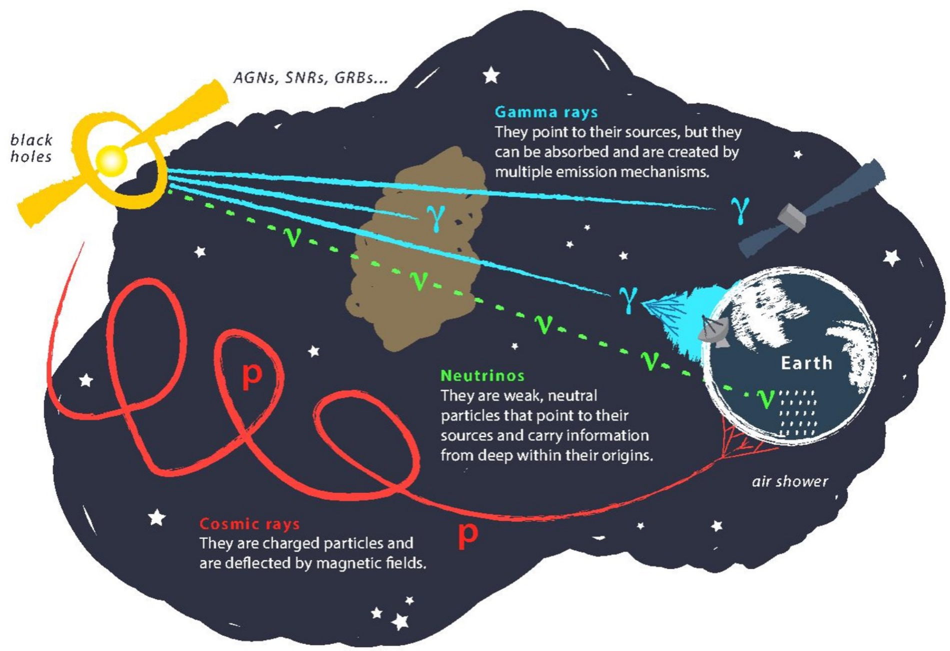
The IceCube search for neutrinos from GRB 221009A

Rachel Procter-Murphy, Bennett Brinson, Karlijn Kruiswijk, Jessie Thwaites, and Nora Valtonen-Mattila on behalf of the IceCube Collaboration

Why search for neutrinos coincident with gamma ray bursts?

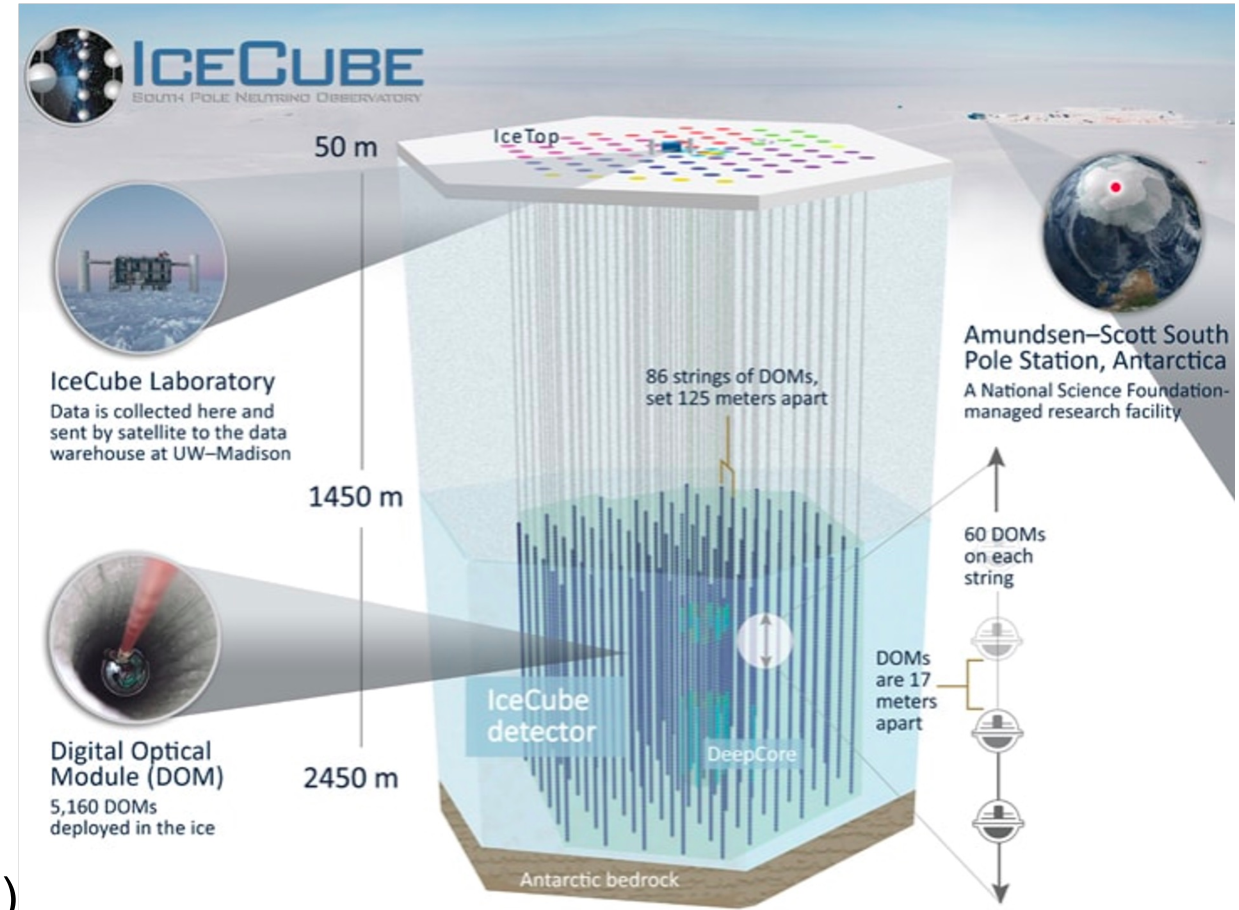
- The origins of ultra high energy cosmic rays (UHECR) remain unknown as hadrons do not point back to their sources
- Neutrinos, which are produced during hadronic acceleration, point back to their sources
- Gamma ray bursts are thought to be a source of UHECR

Finding neutrinos coincident with GRBs would provide smoking gun evidence that GRBs are sources of UHECRs



IceCube Overview

- Cubic kilometer neutrino detector located at the South Pole
- Completed in 2011
- Detects Cherenkov radiation produced from secondary particles
- Sub-detectors:
  - IceCube array (optimized for >TeV neutrinos)
  - DeepCore (optimized for GeV-TeV neutrinos)



