Enhanced low-energy supernova burst detection in large liquid argon time projection chambers enabled by Q-Pix

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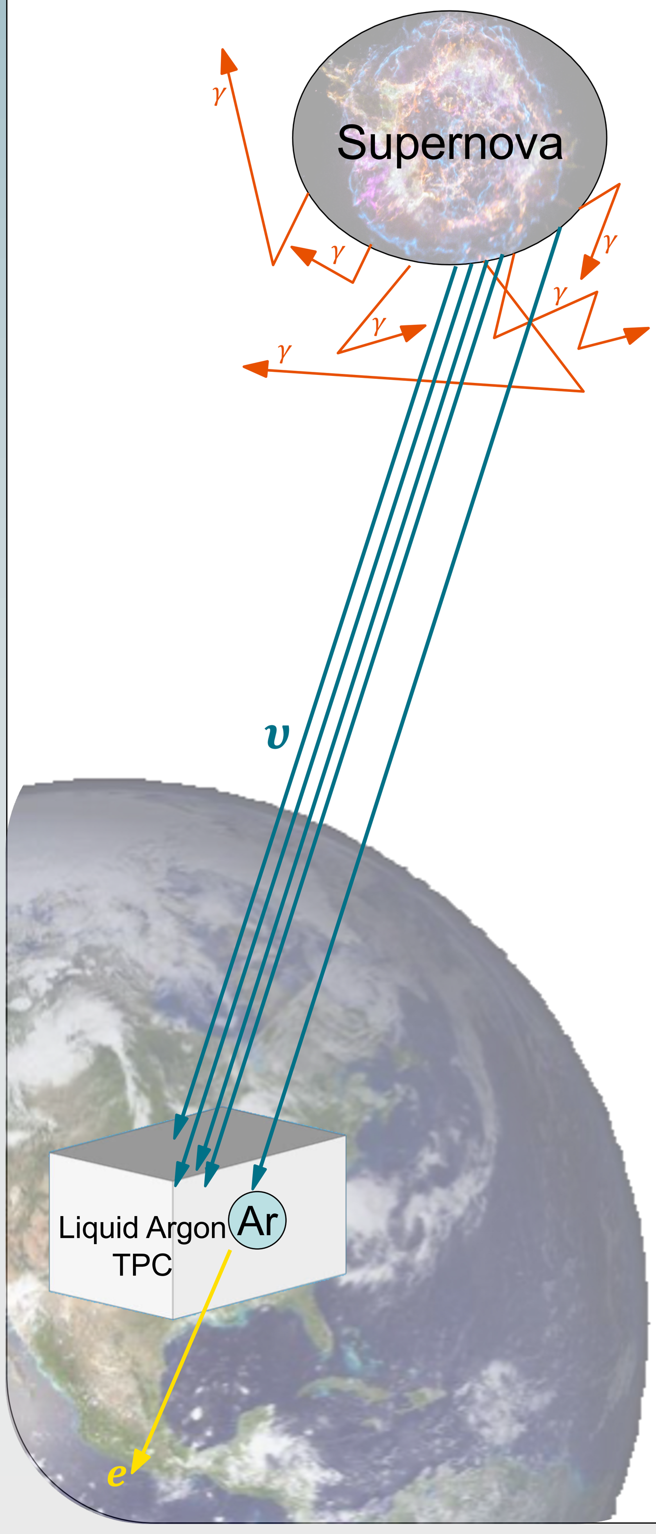
Introduction



- As massive stars reach the end of their life in a core-collapse supernova, neutrinos are produced.
- Supernova neutrinos help us understand the unknown mechanism of supernova burst.
- With its most extreme densities and energies, supernova provides a new and unique laboratory where our understanding of both nuclear and particle physics can be tested, such as neutrino–neutrino interactions and oscillations.

