Supernova detection and triggering with the DUNE Far Detector

Using the Photon Detection System

P. Barham Alzás on behalf of the DUNE Collaboration

XX International Workshop on Neutrino Telescopes 26/10

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1. **Core-collapse supernovae in DUNE**
2. Supernova neutrino burst trigger
3. Prospects

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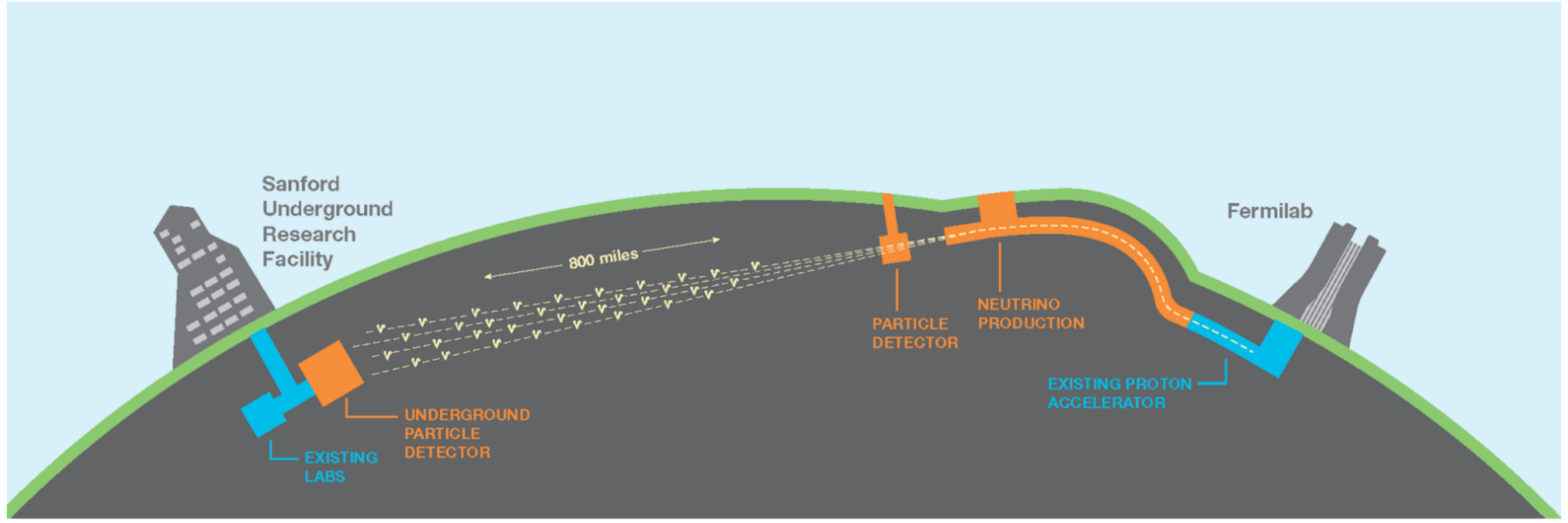
The Deep Underground Neutrino Experiment (DUNE)

DUNE is a planned dual-site long baseline neutrino experiment starting operation in 2029.



- Neutrino beams (ν_μ and $\bar{\nu}_\mu$) are generated by a proton accelerator at Fermilab and propagate for 1300 km before being detected at SURF 1500 metres underground.
- The Far Detector will be composed of four large liquid argon time projection chambers (LArTPCs) of 17 kilotons each.
- DUNE will also have a multi-purpose near detector installed next to the neutrino source.

DUNE Collaboration, DUNE Far Detector Technical Design Report, JINST 15 T08008 (2020).

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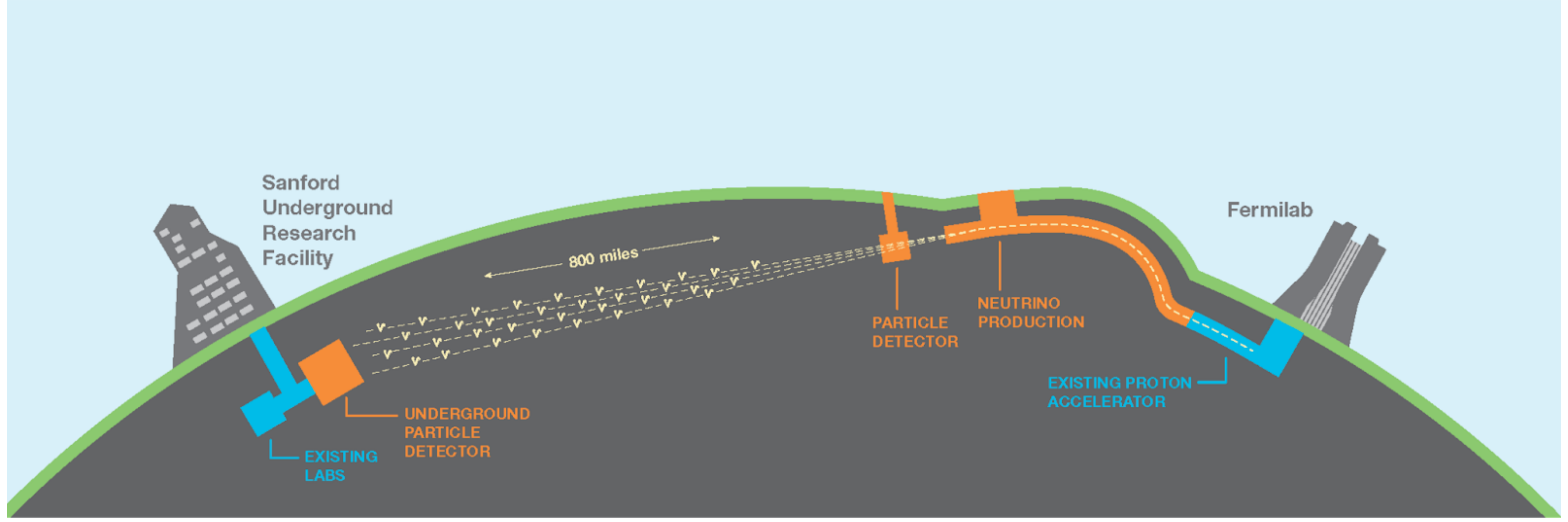

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Physics goals:

Neutrino oscillations. Precision measurements of oscillation parameters: focusing on δ_{CP}, mass ordering, and refinement of mixing angles → Completion of the three-flavour picture.

Beyond the Standard Model (BSM) searches.

Low energy neutrino detection from core-collapse supernovae and the sun.

DUNE Collaboration, DUNE Far Detector Technical Design Report, JINST 15 T08008 (2020).

The DUNE Far Detector

Four 17-kt LAr TPC modules

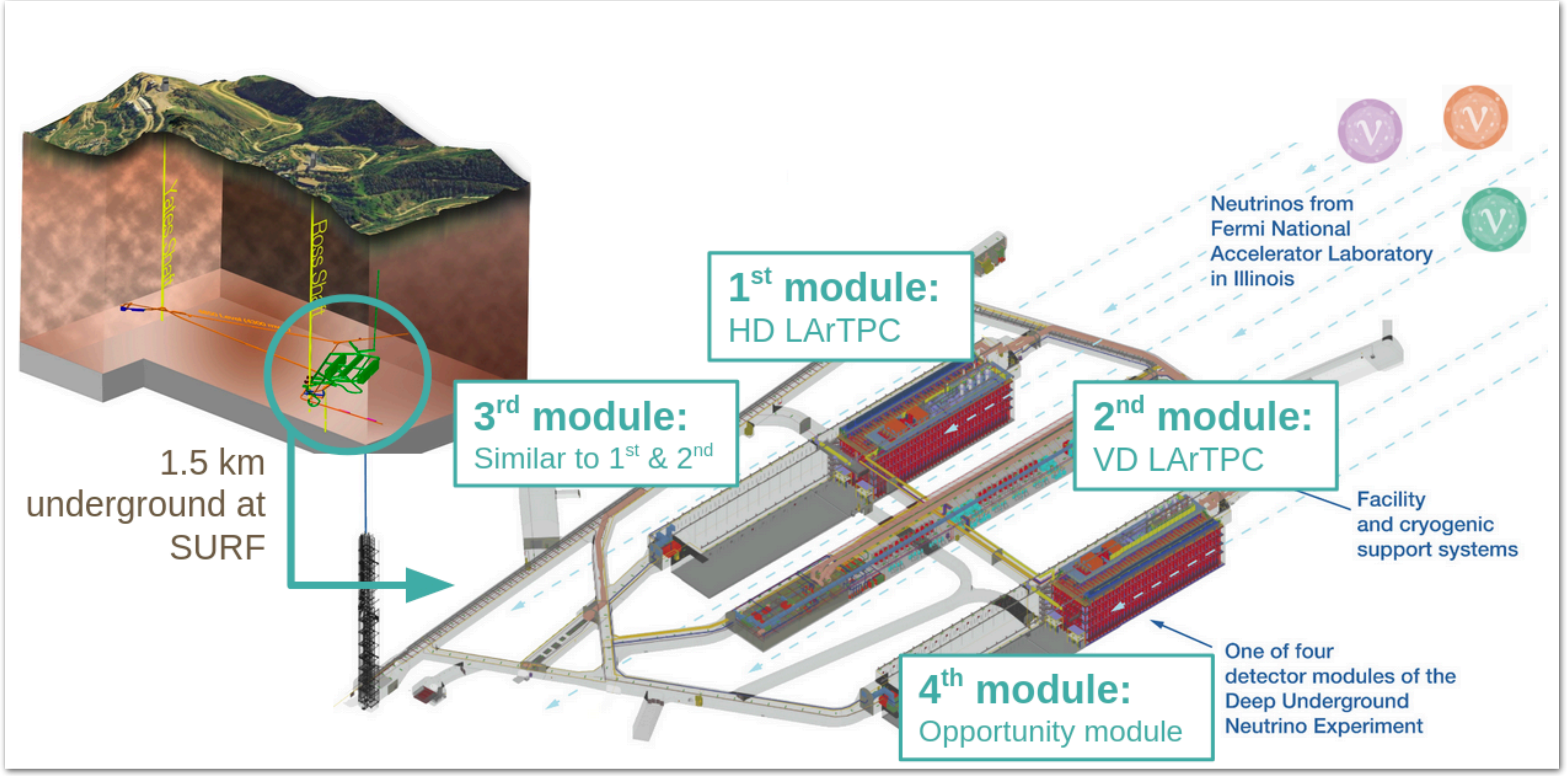
- ***Phase I (2029):***

  FD-1 Horizontal Drift (HD)
  —> **10 kt active mass.**

  FD-2 Vertical Drift (VD)
  —> **10 kt active mass.** Includes a 10 ppm Xenon doping.

- ***Phase II:***

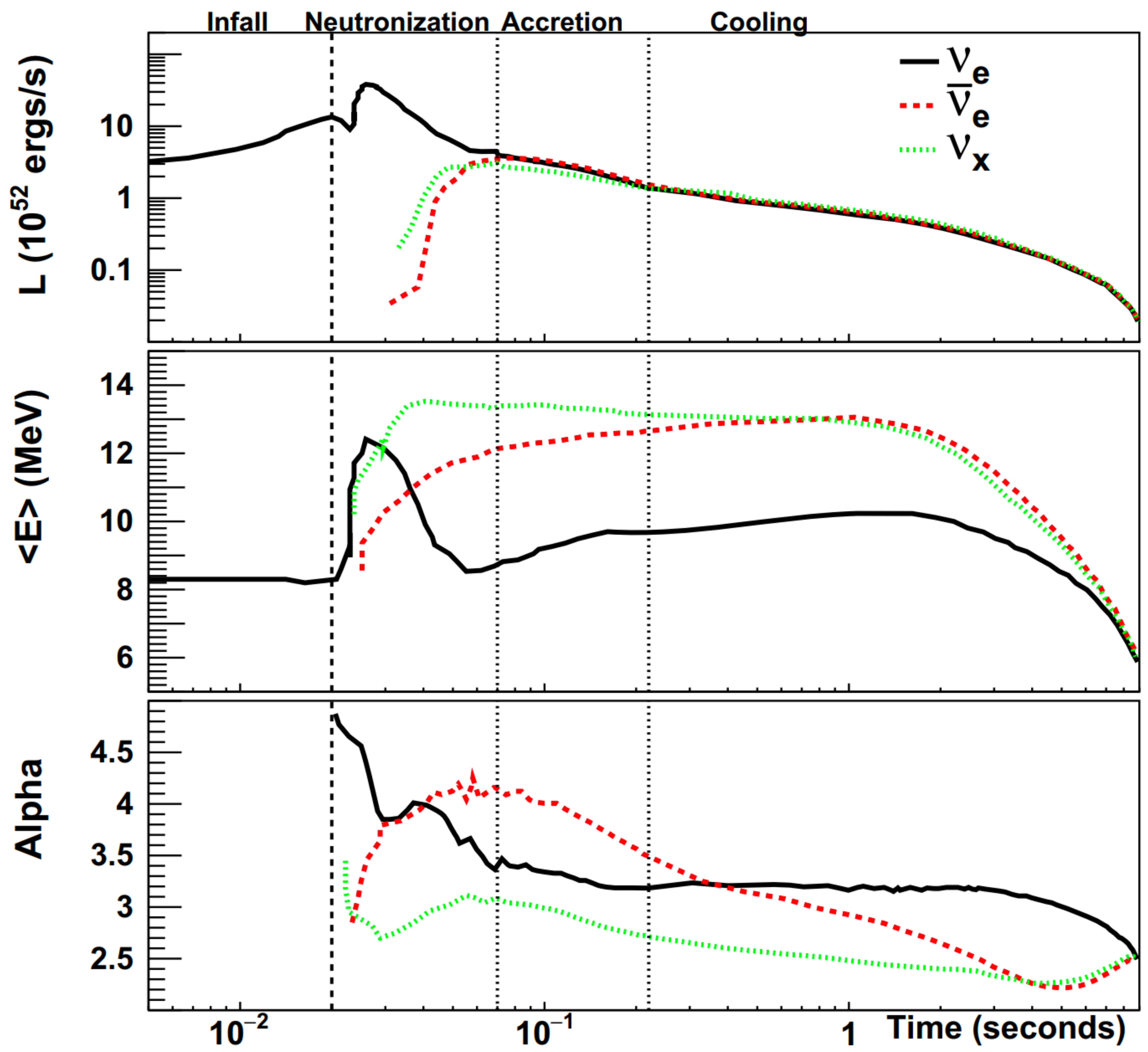
  Module of opportunity: possibility of a low energy enhanced detector!



