Low-latency pointing to a supernova with neutrinos

for Duke University A3D3 group by Kate Scholberg

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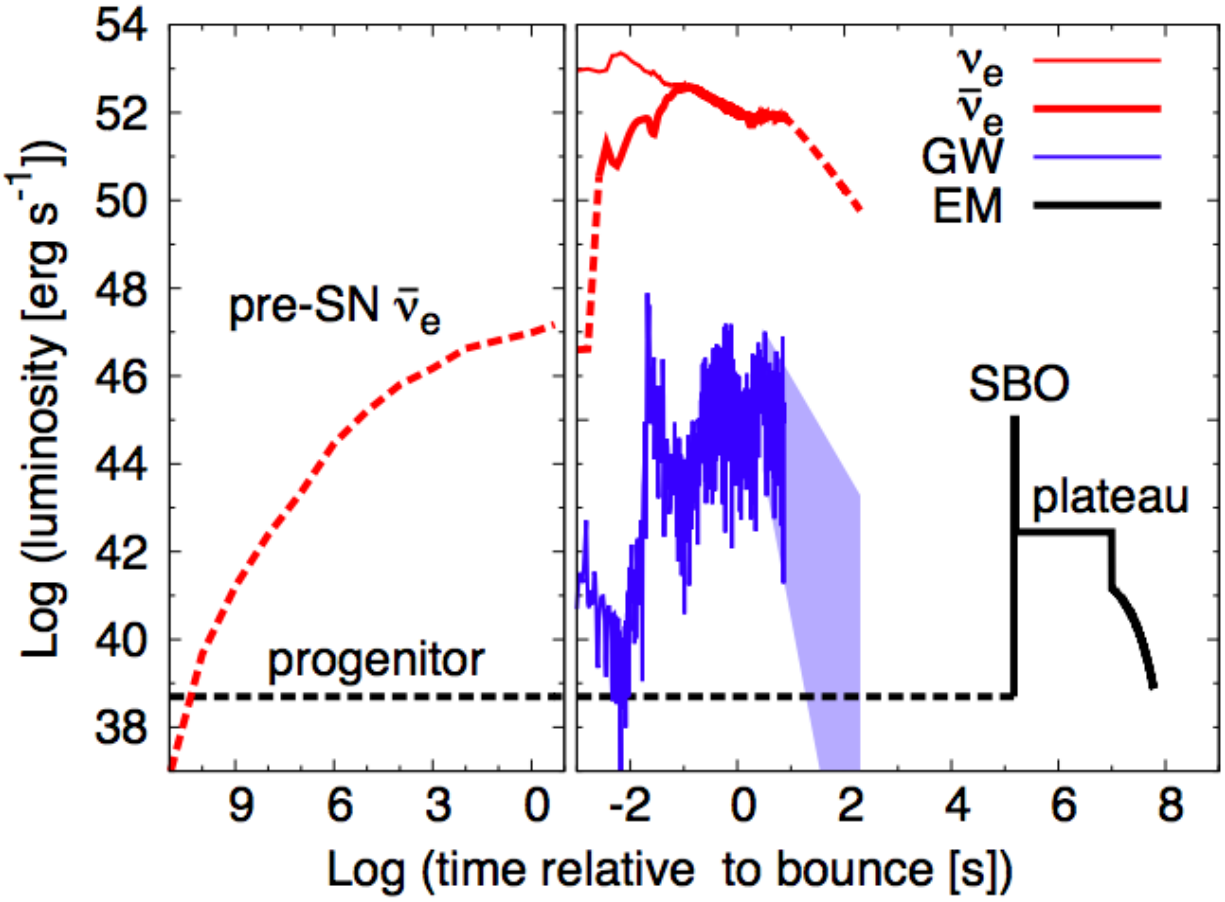
July 10, 2023 - A3D3 High-Throughput AI Methods and Infrastructure Workshop

Figure Crab Nebula: NASA, STScI

Multimessenger astronomy



K. Nakamura et al., MNRAS Vol461 Issue 3 2016

Supernova bursts:

- >99% of energy released in the form of neutrinos
- time scale:
  - neutrinos: 10^{-2}s -10s
  - grav. Waves: 10^{-2}s -10s
  - el.-mag.: >10^{4}s
- neutrinos interact only weakly with a very small cross section

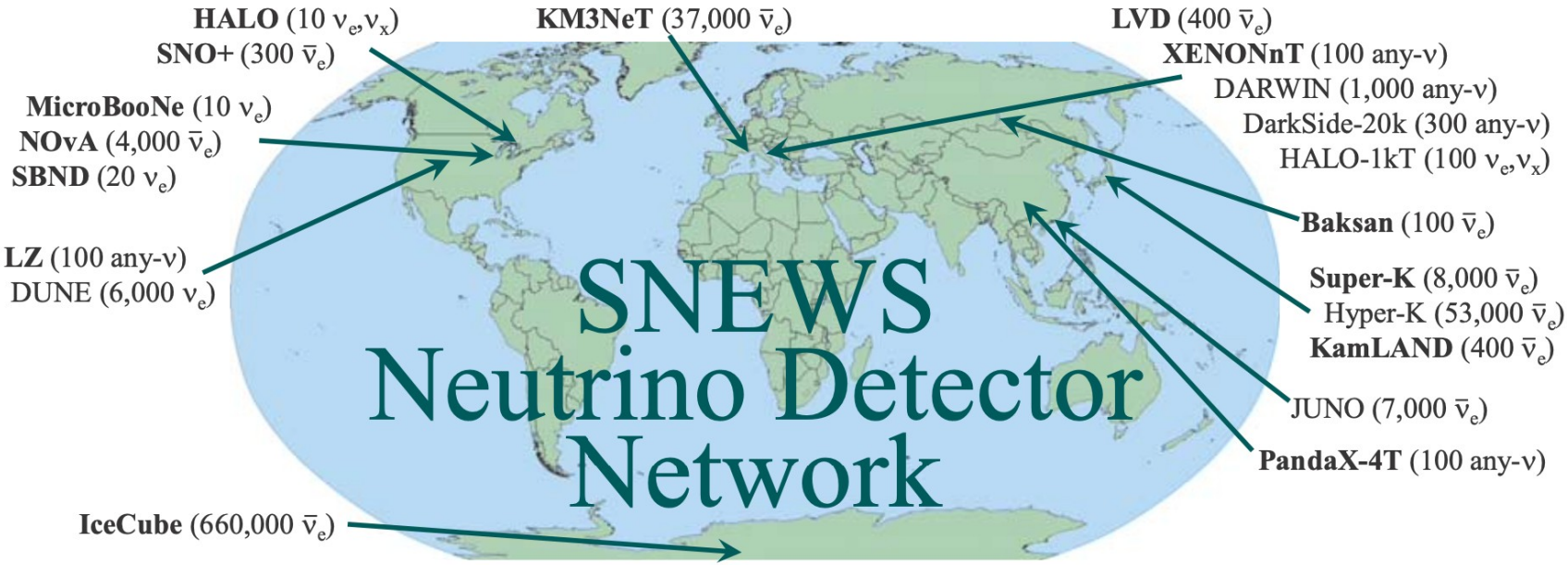
=> neutrino detection for early warning system of burst

