MAYORANA (Multi-Aspect Young ORiented Advanced Neutrino Academy)
Workshop,
13 July 2023 Modica

JUNO detector sensitivity to ^{7}Be, pep and CNO solar neutrinos

Marco Beretta
on behalf of the JUNO collaboration

Why do we study solar neutrinos?

Solar neutrinos are produced in the Sun through the reactions:

$$4\mathrm{p} \rightarrow \alpha + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}}$$

Neutrinos interact through the weak-interaction only:

$$\sigma \approx 10^{-44}\mathrm{cm}^{2} \quad @\,1\,\mathrm{MeV}$$

Photons take about 10^5 years to reach our star surface. Instead, neutrinos only take about 8 minutes to travel from their production site to the Earth.

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Astrophysics ←

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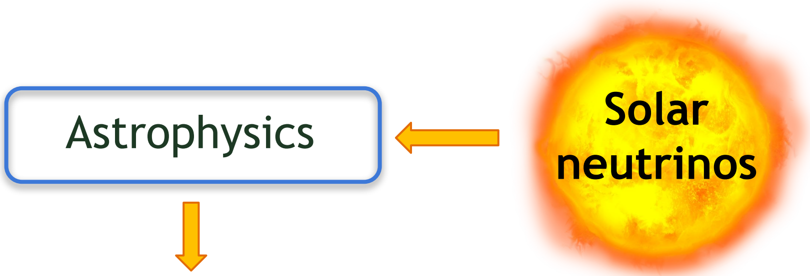
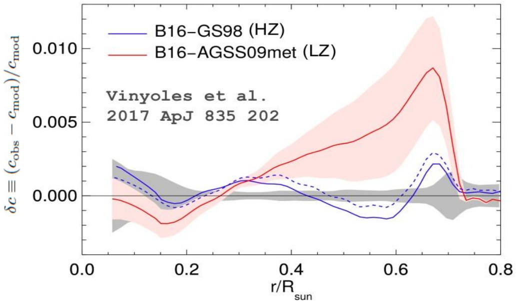


Solar neutrinos as messengers

Main purposes:

- Test and study stellar models
- Solve the solar metallicity problem



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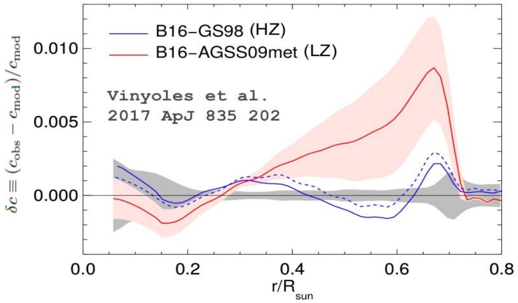

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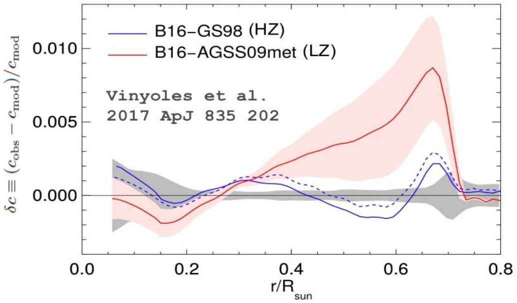


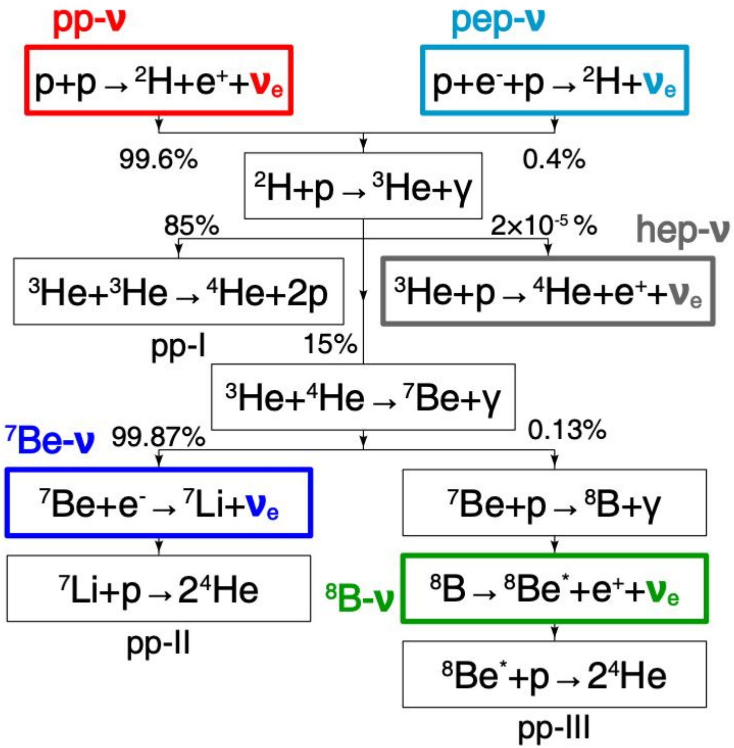
<u>Sun as neutrino source</u>

Flavour oscillations physics:

- θ_{12} and Δm^2_{21} determination
- Matter effects
- Physics beyond the Standard Model

Where are solar neutrinos produced

pp chain: ~ 99% E_{sun}



pp-ν

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

pep-ν

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

99.6%

0.4%

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

85%

2×10^{-5} %

hep-ν

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

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

pp-I

15%

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

⁷Be-ν

99.87%

0.13%

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

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

${}^{7}Li+p \rightarrow 2\,{}^{4}He$

⁸B-ν

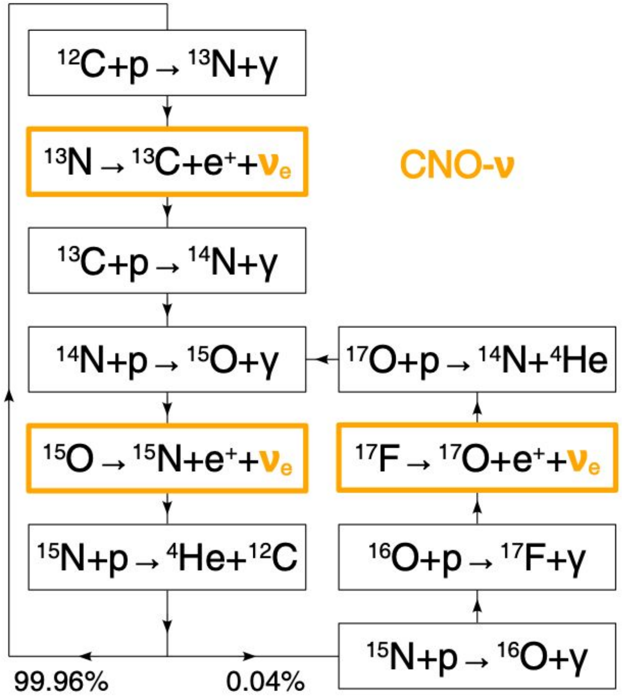
${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$

pp-II

${}^{8}Be^{*}+p \rightarrow 2\,{}^{4}He$

pp-III

CNO cycle: ~ 1% E_{sun}



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

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

CNO-ν

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

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

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

${}^{15}O \rightarrow {}^{15}N+e^{+}+\nu_e$

${}^{17}F \rightarrow {}^{17}O+e^{+}+\nu_e$

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

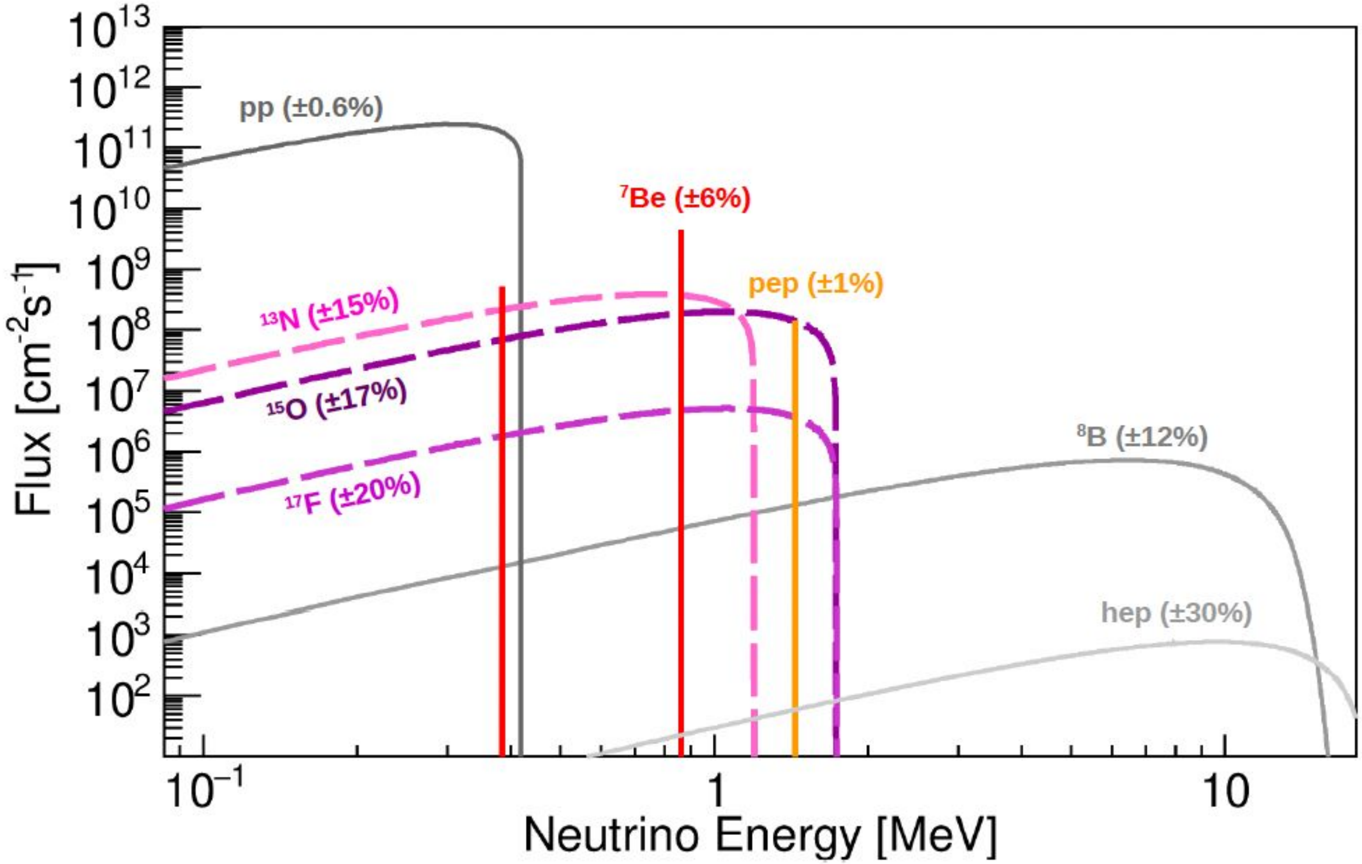
${}^{16}O+p \rightarrow {}^{17}F+\gamma$

