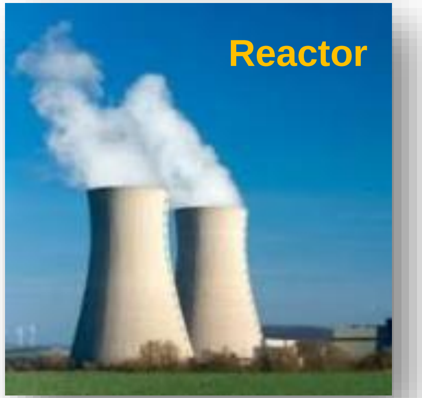
Astrophysics Program at JUNO

Yu-Feng Li
Institute of High Energy Physics, Beijing

2026/07/03

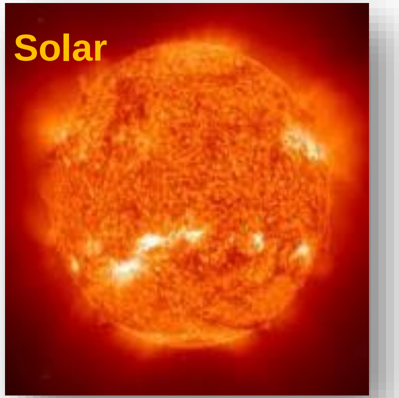
On behalf of the JUNO collaboration

A multi-purpose observatory



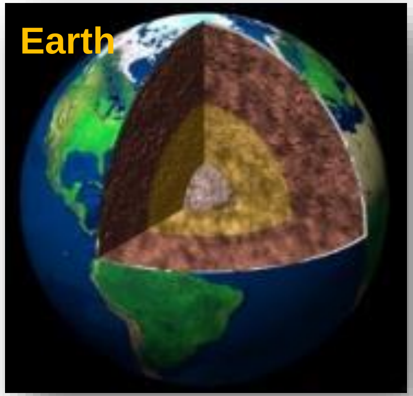
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

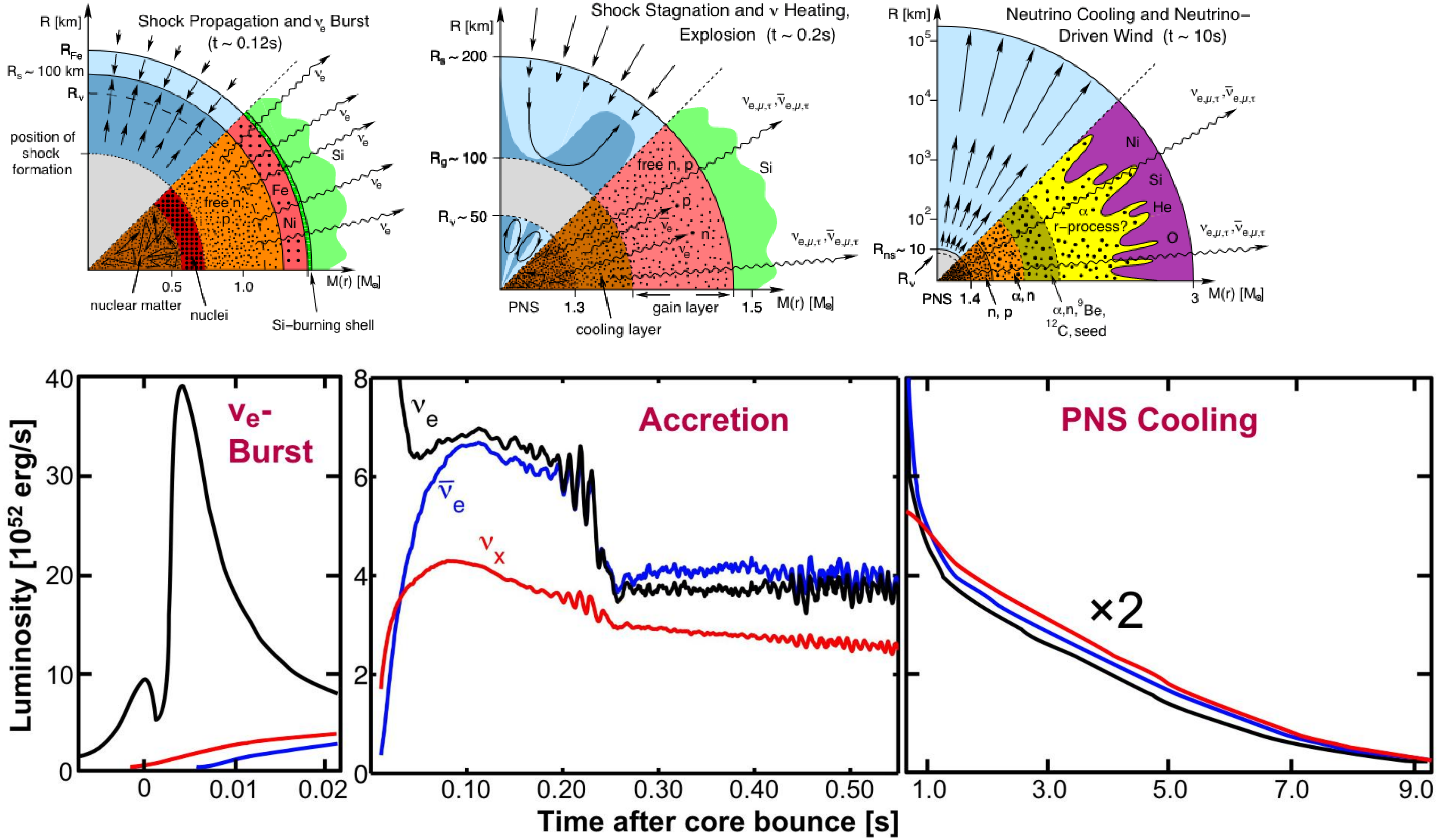
IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

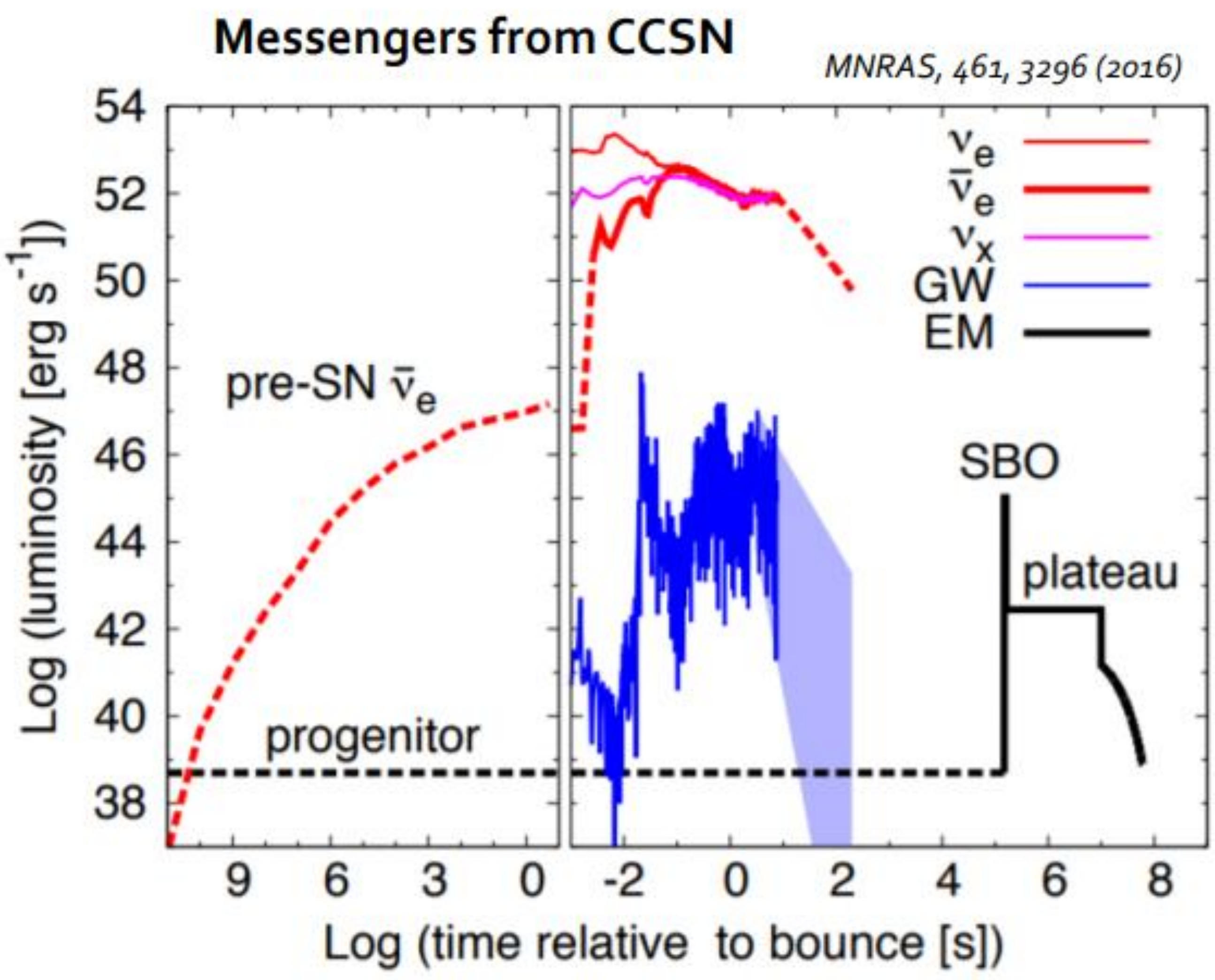
Focus on Supernova neutrino observation at JUNO

