Credit: Martin Wolf, IceCube/NSF

CHIBA UNIVERSITY

ICEHAP

Prospects for GeV Neutrino Transient Searches with the IceCube Upgrade

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TeVPA 2026 @ Tendo

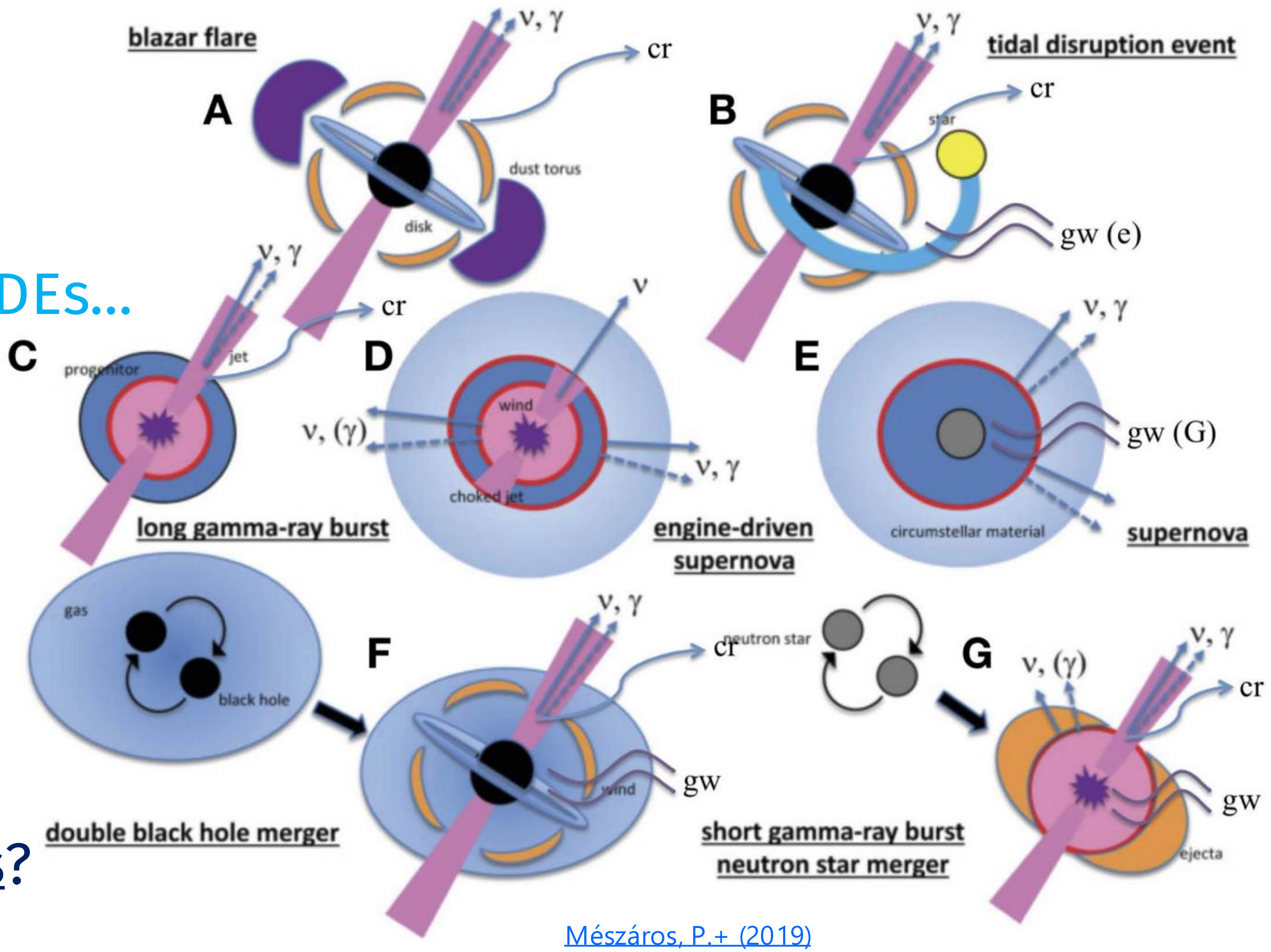
arXiv:2608.28395

ICECUBE UPGRADE

NSF

Neutrinos Expected from Transients

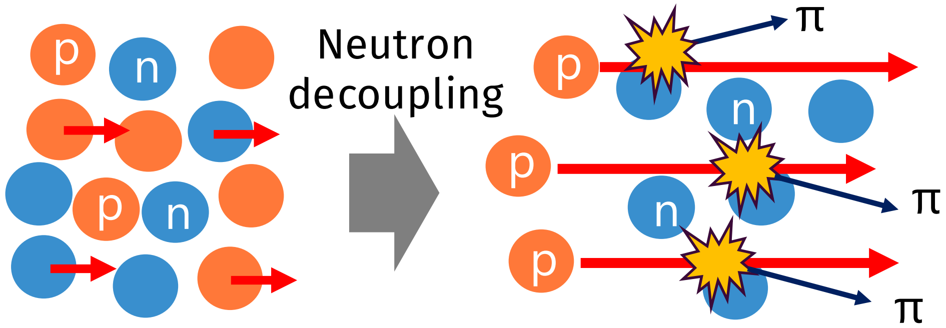
- Various transients are expected to emit **neutrinos and multi-messenger signals**
  - GRB, supernova (SN), novae, TDEs…
- Promising sources of **TeV-PeV neutrinos** observed by IceCube
- Extensive IceCube searches have placed strong constraints
  - GRB (2022), SN (2023), …
- Would it be interesting to extend these searches to **lower energies**?

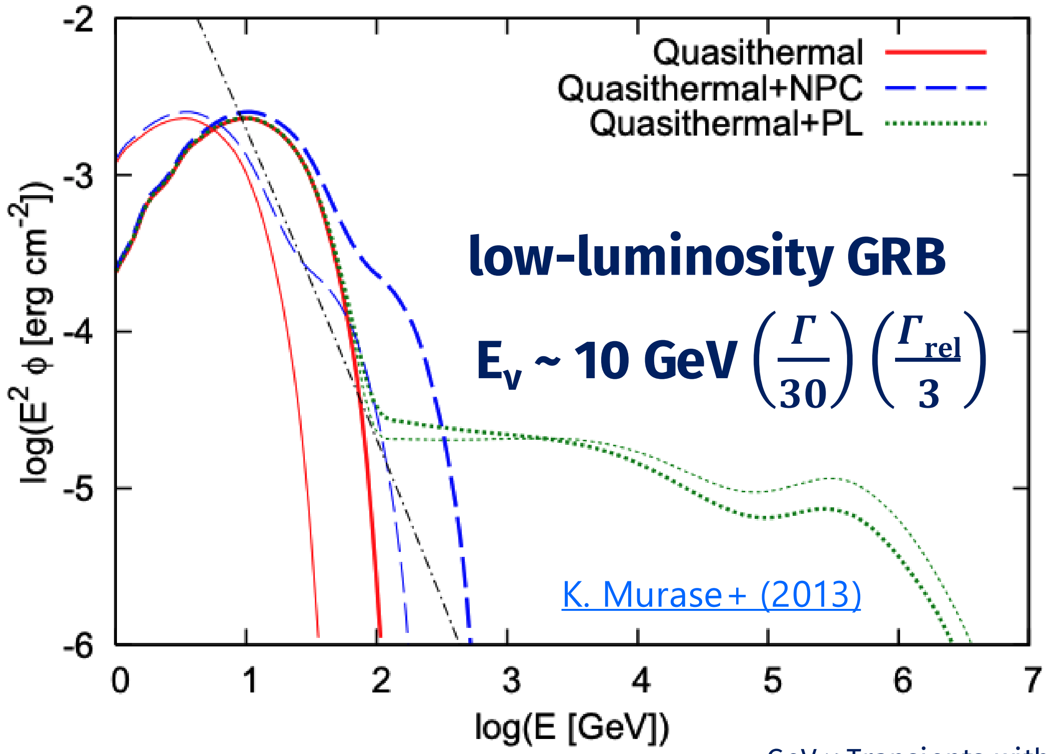


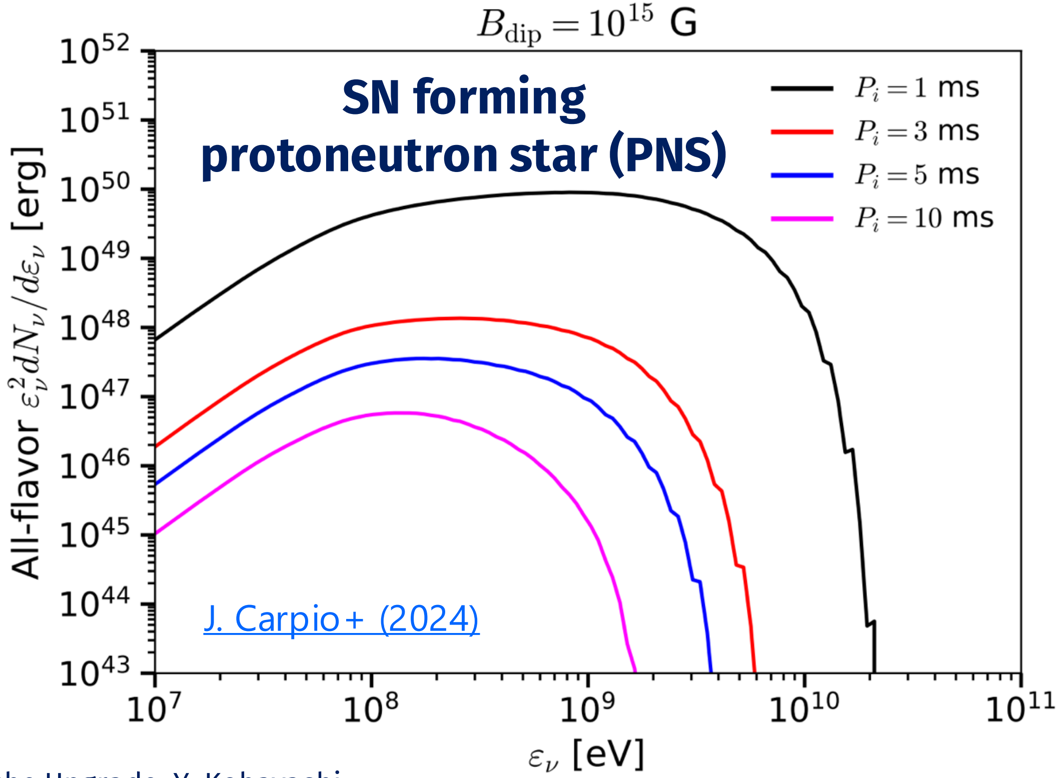
Mészáros, P.+ (2019)

Quasithermal GeV Neutrinos

- From proton-neutron collision in outflow
  - **Does not require CR acceleration**
- Predict **distinct GeV signature** in GRB/SNe
- Unique clue to **subphotospheric processes**



