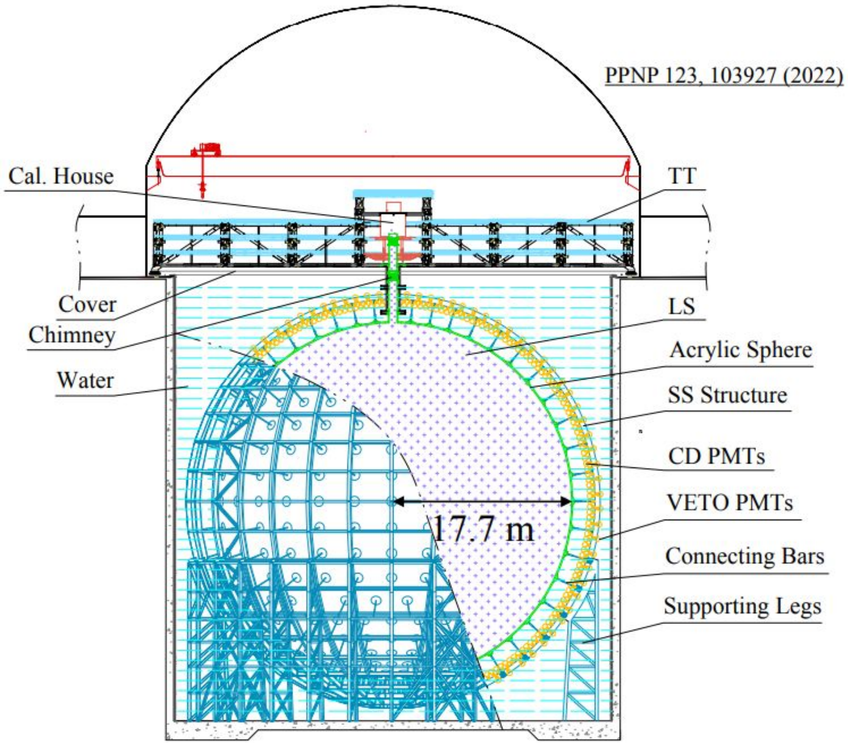
Prospects for neutrinos from natural sources in JUNO

Elisa Percalli
on behalf of the JUNO collaboration

JUNO experiment

A multipurpose neutrino detector

JUNO experiment



JUNO physics and detector - Progress in Particle and Nuclear Physics

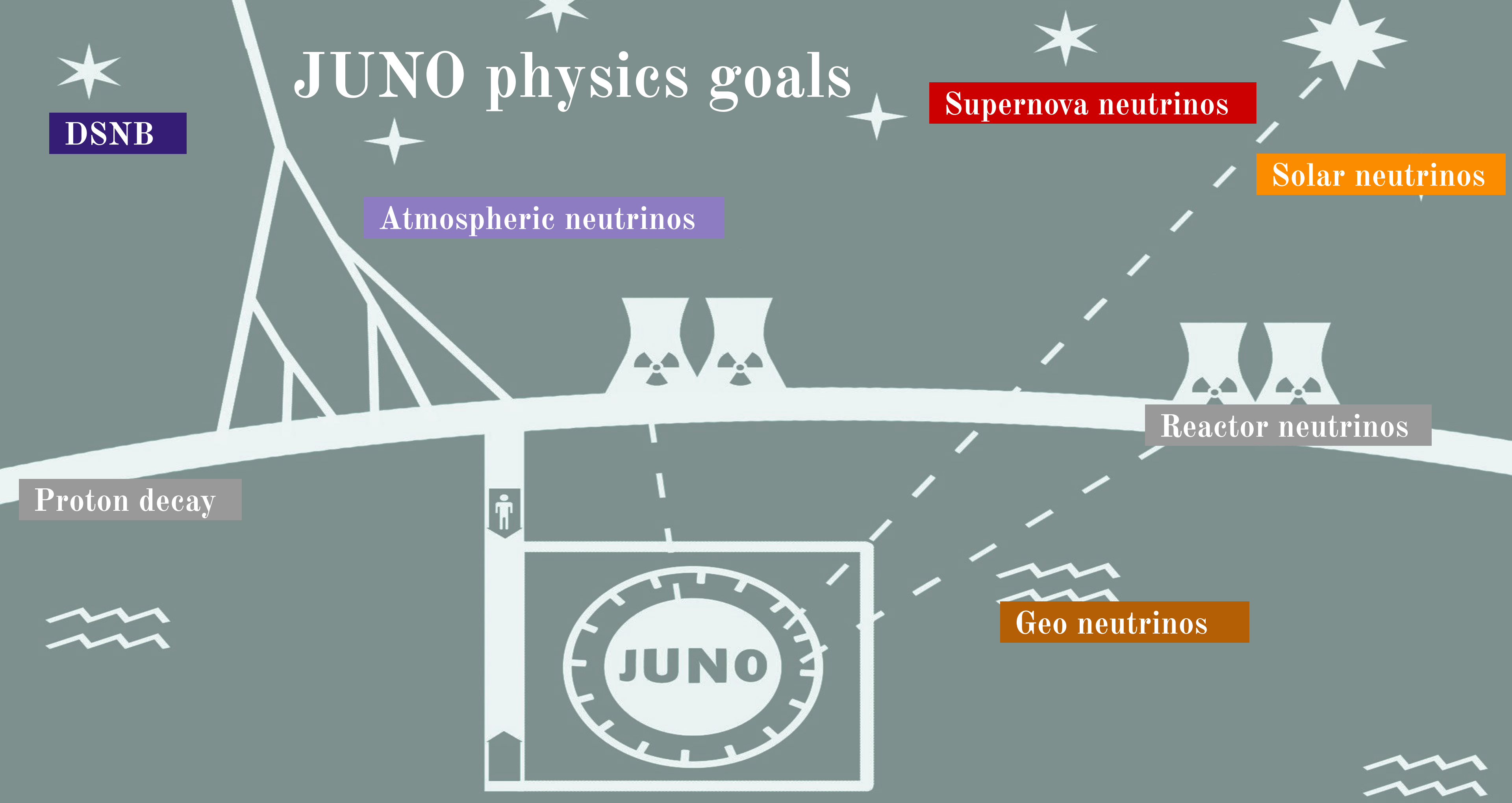
Now under construction in China, in a **700m deep underground** laboratory

- **20k tons** of liquid scintillator
- **17612** 20'' PMTs and **25600** 3″ PMTs
- 17.7 m radius for acrylic sphere
- PMT optical coverage 78%
- High light yield scintillator (10^4 emitted photons/MeV)
- Water cherenkov veto detector + top tracker
- Designed to reach an unprecedented **energy resolution of 3% @MeV**
- Good **radiopurity** expected