Supernova Neutrino Emission

H. T. Janka, et al., “Theory of core-collapse supernovae



Multi-messenger Signals

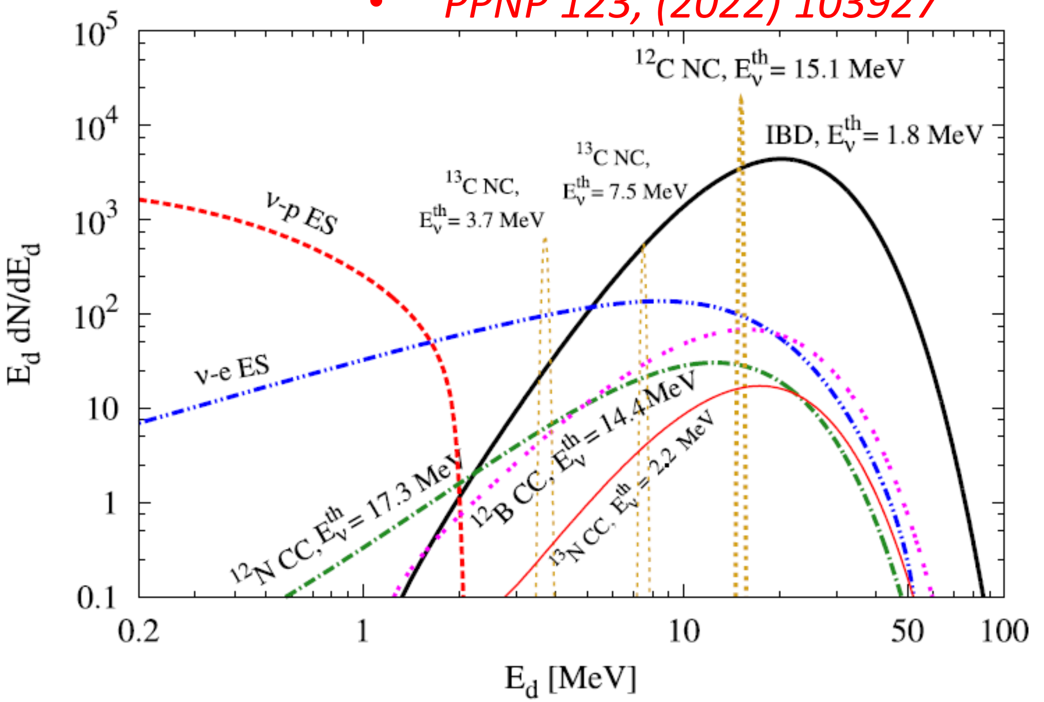


The large liquid scintillator detectors, JUNO, has great potential on detecting both pre-SN and SN

- **Pre-SN neutrinos**
  - **~MeV** neutrinos, much lower luminosity than SN burst neutrino
  - visible **~days** before core collapse for **nearby** galactic progenitors
- **SN burst neutrinos**
  - **Few tens of MeV** neutrinos, last for **~10s** with burst, accretion and cooling stages
  - Background almost **free** for SN burst neutrinos

CCSN potential at JUNO

- *PPNP 123, (2022) 103927*



Multi-channel detection, all flavors

~5000 IBD, ~300 eES, ~2000 pES,
~200 ^{12}C CC, ~300 ^{12}C NC @10 kpc

- Early warning
- CCSN Characteristics
  - Time evolution & Energy spectra
  - Total energy, luminosity,

→ **Test CCSN mechanism!**

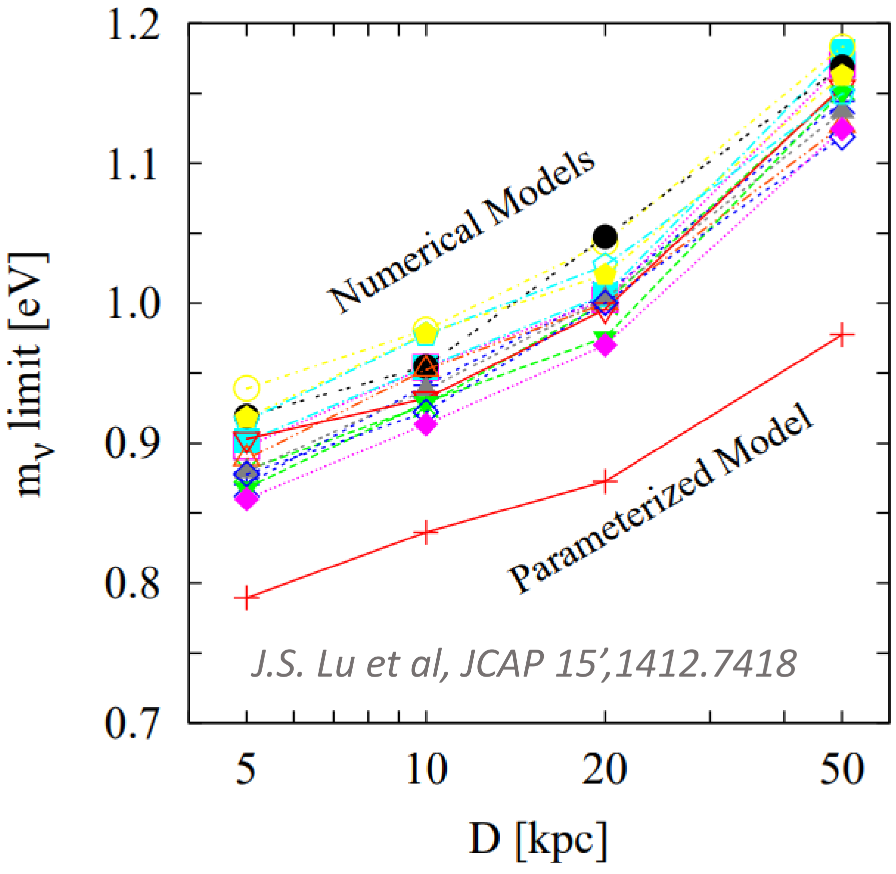
- Neutrino properties
  - Mass ordering
  - Absolute mass
  - New physics

Channel	Type	Events for different $\langle E_\nu \rangle$ values 12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

Particle Physics and Astrophysics

Time delay of massive neutrinos:

$$\Delta t(m_\nu, E_\nu) \simeq 5.14\ \mathrm{ms}\ \left(\frac{m_\nu}{\mathrm{eV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2 \frac{D}{10\ \mathrm{kpc}}$$



- Flavor conversion
  - MSW effects
  - Fast and slow collective oscillations
- Neutrino mass ordering:
  - Spectral comparison
  - Time profile
- New particle and new physics
  - Axion (ALP)
  - keV sterile neutrinos
  - Dipole portal
  - … … …

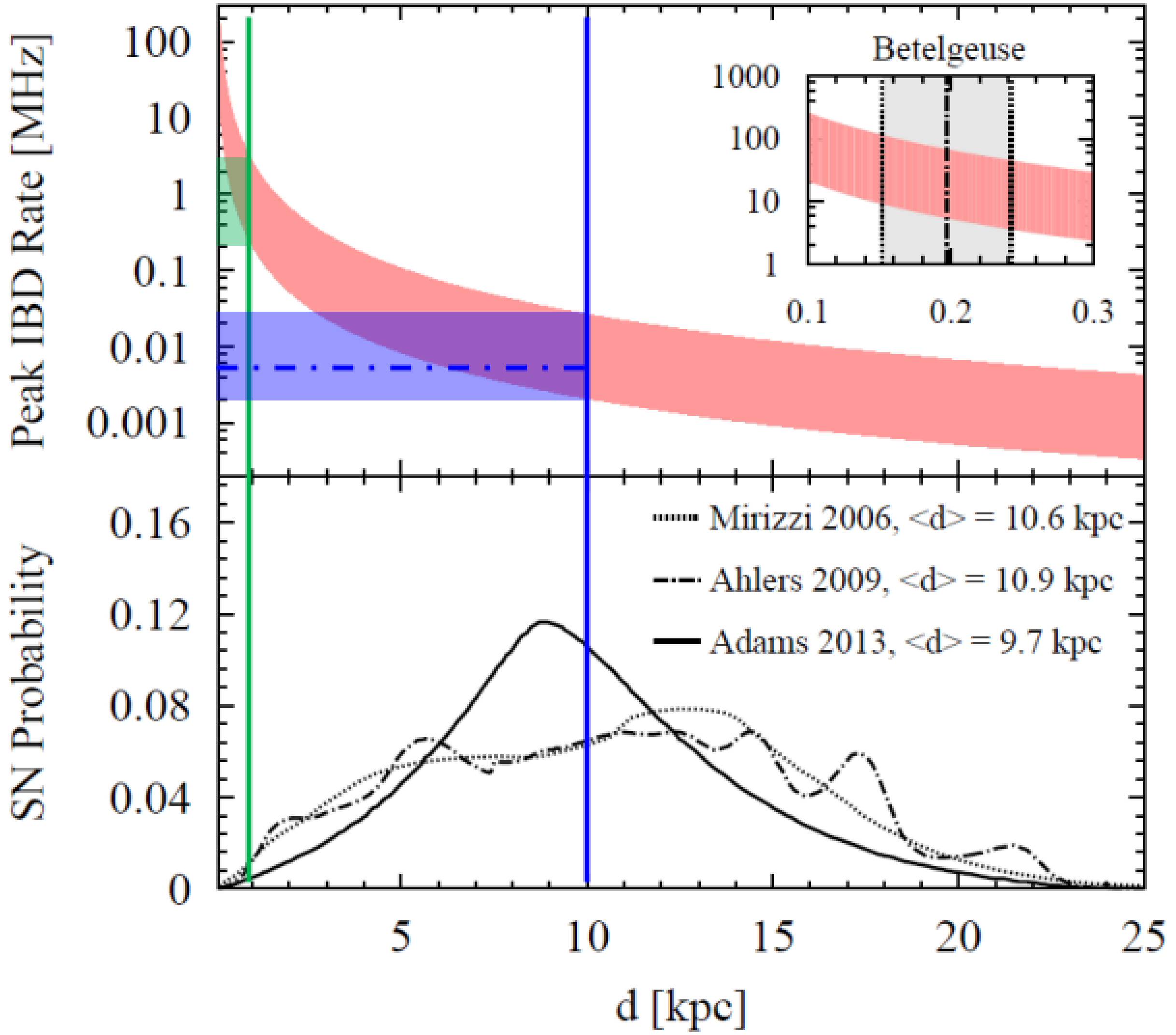
→ Rich program to be explored!

