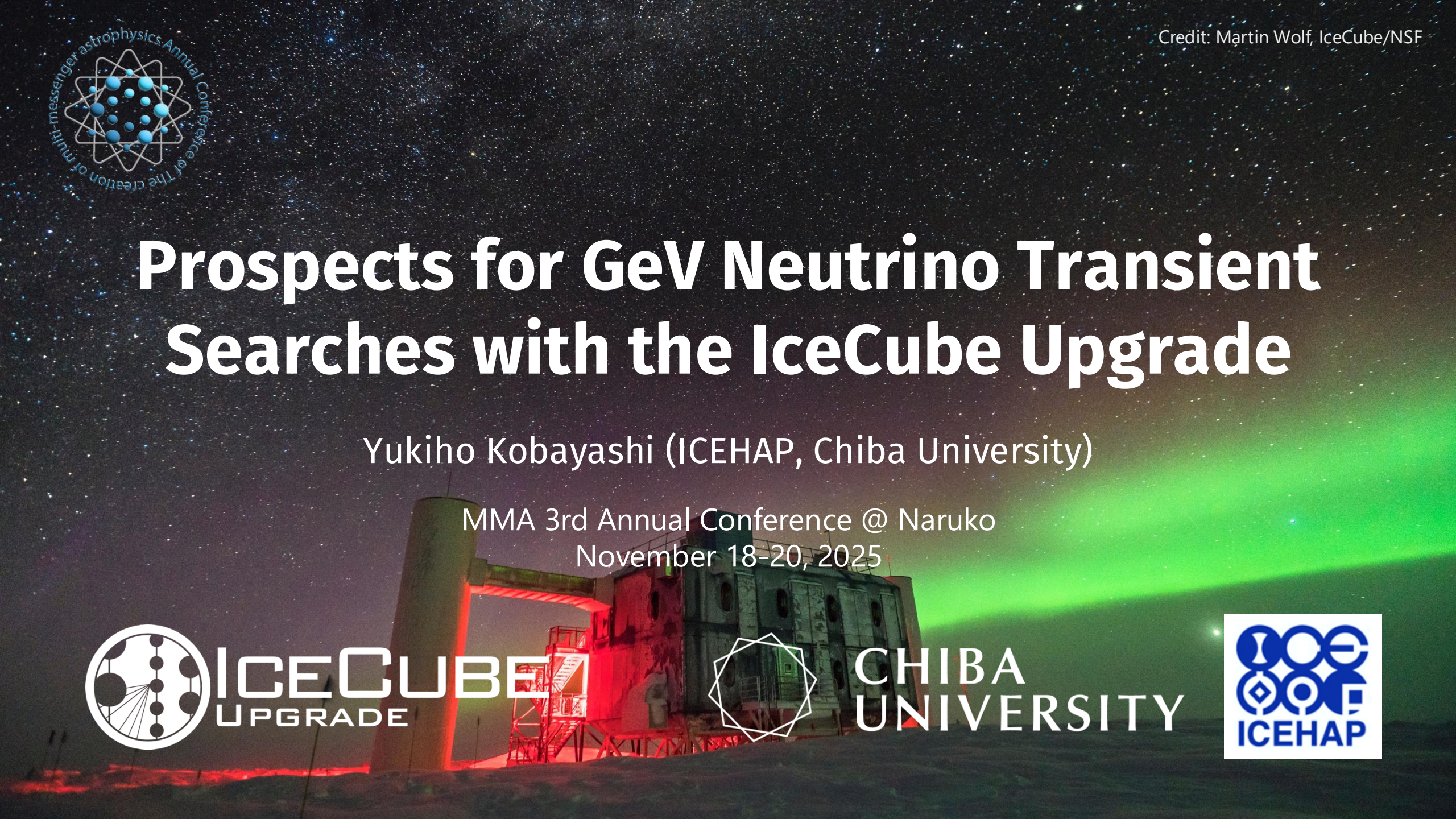


Prospects for GeV Neutrino Transient Searches with the IceCube Upgrade

Yukiho Kobayashi (ICEHAP, Chiba University)

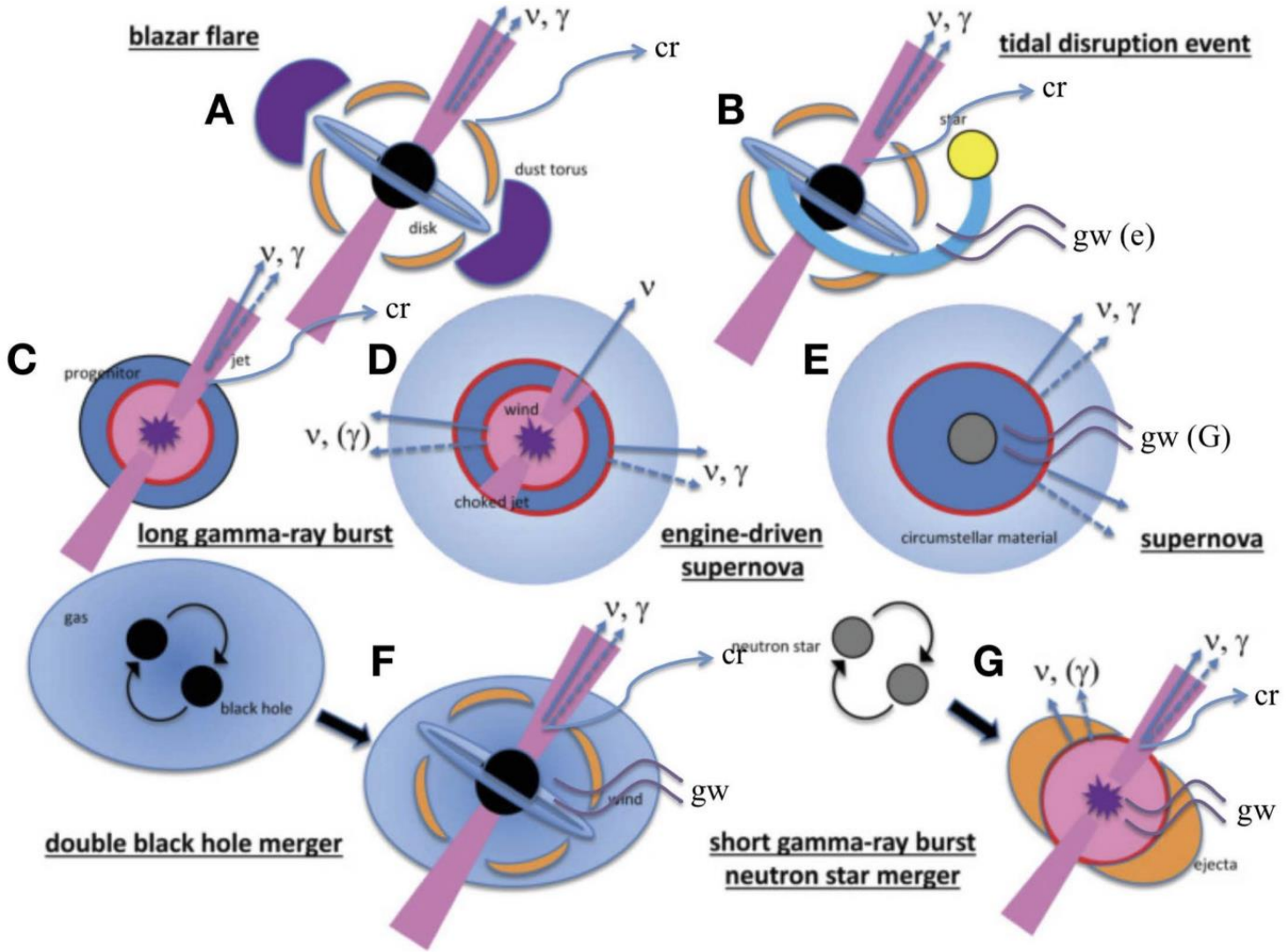
MMA 3rd Annual Conference @ Naruko
November 18-20, 2025

Multi-Messenger (MM) Transients

- Wide variety of MM transients
- GRBs
  - quasithermal/HE neutrinos
  - connection with cosmic rays (CRs)

    Studies with neutrino + X-ray
- Supernovae
  - MeV-PeV neutrinos
  - GW for Galactic event
- Timing info can suppresses atmospheric background

What's interesting in GeV neutrinos?

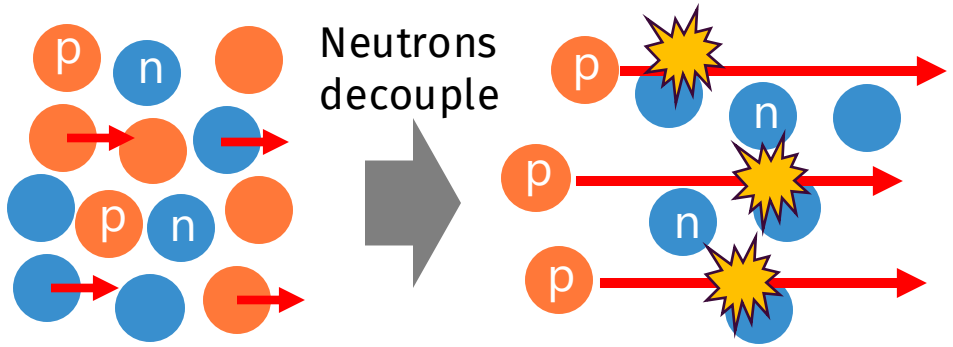


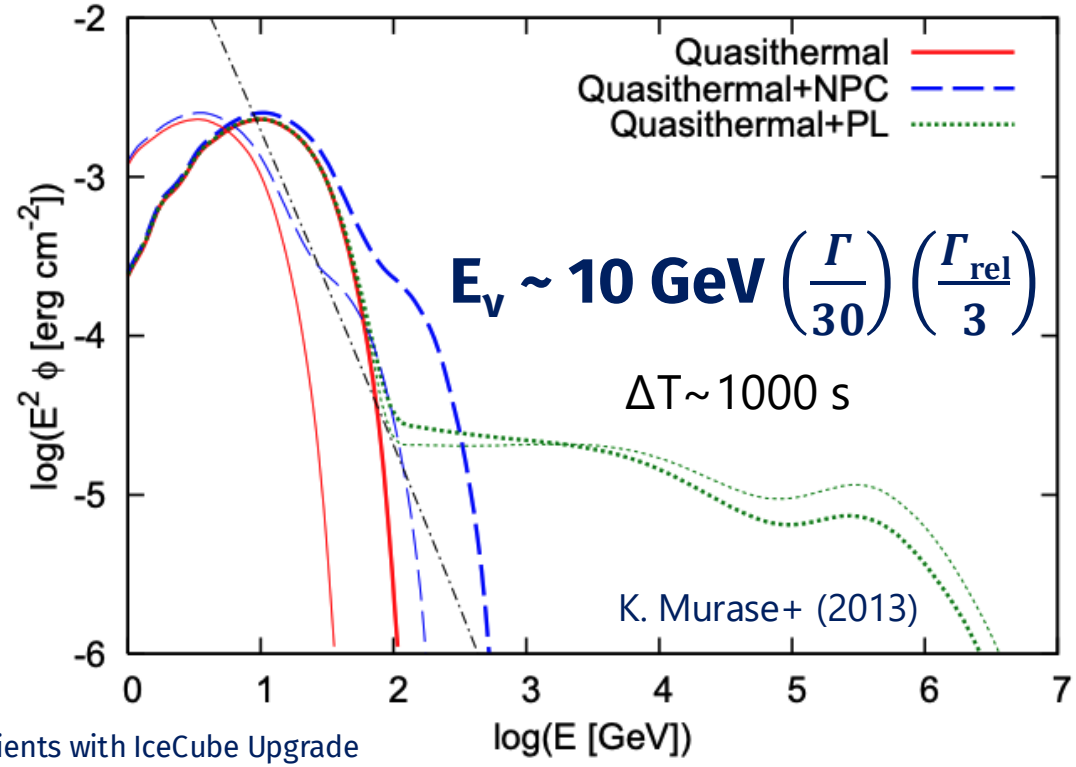
Mészáros, P., Fox, D.B., Hanna, C.& Murase, K. *Nat Rev Phys* **1**, 585–599 (2019)