=> detection has enormous physics potential for **astronomy** and **particles physics**

SNEWS

(SuperNova Early Warning System)

- SNEWS1.0: simple 10s coincidence, running in automatic mode since 2005
- Upgrade to SNEWS2.0: improved latency, neutrino based pointing, including triangulation



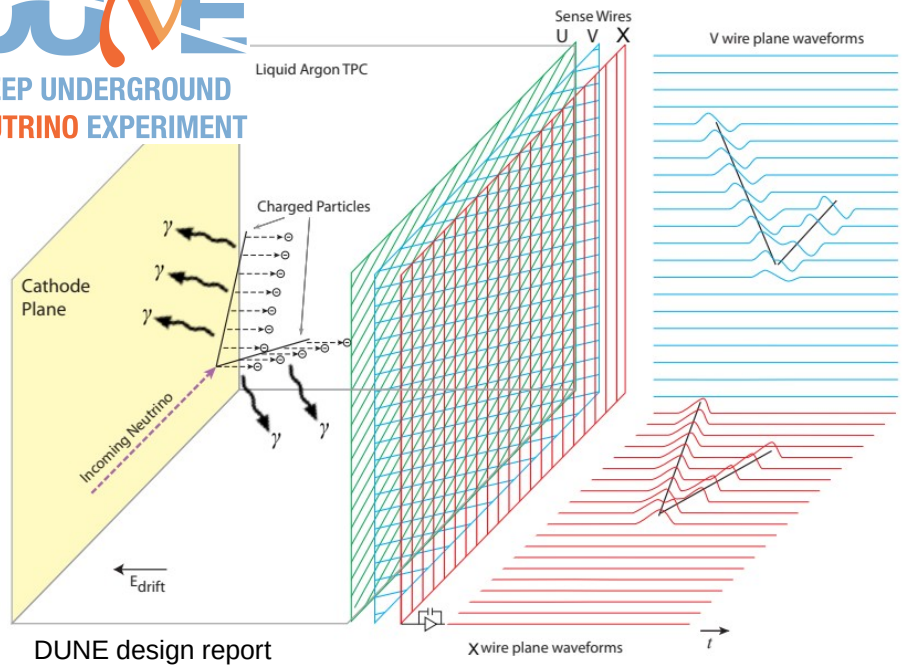
https://snews2.org/

Detection materials: water-based, **argon,** scintillator, lead, noble liquid dark (dark matter exp.)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE

(Deep Underground Neutrino Experiment)



DUNE design report

- liquid argon time-projection chambers:
  ionization and scintillation light
  totally active calorimeter
- far detector in South Dakota: LAr mass 4 x 10kt
- underground: 1.5km rock/4300 m w.e.
- GeV scale: Neutrino oscillations in
  long baseline beam, study of atmospheric
  neutrinos, BSM physics, baryon number violation
- low energies: supenova neutrinos,
  solar neutrinos, diffuse supernova background

large mass	→	high statistics
underground	→	background suppression
excellent 3D imaging	→	pointing to supernova, multi messenger
ν_e detection	→	complementarity to other experiments (JUNO, Hyper-Kamiokande)

Supernova neutrino detection with DUNE

Dominant channels: charge-current interaction (ν_eCC) and elastic electron scattering (eES)

Additional channels: ES of other flavors, NC scattering on Ar, ...

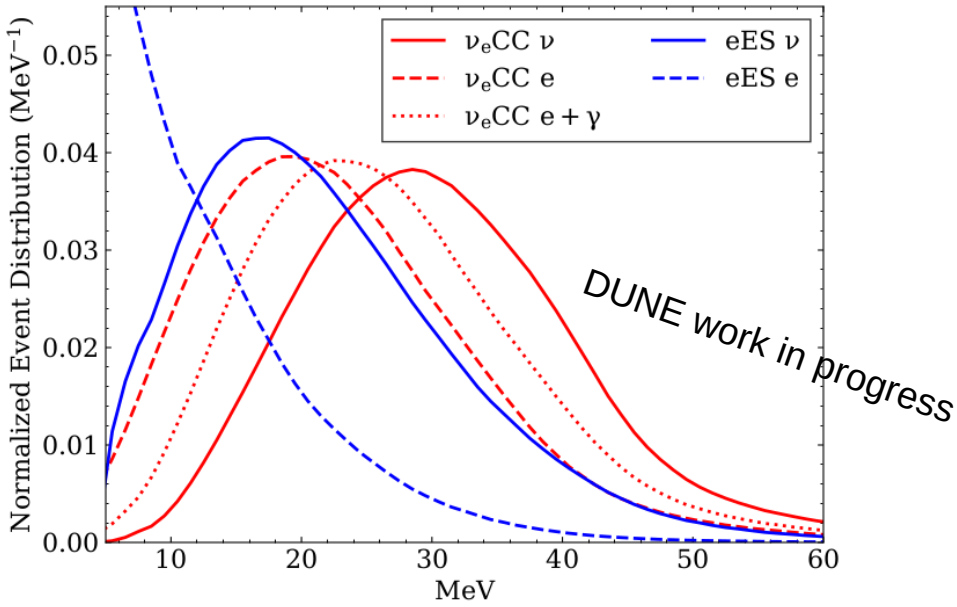
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