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

99.96%

0.04%

Solar neutrinos spectrum: ^{7}Be, pep, CNO



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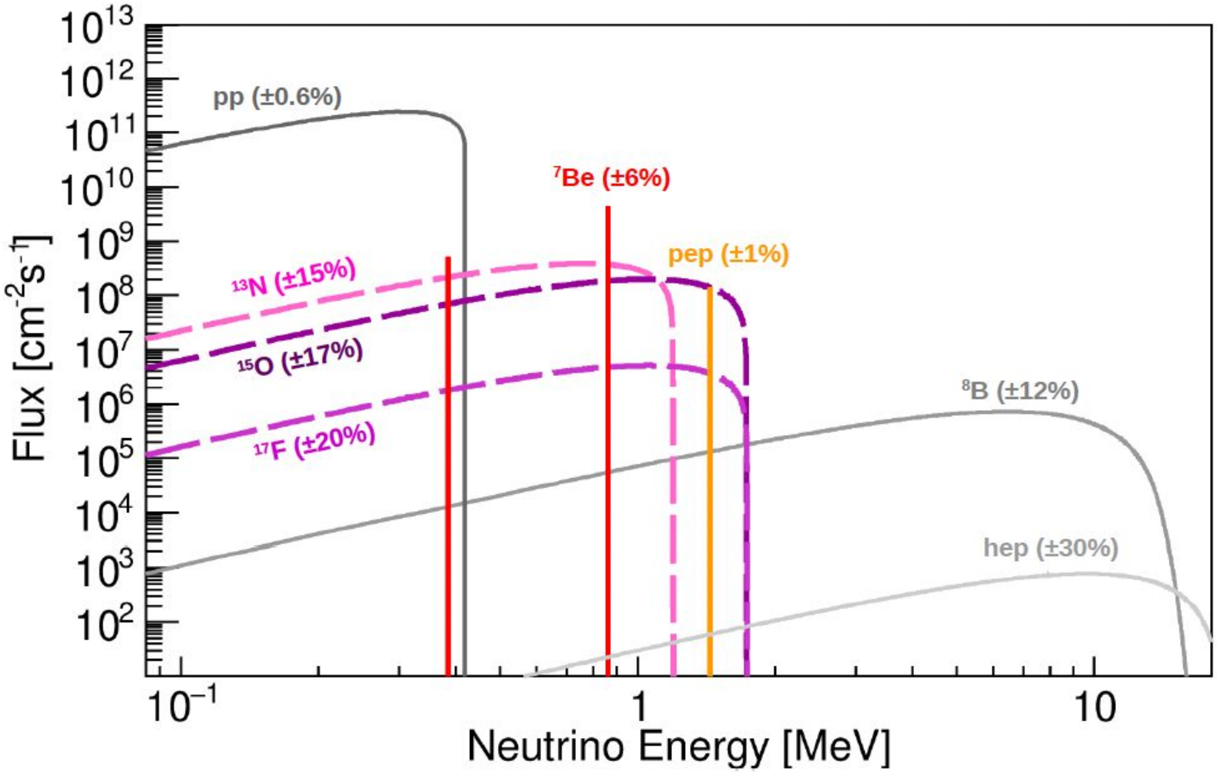


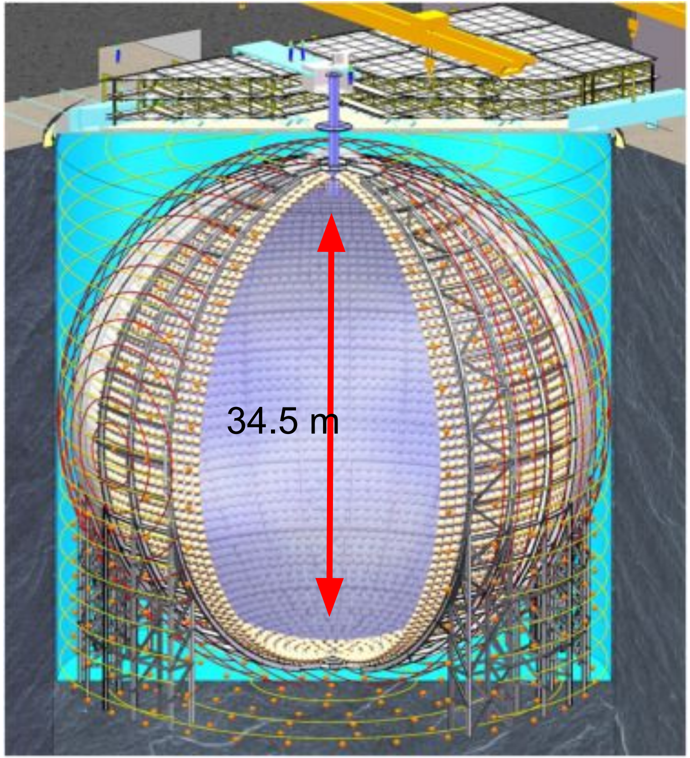
Since other experiment like Borexino detected all the species of solar neutrinos [1]

Now the main open question about the Standard Solar Model is the metallicity

The ^{7}Be and CNO neutrino flux is strictly correlated with the solar metallicity and for this reason our studies are focused on these two species

[1] *M. Agostini et al. (Borexino collaboration). "Comprehensive measurement of pp-chain solar neutrinos". In: Nature 562 (2018), pp. 505–510. doi: https://doi.org/10.1038/s41586-018-0624-y.*

The JUNO experiment



Experimental site:

China, 700 m rock shielding, 53 km distant from two **nuclear power plants**

Detection medium:

20 kton of organic liquid scintillator with 43000 photomultiplier tubes

Goals:

Neutrino mass ordering
Solar neutrino spectroscopy
Supernova neutrino burst
…

Ready for start data taking:

2024

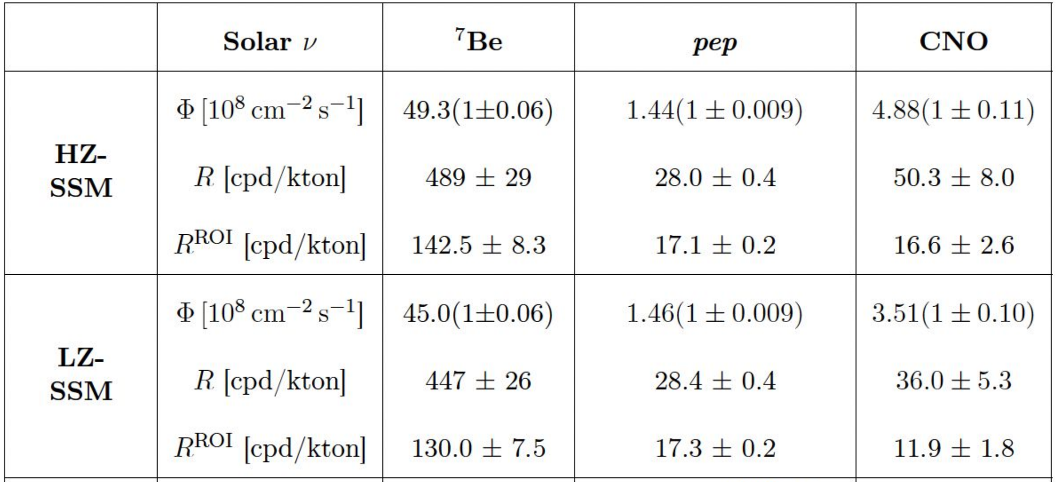
Detecting solar neutrinos in JUNO

Solar neutrinos are detected via elastic scattering on electrons:

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

Fluorescence light produced by solar neutrinos is indistinguishable from the one produced by backgrounds.