Quasithermal Neutrinos from GRBs

- Predicted to arise from **proton-neutron collision** in jet
  P. Mészáros & M. J. Rees (2000), J. N. Bahcall & P. Mészáros (2000)
  - Does **not rely on CR acceleration => Robust prediction**
- Neutrinos produced below photosphere
  - **Uniquely probe of subphotospheric environment**
  - Key to understanding GRB emission
  - Constrain jet dynamics

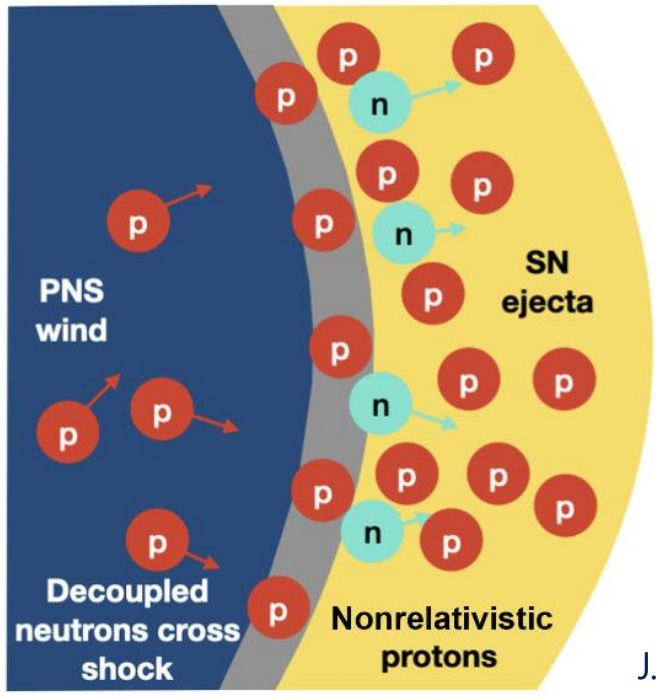
    Studies by Nakama-san & Kashiyama-san
- **GeV neutrinos** are expected in jets with **Γ = O(10): low-luminosity GRBs (LLGRBs)**
  - More GRBs are being found by EP/SVOM
  - Promising CR + neutrino source





Quasithermal Neutrinos from Supernovae

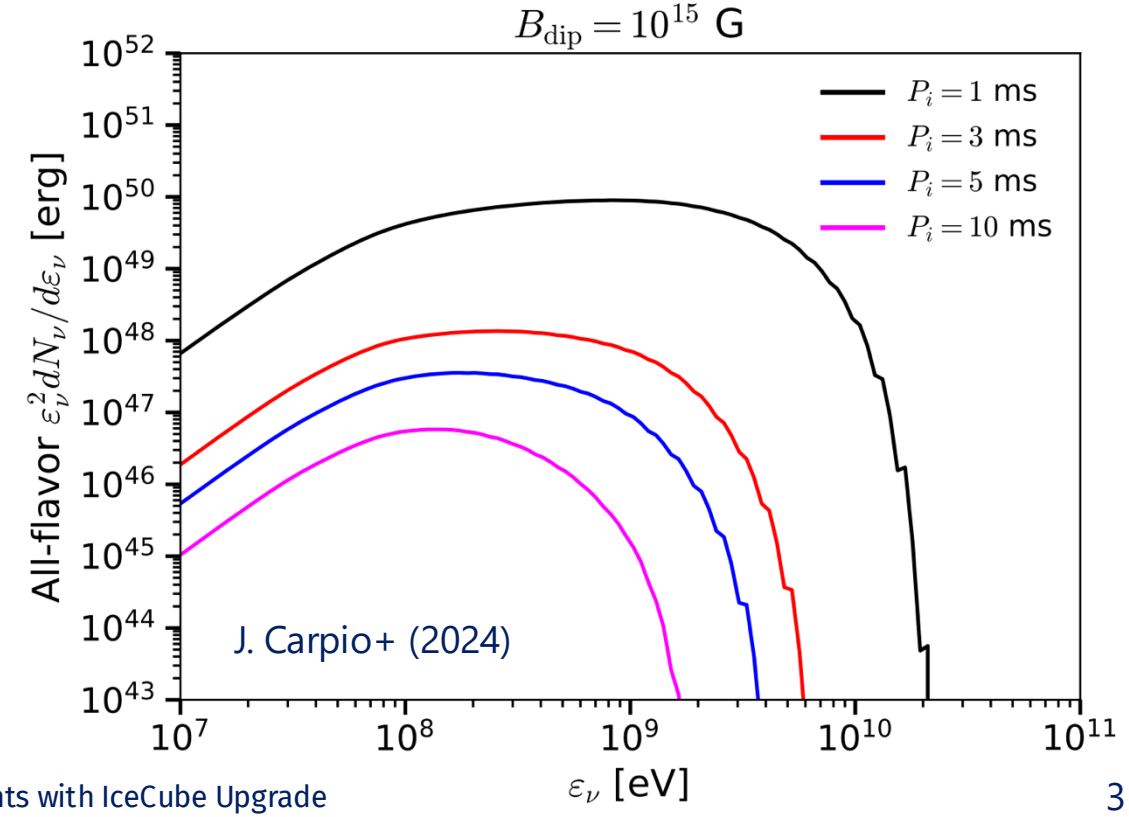
- Quasithermal neutrinos also expected from supernovae (SNe)
- **Dependence on protoneutron star (PNS) properties: magnetic field & rotation period**
- Spectrum expected to extend to GeV energies (ΔT~100 s)
- Simultaneous MeV-PeV neutrino measurement may be possible I. Tambora & K. Murase (2018)



np inelastic collisions in SN ejecta

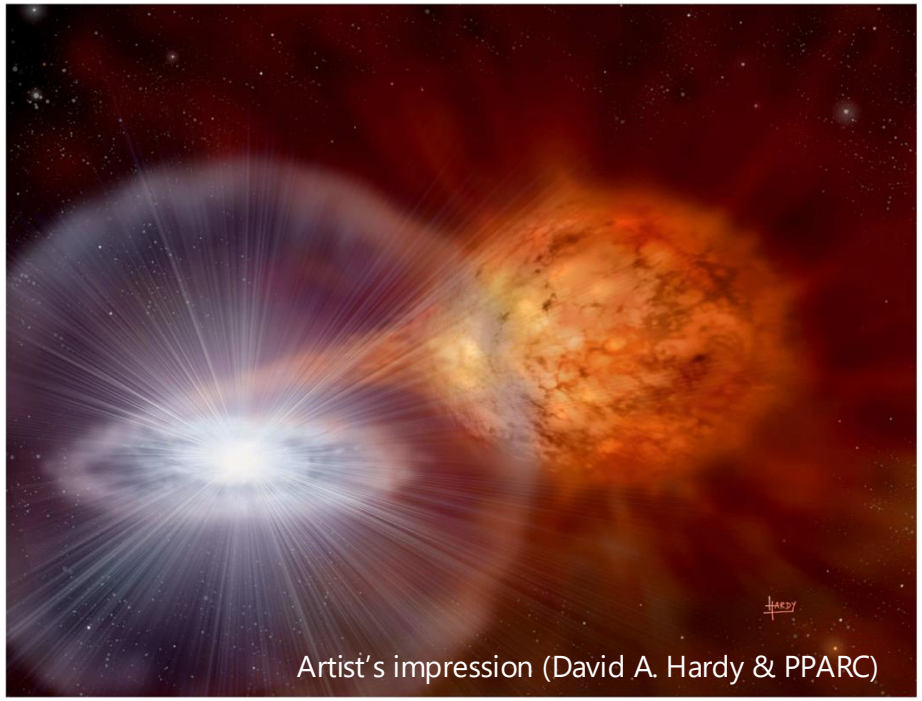
Decoupled neutrons collide with nonrelativistic protons in ejecta

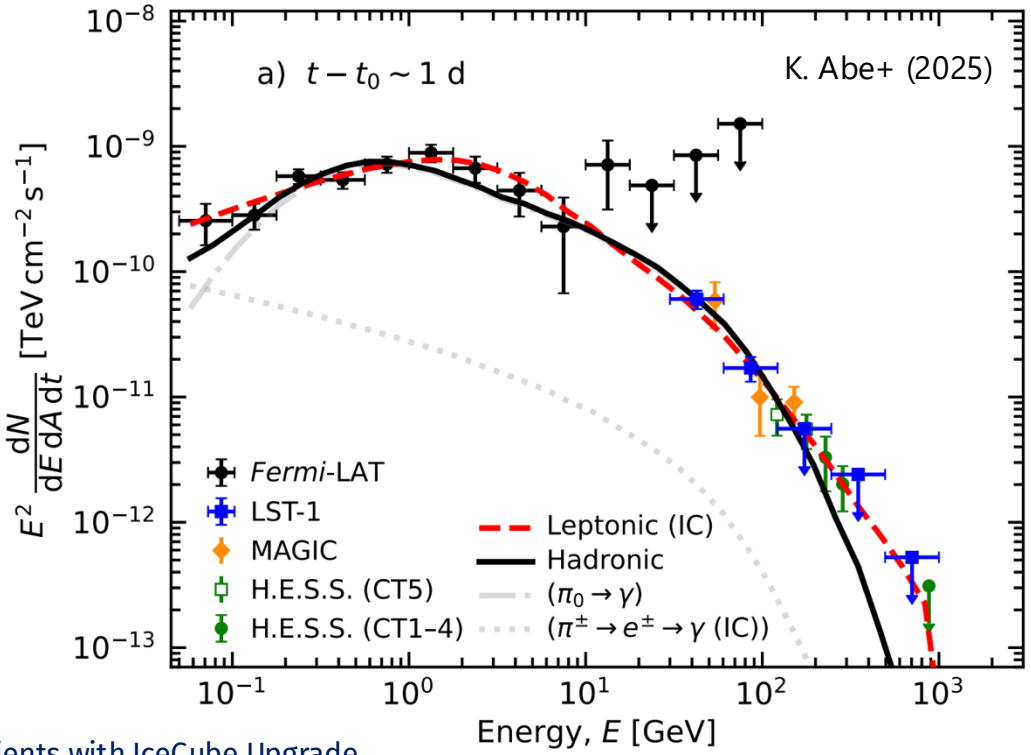
Adapted from J. Carpio+ (2024)