~3000 events @10kpc (GKVM model)
flat angular distribution

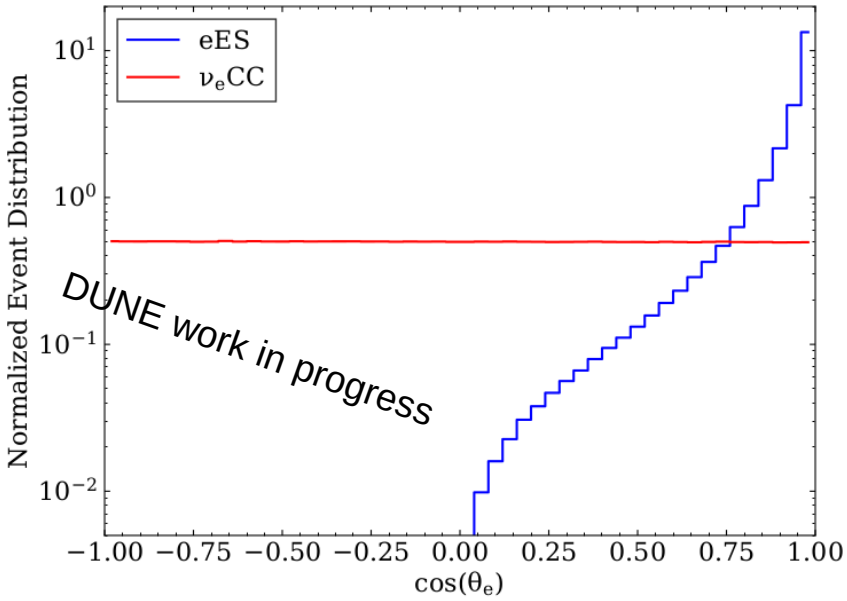
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

~300 events @10kpc (GKVM model)
primary e⁻ direction ~ ν_e direction

Energy spectra:



Overall angular distributions:



→ channel tagging: distinguish ν_e CC and eES

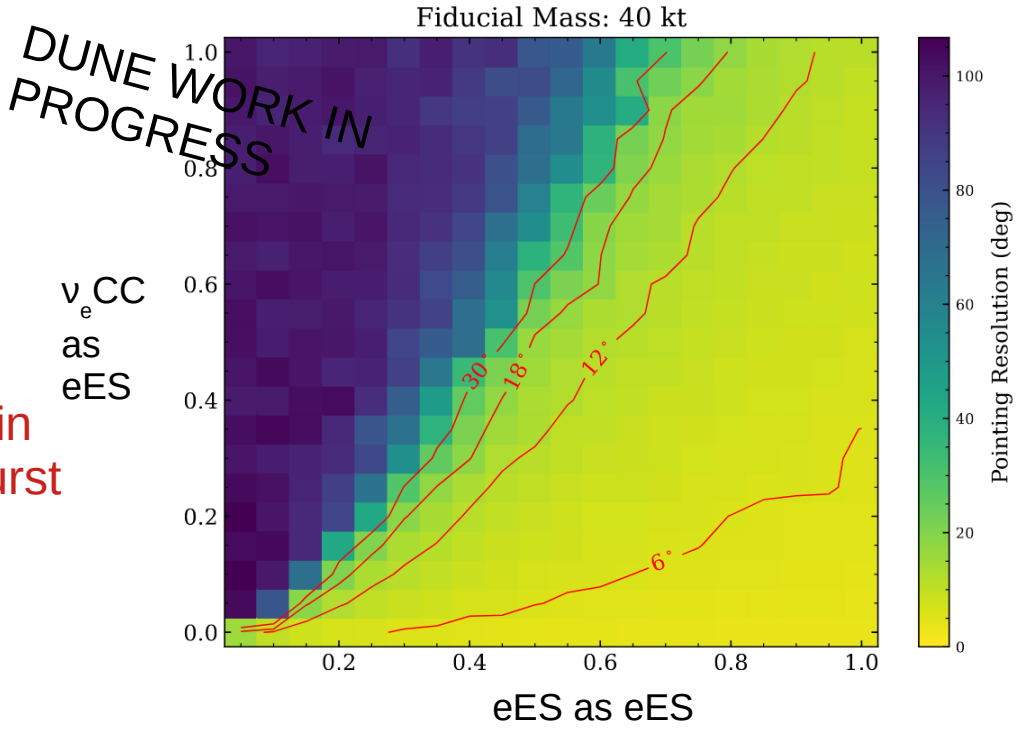
DUNE supernova pointing results

Procedure:

- simulation of supernova events, noise and background
- **reconstruction of single events:**
  - Identification of supernova events
  - energy
  - direction, daughter flipping for head-tail disambiguation
- **combination of events to burst:**
  - minimum energy: 10MeV
  - maximum log likelihood
  - assumptions on channel tagging

→ publication in preparation

>>1min per burst



Likelihood output:

LAr volume	40kt	10kt (one module)
Perfect disambiguation	3.7 deg	7.4 deg
4% ν_eCC as eES	5.0 deg	10.6 deg

(68% confidence level)