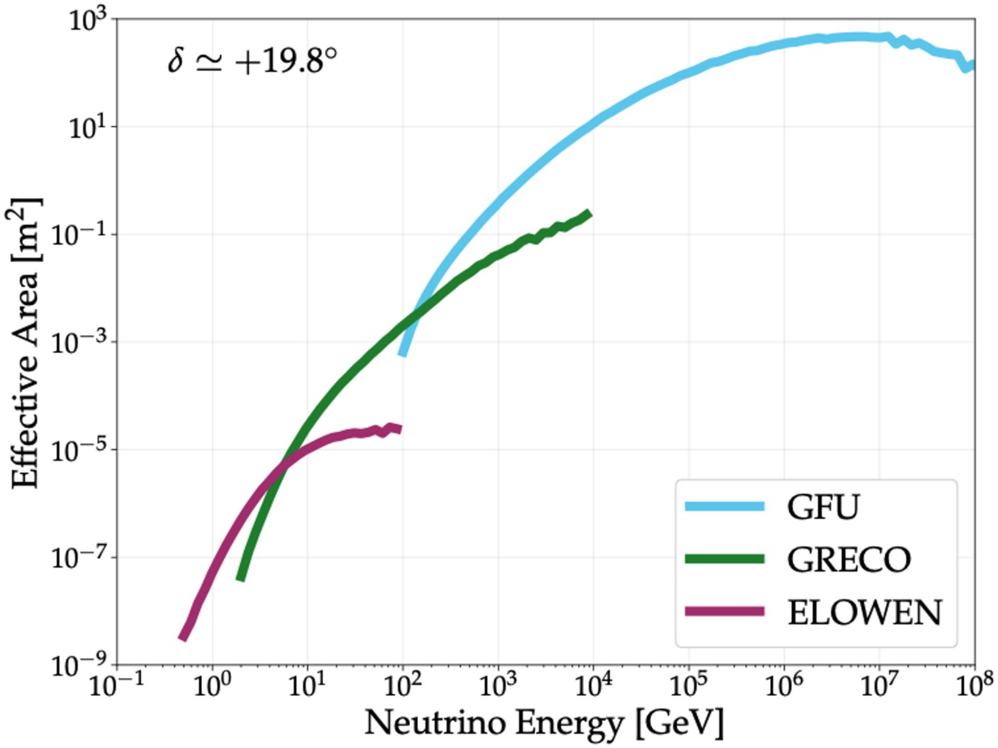
IceCube Datasets

FRA/GFU: Utilized full detector, through going-muon tracks, directional resolution (~0.5°)

GRECO: Utilized full detector, must trigger in DeepCore, events from all neutrino flavors, directional resolution (~30°)

ELOWEN: Utilized DeepCore, no directional reconstruction, look for excess of events

MeV Supernova: Utilized photo-multiplier rates, generally used to search for galactic supernova neutrinos