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

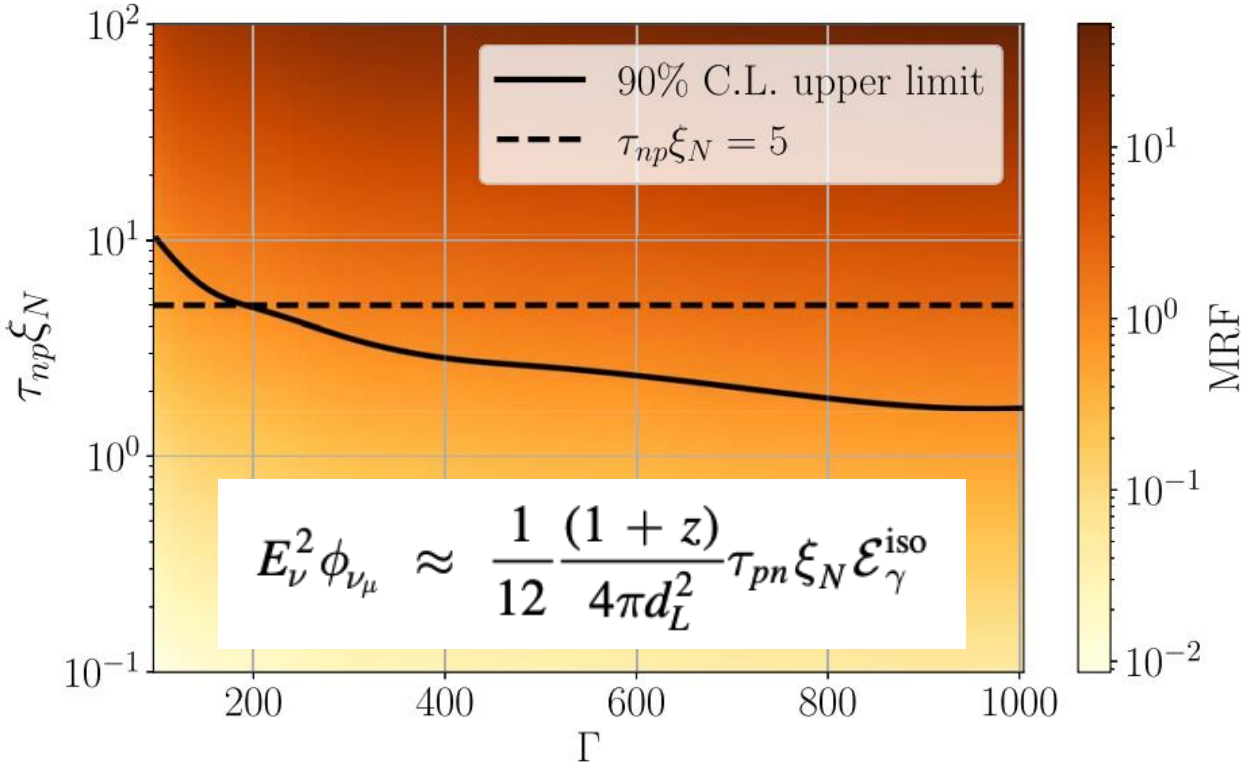




Past Searches with IceCube-DeepCore

- Searches for **sub-TeV transients with IceCube DeepCore** (IceCube infill array)
  - GRBs (2024)
  - novae (2023)
  - GW (2023)
  - supernovae (2023, TeV-PeV)
- No detection yet, but constraining their physical properties
  - e.g. GRB baryon loading factor
- Can we enhance and extend these transient searches?

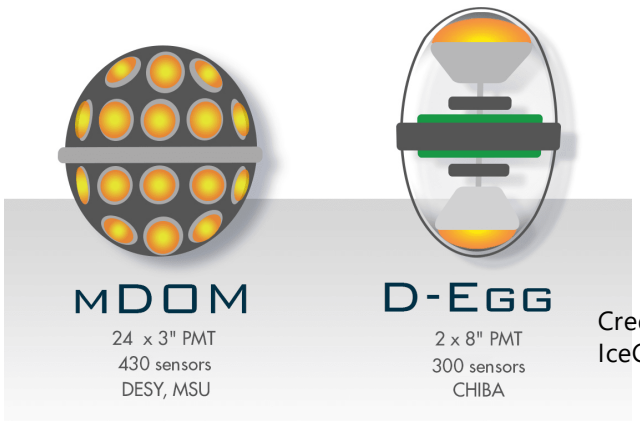
Constraints on GRB221009A baryon loading factor



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

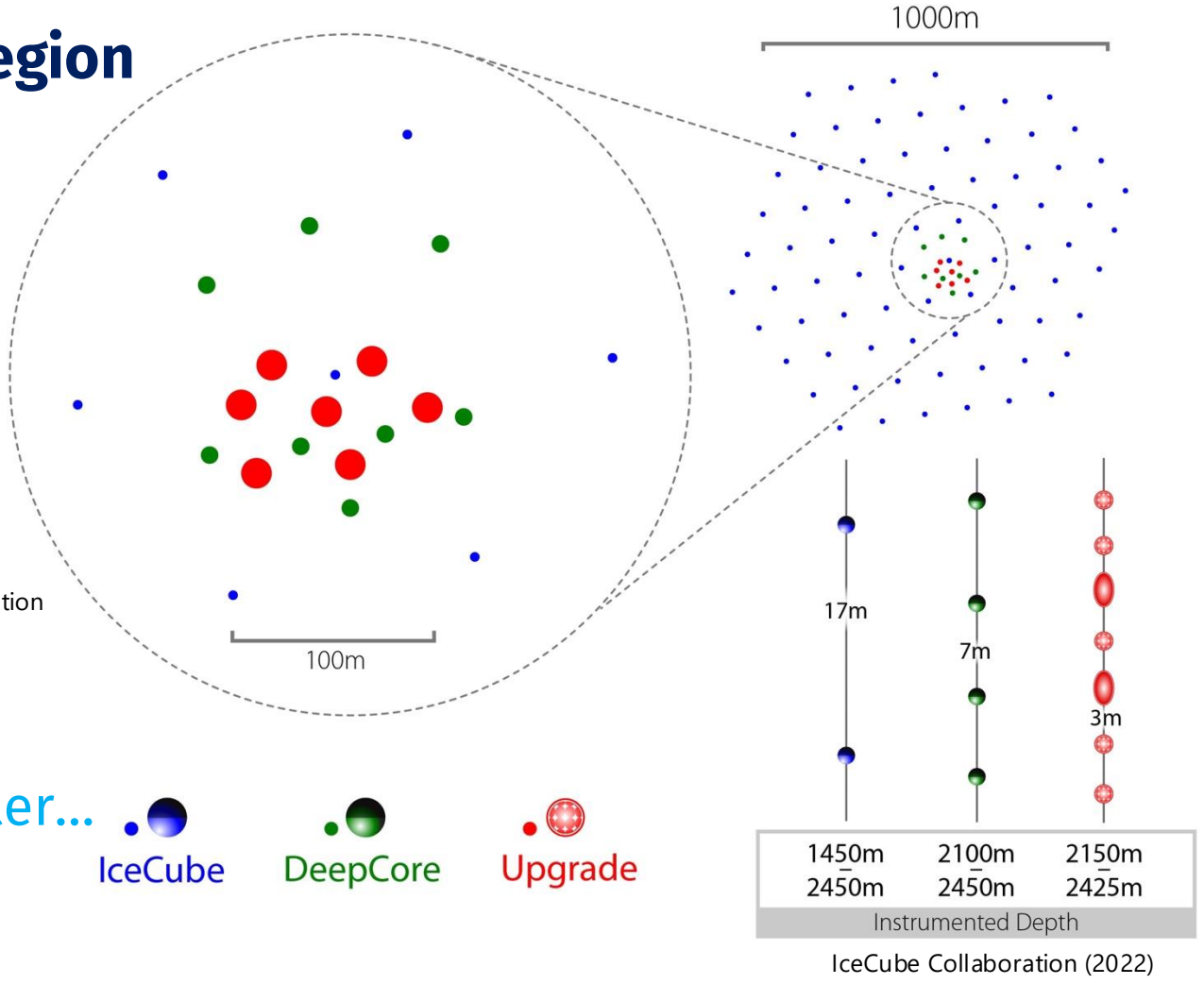
IceCube Upgrade

- **New seven strings in DeepCore region**
  - **100 multi-PMT modules / string**
  - **Denser spacing (20-30 m × 3 m)**



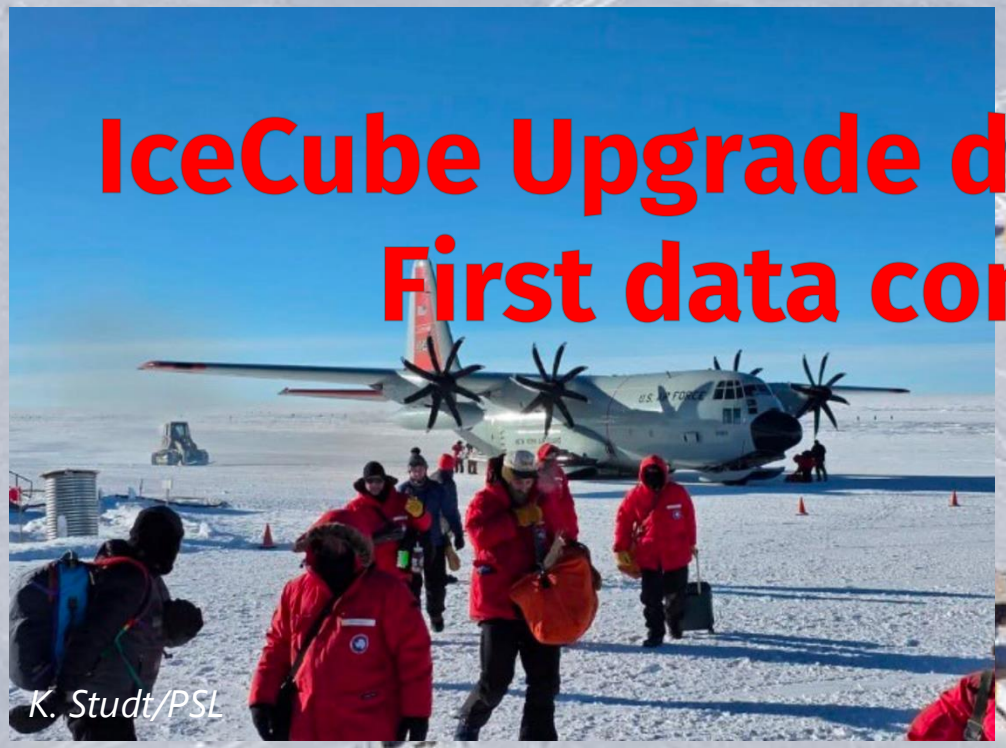
Credit:
IceCube Collaboration

- **Enhance GeV capabilities:**
  - **Transients**, oscillation, dark matter…
- Improve ice calibration



IceCube Collaboration (2022)

IceCube Upgrade deployment now starting!!!
First data coming out next year!!!



K. Studt/PSL

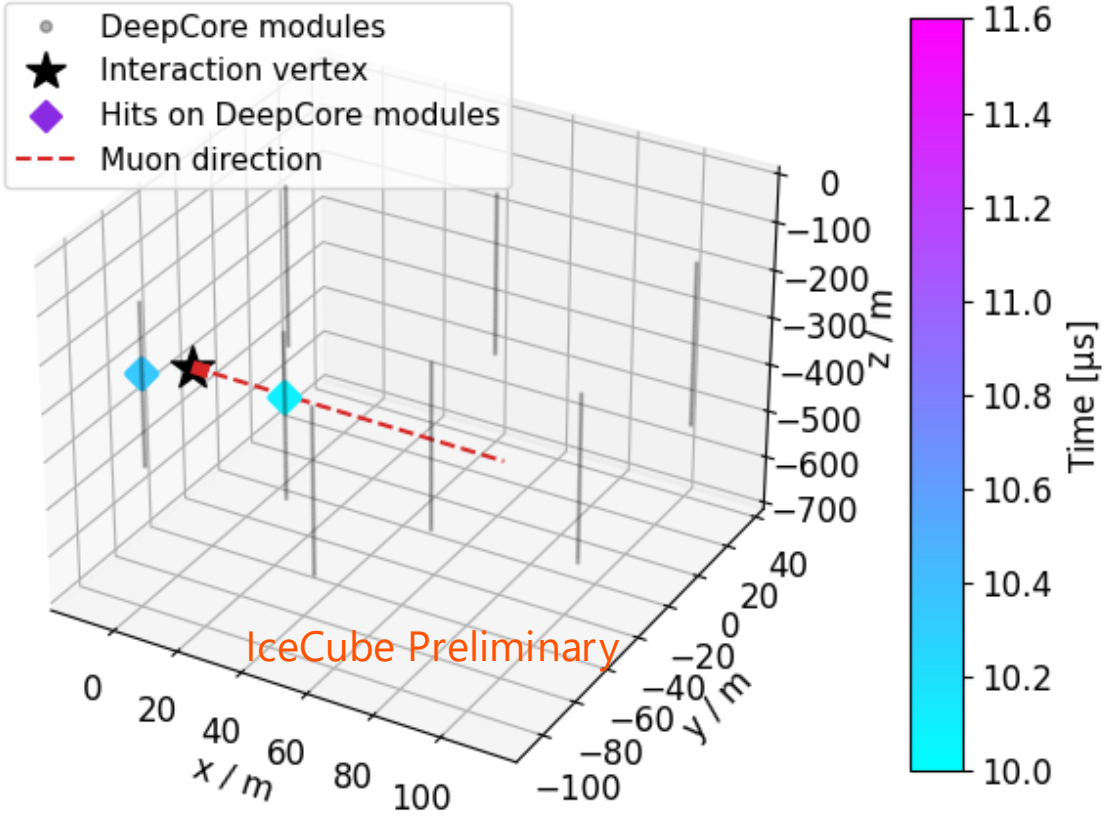

E. Krupczak / MSU

Credit: Michael Rayne/ASC-ARFF

Performance Evaluation with Simulation

- Simulation
  - Extend IceCube+DeepCore simulation with Upgrade modules added
- **DeepCore-based event selection**
  - Coincidence trigger, veto, simple cuts
- Using **machine-learning techniques**
  - Energy and direction reconstruction
  - Noise cleaning and muon rejection

