Overview of the IceCube Supernova Working Group

IceCube Summer School
Madison, WI, June 3-7, 2024

Segev BenZvi
University of Rochester

Introduction to the Working Group

High-uptime monitoring for CCSNe near the Milky Way; multi-messenger alerts; searches for GeV neutrinos from solar, galactic, and extragalactic transients.

WG Lead

Erin O'Sullivan
Uppsala Univ.

WG Lead

Gwen de Wasseige
UC Louvain

Tech Lead

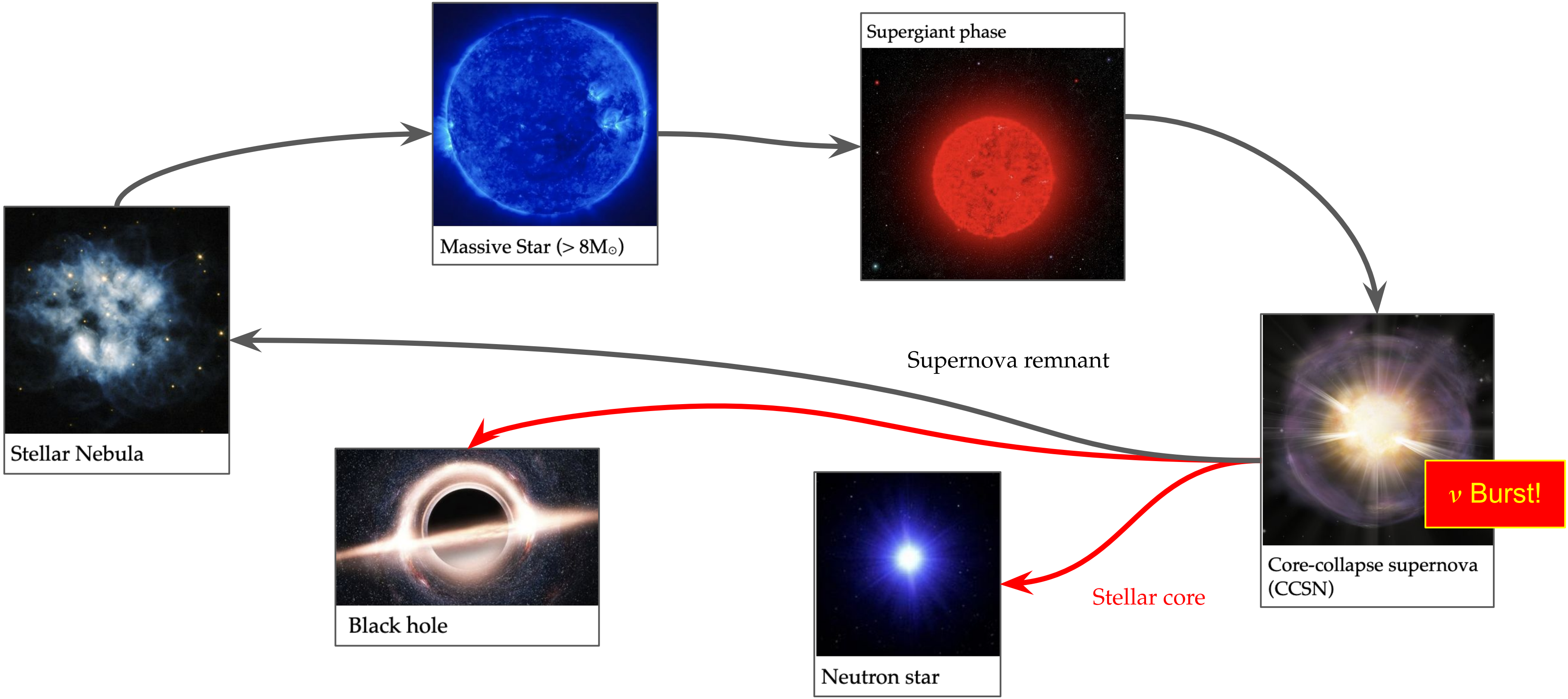
Segev BenZvi
Univ. of Rochester

SNEWS Liaison

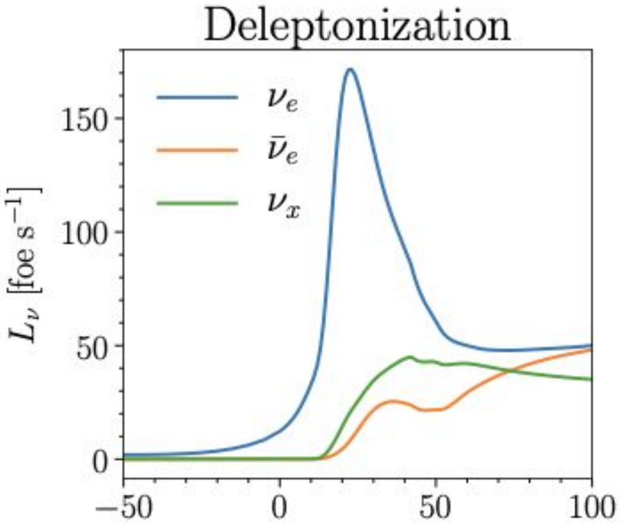
Spencer Griswold
Univ. of Rochester

Telecons: **Mondays at 9 am CT**. #sn-wg on slack + Supernova Wiki Page + SN WG email list (sn-wg@icecube.wisc.edu).