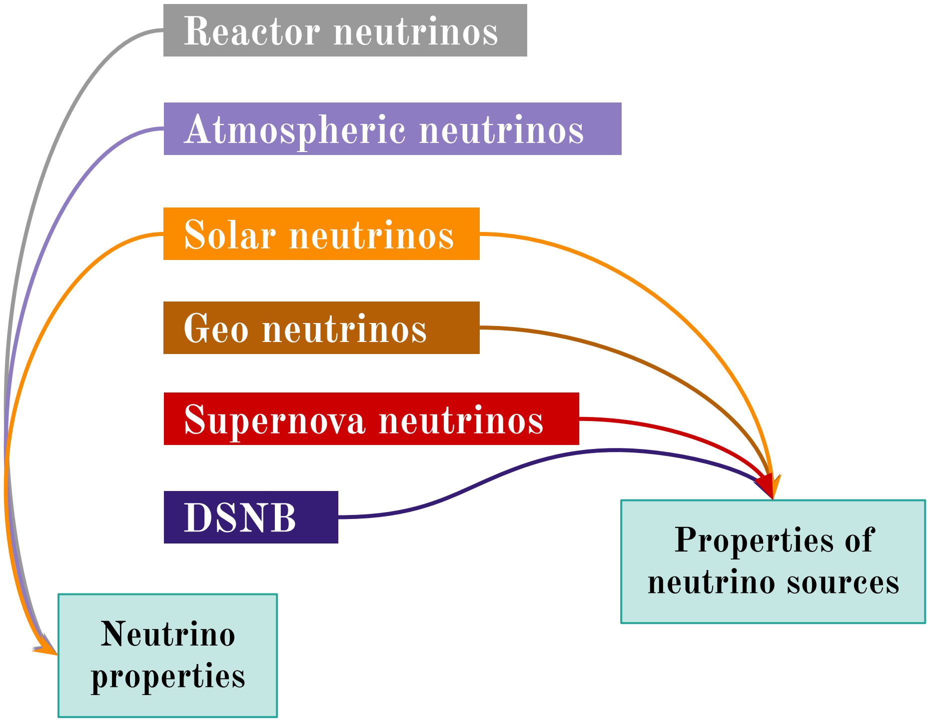
JUNO will start data taking in 2025

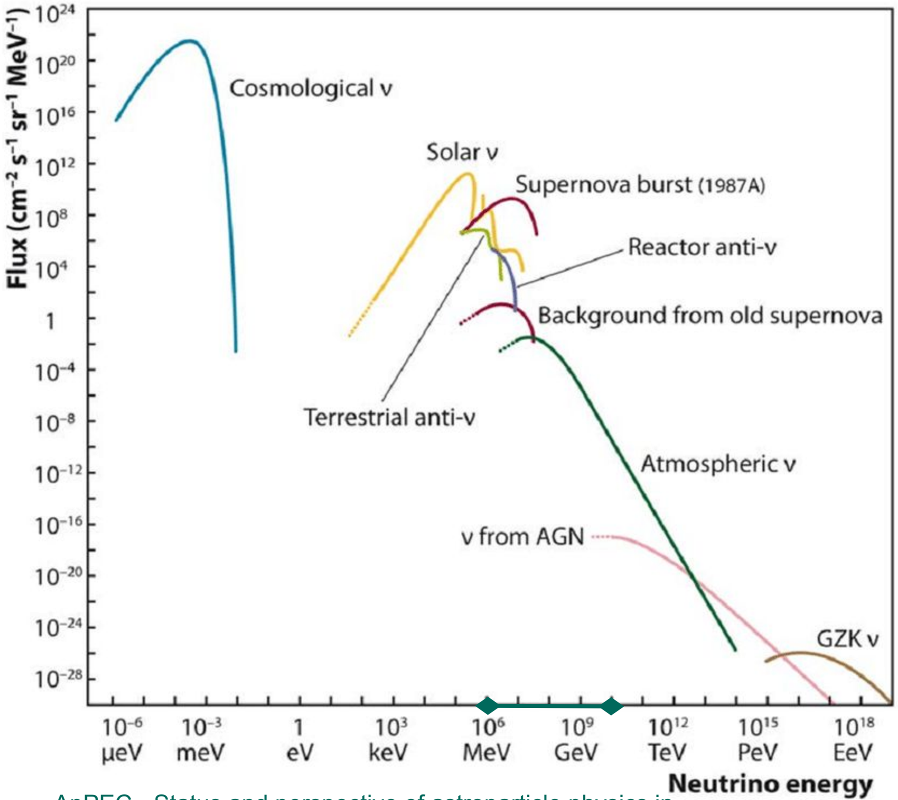
For further information see Stefano Dusini's talk

JUNO physics goals



Neutrino sources





ApPEC - Status and perspective of astroparticle physics in Europe

Neutrino sources

Reactor neutrinos → Dmitrii Dolzhikov's talk

Atmospheric neutrinos

Solar neutrinos

Geo neutrinos

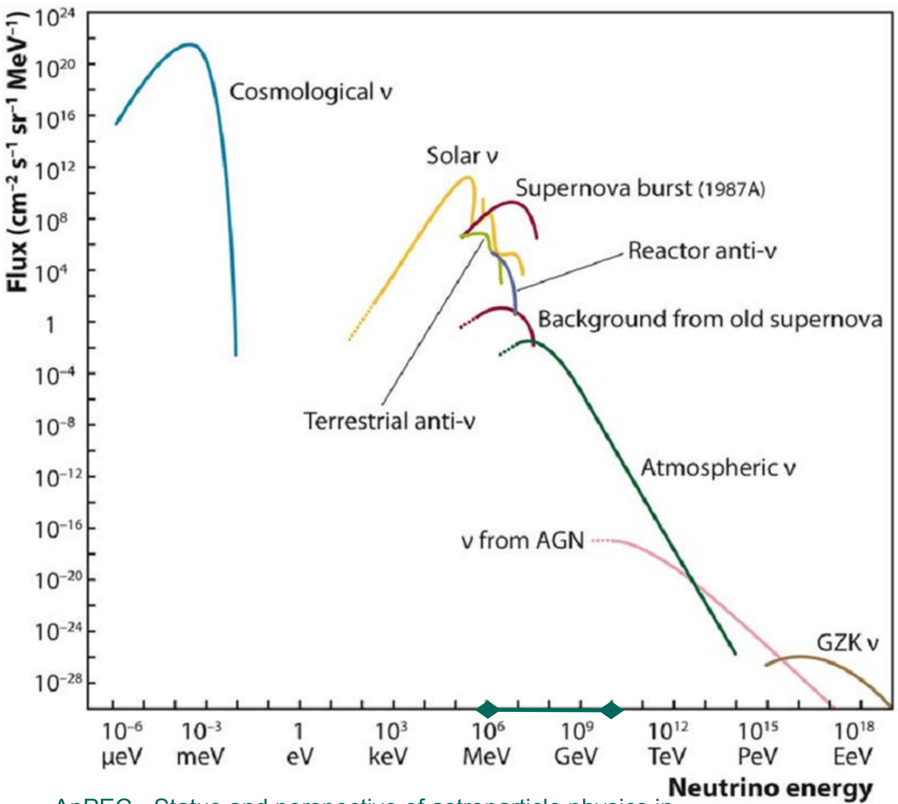
Supernova neutrinos

DSNB

→ This talk

Properties of neutrino sources

Neutrino properties



ApPEC - Status and perspective of astroparticle physics in Europe

[Sub-percent precision measurement of neutrino oscillation parameters with JUNO]

Neutrino mass ordering determination

Source: Reactor neutrinos

Energy: 1.8-10 MeV

Detection method: IBD (inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$)

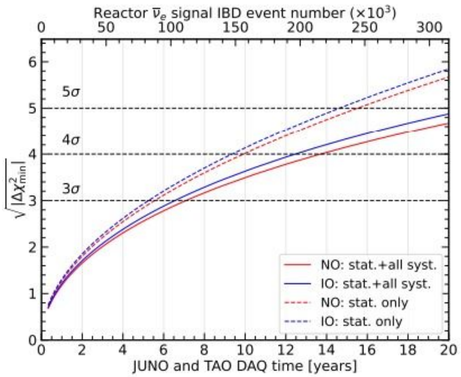
Optimized **distance** for NMO

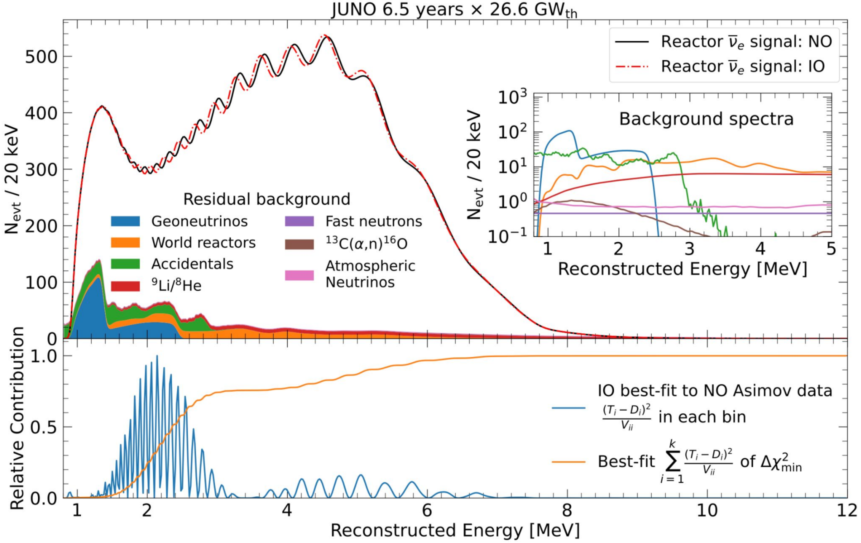
See Dmitrii Dolzhikov's talk after this

[2405.18008] Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO

Expected **sensitivity**

Expected **energy spectrum**





NMO with atmospheric neutrinos

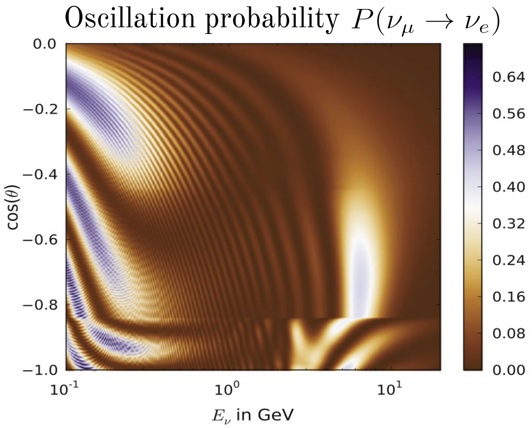
Source: Decay of particles (μ, π, K) in atmosphere, within 10^4-10 km from Earth surface

