JUNO potential for SN, solar, and atmospheric neutrinos

Marco Malabarba[1,2] on behalf of the JUNO collaboration.

07.09.2024 | Neutrino Oscillation Workshop 2024, Otranto

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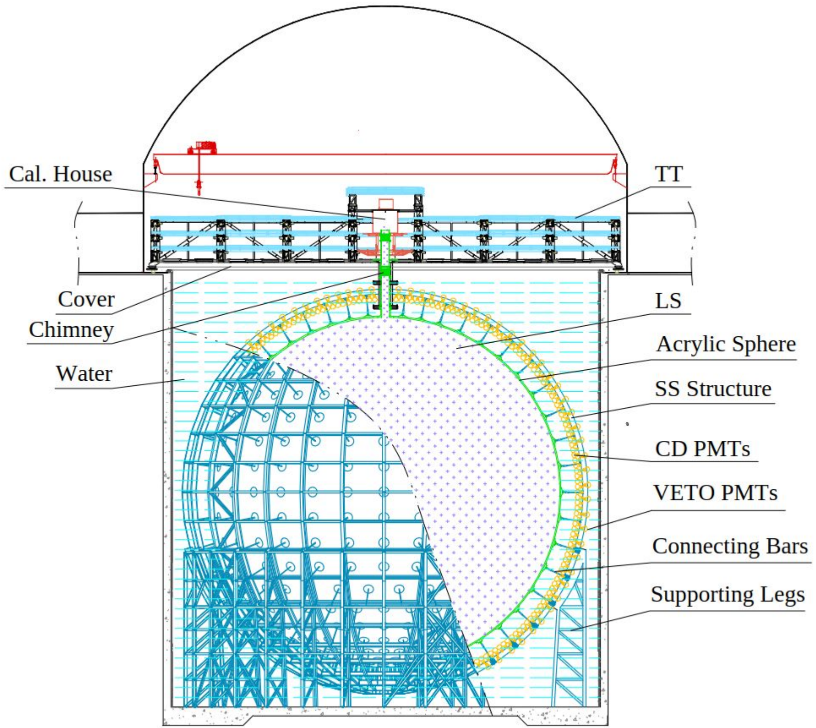
The JUNO detector



Progr. Part. Nucl. Ph. 123 (2022) 103927

JUNO will be the first multi-kton LS detector

- ❖ Construction currently under completion in **South China**, starting of filling end of this year
- ❖ Vertical **overburden** of ~**650 m**
- ❖ **CD:** arXiv: 2311.17314 (2023)
  - ➢ **20 kton** of LAB-based organic liquid scintillator (**LS**)
  - ➢ Acrylic sphere (r = 17.7 m, width = 12 cm)
  - ➢ Stainless steel (SS) structure
  - ➢ **17612 20" PMTs** and **25600 3" PMTs**
- ❖ Veto detectors:
  - ➢ Water Cherenkov detector
  - ➢ Top Tracker *Nucl. Instrum. Meth. A* 1057 (2023) 168680
- ❖ Expected to reach an **unprecedented energy resolution of ~3% @ 1 MeV** arXiv:2405.17860 (2024)
- ❖ **Excellent radiopurity** of all its components *J. High En. Phys.* 11 (2021) 102

For further information refer to Andrea Serafini's plenary talk on Tuesday.

JUNO physics potentials

Reactor antineutrinos:
- ❖ Neutrino Mass Ordering (NMO) determination (3σ)
- ❖ Sub-percent measurement of θ_{12}, Δm^2_{21}, Δm^2_{31}

