IceCube's MeV to sub-TeV KM3-230213A Follow-up

Nora Valtonen-Mattila, Emile Moyaux and **F. Javier Vara Carbonell**

for the IceCube Collaboration

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TeVPa 2026 in Tendo

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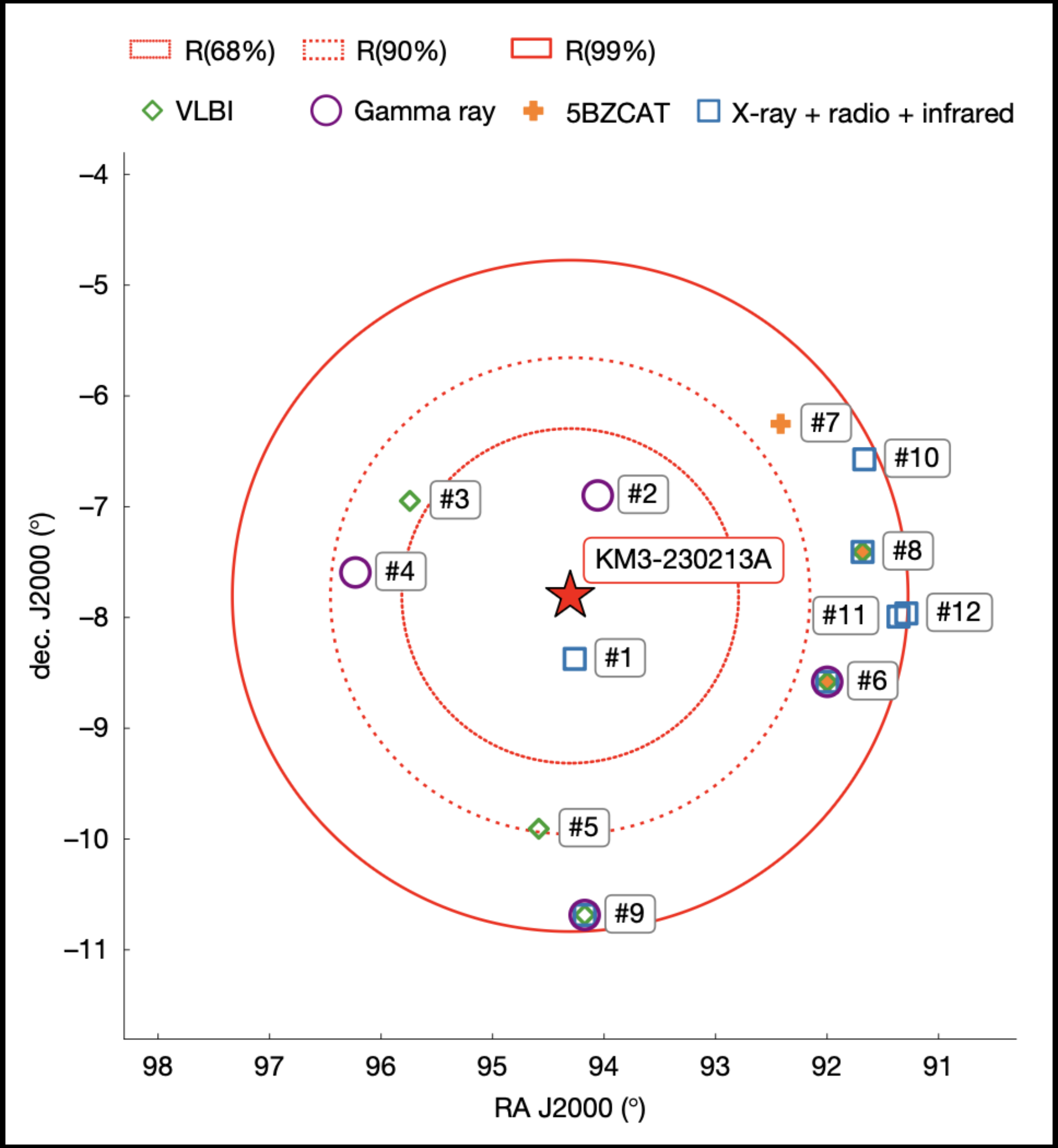
KM3-230213A

- The KM3NeT collaboration detected an ultra-high-energy event on 13 February 2023 at 01:16:47 UTC
- $E_\mu = 120^{+110}_{-60}$ PeV
- RA = 93.4°, dec=—7.8°
- No electromagnetic counterpart detected
- Unknown origin → Multi-energy follow-up:
  - ➢ This work presents IceCube's low-energy counterpart search
  - ➢ See the next presentation for high-energy counterpart search



KM3NeT Coll. Nature volume 638, (2025)

