Detection of Core-Collapse Supernova Neutrinos

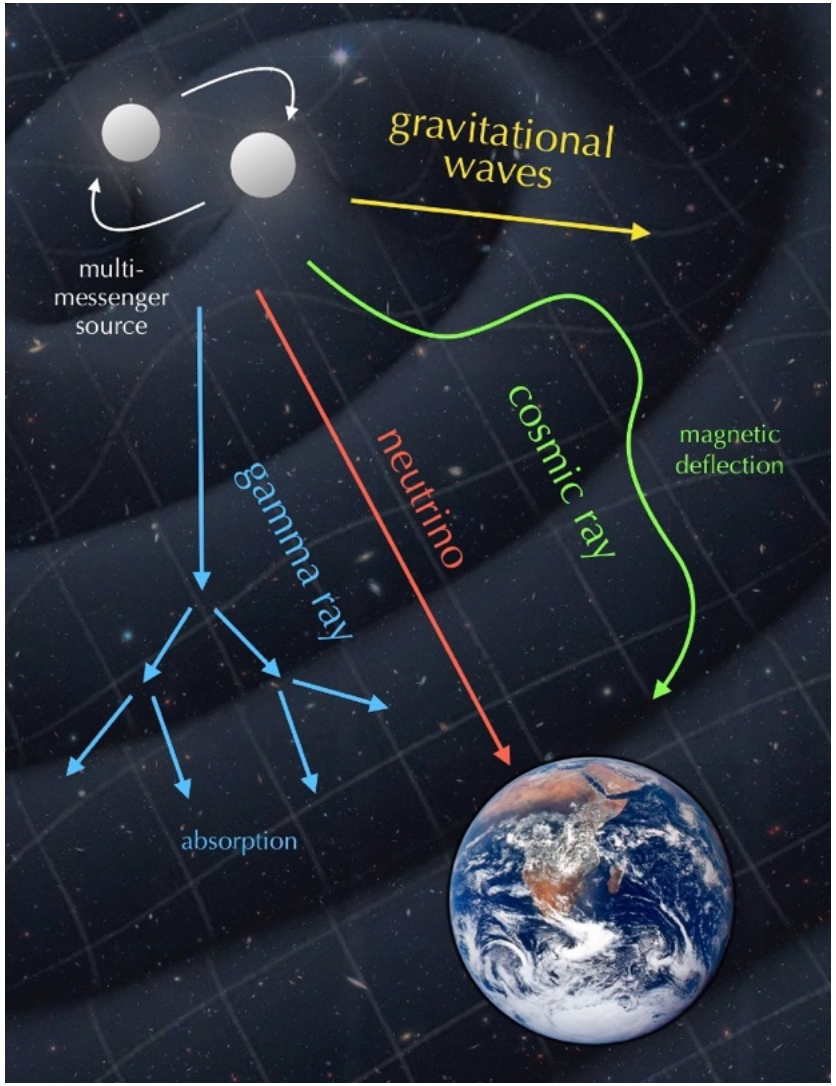
Yi Jia, IHEP



OECE2026 Workshop, BUAA, Beijing

Nov 6, 2026

Supernovae and Neutrinos



Multi-messenger propagation (schematic)

Core-collapse supernovae

- **Expected Galactic rate: ~1–3 per century**
- At the end of a massive star's life, core collapse releases enormous gravitational binding energy.
- **Neutrinos carry away ~99% of the released energy**

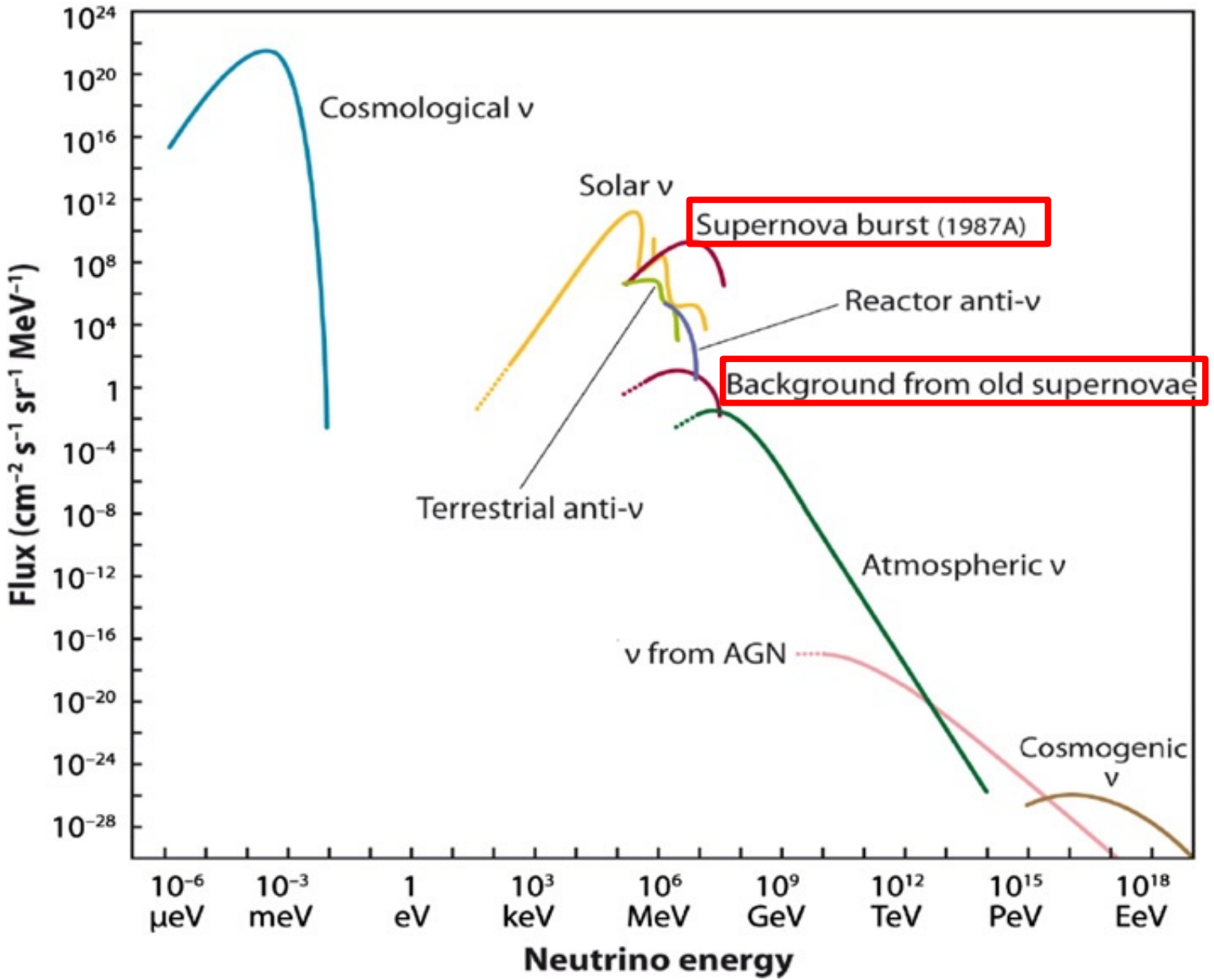
Limitations of other messengers

Photons: dust can absorb or attenuate the signal.
Charged cosmic rays: magnetic fields deflect their paths.
Gravitational waves: weak supernova signals, not yet detected.

Neutrinos: messengers from the core

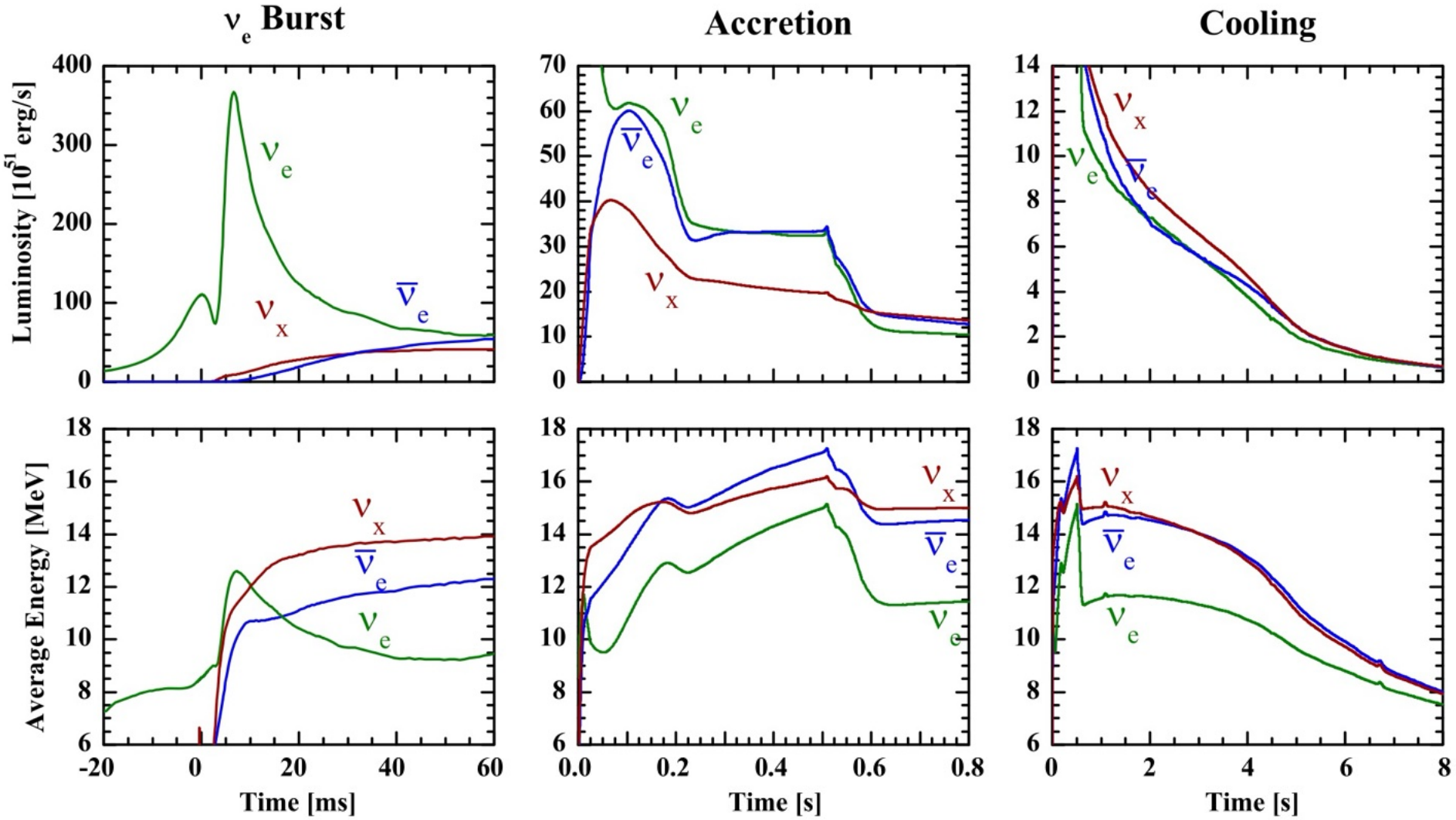
- Electrically neutral particles with tiny masses and very weak interactions with matter.
- **Can arrive before visible light, providing an early warning for optical follow-up.**

Neutrino Spectrum at Earth



U. Katz and C. Spiering, Prog. Part. Nucl. Phys. 67, 651 (2012)

Stages of Supernova Neutrino Emission



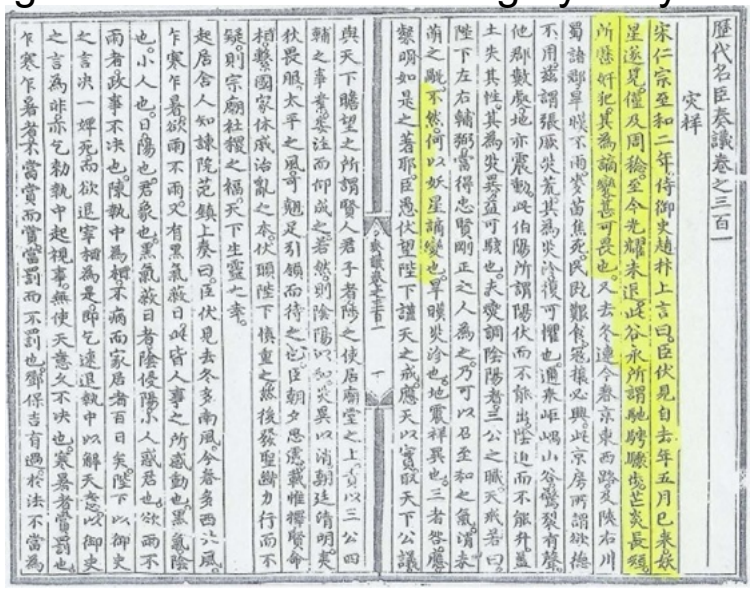
Based on a spherically symmetric Garching model with $27M_{\odot}$.
(explosion triggered by hand during 0.5–0.6 ms)

JUNO Collaboration, J. Phys. G43 (3) (2016) 030401

Historical Supernova Observations

SN 1054

The “guest star” of 1054: a Song-dynasty record



The Crab Nebula: remnant of SN 1054



Hubble Space Telescope image

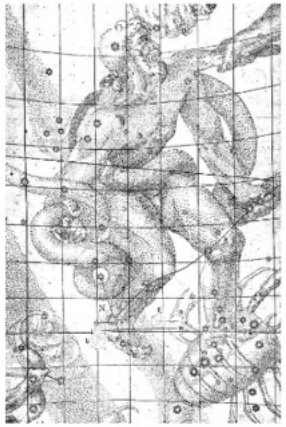
SN 1604

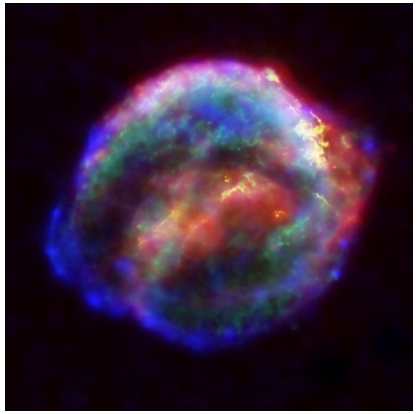
Johannes Kepler



Kepler’s account of the supernova of 1604





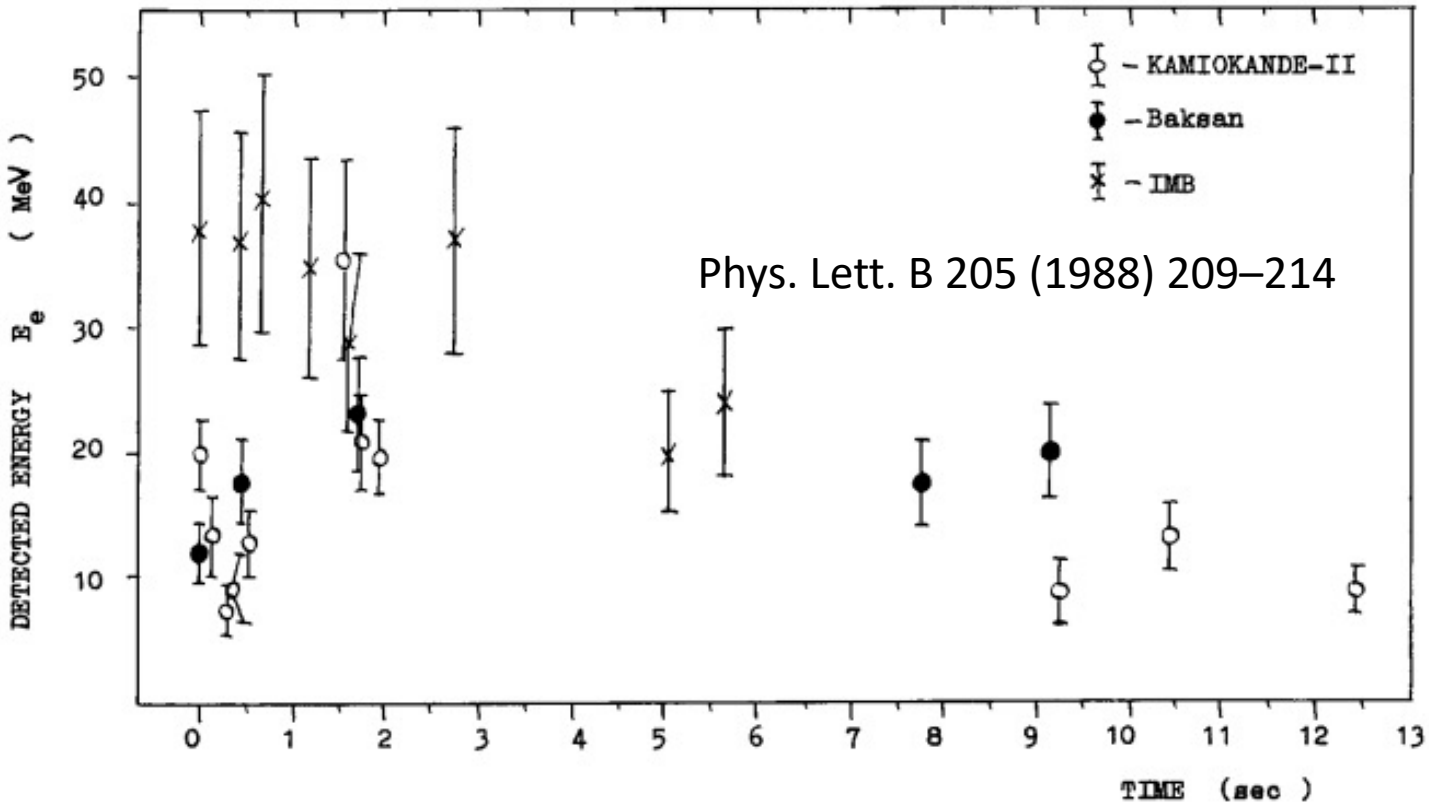


Chandra X-ray image

It has been over 400 years since the last securely recorded naked-eye Galactic supernova!