Early Warning

- *JPG 43 (2016) 3, 030401*

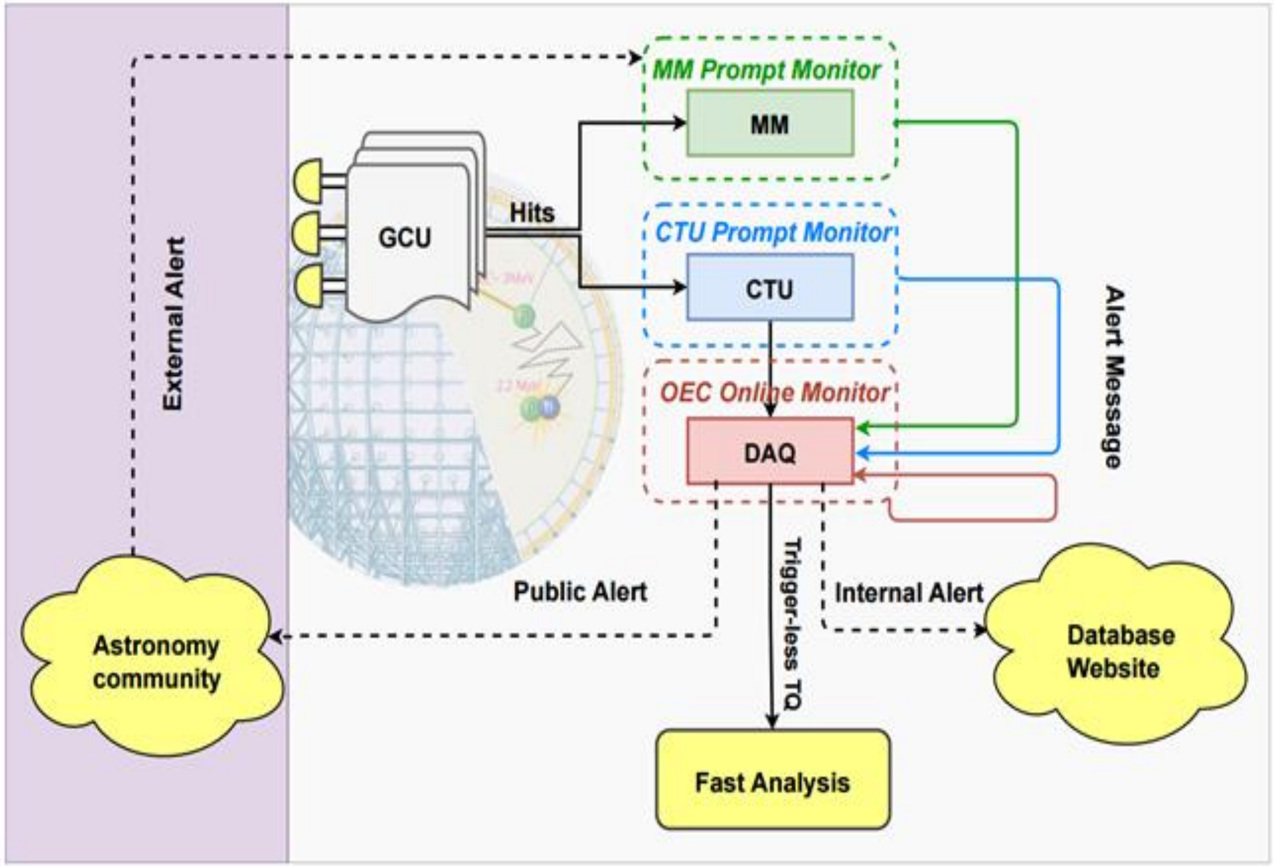
- Prompt and Online monitor systems designed for **SN Early Warning**
  - Non-stop, continuous monitoring
  - Not affected by any Run Modes (physics, calibration, PMT cooling, etc)

- DAQ design can fulfil the requirements on SN data taking
  - CCSN Data stream can **reach MHz at 1 kpc.**
  - No data loss for Time and Charge (TQ) stream at > 0.2 kpc
  - No loss of waveforms at > 3.6 kpc.



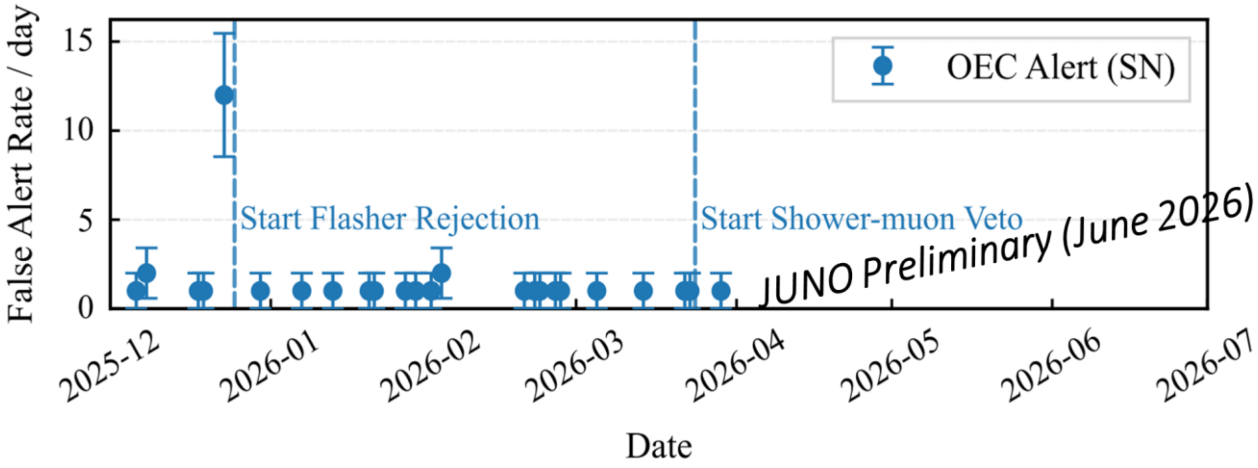
Redundant Monitoring System

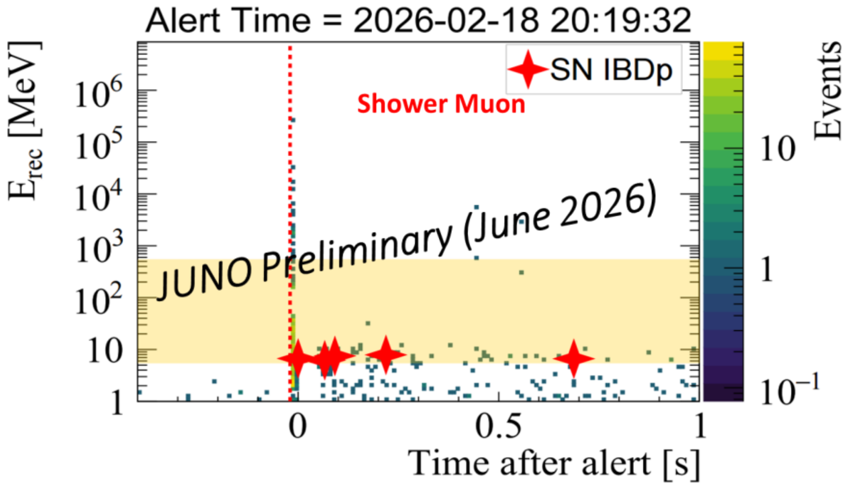
- Three independent monitoring system:
  JCAP 01 (2024) 057 arXiv: 2309.07109 [hep-ex]
- The OEC monitor uses reconstructed event information from the Online Event Classification (OEC) software.
- The Multi-Messenger (MM) Trigger monitor uses a dedicated low energy trigger system.
- The CTU Prompt monitor runs on FPGAs of the electronic boards in the global trigger system (under debugging)
- Alerts to SNEWS 2.0 since 28 Nov 2025
- Fast analysis of CCSN characterization



OEC Monitor: Status

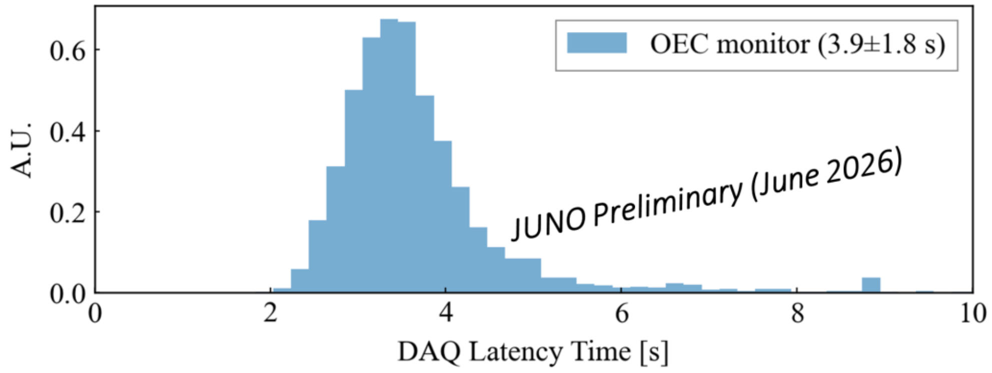
- Live time: **97% (99.8% after upgrade),** reliable during calibration and cooling runs.
- False alert rate: 1–3 alerts/week (early stage), 1/3 months (current configuration).





