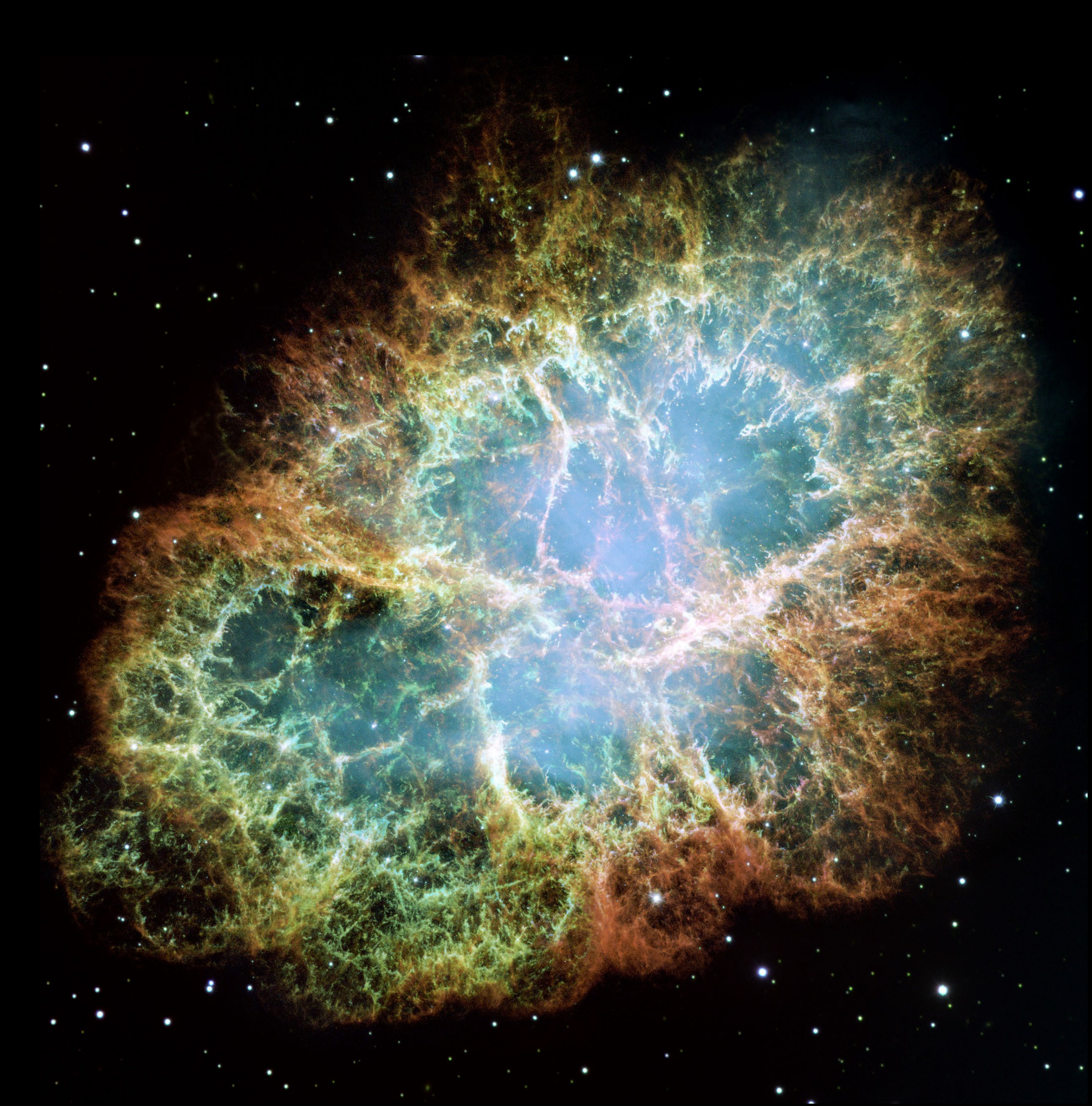


SN1054 (Crab Nebula) by HST

Tsung-Dao Lee Institute

TRIDENT 海铃计划

Capturing neutrons in deep-sea neutrino telescopes

Ruike Cao, with Iwan Morton-Blake,

Yong-Zhong Qian and Donglian Xu

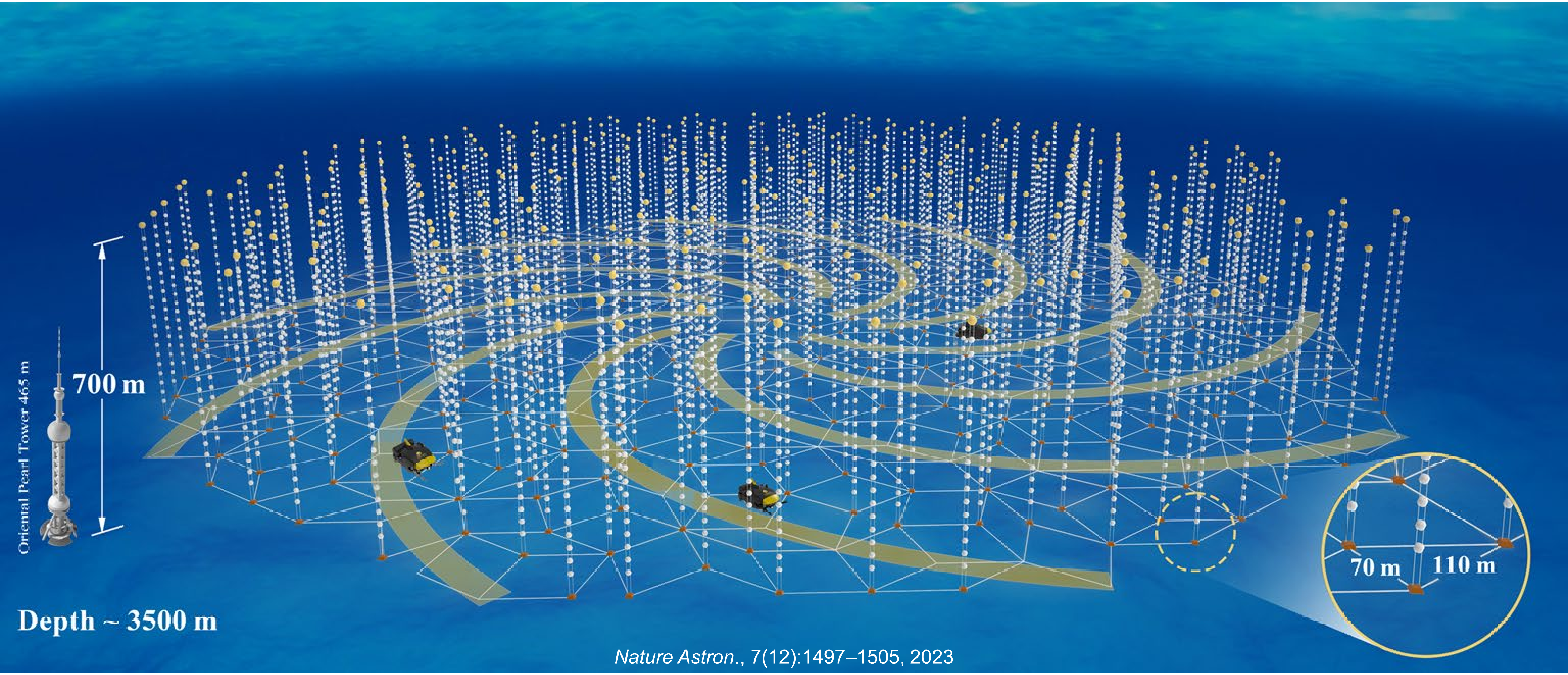
2026.09.02 Tendo, Japan

TeV Particle Astrophysics 2026

ruike_cao@sjtu.edu.cn

TRopIcal DEep-sea Neutrino Telescope (TRIDENT)

Aim: All-flavour TeV~PeV astrophysical & atmospheric neutrinos



Nature Astron., 7(12):1497–1505, 2023

TRopIcal DEep-sea Neutrino Telescope (TRIDENT)

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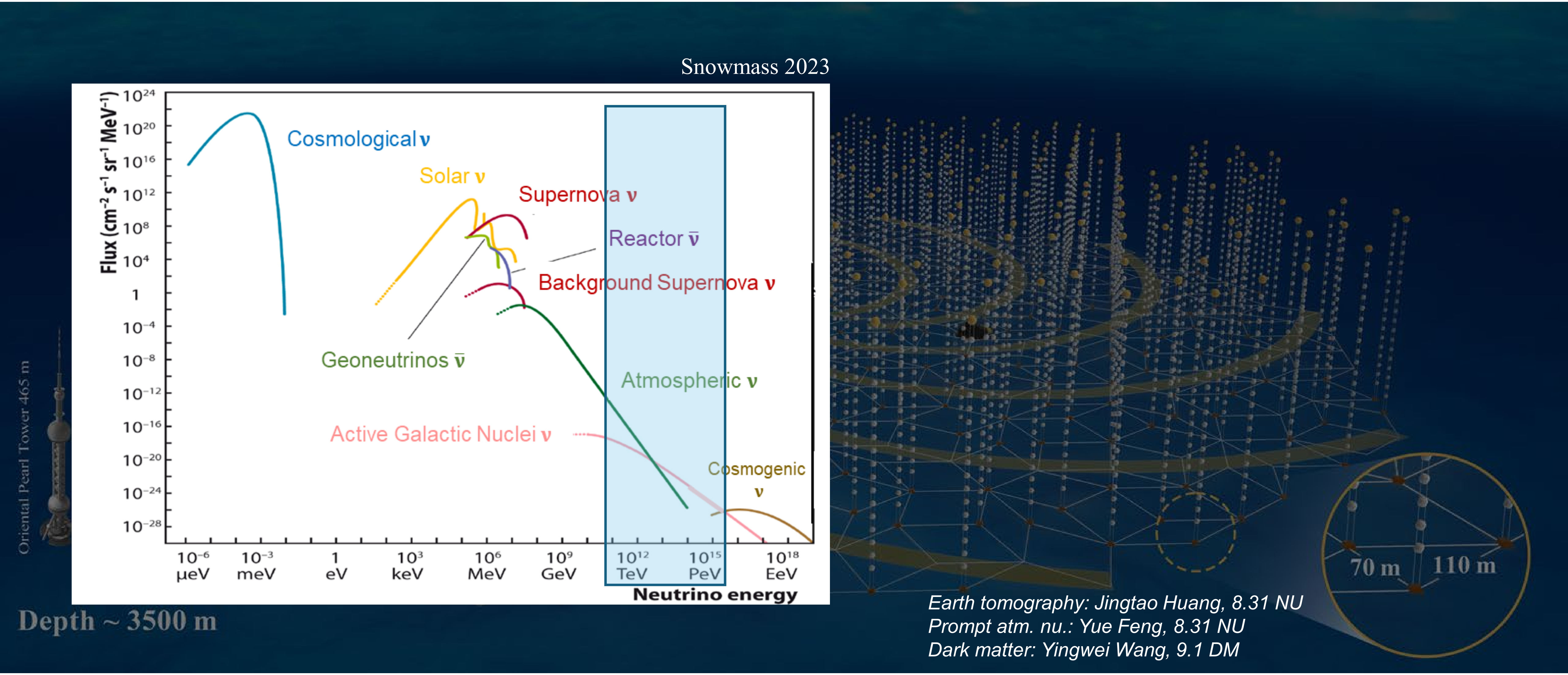
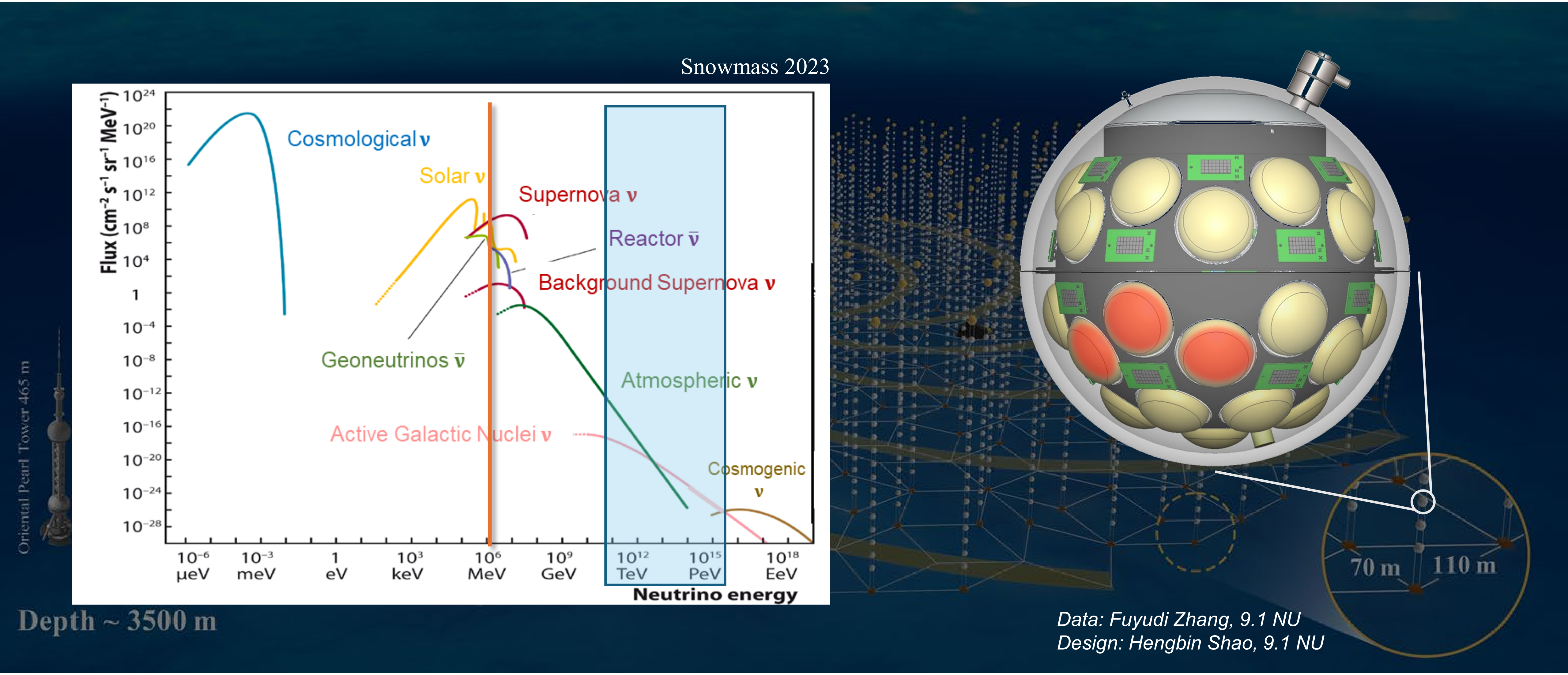


Earth tomography: Jingtao Huang, 8.31 NU
Prompt atm. nu.: Yue Feng, 8.31 NU
Dark matter: Yingwei Wang, 9.1 DM

Hybrid Digital Optical Module (hDOM)

Multi-channel coincidence: Sensitive to MeV events!



