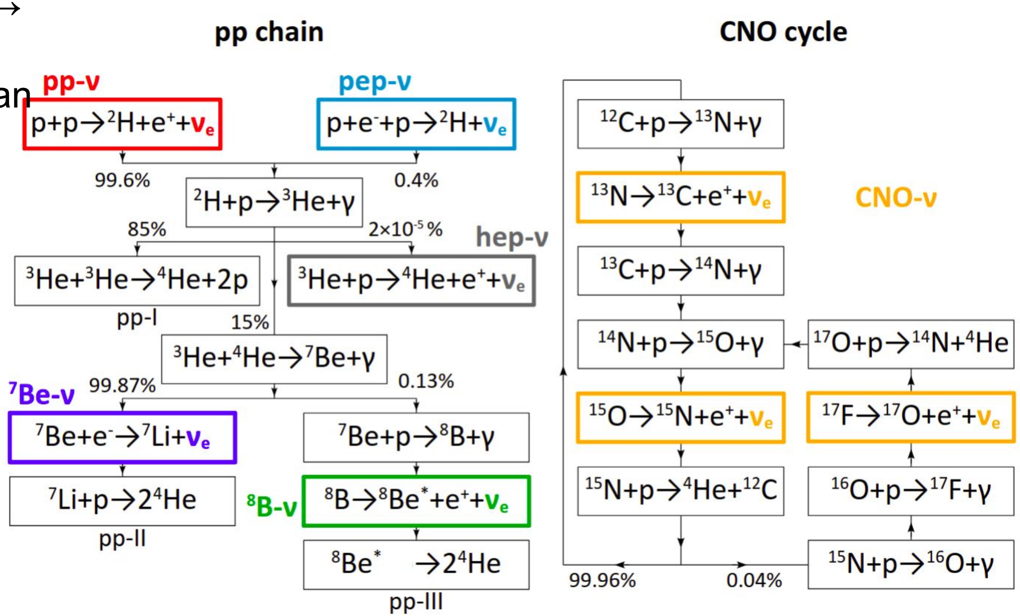
NuFACT 2025

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Milano Bicocca

Solar neutrinos

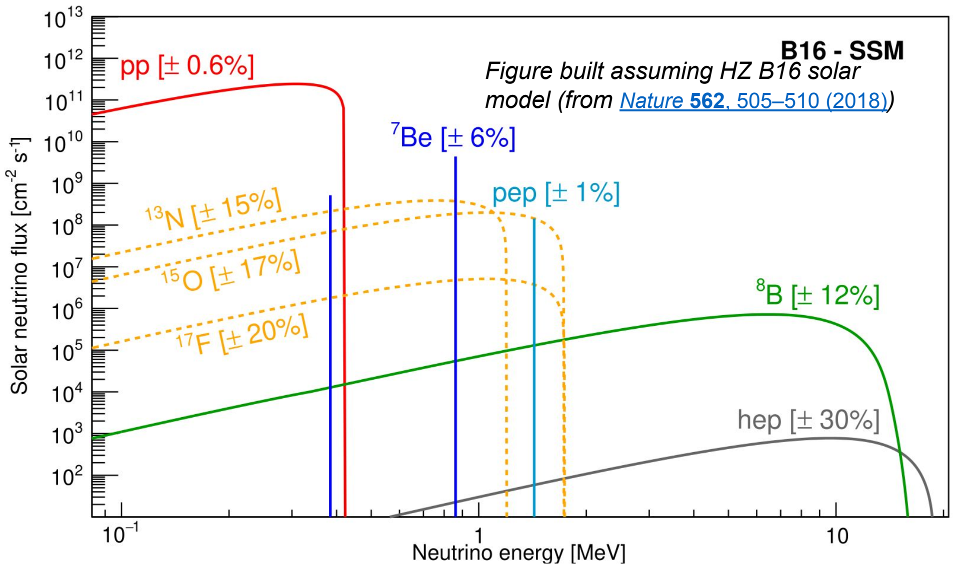
- Products of β^+ decays or e^- captures happening during solar fusion processes → all ν_e **at production**
  - depending on the interaction, they can have a **monochromatic or a continuous spectrum**



*(from Nature **562**, 505–510 (2018))*

Solar neutrinos

- Products of β^+ decays or e^- captures happening during solar fusion processes → all ν_e **at production**
  - depending on the interaction, they can have a **monochromatic or a continuous spectrum**
- Energies **up to ≈ 20 MeV**
- Their flux depends on the **details of the solar model**
  - precise neutrino measurement can **help define the model**



The uncertainty on the solar model is an important limiting factor on solar neutrino measurements.
Better solar model → better measurements of oscillation parameters

Propagation of solar neutrinos

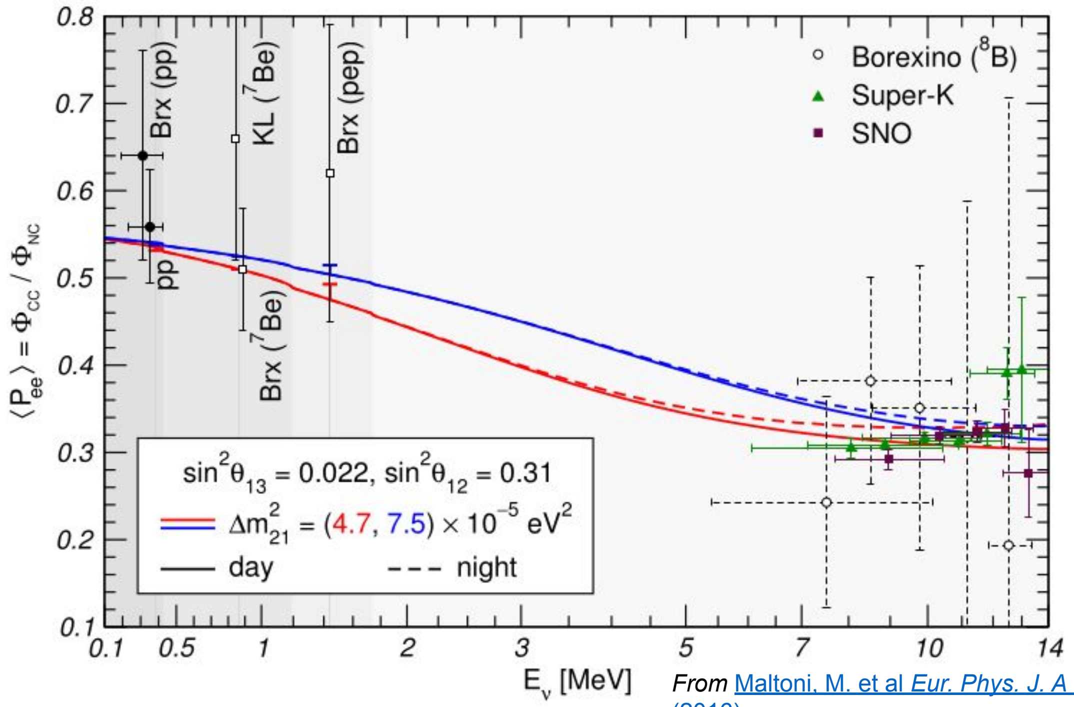
The standard LMA-MSW framework describes how solar neutrinos oscillate during their propagation

- **MSW effect describes how neutrinos interact with matter**

- Two different steps:
    - **Interaction with the Sun's matter**
    - **Interaction with Earth's matter**
        - **only during night**

Propagation of solar neutrinos

The standard LMA-MSW framework describes how solar neutrinos oscillate during their propagation



From Maltoni, M. et al *Eur. Phys. J. A* **52**, 87 (2016)

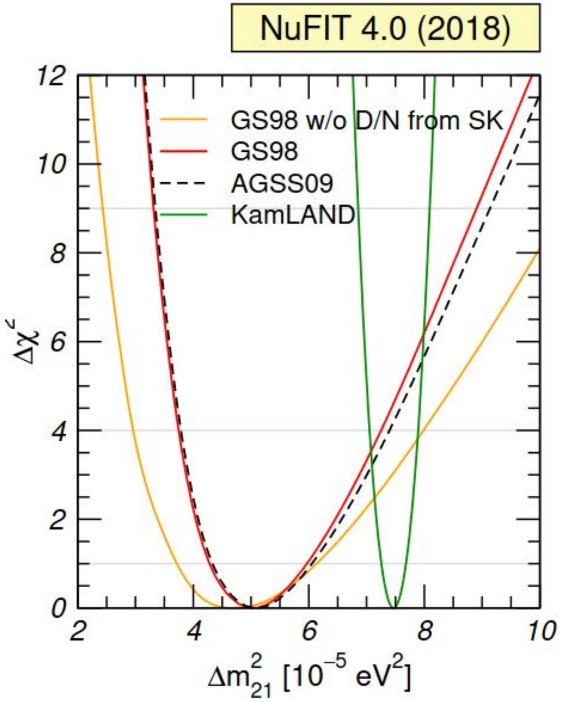
P_{ee} survival probability of solar neutrinos is impacted by:

- **solar parameters Δm^2_{21} and θ_{21}**
- **MSW in the Sun** (see drop after 2 MeV)
- **MSW in the Earth** (day-night asymmetry)

Example of the predicted ν_e survival probability assuming two different Δm^2_{21} values

Solar oscillation parameters

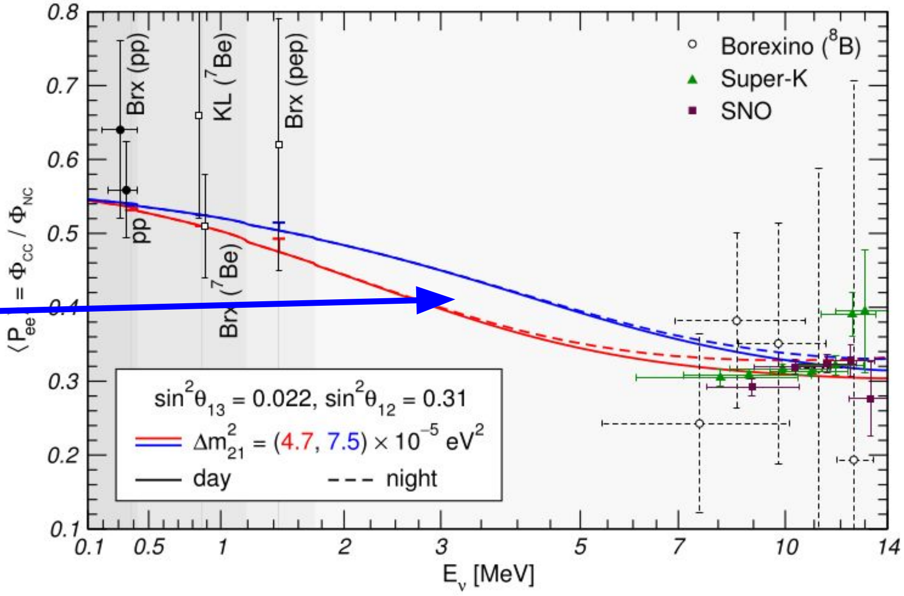
There has been some tension between **solar neutrino measurements** (SNO, Super-K and Borexino) and **reactor experiments** (KamLAND)



