



SuperNova pointing capabilities of DUNE

WIN – 11/06/2025

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for the DUNE collaboration

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DUNE

Long-baseline neutrino experiment in the US, international collaboration with 1500+ members.

Currently under construction, data taking starting at the end of **2029** (low energy, atmospheric, BSM).

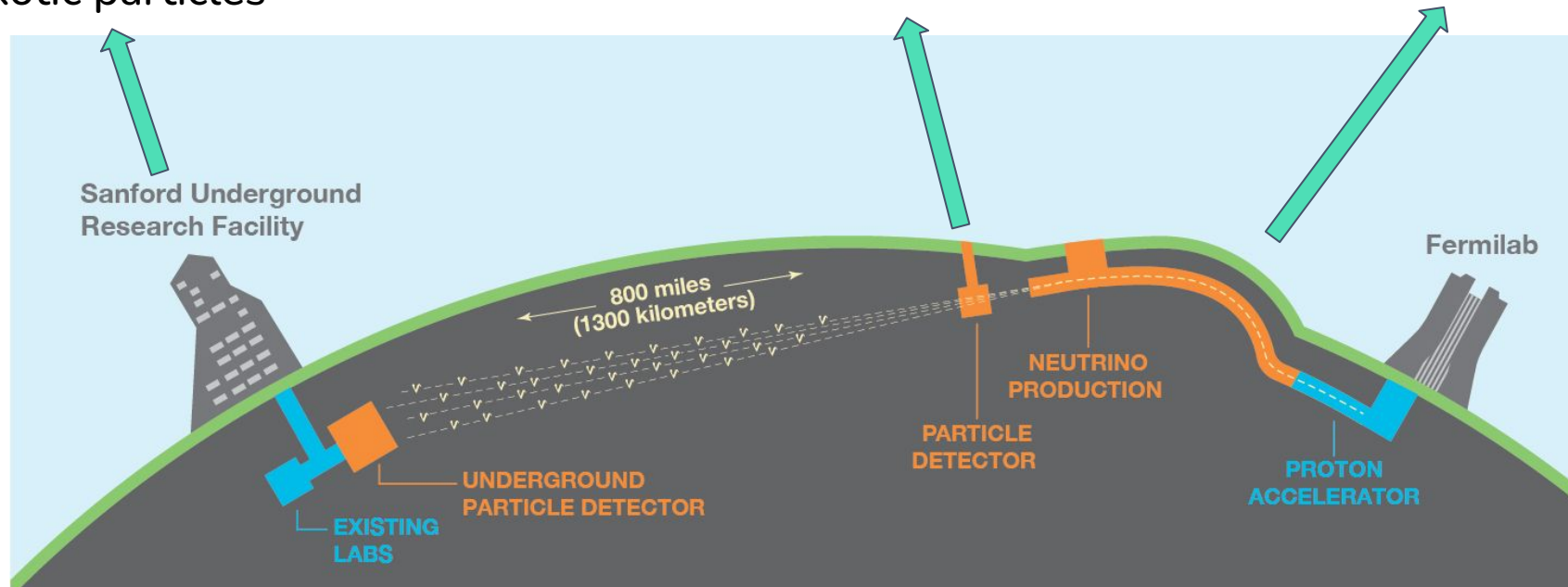
In South Dakota (SURF), there will be **2(+2) far detectors**:

- observe oscillated neutrino flux
- detect neutrinos from other sources, exotic particles

The **near detector** observes the unoscillated neutrino beam:

- constrain flux
- compute systematics

At Fermilab, a proton beam from PIP-II impacts on a fixed target, producing a **neutrino beam (1-7 GeV)**.

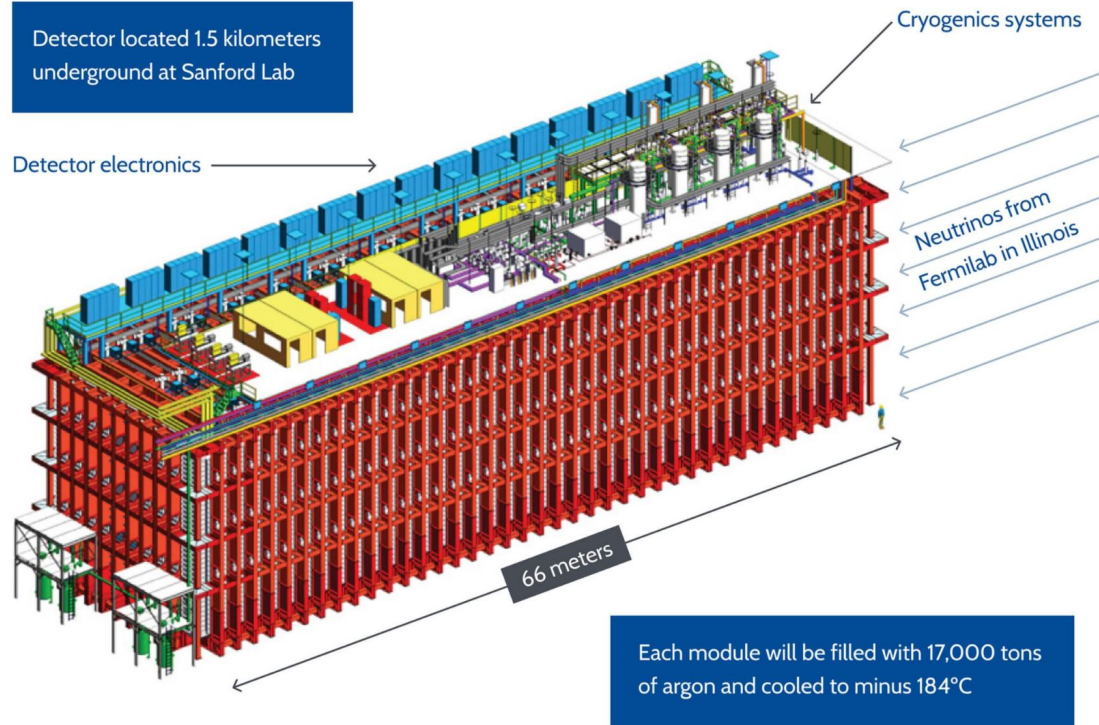


DUNE Far Detector(s)

There will initially (Phase I) be 2 Liquid Argon TPCs:

- FD-VD: Vertical Drift technology
- FD-HD: Horizontal Drift technology.

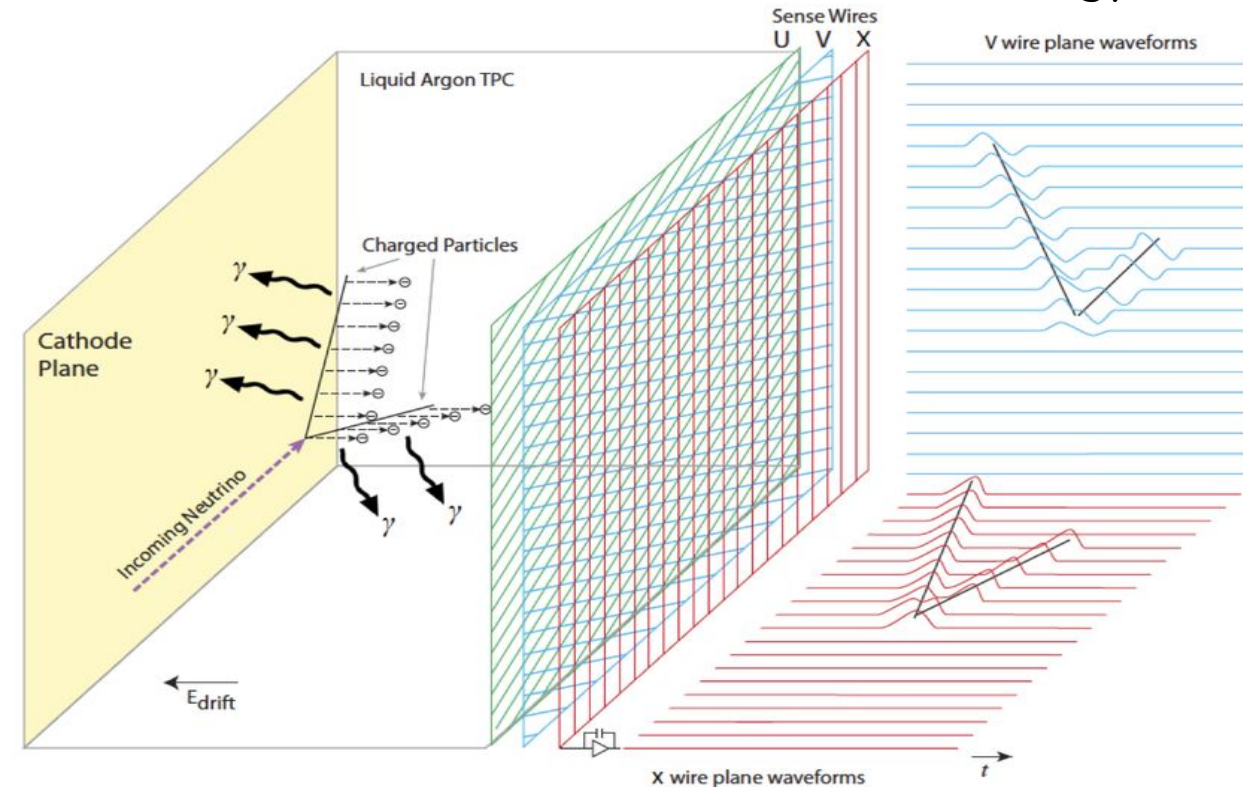
Largest LAr TPCs ever: outer size 66x10x12 m³ (17 kton total of LAr each).



Scheme of a DUNE FD module

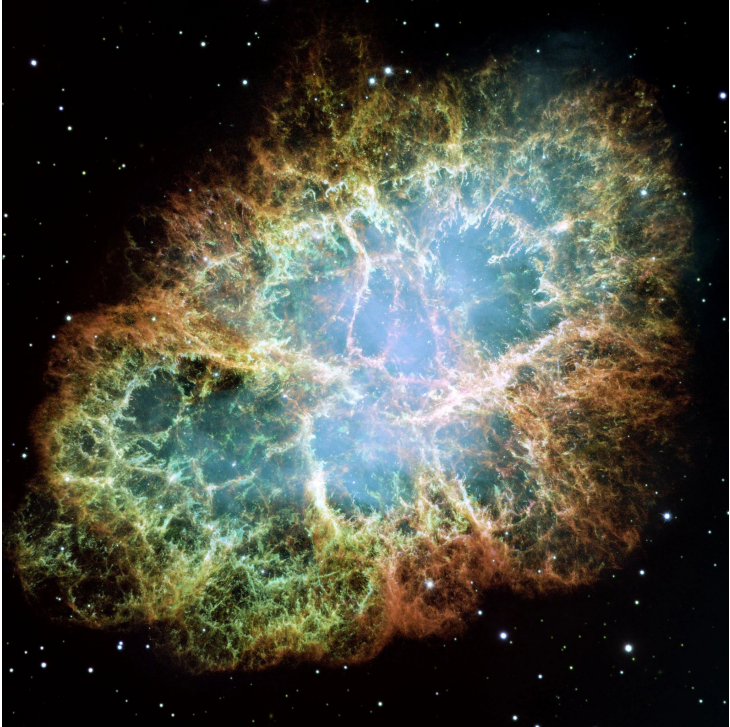
Dual readout:

- **free electrons** produced by **ionization**:
 - charge detected by three layers of wires, reconstruct topology
- **light** coming from **scintillation**:
 - detected by X-ARAPUCAs (SiPM based), needed to reconstruct absolute X coordinate and energy.



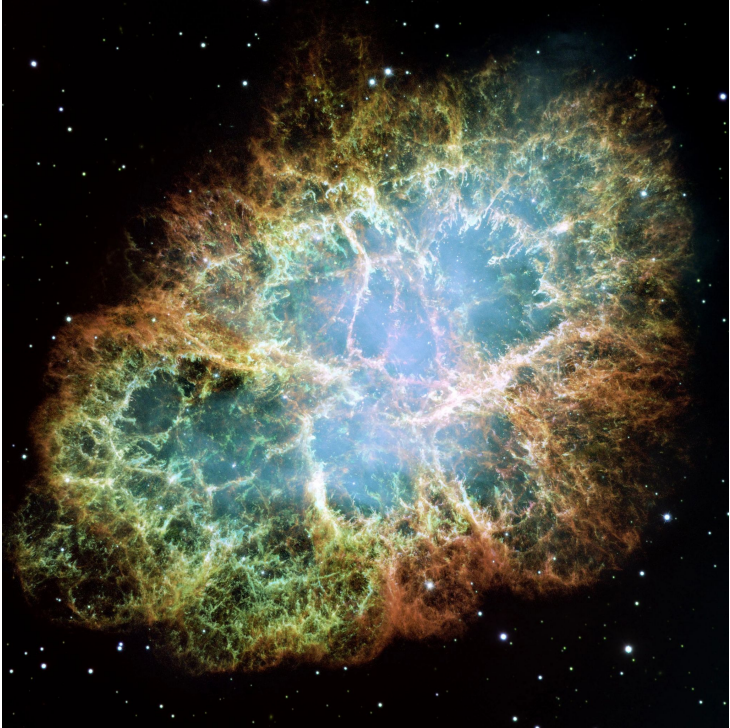
DUNE dual readout single phase TPC

Core-Collapse SuperNova explosion

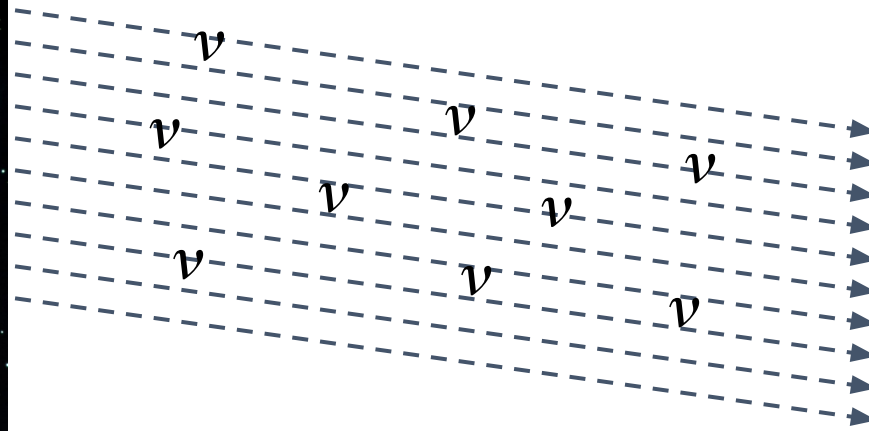


Crab Nebula (NASA)

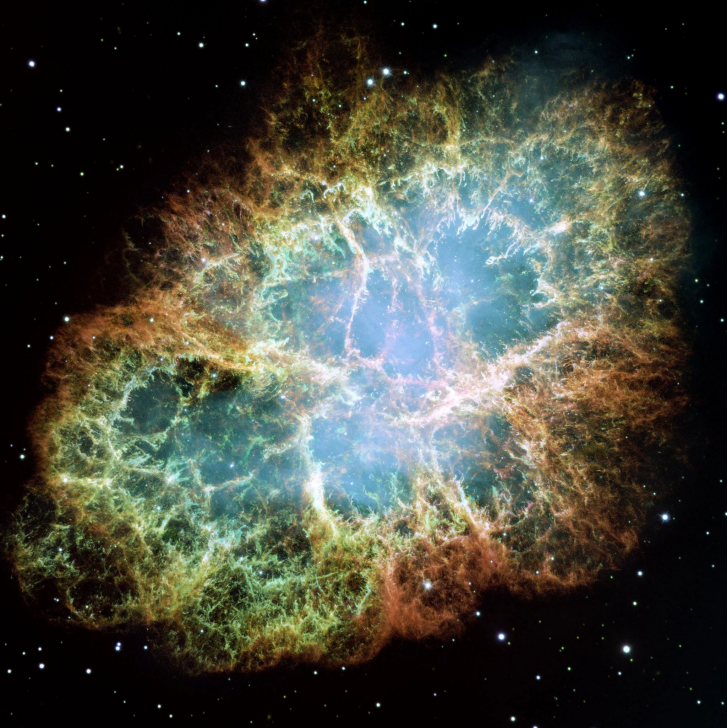
Core-Collapse SuperNova explosion



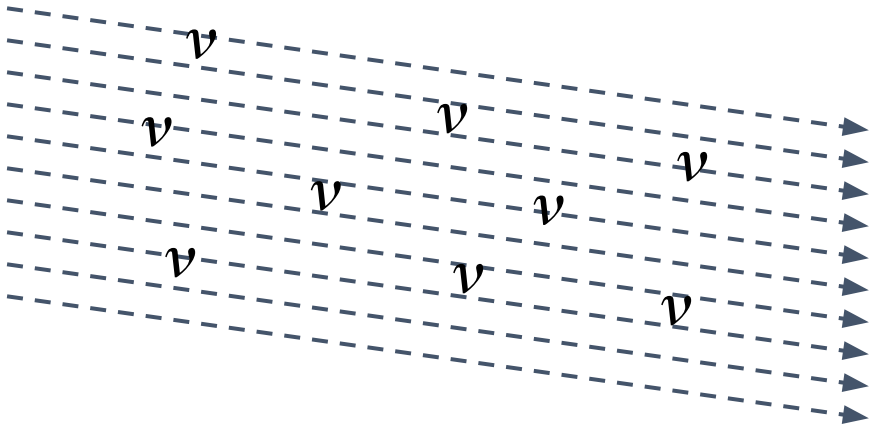
Crab Nebula (NASA)