1.7 GeV ν_μ charged-current event (signal only)



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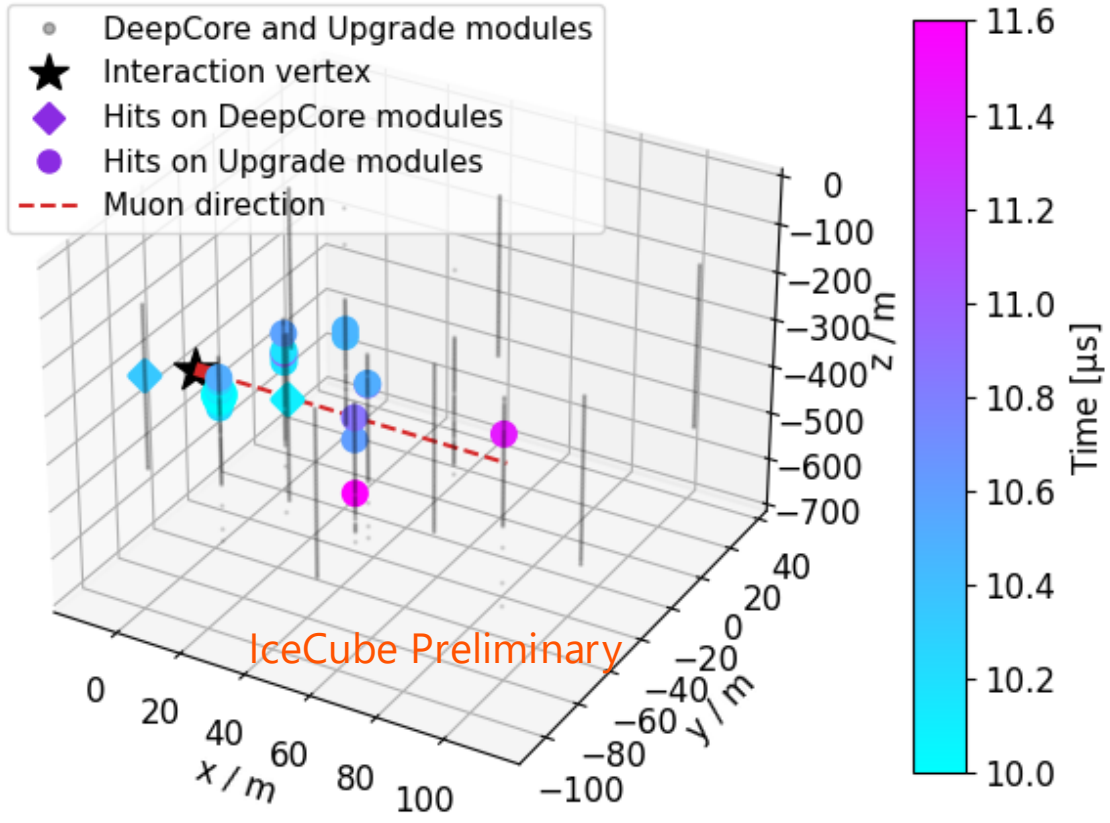
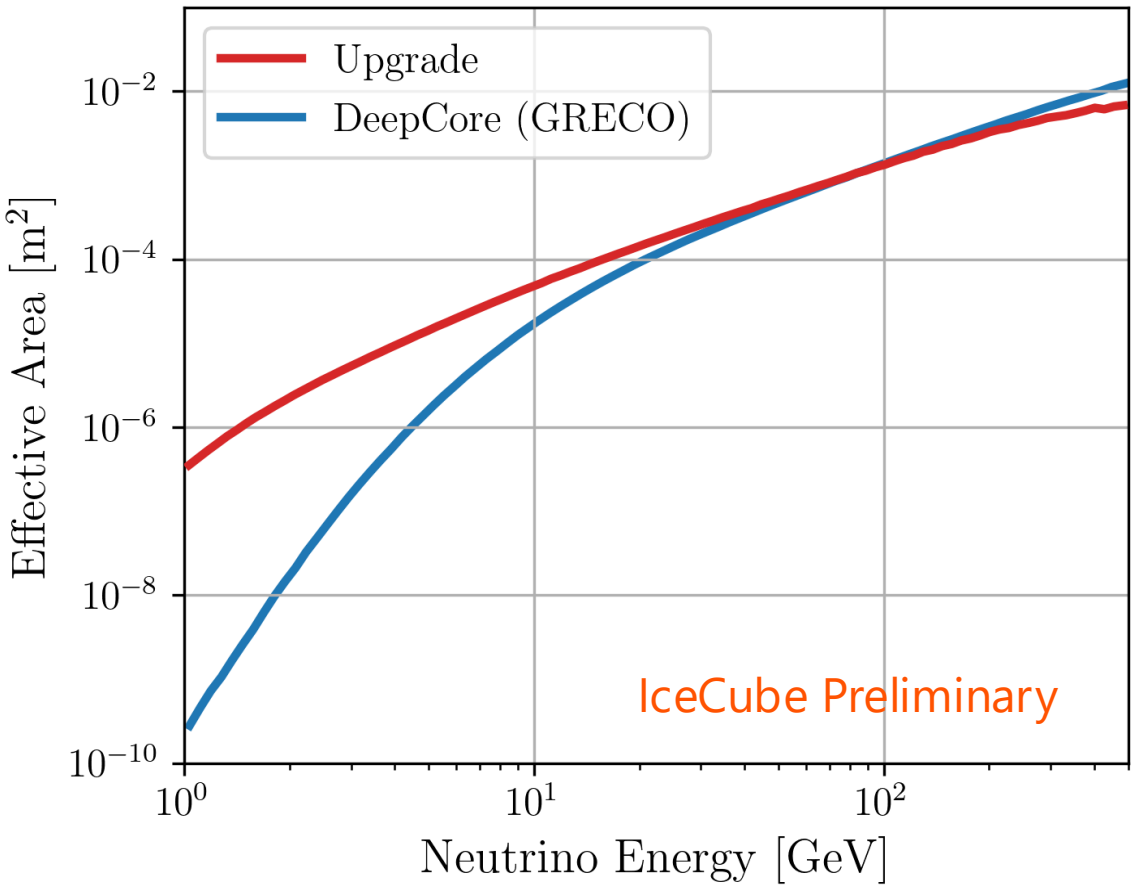
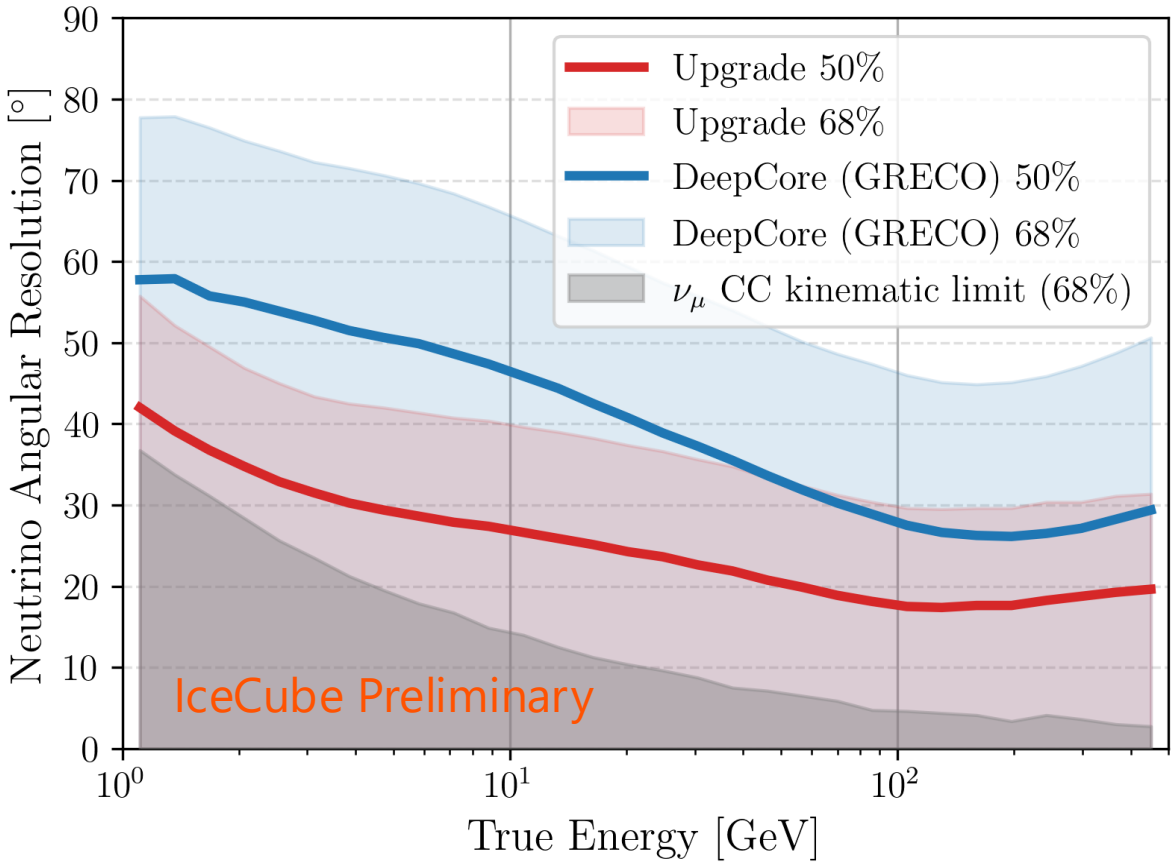