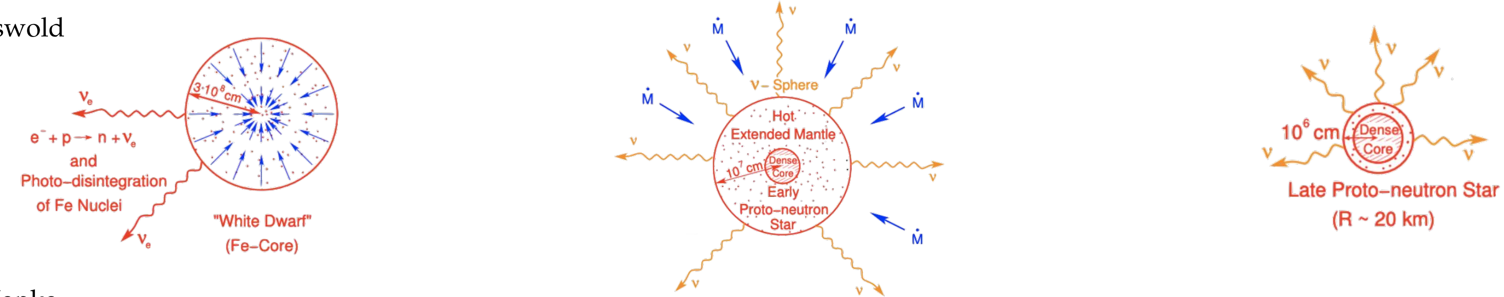
The Life Cycle of a Massive Star



MeV Neutrino Emission in a Supernova

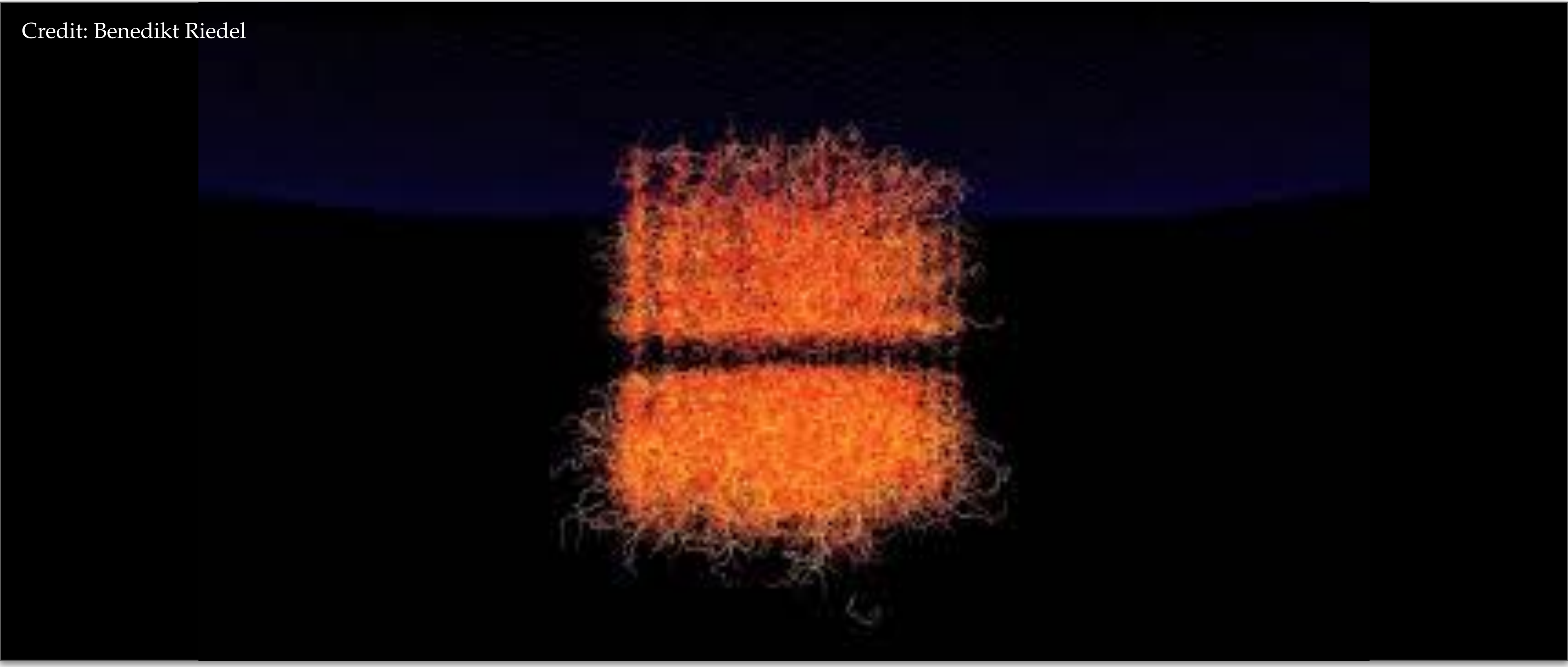


Credit: S. Griswold



Credit: H.-T. Janka

CCSN MeV ν Signal in IceCube

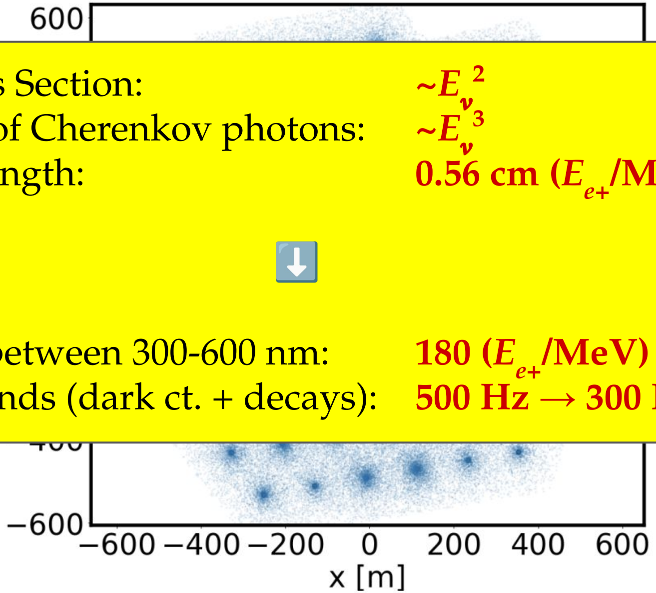


Credit: Benedikt Riedel

CCSN ν Interactions in the IceCube Detector

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

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



IBD Cross Section:	$\sim E_\nu^{\,2}$
Number of Cherenkov photons:	$\sim E_\nu^{\,3}$
e^+ track length:	**0.56 cm (E_{e+}/MeV)**

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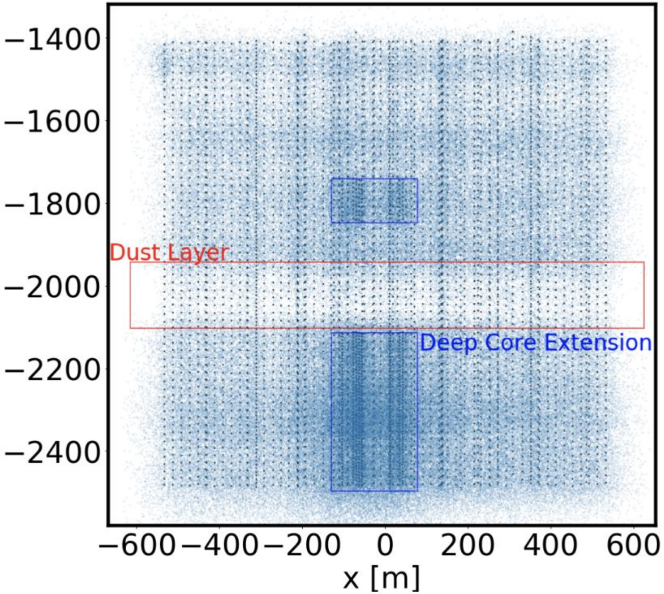
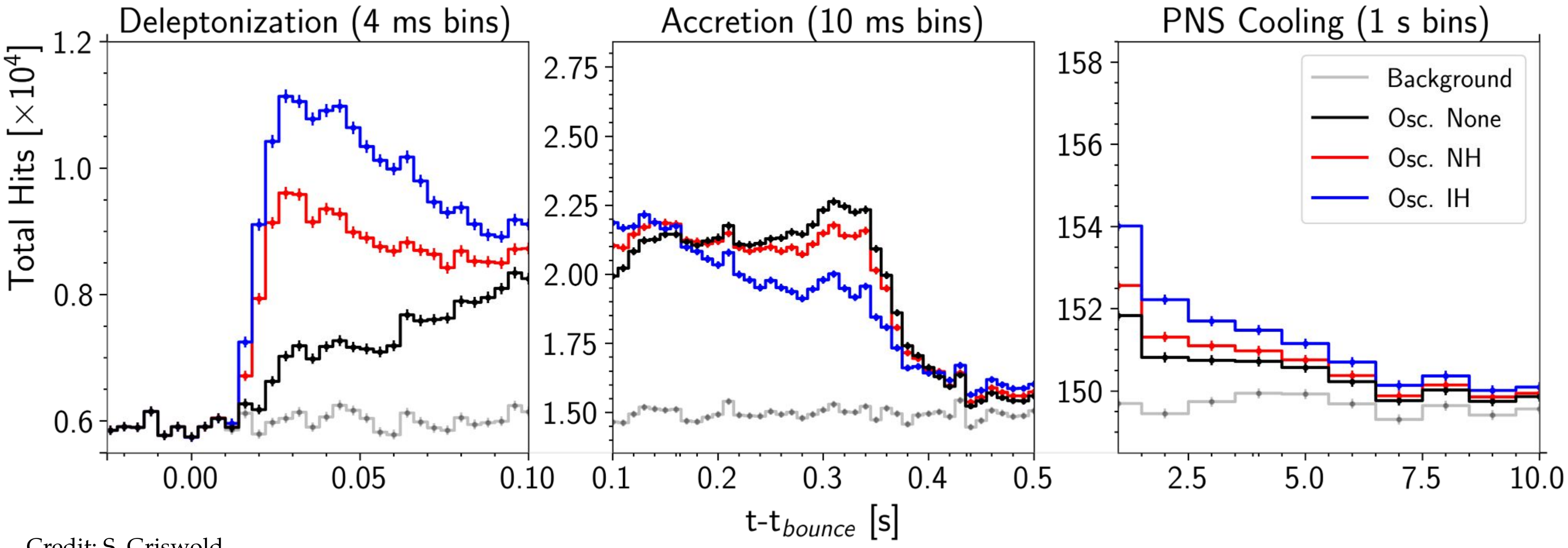
Photons between 300-600 nm:	**180 (E_{e+}/MeV)**
Backgrounds (dark ct. + decays):	**500 Hz → 300 Hz**



