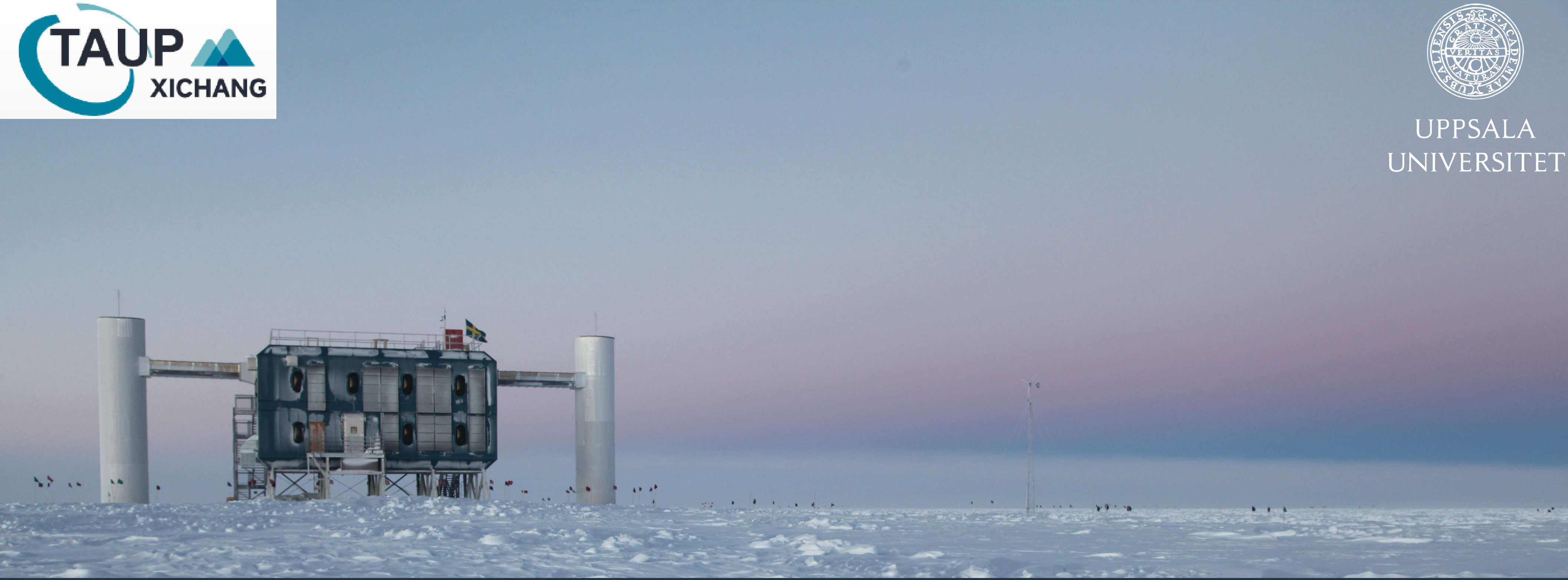


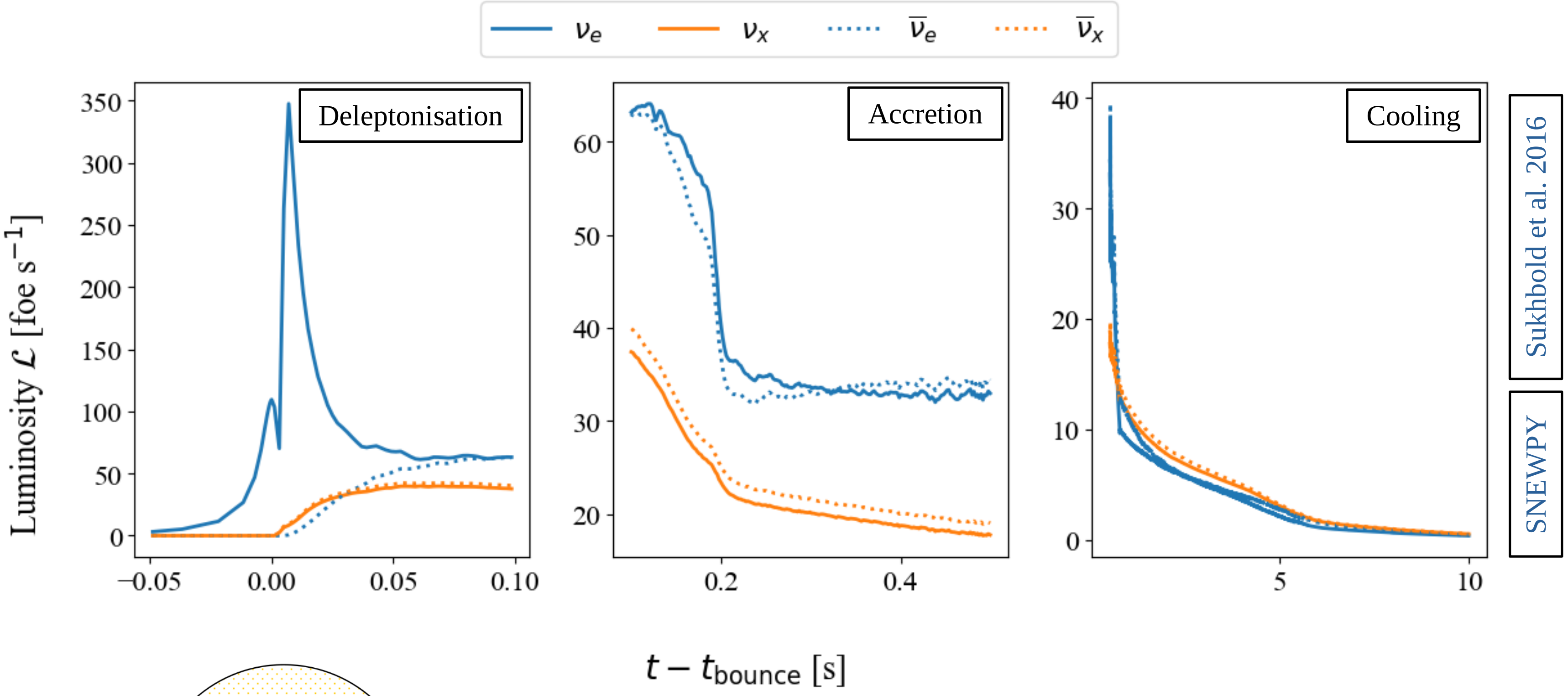
UPPSALA UNIVERSITET

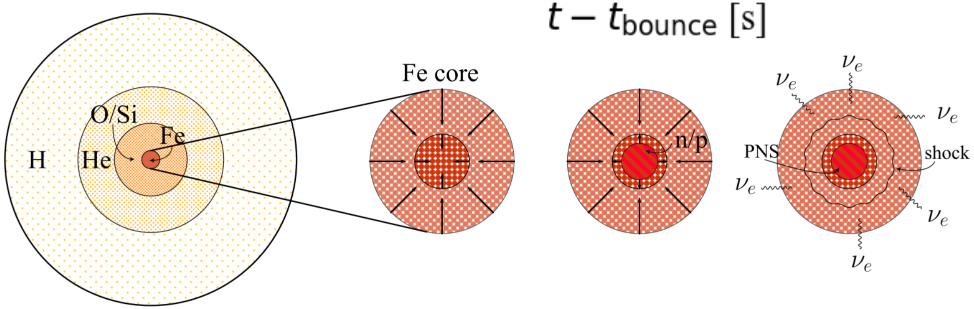
Prospects for detecting fast-time features in the neutrino lightcurve of nearby supernovae in neutrino telescopes

TAUP 2025 – 27 August 2025

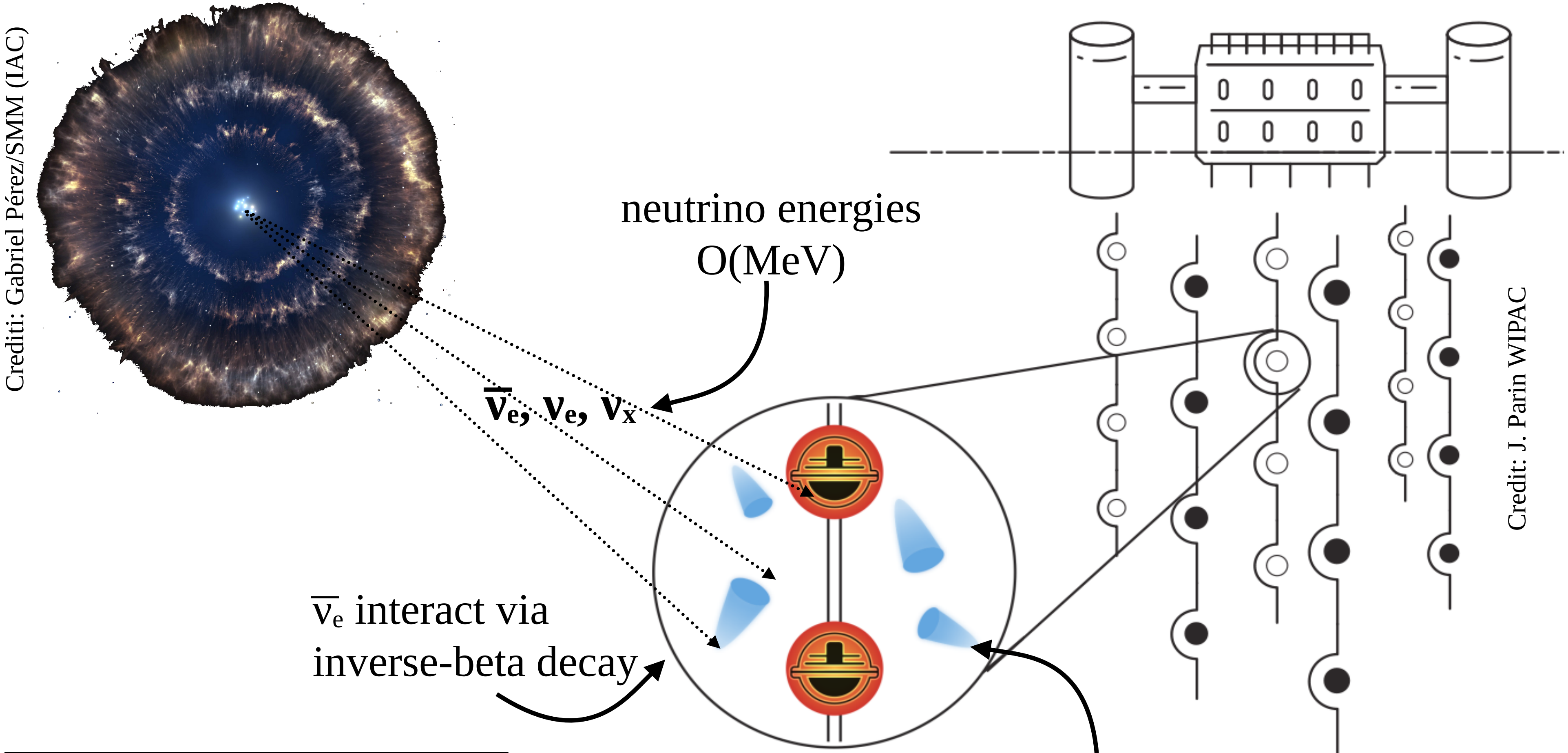
J. Beise, M. Durán de las Heras, S. BenZvi, S. Griswold, N. Valtonen-Mattila, E. O’Sullivan