Upgrade Performance vs. DeepCore





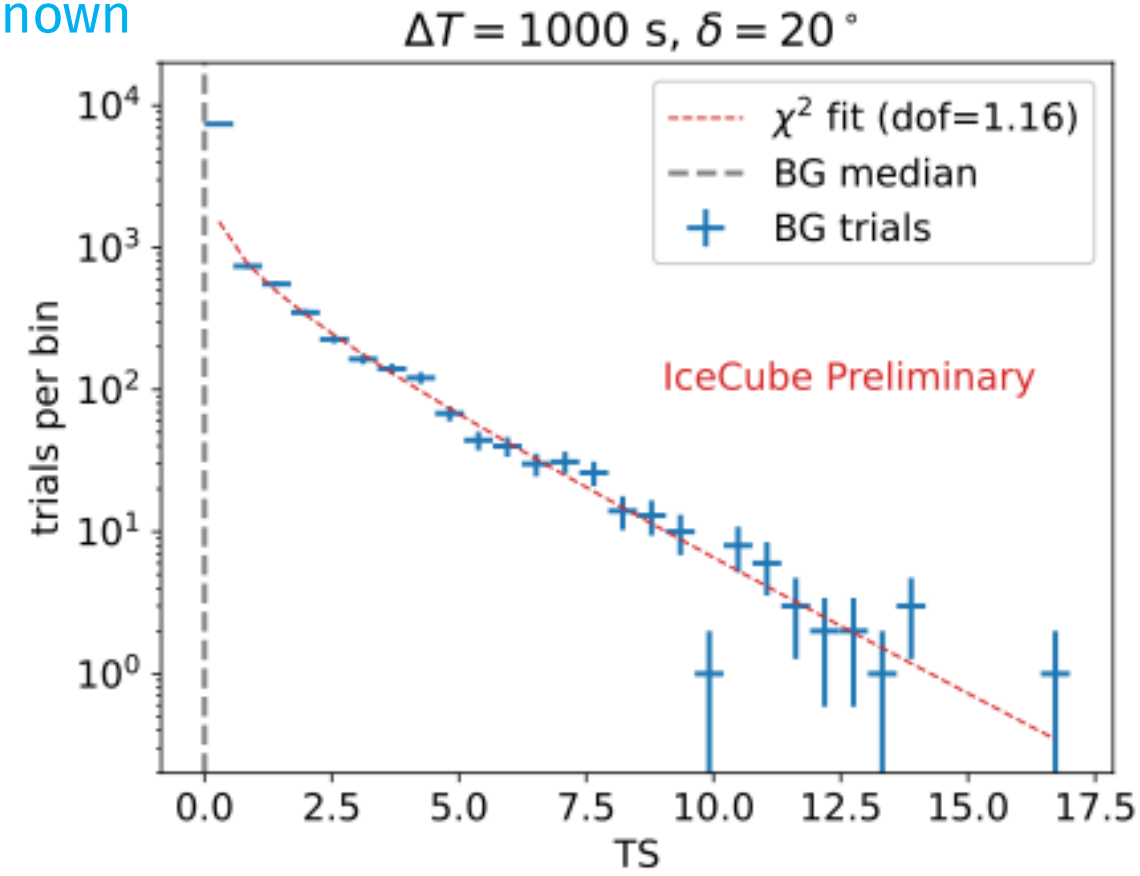
Analysis

- **Unbinned maximum likelihood**
  - Assuming source position and time are known
  - Using spectral and spatial information
  - BG: atmospheric neutrinos
    - Not including muons and noise events (consisting ~10% of BG in sample)

$$\mathcal{L}(n_s,\gamma) = \frac{(n_s+n_b)^N e^{-(n_s+n_b)}}{N!} \times \prod_{i=1}^{N}\left[\frac{n_s}{n_s+n_b}\mathcal{S}(x_i|\gamma) + \frac{n_b}{n_s+n_b}\mathcal{B}(x_i)\right]$$

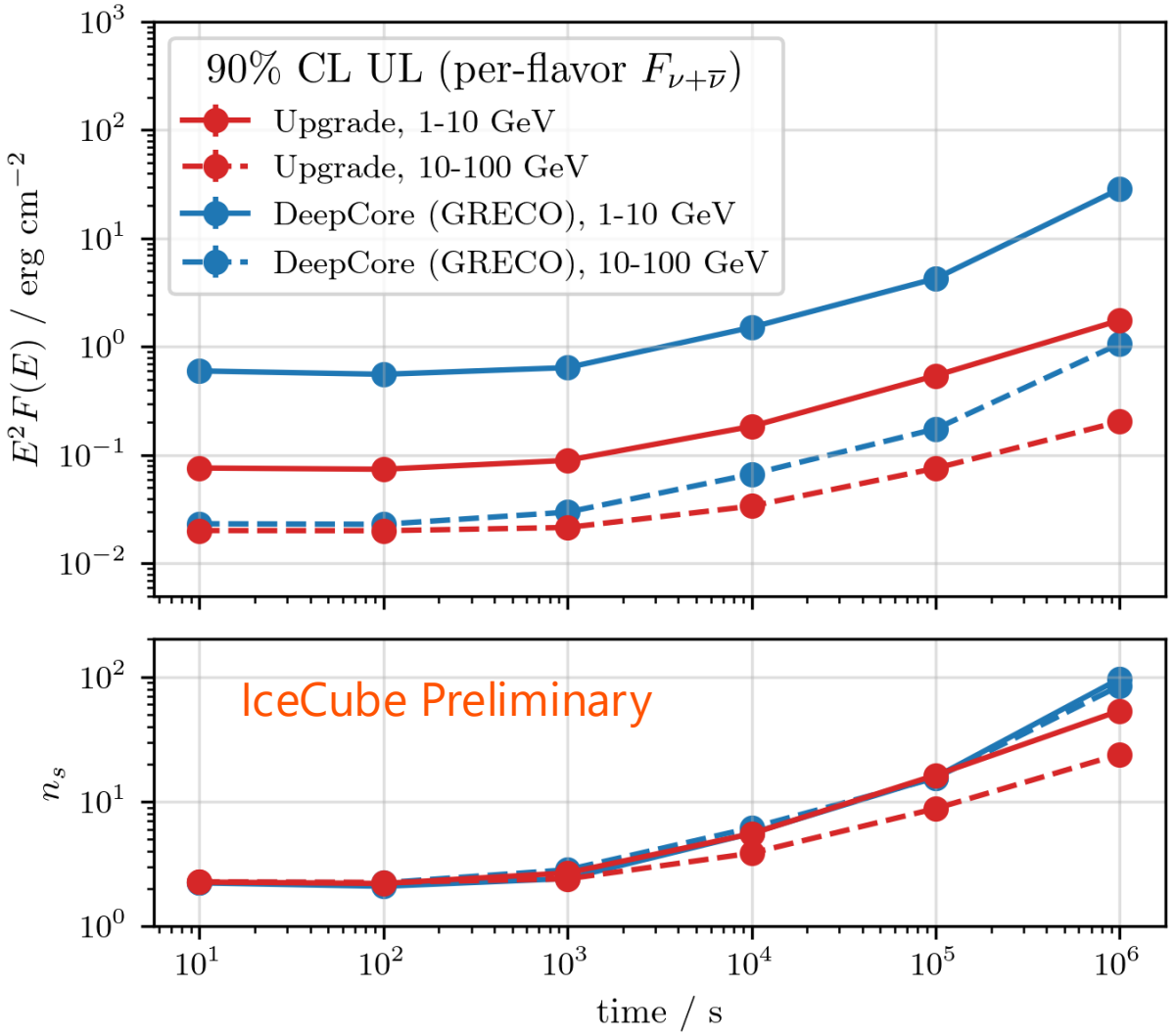
$$\mathcal{TS} = -2\hat{n}_s + 2\sum_{i=1}^{N}\ln\left[\frac{\hat{n}_s\mathcal{S}(x_i|\hat{\gamma})}{n_b\mathcal{B}(x_i)} + 1\right]$$

Example TS distribution from BG trials



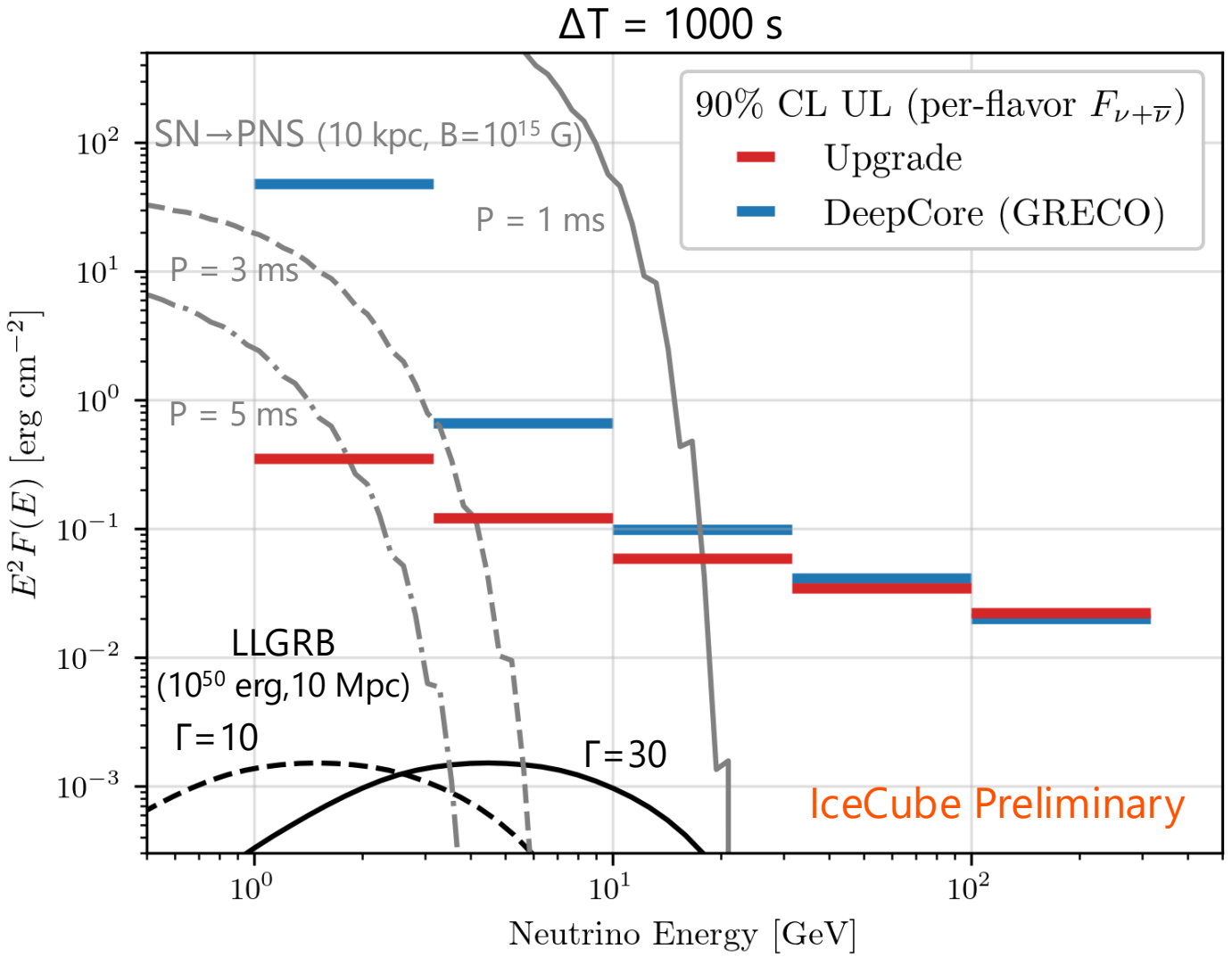
Sensitivity vs Time

- Upgrade achieves one order of magnitude better sensitibity than DeepCore in 1-10 GeV range
  - Attributed to enhanced effective area
- **BG-free time scale is ~1000 s**
  - Include GRB and SN time scale
- Upgrade's efficient background rejection enhances sensitivity at long time scales