Solar oscillation parameters

There has been some tension between solar neutrino measurements (SNO, Super-K and Borexino) and reactor experiments (KamLAND)

- Related to the **absence of the expected upturn in survival probability**



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Solar oscillation parameters

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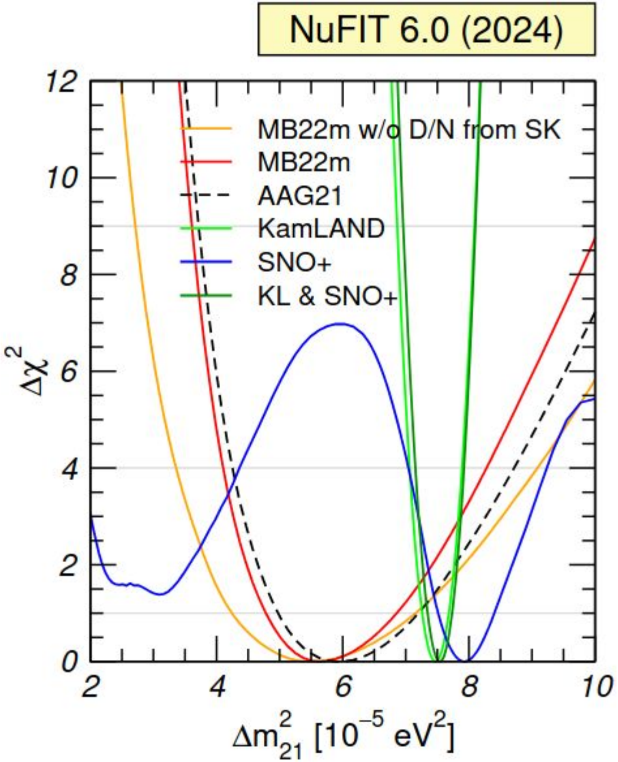
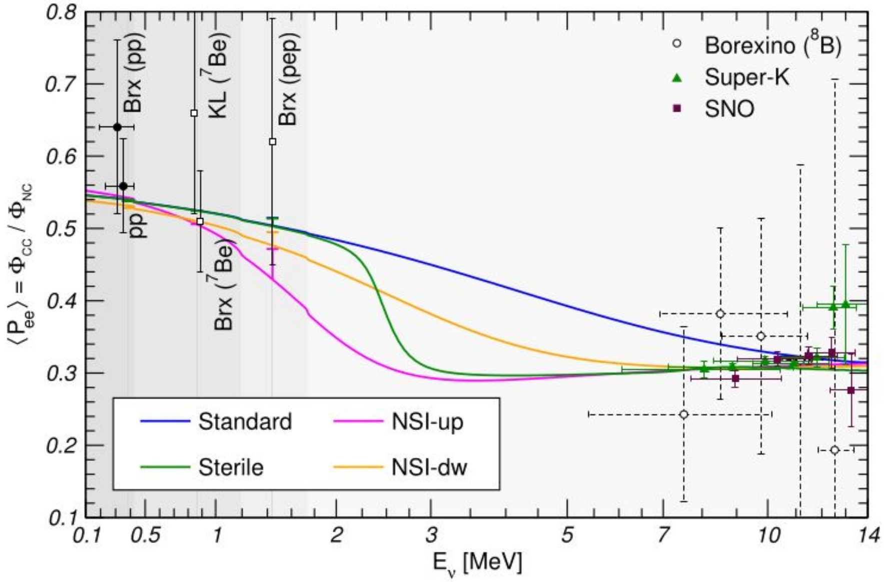


- Related to the absence of the expected upturn in survival probability
- Recent **results changed the picture:**
  - Now there is **≈ 1 σ tension**
  - Latest SNO+ results seems to be in better accord with KamLAND

Searching for Non-Standard Interactions

We can **search for Non-Standard Interaction with solar neutrinos** in different ways:

- Looking at the **survival probability of electron neutrinos P_{ee}**
    - **different interaction with solar matter** → changes in P_{ee} shape
    - provides an alternative explanation to the **absence of the upturn in the spectrum**
    - **the 2-5 MeV region is critical**

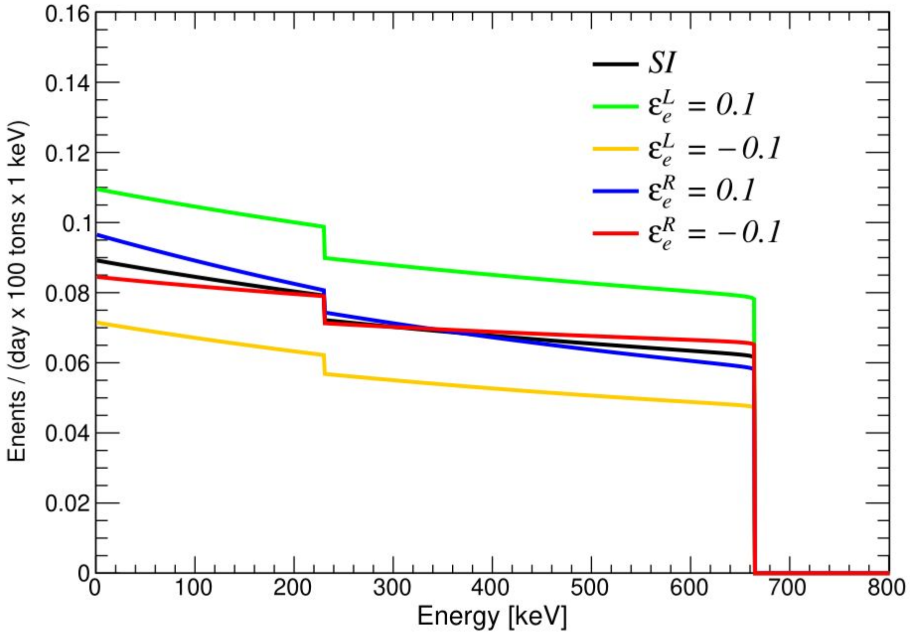


From Maltoni, M. et al *Eur. Phys. J. A* **52**, 87 (2016)

Searching for Non-Standard Interactions

We can **search for Non-Standard Interaction (NSI) with solar neutrinos** in different ways:

- Looking at the **survival probability of electron neutrinos P_{ee}**
  - **different interaction with solar matter** → changes in P_{ee} shape
  - provides an alternative explanation to the **absence of the upturn in the spectrum**
  - **the 2-5 MeV region is critical**
- Looking at **ν - e^- elastic scattering**
  - Non-Standard Interactions cause **distortions in the scattered electron spectrum**



Distortion of the recoiled electron spectrum of ^{7}Be neutrinos in the presence of NSI (from The Borexino collaboration., J. High Energ. Phys. **2020**, 38 (2020))

Solar neutrinos with JUNO

JUNO is the first multi-kton liquid scintillator detector ever built

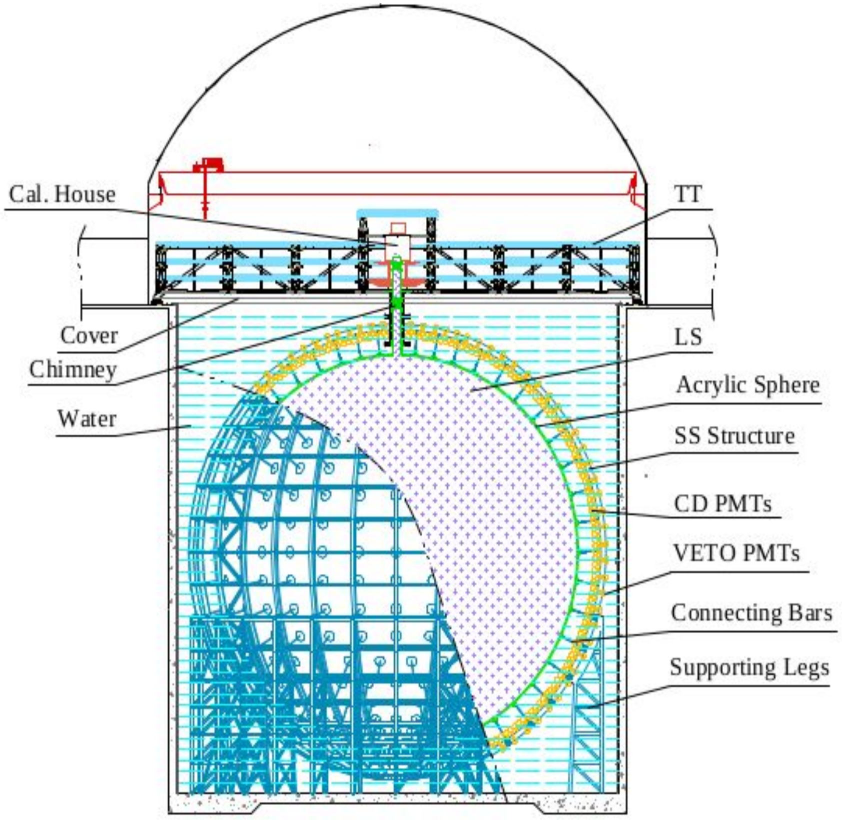
- **<u>Now starting the first data taking</u>**
- Main goal: determination of **Neutrino Mass Ordering (NMO)** via reactor neutrino
  - improve the precision on neutrino oscillation parameters
  - **Δm^2_{21} with uncertainty < 1%** after 1 year of data

Advantages for solar neutrino detection:

- huge mass → **high statistics**
- scintillating detector → **low energy threshold**

Good radiopurity will be a key factor

- **preliminary commissioning results are encouraging**



Detecting solar neutrinos: elastic scattering

The main interaction channel exploited by JUNO to detect solar neutrino is **ν - e^- elastic scattering (ES)**:

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad x = e, \mu, \tau,$$

- **sensitive to all three flavors**, but with a reduced cross section with μ and τ flavors.
  - cannot separate between flavors → the **solar model is a source of uncertainty**

- Because of ES, **all solar neutrino species produce a continuous spectrum in JUNO**
  - **signal similar to a β decay → natural radioactivity is a source of background**

- There are three main sources of backgrounds:
  - **external radioactivity (0-5 MeV)** → can be avoided by applying fiducial volume cuts
  - **cosmogenic radioactivity (1-20 MeV)** → radioisotopes generated by the interaction with cosmic muons → most of it can be eliminated **via muon veto**
  - **internal radioactivity (0-5 MeV)** → contamination of radioisotopes inside the scintillator
    - as it is uncertain, we made the analysis using four different scenarios