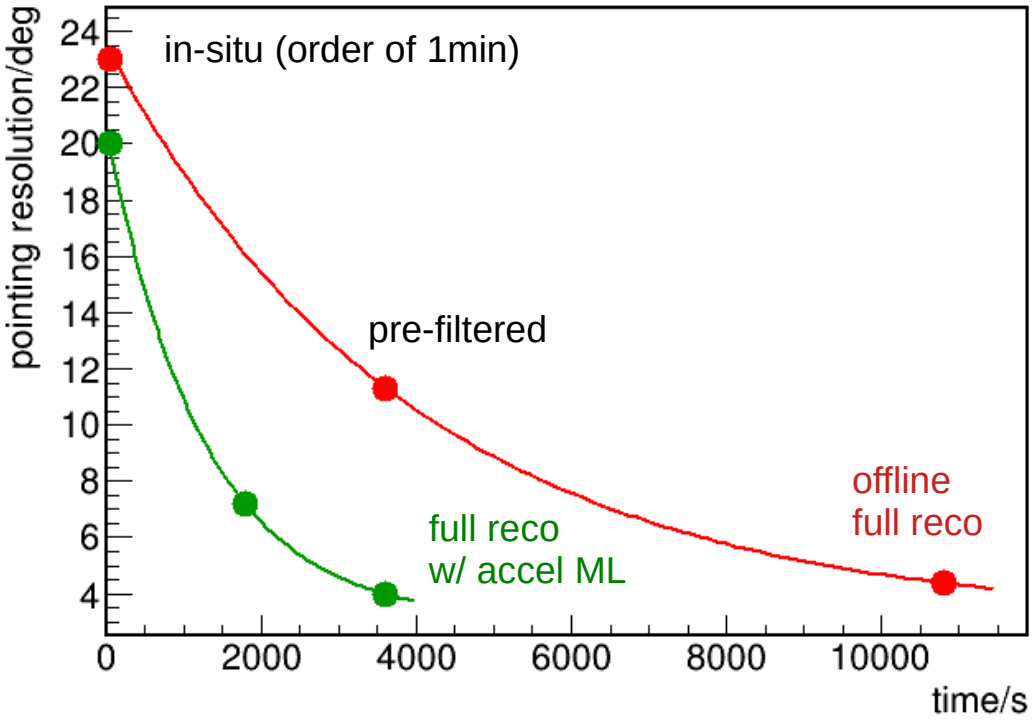
GKVM model, 10kpc distance

Online Pointing and machine learning

Strategy: prompt, low-resolution followed by successive improvements
("kaizen" approach, coined for this by K. Scholberg at Accelerating physics with ML in Boston)

→ convert offline code to complete standalone pipeline, upgrade with ML
→ also test upgrades of offline code with ML

Illustration:

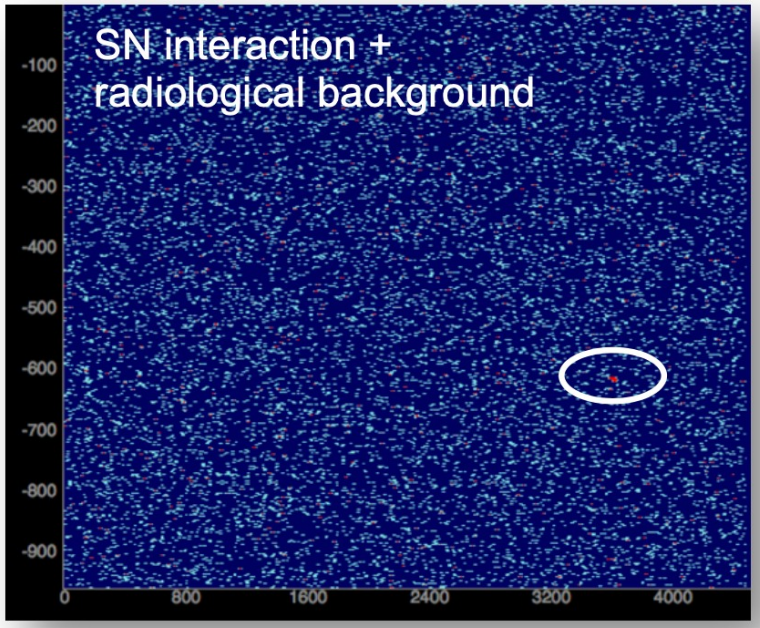


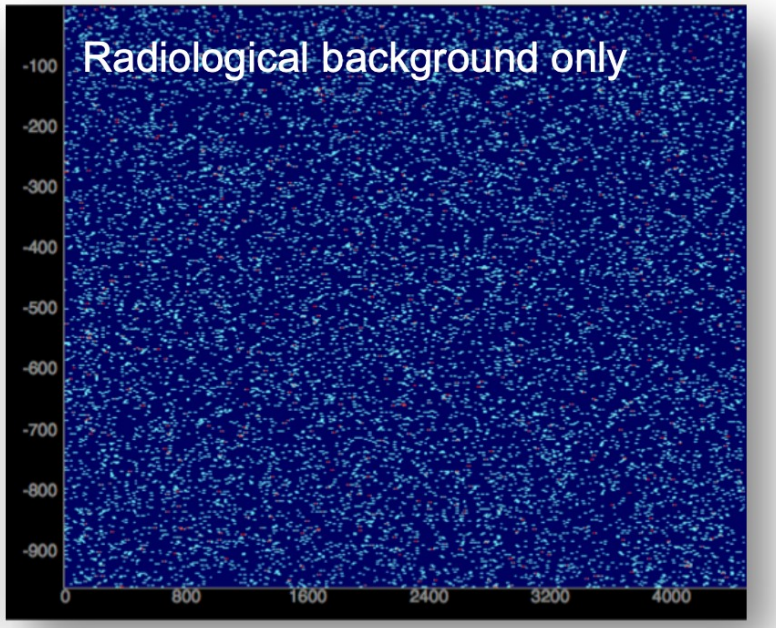
poster by JH

Identifying supernova events

High resolution “video stream”: 11.5 Mega Pixel frames per 2.25ms, 12 bits resolution

Special challenge: **neutrinos from supernova core collapse**
Very low energy and small (in extent) topology, similar to radiological background activity in the detector





Need O(10^4) overall background suppression, while maintaining high efficiency to a frame containing a supernova neutrino interaction

[simulation]