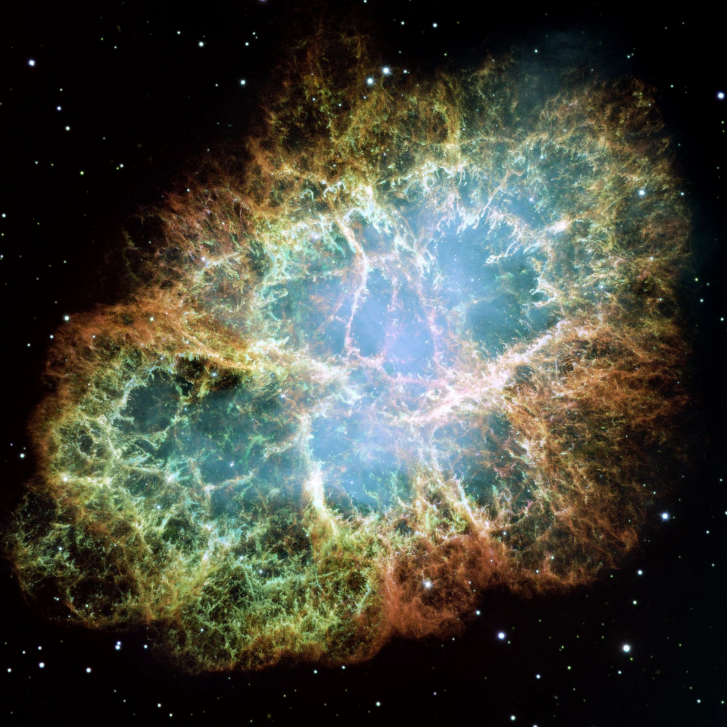
Core-Collapse SuperNova explosion



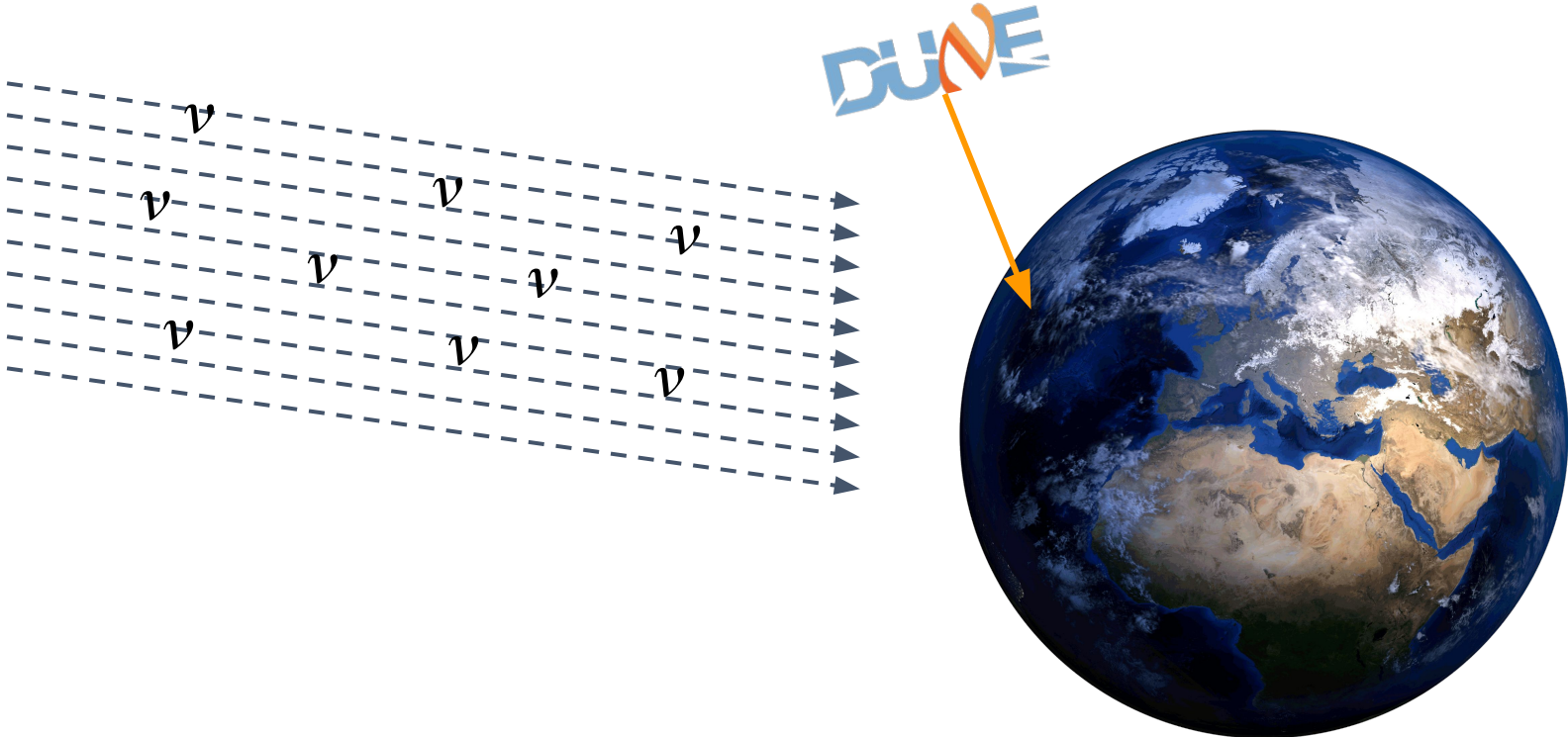
Crab Nebula (NASA)



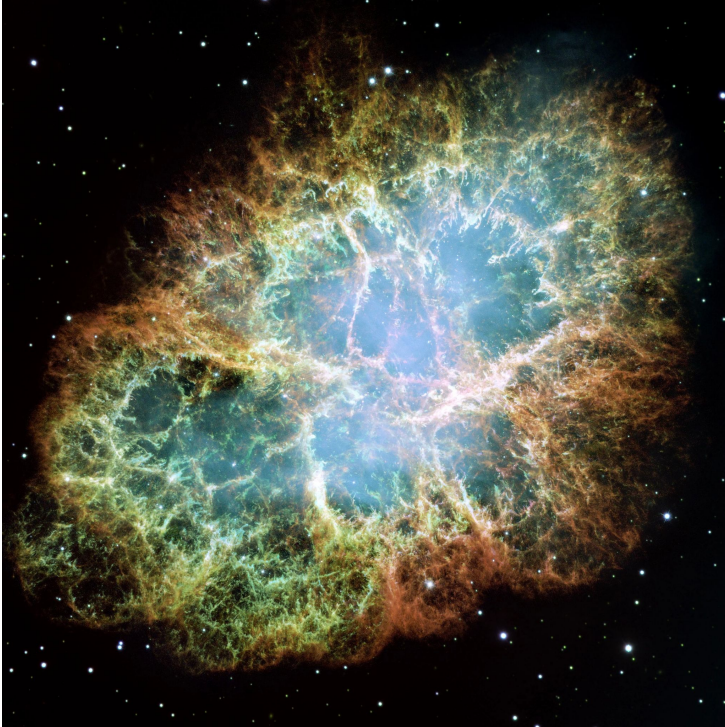
Core-Collapse SuperNova explosion



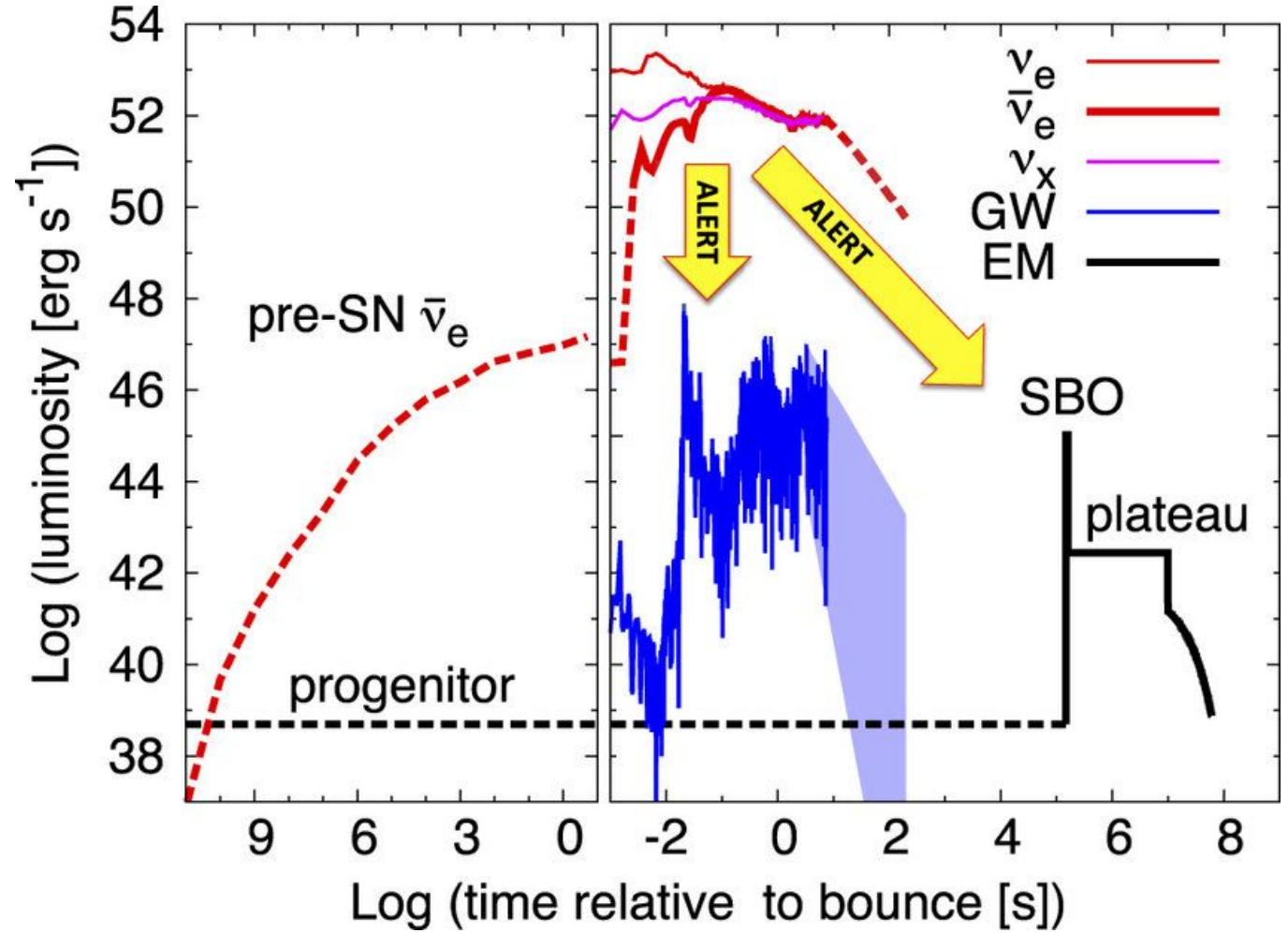
Crab Nebula (NASA)



Core-Collapse SuperNova explosion



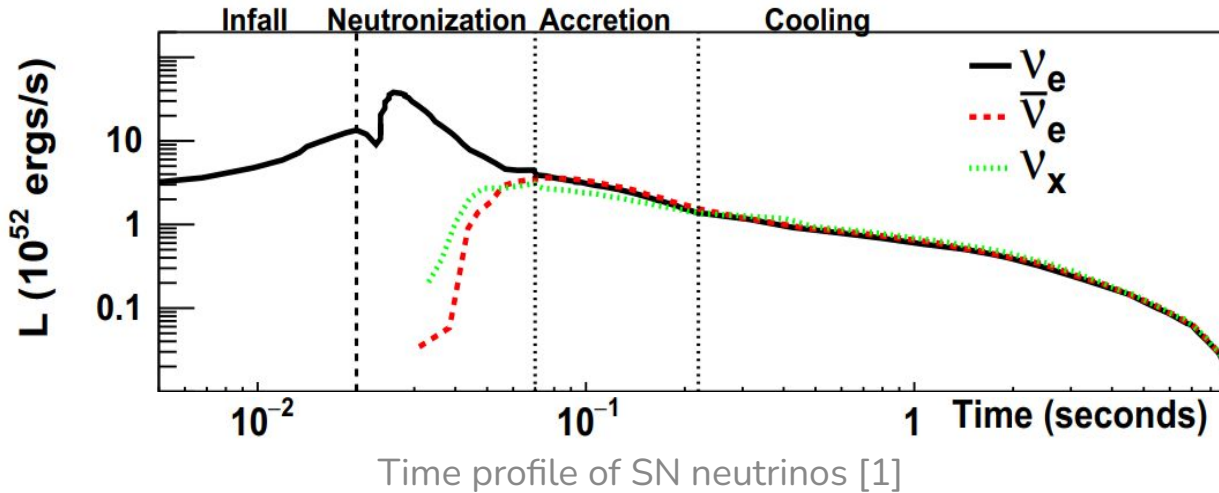
Crab Nebula (NASA)



Time profile of SN signals. For this model [9], light arrives hours after neutrinos.

SN neutrinos in DUNE

Neutrinos carry 99% of energy in a CCSN explosion.
Many different proposed models, DUNE uses GKVM.

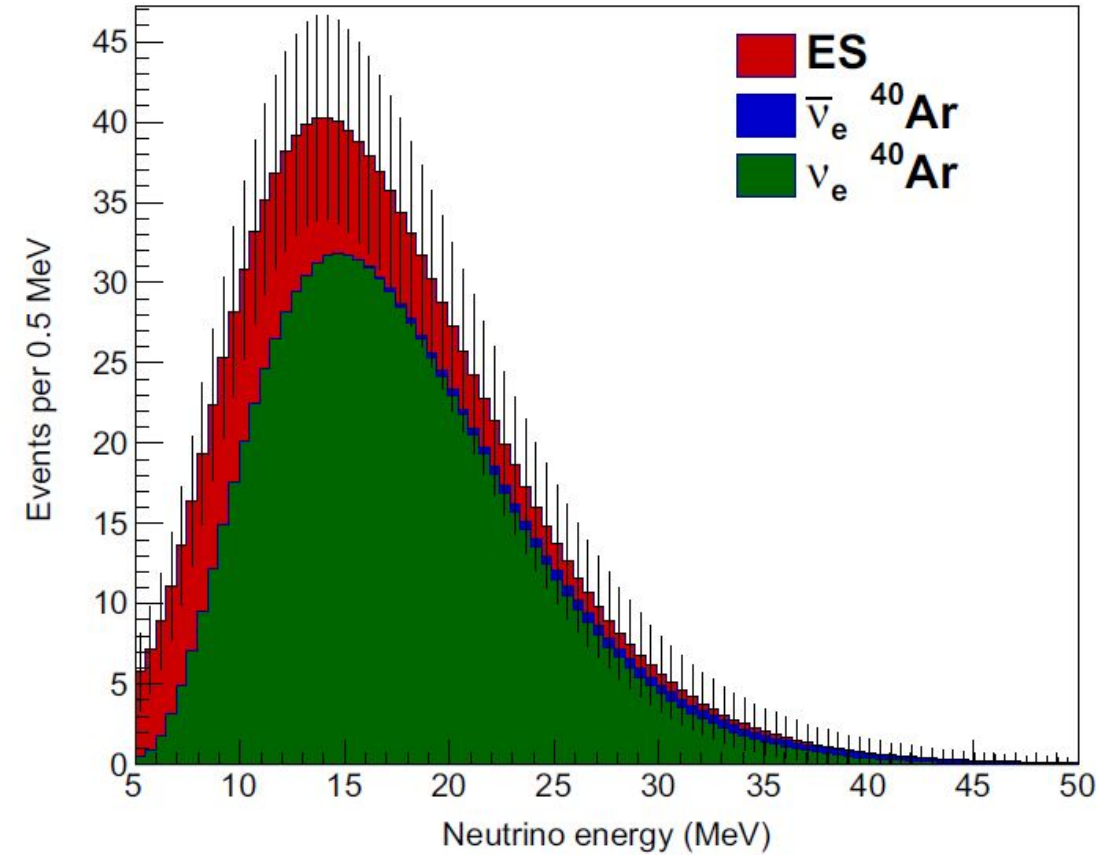


Neutrino burst lasts few seconds, early light can arrive just few minutes later.

→ **Short time for pointing!**

Once a SN trigger (not in this talk) is issued, **100s** of unfiltered data are saved and analyzed.