The DUNE Far Detector complex

Core-Collapse Supernovae

- Core-collapse supernovae are violent astrophysical events presenting a source of neutrinos of all flavours: >99% of the energy is carried by neutrinos!
- The neutrino burst lasts ~10 seconds.
- 1-3 events a century expected in our galaxy.



Luminosity, mean energy and "pinching" parameters evolution for an electron capture supernova (Garching model).

Measurement of spectra can give key physics info:

- Core-collapse mechanism.
- Neutrino physics: absolute masses, mass hierarchy or neutrino self-interactions.
- Exotics like sterile neutrinos or neutrino magnetic moments.

DUNE Collaboration, Eur. Phys. J. C. 81:423 (2021).

Low energy neutrino signal in LAr

DUNE Collaboration, Eur. Phys. J. C. 81:423 (2021).

Three possibilities:

1. Charged current (CC):

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

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

2. Elastic scattering (ES) on electrons:

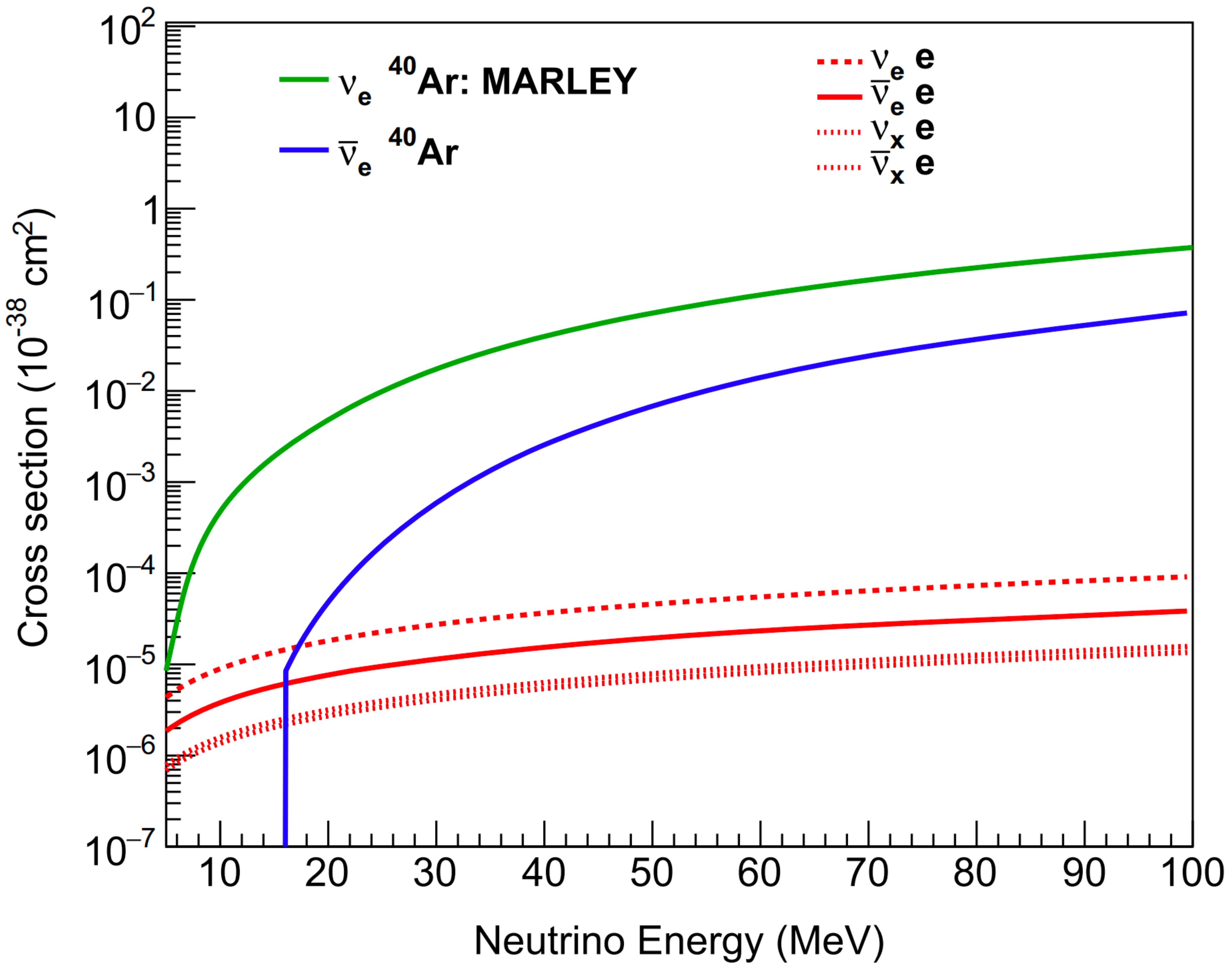
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

3. Neutral current (NC):

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

DUNE is the only experiment that can give us a cleanly tagged sample of the ν_e-CC SN flux!

Possibility to separate different channels (e.g. absence of photons in ES).



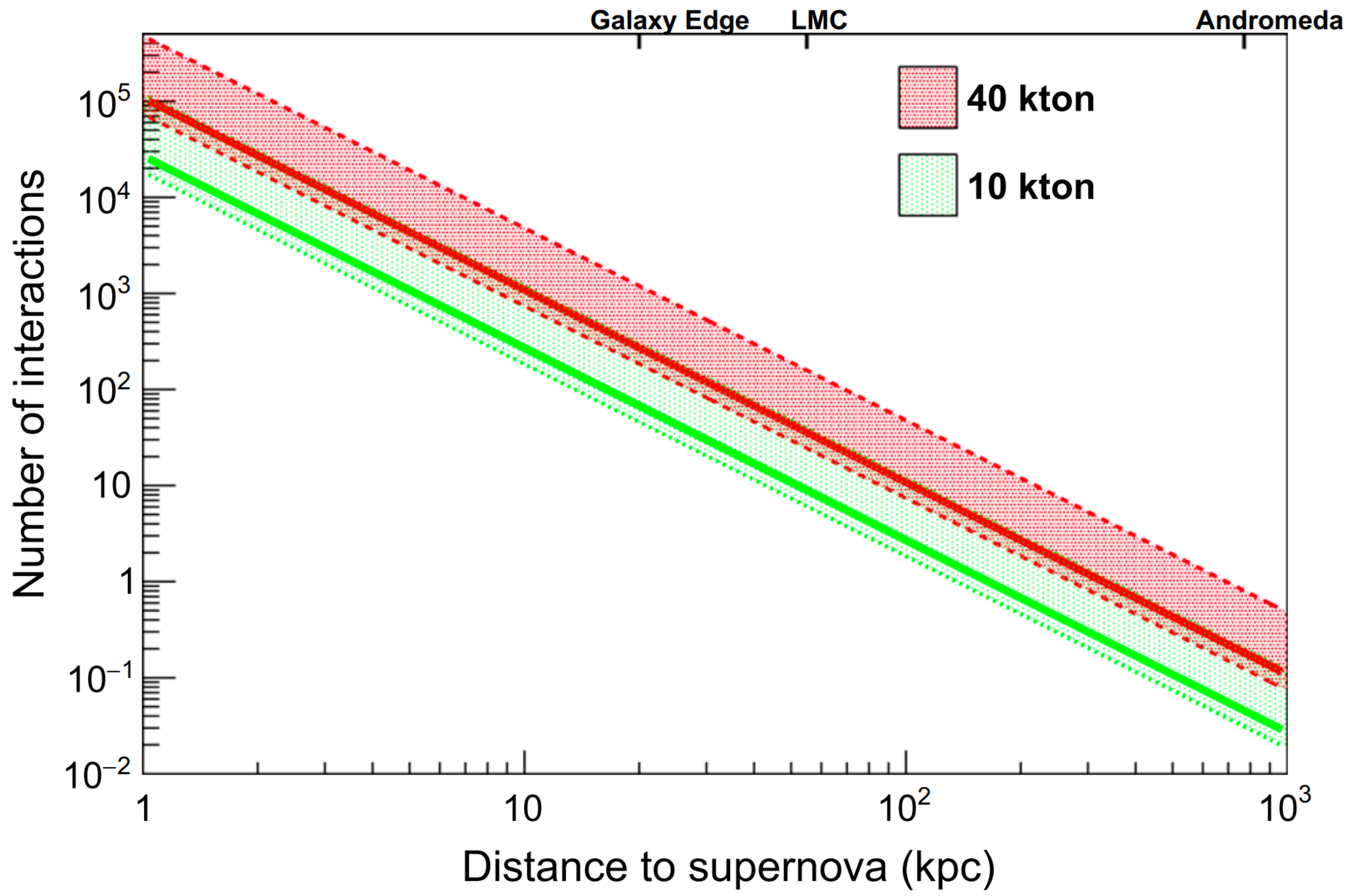
Expected SNB signal in DUNE

Number of events expected in a 40 kt LArTPC for a SNB event at 10 kpc, according to **different SNB models**:

Channel	Liver-more	GKVM	Garching
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

No flavour transitions are assumed for the Livermore and Garching models; the GKVM model includes collective effects.

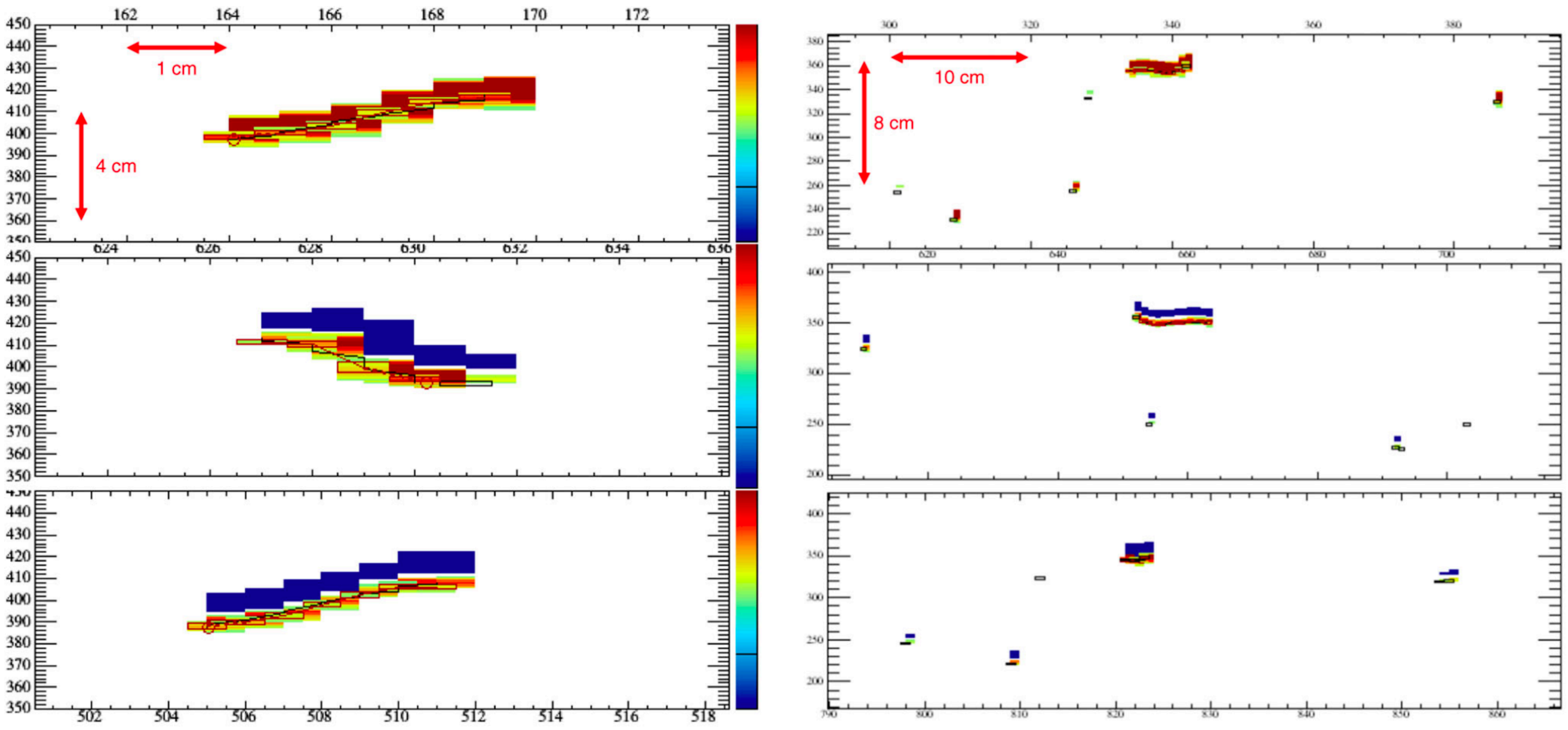
Electron neutrino CC channel heavily dominates → DUNE will have an unmatched sensitivity in this channel.