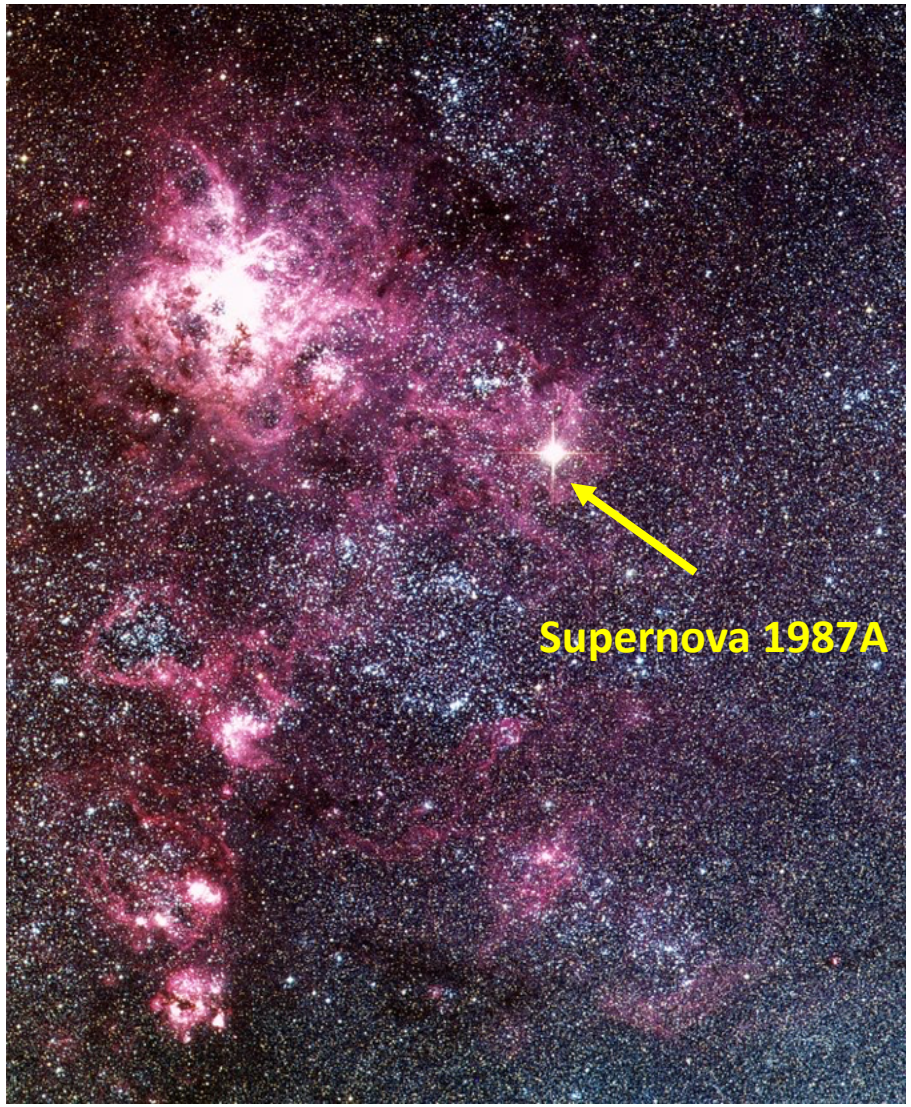
Previous Measurement of Neutrinos from Supernova Burst

Previously, 25 neutrinos were detected from Supernova 1987A by **Kamiokande-II**, **Irvine–Michigan–Brookhaven (IMB)**, and **Baksan** experiments, marking the beginning of neutrino astronomy.



Phys. Lett. B 205 (1988) 209–214

Tarantula Nebula in the Large Magellanic Cloud



What can we learn?

A Galactic supernova offers a rare opportunity for landmark discoveries

Astrophysics



The Crab Nebula

The remnant of a supernova explosion

What makes a star explode?

Test the neutrino-driven explosion mechanism

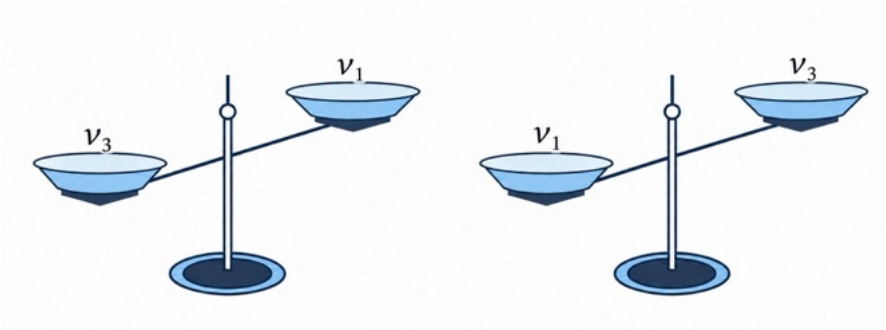
What does the core become?

Trace neutron-star cooling and black-hole formation

How can we catch the earliest moments?

Enable early electromagnetic and GW follow-up

Neutrino properties



Normal: v_3 heavier **Inverted: v_3 lighter**

Which neutrino mass state is heavier?

Probe mass ordering through flavor conversion

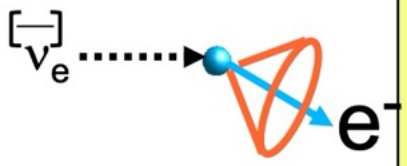
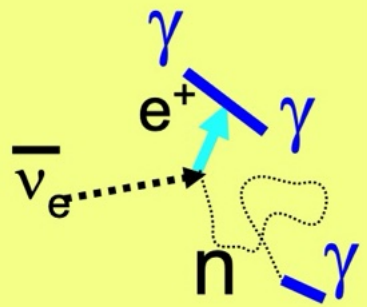
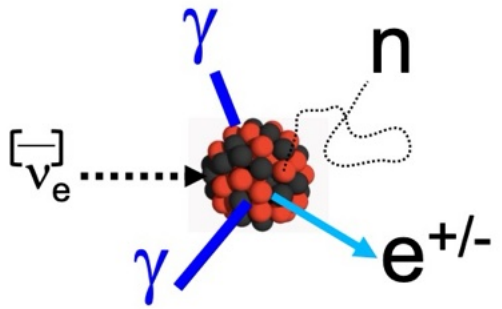
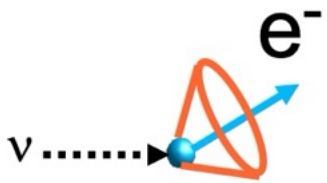
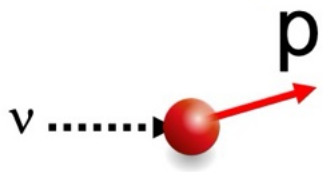
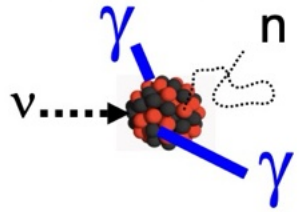
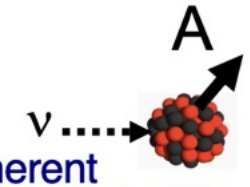
How massive are neutrinos?

Constrain mass via energy-dependent arrival times

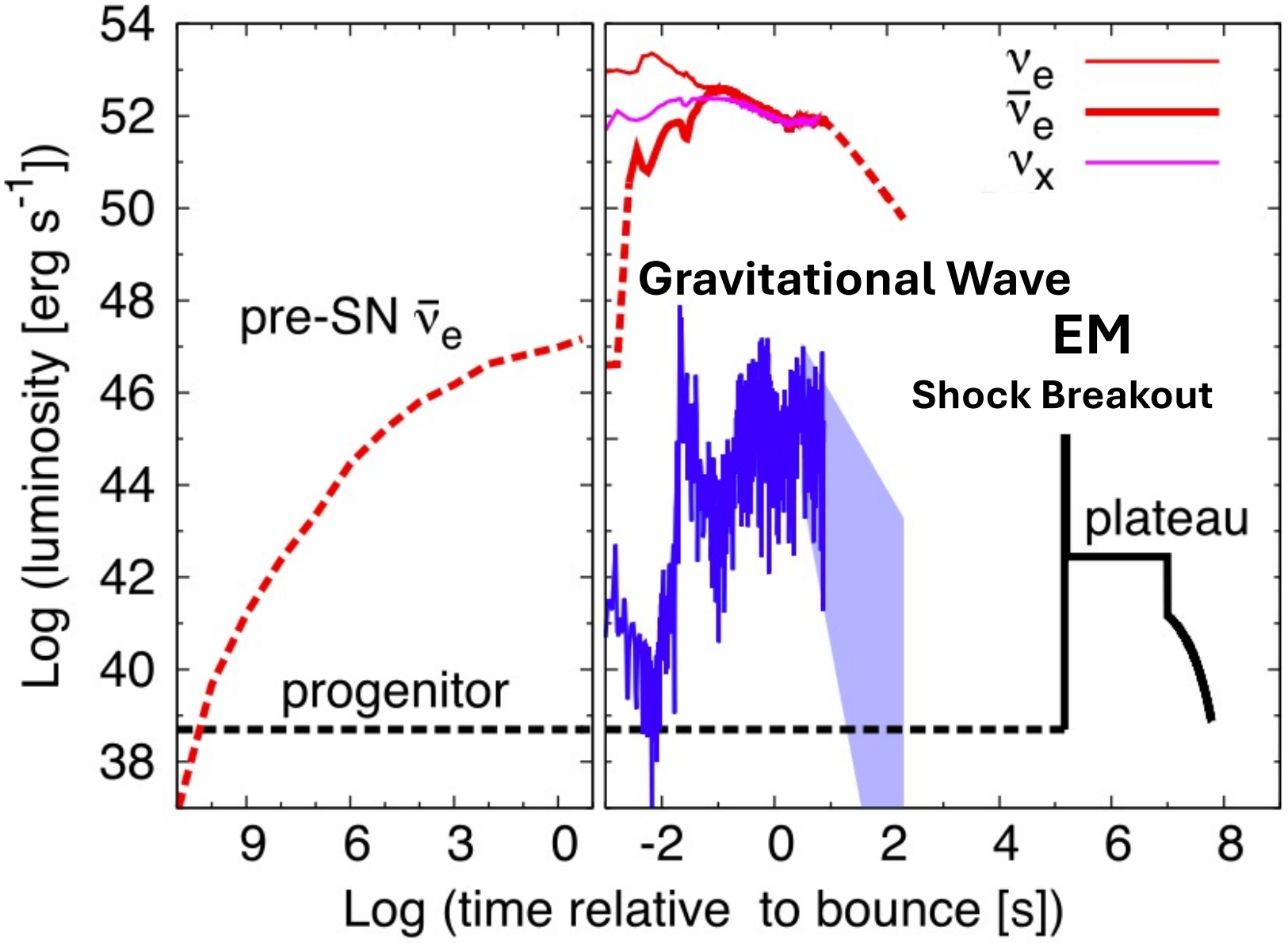
How do neutrinos affect one another?

Study collective oscillations and spectral changes

Neutrino Interactions in the ~10 MeV range

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

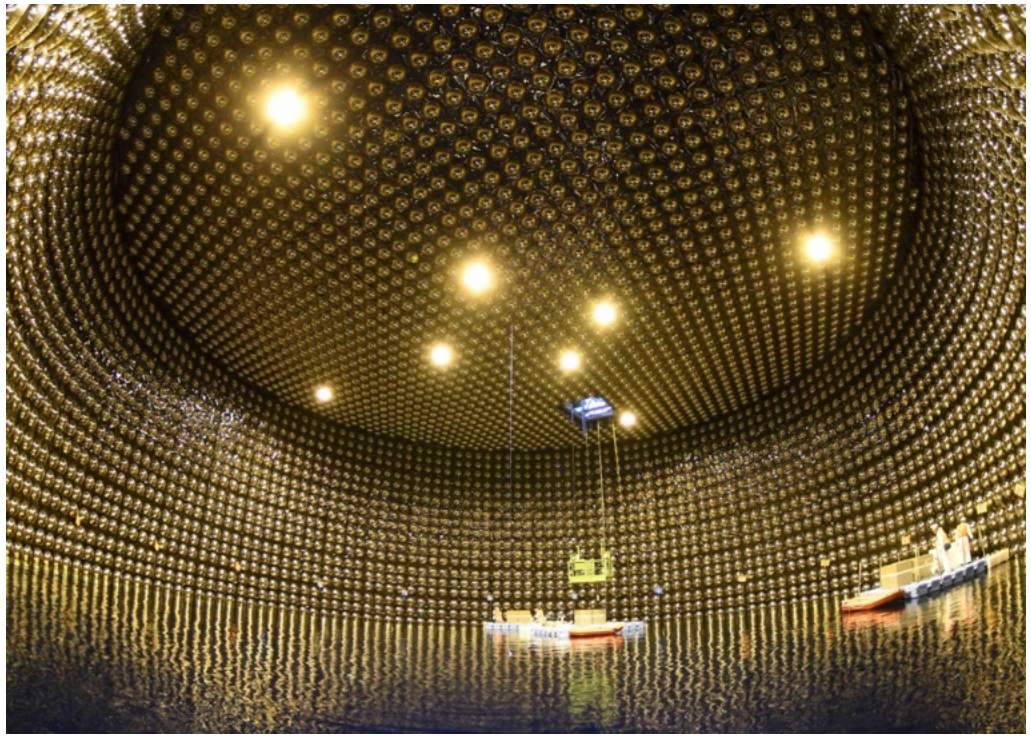
Multi-messenger Astronomy



K. Nakamura et al., Mon. Not. Roy. Astron. Soc. 461, 3296 (2016)

Water Cherenkov detectors: Super-Kamiokande

22.5 kt fiducial mass

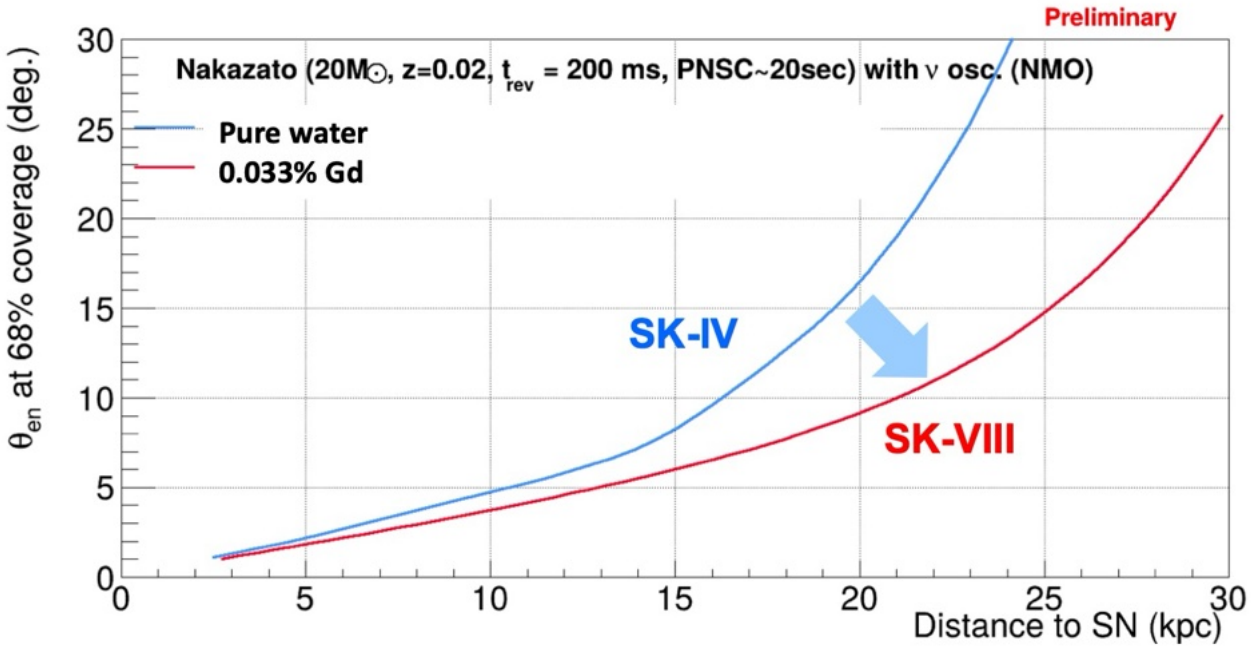


Kamioka mine, Japan. 1,000 m underground
39 m × 41 m tank, instrumented with PMTs
SK-Gd: 0.033% Gd loading

H. Sekiya, Neutrino 2026, arXiv:2604.07702v1

Pointing and rapid alerts

ν–e scattering provides the source direction.
Gd neutron tagging identifies IBD events and improves the pointing accuracy.