Low-energy counterparts

Low-energy counterparts

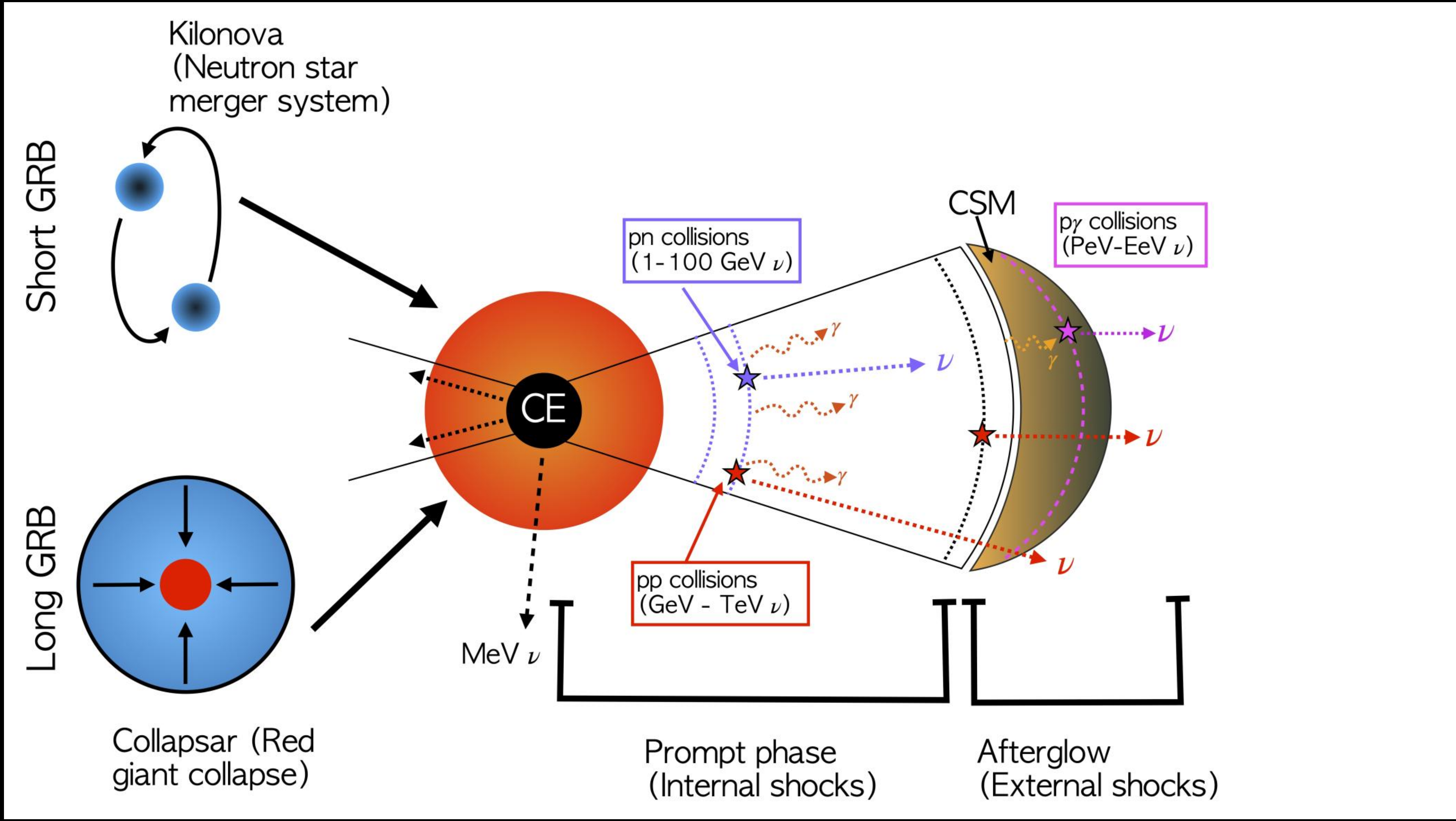
Unknown source

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV

- Nucleon-nucleon interactions in a dense, thermalized environment.
- Cooling via neutrinos
- Emission preceding HE neutrinos

- Inelastic hadronic interactions (pp, pn)
- Synchronous with or preceding HE neutrinos

AN EXAMPLE SOURCE: GAMMA-RAY BURST

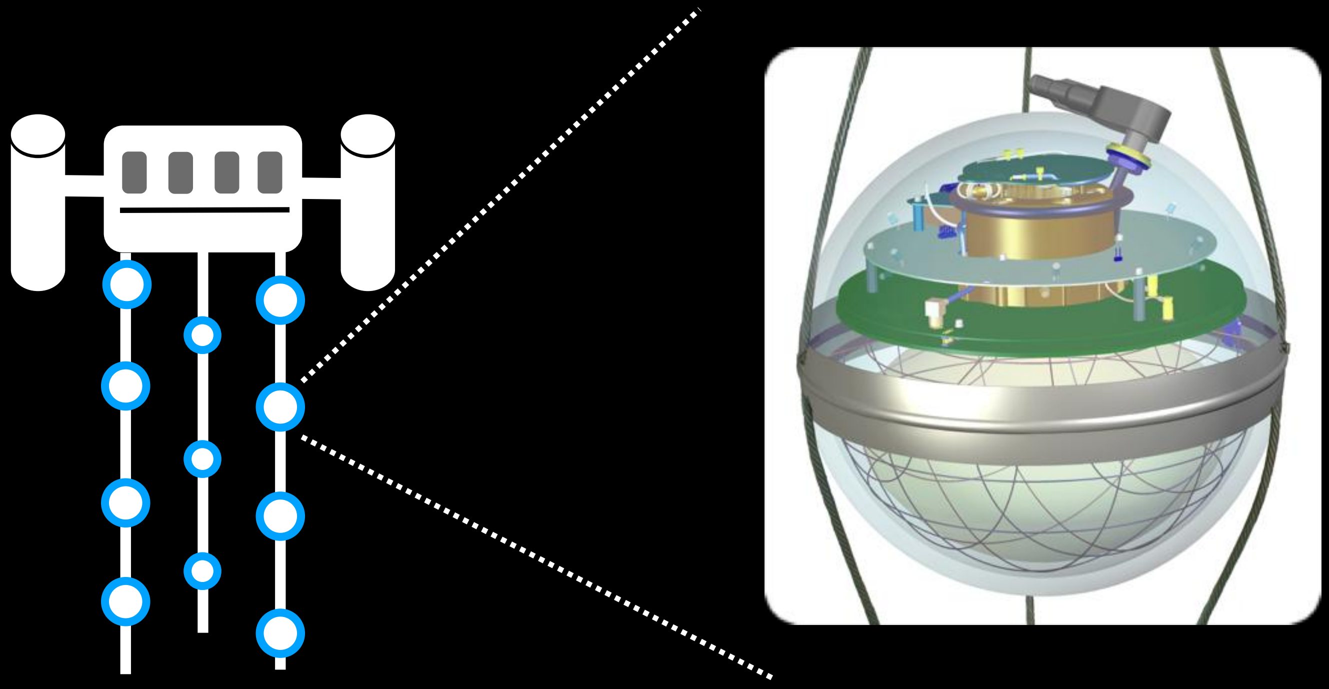


See Abbasi et al., ApJL 946, L26 (2023) and references therein.