Data: Fuyudi Zhang, 9.1 NU

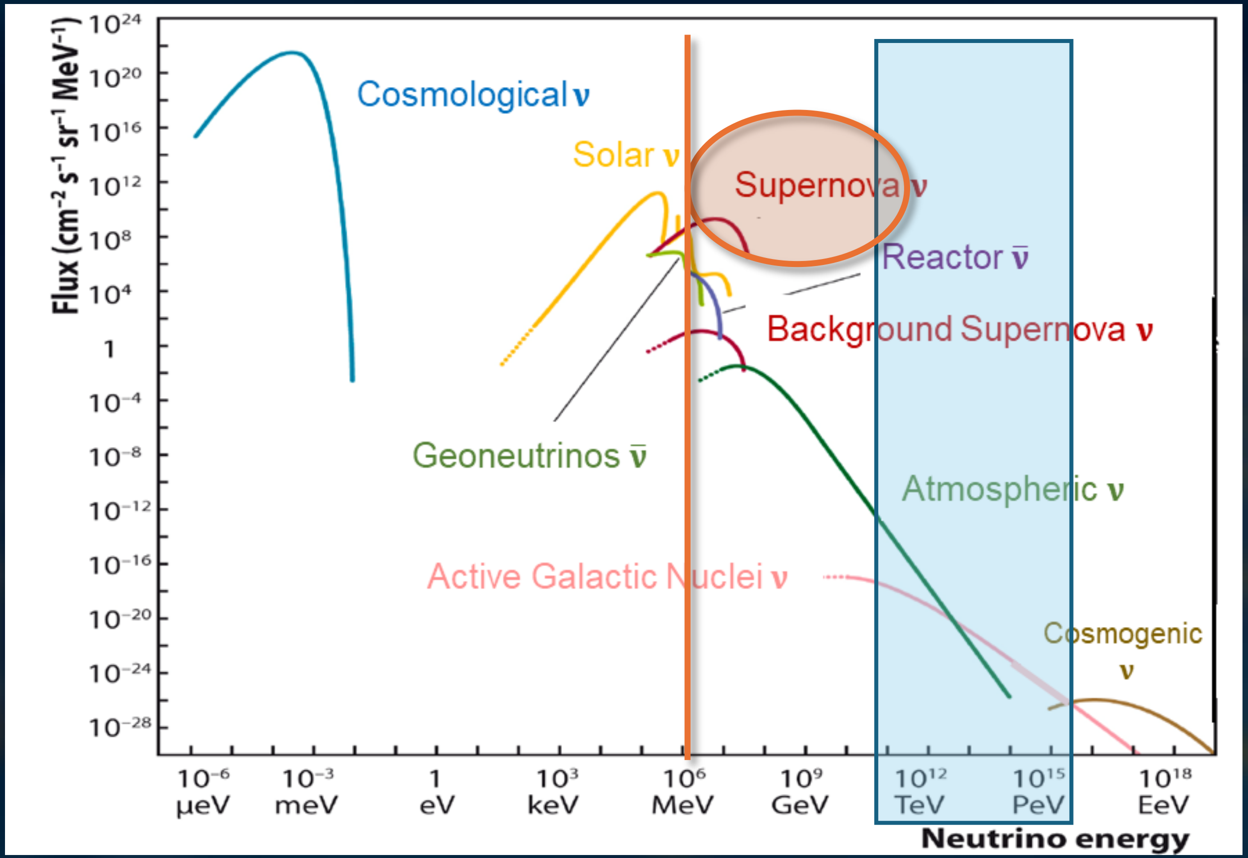
Design: Hengbin Shao, 9.1 NU

Neutrinos from core-collapse supernovae

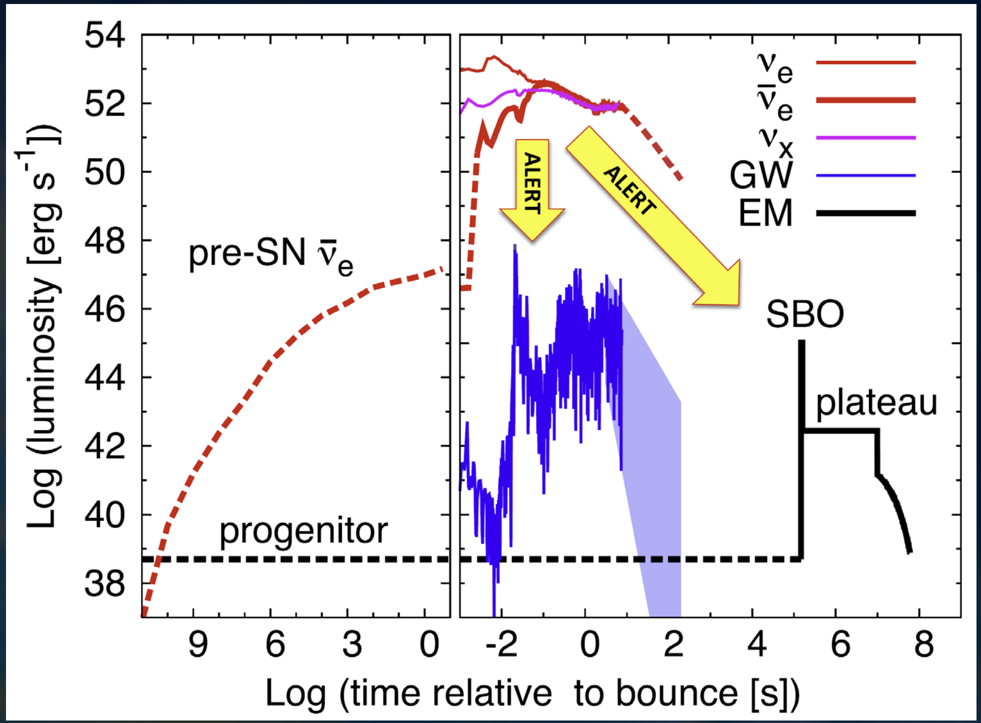
Only CCSN observed in neutrinos: SN1987A

Early emission, rich astro/particle physics

Snowmass 2023



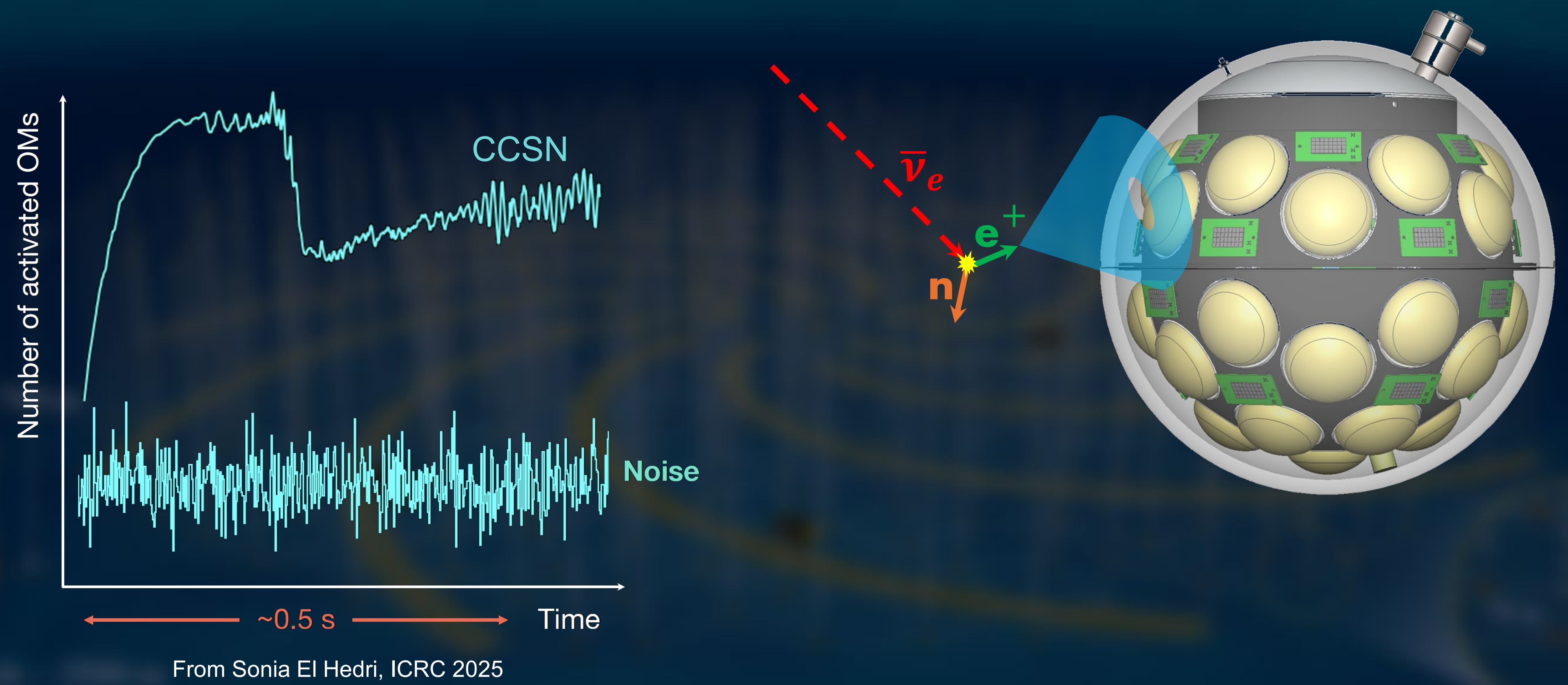
SNEWS, New J.Phys. 23 (2021) 3, 031201



Inverse beta decay

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

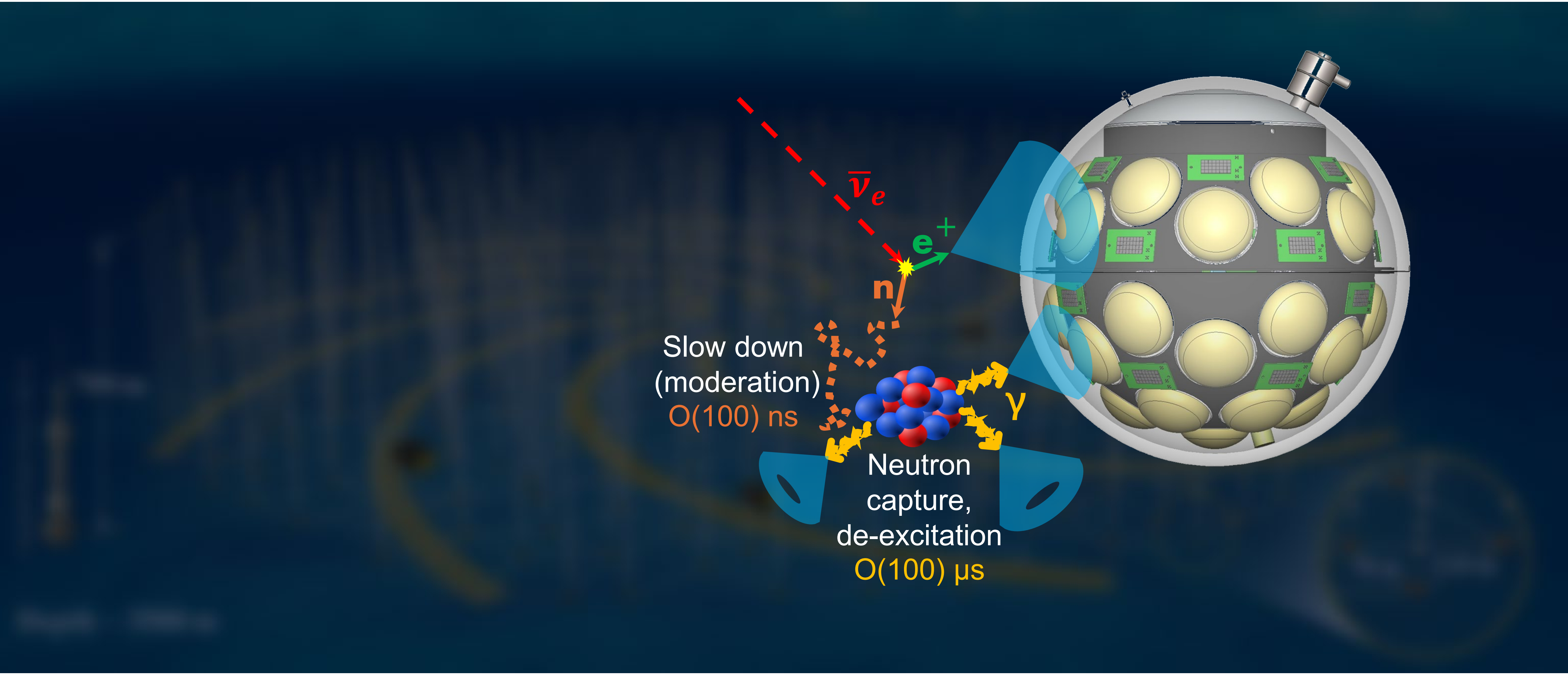
Current CCSN analyses in neutrino telescopes use the prompt positron signal only



Using the neutron

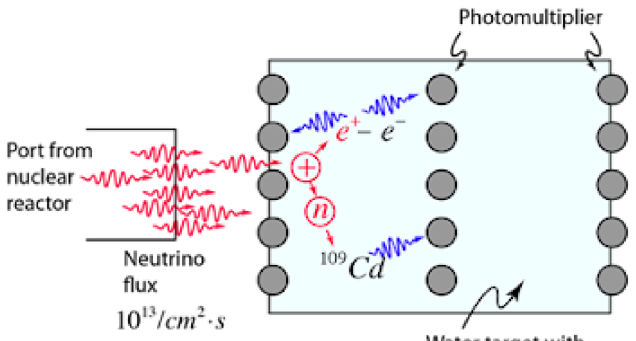
IBD: $\bar{\nu}_e + p \rightarrow \boldsymbol{e^+} + \boldsymbol{n}$

Time coincidence: Prompt + delayed



Using the neutron: Add dopant

Cowan-Reines, 1956: $CdCl_2$



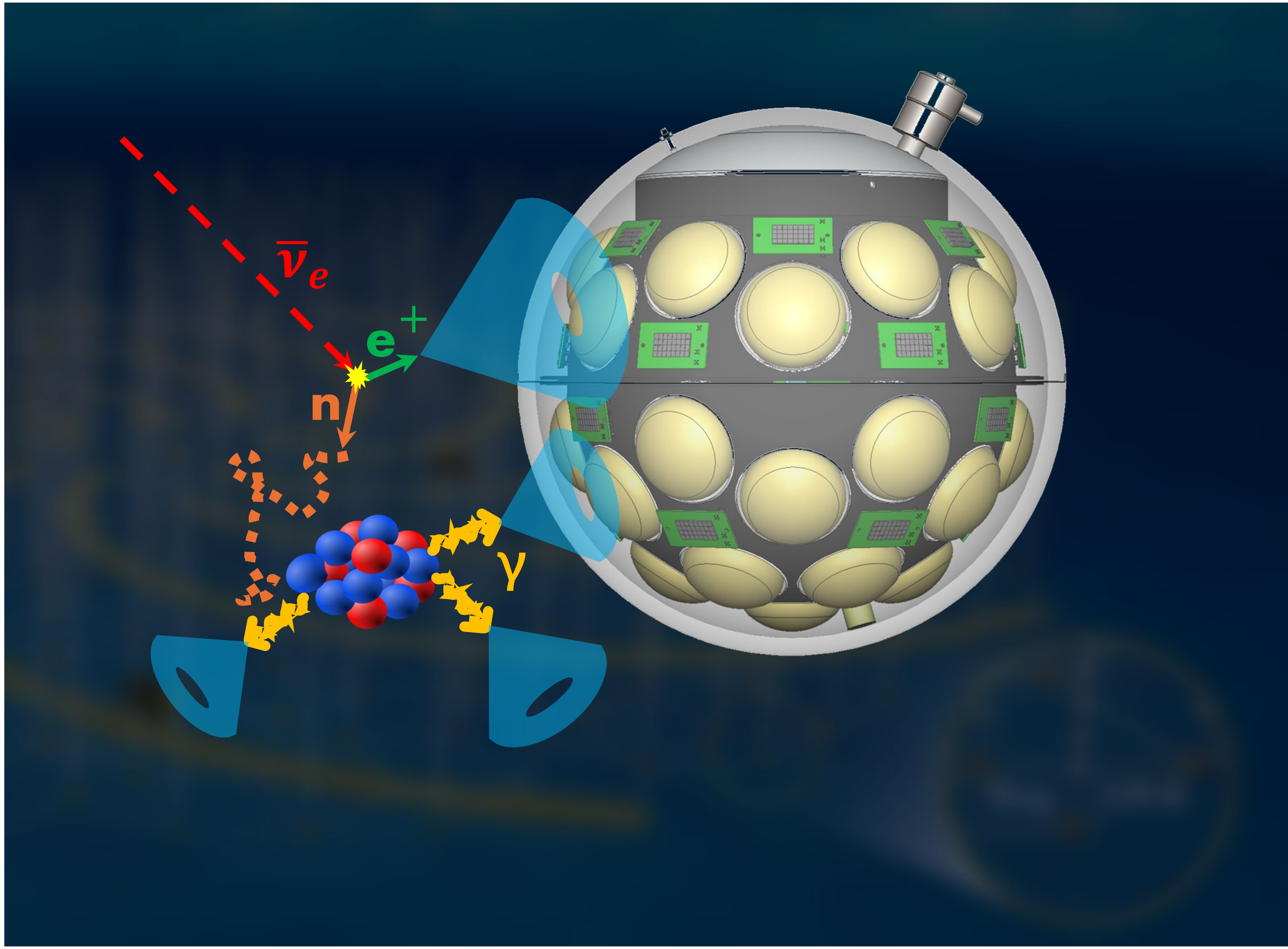
Science 124, 103 (1956)

SNO, 2001: 2‰ NaCl in D_2O

Super-K, 2008: "First Study of Neutron Tagging with a Water Cherenkov Detector"

Astropart.Phys. 31 (2009) 320-328

SK-Gd, 2022: 0.3‰ Gd



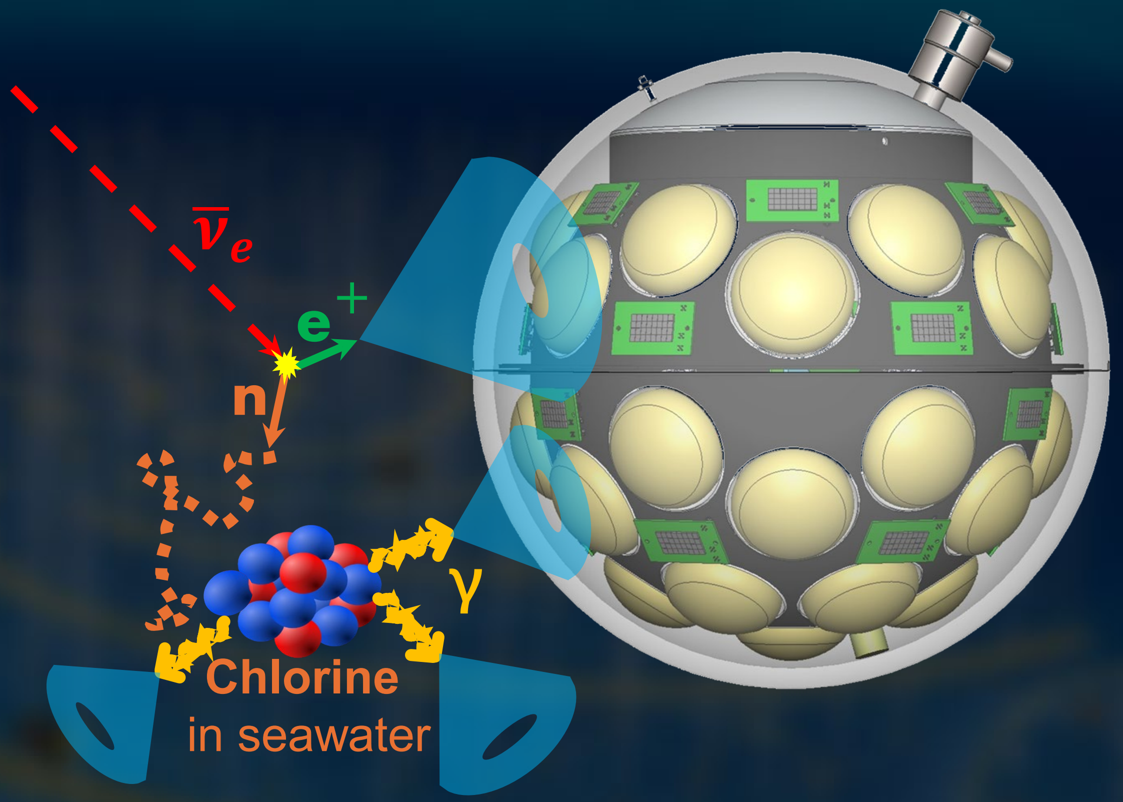
Neutron capture in seawater

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

Naturally abundant Chlorine: First time use in neutrino telescopes!

