Solar neutrinos sensitivity studies: current status

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on behalf of JUNO NuSol analysis group

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Outline

1. **Sensitivity to 7Be, pep and CNO solar neutrinos**
   → recap of the technote updates (docDB#7661)

2. **NuSol modulations:**
   - Day-night asymmetry sensitivity studies → updates (docDB#8899)
   - g-modes

REMINDER

All the results independently **cross-checked** by two groups (**Milano** and **Jülich** or **Munich**).

NuSol spectroscopy
recap of the Technote docDB#7661 updates

docDB#7661

Updated JUNO sensitivity to intermediate energy solar neutrinos, ^{7}Be, *pep*, and CNO: results of the two independent analysis performed by Milano and Jülich

Milano group
Davide Basilico[1], Barbara Caccianiga[1], Federico Ferraro[1], and Alessandra C. Re[1]

Jülich group
Alexandre Göttel[2,4], Livia Ludhova[2,4], Anita Meraviglia[3,4], Luca Pelicci[2,4], Apeksha Singhal[2,4], and Giulio Settanta[2,5]

Updates introduced wrt the version already approved by the referees (shown also in the July 2022 Collaboration Meeting docDB#8699):

1. Fixed a bug in the CNO neutrinos PDF
2. New method for the estimation of the relative uncertainties on the neutrinos rate and their error
3. New study related to ^{13}N and ^{15}O

- ^{7}Be, *pep* neutrinos: no relevant differences wrt previous results
- CNO worsened its precision

but still...

- ➢ Short-term: after 1y, JUNO will match the best ^{7}Be (but for the worst radiopure scenario) and *pep* results
- ➢ Long-term: in optimistic radiopure scenarios, CNO precision improved after 6y + first detection of ^{13}N and ^{15}O separately

approved by the internal reviewers

Looking for solar neutrino modulations

Solar neutrino rate varies in time due to three possible physical motivations:

Day-night modulations	Annual modulations	g-Mode modulations
Driven by the coherent re-generation effect of flavor oscillations	Due to eccentricity of the Earth's orbit	Induced by possible gravitationally driven modes (g-modes) of solar matter
period = 24h	period = 1 year	period ~ 1 h - 10^4 h
Never observed with high significance, to date	Well-established and consistent with solar origin; absence of an annual modulation rejected at 99.99% C.L.	Never observed
	→ **not interesting here**	

Looking for solar neutrino modulations

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Day-night modulations

Driven by the coherent re-generation effect of flavor oscillations

period = 24h

Never observed with high significance, to date

g-Mode modulations

Induced by possible gravitationally driven modes (g-modes) of solar matter

period ~ 1 h - 10^4 h

Never observed

NuSol modulations (7Be, pep, CNO)
two analysis methods

Day-night modulations

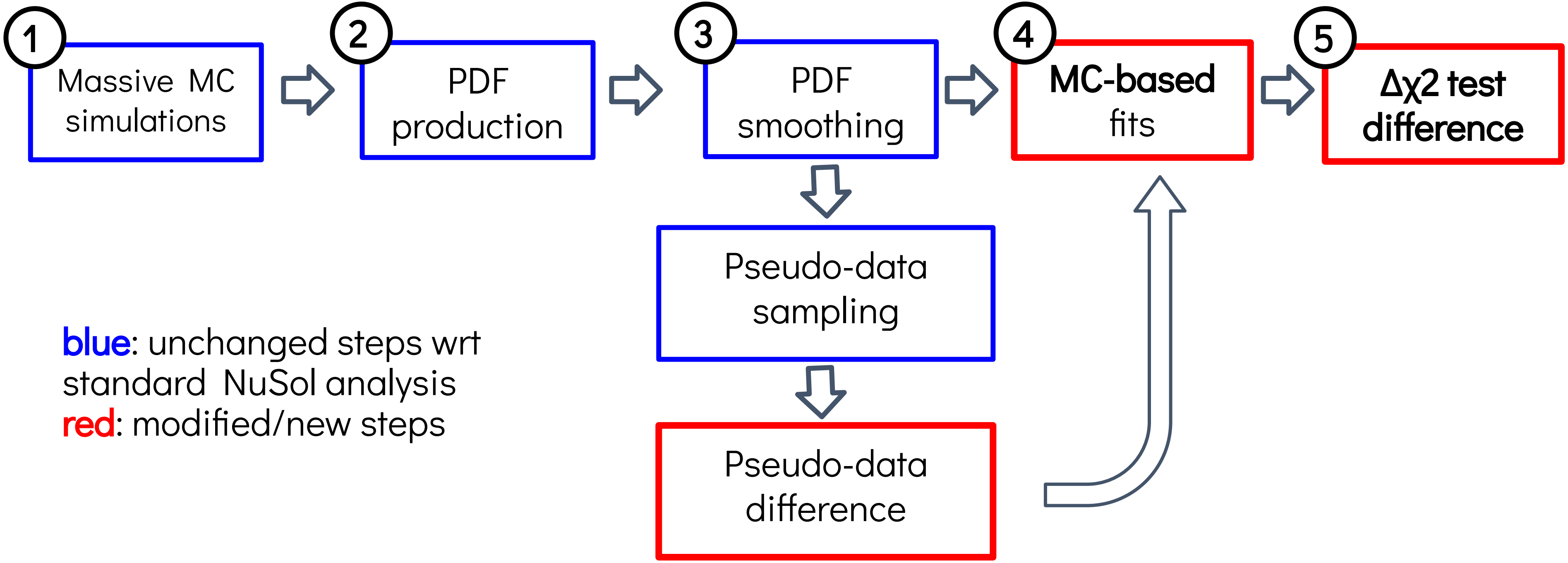
Statistical subtraction method
detailed later on

Lomb-Scargle method
(based on spectral frequency analysis), already discussed for g-modes search

docDB#8179 (Milano Technote)
docDB#7746 (TUM Technote)

g-Mode modulations

Day-night modulations: analysis flow



blue: unchanged steps wrt standard NuSol analysis
red: modified/new steps

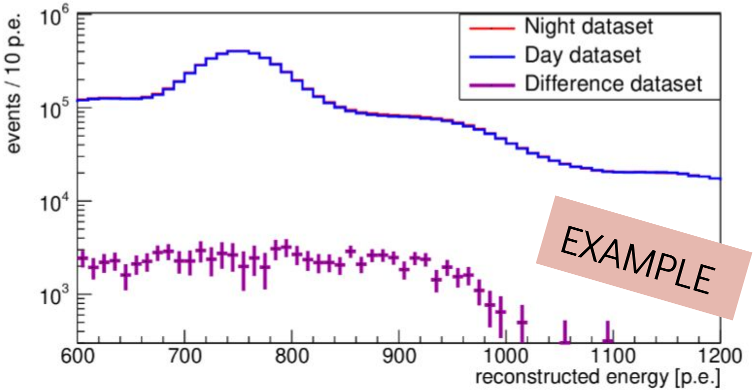
Dataset generation

The generation is based on the assumption that **only the ^{7}Be rate is expected to vary between day and night**

