JUNO's sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos

XX International Workshop on Neutrino Telescopes
23 - 27 October, 2023

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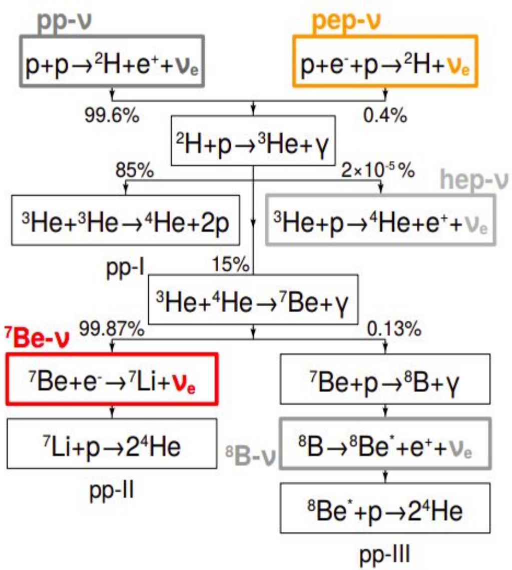
RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

Solar neutrinos

Sun is powered by two sequences of Hydrogen to Helium conversion reactions :

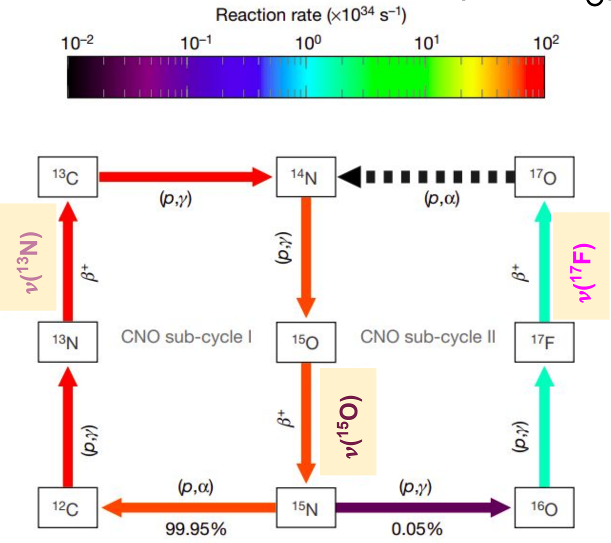
pp-chain (> 99%)



CNO cycle (< 1%)

Catalyzed by C, N, and O

Dominant in massive stars (> 1.3 $M_\odot$)



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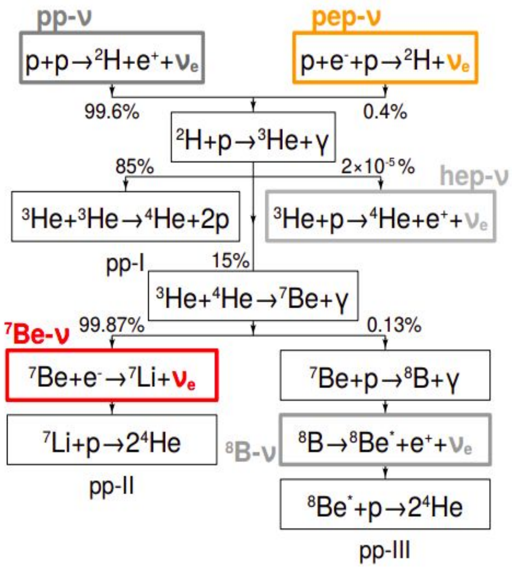

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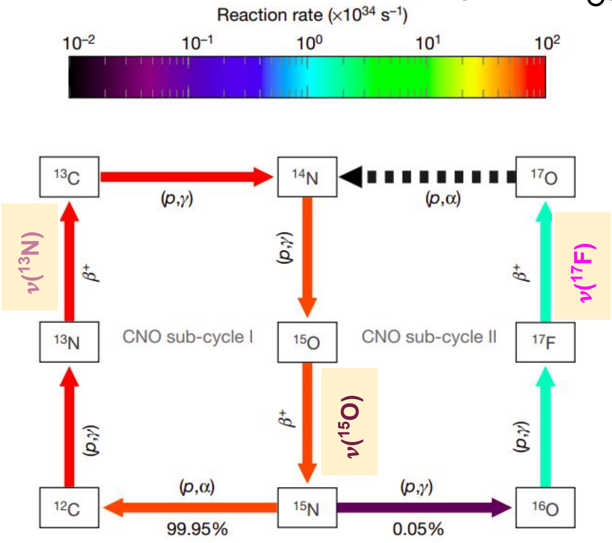
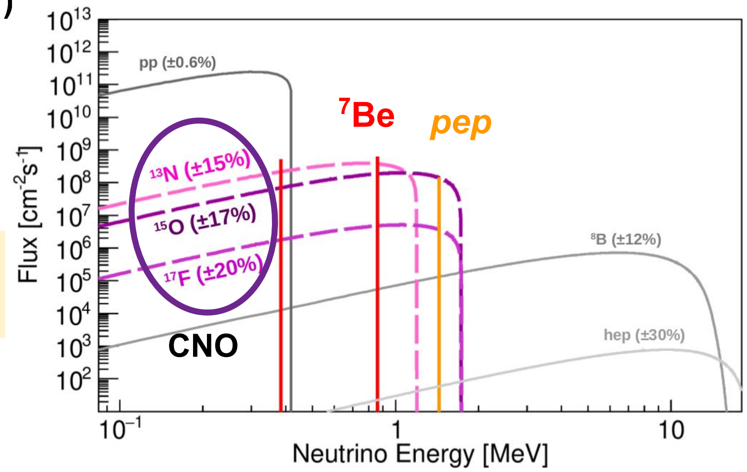