Having an an excellent radiopurity is mandatory to perform solar neutrino spectroscopy



	Solar ν	**^{7}Be**	***pep***	**CNO**
HZ-SSM	Φ [$10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	$49.3(1\pm0.06)$	$1.44(1\pm0.009)$	$4.88(1\pm0.11)$
	R [cpd/kton]	489 ± 29	28.0 ± 0.4	50.3 ± 8.0
	R^{ROI} [cpd/kton]	142.5 ± 8.3	17.1 ± 0.2	16.6 ± 2.6
LZ-SSM	Φ [$10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	$45.0(1\pm0.06)$	$1.46(1\pm0.009)$	$3.51(1\pm0.10)$
	R [cpd/kton]	447 ± 26	28.4 ± 0.4	36.0 ± 5.3
	R^{ROI} [cpd/kton]	130.0 ± 7.5	17.3 ± 0.2	11.9 ± 1.8

Backgrounds

Different types of backgrounds: **internal, external and cosmogenic**

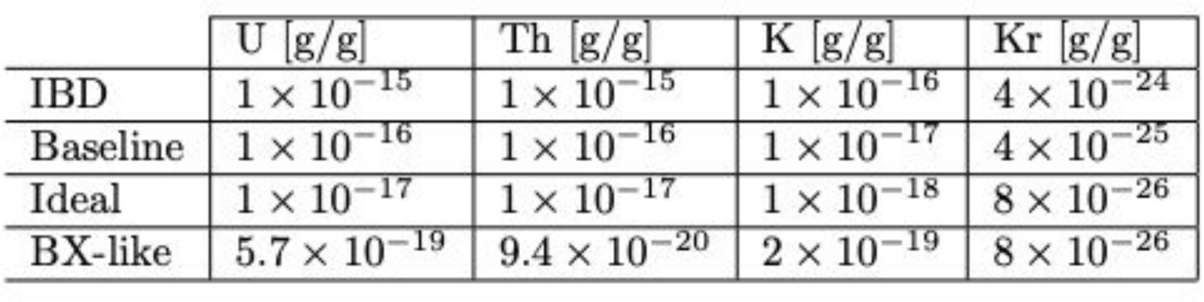
Backgrounds: Internal

Different types of backgrounds: **internal, external and cosmogenic**

Internal backgrounds are mainly due to secular chains like the **^{238}U** and **^{232}Th** ones but also due to **^{40}K** and **^{85}Kr** which could be contained in the liquid scintillator.

Since the internal radiopurity required for solar neutrino is near to the maximum contamination measurable in dedicated setup and the full commissioning of the purification plants of the JUNO liquid scintillator did not finish the commissioning.

We have imagined four different scenarios of internal radiopurity which we called:



	U [g/g]	Th [g/g]	K [g/g]	Kr [g/g]
IBD	1×10^{-15}	1×10^{-15}	1×10^{-16}	4×10^{-24}
Baseline	1×10^{-16}	1×10^{-16}	1×10^{-17}	4×10^{-25}
Ideal	1×10^{-17}	1×10^{-17}	1×10^{-18}	8×10^{-26}
BX-like	5.7×10^{-19}	9.4×10^{-20}	2×10^{-19}	8×10^{-26}

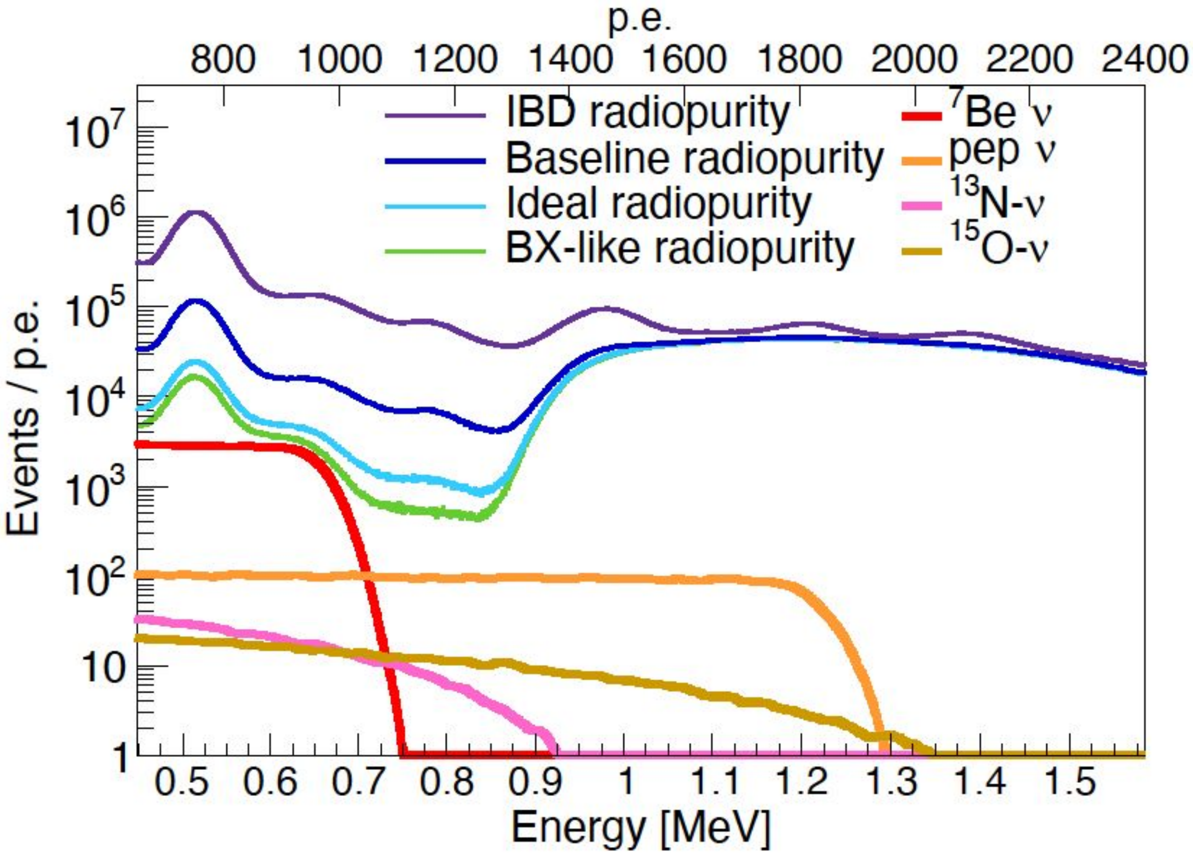
Backgrounds: External & Cosmogenics

Different types of backgrounds: **internal, external and cosmogenic**

External backgrounds are mainly due to the gamma activity of PMTs, stainless sphere and acrylic. It is possible to reduce this kind of contamination considering not the whole detector but an internal volume, called "fiducial volume" with a radius of 15 m.

Cosmogenics, instead, are produced in the by muons which can cross the detector and interact with Carbon mainly producing **^{11}C.**
The cosmogenic background instead are simulated rescaling the rate measured in the Borexino and KamLAND experiments to the JUNO dimension and the expected muon flux

Solar neutrino spectrum in JUNO



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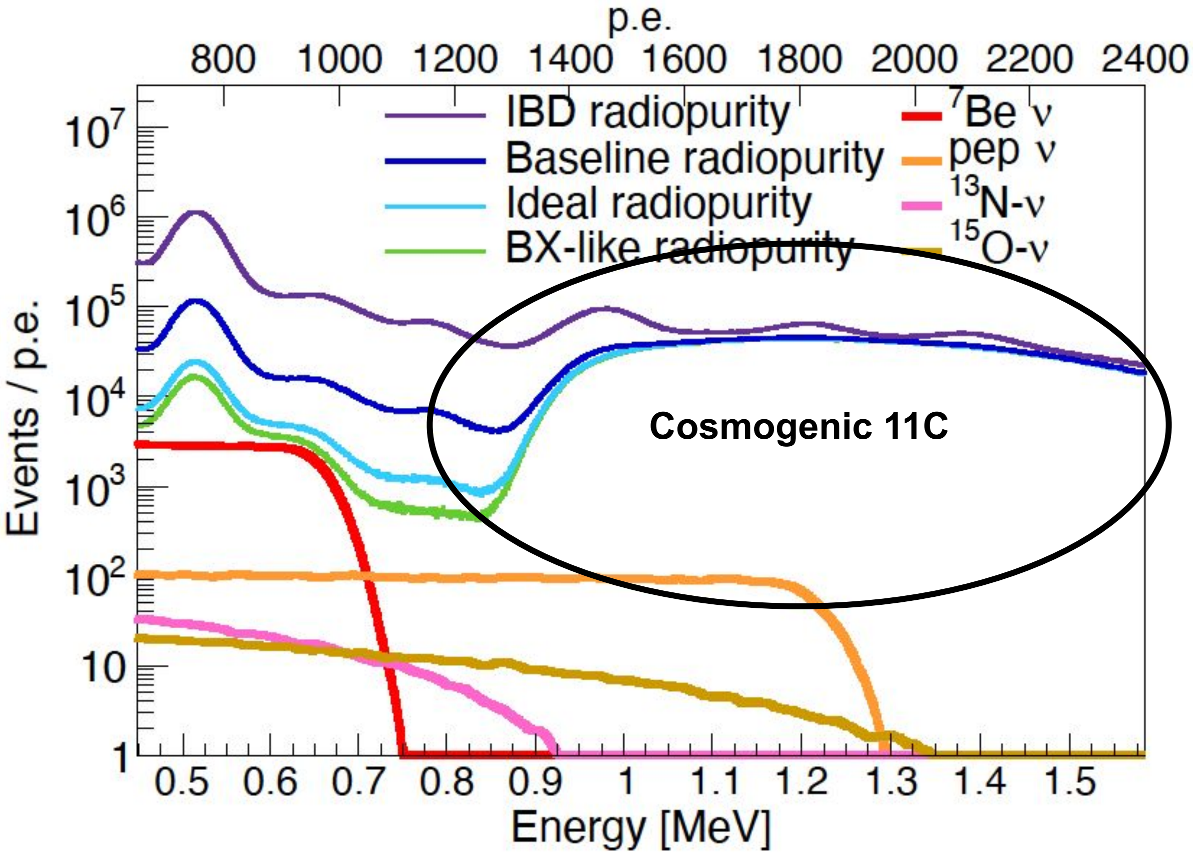
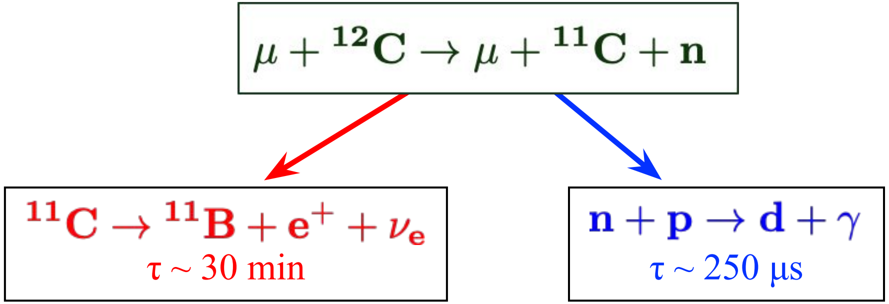


Tagging cosmogenic background: TFC

Using a technique called Three-Fold Coincidence (TFC) it is possible to tag the production of a ${}^{11}C$ isotope in a cylindrical volume along the track of the particle.