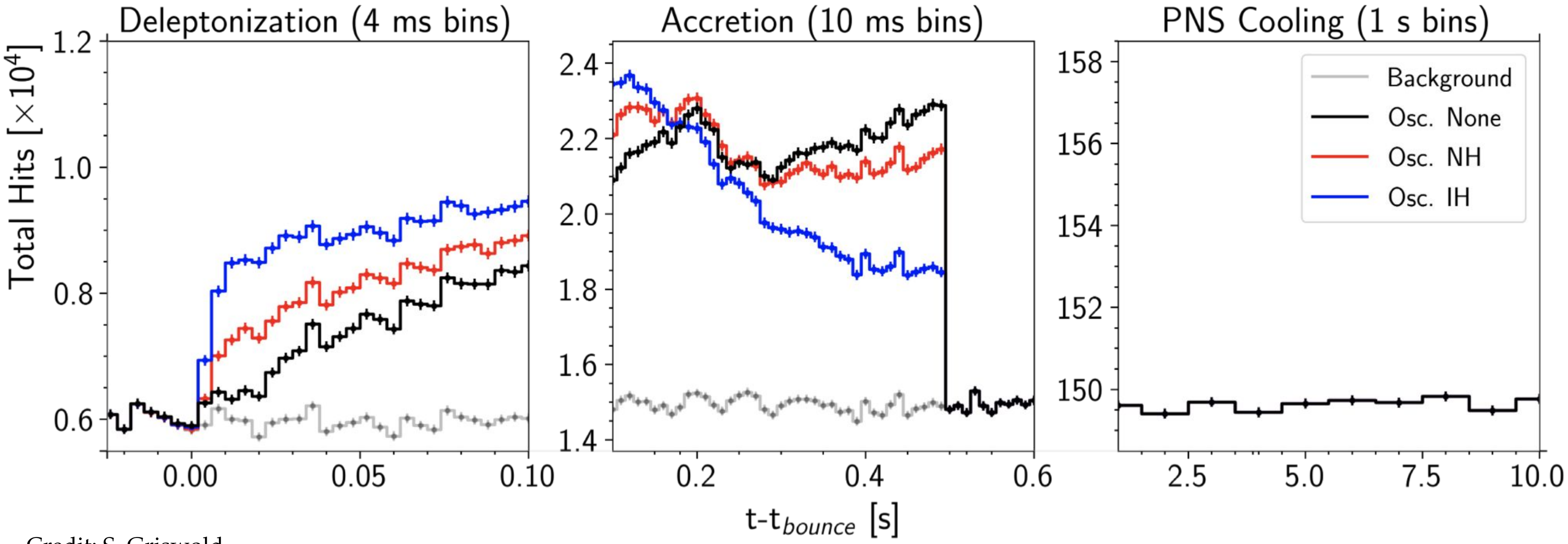
CCSN ν Hits in IceCube Post-Bounce



Credit: S. Griswold

NEUTRON STAR

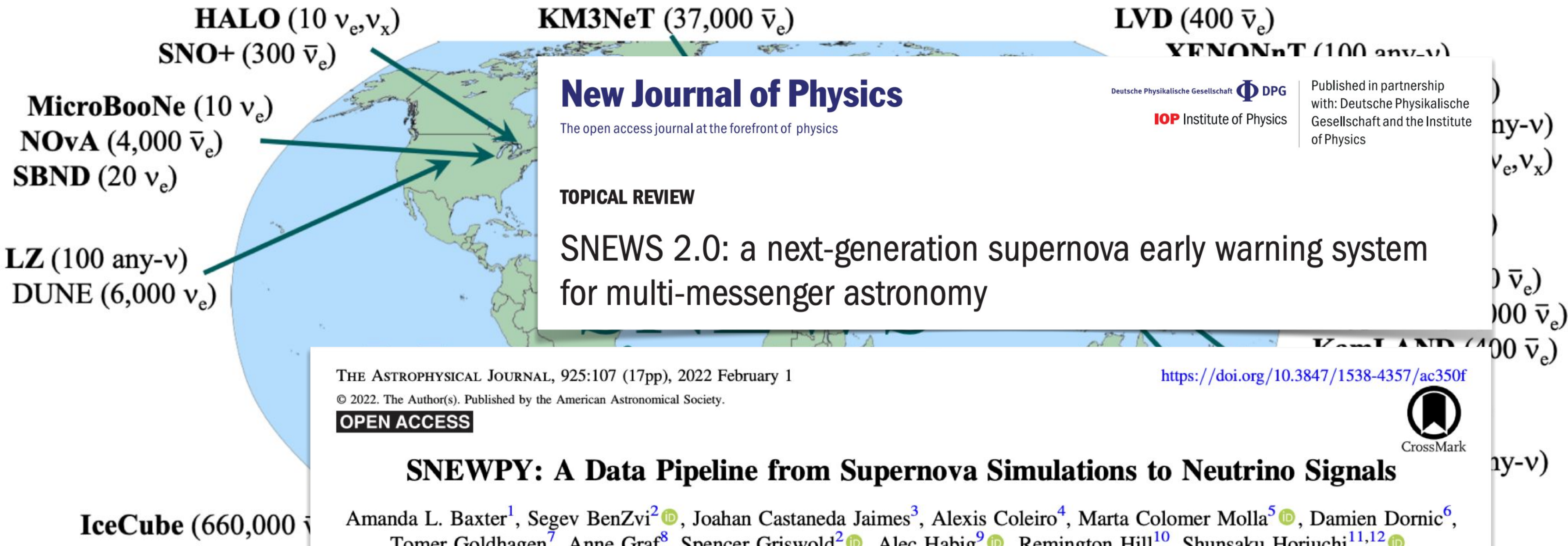
CCSN ν Hits in IceCube Post-Bounce



Credit: S. Griswold

BLACK HOLE

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

SNEWPY: A Data Pipeline from Supernova Simulations to Neutrino Signals

Amanda L. Baxter[1], Segev BenZvi[2], Joahan Castaneda Jaimes[3], Alexis Coleiro[4], Marta Colomer Molla[5], Damien Dornic[6], Tomer Goldhagen[7], Anne Graf[8], Spencer Griswold[2], Alec Habig[9], Remington Hill[10], Shunsaku Horiuchi[11,12], James P. Kneller[8], Rafael F. Lang[1], Massimiliano Lincetto[13], Jost Migenda[14], Ko Nakamura[15], Evan O'Connor[16], Andrew Renshaw[17], Kate Scholberg[18], Christopher Tunnell[19], Navya Uberoi[2], and Arkin Worlikar[20]

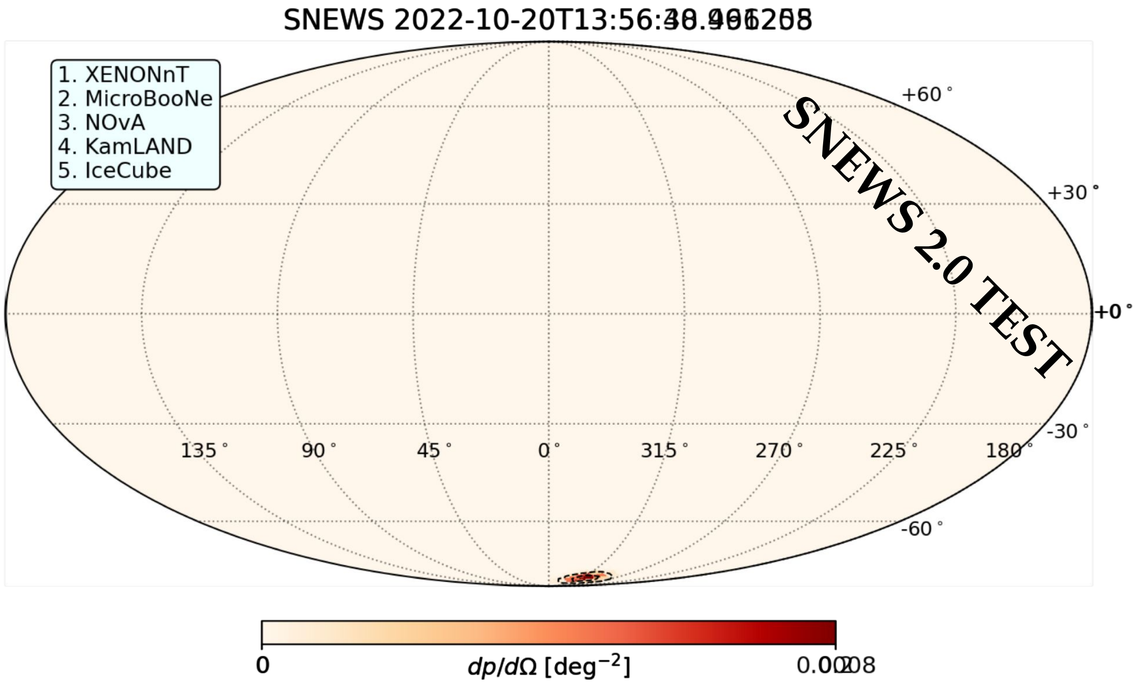
IceCube and SNEWS 2.0

Progenitor localization with SNEWS 2.0 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.

Helpful baseline for triangulation!

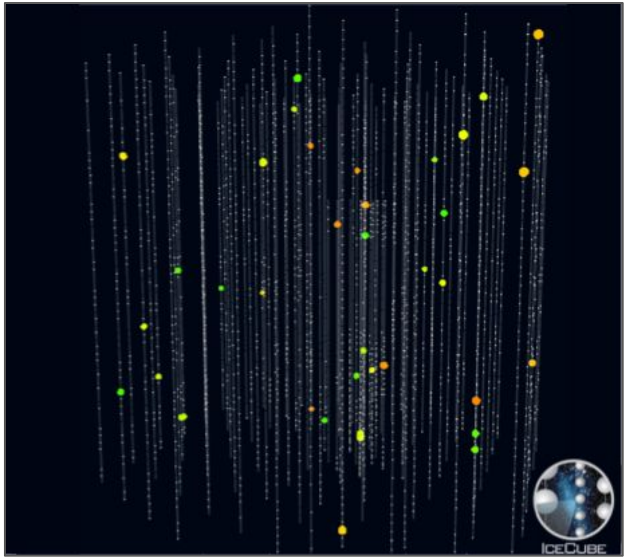


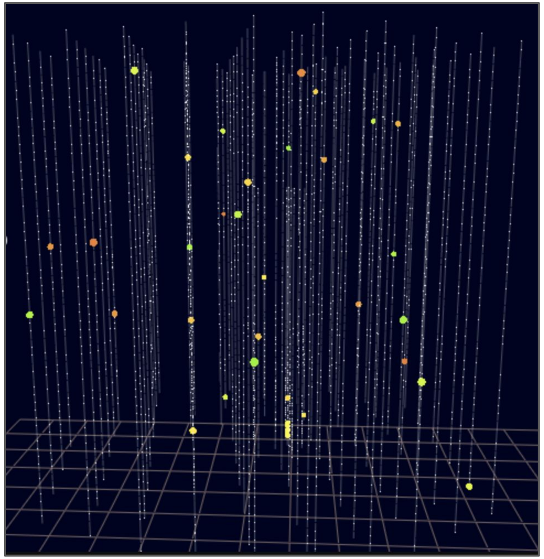
Credit: M. Colomer+, SNEWS 2.0 Collaboration

ELOWEN: Transient Searches at GeV

Transient science below 5 GeV: cosmic ray production in solar flares, neutrino+GW searches, neutrino production in GRBs and other transients.