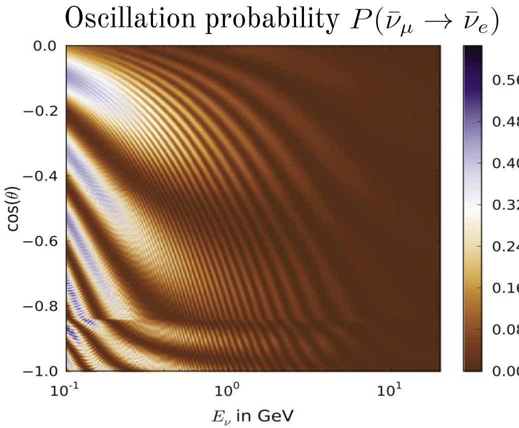
Energy: 10 MeV - 1 PeV

Motivation: We can probe the neutrino mass ordering through "**matter effects**"

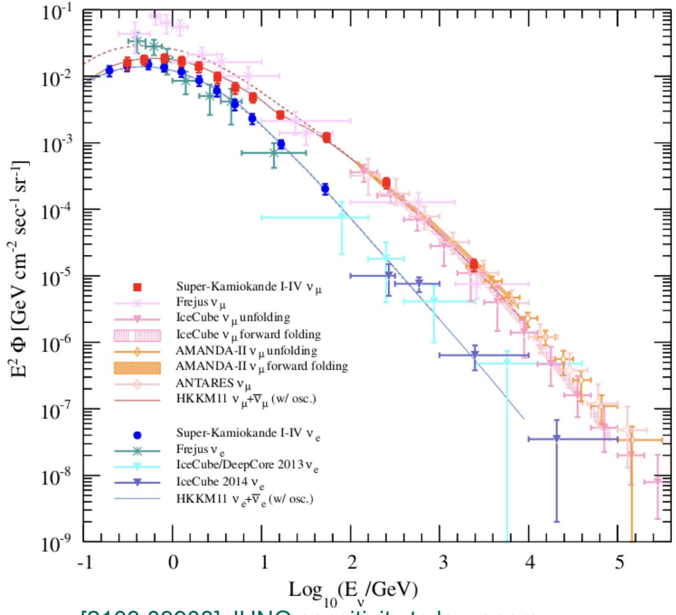
$$P_{\mathrm{NH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{IH}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Normal Ordering





Atmospheric neutrino energy spectrum from previous experiments



[2103.09908] JUNO sensitivity to low energy atmospheric neutrino spectra

NMO with atmospheric neutrinos

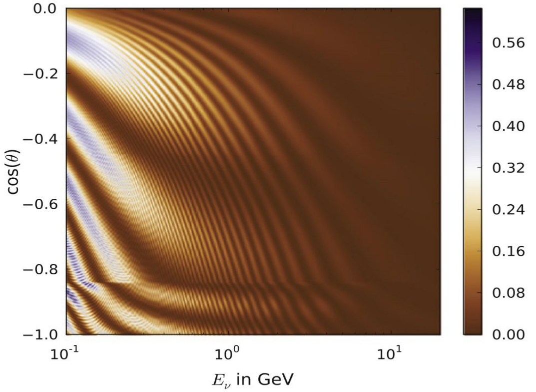
Source: Decay of particles (μ, π, K) in atmosphere, within 10^4-10 km from Earth surface

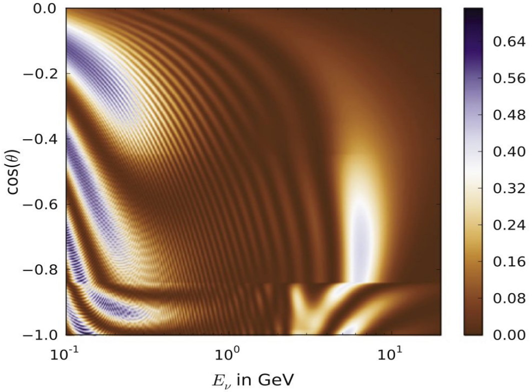
Energy: 10 MeV - 1 PeV

Motivation: We can probe the neutrino mass ordering through “**matter effects**”

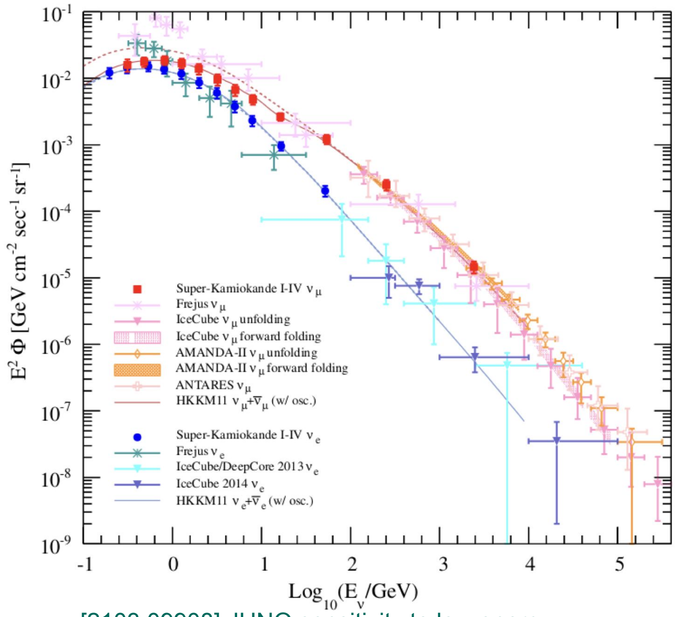
$$P_{\mathrm{NH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{IH}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Inverted Ordering





Atmospheric neutrino energy spectrum from previous experiments



[2103.09908] JUNO sensitivity to low energy atmospheric neutrino spectra

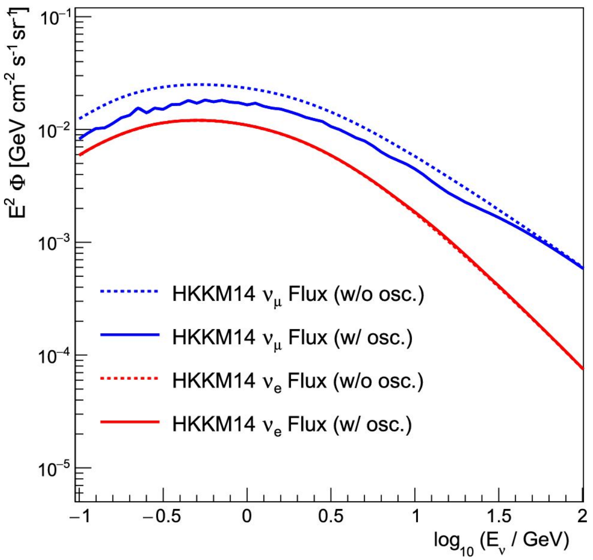
[2103.09908] JUNO sensitivity to low energy atmospheric neutrino spectra

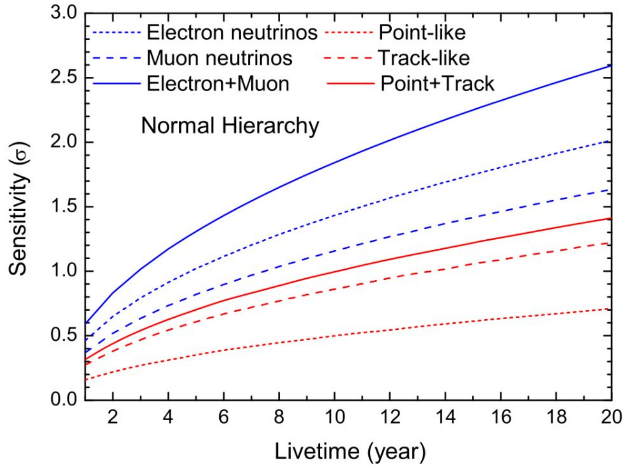
NMO with atmospheric neutrinos

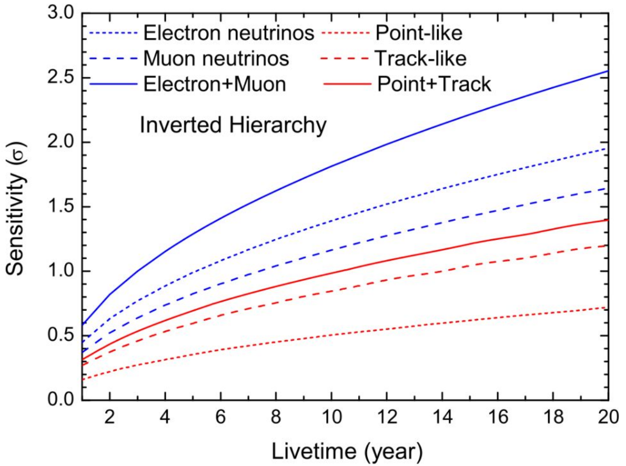
Sensitivity to NMO is enhanced for neutrinos of **few GeV** at **cosθ< -0.8**