Q-Pix concept

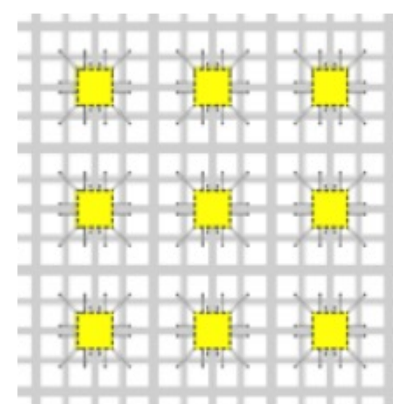


Figure 1

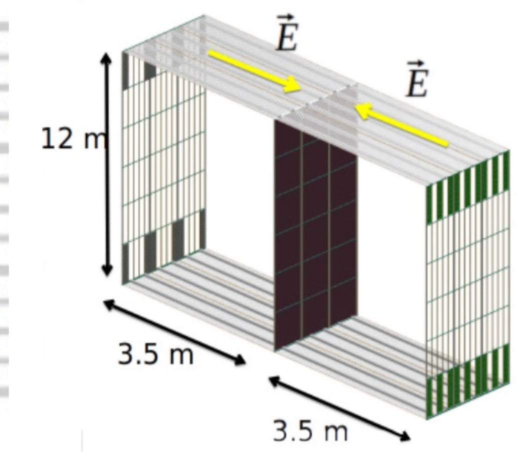


Figure 2

- Q-Pix is a pixel-based charge readout mechanism, proposed as an alternative to the traditional wire-based charge readout. (Fig. 1)
- Pixels could be installed in a DUNE far-detector-like detector as shown on the right. (Fig. 2)

- Each pixel is connected to the electronics readout shown on the left. The charge sensitive amplifier (A) continuously integrates incoming charge on a feedback capacitor (C_f) until a threshold on a Schmitt trigger (S) is met. When this threshold is met, S "resets" and the accumulated charge gets drained. (Fig. 3)
- The time difference between the resets can be used to get current, and waveform can be reconstructed, as presented on the right. (Fig. 4)
- With this scheme, lower energy threshold as well as low data rate can be achieved. (Fig. 5)

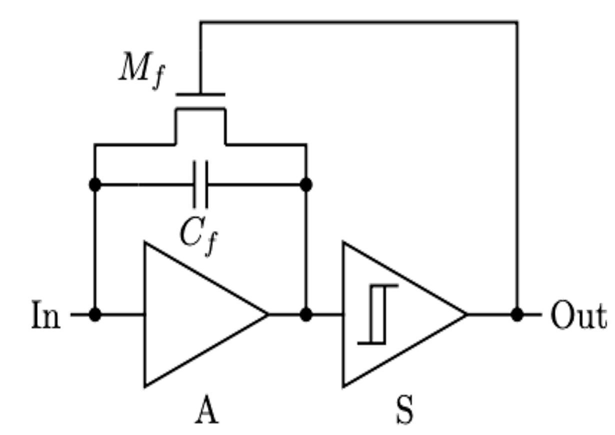


Figure 3

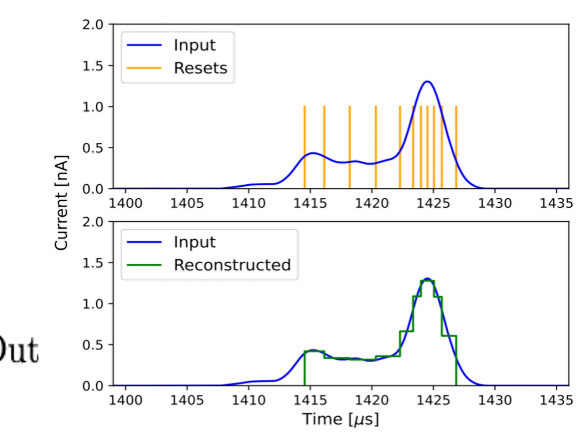
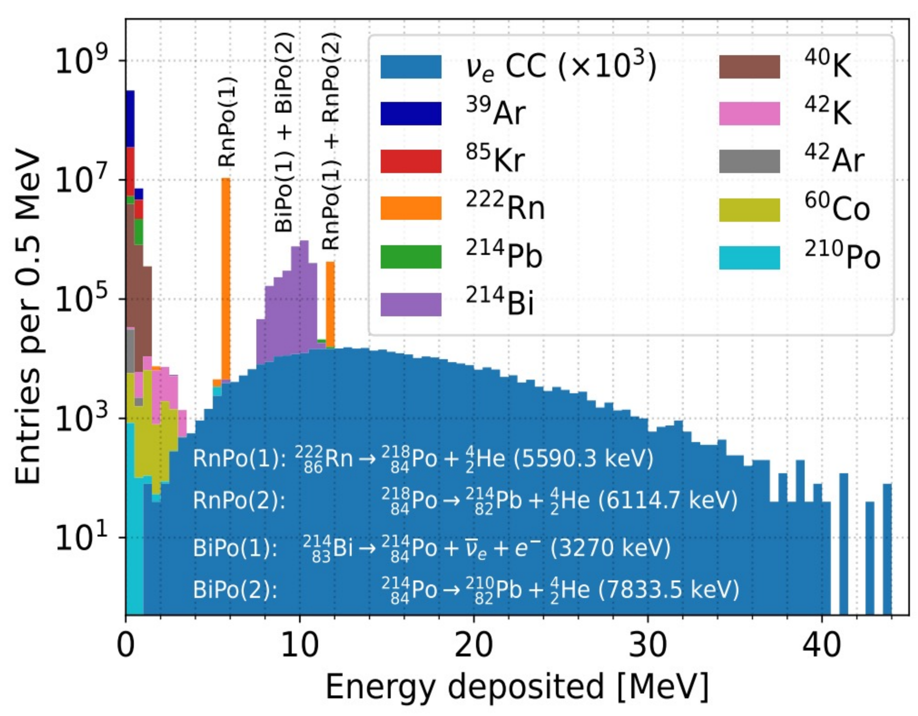