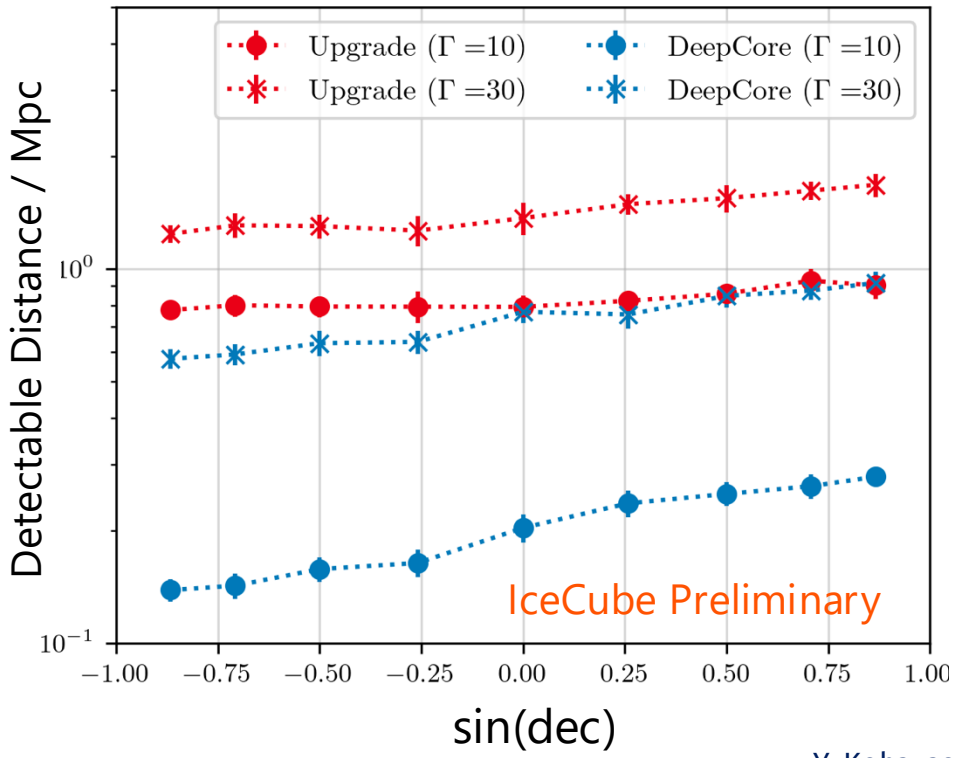
Differential Sensitivity (ΔT = 1000 s)

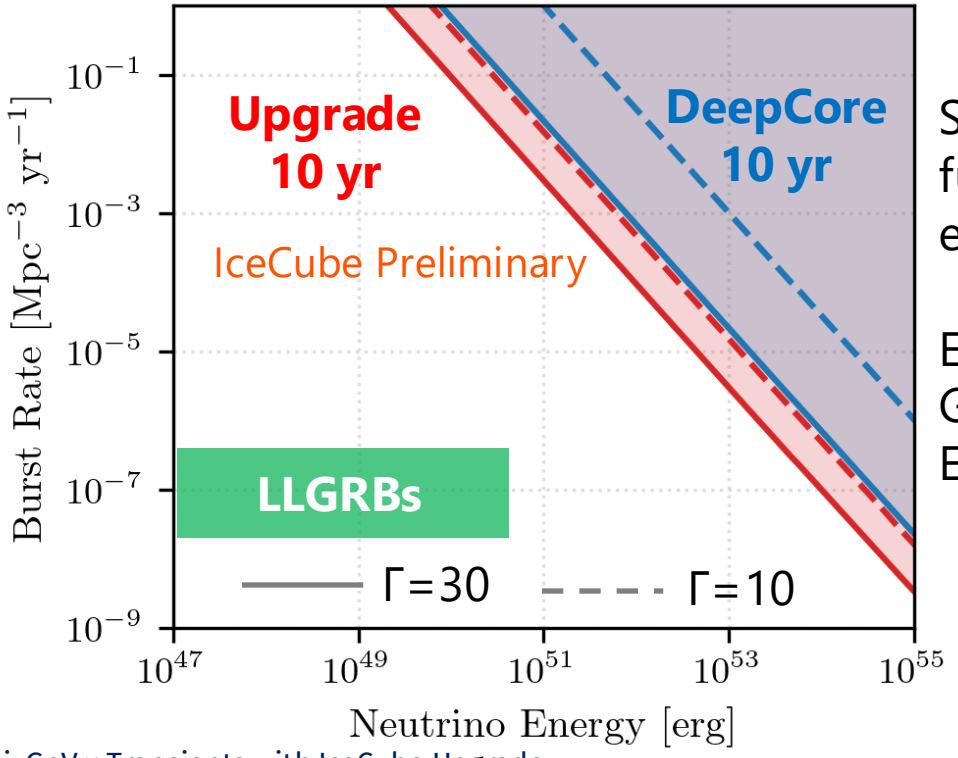
- **Unprecedented sensitivity to 1-10 GeV neutrinos**
  - Improvement by an order of magnitude from DeepCore
  - **Reaching SN quasithermal models with more modest parameters**



Prospects for LLGRB Search

- Upgrade 90% CL UL translates into LLGRB with $E_{iso} = 10^{50}$ erg at ~1 Mpc (ξ_N=5)
  - Extremely rare given the rate estimate of ~10^{-7} Mpc^{-3} yr^{-1}
- We can provide best constraint on burst population at GeV energies (any surprise?☺)
  - => What interesting physics can we extract? Baryon loading? Jet dynamics?



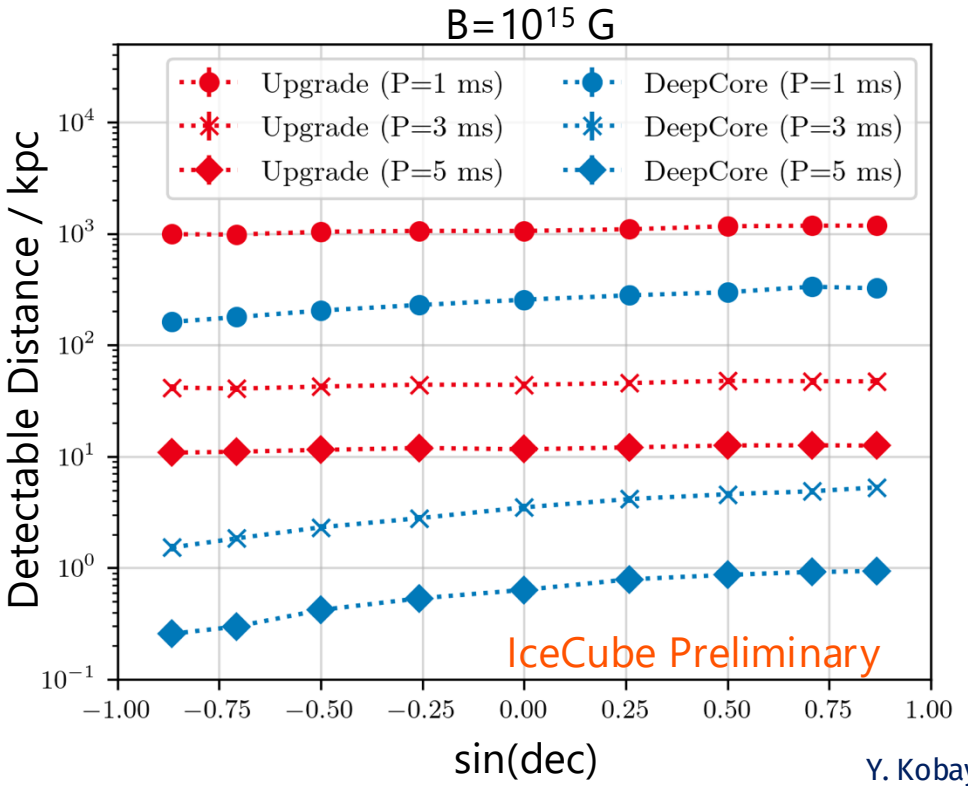


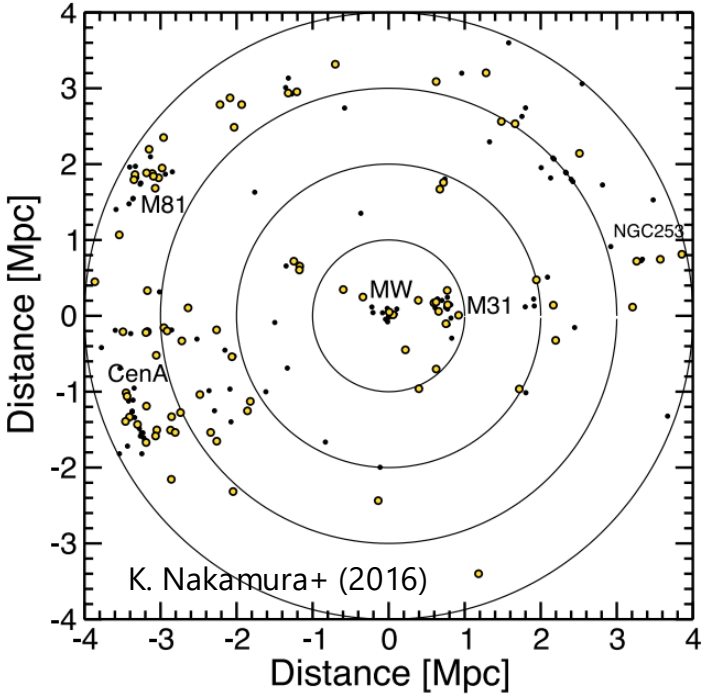
Staking analysis can further enhances sensitivity

Exploit from growing GRB/unID samples of EP and SVOM?

Prospects for SNe Search

- GeV neutrino from **Galactic SNe forming magnetar is within Upgrades' reach**
  - 90% CL UL translates into 10 kpc for PNS parameters B=10^{15} G, T=5 ms
- **Extreme models (B=10^{15} G, T=1 ms) may be constrained in nearby galaxies (~1 Mpc)**
- Stacking SNe at Mpc scale can give interesting constraints on GeV neutrino emission?





CCSN rates estimate:
0.1-0.2 / year within 5 Mpc
(K. Nakamura+ (2016))
⇒ ~1 / year within 10 Mpc?

Stacking ~10 SNe within 10 Mpc may provide **UL of the same order of magnitude as the model**

Knowing SN onset time is crucial for search with best sensitivity

Summary and Outlook

- **IceCube Upgrade's first data** coming out **next year!**
- Expected to provide **unprecedented sensitivity to GeV neutrino transients**
- **Get ready and come up with strategy. What do we want to look for first?**
  - **LLGRBs**
    - Constrain GeV burst population, exploit from growing samples of EP and SVOM
      - How to translate it into physics? Baryon loading, jet dynamics, etc
  - **SNe => magnetar**
    - Galactic SNe & stacking SNe in nearby galaxies may be promising
  - Galactic Novae
    - T Coronae Borealis is expected to undergo outburst in the next few years

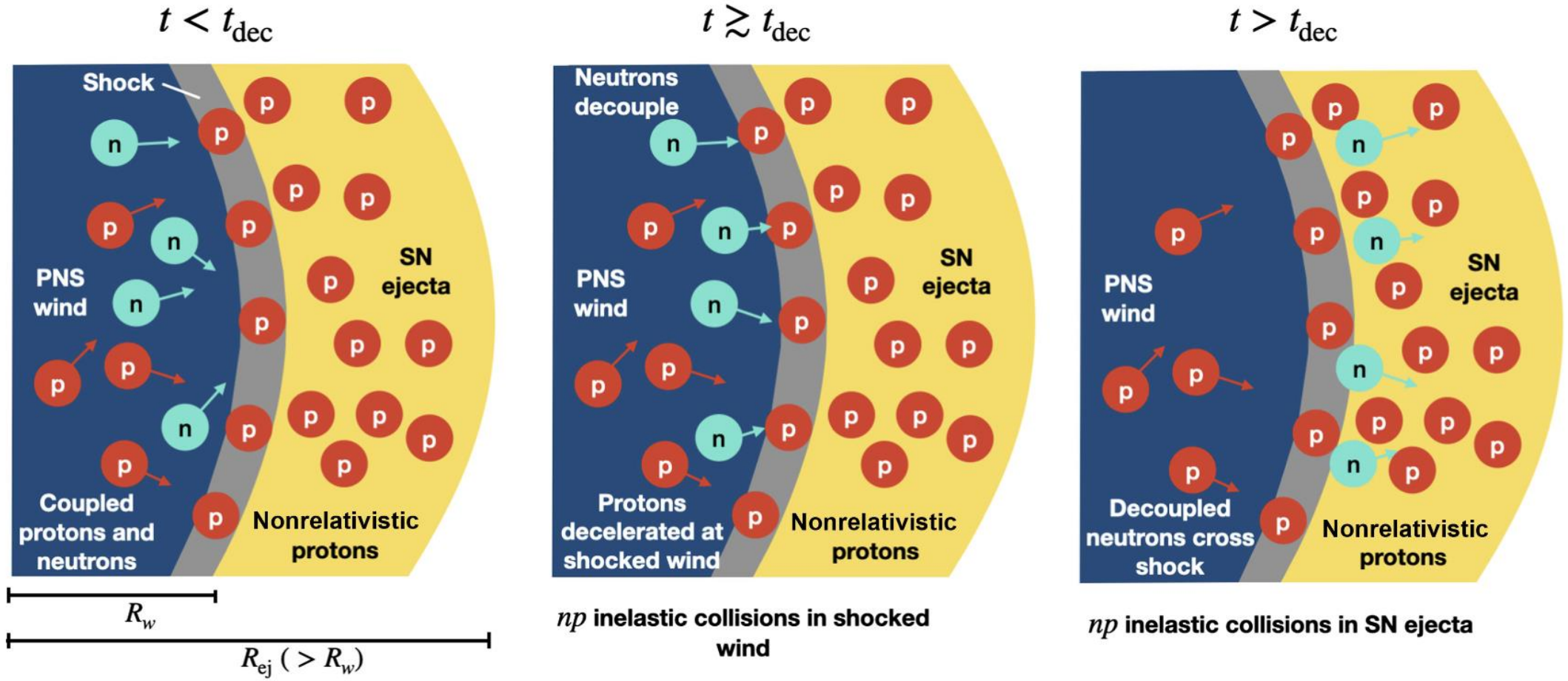
Greatly appreciate any inputs/suggestions!