A brief introduction into CCSNe neutrino emission





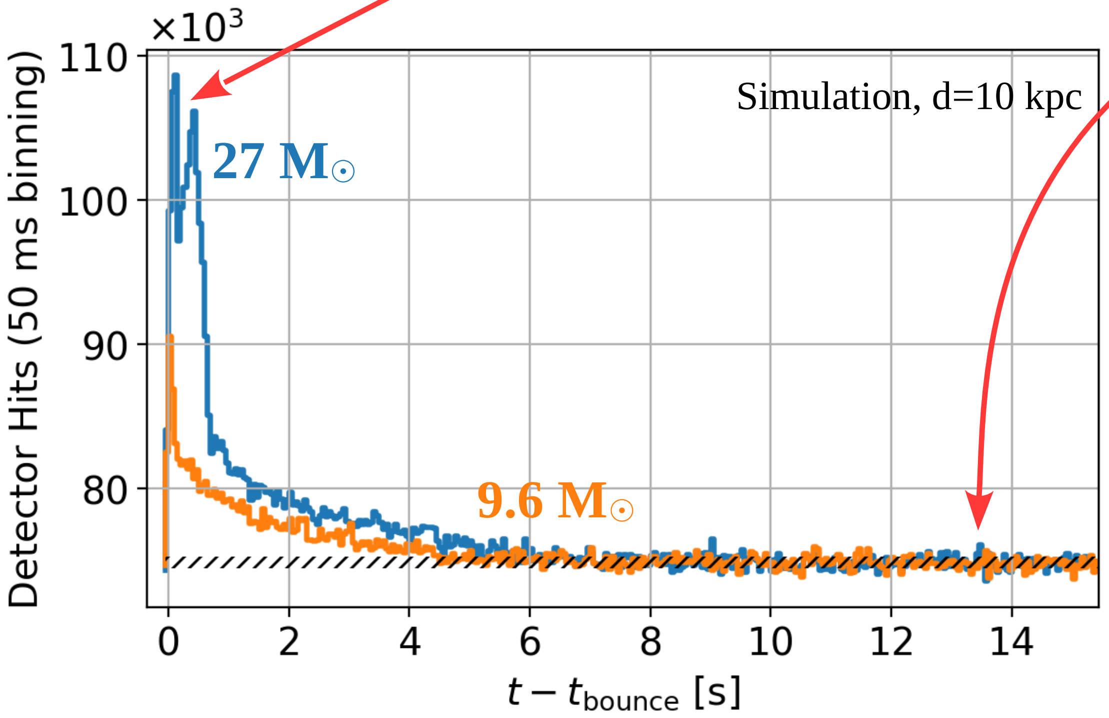
IceCube can detect Core Collapse Supernovae (CCSNe)



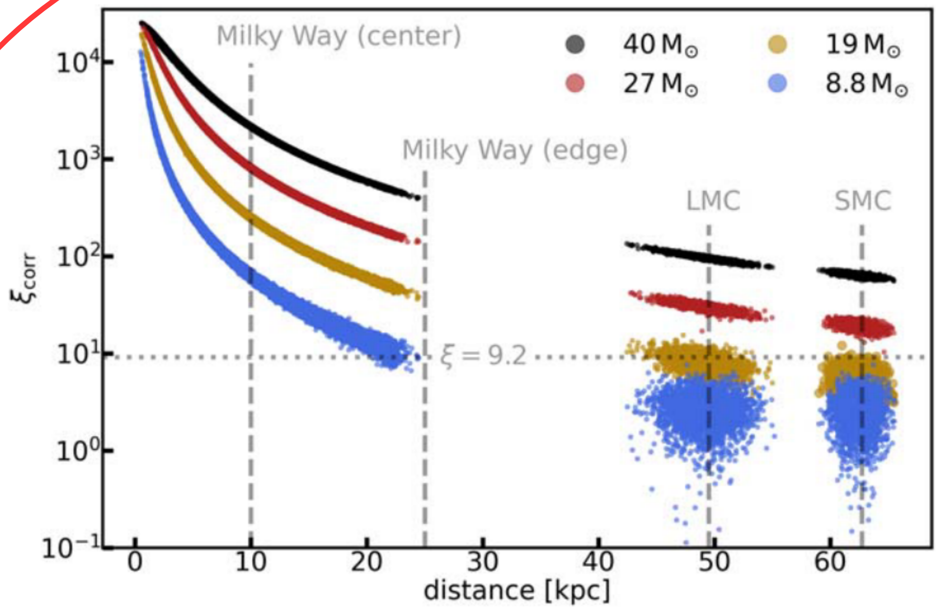
short tracks visible in single modules

See Nora’s talk from Monday

Detection: Excess of detection rate over the background



Abbasi et al. 2024

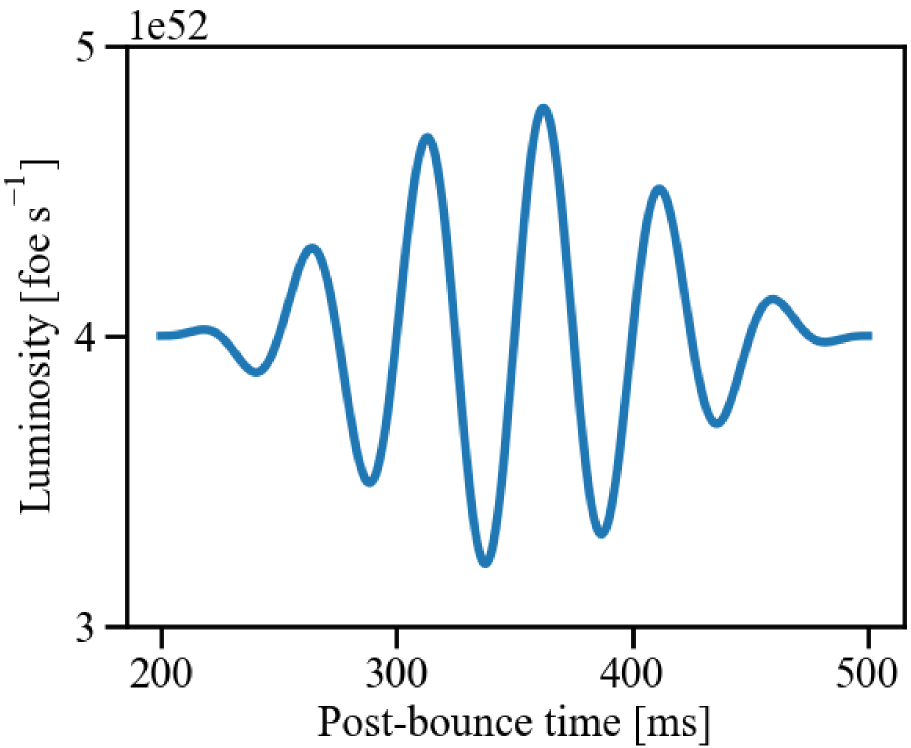


→ IceCube has sensitivity >10σ to detect a galactic CCSN within the Milky Way

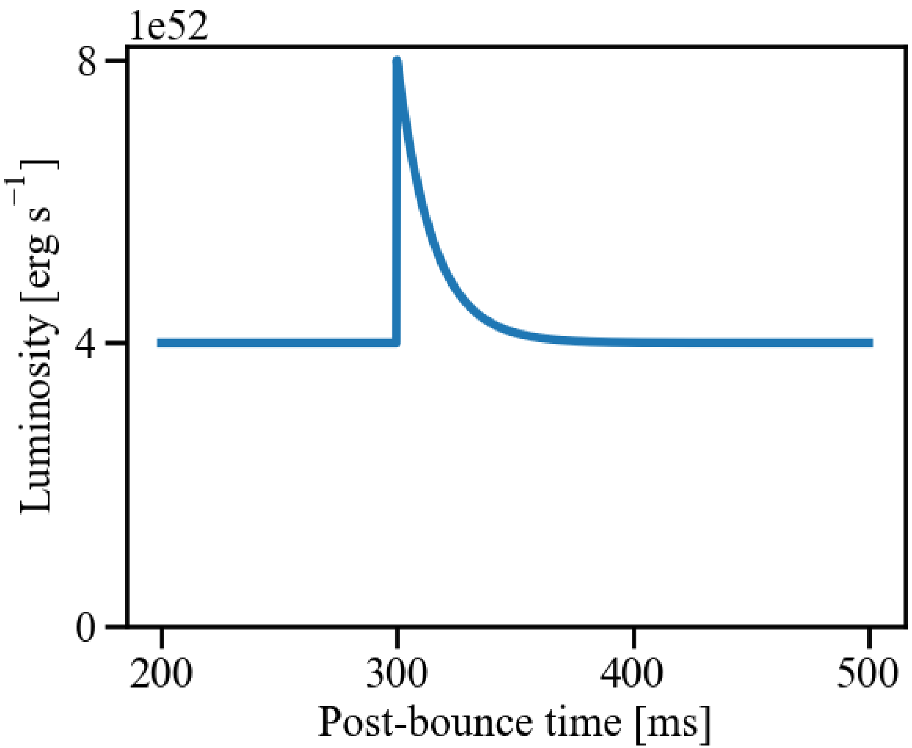
→ What sensitivity do we have for details in the neutrino lightcurve?

Fast-time feature overview

Periodic features

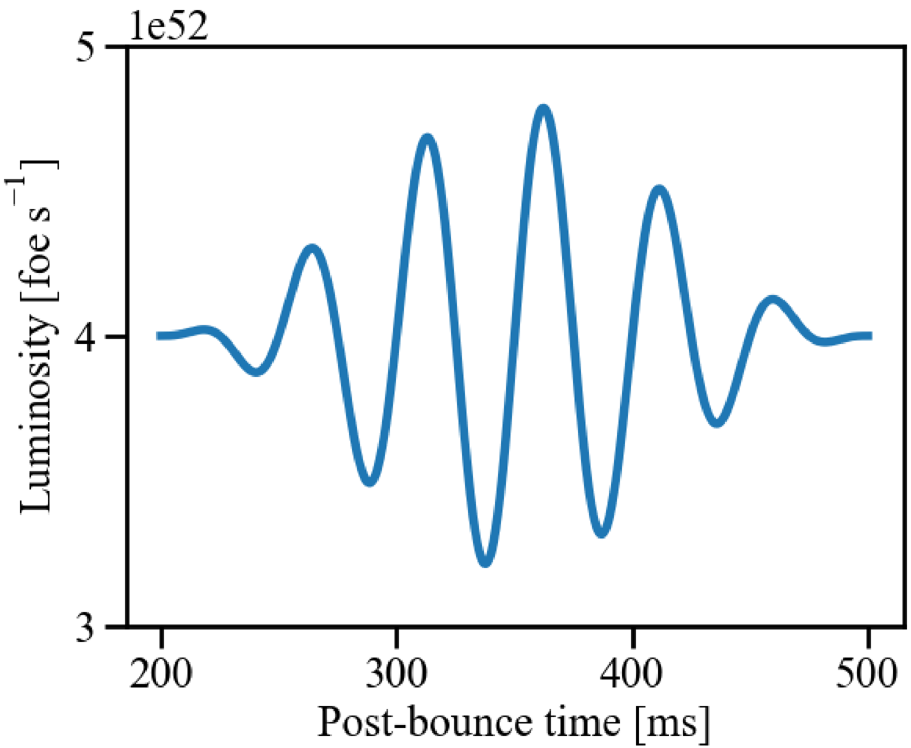


Sharp features

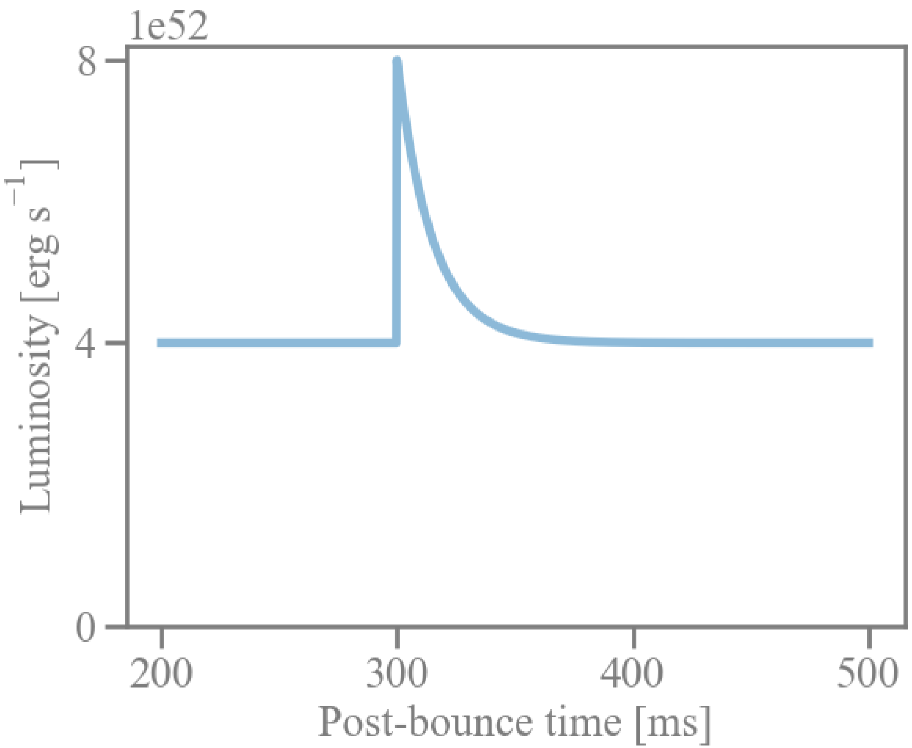


Fast-time feature overview

Periodic features



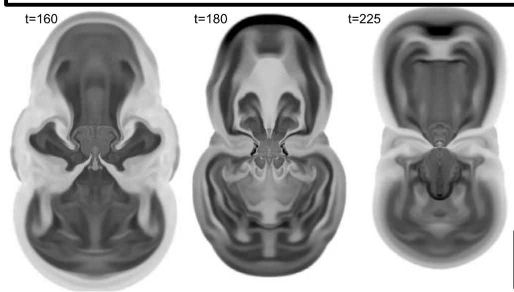
Sharp features



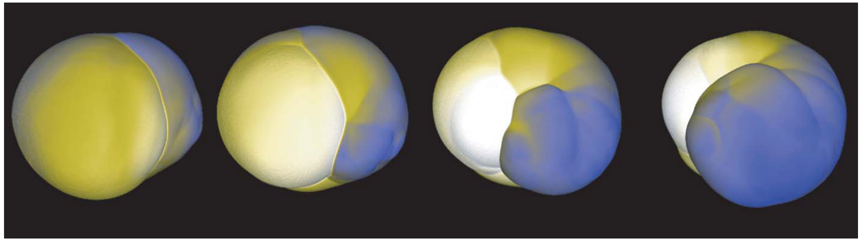
Example I: Standing Accretion Shock Instability