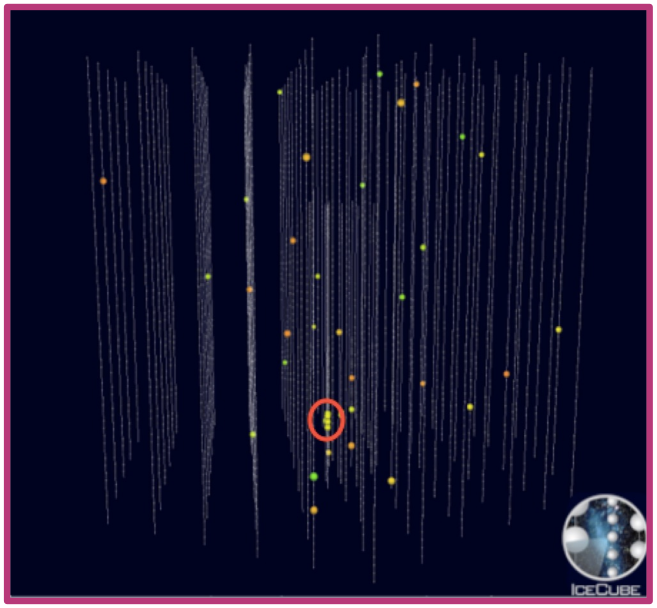


MeV Supernova	ELOWEN	GRECO	FRA/GFU
MeV	0.5-5 GeV	10-1000 GeV	>100 GeV

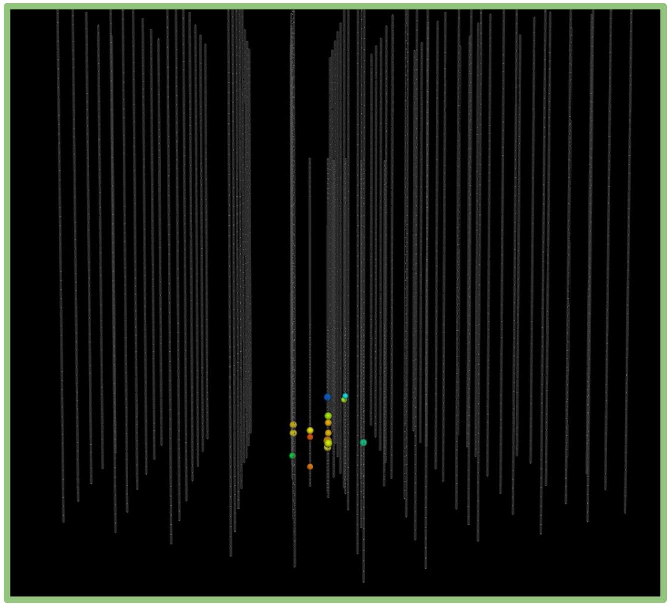
IceCube Analysis: arXiv:2302.05459

IceCube Events

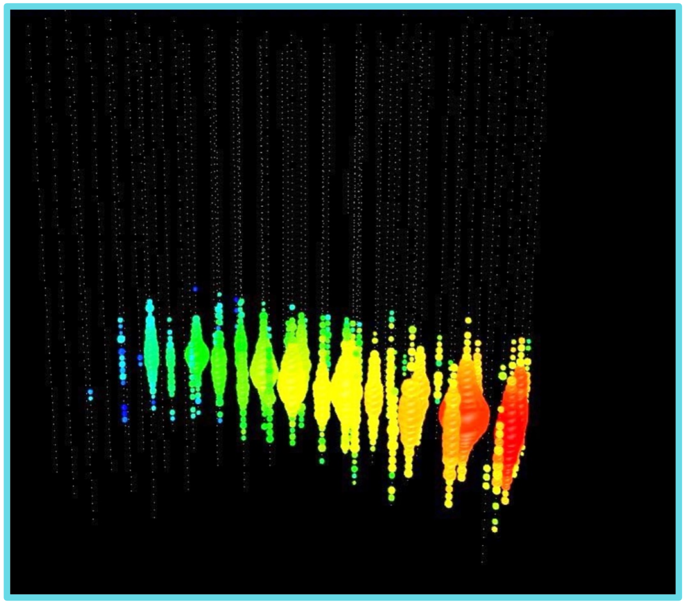
ELOWEN



GRECO



FRA/GFU



MeV Supernova | **ELOWEN** | **GRECO** | **FRA/GFU**

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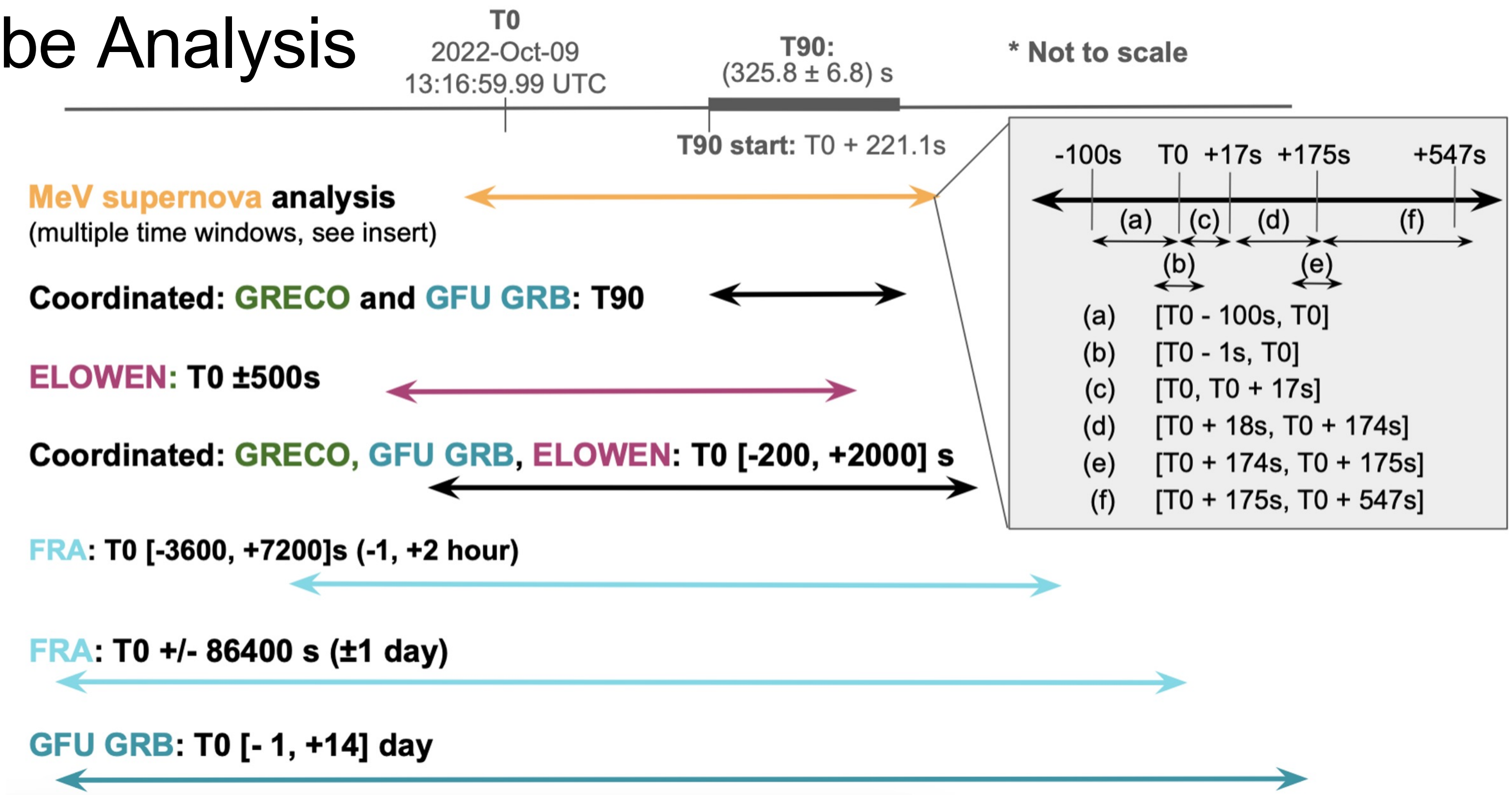
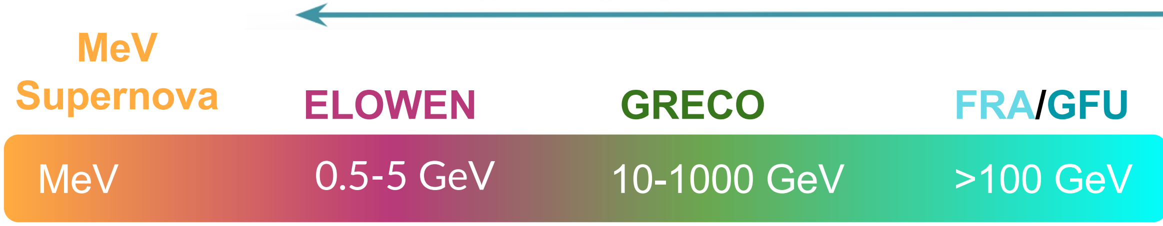
IceCube Analysis