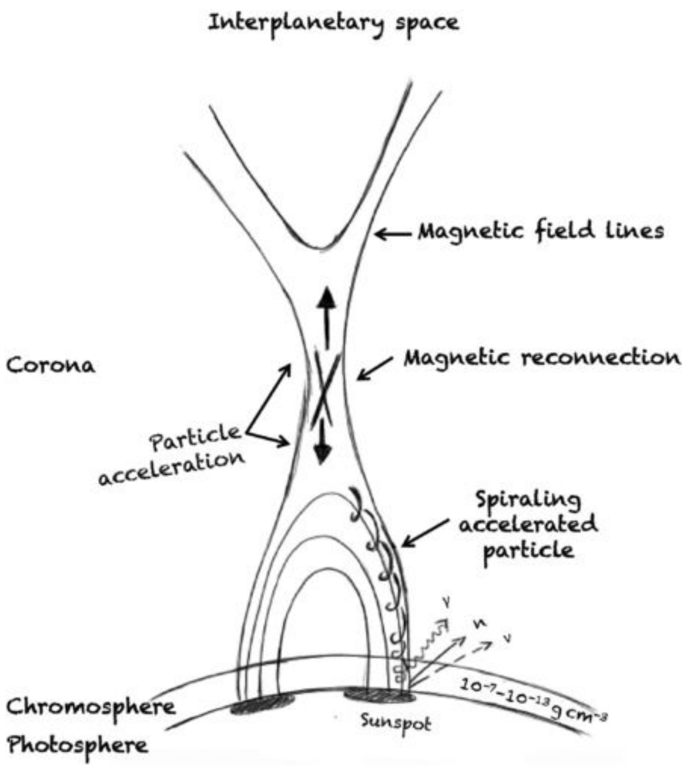
Credit: G. de Wasseige

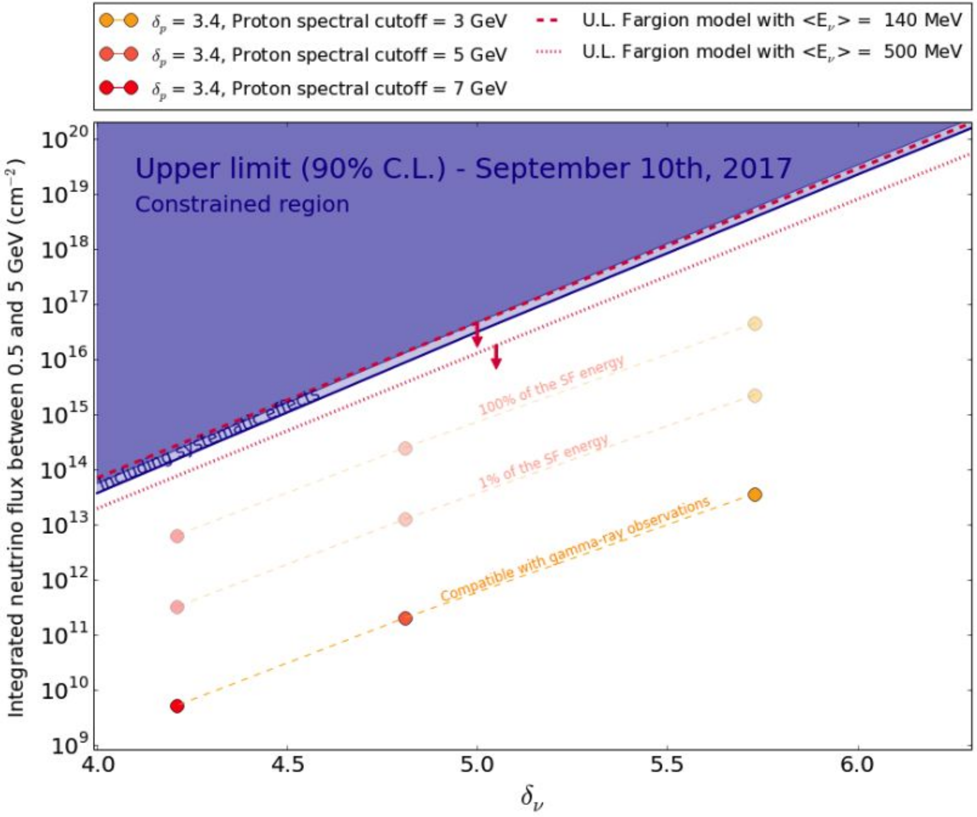




The catch: **backgrounds**. Test: which of these includes an 3 GeV ν_e interaction?

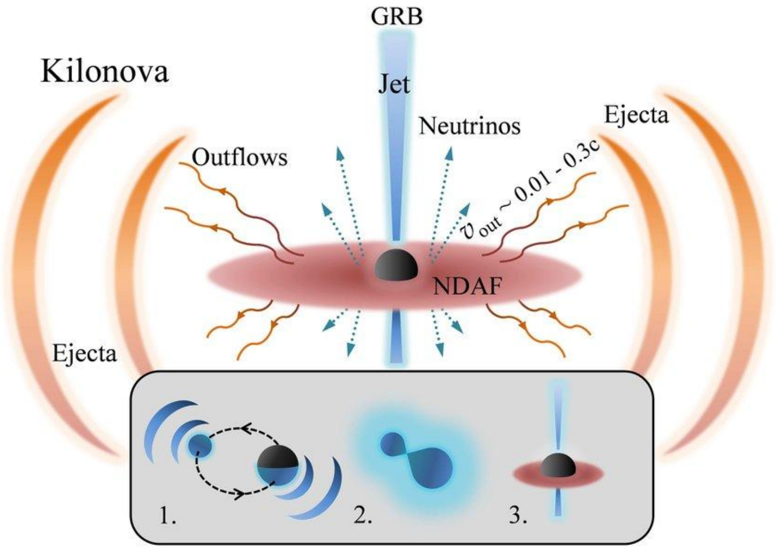
Constraining Neutrinos from Solar Flares

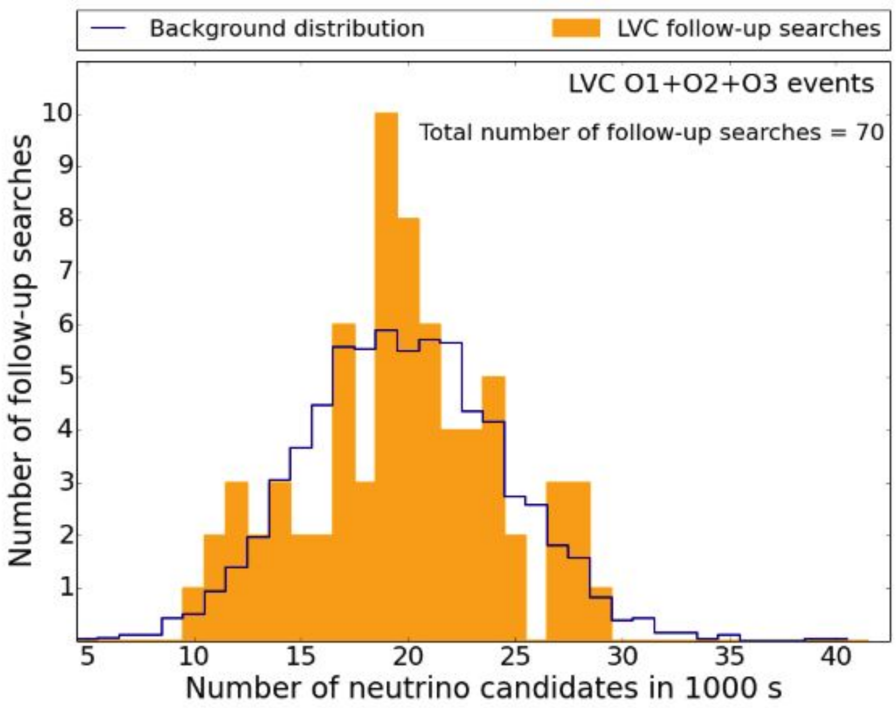




Credit: Abbasi+ PRD 103 (2021)

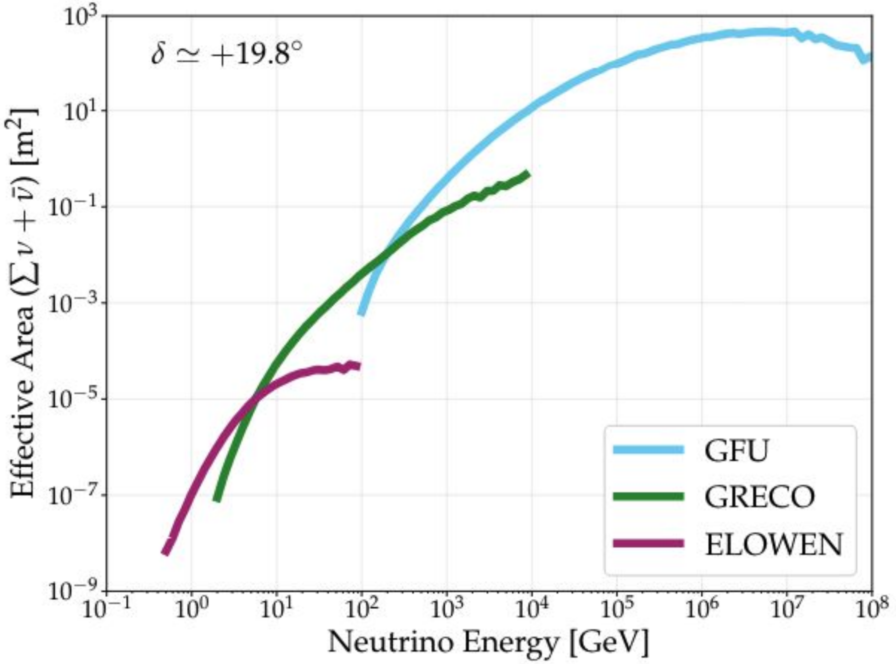
Constraining GeV Neutrinos from Compact Binary Mergers