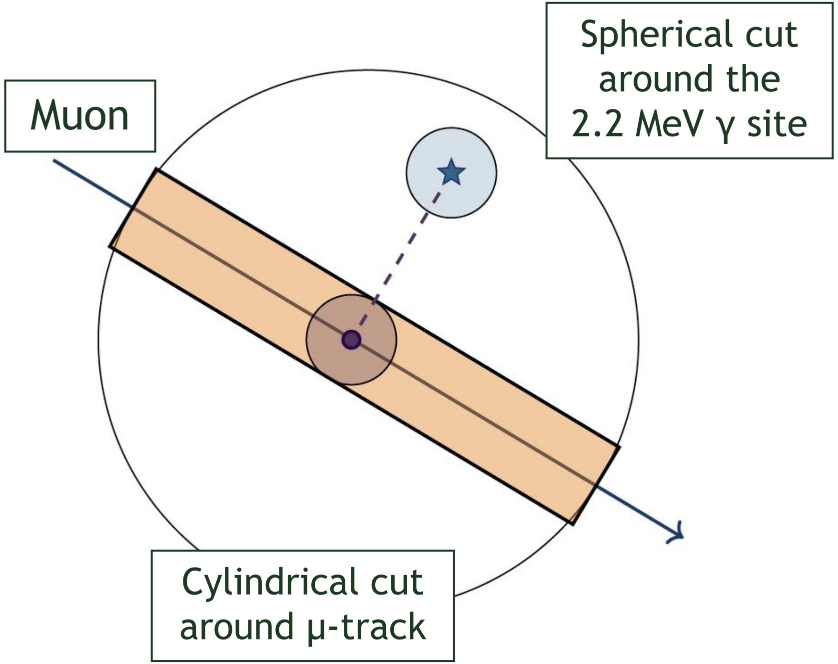
$$\mu + {}^{12}\mathbf{C} \rightarrow \mu + {}^{11}\mathbf{C} + \mathbf{n}$$

$${}^{11}\mathbf{C} \rightarrow {}^{11}\mathbf{B} + \mathbf{e}^{+} + \nu_{\mathbf{e}}$$

$\tau \sim 30$ min

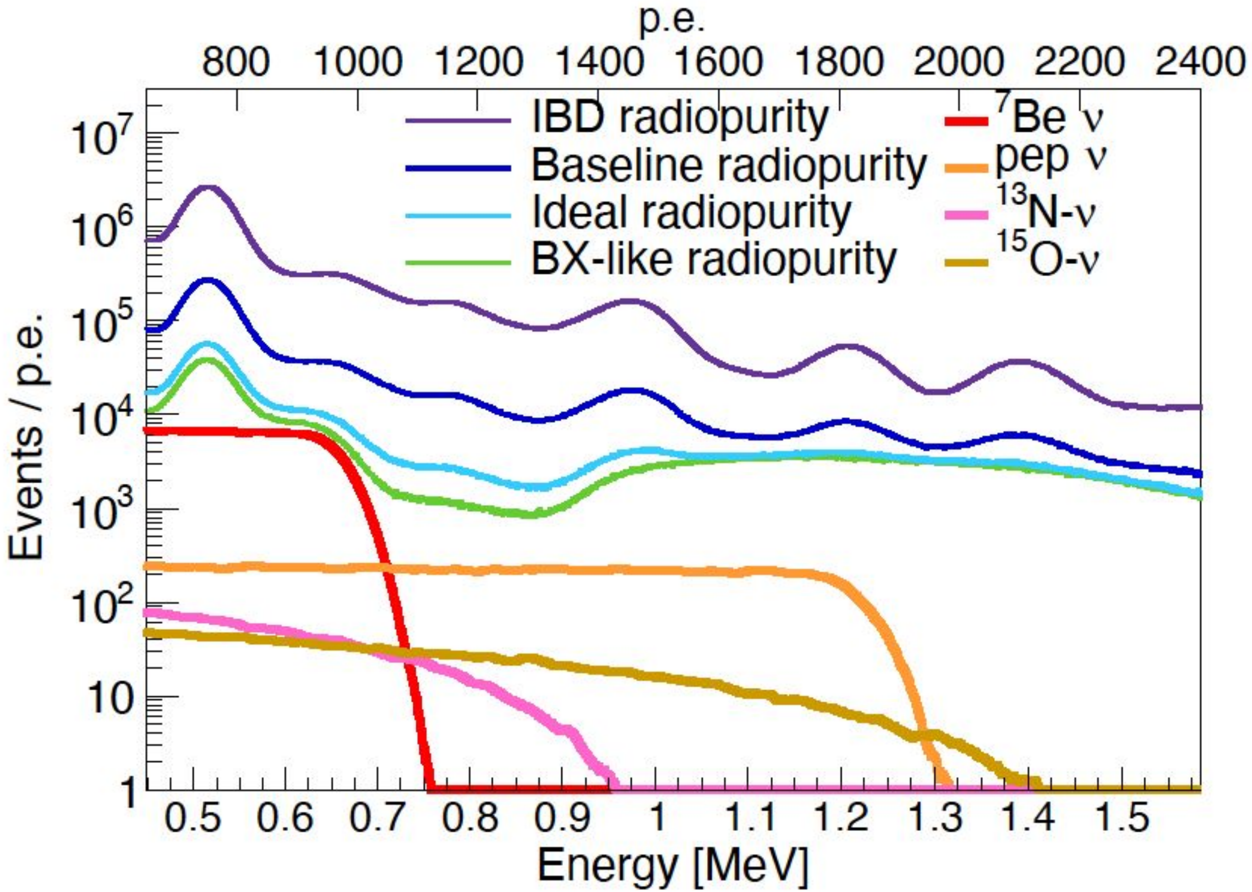
$$\mathbf{n} + \mathbf{p} \rightarrow \mathbf{d} + \gamma$$

$\tau \sim 250$ μs

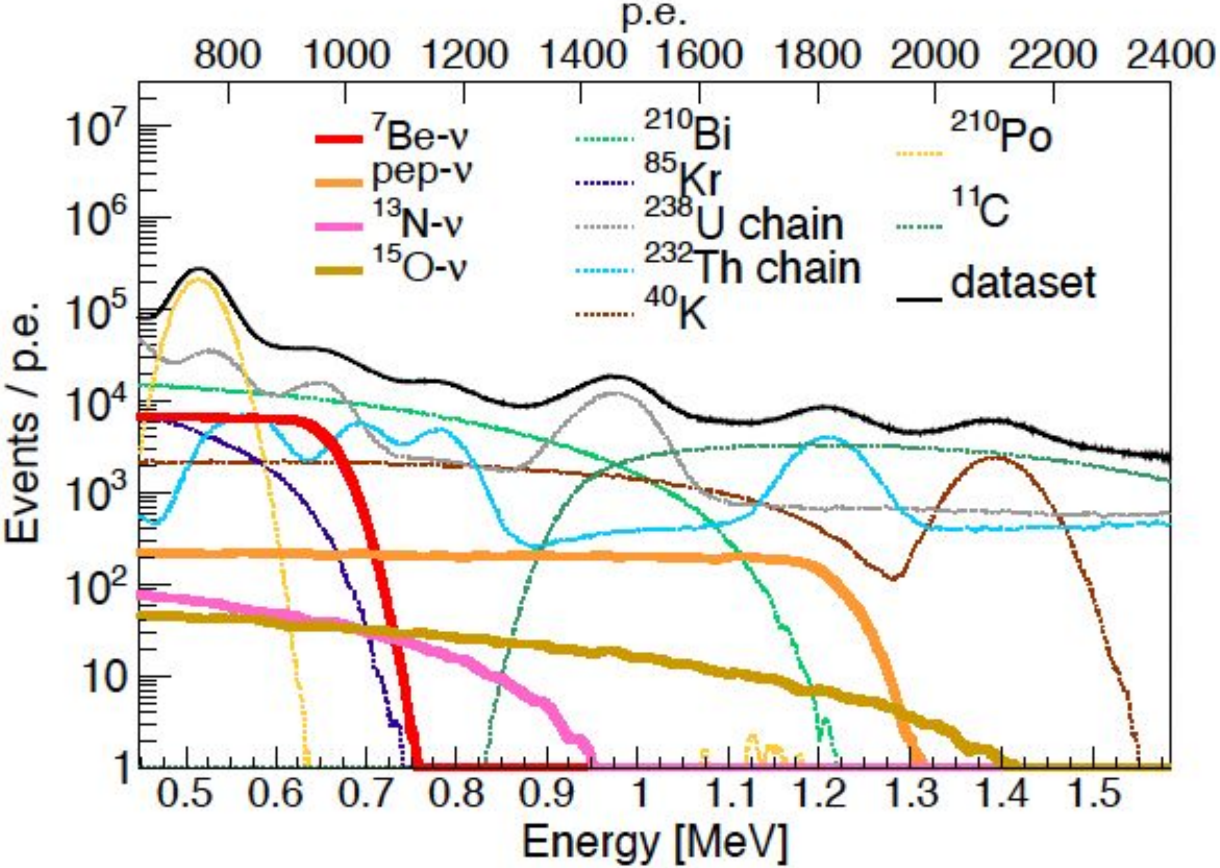


This allows to identify about 90% of the ${}^{11}C$ events reducing this background