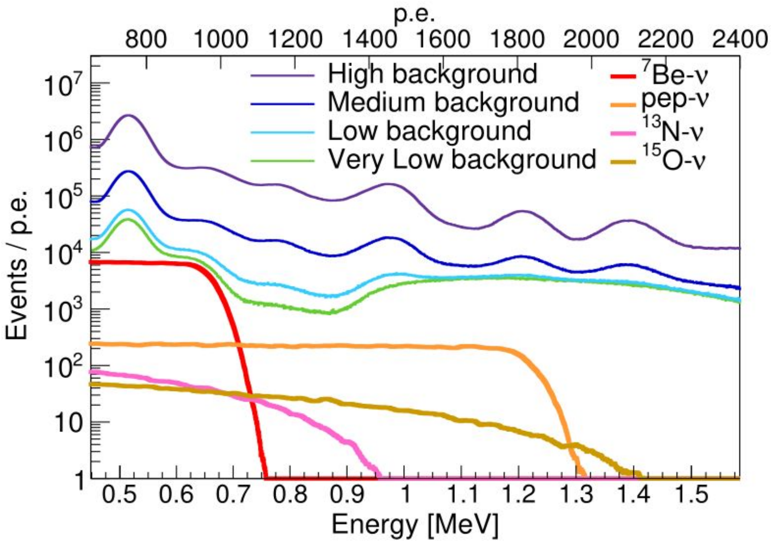
Internal radioactivity in JUNO

The most important radioisotopes for internal radioactivity are the ones coming from **the ^{238}U and ^{232}Th decay chains**

- they are composed by **several isotopes that cover the 0-5 MeV energy range**

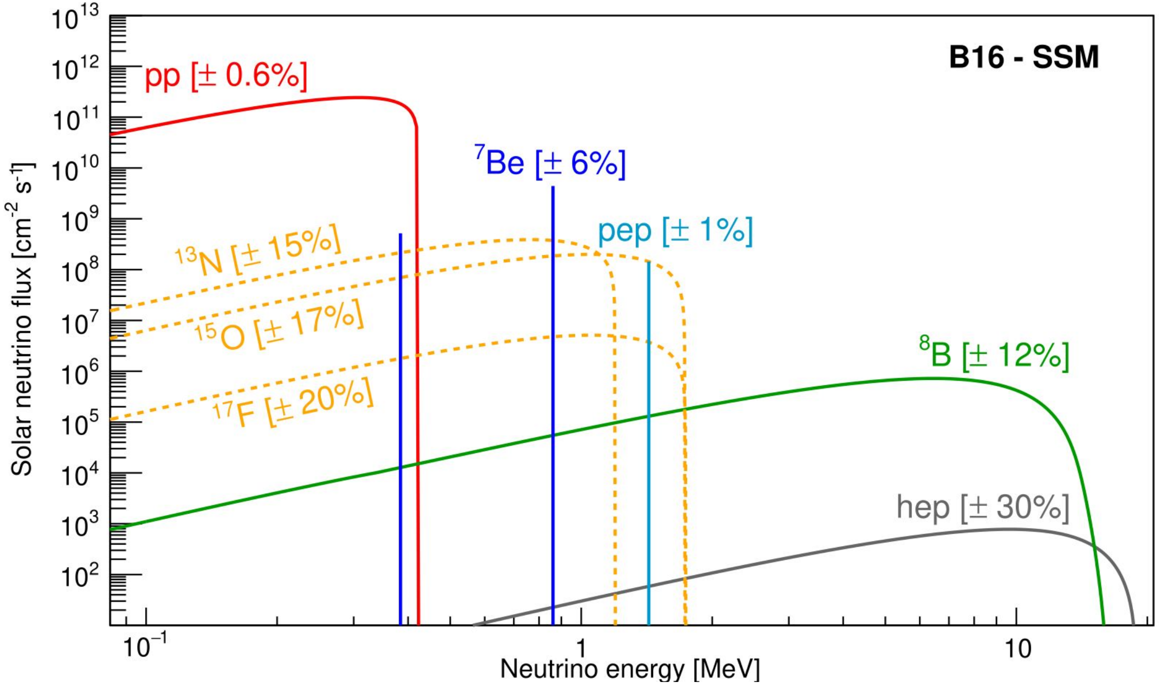
The four different radiopurity scenarios are built using different concentrations of U and Th

- **Very Low backgrounds** : 10^{-18} g/g of U and Th
- **Low backgrounds**: 10^{-17} g/g of U and Th
- **Medium backgrounds**: 10^{-16} g/g of U and Th
- **High backgrounds**: 10^{-15} g/g of U and Th
  - **minimum requirement for JUNO**
  - disfavored by commissioning data



Detecting solar neutrinos: energy regions

Detection of solar neutrinos in different energy regions has different challenges, with different types of backgrounds



Detecting solar neutrinos: energy regions

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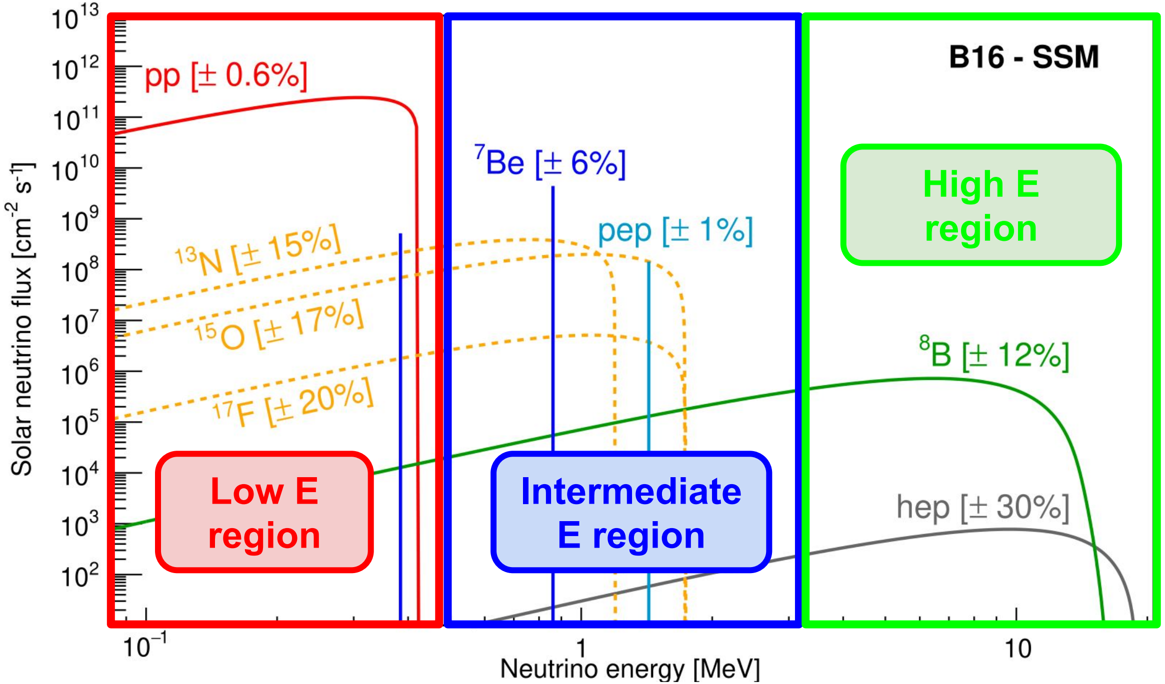
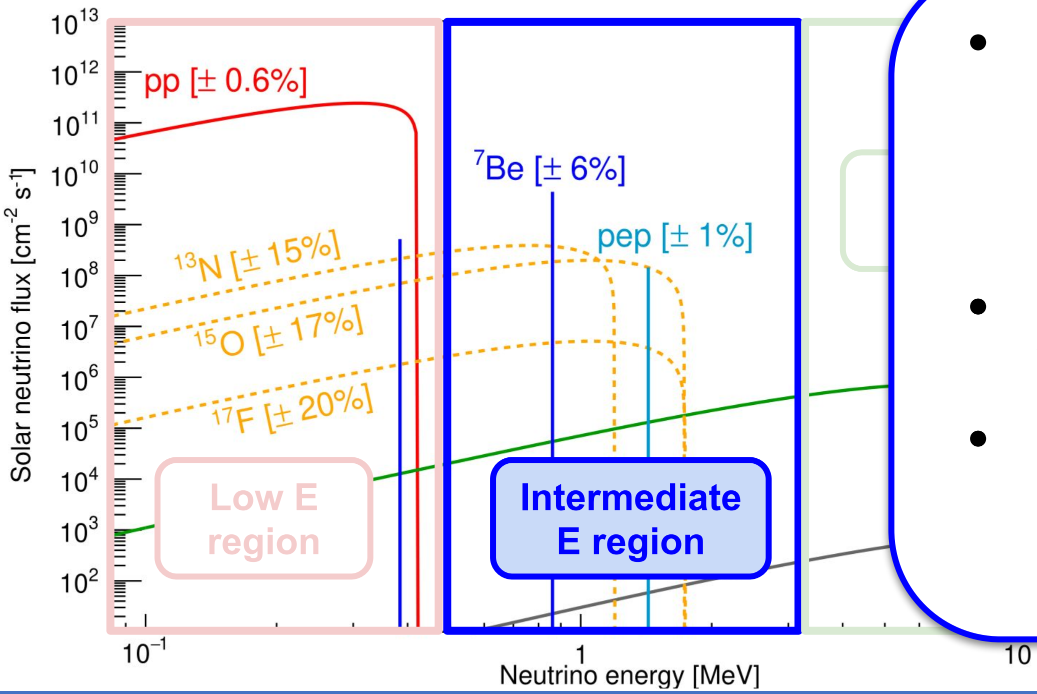


The intermediate energy region

The intermediate energy region is the region between (400-1600) keV

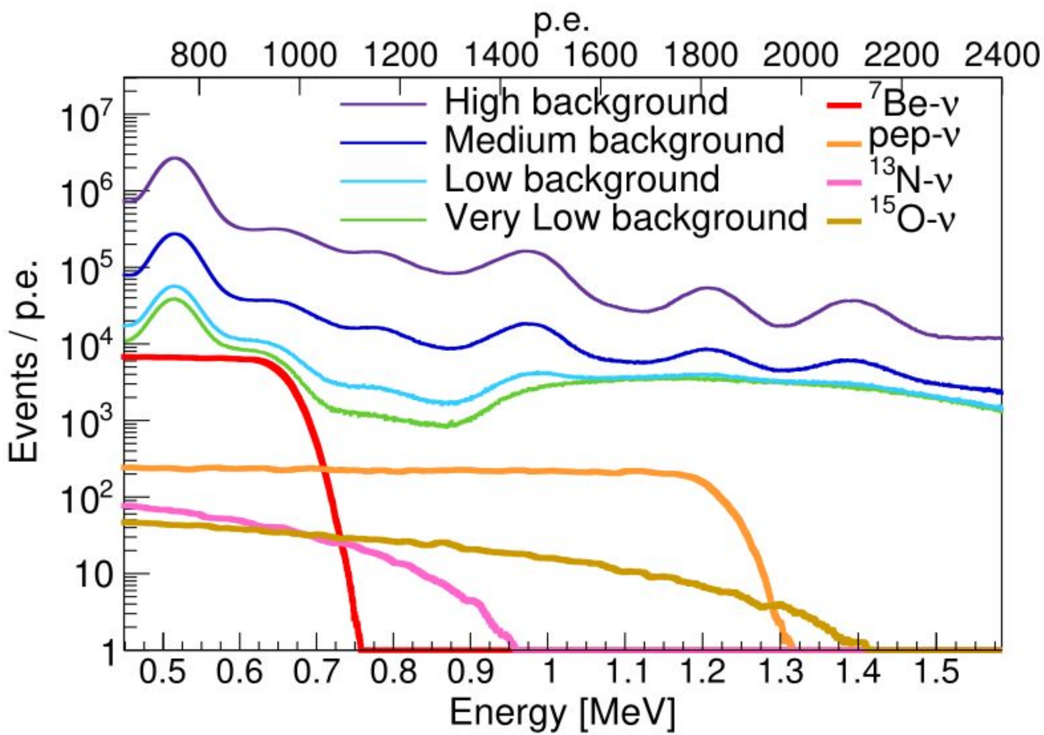


- This energy region is dominated by **^{7}Be, *pep* and CNO neutrinos**
  - relatively high flux (≈ 200 cpd/kton)
- Only interaction channel is **ν - e$^-$ elastic scattering**
- Main source of background is **internal radioactivity**
  - **external** only above ≈ 1 MeV

