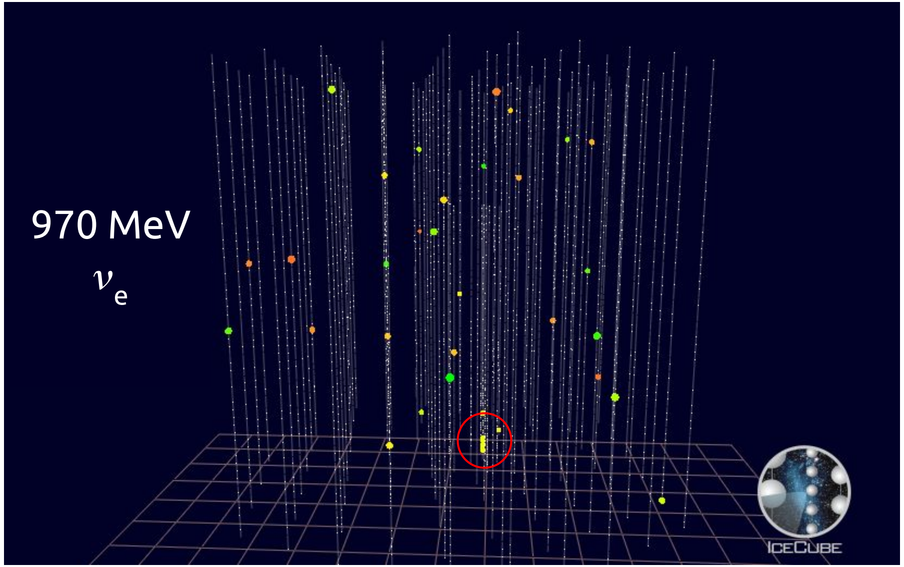
Low GeV neutrino follow-up of transient events with IceCube

Karlijn Kruiswijk on behalf of the IceCube Collaboration

Content

- Current GeV selection
- Transient follow-up
- Improvements to the GeV selection