- DAQ latency time: **around 4 s.**

- Validation with laser tests



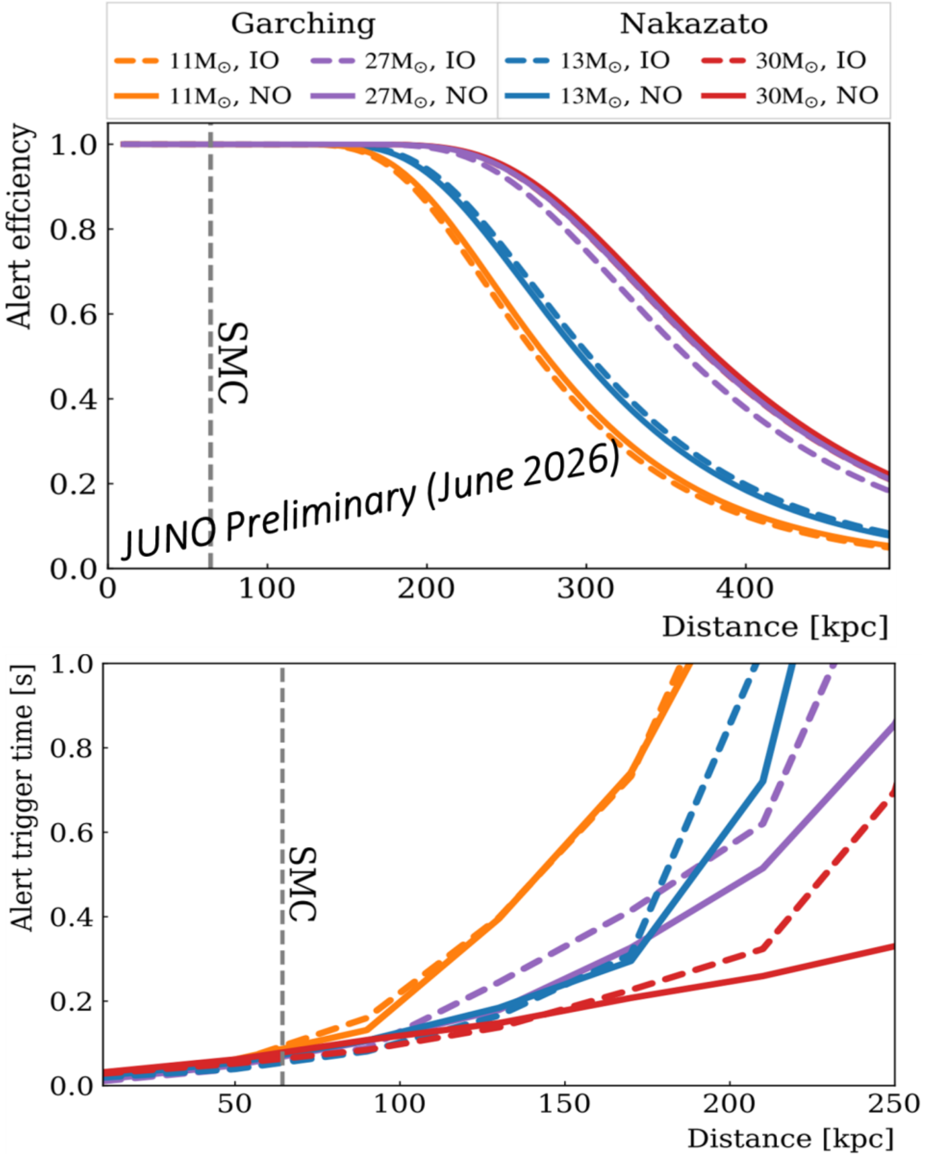
OEC Monitor: Performance

- Evaluated based on real background and signal simulations.
- Signal: 80% efficiency base on MC,
- Background:

  Reactor IBDs and Li9. ~27 candidates/day.

- Alert efficiency > 50% for CCSN within 350 kpc

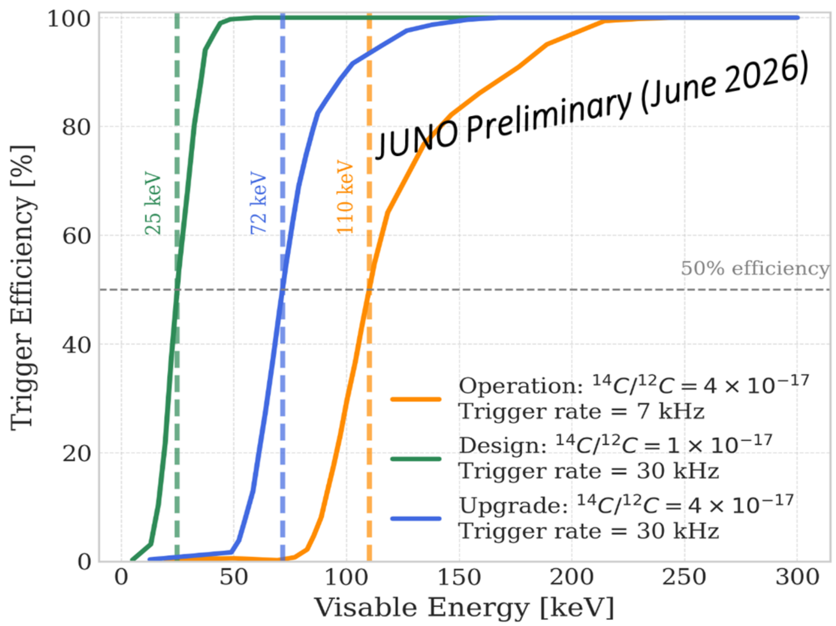
- Alert triggers in 20 ms at 10 kpc after core bounce (DAQ latency at second level)



MM Trigger Monitor: Status

- MM trigger: dedicated system for transient and/or low energy events

	Global trigger	MM trigger
Algorithm	Multiplicity	Likelihood-based
Function	Reactor ν & General physics	Transient bursts & Sub-MeV
Threshold	~ 200 keV	~ 110 keV
Trigger Rate	~ 400 Hz	~ 7 kHz



- Current operation: 110 keV with 7 kHz trigger rate.
- Serve as a fast, low-energy and low-latency monitor for supernova burst and other transients

MM Trigger Monitor: Performance

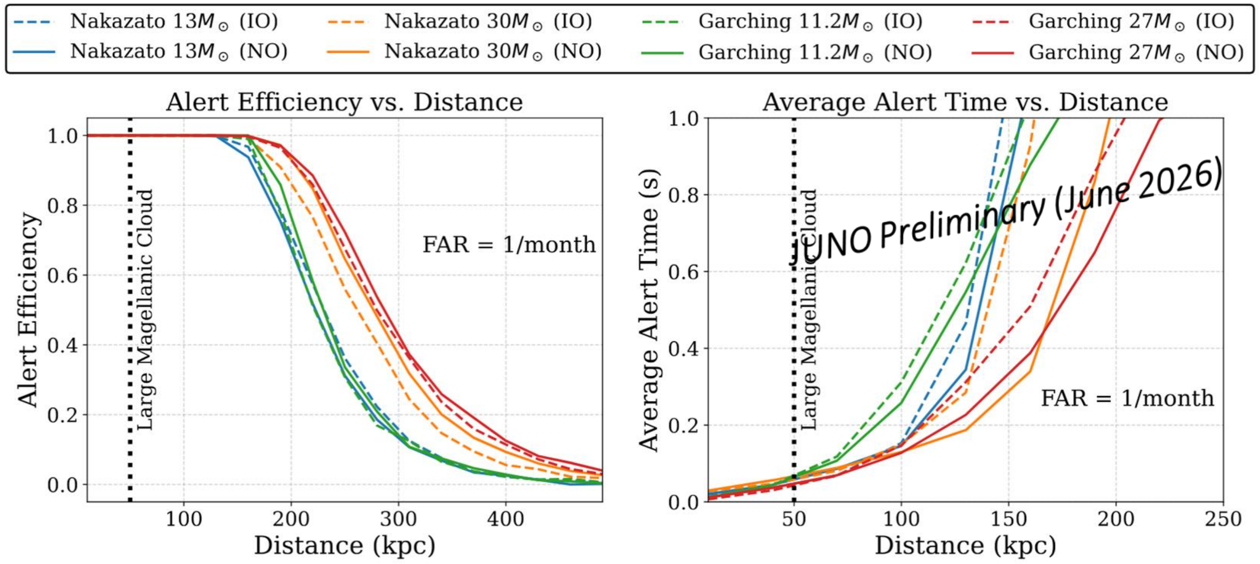
- Running with both high-energy (5-20 MeV, CCSN) and low-energy (0.1-5 MeV) mode.

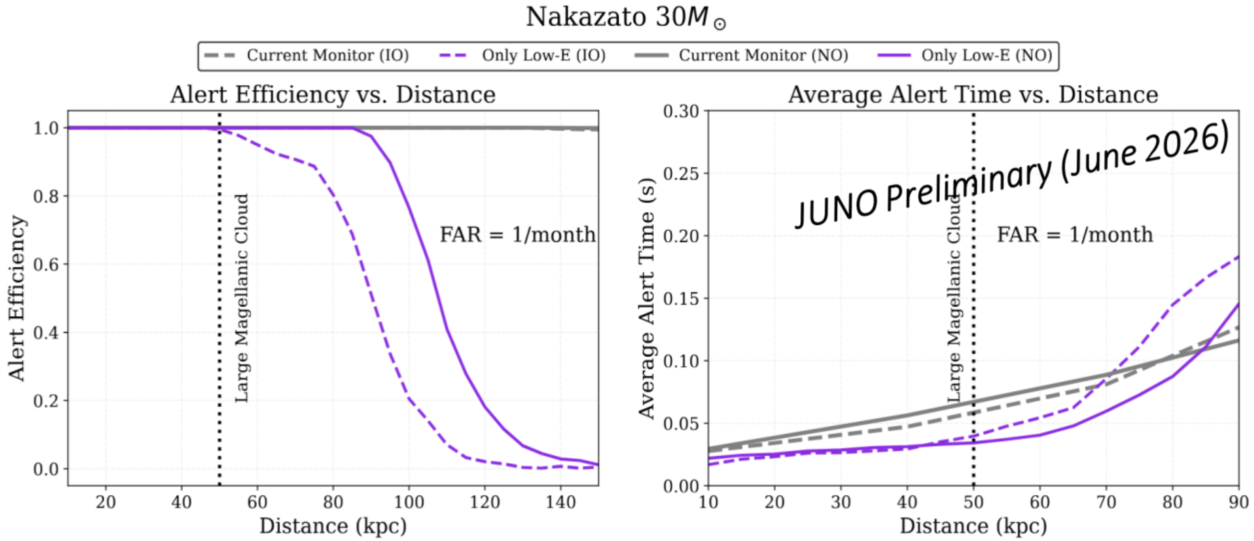
- High energy: complementary to other CCSN monitors

  excellent coverage, and fast (0.1 s)