Figure 4

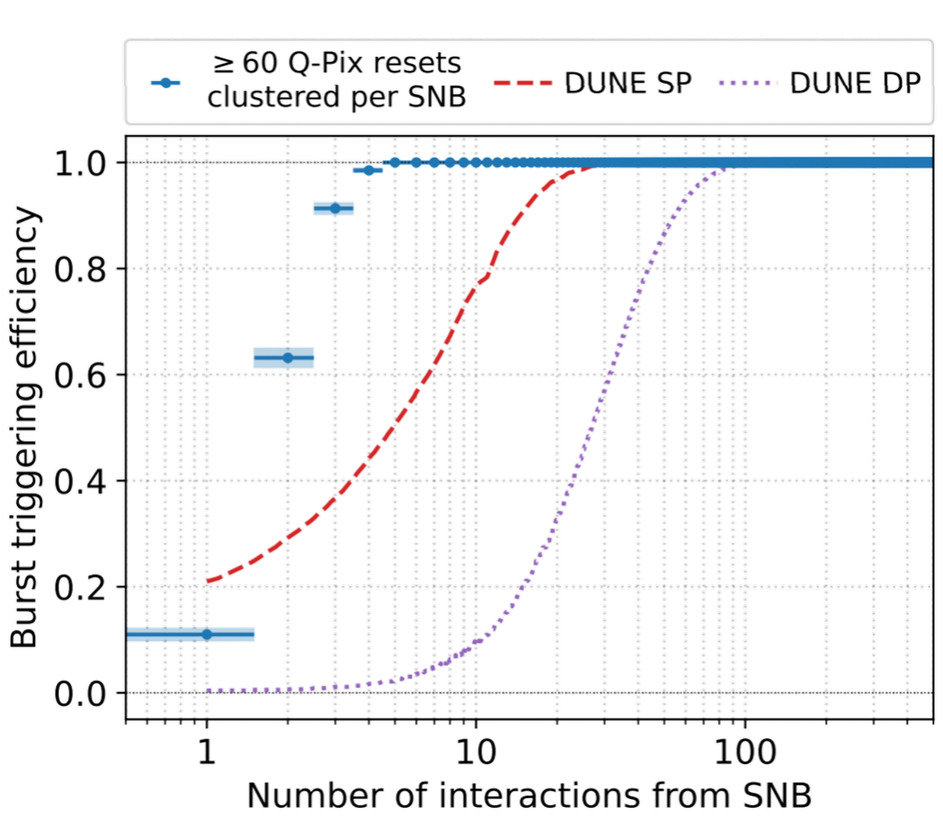
System	Data rate per 10 kton per year (petabytes)	Data rate per channel per second (kilobytes)
Q-Pix 10 kton pixel readout	1.03×10^{-6}	1.9×10^{-10}
DUNE 10 kton projective readout	<2	1.6

Figure 5

Supernovae detection with Q-Pix



Stacked histogram of the Geant4 truth-level deposited energy from ve CC signal events (magnified by ×103) in a typical supernova (SN) simulation over 10 seconds and from the radiogenic background events.



Supernova burst triggering efficiency as a function of the number of ve interactions in a 10-kton Q-Pix-enabled detector module.