ICECUBE

Located at the South Pole

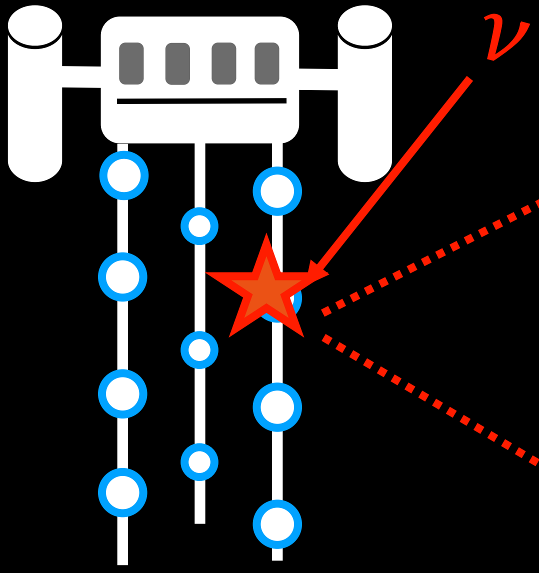
5,160 sensors buried in 1 km^3 of ice



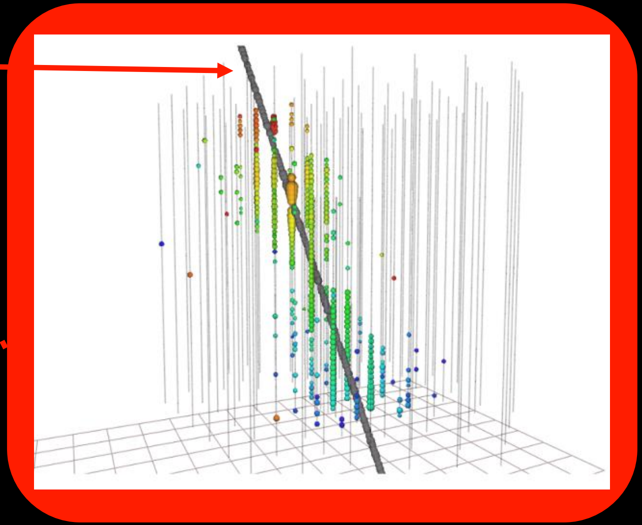
Depth = 1450—2450 m

We detect Cherenkov light produced when charged particles pass through ice

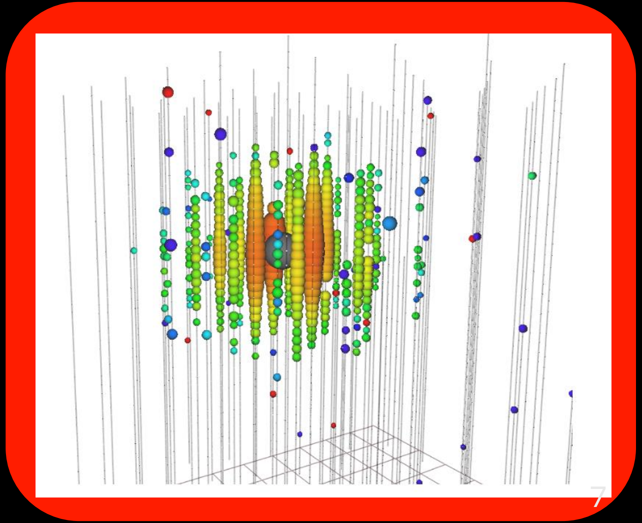
MeV ν — $\gtrsim$100 GeV - PeV ν



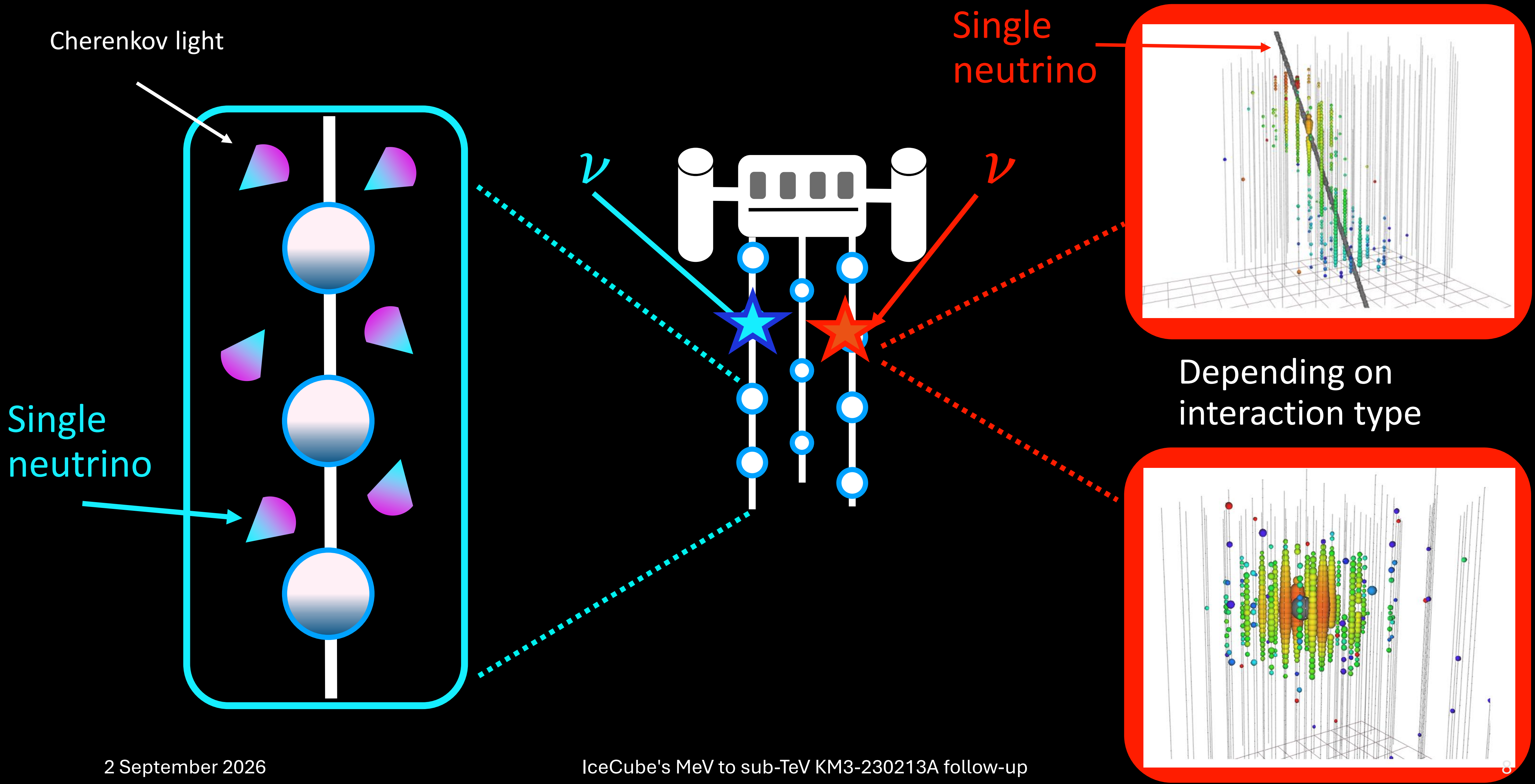
Single neutrino



Depending on interaction type



MeV ν — $\gtrsim$100 GeV - PeV ν



Low-energy counterparts

1-100 MeV	0.5-10 GeV	10 GeV - 1 TeV
SN Data	ELOWEN	GRECO
Collective rate excess	Event counting – time only	Energy + direction reconstruction
T_0 - 100 s , T_0	T_0 - 2000 s, T_0 + 200 s	Median: ν_μ CC $\gtrsim 5°$, ν_e CC $\gtrsim 30°$
T_0, T_0 + 100 s	**$T_0 \pm$ 500 s**	$T_0 \pm$ 3.5 d
T_0 - 10 s, T_0	**$T_0 \pm$ 50 s**	$T_0 \pm 5 \times 10^4$ s
T_0 - 0.5 s, T_0		**$T_0 \pm$ 500 s**
		$T_0 \pm$ 50 s

Methodology

1-100 MeV 0.5-10 GeV 10 GeV - 1 TeV

MeV analysis

Nora Valtonen-Mattila

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We look for a collective increase in hit rate

How significant is the deviation in the bin of interest compared to an average?

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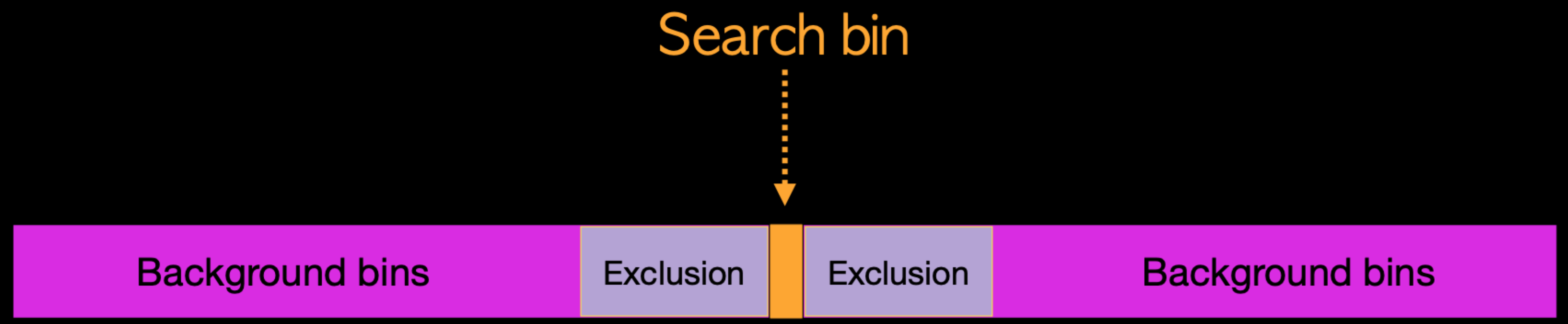

We compare the rate in the search bin to the average rate in the background bins.