- Sloshing of neutrinos spheres by large-scale, convective streams
- Periodic modulations of the neutrino luminosity and mean energy (~O(100 ms) duration, 50-400Hz frequency, ~10% relative amplitude)
- Detectable at 5σ up to 10-25 kpc [Beise et al. 2023]

2D dipole mode/ 3D spiral mode

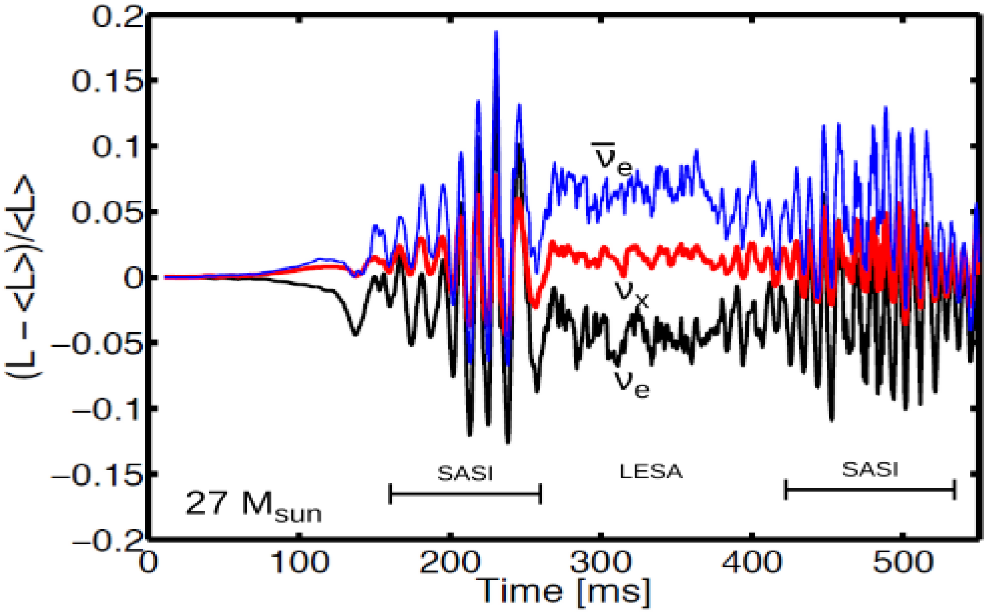


Blondin et al. 2003



Blondin & Mezzacappa 2007

Luminosity variations of the 27M$_o$ model



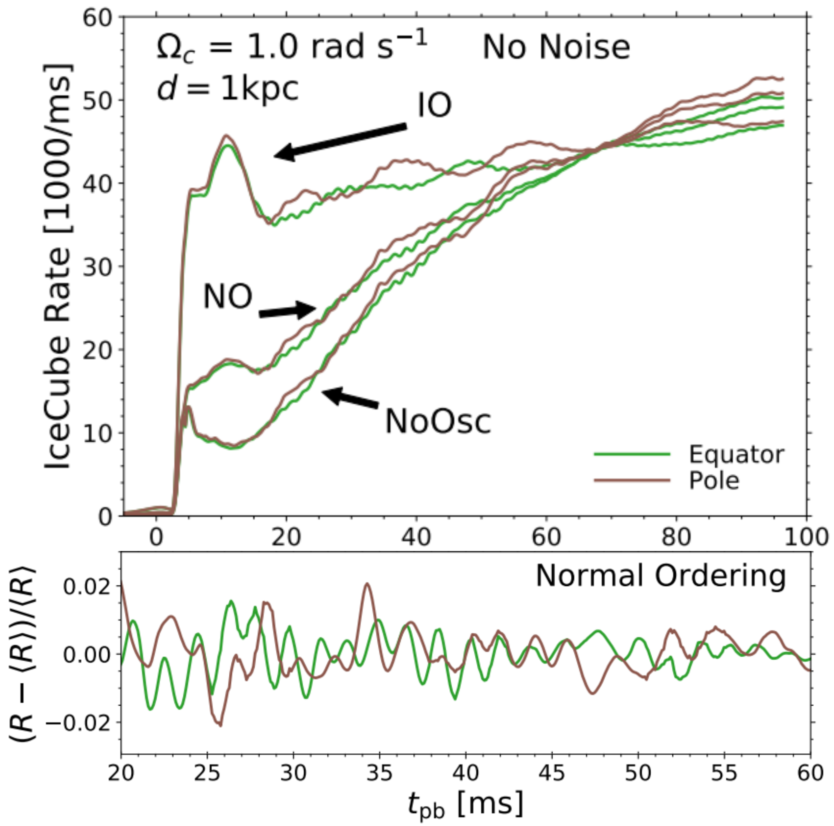
Tamborra et al. 2014

von Zuydtwyck 2015

Example II: Rotating CCSNe

- Fast rotation of the CCSN prior to the explosion can produce a dual imprint on gravitational waves and neutrinos
- Periodic modulations of the neutrino luminosity and mean energy
  - O(100 ms) duration
  - ~550 Hz frequency
  - 1-2% relative amplitude
- Detectable up to 1 kpc

→ Sensitivity to fast-time features **extremely model-dependent**



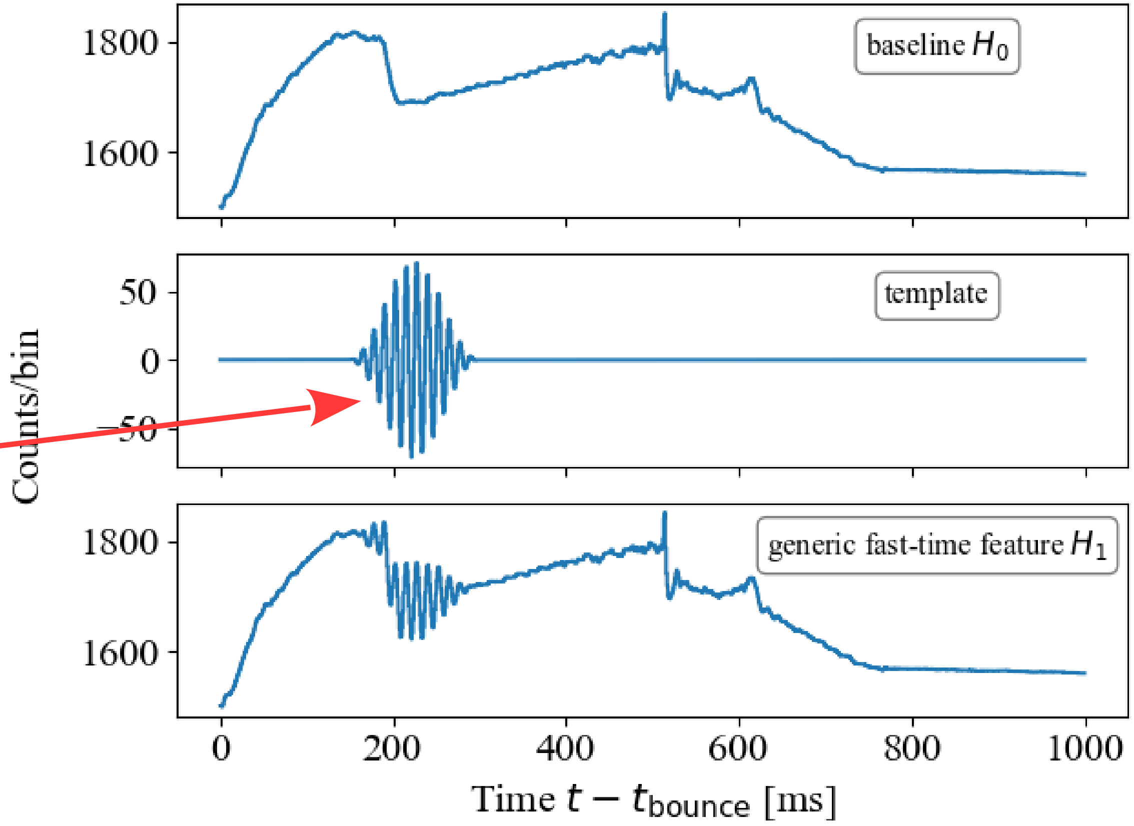
Westernacher-Schneider et al. 2019

Generic, periodic modulations

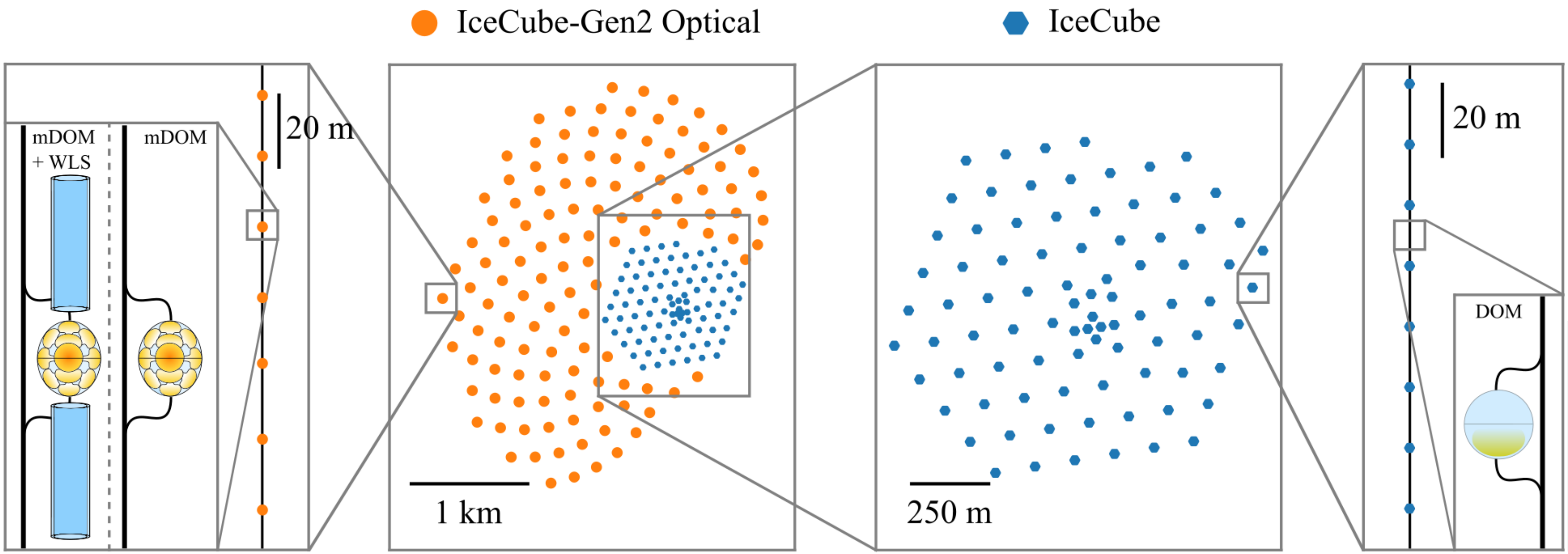
Recently published in PRD!