The day-night asymmetry A_{DN} is defined as:

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

- Expected A_{DN} for Be7: **~0.1%**
  [J. N. Bahcall et al., JHEP 04 (2002), 007;]
- Borexino best result [Phys.Lett.B 707 (2012) 22-26]:
  A_{DN} precision **~ 1.2%**
- Some "non-standard" scenarios proposed by many Beyond the Standard Model theories expect A_{DN}**>0.1%**



R. Plestid , Phys. Rev. D 104, 075027 , "Luminous solar neutrinos. i. dipole portals."
R. Plestid. , Phys. Rev. D 104, 075028, "Luminous solar neutrinos. ii. mass-mixing portals. "
V. Brdar, J. Kopp, J. Liu, P. Prass, and X.P. Wang, Phys. Rev. D 97, 043001, Fuzzy dark matter and nonstandard neutrino interactions.
V. Brdar, A. Greljo, J. Kopp, and T. Opferkuch, JCAP01 (2021) 039, The neutrino magnetic moment portal: cosmology, astrophysics, and direct detection.

Spectral fit of "difference dataset"

EXAMPLE

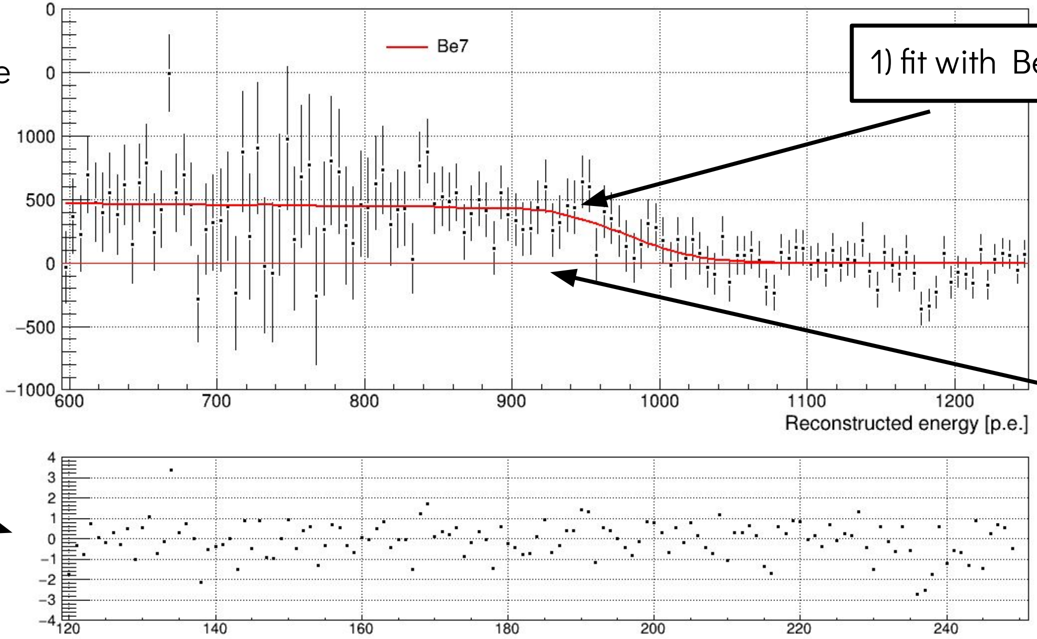
The only free parameter is Be7 rate. For each Difference datasets, two fits are performed:

1. Be7 rate left free to vary → χ^2(Be7 rate free)
2. Be7 rate fixed to zero → χ^2(Be7 rate = 0)

The difference of χ^2 s is calculated to estimate the significance to possible asymmetries

Events (difference dataset)

Dataset example with A_{DN} = 0.1%



1) fit with Be7 rate free to vary

2) fit with Be7 rate fixed to 0

residuals for fit with Be7 rate zero

Spectral fit of “difference dataset”

The only free parameter is Be7 rate. For each Difference datasets, two fits are performed:

1. Be7 rate left free to vary → χ^2(Be7 rate free)
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The difference of χ^2 s is calculated to estimate the significance to possible asymmetries

“Standard” binary hypothesis test, with $\Delta\chi^2$ as test statistics

For each configuration (radiopurity scenario and data-taking time), and fixing A_{DN} value, the dataset generation and fitting procedure is performed twice:

- “Modulated dataset”: injecting $A_{DN} > 0$ → extracting $\Delta\chi^2_A$
- “White noise dataset”: without injecting A_{DN} (that is, $A_{DN}=0$) → extracting $\Delta\chi^2_0$

$\Delta\chi^2$ distributions (example)

The dataset generation and fitting procedure is performed twice:

- "Modulated dataset": once injecting $A_{DN} > 0$ → extracting $\Delta\chi^2_A$
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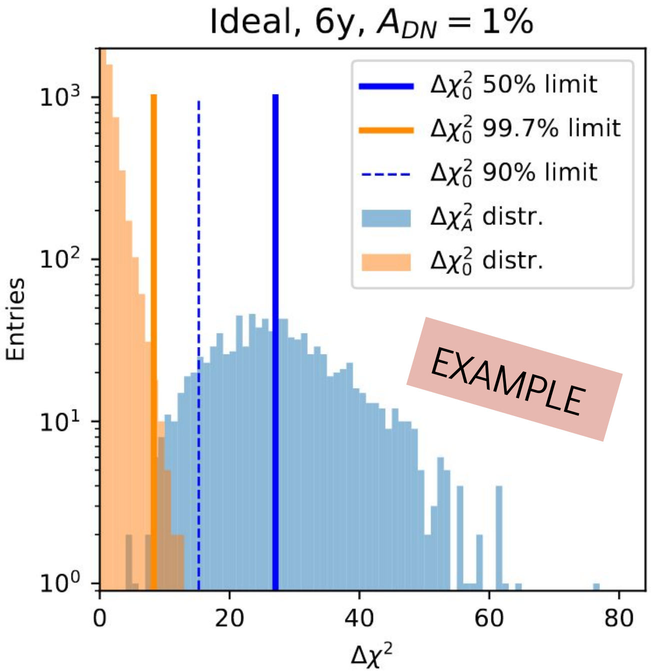