→ Vanessa Cerrone's presentation

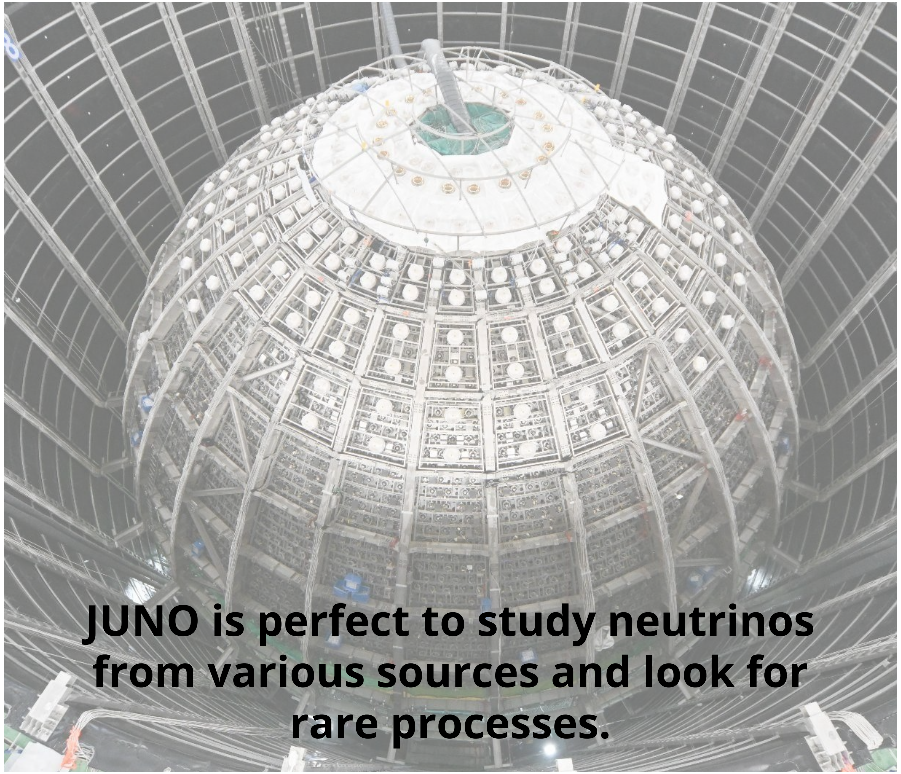
Geoneutrinos

→ Fernanda Rodrigues' presentation

Nucleon decays

→ Wanlei Guo's presentation

and other exotic searches



This talk

Solar neutrinos

Supernova neutrinos

Diffuse supernova neutrino background

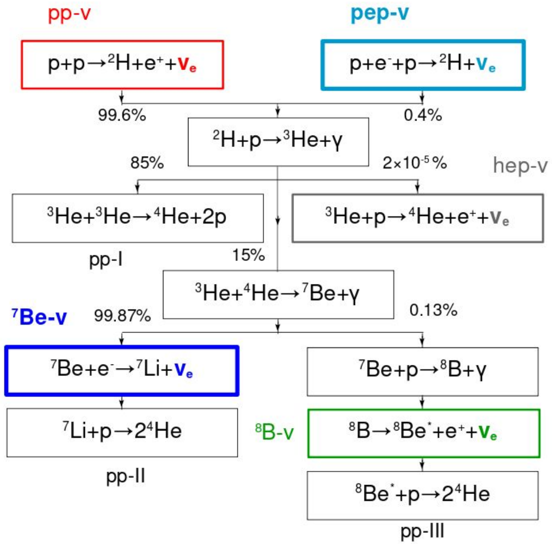
Atmospheric neutrinos

Solar neutrinos

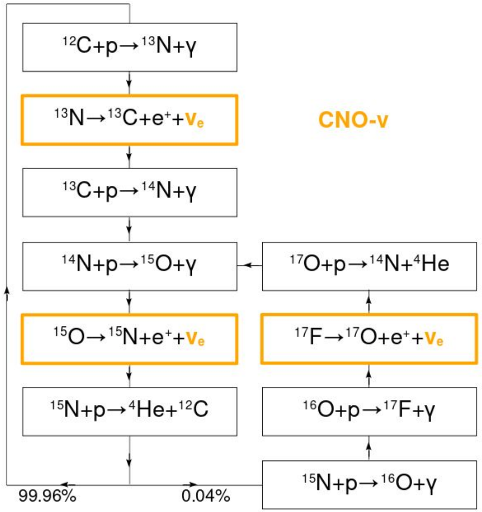
Solar neutrinos

Produced in the core of the Sun through **fusion reactions**:

pp chain

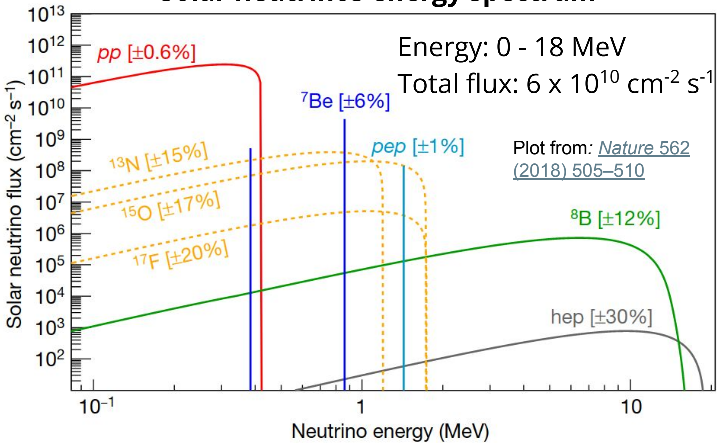


CNO cycle



The ***pp* chain** accounts for **99%** of the total **solar luminosity**
The CNO cycle becomes dominant in heavier stars

Solar neutrinos energy spectrum



Solar neutrinos are helpful to **probe**:

- Physical **quantities** of the **Sun** (i.e. luminosity, metallicity)
- **Neutrino properties**:
  - θ_{12} and Δm^2_{21}
  - Matter effects on neutrino oscillations

Detection of ^{7}Be, *pep*, and CNO neutrinos

Solar neutrinos with energy **< 2 MeV** (^{7}Be, *pep* and CNO) can be detected only through elastic scattering (**ES**) with LS **electrons:**

$$\textbf{ES:} \quad \nu_x + e^- \rightarrow \nu_x + e^- \qquad x = e, \mu, \tau$$

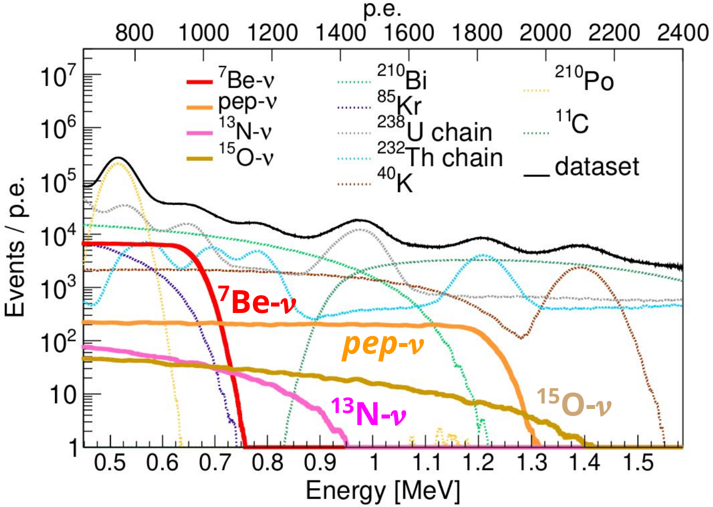
BACKGROUNDS

- **External backgrounds**: negligible with fiducial volume cut
- **Cosmogenic backgrounds**: ^{11}C dominated, tagging with Three-Fold coincidence algorithm [Eur. Phys. Journal C 81 (2021) 1075]
- **Internal backgrounds**: will drive the sensitivity to solar neutrinos, different concentration scenarios studied:

Very low	Borexino phase-III
Low	10 x Very Low
Medium	10 x Low
High	Minimum requirement for NMO studies

[J. Cos. Astro. Phys. 10 (2023) 022]

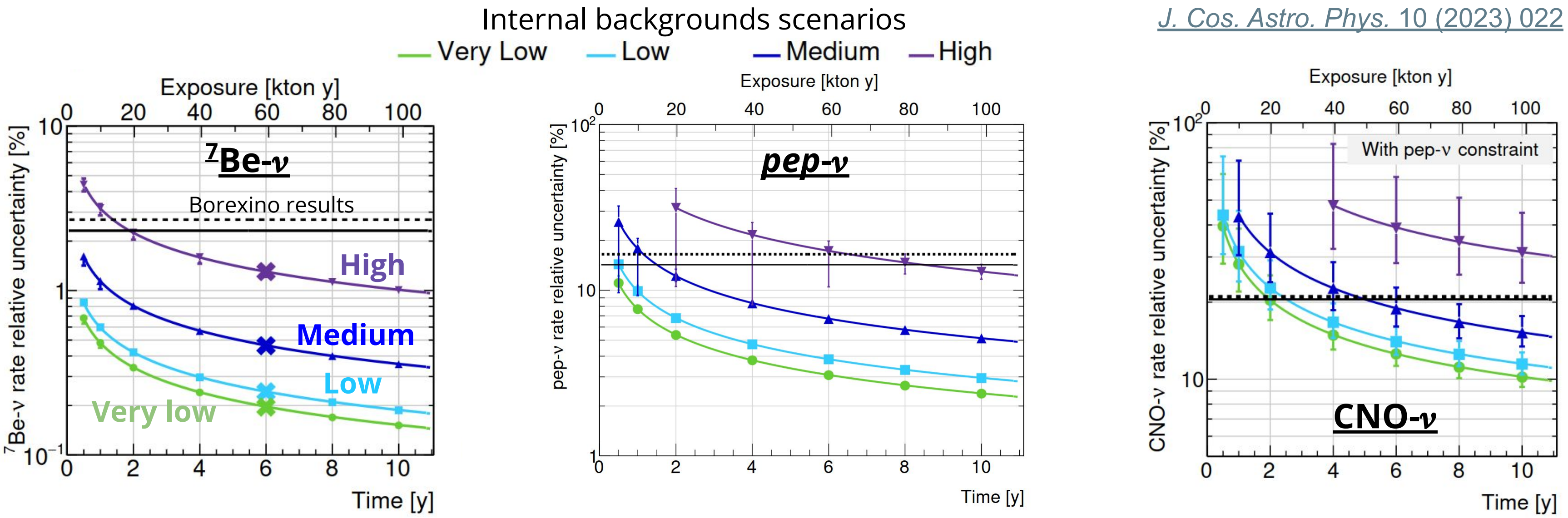
6 years, Medium radiopurity scenario



Solar neutrinos contribution can be extracted thanks to the **different spectral shapes** of the species.