- New: **generic, model-independent** approach to quantify IceCube's and IceCubeGen2's sensitivity to periodic modulations
- Use hypothesis test to distinguish fast-time feature from flat lightcurve
- **Periodic feature:**
  duration ΔT=150 ms
  amplitude A ∈ [2.5,50]%,
  frequency f ∈ [60, 400] Hz
  baseline model: Sukhbold 2015
  no neutrino oscillation considered

Default model (ΔT=150 ms, f=80 Hz, A=20%)



Detector geometries

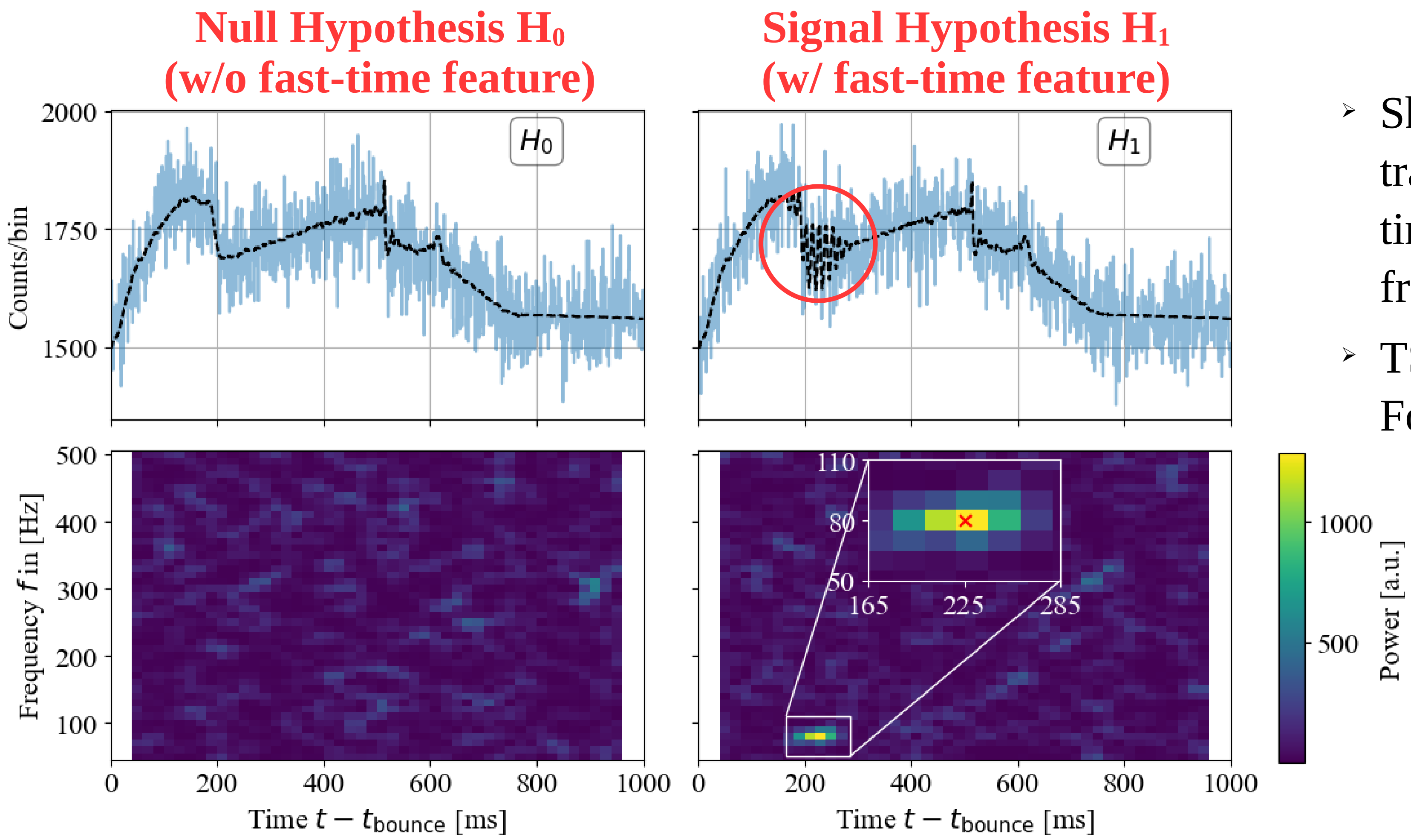


Beise et al. 2025

- IceCube-Gen2: IceCube baseline + 10,000 multi-PMT sensors
- Additional wavelength-shifting tubes further enhance light collection at low additional noise
- IceCube detector response simulated with ASTERIA

Hypothesis test

Beise et al. 2025

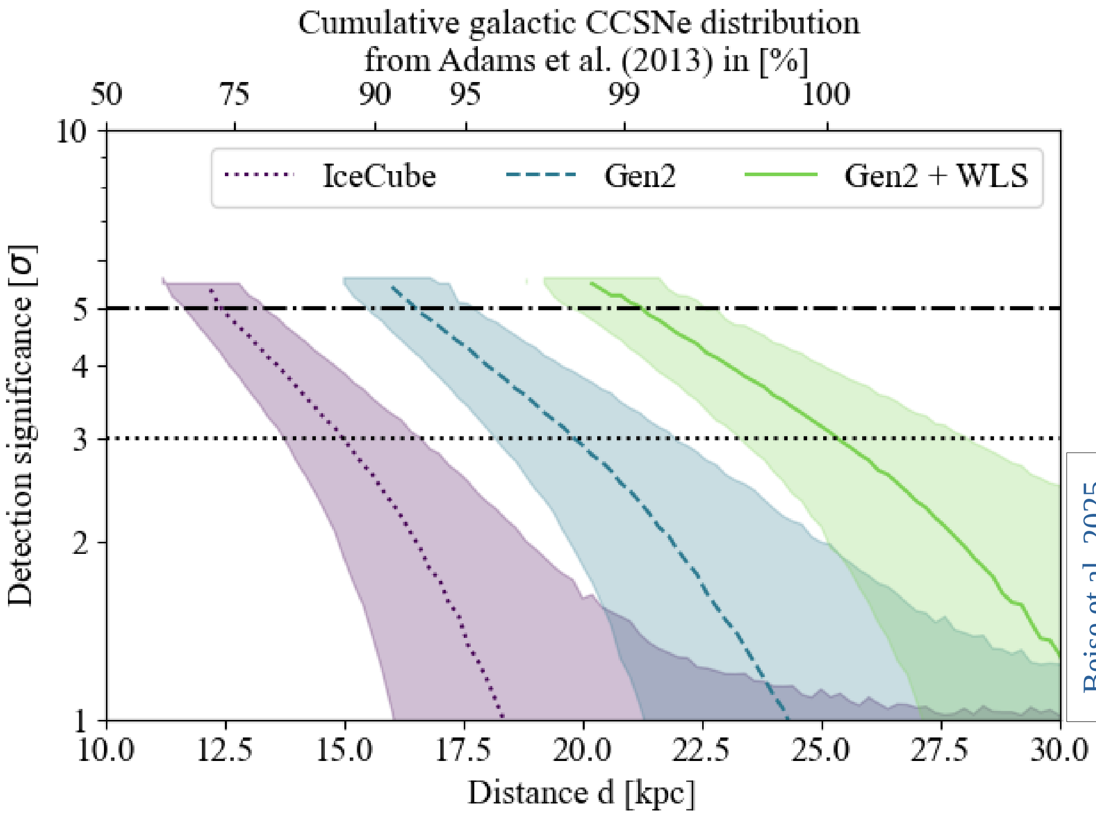


- Short-time Fourier transform reveals time-dependent frequency content
- TS ~ hot spot in Fourier transform

Detection significance and detection horizon

- Detection significance reduces with distance[2]
- Detection horizon = distance at which significance falls below threshold of 3σ (5σ)

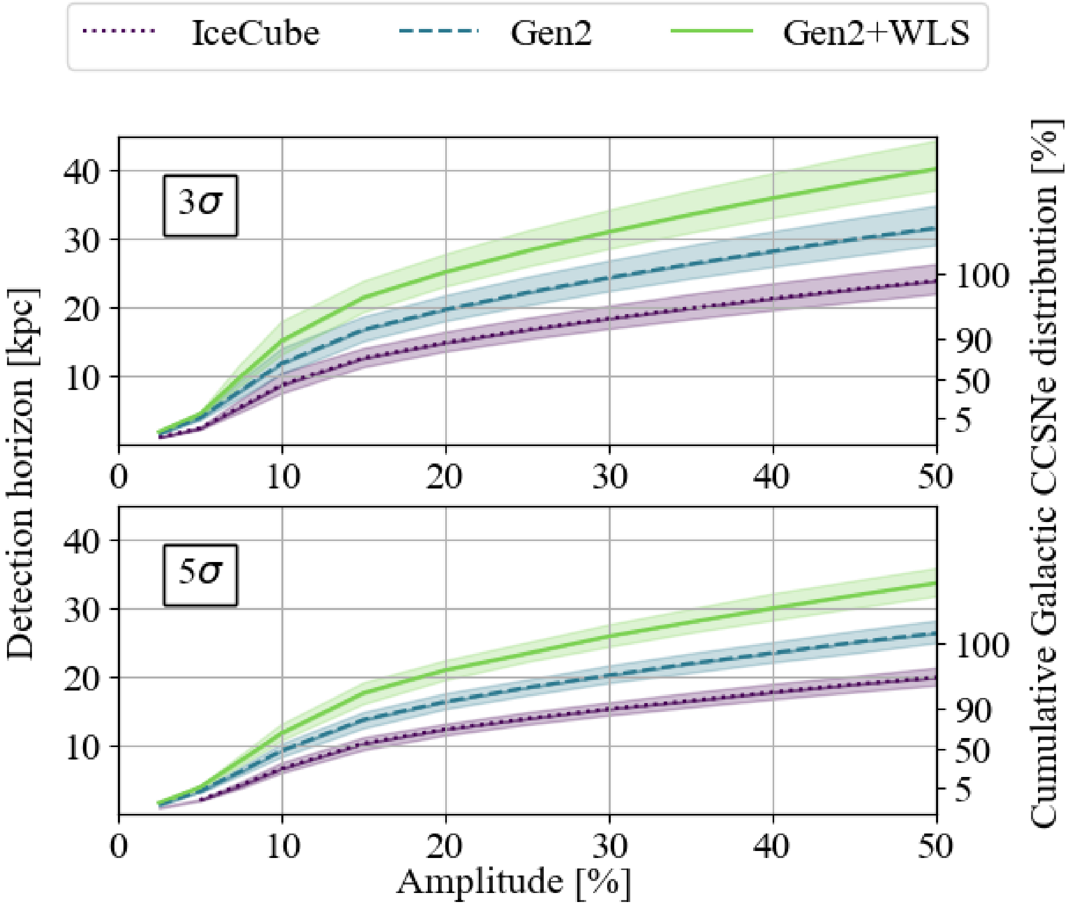
Detection significance for the baseline model