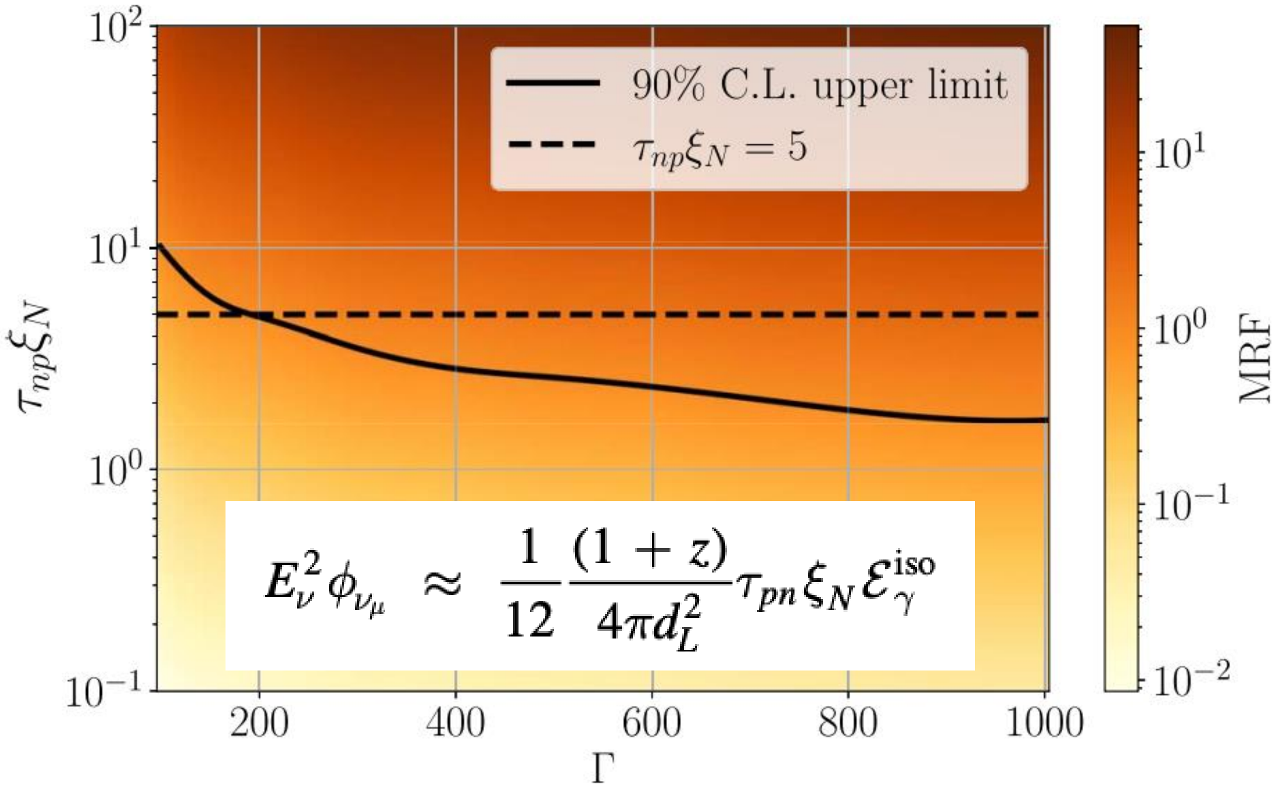




Past Searches with IceCube DeepCore

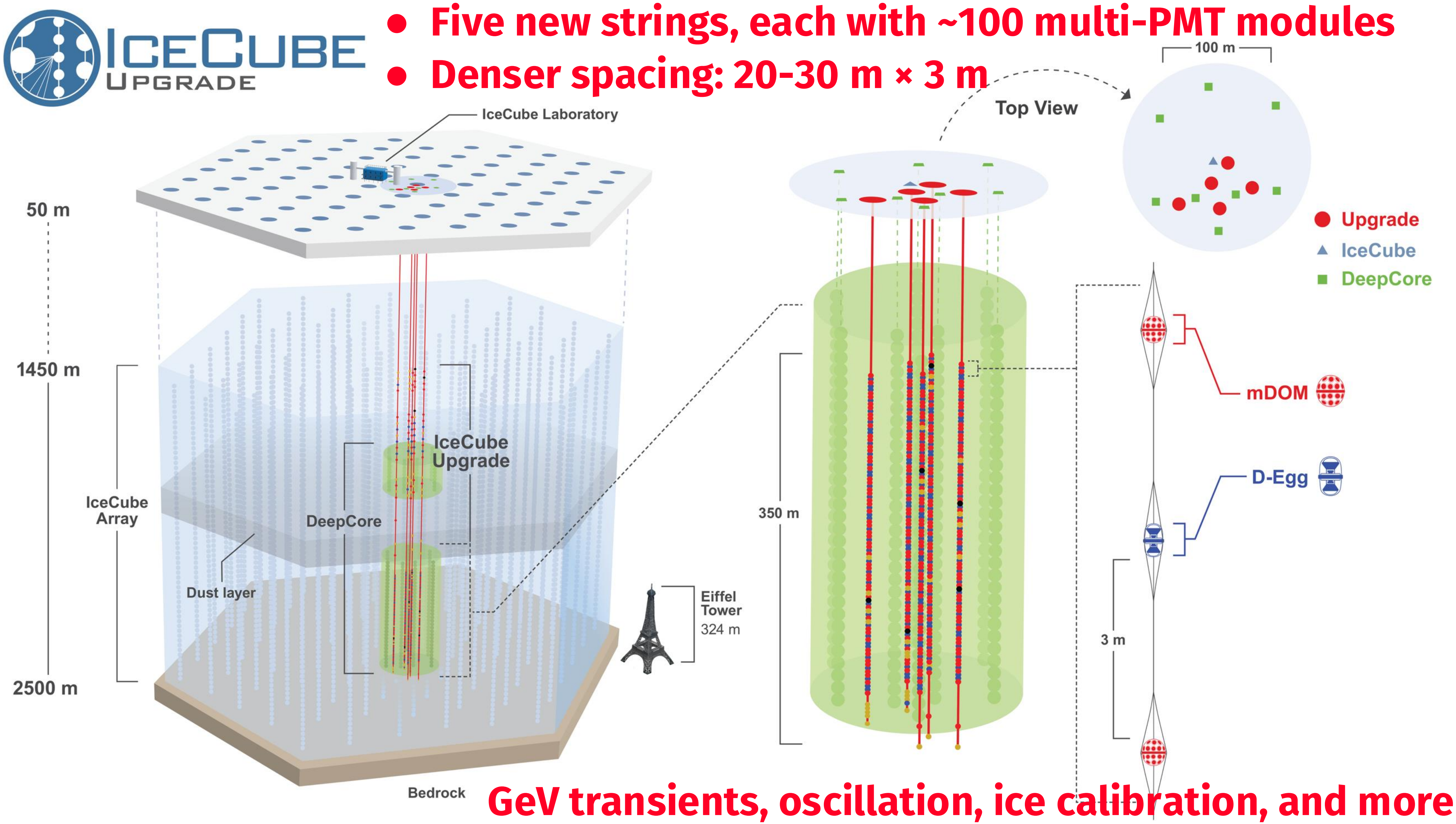
- **IceCube infill array: DeepCore**
  - Low-energy extension of IceCube
- **Transient searches with dedicated event selections**
  - GRECO (sub-TeV)
  - ELOWEN (GeV)
  - **=> GRB, supernova, novae, GW…**
- No detection yet, but **constraining their physical properties**

Constraints on baryon loading factor of GRB221009A



K. Murase+ (2022), IceCube Collaboration (2024)

- **Five new strings, each with ~100 multi-PMT modules**
- **Denser spacing: 20-30 m × 3 m**



GeV transients, oscillation, ice calibration, and more

https://icecube.wisc.edu/gallery/the-icecube-upgrade

Successful Deployment of the IceCube Upgrade

Credit: Ilya Bodo, IceCube/NSF

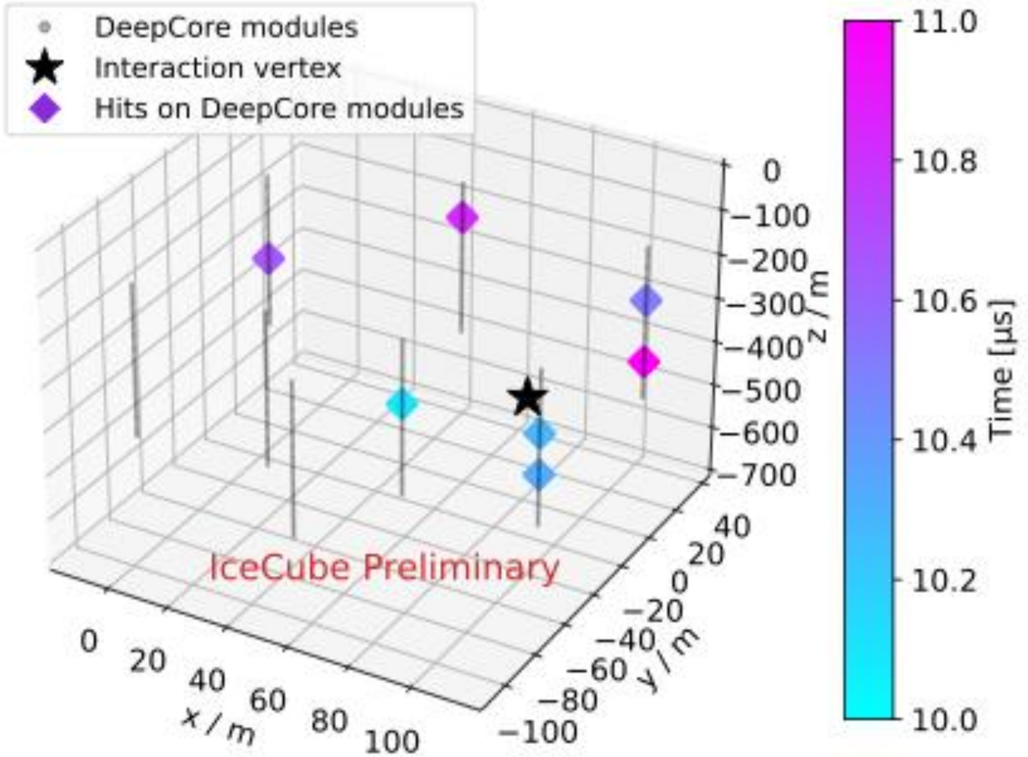
- Over the last austral summer, five new strings (505 optical modules) were successfully deployed!
- Commissioning completion and first run expected by the end of 2026

Credit: IceCube/NSF

Upgrade Simulation and Event Selection

- Simulation [IceCube Collaboration (2026)]
  - Upgrade modules added to IceCube+DeepCore simulation
  - Based on **originally planned seven-string geometry (IC93)**
- DeepCore-like event selection
  - Coincidence trigger, veto, simple cuts
- Exploiting **machine-learning (ML) techniques**
  - Energy and direction reconstruction
  - Noise cleaning and muon rejection