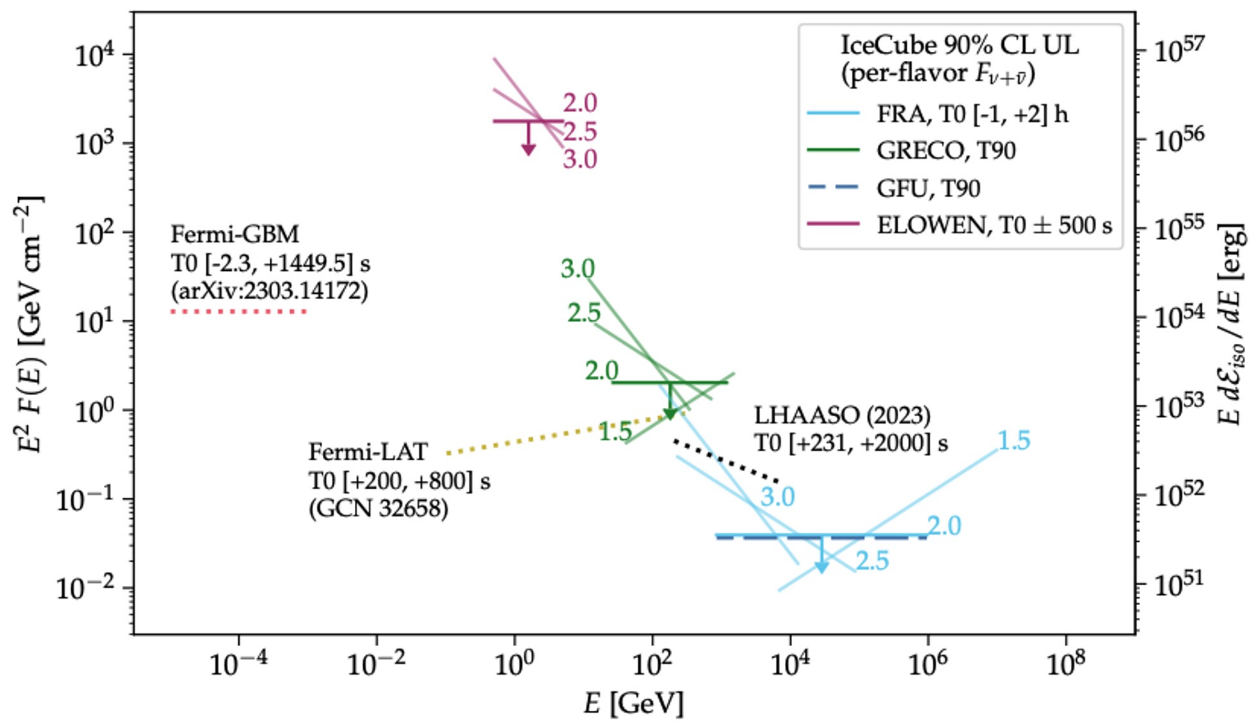


IceCube Analysis: arXiv:2302.05459

IceCube Analysis Results

Found no significant deviation from background in any time window, across the entire energy range

Set strong upper limits in multiple time windows across the energy range, assuming a fixed power law flux

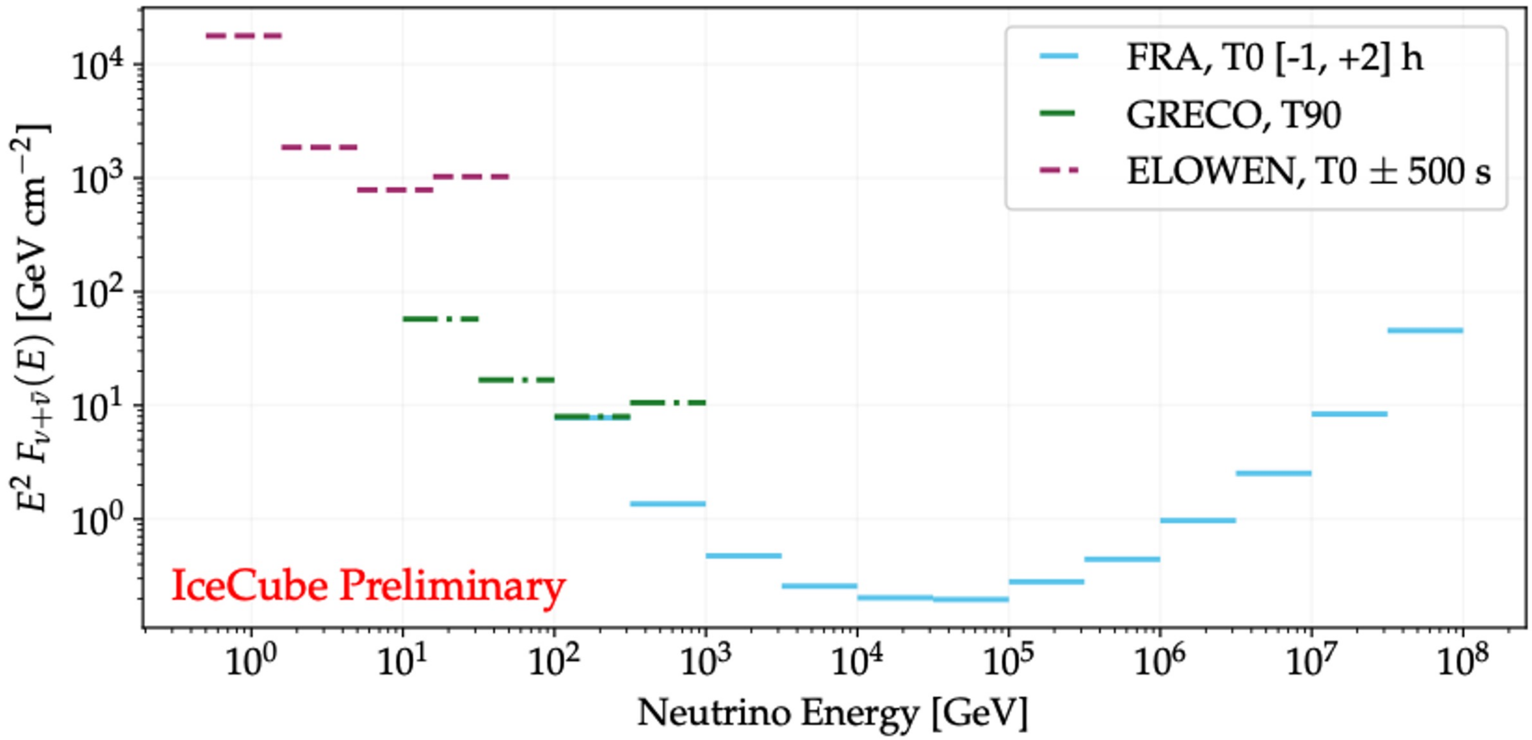


MeV Supernova | **ELOWEN** | **GRECO** | **FRA/GFU**

MeV | 0.5-5 GeV | 10-1000 GeV | >100 GeV

IceCube Analysis: arXiv:2302.05459
Fermi-GBM Observation: arXiv:2303.14172
Fermi-LAT detection: GCN 32658
LHASSO Observation: arXiv:2306.06372