Sensitivity to ^{7}Be neutrinos

^{7}Be neutrinos are an **ideal candidate for JUNO analysis:**

- relatively high rate (≈ 140 cpd/kton)
- **distinct shoulder-like spectral shape**



Cosmogenic backgrounds subtracted via muon veto

Sensitivity to ^{7}Be neutrinos

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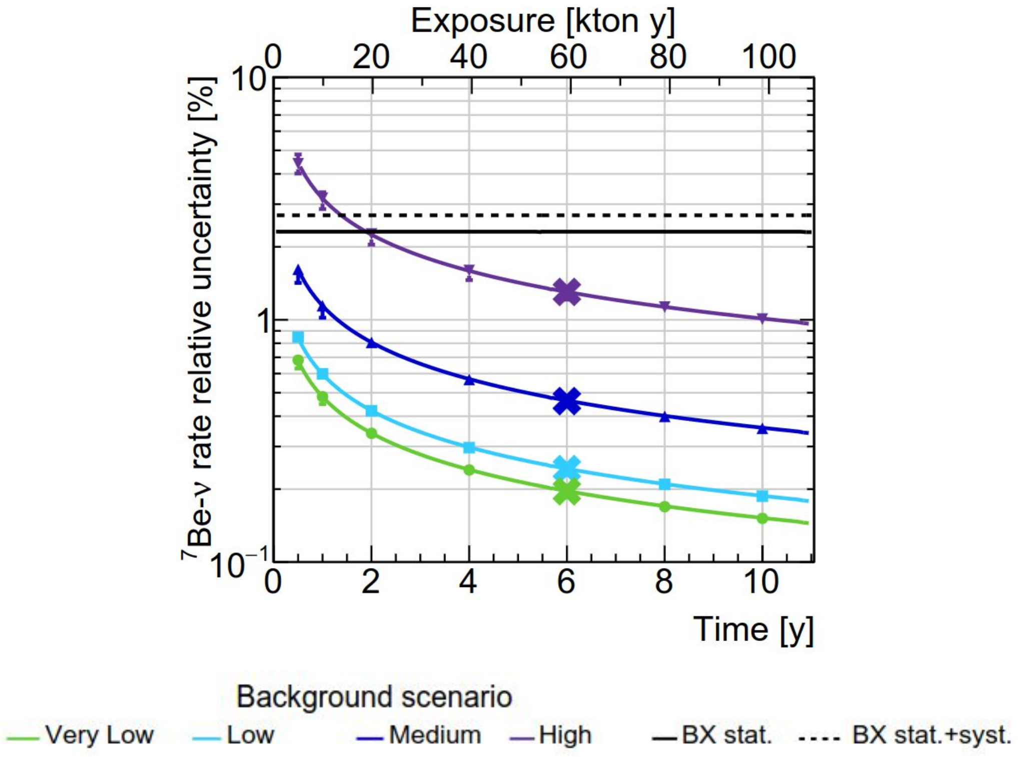
- **distinct shoulder-like spectral shape**

JUNO can improve Borexino results on ^{7}Be with two years of data even in the worse background scenario

This is important for multiple reasons

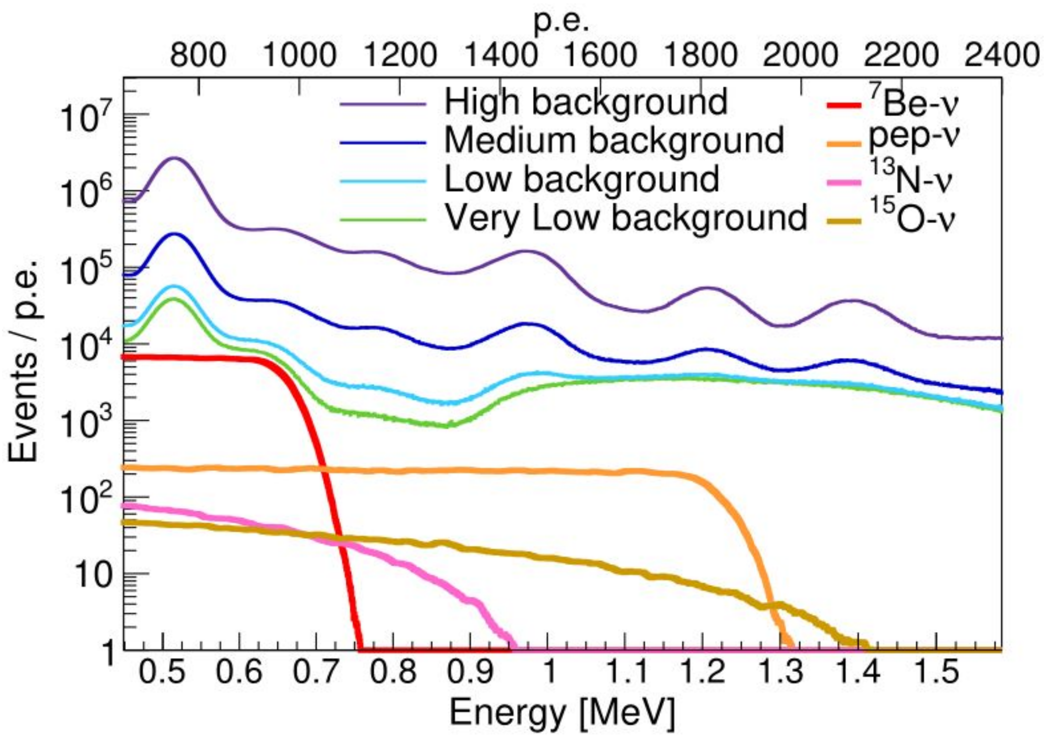
- better defined ^{7}Be flux → **help solar models**
- check for distortions in e^{-} spectrum → **search for NSI**



Sensitivity to *pep* and CNO

Detection of **CNO and *pep* neutrinos is more challenging:**

- **low event rates** (< 20 cpd/kton)
- CNO has no "shoulder"



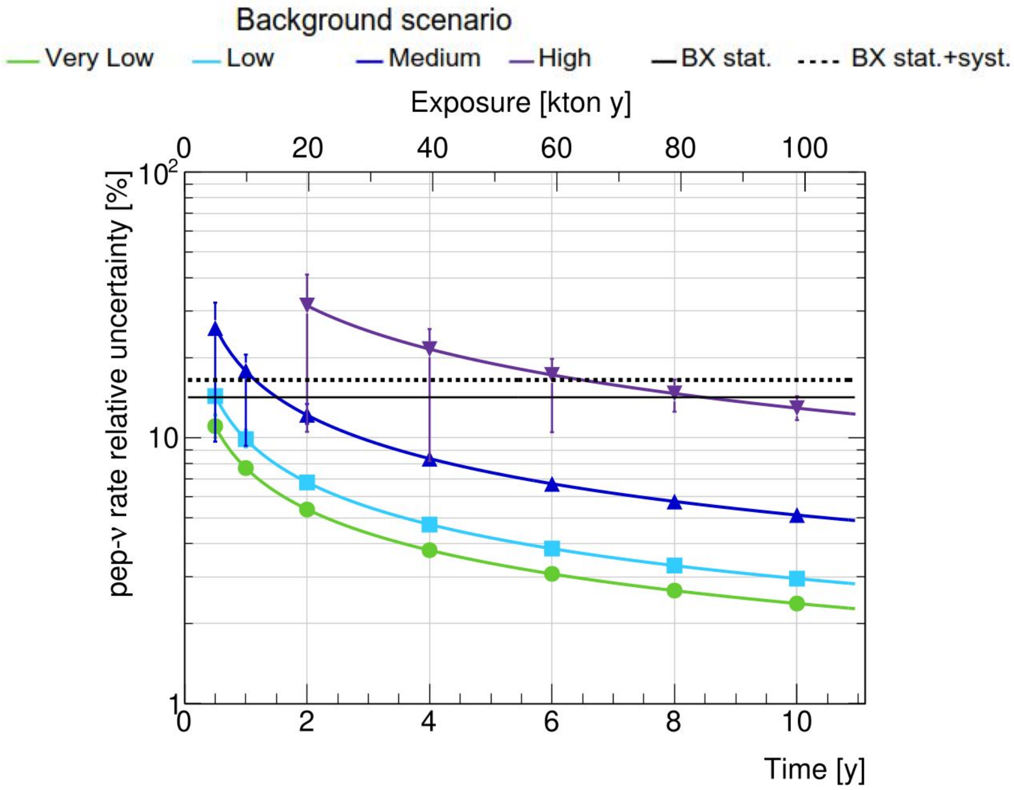
Cosmogenic backgrounds subtracted via TFC

Sensitivity to *pep* and CNO

Detection of **CNO and *pep* neutrinos is more challenging:**

- **low event rates** (< 20 cpd/kton)
- CNO has no “shoulder”

If we are not in the worse background scenario, **JUNO should be able to improve Borexino results on *pep***