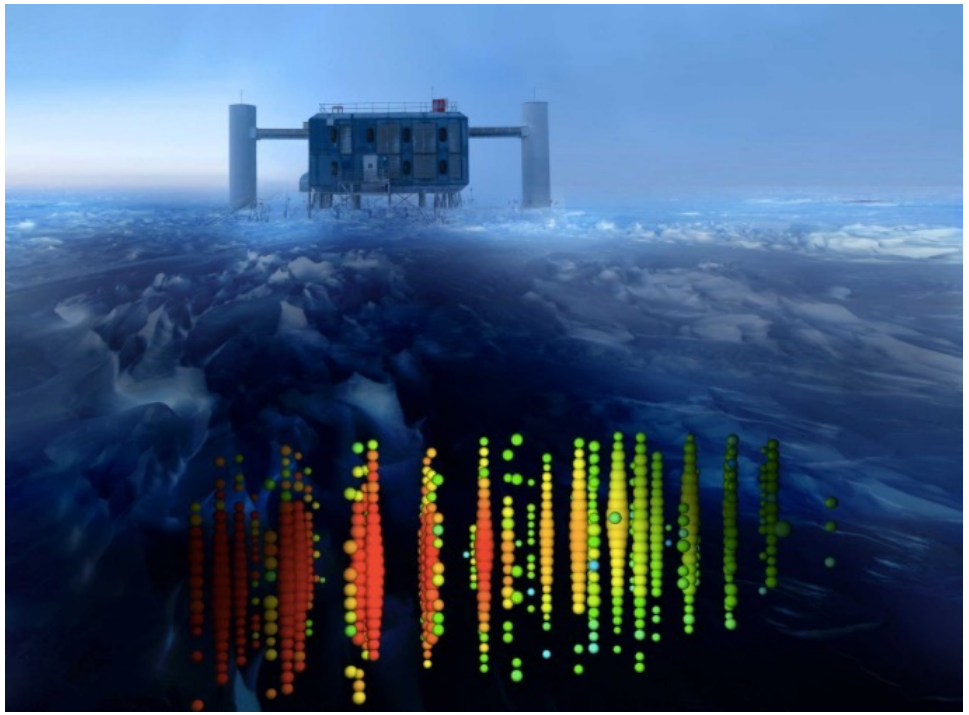


For a supernova at 10 kpc (Nakazato model) :

~2,700 events ~3.8° pointing accuracy (1σ)
GCN alert within ~90 s

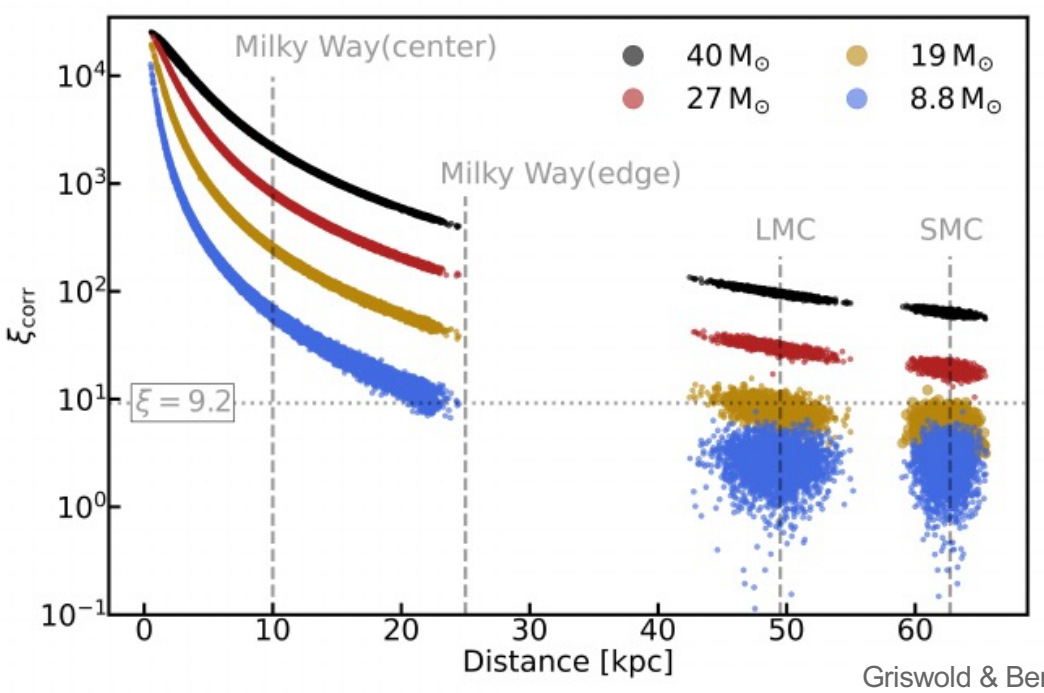
Ice Cherenkov detector: IceCube

1 km³ instrumented ice



South Pole, 1.45–2.45 km below the surface
86 strings with 5,160 optical modules

Coverage: model-dependent Galactic sensitivity



Griswold & BenZvi, PoS(ICRC2023)1111,

>99% trigger-capable uptime since 2015

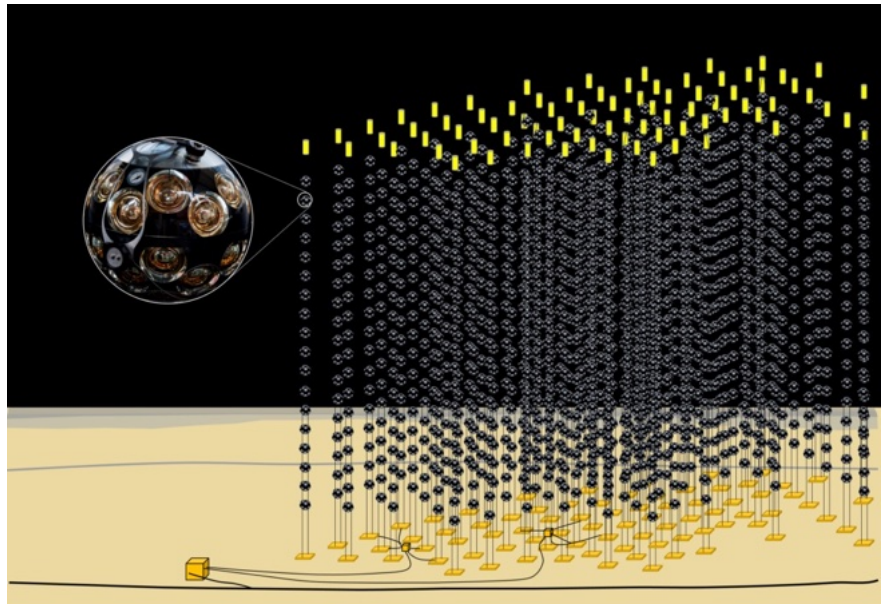
Alert latency: ~5 min to SNEWS Al Kharusi et al., NJP 23, 031201 (2021),

Supernova neutrinos produce a collective increase in photon counts across the detector.

Individual MeV neutrino interactions and their energies cannot be reconstructed.

Deep-sea Cherenkov detectors: KM3NeT

ARCA + ORCA deep-sea arrays



ARCA: off Sicily, 3.5 km below sea level
ORCA: off Toulon, 2.5 km below sea level
18 optical modules per vertical string
31 three-inch photomultiplier tubes per module

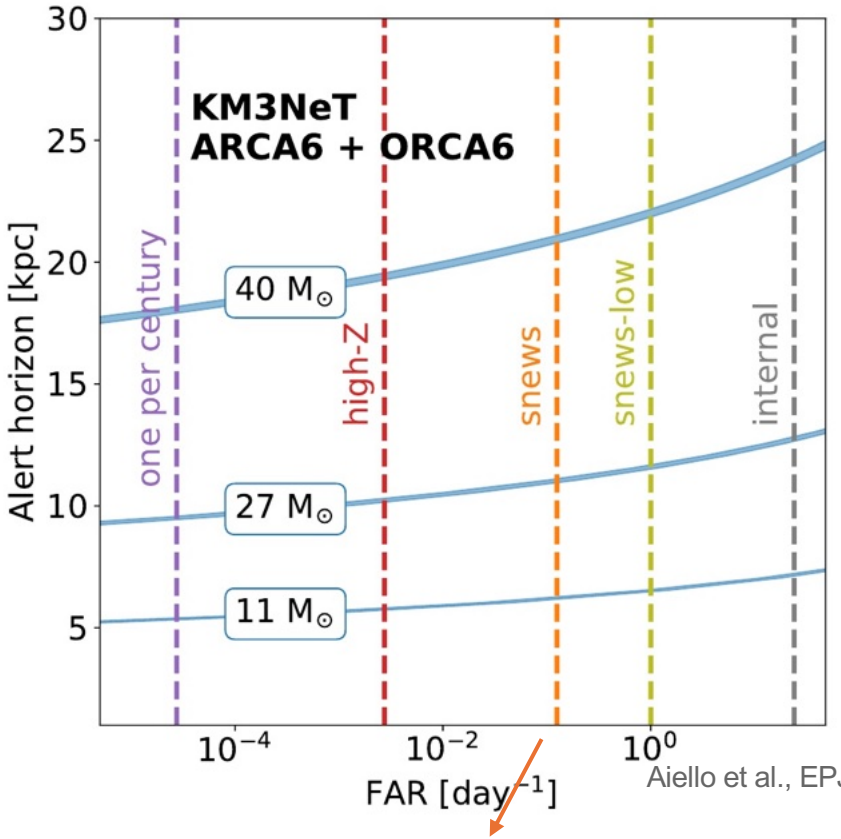
Mastrodicasa et al., PoS(ICRC2025)1115, §1

Under construction; taking data with a partial array

51 ARCA + 33 ORCA strings deployed (April 2026)

Marconi, arXiv:2604.26780, §1.1

Multiple photomultiplier hits in one module suppress optical backgrounds.



Aiello et al., EPJC 82, 317 (2022)

Online false-alert threshold: <1 per 8 days

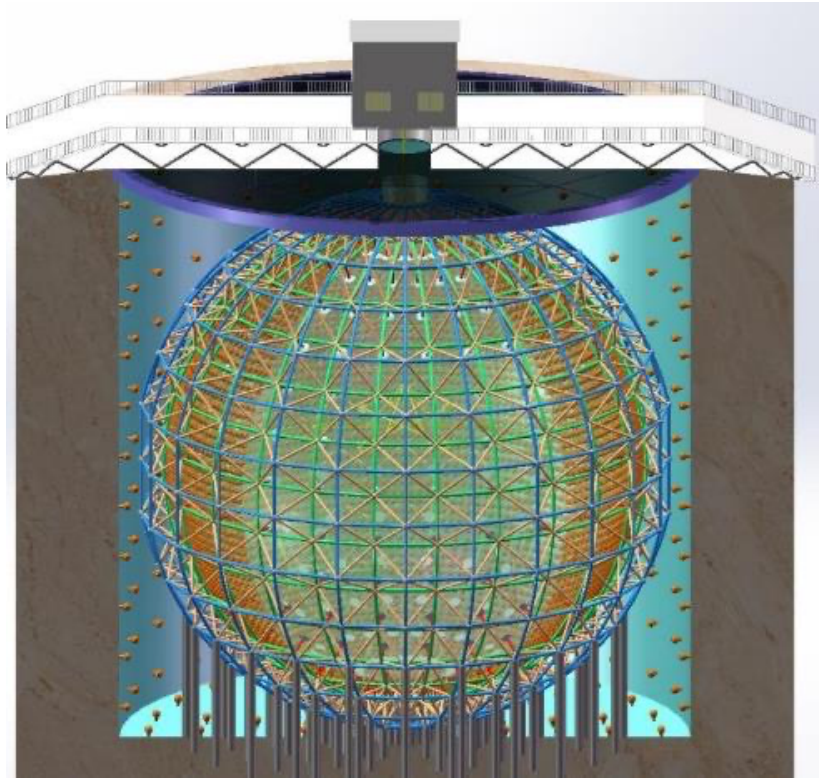
Coverage: ~11 kpc for a 27 M⊙ progenitor