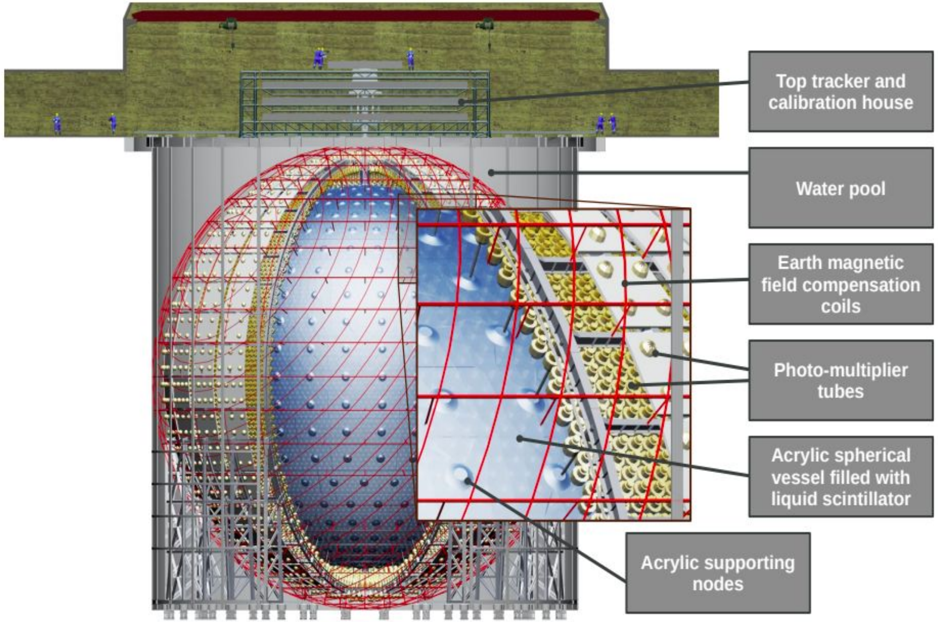
Energy spectrum of solar neutrinos



Measuring solar-ν flux (^{7}Be, ^{8}B, and CNO) helps to investigate the solar metallicity puzzle.

The JUNO experiment

Main Goal: Determine Neutrino mass ordering (NMO) with reactor antineutrinos, via Inverse Beta Decay (IBD).

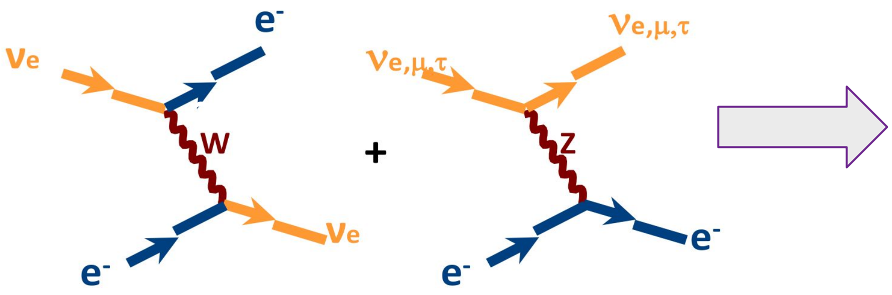


- Located in Jiangmen city in Southern China.
  → Currently under construction!
- A 20 kton liquid scintillator (LS) experiment.
  → the biggest LS detector ever built!
- 17,612 20-inch PMTs and 25,600 3-inch PMTs.
  → Large PMT coverage (~78%)!
- Unprecedented energy resolution.
  → ~3% at 1 MeV!
- Potential to study various sources of neutrinos.

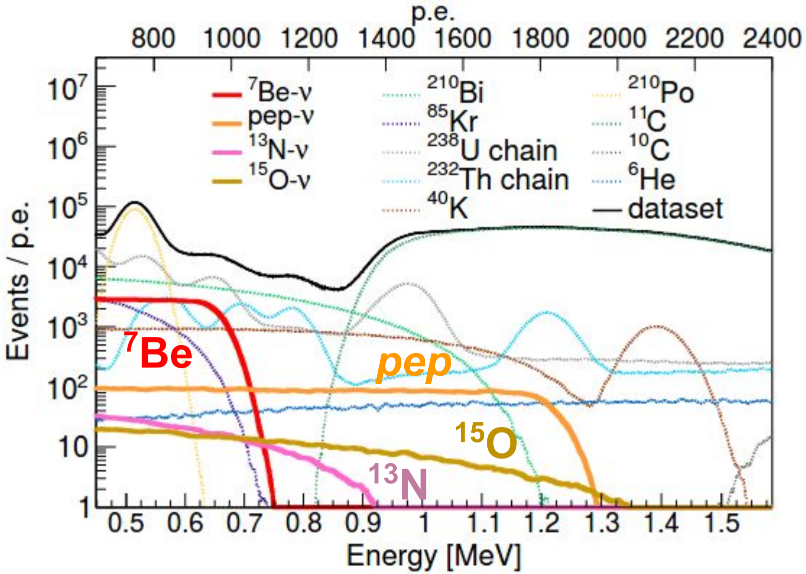
More details in plenary talk by Yury Malyshkin on Wednesday