Expected **10/15 evt** per day

Expected atmospheric (neutrino + antineutrino) flux at the JUNO site







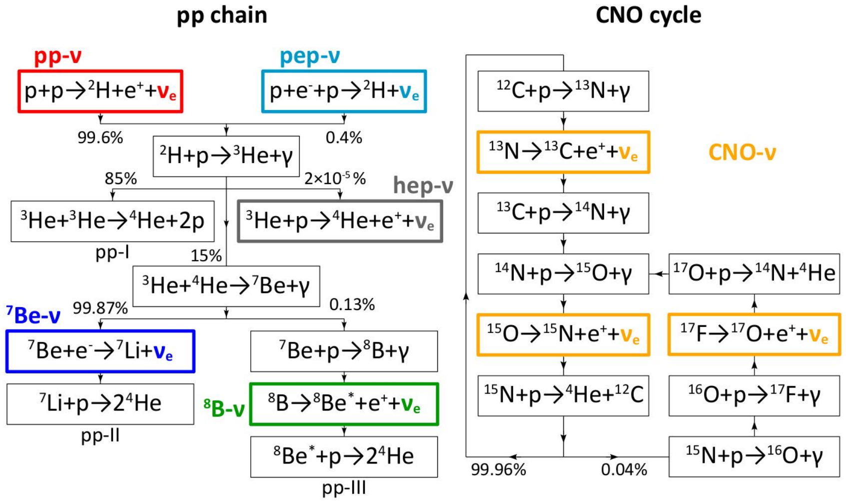
Expected sensitivity around 1σ in 6y
Combined NMO sensitivity studies with **reactor** and **atmospheric** neutrinos is ongoing

Solar neutrinos

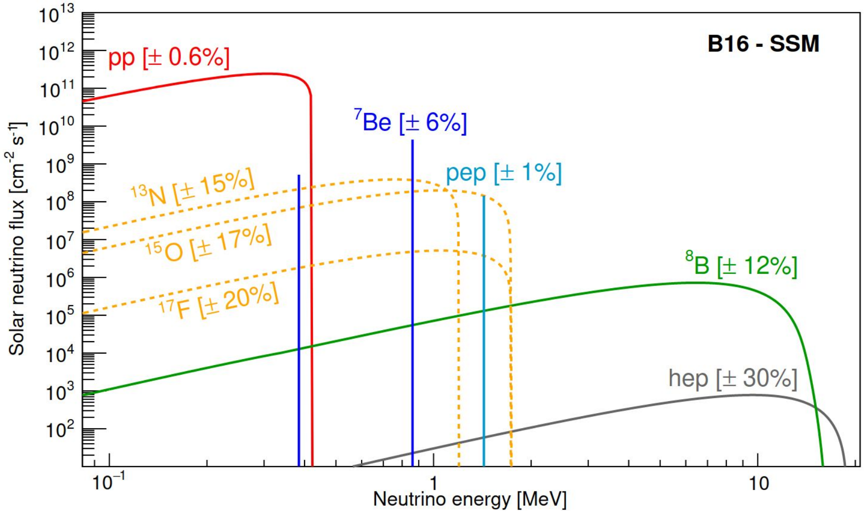
Source: Nuclear fusion reactions inside the Sun

Energy: 0.1-18 MeV

Motivation: We can probe physical quantities of the Sun (e.g. **metallicty**) and neutrino oscillation parameters ($\boldsymbol{\Delta m^2_{21}}$,$\boldsymbol{\theta_{21}}$)



Energy spectra of solar neutrino production channels



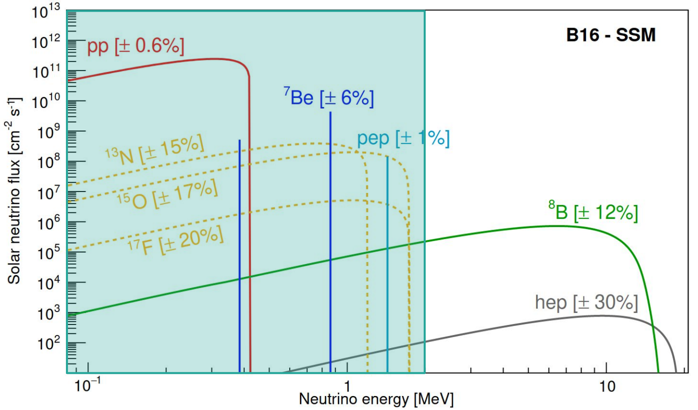
Comprehensive measurement of pp-chain solar neutrinos | Nature

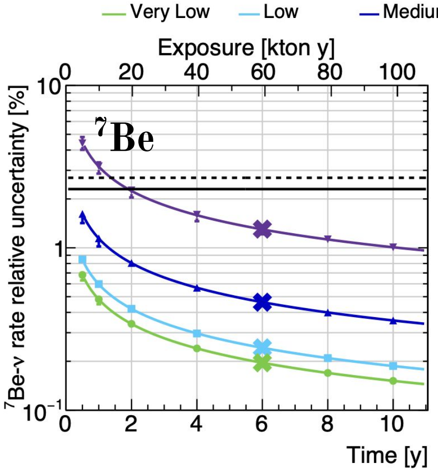
The analysis strategy differs with the neutrino energies

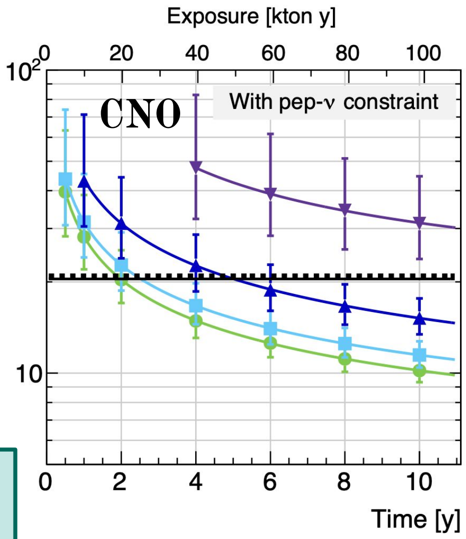
Solar neutrinos - ^{7}Be, *pep*, CNO

Low energy neutrinos (<2MeV) will be detected through **elastic scattering** on electrons

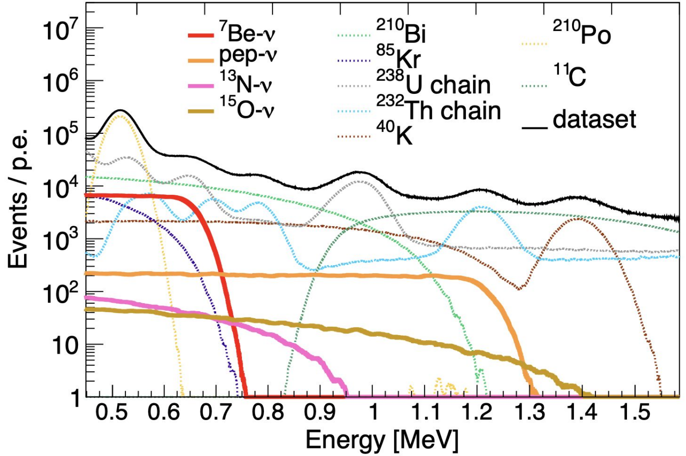
Sensitivity will be highly dependent on the **internal background level**







Expected spectral shape for 6 years



JUNO expects to soon improve upon existing solar neutrino flux measurements

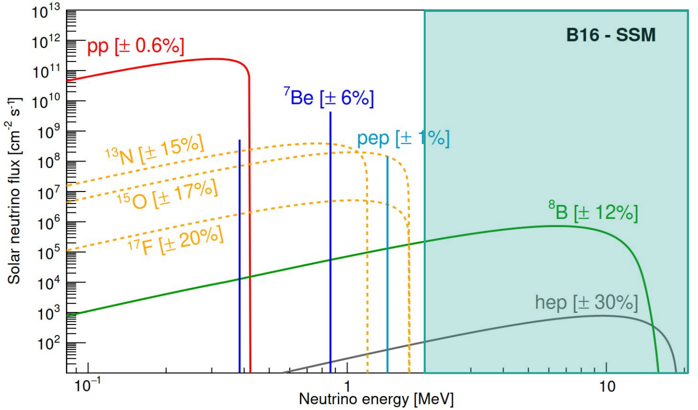
JUNO sensitivity to 7Be, pep, and CNO solar neutrinos

