Supernova Neutrino Detection at the IceCube Neutrino Observatory

SNνD 2023 @ LNGS

International Conference on Supernova Neutrino Detection

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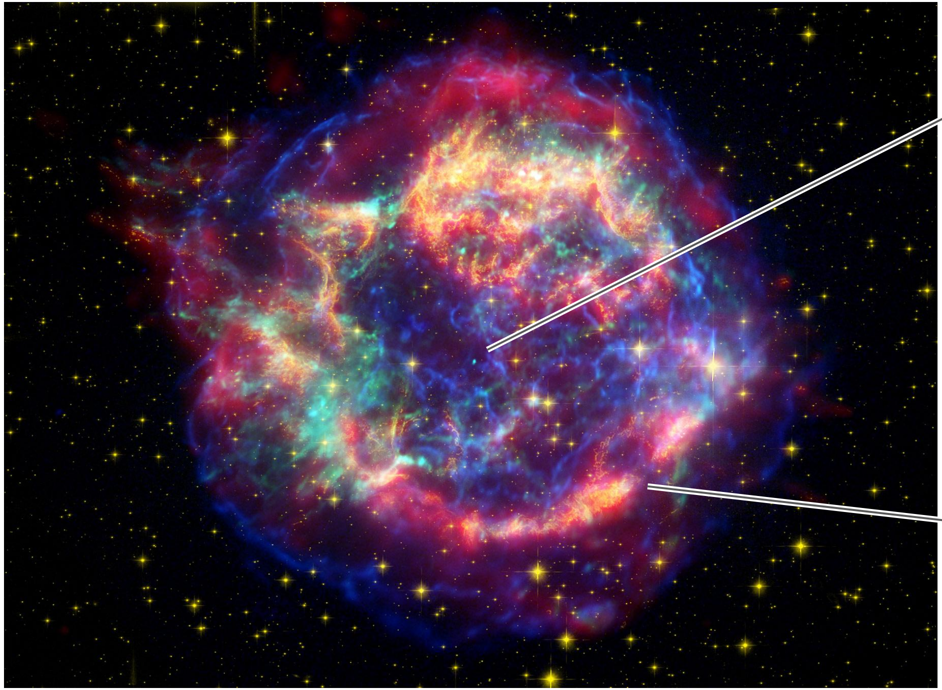
University of Rochester

Supernova Neutrinos in IceCube



Cas A SNR. Credit: NASA/JPL-Caltech/O. Krause

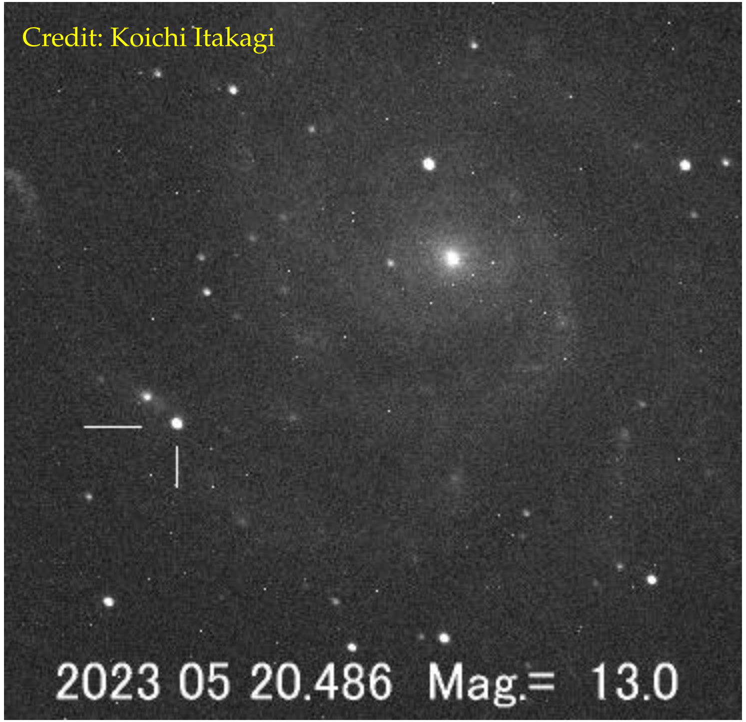
Core-collapse neutrinos (**MeV**):

- 10 s burst, 10^{53} erg in neutrinos.
- GC: 10^5 to 10^6 events in IceCube, no MeV event reconstruction.

Post-explosion neutrinos (**TeV**) produced in shock acceleration:

- >1000 ν weeks to months after collapse; ν_μ localization to <1°.
- Not covered here, but see e.g. Murase+ 2011, Aartsen+ 2015, Necker 2021, Kheirandish & Murase 2022, Valtonen-Mattila & O'Sullivan 2023.

IceCube & SN 2023ixf!



IceCube was running at the time of the breakout of SN 2023ixf (>99% uptime).

The **MeV ν burst** – which could have occurred ~1 week prior to breakout – could not be observed due to $1/r^2$ losses.

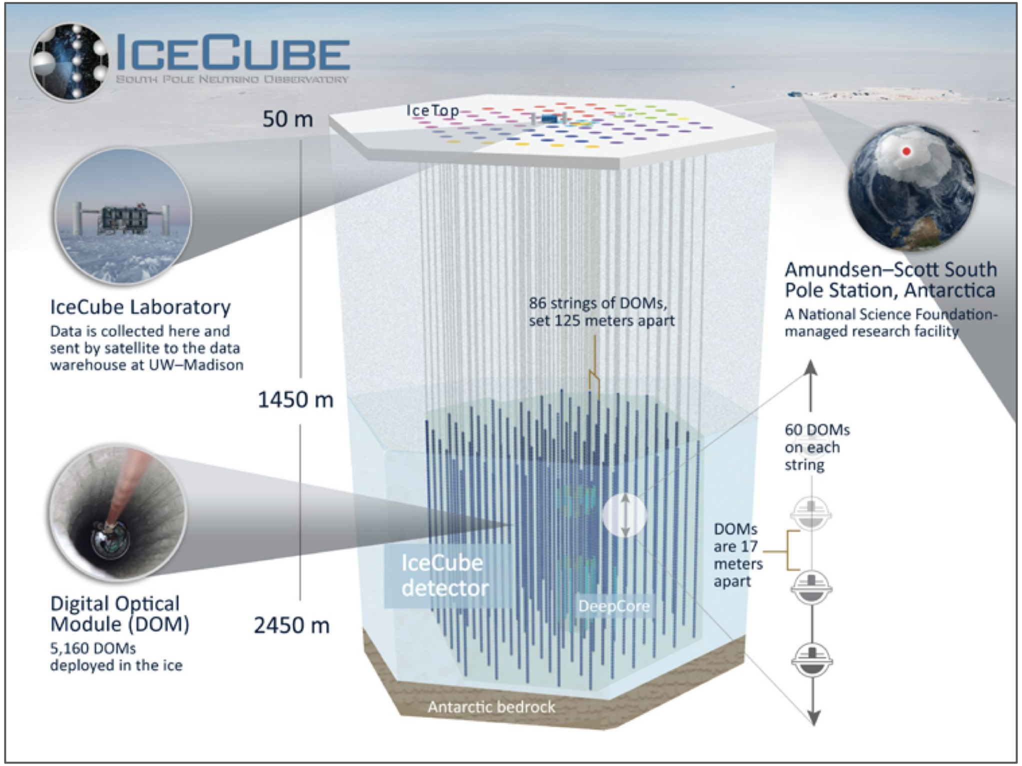
IceCube did search for **TeV ν_μ events** ±2 days from breakout. [ATel #16043](): null result.

The possibility of post-collapse TeV ν production remains. If a coincident ν is found IceCube will publish a realtime alert.

Detecting Neutrinos with IceCube

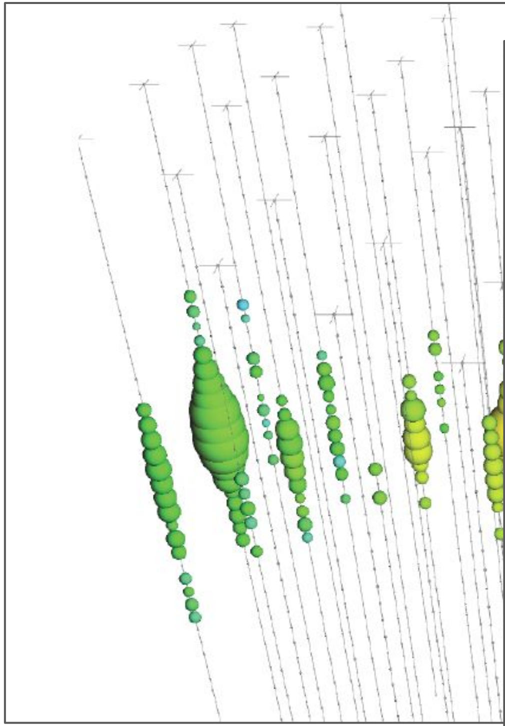
IceCube Neutrino Observatory: the world's largest particle detector.