Solar neutrinos in JUNO

Solar neutrinos detected via elastic scattering off electrons



Expected energy spectrum in JUNO detector in ROI
(Medium Background scenario)



The selected energy range for the analysis (ROI) is ~ (0.45 - 1.6) MeV

JUNO's radiopurity levels

- Internal backgrounds: the decay of radioactive isotopes contained inside the scintillator.
- Relevant isotopes in ROI: ^{40}K, ^{85}Kr, ^{232}Th-chain, ^{238}U-chain, and ^{210}Pb-chain.

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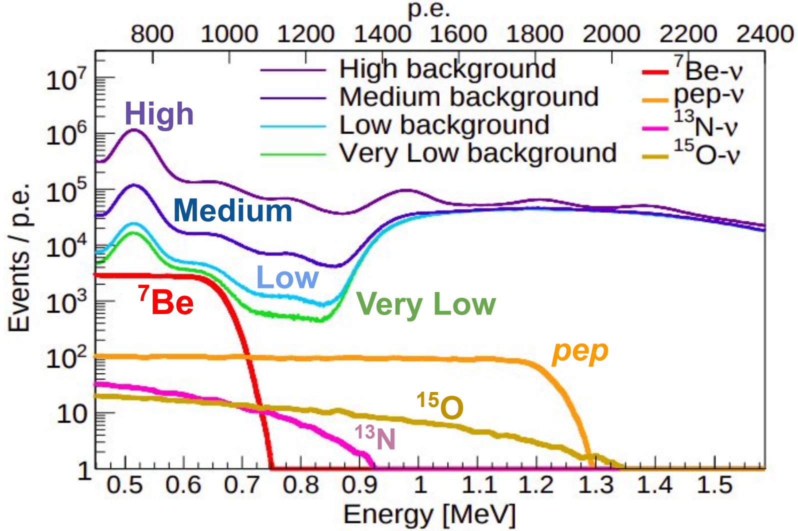
Four scenarios of concentrations

Increasing Radiopurity

High Background: minimum radiopurity requirement for NMO measurement via IBD.
Medium Background: ~ 10 times improvement with respect to High background scenario.
Low Background: ~ 10 times improvement with respect to Medium background scenario (for ^{85}Kr and ^{210}Pb, ~ 5 times improvement).
Very Low Background: Borexino Phase-III contamination[1].

(For 6 years)



- Suppress external backgrounds' contribution using fiducial volume R<14 m.

1. *BOREXINO collaboration, PRL 129 (2022) 252701*

Cosmogenic backgrounds in JUNO

- **Three-Fold Coincidence** (**TFC**) algorithm: identification using space and time correlations between μ, n-capture and cosmogenic decay.
- TFC developed and successfully used in all Borexino[1] analysis.

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

~30 min

$${}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e$$

~260μs

$$n + p \rightarrow d + \gamma$$

1: (*M. Agostini et al., Eur. Phys. Journal C 81 (2021) 1075)*

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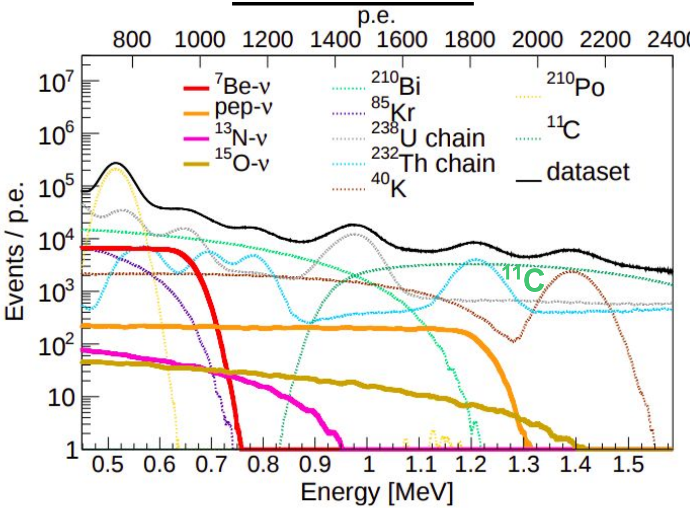
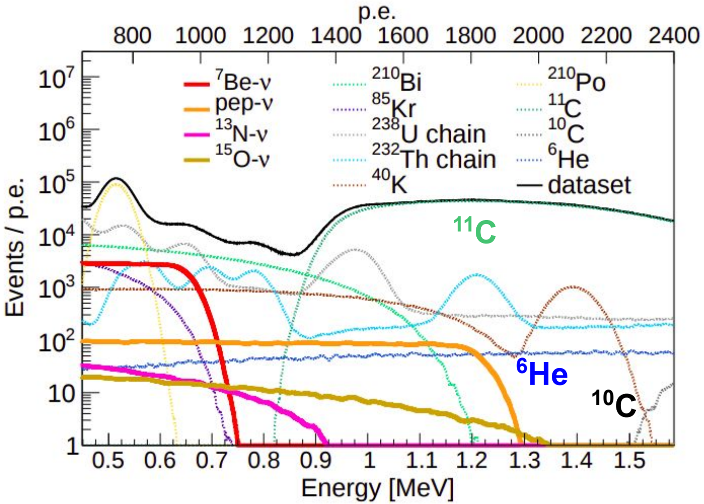
Data is split using TFC:

TFC-subtracted



TFC-tagged



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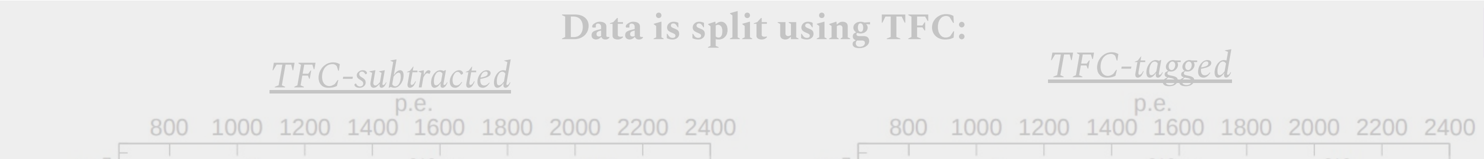
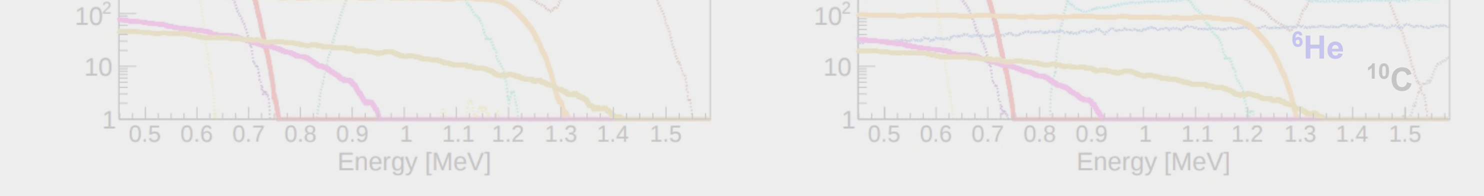


Performance of TFC given by:

Tagging Power (**TP**): % of correctly tagging cosmogenic backgrounds. (Assume similar to Borexino, TP = ~90%).

Subtracted Exposure (**SE**): remaining exposure in TFC-subtracted dataset. (Assume similar to Borexino, SE= ~ 70%).



1: (*M. Agostini et al., Eur. Phys. Journal C 81 (2021) 1075*)

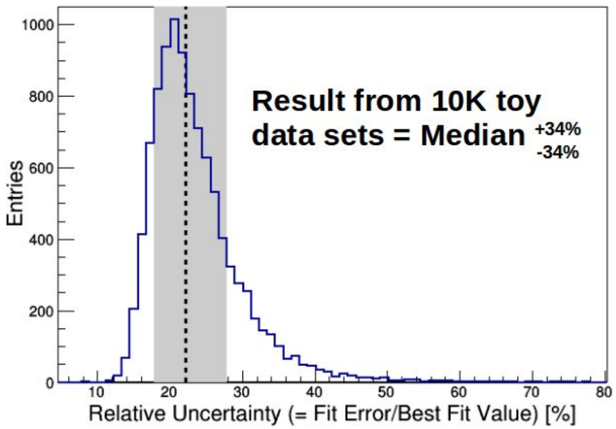
Analysis strategy

Energy Spectra from Monte Carlo Simulations → Sampling → 10K pseudo-datasets (each species with expected rates)

Both → Simultaneous Binned Poisson Likelihood Fit

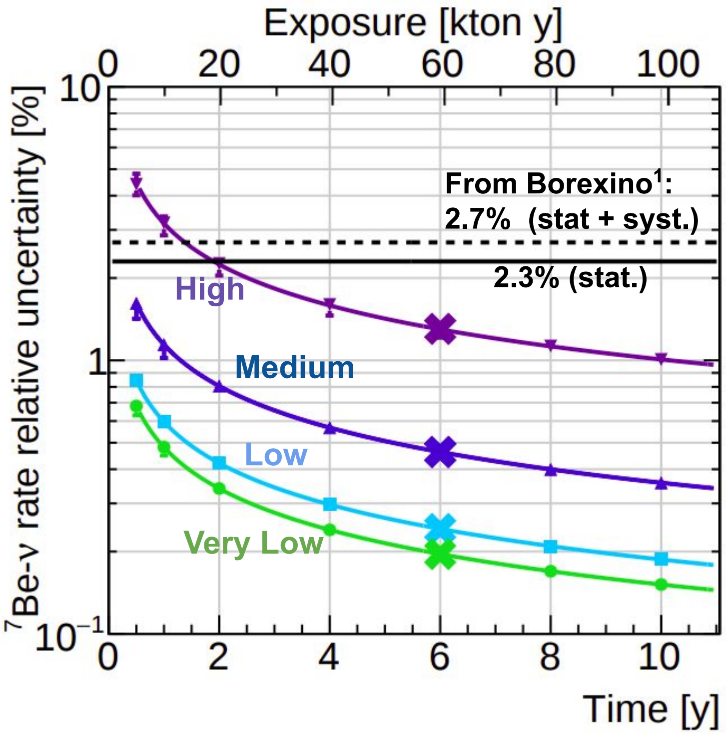
→ Best Fit Value

→ Fit Error (statistical only)