Number of events vs. distance for a range of models.

SN Event simulation and reconstruction

- **MARLEY** used to simulate MC neutrino-nucleus interaction in the MeV to tens-of-MeV range.
- Propagation and detector response simulation using **LArSoft —> Triggering.**
- **Reconstruction** in **LArSoft** to identify interaction channel, incoming neutrino 4-momentum.



ν_e ES event (10.25 MeV e^-) vs. ν_e CC event (20.23 MeV ν)

Simulating low-energy neutrino interactions with MARLEY, arXiv:2101.11867 [nucl-th]

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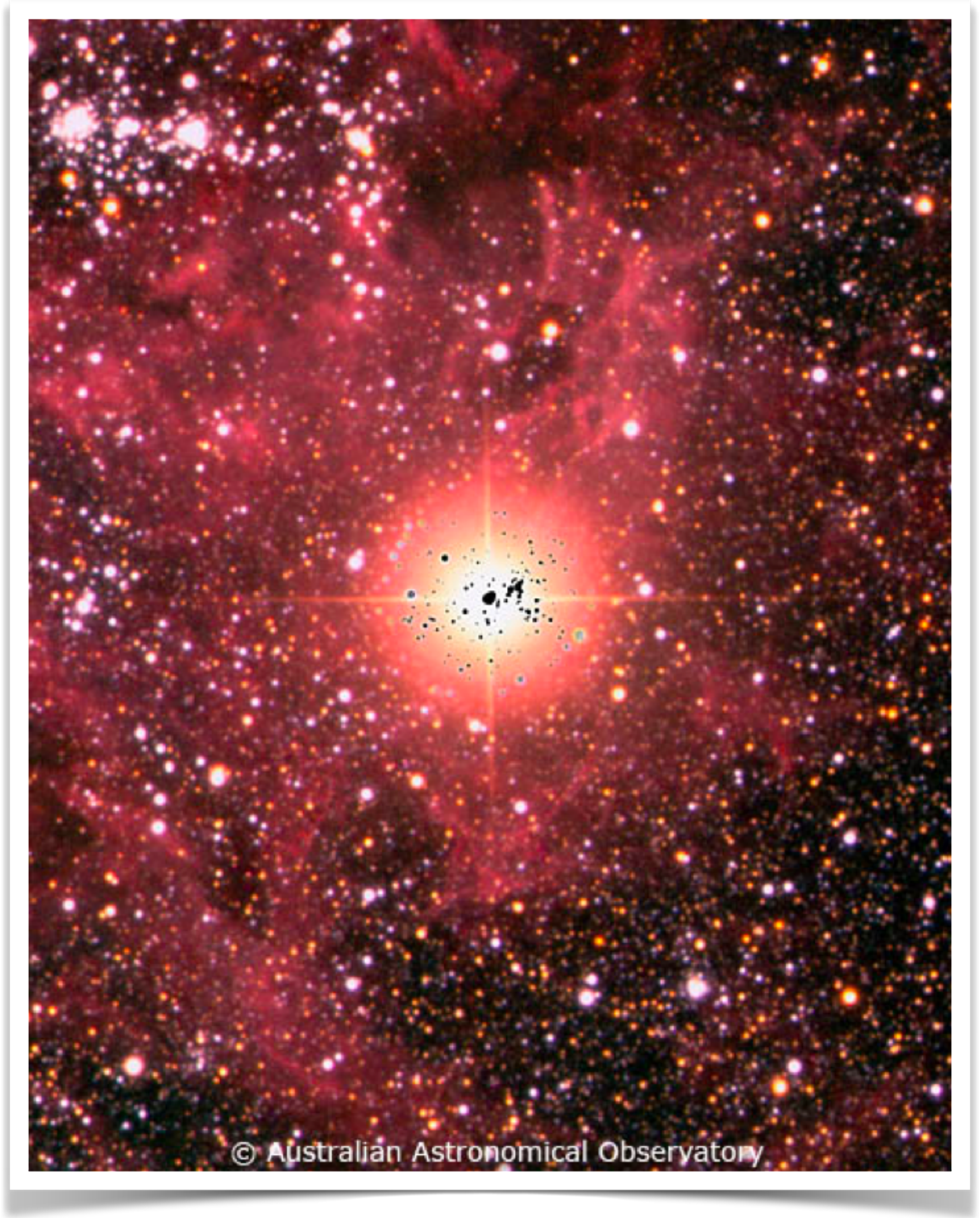
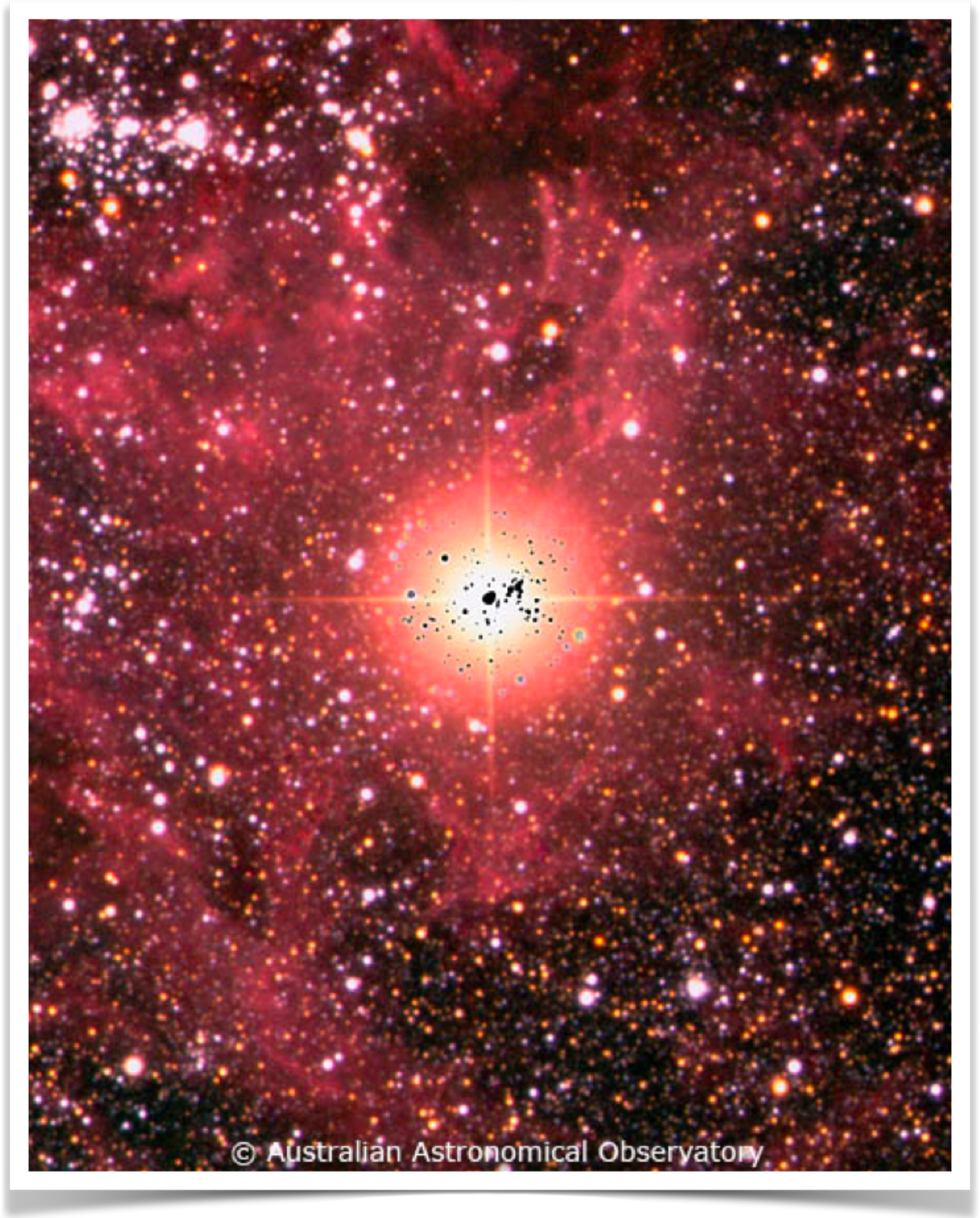
DUNE Supernova Trigger



SN 1987-A

DUNE Supernova Trigger

- DUNE aims to develop a redundant and highly efficient triggering scheme for supernovas. We don't want to miss the next one!



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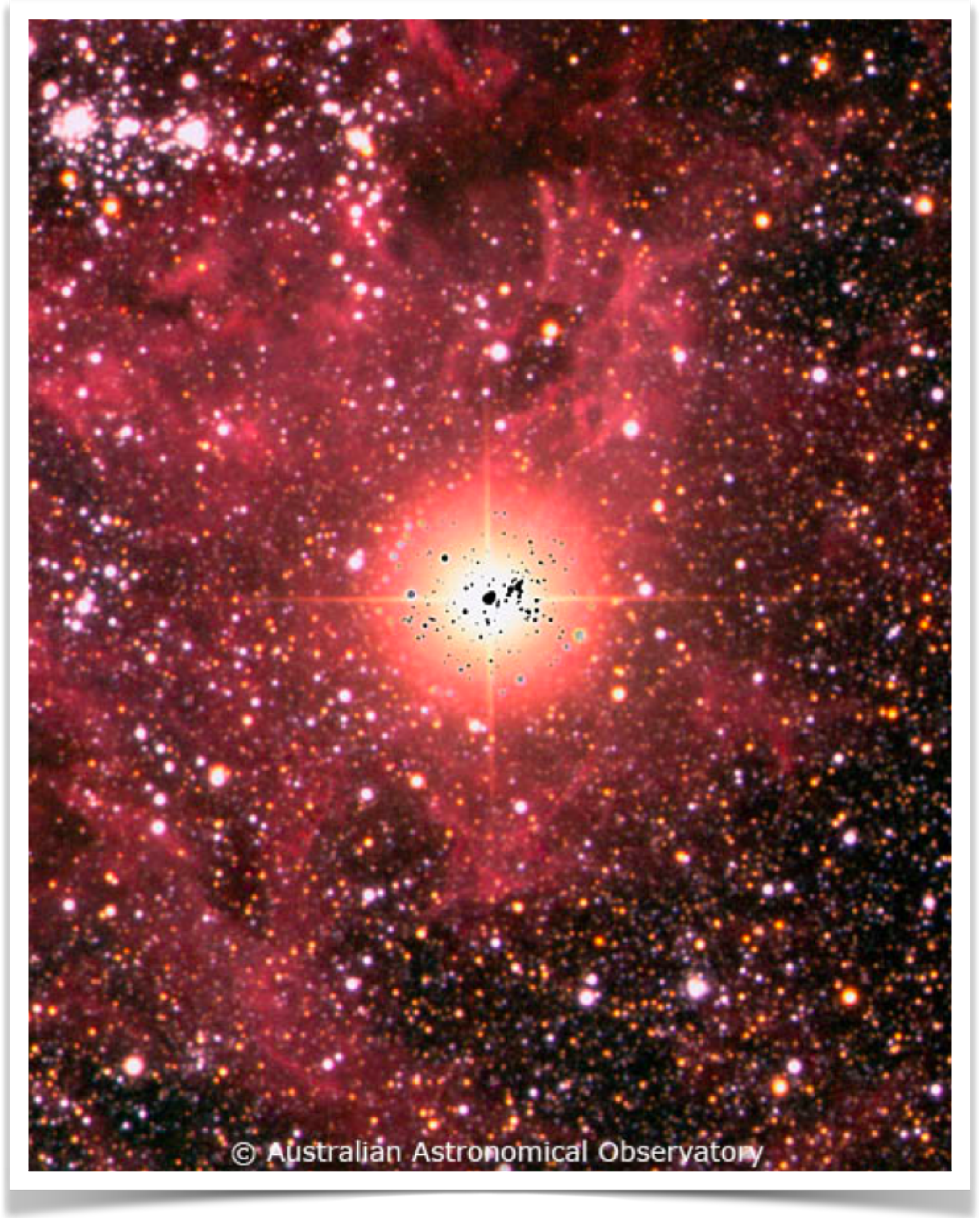