"Chance favors the prepared mind."

Louis Pasteur

Backup

np Collision Mechanism in SN forming PNS

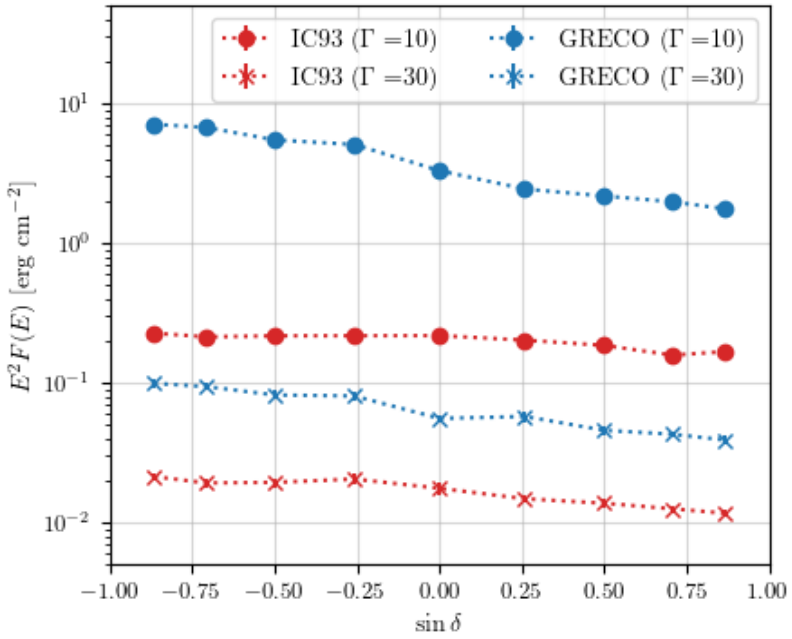


J. A. Carpio et al. (2024)

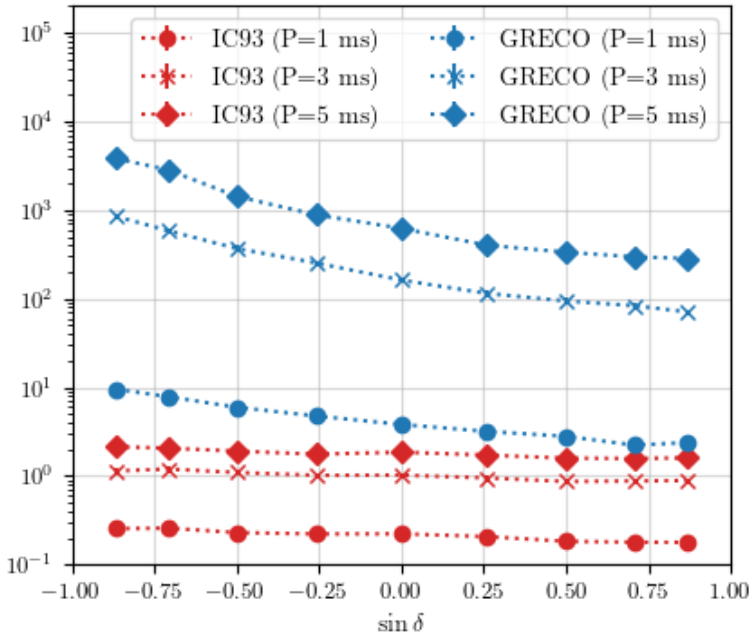
Sensitivity to Model Predictions

- **Significant improvement over GRECO** for every model considered here
- Most promising target may be **Galactic SN forming PNS**

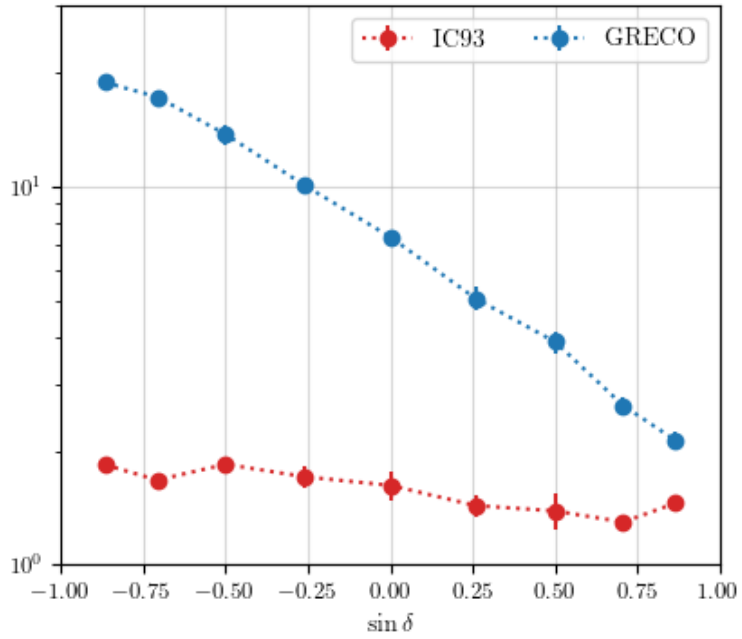
LLGRB



SN→PNS (B=10^{15} G)

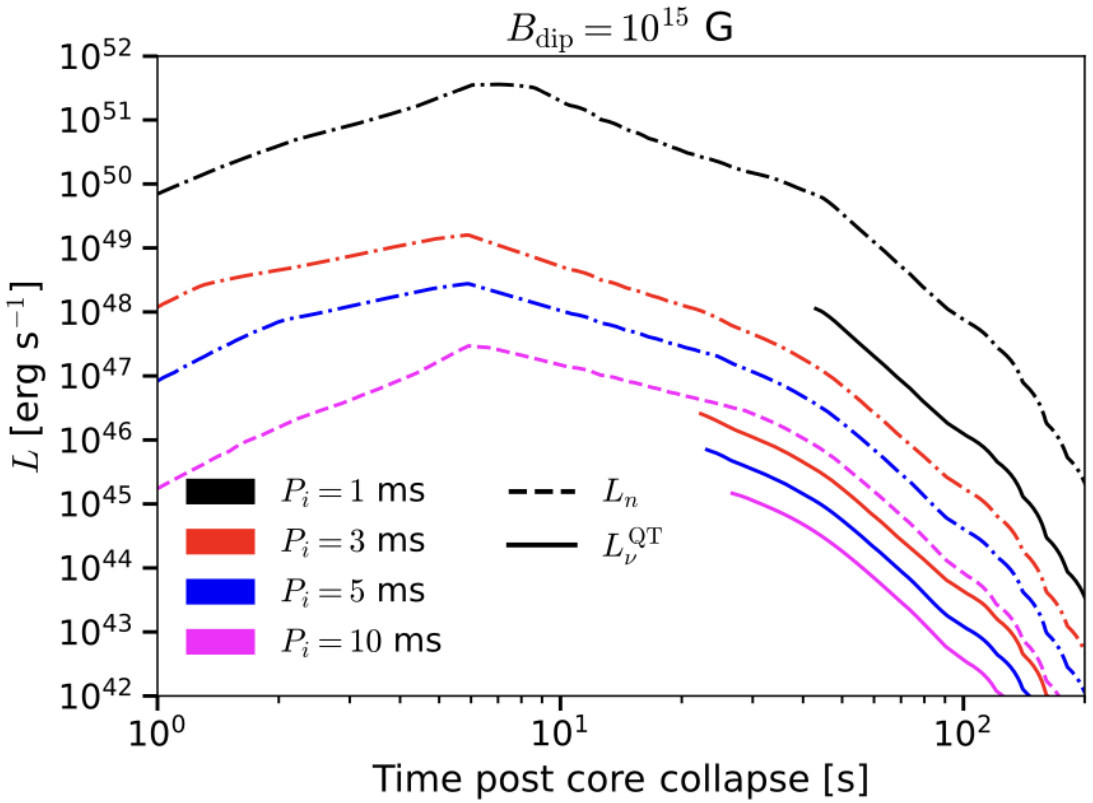


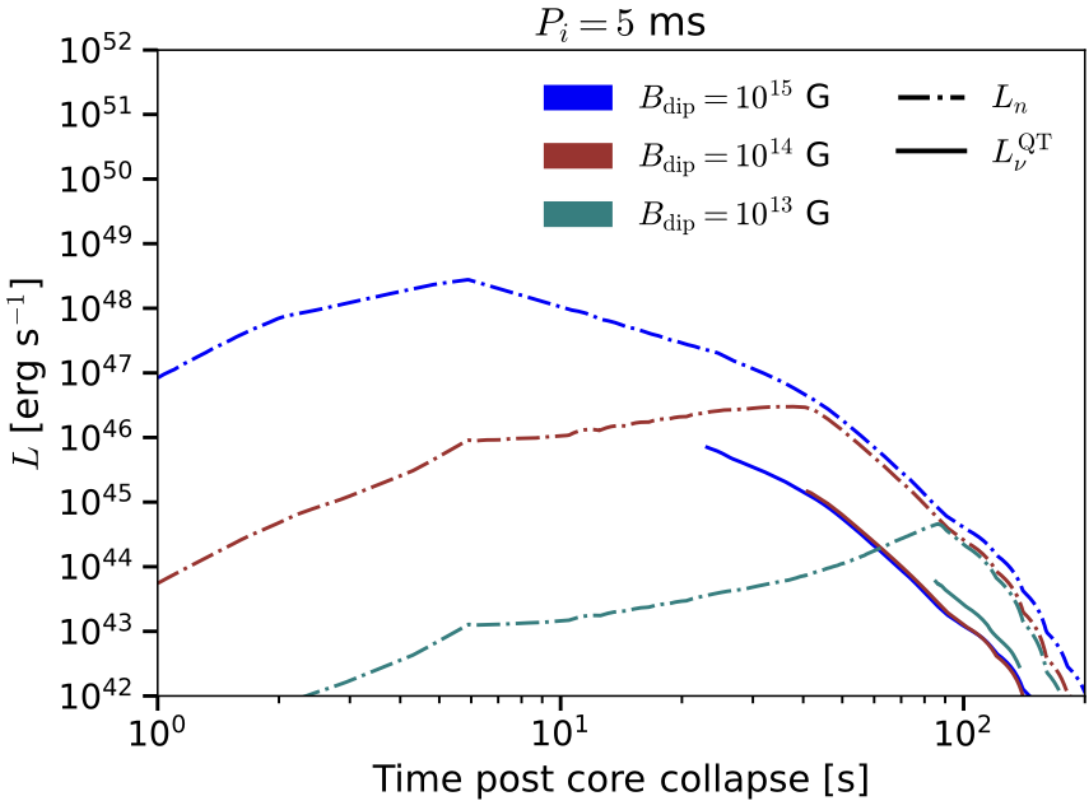
Nova (RS Ophiuchi)