- Design goal: observe origins of high-energy cosmic rays and astrophysical neutrinos.
- 5,160 single-PMT Digital Optical Modules (**DOMs**) buried in clear ice 1.4-2.4 km under South Pole.
- ~100,000 **atmospheric** neutrino candidates per year, > 5 GeV.
- Localized **astrophysical** neutrino candidates, > 100 TeV: ~1 month[1].

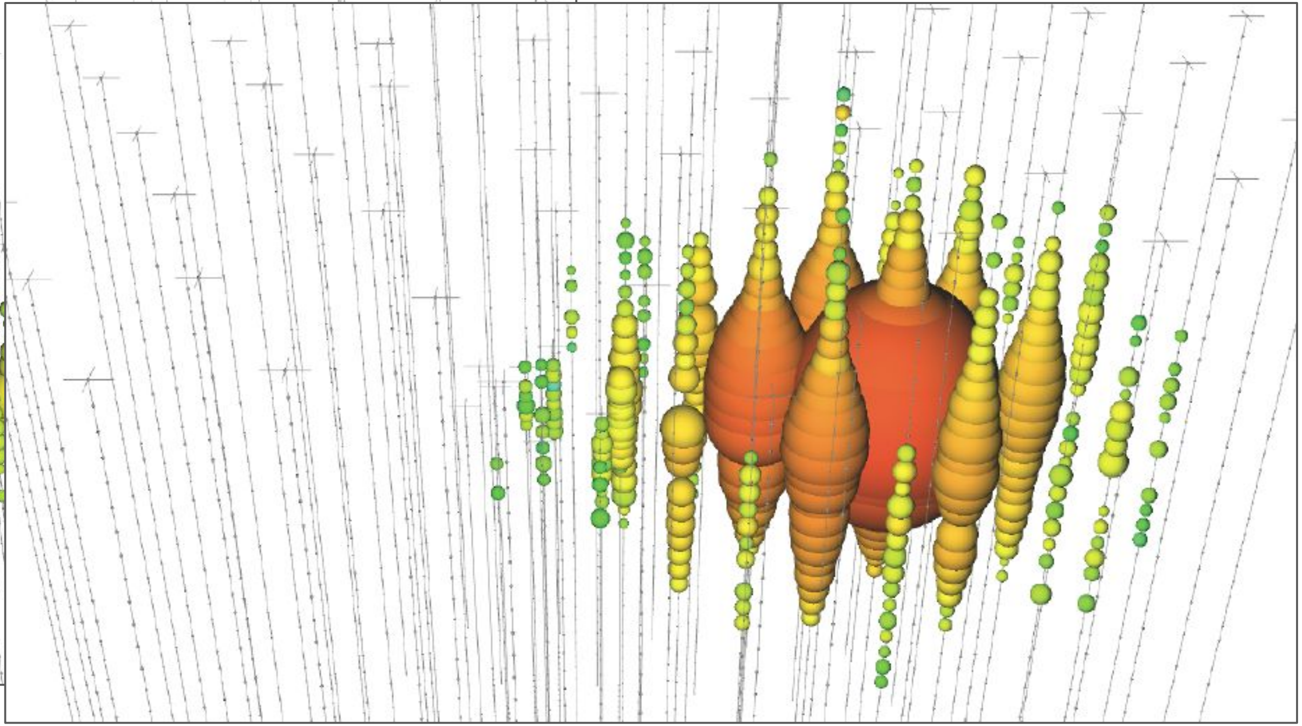


Astrophysical Neutrino Candidates

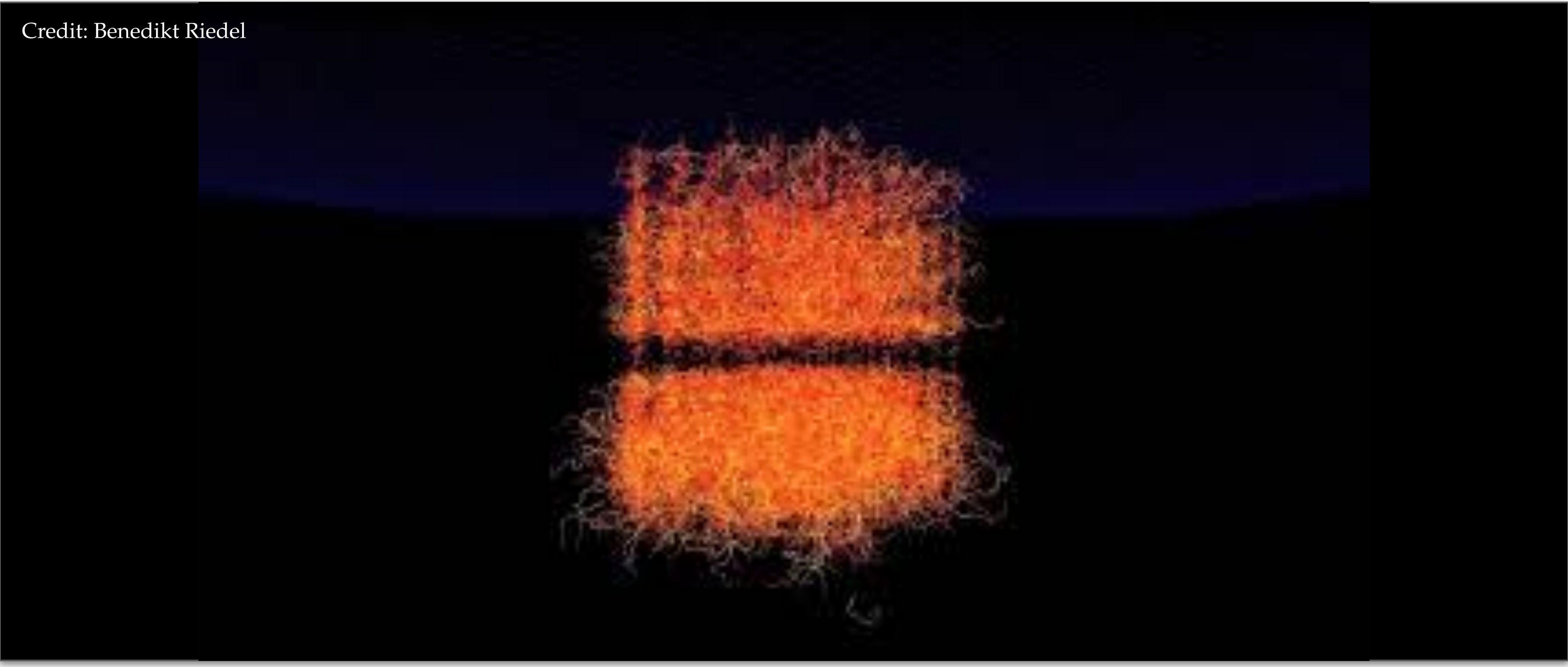
IceCube ν_μ track event.



IceCube ν_e cascade event.



CCSN Neutrinos in IceCube



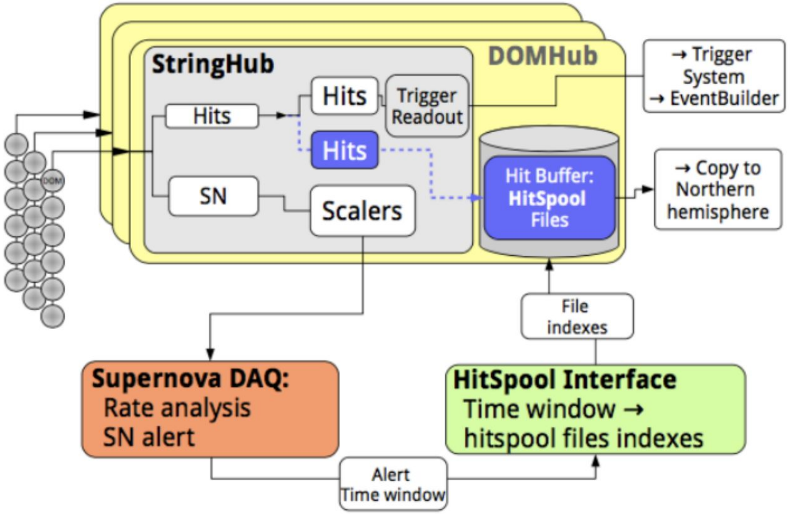
IceCube and other CCSN ν Detectors

Detector	Type	Mass (kt)	Location	Events [10 kpc]
IceCube	**Long string**	**600/DOM***	**South Pole**	**500,000***
Hyper-K	*water*	*374*	*Japan*	*75,000*
KM3Net	*Long string*	*111*	*France/Italy*	*10,000**
DUNE	*LAr*	*40*	*USA*	*3,000*
Super-K	water	32	Japan	7,000
JUNO	scintillator	20	China	6,000
NOvA	scintillator	15	USA	4,000
LVD	scintillator	1	Italy	300
KamLAND	scintillator	1	Japan	300
SNO+	scintillator	0.8	Canada	300
Baksan	scintillator	0.33	Russia	50
Borexino	scintillator	0.3	Italy	100
MicroBooNE	LAr	0.17	USA	17
HALO	Pb	0.08	Canada	30

Adapted from K. Scholberg, J. Phys. G. 45:014002, 2018

MeV ν Detection System in IceCube: Supernova DAQ + HitSpool

Independent DOM triggers at 0.25 PE → discriminator crossings (“hits”) in 2^{16} clock cycles @ 40 MHz → counts in 1.6384 ms → counts in **2 ms** bins.