Tagged solar neutrino spectrum in JUNO



Fitting the solar neutrino spectrum



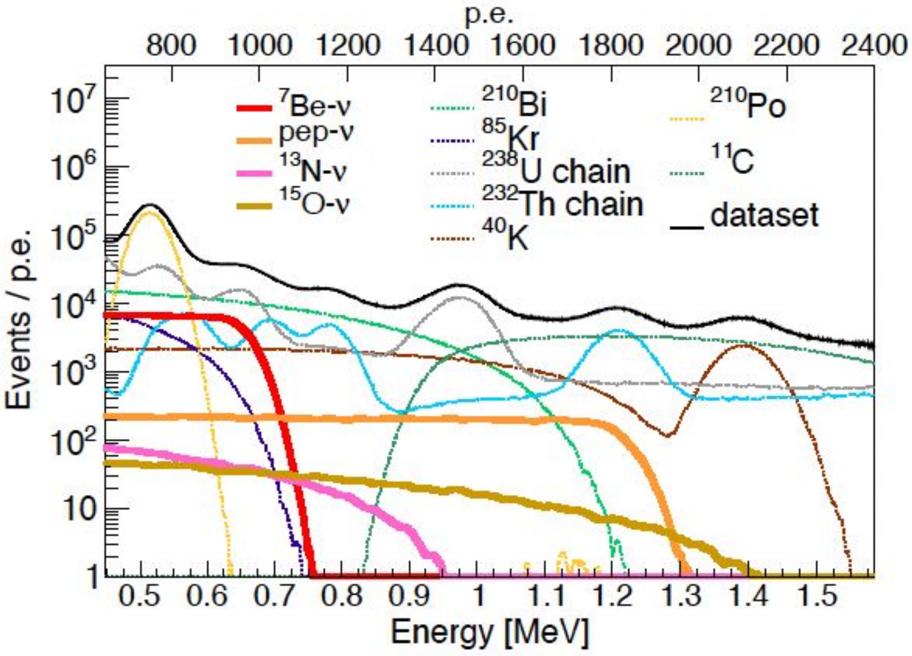
Strategy for solar neutrino sensitivity studies

From the neutrino and background probability density functions (PDFs), it is possible to randomly extract the expected spectrum of solar neutrinos in JUNO. By creating different data-sets

Then a fitter, in which the spectral shape are defined by the PDFs and the weight are free to vary, extracts the rate of solar neutrinos

This both tagging and un-tagging the ^{11}C contribution

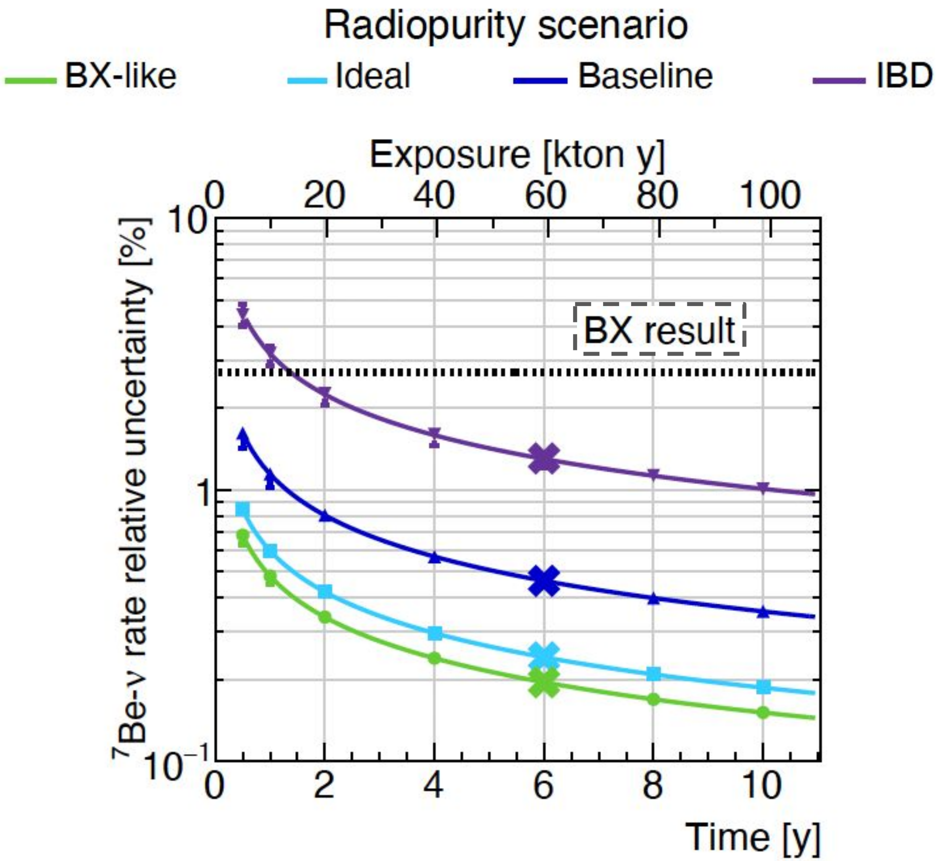
Then simulating different data-set varying the data taking time and the different radiopurity scenarios, it is possible to predict the JUNO sensitivity to ^{7}Be, pep and CNO solar neutrinos



Sensitivity to ^{7}Be solar neutrinos

Thanks to the huge dimension of JUNO and the high flux of ^{7}Be solar neutrino, JUNO will be able to improve the current results (the Borexino one) on this specie in just two years of data-taking.

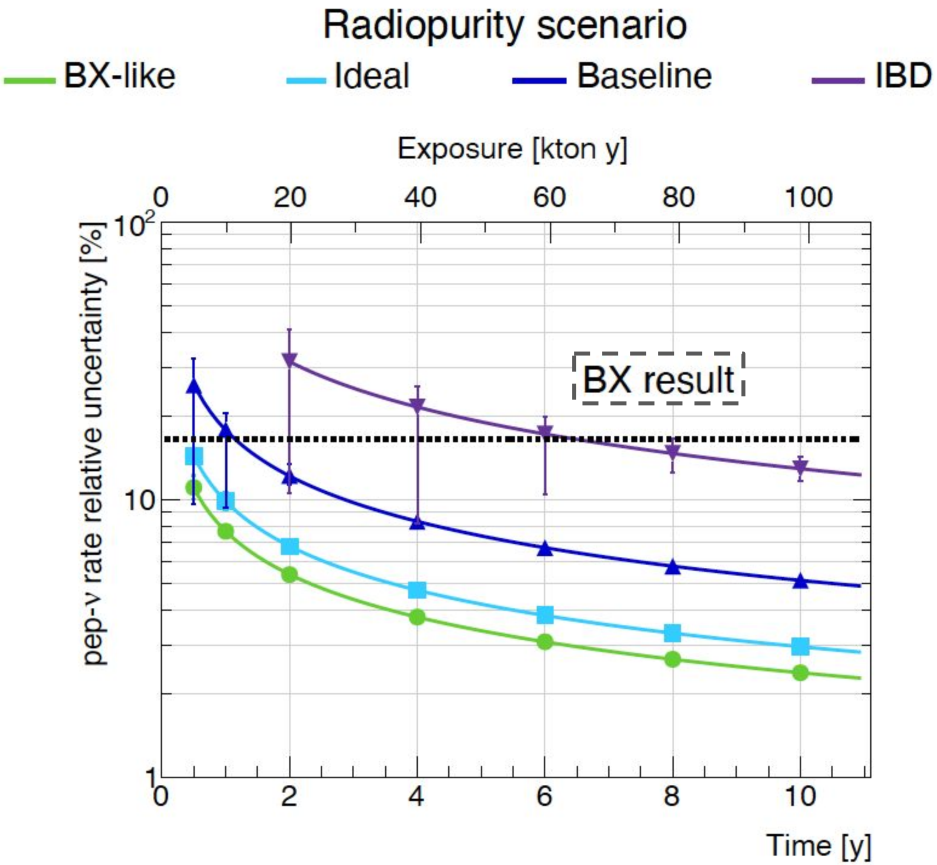
Even in the worst radiopurity scenario **JUNO will reach about 1% of accuracy** in six year of data-taking



Sensitivity to pep solar neutrinos

For pep solar neutrinos we have to wait six year of data taking to improve the Borexino result, but only in the worst radiopurity scenario

In all the other **JUNO will set a new limit** to the accuracy **the pep neutrino flux** in less than two years