Solar neutrinos - ^{8}B

Higher energy neutrinos interact through ES, CC, NC

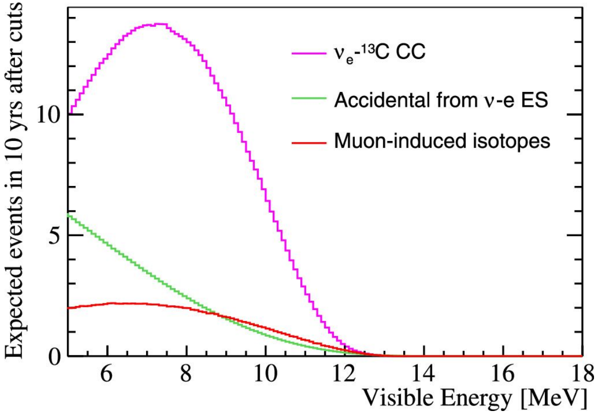
- **ES and CC** are neutrino flavor sensitive, hence probe the **survival probability**

- **NC** occurs for all neutrino flavors, hence allows a **model independent measurement of the ^{8}B flux**

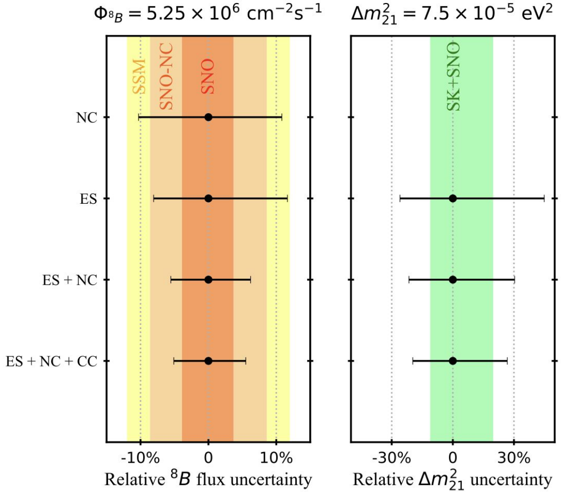


JUNO has potential to both measure Φ(8B), Δm^2_{21}, and $\sin^2\theta_{12}$

Expected prompt visible energy spectra of the CC signal



Expected results in ten years of data-taking



[Feasibility and physics potential of detecting 8B solar neutrinos at JUNO]

[Model-independent Approach of the JUNO 8 B Solar Neutrino Program]

Geoneutrinos $(\bar{\nu}_e)$

Source: Th and U decays in the Earth crust and mantle

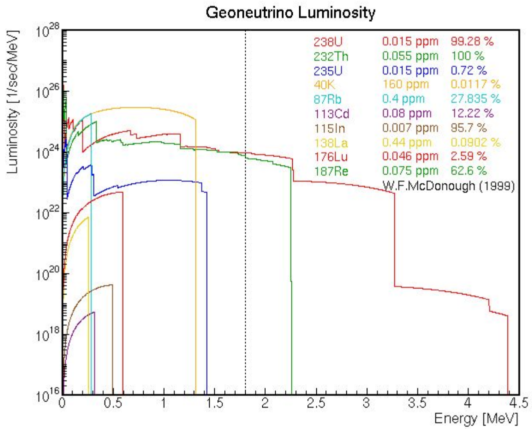
Energy: 0-3 MeV

Motivation: Measuring **U and Th abundances** probes **Earth's properties** (e.g. mantle convection, plate tectonics, Earth's magnetic field production). Measuring **Th/U ratio** is useful for probing Earth's formation, mantle convection, plate tectonics, Earth's magnetic field production

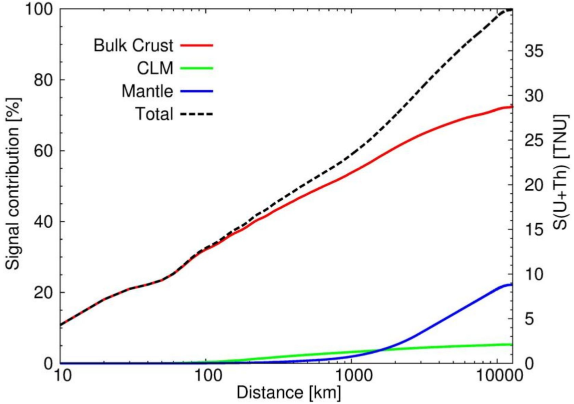
JUNO expects **400 geo-nu events per year** - can overtake **global measurement statistics in 1 year**

$$
\begin{aligned}
{}^{238}_{92}\mathrm{U} &\longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV} \\
{}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\,\mathrm{MeV}
\end{aligned}
$$

Detectable in JUNO via IBD



Geoneutrino Spectrum and Luminosity



Geoneutrino signal contribution at JUNO

(PDF) Expected geoneutrino signal at JUNO

JUNO sensitivity to geoneutrinos

For geoneutrinos analysis the **main background** is the reactor antineutrinos flux

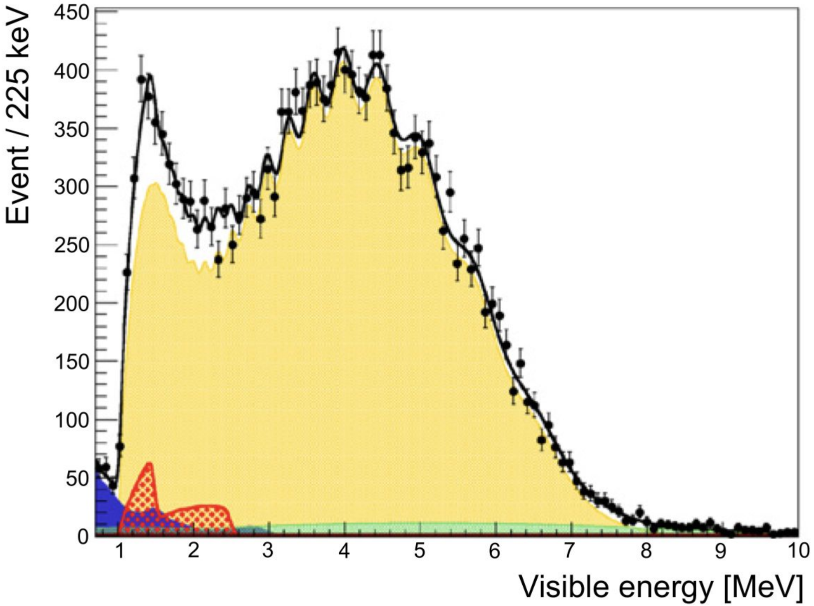
Good sensitivity to the **geoneutrino flux** is needed (different models for lithosphere and mantle)

Main **uncertainties** come from oscillations parameters

The main advantage of JUNO will be its large **exposure**

Borexino: 17% precision in 10 years
Kamland: 15% precision in 18 years

JUNO expects a measurement of geoneutrino flux with ~22% precision in 1 year and ~8% precision in 10 years



Neutrino physics with JUNO

Comprehensive geoneutrino analysis with Borexino

Abundances of Uranium and Thorium Elements in Earth Estimated by Geoneutrino Spectroscopy

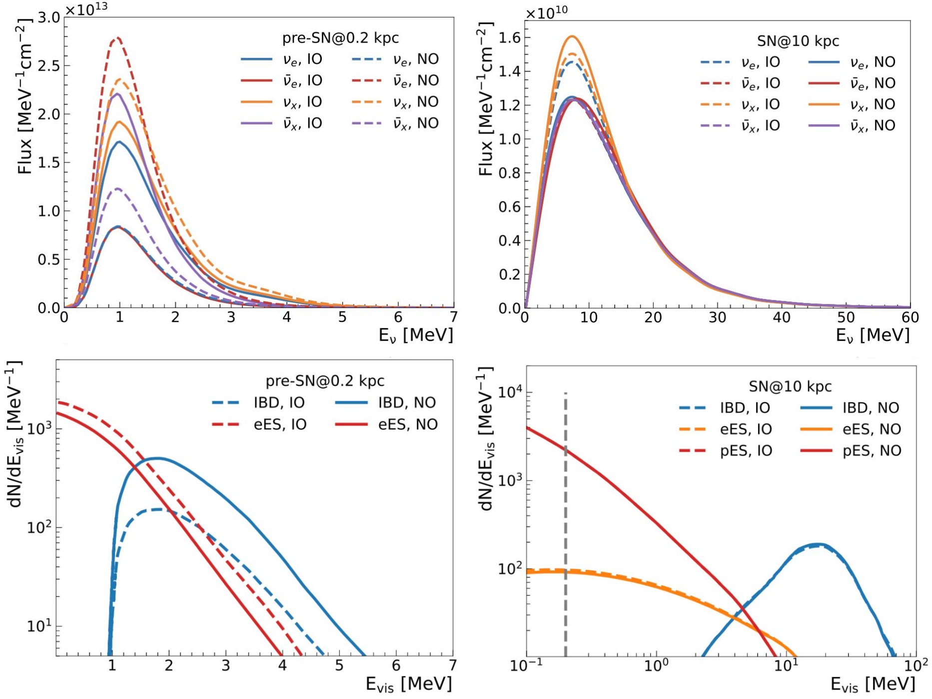
[Real-time monitoring for the next core-collapse supernova in JUNO - IOPscience]

[SNEWS 2.0: a next-generation supernova early warning system for multi-messenger astronomy]

Supernova neutrinos

Source: Supernovae are the final stages of very massive stars. They produces neutrinos in **two phases:**

Pre-SN **SN**



- **Pre-SN neutrinos:** emitted in the days before the collapse. Can be used to **alert** for a SN.
- **SN neutrinos:** emitted during the explosion, in ~10 seconds.