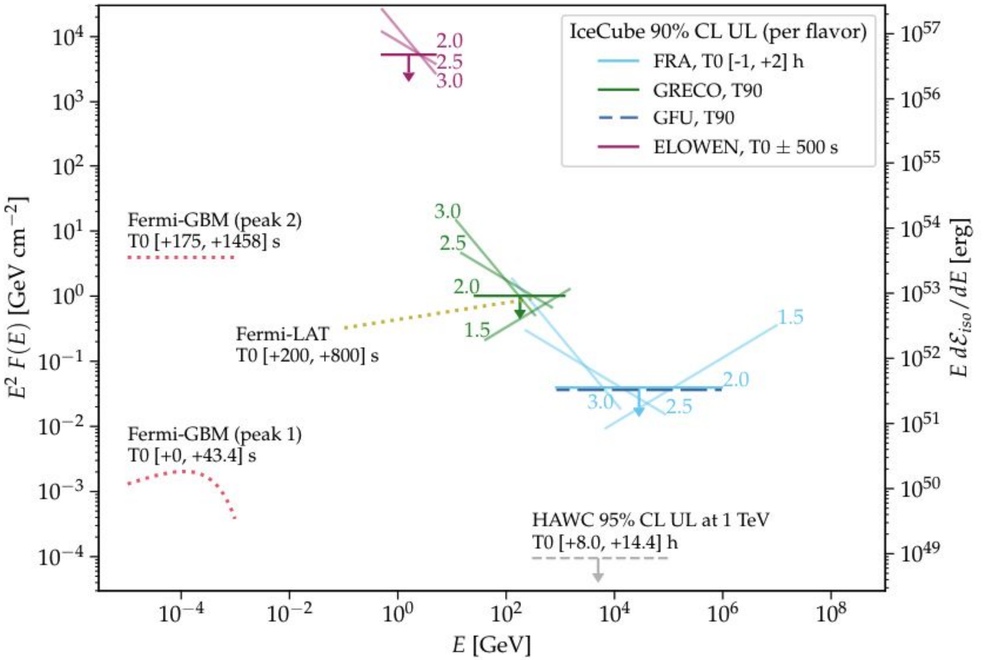




Credit: Yi+ MNRAS 476 (2018); Abbasi+ 2021

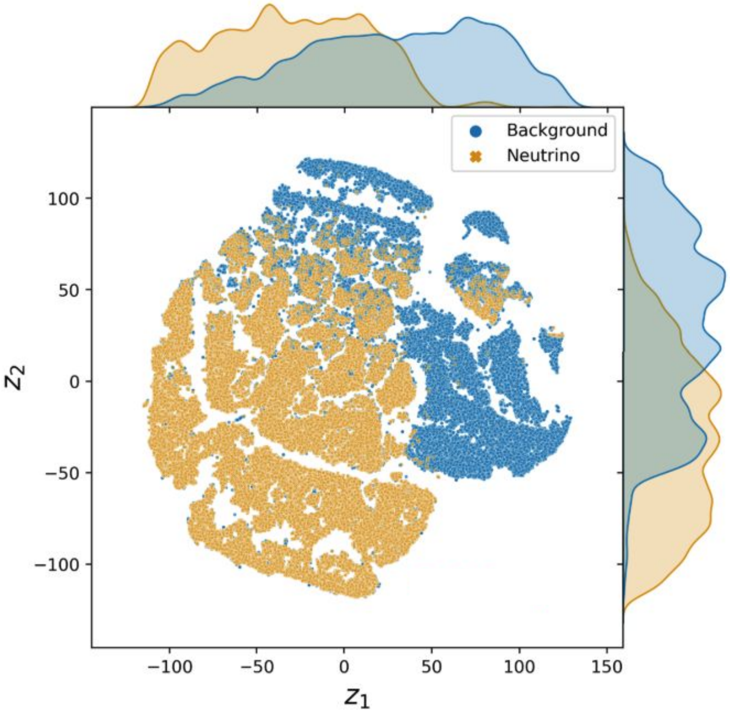
Constraining GeV Neutrinos from GRBs

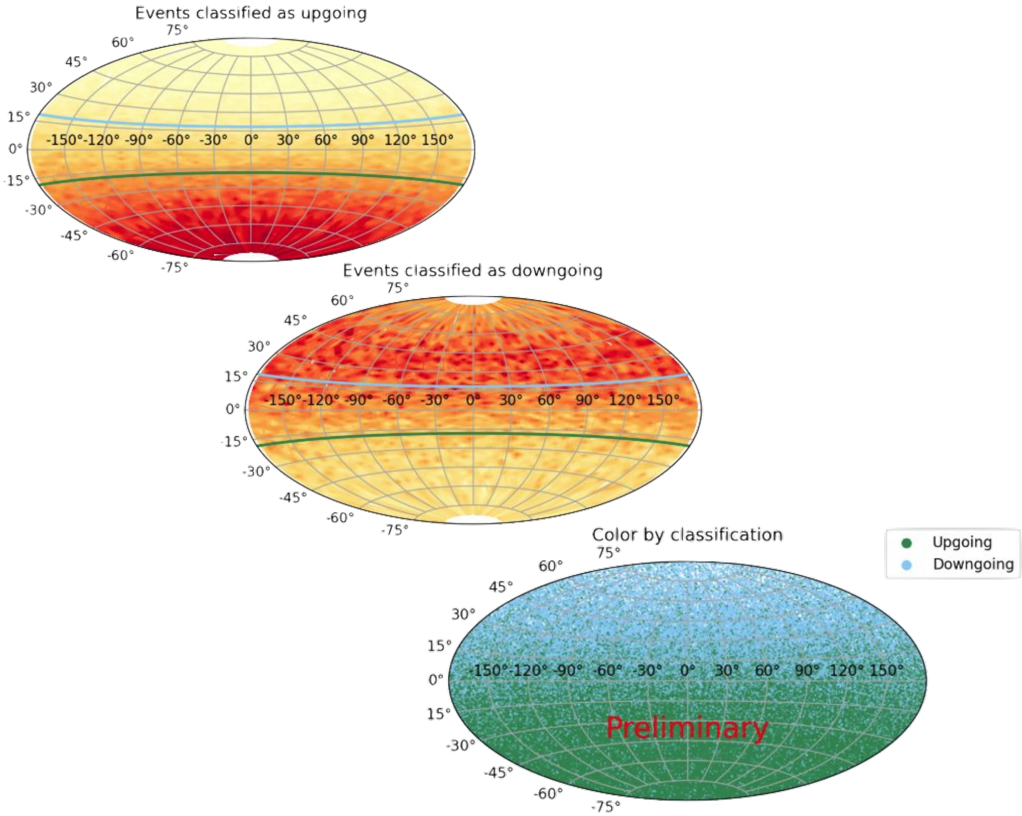




Credit: Abbasi+ ApJL 946 (2023)

Improved Separation of GeV Neutrinos from Backgrounds





Credit: K. Kruiswijk

Summary of Supernova WG Activities

Searches for **MeV neutrinos** from supernovae & other transients:

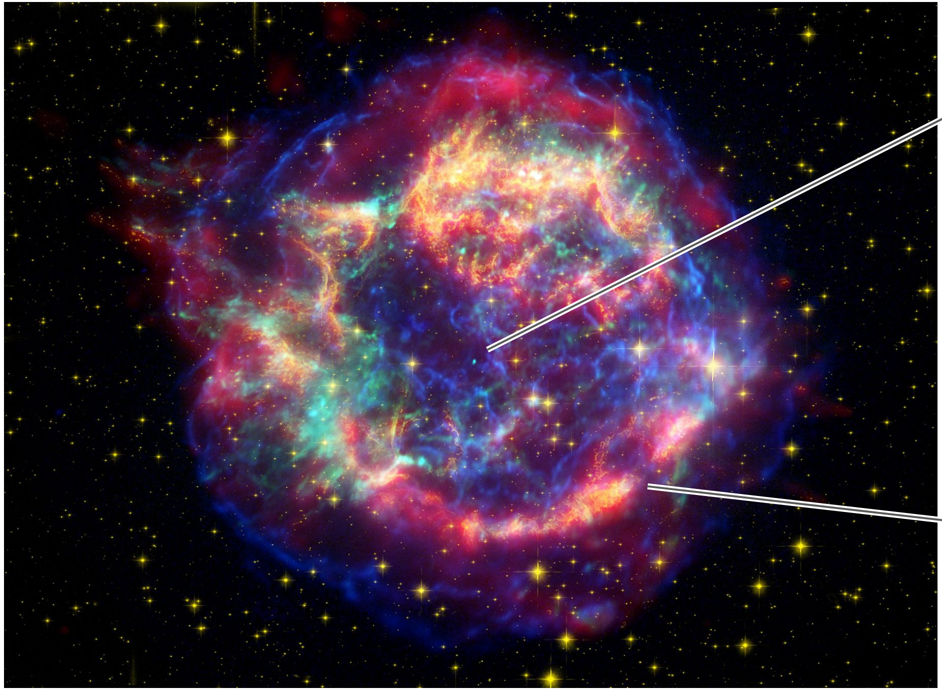
- Sensitivity to astrophysics and fundamental neutrino physics.
- Multi-messenger warnings as part of the SNEWS network.
- Lots of modeling tools (SNEWPY, ASTERIA, SNOwGLoBES, sntools, …)

Constraining **GeV neutrino emission** from energetic transients:

- Sensitivity to a huge range of astrophysical neutrino production mechanisms.
- Background reduction challenge: interesting task in computer vision!

Significant overlap with **Neutrino Sources** & **BSM** Working Groups.

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.