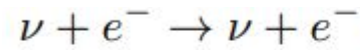
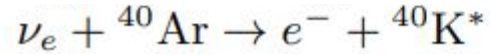
Computed SN direction is sent to telescopes through SuperNova Early Warning System (**SNEWS**) [9].



Energy below 100 MeV, typically around 10 MeV.
Considering cross-sections and efficiencies, spectrum in DUNE peaks at **15 MeV**.

Interaction channels

In this energy range, main interactions are:

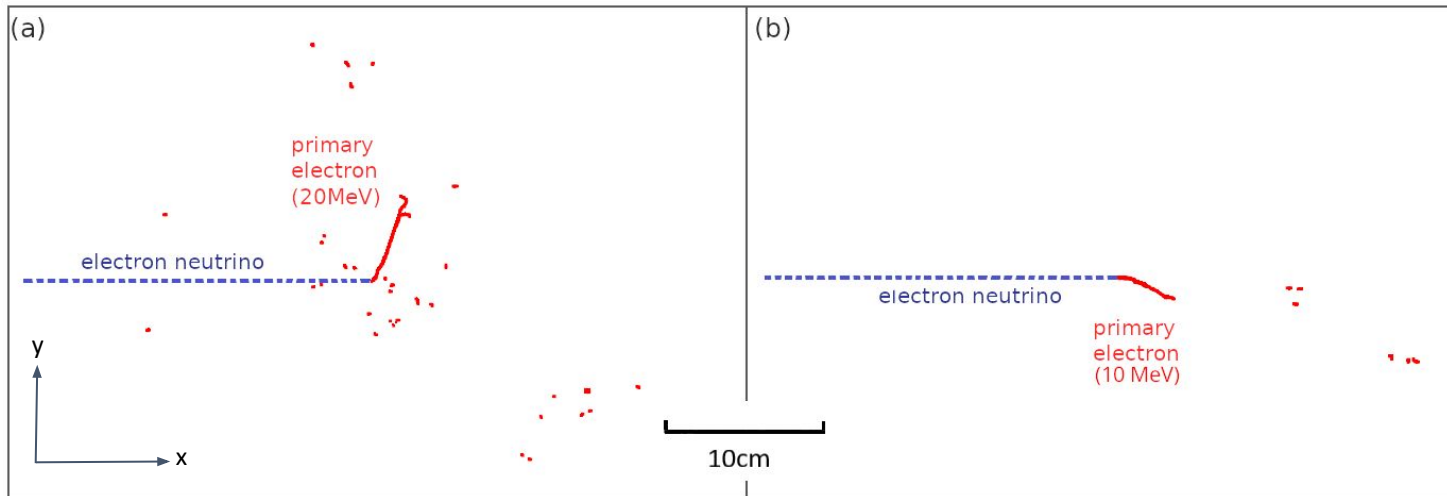


Charged Current (CC):

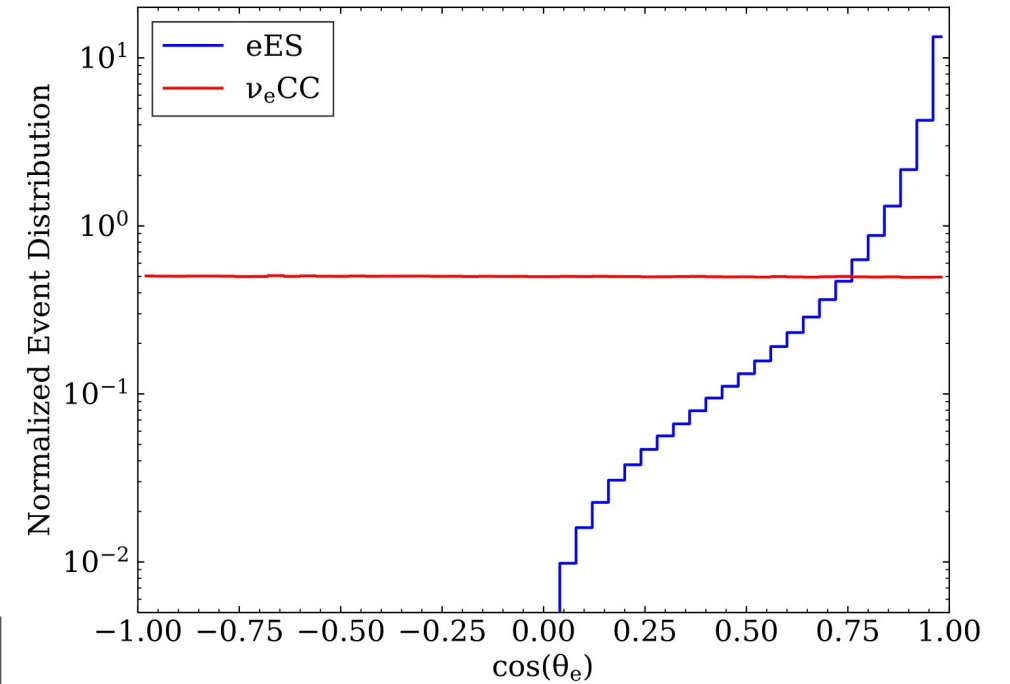
- electron track
- few Compton blips from bremsstrahlung gammas
- several Compton blips from nuclear de-excitation

Elastic Scattering (ES):

- electron track
- few Compton blips from bremsstrahlung gammas



Topology of CC (a) vs ES (b) events, from Geant4 event display [2]



Angular distribution of ES vs CC events [2]

ν_e CC is dominant in rate of events, but angular distribution of outgoing electron is flat.

➡ useless for pointing

eES has less events (one order of magnitude), but with **clear directionality**.

➡ select and use them for pointing!

Publication: sample and conditions

In the next slides, presenting the results of the work carried out mainly by J. Shen, K. Scholberg and J. Hakenmüller [2]: “Supernova pointing capabilities of DUNE, *DUNE collaboration*, Phys. Rev. D **111**, 092006” (find it [here](#)).

- Using **GKVM** model [8]:
 - Intermediate rates in the panorama of models
 - Does not specify a progenitor mass, not a key parameter since statistics will vary up to an order of magnitude over possible progenitor models
 - Spectrum shape variations subdominant, **number of events** is biggest factor (from SNOwGLoBES)
- Considering ν_e flux shape, dominant one
- Reference distance of **10 kpc** (distance to galactic centre, common reference)
 - can vary distance by simply changing N_{events}
- Generated with isotropic direction, later grouped to simulate N_{events} in a burst
 - **CC** interactions simulated using MARLEY [7]
- Reference geometry is FD-HD

Channel	Expected Event Count
$\nu + e^- \rightarrow \nu + e^-$ (all flavors)	325.8 eES
$\nu_e + e^- \rightarrow \nu_e + e^-$	155.5
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	67.3
$\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$	55.2
$\bar{\nu}_{\mu,\tau} + e^- \rightarrow \bar{\nu}_{\mu,\tau} + e^-$	47.8
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	3300.0 ν_e CC

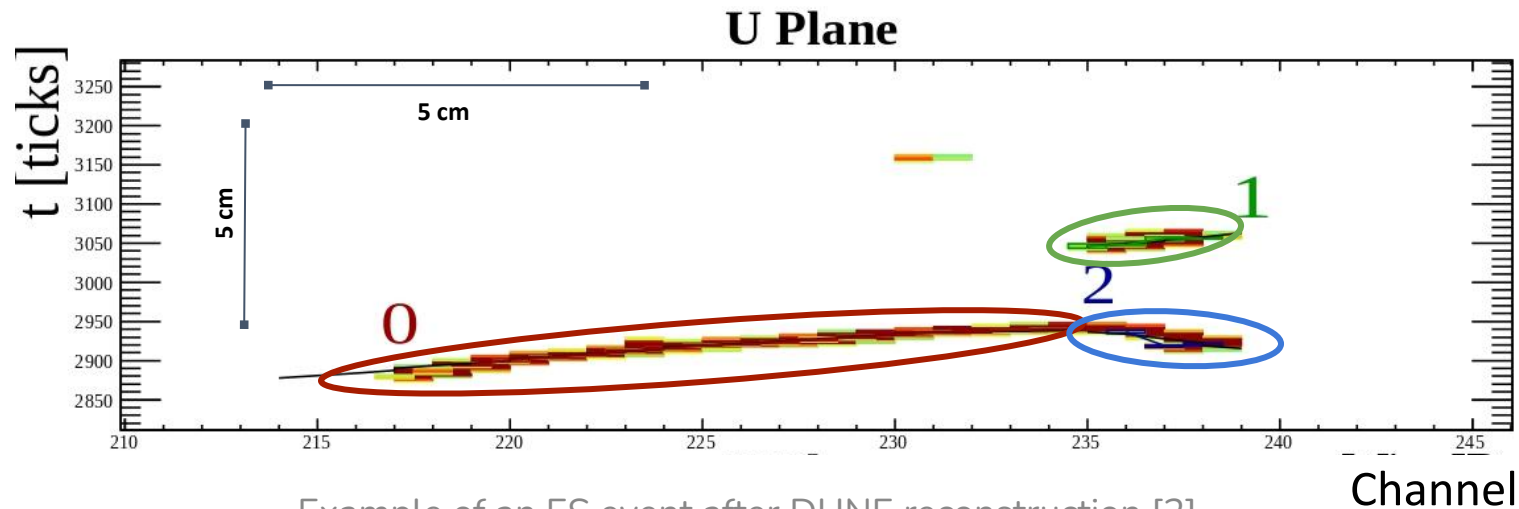
Expected neutrinos for SNB at 10kpc, for 40kt of LAr, using SNOwGLoBES [2]

Publication: reconstruction method

Mainly standard DUNE reconstruction algorithms, with some changes.

For each **neutrino event** in a burst:

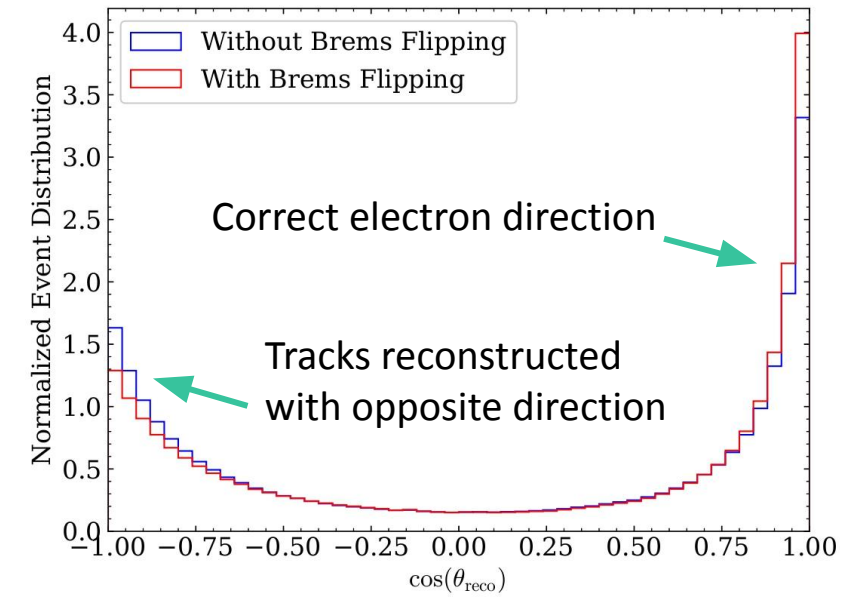
1. First reconstruction returns **energy depositions** associated to the SN event
2. Using Projection Matching Algorithm [5] to identify the **main electron track**:
 - a. Select 10 most energetic tracks, find two closest ones to identify main activity region
 - b. Pick track having **highest charge deposition** as main electron track



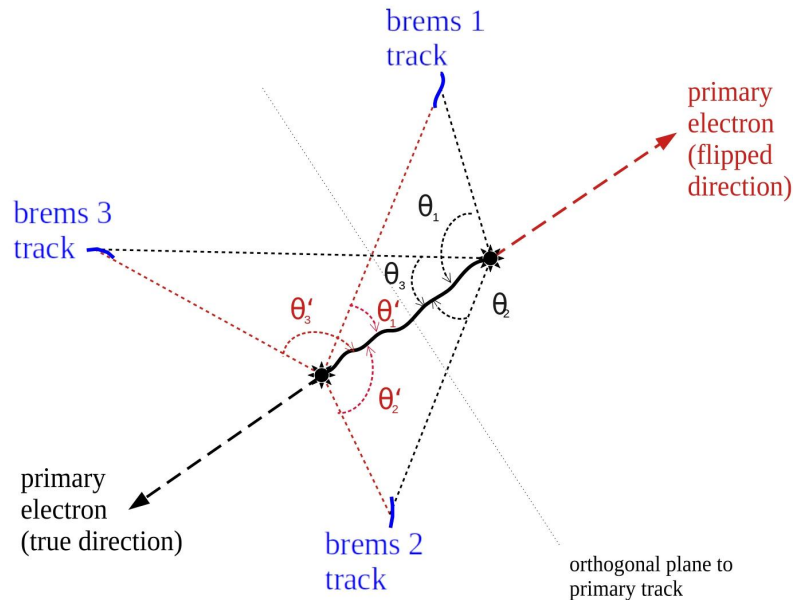
Example of an ES event after DUNE reconstruction [2].
Track "0" is the main electron track, "1" and "2" are children.

Publication: reconstruction method

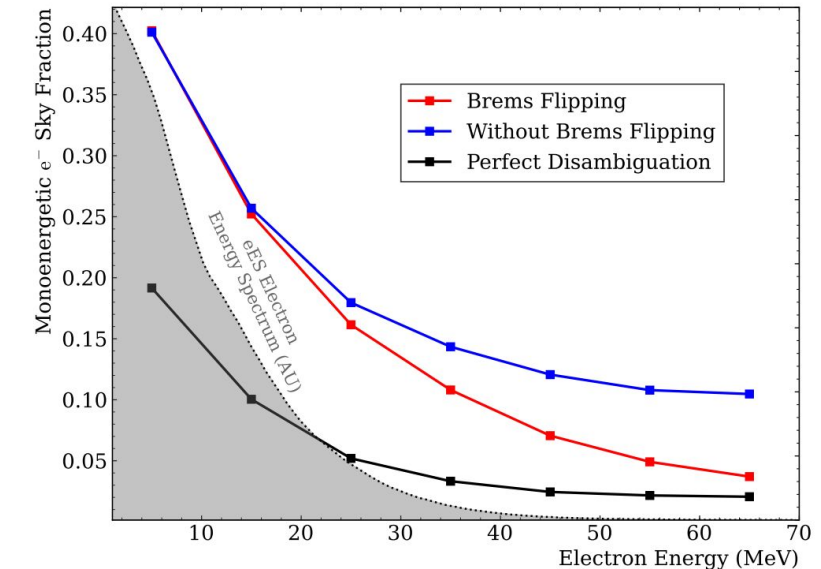
3. Compute energy associated to electron track (all visible charge within $5X_0 = 70\text{cm}$)
 - a. Takes into account electron attenuation (not considered anymore to be an issue, see [6])
 - b. Directionality depends on energy, later excluding $<5\text{ MeV}$
4. **Brems flipping** algorithm (originally developed for this work)
 - a. Disambiguate the direction of short tracks, rather impactful
 - b. More effective at higher energies



Impact of brems flipping algorithm [2]



Sky Fraction: area of the sky covered by 68% quantile of angular distribution.