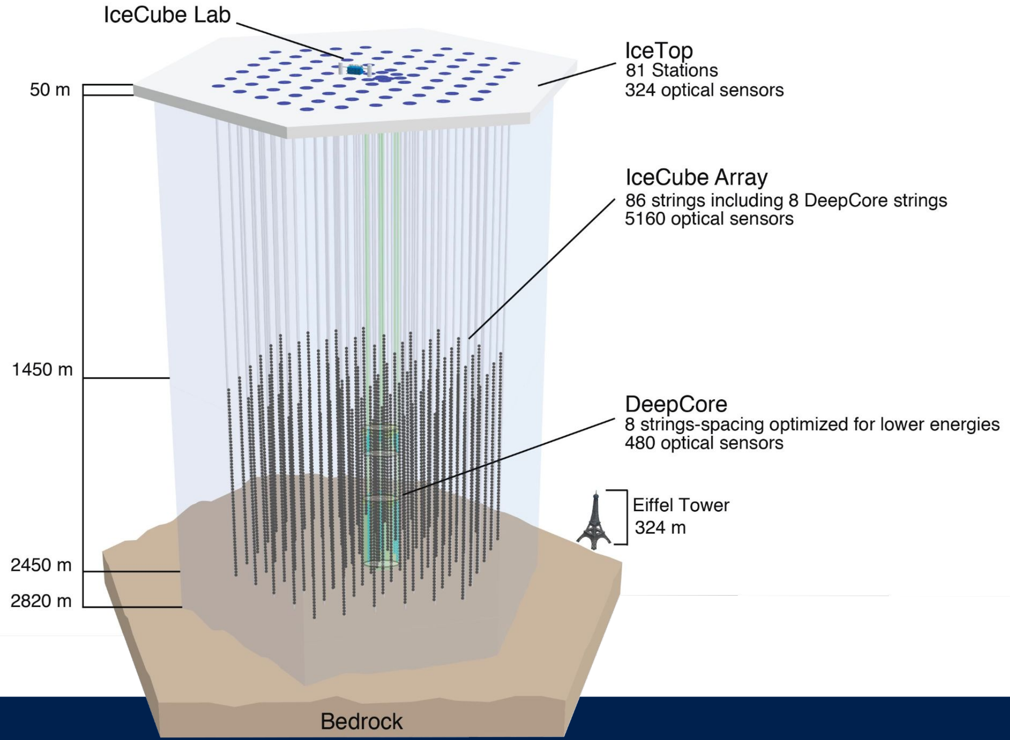
Observing neutrinos in IceCube

Cherenkov radiation can be observed by 5160 PMTs

Optimized for TeV neutrinos

DeepCore optimized for sub-TeV neutrinos

- More sensitive PMTs
- PMTs closer together

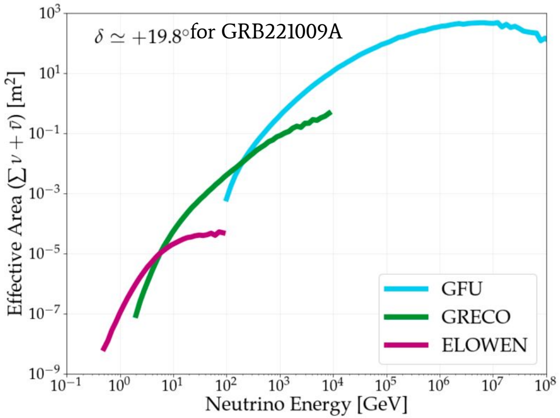


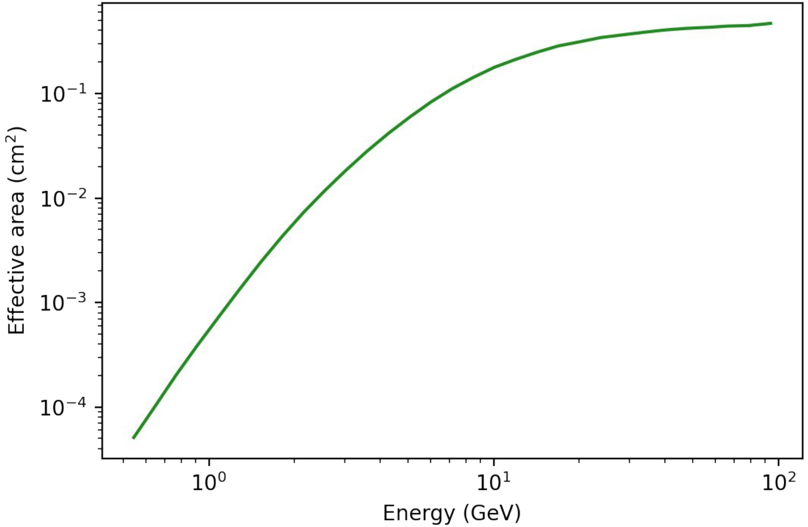
The ELOWEN selection

Lowest energy for observing single neutrino events

Specialized for 0.5 - 5 GeV

Consists of several hard cuts on low-level variables to remove both noise and high-energy events



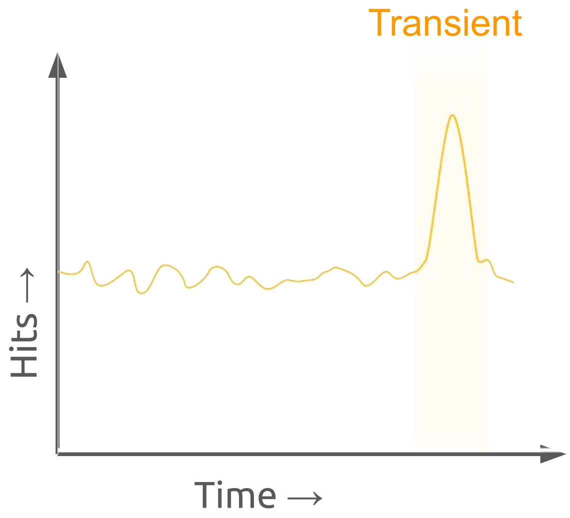


Multi-messenger follow up with ELOWEN

Compare number of neutrino candidates during transient event to background

Search for neutrinos from transients:

- Solar flare searches
- Gravitational wave follow up
    - Catalog search of O1-O3
    - Currently ongoing for O4
- GRB 221009A

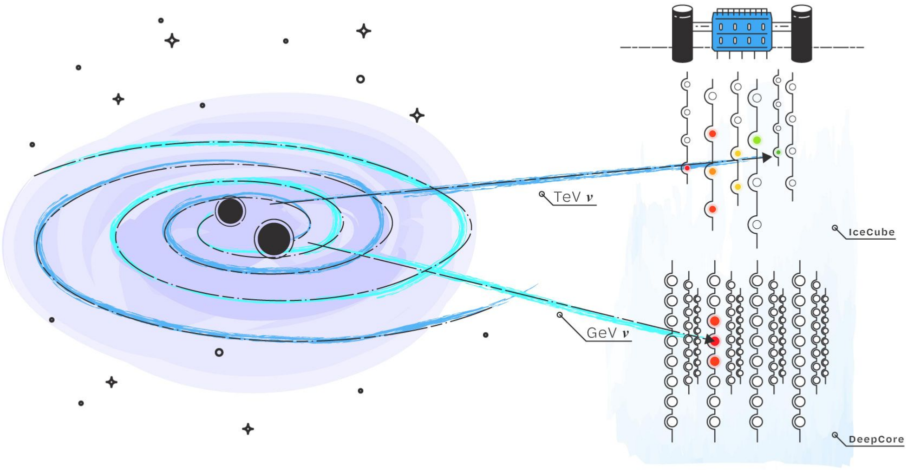


Gravitational wave follow-up

Neutrinos can come from p-n interactions.

2 Time Windows:

- ± 500 s around merger time
- 3 s starting at merger time
  - only for BNS and NSBH



Compare to background distribution: data when no transient events were detected (GRB, GW, solar flares)

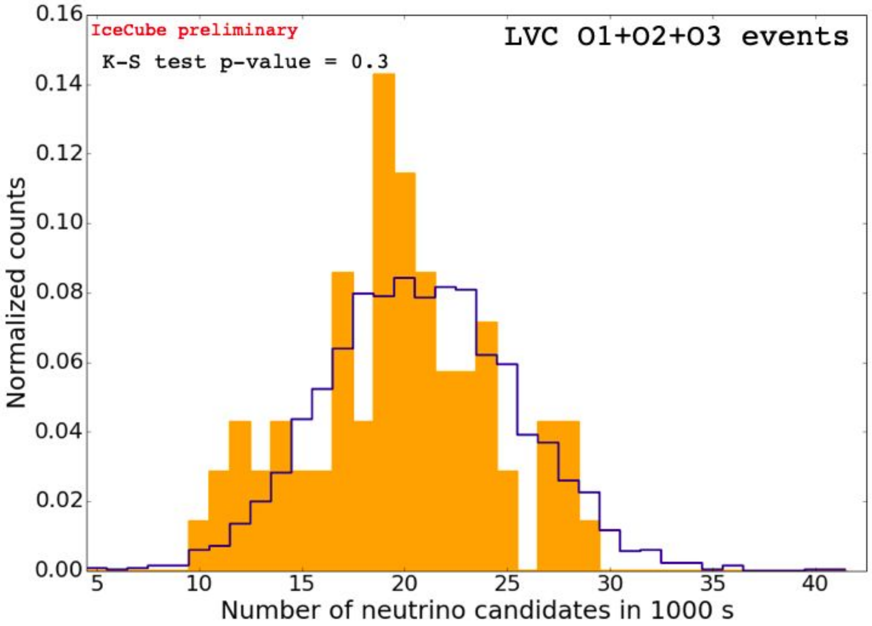
O1-O3 Follow up

72 merger candidates

Results consistent with background

Upper limits:

- $1.2 \cdot 10^4\ \mathrm{cm}^{-2}$ for 3s TW
- $3.9 \cdot 10^4\ \mathrm{cm}^{-2}$ for 1000s TW



arXiv:2105.13160

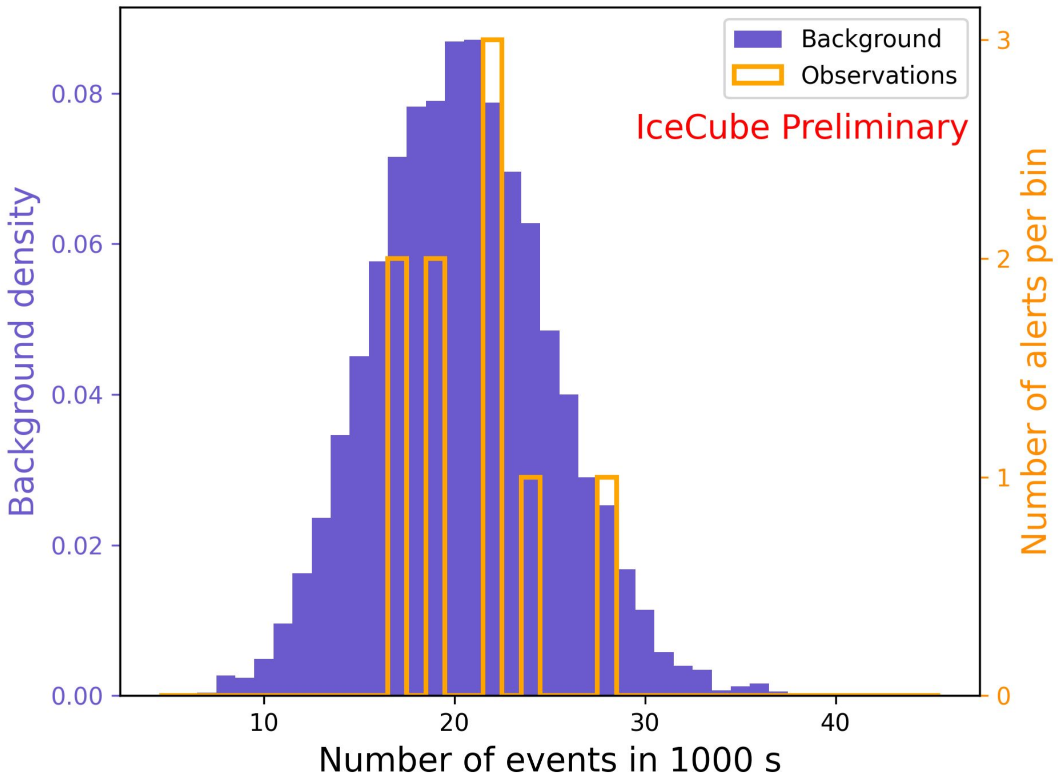
O4 Follow up

Currently ongoing

Offline analysis: no pointing to help with follow up

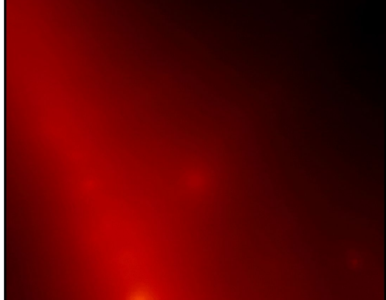
2 NSBH alerts: both 0 neutrinos in 3 s Time Window

So far no significant deviation from background



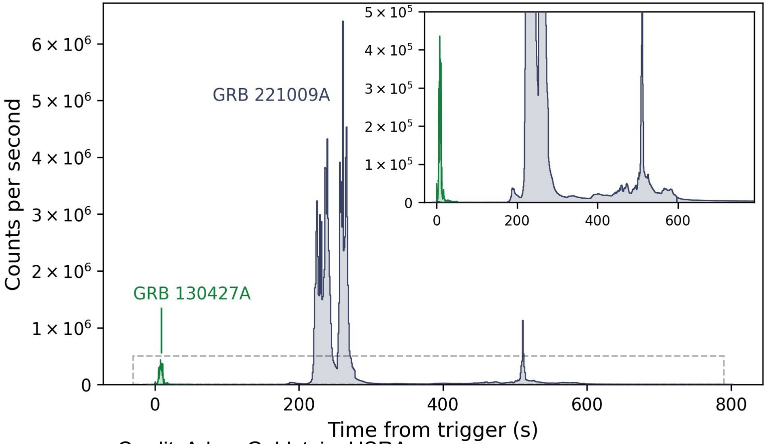
PoS ICRC2023 1571: ArXiv 2307.15902

GRB 221009A:
The Brightest Gamma Ray Burst ever observed



Credit: NASA/DOE/Fermi LAT Collaboration

1. Brightest GRB Observed by Fermi GBM and Fermi LAT
2. Afterglow reported by Swift as a bright X-ray and optical transient
3. Konus-Wind measured the isotropic equivalent gamma-ray energy : $\sim 1.2 \cdot 10^{55}$ erg
4. Detected by LHAASO within 3000 s:
    - Over 64,000 photons
    - Energies between 0.2 TeV and 7 TeV