Beise et al. 2025

Results for generic, periodic feature

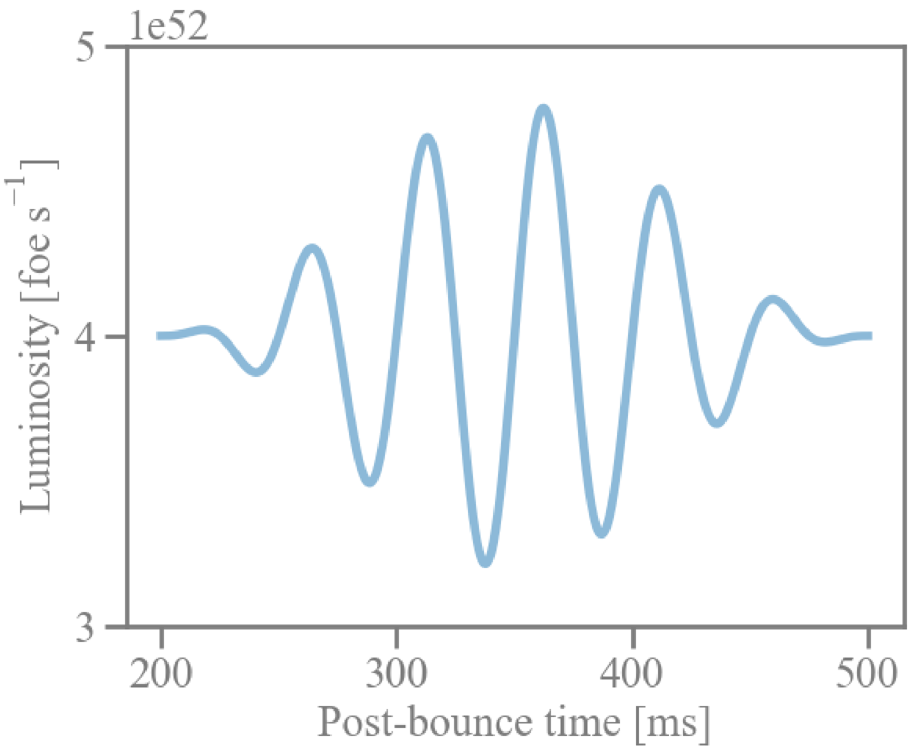
IceCube-Gen2+WLS observes A>20% (A>25%) throughout the entire Milky Way at 3σ (5σ)



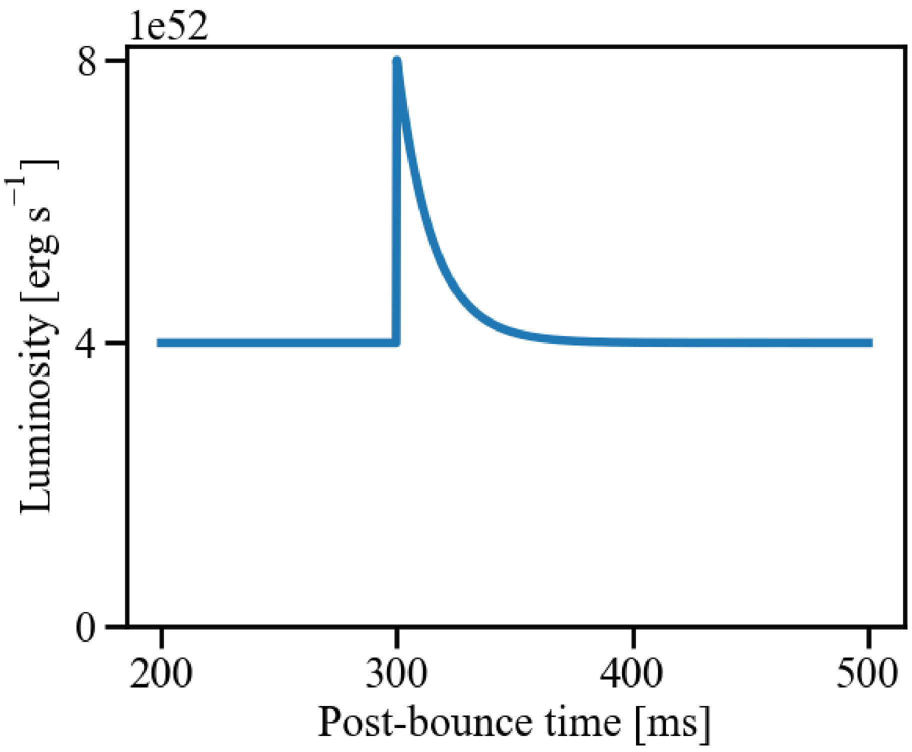
Beise et al. 2025

Fast-time feature overview

Periodic features

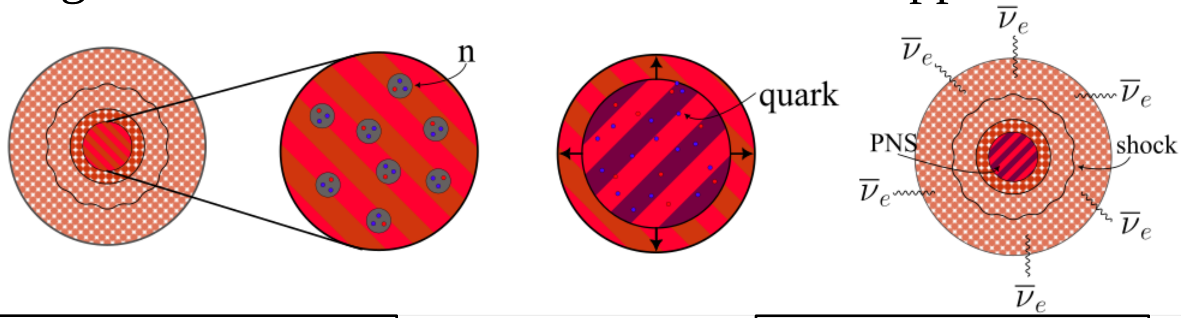


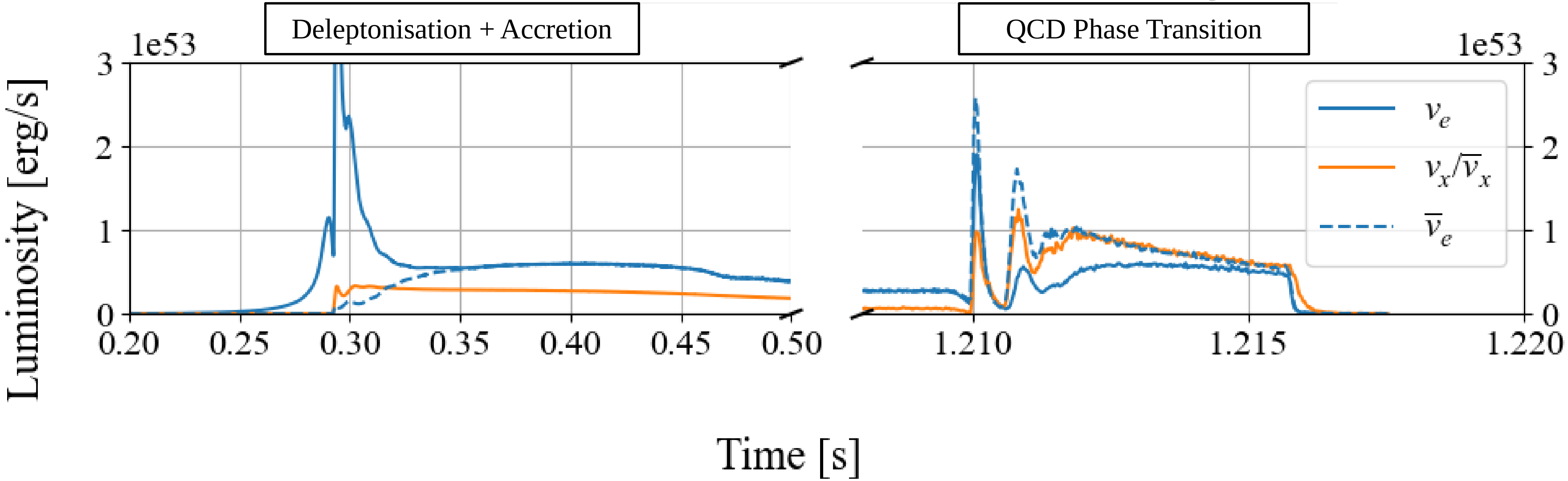
Sharp features



Hadron-quark phase transition could produce burst of ν_e

- Hadron-quark phase transition is a potential shock revival mechanism for some CCSNe
- The second collapse generates a shock wave that releases trapped $\bar{\nu}_e$ in a sudden burst



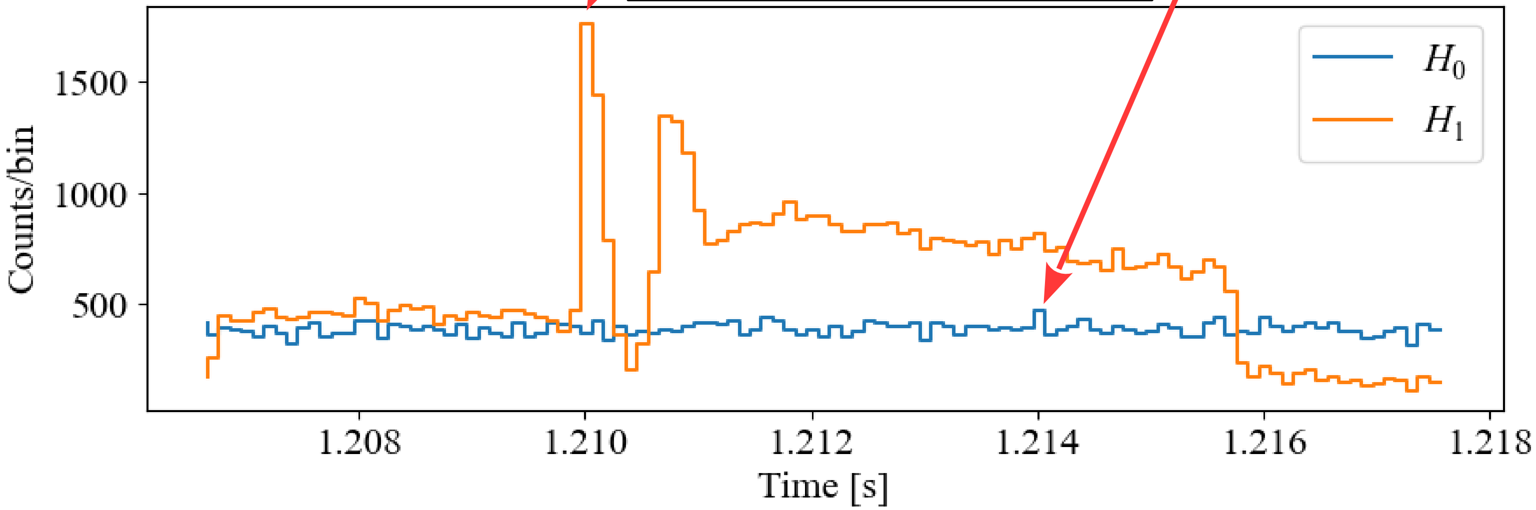


M.Sc. Thesis M. Durán de las Heras, 2025

Models and Analysis method

- Two detailed simulation of QCD phase transition (kindly provided by E. O’Connor):
  - Delayed black hole model RDF-1.7, duration ~ 50 µs
  - Quark star remnant RDF-1.2, duration ~ 100 µs
- Hypothesis test: H_1 = QCD phase transition, H_0 = no phase transition
- Sharp features best extracted by picking the highest amplitude value