Alert latency: <20 s to SNEWS

Mastrodicasa et al., ICRC2025

Liquid scintillator detector: JUNO

20 kt liquid scintillator

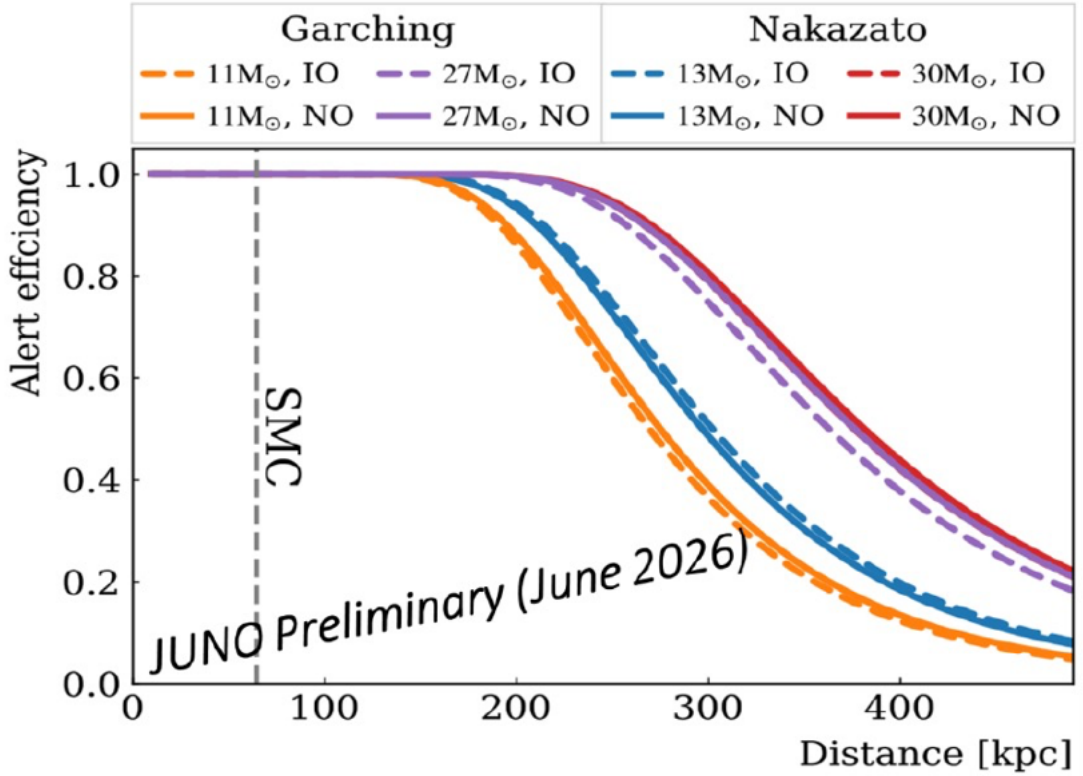


Jiangmen, China. ~700 meters underground
35.4 m diameter acrylic sphere

Physics data taking since August 2025

~5,000 inverse beta decay events at 10 kpc

Wide coverage and fast triggering



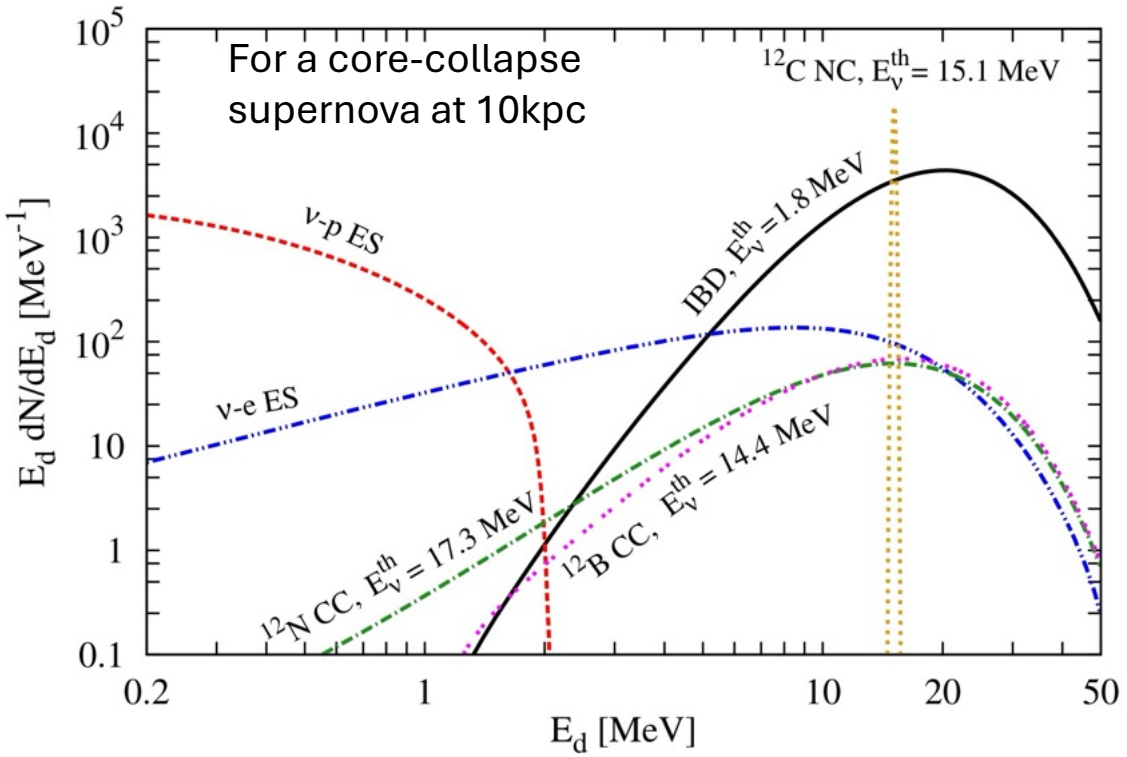
Neutrino2026

Coverage: up to ~350 kpc at 50% efficiency

Trigger time: ~20 ms at 10 kpc

Latency: an additional ~4 s for data acquisition

Multiple Detection Channels with JUNO



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

Inverse beta decay (IBD).
~5000 events
$\bar{\nu}_e$ at ~10MeV

Unique for Liquid Scintillator

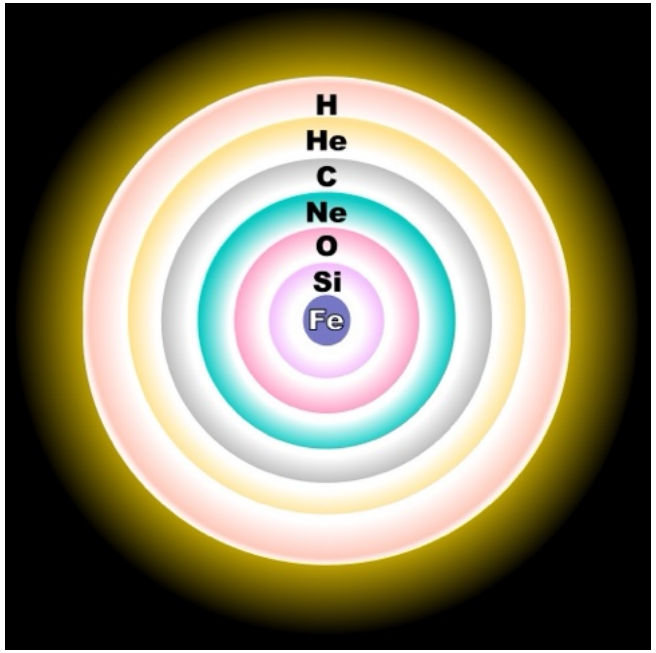
Proton elastic scattering (pES):
~1500 events
all neutrino flavors at lower energy

Electron elastic scattering (eES):
~300 events
all neutrino flavors but larger cross section for ν_e

JUNO Collaboration, J. Phys. G43 (3) (2016) 030401

Pre-SN neutrinos: a countdown to core collapse

Late stages of a massive star

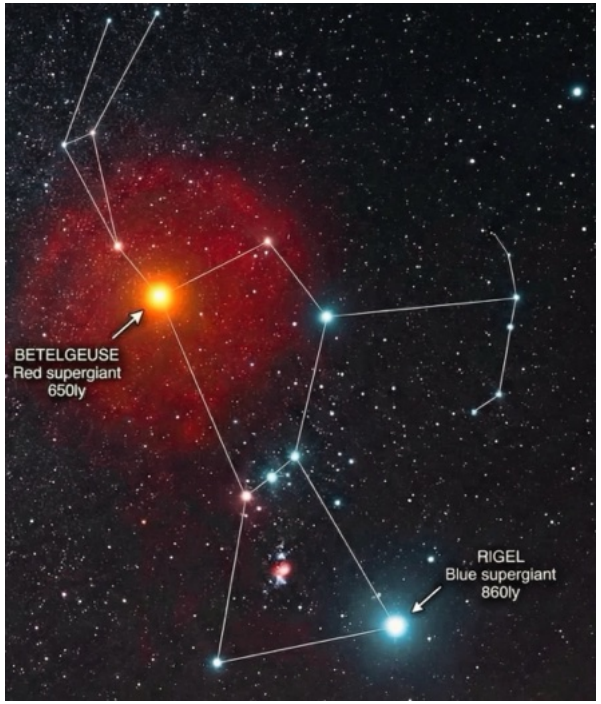


$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

Thermal processes and nuclear weak interactions produce MeV neutrinos. The flux generally rises as core collapse approaches.

Liquid scintillators for pre-SN:

Low energy threshold enables detection of pre-SN neutrinos at a few MeV.



A nearby target (~0.2 kpc): Betelgeuse in Orion

JUNO

20 kt liquid scintillator
50% alert-efficiency reach: ~1.1 kpc
~120 h warning at 0.2 kpc (False-alert rate: 1/year)

Abusleme et al., JCAP 01 (2024) 057

KamLAND

1 kt liquid scintillator
Pre-SN monitoring started in 2015

~8.2 h warning;
~14.7 h combined with SK-Gd
(150 pc; false-alert rate: 1/century)

Saito et al., ApJ (2026)

Both studies: Patton model, 15 M⊙, normal ordering; expected sensitivities

Global Network: The SuperNova Early Warning System (SNEWS2.0)

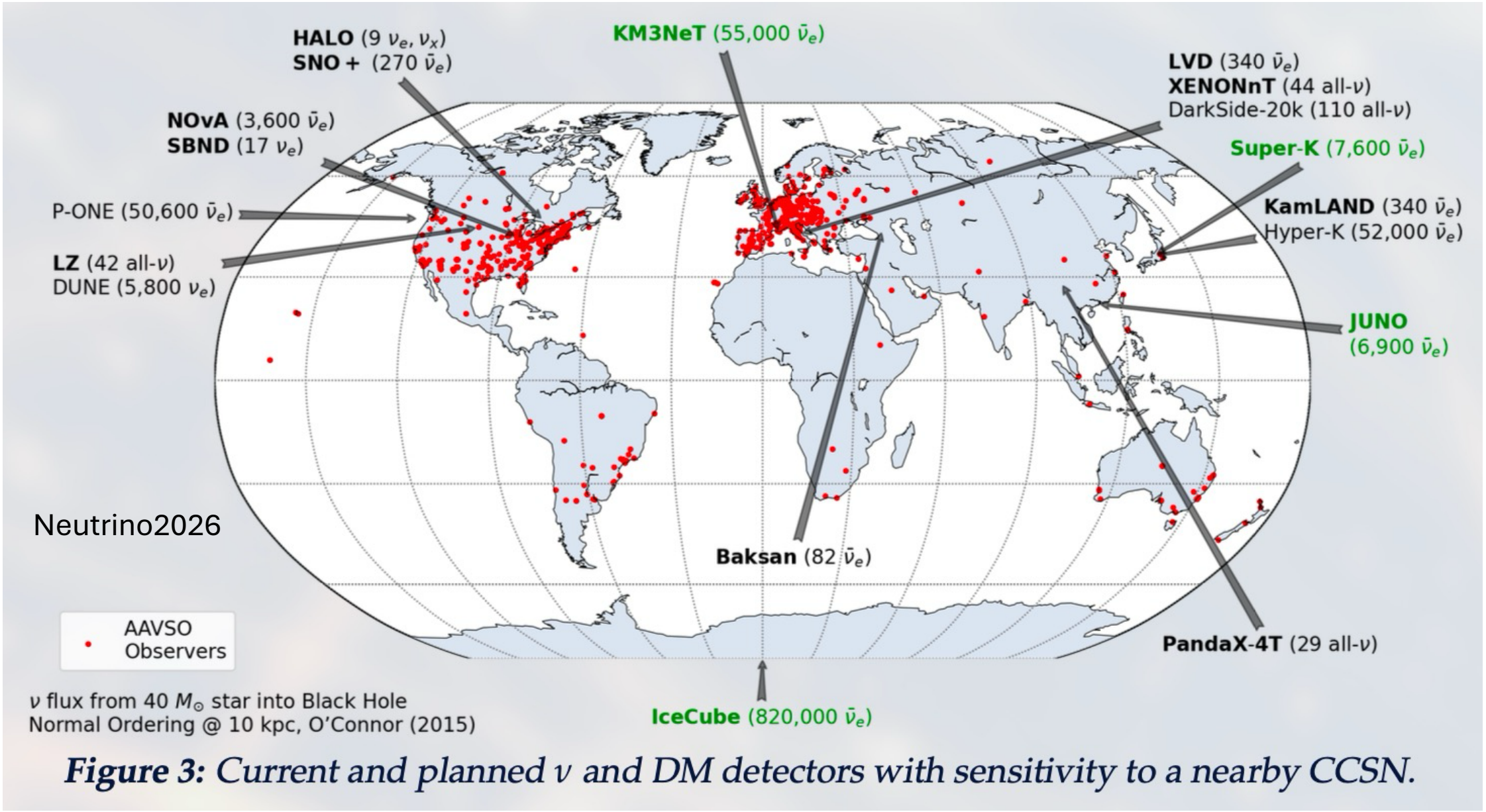
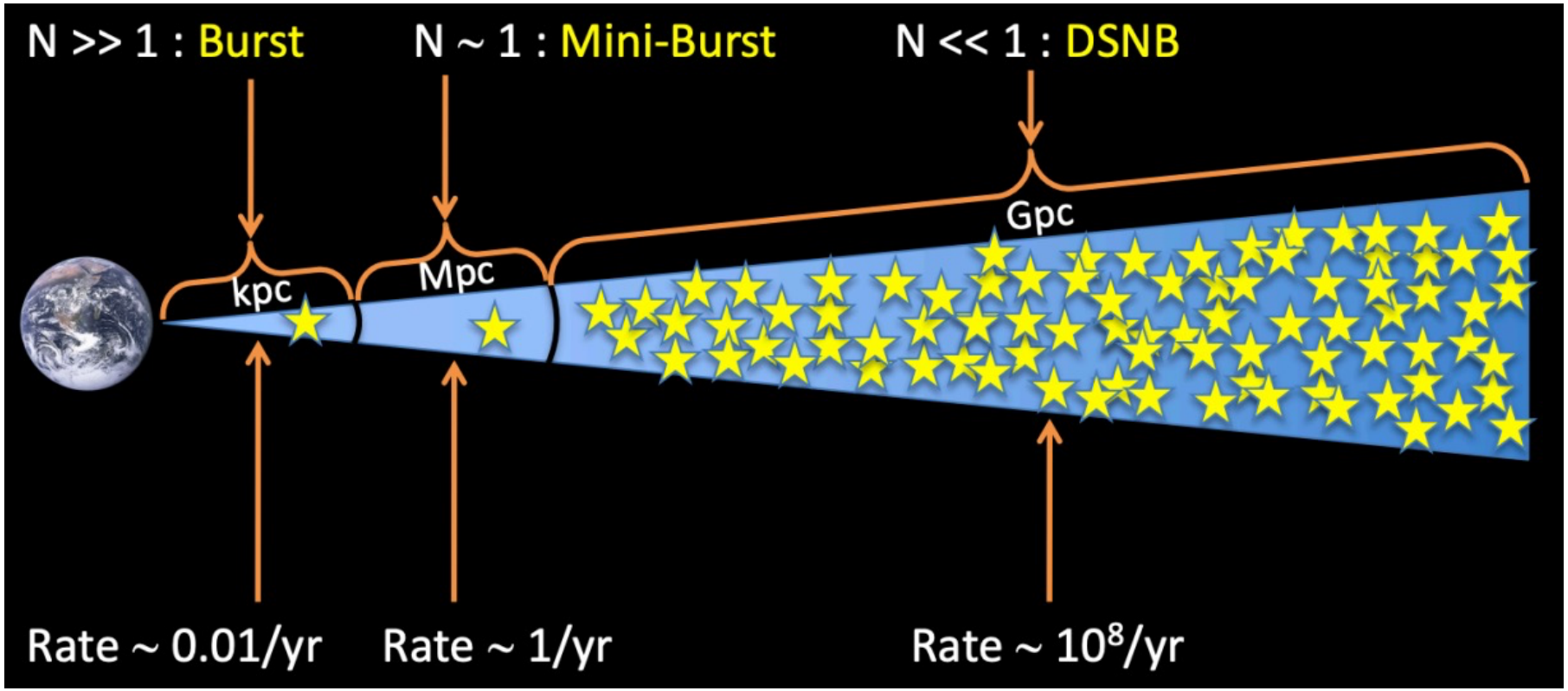


Figure 3: *Current and planned ν and DM detectors with sensitivity to a nearby CCSN.*

Diffuse Supernova Neutrino Background (DSNB)

DSNB: Neutrinos from all core-collapse supernovae throughout cosmic history



- Nearby supernova bursts are rare and unpredictable.
- SN 1987A yielded only ~25 detected neutrino events.

DSNB offers a persistent signal that accumulates over time!

DSNB: astrophysics and cosmic evolution

The DSNB probes the history of core-collapse supernovae across the Universe.