Differential Upper Limits



MeV Supernova	ELOWEN	GRECO	FRA/GFU
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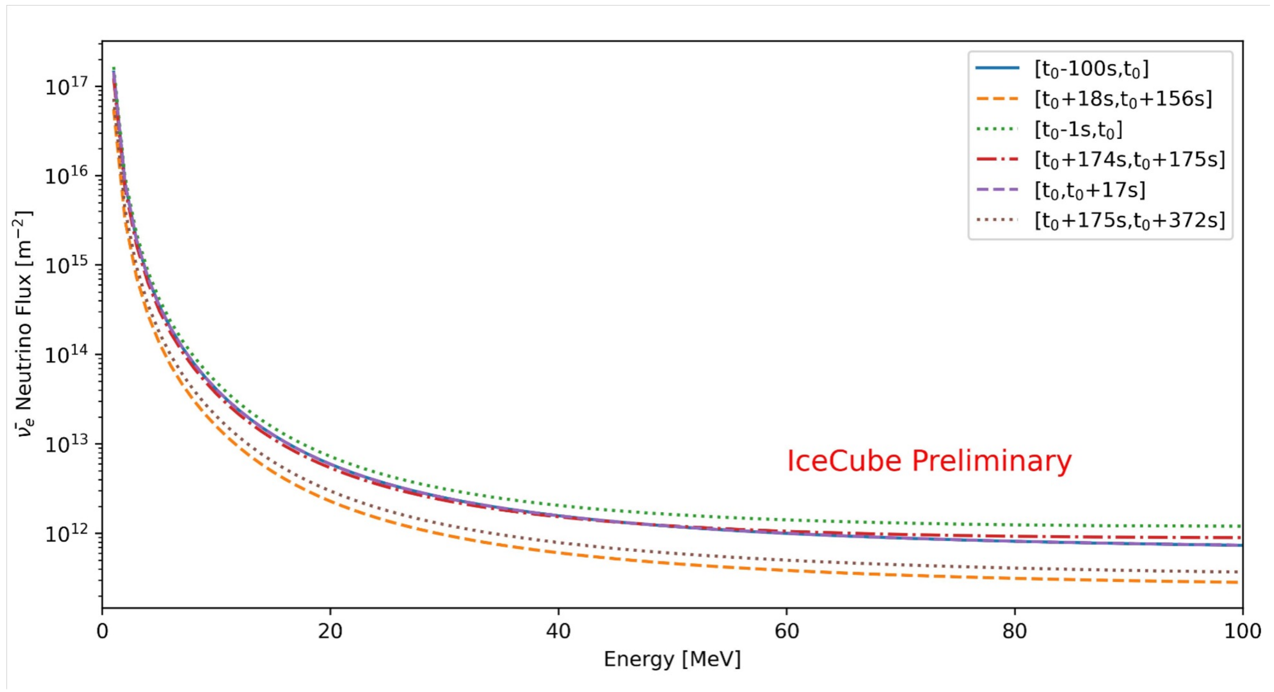
MeV Supernova Differential Upper Limits

Model independent search

Searched for MeV neutrinos by looking for an increase of PMT hit rates

90% CL upper limits for each time window



MeV Supernova | **ELOWEN** | **GRECO** | **FRA/GFU**

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GeV Model Limits

Neutrinos created from neutron-proton interactions

Quasi-Thermal Decoupling Model: Neutrons decouple from jet to produce neutrinos

Quasi-Thermal Collision Model: Neutrons collide with subsequent outflow to produce neutrinos

Decoupling model: arXiv:hep-ph/0004019
Collision Model: arXiv:2210.15625

MeV Supernova	ELOWEN	GRECO	FRA/GFU
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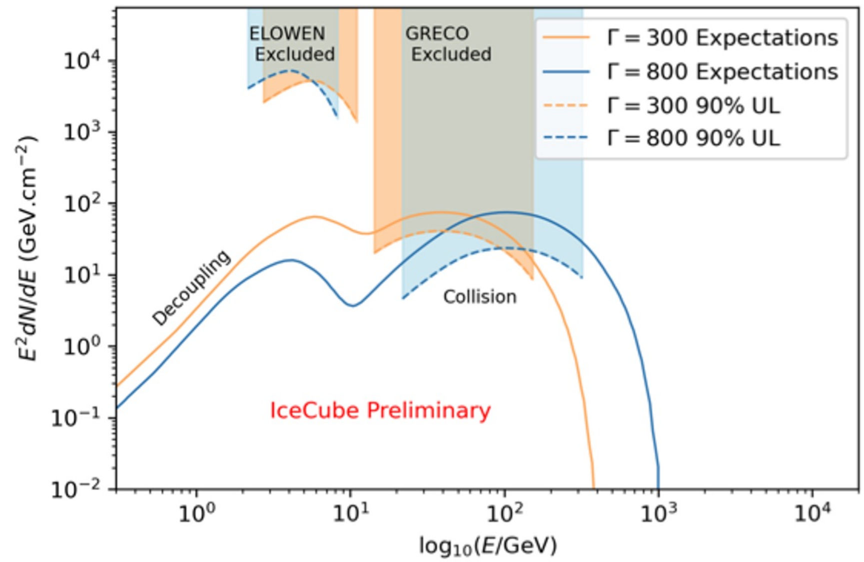
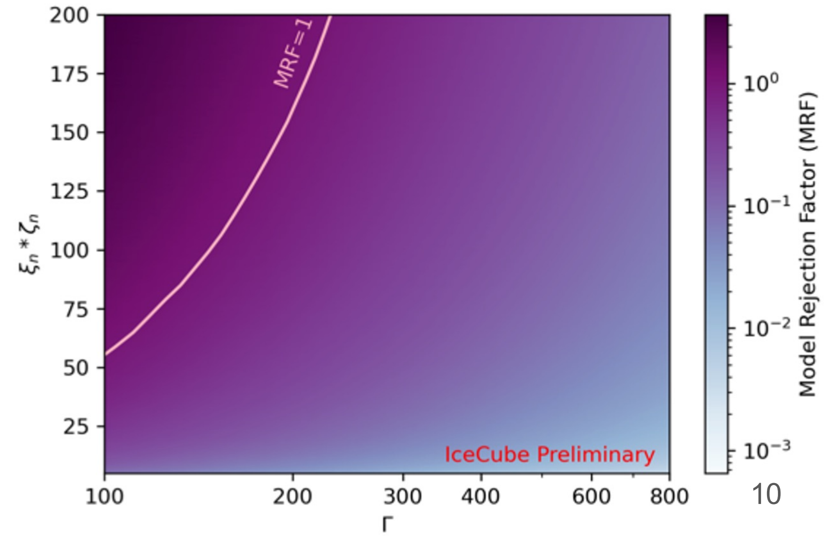