We build two **$\Delta\chi^2$** histograms repeating the procedure 10^4 times (dataset generation → fitting twice → evaluating **$\Delta\chi^2$**)

The sensitivity to DN is defined by "minimum detectable A_{DN}": lowest amplitude (= A_{DN}) **that can be detected at 3σ with 50 % probability**

→ C.L. 50% for modulated dataset and C.L. 99.7% (that is 3σ) for WN dataset are constructed, marked by the vertical solid lines

$\Delta\chi^2$ distributions (example)

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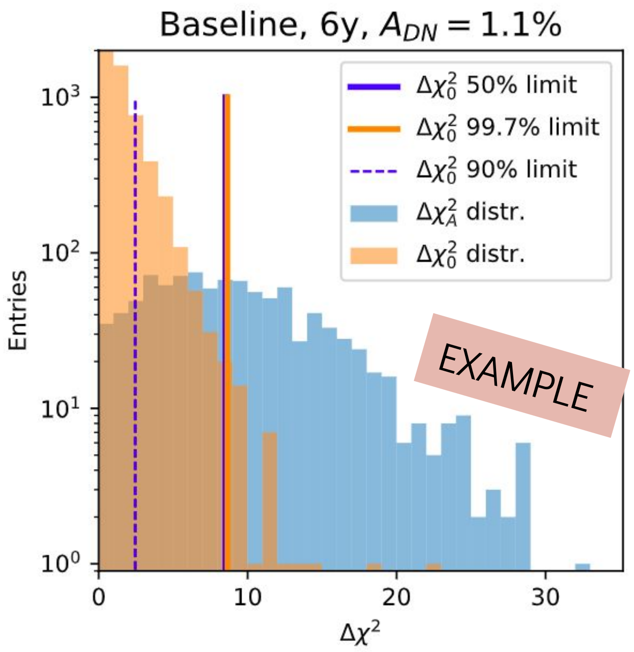

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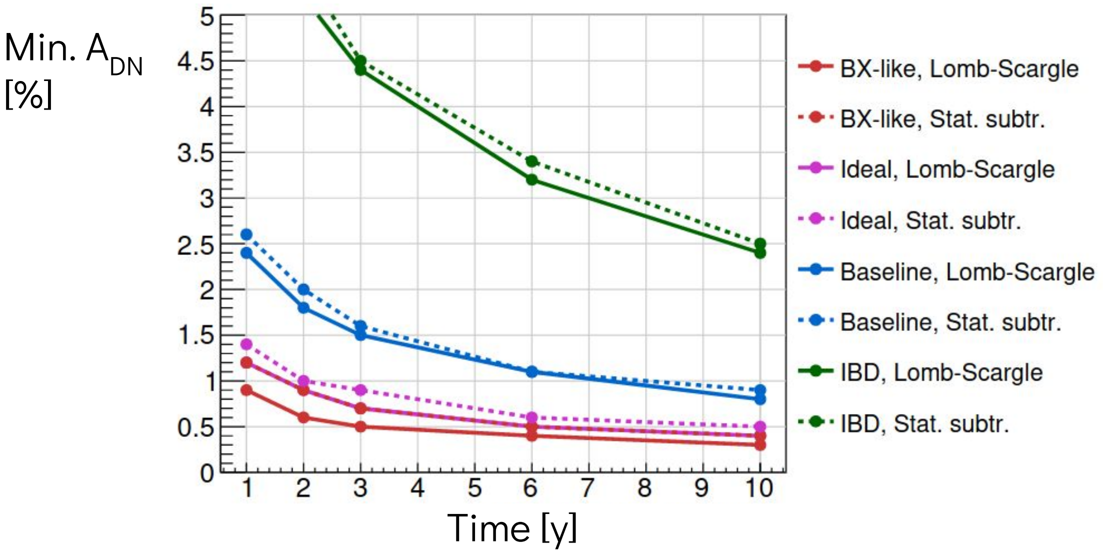
→ **C.L. 50% for modulated dataset** and **C.L. 99.7% (that is 3σ) for WN dataset** are constructed, marked by the vertical solid lines

We choose the minimum detectable asymmetry as the one which gives rise to the overlapping of the blue and orange solid lines

Minimum detectable A_{DN} vs exposure



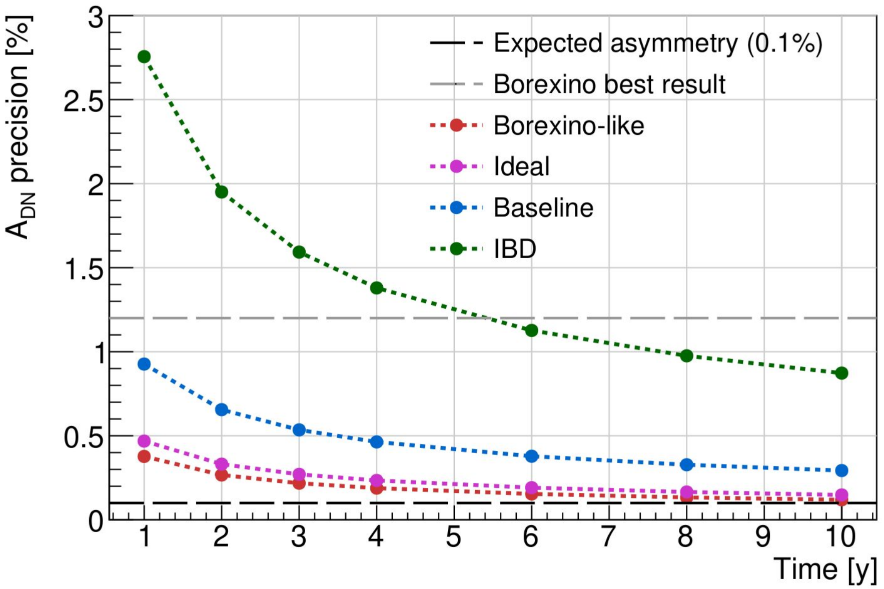
Min detectable A_{DN} after 10y

Scenario	Lomb Sc.	Stat. Sub.
BX-like	0.3%	0.4%
Ideal	0.4%	0.5%
Baseline	0.8%	0.9%
IBD	2.4%	2.5%