- Low energy: unique tool to monitor CCSN and transient bursts

  much quicker thanks to the ve burst

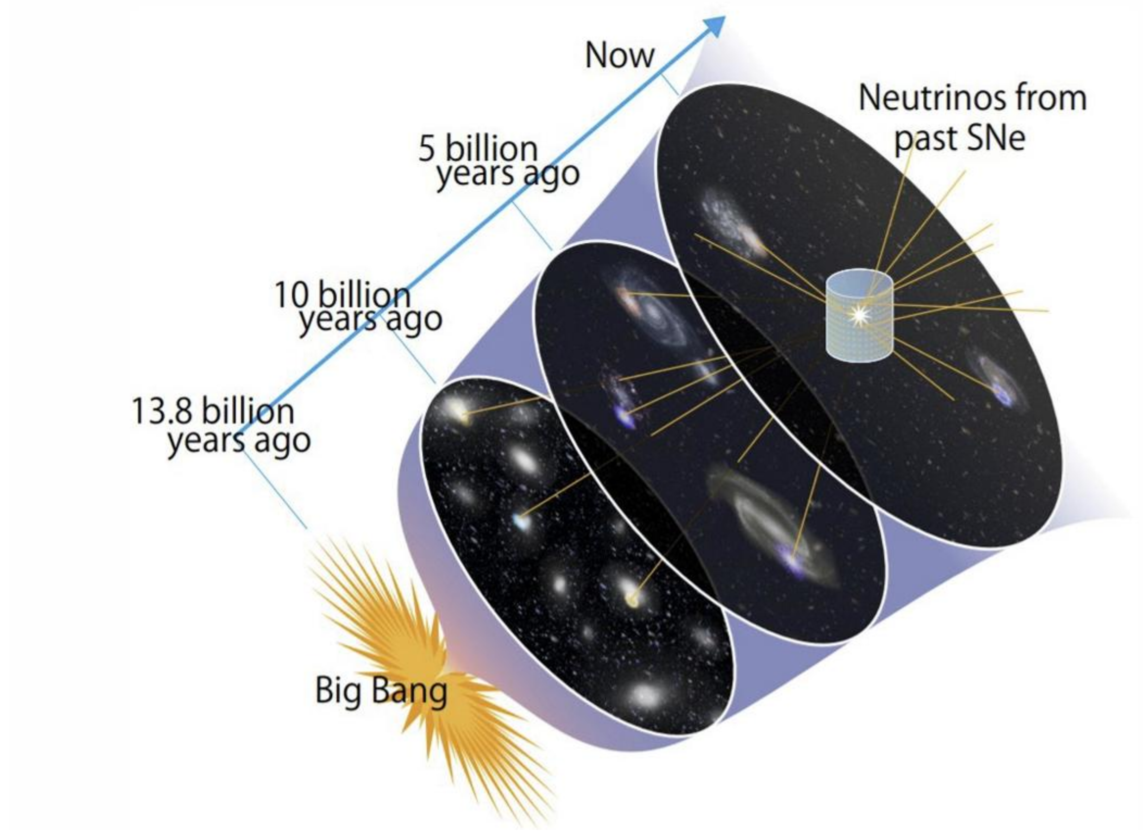




DSNB: another probe of supernova physics

- **We need to wait for the next Galactic (and nearby) supernova neutrino burst**
- Diffuse Supernova Neutrino Background (DSNB):

  → A guaranteed diffuse source of neutrinos from all the past supernovae !



DSNB at JUNO: signal v.s. background

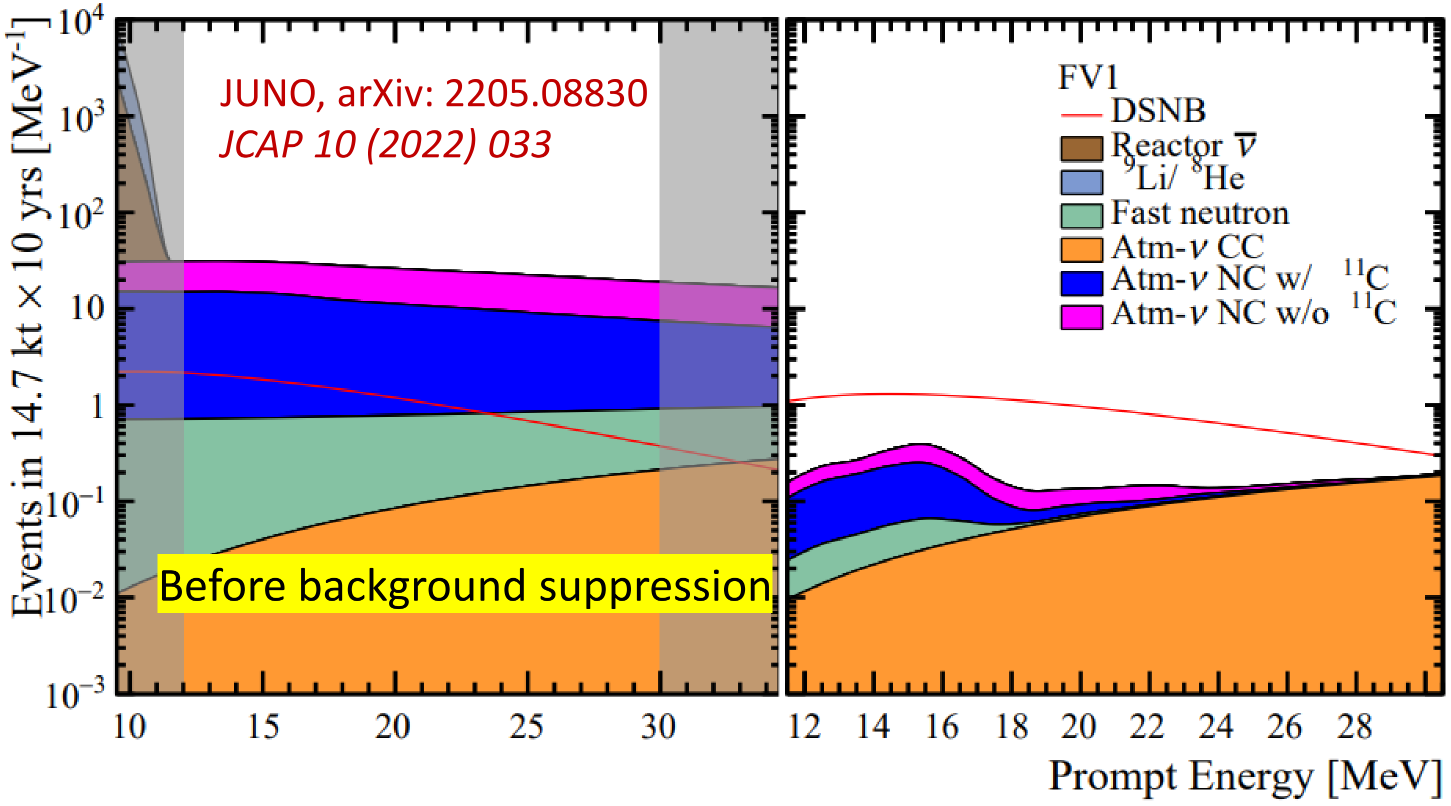
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

Holding:

- Supernova (SN) rate ($\boldsymbol{R_{SN}(0)}$)
- Average energy of SN neutrinos ($\langle \boldsymbol{E_\nu} \rangle$)
- Fraction of black hole ($\boldsymbol{f_{BH}}$)

- Dominant background (above 12 MeV):
  - ✓ Atm-ν NC interactions

- Highlights on background suppression
  - ✓ Muon veto
  - ✓ Pulse shape discrimination (PSD) technique
  - ✓ Triple coincidence (^{11}C delayed decay)