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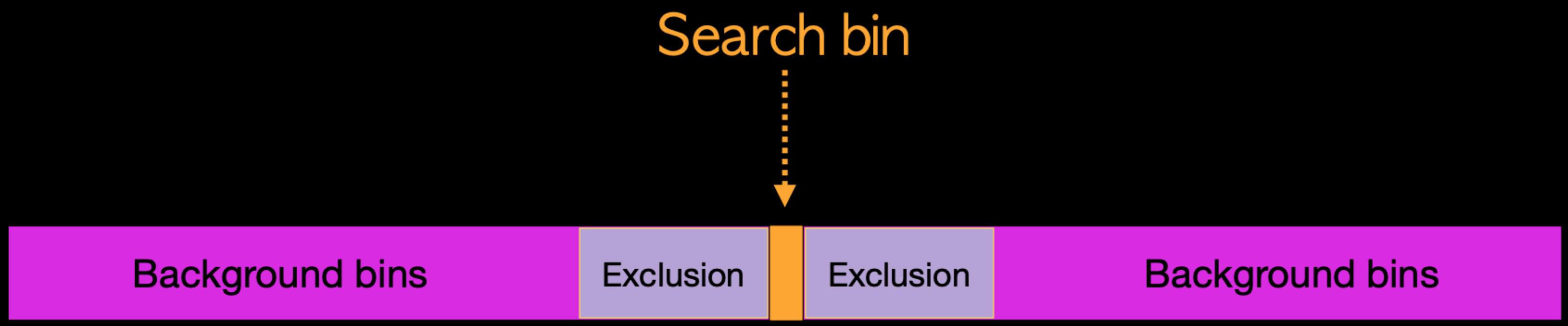

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This results in a test statistic $\xi = \frac{\Delta_\mu}{\sigma_{\Delta_\mu}} = \frac{\text{most likely collective hit rate deviation}}{\text{uncertainty of deviation}}$

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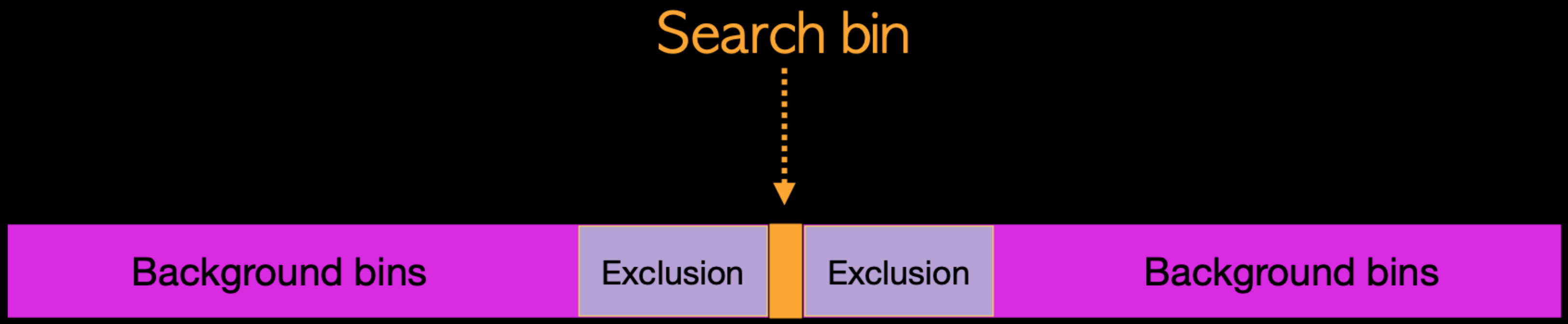

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This results in a test statistic $\xi = \frac{\Delta_\mu}{\sigma_{\Delta_\mu}} = \frac{\text{most likely collective hit rate deviation}}{\text{uncertainty of deviation}}$

We also have to account for the muon contribution, which results in the muon-corrected TS: ξ_{corr}

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV

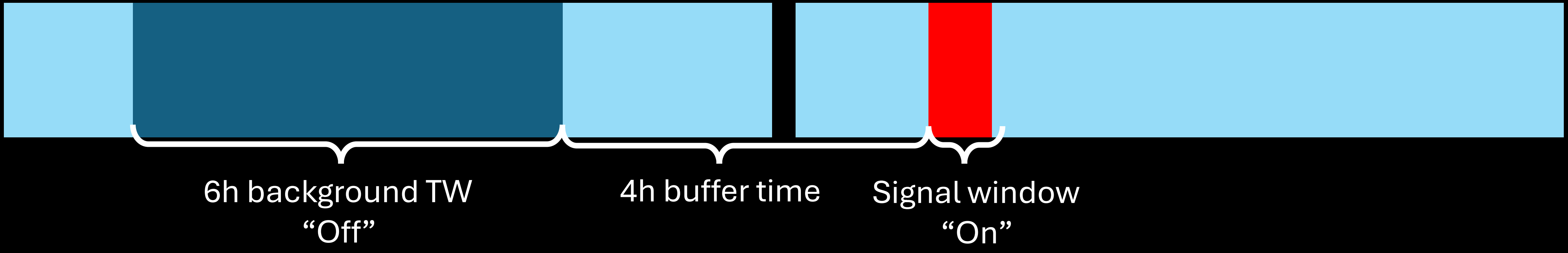
ELOWEN analysis

Emile Moyaux

E-mail: emoyaux@icecube.wisc.edu

UCLouvain

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV



- The analysis observables are the number of events in the signal (on) and background (off) time windows: $N_{\text{on}}, N_{\text{off}}$.
  - We compute the p-value $\boldsymbol{p} = \boldsymbol{I}_{\mathbf{1}/(\mathbf{1}+\boldsymbol{\alpha})}(\mathbf{N_{on}}, \mathbf{N_{off}} + \mathbf{1})$, where $\alpha = \frac{\mathrm{T_{off}}}{\mathrm{T_{on}}}$
  - A Bayesian method is used to compute the 90% U.L. on the per-flavor fluence

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV

GRECO analysis

F. Javier Vara Carbonell

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Universität Münster

- Standard unbinned likelihood transient analysis
- Extended likelihood definition (spectral index fixed to -2.5):

$$\mathcal{L}(n_s) = \frac{(n_s + n_b)^N e^{-(n_s+n_b)}}{N!} \prod_{i=1}^{N} \left(\frac{n_s S_i}{n_s + n_b} + \frac{n_b B_i}{n_s + n_b} \right)$$

- Background modelled by time/RA scrambling of data over the entire dataset's lifetime (~ 11 years)

- Accounting for the reported event's spatial prior:

$$\mathrm{TS_{prior}} = 2 \ln \left[\frac{\mathcal{L}(\widehat{n_s})}{\mathcal{L}(n_s = 0)} \right] + 2 \ln \left(\frac{\mathrm{prior_{pixel}}}{\max(\mathrm{prior})} \right)$$