Seawater components:

Nuclei	n (number fraction)	$\overline{E_\gamma}$ [MeV]	σ [bar]
^{1}H	66.1%	2.22	0.333
^{16}O	33.2%	4.14	0.0002
^{23}Na	0.28%	6.96	0.52
^{35}Cl	0.25%	8.58	43.6
^{37}Cl	0.08%	6.11	0.43
^{24}Mg	0.03%	7.33	0.054



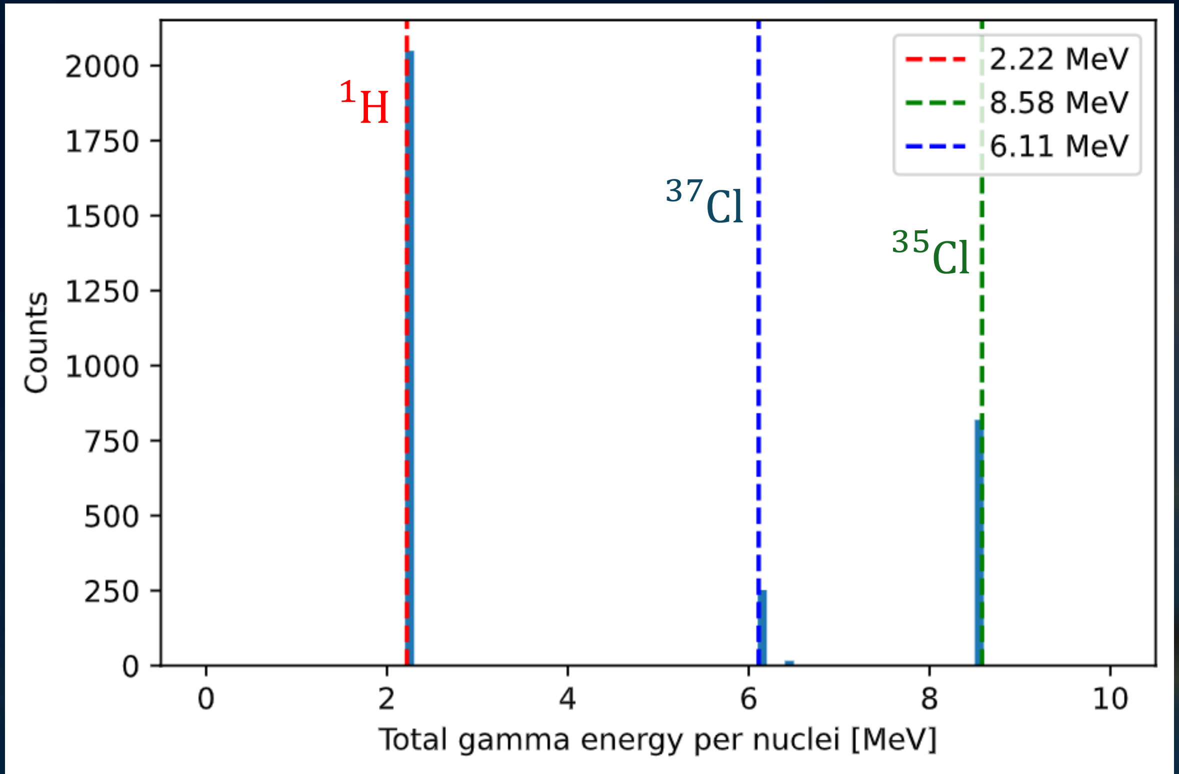
Neutron capture data from NNDC

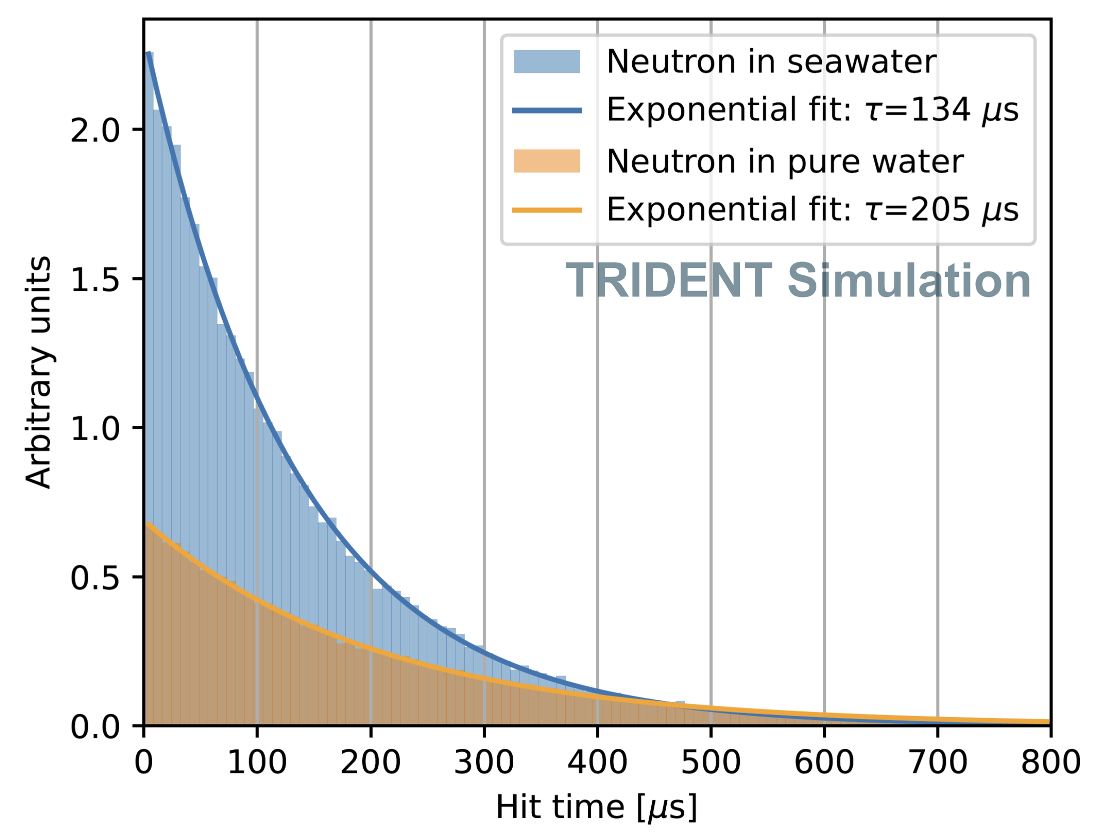
Neutron capture in seawater

Chlorine makes neutron capture brighter and faster

# of photons×2.3, decay time×0.6

Gamma emission by neutron capture

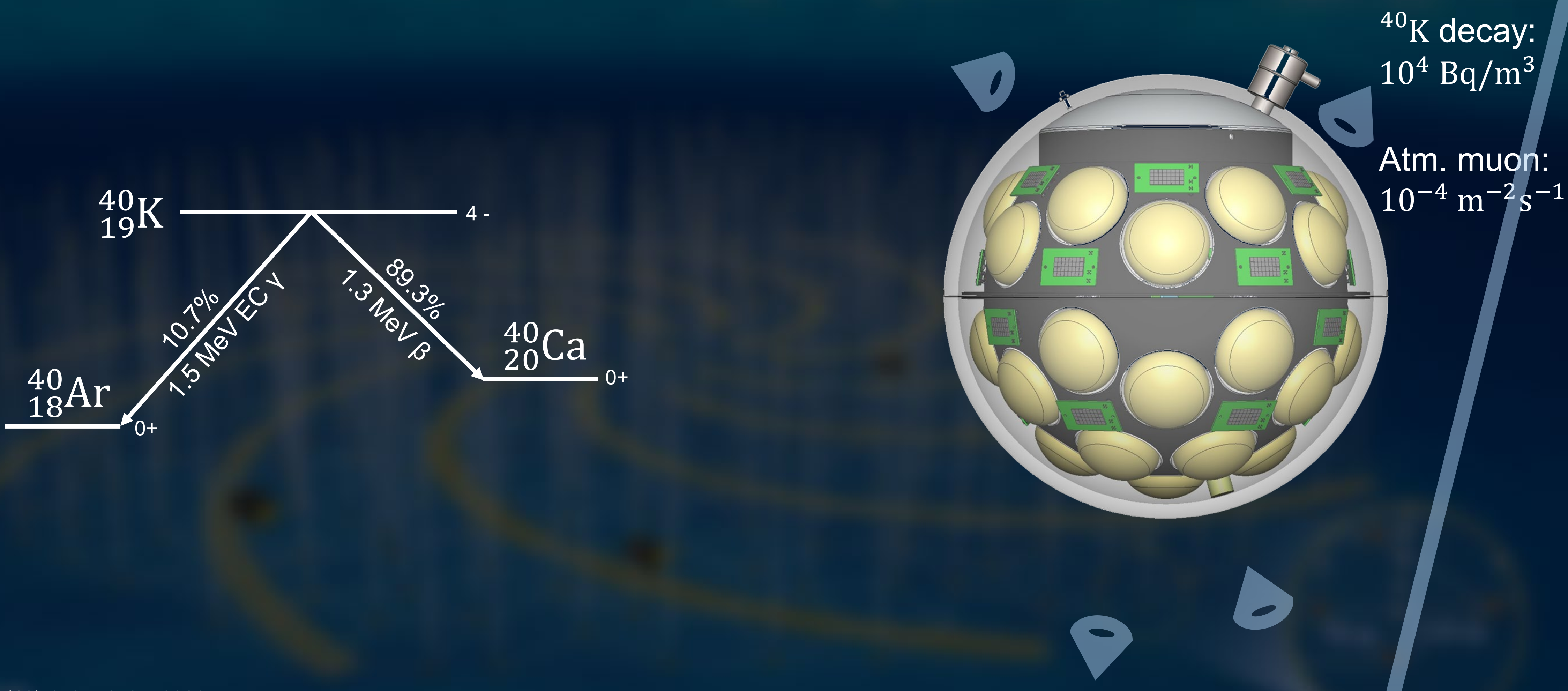




(since prompt positron)

Neutron capture data from NNDC

Backgrounds in the deep-sea

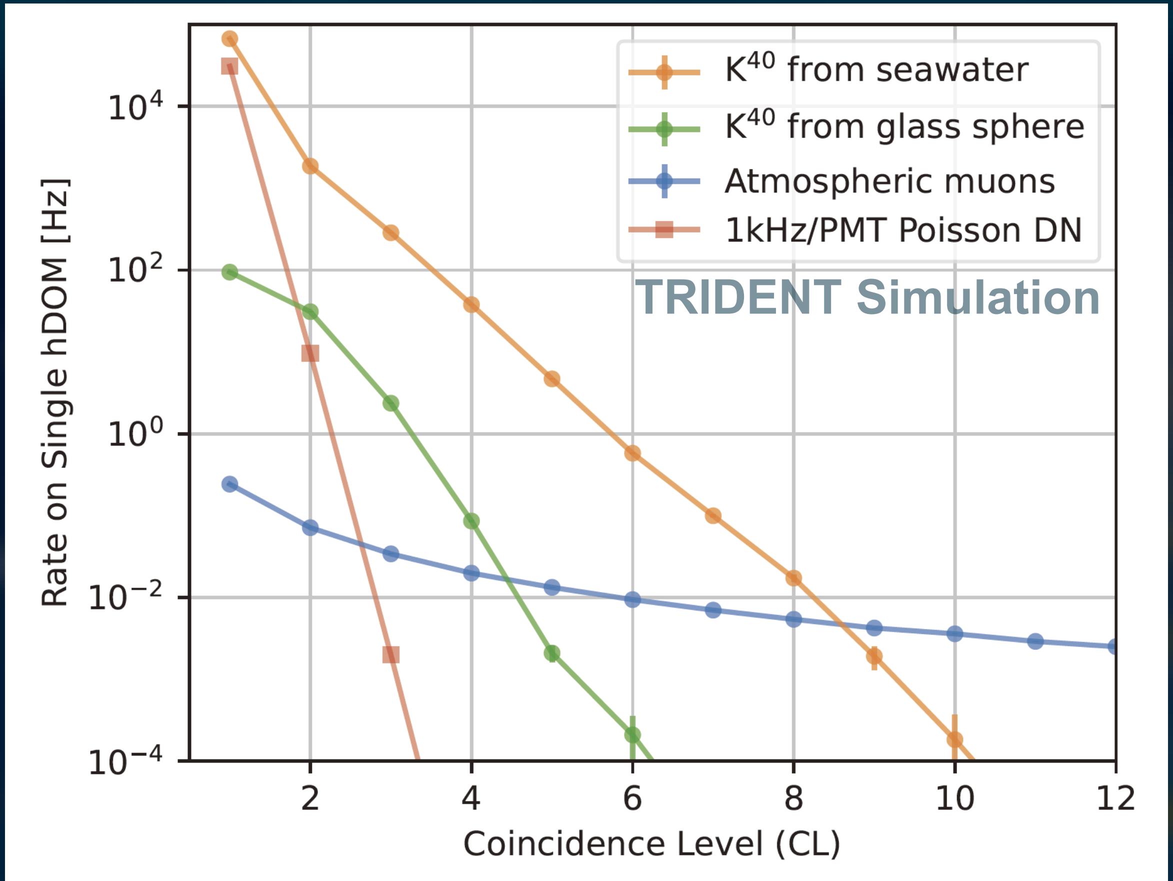


K40: *Nature Astron.*, 7(12):1497–1505, 2023
Atm. muon: *Phys. Rev. D* 58, 054001 (1998)

Backgrounds in the deep-sea

Pixelized detector: Energy proxy

PoS(ICRC2025)1004



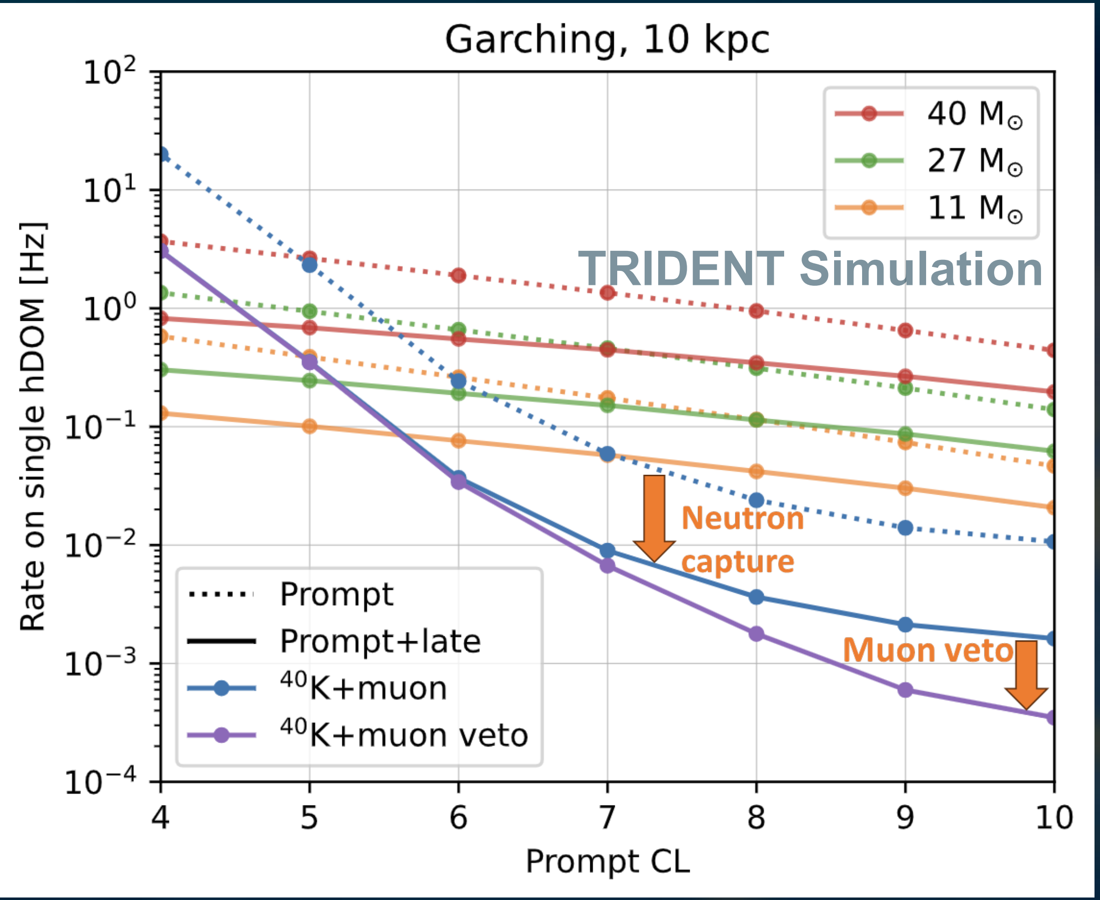
(# of PMT hits in 20ns window)