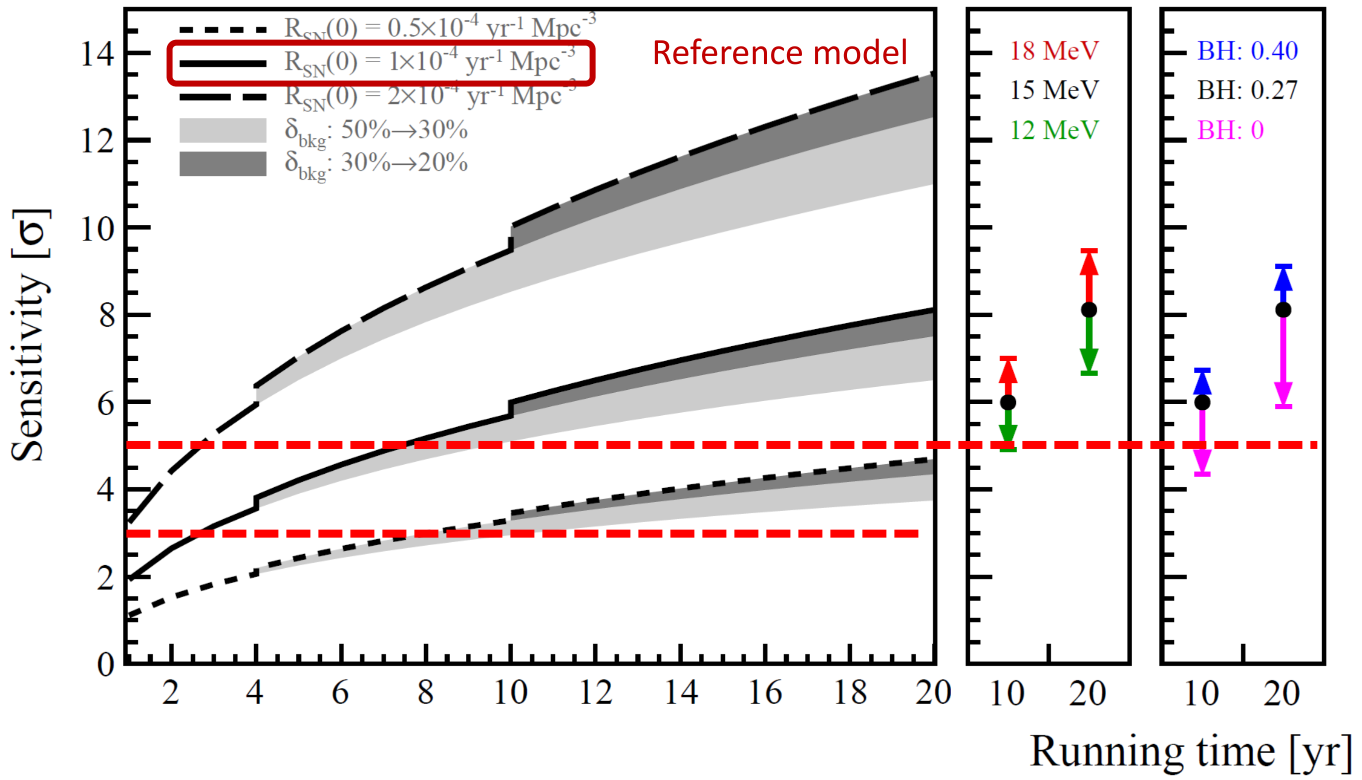


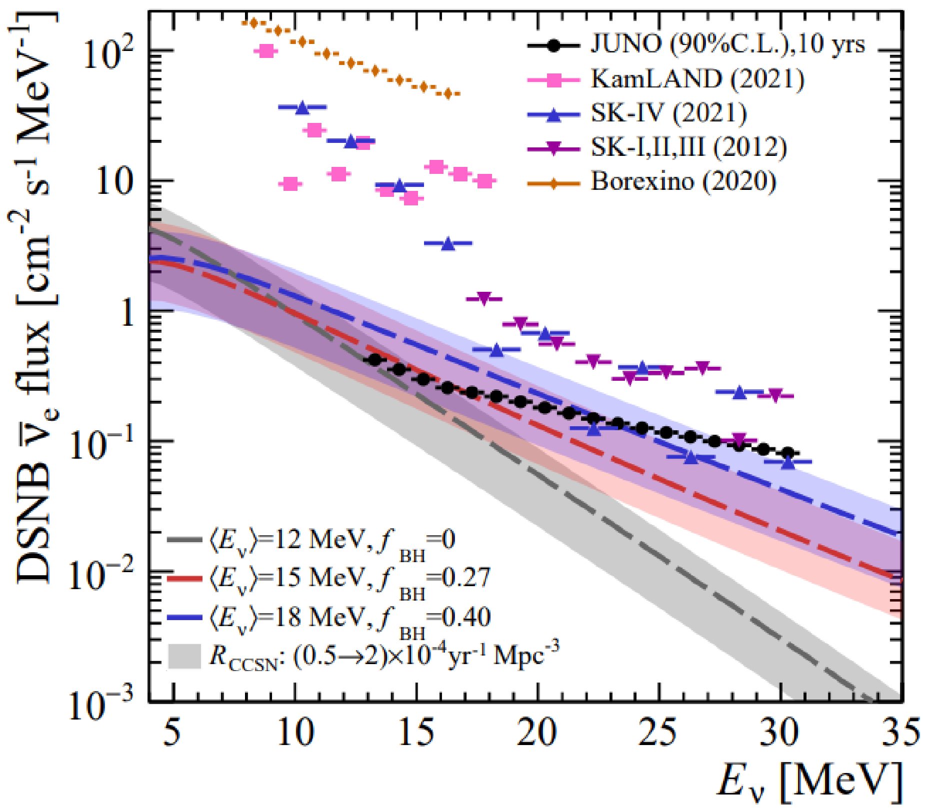
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

➡ S/B improved from **2 to 3.5**

DSNB at JUNO: sensitivity

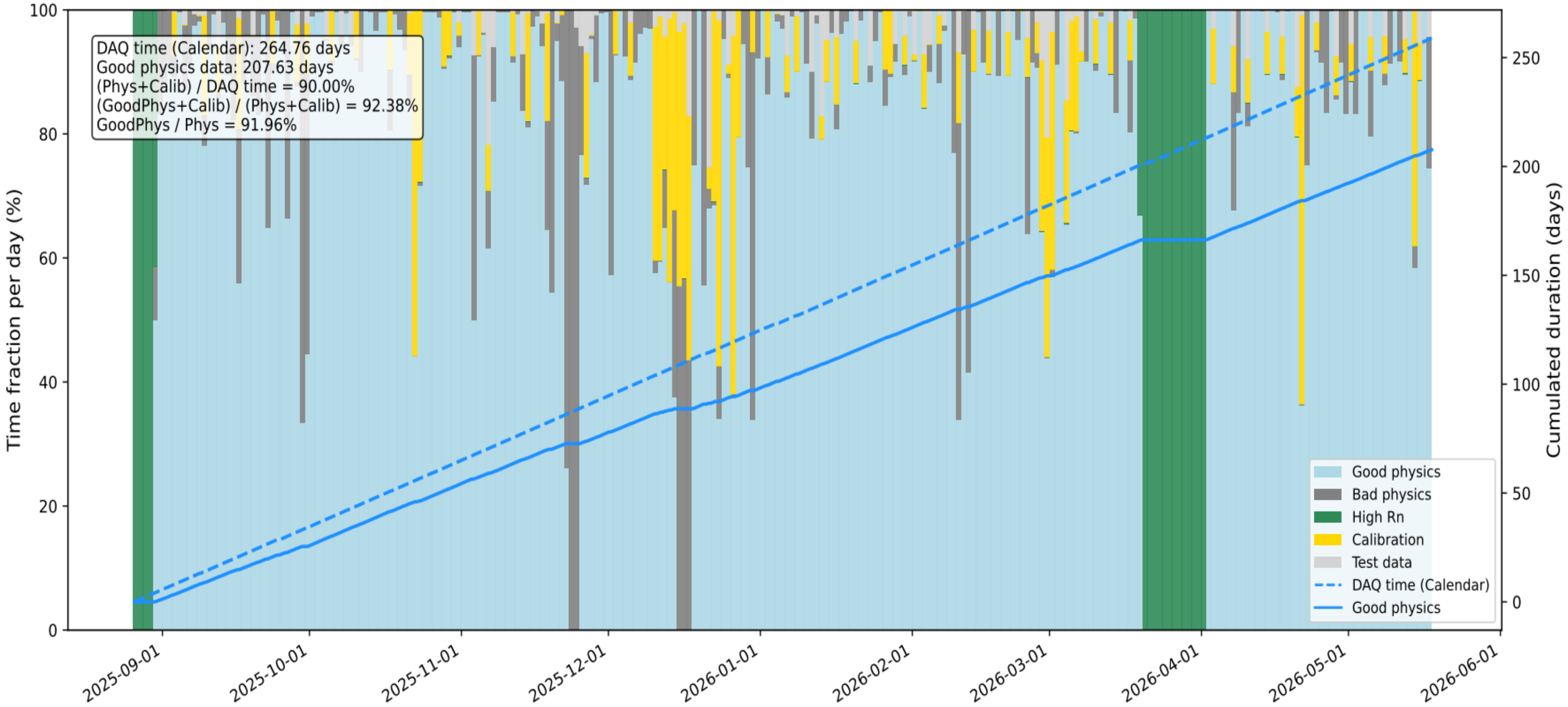
arXiv: 2205.08830, JCAP 10 (2022) 033





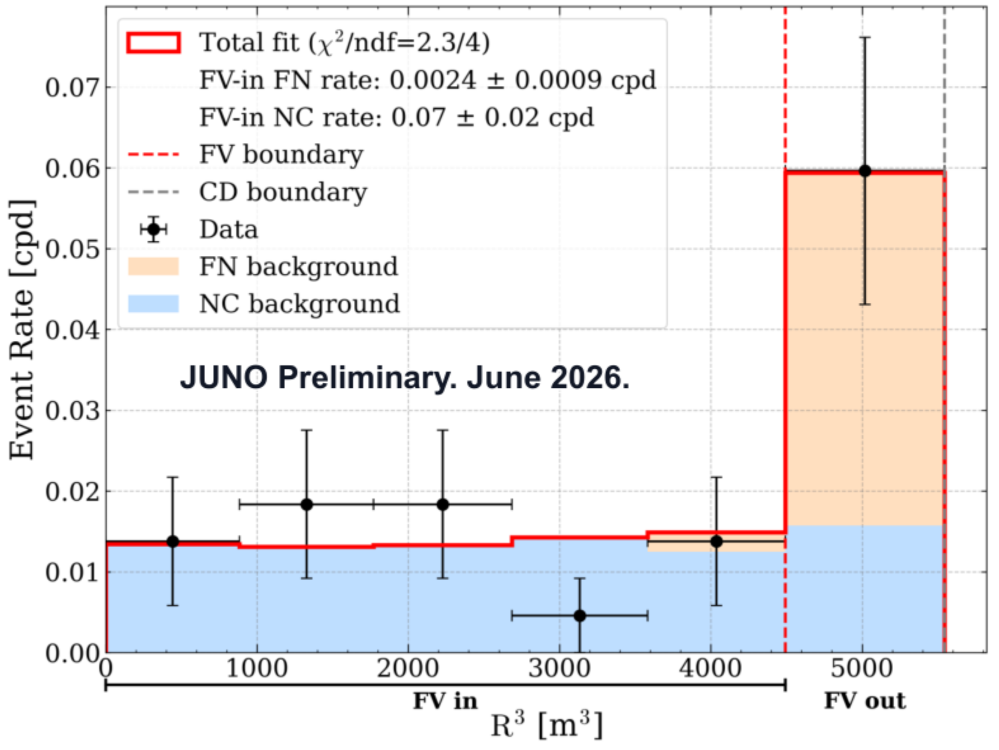
- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

First limit on DSNB (207 days' data)



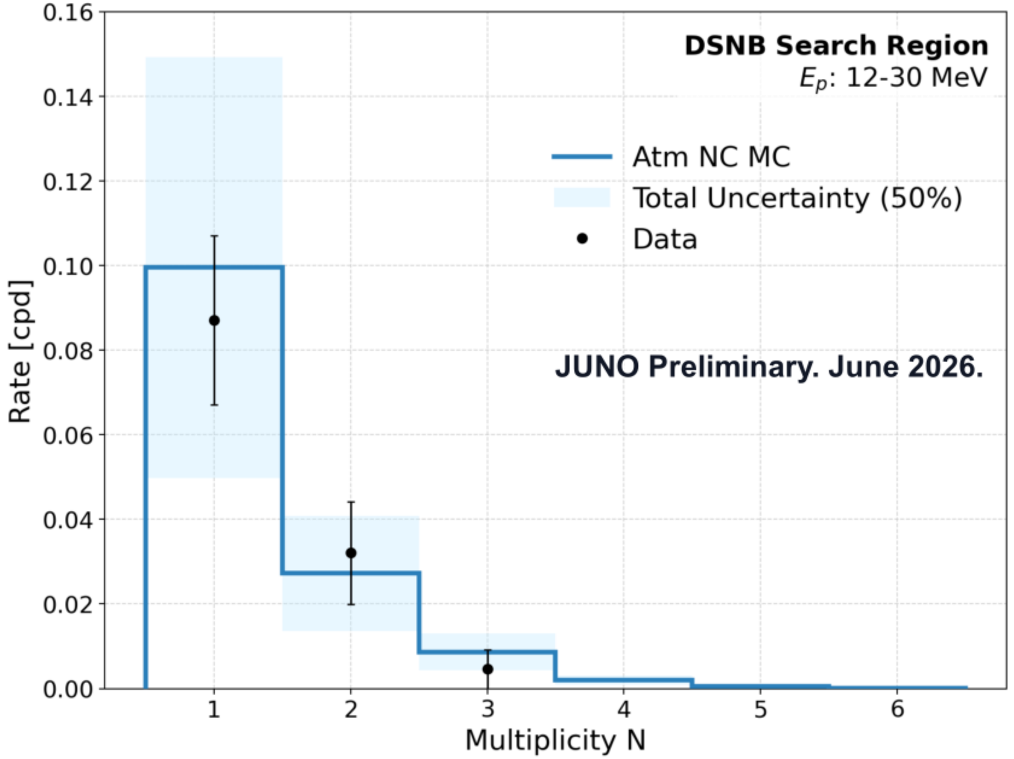
- Similar IBD selection criteria to the reactor neutrinos (with Fiducial Volume 16.5 m).
- **Extended the prompt energy range and increased the muon veto energy.**

First limit on DSNB: backgrounds



Template fit to the $\mathbf{R}^3$ distribution in the 12–30 MeV region.