12 GeV ν_μ charged-current event (signal only)



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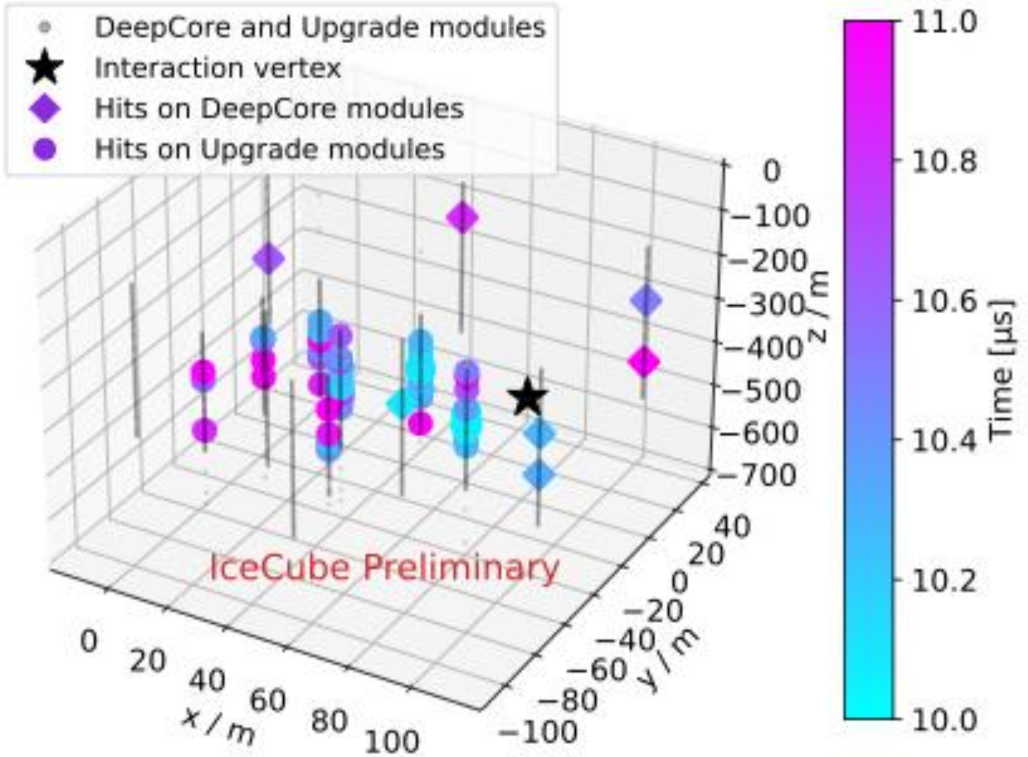
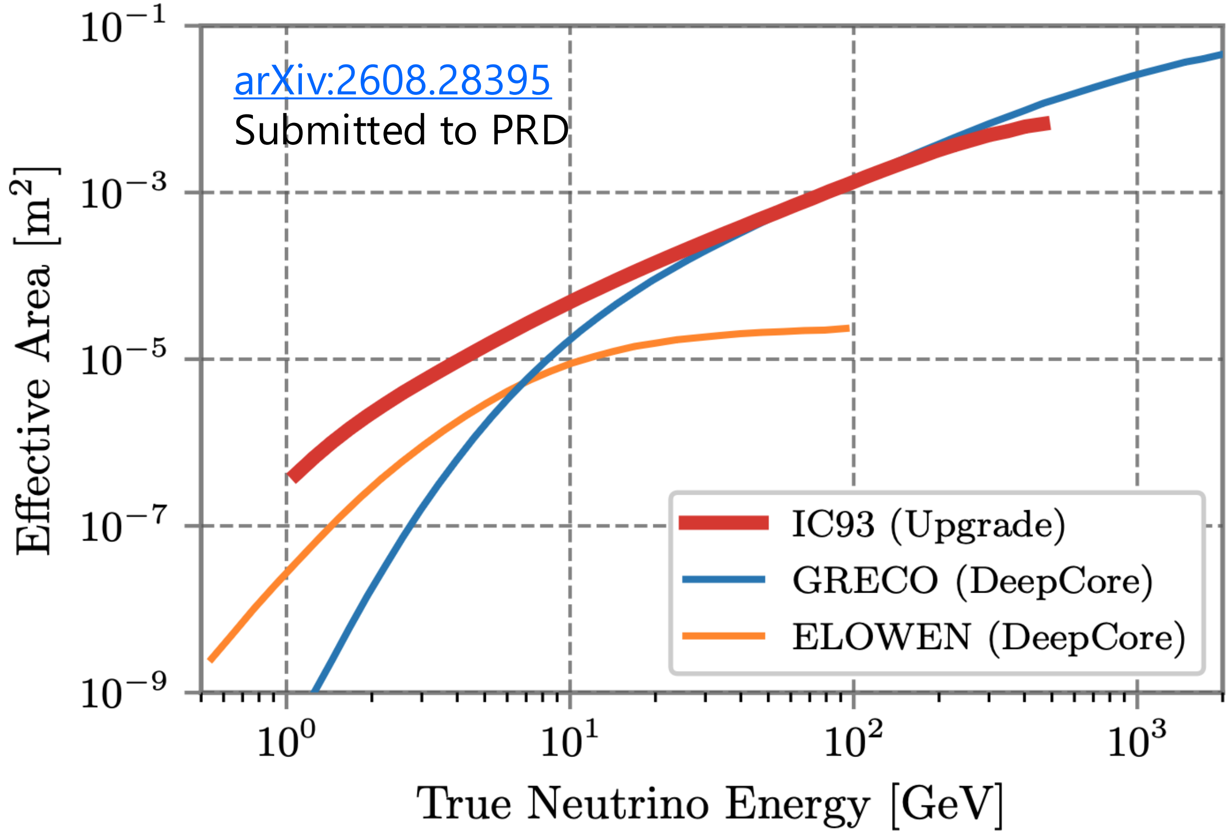
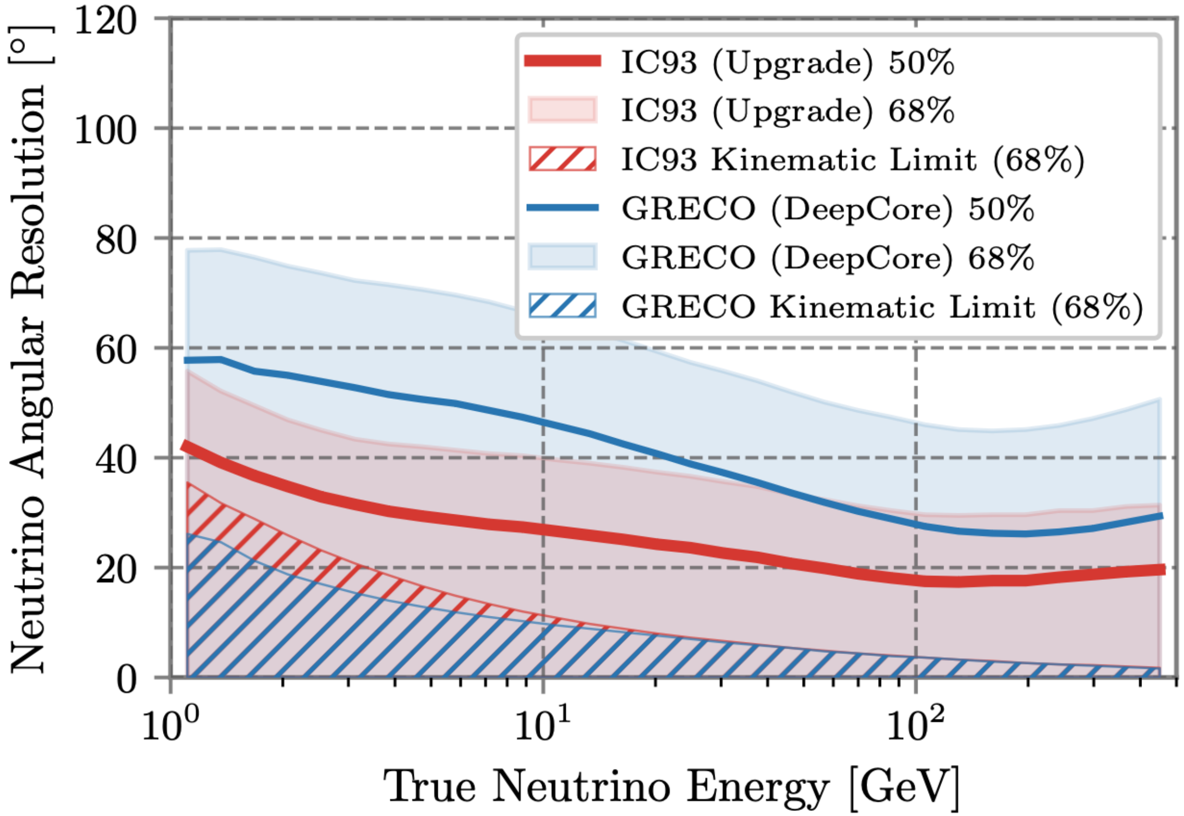


Key Performance Metrics

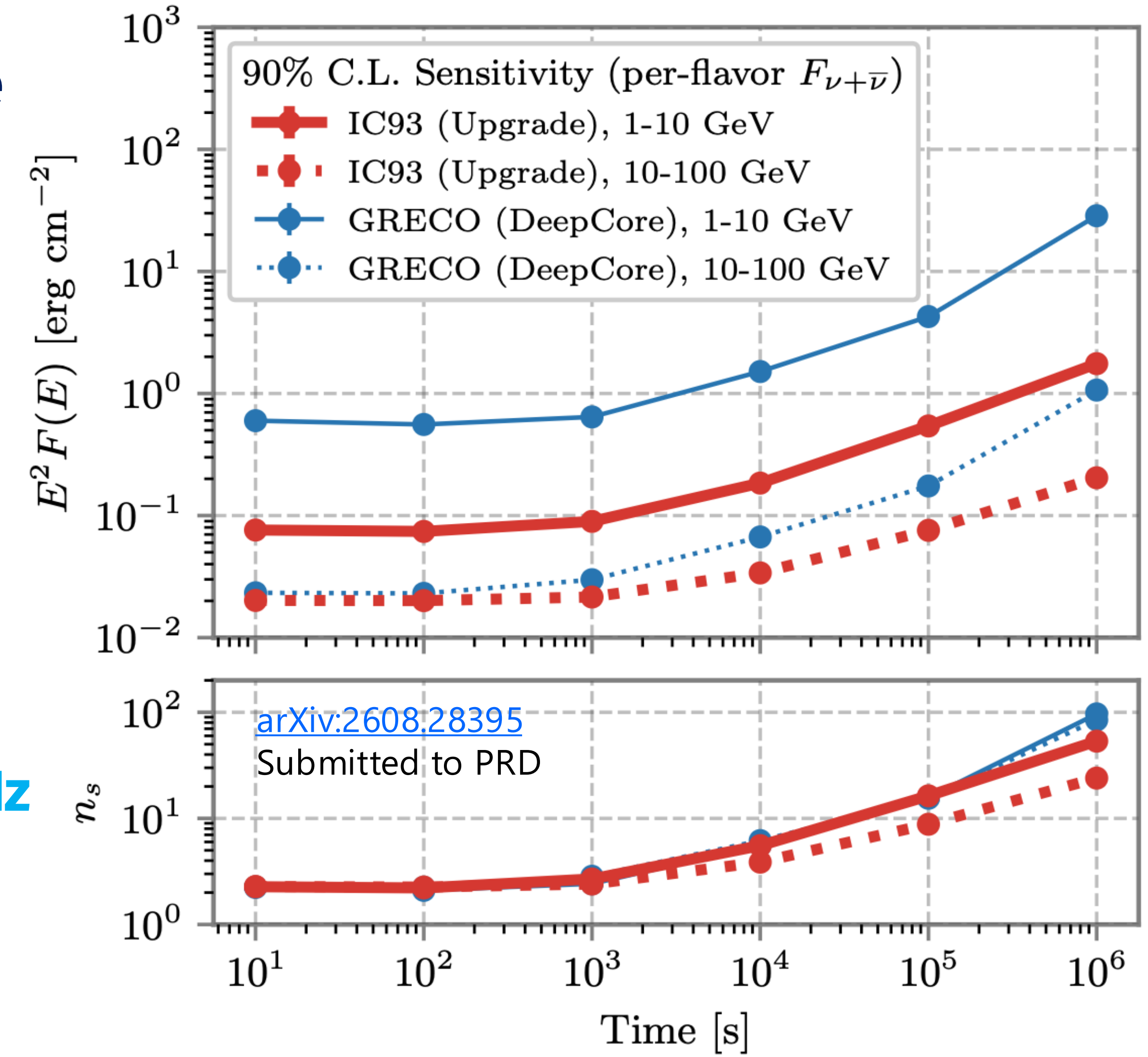
- **Significant improvement in signal acceptance and angular resolution in the GeV energy range ⇨ Better transient sensitivity**