- Performances: two methods almost equivalent. **Lomb-Scargle** slightly better especially for long data takings
- **Able to probe A_{DN} values never reached before**
- Unfortunately, **unable to reach the A_{DN} = 0.1%** expected by SSM+oscillations

Injecting A_{DN} = 0.1%: reconstructed A_{DN} precision

Precision on A_{DN} as a function of the data-taking time, when A_{DN} = 0.1% (expected value) is injected



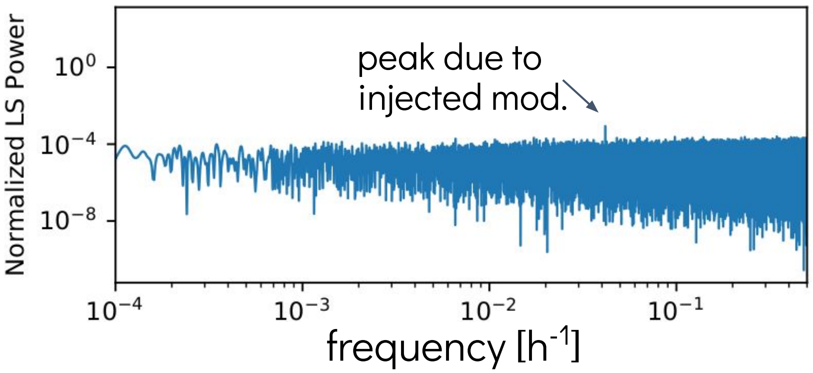
Even only after 1y JUNO will be able to improve the Borexino A_{DN} precision in the **Borexino-like, ideal** and **baseline** raadiopurity scenarios. For the **IBD** one, ~6 years are needed.

In a nutshell, JUNO will be able to highly **improve the current Borexino A_{DN} precision (factor ~5 in Bx-like or Ideal scenarios)**

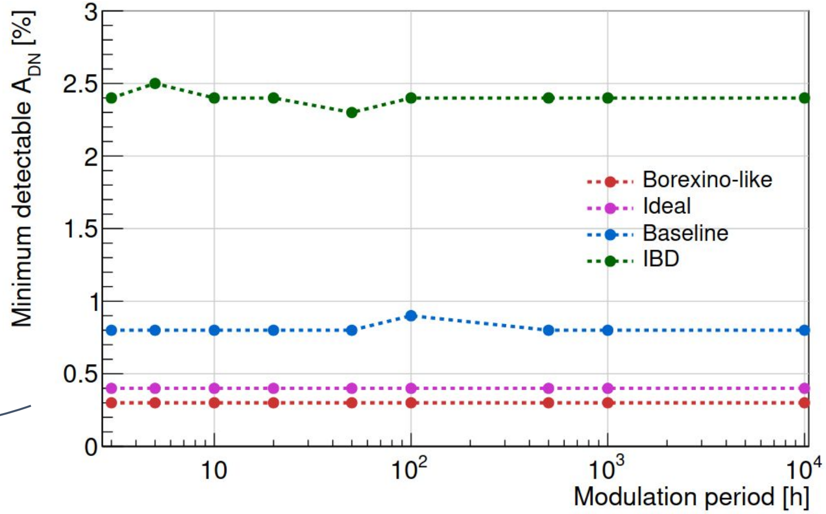
gModes: Lomb-Scargle analysis

Lomb-Scargle: extension of the Fourier Trasform to treat data-sets not evenly distributed in time
We don't know a-priori the period T of the modulation

Frequency periodogram (example, Ideal 10Y ADN=0.2%)



Min detectable A_{DN} (3σ) after 10y



Sensitivity doesn't significantly depend on T
→ **same results of the Day-Night analysis with LS method**

Analysis status: a summary

1. **Sensitivity to 7Be, pep and CNO solar neutrinos** (Milano, Jülich)**:** technote approved (docDB#7661)

2. **Modulations:**
    - Sensitivity to **day-night** asymmetry (Milano, Jülich): technote approved (docDB#8899)
    - Sensitivity to **g-modes**: technotes previously approved (docDB#7746 and docDB#8179)

Analysis entirely approved by the internal reviewers! ✓

The studies will flow into the **"JUNO sensitivity to 7Be, pep and CNO solar neutrinos" paper**.

Writing is under finalization. It will be circulated to the Publication Committee soon (~weeks)

NuSol paper

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

[preliminary]

JUNO Collaboration

Abstract. The Jiangmen Underground Neutrino Observatory (JUNO), the first multi-kton liquid scintillator detector under construction in China, will have a unique potential to perform a real-time measurement of solar neutrinos well below the few MeV threshold typical for Water Cherenkov detectors. JUNO large target mass and excellent energy resolution are pre-requisites for reaching unprecedented levels of precision. In this paper, we provide estimation of the JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos that can be obtained via a spectral analysis above the 0.45 MeV threshold. This study is performed assuming different scenarios of the liquid scintillator radio-purity, ranging from the most optimistic one corresponding to the radiopurity levels obtained by the Borexino experiment, up to the minimum requirements needed to perform the neutrino mass ordering program with reactor antineutrinos - the main goal of JUNO.

Contents

Conclusions

- **NuSol spectroscopy results updated**
  - No substantial change in 7Be, pep, CNO fluxes sensitivity

- **Sensitivity to the ^{7}Be rate neutrinos day-night asymmetry:**
  - JUNO will improve Borexino result in 1 year for each radiopurity scenarios but the worst one, but not confident regarding a **A_{DN}=0.1%** detection
  - Probing some "non-standard" scenarios proposed by many BSM theories)

- **Analysis status:**
  - thoroughly cross-checked independently
  - entirely reviewed and internally approved

- **Paper writing is going to be finalized, will be circulated to the collaboration in weeks**

Thanks!