Sensitivity to *pep* and CNO

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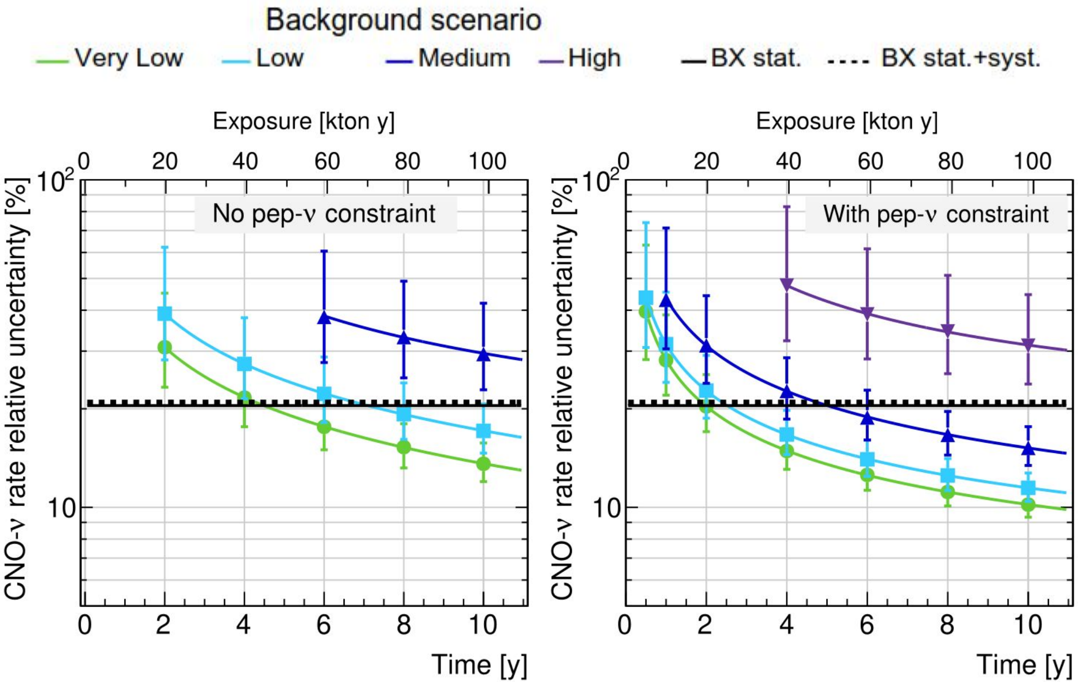
- **low event rates** (< 20 cpd/kton)
- CNO has no “shoulder”

If we are not in the worse background scenario, **JUNO should be able to improve Borexino results on *pep***

CNO to be measured independently from *pep* **needs Low backgrounds or better**

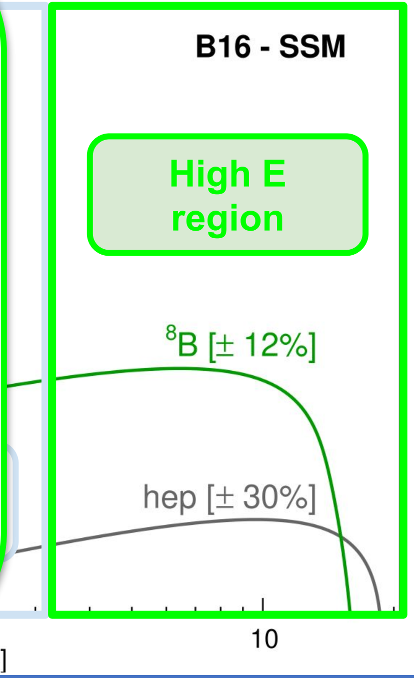
- this measurement is extremely **interesting for solar physics**



The high energy region

The high energy region is the region between (2-16) MeV

- This energy region is dominated by ^{8}**B neutrinos**
  - relatively low flux (≈ 4 cpd/kton for ES)
  - **≈ 10 yrs of data needed** to obtain significant results
- Three possible interaction channels
  - **Elastic Scattering** on e^-
  - **CC and NC interactions** with ^{13}C nuclei
- Main source of background are **cosmogenic backgrounds**
  - **internal** only until 5 MeV

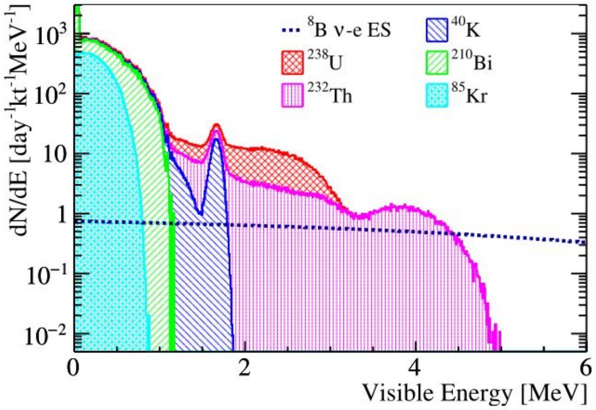


Elastic scattering with ^{8}B neutrinos

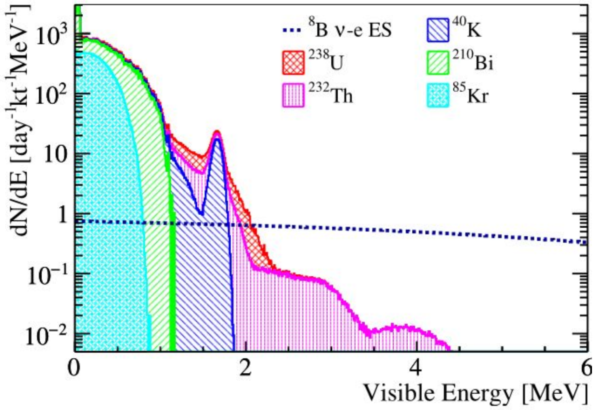
To set the lower limit for ^{8}B neutrino detection around 2 MeV, we have to **reduce background from ^{238}U and ^{232}Th decay chains** by detecting decay cascades

- to do this, the **background needs to be in the medium scenario** (10^{-16} g/g of U and Th) **or better**

Without bkg reduction



With bkg reduction



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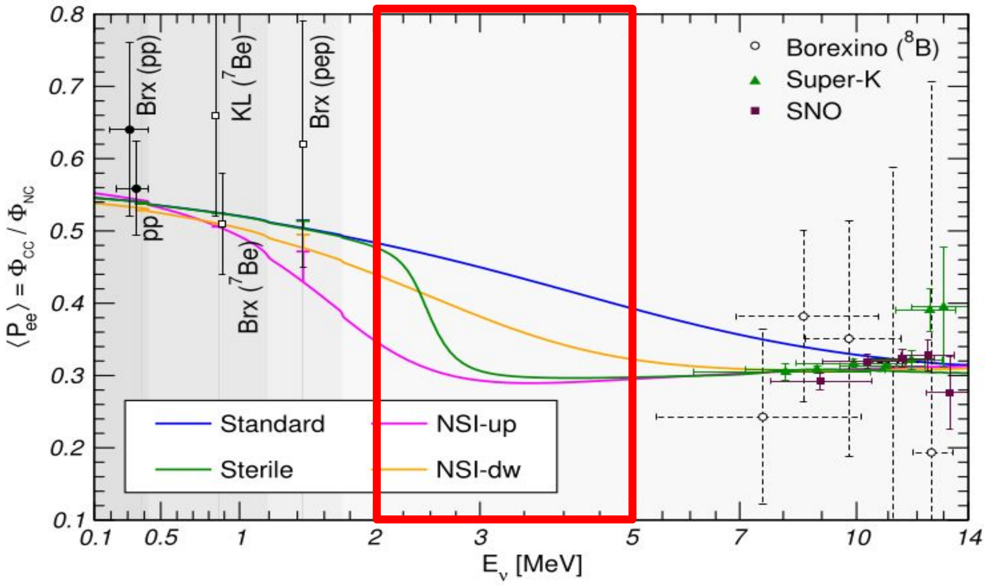


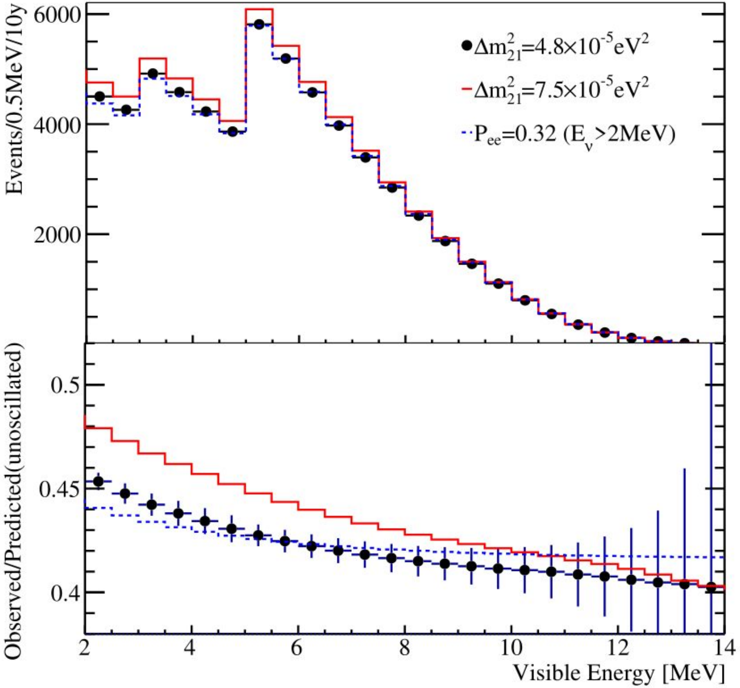
From Maltoni, M. et al *Eur. Phys. J. A* **52**, 87 (2016)

If the radiopurity is better than the high background scenario, **JUNO can make measurements in the critical 2-5 MeV range**

Elastic scattering with ^8B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

- We can measure the **upturn in the spectrum**



Elastic scattering with ^{8}B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

- We can measure the **upturn in the spectrum**

$\Delta\chi^2$	4.8×10^{-5} eV^2	7.5×10^{-5} eV^2
Stat. only	7.1	24.9
Stat. + ^{8}B flux error	6.8	24.2
Stat. + ^{8}B shape error	3.6	11.8
Stat. + energy scale error	4.7	15.5
Stat. + background error	3.6	14.0
Final	2.0	7.3

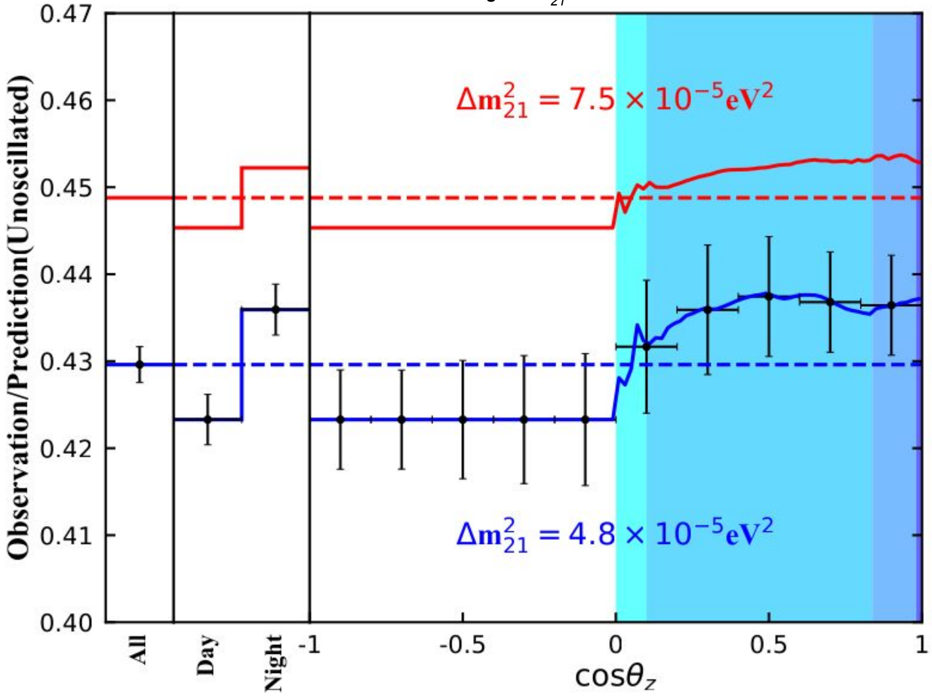
Rejection sensitivity for the absence of the upturn in P_{ee} at low energies assuming two different Δm^2_{21} values