Upgrade Sensitivity to Transients

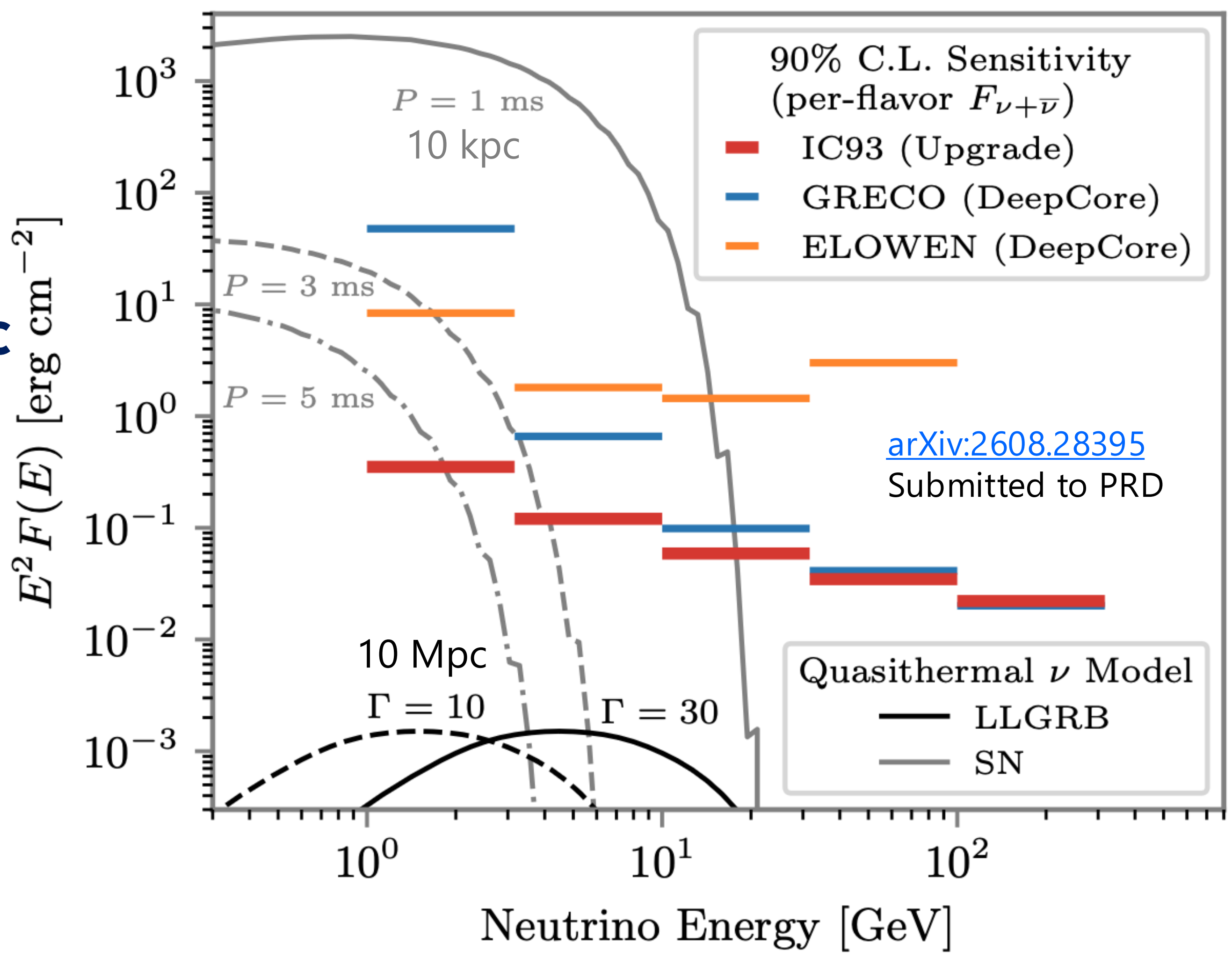
- Assuming **source position and time are known** (follow-up observation)
- Point-source analysis with **unbinned maximum likelihood**
- **Significant improvement over DeepCore in 1-10 GeV range**
- **Quasi background-free timescale of $\lesssim 1000$ s**
  - **Effective background rate of ~1 mHz**
  - Quasi background-free for GRB and SN observations



Differential Sensitivity with Singal Predictions

- **Unprecedented sensitivity to 1-10 GeV neutrinos**
  - Improvement by an order of magnitude from DeepCore
- **Access to more modest Galactic SN models: PNS with B=10^{15} G and P $\lesssim$ 5 ms will be detectable**
- Sensitivity **reach for low-luminosity GRBs is ~1 Mpc**
  - May be challenging to detect, given a burst rate estimate of ~10^{-7}-10^{-6} Mpc^{-3}yr^{-1}

ΔT = 1000 s

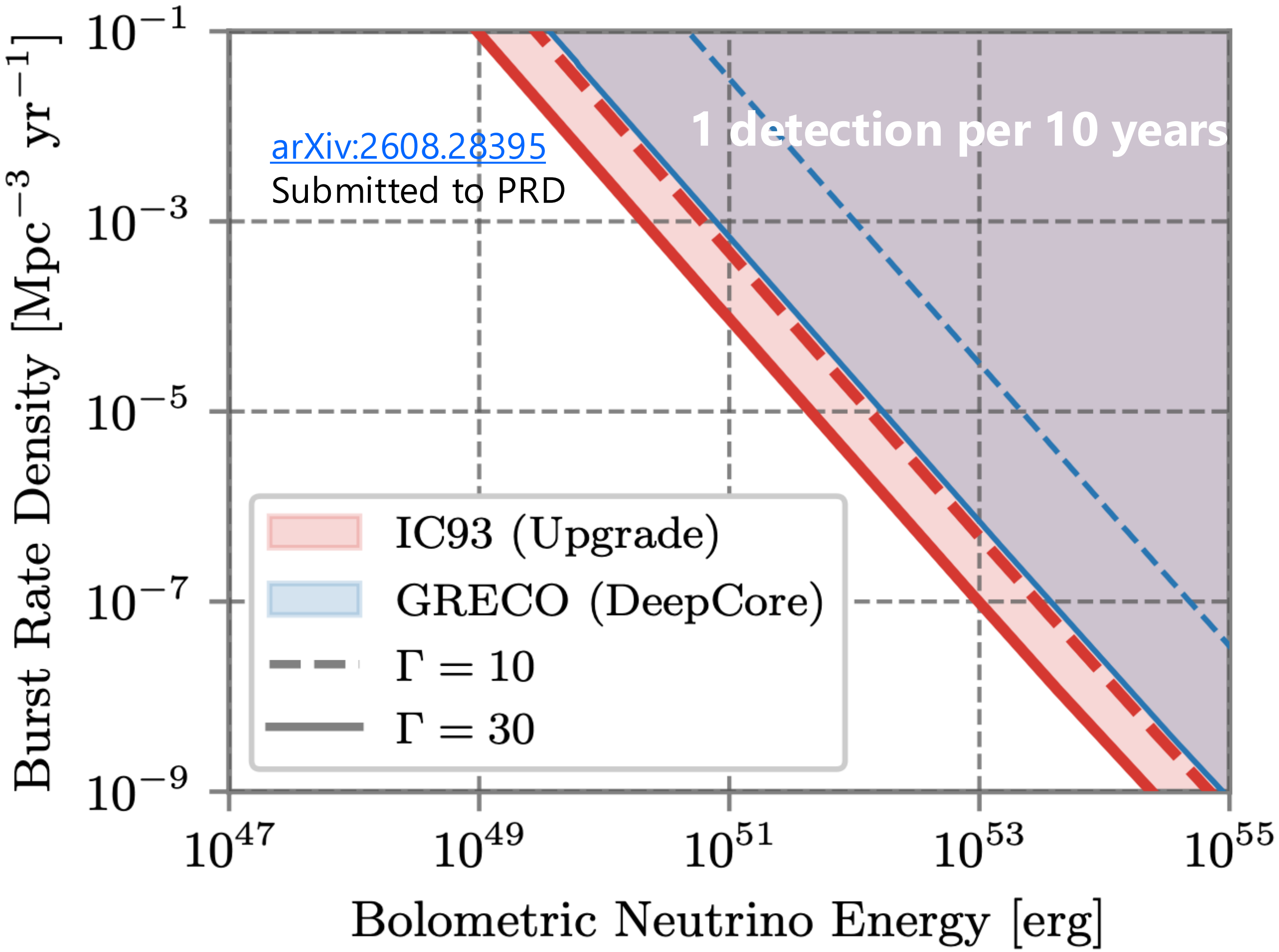


arXiv:2608.28395
Submitted to PRD

Constraints on Burst Population

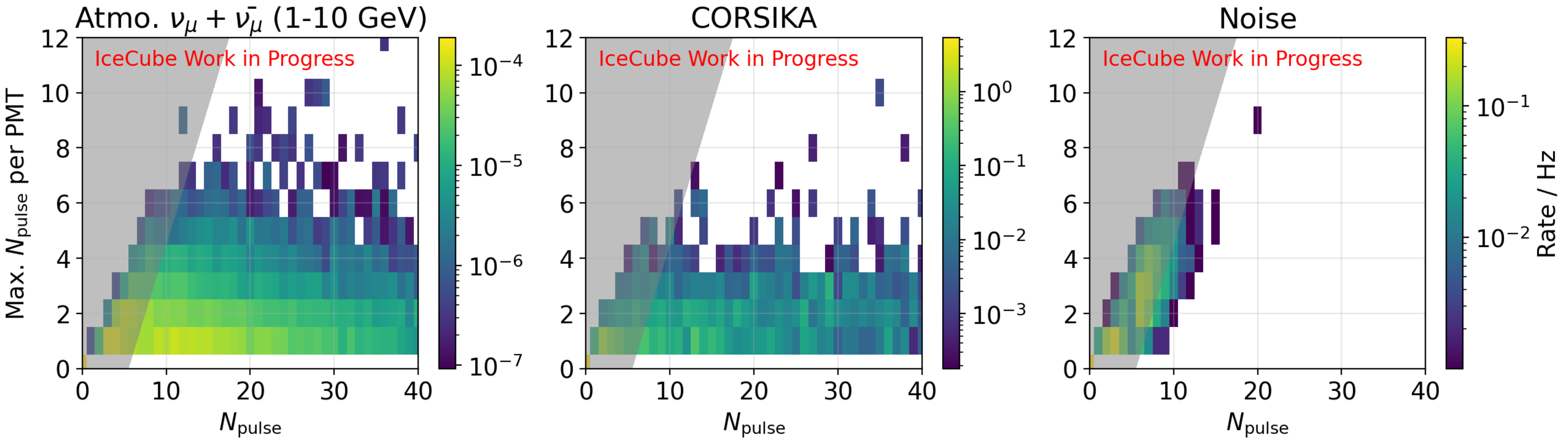
- **IceCube Upgrade will provide unprecedented constraints on the GeV transient population**