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

[J. Cos. Astro. Phys. 10 (2023) 022]



JUNO can provide the **most precise measurements** within:

~2 years

~2 years, **apart** from **High** radiopurity scenario

~6 years, **apart** from **High** radiopurity scenario

No constraint on ^{210}Bi needed

Separation of ^{13}**N-ν** and ^{15}**O-ν** possible with **good radiopurity**

JUNO detection of ^{8}B solar neutrinos

Chin. Phys. C 45 023004 (2021) 1
Ap. J. 965 (2024) 122

Interaction channels of ^{8}B-ν:

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

- No threshold
- All flavours & $\sigma(\nu_{\mu,\tau}) / \sigma(\nu_e) = 1/6$
- Single events - continuous spectrum

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

- $E_{thr} = 2.2$ MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

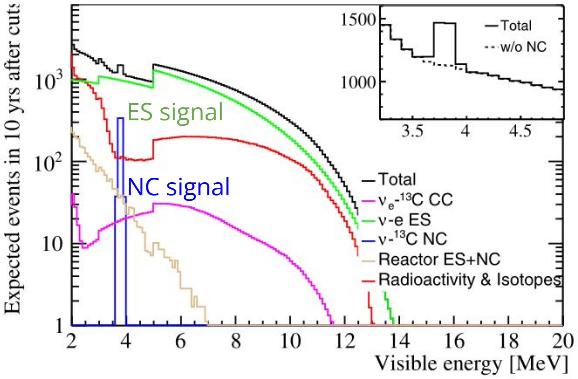
NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C^*$

- $E_{thr} = 3.685$ MeV
- All flavors & equal σ
- Single events - monochromatic γ

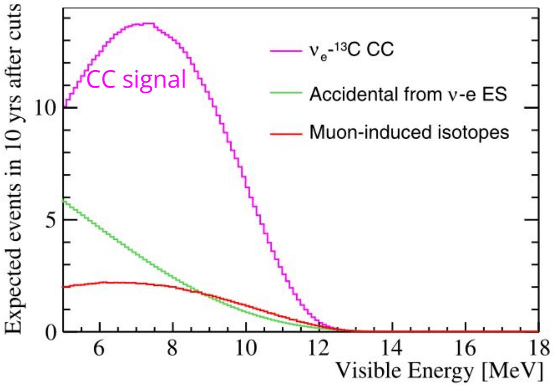
Backgrounds:

- **Externals**: can be neglected after FV cuts
- **Internals**: unstable nuclei in ^{232}Th and ^{238}U chains with high Q values
- **Cosmogenics**: can be reduced after Three-Fold Coincidences cuts
- **Accidental** coincidences (specific for CC)

10 years, single events after cuts



10 years, correlated prompt events after cuts



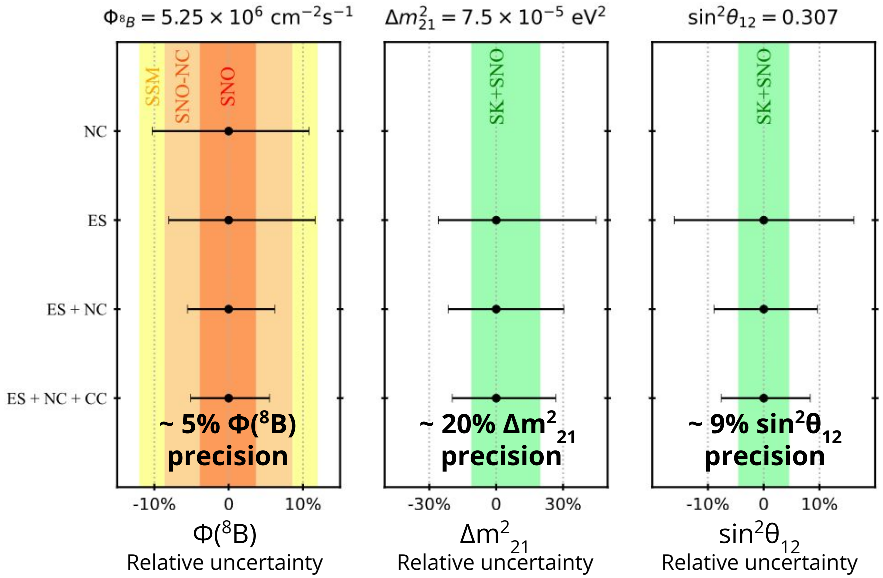
JUNO's ^{8}B solar neutrino program

CC & ES: their event **rate** depends on the neutrino flux and on the ν_e **survival probability** model
NC: it will allow a **model independent measurement** of **Φ(^{8}B)**, first after SNO

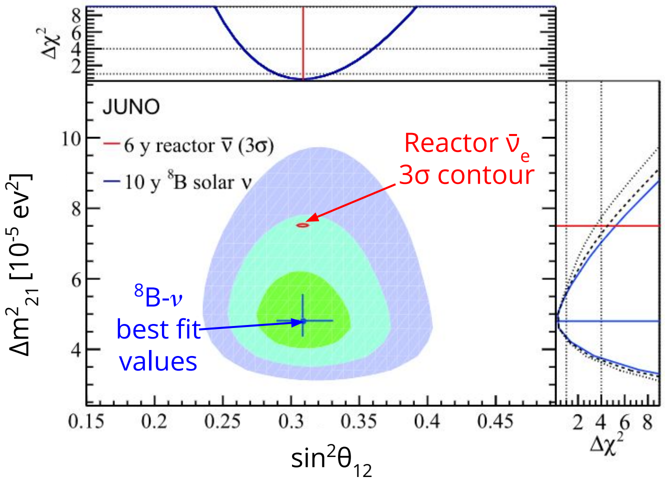
→ **Simultaneous measurement** of **Φ(^{8}B), Δm^2_{21}, and $\sin^2\theta_{12}$**

Chin. Phys. C 45 023004 (2021) 1
Ap. J. 965 (2024) 122

JUNO results with 10 years of data-taking



Δm^2_{21} and **$\sin^2\theta_{12}$** with **^{8}B-ν & reactor $\bar{\nu}_e$**



Potential to search for possible discrepancies

Supernova neutrinos

Supernova neutrinos

The life of a massive star ends with a staggering emission of neutrinos.