Detector hits in IceCube for RDF-1.2



M.Sc. Thesis M. Durán de las Heras, 2025

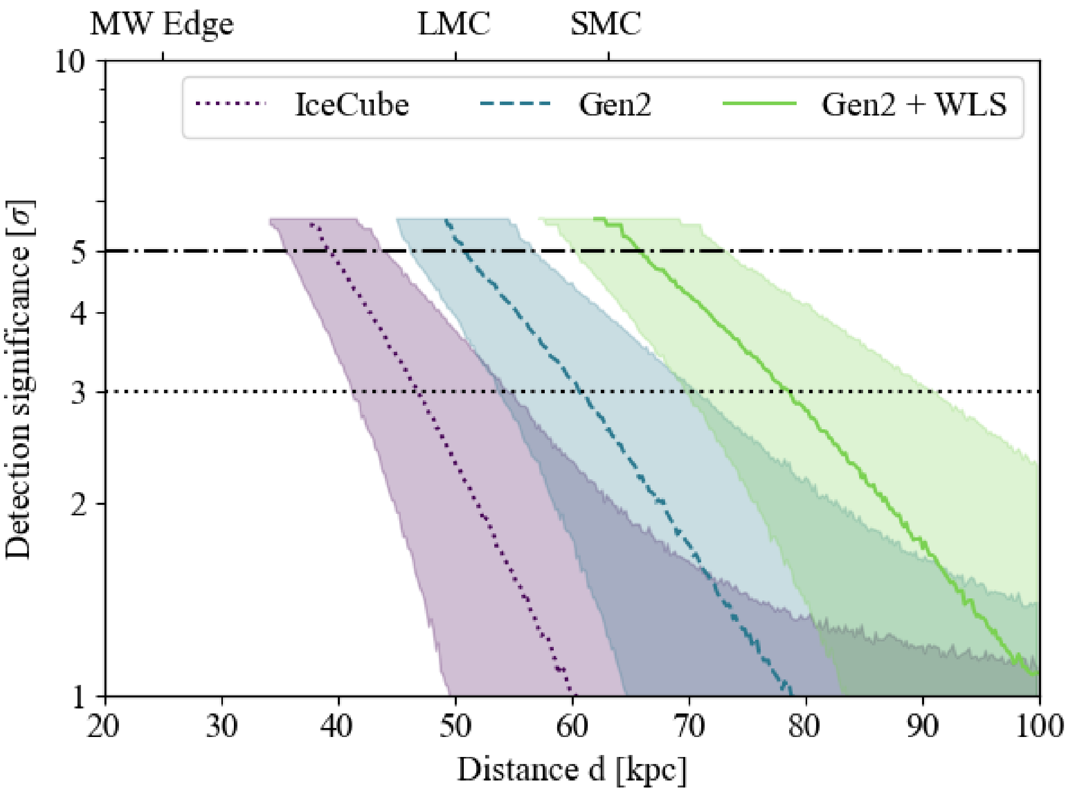
Results for sharp features

M.Sc. Thesis M. Durán de las Heras, 2025

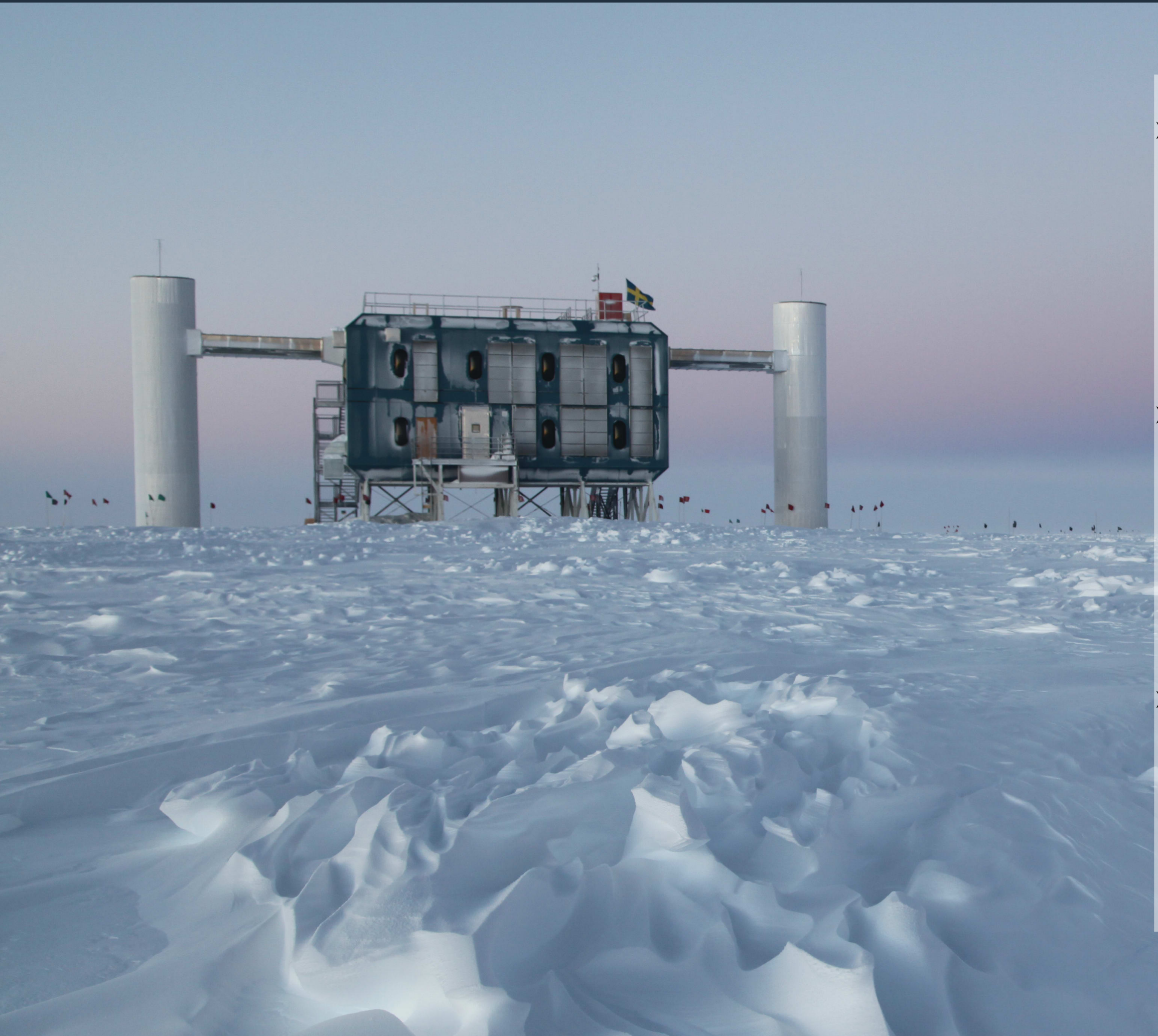
	5σ detection horizon [kpc]	
Detector geometry	Delayed black hole RDF-1.7	Quark star remnant RDF-1.2
IceCube	8.8	39
Gen2	11.0	51
Gen2+WLS	15.2	66

- Quark star remnant RDF-1.2 visible up to the Small Magellanic Cloud (SMC) with Gen2-WLS

Detection significance for RDF-1.2



Conclusion

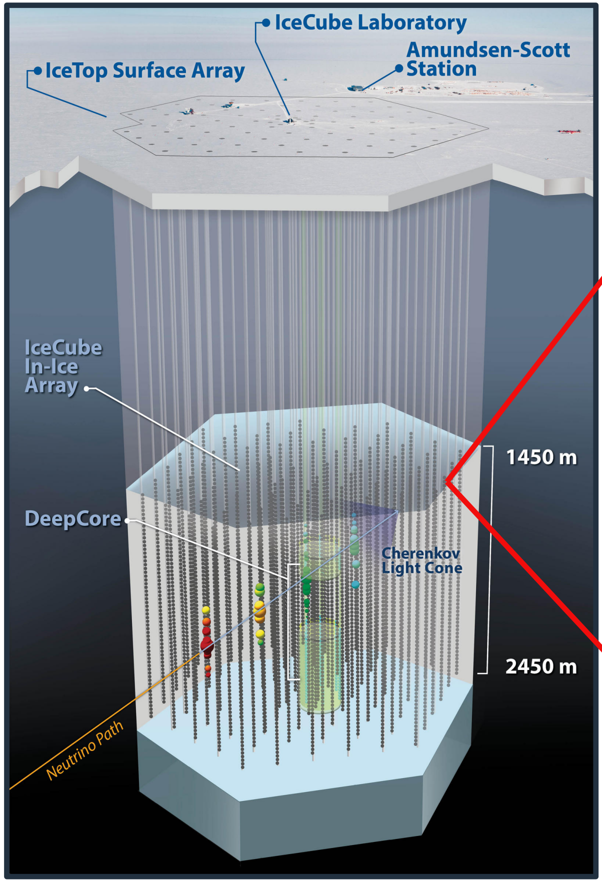


- The next Galactic CCSN will be detected with IceCube or a future extension
- IceCube-Gen2 will detect periodic fast-time features throughout the Milky Way for A>30%
- Sharp features from QCD phase transitions are detectable in IceCube-Gen2 up to the SMC

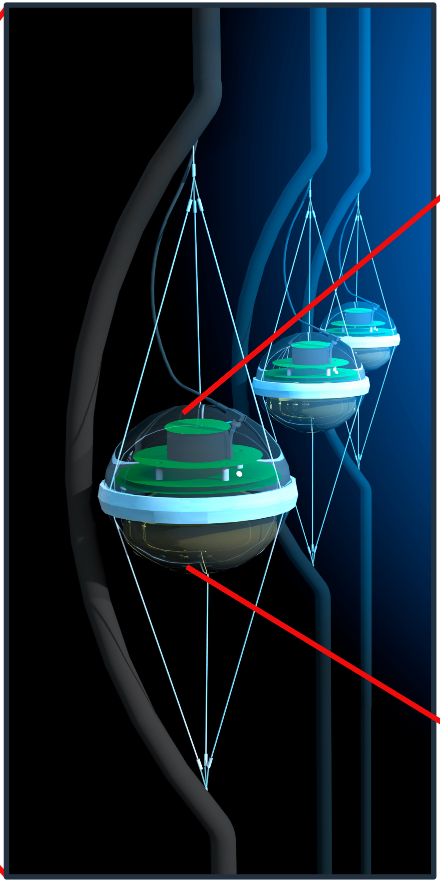

Thank you!

IceCube is a 1 km^3 detector frozen into the South Pole glacier

5160 sensors over 1 km^3 (1 Gton)

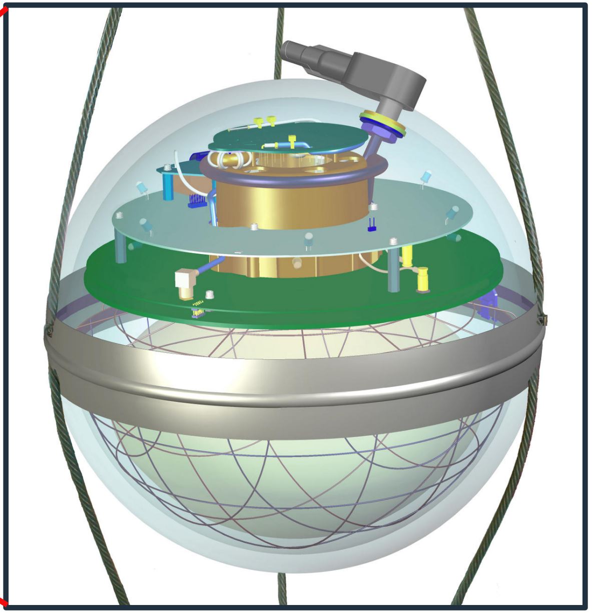


86 cables (“strings”)

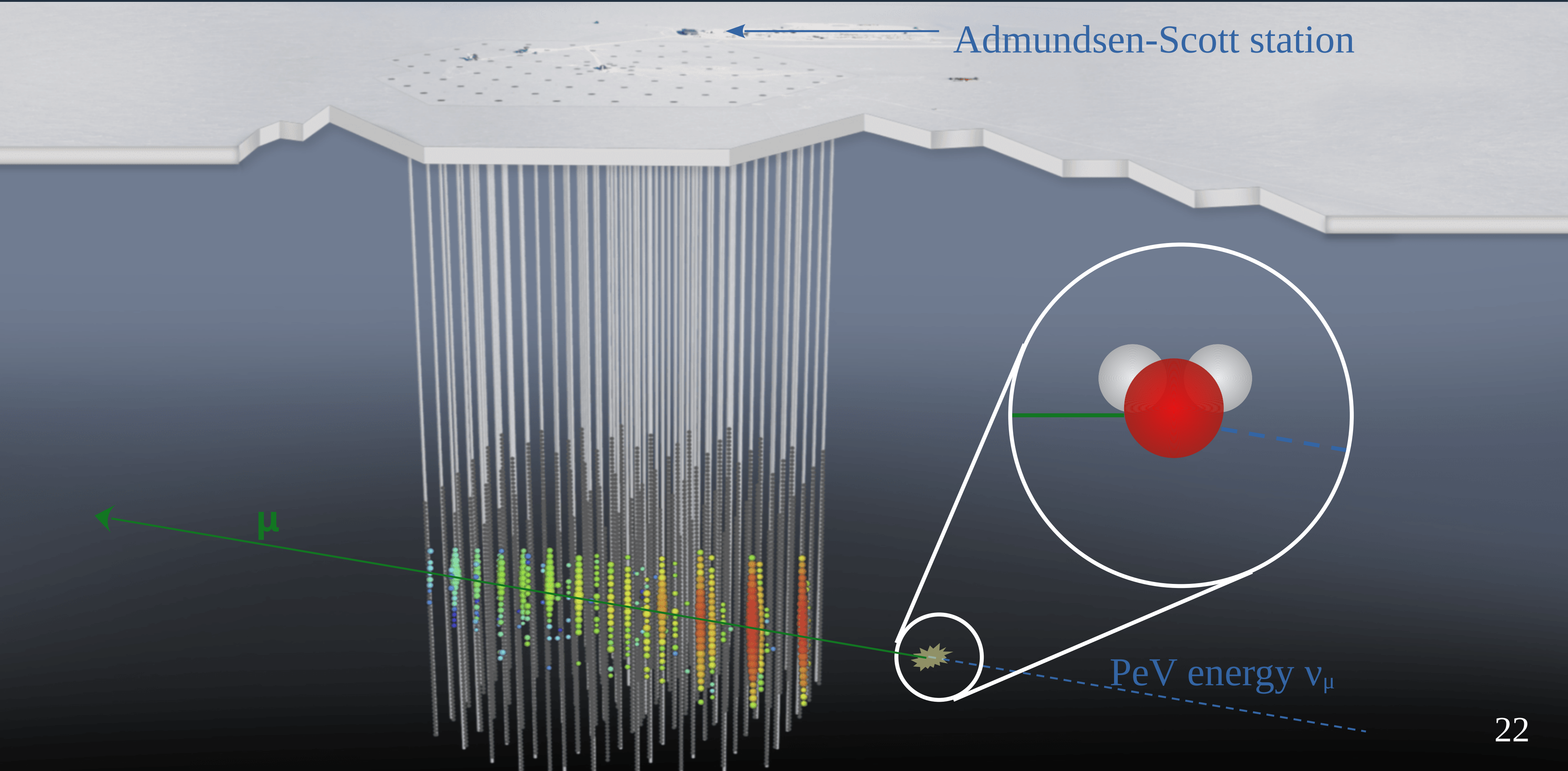


Digital Optical Module (DOM)