Backup

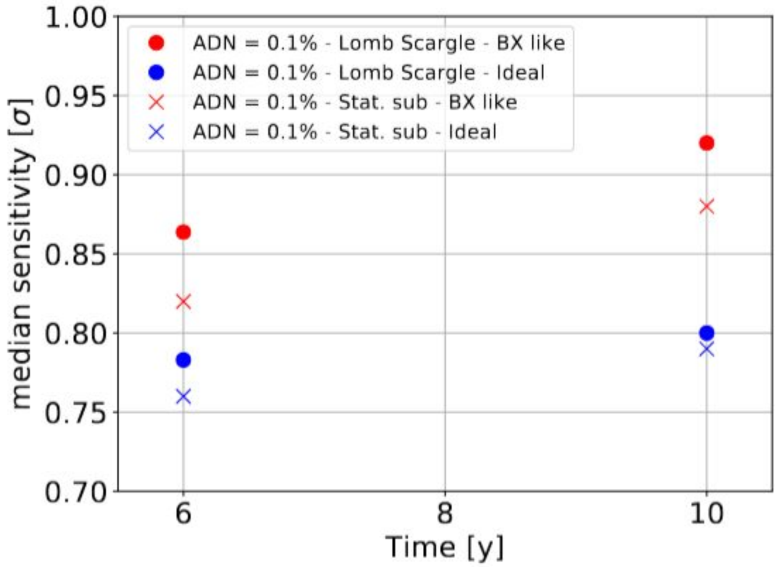
Minimum detectable A_{DN} vs exposure

EXAMPLES

Time [y]	Borexino-like		Ideal		Baseline	
	Min. $A_{\rm DN}$ Milano	Min. $A_{\rm DN}$ Jülich	Min. $A_{\rm DN}$ Milano	Min. $A_{\rm DN}$ Jülich	Min. $A_{\rm DN}$ Milano	Min. $A_{\rm DN}$ Jülich
1y	1.2%	1.1%	1.4%	1.4%	2.6%	2.7%
6y	0.5%	0.5%	0.6%	0.6%	1.1%	1.1%
10y	0.4%	0.4%	0.5%	0.4%	0.9%	0.9%

They differ at <0.1% level: **very good agreement**

Injecting A_{DN} = 0.1%: median sensitivity



Median discovery significance injecting ADN = 0.1% for the Borexino-like and Ideal scenarios, as a function of time.

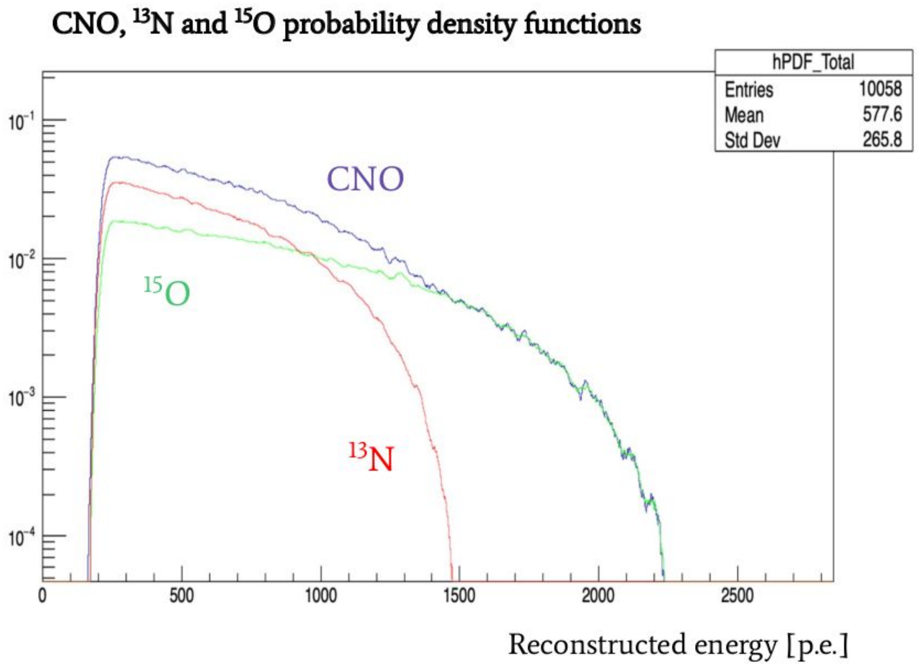
× → statistical subtraction method

● → Lomb-Scargle method

In both cases, JUNO will have a significance lower than 1σ for a ADN = 0.1% detection even after 10 years of data-taking time

So, JUNO will probably not able to detect A_{DN} = 0.1%, but **what is the minimum detectable A_{DN}?** (see next slide)

Recap of the Technote docDB#7661 updates (under review)



- Due to a mistake, the previous PDF considered the CNO as if it is only composed by ^{15}O, while the ^{13}N contribution was not present.
- ^{15}O is easier to identify wrt ^{13}N
- Once creating the CNO PDF with the correct mixture of ^{13}N and ^{15}O, this impacts relevantly on the analysis

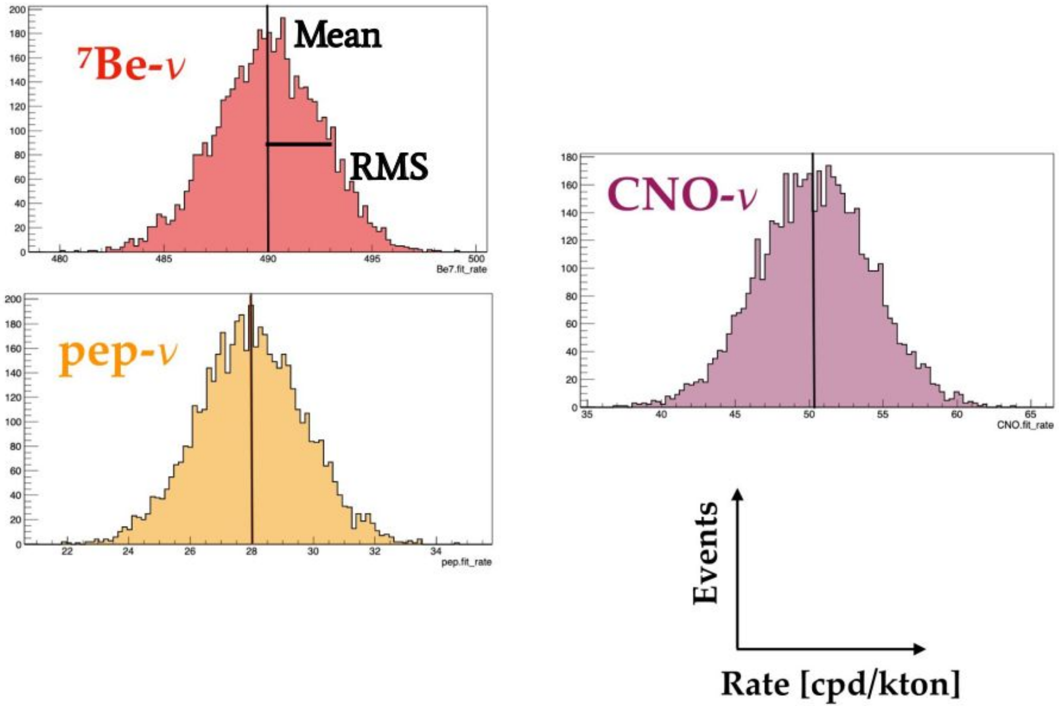
the CNO precision is worsened and the *pep* precision is improved

Recap of the Technote docDB#7661 updates (under review)

Before...