Results on ^{7}Be solar neutrinos

Statistical error only



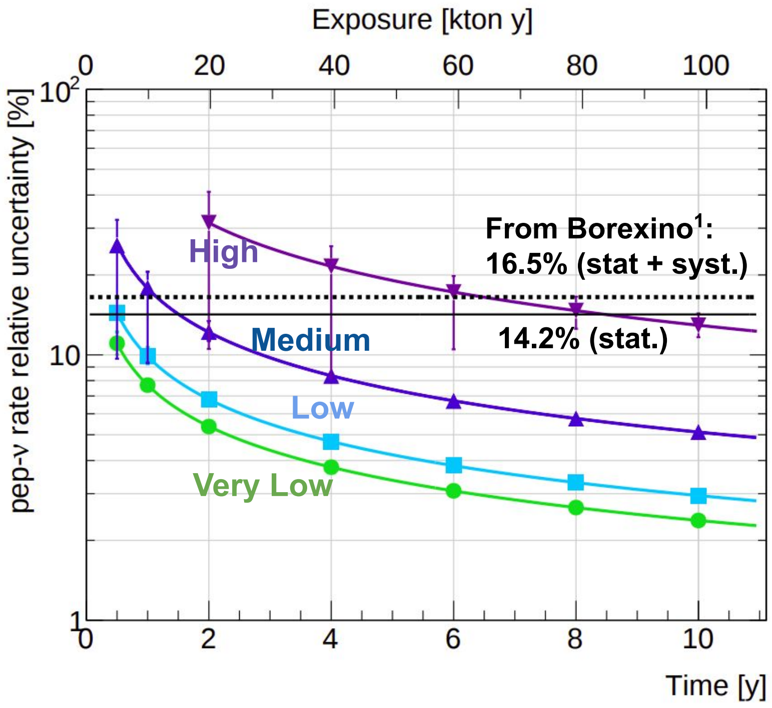
Impact of the exposure on ^{7}Be-ν sensitivity

- Highly competitive after 1 year of data taking.
- For longer data taking, reaching unprecedented statistical errors.
- E.g.: from ≈1.0 % in the pessimistic High background scenario to ≈0.15 % in the Very Low background case.

1. *BOREXINO collaboration, Nature 562 (2018) 505*

Results on *pep* solar neutrinos

Statistical error only



Impact of the exposure on pep-ν sensitivity

- Measurement possible for the first time without fixing the CNO rate to the SSM prediction.
- After ~2 years of data-taking (except for the High background level), JUNO will exceed the current best result.
- For long data taking, JUNO will exceed the Borexino best result in all radiopurity scenarios.

1. *BOREXINO collaboration, Nature 562 (2018) 505*

Results on CNO solar neutrinos

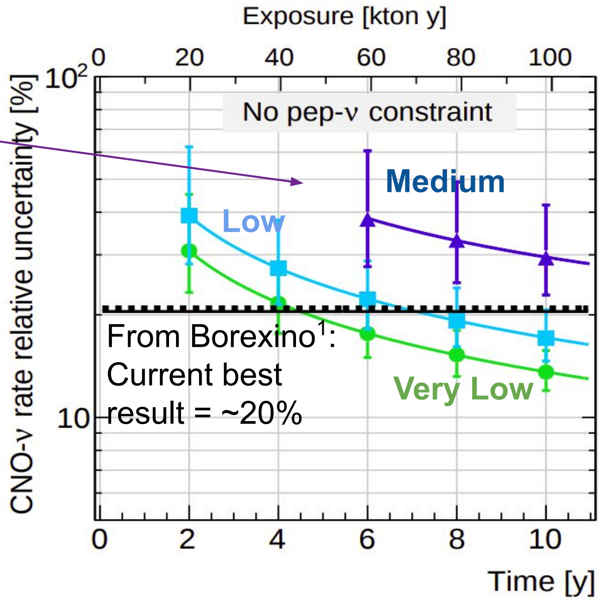
Statistical error only

Fitting summed individual components from CNO cycle.

CNO rate **can not** be determined in **High** background scenario

pep-CNO spectral degeneracy is the limiting factor.