25 cm down-wards facing PMT



IceCube detects the Cherenkov light from charged secondaries

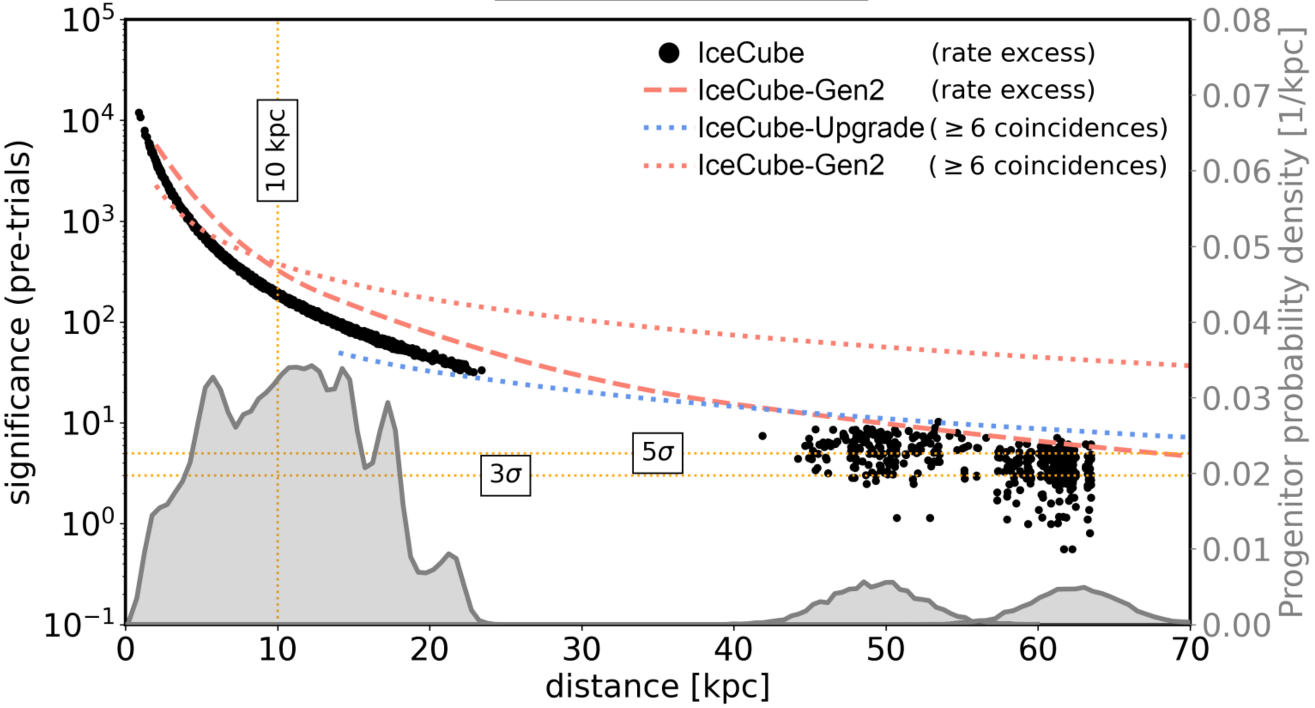


Segmented sensors can reduce noise

Requiring local coincidences between PMTs of the same sensor efficiently reduces sensor noise

Lozano Mariscal et al. 2021

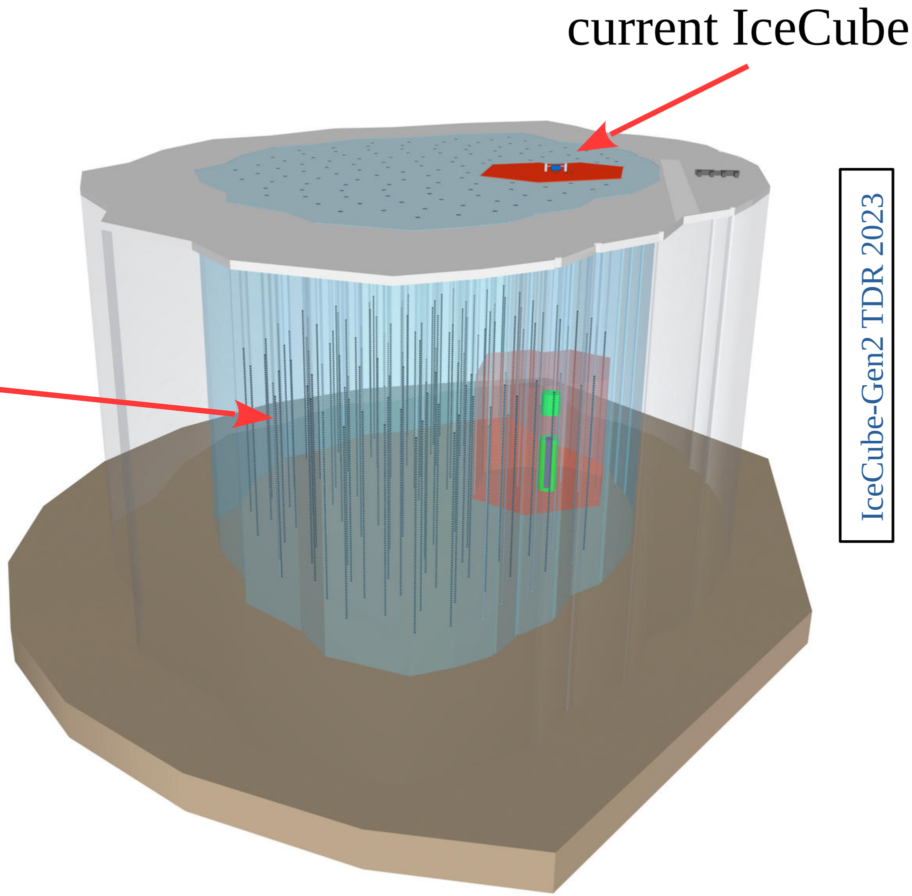
IceCube-Gen2 TDR 2023



Local coincidences can extend the sensitivity to the entire Milky Way + LMC + SMC

More sensors will increase sensitivity

10,000
new photo-
sensors
over 120
new strings

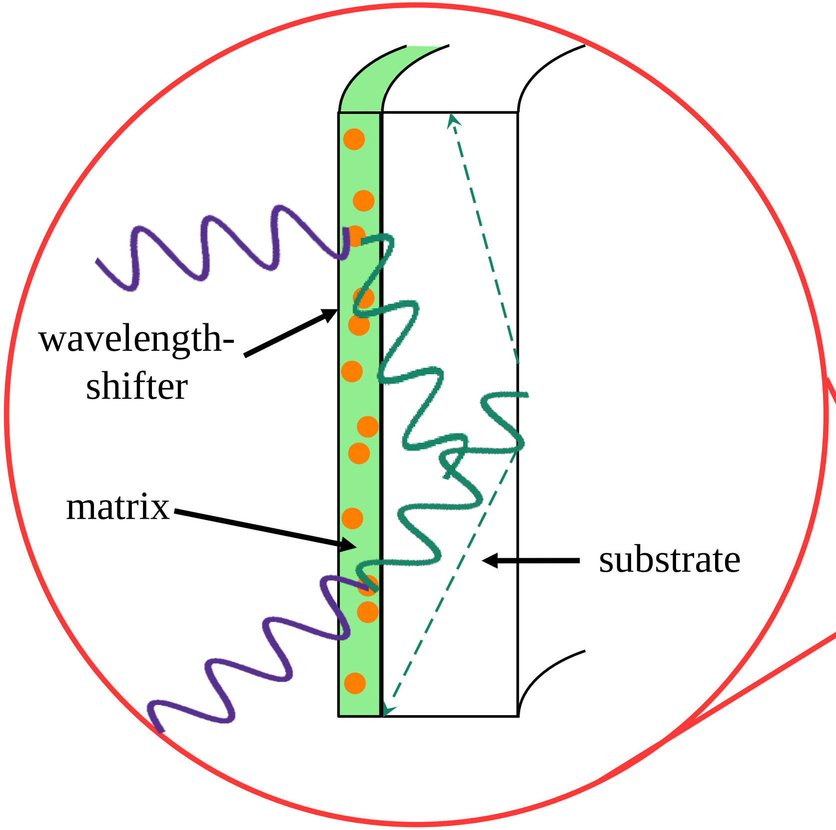


IceCube-Gen2 TDR 2023

Wavelength shifters improve photon collection

Advantages:

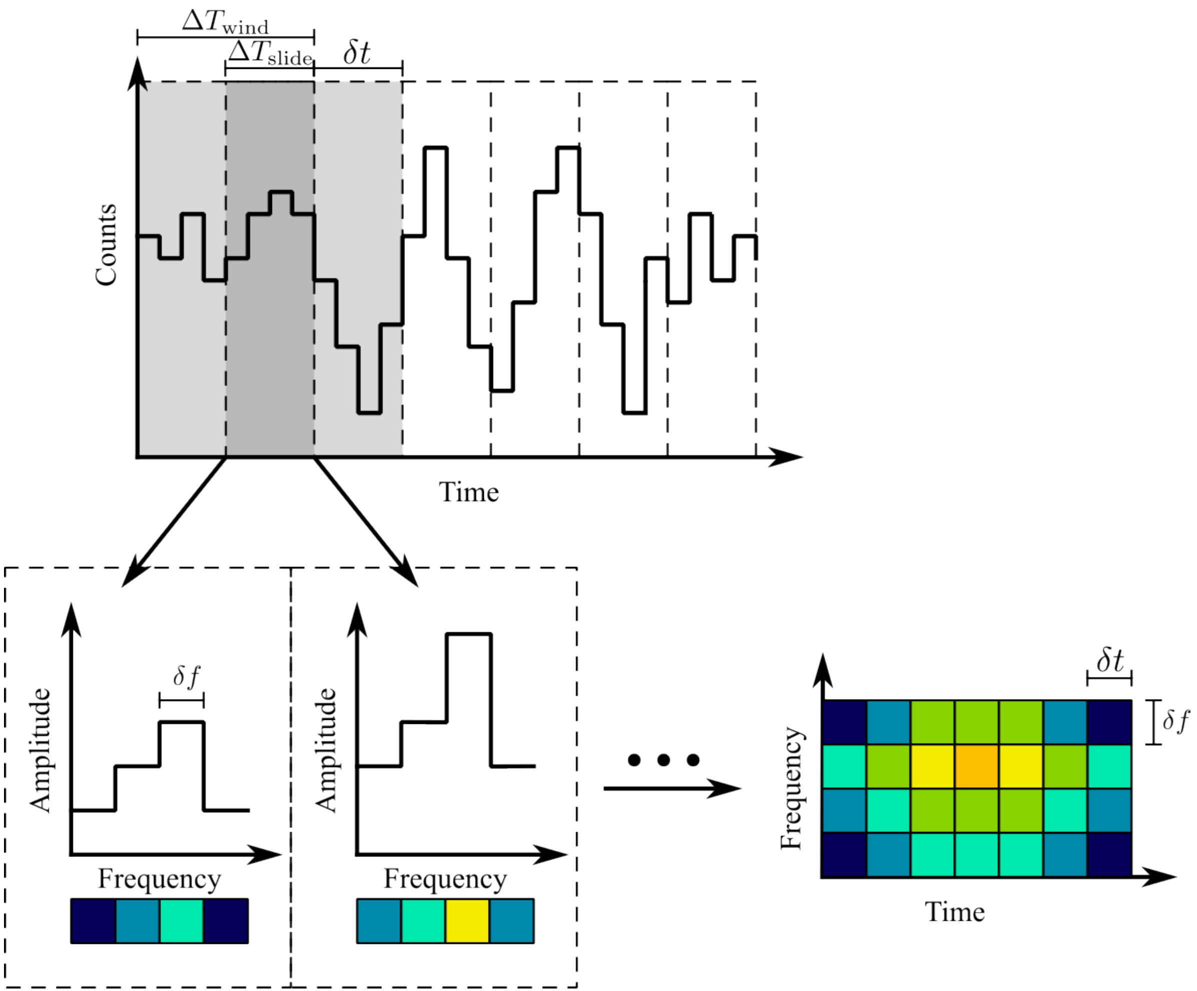
- Low-cost add-on
- Increase photo collection
- Extend acceptance to UV
- Less sensor noise than additional PMTs