The GRB neutrino emission model and ΔT = 1000 s are used



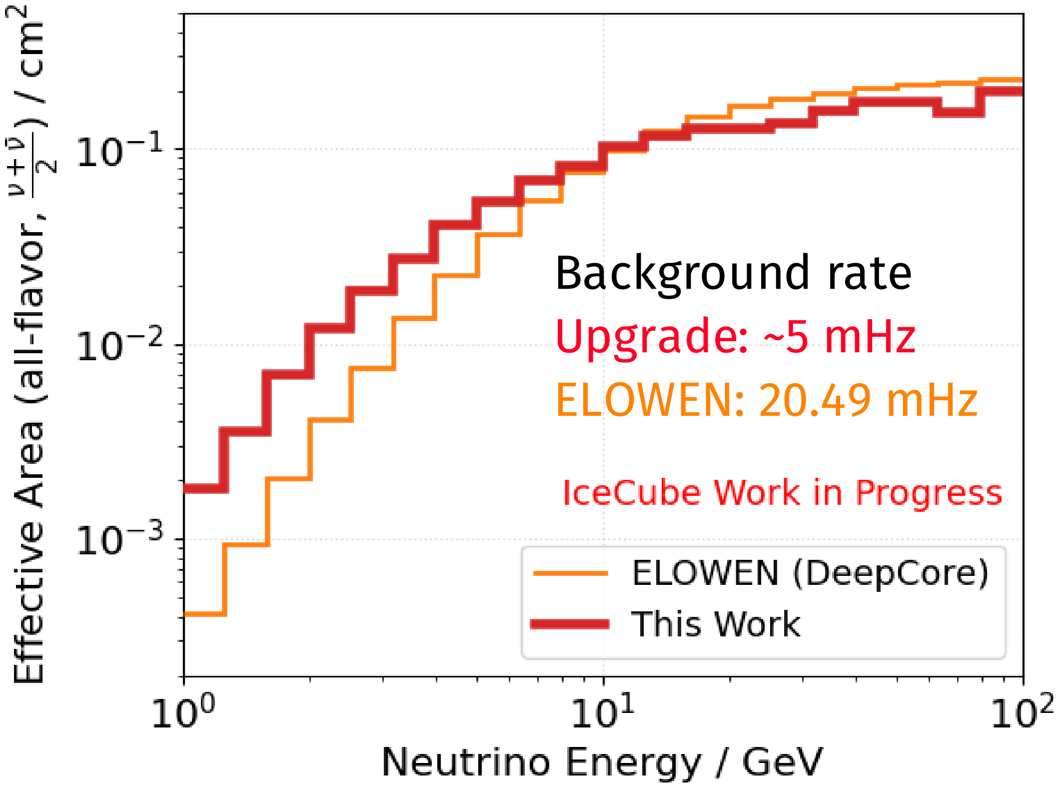
Towards First Transient Search with Upgrade

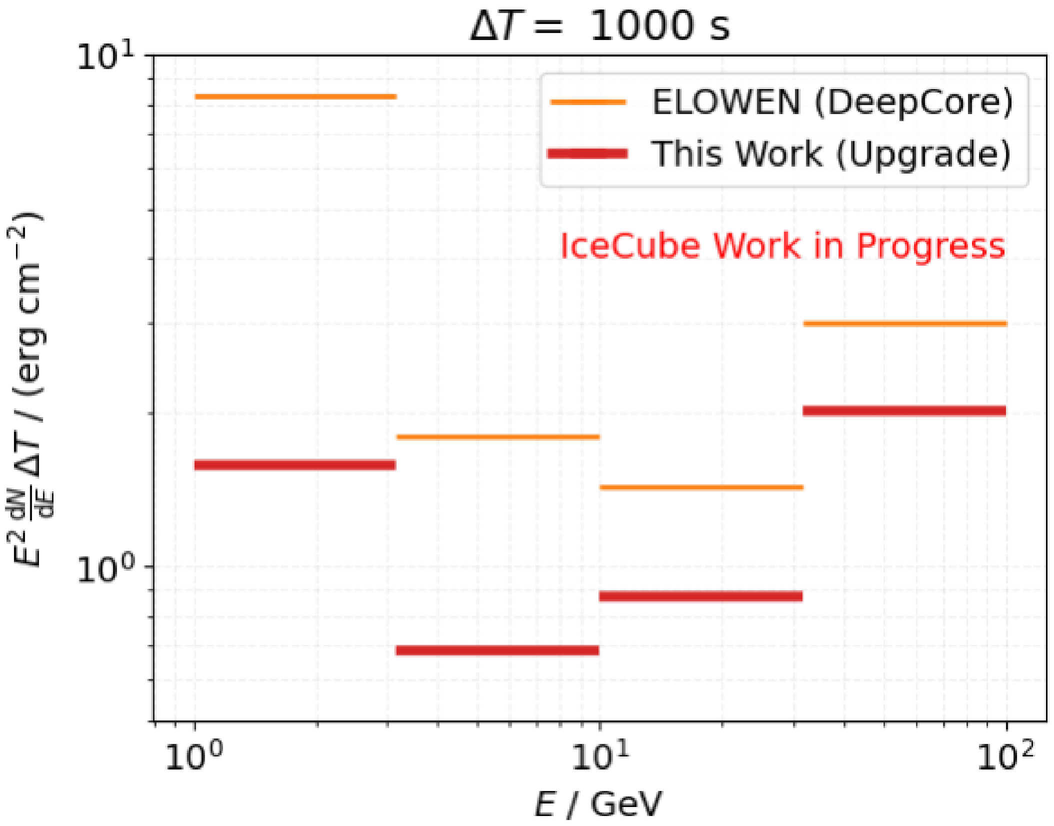
- IC93 simulation may be optimistic: planned geometry and advanced ML techniques
- **A simpler, robust event selection with deployed geometry is under development for initial analysis of IceCube Upgrade**
  - **Only using simple straight cuts** for background rejection, without reconstruction



Upgrade Performance with Simple Selection

- Even with **a simple event selection** without reconstruction, IceCube Upgrade is expected to **significantly improve sensitivity at GeV energies**
- **First search, even with simple analysis, will provide unprecedented sensitivity**





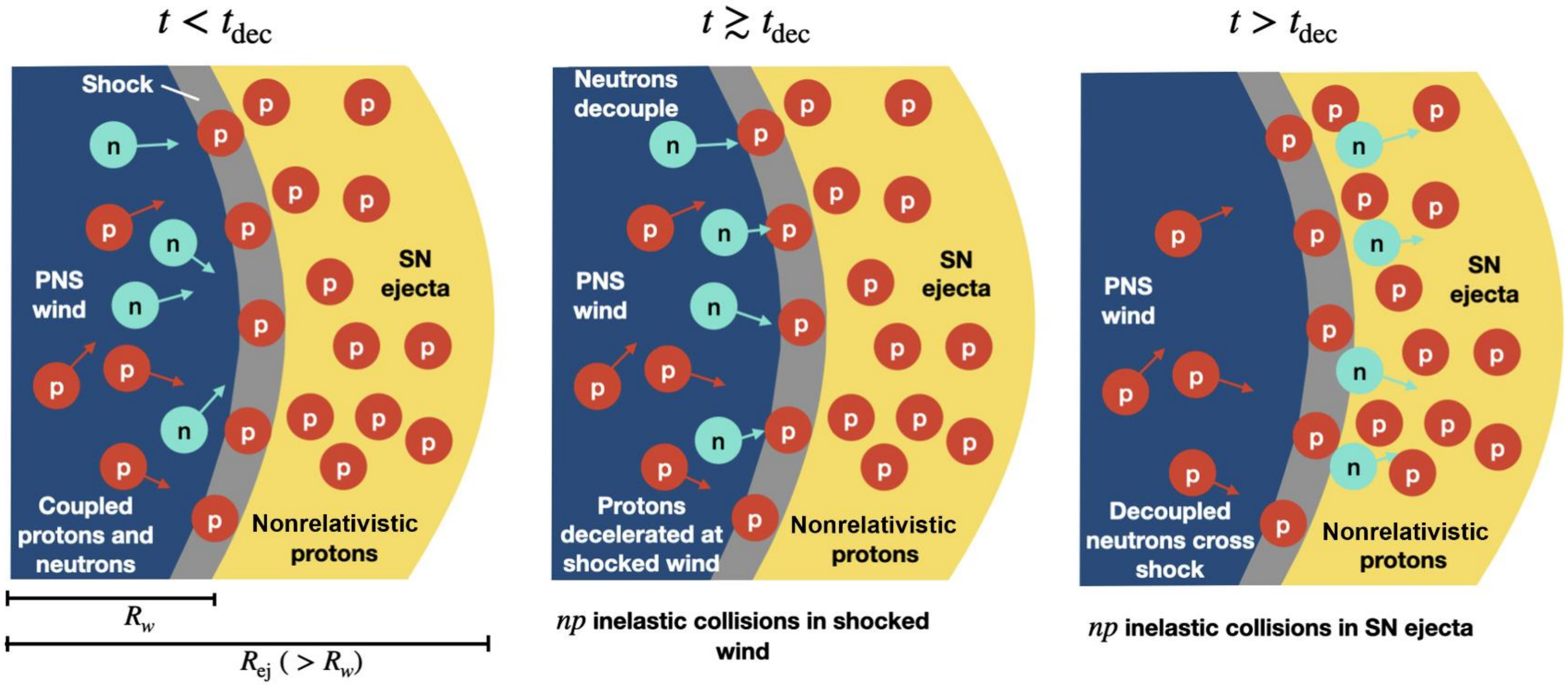
Summary and Outlook

- **Quasithermal GeV neutrinos** are key to probing the physical environment in GRBs and SNe outflows
- **IceCube Upgrade was successfully deployed in the last austral summer!**
- From simulation, **IceCube Upgrade is expected to significantly improve sensitivity to transients in the 1-10 GeV energy range**
  - Enhances chance of detecting low-luminosity GRBs, SNe, novae, etc
- Ongoing work indicates **even a simple, robust analysis can provide unprecedented sensitivity to GeV transients**
- **First physics run with Upgrade is expected to start by the end of 2026**
- Further work to maximize sensitivity and perform first analysis with data

Stay tuned! Thank you!