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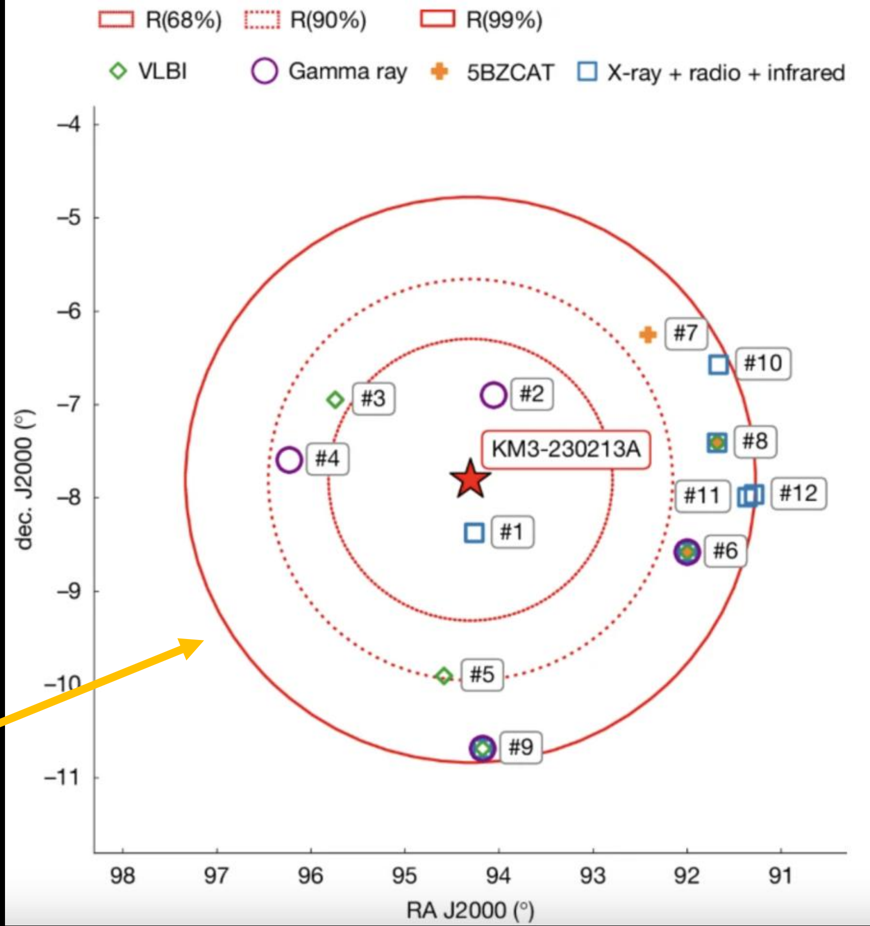
Modelled by a 2D Gaussian with $\sigma = 1°$
(see next presentation by Riya Shah)



KM3NeT Coll. Nature volume 638, (2025)

Unblinding results

Unblinding results: pre-trial p-values

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV

SN Data

$[T_0$ - 0.5s, $T_0]$: 0.28

$[T_0$ - 10s, $T_0]$: 0.74

$[T_0$ - 100s , $T_0]$: 0.87

$[T_0, T_0$ + 100s]: 0.97

ELOWEN

$[T_0$ - 2000s, T_0 + 200s]: 0.64

$[T_0 \pm 5 \times 10^1 s]$: 0.87

$[T_0 \pm 5 \times 10^2 s]$: 0.91

GRECO

$[T_0 \pm 5 \times 10^1 s]$: 1

$[T_0 \pm 5 \times 10^2 s]$: 1

$[T_0 \pm 5 \times 10^4 s]$: 0.09

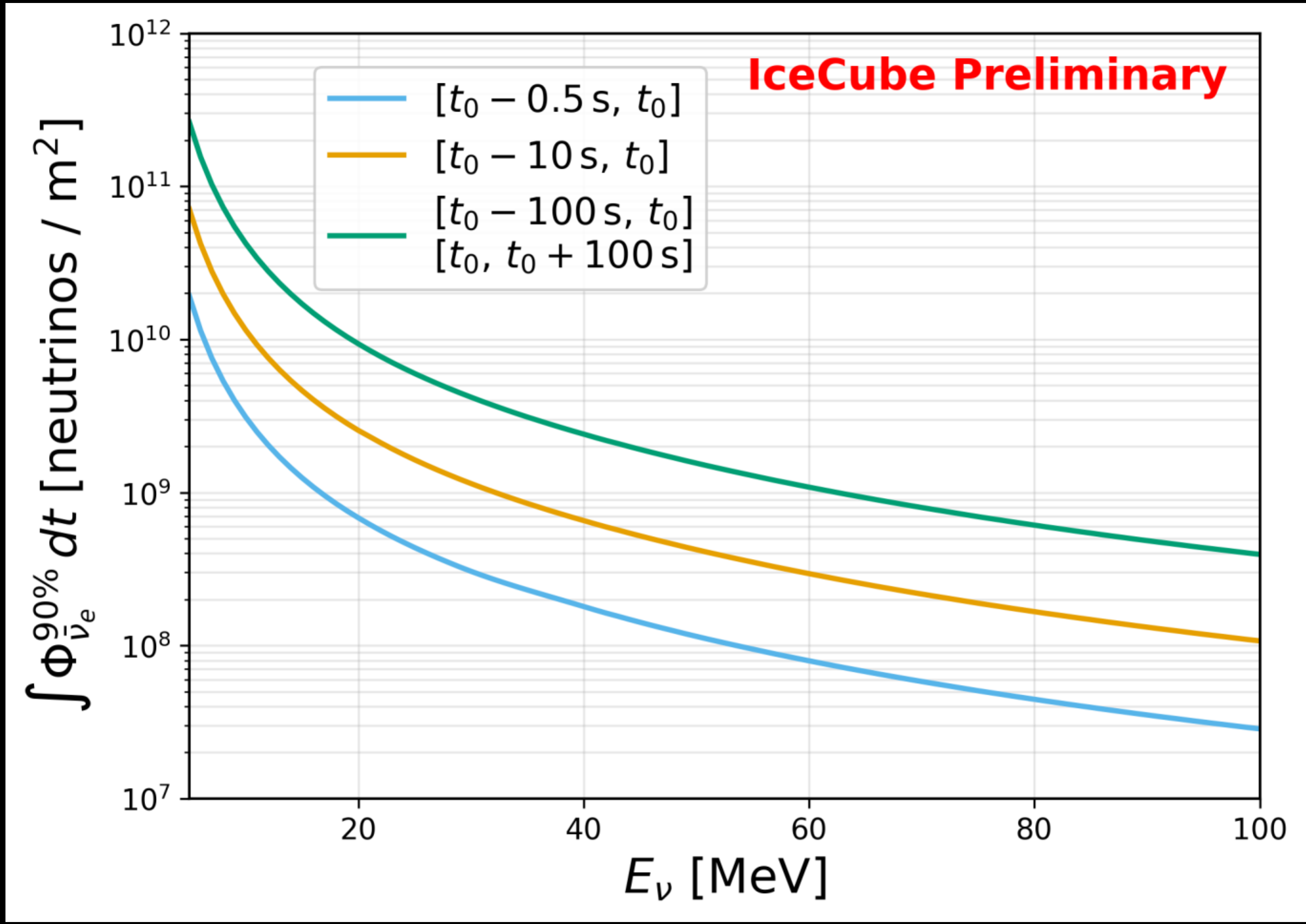
(0.29 post-trial)