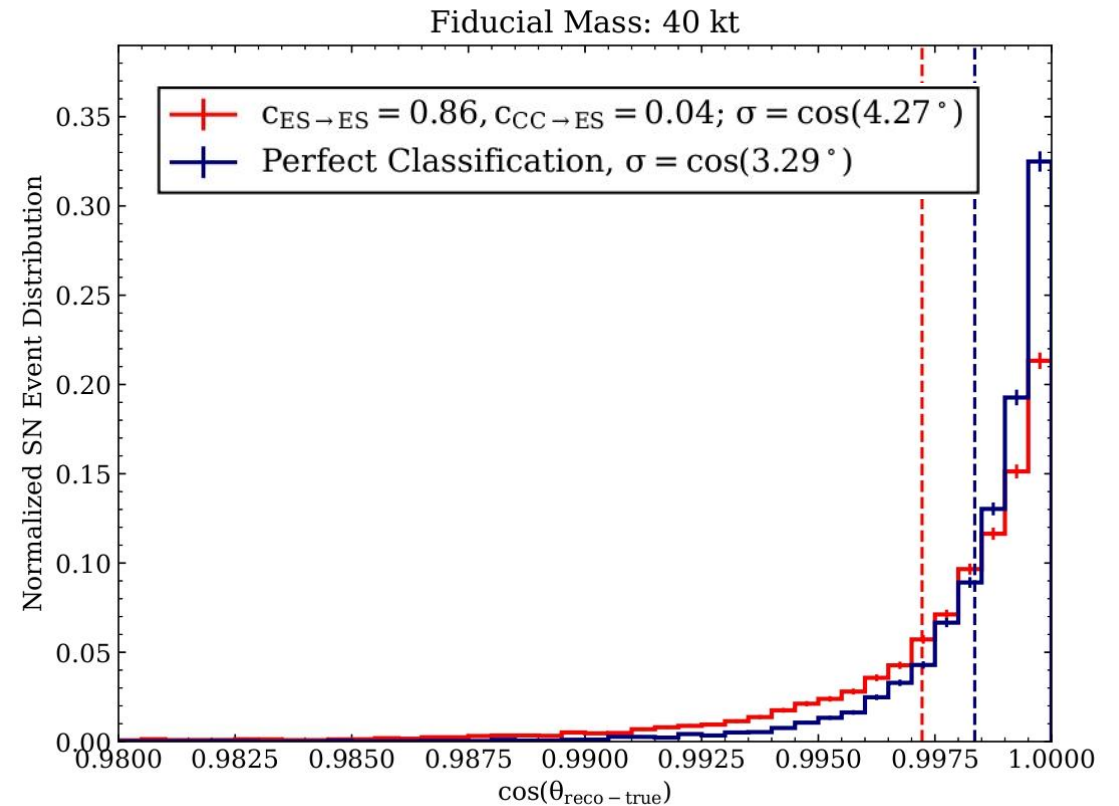
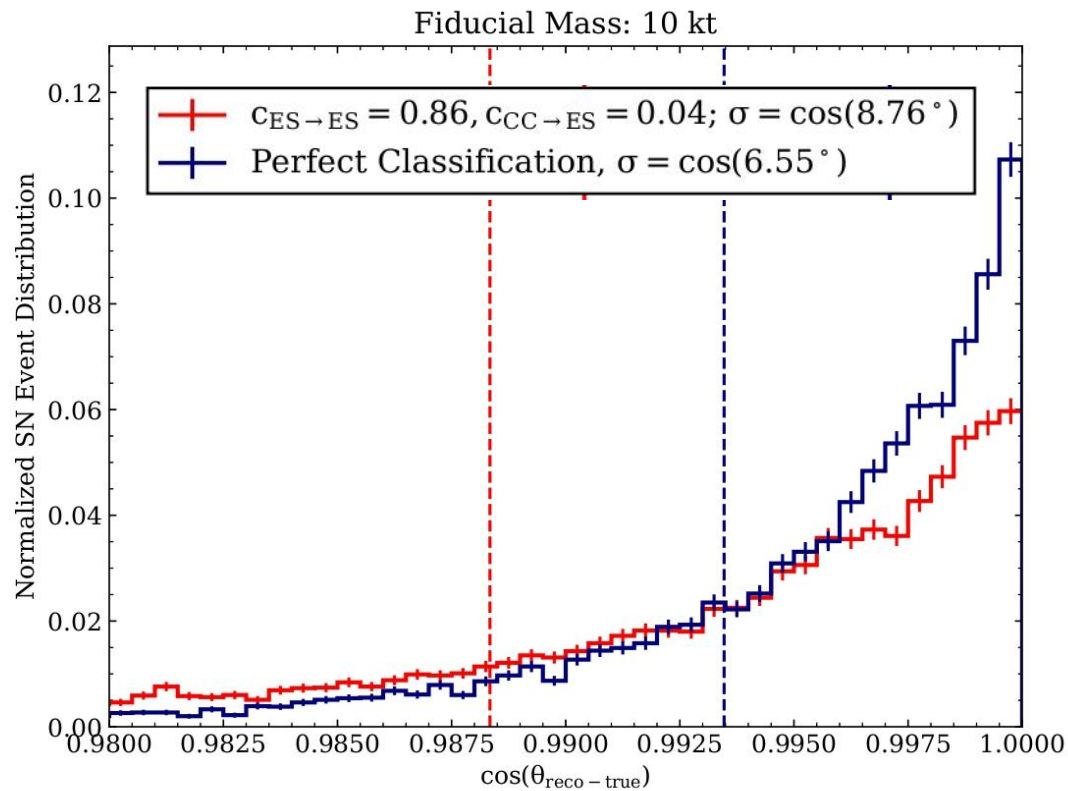


Publication: results

Computed pointing resolution for **perfect channel tagging** and, more realistically, assuming **86% efficiency ES->ES** and **4% contamination CC->ES**.

Resolution defined as **68% quantile** of distribution of reconstructed tracks.

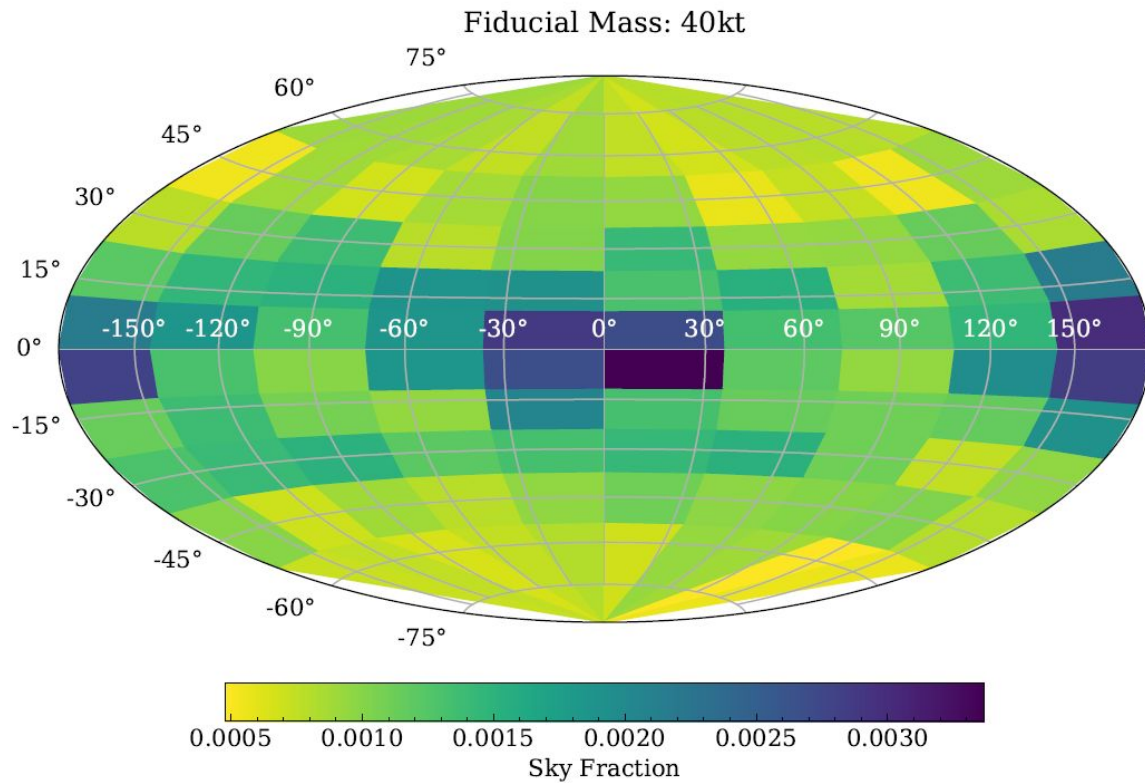
Results for one FD-HD module (**10kt**), and for 4 HD modules (**40 kt**):



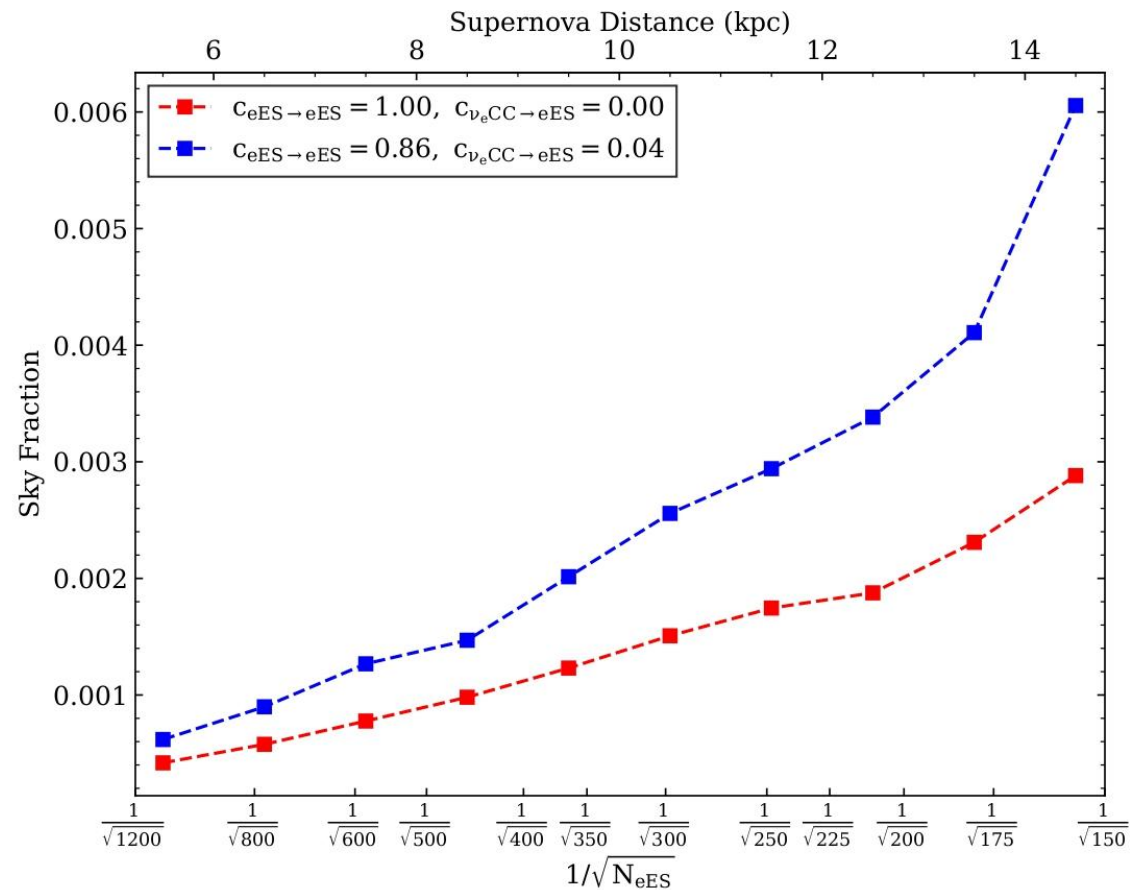
Resolution for 10kt and 40kt [2]

Publication: results

Resolution varies with **direction** of the SN in respect to detector (not isotropic!), and with **distance** from explosion.



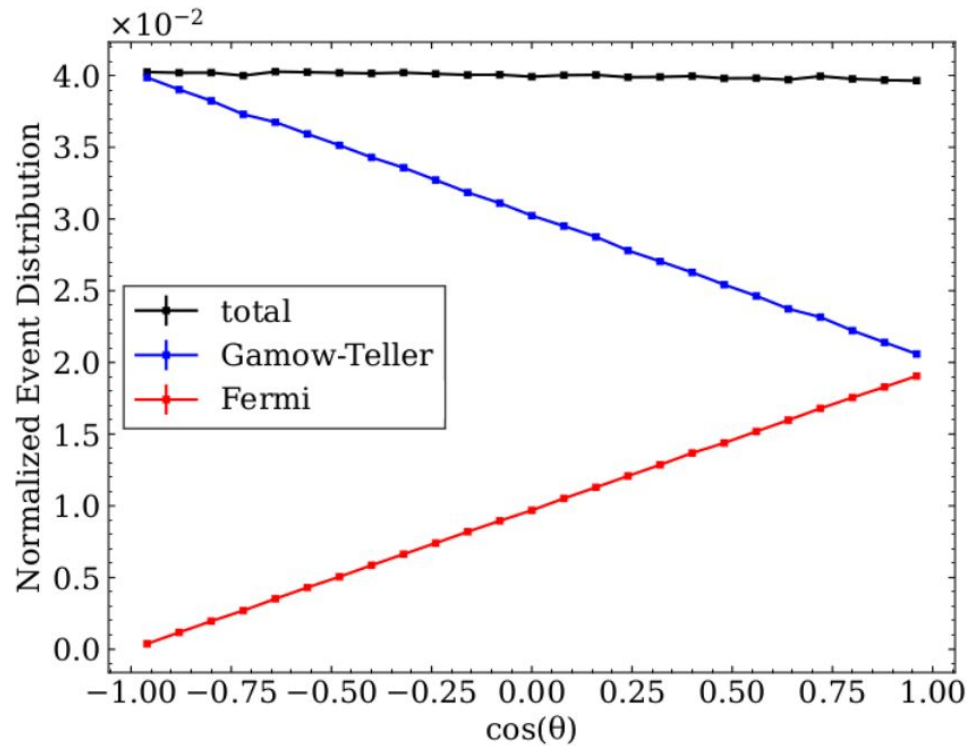
Resolution as function of direction of SN, in respect to detector.
Worse when perpendicular to readout planes [2]



Resolution as function of number of events, or distance [2]

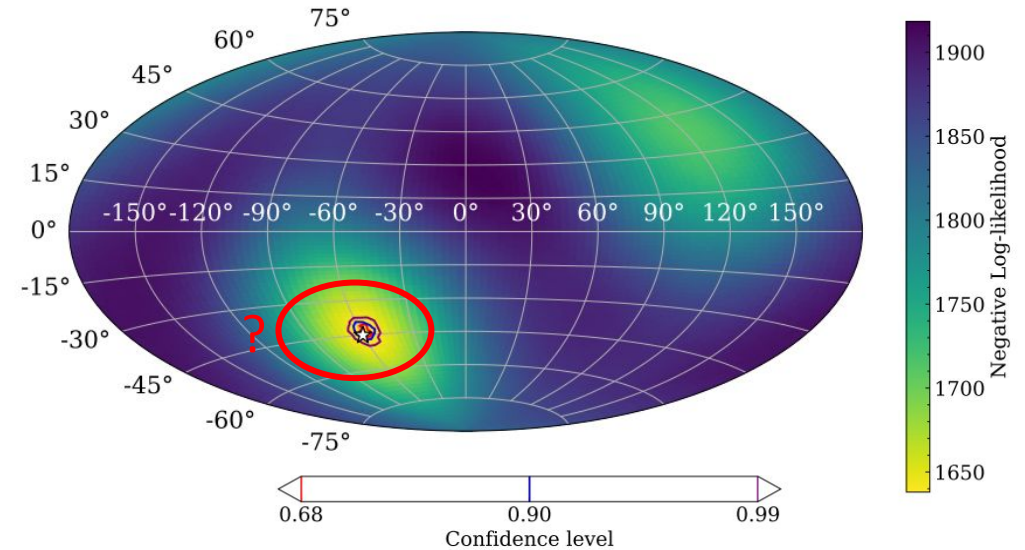
SN pointing: other ongoing approaches

First attempts at exploiting CC by classifying between **Gamov-Teller** and **Fermi** interactions (DUKE).



Angular distribution of electrons from CC F/GT interactions in DUNE, GKVM spectrum [2]

Transfer time of data from SURF to Fermilab takes ~hours, very large data size. **Iterative approach** is desirable: first fast with lower precision, then slower but more accurate.