Data: Fuyudi Zhang, 9.1 NU
Calibration: Tailin Zhu, 9.1 NU

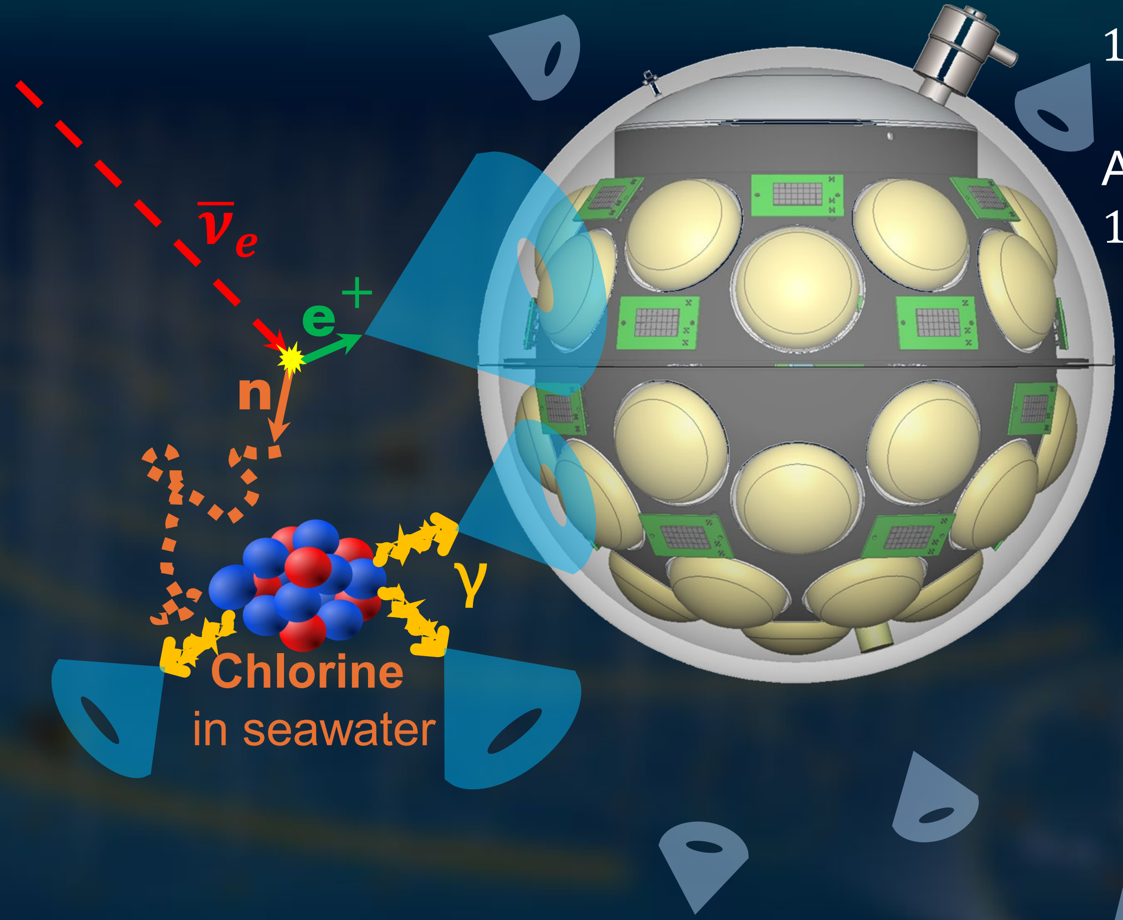
CCSN signal selection

Space: Multi-PMT coincidence

PoS(ICRC2025)1004



(# of PMT hits in 20ns window)



^{40}K decay: 10^4 Bq/m^3

Atm. muon: 10^{-4} m^{-2}s^{-1}

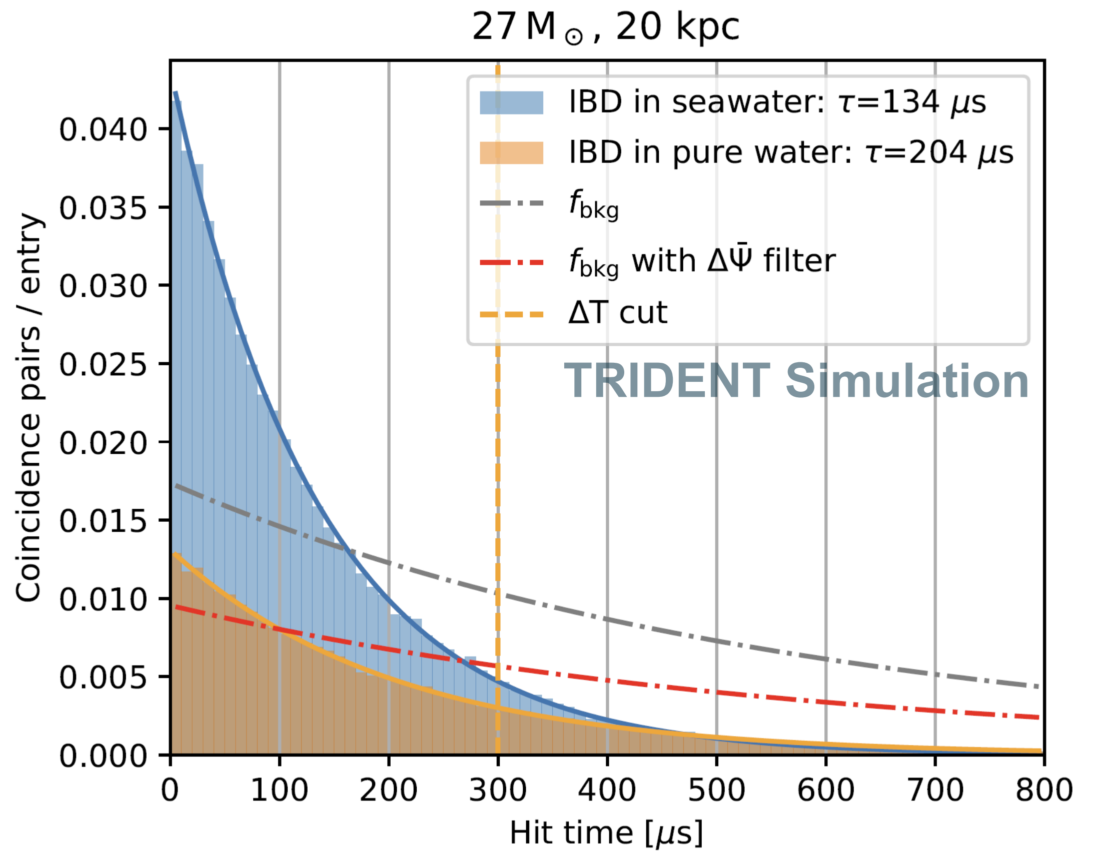
CCSN model: *Phys. Rev. D* 90, 045032 (2014)

CCSN signal selection

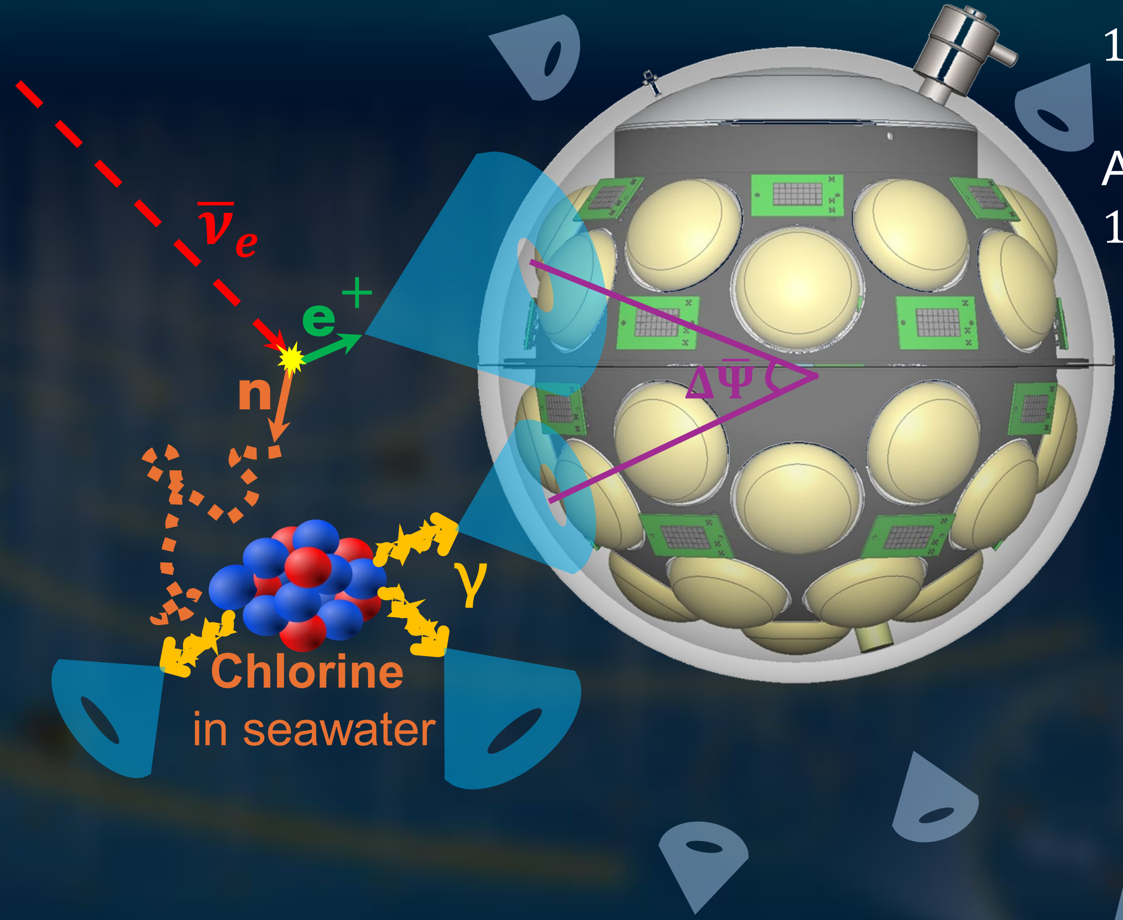
Space: Multi-PMT coincidence

Time: Prompt + late coincidence

PoS(ICRC2025)1004



(since prompt positron)



^{40}K decay: 10^4 Bq/m^3

Atm. muon: 10^{-4} m^{-2}s^{-1}

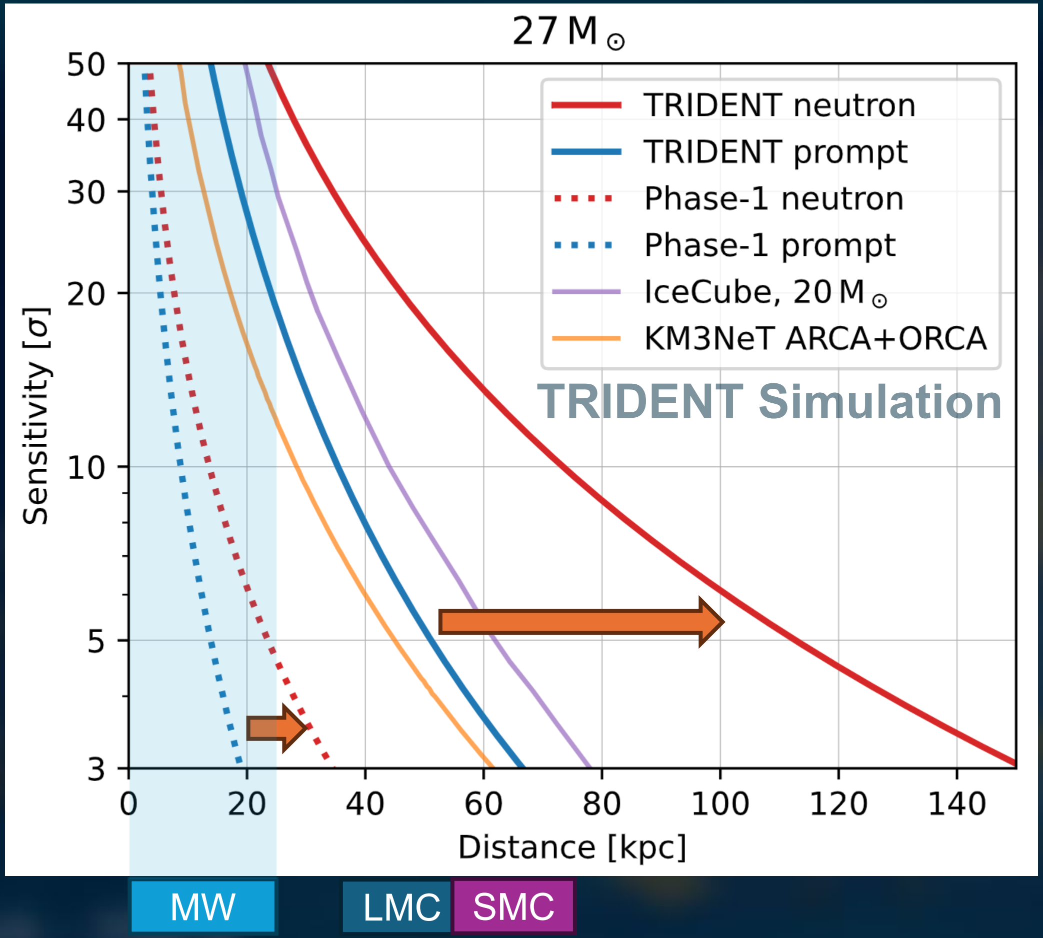
CCSN model: *Phys. Rev. D* 90, 045032 (2014)

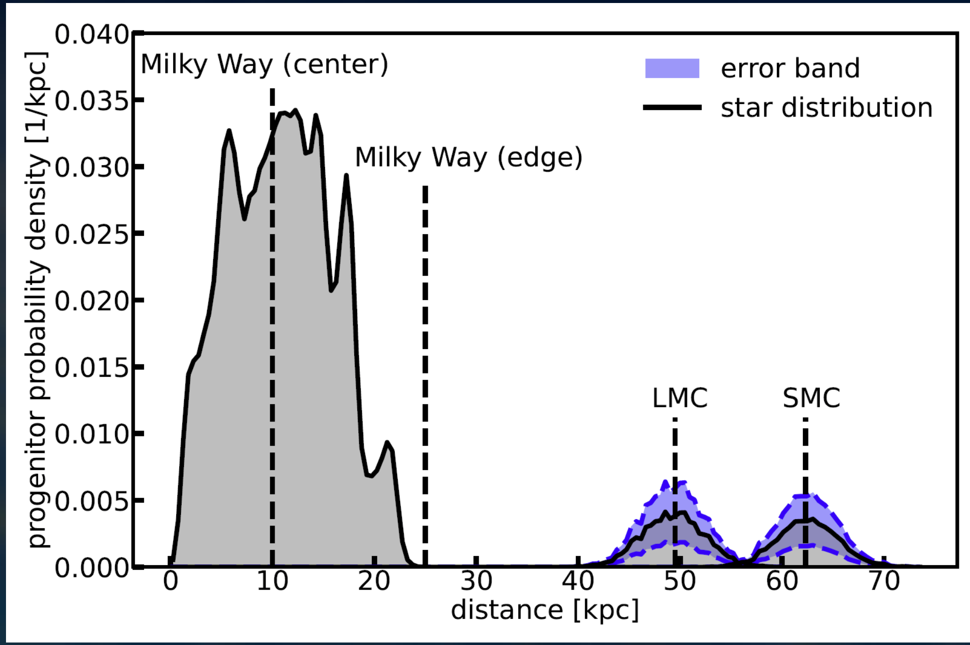
Discovery horizon

Using neutron: Discovery distance×2

TRIDENT Phase-1 in 2027: Galactic CCSN coverage

PoS(ICRC2025)1004





Astrophys.J. 961 (2024) 1, 84

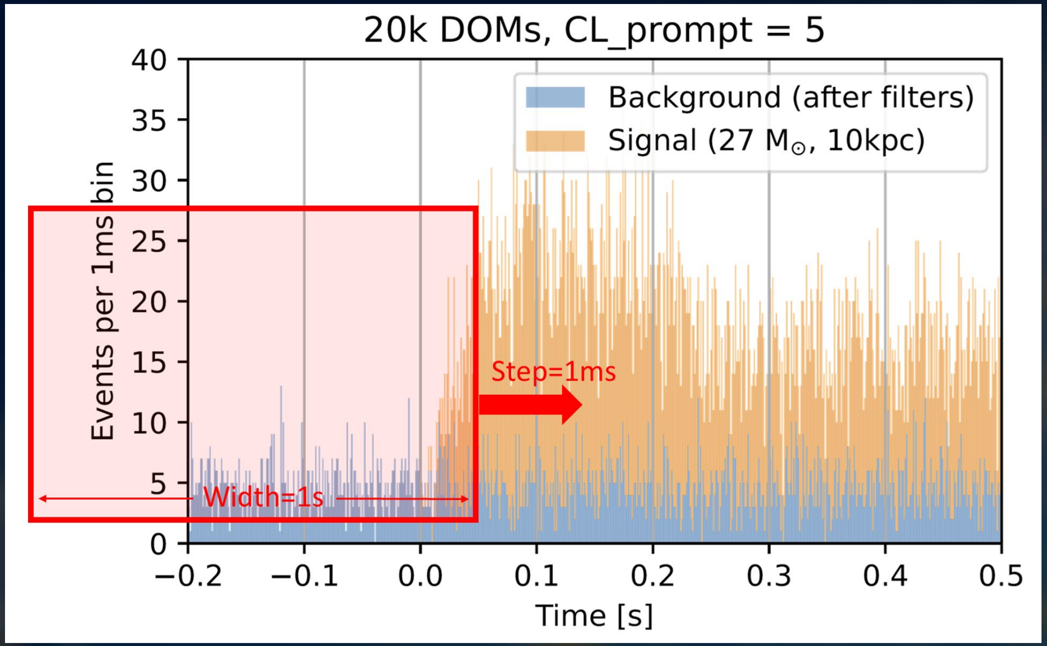
IceCube: *Astron. Astrophys.* 535, A109 (2011)