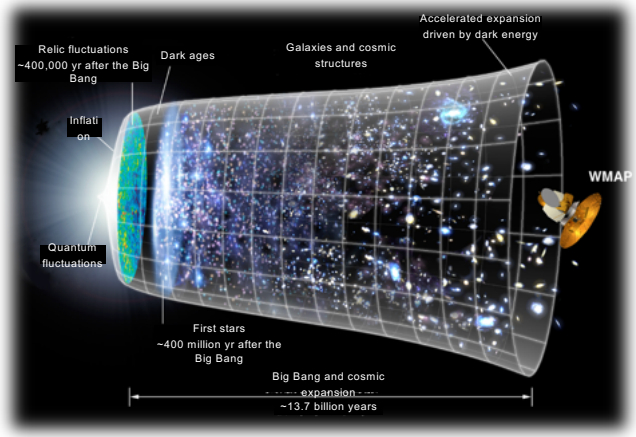
The fate of massive stars

Key Question: Which massive stars explode, and which collapse into black holes?
DSNB constrains the total neutrino emission and the fraction of failed explosions.



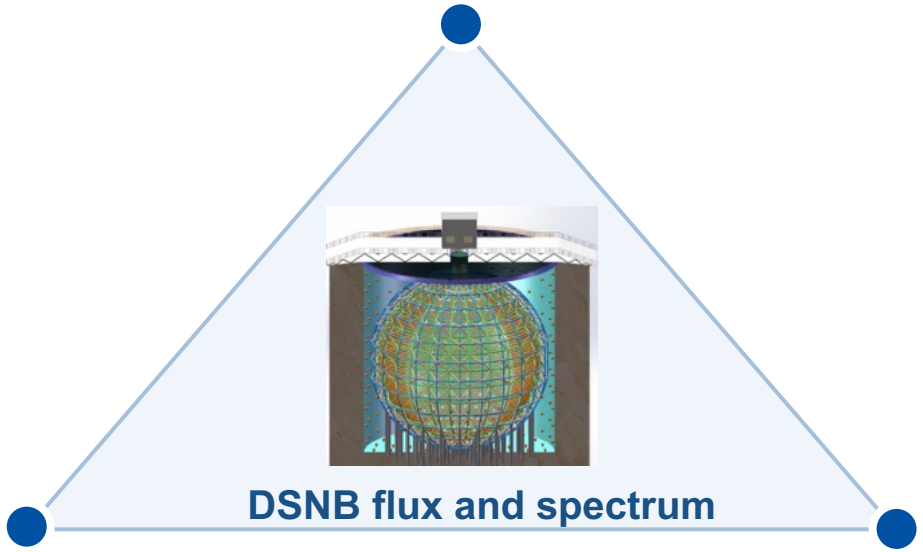
Cosmic evolution

Key Question: How has the core-collapse rate evolved over cosmic time?
DSNB combines neutrino signals from different epochs to constrain the cosmic core-collapse rate.



DSNB and fundamental neutrino properties

Flavor conversion and collective oscillations

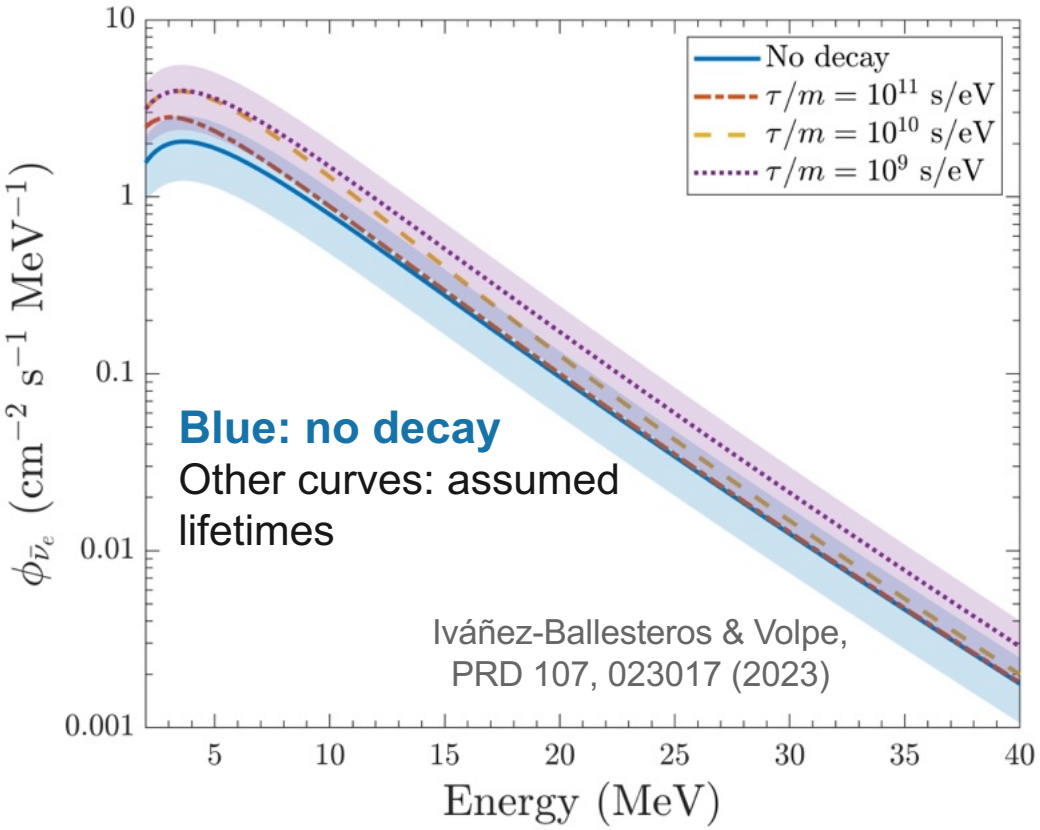


DSNB flux and spectrum

Are neutrinos stable?

New neutrino interactions

Search for neutrino-decay signatures over cosmological distances

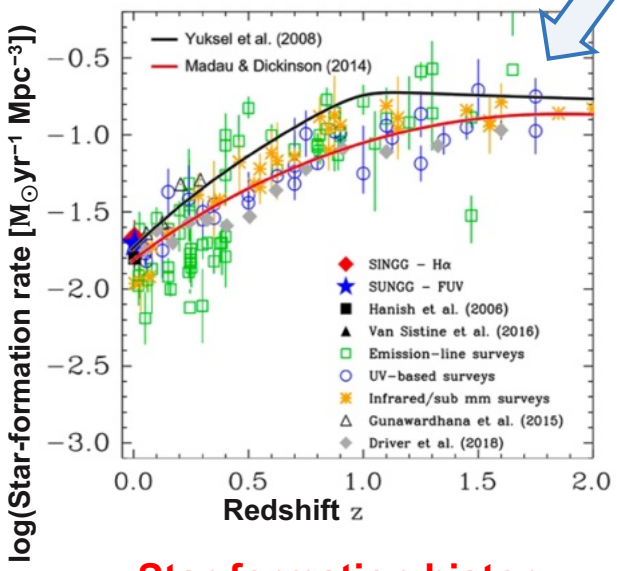


The DSNB probes neutrino physics in dense stellar cores and over cosmological distances

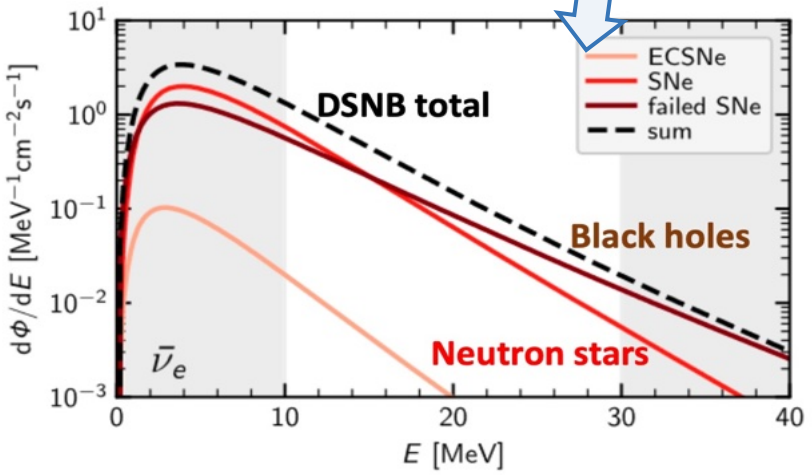
Predicting the DSNB flux

$$\frac{d\phi}{dE_\nu} = \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN\,(E'_\nu)}{dE'_\nu} (1+z) \left| \frac{cdt}{dz} \right| dz,$$

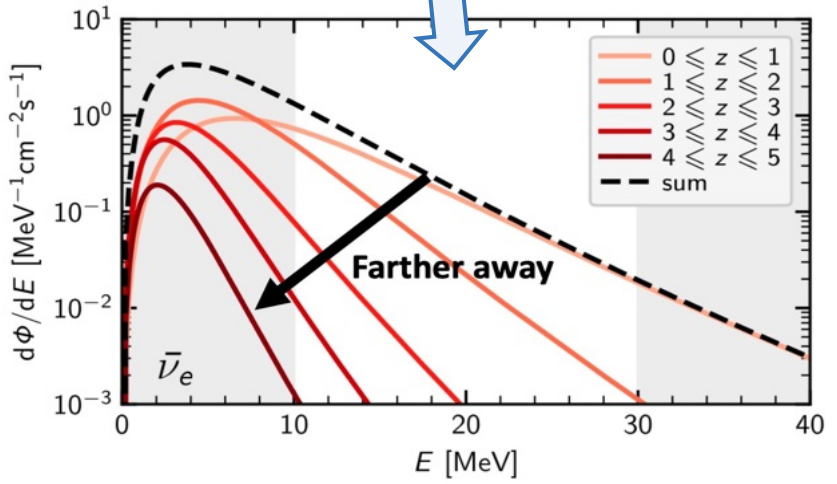
DSNB = **Supernova rate** × **Emission spectrum** × **Cosmic expansion**



Star-formation history



Black-hole fraction

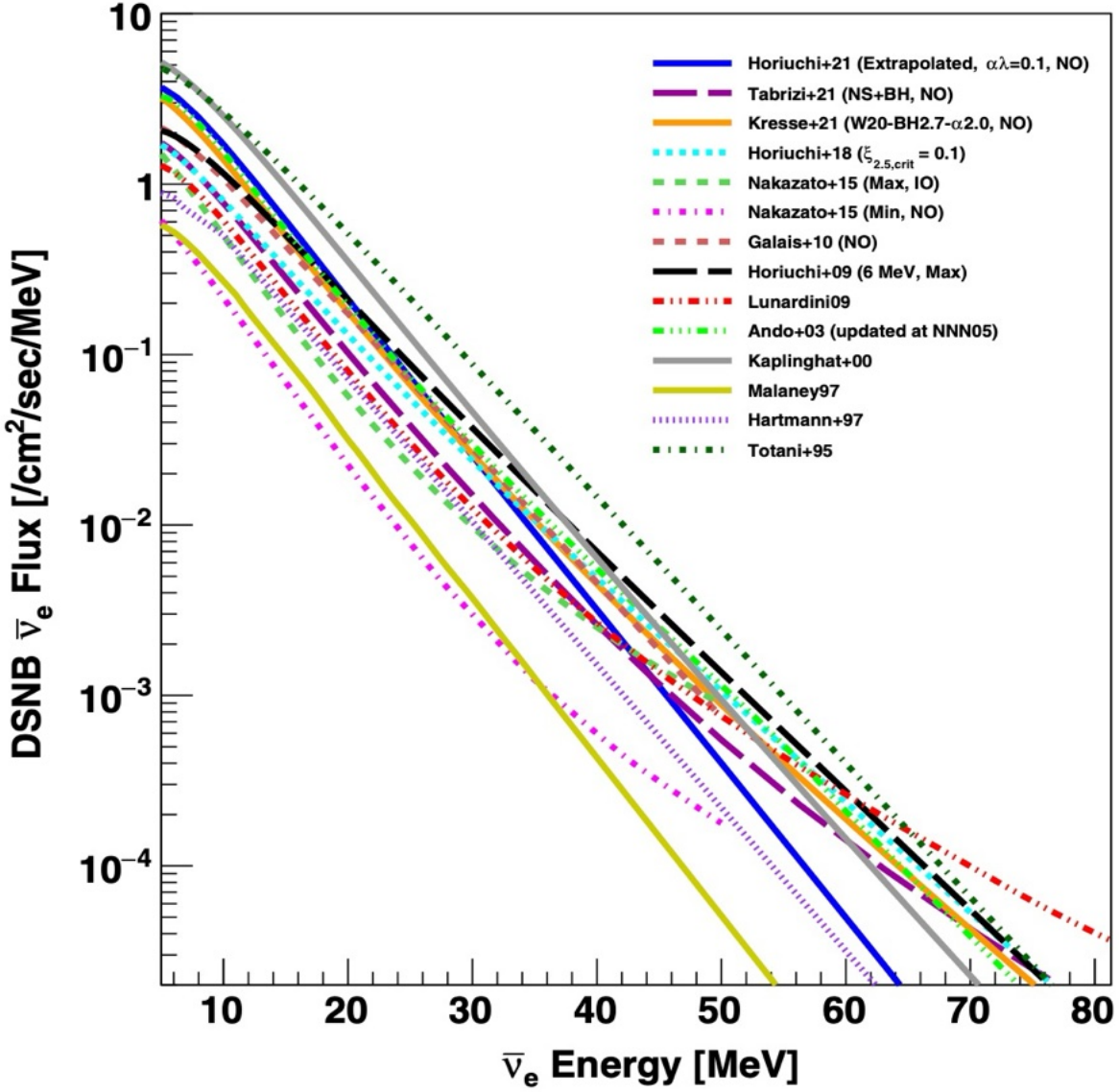


Redshift effects

Optical surveys mainly detect visible supernovae. The DSNB also includes optically faint and failed explosions, providing a more complete view of core collapse.

DSNB Theoretical Predictions

Predicted electron antineutrino spectra

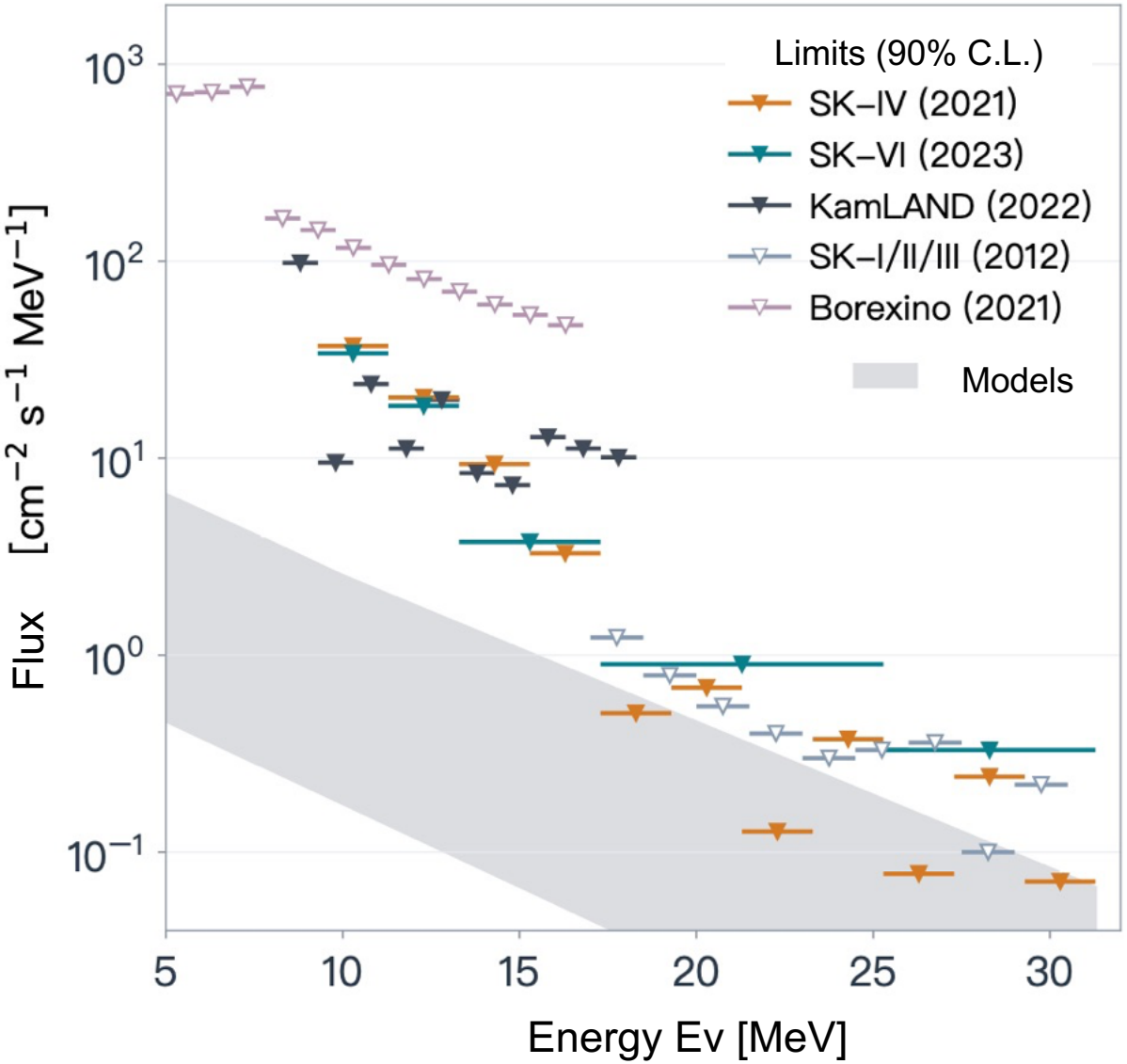


Models predict very different fluxes and spectral shapes.