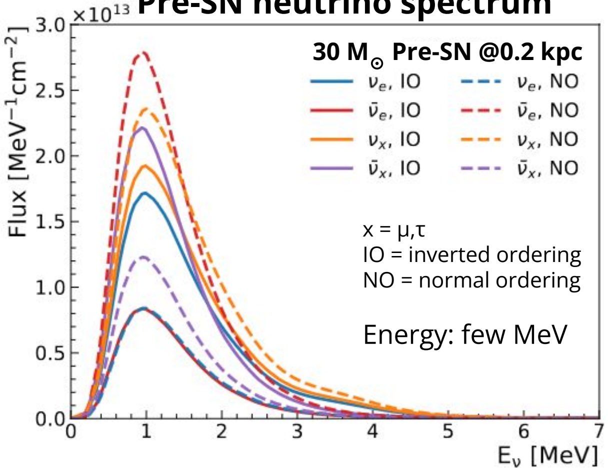
Pre-Supernova (Pre-SN) neutrinos

- Emitted in the **last hours before** the **collapse**, when the neutrino luminosity significantly increases
- **Alert** of the subsequent **SN**
- **Never** been **detected**

Supernova (SN) neutrinos

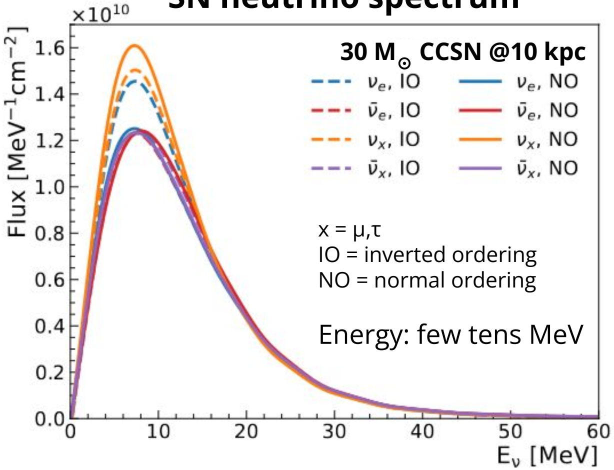
- Emitted **during** the SN **explosion**, burst of **few tens seconds** in three phases (shock breakout, accretion, cooling)
- **Direct telescopes** for electromagnetic observation
- Sparse neutrinos were **observed from SN1987A**

Pre-SN neutrino spectrum



Combining with **electromagnetic** and **gravitational** waves observations → deeper **understanding** of **SN explosion**

SN neutrino spectrum



J. Cos. Astro. Phys. 01 (2024) 057

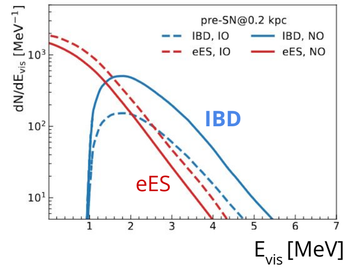
Detection of supernova neutrinos in JUNO

Given their **different flavors** and **energies**, Pre-SN and SN neutrinos have **multiple interactions channels** in JUNO:

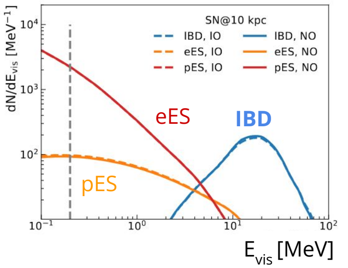
- ❖ **IBD**: $\bar{\nu}_e + p \rightarrow e^+ + n$
- ❖ eES: $\nu_x + e^- \rightarrow \nu_x + e^-$
- ❖ pES: $\nu_x + p \rightarrow \nu_x + p$
- ❖ CC & NC channels on carbon are also desirable

Golden channel in JUNO is the **IBD**
Prompt signal: annihilation of e^+
Delayed signal (ΔT ~ 200μs): capture of n
→ Peculiar signature, low backgrounds

Pre-SN interaction channels



SN interaction channels

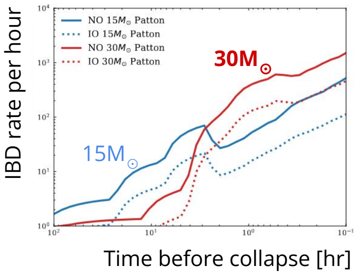


Signature of Pre-SN and SN neutrino bursts is a **sudden increase** in the steady **IBD event rate** (~ 60/day)

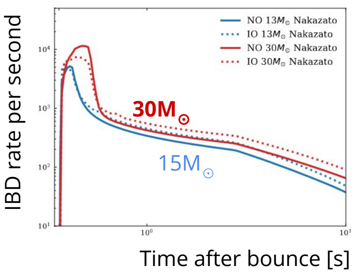
Integrated signal for a **30M$_\odot$** progenitor:

- **Pre-SN @0.2 kpc**: **400 - 1200 IBDs** in few **hours**
- **SN @10 kpc**: **~ 5000 IBDs** in few **seconds**

IBD rate from Pre-SN



IBD rate from SN



Significant dependence on NMO scenario

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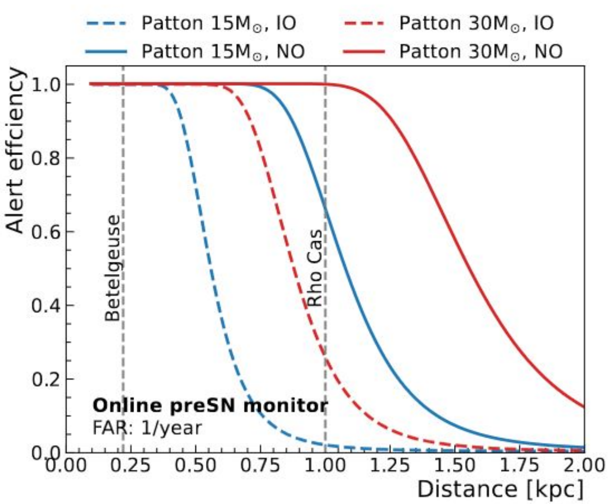
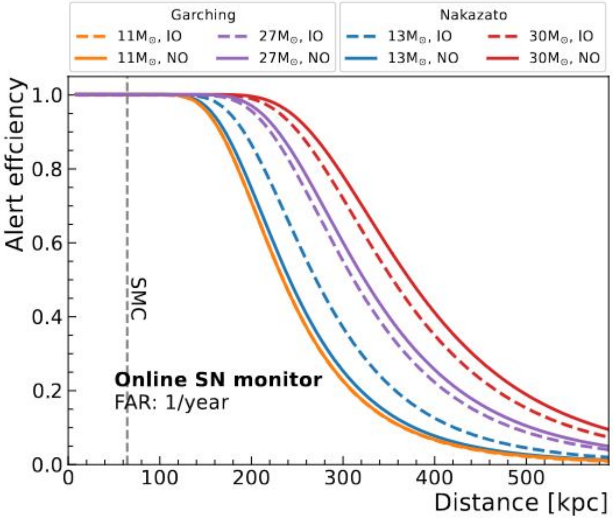
JUNO's sensitivity to Pre-SN & SN neutrinos

[J. Cos. Astro. Phys. 01 (2024) 057]