Credit: D. Heereman (Ph.D., 2015)

Non-paralyzing artificial deadtime applied: results in ~300 Hz background per DOM.

Online alerts: rebinned counts in sliding windows (0.5 s, 1.5 s, 4.0 s, 10.0 s) with ±5 min sidebands to compute background count.

Offline alerts: HitSpool requests give access to full DOM waveforms 24 to 48 hr after alert, including readout sidebands. **25 ns** resolution.

Maximum Likelihood of Correlated Rise in DOM Counts

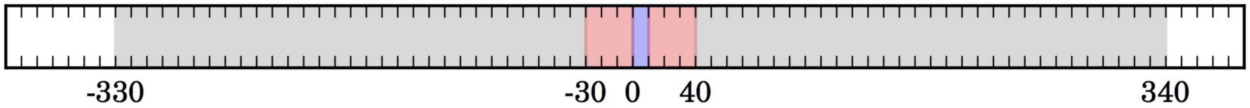
Count rate in DOM i.

Efficiency of DOM i.

$$\ln \mathcal{L}(\Delta\mu) = -\sum_{i=1}^{N_{\mathrm{DOM}}} \left(-\frac{[r_i - (\langle r_i \rangle + \epsilon_i \Delta\mu))]]}{2\langle \sigma_i \rangle^2} + \frac{1}{2} \ln 2\pi \langle \sigma_i \rangle^2 \right)$$

Correlated rise in DOM hits across the detector.

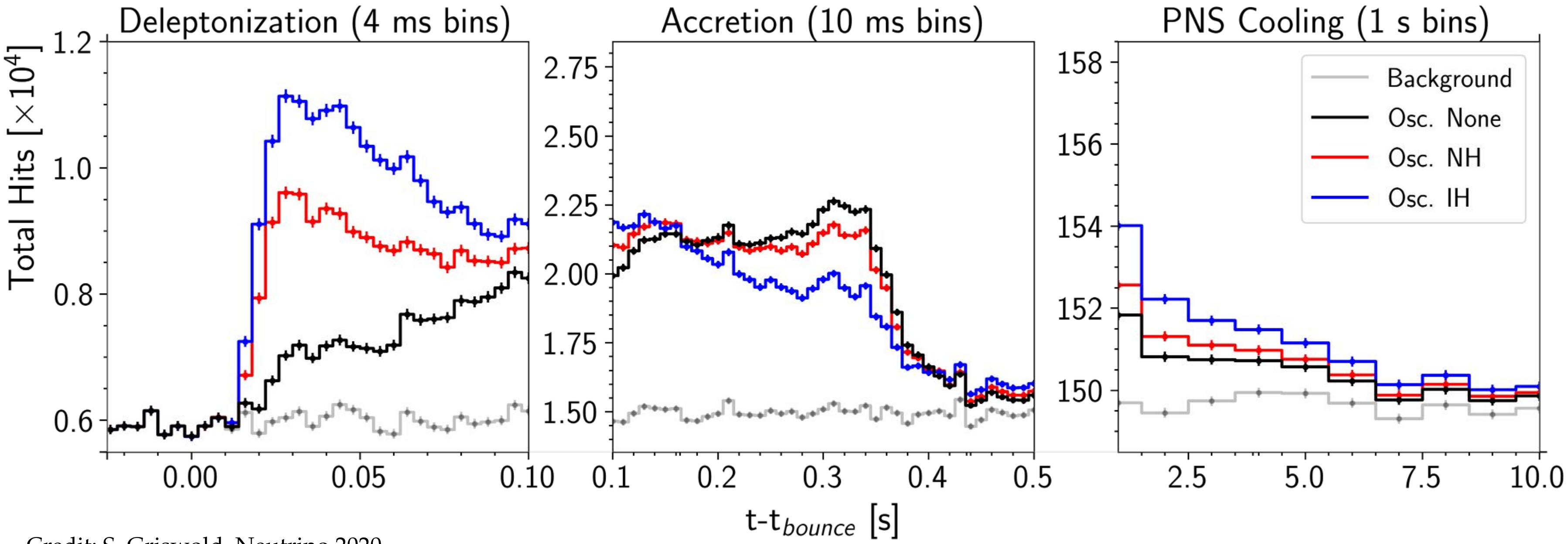
Count rate unc. of DOM i.



Time since left edge of bin of interest (s)

$$\Delta\hat{\mu} = \sigma^2_{\Delta\mu} \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i (r_i - \langle r_i \rangle))}{\langle \sigma_i \rangle^2}, \qquad \sigma^2_{\Delta\hat{\mu}} = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\langle \sigma_i \rangle^2} \right)^{-1}, \qquad \xi = \frac{\Delta\hat{\mu}}{\sigma_{\Delta\hat{\mu}}}$$