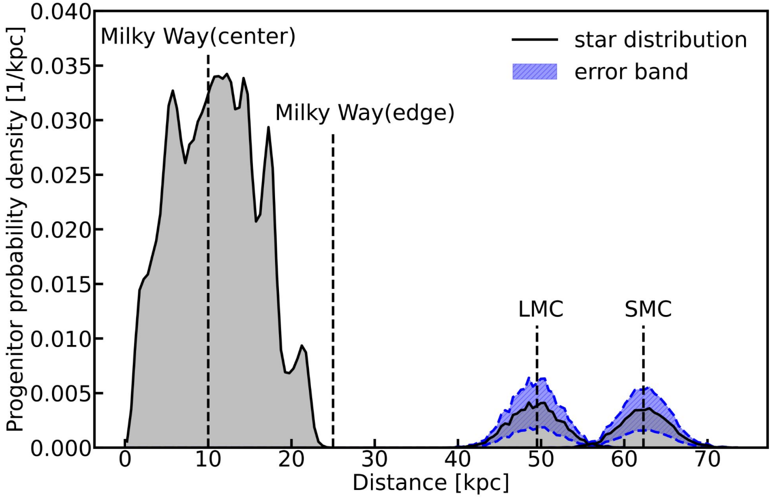
IceCube and other CCSN ν Detectors

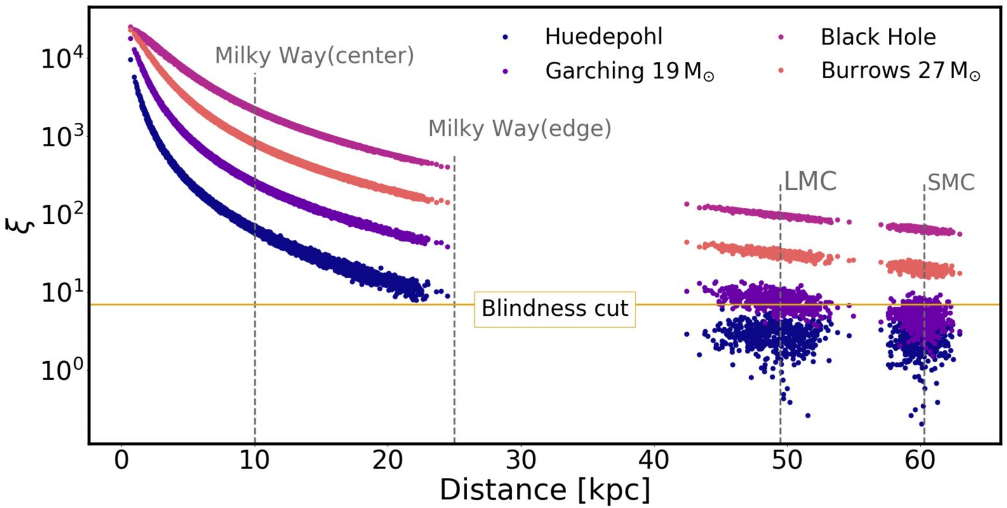
Detector	Type	Mass (kt)	Location	Events [10 kpc]
IceCube	**Long string**	**600/DOM***	**South Pole**	**500,000***
Hyper-K	*water*	*374*	*Japan*	*75,000*
KM3Net	*Long string*	*111*	*France/Italy*	*10,000**
DUNE	*LAr*	*40*	*USA*	*3,000*
Super-K	water	32	Japan	7,000
JUNO	scintillator	20	China	6,000
NOvA	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

IceCube Sensitivity: Model Dependence

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

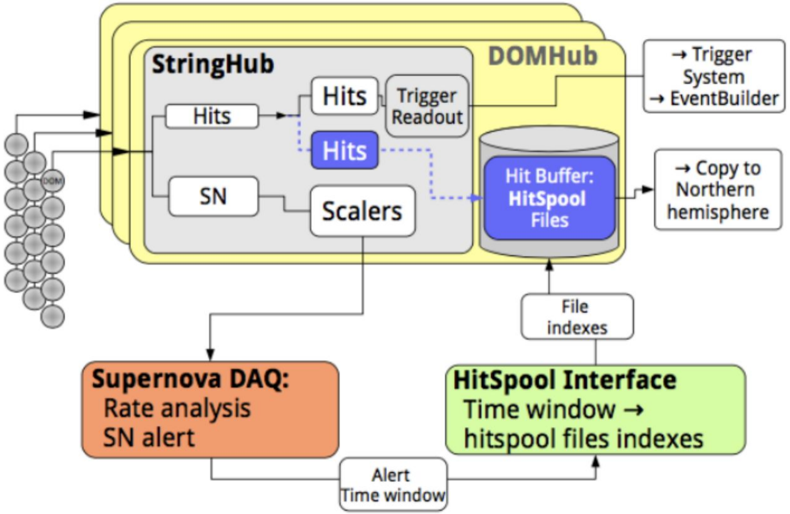




8M$_\odot$ e^- capture CCSN, O-Ne-Mg core, 9 s 1D simulation. **Hüdepohl** et al., PRL 104:251101, 2010.	19M$_\odot$ 3D simulation to 1.756 s after core bounce. Bollig et al. [**Garching**], ApJ 915:28, 2021.
27M$_\odot$ axisymmetric model to 4.5 s after core bounce. **Burrows & Vartanyan**, Nature 589:29,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

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

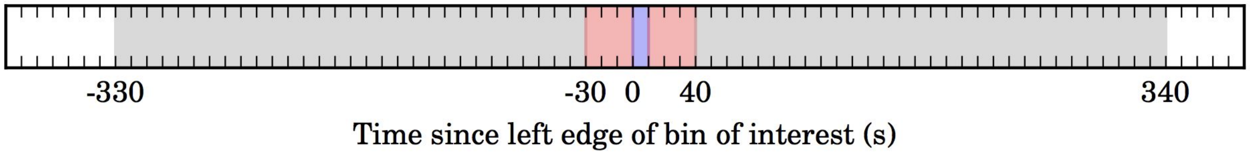
Count rate in DOM i.

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.

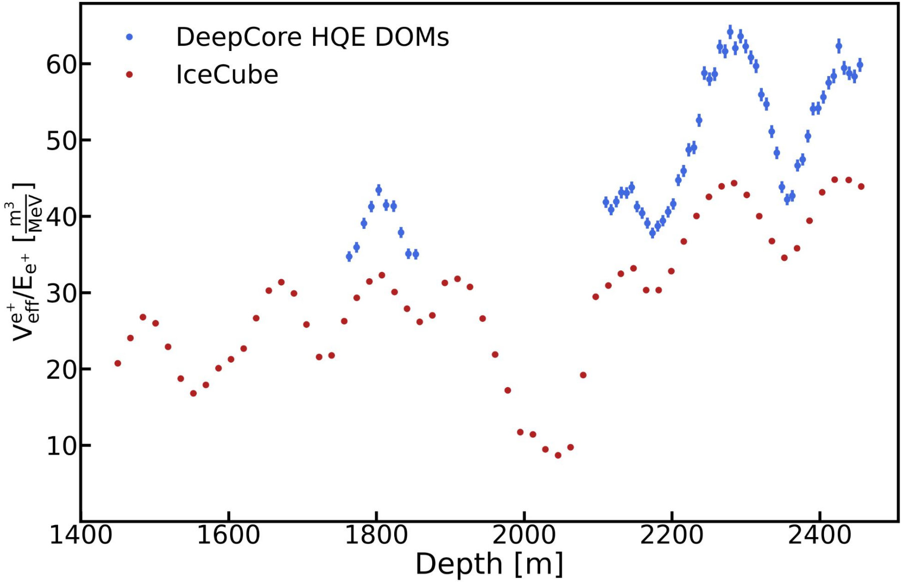


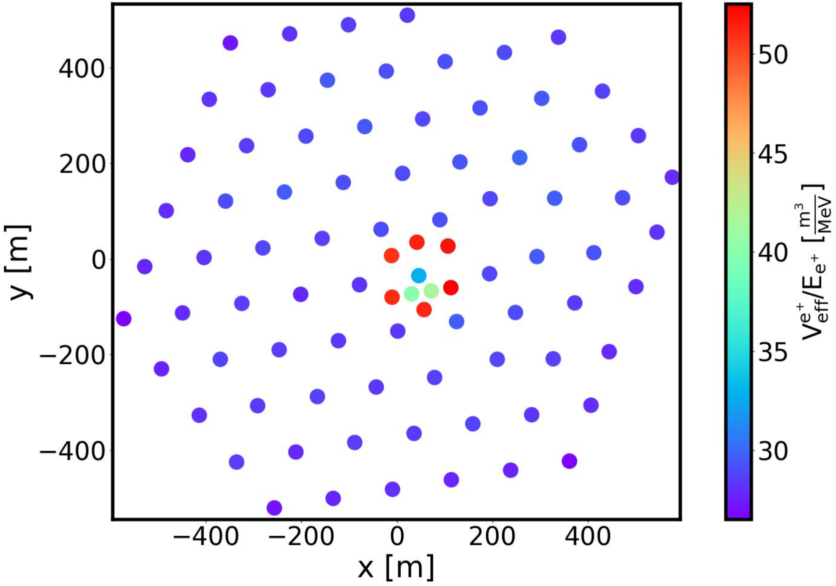
$$\Delta\hat{\mu} = \sigma^2_{\Delta\mu} \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i (r_i - \langle r_i \rangle))}{\langle \sigma_i \rangle^2}, \qquad \sigma^2_{\Delta\hat{\mu}} = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\langle \sigma_i \rangle^2} \right)^{-1}, \qquad \xi = \frac{\Delta\hat{\mu}}{\sigma_{\Delta\hat{\mu}}}$$

DOM Effective Volume vs. Location

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

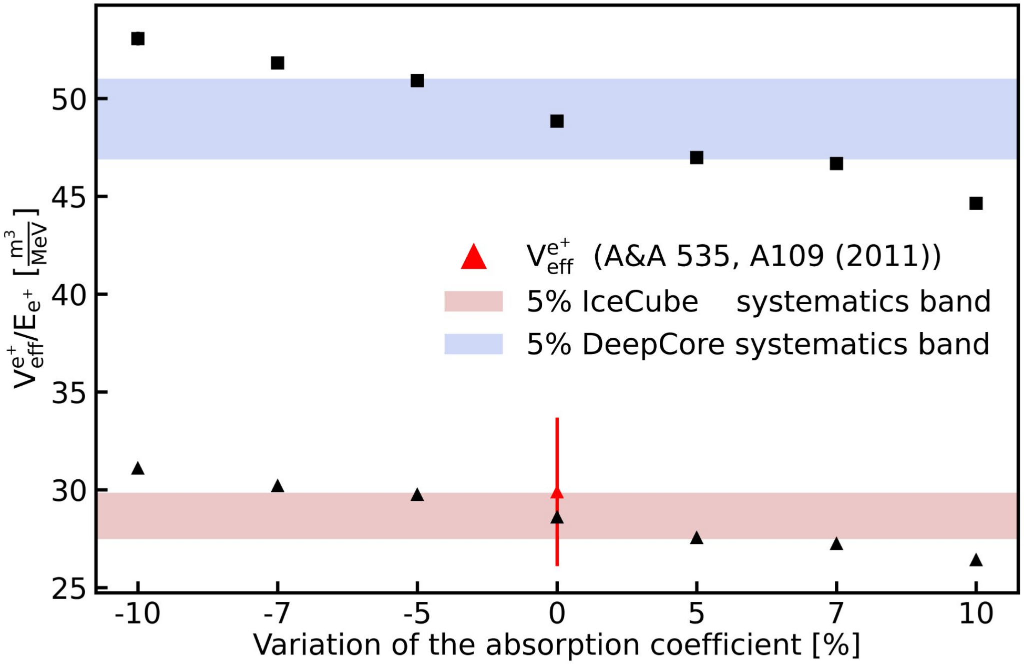
Credit: A. Fritz, IceCube Collaboration [in prep.]