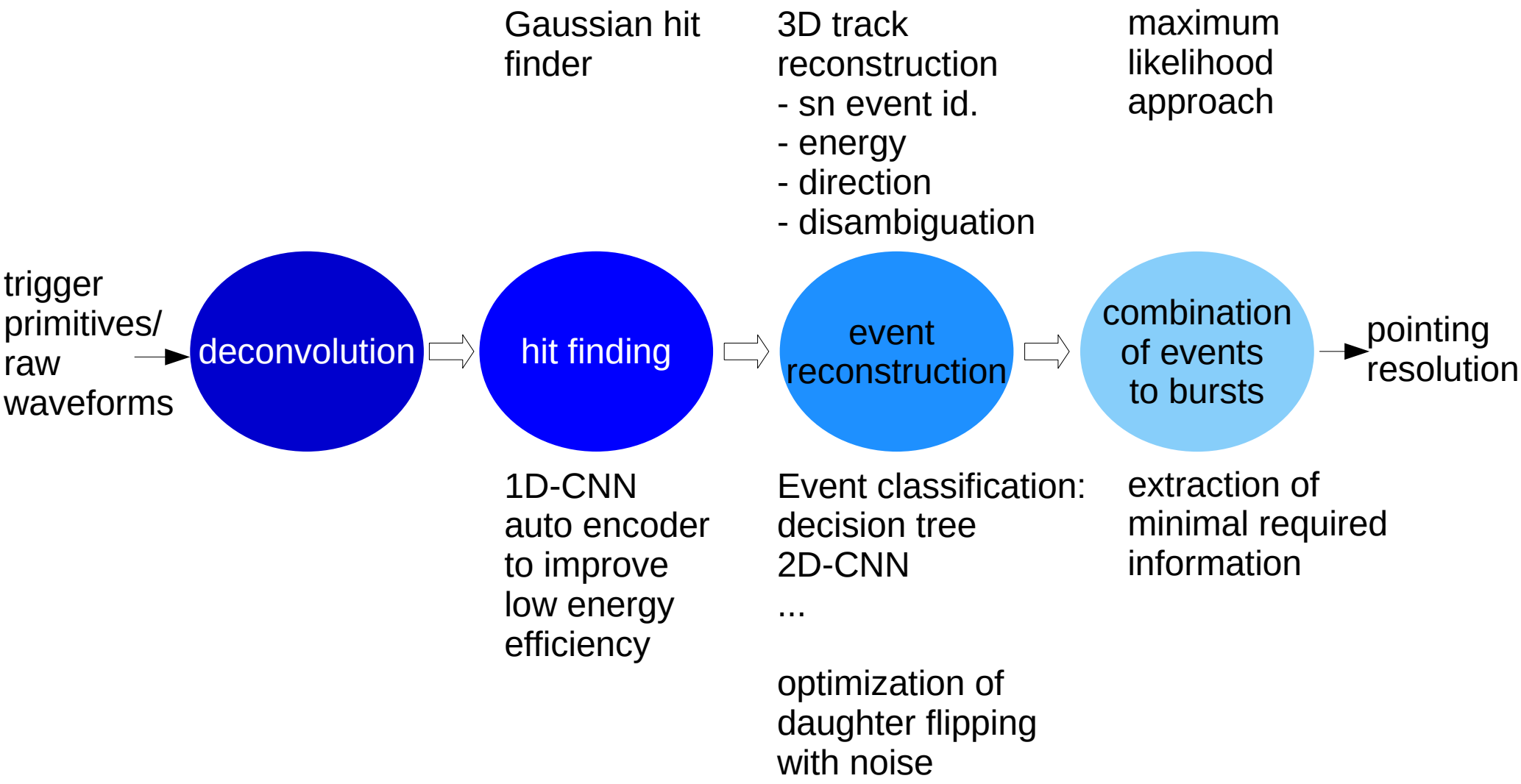
Real-Time Inference With 2D Convolutional Neural Networks on Field Programmable Gate Arrays for High-Rate Particle Imaging Detectors

Yeon-jae Jwa (Columbia U.), Giuseppe Di Guglielmo (Columbia U.), Lukas Arnold (Columbia U.), Luca Carloni (Columbia U.), Georgia Karagiorgi (Columbia U.) (Jan 14, 2022)

Published in: *Front.Artif.Intell.* 5 (2022) 855184 • e-Print: 2201.05638 [physics.ins-det]

by G. Karagiorgi group, Columbia

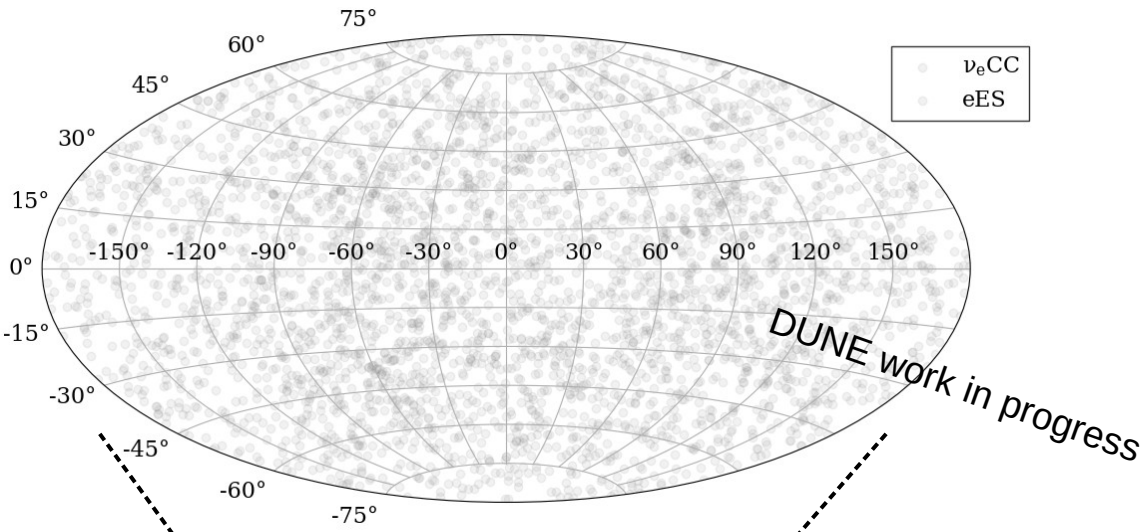
Standalone pointing code for DUNE

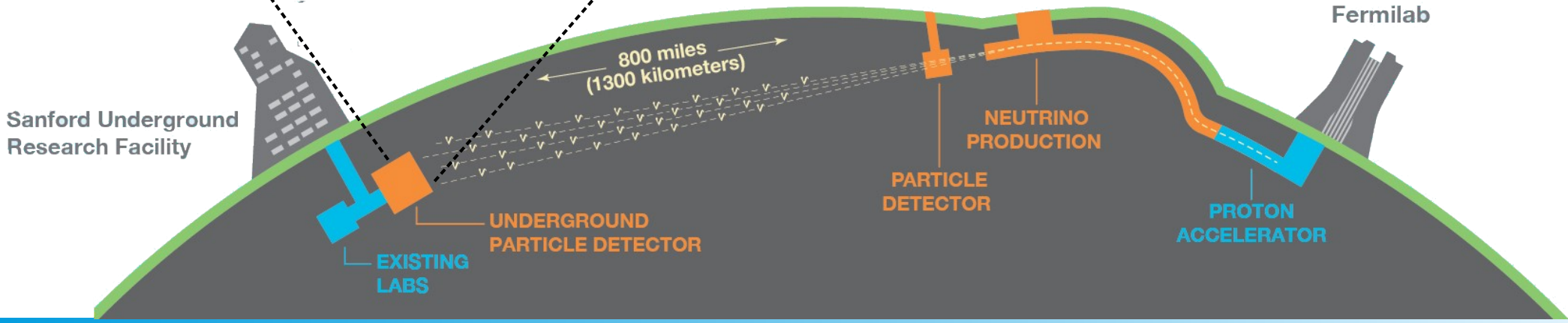


Remark: This list of ML efforts is for sure not complete.