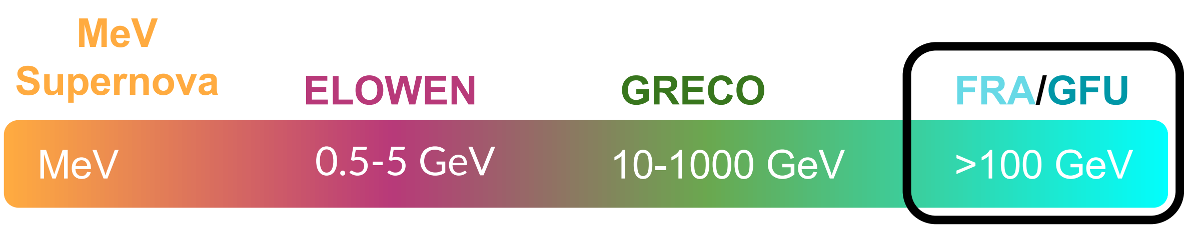
>100 GeV Models

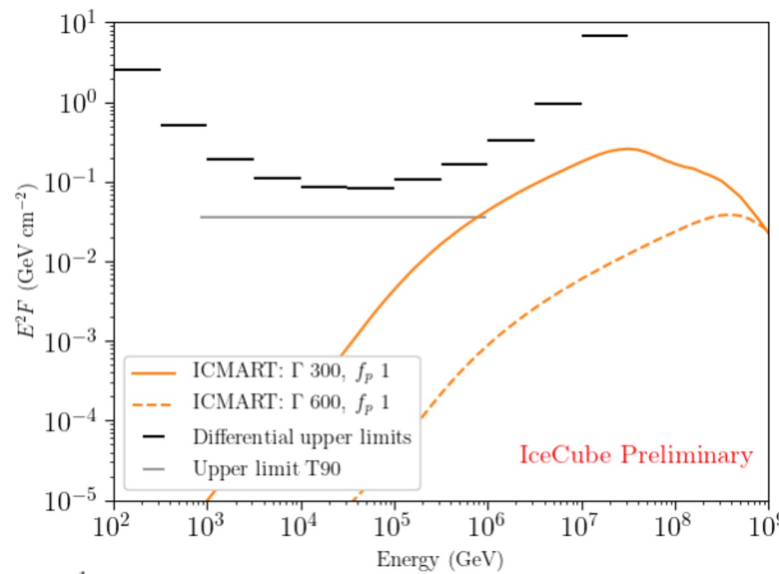
Neutrinos created through photo-hadronic interactions

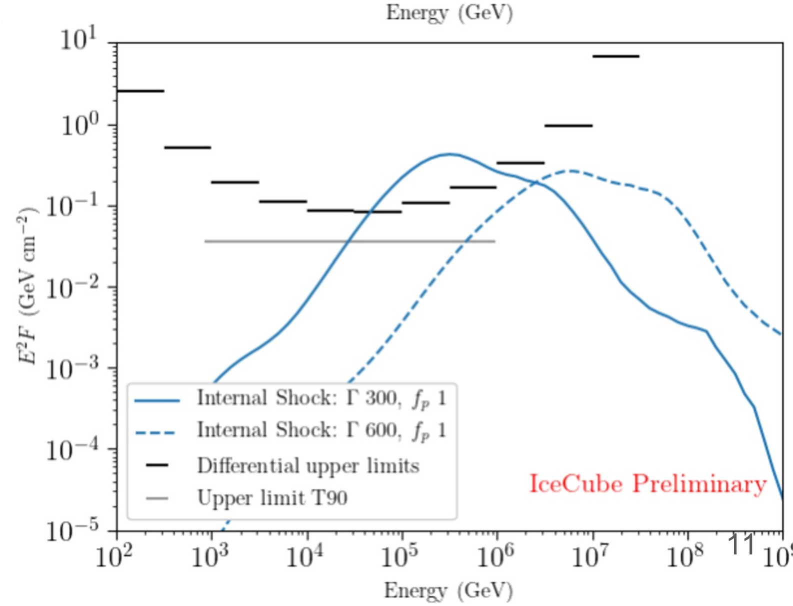
Tested two fireball models

- Internal Collision-Induced Magnetic Reconnection and Turbulence (ICMART):
  - Magnetic reconnection
  - Larger radius
- Internal shock model

ICMART:arXiv:1011.1197, arXiv:1210.0647
Internal Shock: arXiv:astro-ph/9701231, arXiv:1210.0647







>100 GeV Model Limits

90% upper limits for ICMART and Internal Shock compared to previous IceCube limits of 800 stacked GRBs

At Fermi-GBM's lower limit of $\Gamma \geq 780$, we set a limit of $f_p \leq 60.6$ for the internal shock model