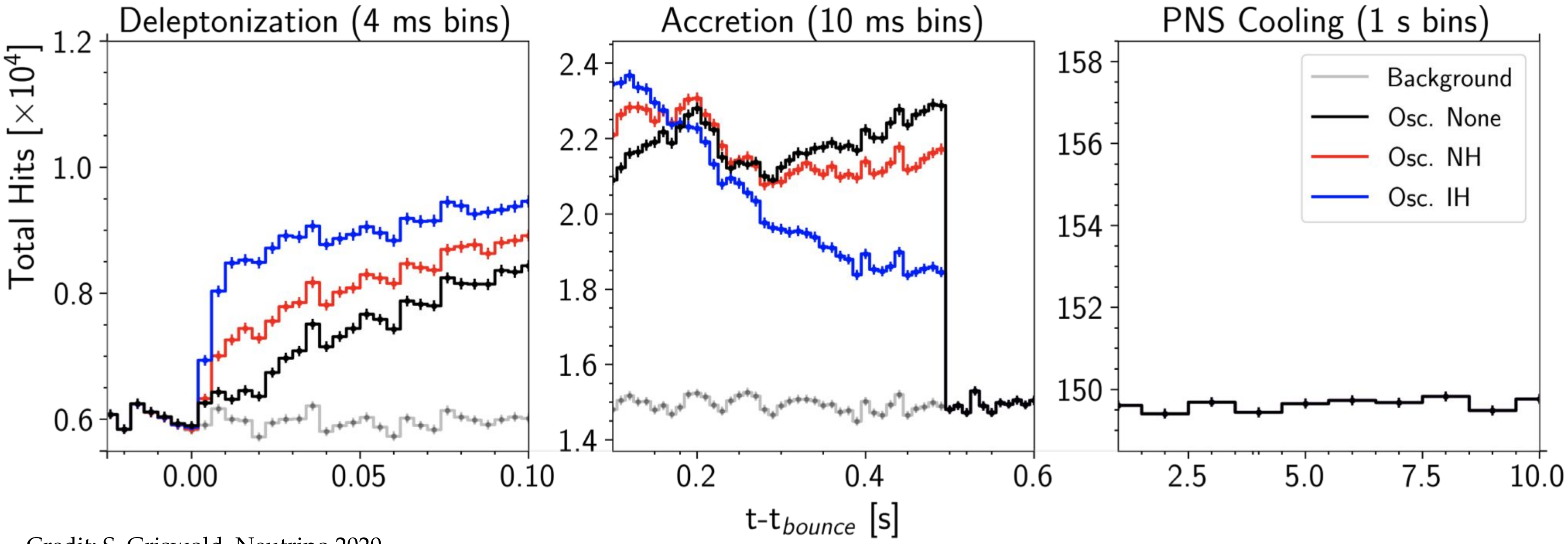
CCSN ν Hits in IceCube Post-Bounce



Credit: S. Griswold, Neutrino 2020

NEUTRON STAR

CCSN ν Hits in IceCube Post-Bounce



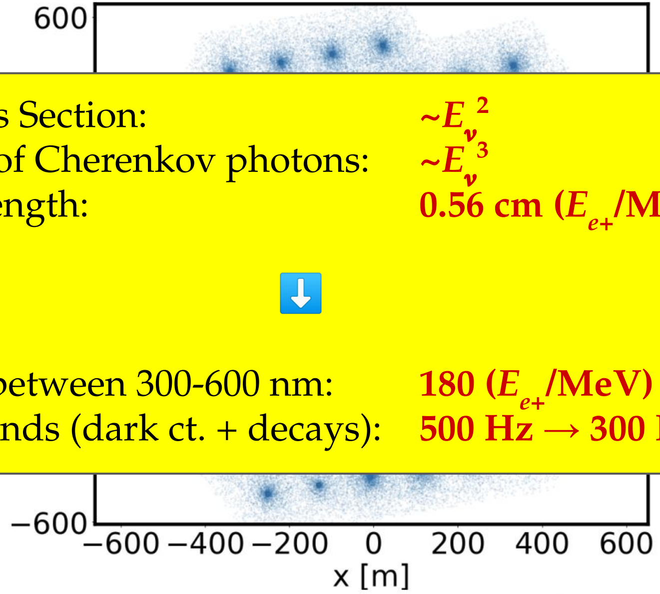
Credit: S. Griswold, Neutrino 2020

BLACK HOLE

CCSN ν Interactions in Ice Sheet

Simulated CCSN ν interaction vertices producing PEs detected by IceCube DOMs.

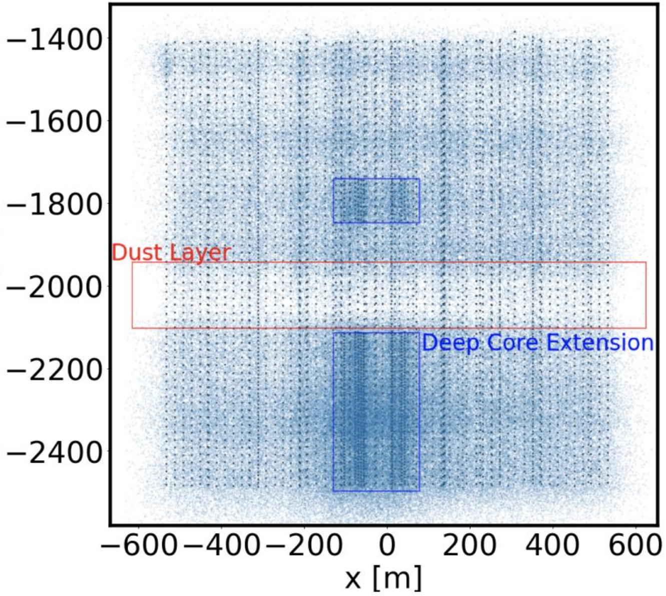
Credit: R. Cross, A. Fritz, S. Griswold, PoS(ICRC19), arXiv:1908.07249



IBD Cross Section:	~E_ν^2
Number of Cherenkov photons:	~E_ν^3
e^+ track length:	0.56 cm (E_{e+}/MeV)

⬇️

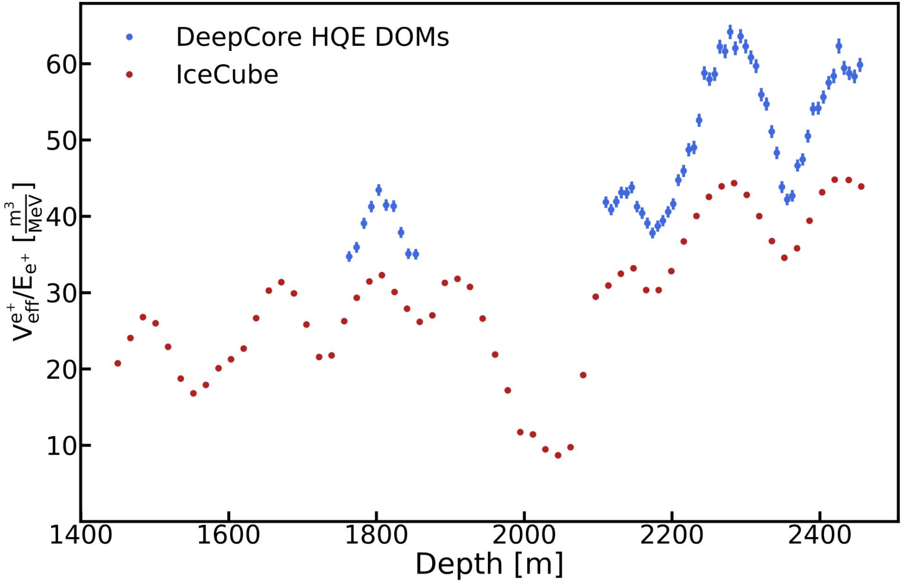
Photons between 300-600 nm:	180 (E_{e+}/MeV)
Backgrounds (dark ct. + decays):	500 Hz → 300 Hz

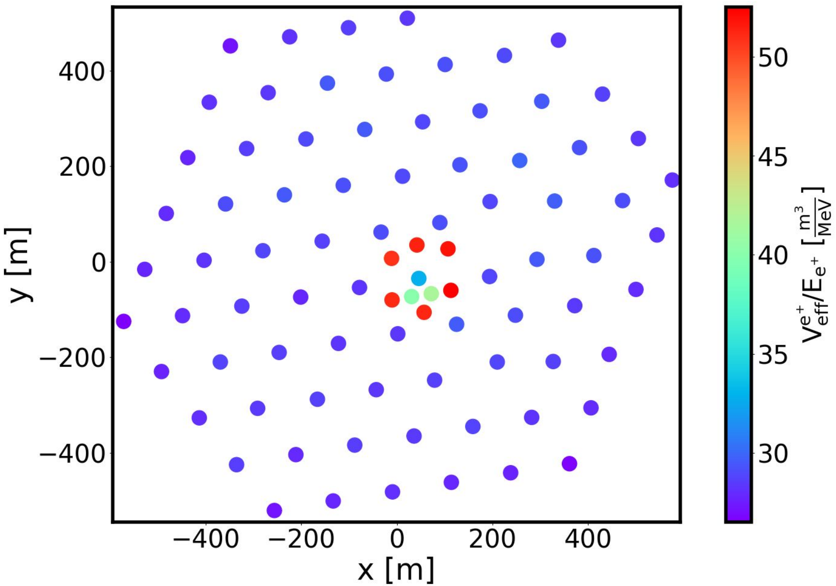


DOM Effective Volume vs. Location

Variation in V_{eff}/DOM due to optical properties of the ice & QE of the PMTs.

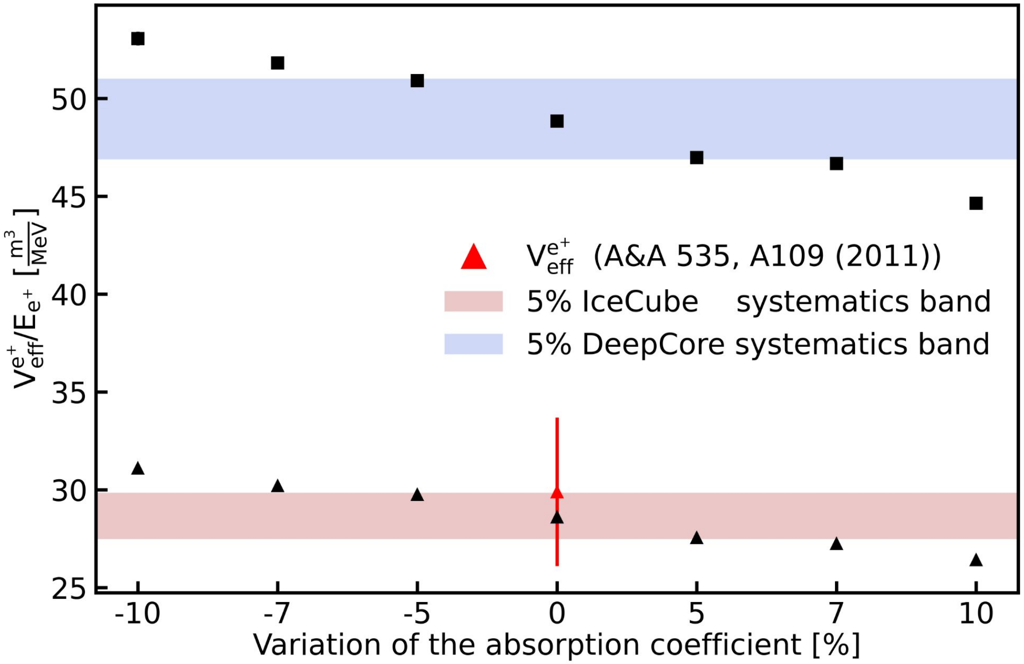
Credit: A. Fritz, IceCube Collaboration [in prep.]