Visualization of offline + possible lower-precision online pointing result [2]

Different options for **fast online pointing** being explored:

- Making current reconstruction standalone and faster (FNAL)
- FPGA-boostered data reduction and ROI finding (Columbia U.)
- Trigger-level reconstruction (CERN)

Online pointing using Trigger Primitives

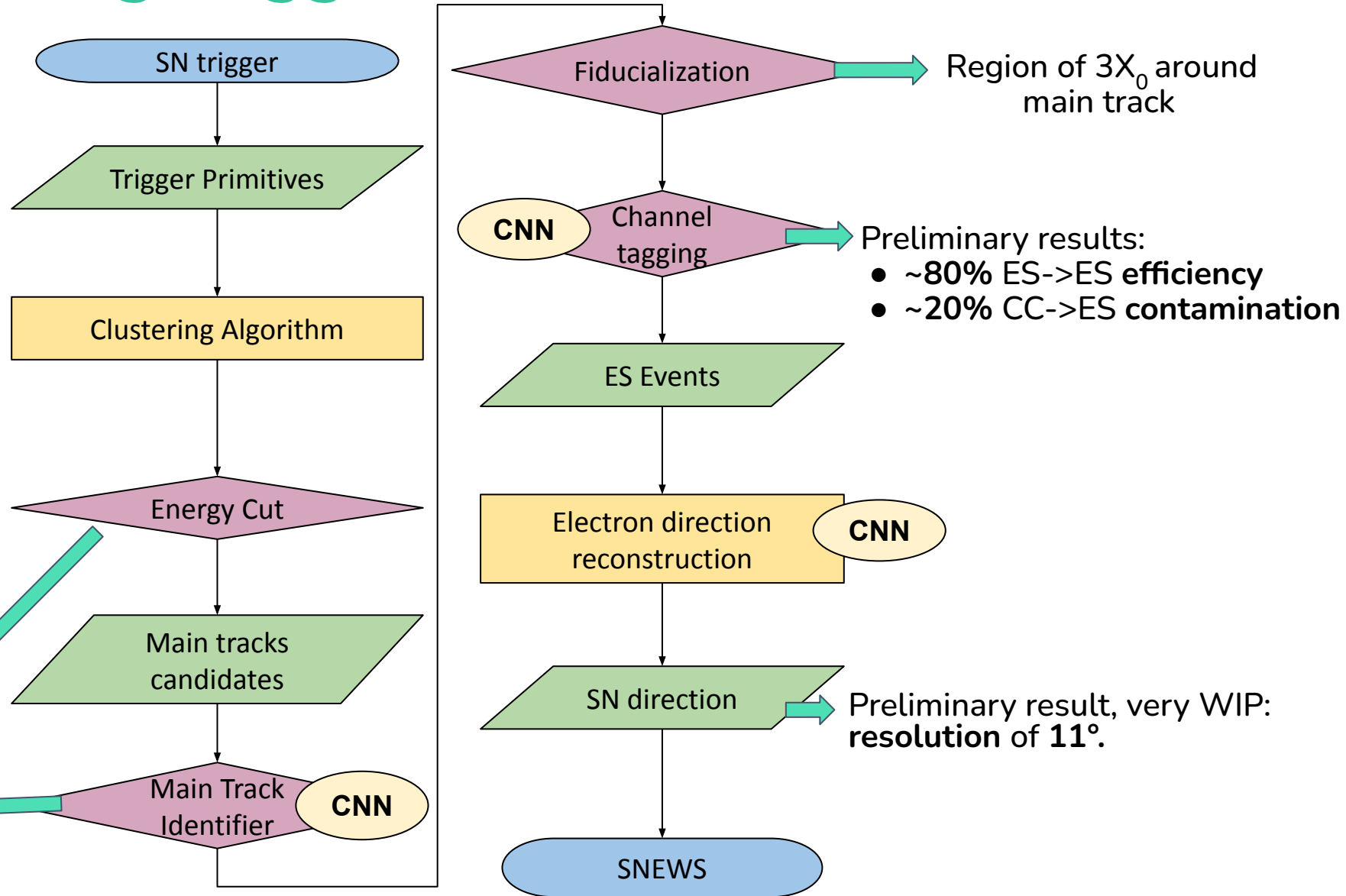
Option for **fast online pointing**:
DAQ-level information, Trigger Primitives (TPs):

- Very small data size (<1% of standard raw data), almost real-time accessible
- Minimal loss of information

Fragmented problem and developed **standalone fast analysis pipeline** (mix classical/ML algorithms).

Precise **execution time** being assessed, dominated by clustering phase.

Background rejection



Summary

- Neutrinos from **Core-Collapse SuperNova** bursts are of high interest for the whole physics community
- **DUNE** can see SN neutrinos and contribute to **SNEWS**
 - Goal: achieve **pointing** as soon as possible, as good as possible
- First published comprehensive study on DUNE SN pointing
 - Resolution **4.3°** for 40kt of LAr for a SN at 10 kpc, with assumptions on channel tagging
 - Studies still progressing (new background model, new detector simulation, implementing channel tagging)
- Efforts for **online pointing** with trigger information or fast data processing



THANK YOU!

References

- [1] *DUNE collaboration*, Supernova neutrino burst detection with the Deep Underground Neutrino Experiment. Eur. Phys. J. C 81, 423 (2021). <https://doi.org/10.1140/epjc/s10052-021-09166-w>
- [2] *DUNE collaboration*, Supernova pointing capabilities of DUNE, Phys. Rev. D 111, 092006. <https://doi.org/10.1103/PhysRevD.111.092006>
- [3] *DUNE collaboration*, TDR Volume I. Introduction to DUNE, 2020 JINST 15 T08008. <https://dx.doi.org/10.1088/1748-0221/15/08/T08008>
- [4] S. Gardiner, Nuclear de-excitations in low-energy charged-current ν_e scattering on ^{40}Ar , Phys. Rev. C 103, 044604. <https://doi.org/10.1103/PhysRevC.103.044604>
- [5] M. Antonello et al., Precise 3d track reconstruction algorithm for the icarus t600 liquid argon time projection chamber detector, Advances in High Energy Physics 2013 (2013).
- [6] *DUNE collaboration*, Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC, 2022 JINST 17 P01005
- [7] S. Gardiner, Simulating low-energy neutrino interactions with MARLEY, Computer Physics Communications 269, 108123 (2021).
- [8] J. Gava et al., Dynamical Collective Calculation of Supernova Neutrino Signals, Phys. Rev. Lett. 103, 071101
- [9] Al Kharusi et al., SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy. New Journal of Physics. 23. 10.1088/1367-2630/abde33

Backup

SN neutrinos, different time scale and bins

From <https://arxiv.org/pdf/2008.06647>: “Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment”

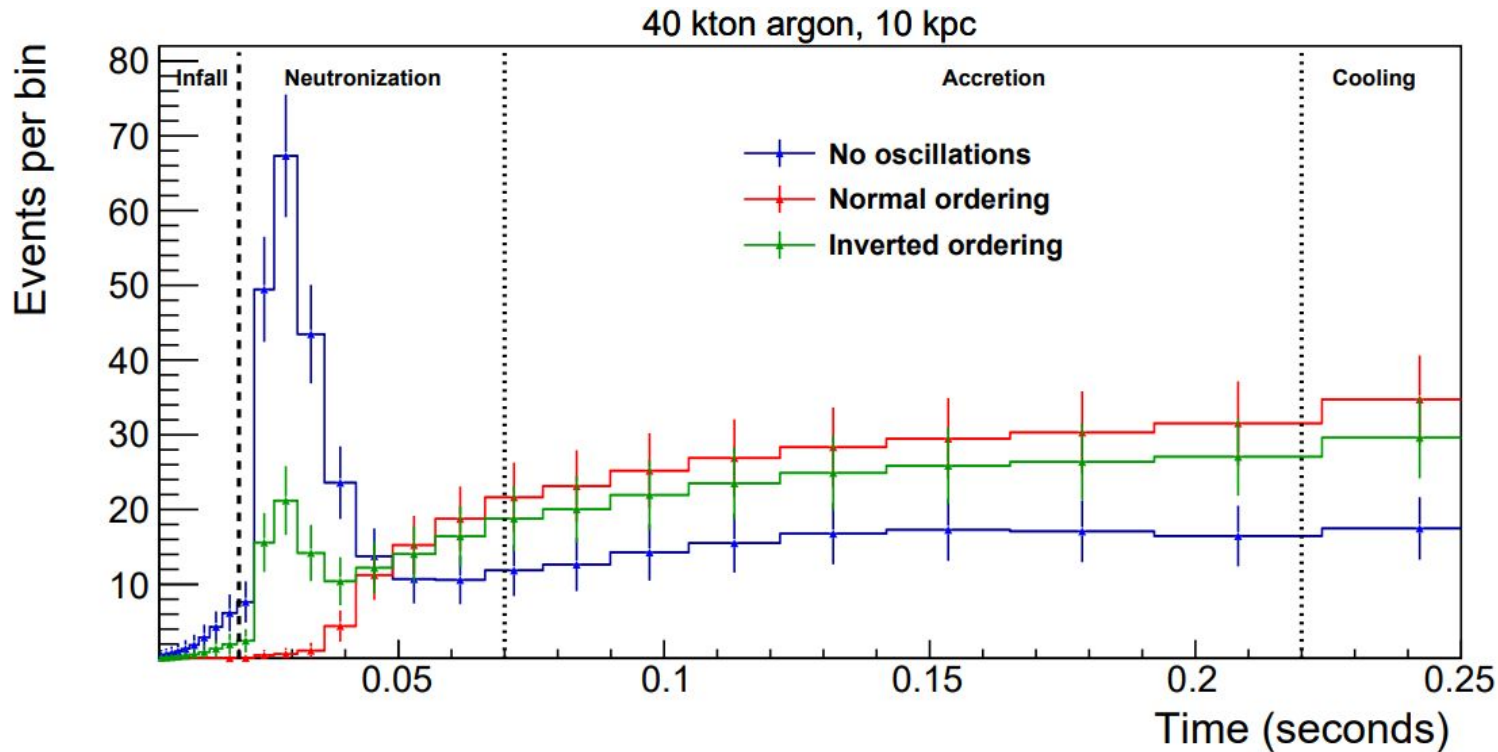
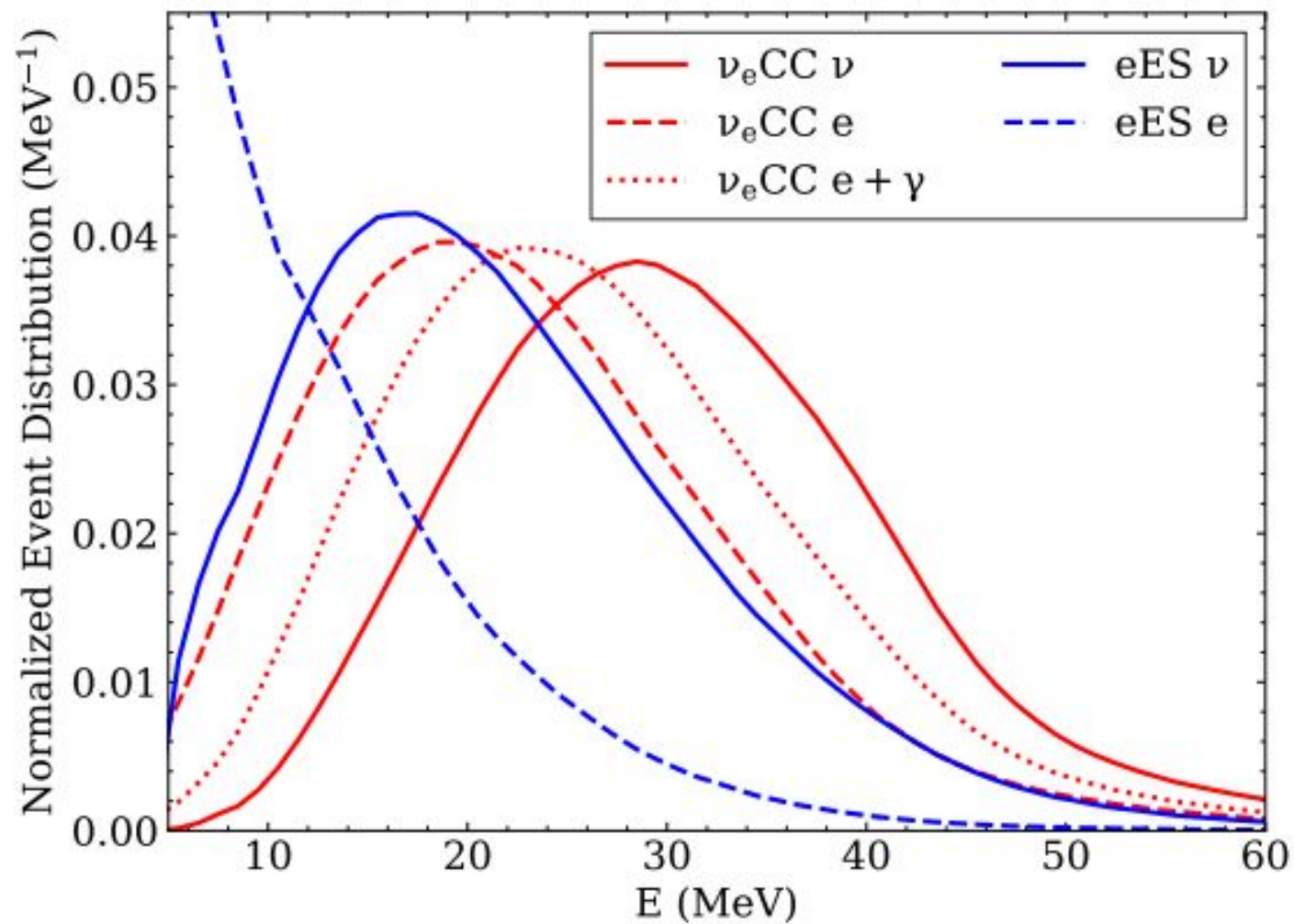
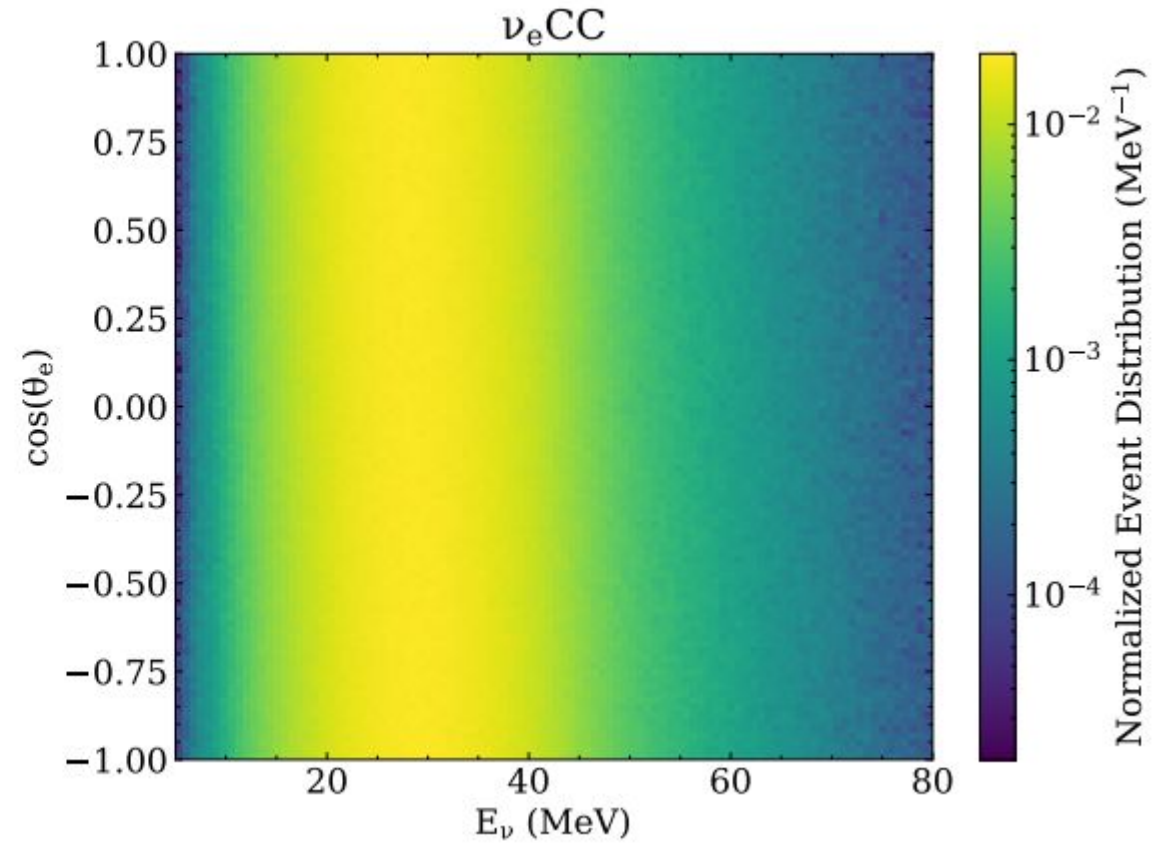
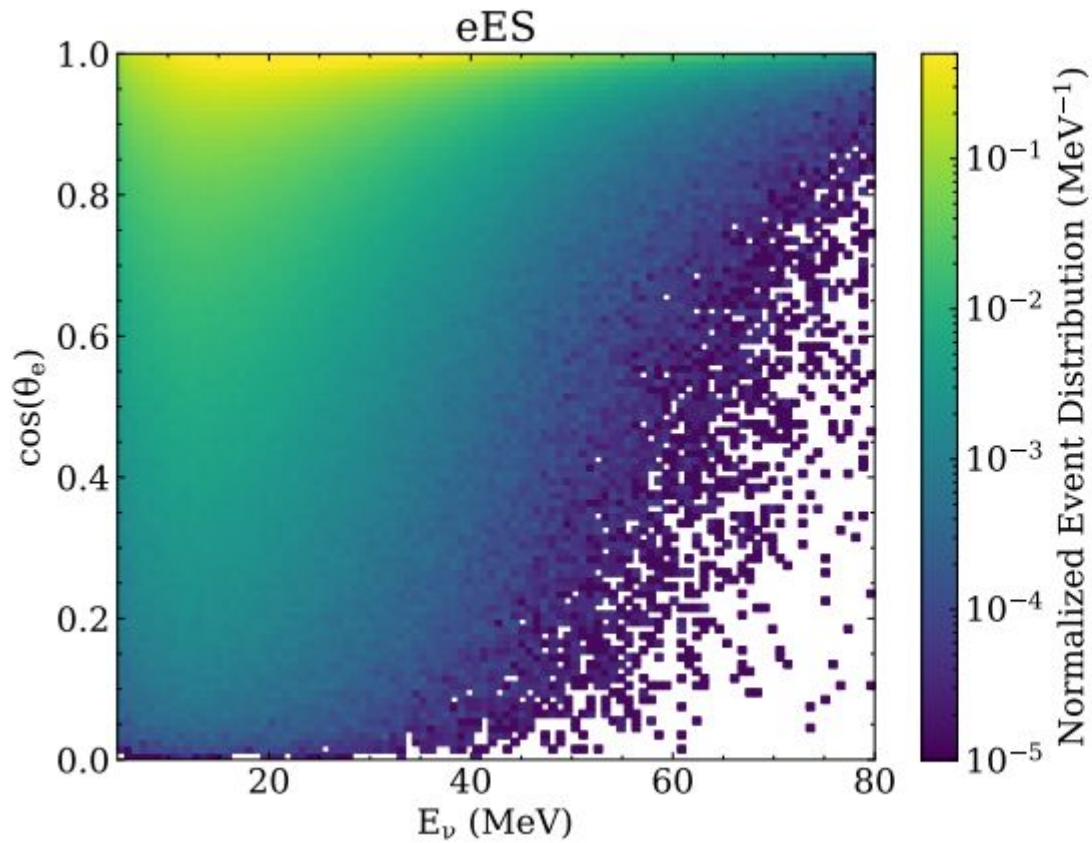


Fig. 11 Expected event rates as a function of time for the electron-capture model in [8] for 40 kton of argon during early stages of the event – the neutronization burst and early accretion phases, for which self-induced effects are unlikely to be important. Shown are: the event rate for the unrealistic case of no flavor transitions (blue) and the event rates including the effect of matter transitions for the normal (red) and inverted (green) orderings. Error bars are statistical, in unequal time bins.