$[T_0 \pm$ 3.5d]: 1

All consistent with background, setting upper limits

Unblinding results: MeV upper limits

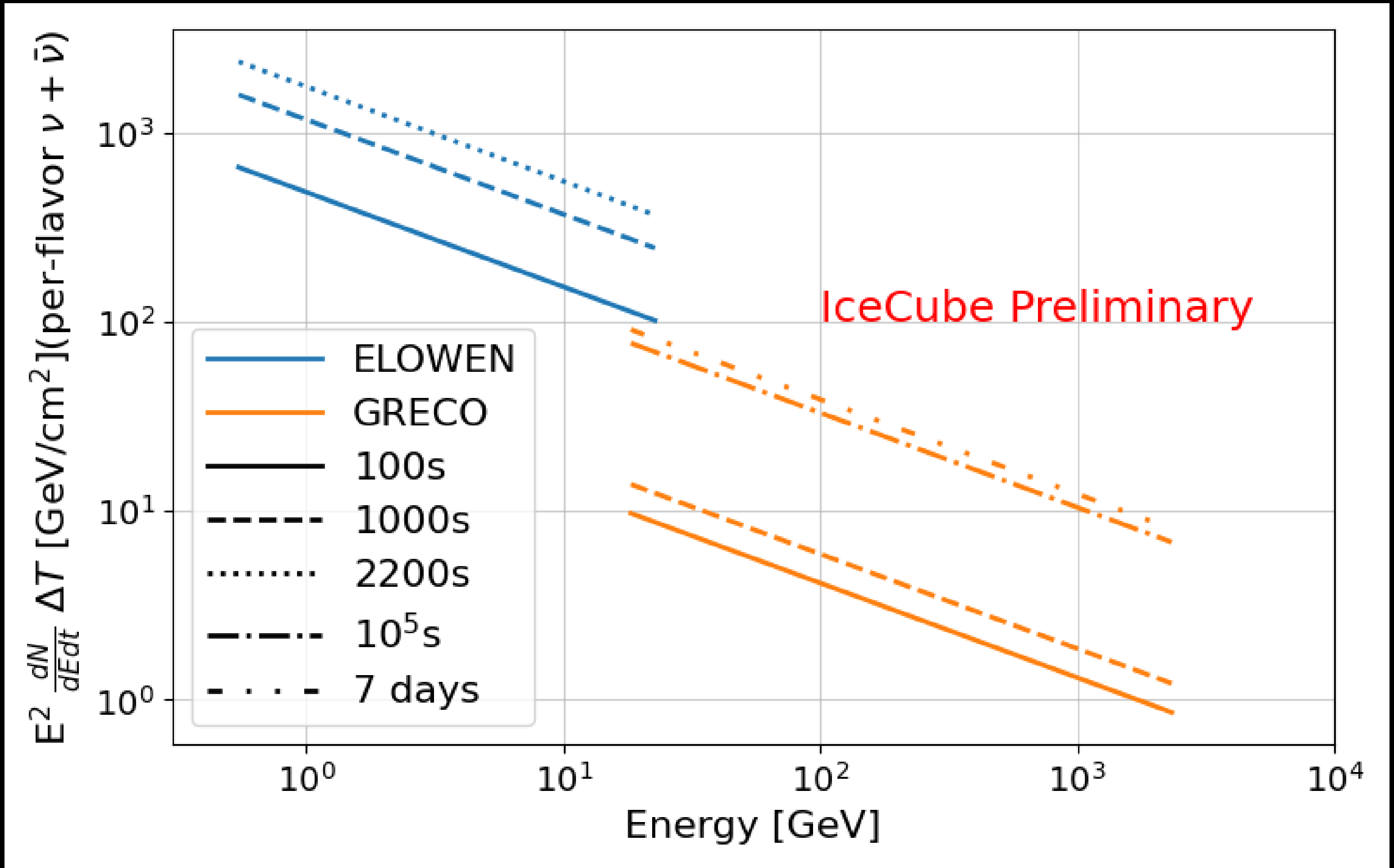
Mono-energetic $\overline{\nu_e}$ 90% C.L. upper limits as a function of neutrino energy for the four search time windows



Unblinding results: ELOWEN/GRECO upper limits

- Per-flavor 90% C.L. upper limits on the time-integrated spectral neutrino flux, assuming an $E^{-2.5}$ spectrum

- The horizontal extent of each curve shows the central 85% true-neutrino-energy interval of the expected signal



Summary

- MeV to sub-TeV follow-ups of KM3-230213A: no significant excess observed
  - ➢ smallest pre-trial p-values: MeV = 0.28, ELOWEN = 0.64, GRECO = 0.09 (0.29 post-trial)

- 90% C.L. upper limits are set on the time-integrated per-flavor neutrino flux for ELOWEN and GRECO

- Mono-energetic $\bar{\nu}_e$ 90% C.L. upper limits are set for the MeV analysis

- Outlook: Differential upper limits and systematic studies are under consideration