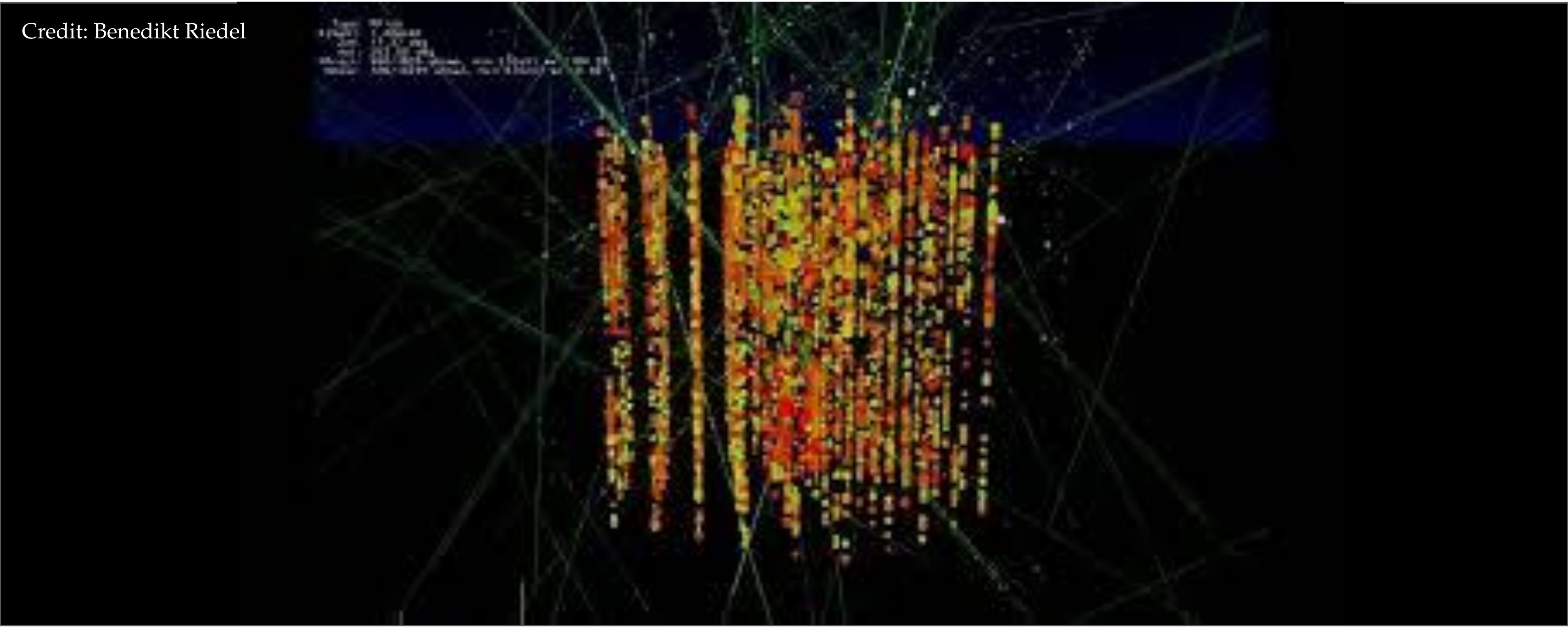
DOM Effective Volume: Systematics

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

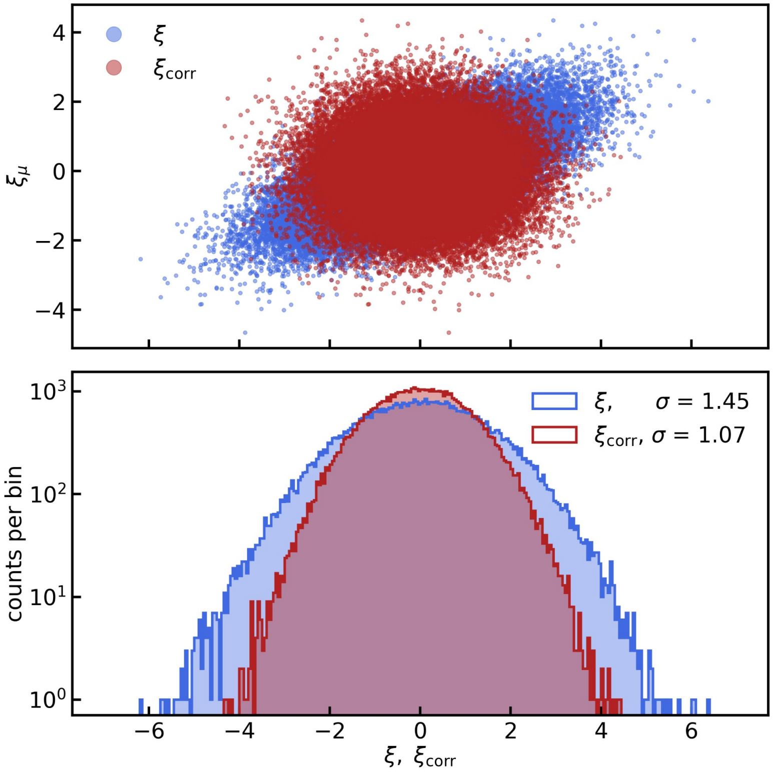
Atmospheric muons (3 kHz trigger rate) prod
MeV system during CCSN signal windows.

Effect visible in correlation between ML test s
proxy $\xi_\mu = (R_\mu^{hit} - \langle R_\mu^{hit} \rangle) / \sigma(R_\mu^{hit})$.

Zero out the correlation to produce a muon-c

Discussion in Aartsen+ ApJ 890:111, 2020.

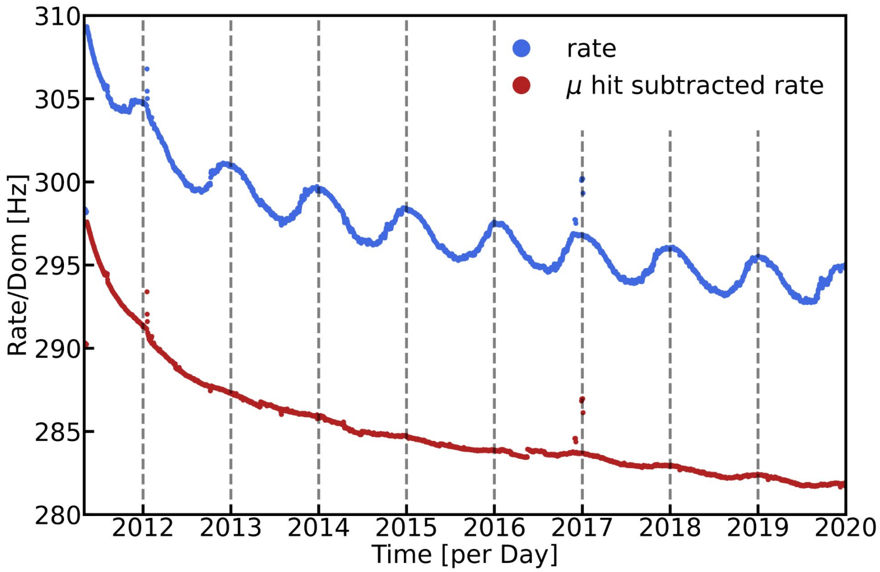
Credit: A. Fritz, IceCube Collaboration [in prep.]