DOM Effective Volume: Systematics

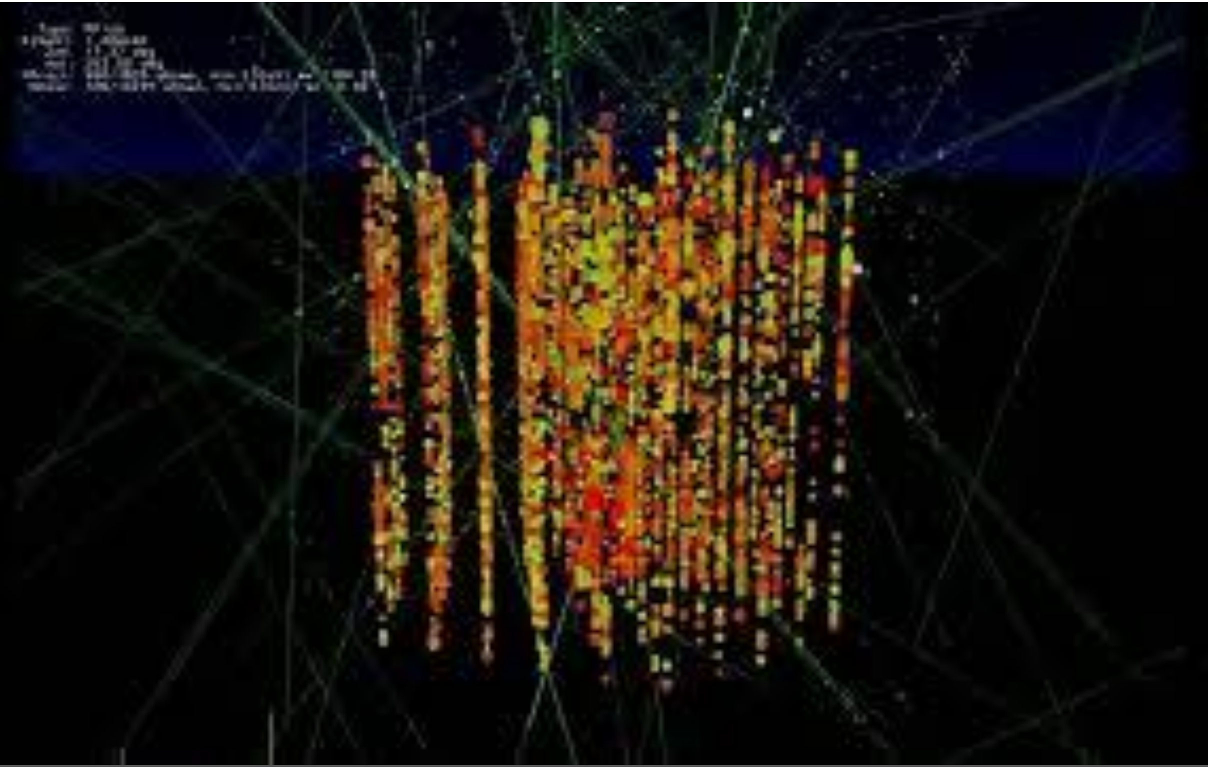
Credit: A. Fritz, IceCube Collaboration [in prep.]



Systematic Uncertainty	Relative Size [%]
Rate deviation in sliding average window	± 1.6
Ice density vs. depth	± 0.2
Mean $e^{\pm}$ track length in ice	± 5.0
Ice optical properties	[-3.6, +4.1]
DOM efficiency	± 10.0
Artificial deadtime	± 3.0
Cross Sections (e^+p, e^-p, e-O)	< ± 1, < ± 1, ± 0.2
zenith-dependent neutrino oscillation in Earth	[-0.2, +4.9]
Total	[-15.0, +16.2]

Seasonal Backgrounds: TeV Muons

Credit: Benedikt Riedel



Seasonal Muon Rate Correction

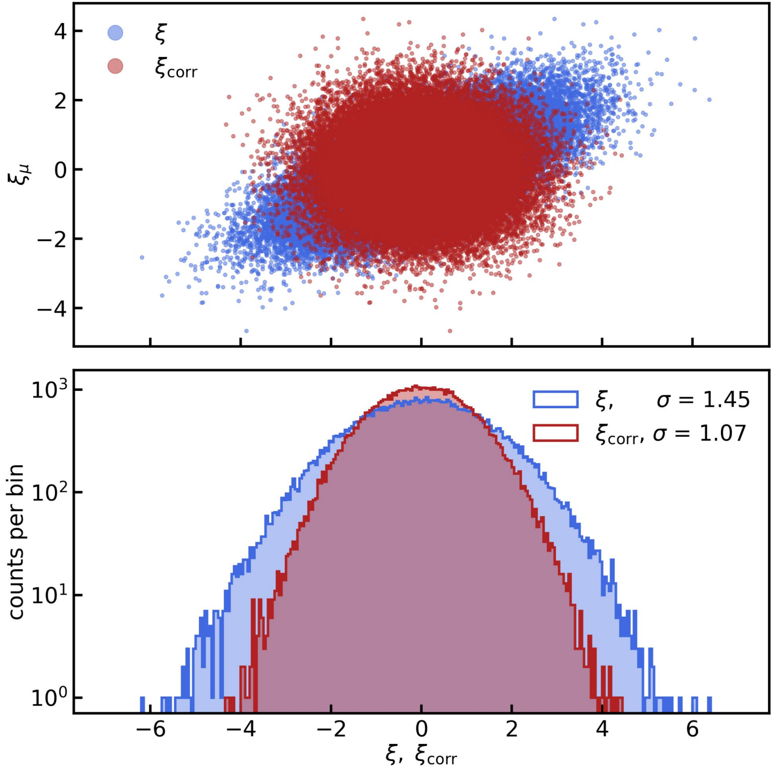
Atmospheric muons (3 kHz trigger rate) produce clusters of hits that trigger the MeV system during CCSN signal windows.

Effect visible in correlation between ML test statistic ξ and muon rate significance proxy $\xi_\mu = (R_\mu^{\text{hit}} - \langle R_\mu^{\text{hit}} \rangle) / \sigma(R_\mu^{\text{hit}})$.

Zero out the correlation to produce a muon-corrected significance ξ_{corr}.

Discussion in Aartsen+ ApJ 890:111, 2020.

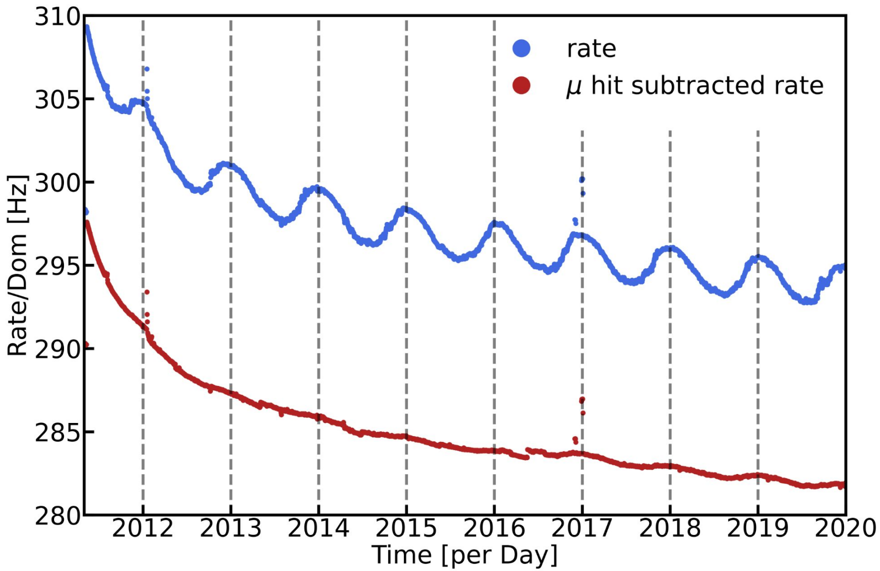
Credit: A. Fritz, IceCube Collaboration [in prep.]