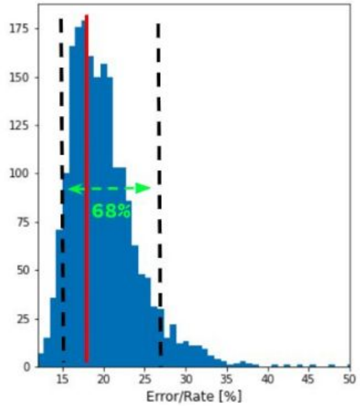
We extracted the neutrinos sensitivity as **RMS / Mean of the reconstructed rate distributions**, while we did NOT consider the error on these uncertainties

Example of reconstructed rate distributions



Recap of the Technote docDB#7661 updates (under review)

Now... → new and more robust method to calculate both the average uncertainty and its error

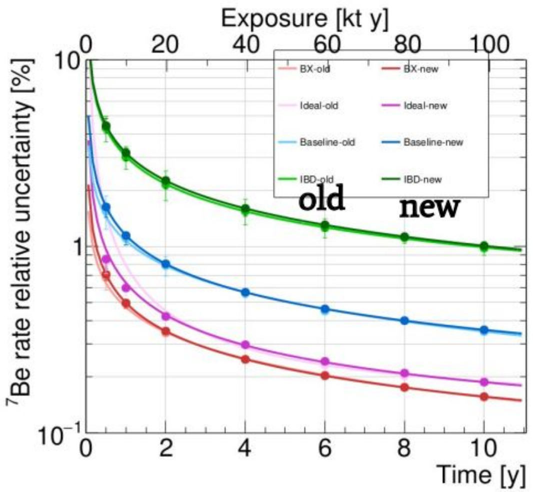


- For each species, we build the distribution of $Error_i/Rate_i$ where $i = 1,...,10^4$ is the index of the single fit
- We then extract the following quantities:
  - average uncertainty as the median of this distribution
  - left and right errors on the uncertainty as the distance between the median itself and the 68% C.L.

By doing so,

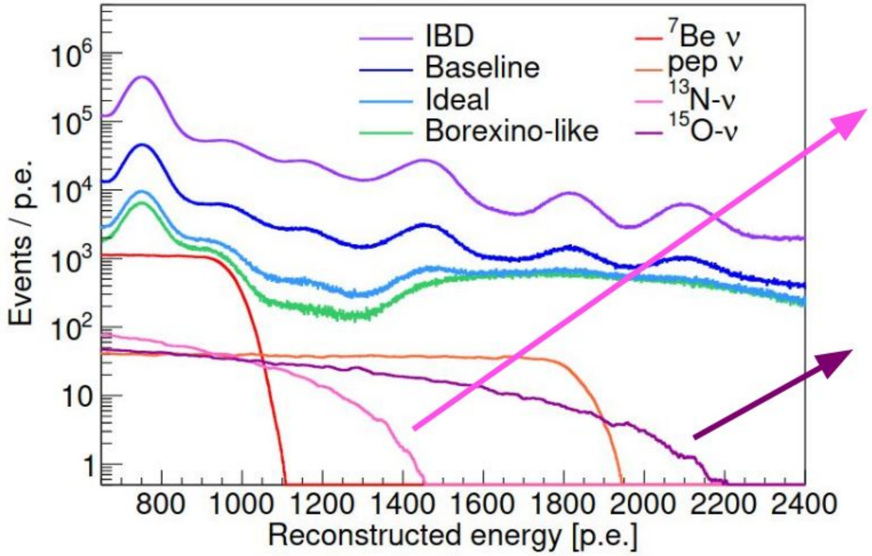
- we take into account possible correlations among the species
- the best values don't change significatively wrt the previous method

example



Recap of the Technote docDB#7661 updates (under review)

- **possible first detection ever**, allowed by the huge JUNO statistics
- only for the two most radiopure scenarios
- astrophysical importance to infer the direct C and N abundances in the Sun



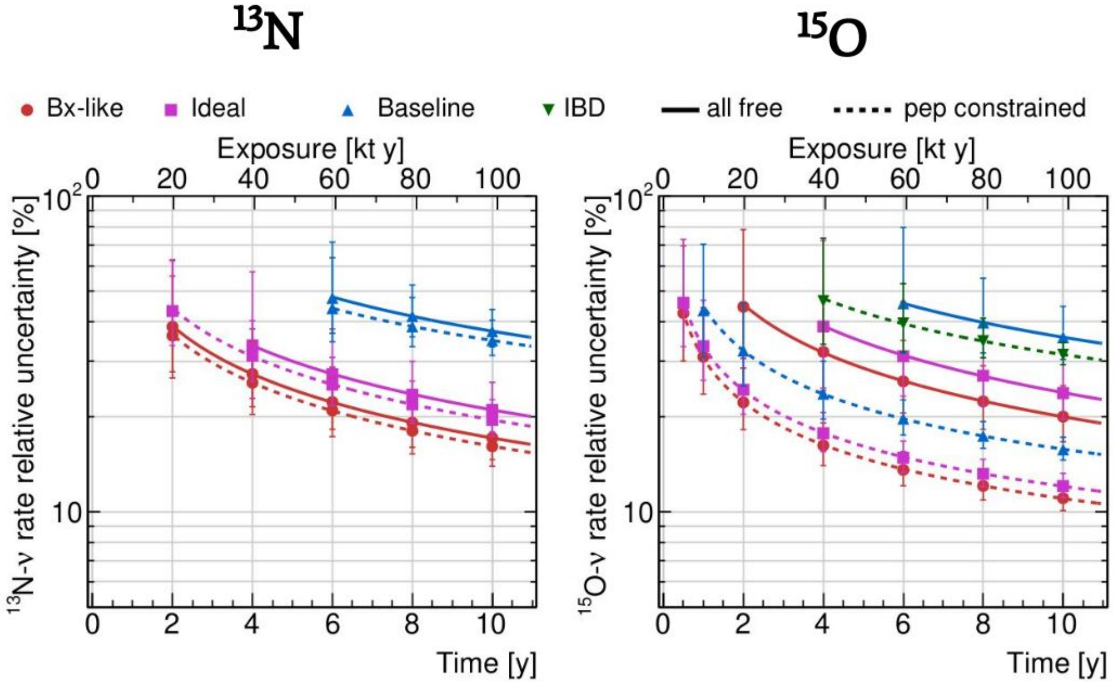
^{13}N neutrinos:

- lower Q-value, **lower s/b ratio**
- less anti-correlation with *pep*

^{15}O neutrinos:

- **strong anti-correlation** with *pep* due to shape similarity, lower rate
- **degeneracy can be broken** via *pep* constraint

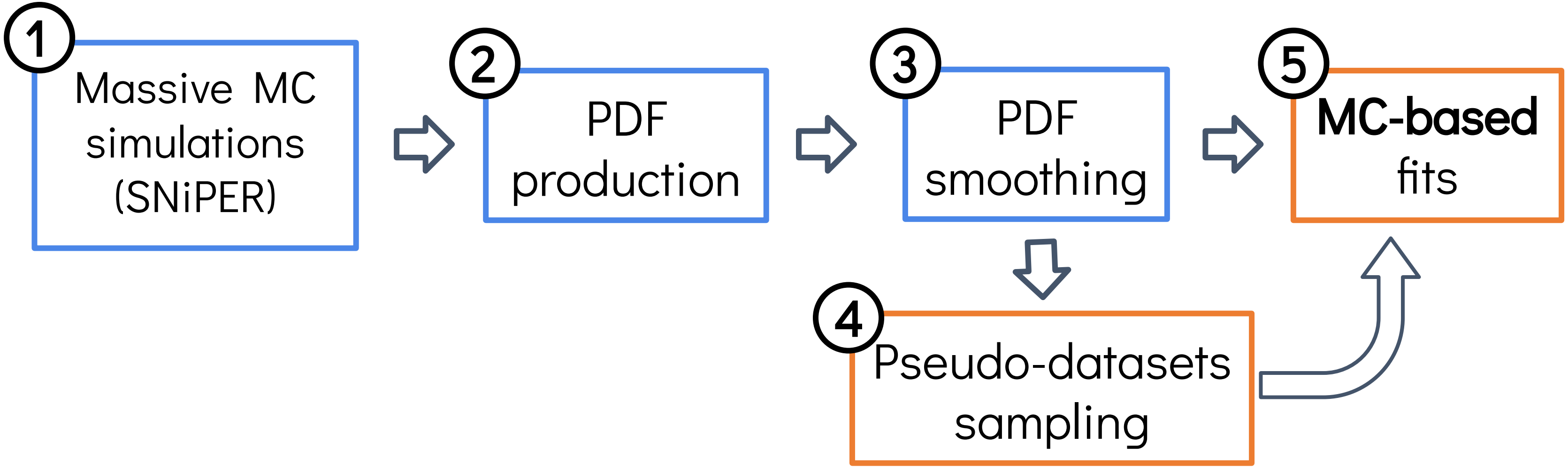
Recap of the Technote docDB#7661 updates (under review)



pep constraint (dashed) does not help significantly

pep constraint (dashed) improves significantly

Sensitivity studies work-flow



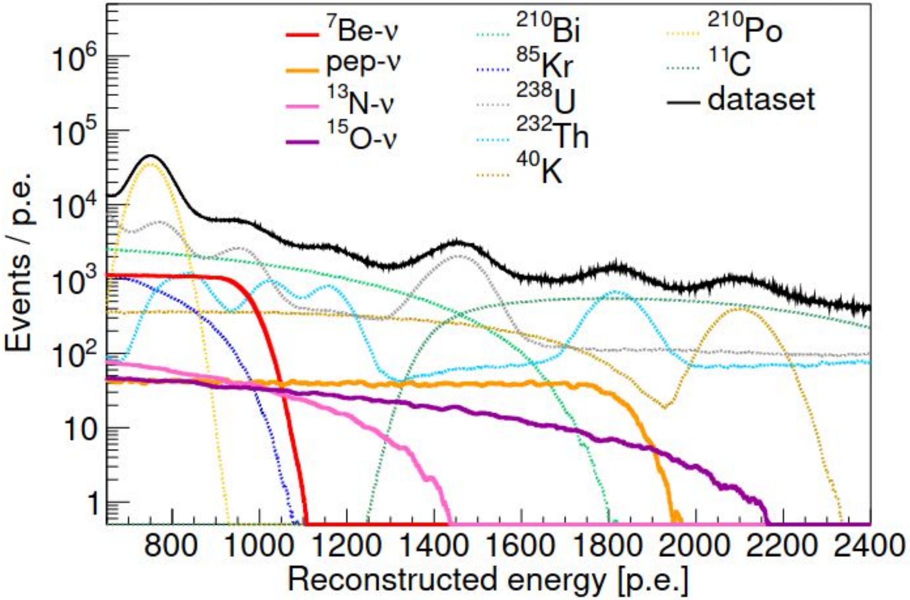
1, 2, 3: common ground

4, 5: independent software frameworks from Milano and Juelich (**MUST** and **JUST** tools)

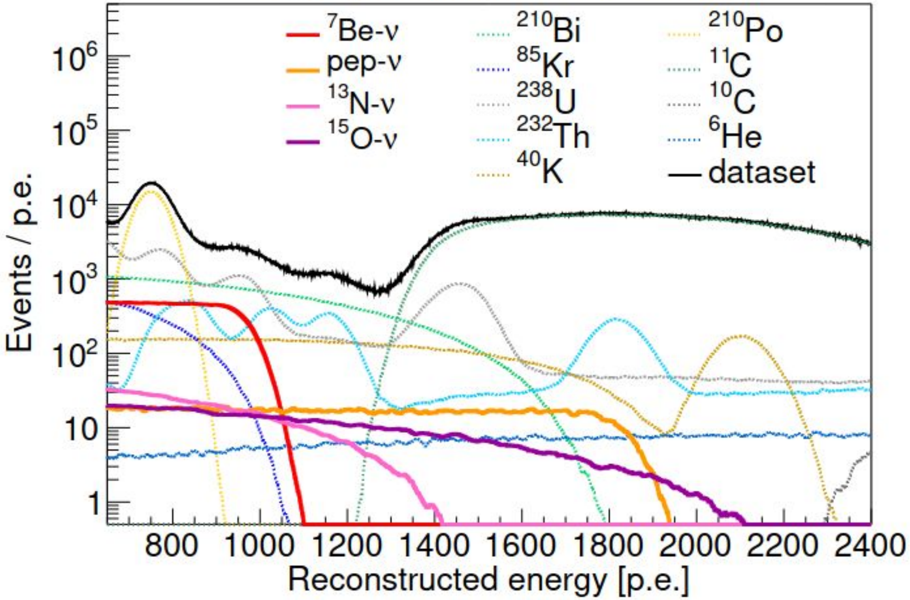
Milano nUsol Sensitivity Tool
Juelich nUsol Sensitivity Tool

Subtracted/Tagged spectra (Baseline scenario)

Baseline Subtracted spectrum
(Depleted in ^{11}C)



Baseline Tagged spectrum
(More populated by ^{11}C)



g-Mode modulations - Summary

What is the JUNO sensitivity to ≳ hour period neutrino modulations with ~% level amplitude?