- Fast neutrons concentrate near the detector edge.
- Fast-neutron (FN) template: WP-only neutron data control sample.
- Fit performed after removing the fiducial-volume requirement.
- Fitted FN rate: 0.0024 ± 0.0009 cpd.

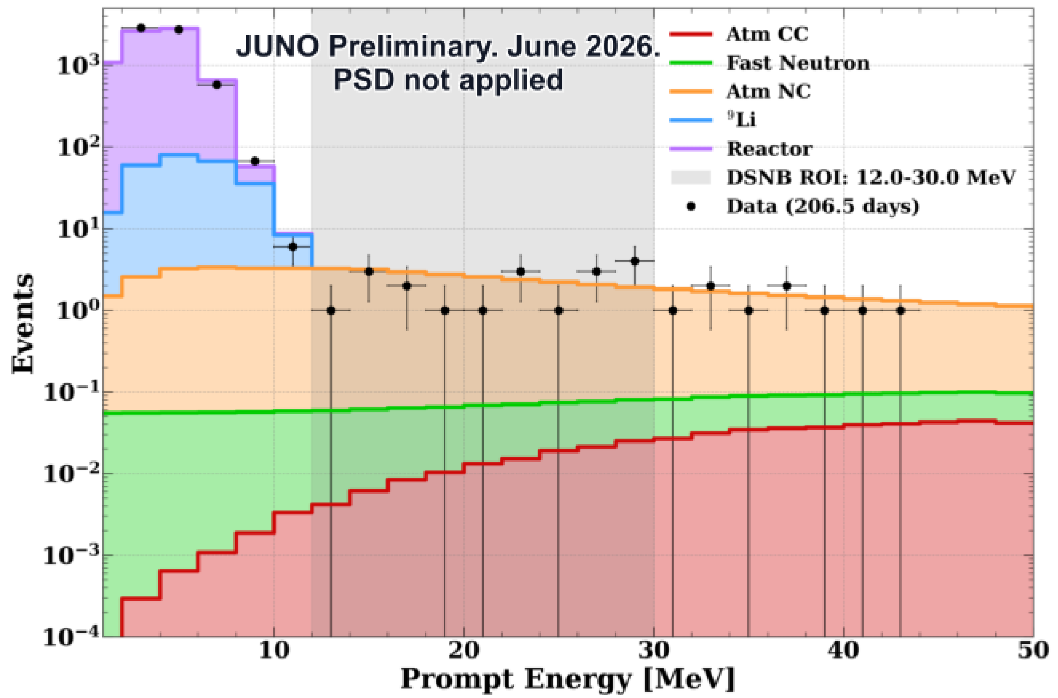


Neutron multiplicity after relaxing the nominal one-neutron requirement.

- Atmospheric-NC interactions can produce multiple neutrons in the final state, providing a validation region for background modeling.
- The nominal NC rate is taken from the bin-by-bin average of five dedicated MC model predictions from GENIE 3.4.2 [1] and NuWro 21.09 [2].
- The observed multiplicity distribution is consistent with the NC MC within uncertainty.

First limit on DSNB: results

Energy spectrum and flux limits

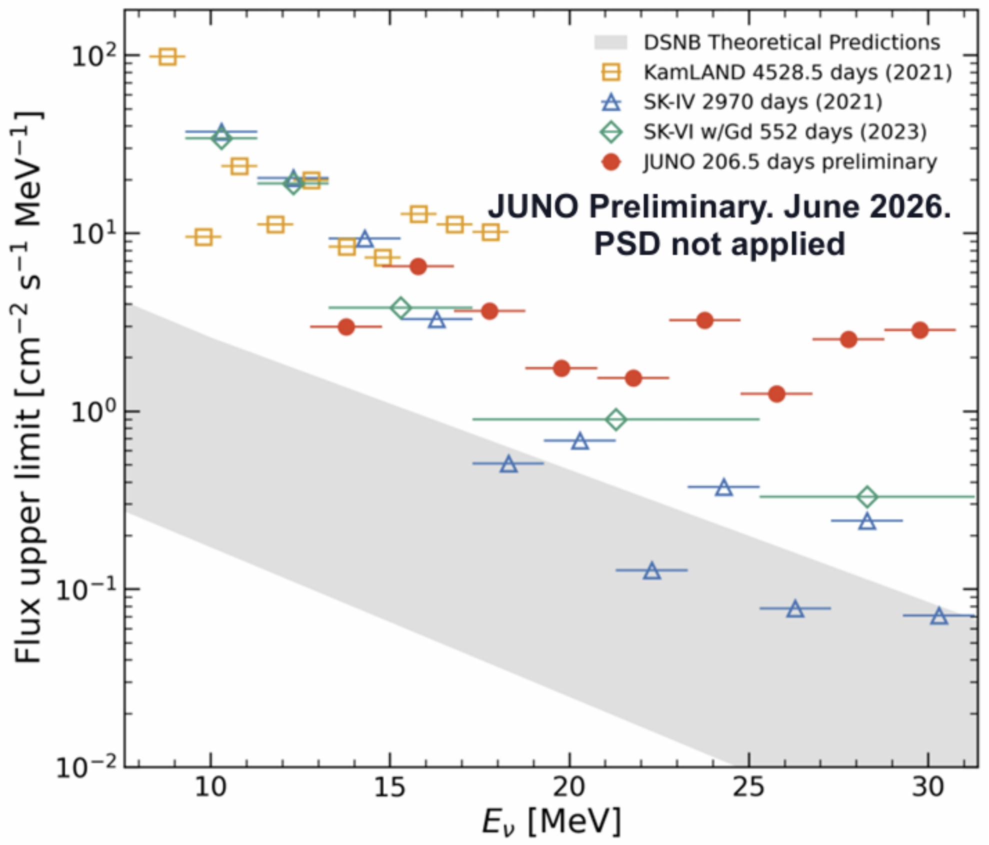


Prompt-energy spectrum; the shaded band marks the DSNB search region.

- 12–30 MeV window: 19 candidates with 206.5-day exposure.
- Total predicted background: 21.3 ± 10.5 events.

$$\phi_{90} = \frac{N_{90}}{N_p \cdot \sigma \cdot \epsilon_{\mathrm{IBD}} \cdot T},$$

N_{90}: Feldman-Cousins 90% C.L. signal-event limit
N_p: target protons
σ: IBD cross section
$\varepsilon_{\mathrm{IBD}}$: efficiency
T: exposure



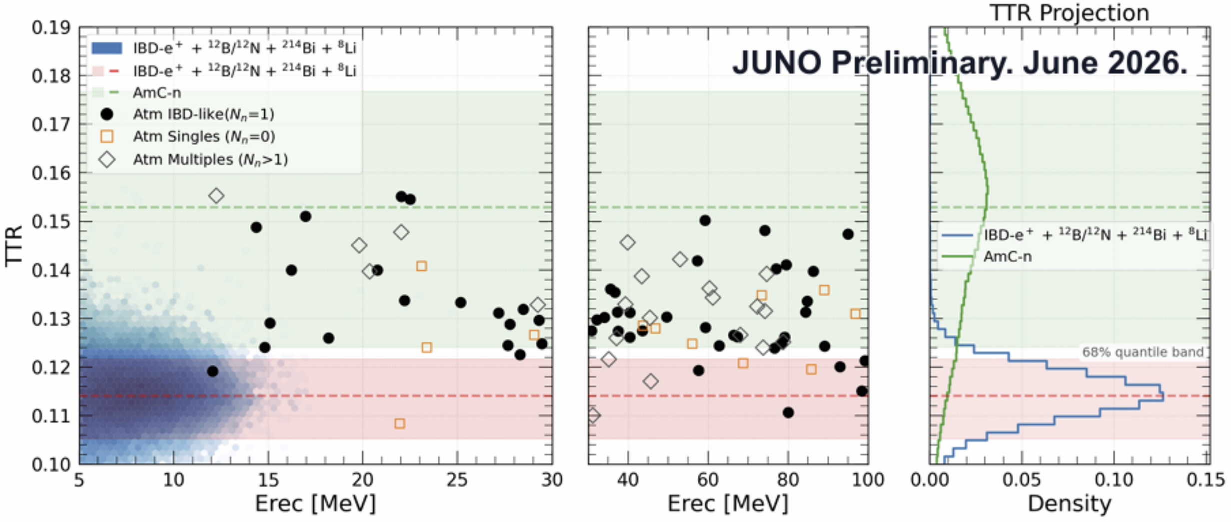
Model-independent 90% C.L. upper limits on the DSNB $\bar{\nu}_e$ flux, compared with SK-IV [3], KamLAND [4], SK-IV-Gd [5] and DSNB predictions [6].