Supernovae directionality studies with Q-Pix

- In a LArTPC, supernova neutrinos can create electrons, either via charged-current (CC) interactions or by neutrino-electron elastic scattering (ES).
- Only ES electrons preserve the directionality of incoming supernova neutrinos. (Fig. 6)

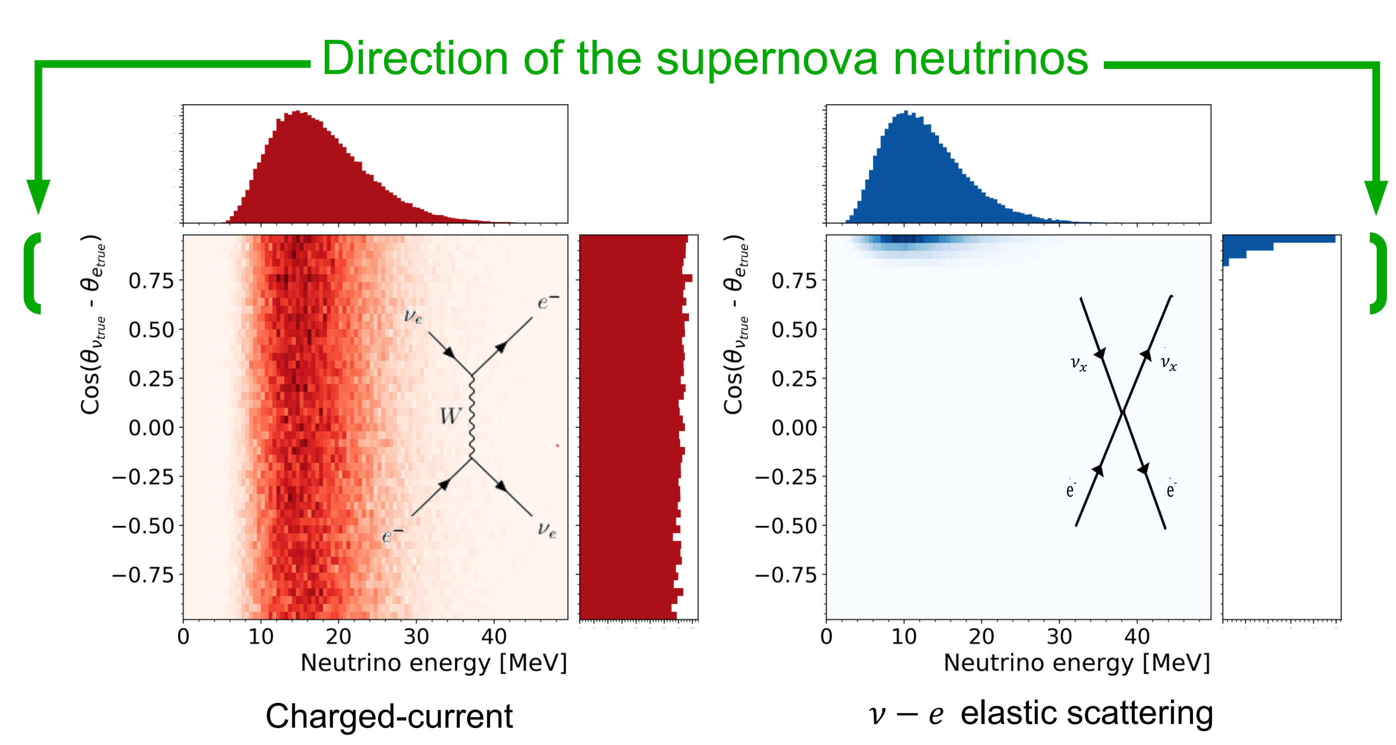


Figure 6

- With Q-Pix, the directionality of supernova neutrinos can be reconstructed based on the directionality of ES electrons, with principal component analysis (PCA) (Fig. 7).
- By our simulation work, we have determined that we are capable of pointing the position of 10 kpc supernovae within θ = 33◦ and φ = 45◦ at 1σ, and θ = 99◦ and φ = 135◦ at 3σ (Fig. 8).