Impact of the exposure on CNO-ν sensitivity



1. BOREXINO collaboration, PRL 129 (2022) 252701

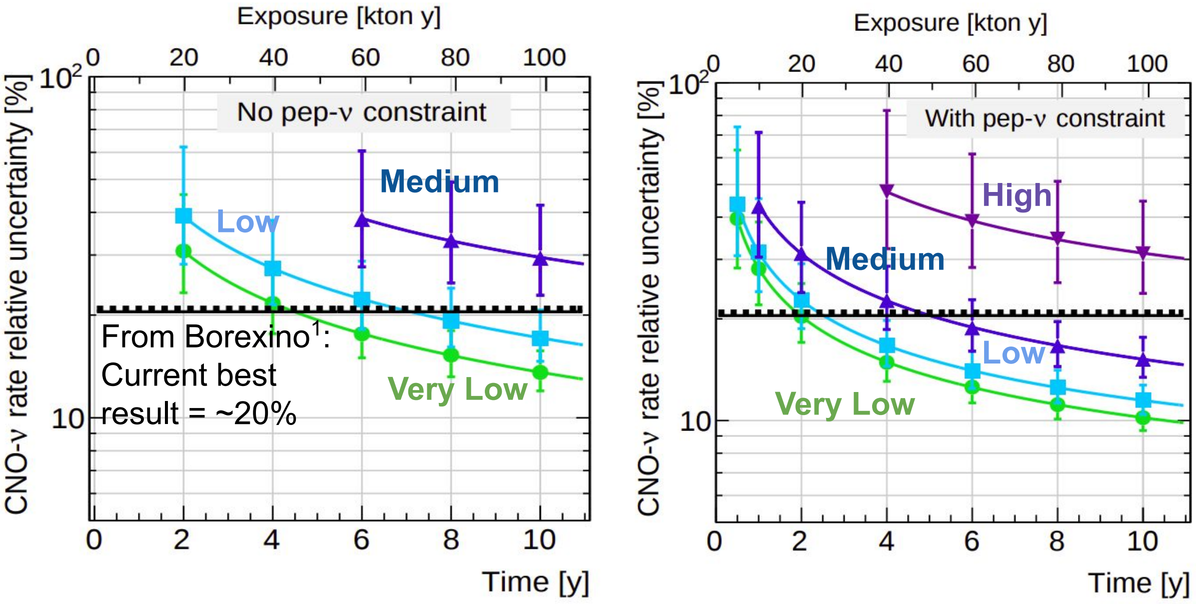
Results on CNO solar neutrinos

Statistical error only

Fitting summed individual components from CNO cycle.

→ Constraining *pep-ν* rate at 1.4% based on HZ-SSM predictions+global analysis of solar-**ν** data[2]+solar luminosity constraint.

Impact of the exposure on CNO-ν sensitivity



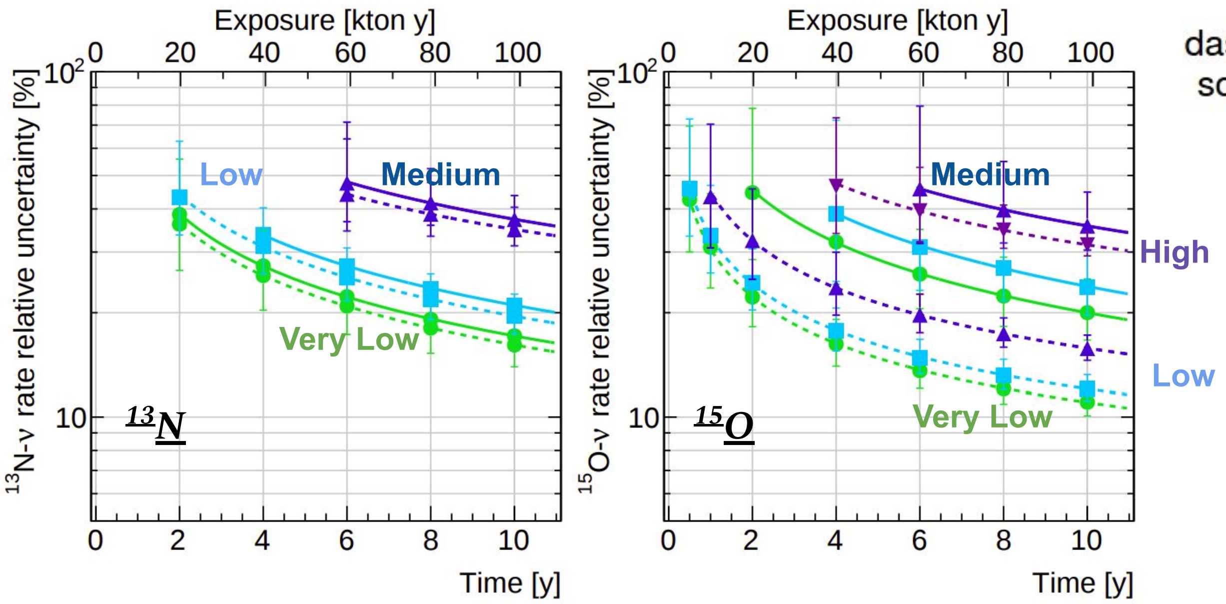
After applying *pep-ν* rate constraint, the CNO sensitivity greatly improves.
For long data taking period, JUNO can overcome the best result on CNO solar neutrinos except in the High background scenario.

2: (*J. Bergstrom et al., JHEP 03 (2016) 132)*

Results on ^{13}N and ^{15}O solar neutrinos

Statistical error only

dashed: w/ *pep* constraint
solid: w/o *pep* constraint



For the first time, it will be possible with JUNO to extract rates of ^{13}N and ^{15}O neutrinos individually.

Conclusions

- After the first data-taking year, JUNO will be able to provide **unprecedented ^{7}Be** and (except for the worst radiopurity scenario) ***pep*** solar neutrino results.

- JUNO will also be able to provide the **first simultaneous ^{7}Be, pep, CNO measurement for > six years** data taking in case of optimistic radiopurity scenarios.

- Except for the High background scenario, JUNO will be **highly competitive for the CNO** measurement for long data-taking, **using pep constraint**.