Previous IceCube limits: arXiv:1601.06484
Fermi-GBM limits: arXiv:2303.14172

MeV Supernova	ELOWEN	GRECO	FRA/GFU
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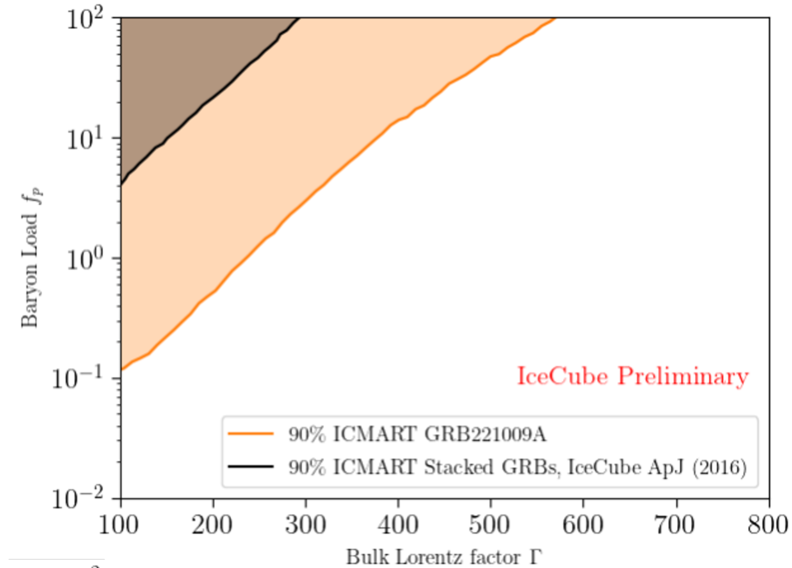
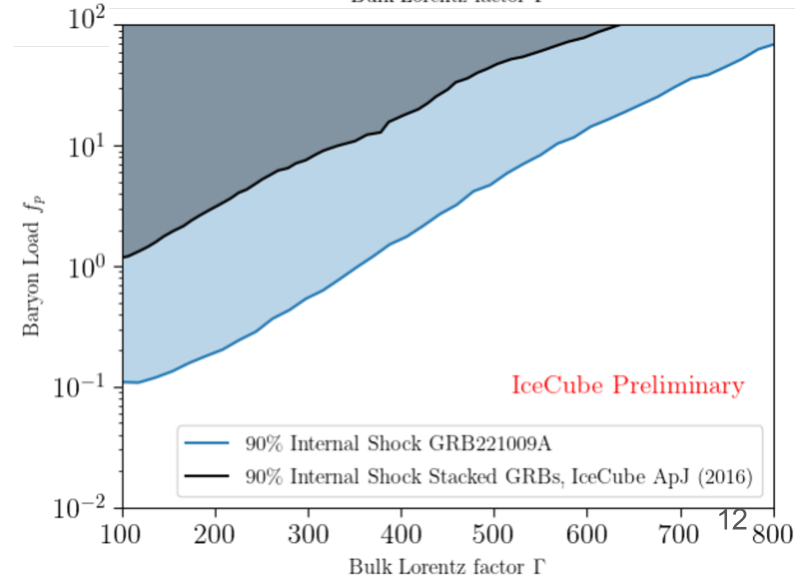
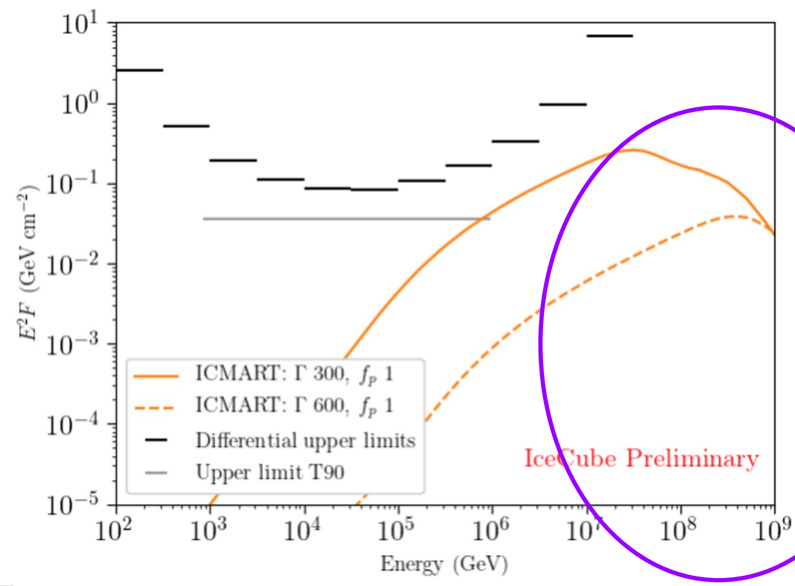
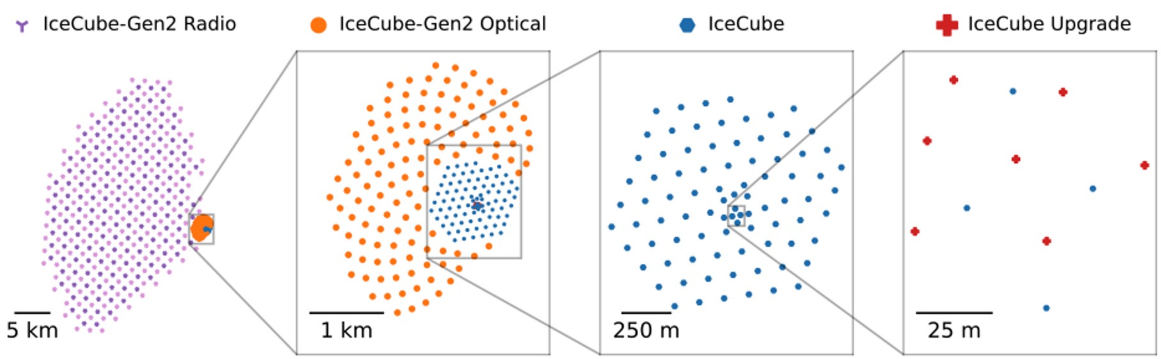




Future Prospects

- Limited at high energies with current detector size → IceCube Gen2
- Improve sensitivity in current energy range and expand energy range up to 10^{18} GeV with Gen2 Radio Array



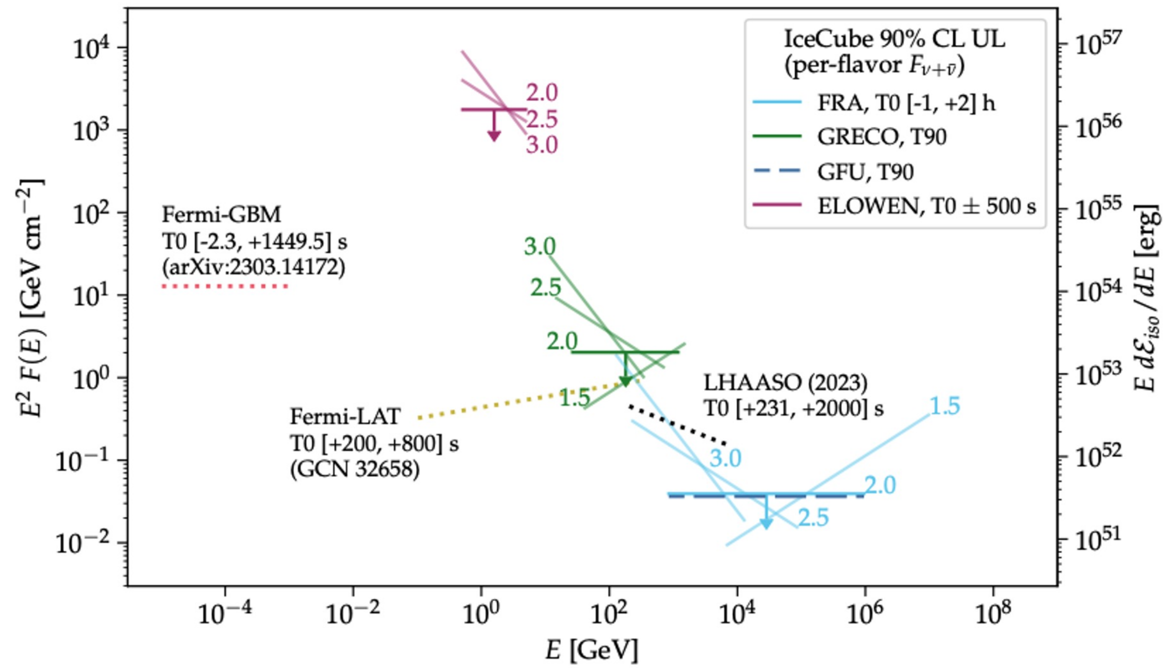


MeV Supernova	ELOWEN	GRECO	FRA/GFU	Gen2
MeV	0.5-5 GeV	10-1000 GeV	>100 GeV	PeV-EeV