First limit on DSNB: further improvement

Pulse-shape discrimination (PSD) exploits particle-dependent differences in LS scintillation time profiles. Here, PSD is evaluated using the Tail-to-Total Ratio (TTR):

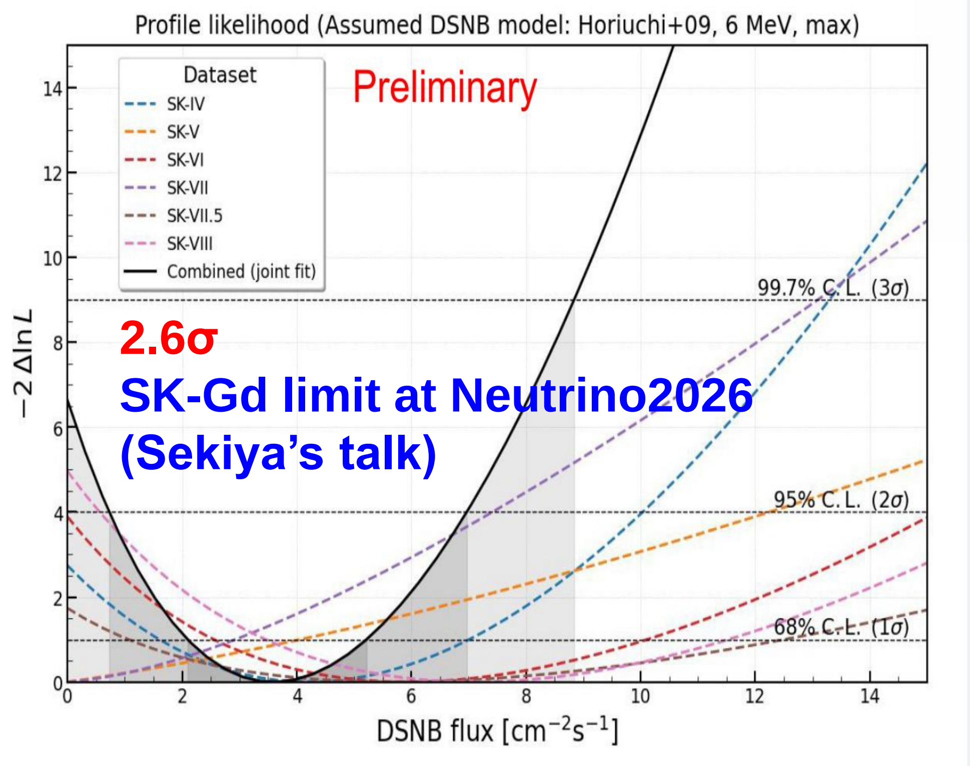
$$\mathrm{TTR} = \frac{Q_{\mathrm{tail}}}{Q_{\mathrm{total}}}$$

Q denotes the integral of the charge-weighted time profile after dark-noise subtraction.



Comparison of TTR distributions for different data samples.

- Candidates and atmospheric-neutrino samples have larger TTR, consistent with NC-like backgrounds.
- PSD is used as a cross-check in the current analysis and shows potential for further background rejection.



➢ **JUNO may be able to test this flux level in a short running time !**

China-French Cooperation (FCPPN/L)

- Supernova neutrino is one of the well cooperated topics between institutions of China and French within the JUNO Collaboration.
  - → **Co-Coordinators of supernova neutrino group** (SUBATECH Nantes and IHEP Beijing):
  - Lead the realization and optimization of CCSN monitoring
  - Monitoring with 3-inch PMTs
  - Various physics studies and detector simulation task

- JUNO-ASTRO project from FCPPN
  - → **Visiting student from SUBATECH to IHEP this year.**

Summary

- JUNO has been in stable operation since August 2025, with many exciting results.
- **World leading capability in supernova neutrino observation**

- **CCSN:** testing the mechanism of supernova burst, and neutrino properties.
  Status: several redundant monitor systems have been running
  A: Good coverage (~ 350 kpc alert distance), B: Fast (~ tens of ms alert time)
  C: Stable DAQ operation (~4 s latency, stable data storage handling)
  D: Alert issued to SNEWS 2.0 since last Nov.
- **DSNB:** guaranteed source of supernova neutrinos, yet to be observed.
  Status: first JUNO limit has been obtained with 207 days' data
  Good understanding of background, and world competitive limits achieved.

- **Excellent China/French cooperation in supernova related studies.**


LOOKING FORWARD TO THE NEXT
GALACTIC SN !
Thank you!

Energy spectral reconstruction

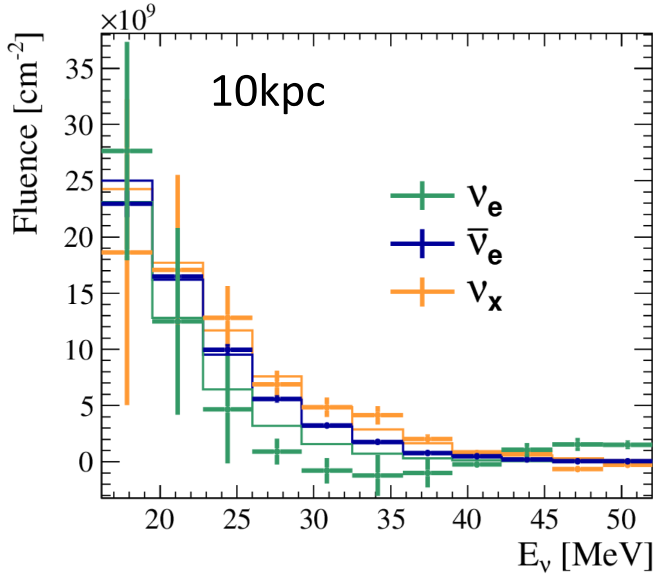
Cross section && Detector effects | **SN neutrinos spectra** | **Observed spectra**

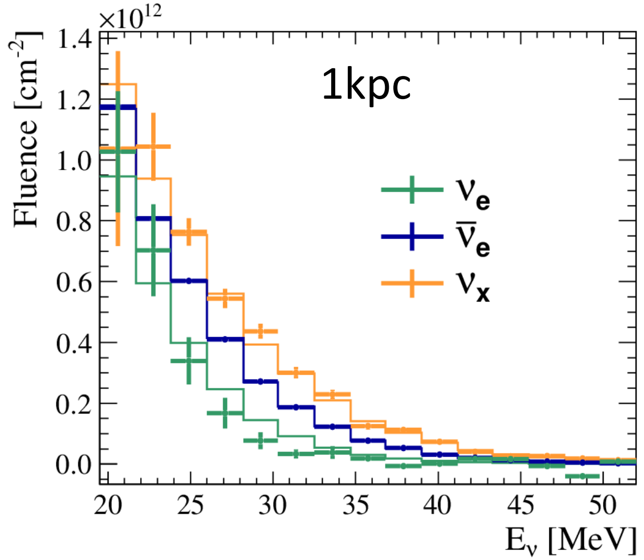
$$\begin{bmatrix} N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\boldsymbol{\sigma}^\mathrm{IBD}_{\nu_e} & N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\boldsymbol{\sigma}^\mathrm{IBD}_{\bar{\nu}_e} & N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\sum\boldsymbol{\sigma}^\mathrm{IBD}_{\nu_x} \\ N_\mathrm{p}\boldsymbol{D}_{p\mathrm{ES}}\boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_e} & N_\mathrm{p}\boldsymbol{D}_{p\mathrm{ES}}\boldsymbol{\sigma}^{p\mathrm{ES}}_{\bar{\nu}_e} & N_\mathrm{p}\boldsymbol{D}_{p\mathrm{ES}}\sum\boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_x} \\ N_\mathrm{e}\boldsymbol{D}_\mathrm{eES}\boldsymbol{\sigma}^\mathrm{eES}_{\nu_e} & N_\mathrm{e}\boldsymbol{D}_\mathrm{eES}\boldsymbol{\sigma}^\mathrm{eES}_{\bar{\nu}_e} & N_\mathrm{e}\boldsymbol{D}_\mathrm{eES}\sum\boldsymbol{\sigma}^\mathrm{eES}_{\nu_x} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{F}_{\nu_e} \\ \boldsymbol{F}_{\bar{\nu}_e} \\ \boldsymbol{F}_{\nu_x} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_\mathrm{IBD} \\ \boldsymbol{S}_{p\mathrm{ES}} \\ \boldsymbol{S}_\mathrm{eES} \end{bmatrix}$$

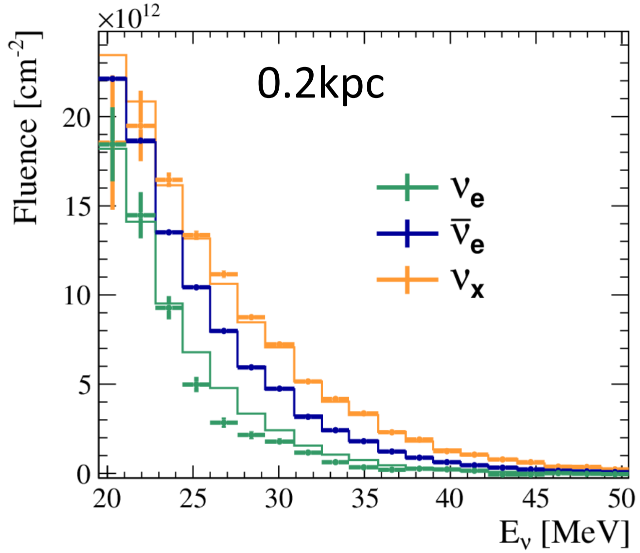
Full flavor SN neutrino energy spectra reconstruction in JUNO detector

- Model independent
- ν_x spectra reconstructed via pES
- promising for global analysis with all channels and other WC, Lar-TPC, et.al detectors.

Li, Li, Wang, Wen, Zhou, PRD, 2018
Li, Huang, Li, Wen, Zhou, PRD, 2019







Energy threshold: < 0.2 MeV

Event Selection

Table 1: Summary of IBD selection criteria.

Criterion	Selection A1 (IHEP)
~~PMT flasher~~	~~Applied~~
Fiducial volume	$r_p < 16.5$ m, $\lvert z_p \rvert < 15.5$ m
Prompt energy	$\boxed{(0.7, 12)\ \text{MeV}}$
Delayed energy	$(2.0, 2.5)\boxed{\cup (4.5, 5.5)\ \text{MeV}}$
Coincidence time	$(5, 1000)$ μs
Relative distance	< 1.5 m
Multiplicity cut	No other events > 0.7 MeV in the FV or $\boxed{(2.0, 6.0)}$ MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed event is within $\boxed{(0, 2)\ \text{ms after}}$ NPE > 700 in WP
CD muon veto	Veto if the delayed event is within $(0, 5)$ ms after $\boxed{\text{NPE} > 3 \times 10^4 \text{ in CD}}$
Spallation neutron veto	Veto if the delayed event satisfies $\Delta r < 4$ m and $\Delta t < 1.2$ s after spallation neutrons with $\text{NPE}_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000)$ μs
$\boxed{\text{Muon track veto}}$	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\,\text{m}} + \frac{\Delta t_{\mu d}}{0.5\,\text{s}} < 1$

Changes:

- ✓ Prompt energy (0.7, 100) MeV
- ✓ CD muon threshold 100 MeV
- ✓ No flasher cut
- Delay energy add n-C (4.5, 5.5) MeV
- Multiplicity cut range (2.0, 2.5) -> (2.0, 6.0)
- WP muon veto time 5ms -> 2ms
- Muon track veto