E_0=1 GeV

SN => PNS Light Curves

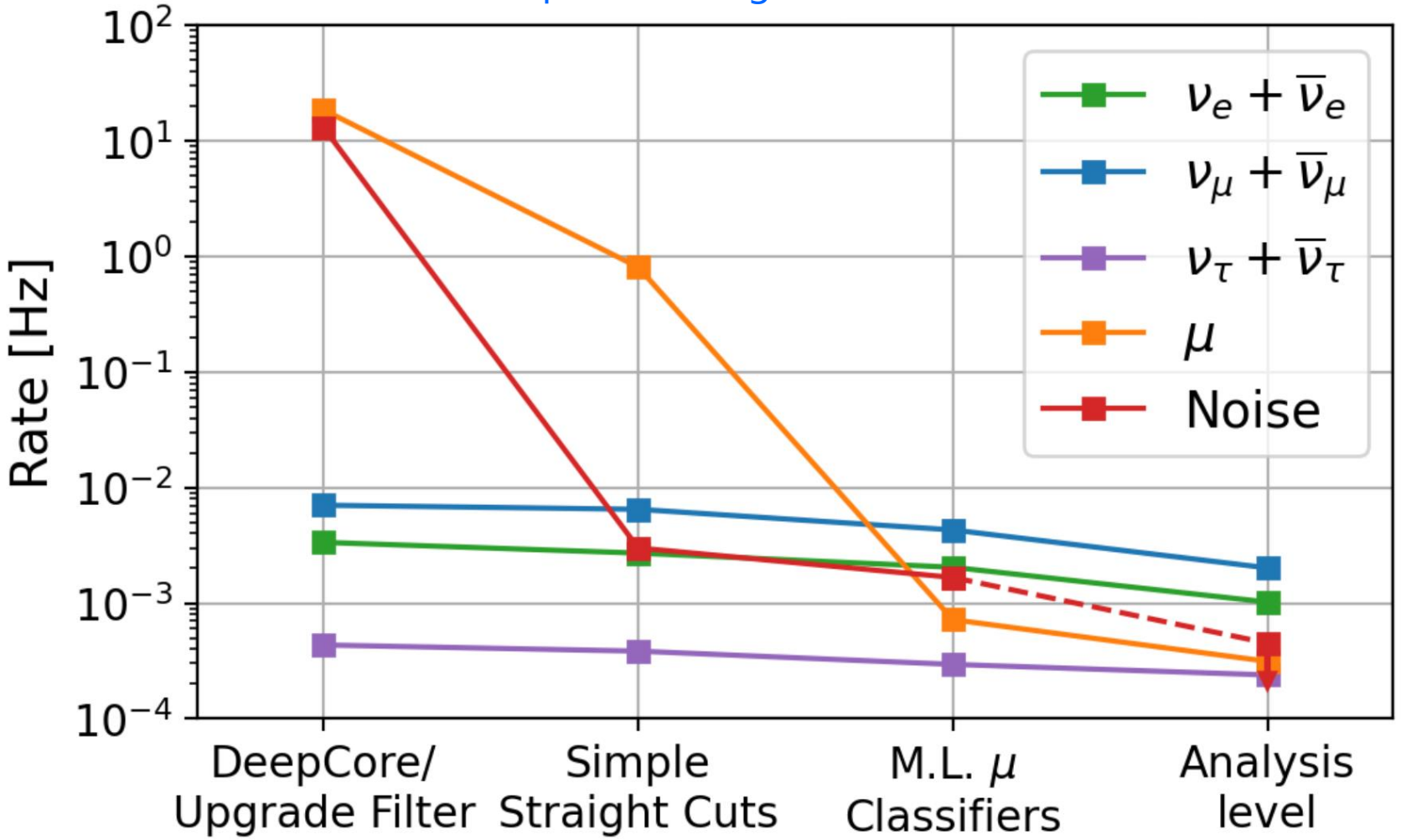




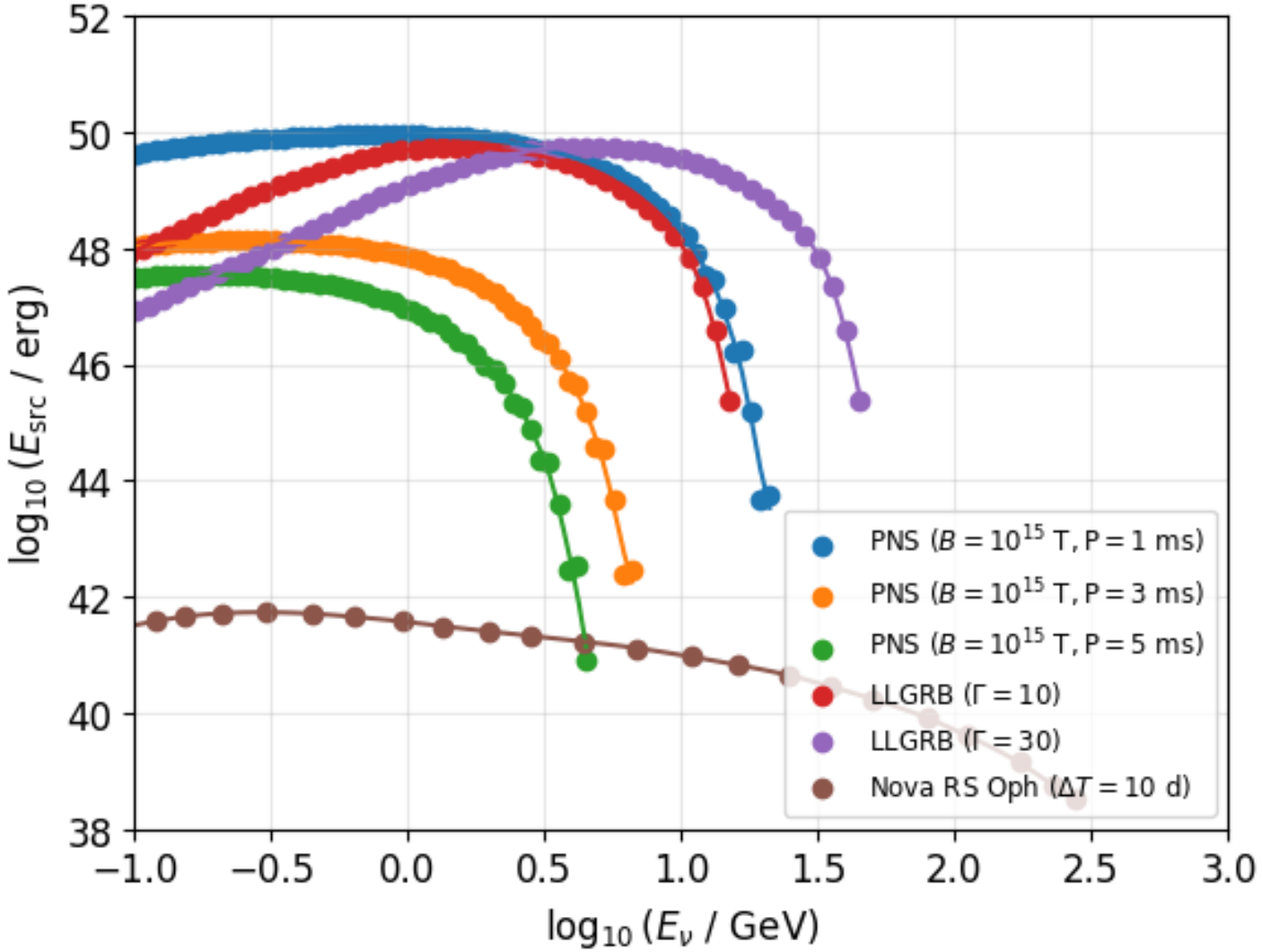
J. A. Carpio et al. (2024)

Upgrade Event Rates at Each Analysis Step

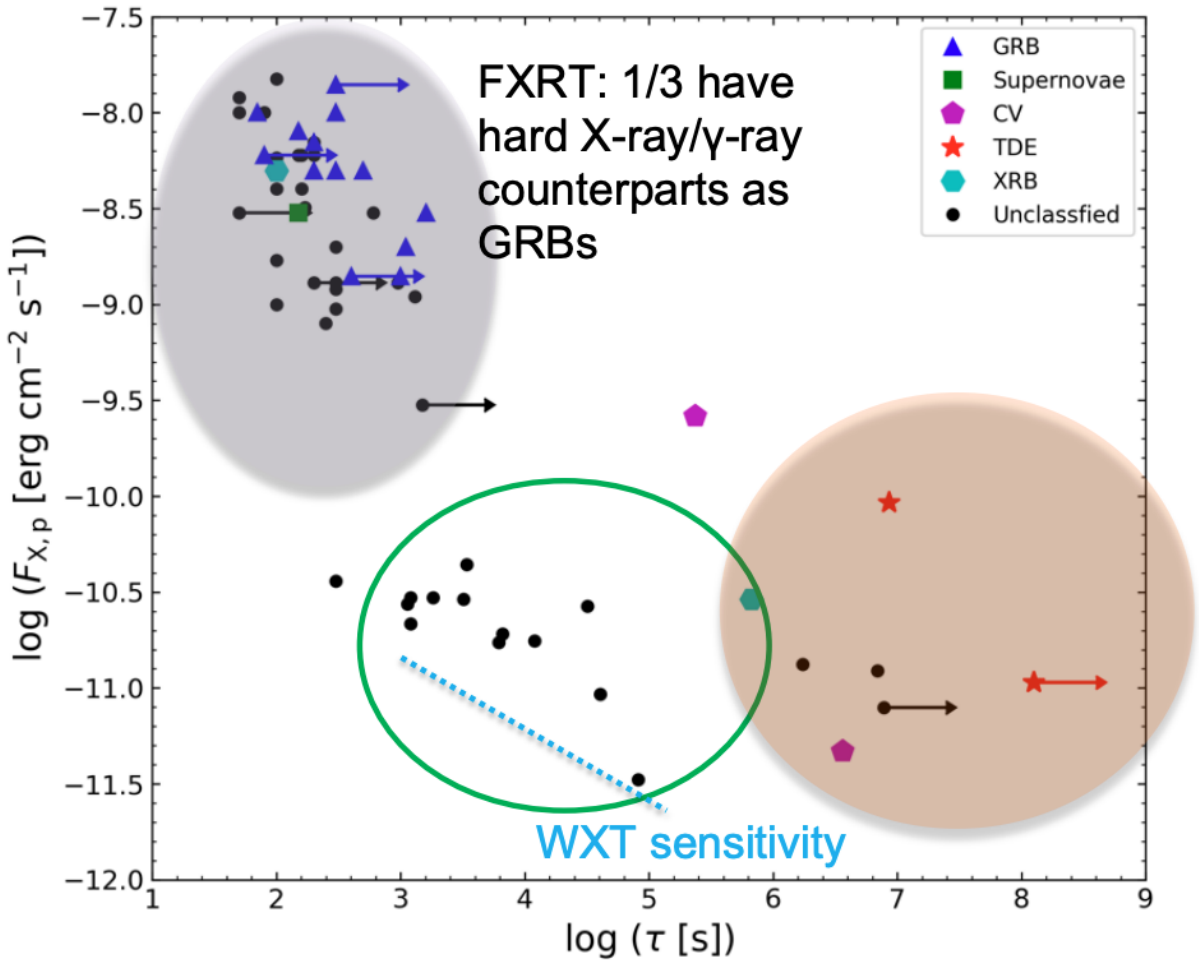
https://arxiv.org/abs/2509.13066



GeV Neutrino Spectral Models



peak flux vs. timescales for EP-WXT transients



from Hua Fen's slides