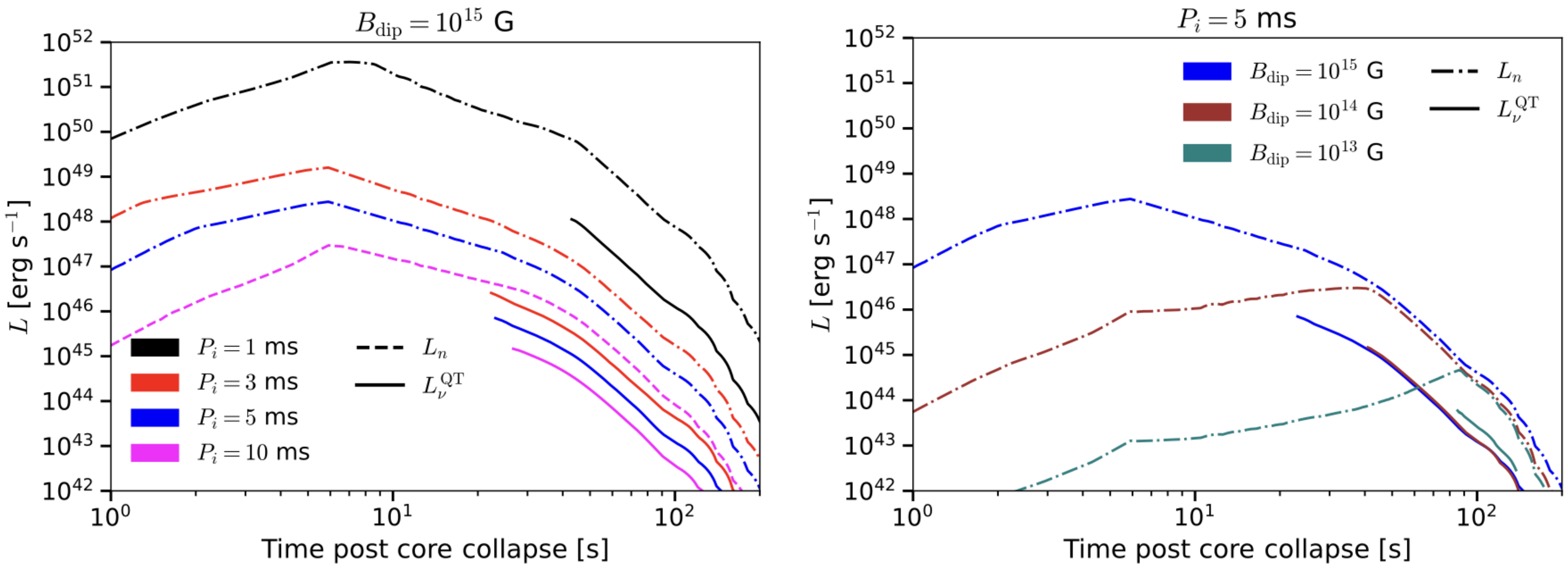
Backup

np Collision Mechanism in SN forming PNS



J. A. Carpio et al. (2024)

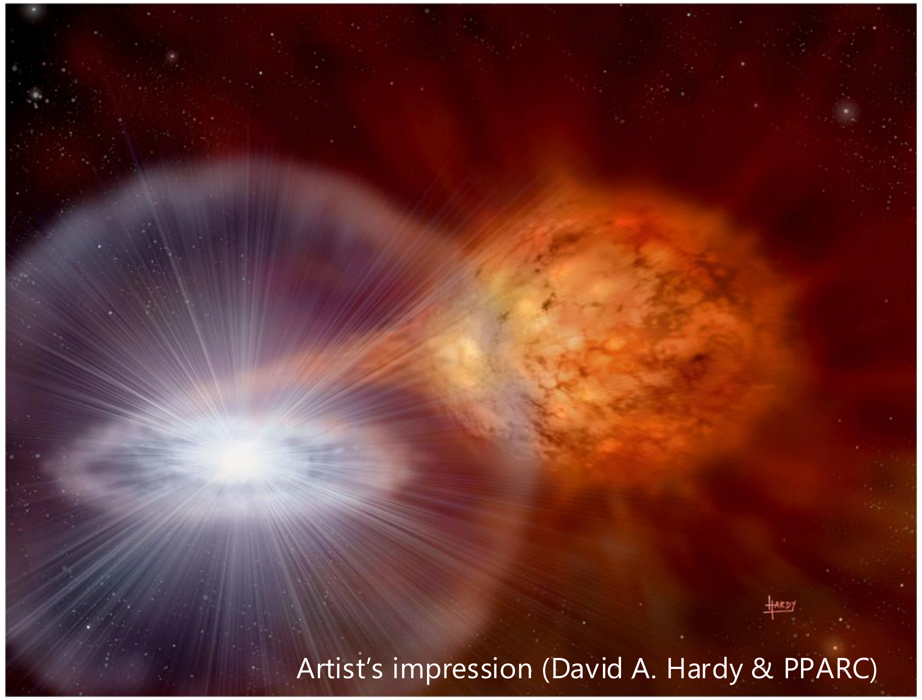
SN => PNS Light Curves

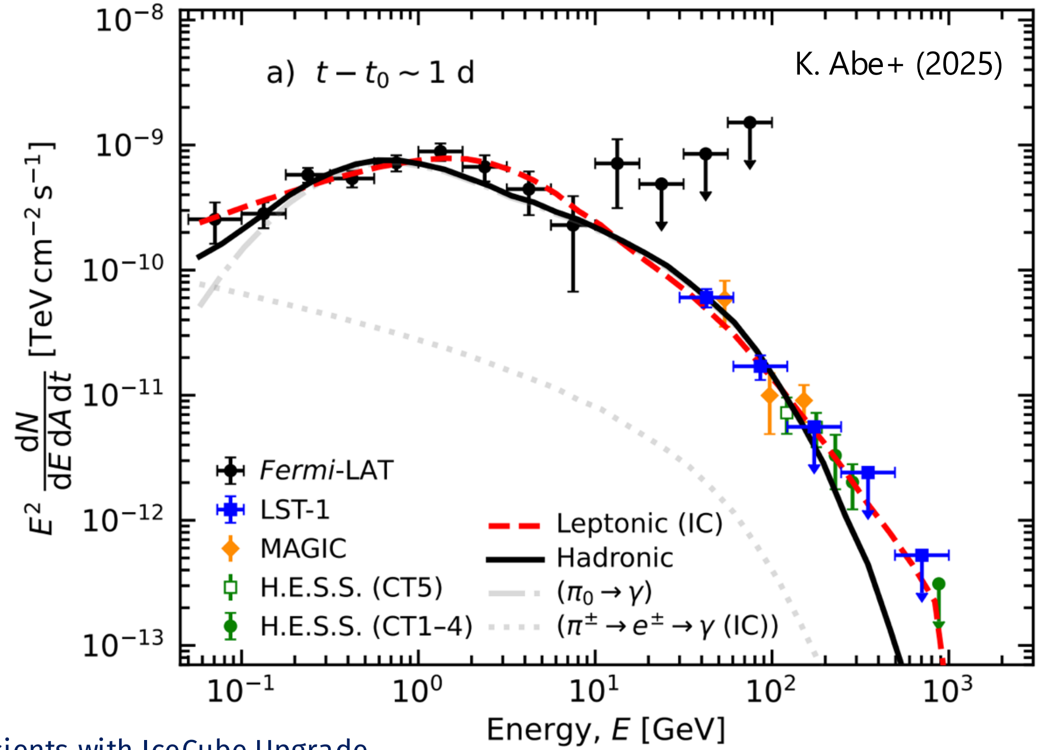


J. A. Carpio et al. (2024)

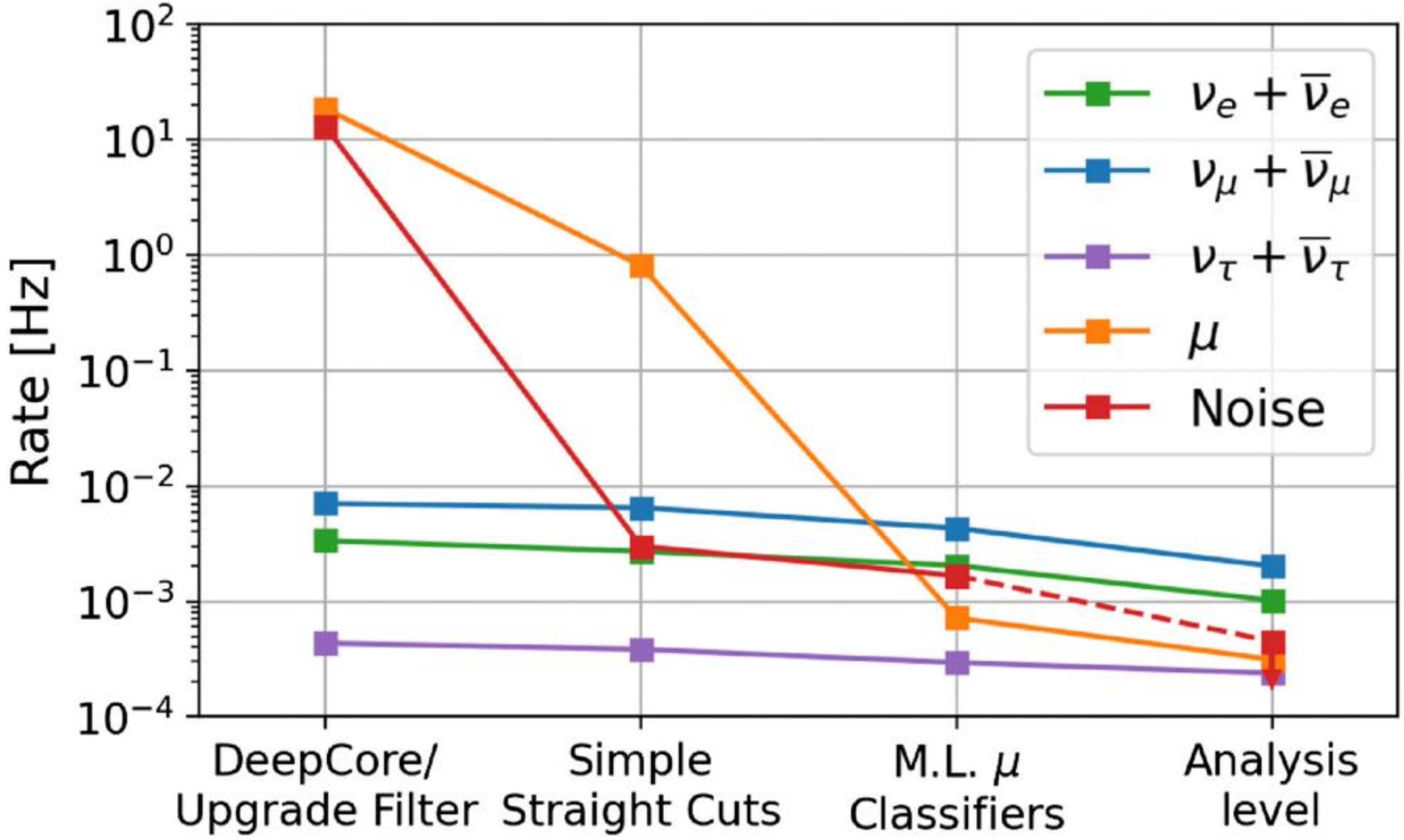
Galactic Novae

- Thermonuclear explosion in binaries hosting white dwarf
- **GeV-TeV gamma rays** detected from 2021 outburst of RS Ophiuchi
  - **Observations support hadronic emission. Should be accompanied by neutrinos**
- T Coronae Borealis predicted to erupt in the next few years with ~7 times higher flux


Artist's impression (David A. Hardy & PPARC)



IC93 Simulation Event Rates



IC93 Simulation Simple Cuts

- # of hit modules >= 4
- # of hits >= 6
- First hit depth vertex <= -120 m
- Duration (after cleaning) <= 3 us
- Duration (before cleaning) <= 15 us