Aim to contribute to Supernova Early Warning System [SNEWS]

Some of JUNO channel of **detection** (both ν and $\bar{\nu}$)

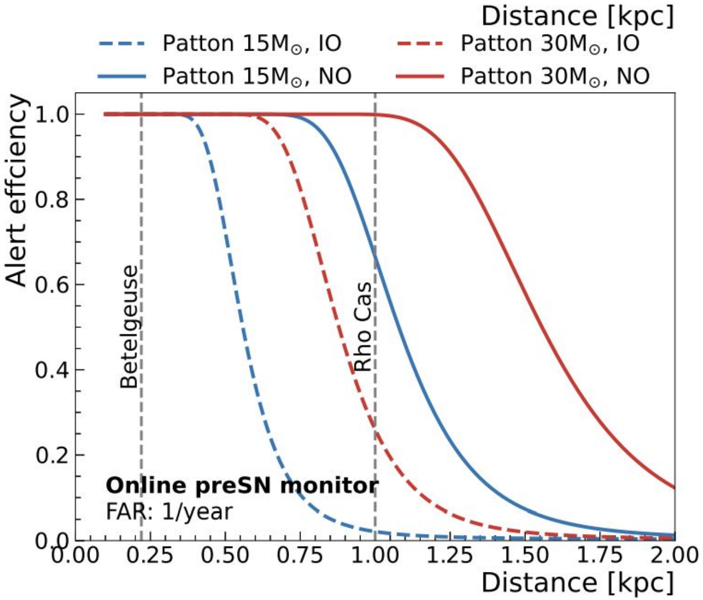
- **IBD** (only $\bar{\nu}_e$) has a prompt-delayed signature
- eES (elastic scattering on electrons, all ν)
- pES (elastic scattering on protons, all ν)

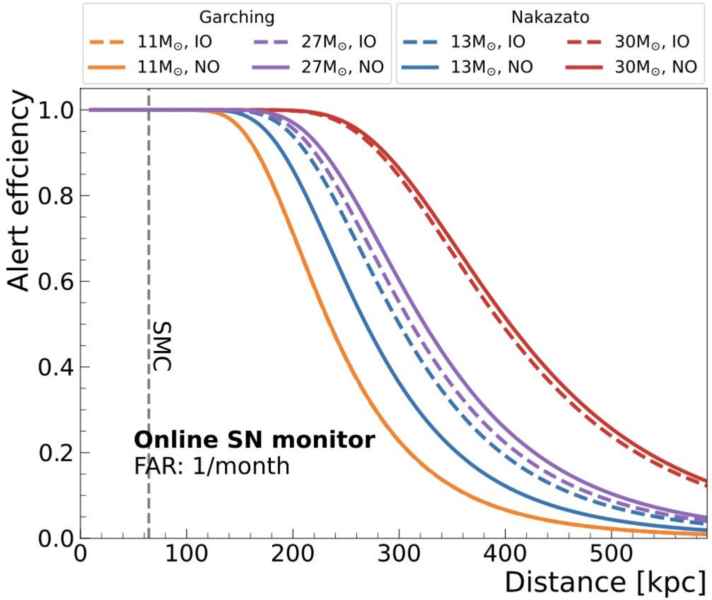
The energy distributions are highly dependent on the **mass ordering**

Supernova neutrinos

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)





Diffusive supernova neutrino background

Source: All the neutrinos from past SN explosions

Motivation: Useful probe for important **cosmological** parameters :
- Rate of SN ($\mathbf{R_{SN}}$)
- Average CCSN ν energy ($\mathbf{<E_\nu>}$)
- Fraction of failed BH formation ($\mathbf{f_{BH}}$)

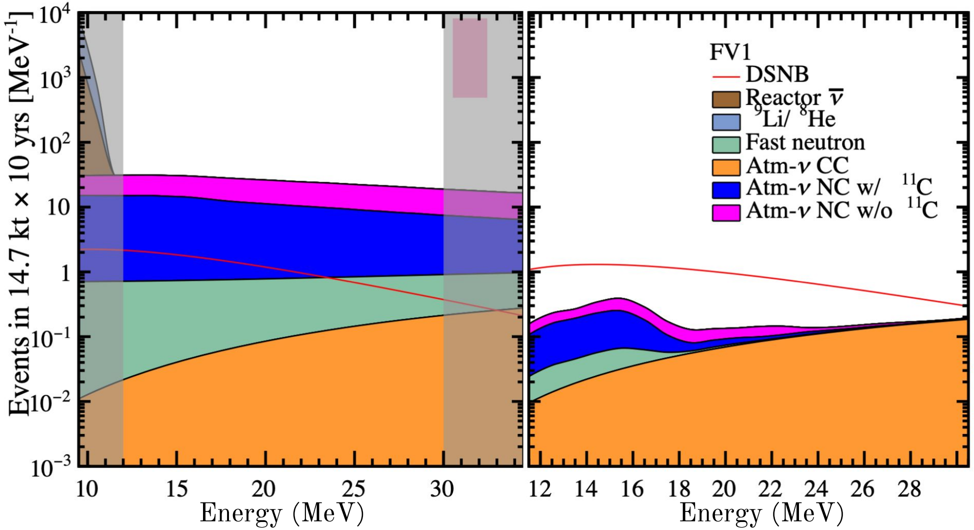
Very low statistics expected before the cuts

(~0.14 events/y/kton)

Detection channel with fewer background is **IBD,** with energy over **12 MeV** (avoid reactor $\bar{\nu}$)

Remaining background are induced by **atmospheric (νNC and fast neutrons from muons)**

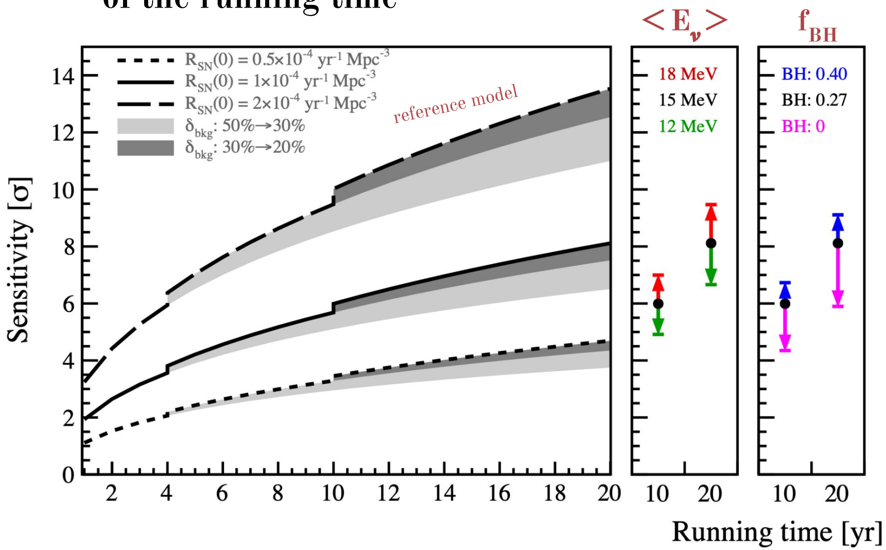
Energy spectrum in JUNO after 10 years before and after the cuts



Prospects for detecting the diffuse supernova neutrino background with JUNO - IOPscience