Elastic scattering with ^8B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

- We can measure the **upturn in the spectrum**
- We can measure **day-night asymmetry with ≈ 1% uncertainty**

Monte Carlo simulation made assuming $\Delta m^2_{21} = 4.8 \times 10^{-5}$ eV^2



Elastic scattering with ^{8}B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

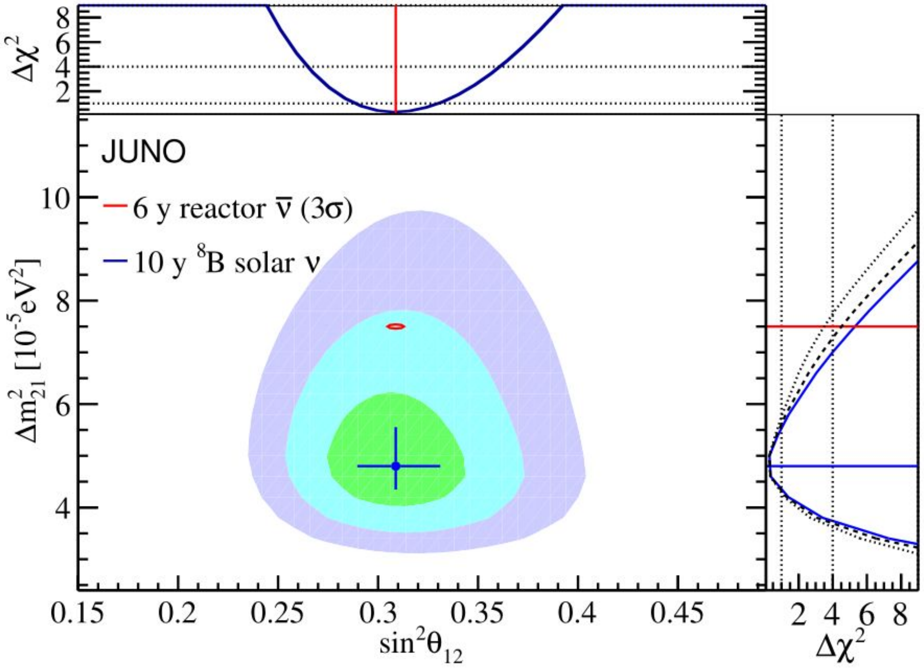
- We can measure the **upturn in the spectrum**

- We can measure **day-night asymmetry with ≈ 1% uncertainty**

Combining the observed spectrum with day-night asymmetry, **JUNO can measure Δm^2_{21} with solar neutrinos with ≈ 30% uncertainty**

- this can be combined with the **reactor neutrino measurement with the same experiment**

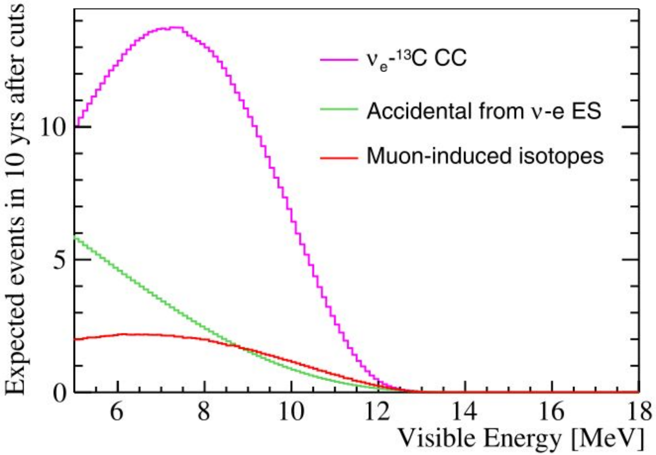
Monte Carlo simulation made assuming Δm^2_{21} = 4.8 x 10^{-5} eV^2 for solar and Δm^2_{21} = 7.5 x 10^{-5} eV^2 for reactor neutrinos

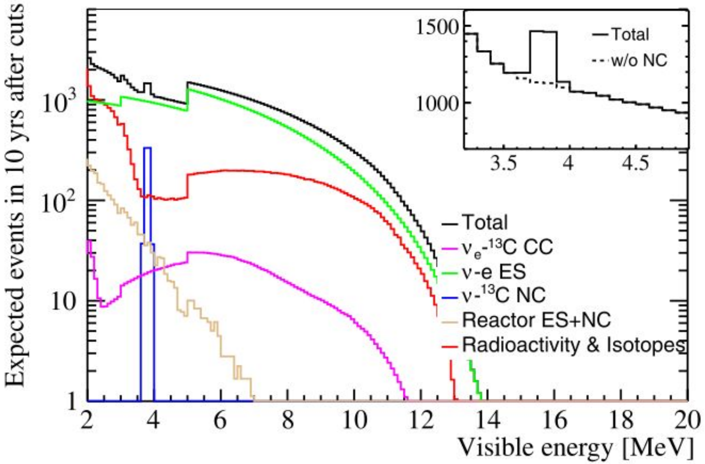


CC and NC interactions with ^{8}B neutrinos

Elastic scattering interactions with ^{8}B neutrinos have by far the largest cross-section, but **they are not the only interactions possible**

- We can also detect:
  - the **CC interaction** $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$ (½$^+$; ground)
    - produces an **e^- and a β^+ decay in a strict time coincidence** (≈ 400 events/yr)
  - the **NC interaction** $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C$ (3/2$^-$; 3.685 MeV)
    - produces a **3.685 MeV gamma** (≈ 300 events/yr)



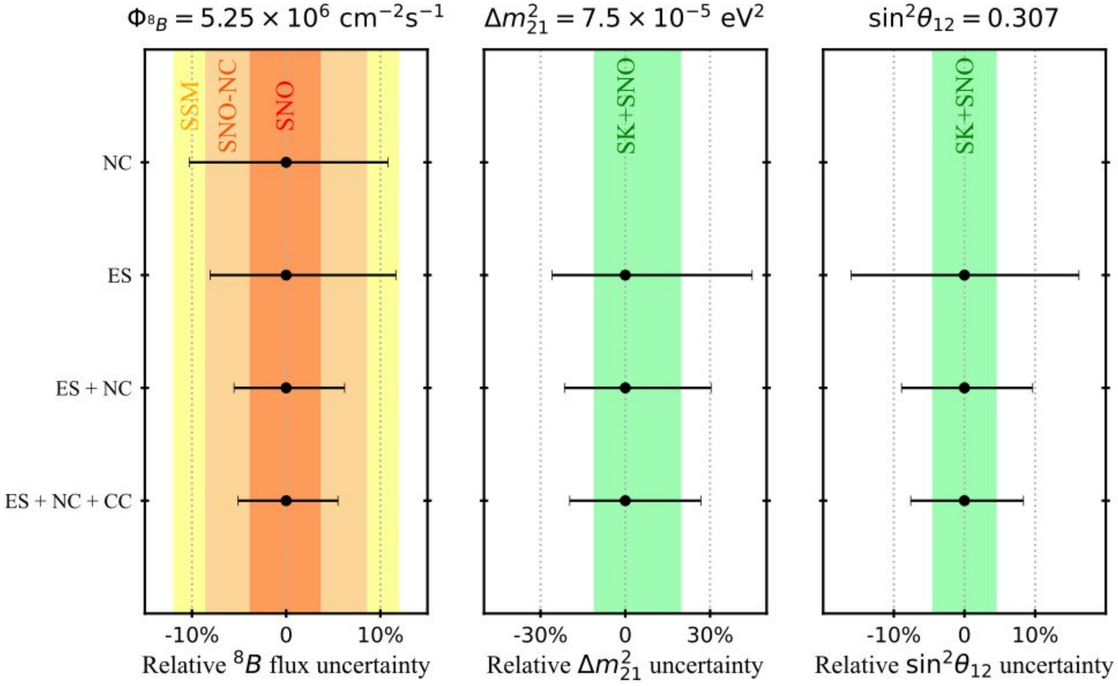


CC and NC interactions with ^{8}B neutrinos

CC and NC interaction channels allow to **make a measure independently from the solar model** and to enhance the precision of elastic scattering measurement

After 10 years of data taking JUNO will be able to:

- **measure the ^{8}B neutrino flux** with precision comparable to SNO (and better than the current solar model uncertainty)
- **Measure solar oscillation parameters** with precision comparable to SNO + Super-K combined fit



Conclusions

JUNO can scan most of the solar neutrino spectrum:

- **Intermediate energy region (400-1600 keV)**
    - it can perform measurement of the **^{7}Be spectrum with sub-percent precision,** improving the best results to date obtained by Borexino
        - this can put **more stringent limits on NSI**
    - if the radioactivity is good enough (≈ 10^{-17} g/g U and Th contamination), it can obtain **world-leading results also on pep and CNO neutrinos**
        - can be important to i**mprove current solar models**
- **High energy region (2-20 MeV)**
    - given a radioactivity lower than 10^{-16} g/g of U and Th, **JUNO can measure solar neutrinos in the critical 2-5 MeV region**
        - important to **investigate potential NSI or sterile neutrino theories**
    - using also CC and NC interactions to decouple from the Solar model, can obtain a **Δm^2_{21} measurement with ≈ 15% uncertainty**
        - precision similar to combined fit from SNO and Super-Kamiokande

- **We have just started data taking → first results are coming!**

BACKUP

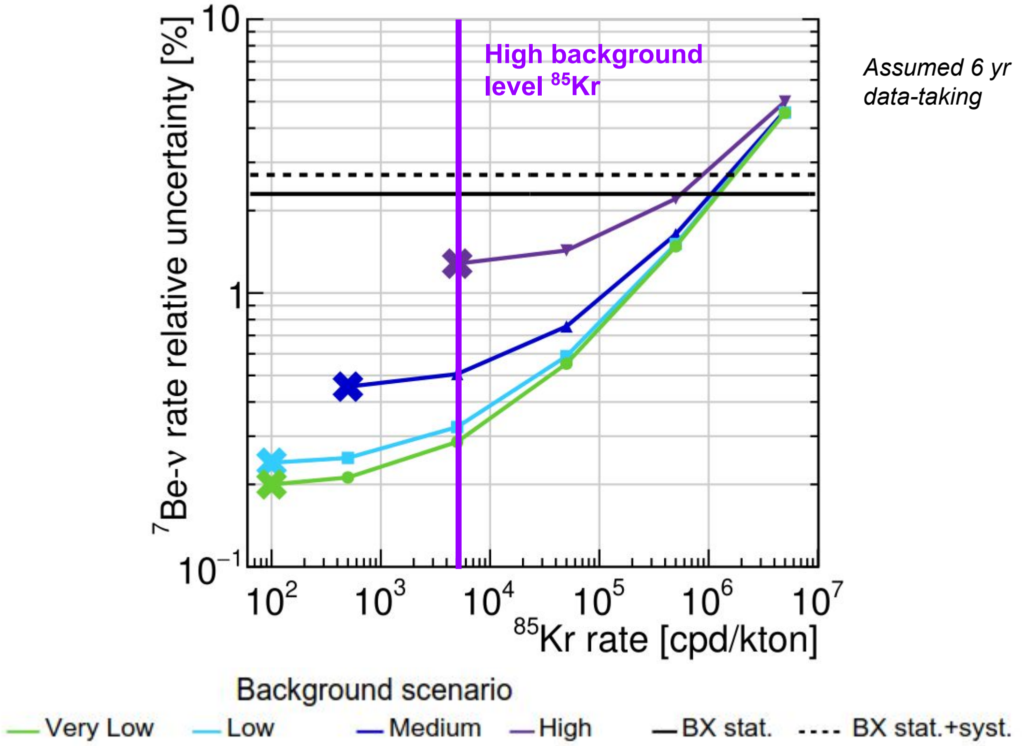
Sensitivity to ^{7}Be neutrinos

^{7}Be neutrinos are an **ideal candidate for JUNO analysis:**

- relatively high rate (≈ 140 cpd/kton)
- **distinct shoulder-like spectral shape**