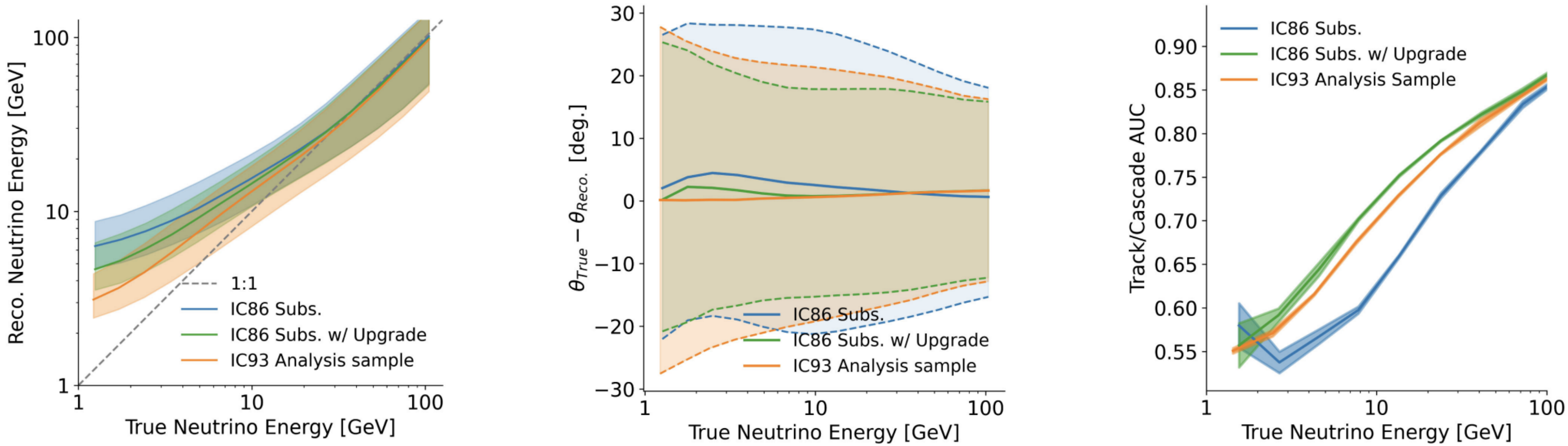
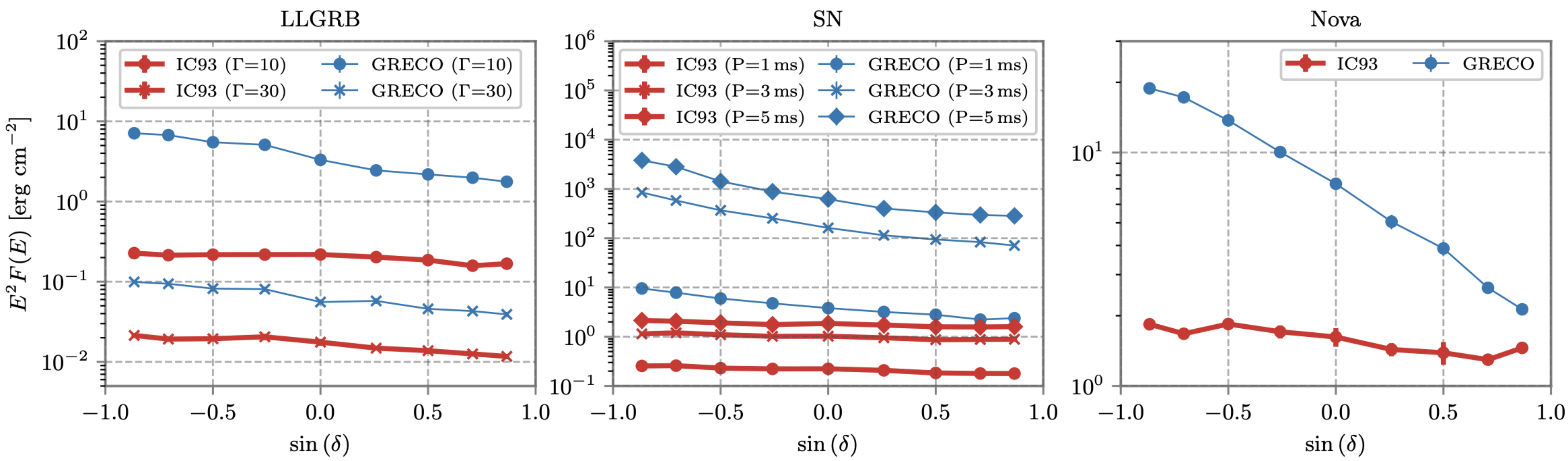


FIG. 5. Performance of reconstruction models on analysis sample (orange) and the IC86 subsample with and without the information on the upgrade strings (green and blue, respectively). Left: reconstructed neutrino energy vs true neutrino energy. Bands depict the 1σ range, and the median is shown in solid. Middle: angular resolution of the zenith reconstruction. Bands represent the 1σ range of the residual distribution around the median shown in solid. Right: area under curve (AUC) score of $\mathcal{T}/\mathcal{C}$ classifier binned in neutrino energy. Uncertainty bands on the AUC curves result from bootstrapping and represent the expected statistical 1σ deviation. A value of 0.5 indicates random classification, and a value of 1.0 indicates perfect classification. There is a moderate improvement in energy and zenith reconstruction, while the improvement in $\mathcal{T}/\mathcal{C}$ classification is quite substantial especially around 10 GeV.

IceCube Collaboration (2026)

Sensitivity to Models vs Declination



arXiv:2608.28395, submitted to PRD

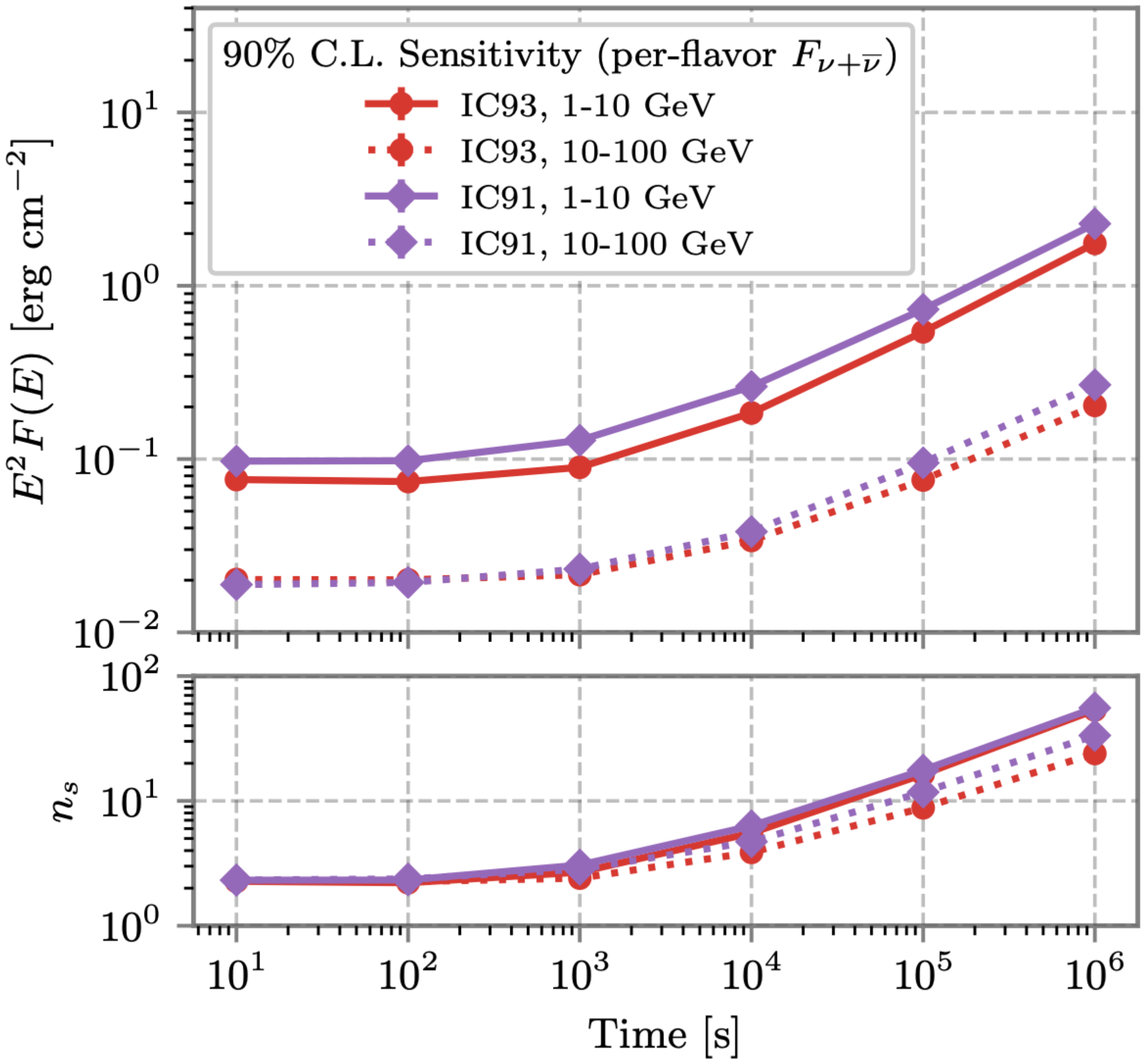
Signal and Background Counts

TABLE I. Expected all-sky background and signal event counts for the IceCube Upgrade and DeepCore datasets in a 1000 s observation, assuming the GRB quasi-thermal neutrino emission model [62] with $\Gamma = 10$ and 30, scaled to a proxy distance of 1 Mpc [62]. The bolometric nucleon energy is assumed to be $\mathcal{E}_N = 5 \times 10^{50}$ erg, corresponding to a neutrino fluence of $\sim 0.4\,\mathrm{erg\,cm^{-2}}$. The IC93 background consists only of atmospheric neutrinos.

Dataset	IC93	GRECO	ELOWEN
Background Count	6.6	4.6	20
Signal Count ($\Gamma = 10$)	1.8	0.10	0.29
Signal Count ($\Gamma = 30$)	5.4	1.4	0.95

arXiv:2608.28395
Submitted to PRD

IC91 vs IC93 Sensitivity



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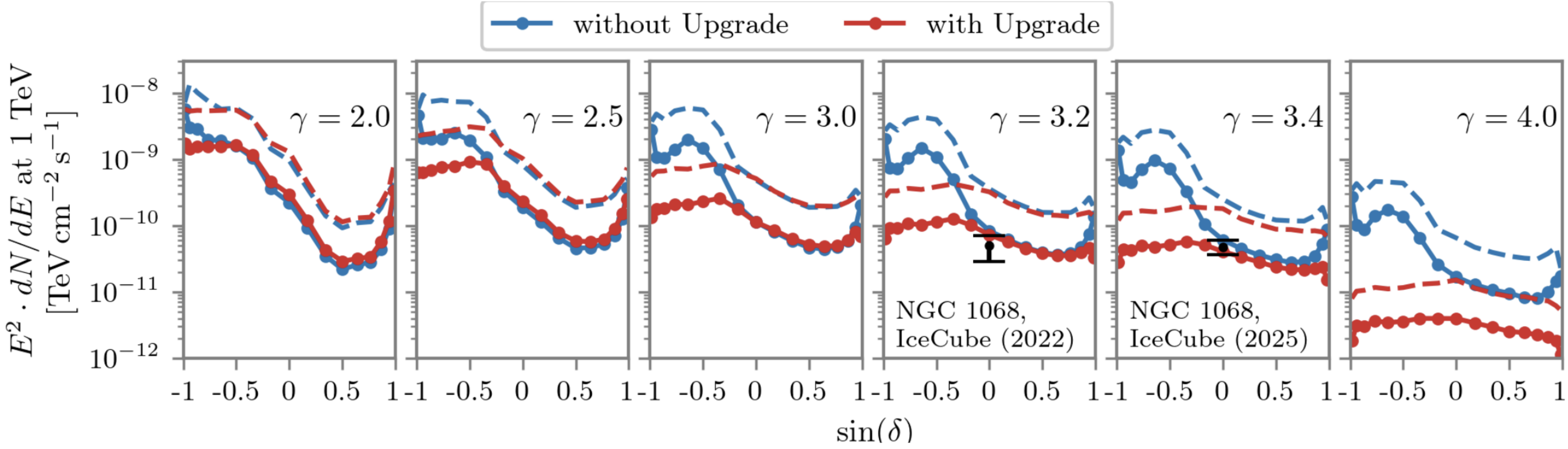
Steady-source Sensitivity