Supernova detection with DUNE

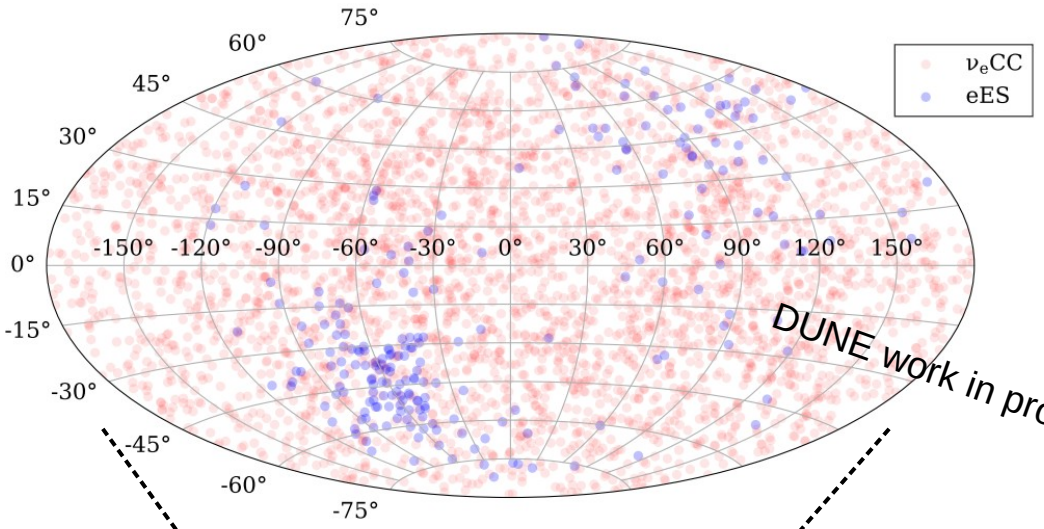
Skymap

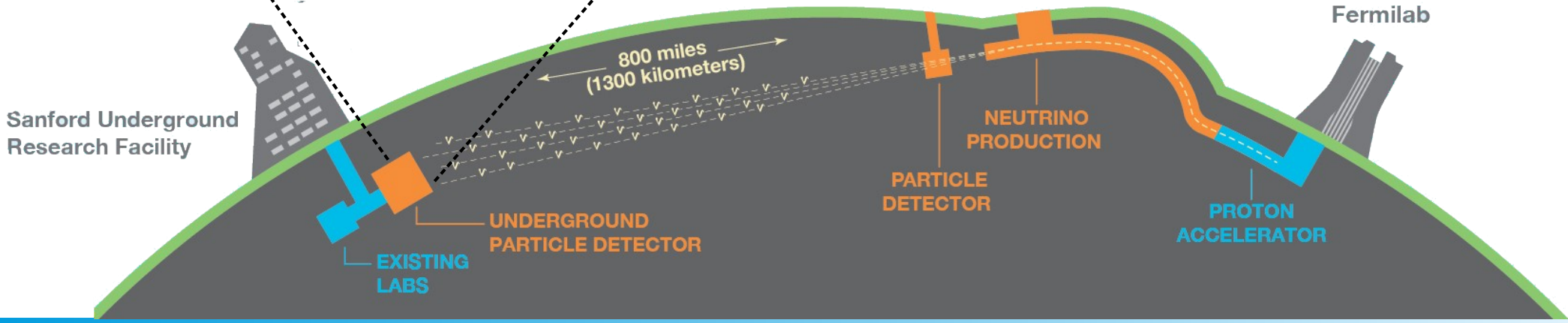




Supernova detection with DUNE

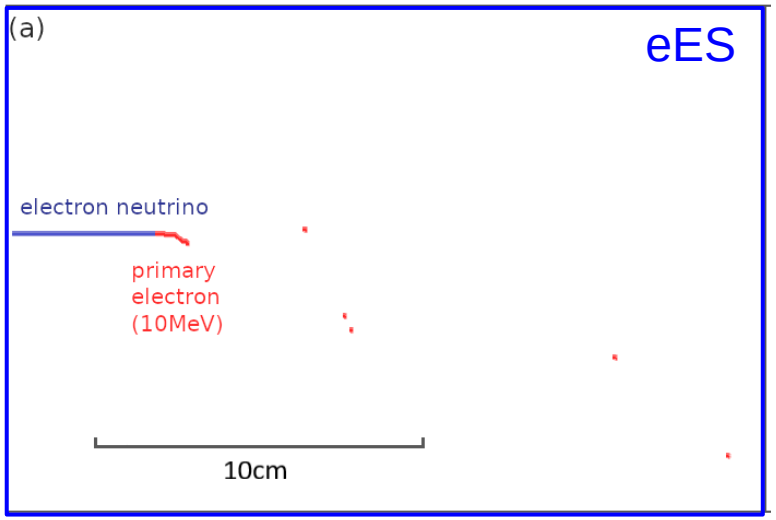
Skymap

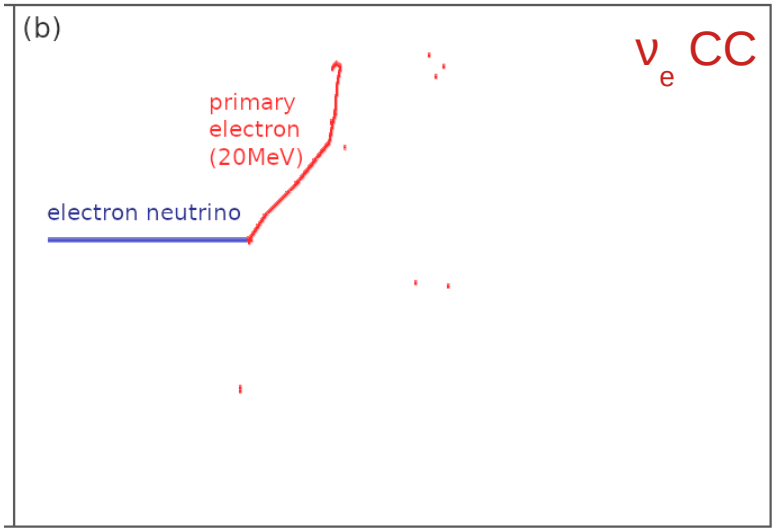




Event classification

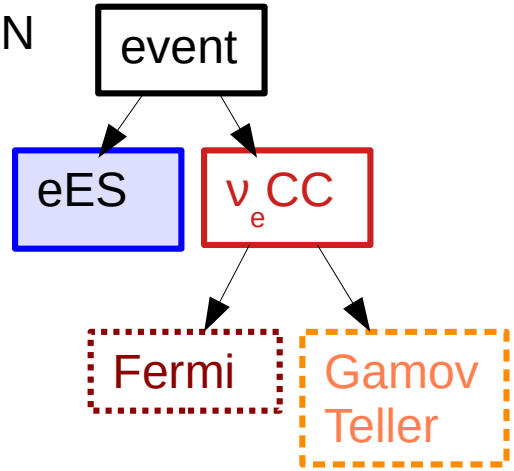
Geant4 event displays:





ML approaches ongoing:

- E. Conley (Duke) https://zenodo.org/record/4122909#.Y9pfpy-B3pA
  → boosted decision tree (ave. track length, charge,...)