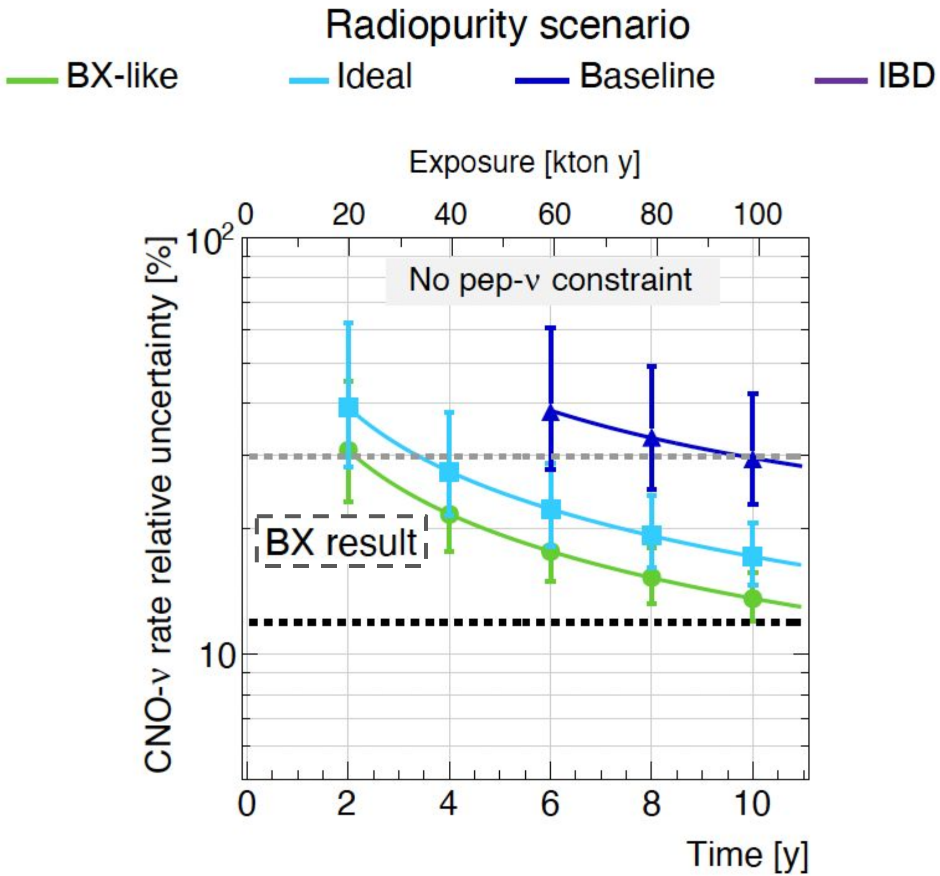


Sensitivity to CNO solar neutrinos

CNO neutrinos are much more complicated to be detected due to the low flux and the spectral shape.

This also because the CNO neutrinos have very similar spectral shape to the pep ones

JUNO needs to be very radiopure to improve the accuracy on this measure



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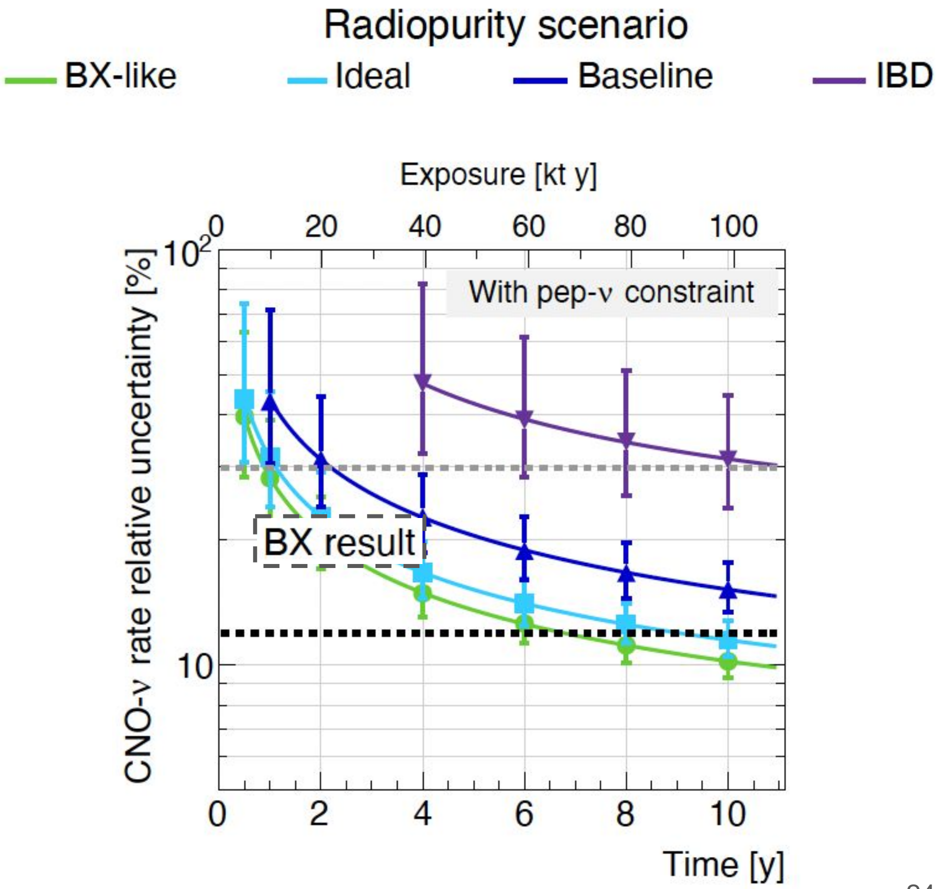
It is possible to improve the results on the CNO neutrinos setting a constraint on the rate of pep neutrinos.



Conclusion

- We produced the spectral probability density functions (PDFs) for the three different species of neutrinos in particular for ^{7}Be, pep and CNO
- We produced the PDF also for backgrounds at different level of internal radiopurity
- We wrote a fitter starting from the PDFs to extract the solar neutrino fluxes
- We studied the sensitivity to this three species in function of JUNO data taking time

We demonstrated the JUNO will be able to improve the current “state-of-art” for solar neutrinos in six year of data-taking measuring simultaneously the ^{7}Be, pep and CNO flux.

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Thanks for your attention

Backup

CNO MEASUREMENT:ASTROPHYSICAL IMPLICATIONS

PRL 129 (2022) 252701

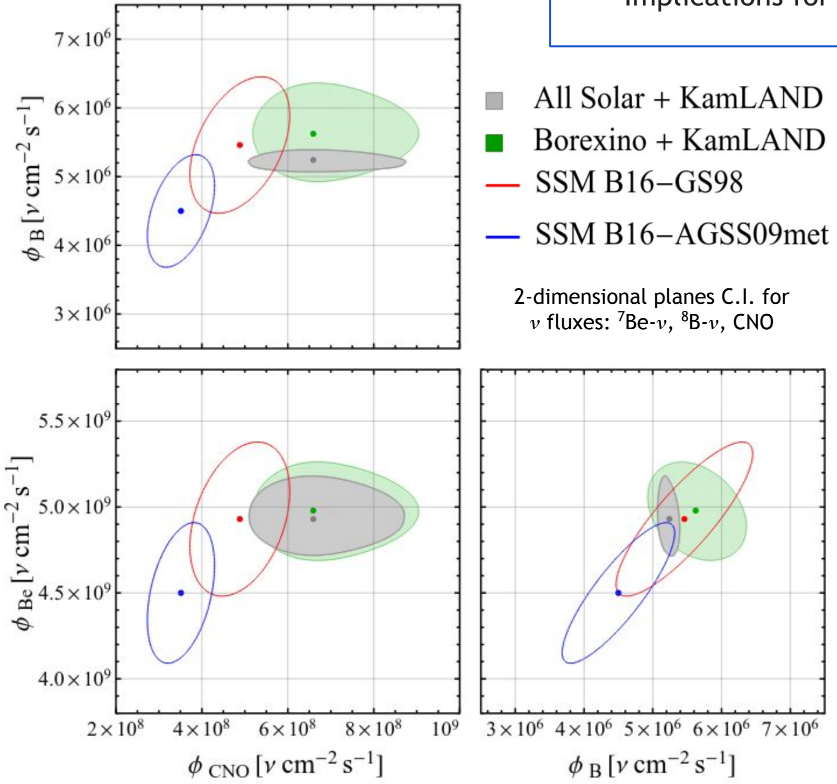
"Improved Measurement of Solar Neutrinos from CNO cycle and Its Implications for the SSM".

Global analysis of solar ν fluxes

- General agreement with SSM-HZ scenario
- Binary hypothesis test: HZ vs LZ

Assuming SSM-HZ, Borexino results on ^{7}Be-ν + ^{8}B-ν + CNO-ν,

➡ **the SSM-LZ scenario is disfavored at ~3.1σ level**



2-dimensional planes C.I. for ν fluxes: ^{7}Be-ν, ^{8}B-ν, CNO

CNO MEASUREMENT: ASTROPHYSICAL IMPLICATIONS

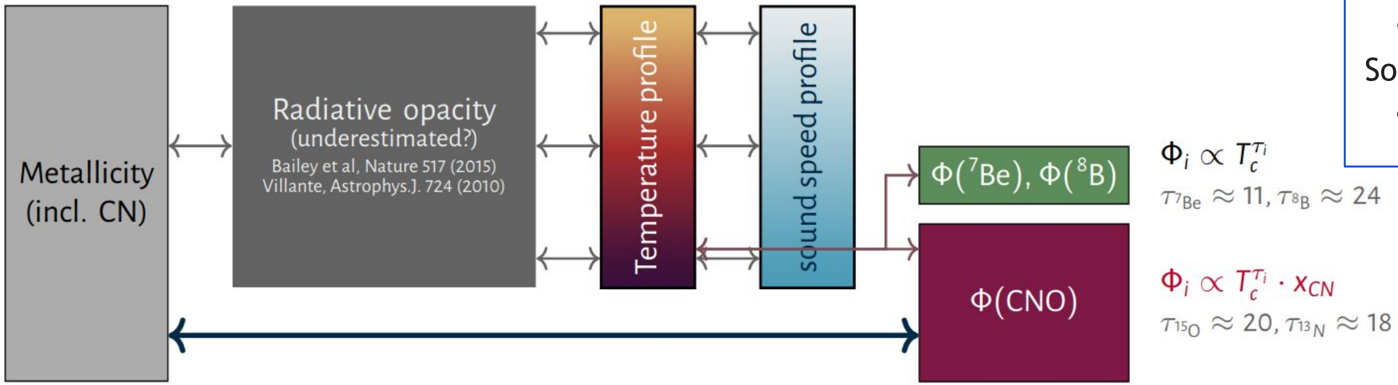
Determination of Carbon + Nitrogen core abundance

Solar neutrino fluxes (both from pp-chain and CNO cycle) depend on the sun “environmental” parameters (metallicity, opacity,...) indirectly, through the core temperature T_c. ^{8}B-ν flux is the most sensitive (~ T_c^{24}).