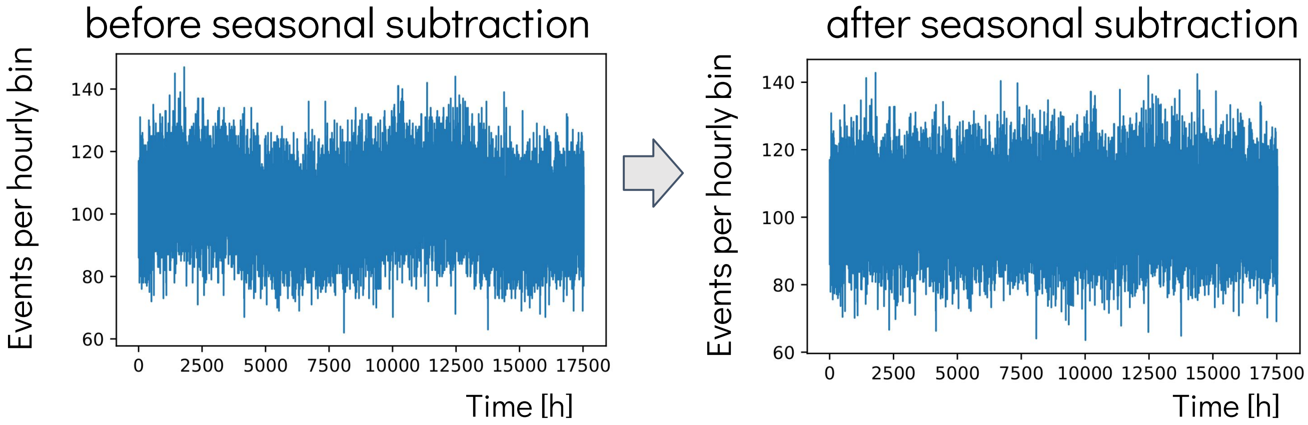
→ physical input: gravitationally driven modes ("g-Modes") mainly driven by the buoyancy force
→ references: g-modes [Apporchaux et al 2010], influence of g-modes on solar neutrino flux [Bahcall and Kumar 1993]

Work performed independently by two groups: TUM (docDB#7746-v3) and Milano (this slides)

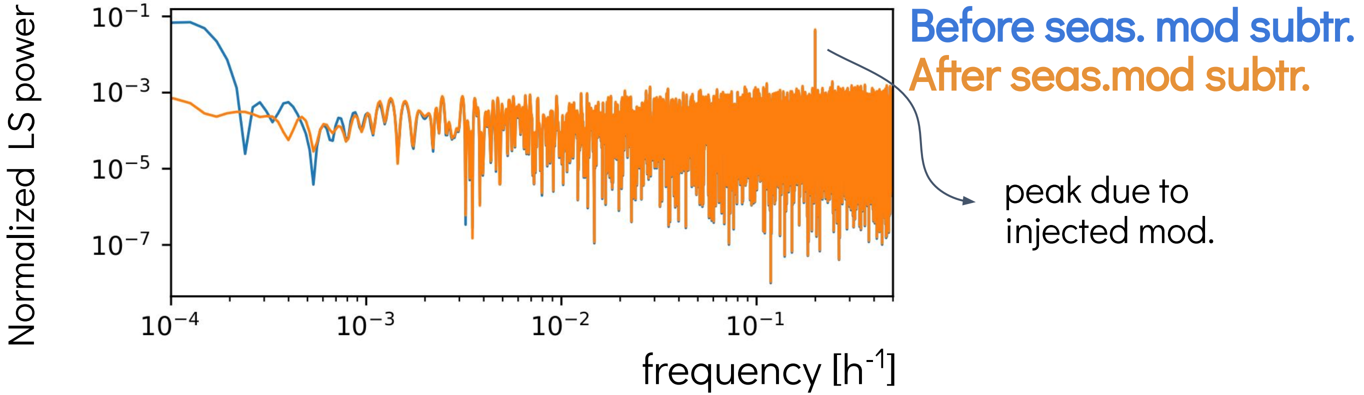
1. "Time" dataset generation → 2. Lomb-Scargle periodogram generation → 3. C.L. extraction

Analysis workflow

1. "Time" dataset generation



2. Lomb-Scargle periodogram generation



Analysis workflow

1. "Time" dataset generation

Based on MC PDFs used for the Be7, pep, CNO sensitivity analysis
Three radiopurity scenarios: Ideal, Baseline, IBD
→ three optimized energy ROIs (in p.e.)

Inputs:

- Neutrino events in ROI (separately Be7, pep, CNO)
- Background events in ROI
  (α are supposed to be 100% excluded thanks to α/□ discrimination)
- Modulation amplitudes: $A_{seasonal}$ = 6.7% $A_{daynight}$ = 0.5% A_{gMode}
- Modulation periods: $T_{seasonal}$ = 1 y $T_{daynight}$ = 1 d T_{gMode}

Two datasets are created:

1) **Dataset w/modulations:**
   - including events as a function of time
   - [technicality] removing the seasonal modulation part
     (this is done since seasonal modulation is well known - not of interest of this analysis - and its removal is essential to make the LS algorithm working)
2) **White Noise**: without modulations

Analysis workflow

3. C.L. extraction

We construct the histograms of LS power evaluated at gMode frequency, for dataset and WN (10^4 entries each one)
The sensitivity defines the relative amplitude of a periodic modulation inside of the solar Be7+pep+CNO signal **that can be detected at 3σ with 90 % probability** → C.L. 90% for dataset and C.L. 99.7% for WN are constructed