  → ~5% missidentification seems feasible
- G. Karagiorgi's group: YOLO
  (CNN for object detection)
- M. H.L.S. Wang et al.: 2D CNN
- ...



Possible to derive
information for pointing?
overall flat angular distribution,
BUT:
the two types of deexcitation of $^{40}K^*$ carry
directional information

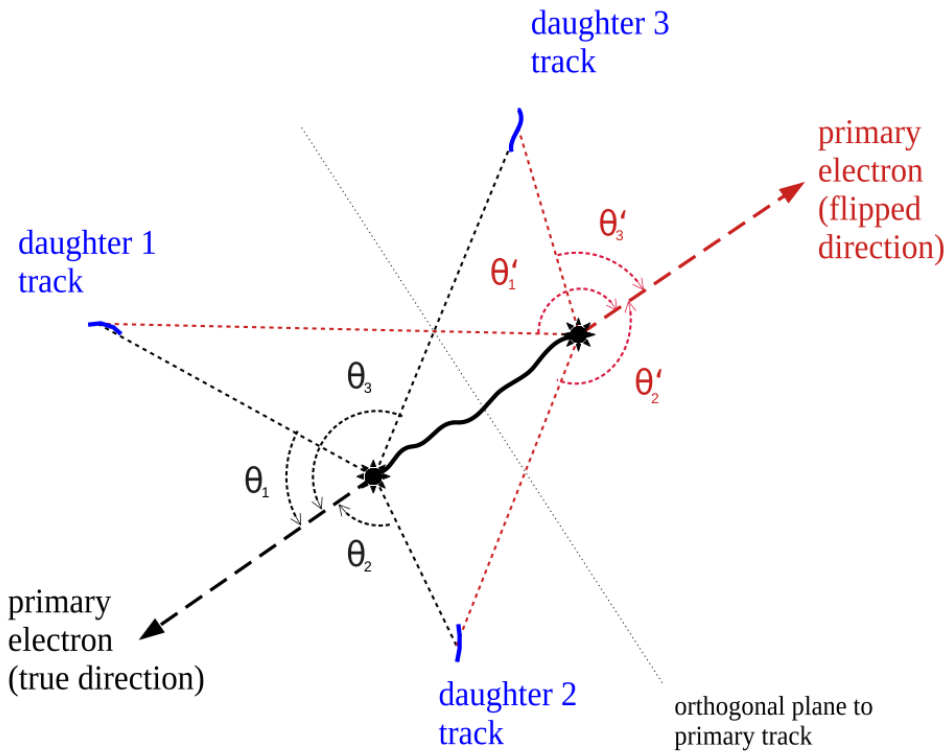
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Directional head-tail disambiguation

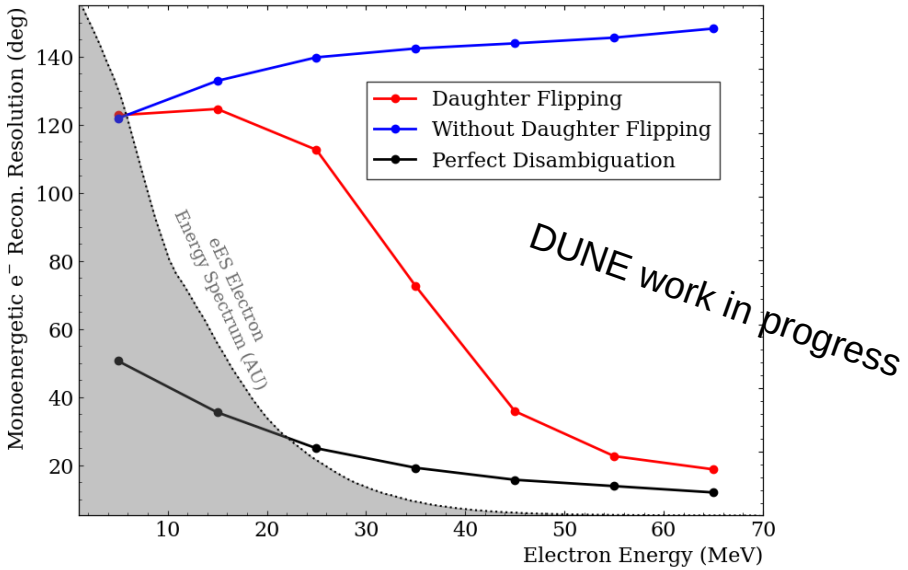
Daughter flipping:

mean cos(θ_i) > mean cos(**θ'_i**)