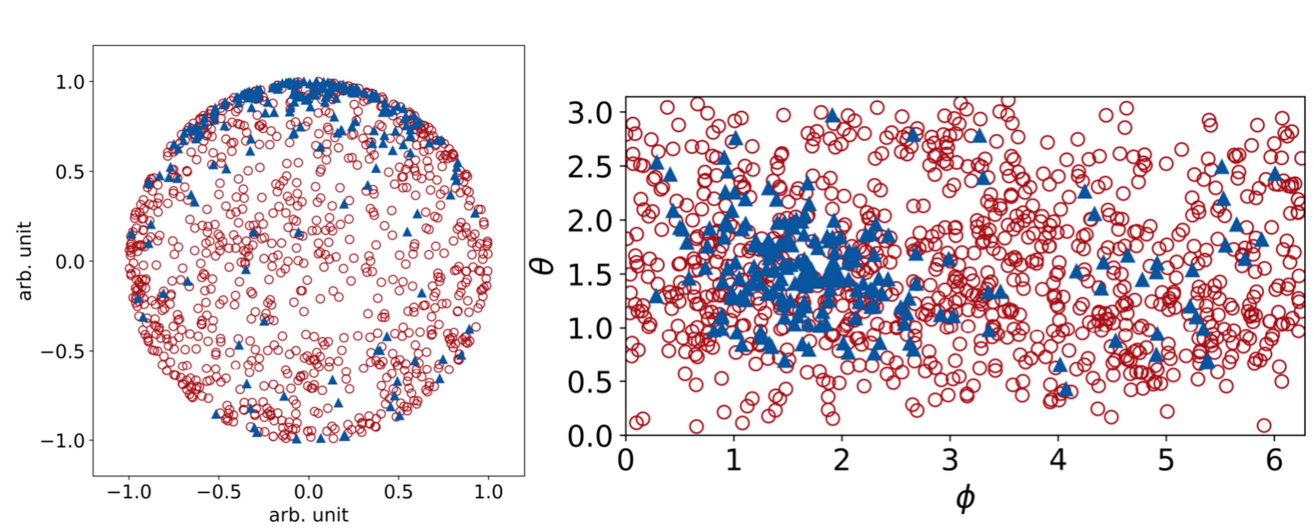


Figure 7: Representation of the direction vector generated for each neutrino interaction shown on a unit sphere (left) and projected onto a θ–φ plane. Solid blue triangles represent events from ES interactions and hollow red circles represent events from CC interactions.

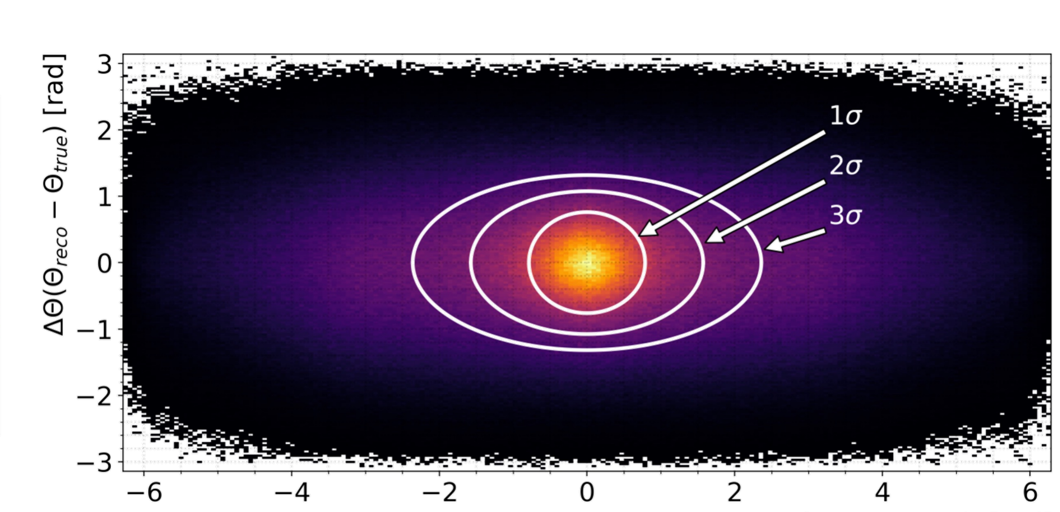


Figure 8

- Combined with the low energy threshold, a detector module with Q-Pix readout can contribute to the SuperNova Early Warning System (SNEWS).

Reference

Q-Pix: Pixel-scale Signal Capture for Kiloton Liquid Argon TPC Detectors: Time-to-Charge Waveform Capture, Local Clocks, Dynamic Networks, D. Nygren and Y. Mei, (2018), arXiv:1809.10213 [physics.ins-det].
Enhanced low-energy supernova burst detection in large liquid argon time projection chambers enabled by Q-Pix, Q-Pix Collaboration, S. Kubota(Harvard U) et al. (Mar 22, 2022)