Credit: Adam Goldstein, USRA

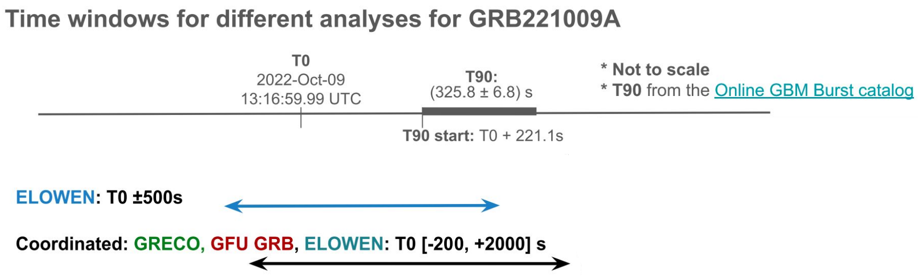
[1] GCN32636 and GCN32642, [2] GCN32632, [3] arXiv:2302.13383, [4] arXiv:2306.06372

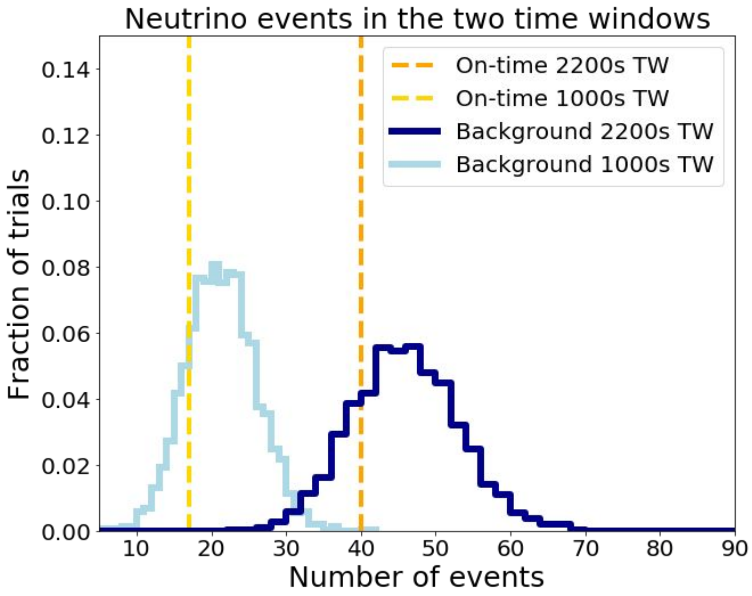
GRB221009A follow-up

- Together with other IceCube searches
  - Covering MeV to PeV
- Time windows:
  - T0[-200s,+2000s] and T0[-500s,500s]
- Search for quasi-thermal neutrinos
  - p-p /p-n interactions

No significant excess of neutrinos found

Can test theoretical model





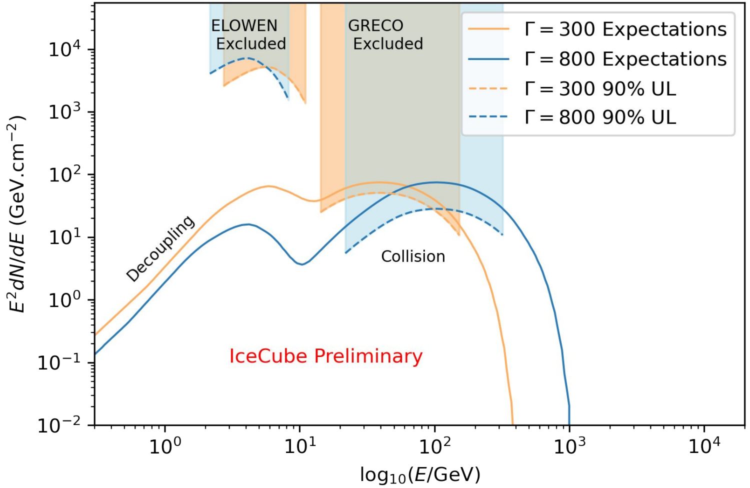
IceCube GRB 221009 analysis: ApJL 946 L26 (2023)

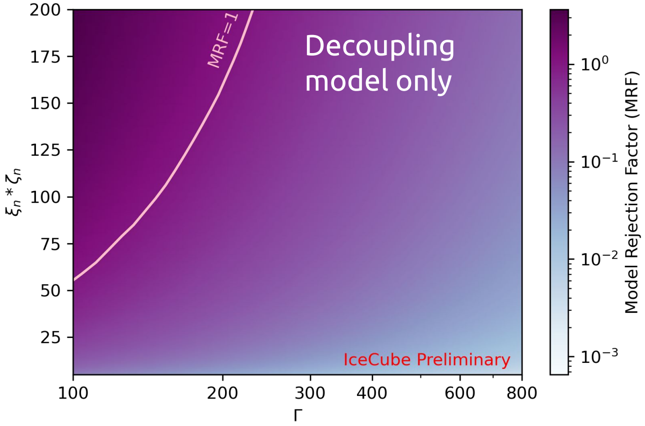
Quasi-thermal Decoupling and Collision models

Created from p-n interactions:

- Decoupling model
  - Neutrons decouple from jet
- Collision model
  - Neutrons collide with subsequent outflow

Decoupling model tested with ELOWEN





Reference: ApJL 941 L10 (2023)