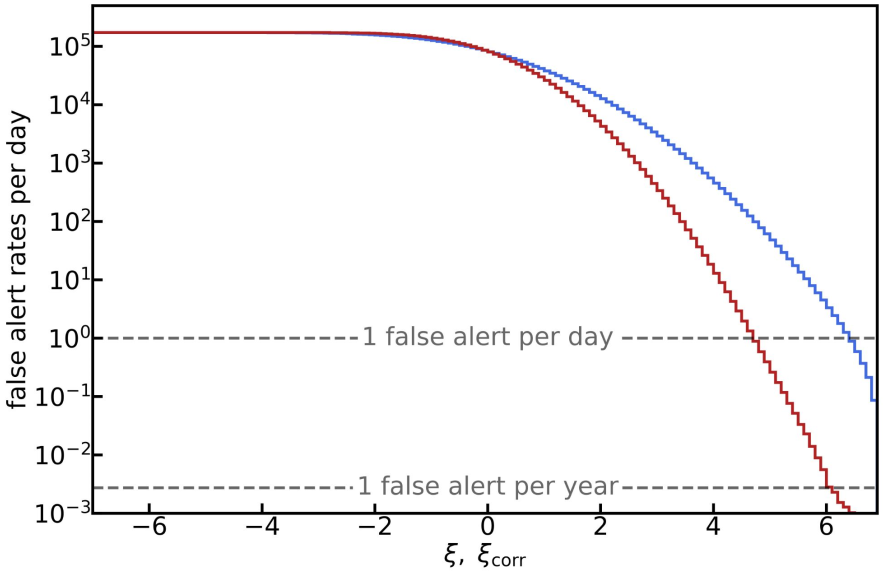


Seasonal Muon and False Alarm Rates: Before & After

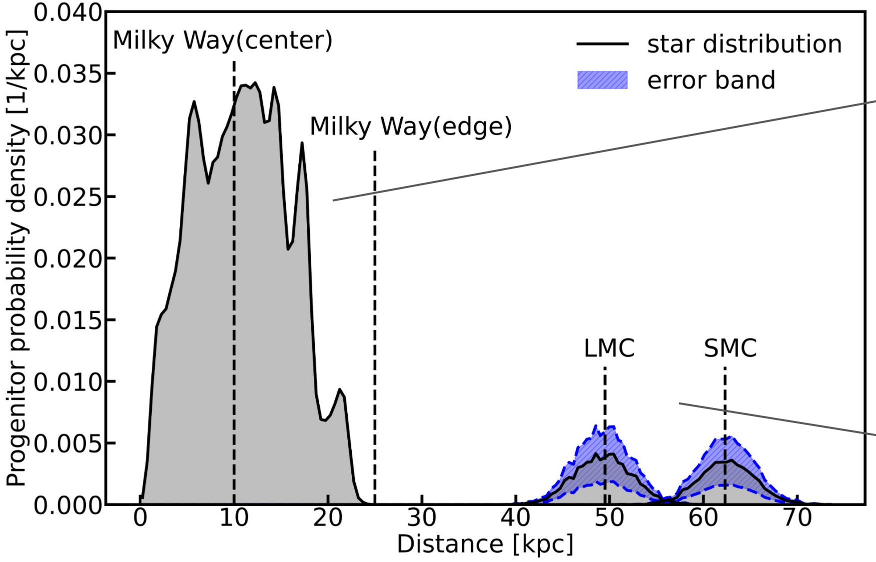
Muon correction has a significant effect on the FAR of events with large TS (**ξ**).

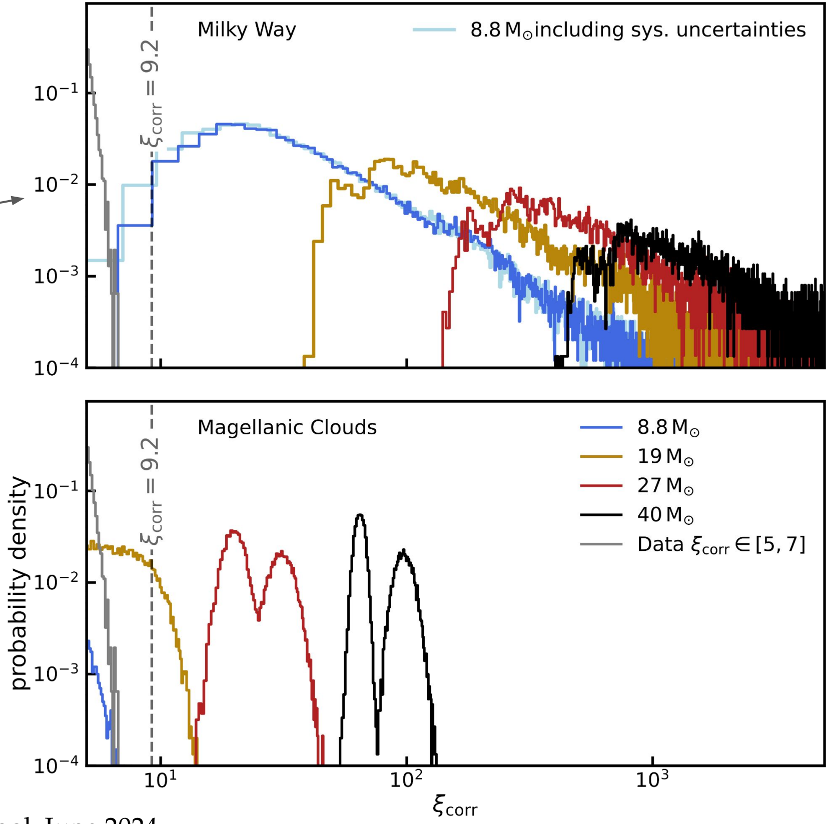
Credit: A. Fritz, IceCube Collaboration [in prep.]



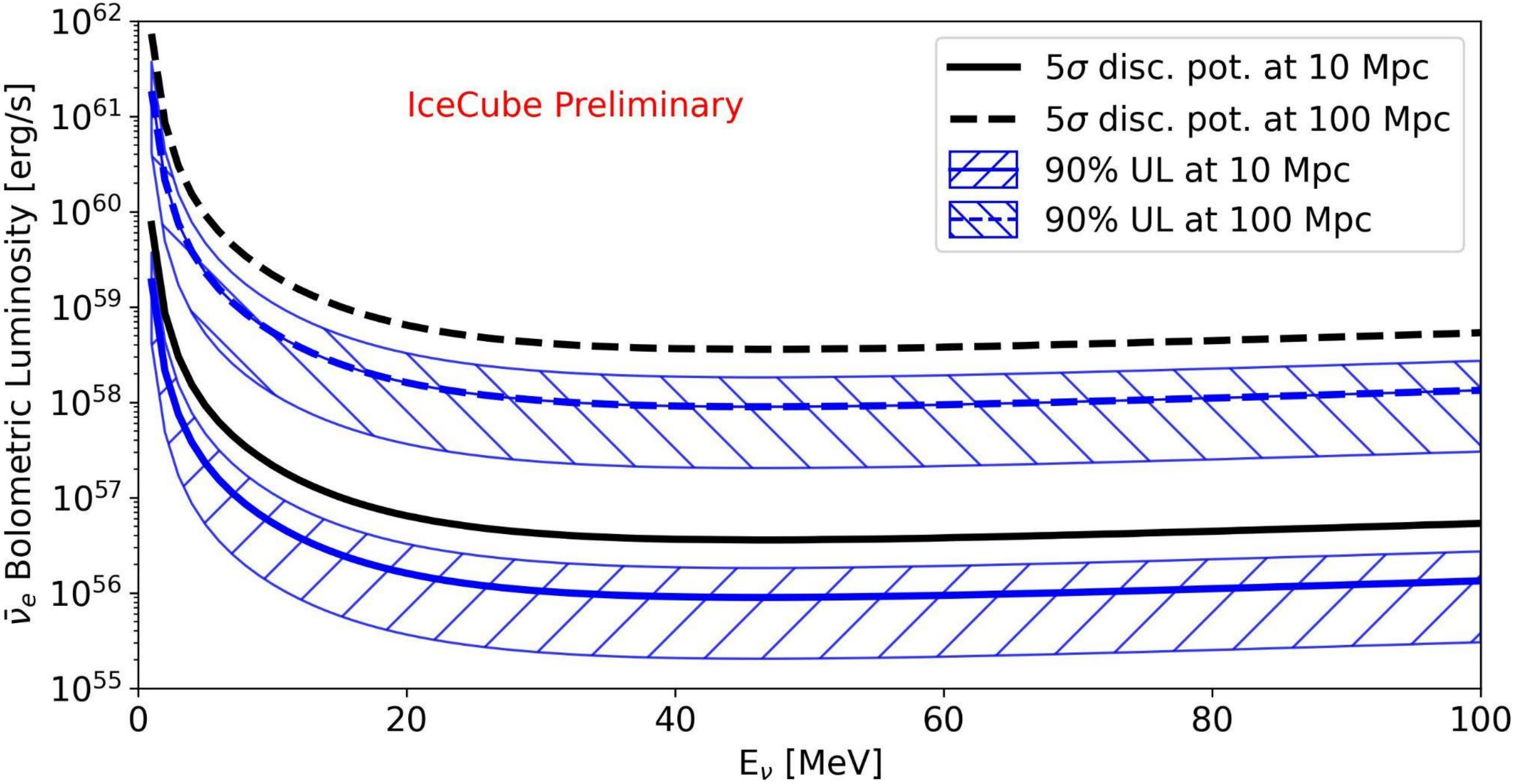


IceCube Sensitivity: TS Distribution of ξ_{corr}

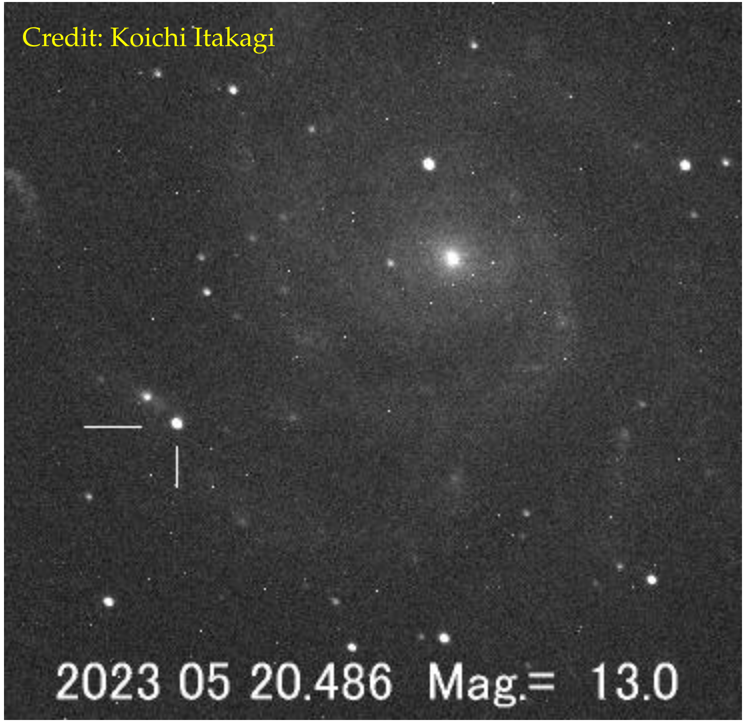




Sensitivity & Discovery Potential



IceCube & SN 2023ixf



IceCube was running at the time of the breakout of SN 2023ixf (>99.7% duty cycle).

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.

SN 2023ixf: MeV ν Emission Limit