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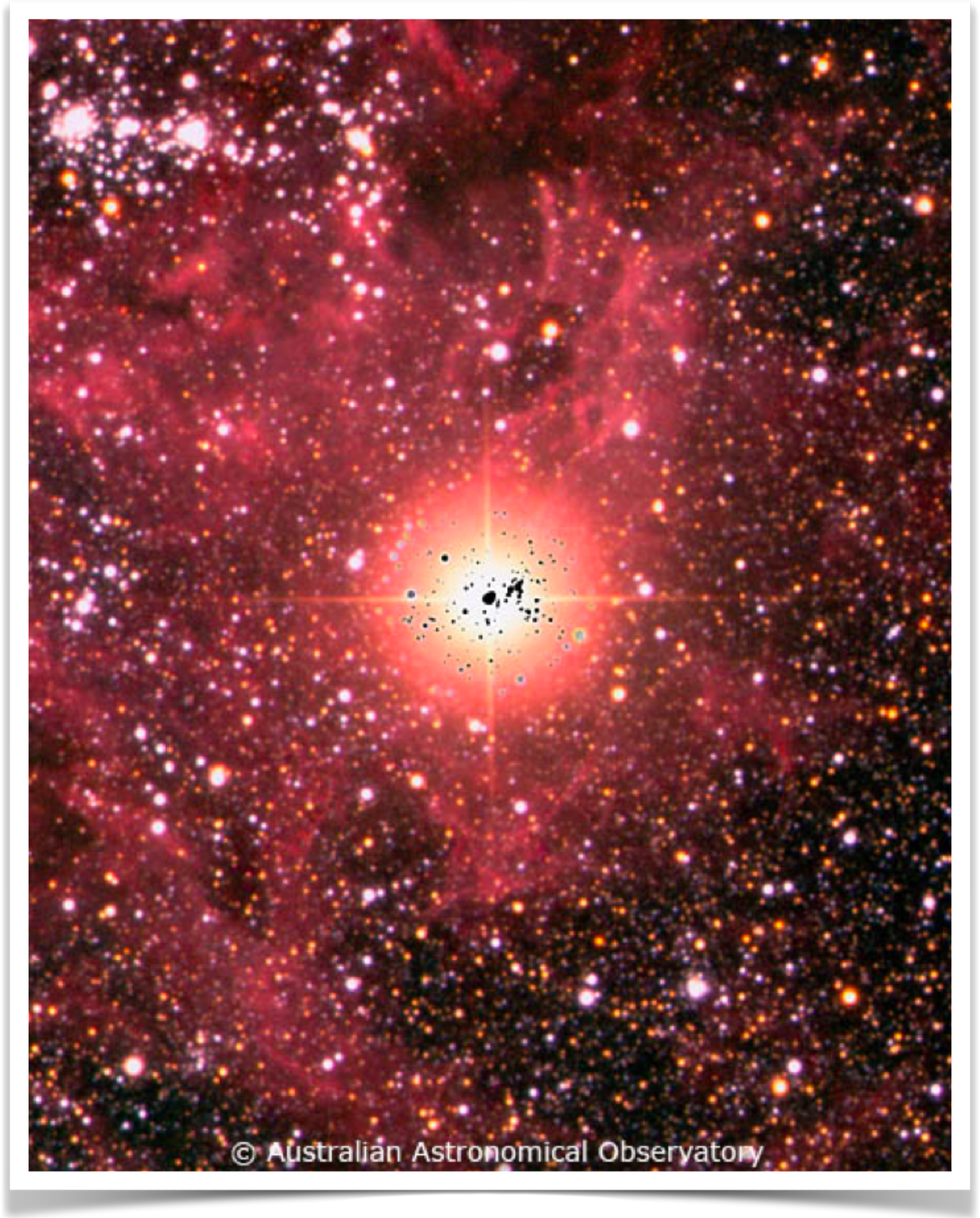

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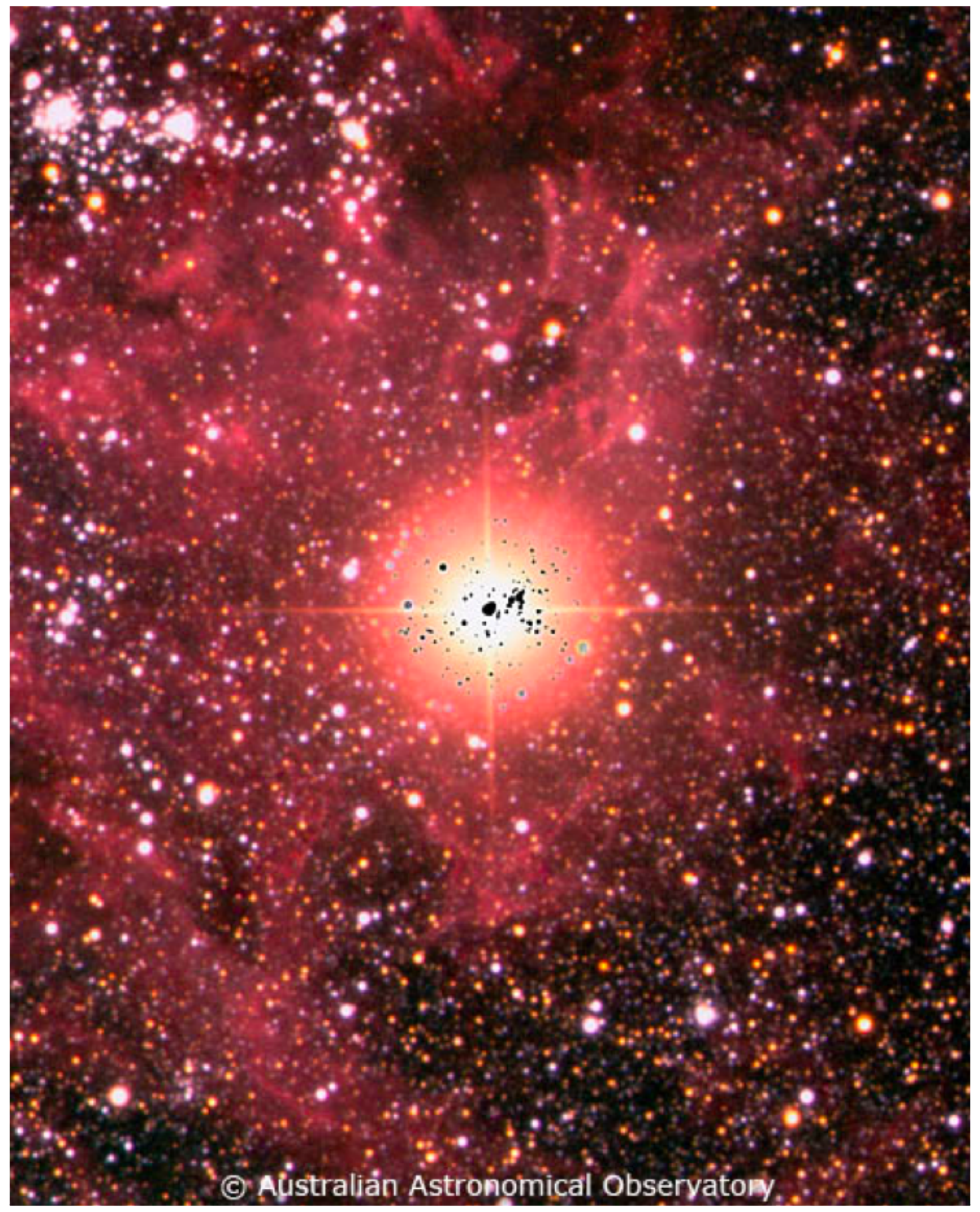

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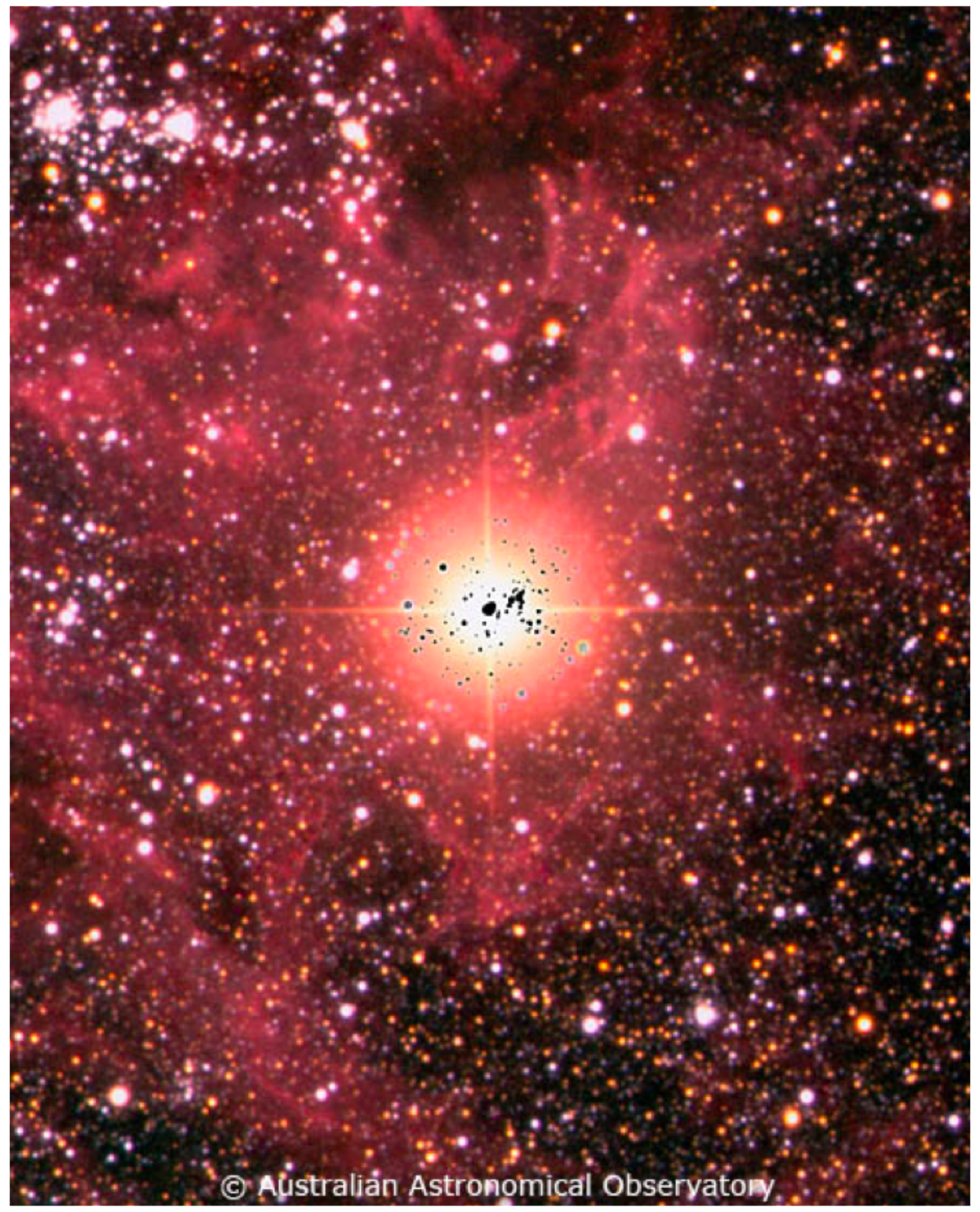
- DUNE will be part of the Supernova Early Warning System (**SNEWS**).