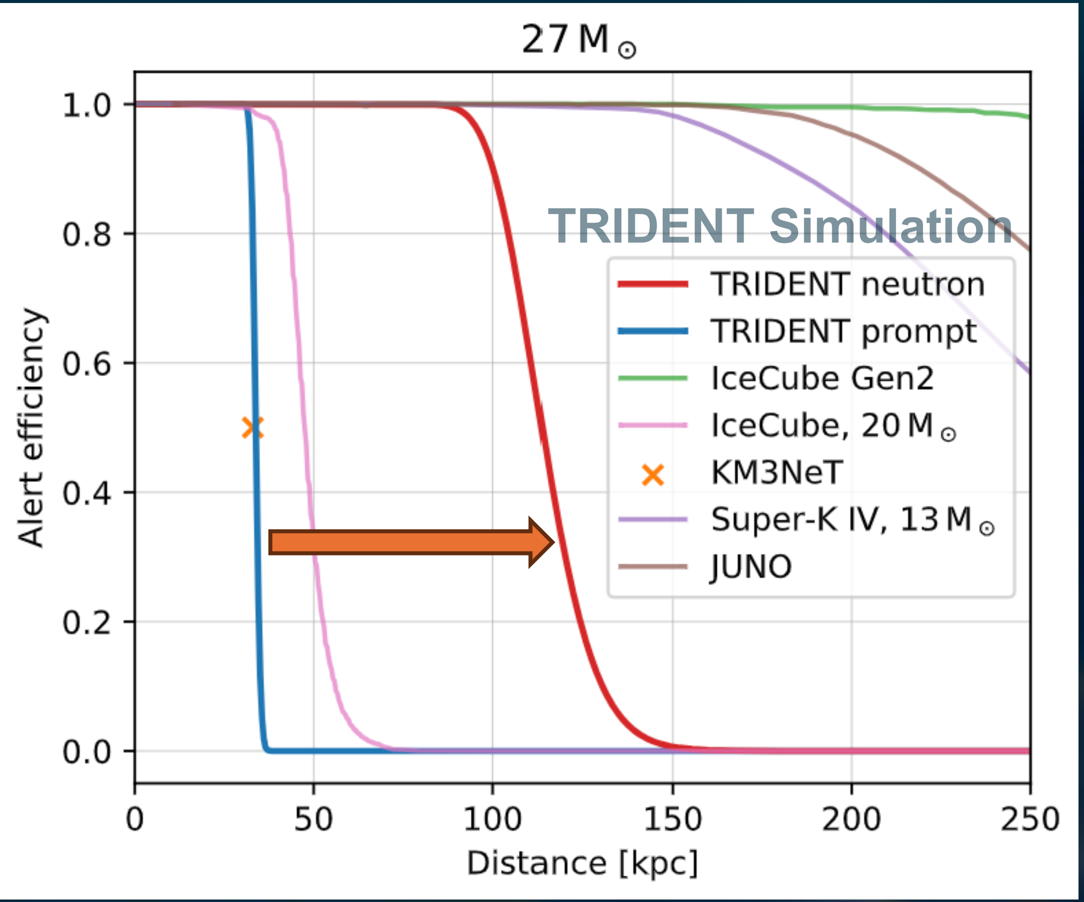
KM3NeT: *JCAP* 04 (2026) 038

CCSN alert

Sliding window → count hDOMs passing the filter → alert
False alert rate (FAR): < 1/week

PoS(ICRC2025)1004



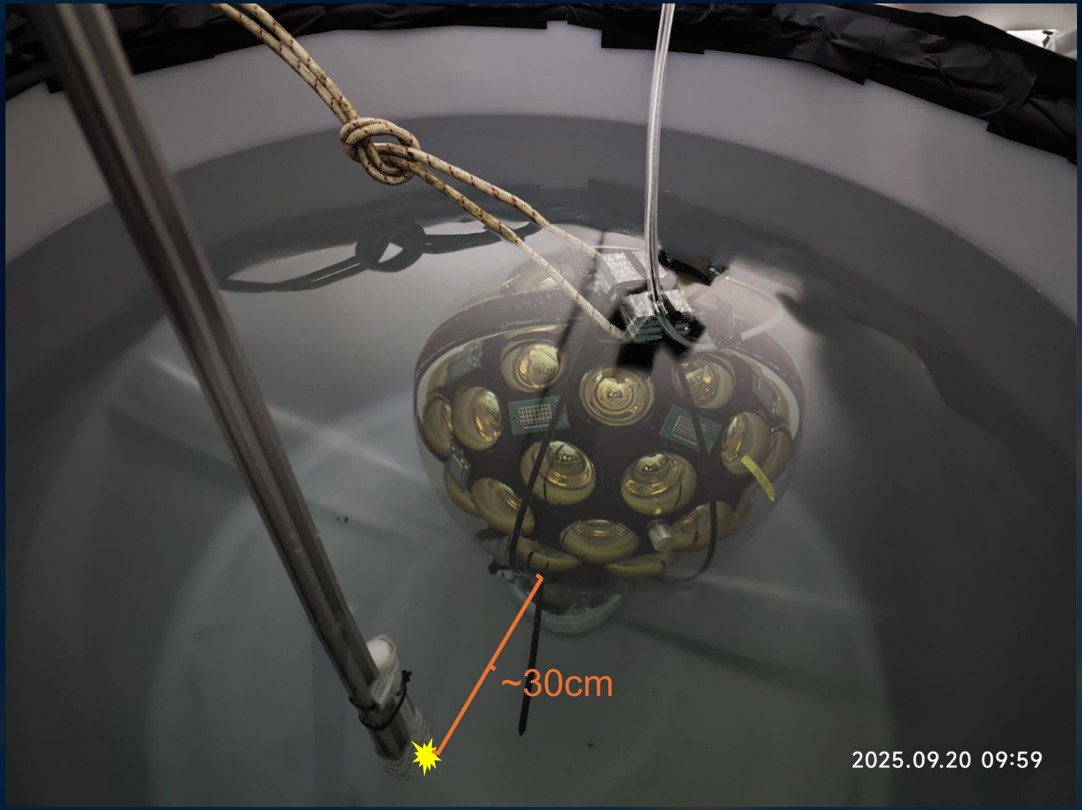


IceCube: *Astron. Astrophys.* 535, A109 (2011)
IceCube-Gen2: *Eur. Phys. J. C*, 81,1058 (2021)
KM3NeT: *Eur. Phys. J. C* 82, 317 (2022)
SuperK: *Astrophys. J.*, 938(1):35, 2022
JUNO: *JCAP*, 01:057, 2024

Experimental demonstration

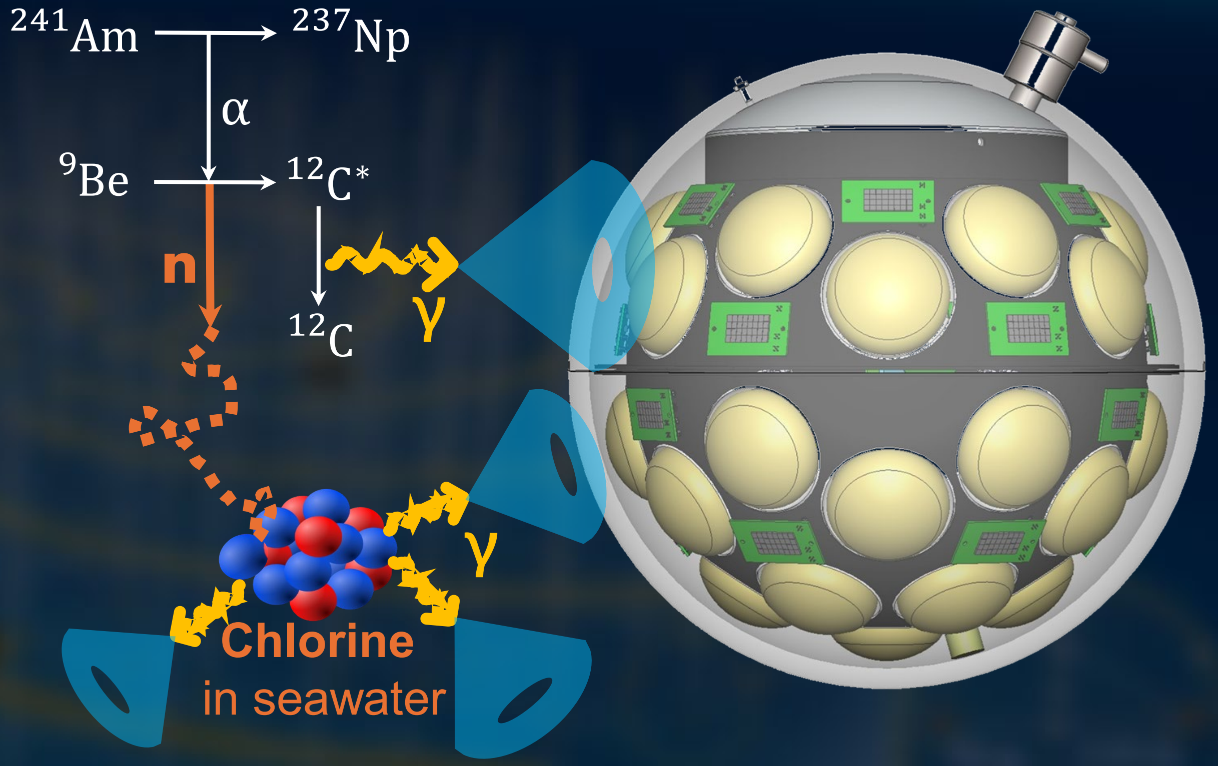
Take an hDOM to CJPL (China Jinping Underground Laboratory)

CJPL, ~2.4km rock



AmBe source, ~10Bq

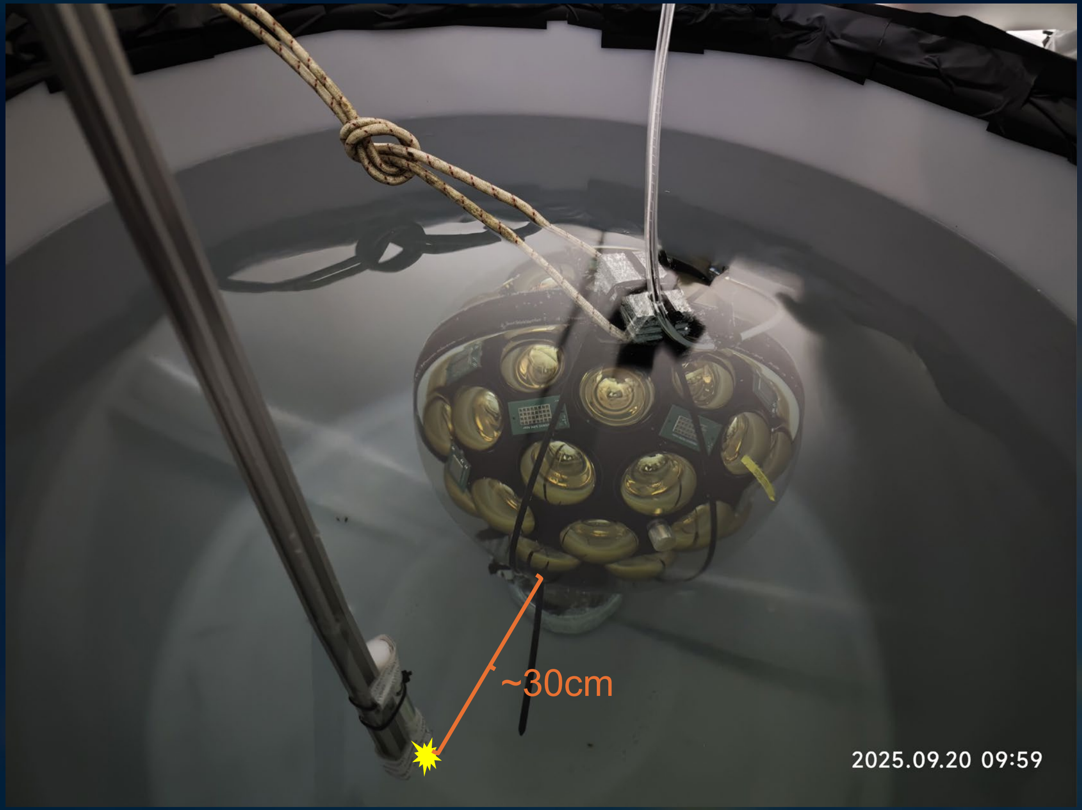
4.4MeV γ, 4~5MeV n



Experimental demonstration

Take an hDOM to CJPL (China Jinping Underground Laboratory)
Observe AmBe neutron source in pure and salted water

CJPL, ~2.4km rock



AmBe source, ~10Bq
4.4MeV γ, 4~5MeV n

3×3 sets	day1	day2	day3
Pure water	-	AmBe	-
NaCl water	AmBe	-	AmBe
NaCl+KCl water	-	AmBe	-

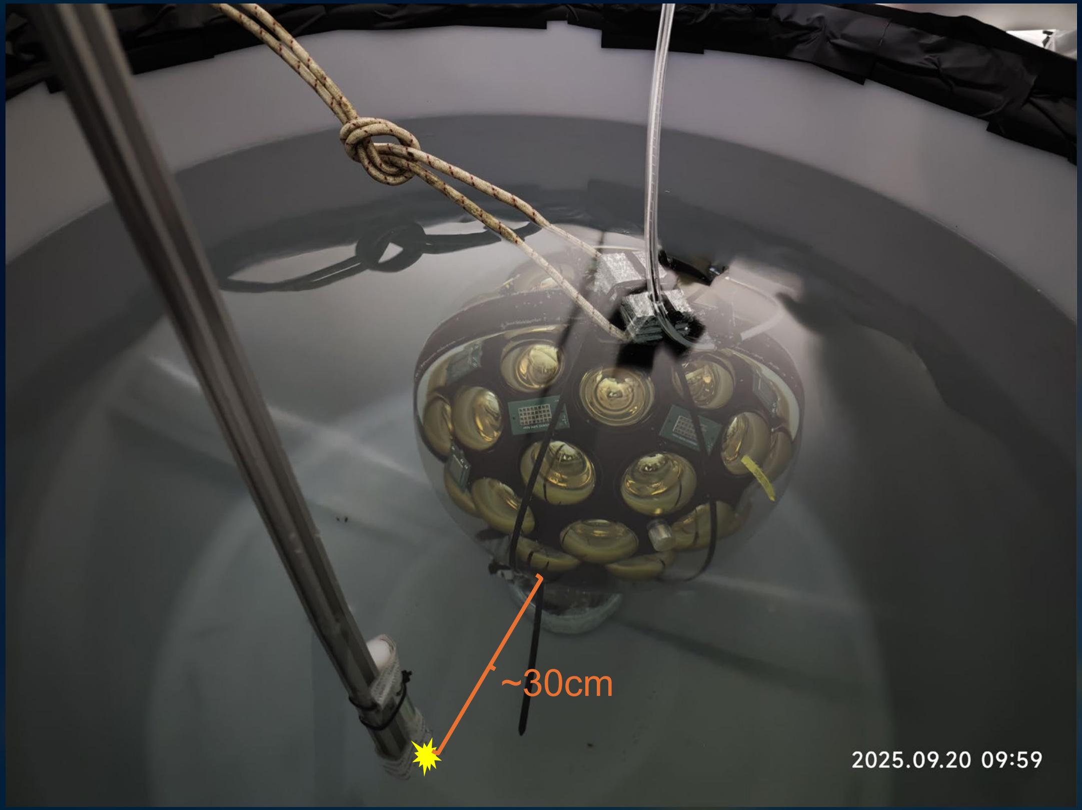
Neutron capture observed with a single hDOM

Observe AmBe neutron source in pure and salted water

Fit and remove the backgrounds: Data consistent with simulation

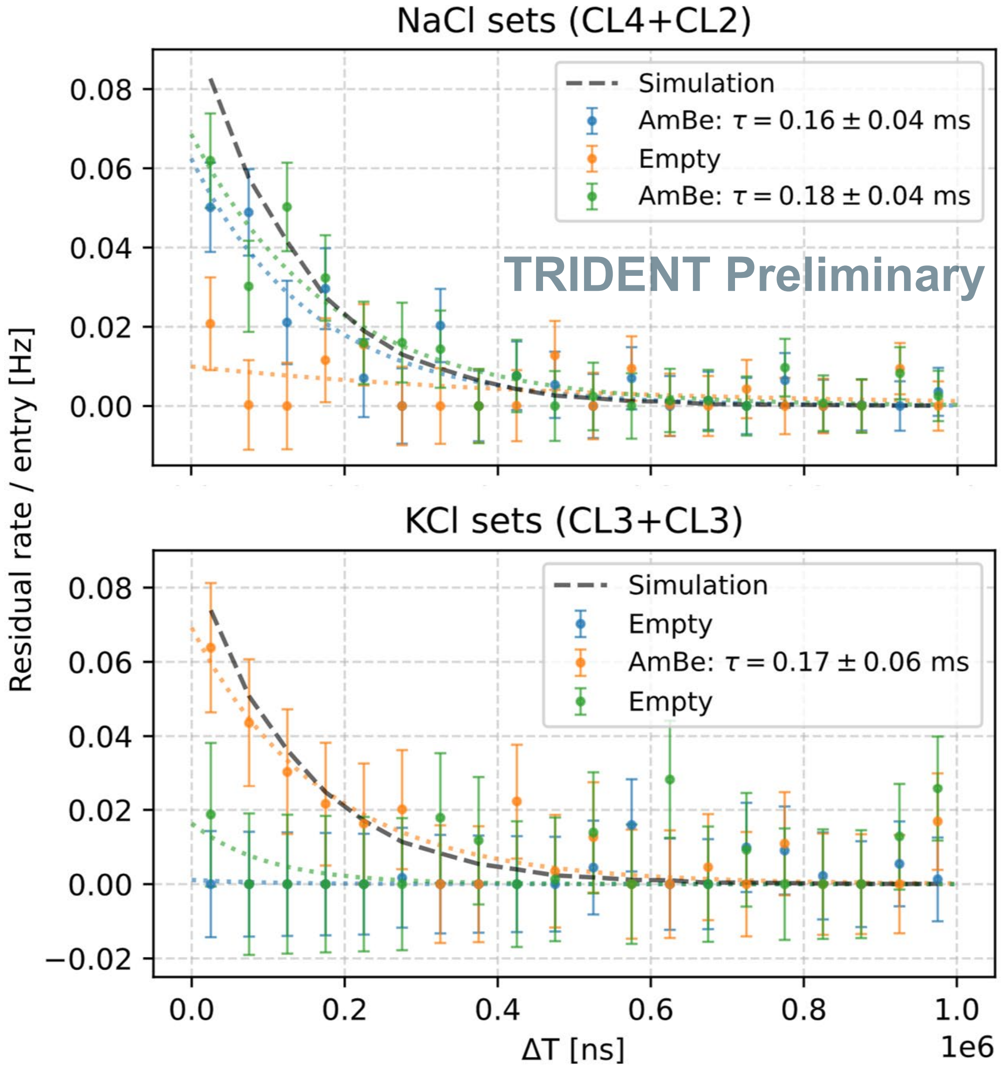
Publication in prep.