→ resolving head-tail direction disambiguties



Performance (from simulations):



test daughter flipping performance with Michel electrons (from cosmic muons) in **ICEBERG** (~1t LArTPC with Dune electronics)

→ study daughter flipping with data in presence of noise

→ acquire test data set for ML applications

→ examine performance improvements with ML

poster by Joshua Queen

Low energy events

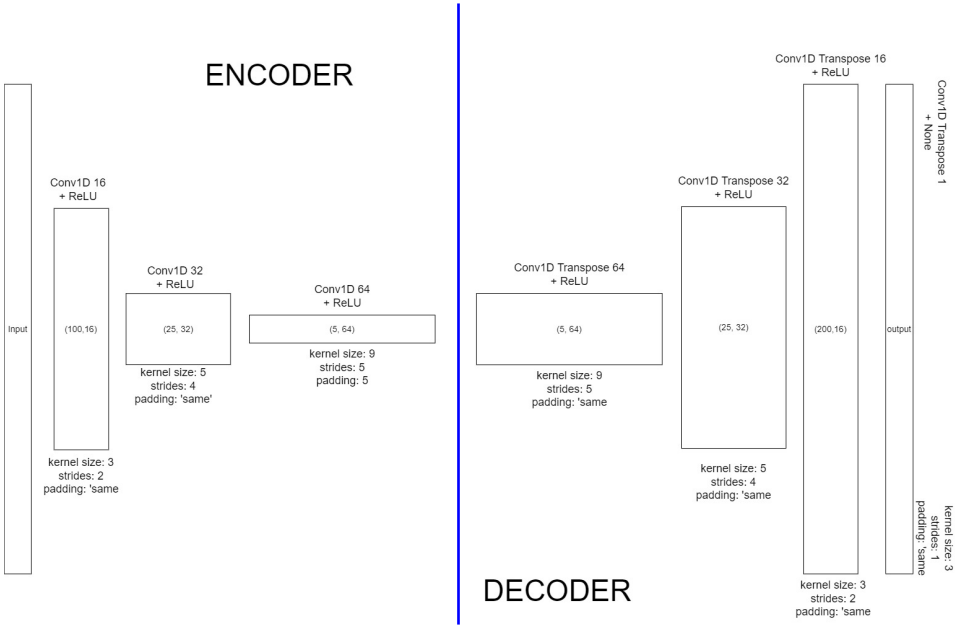
In cooperation with Michael H.L.S. Wang (Fermilab):

Extracting low energy signals from raw LArTPC waveforms using deep learning techniques — A proof of concept #

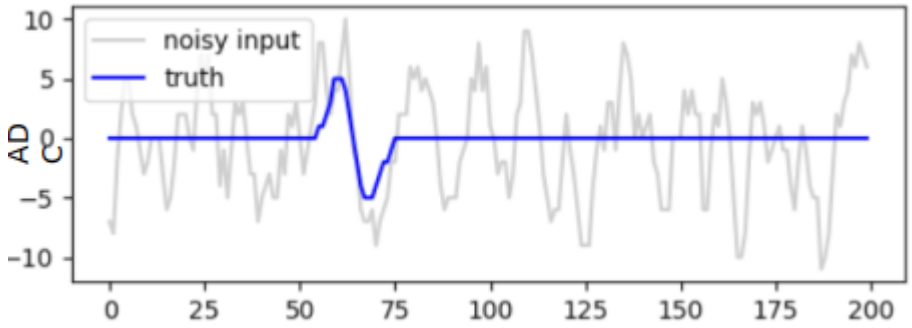
Lorenzo Uboldi (CERN), David Ruth (Unlisted, US, IL), Michael Andrews (Carnegie Mellon U.), Michael H.L.S. Wang (Fermilab), Hans Joachim Wenzel (Fermilab) et al. (2021)

Published in: *Nucl.Instrum.Meth.A* 1028 (2022) 166371 • e-Print: 2106.09911 [physics.ins-det]

→ 1D-CNN => next step auto encoder



induction plane signal



- improve LAr TPC detection efficiency at low energies (<1 MeV energy deposition)
- method to denoise input waveforms

poster by Van Tha Bik Lian

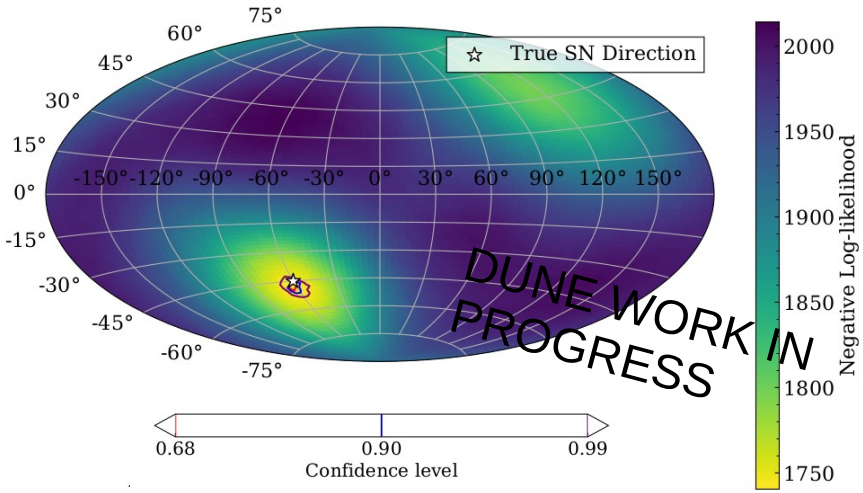
Summary and outlook

Multimessenger astronomy for supernova burst detection:

- Neutrino emission: high luminosity, fast, direct pointing back to source
  → detect all the neutrinos to provide direction for el-mag. detection systems
- SNEWS early warning system

DUNE: 4 x 10kt LArTPC

- detection of electron neutrinos
- 3D imaging reconstruction
- Offline pointing resolution without ML:
  3.7 deg in 40kt (perfect channel tagging)
  5.0 deg in 40kt (4% ν_eCC as eES)



→ online pointing code and ML

- "kaizen": provide first result ~1min, improve precision over time
- set up complete pipeline, upgrade with ML: channel tagging, directional reconstruction and daughter flipping, low energy events, combination to burst,...

Thank you for your attention!