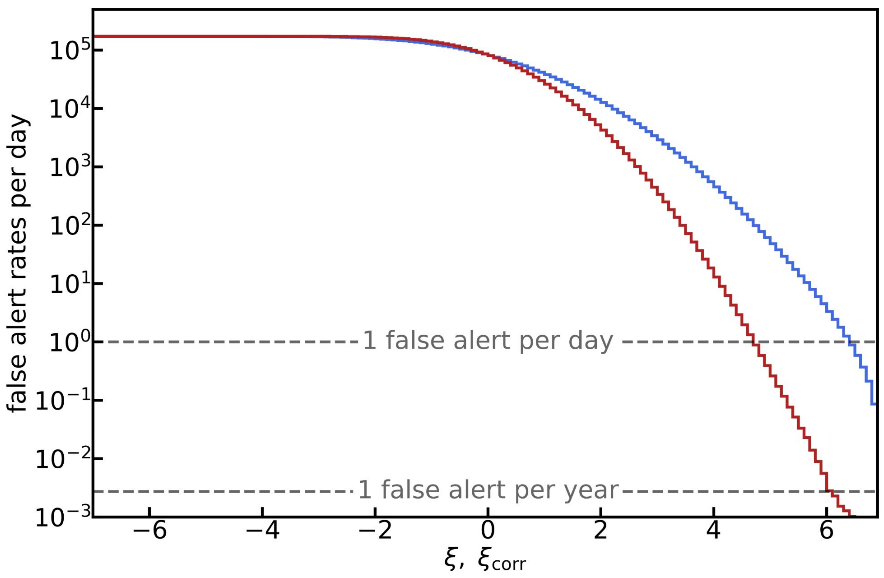


Seasonal Muon and False Alarm Rates: Before & After

Muon correction has a significant effect on the FAR of events with large TS (**ξ**).

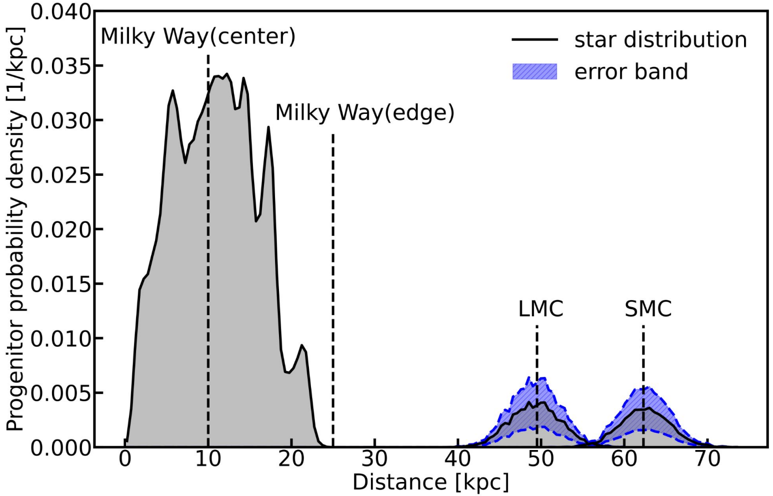
Credit: A. Fritz, IceCube Collaboration [in prep.]

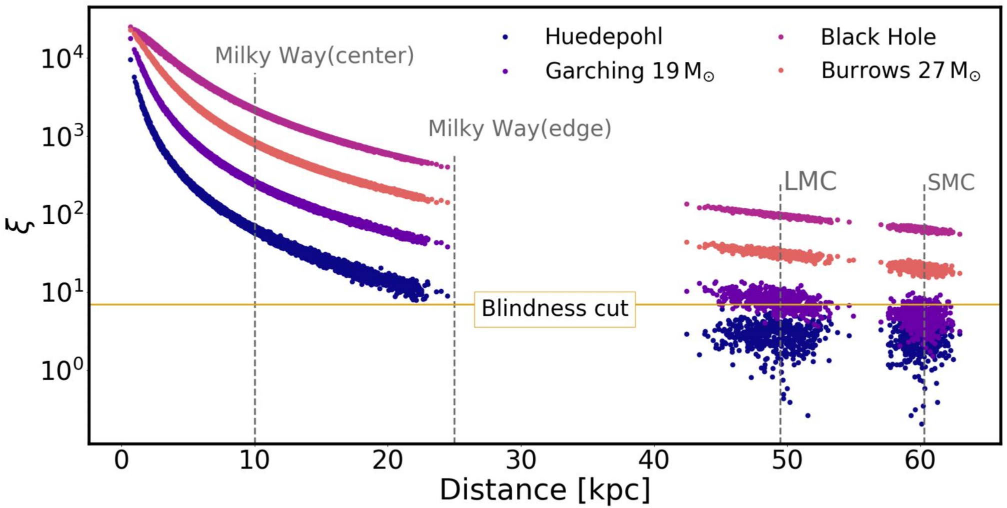




IceCube Sensitivity: Model Dependence

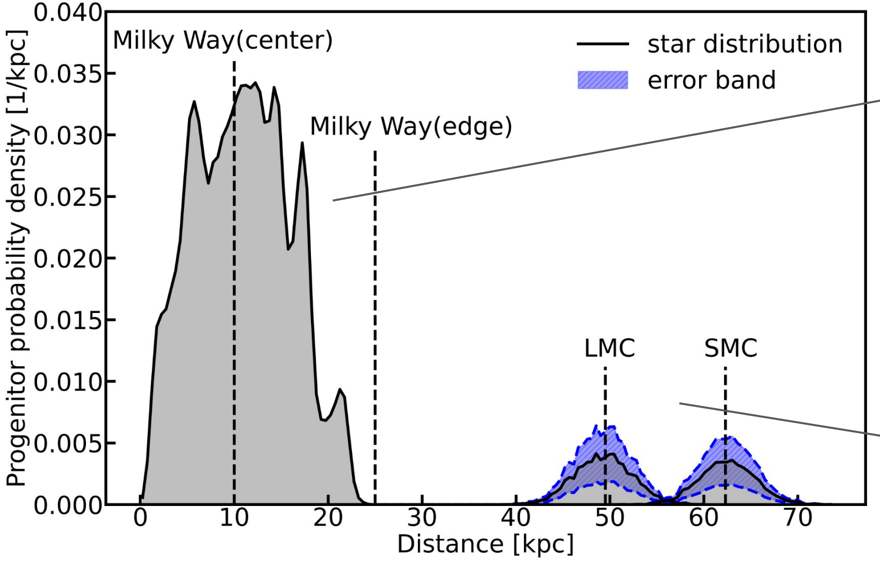
Credit: A. Fritz, IceCube Collaboration [in prep.]