- The first separate detection of ^{13}N and ^{15}O neutrinos is also possible!

- Study in progress for the possible improvement in the sensitivity results using Correlated and Integrated Directionality (CID) method, developed by Borexino collaboration (**Details in Luca Pelicci talk today**).

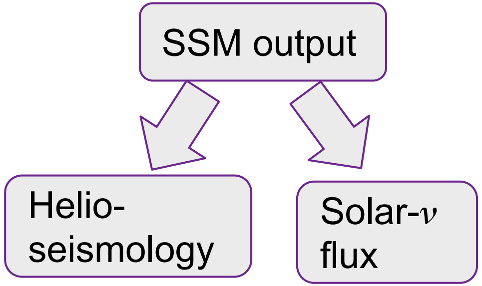
"**JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos**" @ *JCAP10(2023)022.*

Thank you for your attention

Backup

The Solar Metallicity Problem

Metallicity (**Z/X**): abundance of elements with Z>2 in the Sun. Can be inferred from spectroscopic measurement of the photosphere.



Two Classes of Standard Solar Models (SSMs) with different metallicity input:
1) **High-Metallicity HZ-SSM**: older GS98 metallicity input: Z/X = 0.0229
2) **Low-Metallicity LZ-SSM:** newer AGSS09 metallicity input: Z/X = 0.0178

Solar neutrino fluxes depends on the HZ/LZ SSM

Species	HZ-Flux ($cm^{-2}s^{-1}$)*	LZ-Flux ($cm^{-2}s^{-1}$)**	Relative difference(%)
pp	$5.98(1 \pm 0.006)\times10^{10}$	$6.03(1 \pm 0.005)\times10^{10}$	-0.8
pep	$1.44(1 \pm 0.01)\times10^{8}$	$1.46(1 \pm 0.009)\times10^{8}$	-1.4
^{7}Be	$4.93(1 \pm 0.06)\times10^{9}$	$4.50(1 \pm 0.06)\times10^{9}$	8.9
^{8}B	$5.46(1 \pm 0.12)\times10^{6}$	$4.50(1 \pm 0.12)\times10^{6}$	17.6
^{13}N	$2.78(1 \pm 0.15)\times10^{8}$	$2.04(1 \pm 0.14)\times10^{8}$	26.6
^{15}O	$2.05(1 \pm 0.17)\times10^{8}$	$1.44(1 \pm 0.16)\times10^{8}$	29.7
^{17}F	$5.29(1 \pm 0.20)\times10^{6}$	$3.26(1 \pm 0.18)\times10^{6}$	38.3

Low metallicity inputs spoil the agreement of the HZ-SSM (using older metallicity) with the helio-seismological data.

Measuring the flux of solar neutrinos could provide a crucial input to solve the puzzle

** SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (2017) 202 + Grevesse et al.,Space Sci.Rev. (1998)85 12*
*** SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (2017) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

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Solar neutrinos in JUNO

	Solar ν	^{7}Be	*pep*	CNO
HZ-SSM	$\Phi\,[10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$49.3(1\pm0.06)$	$1.44(1\pm0.009)$	$4.88(1\pm0.11)$
	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	$\Phi\,[10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$45.0(1\pm0.06)$	$1.46(1\pm0.009)$	$3.51(1\pm0.10)$
	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
Borexino results	$\Phi\,[10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$49.9\pm1.1^{+0.6}_{-0.8}$	$1.27\pm0.19^{+0.08}_{-0.12}$ (LZ) $1.39\pm0.19^{+0.08}_{-0.13}$ (HZ)	$6.6^{+2.0}_{-0.9}$