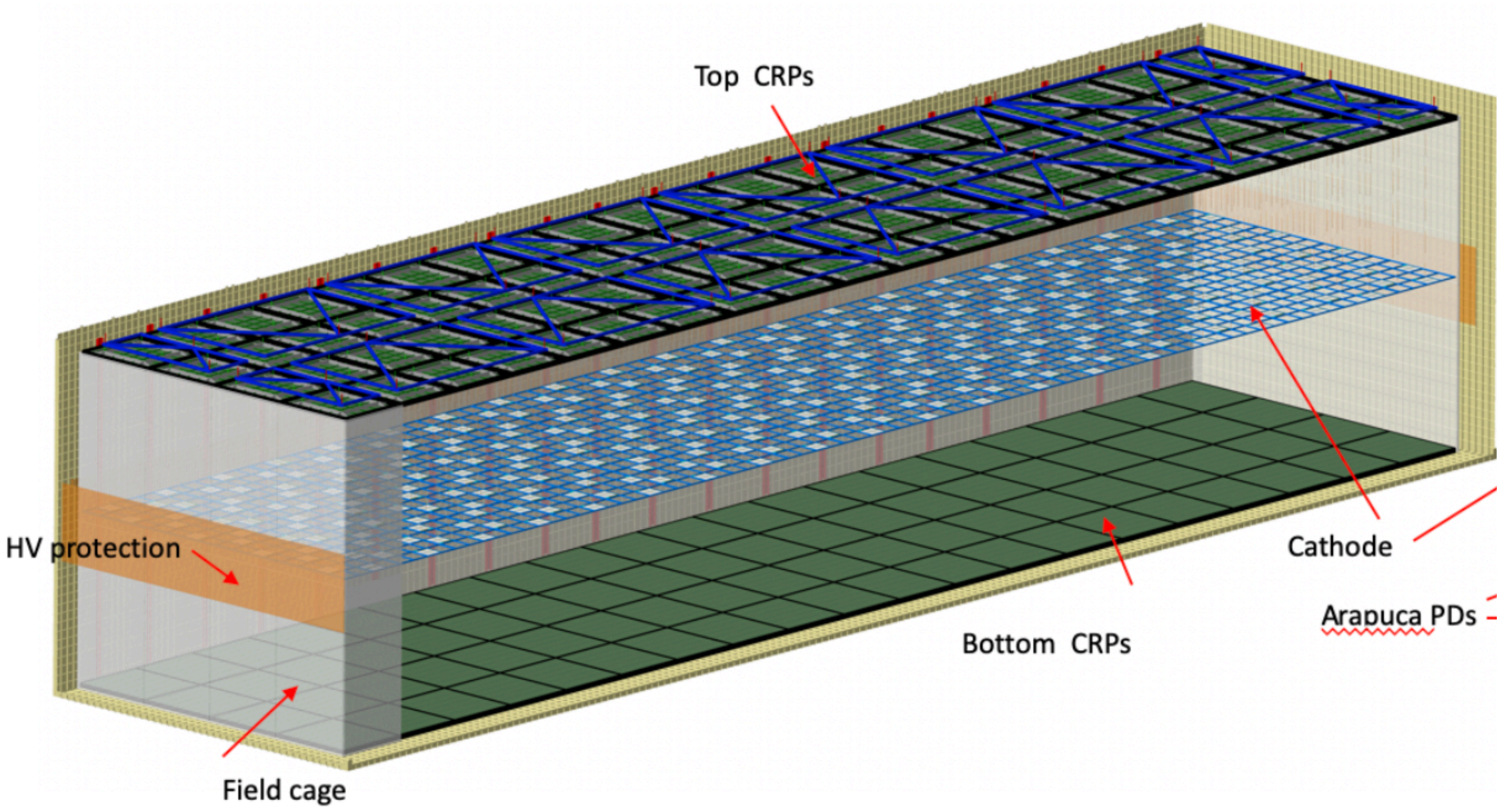


SN 1987-A

Geometry: FD2-VD

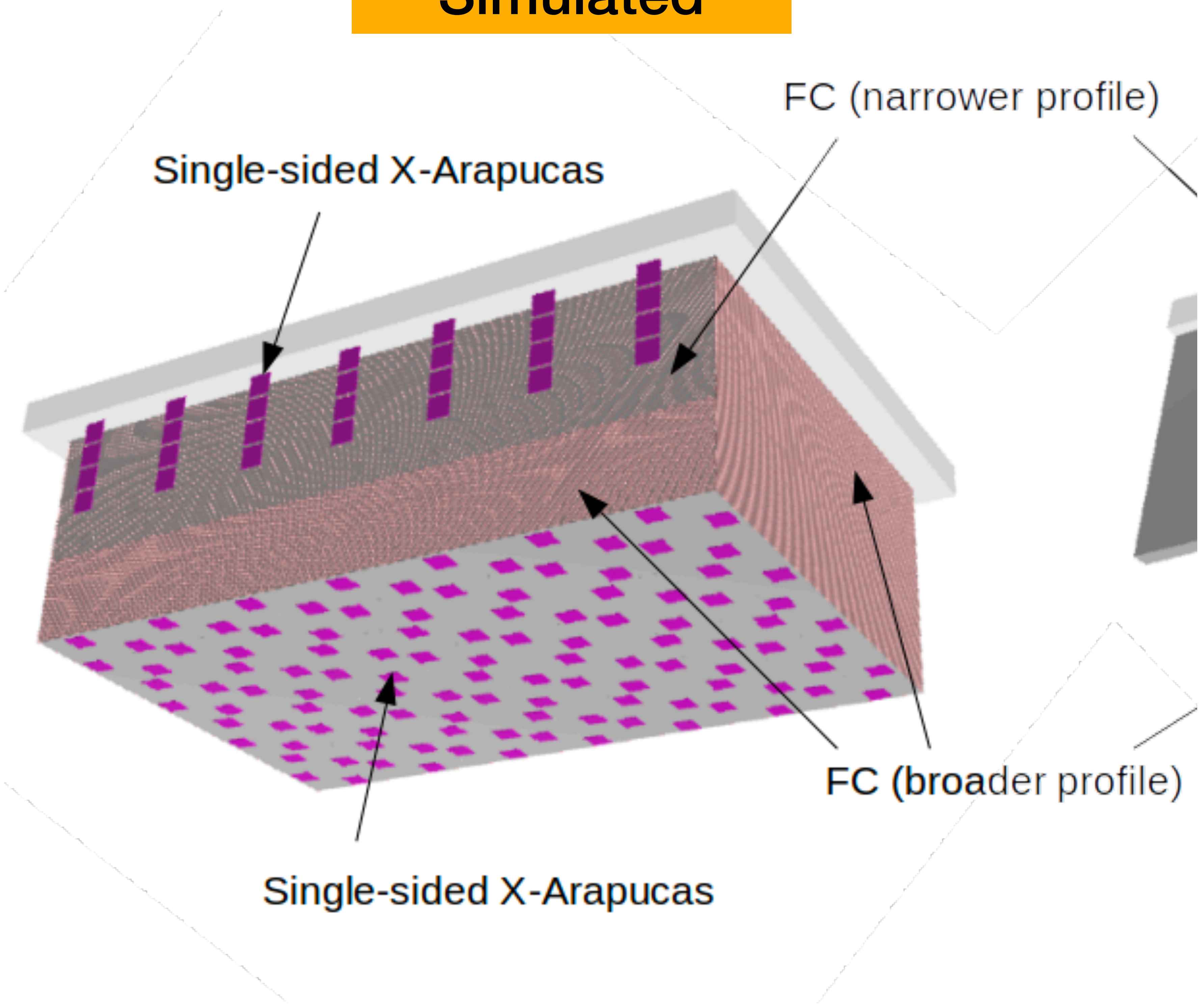
DUNE aims to have a redundant trigger with the charge and light systems. Here we focus on the light (PDS).

Full



Far Detector Vertical Drift (FD-VD) module.
X-ARAPUCAS on the cathode and membrane (side) walls.

Simulated

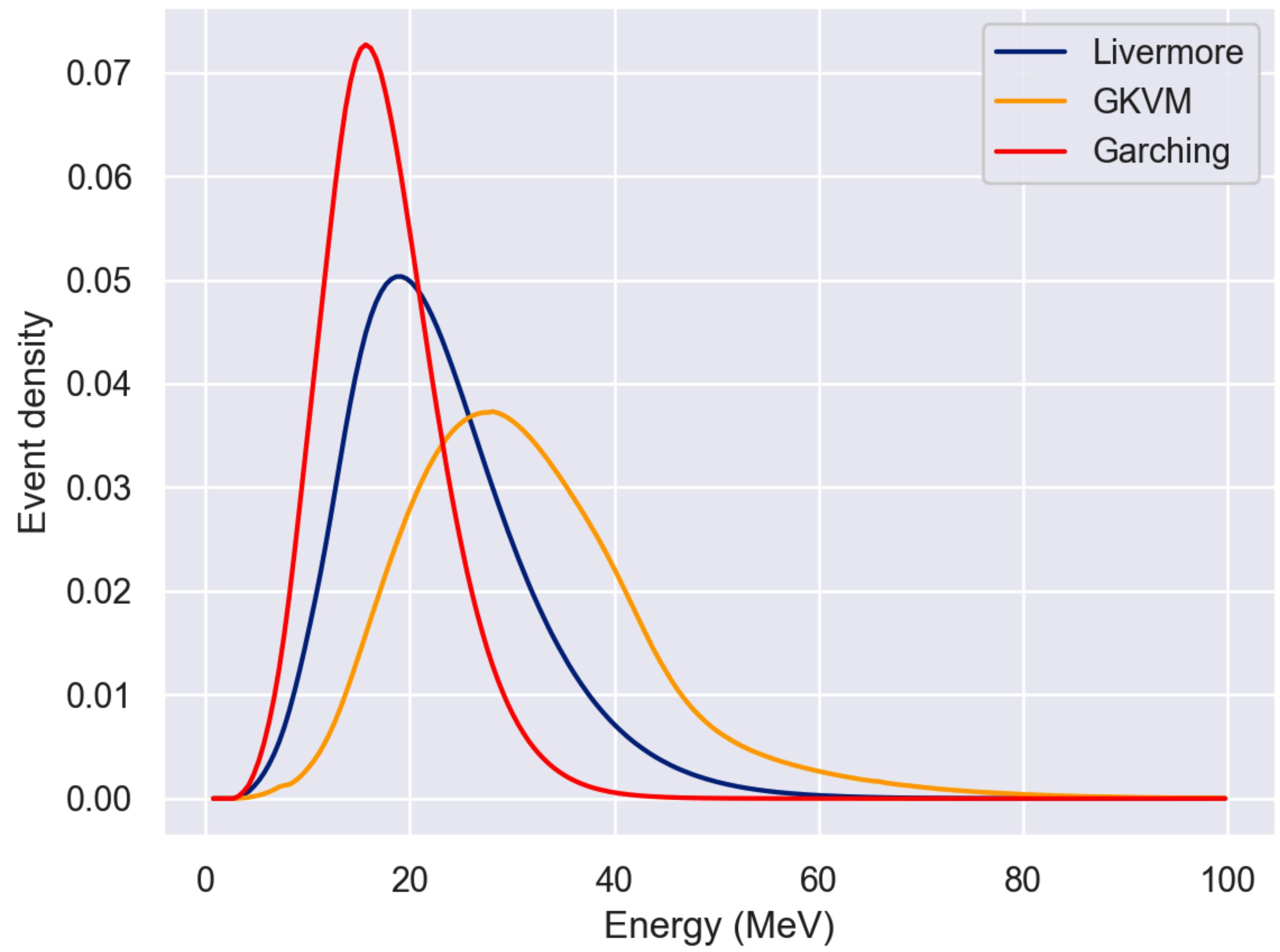


FD-VD 1x8x14 geometry (6x12x21 m).
184 optical channels (112 on cathode, 72 on membrane walls)

Event and BG generation

Supernova neutrino signal:

- 10^6 ν_e-CC PDS events using the MARLEY event generator covering a 4-100 MeV energy range.



Interacted energy spectra for different SN models

Radiological backgrounds:

- ^{39}Ar, ^{42}Ar, ^{85}Kr, ^{42}K from ^{42}Ar and ^{222}Rn in LAr.
- ^{222}Rn in PDS.
- ^{238}U Chains in cathode and anode.
- Neutrons from rock.
- Gammas from rock.

200k events for each BG channel (DUNE Radiological Model v2).

Component	Activity (mBq/cm^3)
^{39}Ar in LAr	1.41
^{42}Ar and ^{42}K in LAr	0.128 $\times 10^{-3}$
^{85}Kr in LAr	0.16
^{222}Rn chain in LAr	1.395 $\times 10^{-3}$
^{40}K in cathode	9.1
^{238}U chain in cathode	0.113
^{60}Co in anode	0.361
^{238}U chain in anode	95
^{222}Rn chain in PDS	0.021
External neutrons (rocks, concrete walls, etc)	7.6 $\times 10^{-3}$
Cavern gammas	64

Reference background activities used by the decay0 module.

Event generation: backgrounds

Three main backgrounds (in terms of **hit rate**) are: Ar39 in LAr, Rn222 in LAr and Kr85 in LAr, followed by cavern gammas.

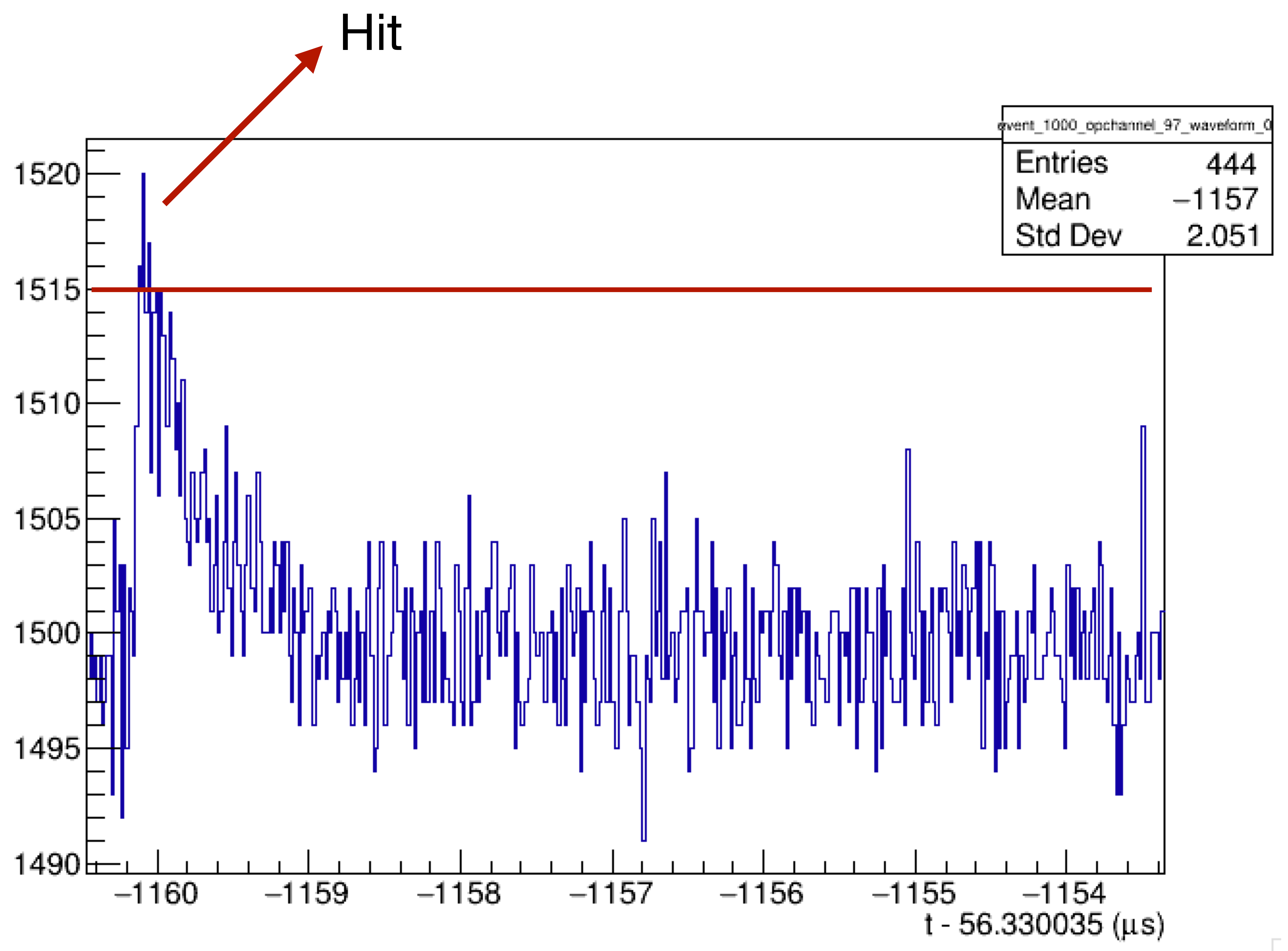
	Cathode (kHz/channel)	Wall (kHz/channel)	Total (kHz/channel)
Ar39 in LAr	1.521	1.473	1.5022
Kr85 in LAr	0.161	0.155	0.1587
Rn222 in LAr	0.709	0.623	0.6753
Neutrons	1.48E-03	1.77E-03	1.5935E-03
Ar42 in LAr	1.72E-04	2.55E-04	2.0448E-04
K42 in LAr	4.9E-04	8.61E-04	6.3517E-04
U238 in CPA	1.31E-03	7.26E-05	8.2580E-04
U238 in APA	1.35E-03	3.55E-04	9.6065E-04
Rn222 in PDS	2.74E-04	3.27E-04	2.9474E-04
Gammas	0.059	0.127	0.0856

Algorithm: optical hits

A hit is defined as a peak of the digitised waveform that is above a certain threshold. In our case threshold = 15 ADC = 1.5 PE.