ES and CC spectra in DUNE [2]



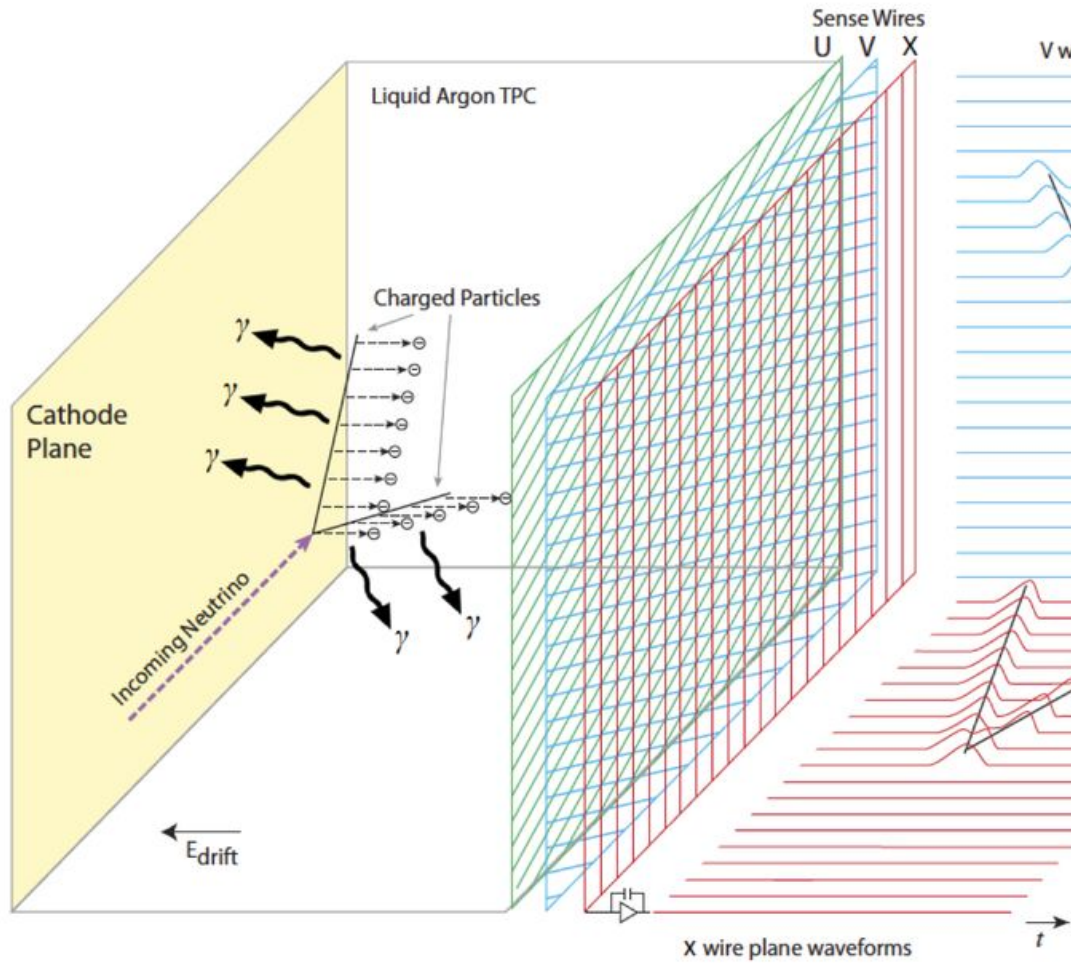
ES and CC directionality in DUNE [2]



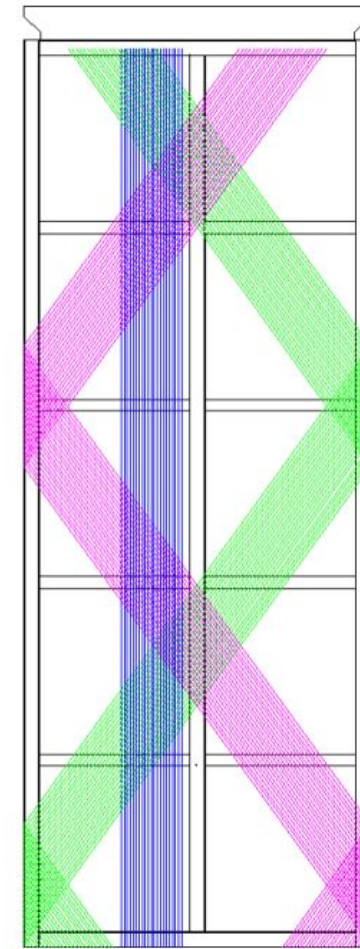
DUNE Far Detector

FD-HD and FD-FD are both **Liquid Argon TPCs** with dual readout (to exploit both ionization and scintillation):

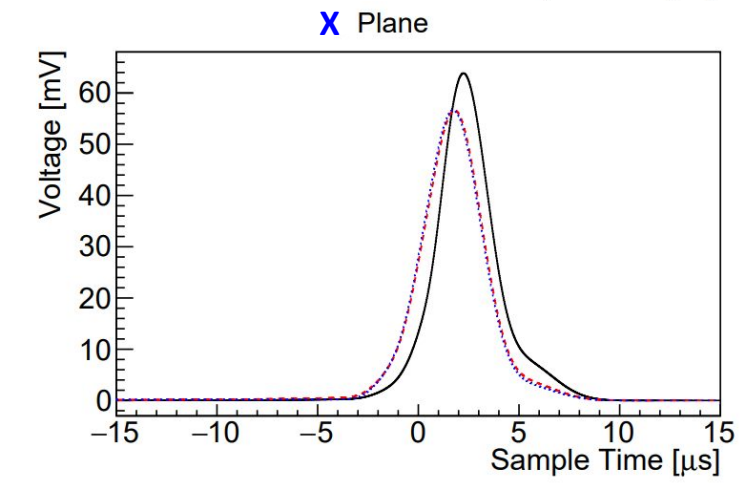
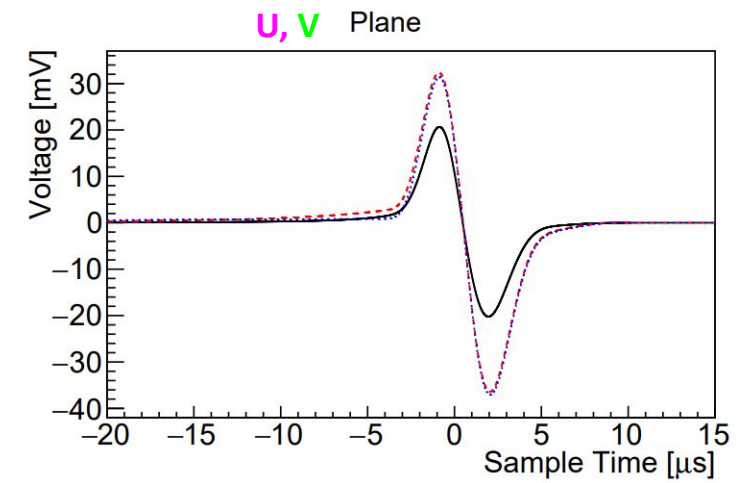
- **light:** X-ARAPUCAs (SiPM based), needed to reconstruct absolute X coordinate and energy.
- **charge:** three layers of wires: 2 induction (U, V, bipolar waveform) and 1 collection (X, unipolar wf).



DUNE dual readout single phase TPC



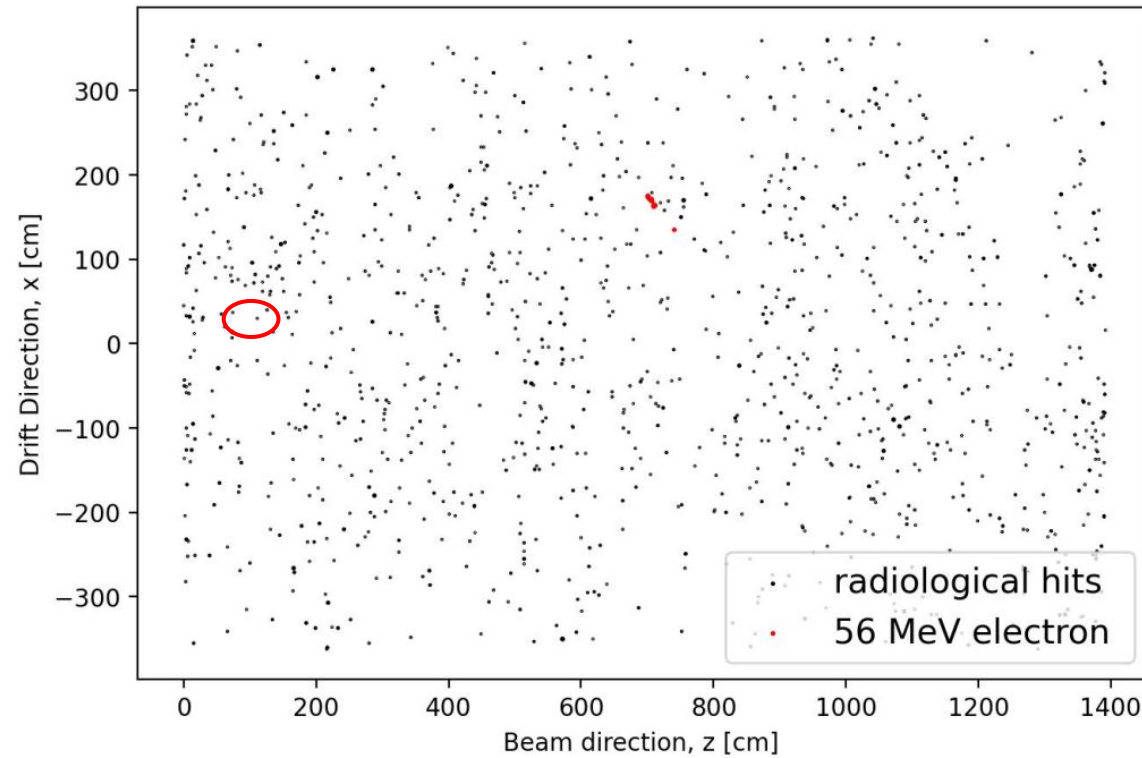
DUNE detector (Anode)



DUNE signals on a wire

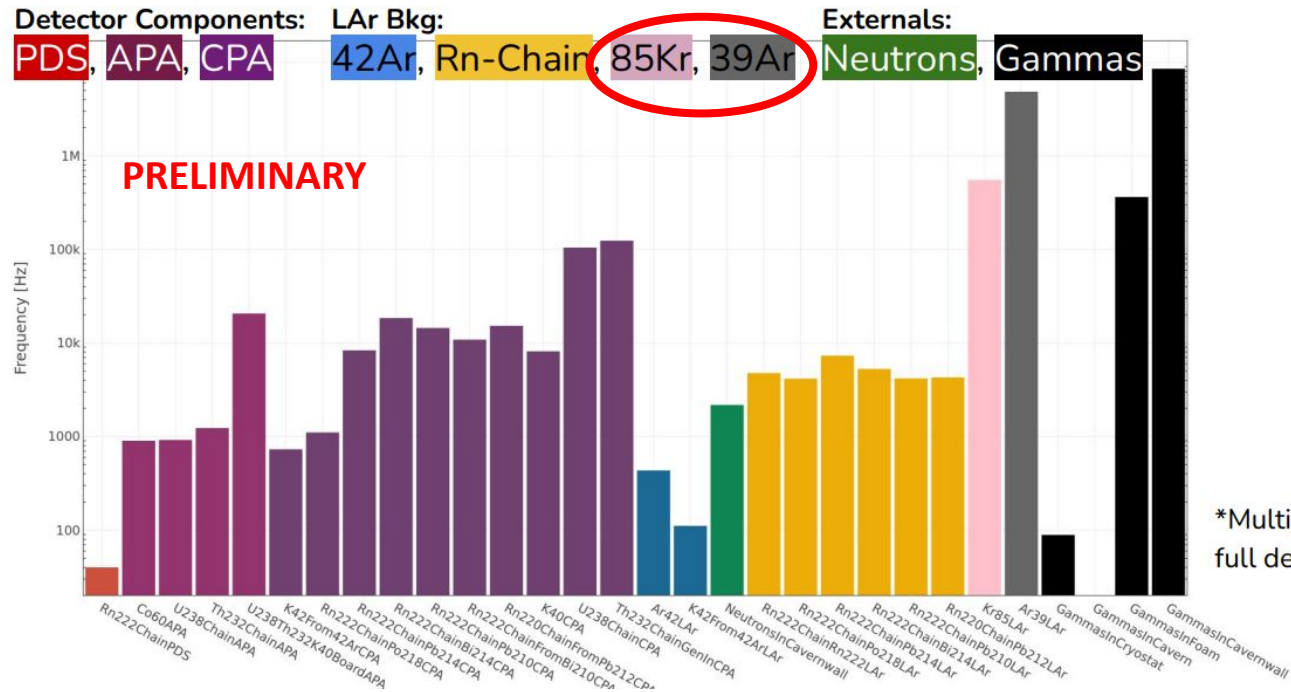
Backgrounds in DUNE

Radiologicals are relevant at low energy.
Highest hit rates from ^{39}Ar , ^{85}Kr .

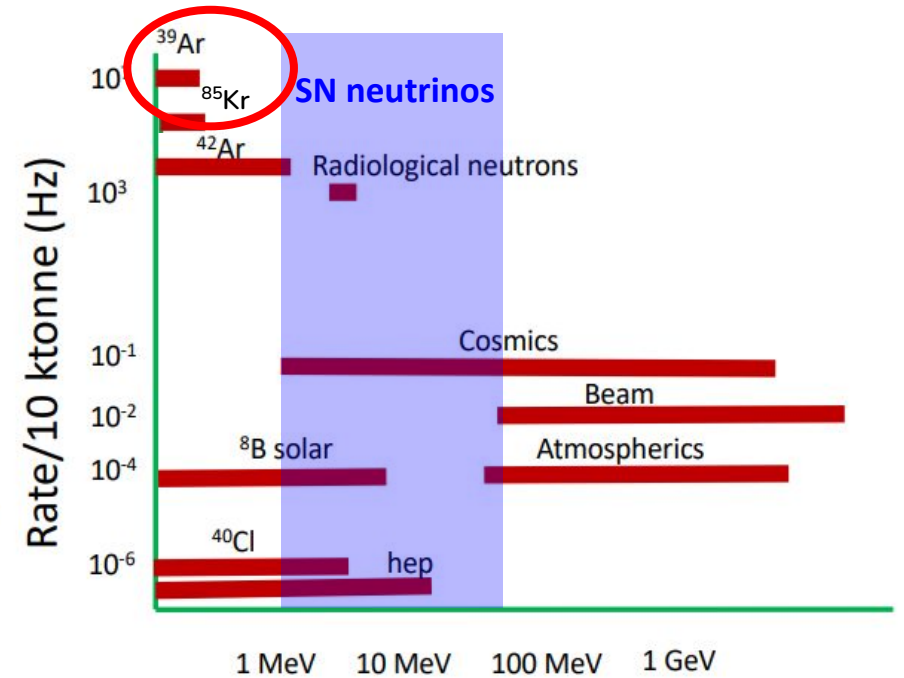


Publication: backgrounds

- Impact of radiological backgrounds considered negligible:
 - very low energy deposition, distant from one another
 - fiducialization to identify SN activity regions, small volumes
 - some are localized near cryostat walls (neutrons, gammas) or detectors
 - precise background characterization in the first period of data taking and periodically



DUNE radiological backgrounds, newest model (from S. Manthey).
Not the model used for the publication, here just as reference.



Most frequent backgrounds are at very low energy. Adapted from [3]

Trigger Primitives: compact, but useful

TPs are generated continuously by the dune readout and used by trigger algorithms to issue trigger decisions.