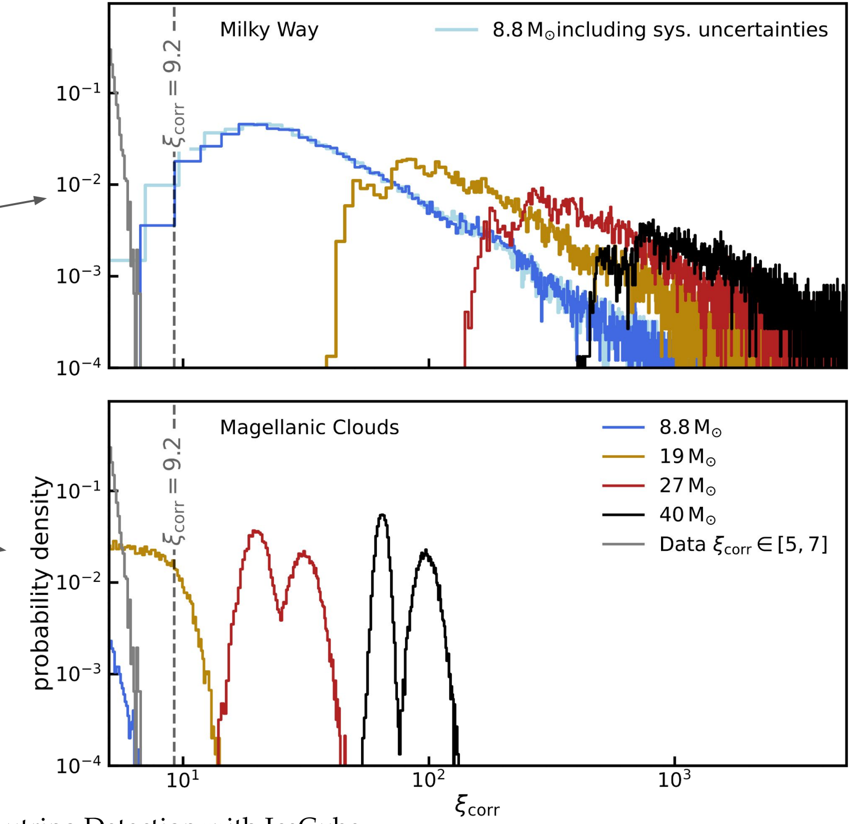




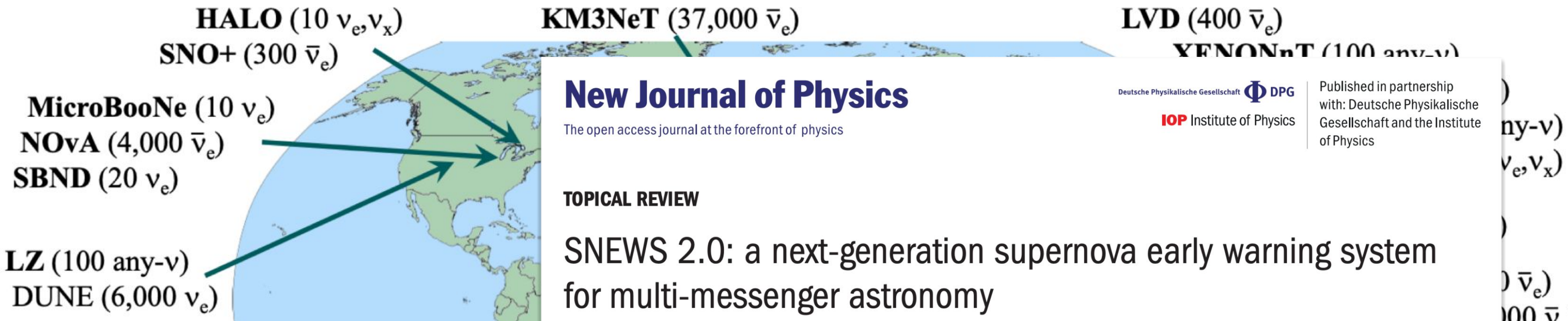
$8M_\odot$ e^- capture CCSN, O-Ne-Mg core, 9 s 1D simulation. **Hüdepohl** et al., PRL 104:251101, 2010.	$19M_\odot$ 3D simulation to 1.756 s after core bounce. Bollig et al. [**Garching**], ApJ 915:28, 2021.
$27M_\odot$ axisymmetric model to 4.5 s after core bounce. **Burrows & Vartanyan**, Nature 589:29, 2021.	$40M_\odot$ failed supernova producing a **black hole**. Nakazato et al., PRD 78:083014, 2008.

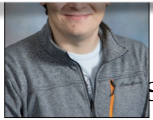
IceCube Sensitivity: TS Distribution of ξ_{corr}





SuperNova Early Warning System





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TOPICAL REVIEW

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

The Astrophysical Journal, 925:107 (17pp), 2022 February 1 https://doi.org/10.3847/1538-4357/ac350f

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SNEWPY: A Data Pipeline from Supernova Simulations to Neutrino Signals

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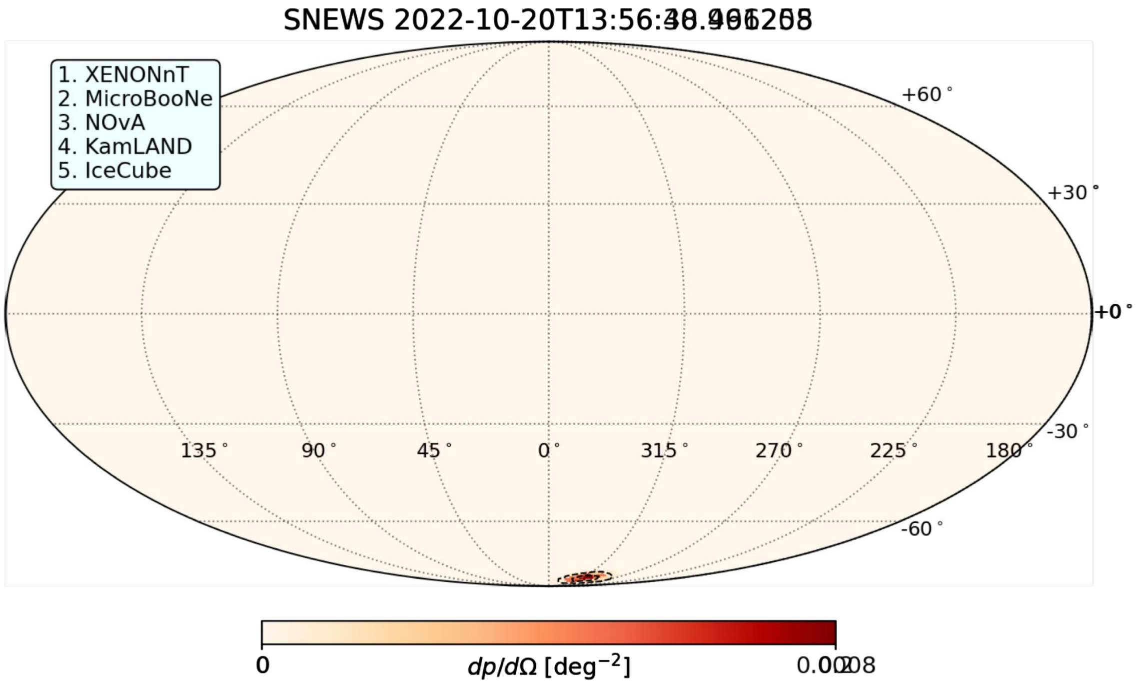
IceCube and SNEWS

Progenitor localization with SNEWS is possible by combining signals from many neutrino detectors.

Produce credible regions on the sky where telescopes should point.

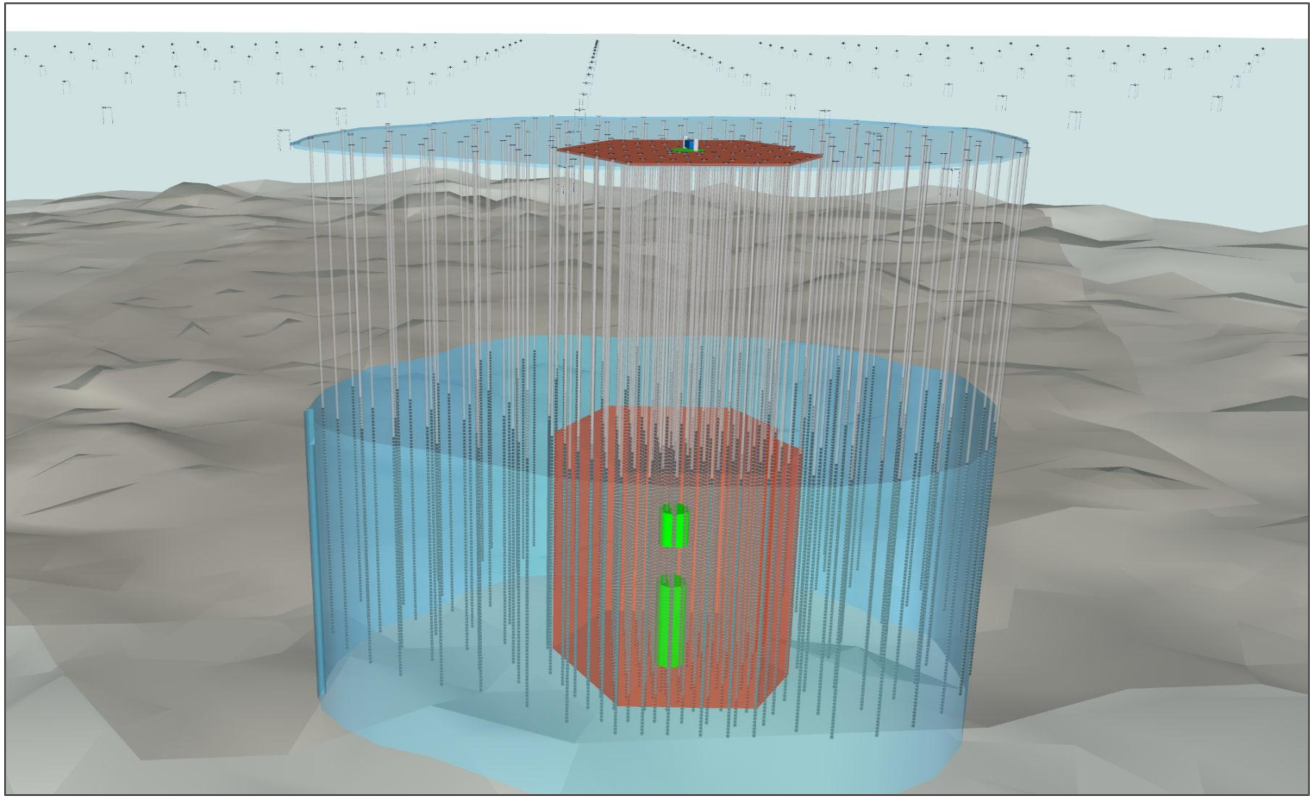
Right: SNEWS 2.0 firedrill alert localization without and with IceCube.