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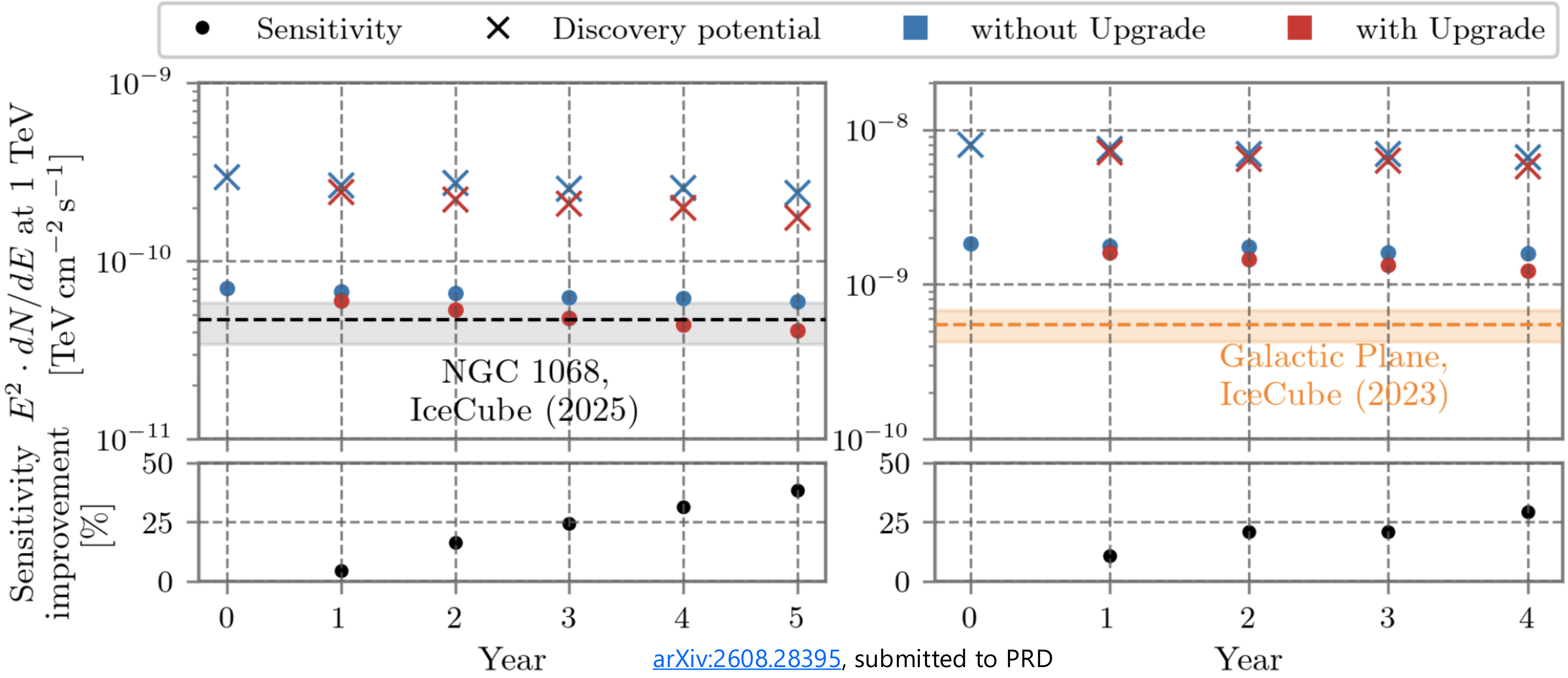

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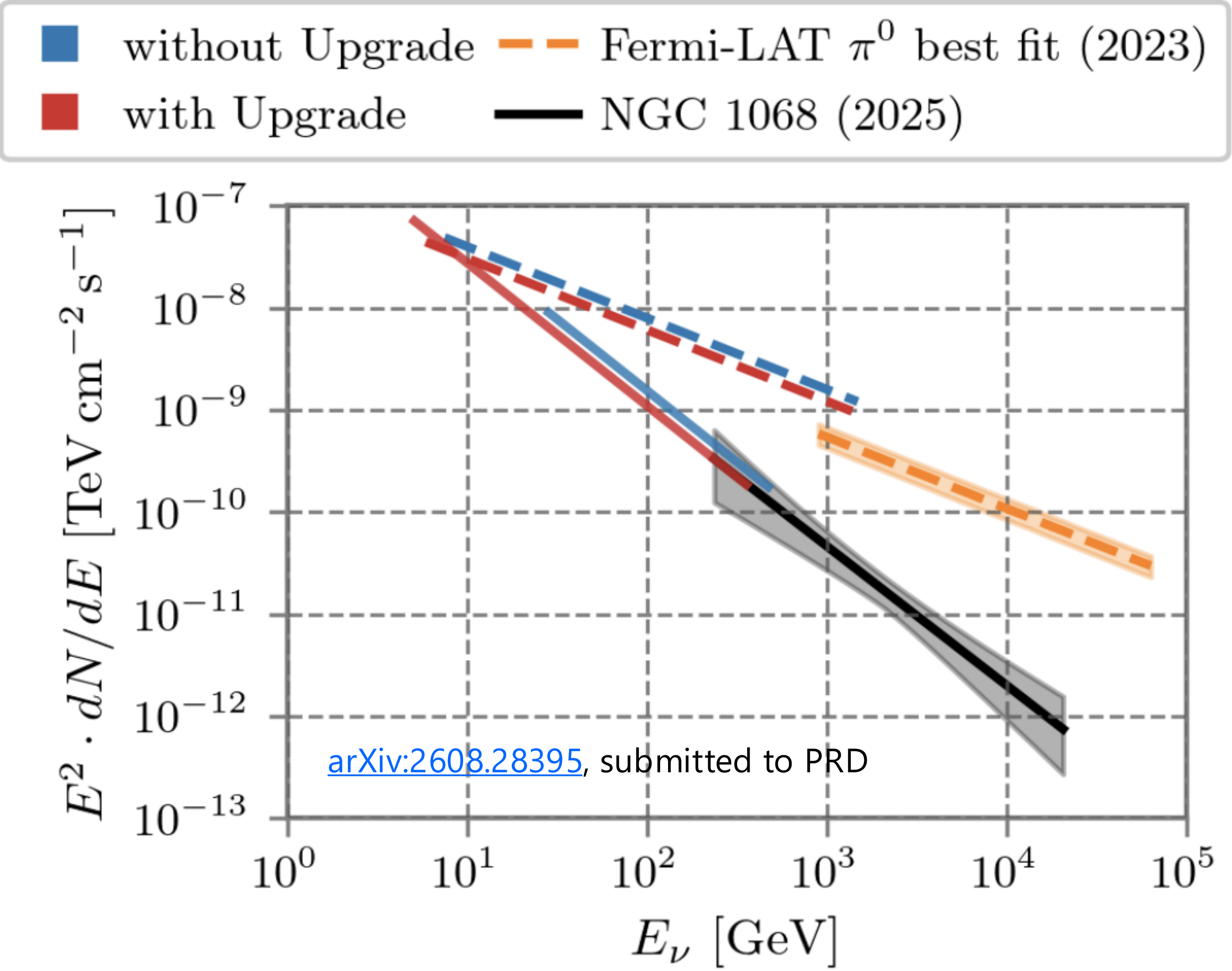

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Preliminary Rate Summary

Item	cut value	$\nu_\mu + \overline{\nu_\mu}$	$\nu_e + \overline{\nu_e}$	CORSIKA	Noise
Trigger		12 mHz	3.0 mHz	370 Hz	2.4 Hz
Filter		11 mHz	3.0 mHz	17 Hz	2.4 Hz
Ballon cut		8.0 mHz	2.2 mHz	8.3 Hz	0.17 Hz
LineFit RMS	<3000 m	8.0 mHz	2.2 mHz	7.6 Hz	53 mHz
N_{pulse} in veto region	<10 hit	5.0 mHz	1.7 mHz	0.78 Hz	53 mHz
First LC Dt	<= 100 ns	3.8 mHz	1.3 mHz	0.49 Hz	17 mHz
Duration	<= 800 ns	1.9 mHz	0.79 mHz	45 mHz	0 mHz
sigma_z	<= 30 m	1.4 mHz	0.60 mHz	9 mHz	0 mHz
DC Depth	< -200 m	1.3 mHz	0.59 mHz	5 mHz	0 mHz
N_{pulse} in sliding window	>= 5 hit	**1.3 mHz**	**0.58 mHz**	**3 mHz**	**0 mHz**

ELOWEN Selection

TABLE II. Summary of the cuts applied in the event selection.

Variable	Passing conditions
	Initial data rate: 1400 Hz
Passing filters	Events contained in DeepCore and failing every other software filters except two targeting low-energy events
	Data rate: 15 Hz—Passing signal events: 98%
Number of HLC in IceCube w/o DeepCore, N_1, and number of HLC in DeepCore, N_2	$N_1 = 0$ and $N_2 \leq 9$ OR $N_1 \leq 6$ and $N_2 \leq 7$
Number of SRT hits	≤ 10
	Data rate: 5.5 Hz—Passing signal events: 93%
Noise algorithm variables Step 1 $[W, N, v_{\mathrm{min}}, v_{\mathrm{max}}]$	$[100\ \mathrm{s}, 2, 0.20\ \mathrm{m/ns}, 0.90\ \mathrm{m/ns}] = \mathrm{TRUE}$ $[100\ \mathrm{s}, 0, 0.20\ \mathrm{m/ns}, 0.90\ \mathrm{m/ns}] = \mathrm{TRUE}$ AND $[1000\ \mathrm{s}, 0, 0.00\ \mathrm{m/ns}, 0.10\ \mathrm{m/ns}] = \mathrm{FALSE}$
Noise algorithm variables Step 2 $[W, N, v_{\mathrm{min}}, v_{\mathrm{max}}]$	$[300\ \mathrm{s}, 2, 0.20\ \mathrm{m/ns}, 0.40\ \mathrm{m/ns}] = \mathrm{TRUE}$ $[300\ \mathrm{s}, 2, 0.10\ \mathrm{m/ns}, 0.90\ \mathrm{m/ns}] = \mathrm{TRUE}$ AND $[800\ \mathrm{s}, 0, 0.00\ \mathrm{m/ns}, 0.10\ \mathrm{m/ns}] = \mathrm{FALSE}$ $[500\ \mathrm{s}, 2, 0.20\ \mathrm{m/ns}, 0.30\ \mathrm{m/ns}] = \mathrm{TRUE}$
	Data rate: 0.2 Hz—Passing signal events: >55%
Charge ratio	>0.26
Depth of the first HLC in DeepCore	$[-2453\ \mathrm{m}, -2158\ \mathrm{m}]$
Distance and delay between 1st and 2nd HLC in DeepCore	<70 m <50 ns
Total charge	<60 photoelectrons
	Data rate: 0.02 Hz—Passing signal events: >35%

IceCube Collaboration (2021)

Elowen Sensitivity Calculation

Likelihood

$$\mathcal{L}(N_{\pm 500\,\mathrm{s}}, N_{8\,\mathrm{h}} | \mu_{\mathrm{sig}}, \mu_{\mathrm{bkg}}, \alpha) = \mathrm{Poisson}(N_{\pm 500\,\mathrm{s}}; \mu_{\mathrm{bkg}} + \mu_{\mathrm{sig}}) \times \mathrm{Poisson}(N_{8\,\mathrm{h}}; \alpha\mu_{\mathrm{bkg}}),$$

Prior

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

90% C.L. UL on mu_sig

$$\int_0^{\mu_{\mathrm{sig}}^{90\%}} P(\mu_{\mathrm{sig}}) \mathrm{d}\mu_{\mathrm{sig}} = 0.90$$

90% C.L. UL on flux

IceCube Collaboration (2026)

$$\phi^{90\%} = \frac{6 \times \mu_{\mathrm{sig}}^{90\%}}{\int_{0.5\,\mathrm{GeV}}^{100\,\mathrm{GeV}} A_{\mathrm{eff}}(E) \times (E/\mathrm{GeV})^{-\gamma} \mathrm{d}E},$$