JUNO can improve Borexino results on ^{7}Be with two years of data even in the worse background scenario

Assuming unexpectedly high ^{85}Kr, sensitivity can worsen, but should still remain better than Borexino



Assumed 6 yr data-taking

Propagation of solar neutrinos

The standard LMA-MSW framework describes how solar neutrinos oscillate during their propagation

- they are mainly influenced by **solar parameters Δm^2_{21} and θ_{21}**, other PMNS matrix elements are mostly negligible

- MSW effect in the Sun sets **the resonance condition**

$$V_e(n^{\text{res}}) = \cos 2\theta \frac{\Delta m^2}{2E} \qquad V_e = \sqrt{2} G_F n_e$$

causing the **strongest change of flavor in the eigenstates for E > 2 MeV** (given the number density of electrons in the Sun n_e)
  - this causes a decrease in ν_e survival probability P_{ee} at high energies

- MSW effect in the Earth causes a **day-night asymmetry** in the solar neutrino flux
  - its effect is **expected to be between (2-6)% for high-energy neutrinos**
  - negligible for low energy neutrinos

Elastic scattering with ^{8}B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

- We expect **≈ 2:1 signal to noise ratio**
  - using different cuts for different energy range to minimize external backgrounds

This would allow to:

- **measure the upturn in survival probability** after 2 MeV
  - sensitivity depends on the value of Δm^2_{21}
- the **day-night asymmetry**

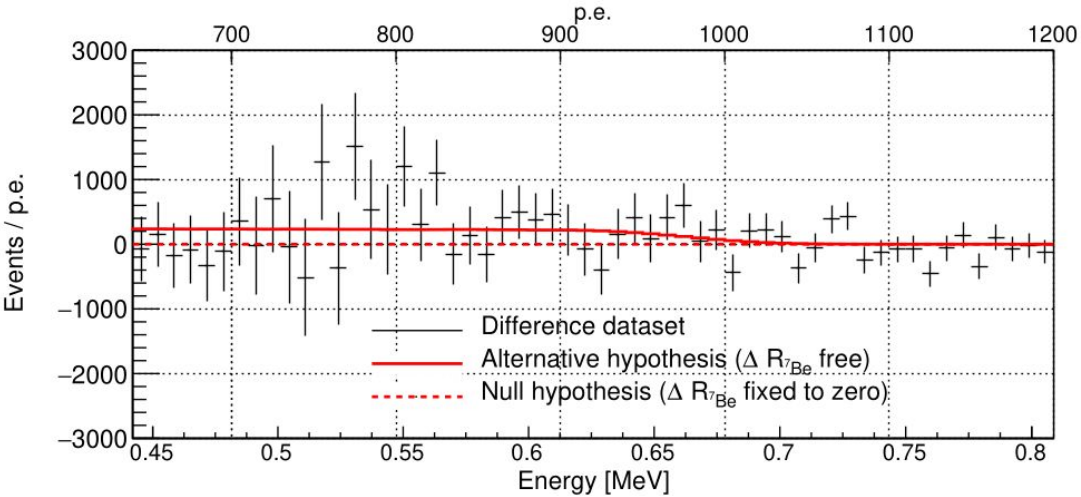
Monte Carlo simulation made assuming Δm^2_{21} = 4.8 x 10^{-5} eV^2

Energy	Exposure	Day	Night	A_{DN}
2~3 MeV	41 kt·y	4334	4428	(-2.1 ±3.2)%
3~5 MeV	51 kt·y	8686	8906	(-2.5 ±1.7)%
5~16 MeV	84 kt·y	17058	17644	(-3.4 ±1.2)%
2~16 MeV	N/A	30078	30977	(-2.9±0.9)%

Sensitivity to day-night asymmetries

Standard LMA-MSW theory expects a **small asymmetry between day and night in this energy region (400-1600 keV)**

We can measure it using both **Lomb-Scargle method** and **statistical subtraction** between day and night data



Difference dataset obtained via Monte-Carlo injecting a 0.6% difference between day and night solar neutrino rate

Limits on NSI from solar neutrinos

It is possible to constrain Non-Standard Interactions (NSI) parameters also **by looking at the ν - e$^-$ elastic scattering**

Given the ν-e$^-$ elastic scattering cross-section:

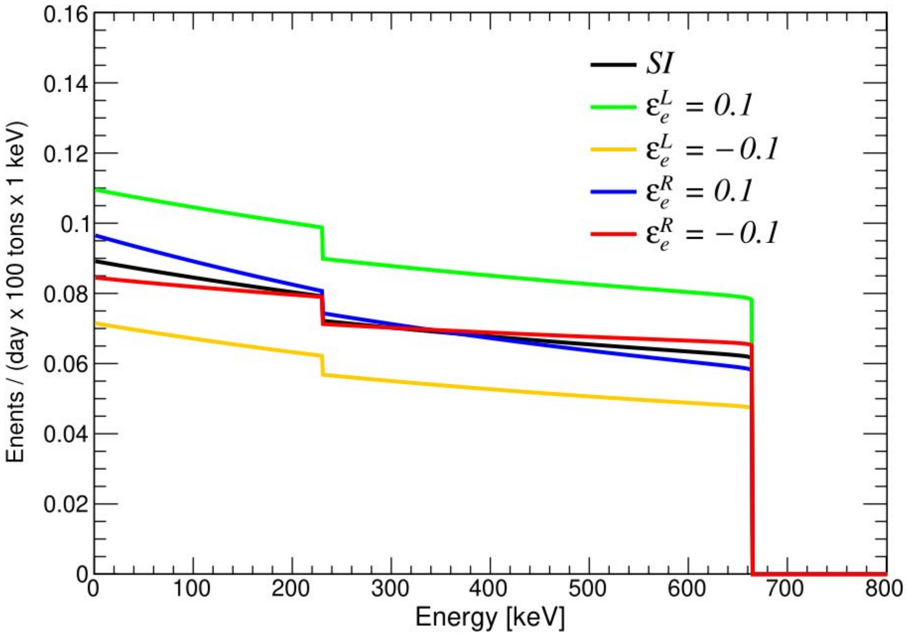
$$\frac{d\sigma_\alpha(E,T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_{\alpha L}^2 + g_{\alpha R}^2 \left(1 - \frac{T}{E}\right)^2 - g_{\alpha L} g_{\alpha R} \frac{m_e T}{E^2} \right]$$

Generic NSI can be modeled by adding the parameters ε_α^L and ε_α^R

$$g_{\alpha R} \rightarrow \tilde{g}_{\alpha R} = g_{\alpha R} + \varepsilon_\alpha^R ,$$
$$g_{\alpha L} \rightarrow \tilde{g}_{\alpha L} = g_{\alpha L} + \varepsilon_\alpha^L .$$

$$\alpha = e, \mu, \tau$$

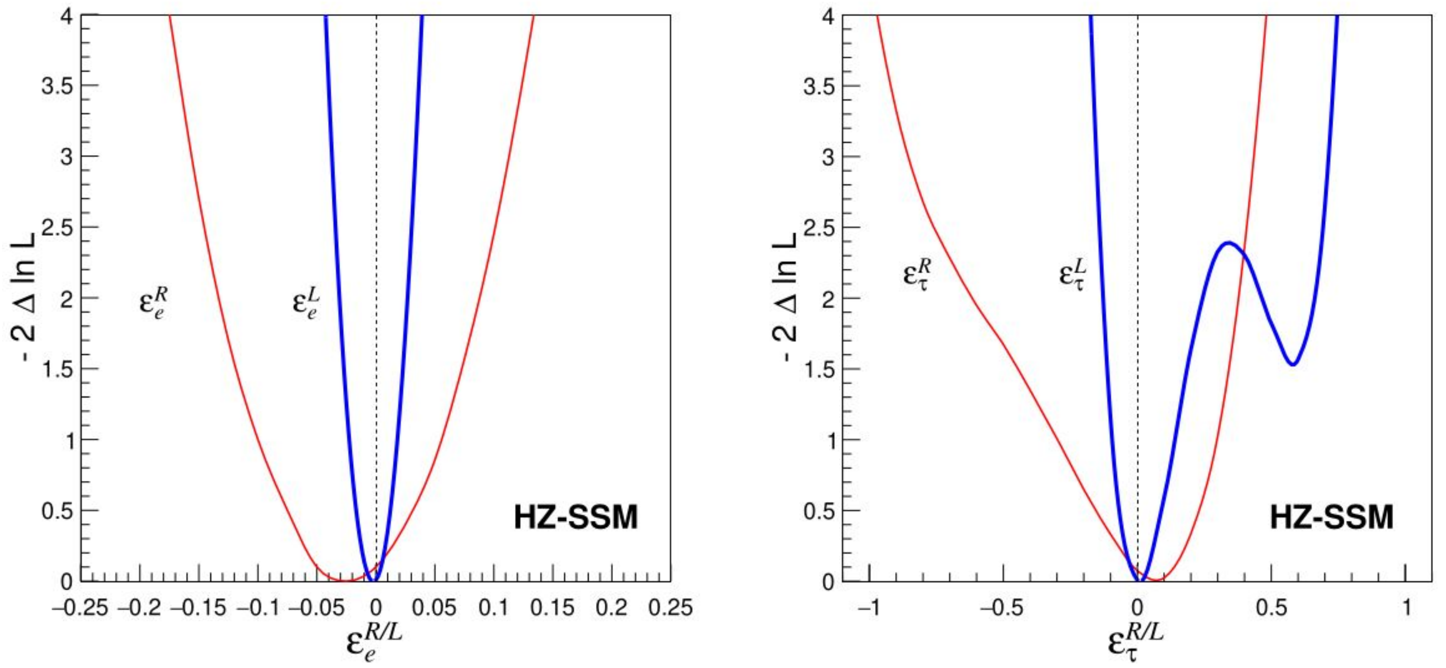
Causing a distortion in the recoiled electron spectrum