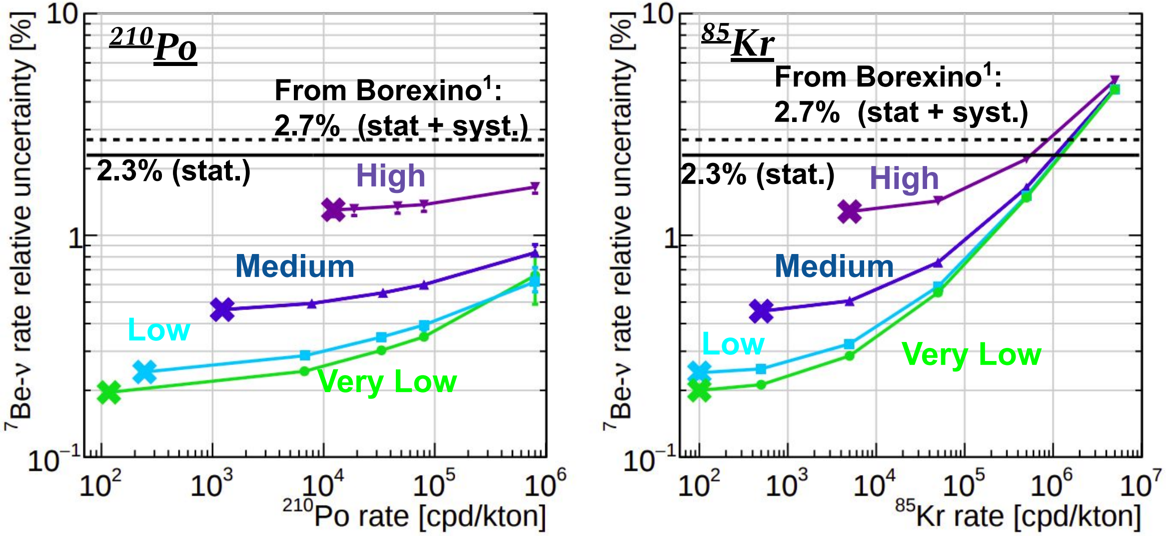
JUNO radio-purity levels

	^{40}K	^{85}Kr	^{232}Th chain	^{238}U chain	^{210}Pb chain
	High Background scenario				
$c\ [\frac{g}{g}]$	1×10^{-16}	4×10^{-24}	1×10^{-15}	1×10^{-15}	5×10^{-23}
	Very Low Background scenario				
$c\ [\frac{g}{g}]$	2×10^{-19}	8×10^{-26}	5.7×10^{-19}	9.4×10^{-20}	5×10^{-25}

Results on ^{7}Be solar neutrinos

Impact of ^{210}Po and ^{85}Kr Background Levels

Stat. error only



- Measured ^{7}Be rate precision worsens as a function of increased backgrounds levels.
- If JUNO experiences out-of-equilibrium ^{210}Po contamination as same level of Borexino (~8×10^{4} cpd/100t), JUNO can still improve the current results on ^{7}Be solar neutrinos.
- When ^{85}Kr rate is kept below 10^{6} cpd/100t, JUNO can still overcome the current results on ^{7}Be solar neutrinos

1. BOREXINO collaboration, Nature 562 (2018) 505

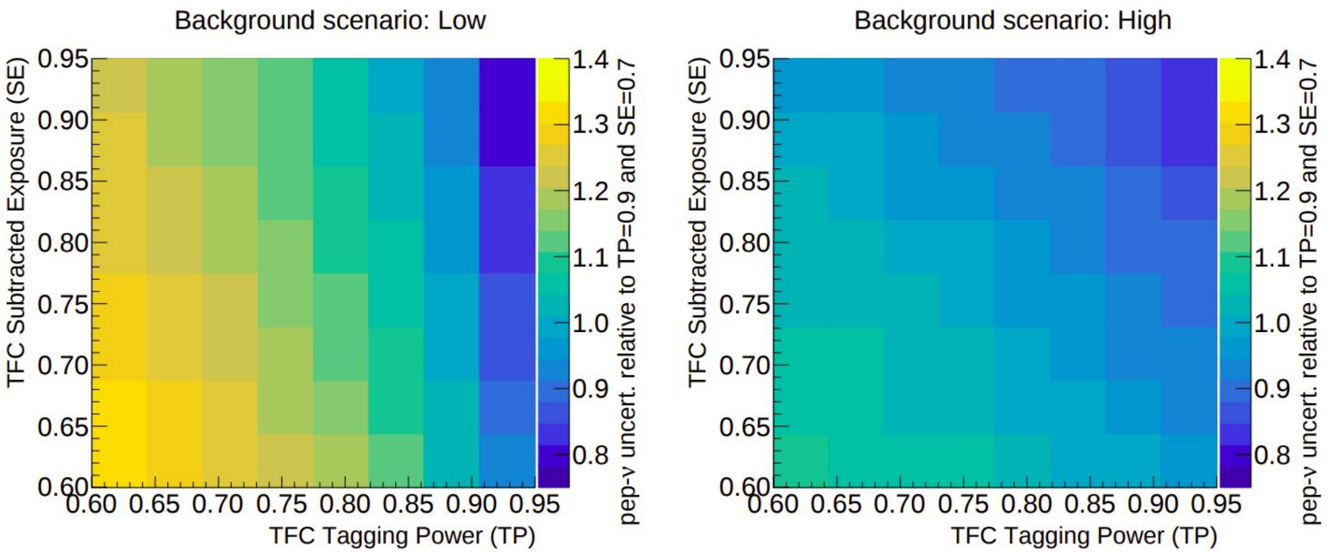
Cosmogenic backgrounds in JUNO

Isotope	$R_{\text{Scaling exp.}}$ [cpd/kton]	R [cpd/kton]	$\langle R \rangle$ [cpd/kton]	$\langle R \rangle_{\text{ROI}}$ [cpd/kton]
^{11}C	$R_{\text{Bx}} = 274 \pm 3$ $R_{\text{KL}} = 1106 \pm 8$	1890 ± 199 1959 ± 254	1916 ± 157	1761 ± 144
^{10}C	$R_{\text{Bx}} = 6.2 \pm 2.2$ $R_{\text{KL}} = 21.1 \pm 1.8$	41.4 ± 15.3 36.5 ± 5.7	37.1 ± 5.3	0.25 ± 0.04
^{6}He	$R_{\text{Bx}} = 11.1 \pm 4.5$ $R_{\text{KL}} = 15.4 \pm 2$	74 ± 31 26.6 ± 4.9	27.8 ± 4.8	12.7 ± 2.19

Results on *pep* solar neutrinos

Impact of TFC performance on pep-ν sensitivity

Stat. error only



- TP parameter is more impactful parameter with respect to SE
- As the internal background levels increase, the precision of measurement is not significantly influenced by ^{11}C discrimination performance.