A hit contains the following information:

- PeakTime (in ns)
- Width (time spent above threshold, in ticks - 1 tick = 16 ns)
- Amplitude (at peak time in ADC)
- Area (area in ADC * ticks)
- PE (number of PEs, that is computed by dividing the Area by 130, considered the area of a SPE).

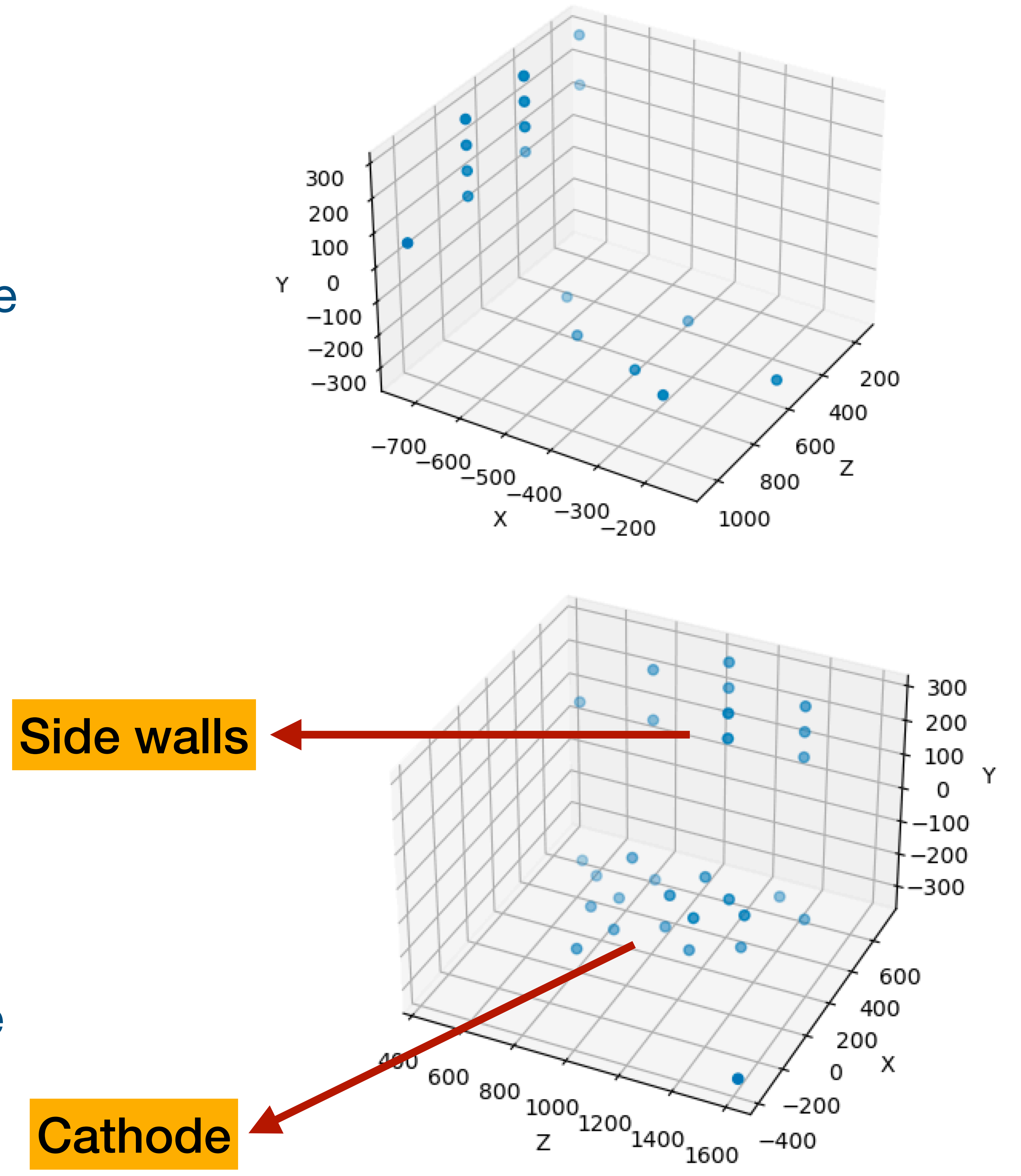


Algorithm: clustering

Optical cluster: collection of optical hits presenting space and time correlations that indicate that make us believe they were induced by the same underlying event.

Parameters for defining an optical cluster:

- **Maximum cluster duration.**
- **Maximum time difference between consecutive hits.**
- **Maximum spatial distance between neighbouring optical channels detecting the hits.**
- **Minimum hit multiplicity** (minimum number of hits in a group to be considered a cluster)**.**



Optical hits for two example SN events (top, bottom) in the FD-VD PDS.

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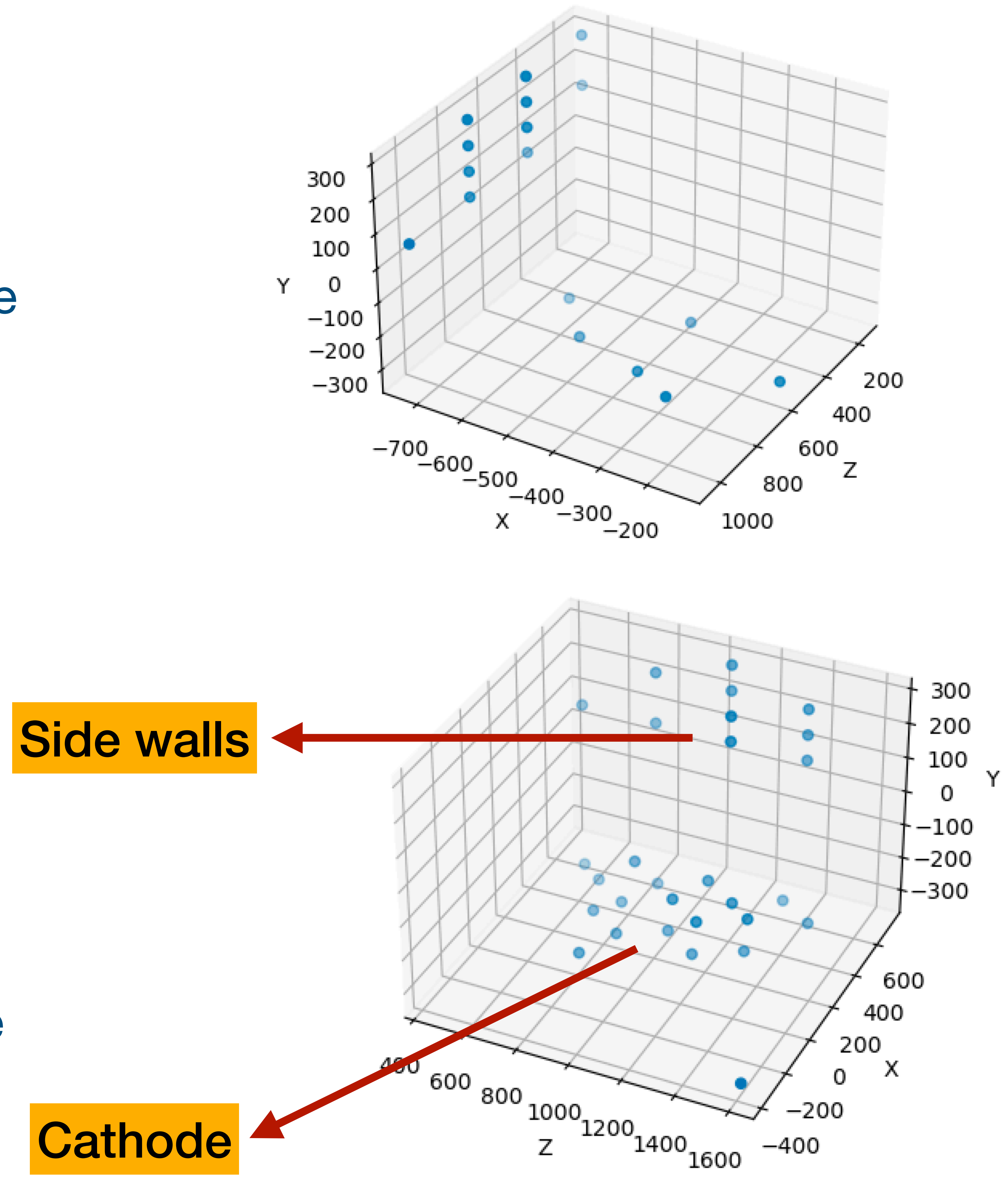
New: We iterate over a much larger set of parameters with low statistics. Once the optimal parameters are estimated, we re-evaluate with full stats.



Optical hits for two example SN events (top, bottom) in the FD-VD PDS.

Algorithm: clustering

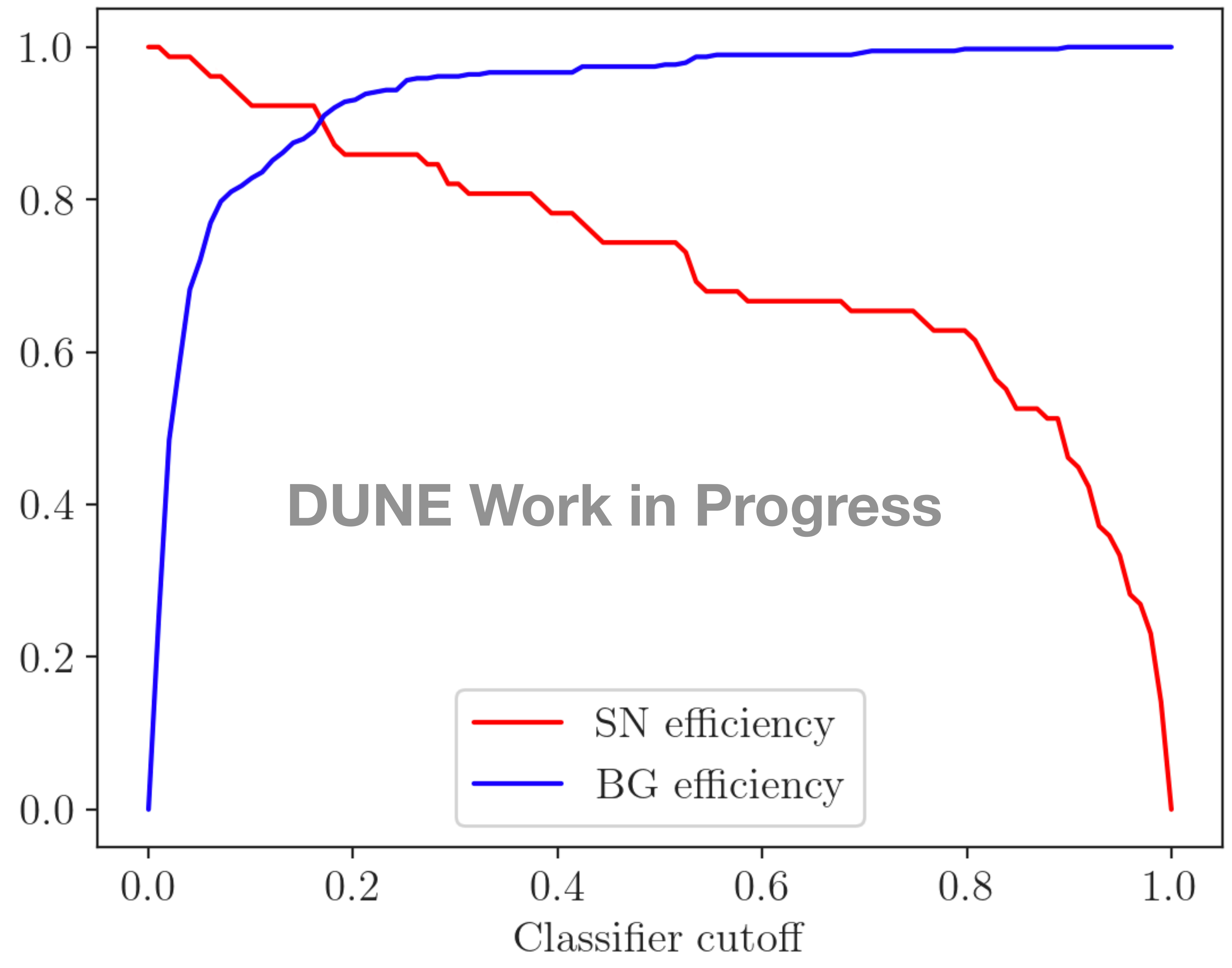
Once we have defined the clustering parameters, we apply the clustering algorithm to all of our SN events and our BG.

From here we go on to define the following cluster properties, which will be used to train a BDT:

- Average (per hit) and total PEs for the cluster.
- Average and total width.
- Average and total amplitude.
- Average and max t, x, y and z differences between consecutive hits (in each axis).
- Wall hit fraction (fraction of hits that arrive at detectors mounted in the wall).

Algorithm: BDT

- A histogram gradient boosted BDT is trained to distinguish between background and SN clusters —> Probabilistic output.
- Trained on a different set of clusters than those used for computing the trigger efficiency.
- We optimise the cutoff for the overall trigger efficiency.