Bastian-Querner et al. 2022

Improved photon collection
→ Improved measurement of the CCSNe signal

Short Time Fourier Transform



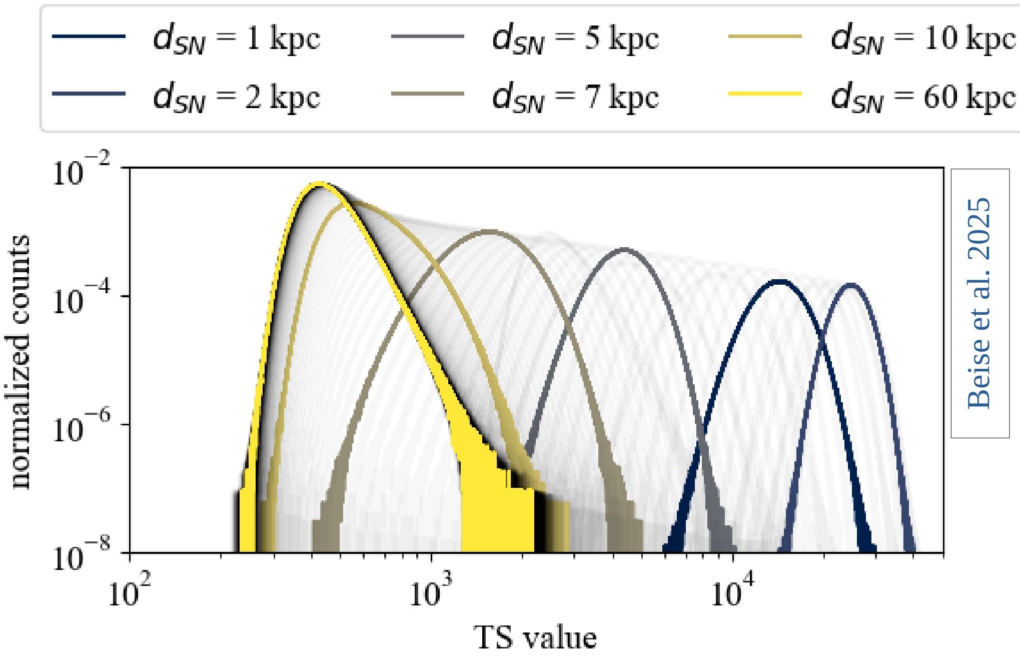
Beise et al. 2025

- Δt_{win}=100 ms sliding window of Δt_{slide}=20 ms stride
- δt=20 ms, δf=10 Hz
- 1 ms time binning fixed for analysis but finer binning possible (IceCube can extract ns timestamps for a CCSN event)

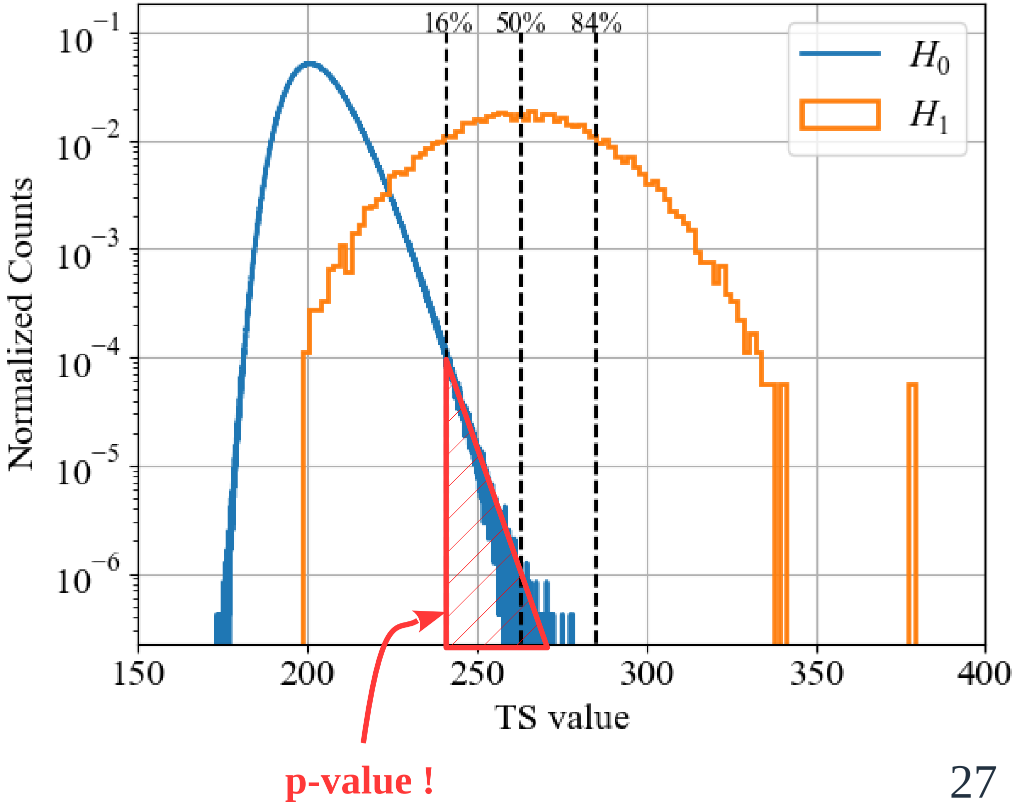
Background TS trials and p-value

- Pre-generate high-statistics TS distribution for H_0 (10^8 trials)
- Modes of distribution statistically more stable
  → "only" 10^4 trials for H_1

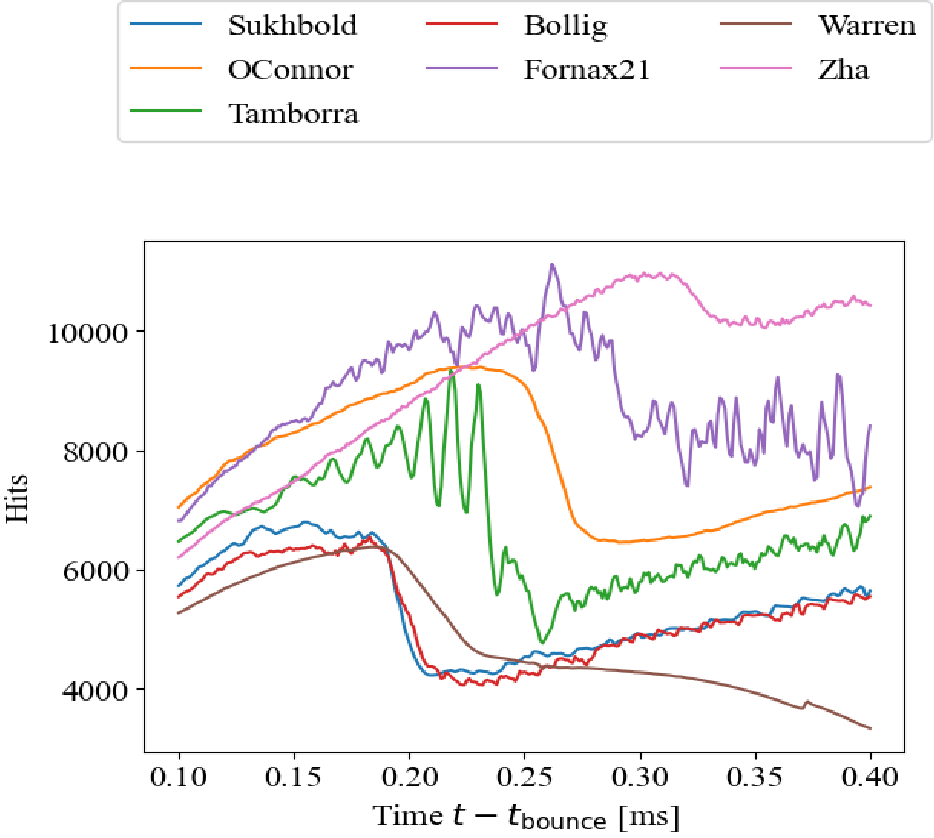
TS_{H0} at various distances



TS_{H0} and TS_{H1}

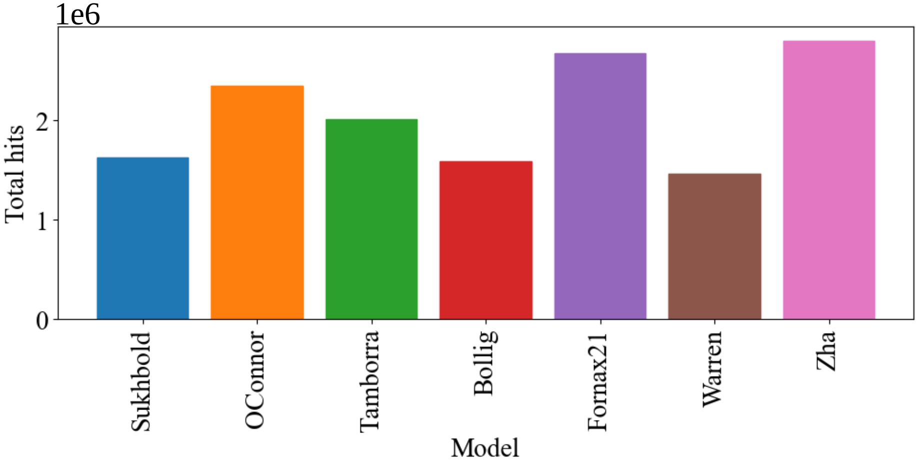


Model uncertainties



Model	5σ Detection horizon [kpc]		
Uncertainty	IceCube	Gen2	Gen2+WLS
Default	$12.4^{+0.8}_{-0.8}$	$16.4^{+1.2}_{-1.0}$	$21.0^{+1.5}_{-1.4}$
$\Delta T = 50\,\mathrm{ms}$	$6.8^{+0.9}_{-0.7}$	$9.4^{+1.2}_{-0.9}$	$12.0^{+1.5}_{-1.1}$
$\Delta T = 250\,\mathrm{ms}$	$13.1^{+0.9}_{-0.7}$	$17.4^{+1.2}_{-1.0}$	$22.4^{+1.5}_{-1.3}$
Complete Exchange	$10.4^{+0.8}_{-0.6}$	$13.7^{+1.0}_{-0.8}$	$17.6^{+1.3}_{-1.0}$
Adiabatic MSW NH	$11.4^{+0.8}_{-0.7}$	$15.0^{+1.1}_{-0.9}$	$19.3^{+1.4}_{-1.1}$
Adiabatic MSW IH	$10.4^{+0.8}_{-0.6}$	$13.7^{+1.0}_{-0.8}$	$17.7^{+1.2}_{-1.0}$

Beise et al. 2025



Sukhbold 2015 baseline model yields conservative detector rates as compared to other baselines