The CNO-ν fluxes also directly depend on C and N content in solar core: $N_{CN} = (N_C + N_N)$ → strong dependency on metallicity scenario (~28% variation).

PRL 129 (2022) 252701

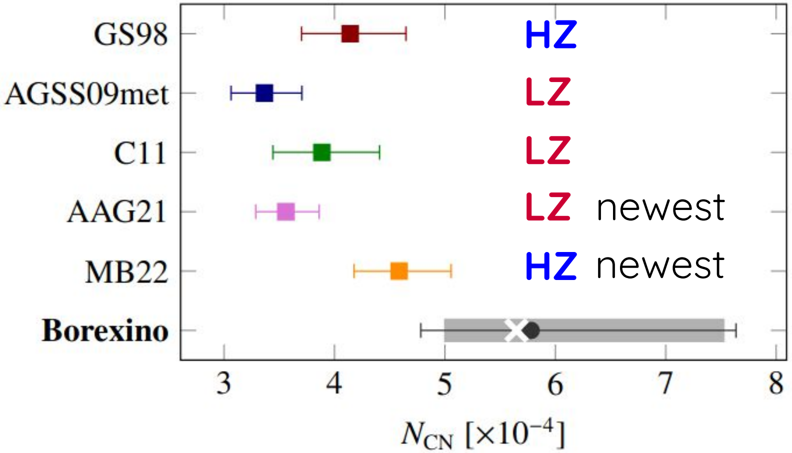
“Improved Measurement of Solar Neutrinos from CNO cycle and Its Implications for the SSM”.



CNO MEASUREMENT: ASTROPHYSICAL IMPLICATIONS

Determination of Carbon + Nitrogen core abundance

Strategy: Use precision measurement of ^{8}B-ν to constrain T_c and so to extract the C-N abundance (N_{CN}) in the core of the Sun.



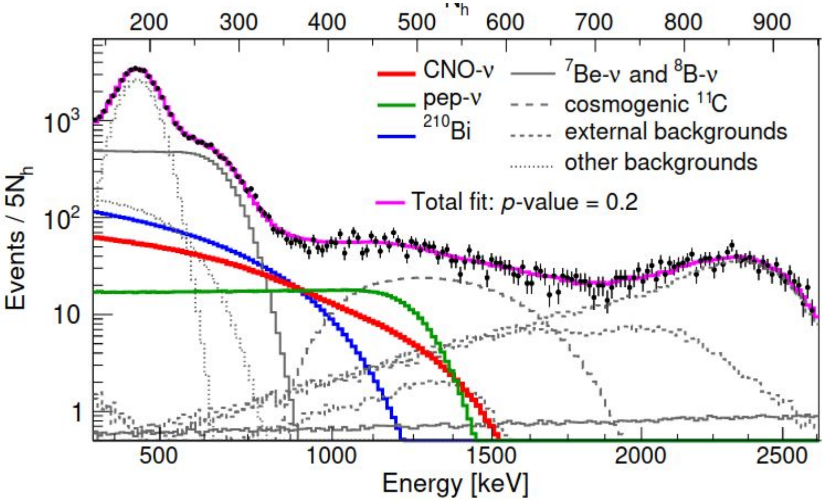
First estimate of solar C+N abundance based on CNO neutrinos measurement

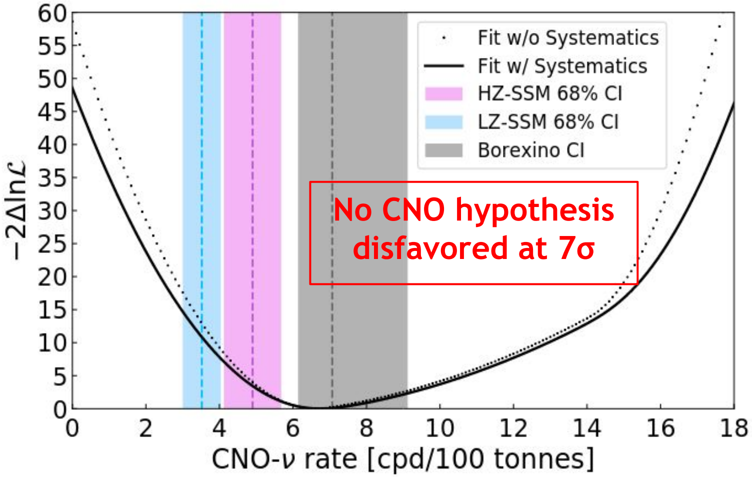
- Agreement with HZ (GS98, MB22), while ~2σ tension with LZ (AGSS09met, C11, AAG21).
- Error currently dominated by experimental uncertainty

PRL 129 (2022) 252701

“Improved Measurement of Solar Neutrinos from CNO cycle and Its Implications for the SSM”.

THE 2022 CNO MEASUREMENT: DETECTION SIGNIFICANCE





No CNO hypothesis disfavored at 7σ

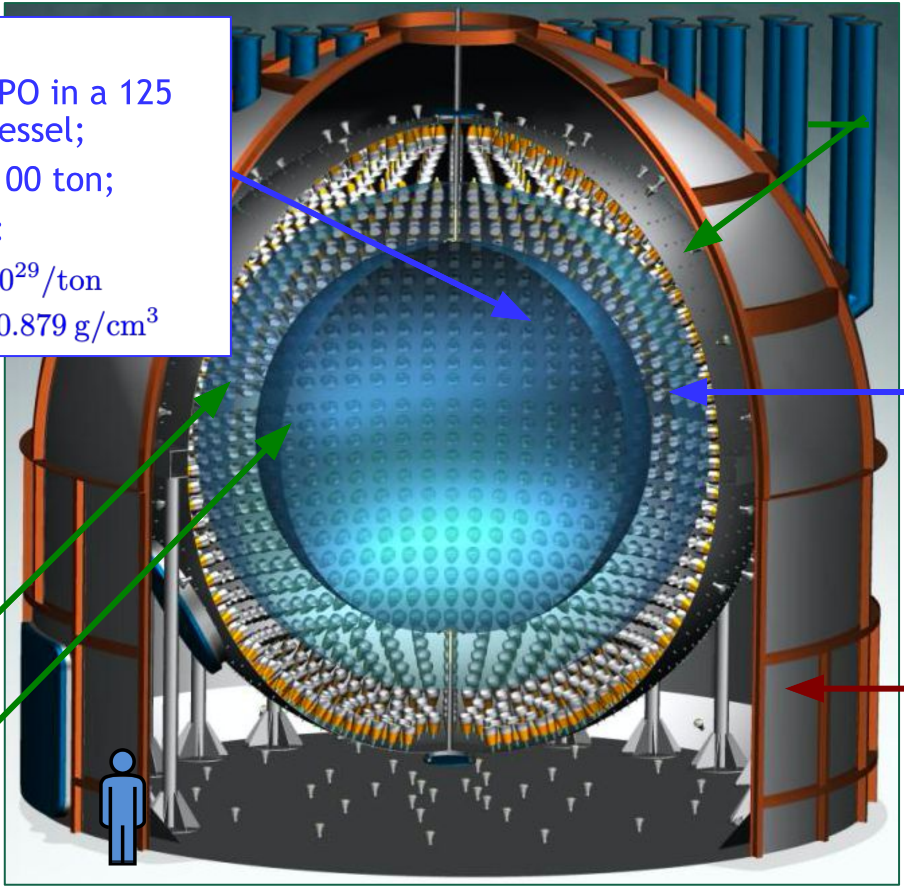
$$\mathcal{R}(\mathrm{CNO}) = \mathbf{6.8}^{+2.0}_{-0.8}\ \mathrm{cpd}/100\,\mathrm{t}\ \ (\mathrm{stat}+\mathrm{sys})$$

$$\Phi(\mathrm{CNO}) = \mathbf{6.6}^{+2.0}_{-0.9} \times \mathbf{10^8}\ \nu/\mathrm{cm}^2/\mathrm{s}\ \ (\mathrm{stat}+\mathrm{sys})$$

PRL 129 (2022) 252701

"Improved Measurement of Solar Neutrinos from CNO cycle and Its Implications for the SSM".