The main uncertainties are due to core-collapse rate, the emission spectrum and the black-hole fraction.

A measured flux would be very helpful in constraining the parameter phase!

Searching for the DSNB



Flux limits are approaching the predicted range

Super-Kamiokande, Japan

1996–2008 Positron searches in pure water (SK-I to SK-III)

2008–2018 Neutron tagging via capture on hydrogen (SK-IV)

2004 Gadolinium proposed for DSNB searches

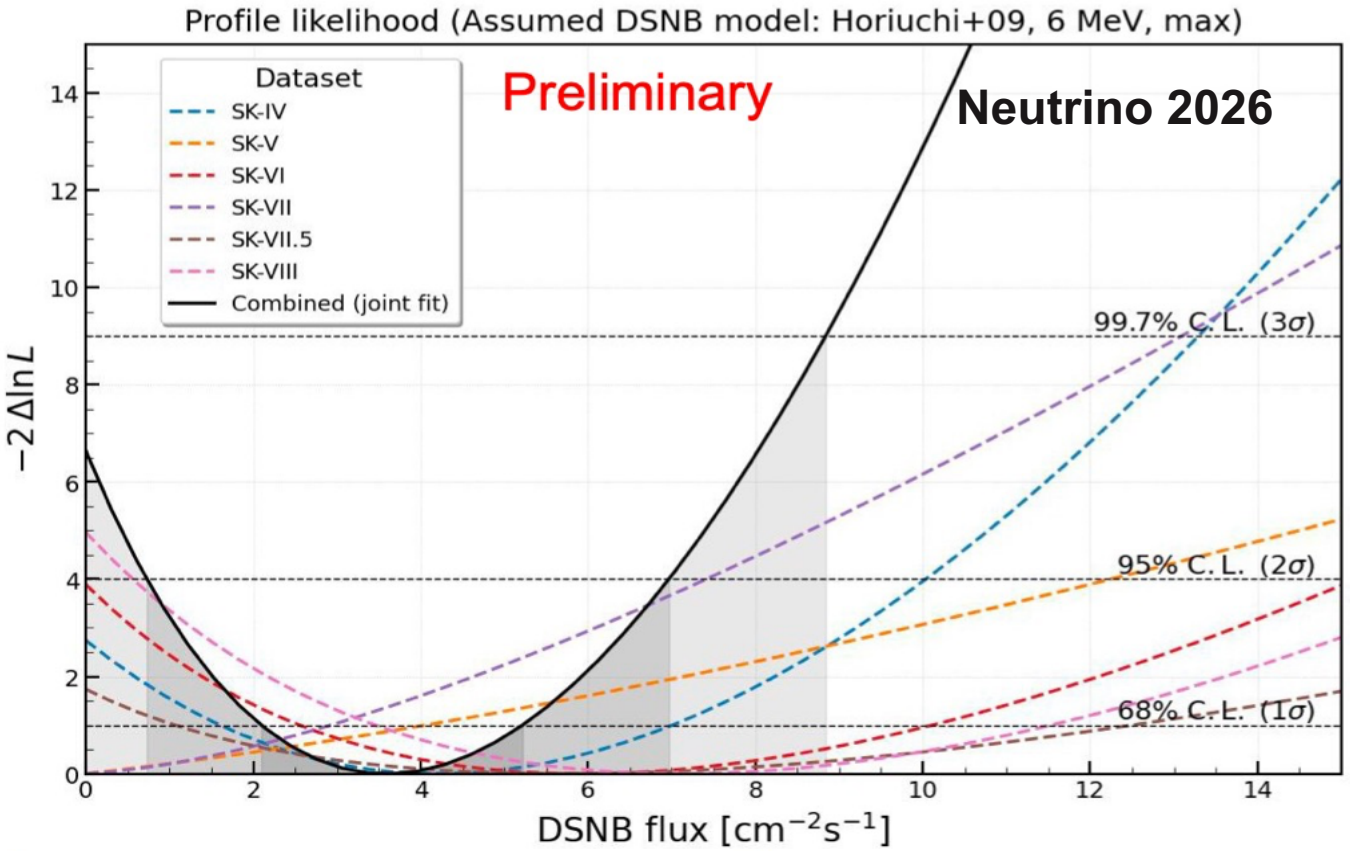
2018–2019 Detector prepared for gadolinium loading

2020 onward Data taking with gadolinium (SK-Gd)

With the first DSNB results on the horizon, we are entering an exciting new phase in the search.

Super-K favors a nonzero DSNB flux

A hint of a signal in the combined fit

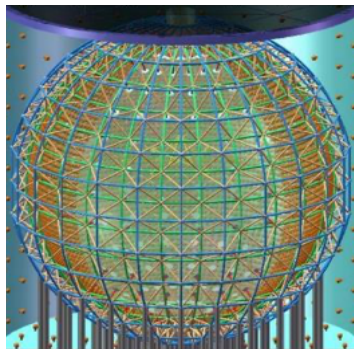


Joint fit significance = 2.6σ 99.5% CL

- **The fit combines about 5,000 live days of Super-K data since 2008.**
- **The excess above background is ~2.6σ.**

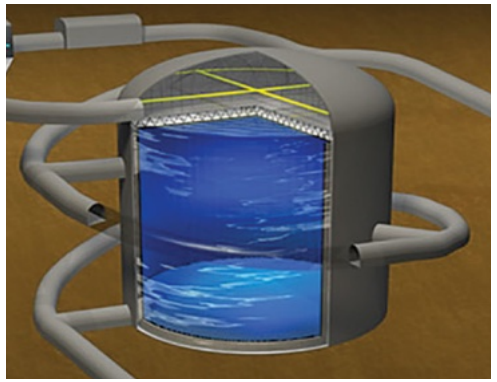
Current and Future Experiments

JUNO
Liquid scintillator



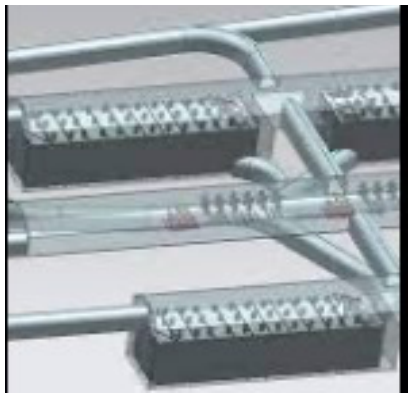
2025

Hyper-Kamiokande (Japan)
Water Cherenkov



2028

DUNE (USA)
Liquid argon time projection chamber (TPC)



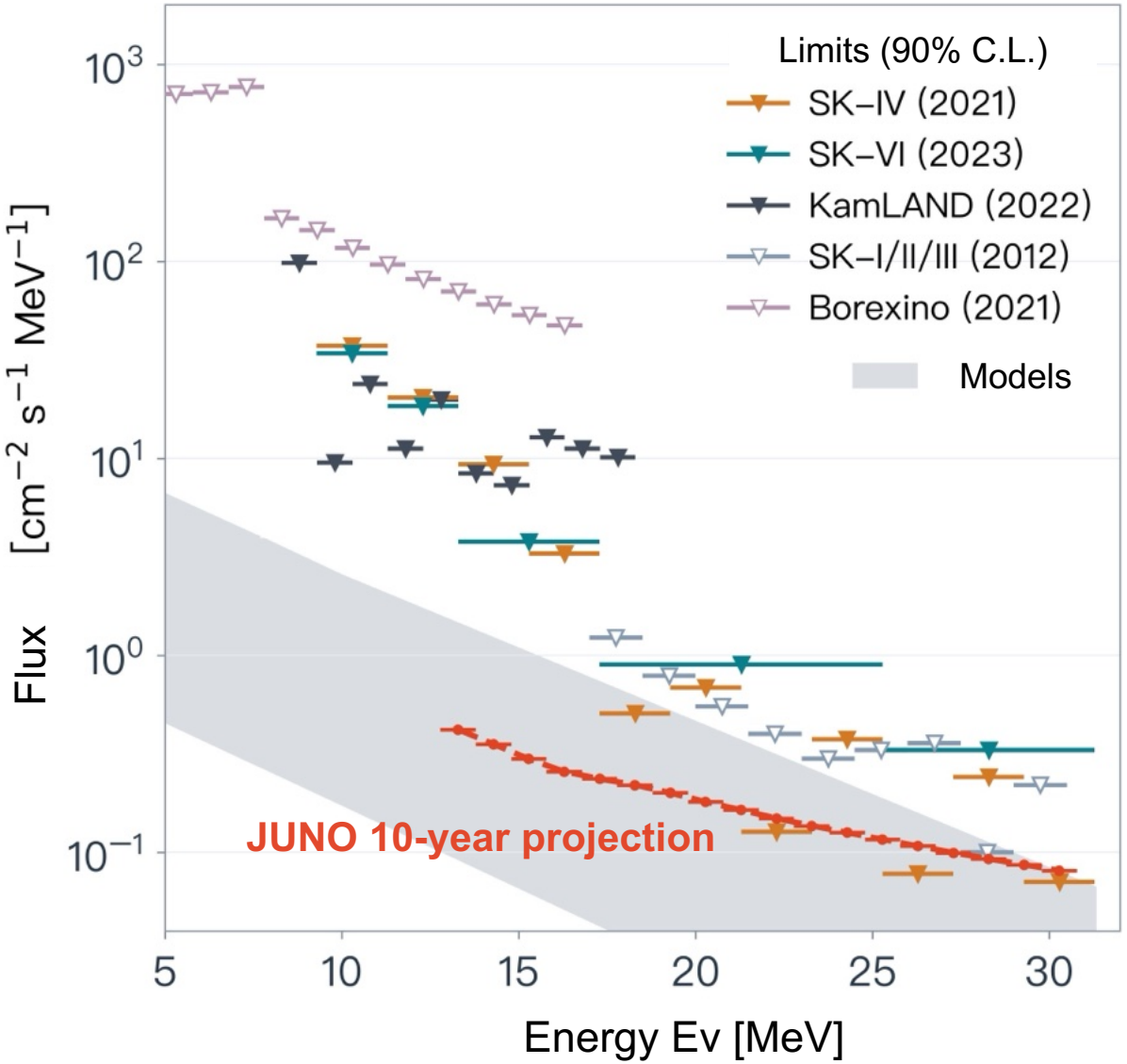
Early 2030s

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

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

JUNO and Hyper-K can detect electron antineutrinos through inverse beta decay. DUNE can probe electron neutrinos in argon.

Liquid scintillator and water Cherenkov detectors



JUNO Collaboration, JCAP 10 (2022) 033

Liquid scintillator and water Cherenkov detectors are the two main approaches to DSNB searches.

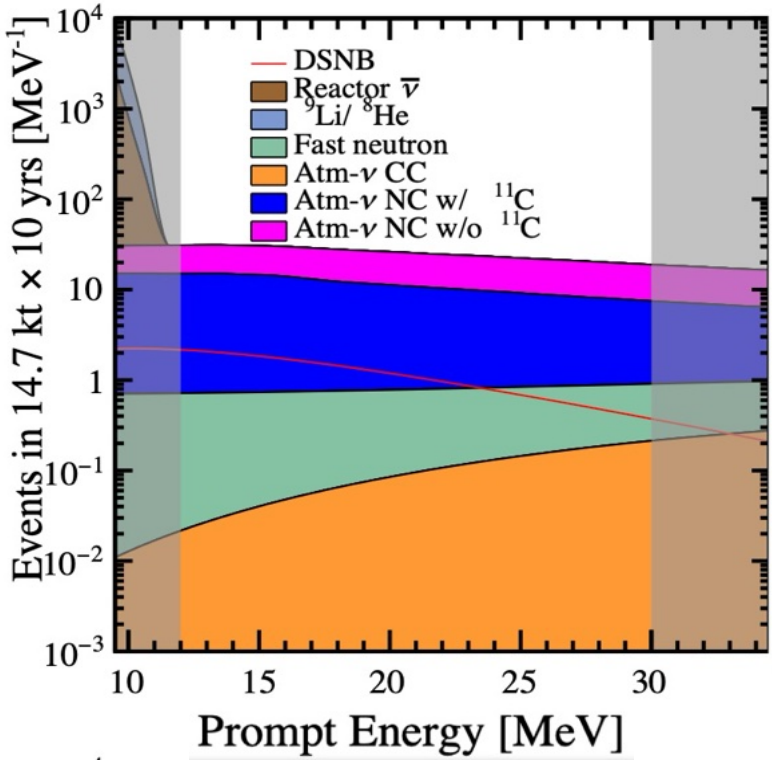
Experiment	Type	Mass	Period	Signal efficiency	Signal (bkg.) rate [yr⁻¹]
SK-Gd	Gd-loaded water	22.5 kt	2020–2028	50% → 75%	1.7 (0.8) → 2.5 (1.2)
JUNO	Liquid scintillator	20 kt	2025–	74%	1.9 (0.54)
Hyper-K	Water Cherenkov	180 kt	2028–	20–30% (pure water)	7 (14) (pure water)

Y. F. Li, M. Vagins and M. Wurm, Universe 8, 181 (2022)
JUNO Collaboration, JCAP 10 (2022) 033

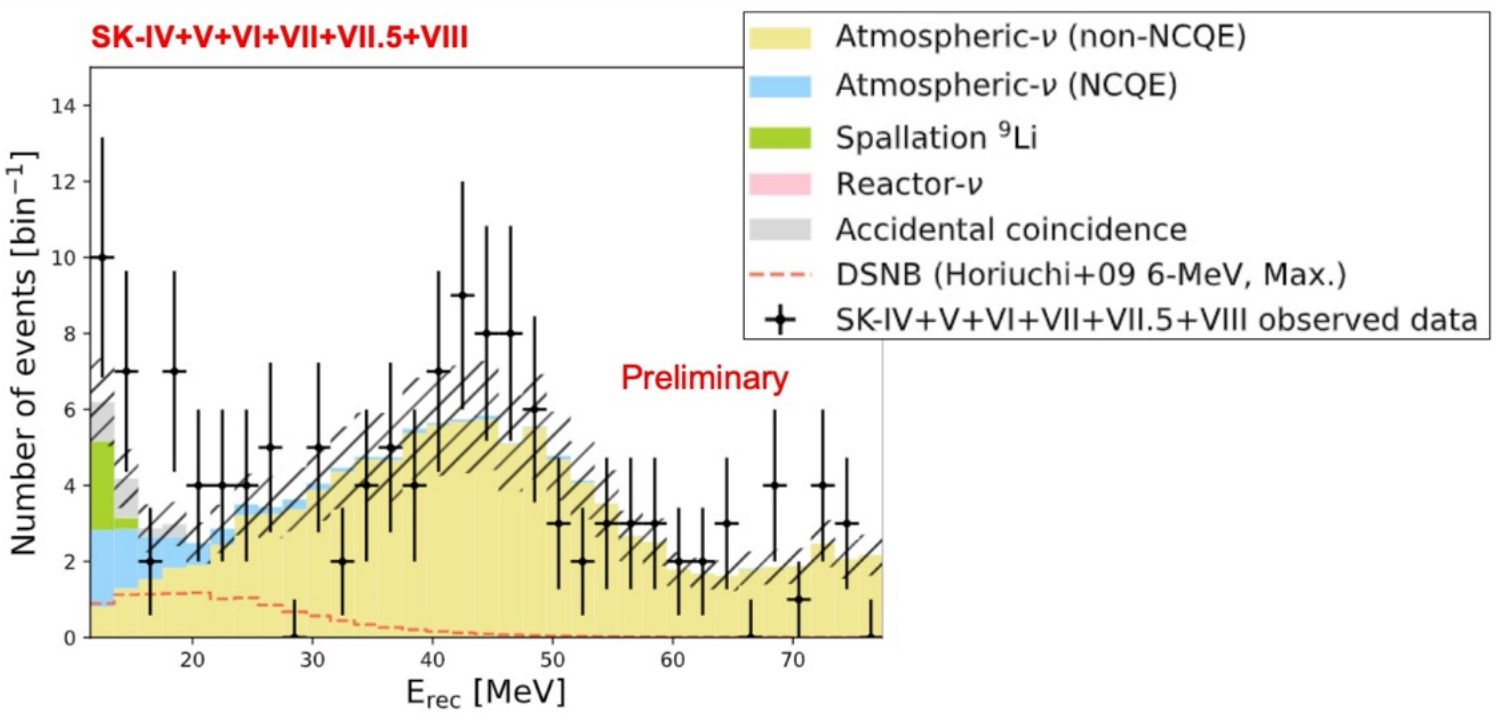
Common Challenges

The low DSNB event rate and overlapping background spectra make signal identification challenging.