CJPL, ~2.4km rock



AmBe source, ~10Bq

4.4MeV γ, 4~5MeV n

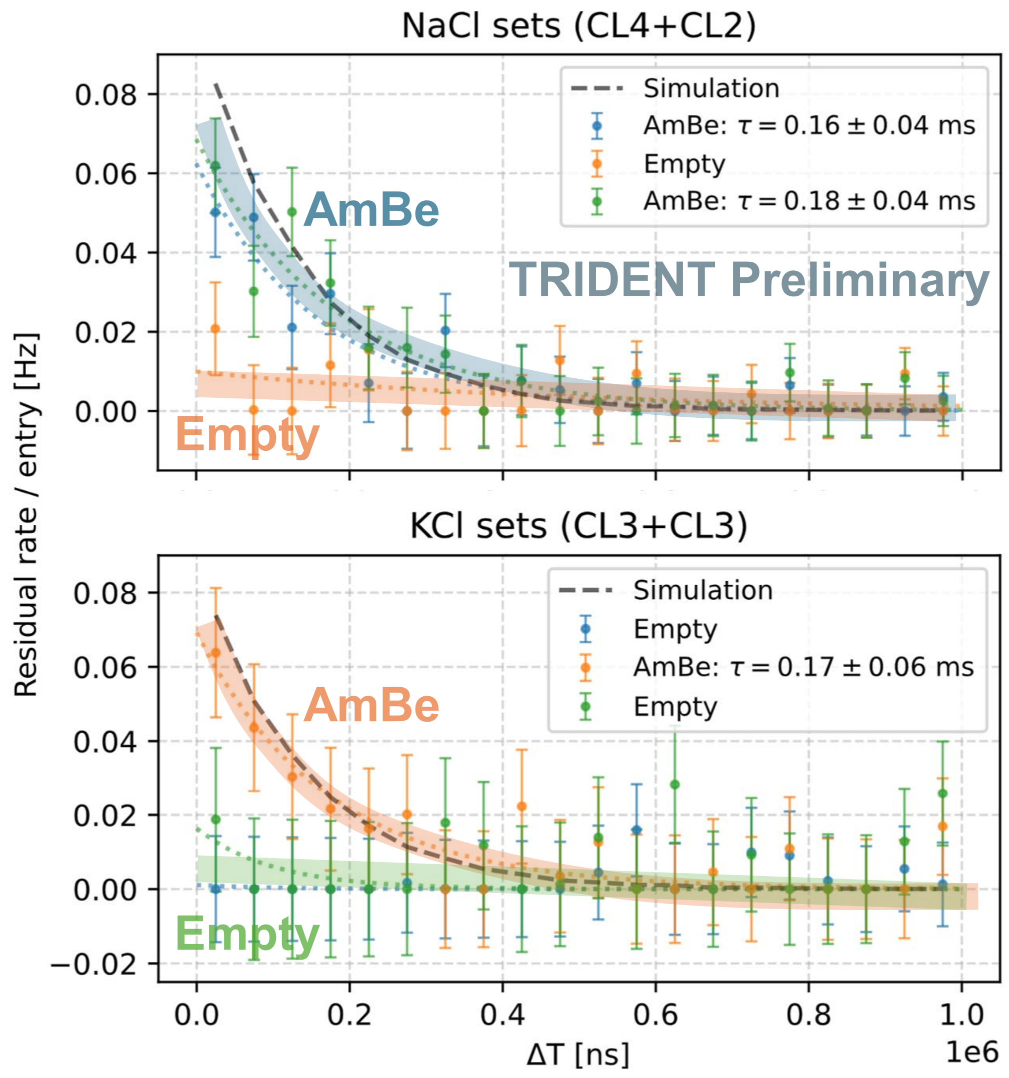


Neutron capture observed with a single hDOM

Observe 10Bq AmBe source for ~10h each
Likelihood-based analysis: >3σ significance

Publication in prep.

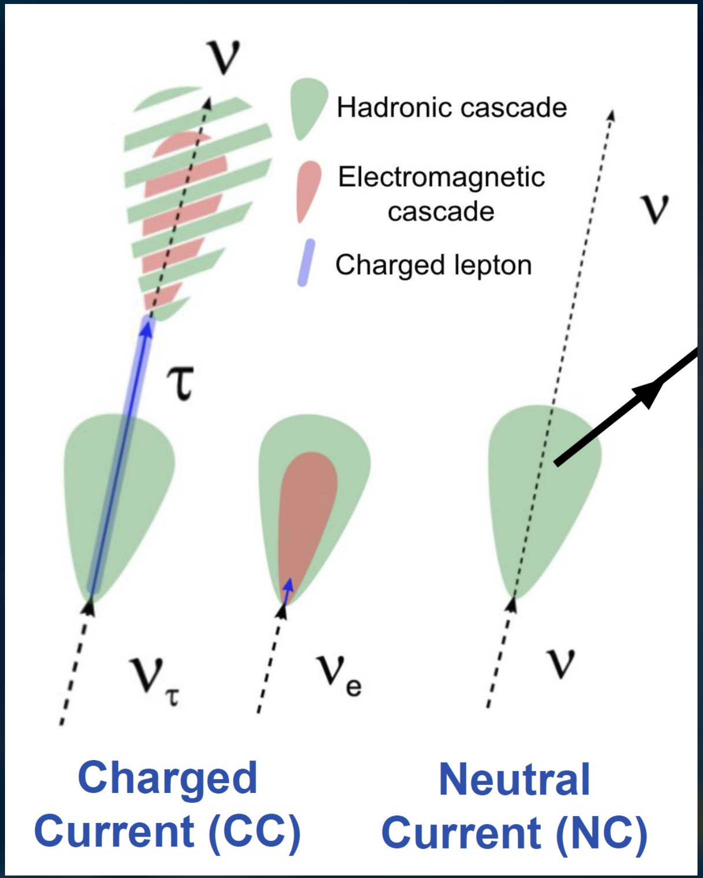
Groups	Sets	TS	Significance [σ]
NaCl	AmBe	15.20	**3.48**
	Empty	-2.77	0.00
	AmBe	16.59	**3.66**
	Empty	-3.99	0.00
NaCl +KCl	AmBe	5.92	**1.94**
	Empty	-9.28	0.00



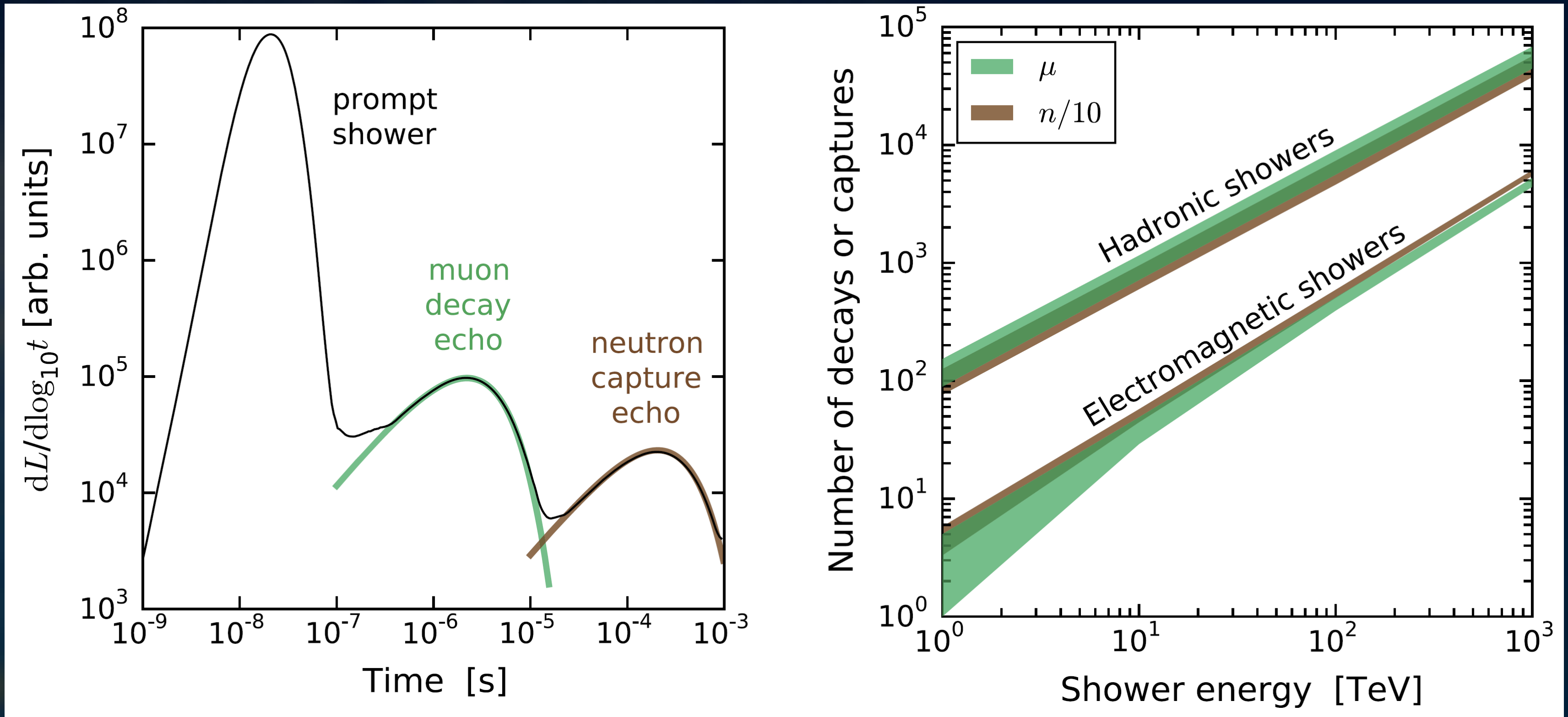
Beyond MeV: neutrons at high energies

Neutron echo from hadronic cascade: Rich physics

PoS(ICRC2025) 1030



Phys.Rev.Lett. 122 (2019) 15, 151101



Conclusion

For the first time, we use natural Chlorine in seawater to enhance neutron capture signal

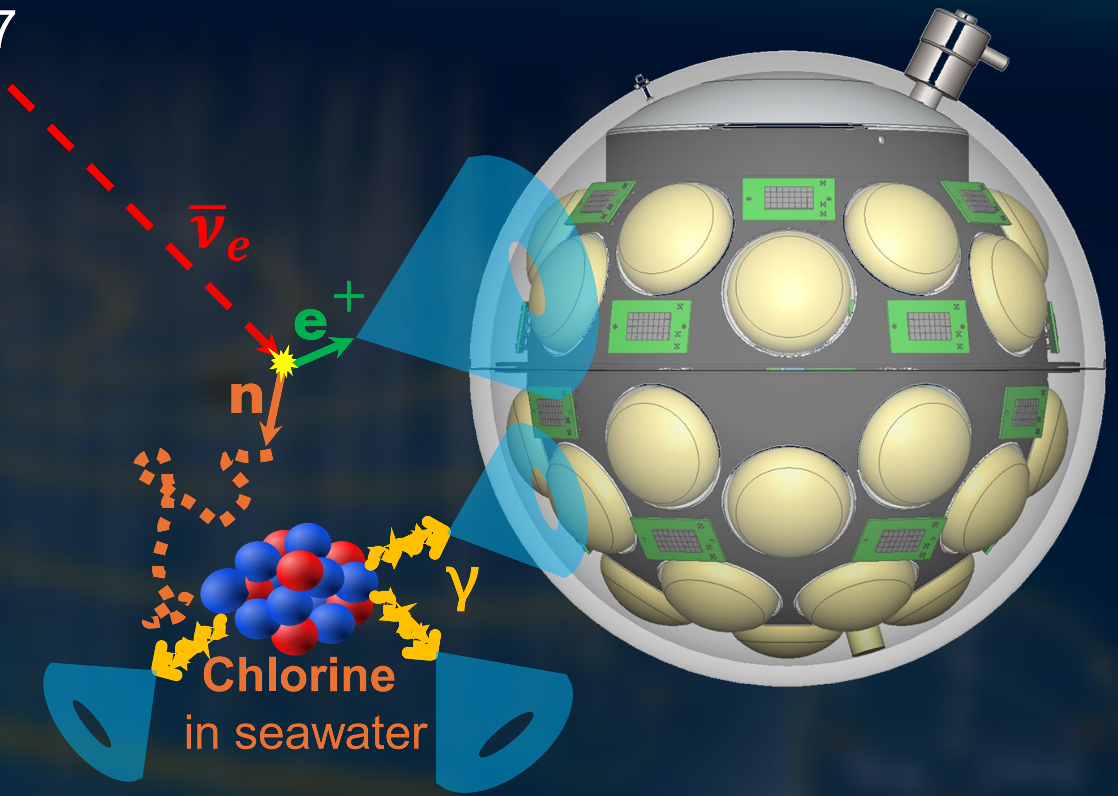
Neutron coincidence more than doubles the CCSN discovery horizon

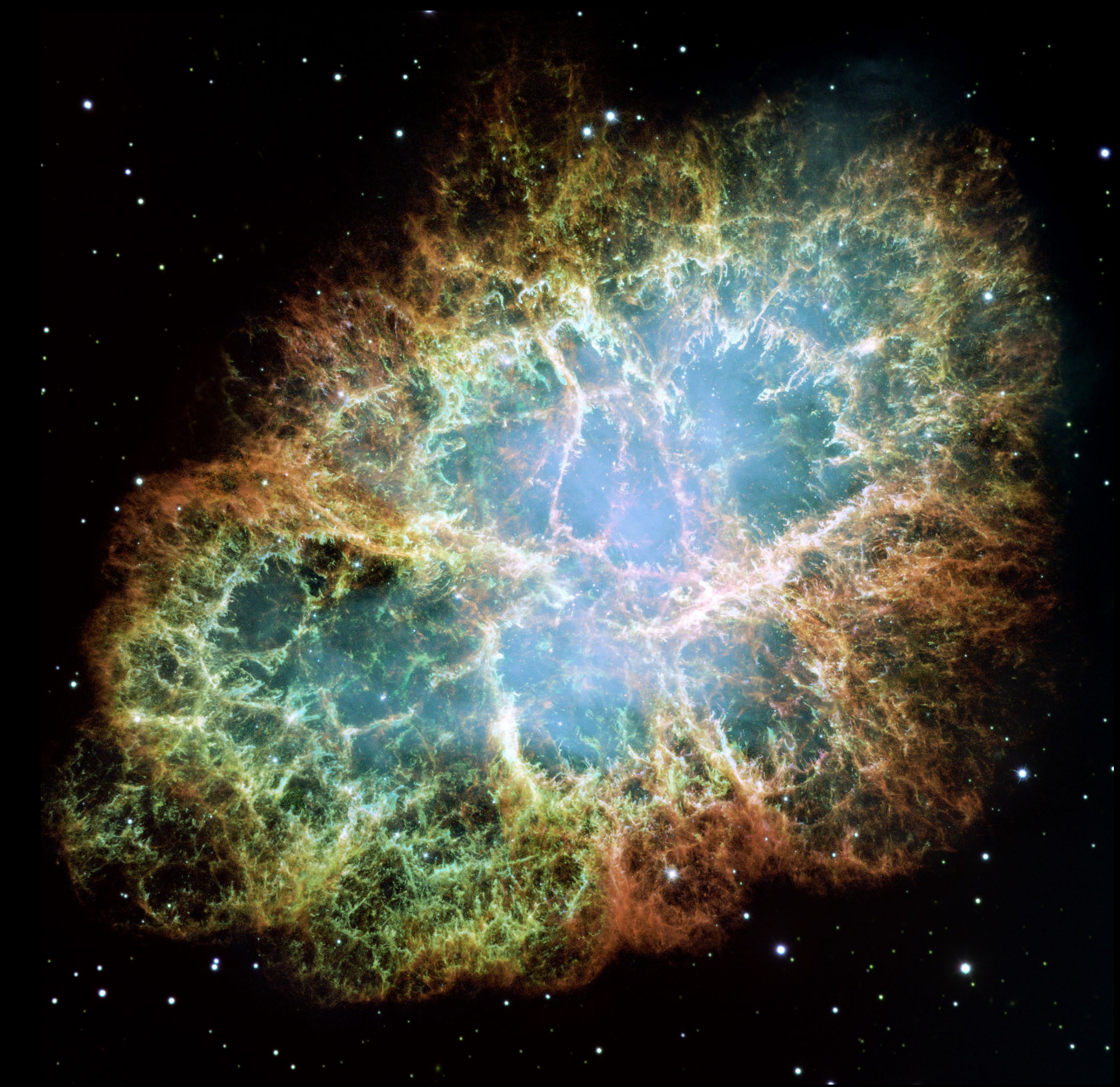
TRIDENT Phase-1: Galactic CCSN coverage from 2027

Experimental demonstration:
3σ detection of AmBe source by single hDOM in CJPL

High-energy potential:
Neutron echo from hadronic shower

Towards the first neutron detection in deep-sea:
Stay tuned!