Further plans for follow-up

- Continue with O4
- More Gamma Ray Burst follow-up
  - Stacked over different populations
- Other (short) transient events

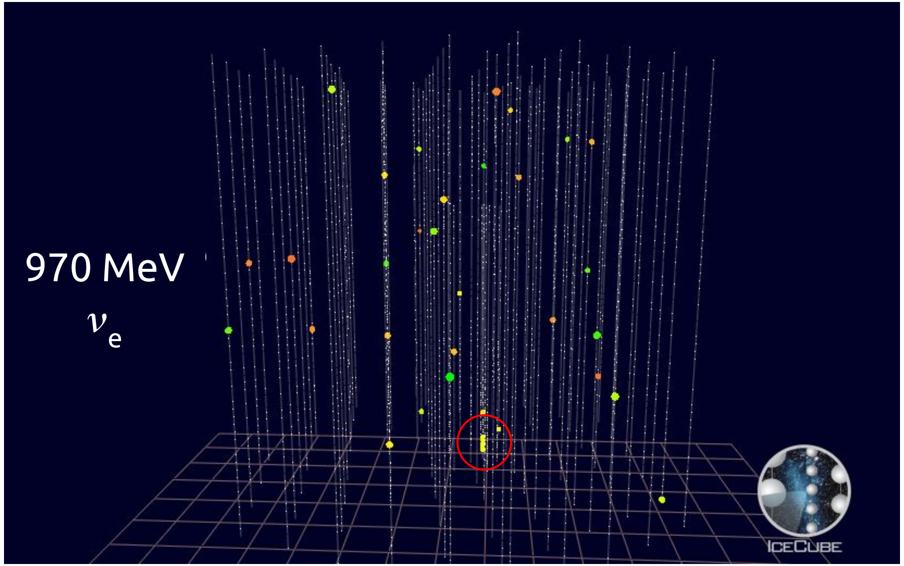
Plan to further improve the elowen selection for better sensitivity

Improving the ELOWEN selection

Right now limited by detector noise, no direction reconstruction present.

Currently working to improve (with data science tools)

- Noise reduction
  - Combining filters
  - Specialising filter stages
- Direction reconstruction
  - Zenith direction