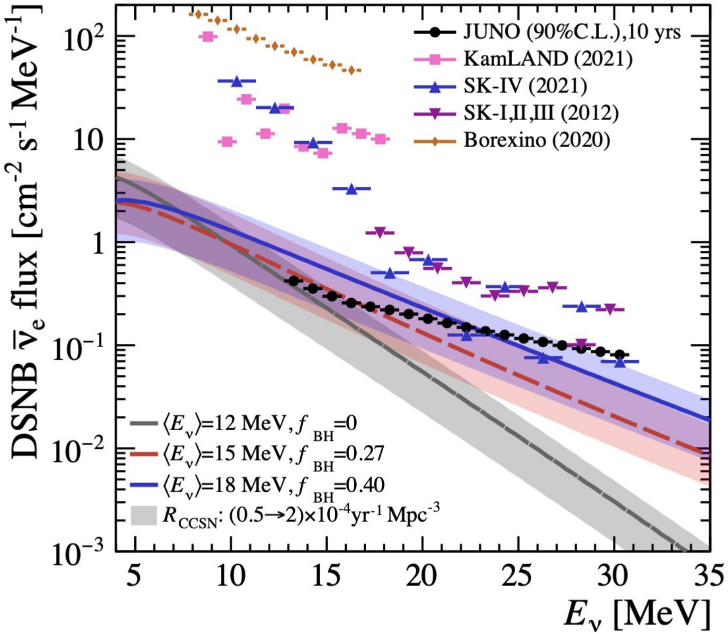
JUNO sensitivity to DSNB

Discovery potential (σ) at JUNO as a function of the running time



Sensitivity > 3σ in 10 y for all DSNB signal models (in 3 yr for reference model)

If there is **no positive DSNB detection**, JUNO can also significantly improve upon the **current best limits on the DSNB** fluxes.



Prospects for detecting the diffuse supernova neutrino background with JUNO

Conclusions

JUNO has great potential to study neutrinos from natural sources

Atmospheric neutrinos

Will enhance sensitivity to NMO through “matter effects”

Solar neutrinos

Potential for the most precise model-independent measurements of solar neutrino fluxes and oscillation parameters

Geo neutrinos

Can quickly collect world-leading statistics. Will allow to probe Earth's mantle properties.

Supernova neutrinos

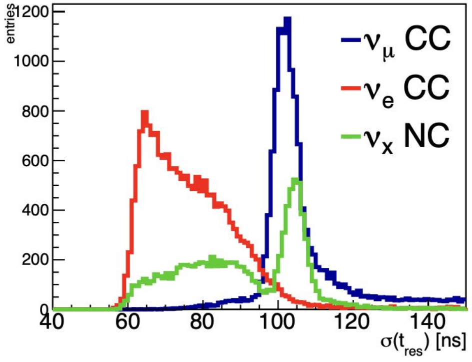
Can detect both SN and Pre-Sn neutrinos, to boost source understanding and make fast alert for SN explosions.

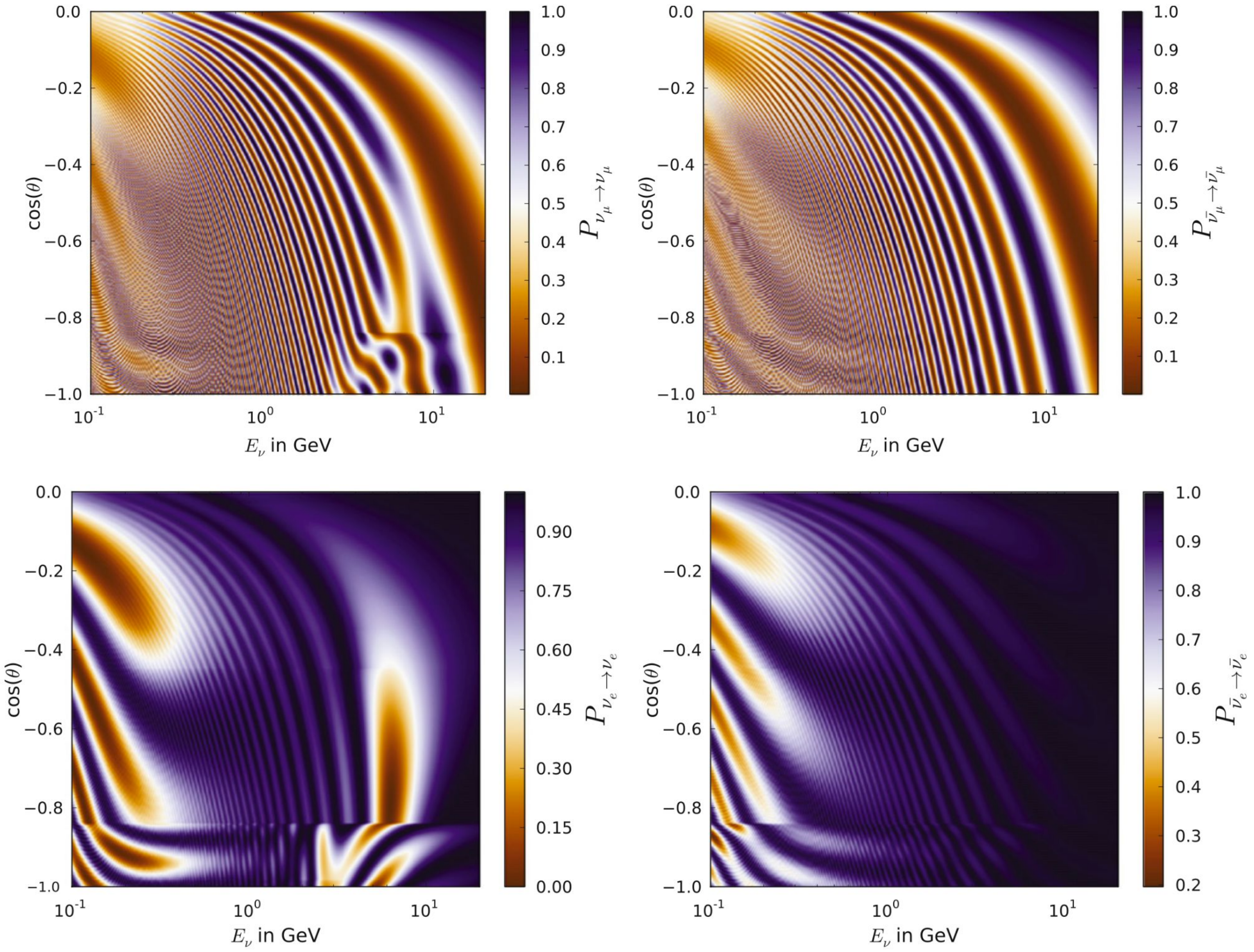
DSNB

High sensitivity in just a few years.

Thanks for your attention

CC are the favourite detection channels (electron and muons are very distinguishable, due to different track lengths). The NC component appears to be overlapped mainly to νμ CC events, with a tail also in the νe CC region.





	^{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

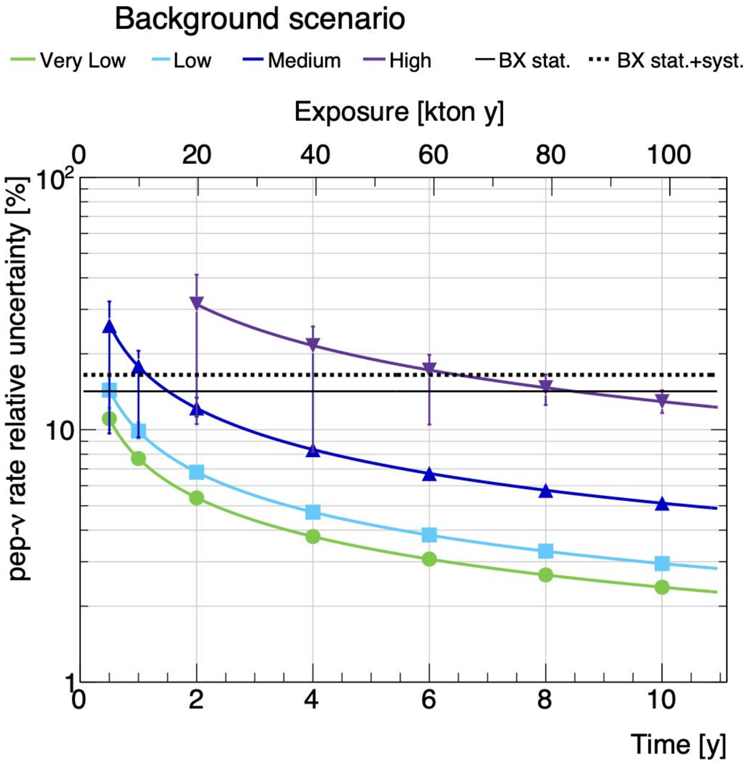
The **High Background** scenario corresponds to the minimum radiopurity requirements needed for the neutrino mass ordering measurement

The **Medium Background** scenario corresponds to a factor 10 improvement with respect to the High background scenario for all isotopes.