SN1054 (Crab Nebula) by HST

Tsung-Dao Lee Institute

TRIDENT 海 | 铃 | 计 | 划

Thanks!

Ruike Cao, with Iwan Morton-Blake,

Yong-Zhong Qian and Donglian Xu

2026.09.02 Tendo, Japan

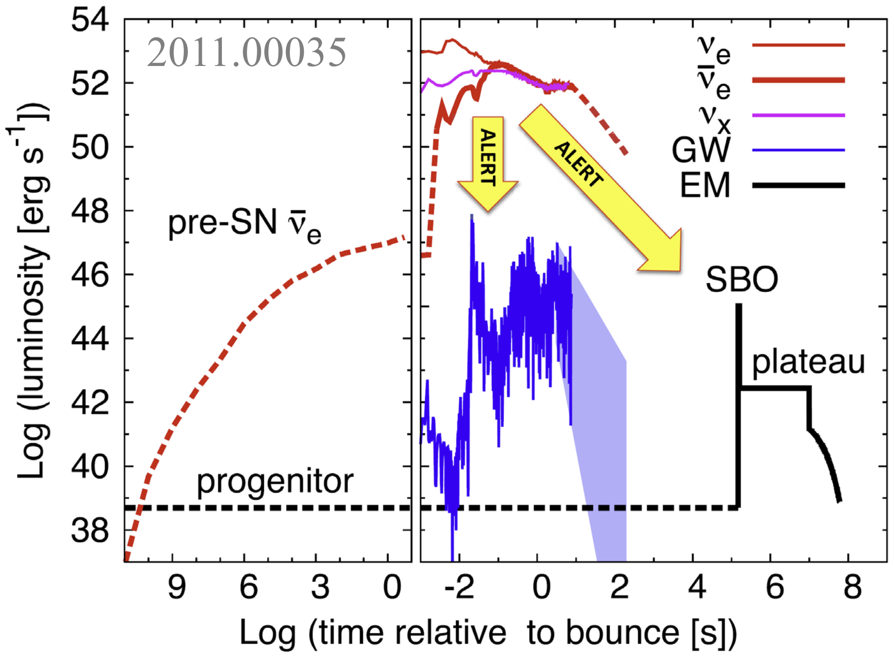
TeV Particle Astrophysics TeVPA 2026

ruike_cao@sjtu.edu.cn

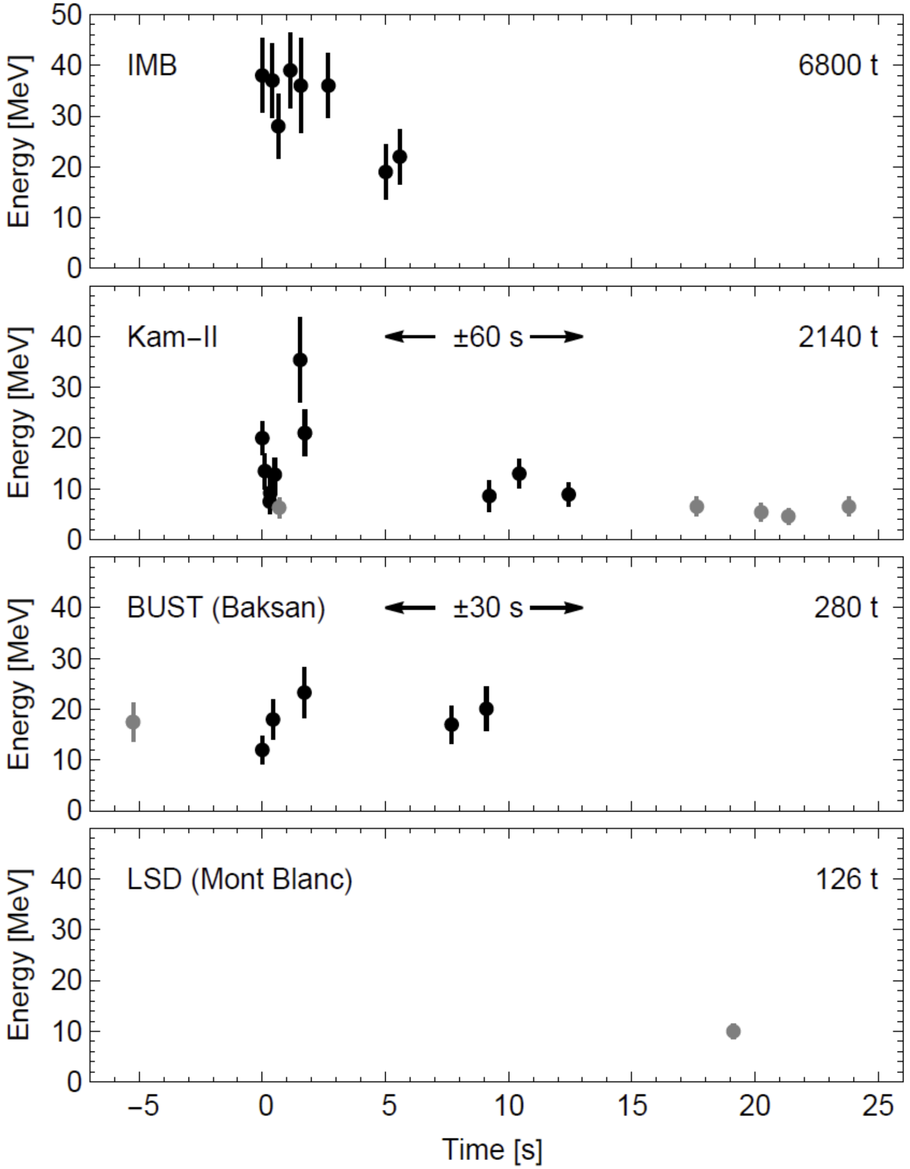
CCSN neutrino

Neutrinos take >99% of total energy
Only CCSN by nu: SN1987A. Still explaining the data!

Advance emission: multi-messenger alert
Leading edge: crucial to distinguish models
reveal neutrino absolute mass
Need large statistics!

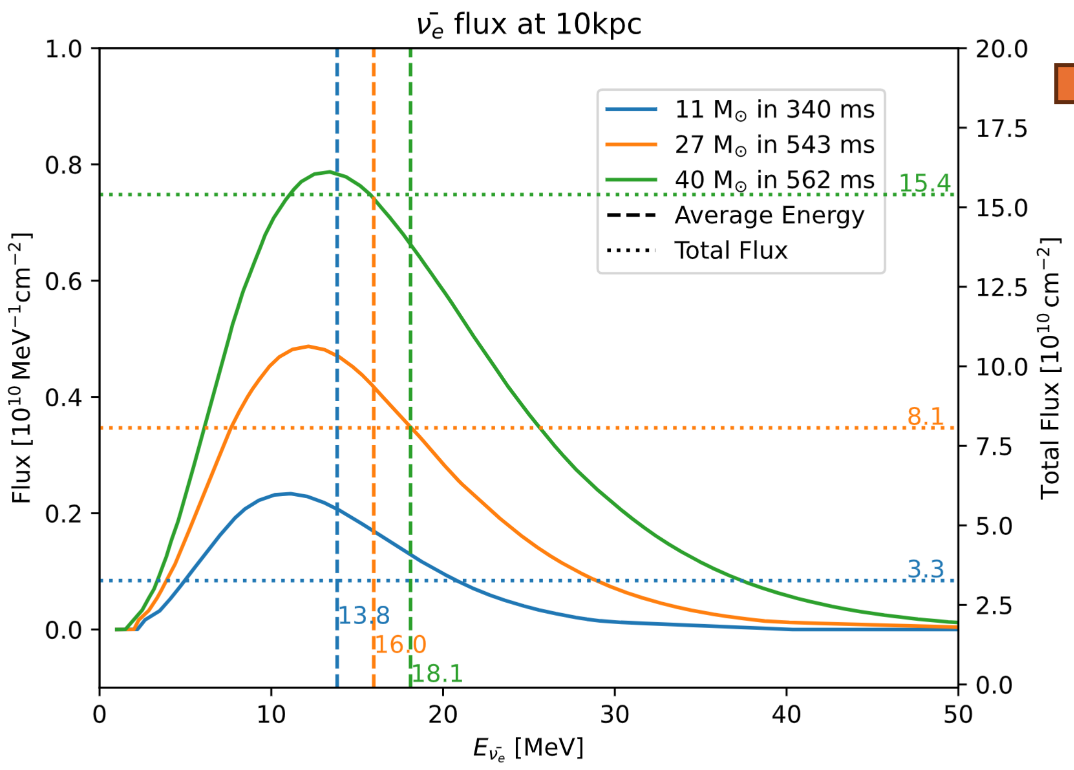


2509.16306

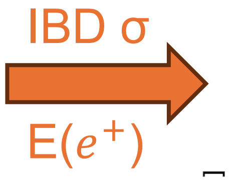


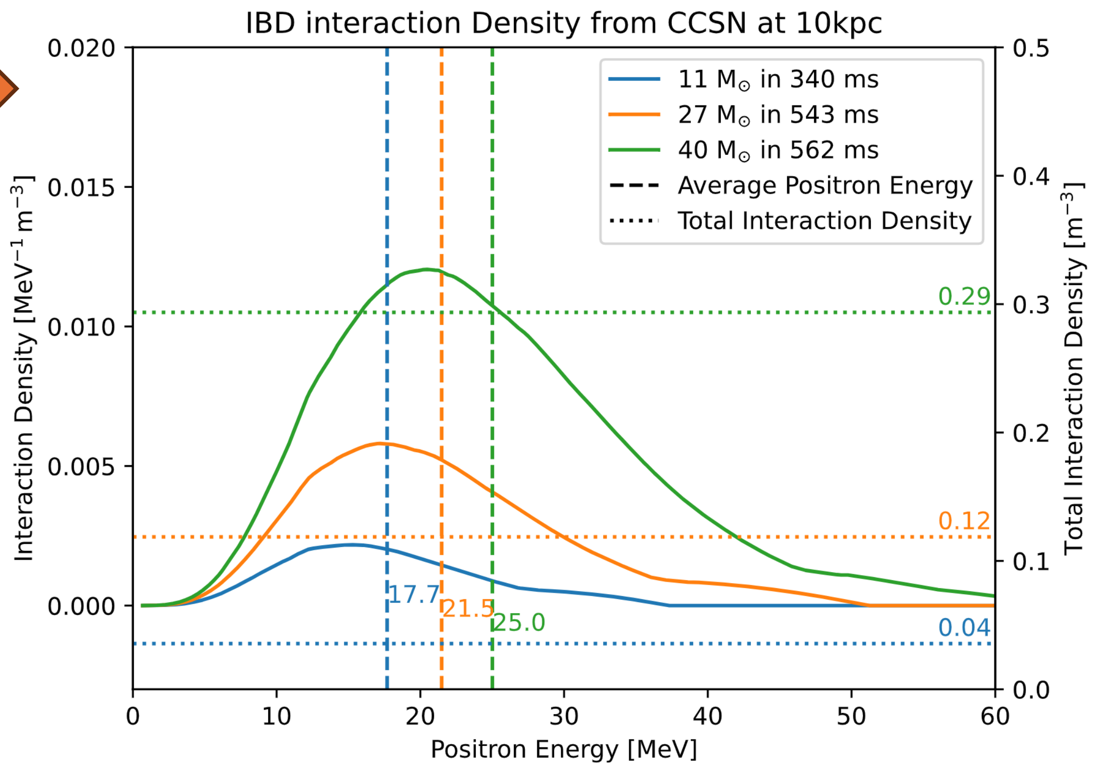
CCSN neutrino flux

Using Garching model [1307.7936] with 3 progenitors
Typical IBD interaction rate: O(0.1 $\mathrm{m}^{-3}s^{-1}$)
Mean deposited energy: ~20MeV



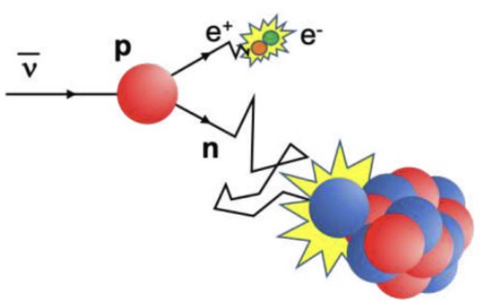
Neutrino spectrum

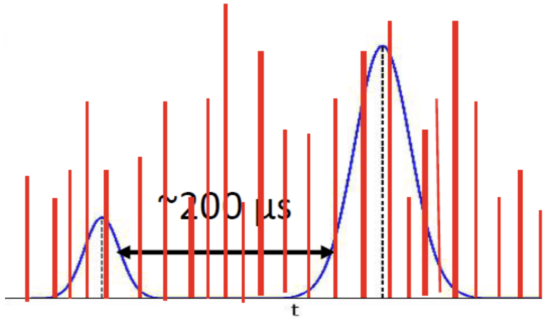




Positron spectrum

CCSN neutrino with NuTel



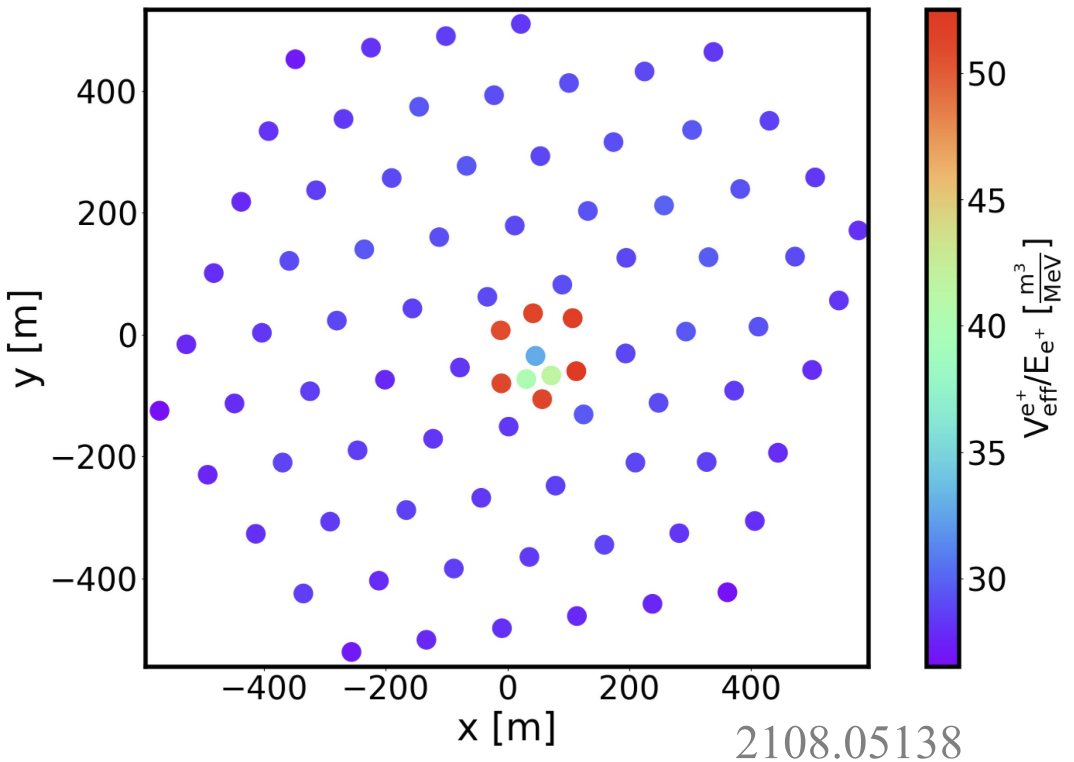


Main channel: Inverse beta decay (IBD).