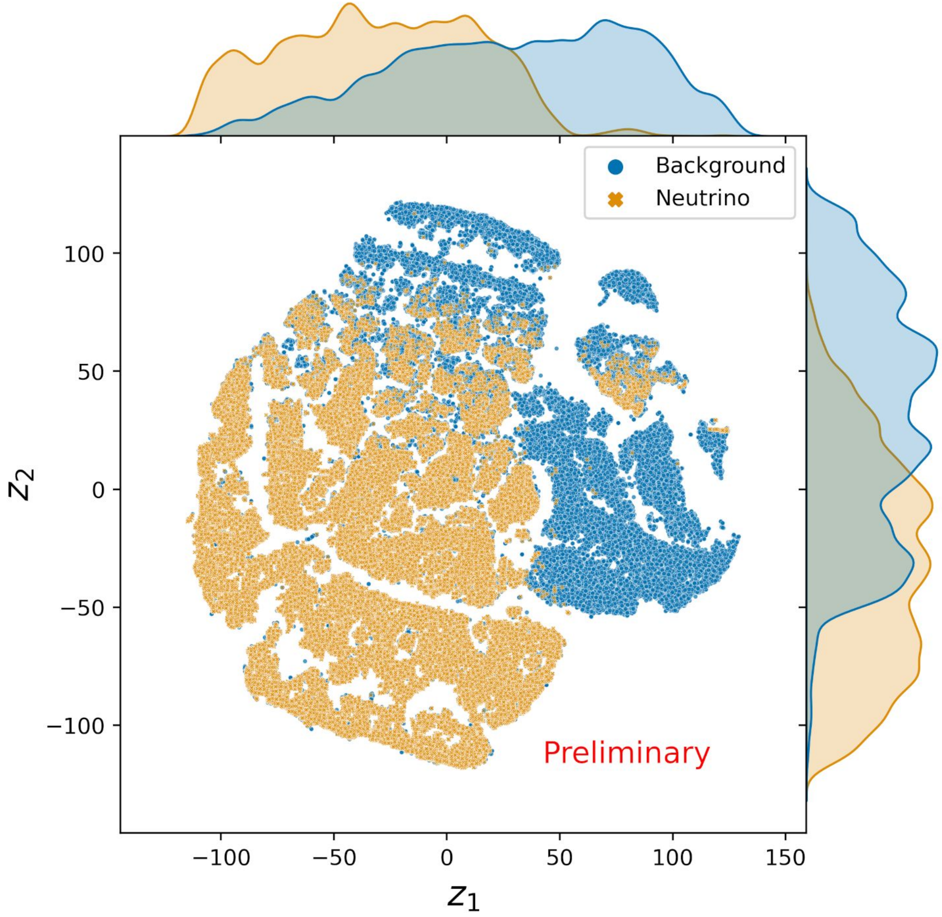
Noise reduction

Combining all filtering stages instead of just hard cuts

Flexibility with global filtering

Dimensionality reduction: separation already visible with t-SNE

This allows us to see what (combination of) variables is best for filtering



Noise reduction: specialising filters

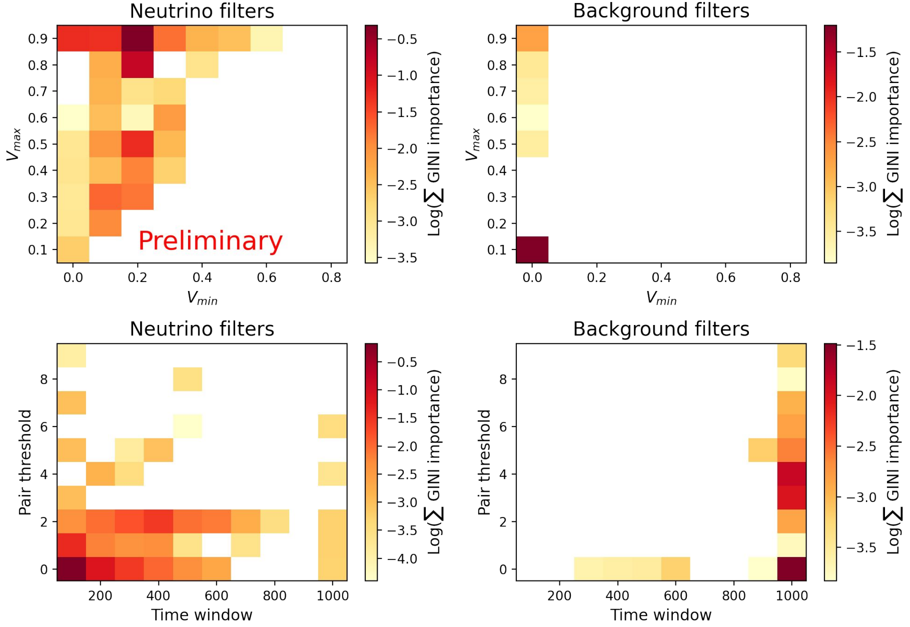
Special filters called NoiseEngine: filtering out detector noise based on causality between hits

Parameters:

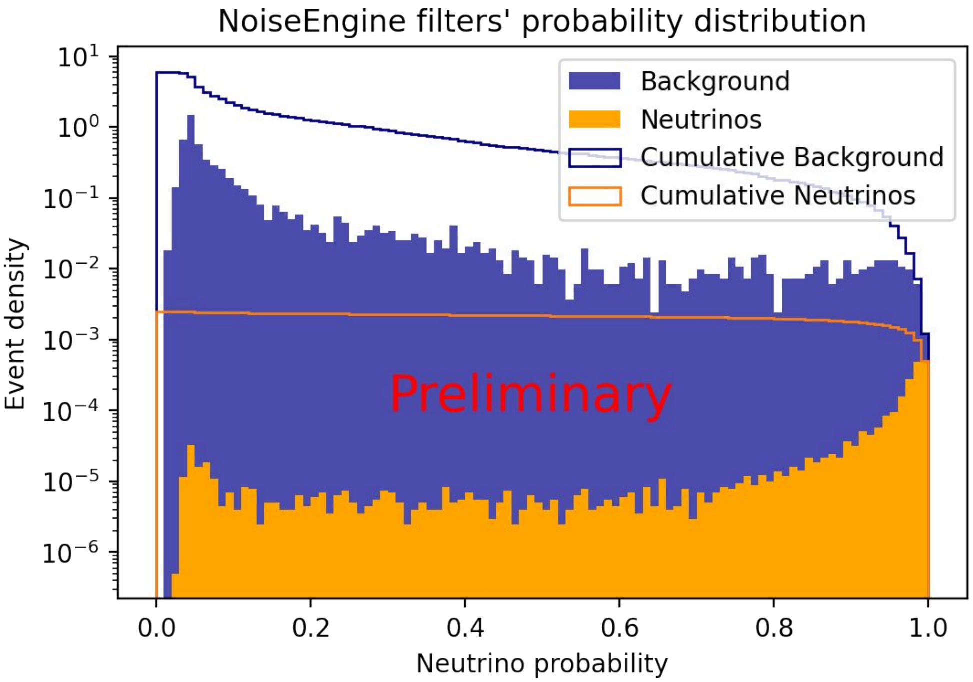
- Number of hit-pairs necessary
- Minimum velocity
- Maximum velocity
- Time window

Combining different settings with a boosted decision tree

Histograms of the NoiseEngine filters' parameters



Noise reduction: specialising filters



Result:

Using 109 (out of 4500 possible) filters

- 0.17% of noise passes
- 39% of neutrinos pass

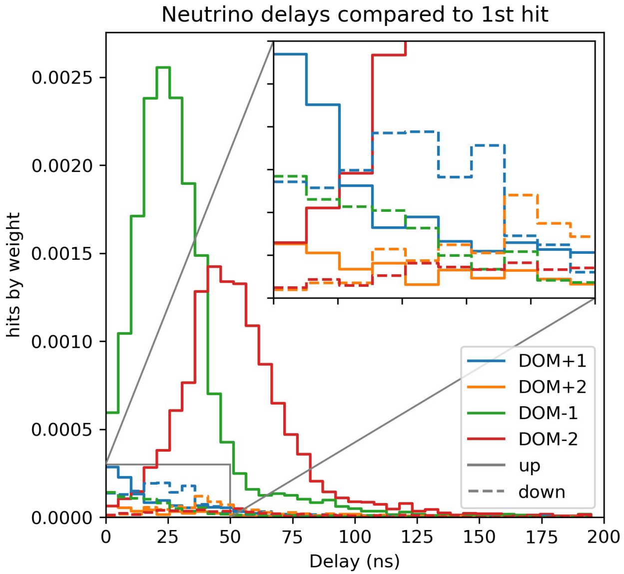
Directional reconstruction

Does not yet exist at this energy level: interactions are too small compared to string spacing

PMT spacing and PMT position allow for rough distinction between up- and down-going neutrinos

Data used:

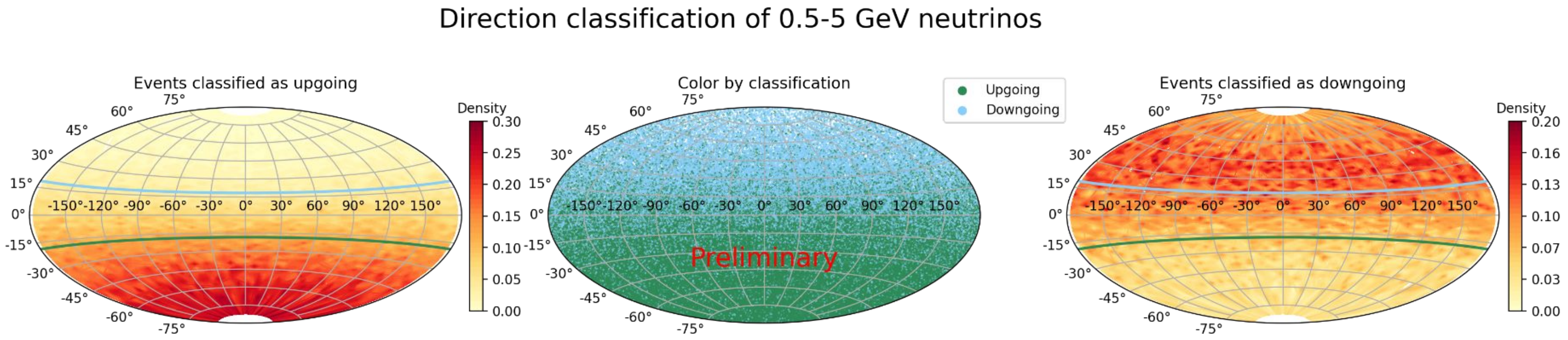
- 6 PMTs surrounding PMT of 1st hit
  - Detections and delays of hits



Directional reconstruction

2 Boosted decision trees: for up- and downgoing

- Able to reconstruct 60%
- Balanced accuracy: 77%



Conclusion & Prospects

- Transient events can be followed up with ELOWEN
  - GRB221009A
  - O4 follow up ongoing
  - More searches planned in the future
- Improvements planned in noise reduction
  - Combination of filtering steps
  - More precise filtering
- Direction reconstruction of GeV neutrinos
  - Zenith direction
  - Using detector configuration

Thank you for listening!

Thanks

감사해
요

Merci

Tack

Grazie

ありがとう

謝謝

Danke

Tak

Dankjewel

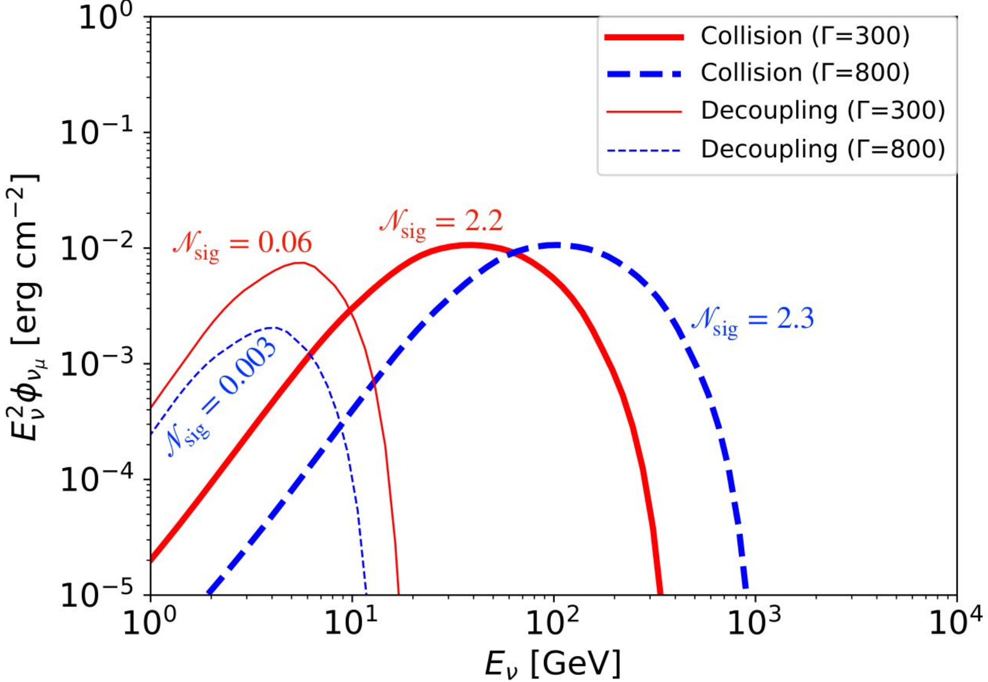
Decoupling model

Model by Kohta Murase

only works when

$$\Gamma_{max} > \Gamma_{np} \approx \left(\frac{\sigma_{np} L_p \Gamma_*}{4\pi m_p c^3 R_*}\right)^{1/4}$$

Assumes $\Gamma_{max} = \Gamma$



$$E_\nu^2 \phi_{\nu_\mu} \approx \frac{1}{12} \frac{1+z}{4\pi d_L^2} \left(\frac{\Gamma_{n,dec}}{\Gamma}\right) \zeta_n \xi_N \mathcal{E}_\gamma^{iso}$$

$$\Gamma_{n,dec} \approx 65 L_{p,53}^{1/3} R_{*,11}^{-1/3} \Gamma_{*,1}^{1/3} \Gamma_{max,2.9}^{1/3}$$

Reference: ApJL 941 L10 (2023)