Distortion of the recoiled electron spectrum of ^{7}Be neutrinos in the presence of NSI (from The Borexino collaboration., *J. High Energ. Phys.* **2020**, 38 (2020)*)*

Limits on NSI from solar neutrinos

Current results are compatible with the absence of NSI, but **ε_τ has very high uncertainty.** Precision measurement of solar neutrinos can give us a clearer picture

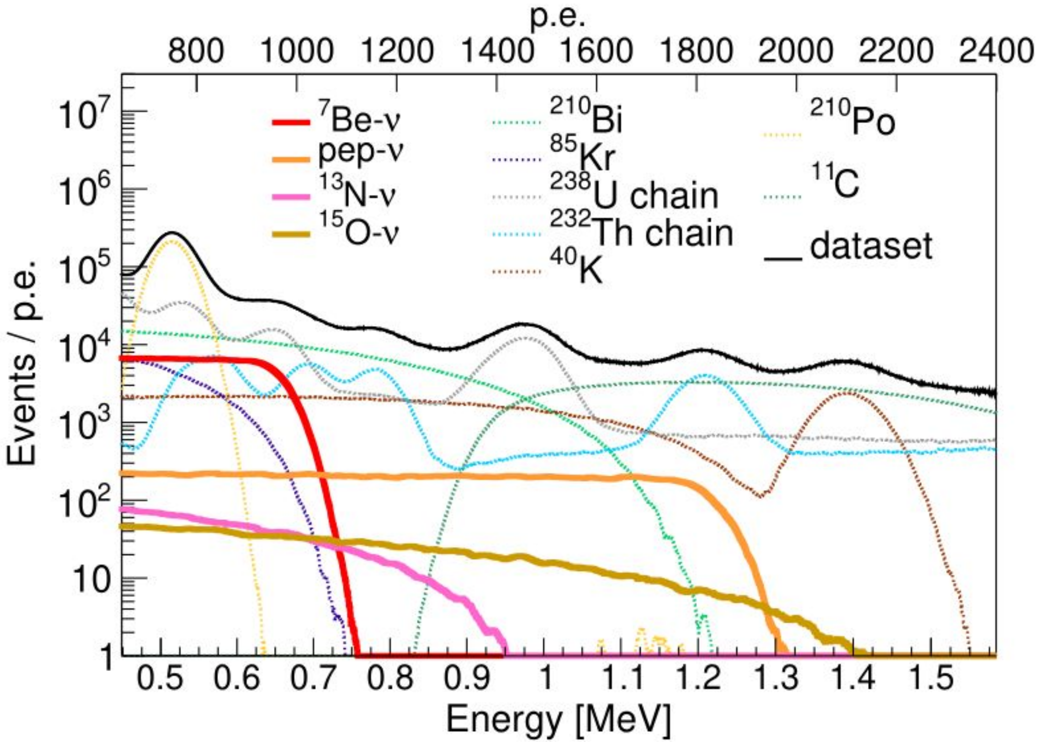


from The Borexino collaboration., *J. High Energ. Phys.* **2020**, 38 (2020)

The intermediate energy spectrum

We built a **Monte Carlo simulated energy spectrum** by combining solar neutrino signal with expected backgrounds

- the “visible spectrum” in the detector is the one of the **ν-recoiled electron**



Plot made assuming Medium backgrounds scenario and with cosmogenic backgrounds subtracted via TFC

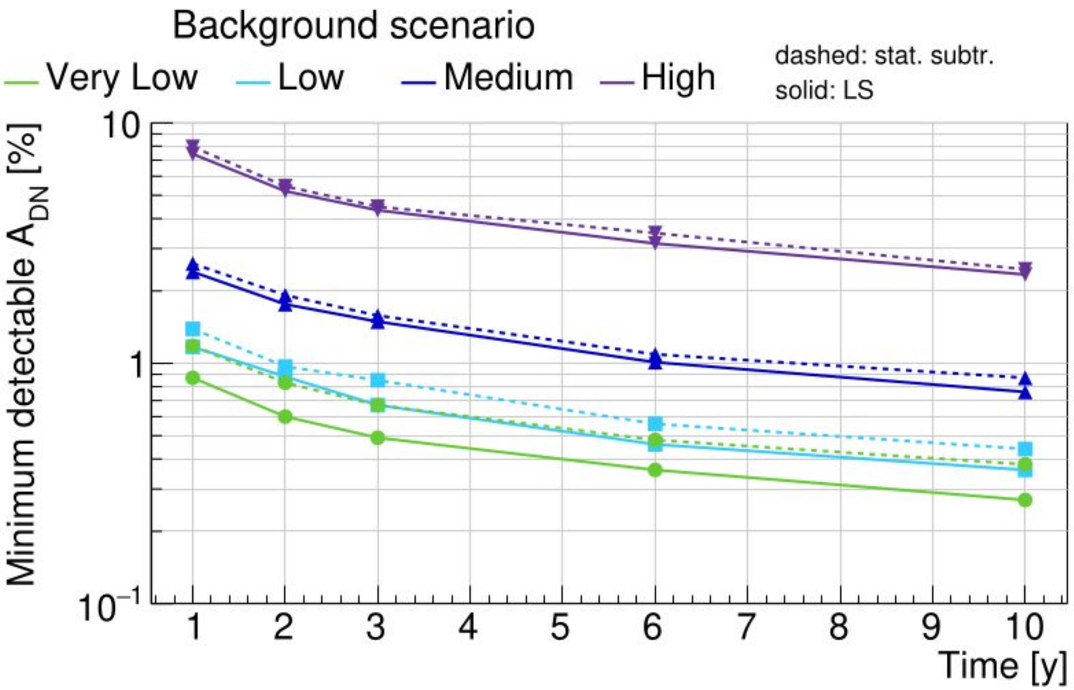
Sensitivity to day-night asymmetries

Standard LMA-MSW theory expects a **small asymmetry between day and night in this energy region (400-1600 keV)**

We can measure it using both **Lomb-Scargle method** and **statistical subtraction** between day and night data

Sensitivity to day-night asymmetry will be very dependent on the background scenario

- In Monte-Carlo, **Lomb-Scargle method has better performance** than statistical subtraction



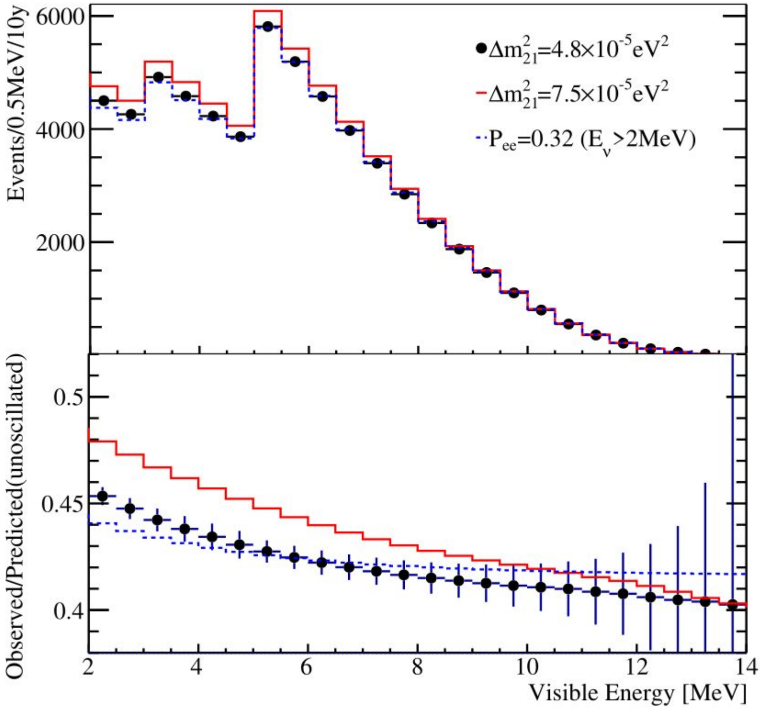
Elastic scattering with ^{8}B neutrinos

Assuming 10^{-17} g/g of U and Th contamination (**low bkg scenario**) and **10 years of data-taking:**

- We expect **≈ 2:1 signal to noise ratio**

This would allow to:

- measure the **upturn in survival probability** after 2 MeV



Monte Carlo simulation made assuming Δm^2_{21} = 4.8 x 10^{-5} eV^2

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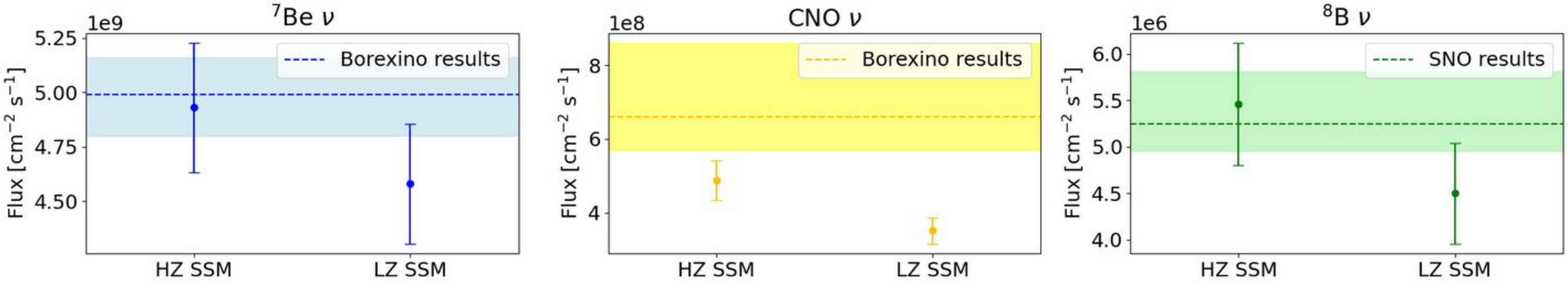
- measure the **upturn in survival probability** after 2 MeV
  - sensitivity depends on the value of Δm^2_{21}

$\Delta\chi^2$	4.8×10^{-5} eV^2	7.5×10^{-5} eV^2
Stat. only	7.1	24.9
Stat. + ^{8}B flux error	6.8	24.2
Stat. + ^{8}B shape error	3.6	11.8
Stat. + energy scale error	4.7	15.5
Stat. + background error	3.6	14.0
Final	2.0	7.3

Rejection sensitivity for the absence of the upturn in P_{ee} at low energies assuming two different Δm^2_{21} values

Solar neutrinos

- Solar neutrino flux flux depends on the **details of the solar model**
  - **competing High-Z and Low-Z** models (Z → solar metallicity)
  - precise neutrino measurement can **help define the model**
  - Currently, solar ν **slightly favor HZ**
  - **CNO neutrino measurement is the most relevant to determine the solar model**



Data taken from Núria Vinyoles *et al* 2017 *ApJ* **835** 202,
Aharmim, B. et al. 2013 PhRvC **87** 015502
and Angel Abusleme et al JCAP10(2023)022

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