SN and BG classification efficiencies as a function of classifier cutoff

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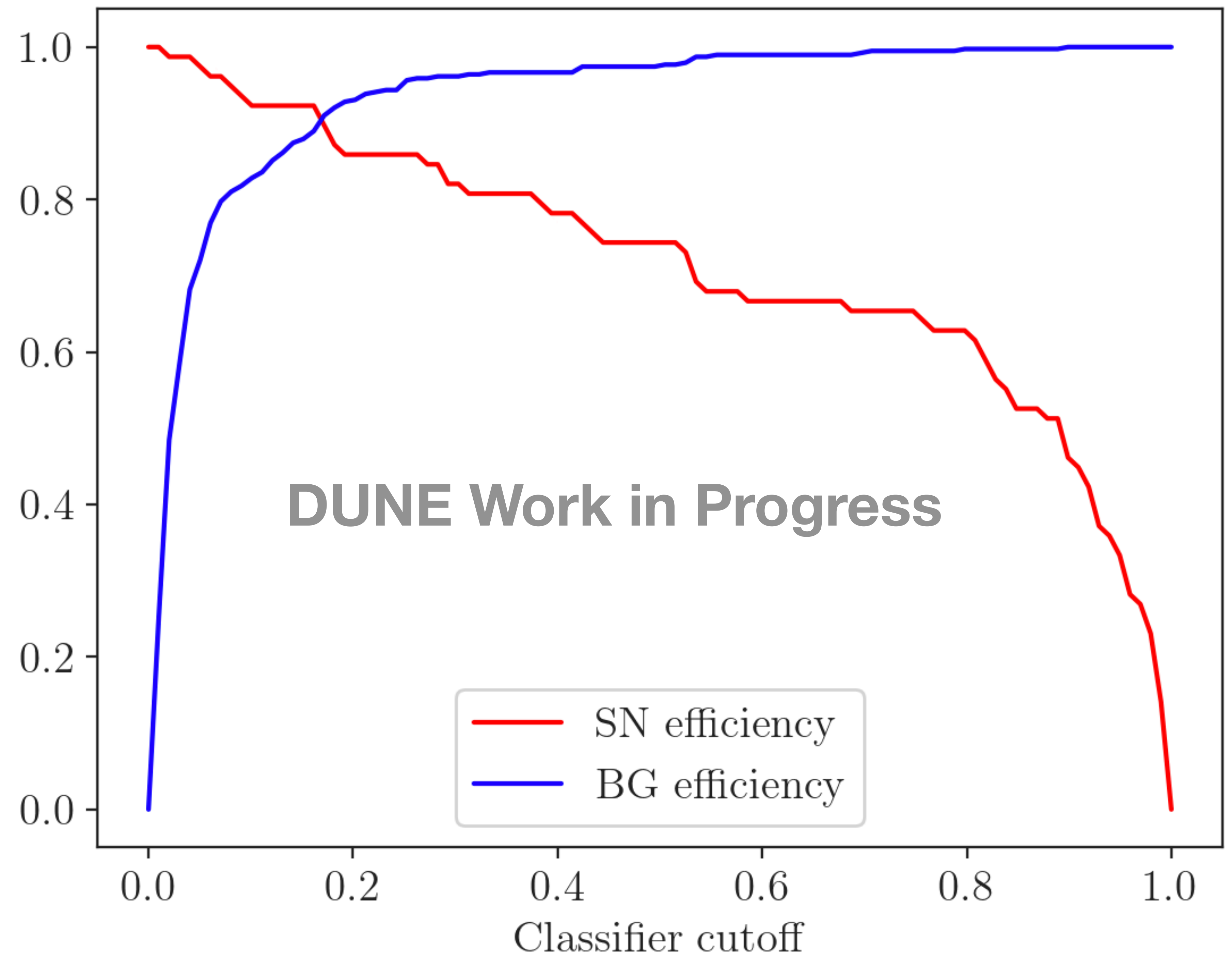
New: We train a BDT with "standard" hyperparameters for each clustering parameter combination.
Once the optima is found, we retrain introducing hyperparameter optimization with Random Halving.

Reduces the dependence on the clustering parameters and improves the trigger efficiency.



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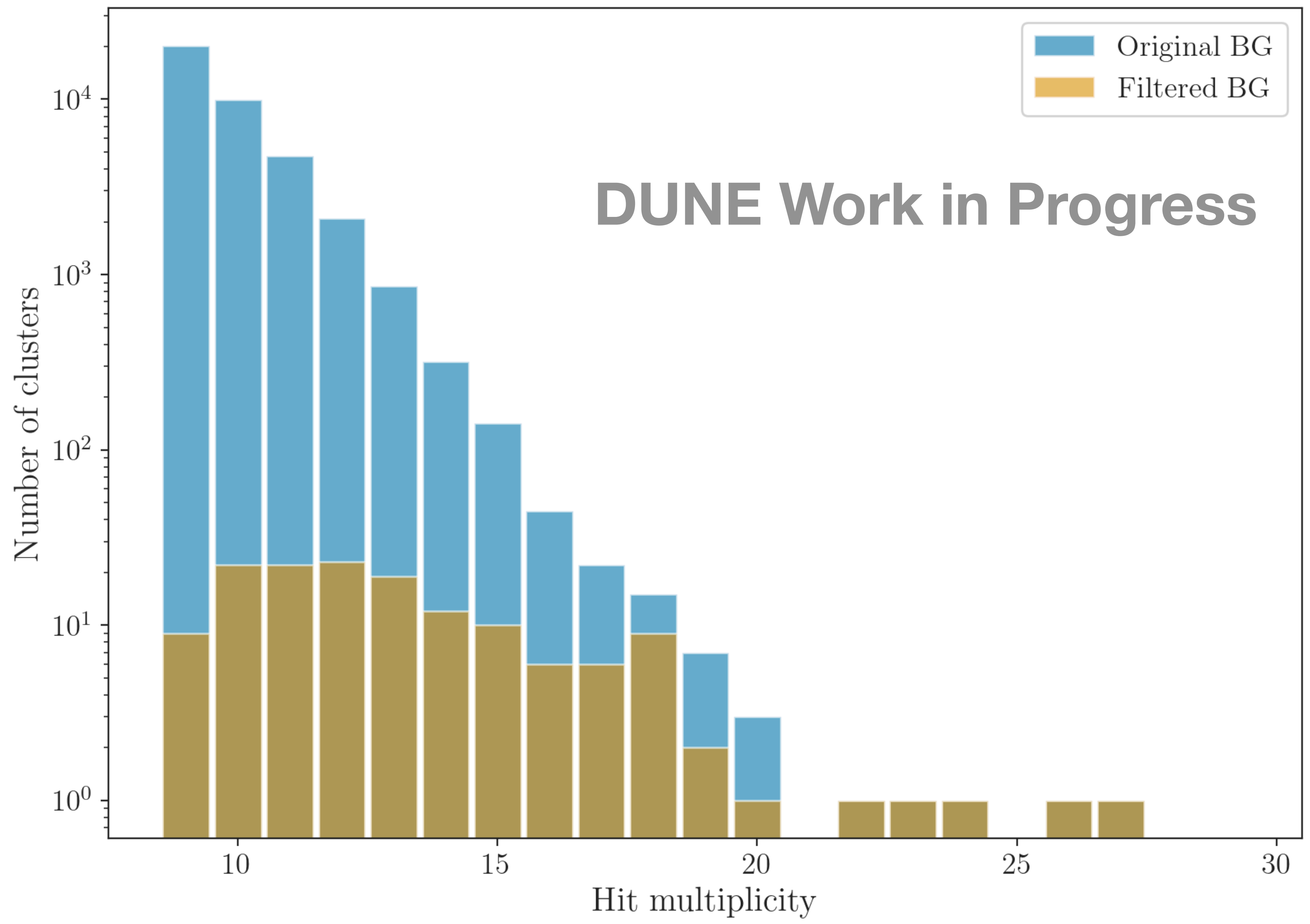
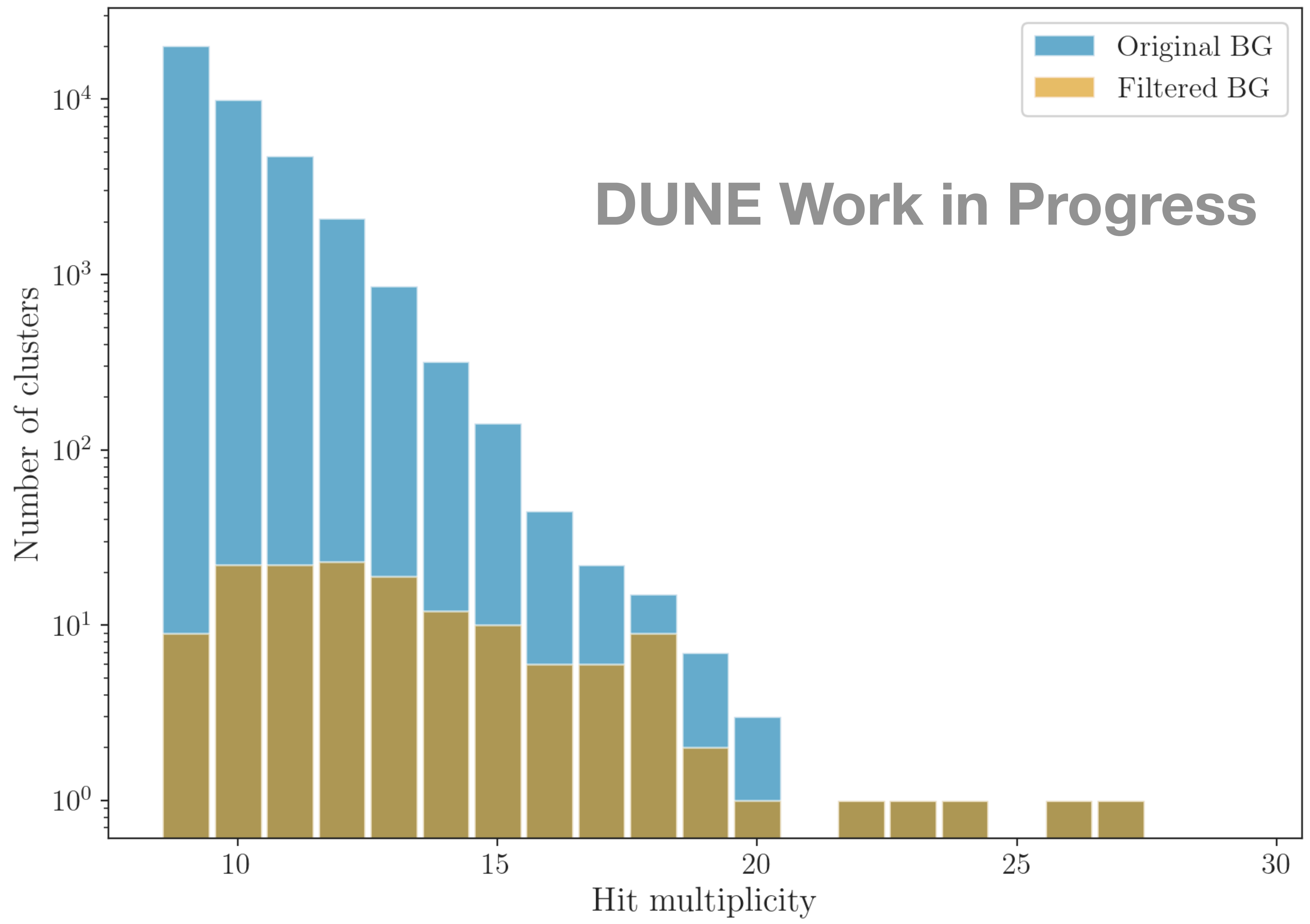


Background spectra before and after filtering the clusters through the BDT

Trigger algorithm

- Our BDT is applied to all BG clusters to generate the expected background histogram. The histogram variable is hit multiplicity, as we found it to have the highest discriminating power.