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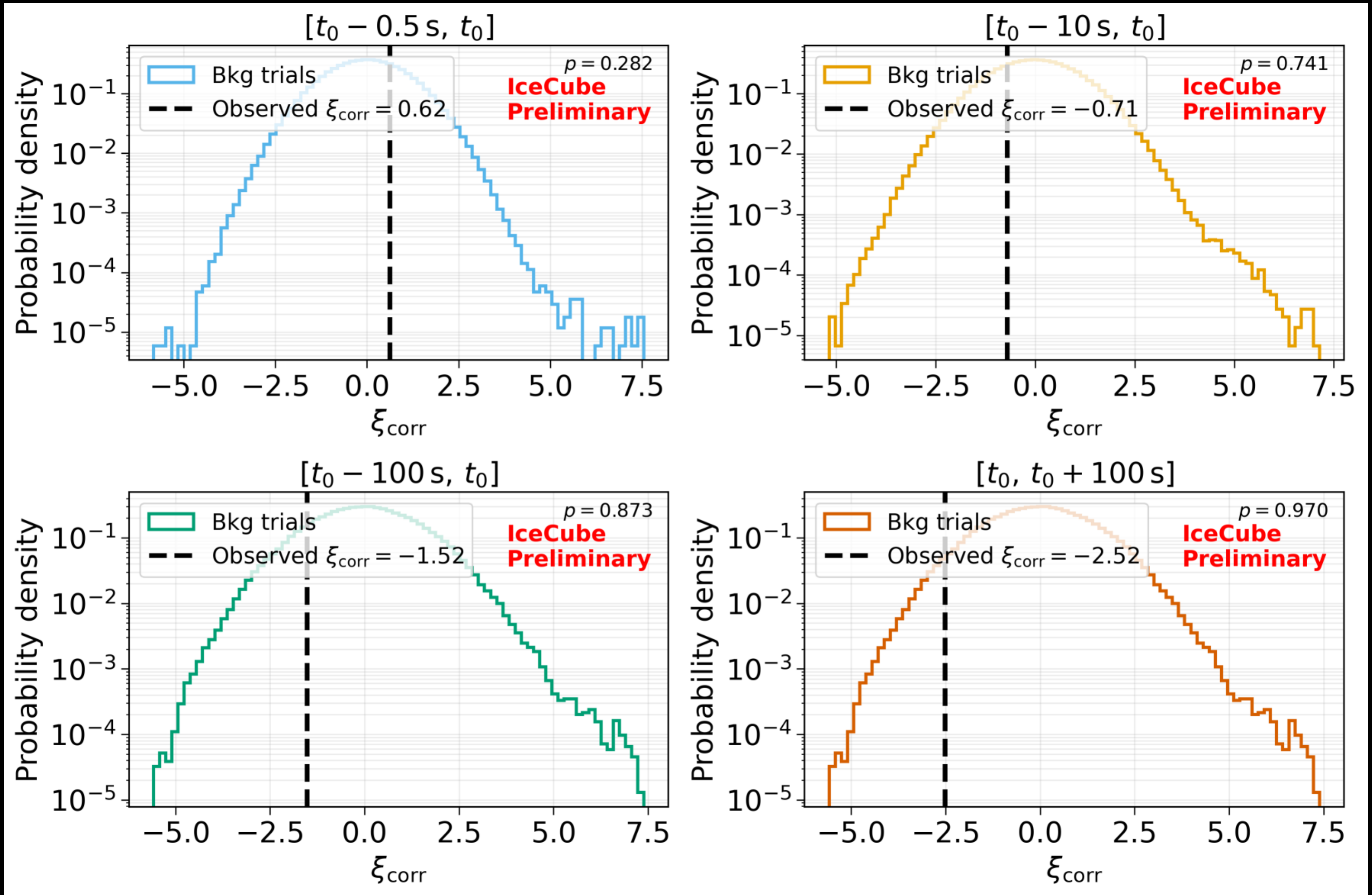
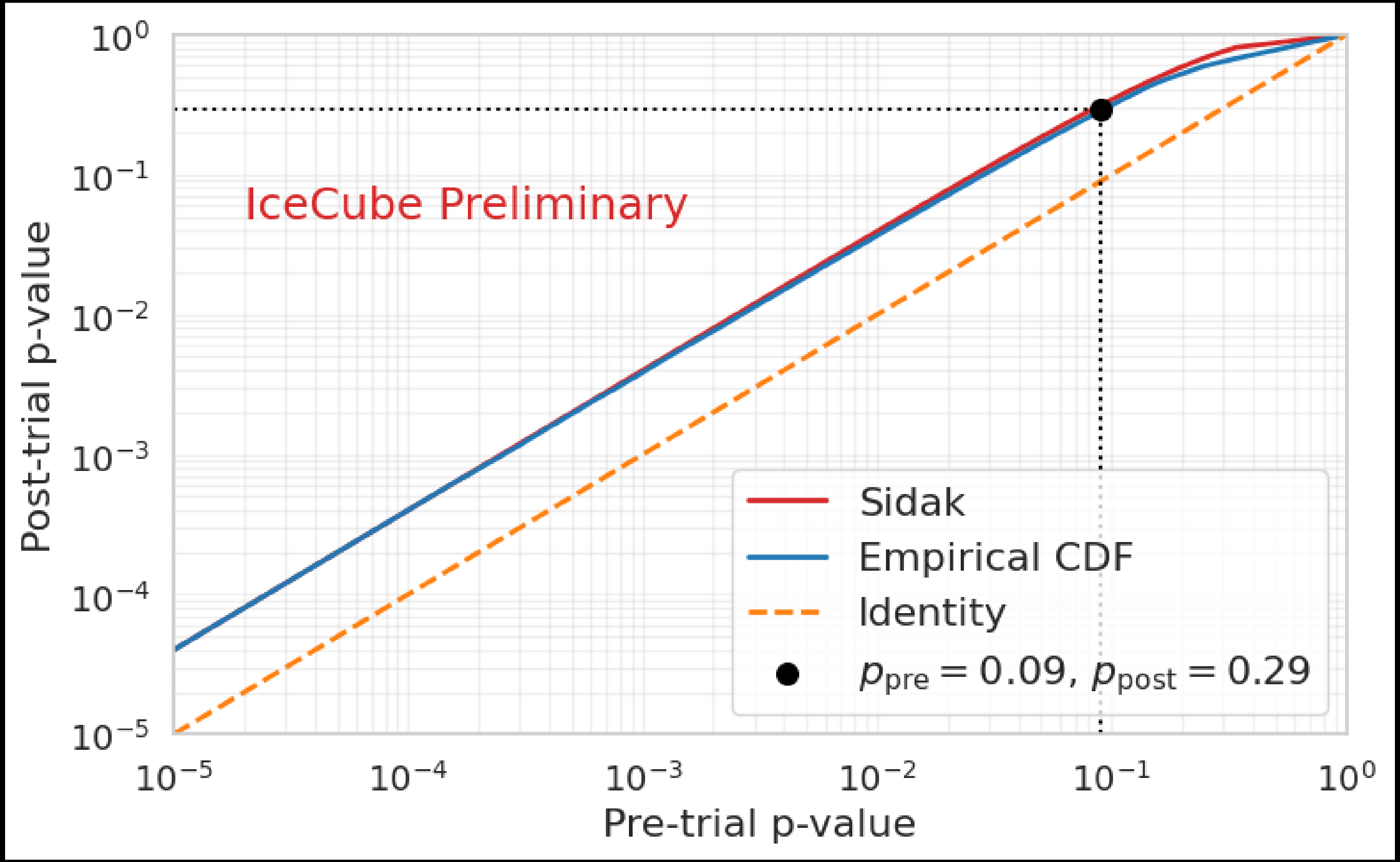
FREEDOM OF RESEARCH