Simple concept: when going above threshold, start counting samples over threshold and ADC integral.

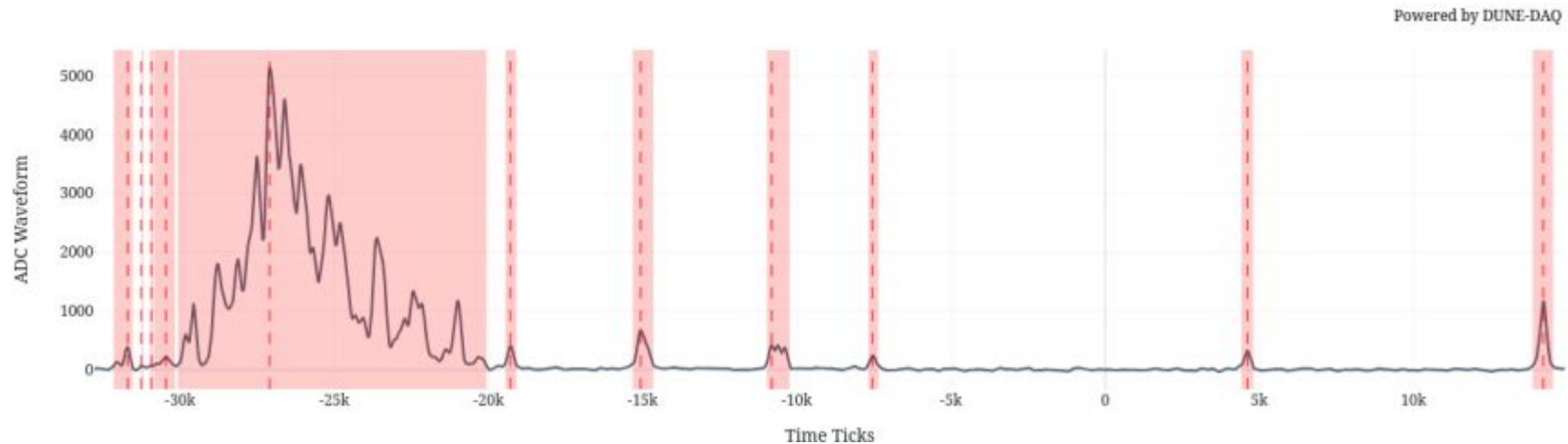
- Fast generation in readout, all hits are saved
- Compact format, just few variables. Each TP is now only 24 bytes.
- Easily accessible from TPstream

time_start	in clock ticks
samples_over_threhsold	in TPC ticks
samples_to_peak	in TPC ticks
adc_peak	ADC value of waveform peak
adc_integral	integral over threshold in ADC counts
channel	
version	currently 2 (freshly updated)

Trigger Primitive v2 format

But:

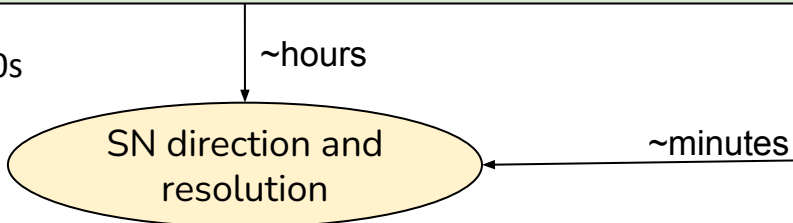
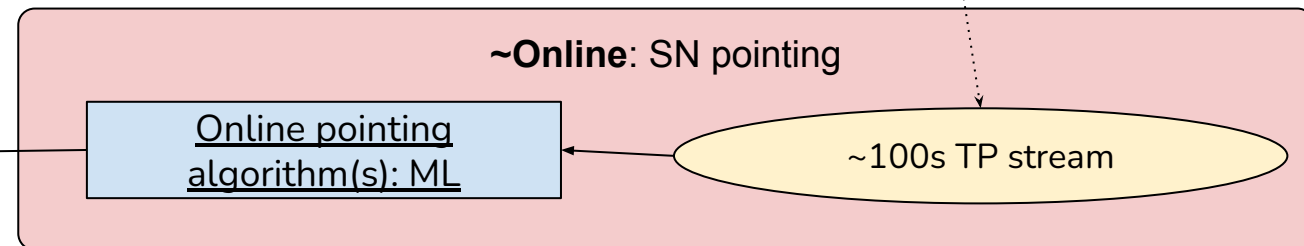
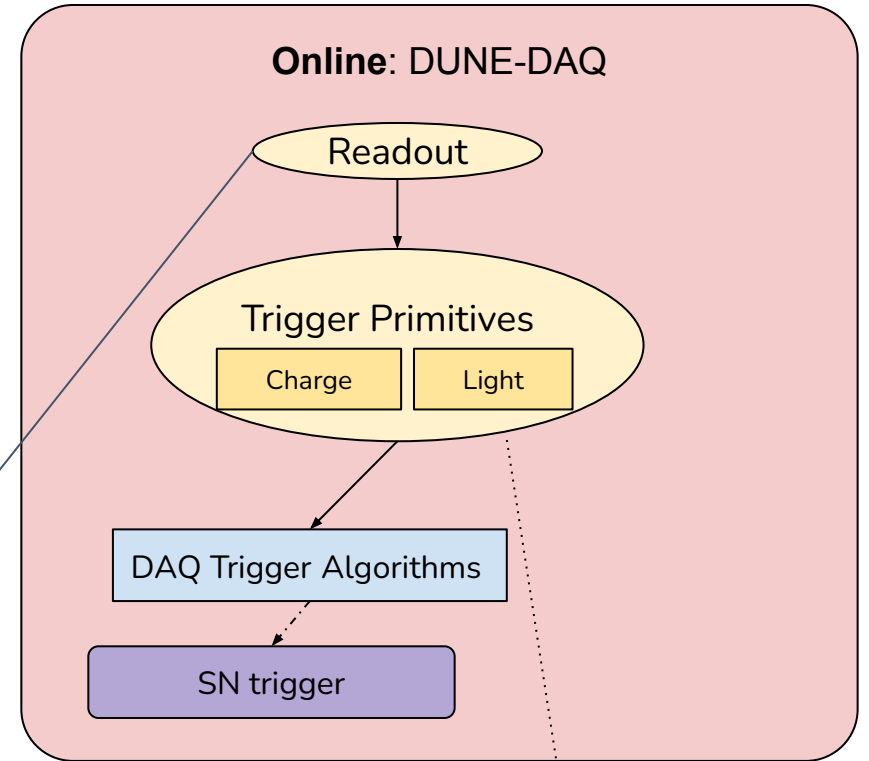
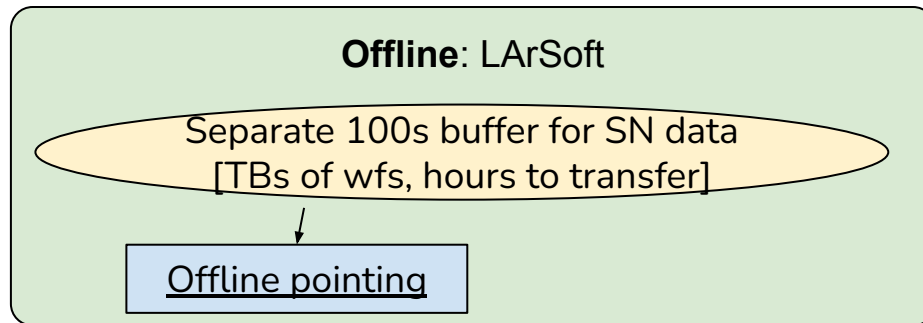
- Missing anything below threshold
- Losing information about shape of waveform, pile-ups
- Losing some charge in the integral (see [backup](#))



DUNE SN burst workflow

Once a **SuperNova Trigger Decision** is made, two things happen:

- 100s of continuous **waveforms** are stored for offline analysis
 - size >100 TB, transferred to Fermilab in hours
- 100s of **TPstream** used for **standalone online analysis and pointing**:
 - Size <100GB, transferred to Fermilab in minutes (continuously)
 - Receiving also the trigger timestamp and accessing the relevant bit of the TPstream



[Actually, we'll have two 100s buffers for safety (pre-SN neutrinos, false triggers.)]

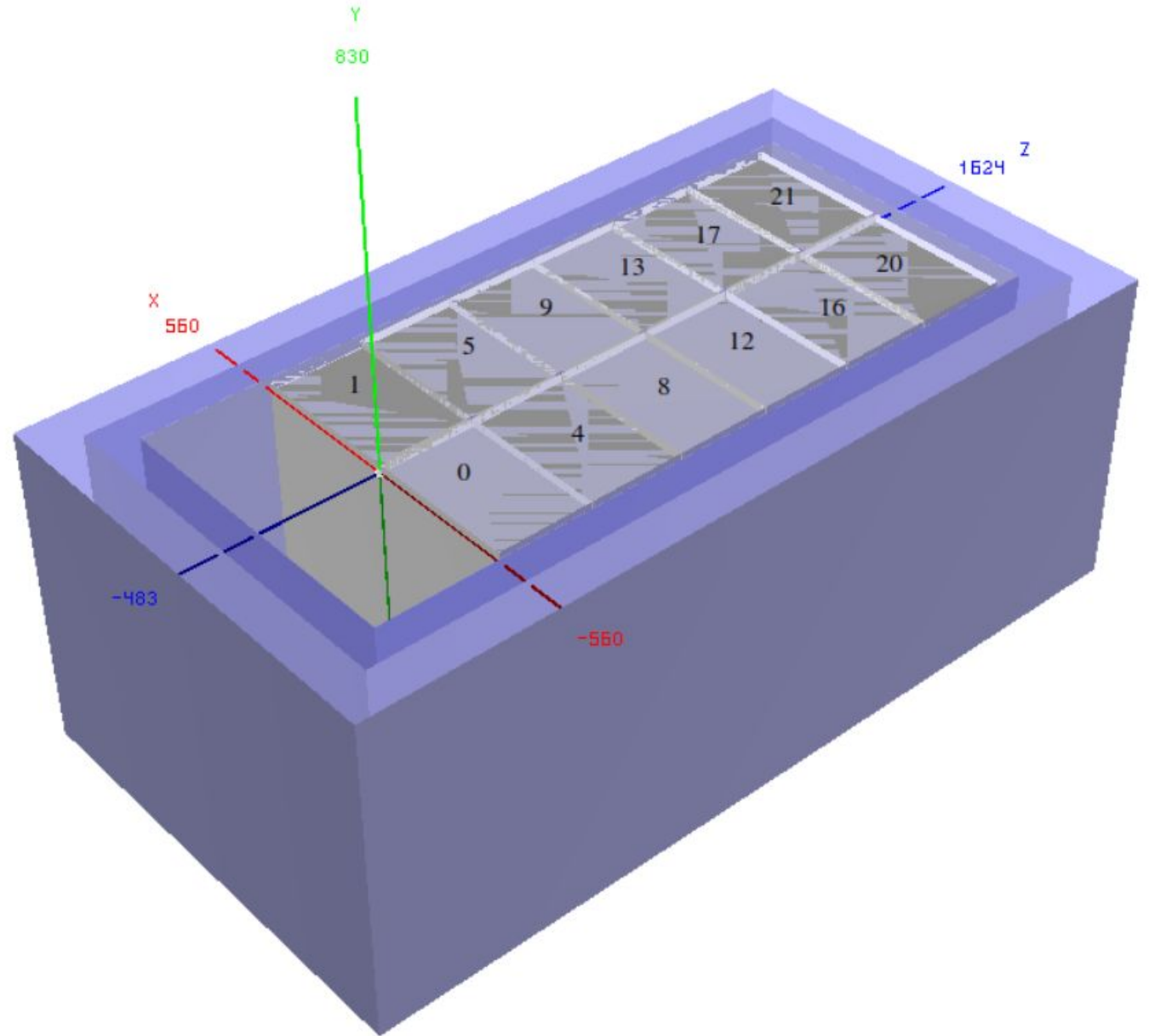
1x2x6 geometry

Simulating a full 10kt DUNE FD module has been only recently enabled by the reconstruction team.

The design of FD-HD features three rows of 25 detectors (called APAs, or Anode Plane Assemblies). In each row, two APAs are stacked on top of each other. The total number of TPC volumes is 200.

For these studies, a smaller geometry is being used, featuring a single row of 6 couples of stacked APAs.

The number of TPCs is therefore 24 (one per each side of each APA).



Sky fraction

To go from sky fraction (SF) to angle:

$$\text{square angle (sr)} = 4\pi * \text{SF}$$

$$\text{square angle (deg)} = 4\pi * \text{SF} * (180 / \pi)^2$$

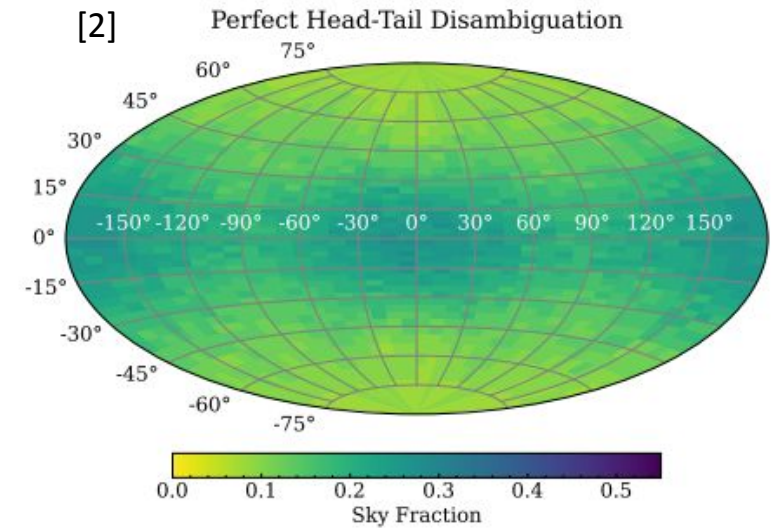
$$\text{angle (deg)} = \text{sqrt}(4\pi * \text{SF} * (180 / \pi)^2)$$

E.g.:

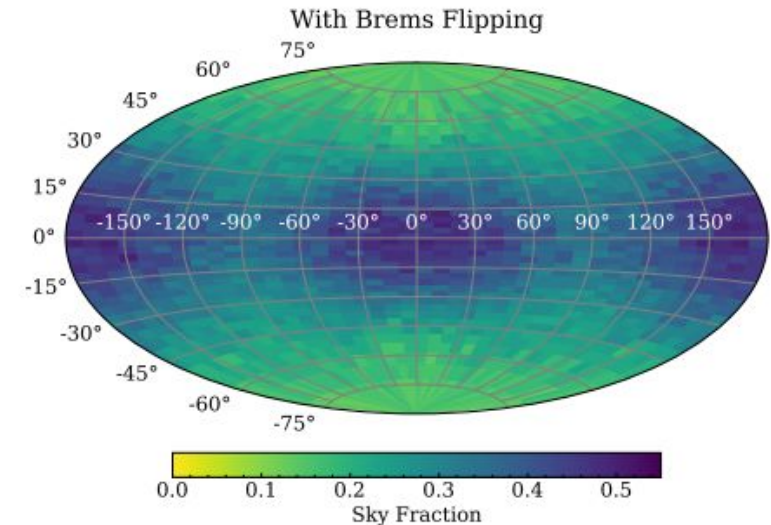
$$0.001 \text{ SF} = 6.41^\circ$$

$$0.005 \text{ SF} = 14.4^\circ$$

$$0.05 \text{ SF} = 45.4^\circ$$

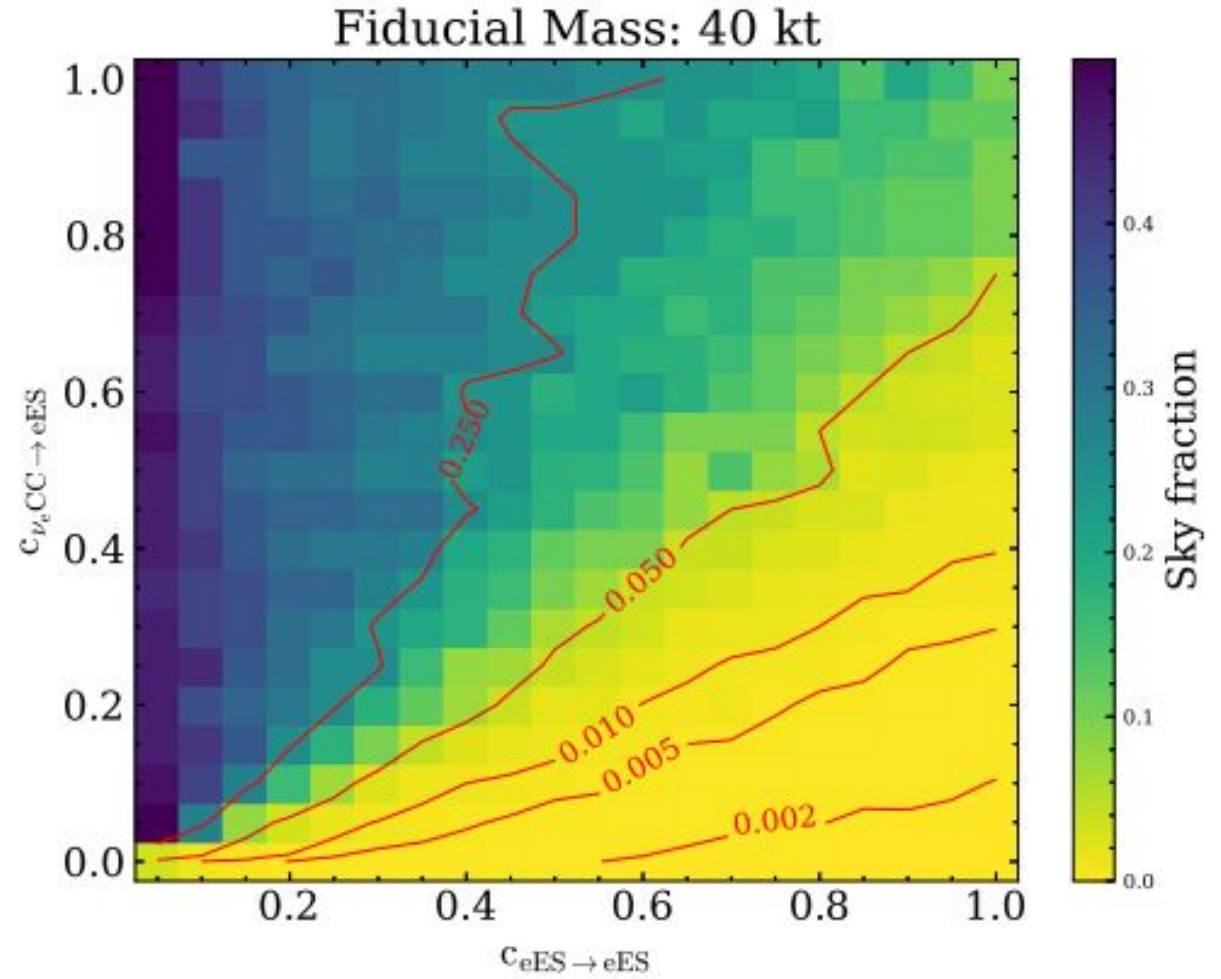
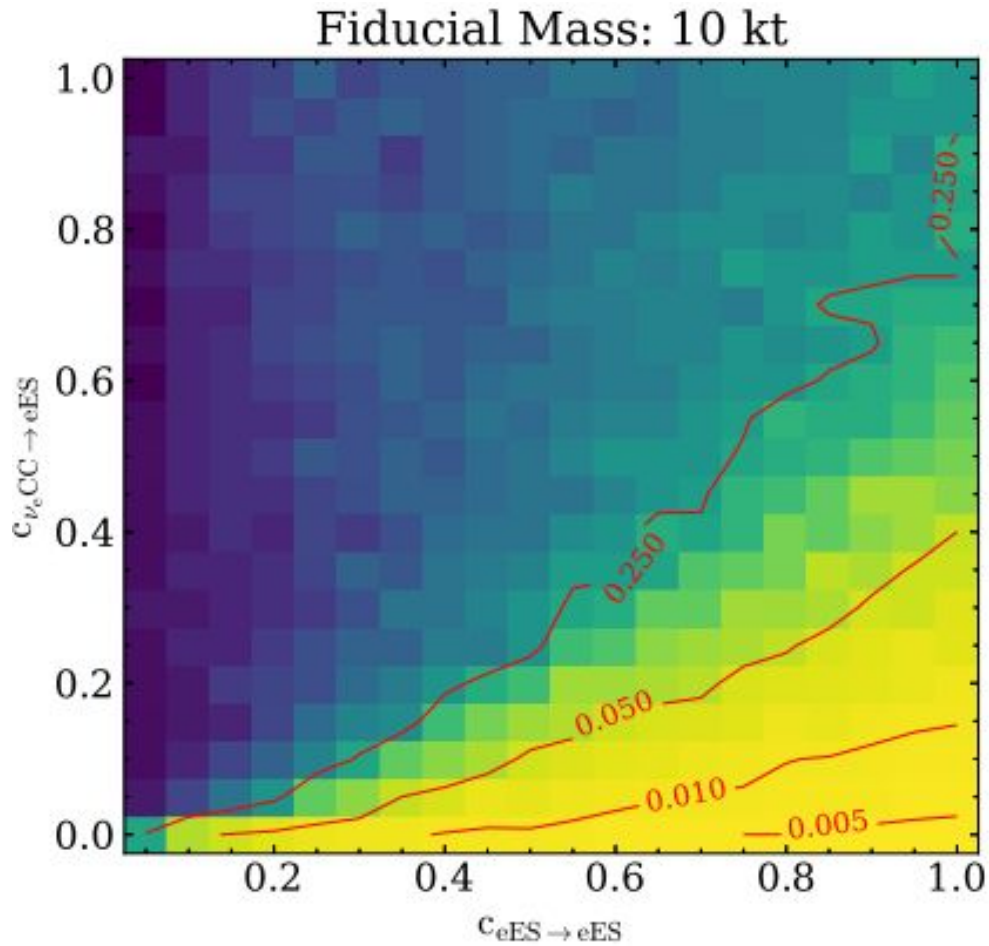


(a)



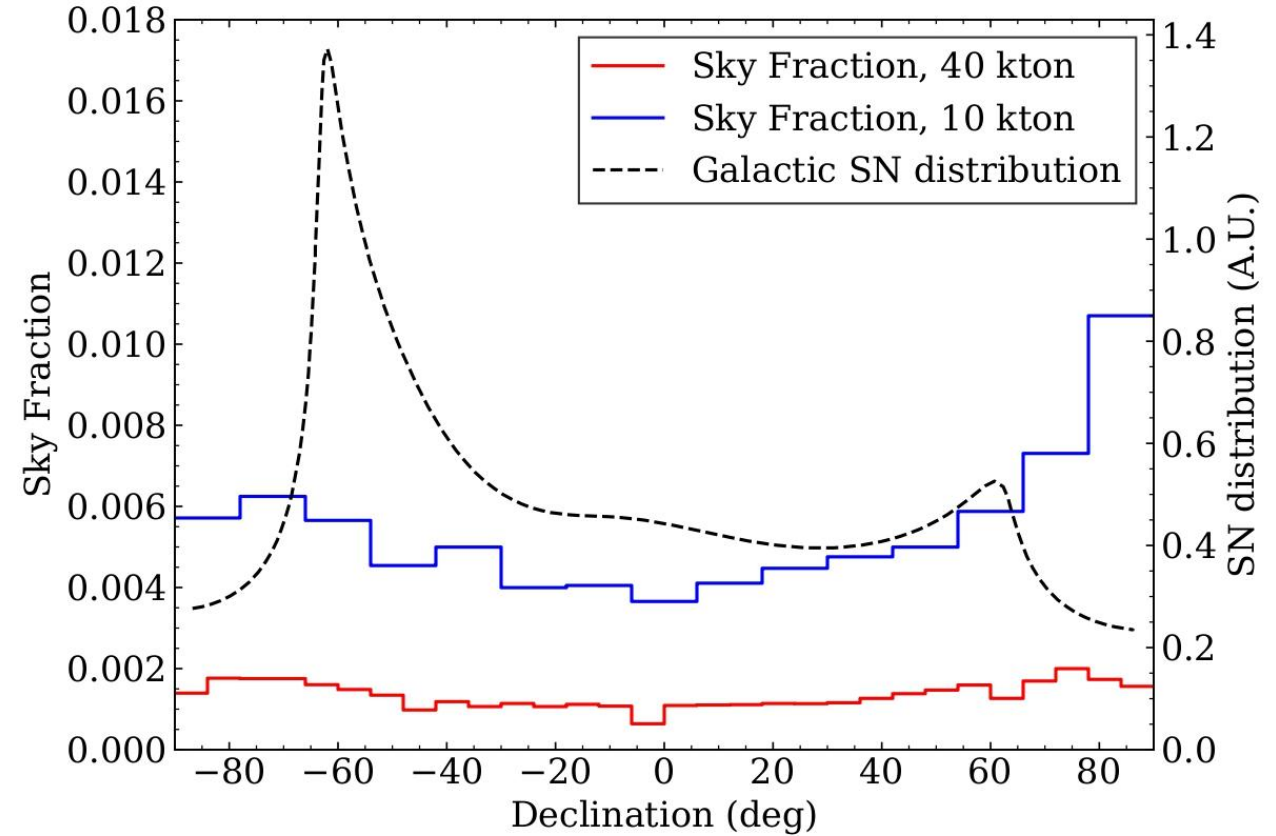
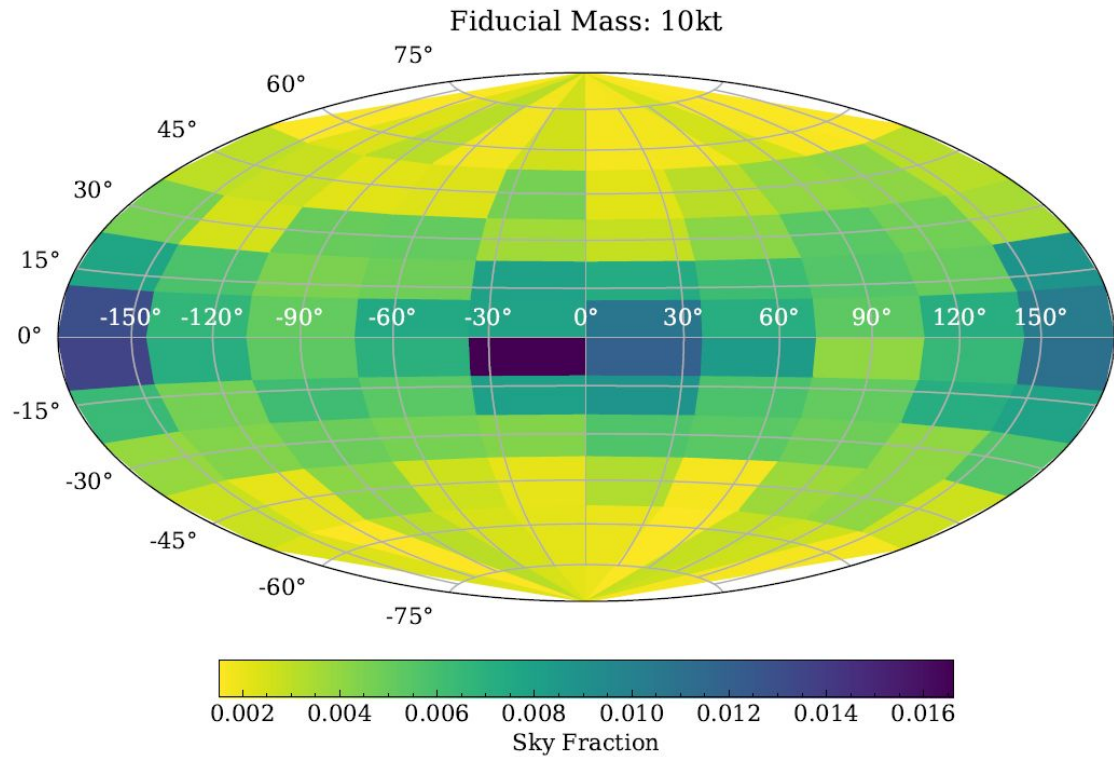
Resolution map for different channel tagging

[2]



Resolution for different directions

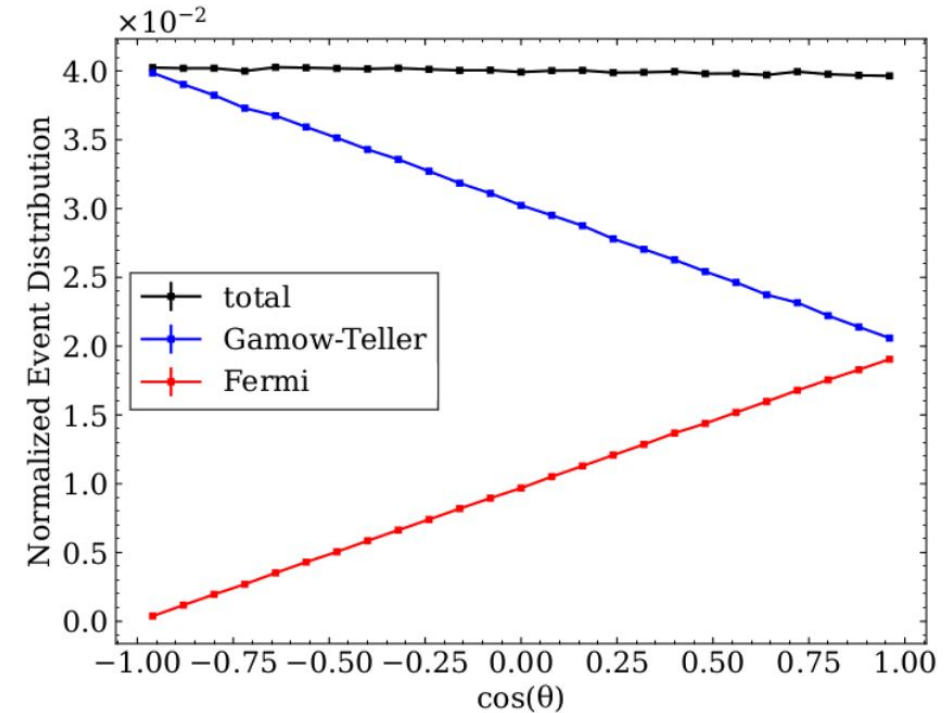
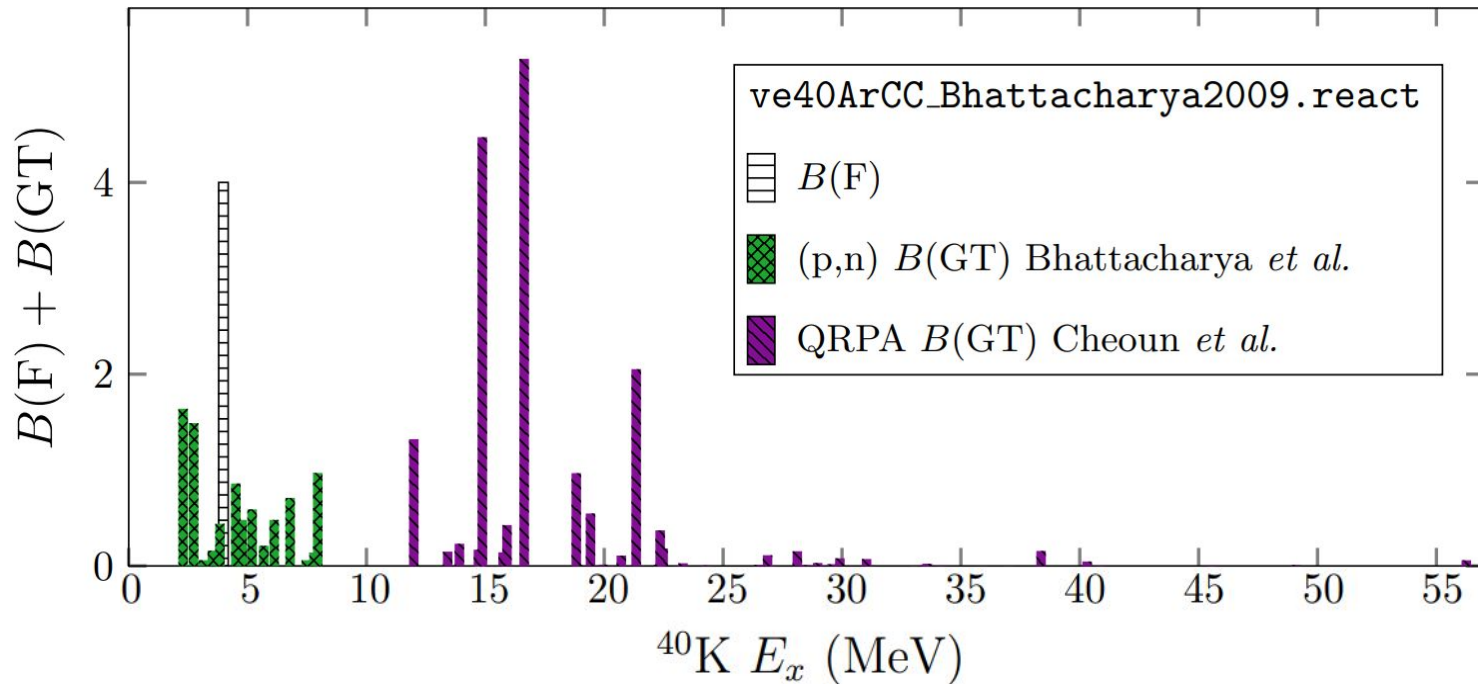
[2]



Resolution as function of SN direction, transformed from the local surface coordinate system to RA-Dec. Averaged over RA [2]

CC channel for pointing

First attempts at exploiting CC by classifying between Gamov-Teller and Fermi interactions (DUKE): different electron energy, number of gammas.



Angular distribution and energy of electrons from CC F/GT interactions [2][4]