IceCube Gen2: arXiv:2008.04323

Conclusion

- Saw no significant deviation from background
- Set strong upper limits on neutrino emission across a wide energy range
- Constrained several models predicting neutrino emission
- Future improvements to IceCube will extend energy range (proposed IceCube Gen2)



MeV Supernova	ELOWEN	GRECO	FRA/GFU	Gen2
MeV	0.5-5 GeV	10-1000 GeV	>100 GeV	PeV-EeV

IceCube Analysis: arXiv:2302.05459
IceCube model testing: arXiv:2307.16354

Backup

Upper limits

Dataset	Time Window & Index[♯]		90% C.L. Upper Limits (ULs) on the Time-integrated Neutrino Flux $F(E)$				
			Power-law $F_{\nu+\bar{\nu}}(E) \propto E^{-\gamma}$: per-flavor ULs show $E^2 F_{\nu+\bar{\nu}}(E)$ [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	2.104	2.030	1.122	0.348
	[T0 − 200 s , T0 + 2000 s]	*(d)*		2.774	2.676	1.480	0.458
ELOWEN	T0 ± 500 s	*(f)*	1 GeV	⋯	1.8×10^3	2.9×10^3	0.47×10^4
	[T0 − 200 s , T0 + 2000 s]	*(d)*		⋯	2.6×10^3	0.43×10^4	0.67×10^4

			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

NOTE—[♯]The different time windows are discussed in section 4 and are referenced by their inline text indices.

NOTE—*Values corresponding to the real-time FRA results published in Thwaites (2022).

>100 GeV Model Assumptions

- Proton spectrum follows E^{-2} power law
- Parameters given by Fermi-GBM (arXiv:2303.14172):
  - Redshift ($z = 0.151$)
  - Isotropic equivalent luminosity ($L_{ISO} = 9.9 \times 10^{53}$ erg/s)
  - Low energy photon index ($\alpha = -1.583$)
  - High energy photon index ($\beta = -3.77$)
  - Break energy ($E_{break} = 1387$ keV)

  Calculated from the lightcurve between 277−323 s from GBM, in T90 time window tested, no data issues during this time period
- Time variability
  - $T_{var} = 0.1$ s (internal shock model, matched GBM model)
  - $T_{var} = 1$ s (match previous IceCube method for ICMART to account for larger radius, arXiv:1601.06484)

GeV Model Assumptions

Quasi-Thermal Decoupling Model:

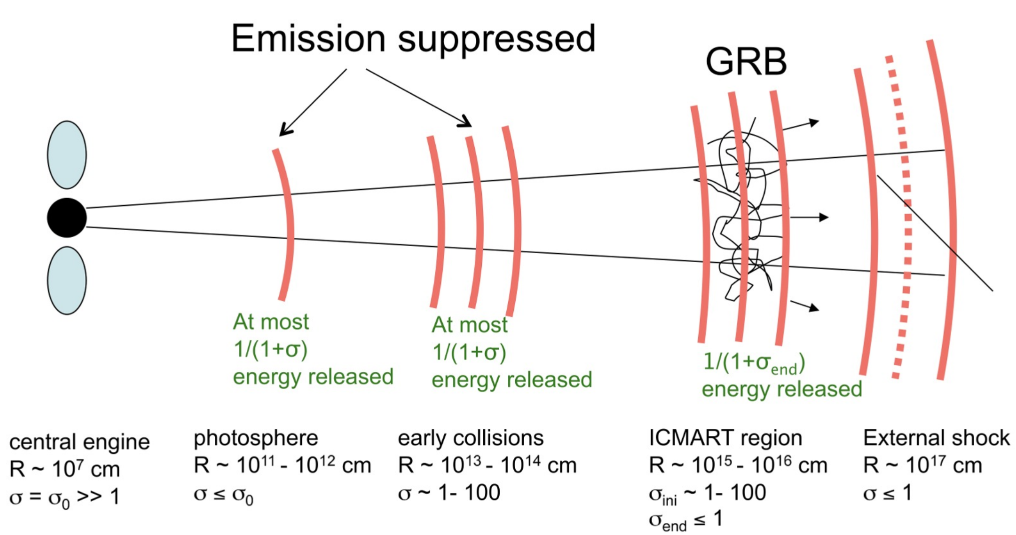
- Neutron to proton ratio, baryon load ($\zeta_n \xi_N$ = 5) (arXiv:hep-ph/0004019)
- Isotropic equivalent gamma-ray energy (E_γ^{iso}= 1.2 x 10^{55} erg) (Fermi-GBM: arXiv:2303.14172)

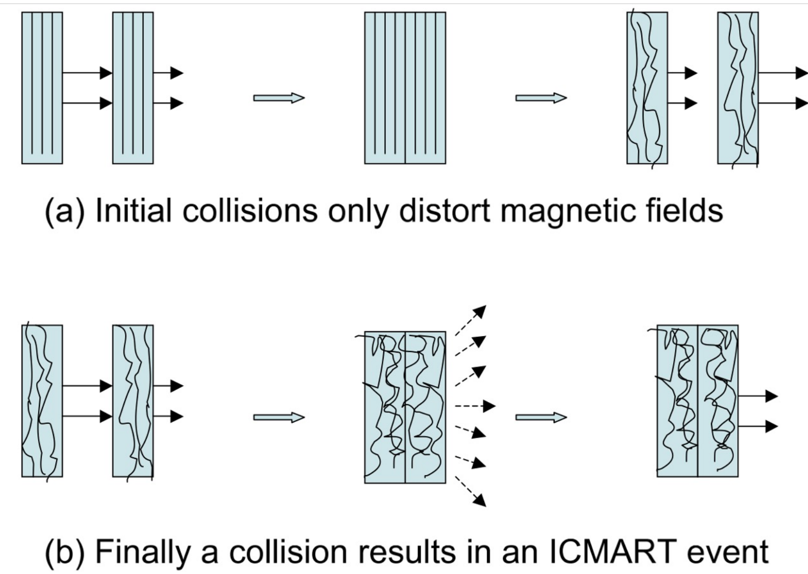
Quasi-Thermal Collision Model:

- Neutron-proton optical depth, baryon load ($\tau_{np} \xi_N$ = 5) (arXiv:2210.15625)
- Isotropic equivalent gamma-ray energy (E_γ^{iso}= 1.2 x 10^{55} erg)

ICMART

Distance Scales in the ICMART Model





ICMART: arXiv:1210.0647