The **Low Background** scenario corresponds to a factor 10 improvement with respect to the Medium background scenario for all isotopes, except for ^{210}Pb and ^{85}Kr for which the improvement is only of a factor 5.

The **Very Low Background** scenario corresponds to the radiopurity levels reached on ^{40}K, ^{85}Kr, ^{232}Th chain and ^{238}U chain by the Borexino experiment in Phase-III in the
Fiducial Volume

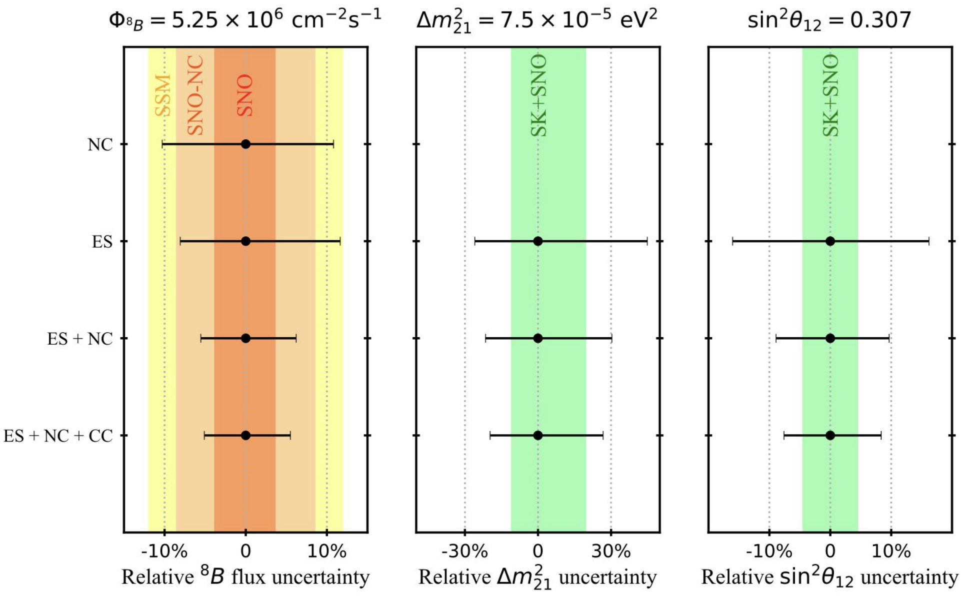
pep sensitivity

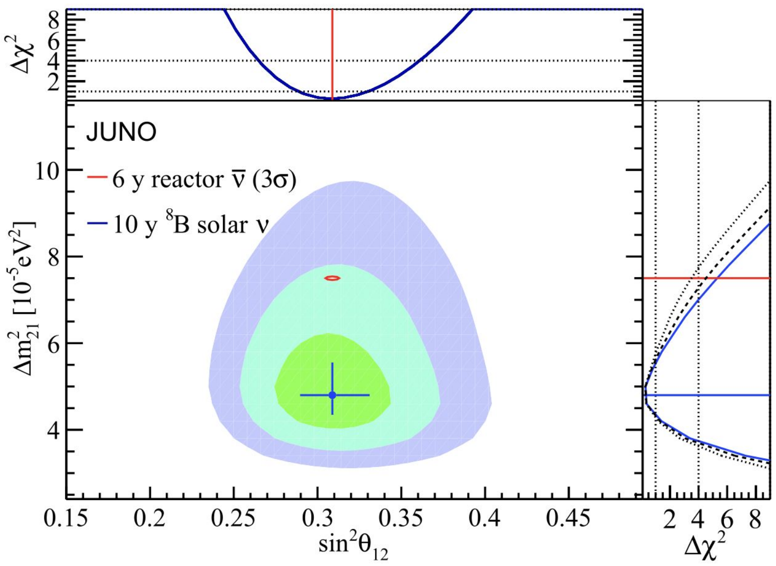


3FC

Due to their long lifetimes, the events from ^{11}C, ^{10}C, and ^{6}He backgrounds can not be removed by a short-time veto cut following a muon event.
The spallation reaction by the parent muon is followed by a cosmogenic decay and a neutron capture, followed by the emission of a characteristic 2.2MeV γ-ray, which allows us to use the so-called Three-Fold-Coincidence (TFC) algorithm.

^8B sensitivity





Lithosphere model	Signal [TNU]
Global model Prog. in Earth and Planet. Sci. **2**, 5 (2015)	$30.9^{+6.5}_{-5.2}$
JULOC model Phys.Earth Planet.Interiors 299 (2020) 106409	$40.4^{+5.6}_{-5.0}$

Mantle model	Signal [TNU]
Cosmochemical (CC)	~ 2
Geochemical (GC)	~ 10
Geodynamical (GD)	~ 20

1 TNU (Terrestrial Neutrino Unit): one interaction over a year-long fully efficient exposure of 10^{32} free protons.

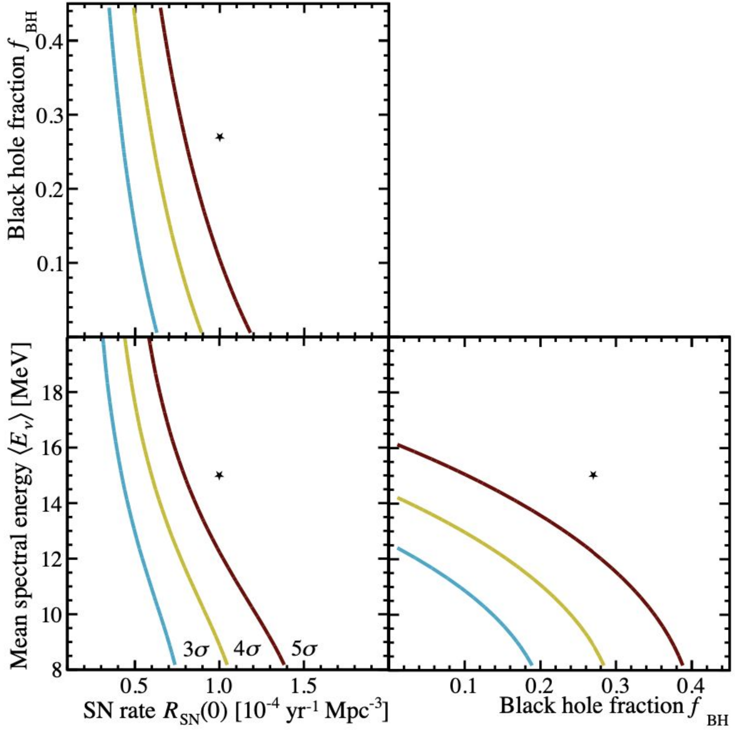
In this work, we employ different numerical models for the fluxes of pre-SN neutrinos and SN neutrinos to study the influence of different models. The pre-SN models are from Patton et al. [17] for the 15 $M_\odot$ and 30 $M_\odot$ progenitor stars, where both thermal processes and nuclear weak interactions are taken into account in the pre-SN simulation. The SN neutrino models are provided by the Nakazato group [21] and the Garching group [22]. The Nakazato models are simulated for progenitor masses of 13 $M_\odot$ and 30 $M_\odot$ with metallicities and shock revival times of (0.004, 100ms) and (0.002, 300ms) respectively. The Garching

31 SN candidates within 1 kpc: Presupernova Neutrinos: Directional Sensitivity and Prospects for Progenitor Identification - IOPscience
56 galaxies in 360 kpc: UPDATED NEARBY GALAXY CATALOG - IOPscience

Supernova neutrinos

	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

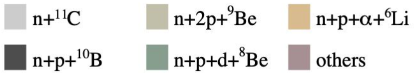
Upper limits for discovery



DSNB discovery potential (σ) at JUNO as a function of **DSNB model parameters** for **10** years of data taking

Backgrounds

- Reactor (we can't go to too high energy, due to atmospheric antinu arriving)
- Atmospheric antinu (compute the flux from theoretical models)
- Cosmogenic $^{9}Li/^{8}He$ (low energy)
- Fast neutron from atm. muons (cut on fiducial volume $<$16m)
- Atmospheric nu NC (interacts on $^{12}C \rightarrow n + ^{11}C$
  CC under 100 MeV suppressed neutron production



Cuts

- Muon veto
- PSD to veto atmo nu NC. Exclude final states with alpha.
- TFC cuts, some final states of nu NC are ^{11}C that has three fold signature (1 fast neutron recoil, 2 neutron capture, 3 beta decay of ^{11}C)