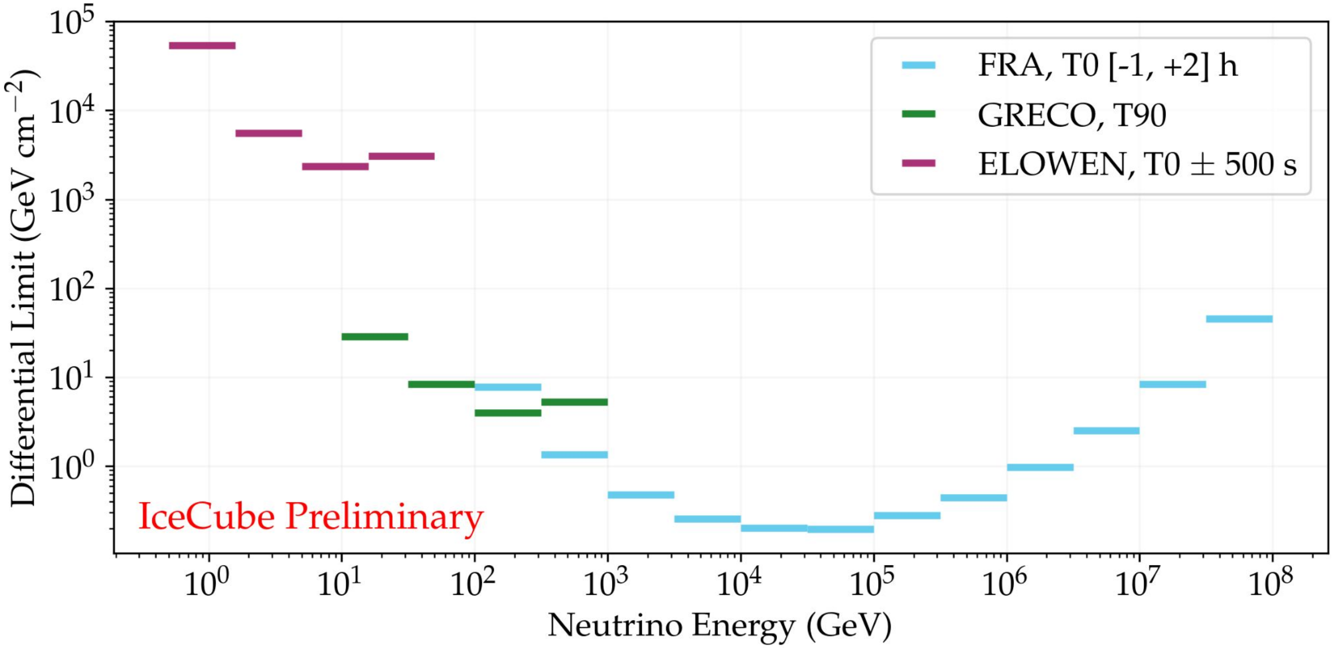
All upper limits GRB221009A

Dataset	Time Window & Index[♯]		90% C.L. Upper Limits (ULs) on the Time-integrated Neutrino Flux $F(E)$. Power-law $F(E) \propto E^{-\gamma}$: per-flavor ULs show $E^2 F(E)$ [GeV cm^{-2}] at E_0				
			E_0	$\gamma = 1.5$	$\gamma = 2.0$	$\gamma = 2.5$	$\gamma = 3.0$
GFU	[T0 − 1 hr , T0 + 2 hr]	*(a)*	100 TeV	0.0359	0.0393⋆	0.0143	0.00240
	T0 ± 1 d	*(b)*		0.0370	0.0410⋆	0.0176	0.00345
	T90 phase	*(c)*		⋯	0.0364	⋯	⋯
	[T0 − 200 s , T0 + 2000 s]	*(d)*		⋯	0.0369	⋯	⋯
	[T0 − 1 d , T0 + 14 d]	*(e)*		⋯	0.0471	⋯	⋯
GRECO	T90 phase	*(c)*	1 TeV	1.052	1.015	0.561	0.174
	[T0 − 200 s , T0 + 2000 s]	*(d)*		1.387	1.338	0.740	0.229
ELOWEN	T0 ± 500 s	*(f)*	1 GeV	⋯	5.3×10^3	8.7×10^3	1.4×10^4
	[T0 − 200 s , T0 + 2000 s]	*(d)*		⋯	7.9×10^3	1.3×10^4	2.0×10^4

Dataset	Time Window & Index		Quasi-thermal $F_{\bar{\nu}_e}(E) \propto E^2 \exp(-3E/\langle E \rangle)$: $\bar{\nu}_e$ UL on total and peak flux		
			$\langle E \rangle$	Total $\bar{\nu}_e$ Flux [cm^{-2}]	$E^2 F_{\bar{\nu}_e}(E)$ [GeV cm^{-2}] at $\langle E \rangle$
SNDAQ	[T0 − 100 s , T0]	*(g)*	15 MeV	7.98×10^8	8.05×10^6
	[T0 − 1 s , T0]	*(h)*		1.81×10^9	1.82×10^7
	[T0 , T0 + 17 s]	*(i)*		8.00×10^8	8.07×10^6
	[T0 + 18 s , T0 + 174 s]	*(j)*		3.08×10^8	3.11×10^6
	[T0 + 174 s , T0 + 175 s]	*(k)*		1.35×10^9	1.36×10^7
	[T0 + 175 s , T0 + 547 s]	*(l)*		4.00×10^8	4.03×10^6

Reference: ApJL 946 L26 (2023)

Differential upper limits GRB221009A



Reference: ApJL 946 L26 (2023)