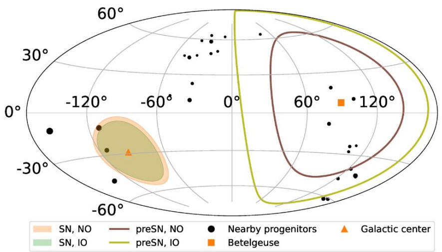
JUNO's sensitivity to Pre-SN



JUNO's sensitivity to SN



Directionality of **IBD** events → Possible to **point** to the **source**, crucial to help telescopes to detect early electromagnetic radiation



Alert efficiency: **probability** to identify Pre-SN/SN neutrinos burst
Sensitivity: **distance** at which the **alert efficiency is 50%**

For an exploding star of **30M$_\odot$ JUNO is sensitive** to:
- **Pre-SN up to 1.6 kpc (0.9 kpc)** in case of **NO (IO)**
- **SN up to 370 kpc (360 kpc)** in case of **NO (IO)**

- 31 SN candidates within 1 kpc [Astrophys. J. 899 (2020) no.2, 153]
- 56 galaxies in 360 kpc [Astron. J. 145 (2013) no.4, 101]

Diffuse supernova neutrino background

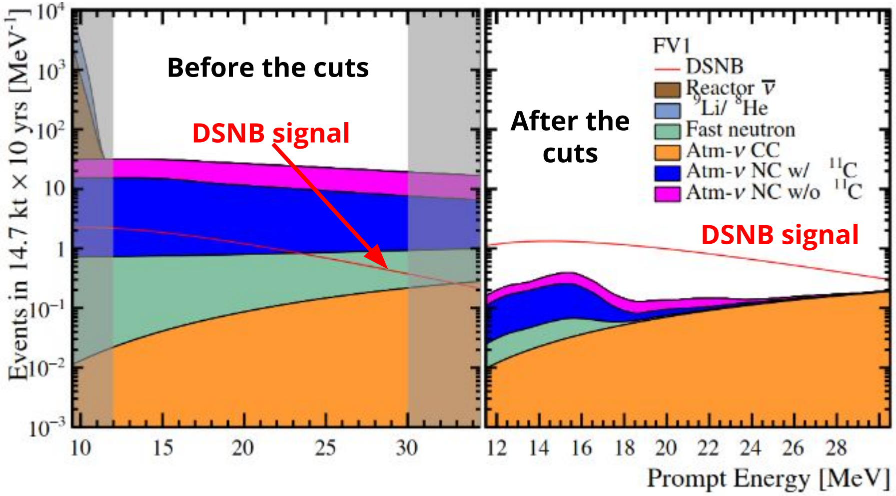
DSNB detection in JUNO

J. Cos. Astro. Phys. 10 (2022) 033

Diffuse Supernova Neutrino Background (DSNB):

- **Integrated neutrino** signal of **all the past SN explosions**
- **Important** for **cosmology** since its **flux depends** on:
  - Supernova rate (**R_{SN}**)
  - Average CCSN neutrino energy (**$<E_\nu>$**)
  - Fraction of failed SN forming black holes (**f_{BH}**)

Events spectrum in JUNO after 10 years



Detection via **IBD**:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

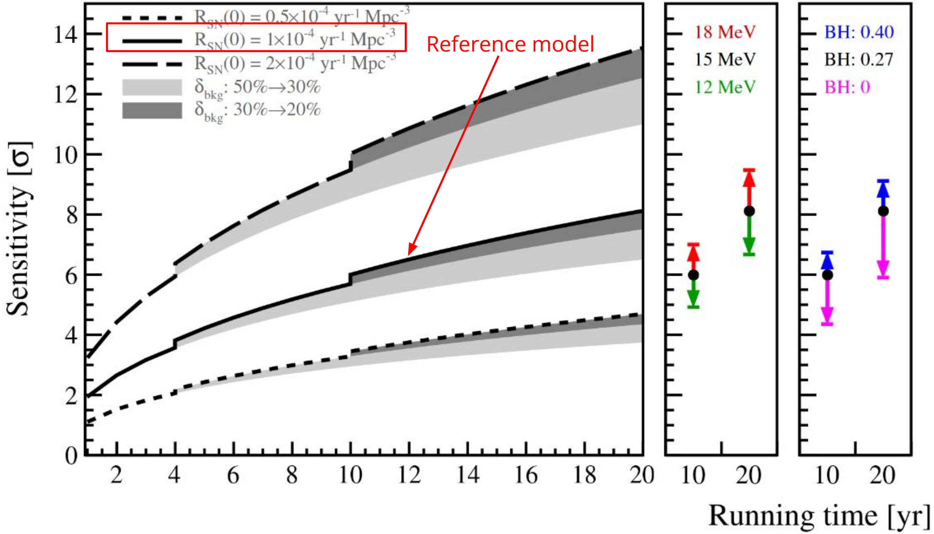
in JUNO, expected **~0.14 y^{-1} $kton^{-1}$ events** before the cuts.

Backgrounds:

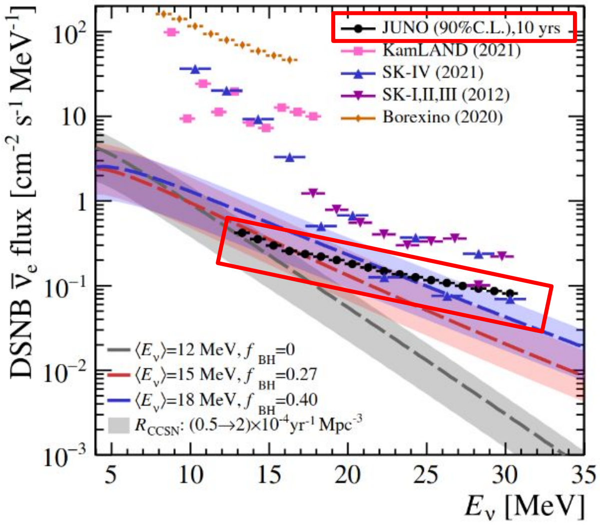
- **Reactor antineutrinos & cosmogenics:**
  - Energy region above 12 MeV
- **Fast neutrons & atmospheric neutrinos NC** interactions:
  - Fiducial volume cuts
  - Pulse-shape discrimination
  - Three-Fold Coincidences

JUNO's sensitivity to DSNB

DSNB discovery potential in JUNO



JUNO's upper limits on DSNB flux



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Reference model for cosmological parameters:

- **~3σ** in **3 years**
- **>5σ** in **10 years**

Sensitivity > 3σ in 10 y for all DSNB signal models

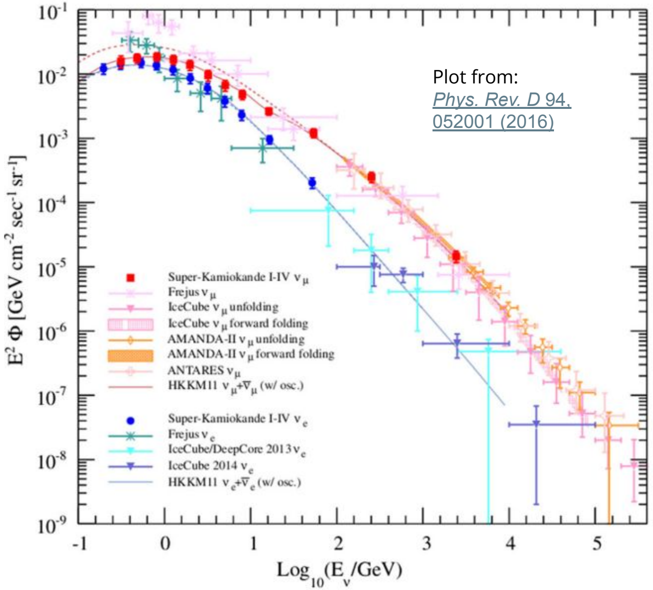
If **no signal** will be observed, in 10 years JUNO will provide **very competitive** upper **limits** to the **DSNB flux**

Atmospheric neutrinos

Atmospheric neutrinos

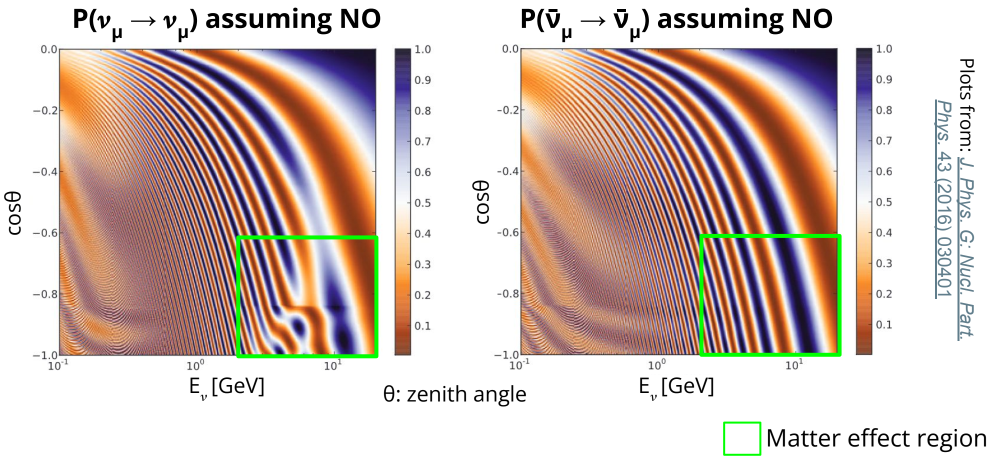
- **Production**: decays of particles (μ, π, K…) in air showers initiated by cosmic rays
- **Energy**: 10 MeV – PeV
- **Production-interaction distance**: 10 - 10^4 km

Atmospheric neutrinos energy spectrum



Atmospheric neutrinos allow to probe several neutrino properties and parameters:

- **Neutrino Mass Ordering** (through matter effects)
- Oscillation parameters θ_{23}, Δm^2_{32}



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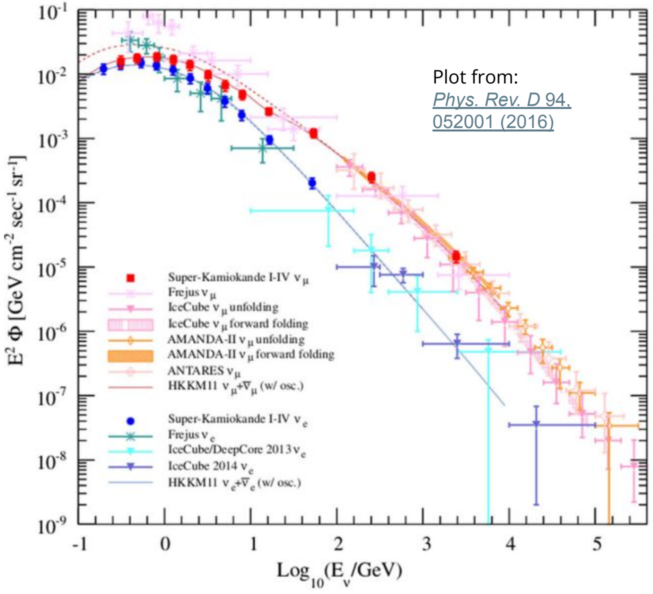

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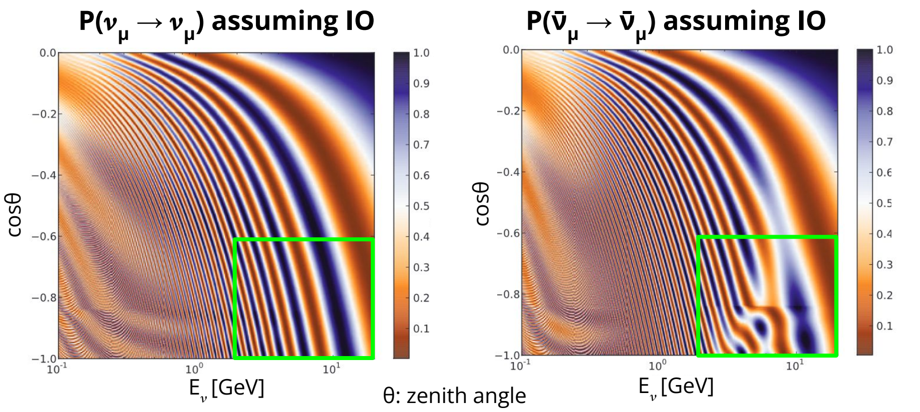


Plots from: *J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401*

$$P_{\mathrm{NO}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{IO}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Matter effect region

Dependence on NMO is **significant** for neutrinos of **few GeVs** with **cosθ < -0.8**

Atmospheric neutrinos in JUNO

Motivation: boost the **sensitivity to NMO:**

- **Reactor antineutrinos**: expected sensitivity of **3σ** in ~6.5 years exploiting **vacuum oscillations** of **~MeV $\bar{\nu}_e$** arXiv:2405.18008 (2024)
- **Atmospheric neutrino**: provide an **independent channel** exploiting **matter oscillation** of **~GeV ν**

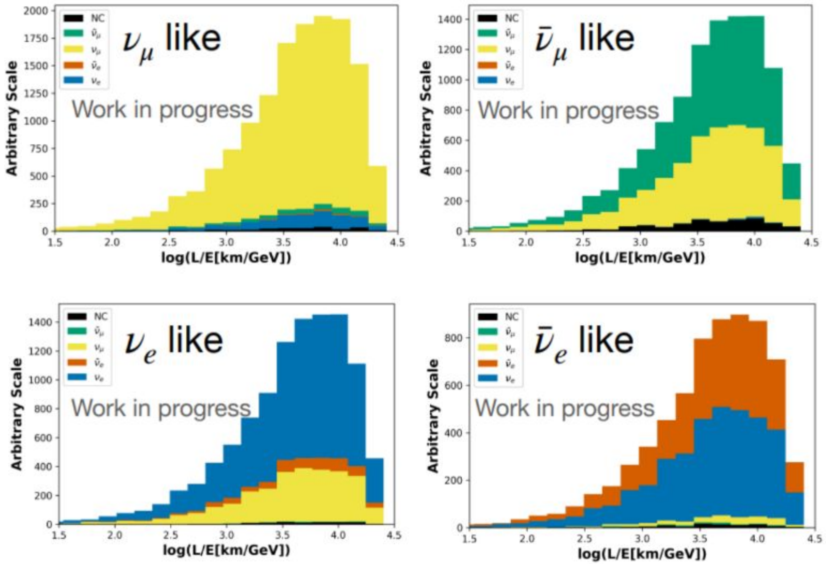
JUNO will become the **first LS detector** able to **measure** atmospheric neutrinos.