JUNO prediction before background cuts



Super-K data and estimated backgrounds

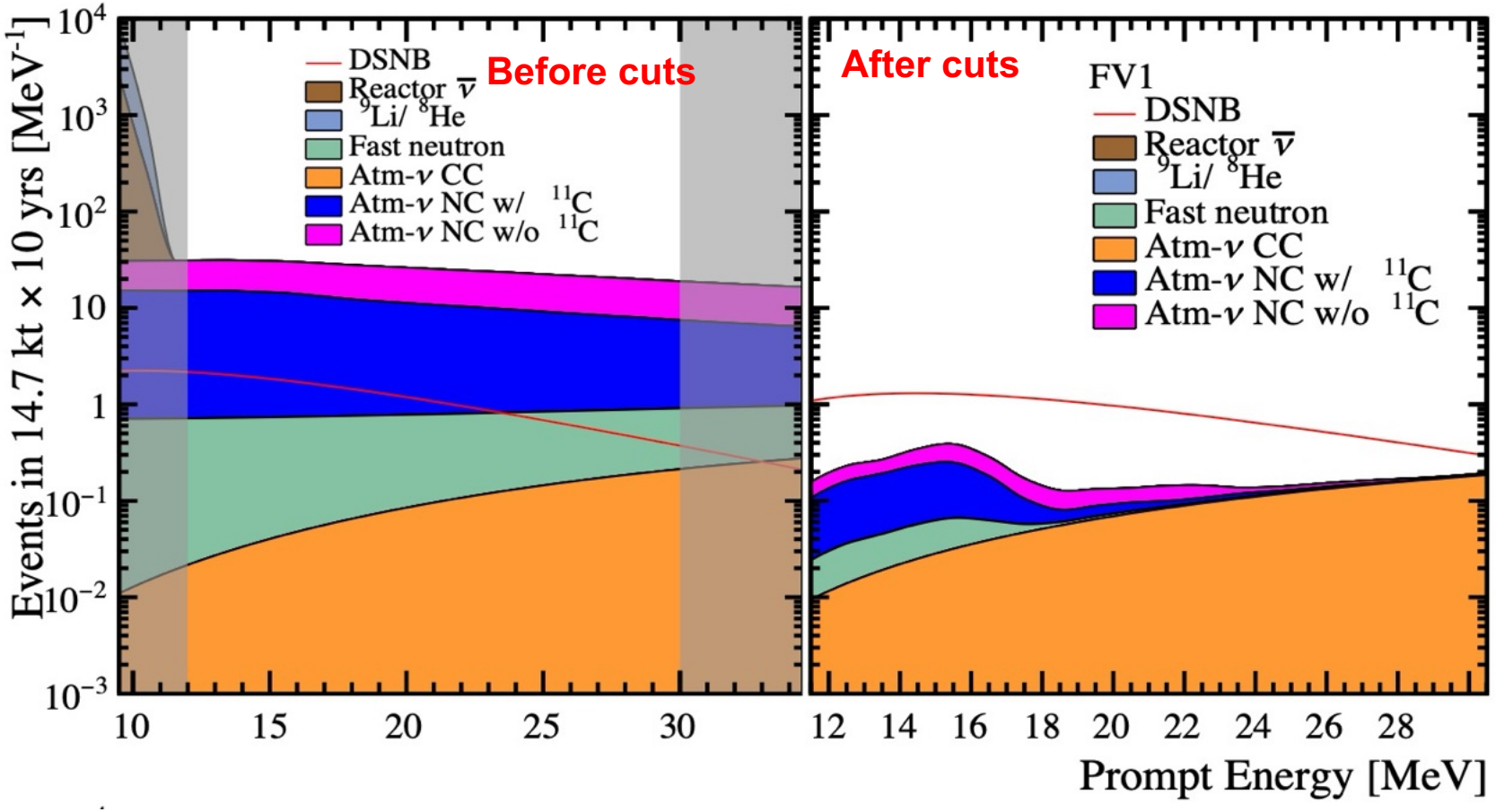


Only a few signal events per year in a 10 kt detector

Atmospheric neutrino interactions are one of the major backgrounds.

Background Rejection with Liquid Scintillator

Expected signal and backgrounds in JUNO



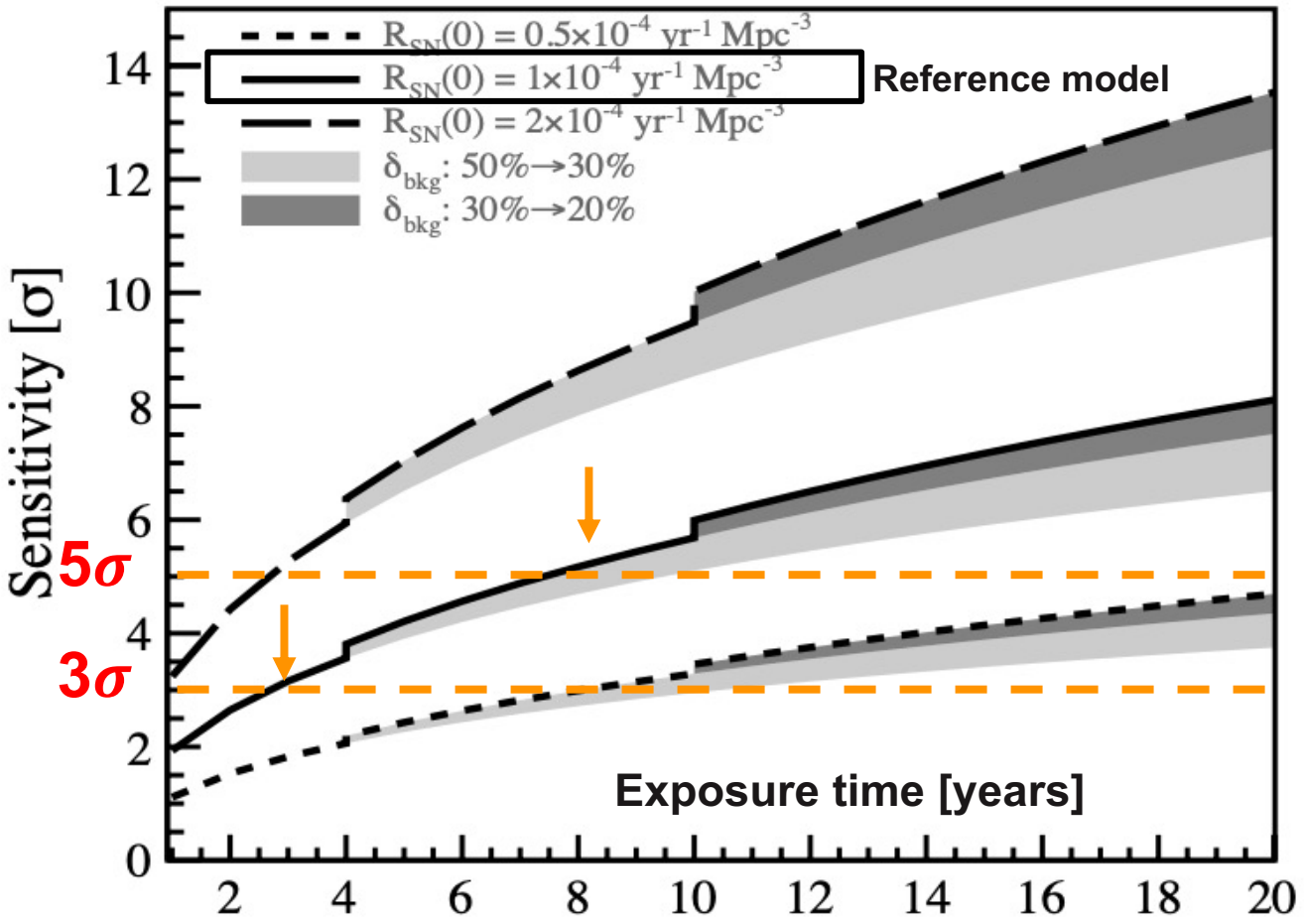
Pulse-shape discrimination (PSD): Different particles produce different scintillation pulses.

The cut keeps >80% of the signal and only 1% of the dominant atmospheric neutrino background.

JUNO Collaboration, JCAP 10 (2022) 033

JUNO's projected DSNB sensitivity

Reference model: ~3σ in 3 years, >5σ in 10 years



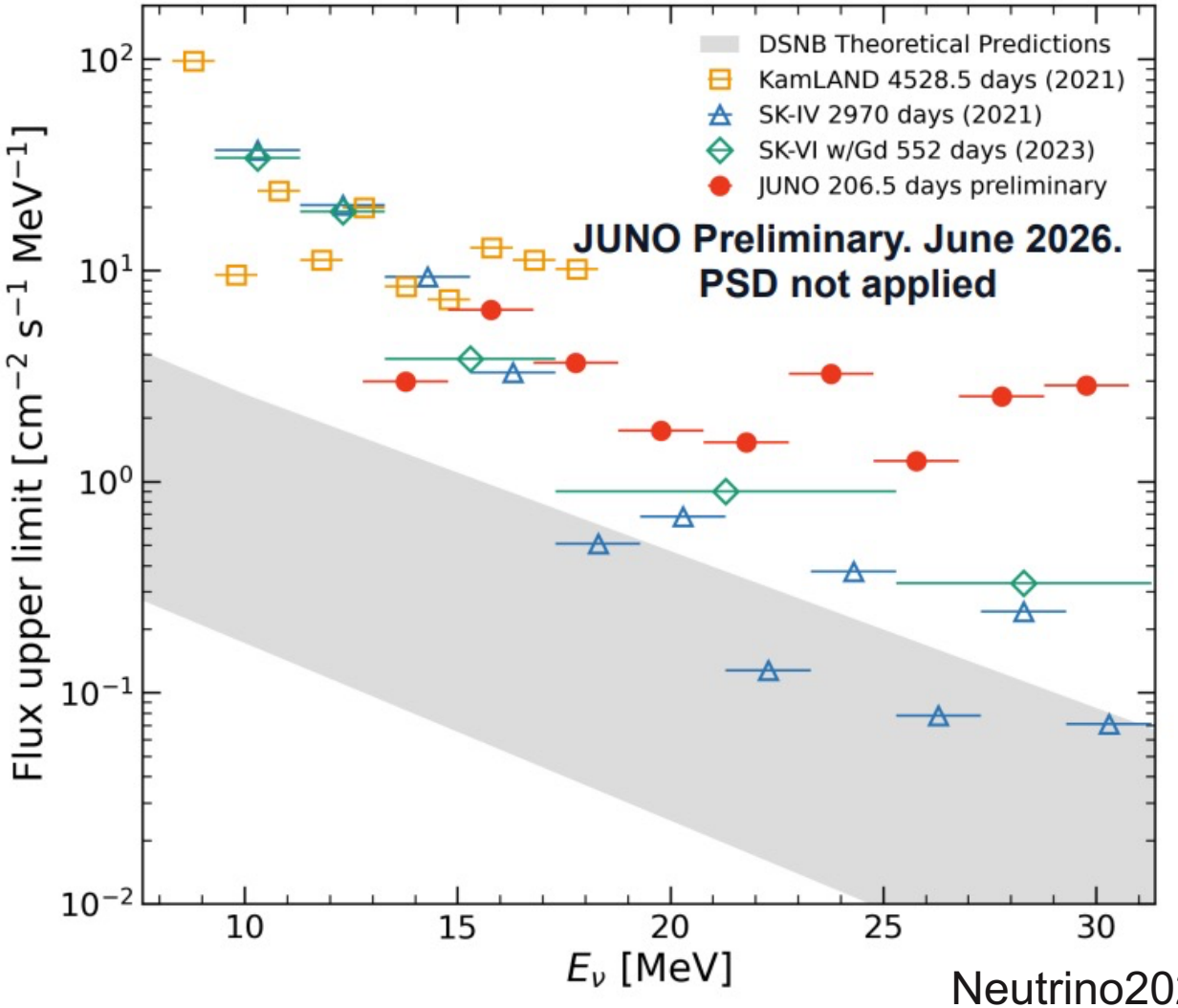
JUNO Collaboration, JCAP 10 (2022) 033

Advantages of JUNO:

- Low energy threshold
- Pulse-shape discrimination suppresses the main background.

JUNO's first DSNB flux limits

- DSNB: The accumulated neutrino signal from all core-collapse supernovae throughout cosmic history
- 19 DSNB candidate events were observed in 12–30 MeV
  - Consistent with the predicted background of 21.3 ± 10.5 events
  - A competitive upper limit on the DSNB flux was obtained
- A preliminary pulse-shape-discrimination (PSD) study suggests that most of these candidate events likely originate from **atmospheric neutrino** interactions



Neutrino2026

Summary

Supernova bursts

- Supernova neutrinos probe **core-collapse** dynamics and **neutrino properties**.
- Neutrino **alerts** support early electromagnetic follow-up and joint gravitational-wave searches.

Pre-supernova neutrinos

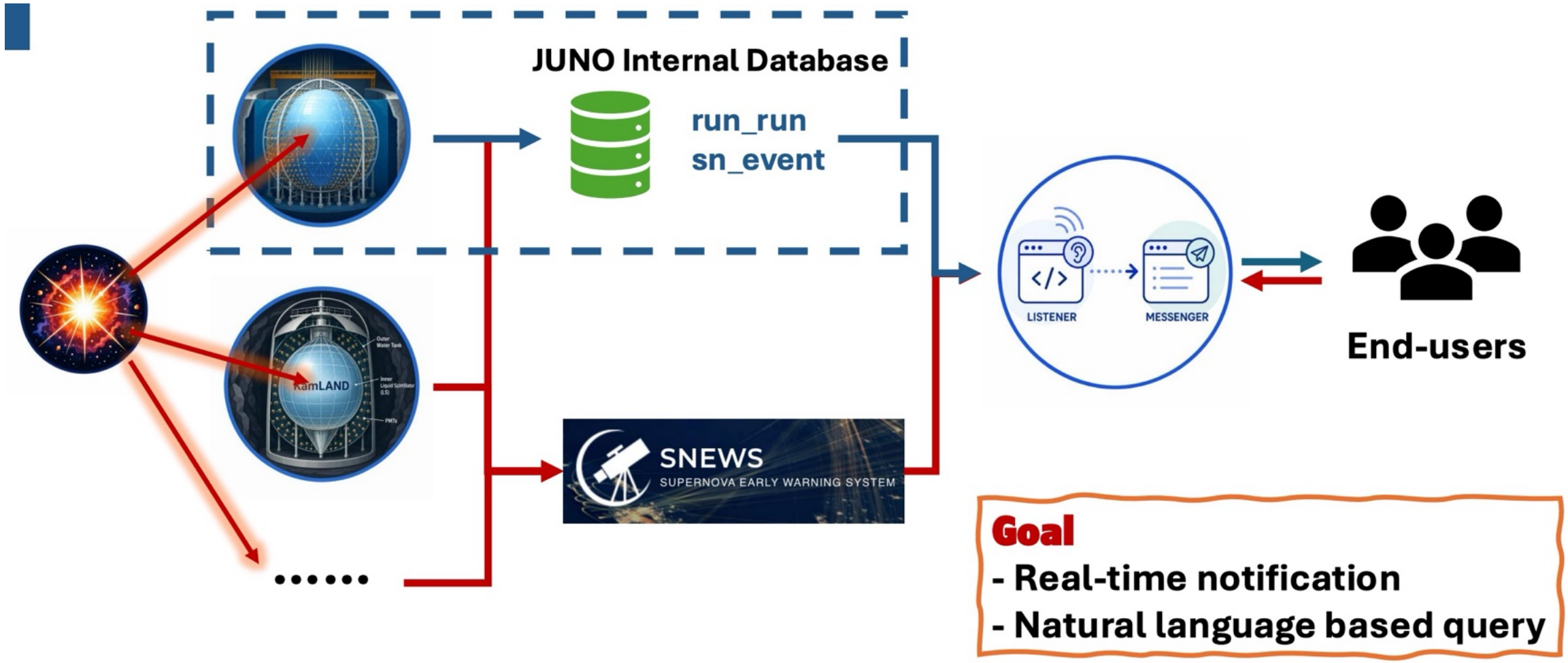
- Pre-supernova neutrinos can provide **hours to days** of warning for nearby progenitors.
- Liquid scintillator detectors are well suited to detecting pre-supernova neutrinos because of their **low energy thresholds**.