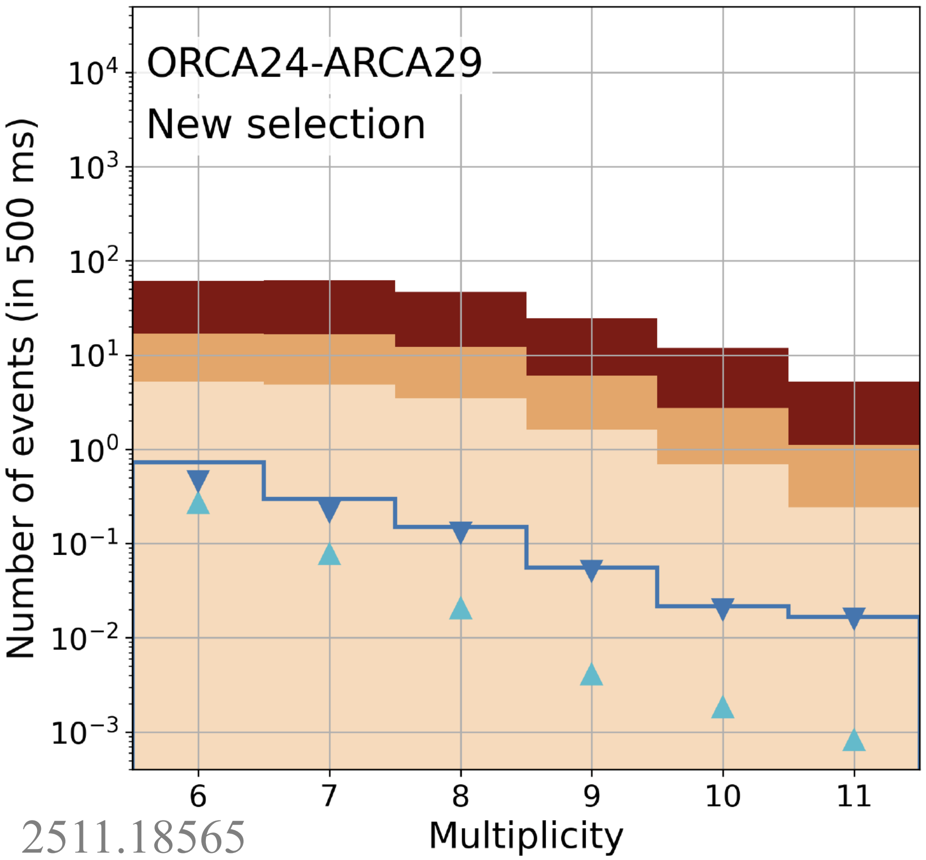
Existing analysis: e^+ detection.

IceCube: low bkg., 1 PMT

KM3NeT: high bkg., multi-PMTs



2108.05138



2511.18565

Single-DOM level filter for IBD events

Triple filters on single hDOM:

Prompt: Positron

$\mathrm{CL_{prompt}} \geq 9$
$\bar{\Psi}_{\mathrm{prompt}} \leq 80°$

Bkg:
K40+muon×0.3

Late: Neutron capture

$\mathrm{CL_{late}} \geq 2$
$\Delta\mathrm{T} \leq 0.3\mathrm{ms}$
$\Delta\bar{\Psi} < 100°$

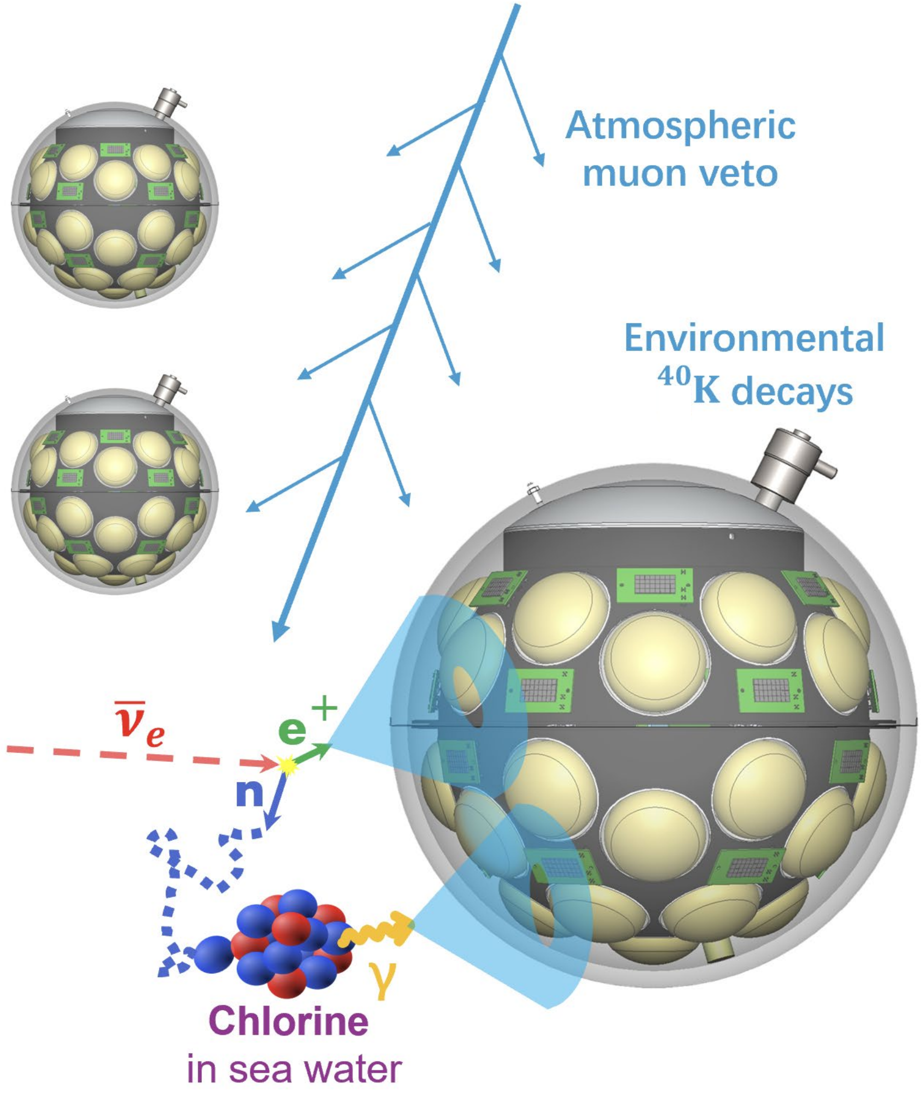
Bkg×0.1
(from K40)
Sig×0.3

Muon Veto:

2* $\mathrm{CL} \geq 2$ in ~200ns, ~120m

Muon bkg×0.2
(on Prompt filter)

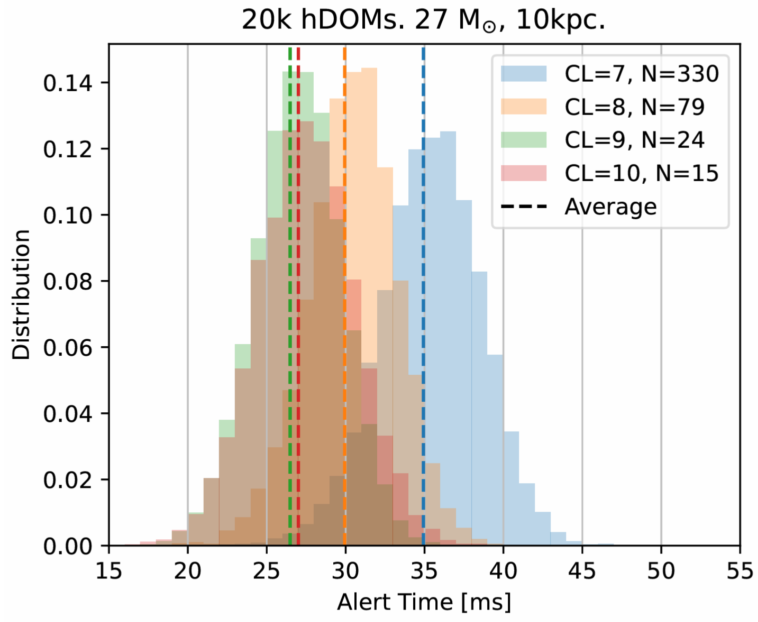
(Numbers are optimized for best CCSN sensitivity & alert capability)



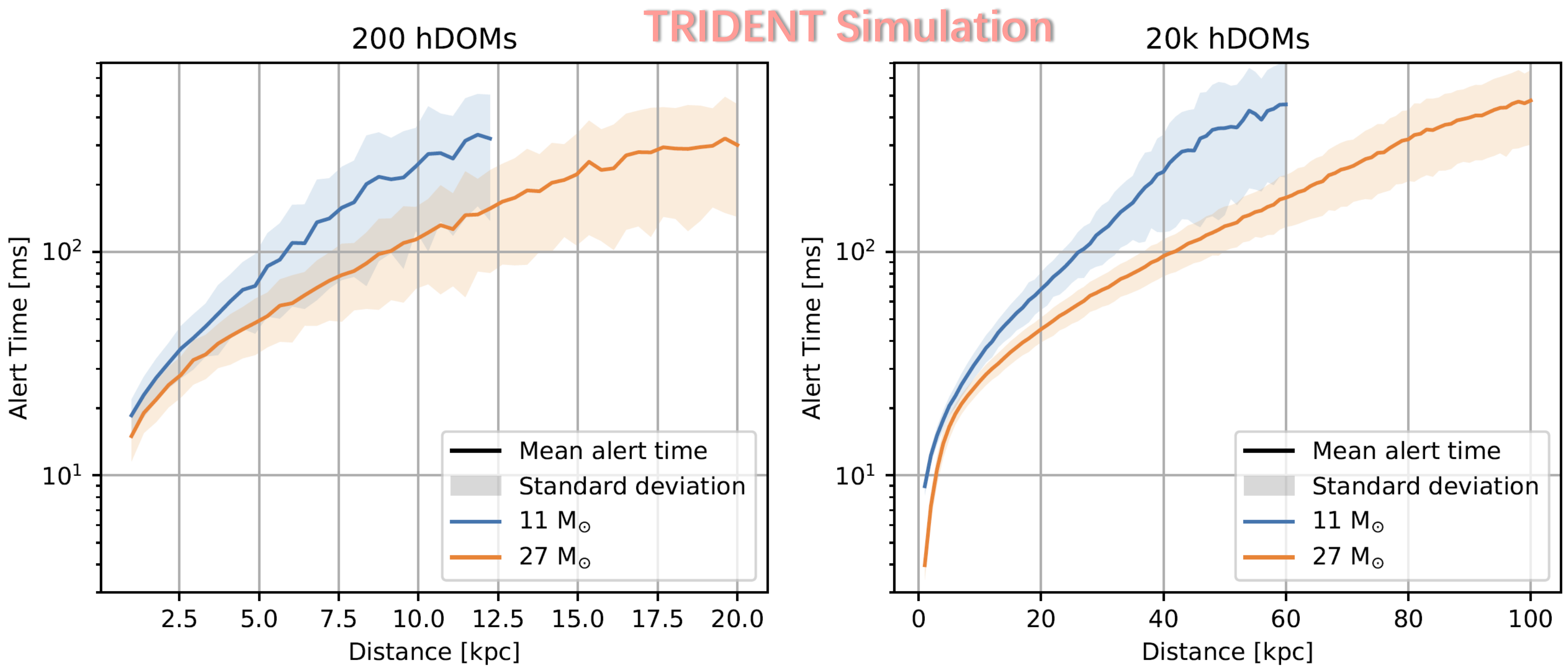
CCSN alert time

Leading edge:
- Distinguish explosion models
- Reveal neutrino absolute mass
- Direction triangulation by inter-detector time-delay

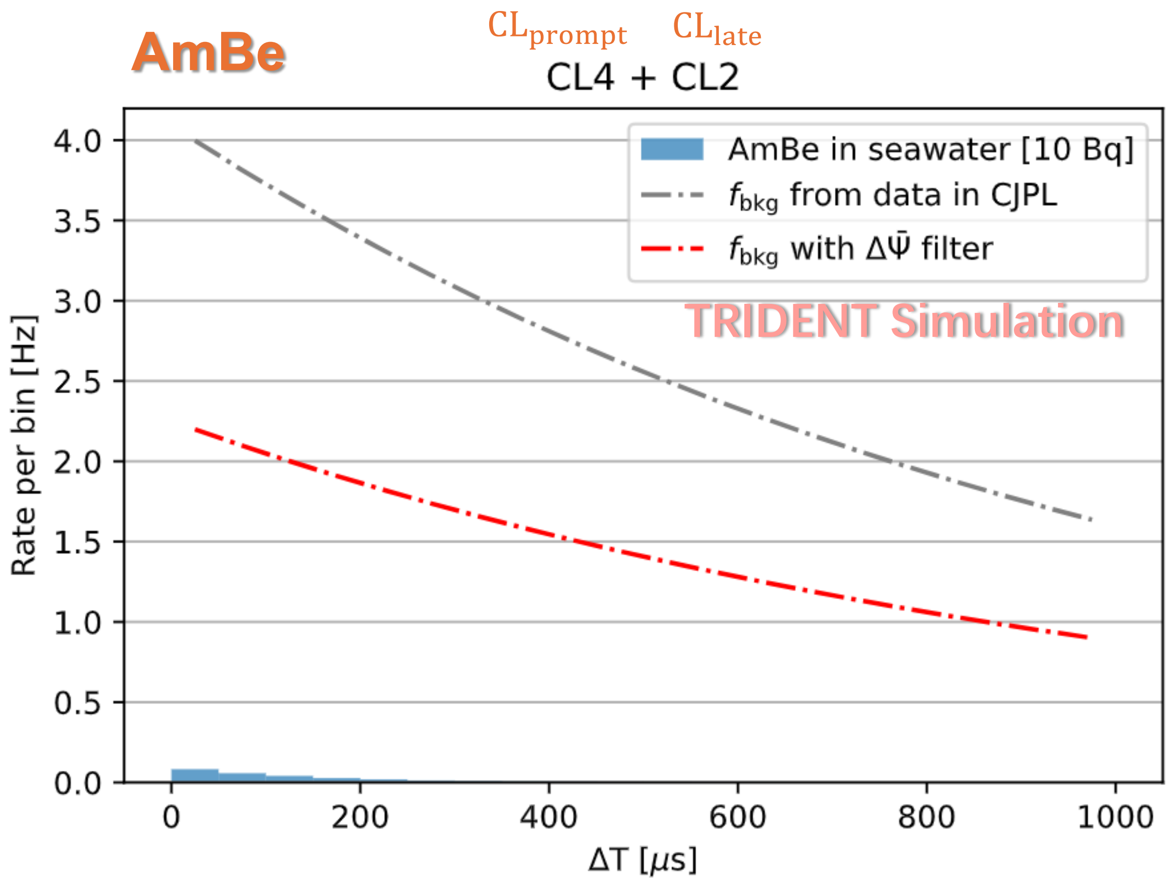
σ(t): Toward 1 ms level

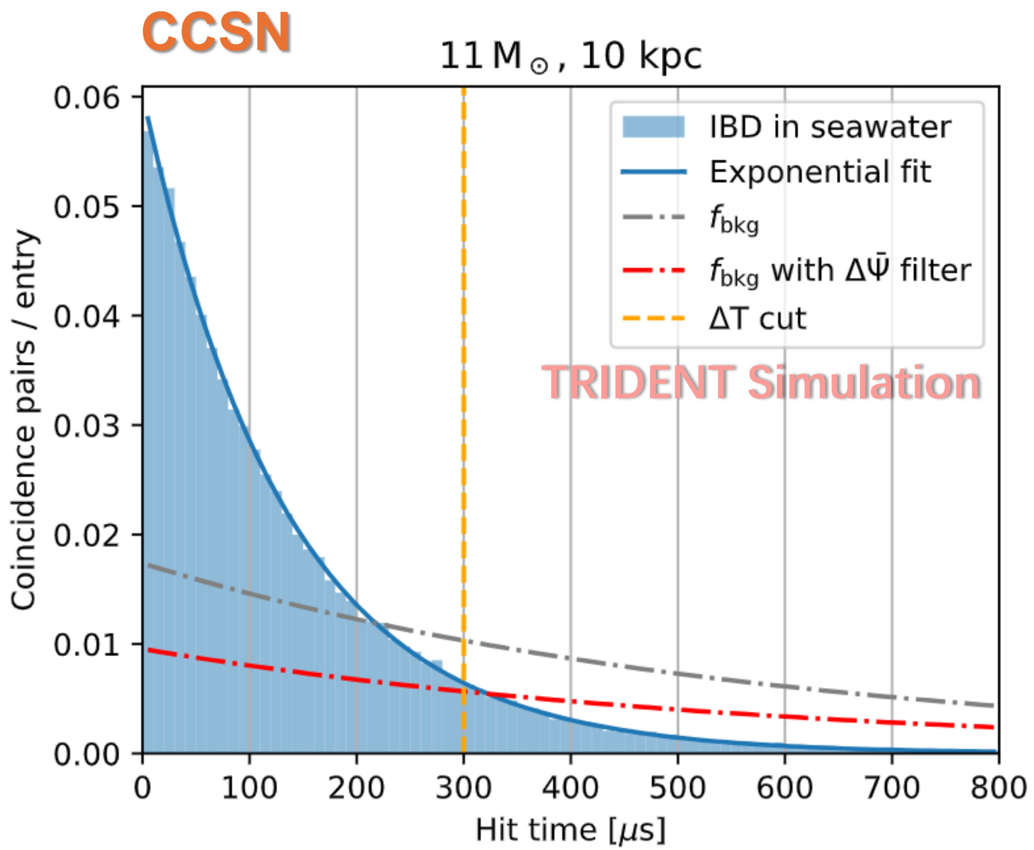


For 10kpc 27$M_\odot$ CCSN:
Alert time delay ~ 25ms
σ (alert time) ~ 3ms



AmBe is more difficult than CCSN





Significance study

H_0: Uniform background
H_1: Uniform background + exponential signal

$$\mu_i(H_1) = \mu_{i,\text{bkg}} + b + S \cdot \int_{\Delta T_i}^{\Delta T_{i+1}} \frac{1}{\tau_n} e^{-t/\tau_n} dt,$$

Minimize the negative log-likelihood

$$NLL = \sum_i \mu_i - \sum_i (n_i \cdot \ln \mu_i)$$

Gaussian significance by test statistics

$$\text{TS} = -2 \ln \left(\frac{\mathcal{L}(H_0)}{\mathcal{L}(H_1)} \right) = 2\left[\text{NLL}(H_0) - \text{NLL}(H_1)\right]$$