THE BOREXINO EXPERIMENT



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

Nylon vessels:

Outer: 5.50 m

Inner: 4.25 m

Water Tank:

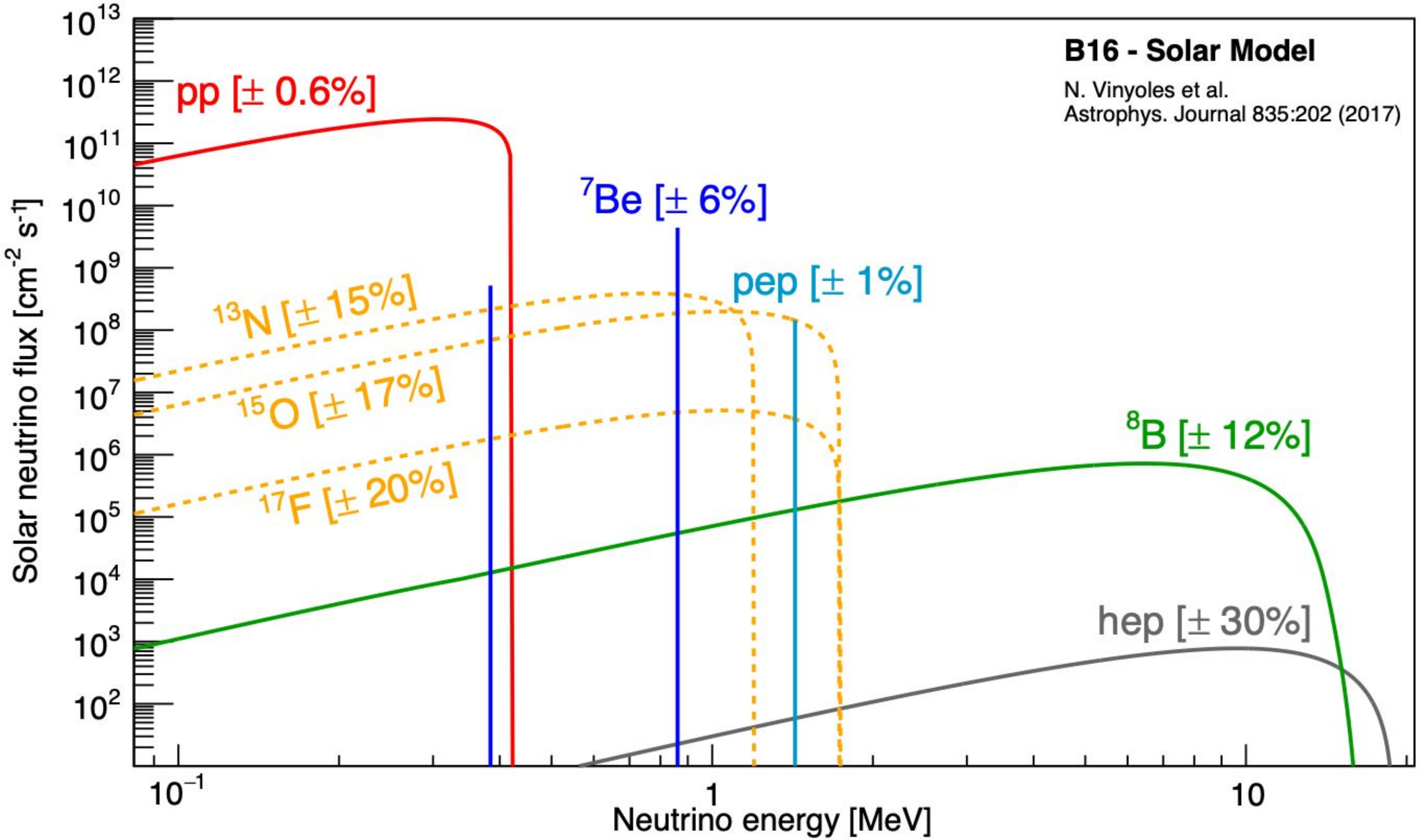
2.8 kton of pure H_2O

γ and n shield

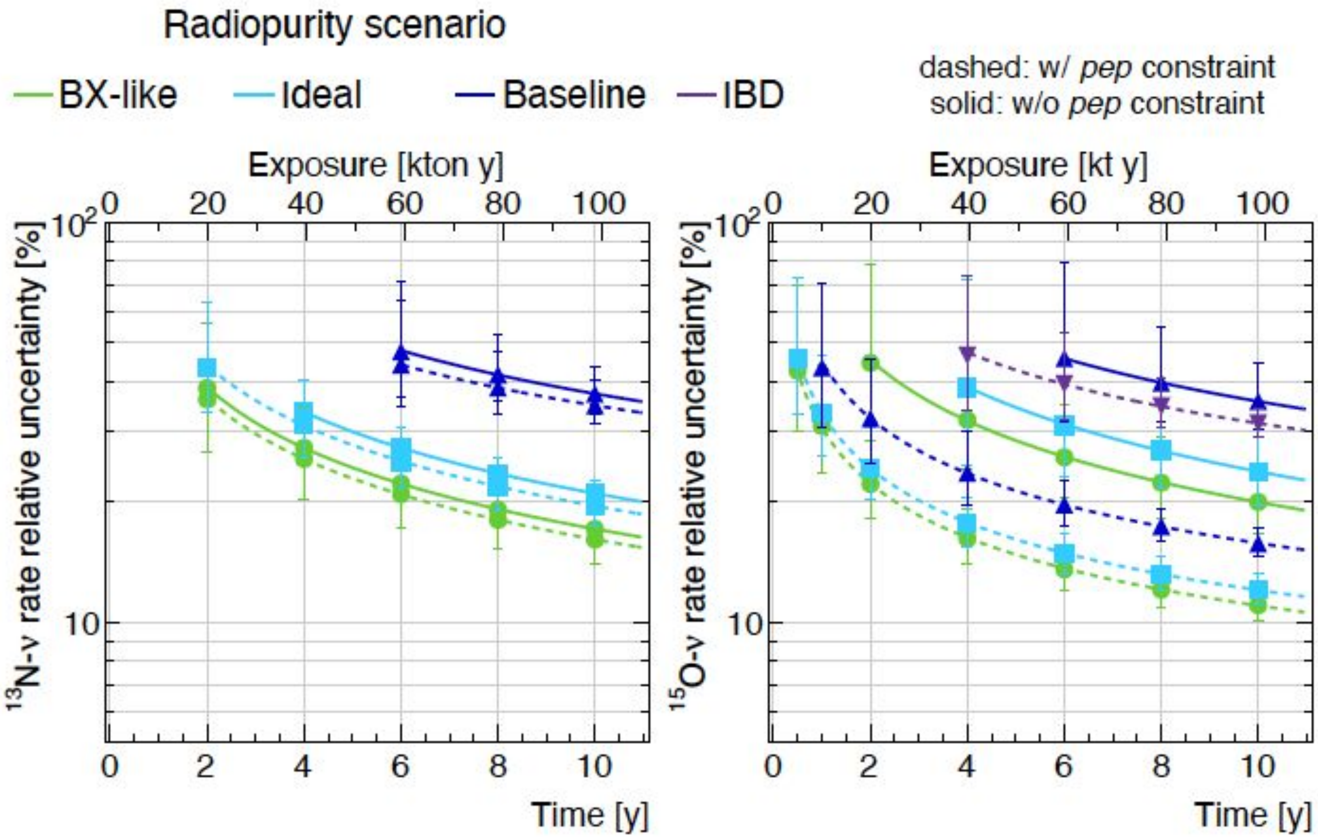
µ water Č detector

208 PMTs in water

Solar neutrinos spectrum



N & O neutrino measurement



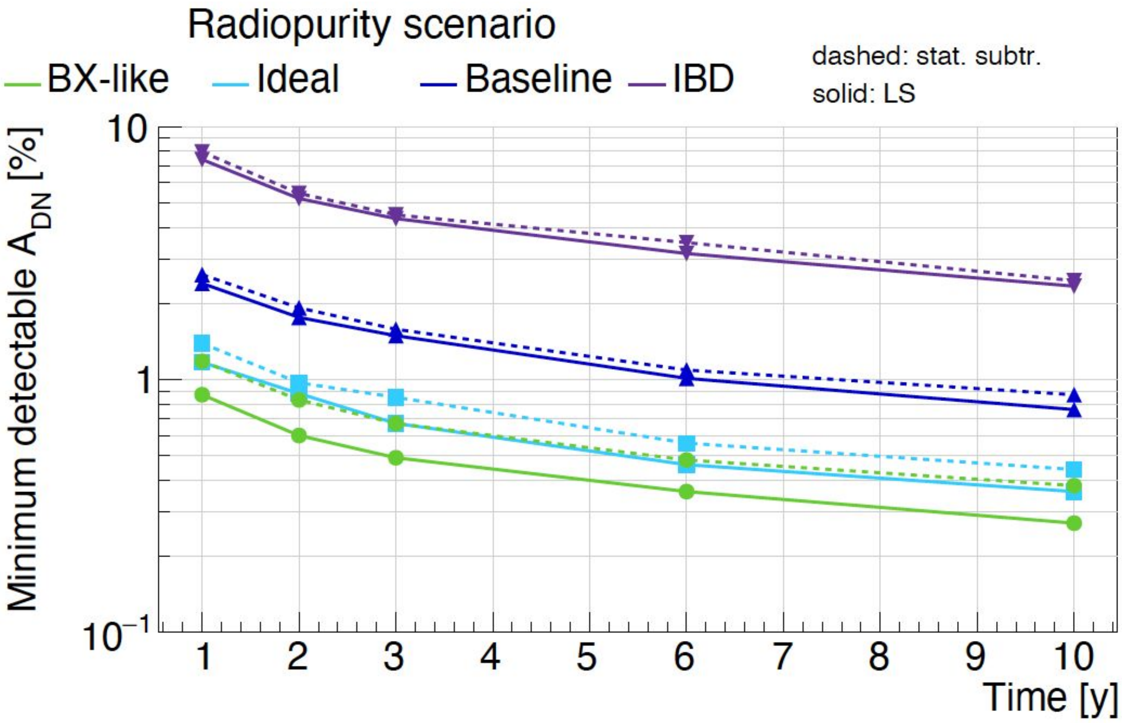
Day - Night asymmetry

$$A_{\mathrm{DN}} = \frac{\Delta R}{\langle R \rangle} = 2\frac{R^N_{\mathrm{Be}} - R^D_{\mathrm{Be}}}{R^N_{\mathrm{Be}} + R^D_{\mathrm{Be}}} \implies R^N_{\mathrm{Be}} = \frac{2 + A_{\mathrm{DN}}}{2 - A_{\mathrm{DN}}} R^D_{\mathrm{Be}}.$$

From theory we expected a day-night asymmetry lower than 0.1%

Not yet seen, Borexino exclude a Day-Night asymmetry at 1% level

The rate at night is higher than the one during the day thanks to electron neutrino regeneration



g-Modes asymmetry