The diffuse supernova neutrino background

- **Super-K** recently reports a ~2.6σ excess, while **JUNO** has showed its first DSNB flux limits this year.
- The prospects for a first DSNB detection are increasingly promising.

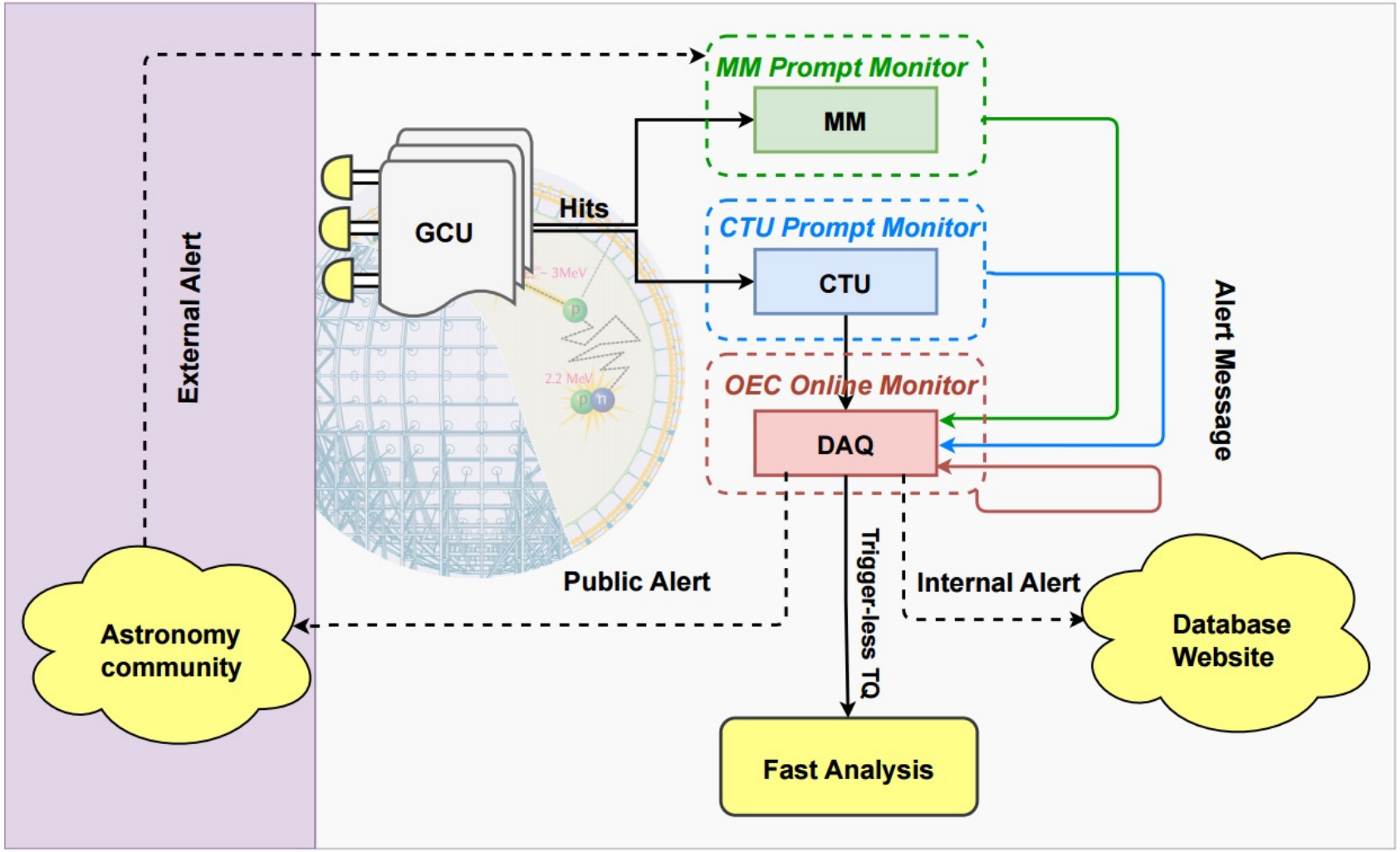
Back Up

自动化预警监控



To do: Automatically launch or request follow-up searches when a relevant SN alert is received.

超新星预警系统设计



- 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)

pre-SN:
0.6 - 1.7 kpc with 50% probability,
alert > ~100 hr in advance if 0.2 kpc

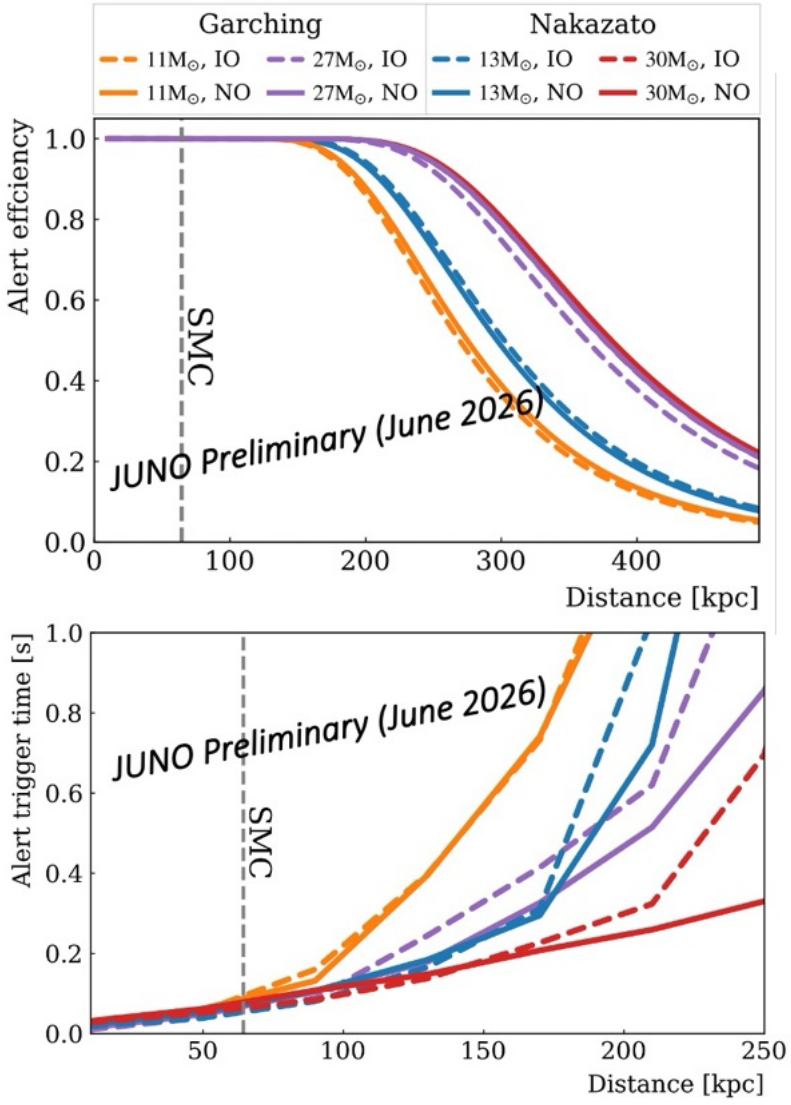
SN:
200 - 400 kpc with 50% probability,
alert in 10 - 30 ms if 10 kpc

超新星预警系统性能

- **Stable operation since the start of physics data taking in August 2025;**
- **Alerts have been broadcasted to SNEWS 2.0 since November 2025.**

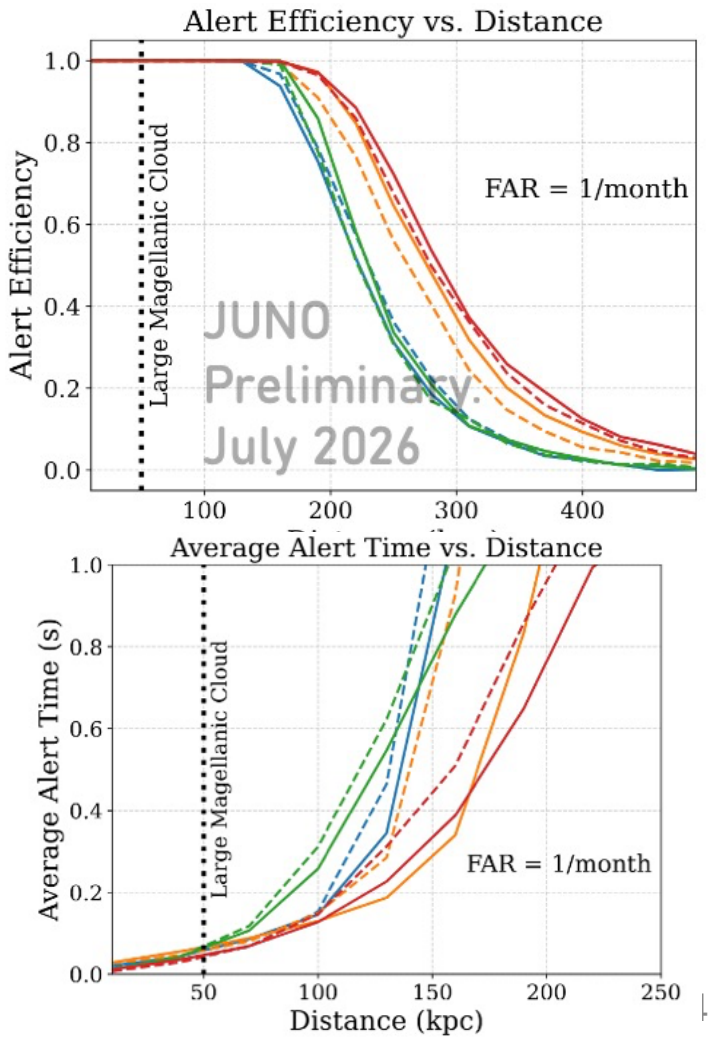
Alert trigger time after core bounce: < 20 ms at 10 kpc
DAQ latency time: one to few-seconds level
False alert rate: <1/month
Coverage: >50% CCSN alert efficiency within ~200 kpc

OEC performance



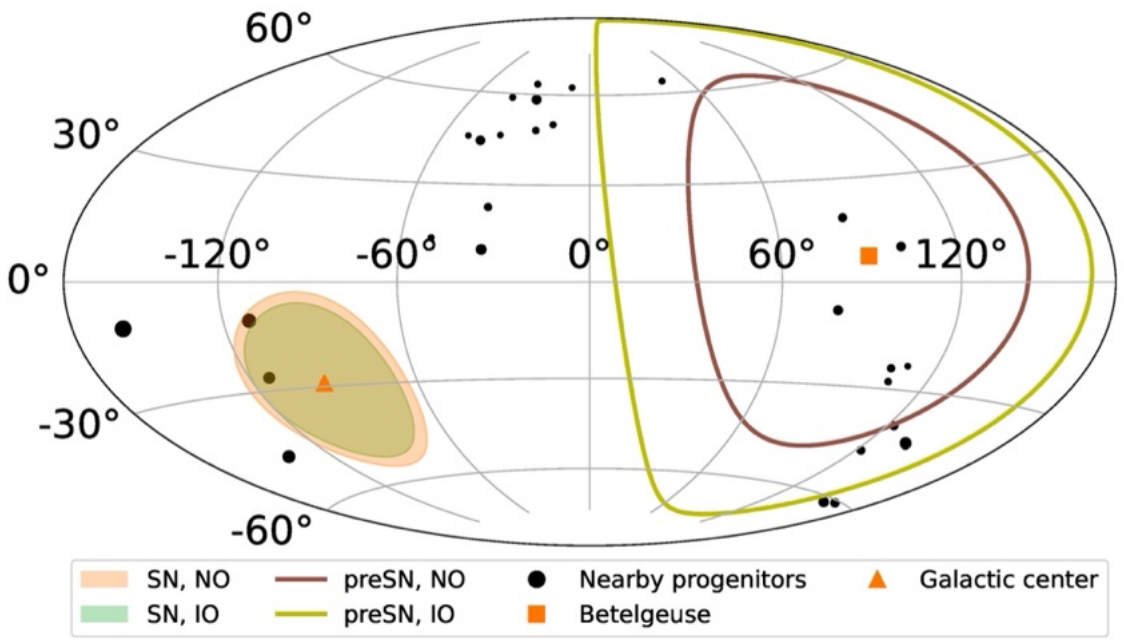
MM performance

threshold ~ 110 keV



Directional Information

The direction between the IBD prompt positron and delayed neutron capture gives the SN direction.

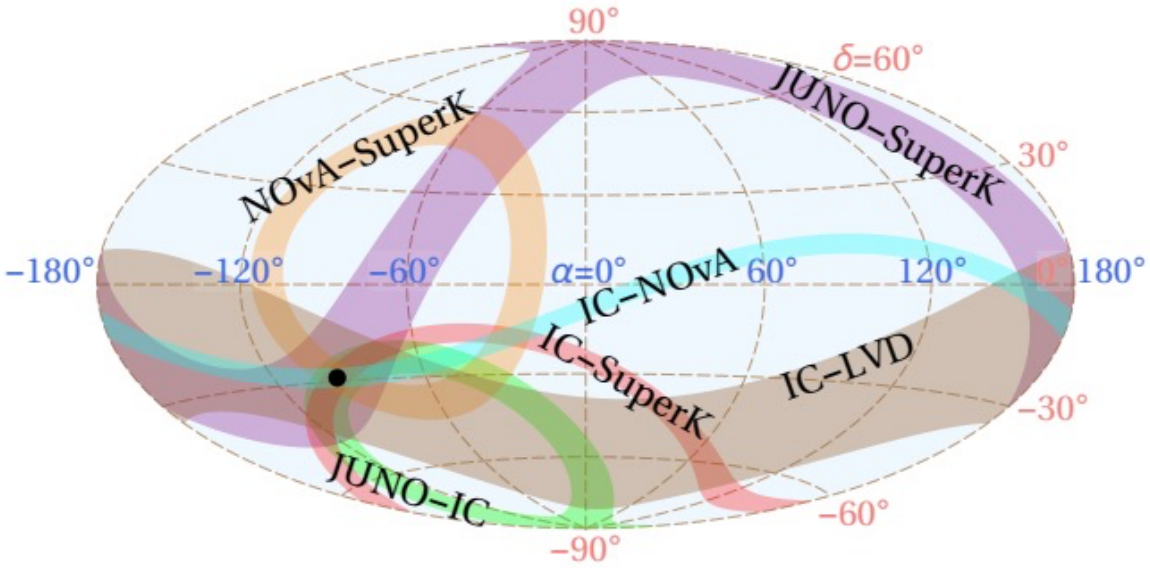


JUNO Collaboration, JCAP 01 (2024) 057

Betelgeuse-like star pre-SN pointing:
56° (81°), NO (IO) for 15 M⊙.

Triangulation

The time delay between the signal at different detectors define a sky region



V. Brdar et al., JCAP 04(2018) 025

Typical core-collapse supernova at 10 kpc SN pointing:
26° (23°), NO(IO) for 13 M⊙.