Back-up

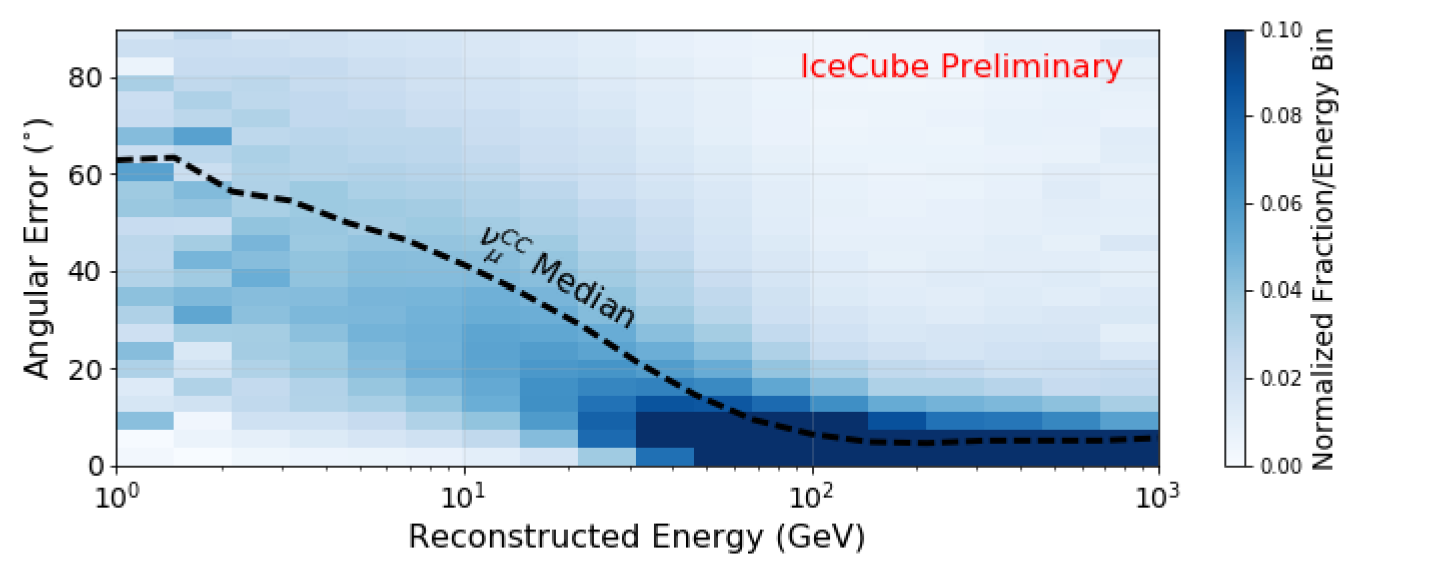
MeV: TS distributions

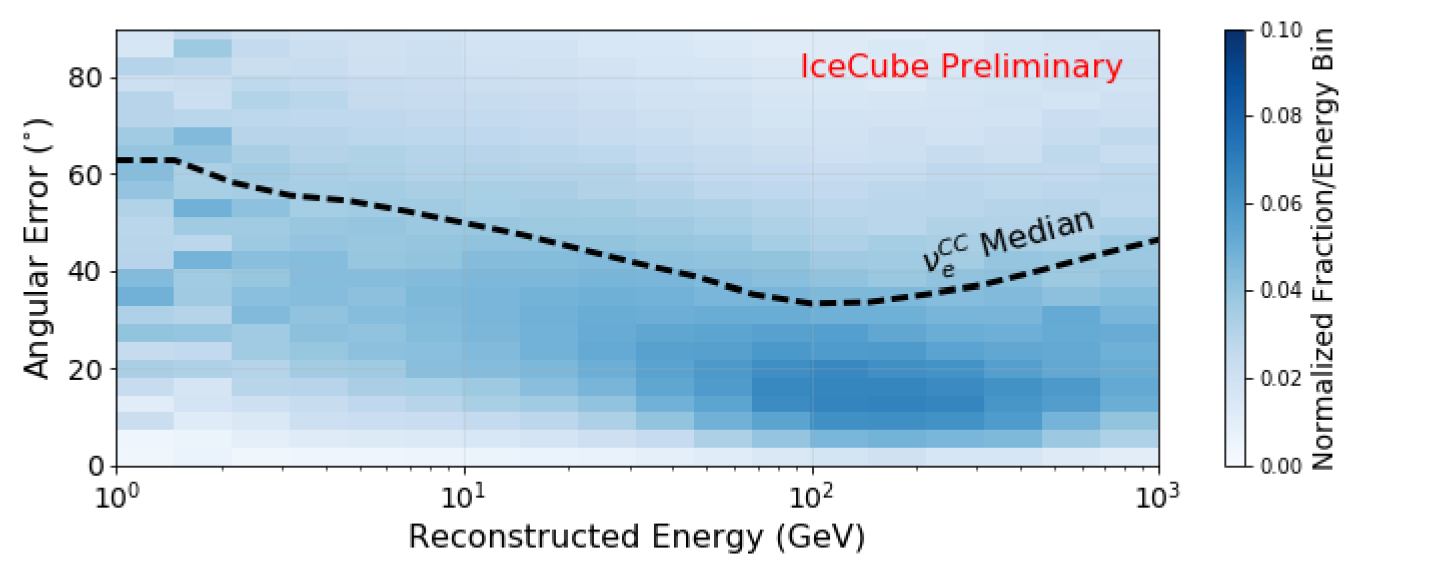


GREco: Trial correction



GRECO: Angular resolution





Jeffrey's uninformative prior:

$$\pi(\mu_{sig}, \mu_{bkg}) = \left[\mu_{bkg} \times (\mu_{bkg} + \mu_{sig})\right]^{-1/2}$$

Data

(N_{sig}, N_{6h})

Bayes' Formula

Likelihood:

$$\mathcal{L}(N_{sig}, N_{6h} \mid \mu_{sig}, \mu_{bkg}, \alpha)$$
$$= \text{Poisson}(N_{sig}; \mu_{bkg} + \mu_{sig})$$
$$\times \text{Poisson}(N_{6h}; \alpha\mu_{bkg})$$

1-100 MeV | 0.5-10 GeV | 10 GeV - 1 TeV

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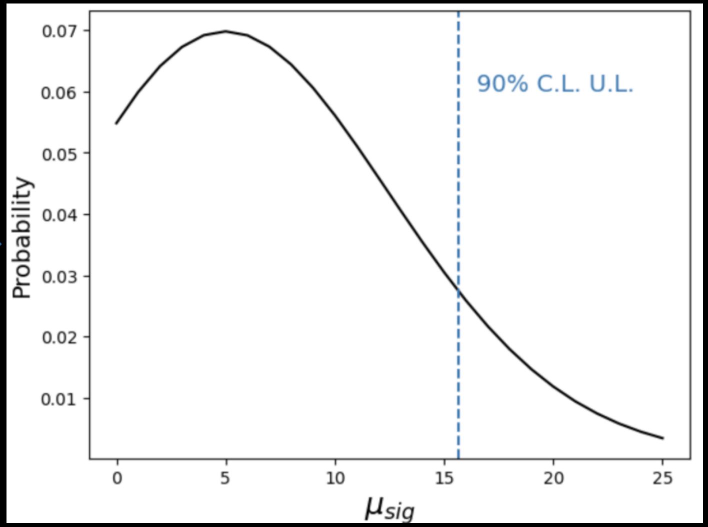
$\boldsymbol{P(\mu_{sig}, \mu_{bkg})}$

Marginalize over μ_{bkg}



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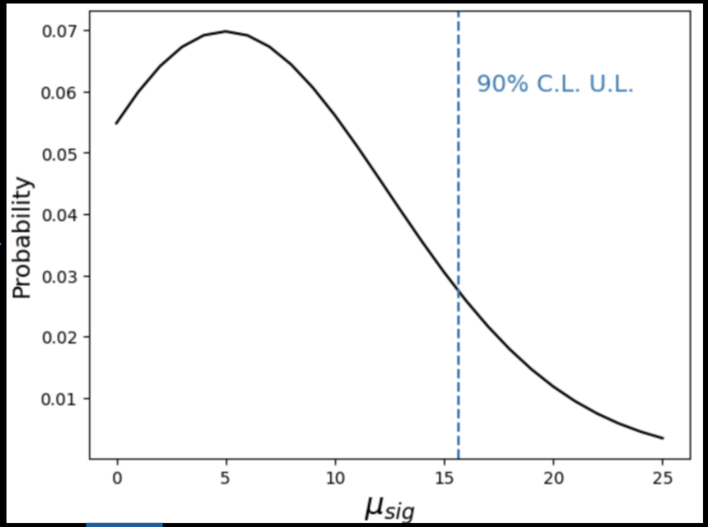

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Per-flavor flux upper-limit:

$$\phi^{90\%} = \frac{2 \times \mu_{sig}^{90\%}}{\int_{0.5\,GeV}^{100\,GeV} A_{eff}(E)\,(E/GeV)^{-\gamma}\,dE}$$