Triangulation baseline matters!



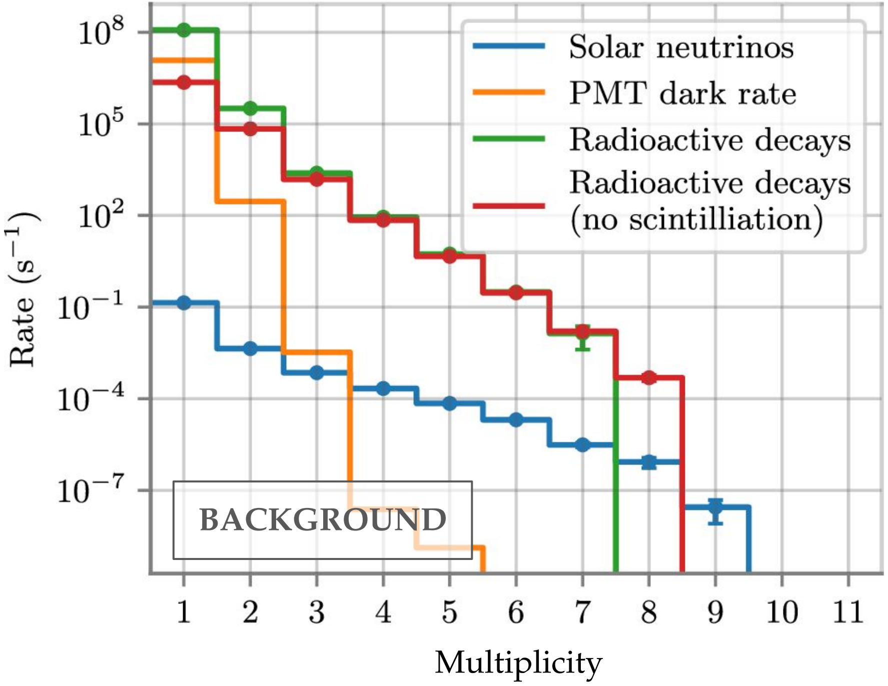
Credit: M. Colomer+, SNEWS 2.0 Collaboration

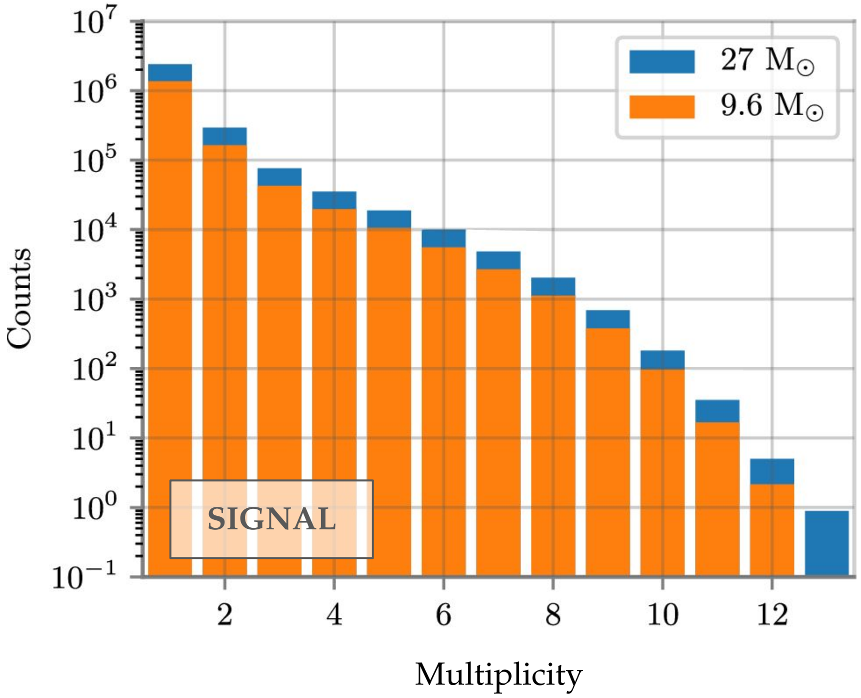
Future: IceCube-Gen2 Detector



Multi-PMT DOMs and CCSN ν's

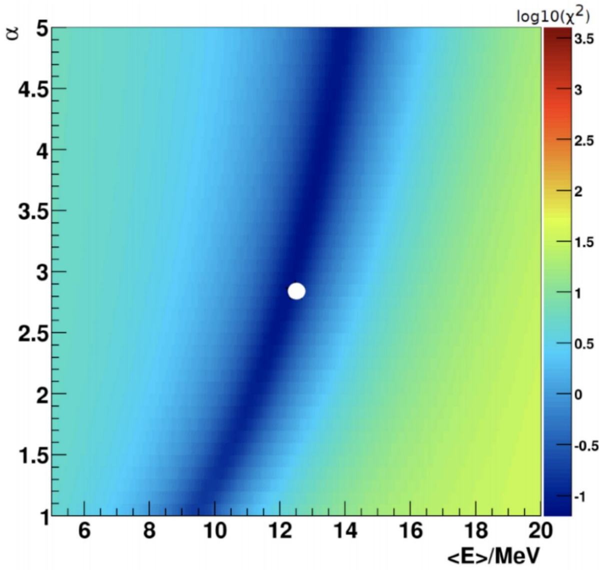
Similar to KM3Net, IceCube-Gen2 will have some version* of multi-PMT DOMs.





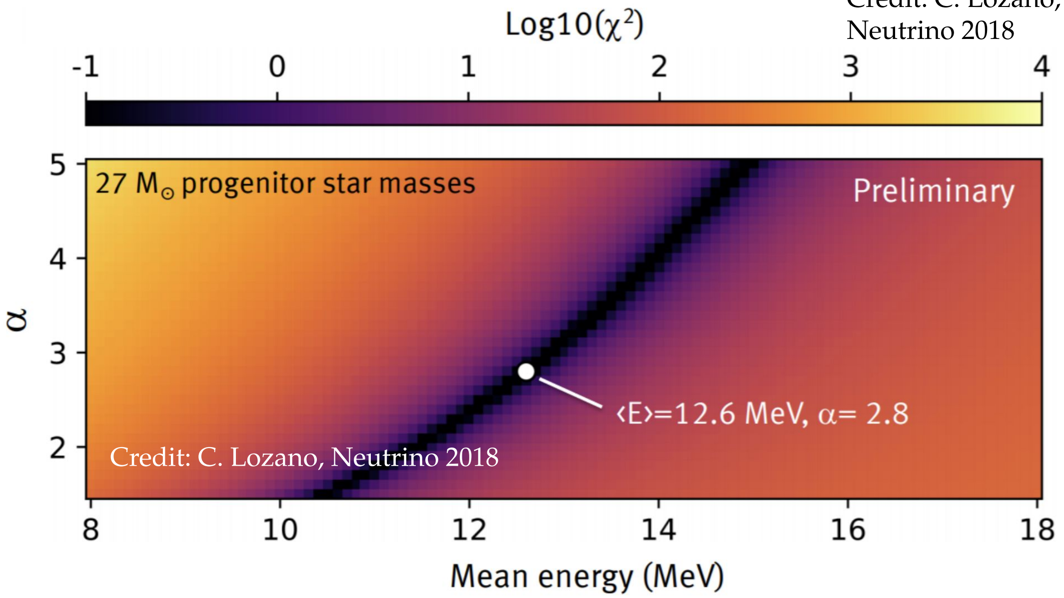
Multi-PMT DOMs and CCSN ν's

Improved sensitivity vs. progenitor distance; considerable improvement in resolution of quasi-thermal CCSN neutrino spectrum.



Credit: L. Köpke
8th Symp. Large TPCs, 2017

Credit: C. Lozano, Neutrino 2018



Summary

IceCube as an MeV neutrino detector: no event reconstruction but excellent timing resolution (2 ms online, 25 ns offline), high statistics, and >99.7% uptime.

The observatory has **model-independent sensitivity at $\gg 5\sigma$** to even the most conservative CCSN ν flux predictions for progenitors anywhere in the Milky Way and $>5\sigma$ sensitivity to most progenitors in the Magellanic Clouds.

IceCube is a core participant in SNEWS 2.0 and participates actively in detection and triangulation fire drills.

IceCube-Gen2 will incorporate multi-PMT DOMs: significant background reduction with coincidence cuts, improved sensitivity to CCSN ν spectrum.