Expected **~10/15** events **per day** before the cuts.

Required:

- **Standard** and **neural network** reconstruction algorithms
- **Charged current interaction events selection**
- **Neutrino energy** → total deposited energy *Eur. Phys. J. C 81 (2021) 887*
- **Neutrino direction** → charged lepton track reconstruction *Phys. Rev. D 109.052005*
- **Flavor identification (e/μ)** → different temporal distribution between e/μ events *Eur. Phys. J. C 81 (2021) 887*
- **$\bar{\nu}$/ν discrimination** → ν neutrino events transfer more energy to hadron secondaries than $\bar{\nu}$ events

Demonstration of flavor identification in JUNO



NMO sensitivity with **combined** reactor and **atmospheric** neutrinos is **ongoing**

Conclusions

JUNO will be a **next-generation 20 kton LS detector**, construction to be completed in a few months

Main goal: determine the **Neutrino Mass Ordering** with **reactor antineutrinos**: expected sensitivity of 3σ in ~6.5 years

Thanks to its unprecedented features, **JUNO** is **perfect** to study **neutrinos** from **natural sources**:

- **Solar neutrinos:**
  - **^{7}Be-ν, *pep*-ν, CNO-ν**: **can overcome Borexino results** in a few years in case of good radiopurity of the liquid scintillator.
  - **^{8}B-ν**: can provide **simultaneous** measurement of **Δm^2_{21}, $\sin^2\theta_{12}$, and $\Phi(^8B)$**; first **model independent** measurement of **$\Phi(^8B)$** since SNO; first experiment to measure **Δm^2_{21} and $\sin^2\theta_{12}$ both** with **solar** neutrinos and **reactor** antineutrinos.

- **Pre-SN and SN neutrinos:** in case of a **nearby Supernova** explosion, JUNO is able to **detect** both **Pre-SN** and **SN neutrinos**; **pointing** to the **source** can also be provided.

- **Diffuse Supernova Neutrino Background: high sensitivity** expected, **discovery** can be achieved in a **few years**.

- **Atmospheric neutrinos: first LS** detector to **measure** them; measurement to be **combined** with **reactor** antineutrinos to **boost** the **Neutrino Mass Ordering** sensitivity.

Thank you for your attention!

Backup

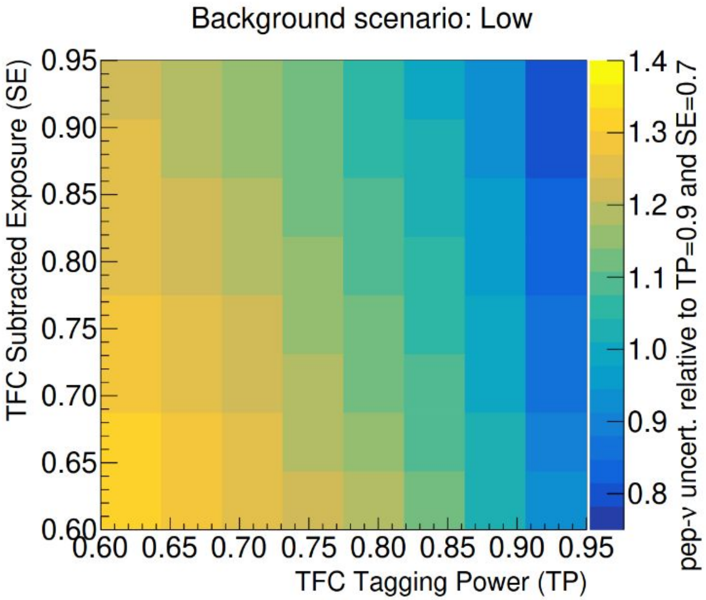
Internal backgrounds concentrations

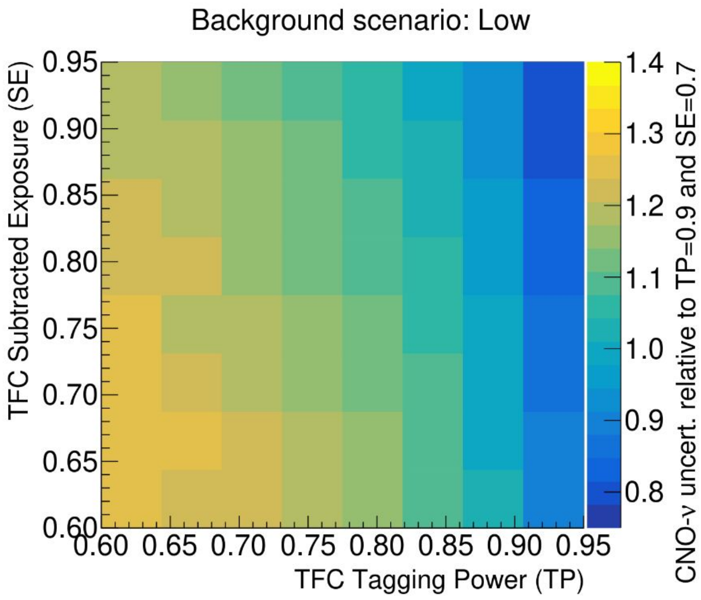
J. Cos. Astro. Phys. 10 (2023) 022

	^{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}
$R\ [\frac{cpd}{kton}]$	2289	5000	3508	15047	36817
$R^{ROI}\ [\frac{cpd}{kton}]$	1562	705	2100	7368	17269
	Medium Background scenario				
$c\ [\frac{g}{g}]$	1×10^{-17}	4×10^{-25}	1×10^{-16}	1×10^{-16}	5×10^{-24}
$R\ [\frac{cpd}{kton}]$	229	500	351	1505	3682
$R^{ROI}\ [\frac{cpd}{kton}]$	156	70	210	737	1727
	Low Background scenario				
$c\ [\frac{g}{g}]$	1×10^{-18}	8×10^{-26}	1×10^{-17}	1×10^{-17}	1×10^{-24}
$R\ [\frac{cpd}{kton}]$	23	100	35	150	736
$R^{ROI}\ [\frac{cpd}{kton}]$	16	14	21	74	345
	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}
$R\ [\frac{cpd}{kton}]$	4.2	100	2	1.4	347
$R^{ROI}\ [\frac{cpd}{kton}]$	2.9	14	1	1	163

Impact of TFC on solar neutrino sensitivity

J. Cos. Astro. Phys. 10 (2023) 022





^{8}B neutrinos - signals and backgrounds

Single events, after cuts

cpd/kt	FV	^{8}B signal eff.	^{12}B	^{8}Li	^{10}C	^{6}He	^{11}Be	^{238}U	^{232}Th	$\bar{\nu}$-e ES	Total bkg.	Signal rate at $\Delta m^{2\star}_{21}$	Signal rate at $\Delta m^{2\dagger}_{21}$
(2, 3) MeV	7.9 kt	~51%	0.005	0.006	0.141	0.084	0.002	0.050	0.050	0.049	0.39	0.32	0.30
(3, 5) MeV	12.2 kt	~41%	0.013	0.018	0.014	0.008	0.005	0	0.012	0.016	0.09	0.42	0.39
(5, 16) MeV	16.2 kt	~52%	0.065	0.085	0	0	0.023	0	0	0.002	0.17	0.61	0.59
Syst. error	1%	<1%	3%	10%	3%	10%	1%	1%	2%				

Correlated events, cuts efficiencies

	Cuts	CC Signal Efficiency	CC Signal	Background for CC Channel: Solar ES Accidental	Background for CC Channel: Muon-induced Isotopes Accidental	Background for CC Channel: Muon-induced Isotopes Correlated
...	...	...	3929	...	...	...
Time cut	4 ms $< \Delta T <$ 900 s	65%	2554	10^{10}	10^{13}	10^{12}
Energy cut	5 MeV $< E_p <$ 14 MeV 1 MeV $< E_d <$ 2 MeV	79% 91%	1836	10^9	10^{10}	10^9
Fiducial volume cut	$R <$ 16.5 m (Abusleme et al. 2021a)	81%	1487	10^7	10^7	10^8
Vertex cut	$\Delta d <$ 0.47 m	87%	1293	328	10^5	10^6
Muon veto	Muon and TFC veto (Abusleme et al. 2021a)	50%	647	164	53	58
Combined	...	17%	647		275	

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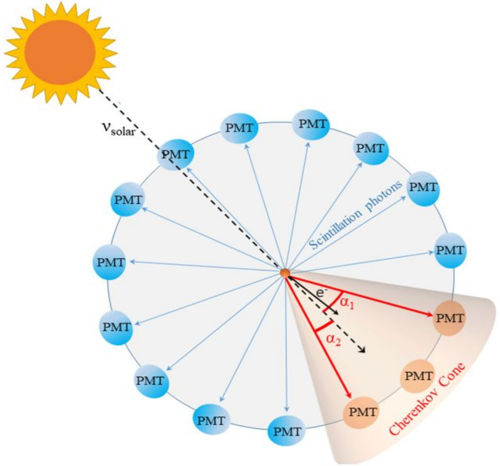
Directional solar neutrino measurement

JUNO's **sensitivity** to **solar neutrinos** might be further **enhanced** with the Correlated and Integrated (**CID**) technique that exploits the **directionality of the scattered electron.**

Solar neutrino events

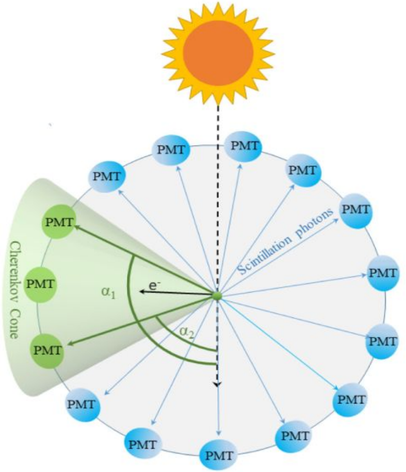


Correlation between **Sun position** and **Cherenkov photons**

Cherenkov light subdominant in LS detectors, but emitted instantaneously

No correlation between **Sun position** and **scintillation light**

Background events

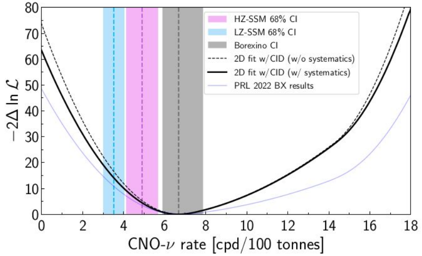


No Correlation between **Sun position** and **Cherenkov photons**

CID was **developed** and **exploited** by **Borexino** to **improve** its **sensitivity** on **CNO-ν**

Phys. Rev. D 105 (2022) 052002

Phys. Rev. D 108 (2023) 102005



Feasibility studies in JUNO are ongoing

JUNO's sensitivity to Pre-SN & SN neutrinos - summary table

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	Model	Mass $[M_\odot]$	Mass ordering	r_{bkg} $[day^{-1}]$	N_{IBD}	N_{sel}	Alert distance [kpc]		Alert time	
							FAR<1/month	FAR<1/year	FAR<1/month	FAR<1/year
SN	Garching	11	NO	39 (83)	1675	1414 (1204)	230 (220)	230 (190)	(16 ms)	(17 ms)
			IO		1676	1413 (1228)	230 (220)	230 (200)	(13 ms)	(14 ms)
		27	NO		3132	2651 (2466)	320 (310)	320 (280)	(15 ms)	(16 ms)
			IO		2958	2502 (2366)	310 (300)	310 (270)	(13 ms)	(13 ms)
	Nakazato	13	NO		2326	1934 (1698)	270 (240)	240 (200)	(20 ms)	(21 ms)
			IO		2827	2365 (2190)	300 (280)	270 (240)	(16 ms)	(17 ms)
		30	NO		5074	4098 (4217)	400 (390)	370 (350)	(31 ms)	(31 ms)
			IO		4972	4131 (4145)	390 (370)	350 (330)	(31 ms)	(31 ms)
pre-SN	Patton	15	NO	21	659	556	1.3	1.1	-140 h	-120 h
			IO		196	156	0.7	0.6	-90 h	-30 h
		30	NO		1176	930	1.7	1.6	-220 h	-180 h
			IO		379	302	1.0	0.9	-100 h	-3 h

Cut efficiencies for DSNB

Signal	Rate[147 kt × yr]	muon veto		PSD	TC cut	
12 MeV	16.2	93.6%	15.2	12.9	93.6%	12.1
15 MeV	20.8		19.4	16.7		15.6
18 MeV	25.2		23.6	20.4		19.1
21 MeV	29.0		27.2	23.7		22.1
Backgrounds						
Fast neutron	12.5		11.7	0.2		0.2
Atm-ν CC	2.0		1.9	1.6		1.5
Atm-ν NC without ^{11}C	258.2		241.7	0.9		0.9
Atm-ν NC with ^{11}C	186.7		174.8	3.6	25.5%	0.9
Total backgrounds	459.4		430.0	6.3		3.5

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