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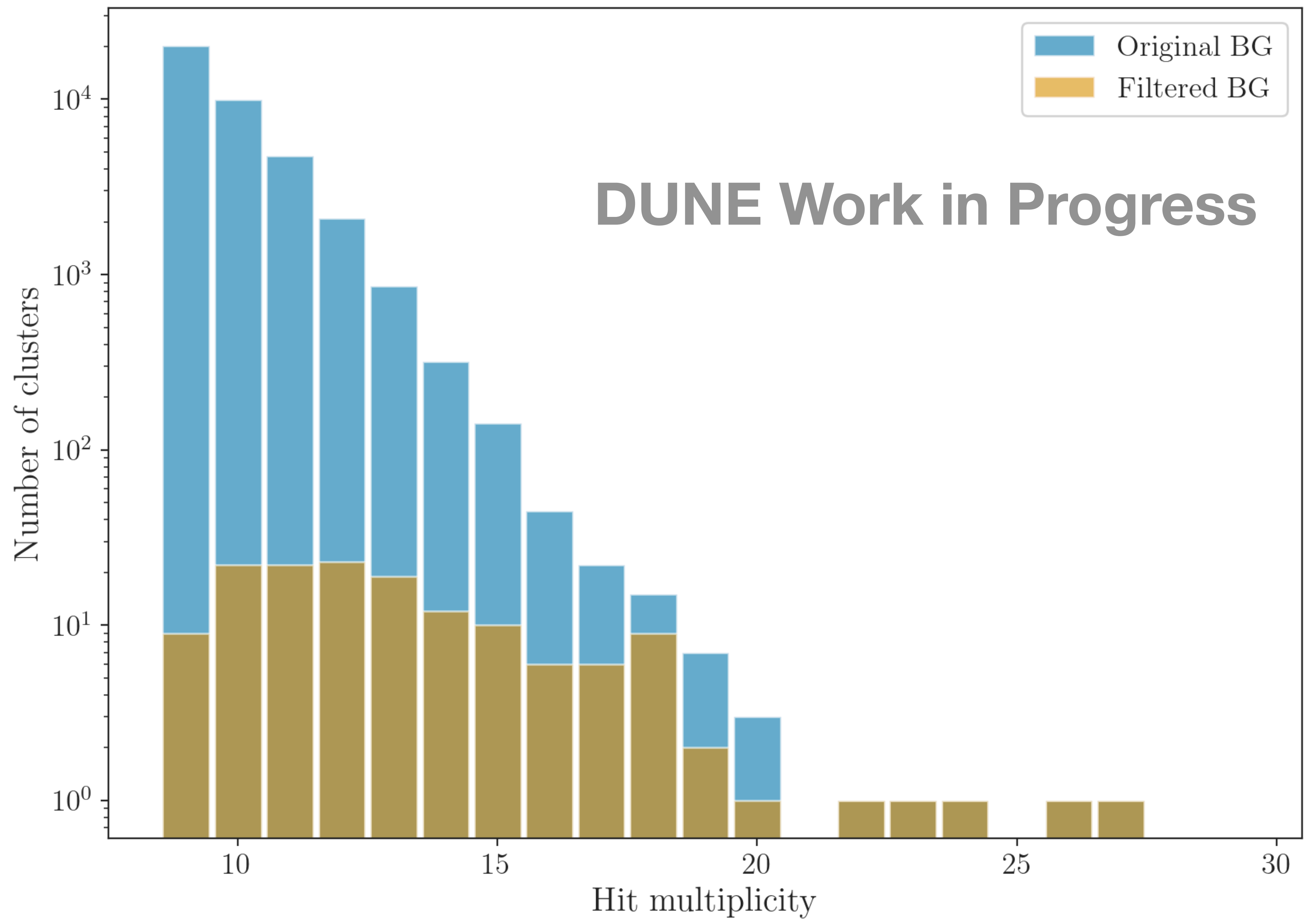

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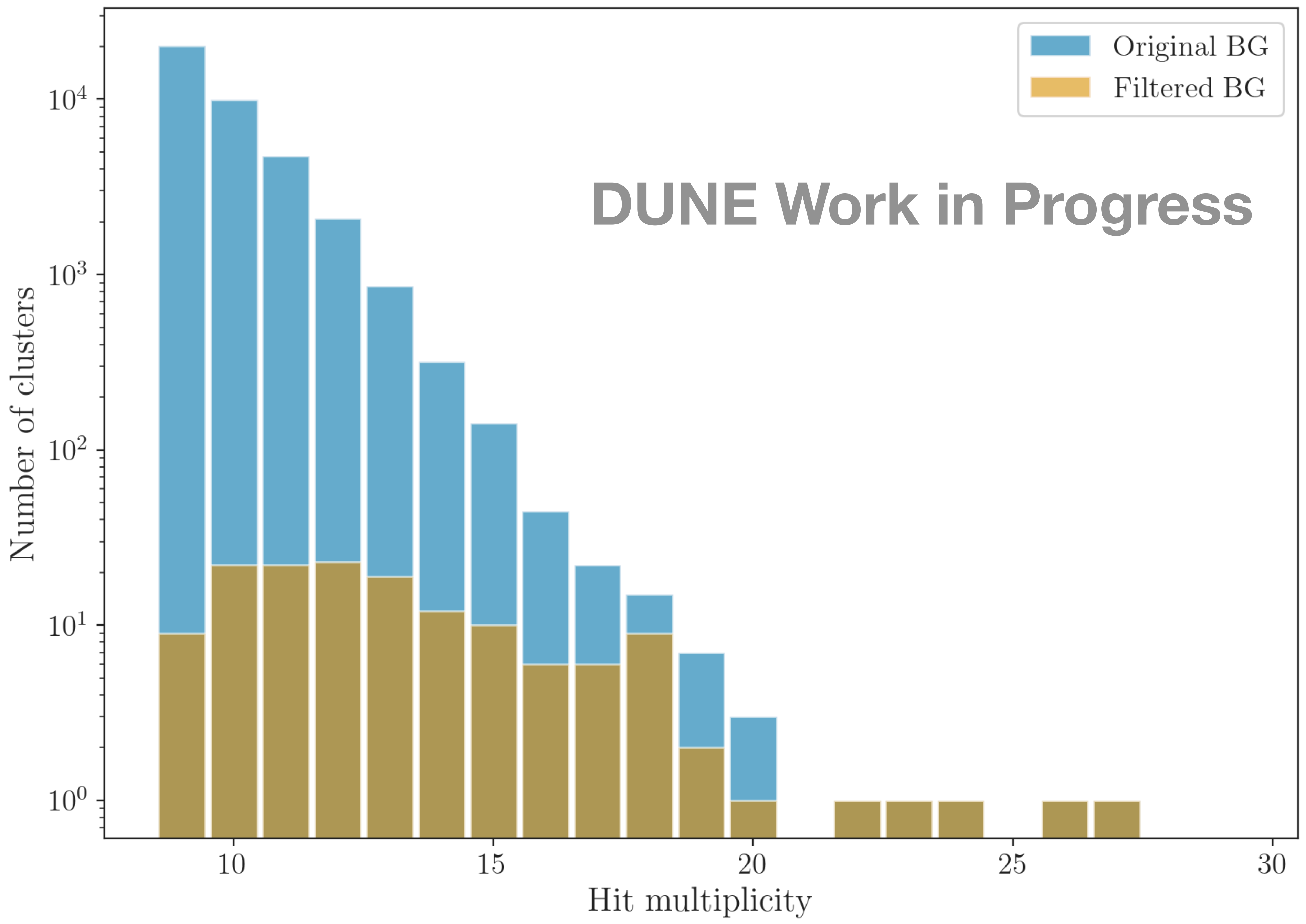

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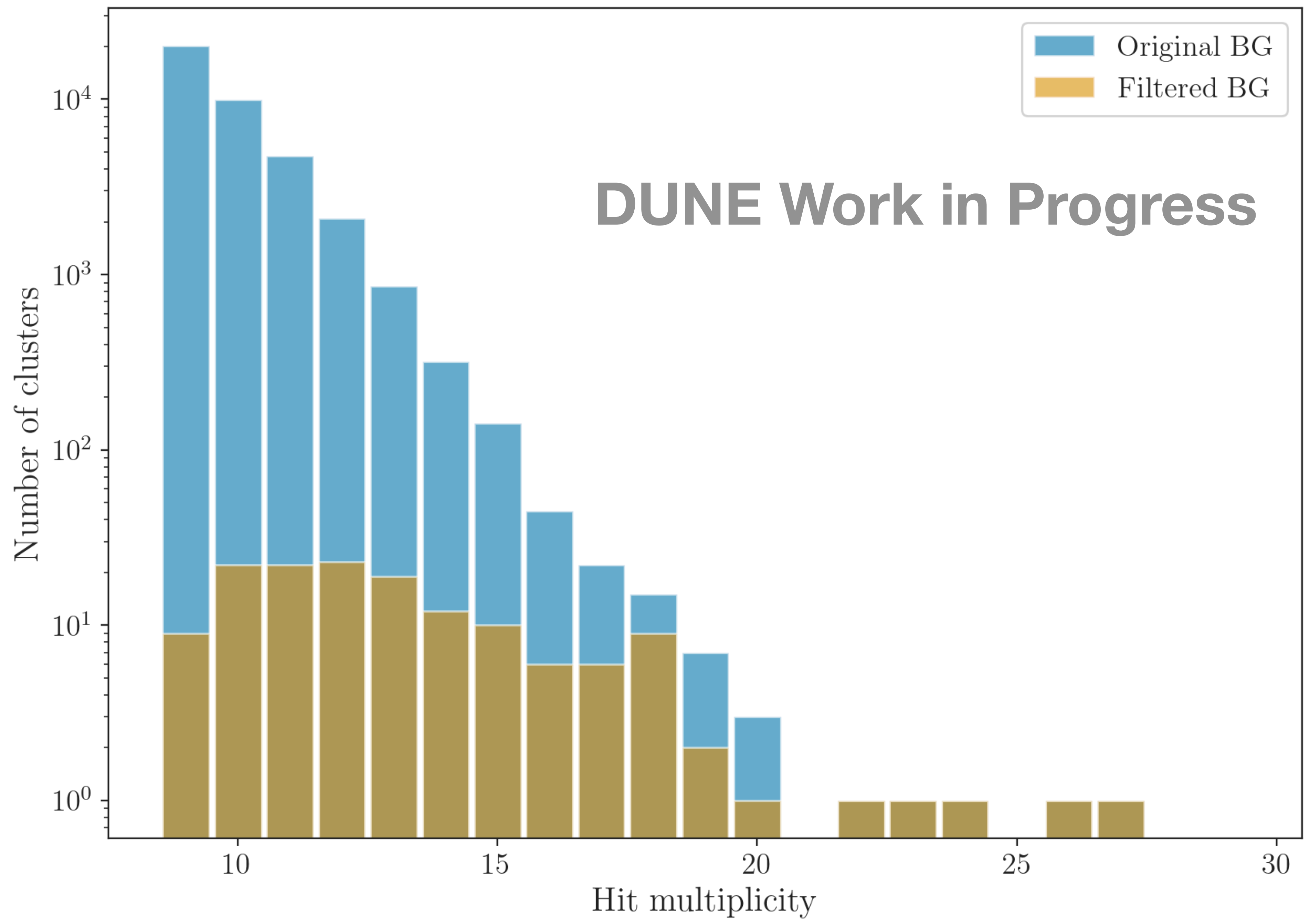
- Trigger when $P(\chi^2 > \chi^2_{\text{crit}}) \geq 1/$month (DUNE and SNEWS requirement) in our burst time window (~1 second).



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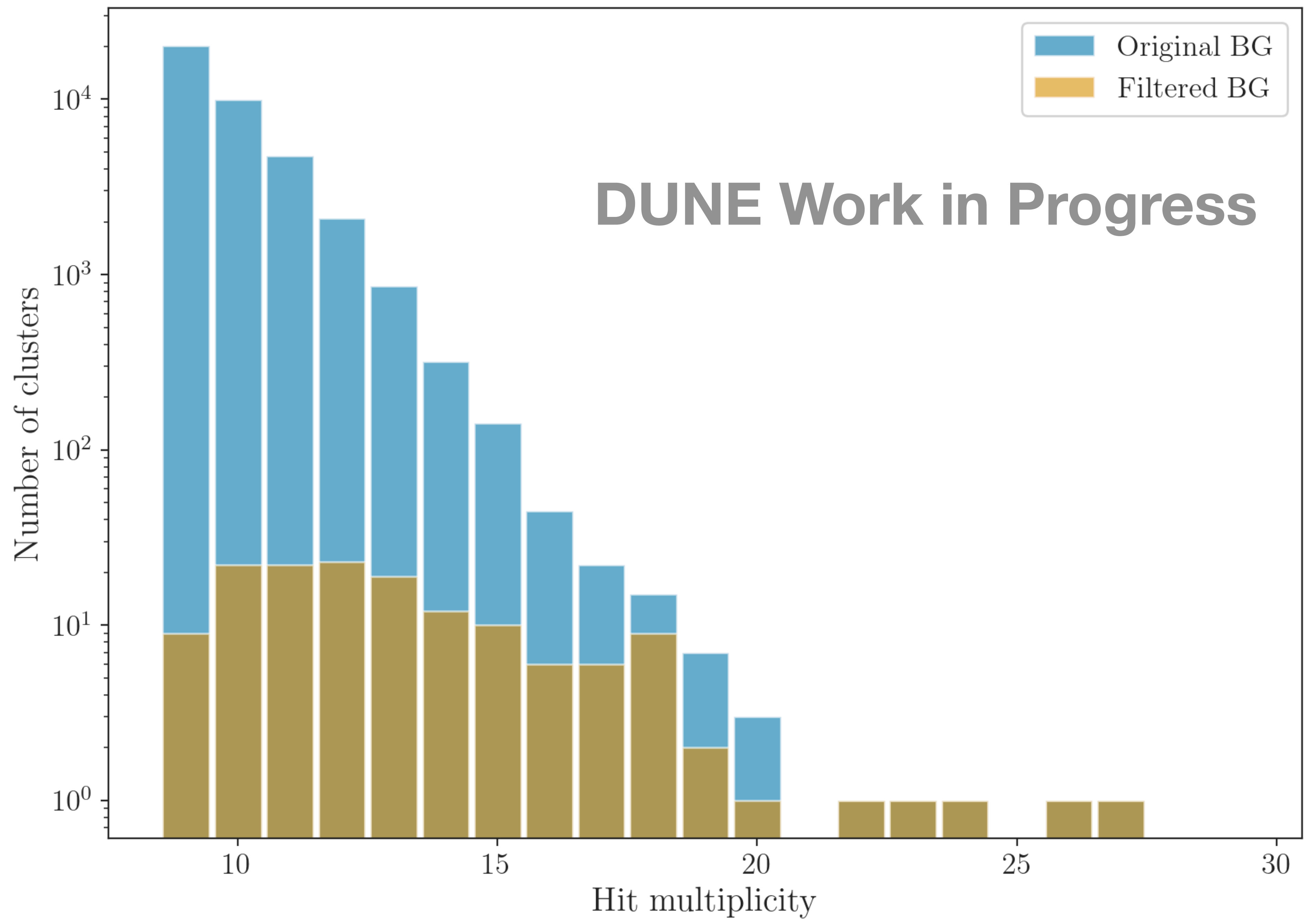
- Trigger when $P(\chi^2 > \chi^2_{\text{crit}}) \geq 1/$month (DUNE and SNEWS requirement) in our burst time window (~1 second).
- Trigger efficiency for a set of parameters estimated as the number of successful triggers over the total number of SNBs *k*.



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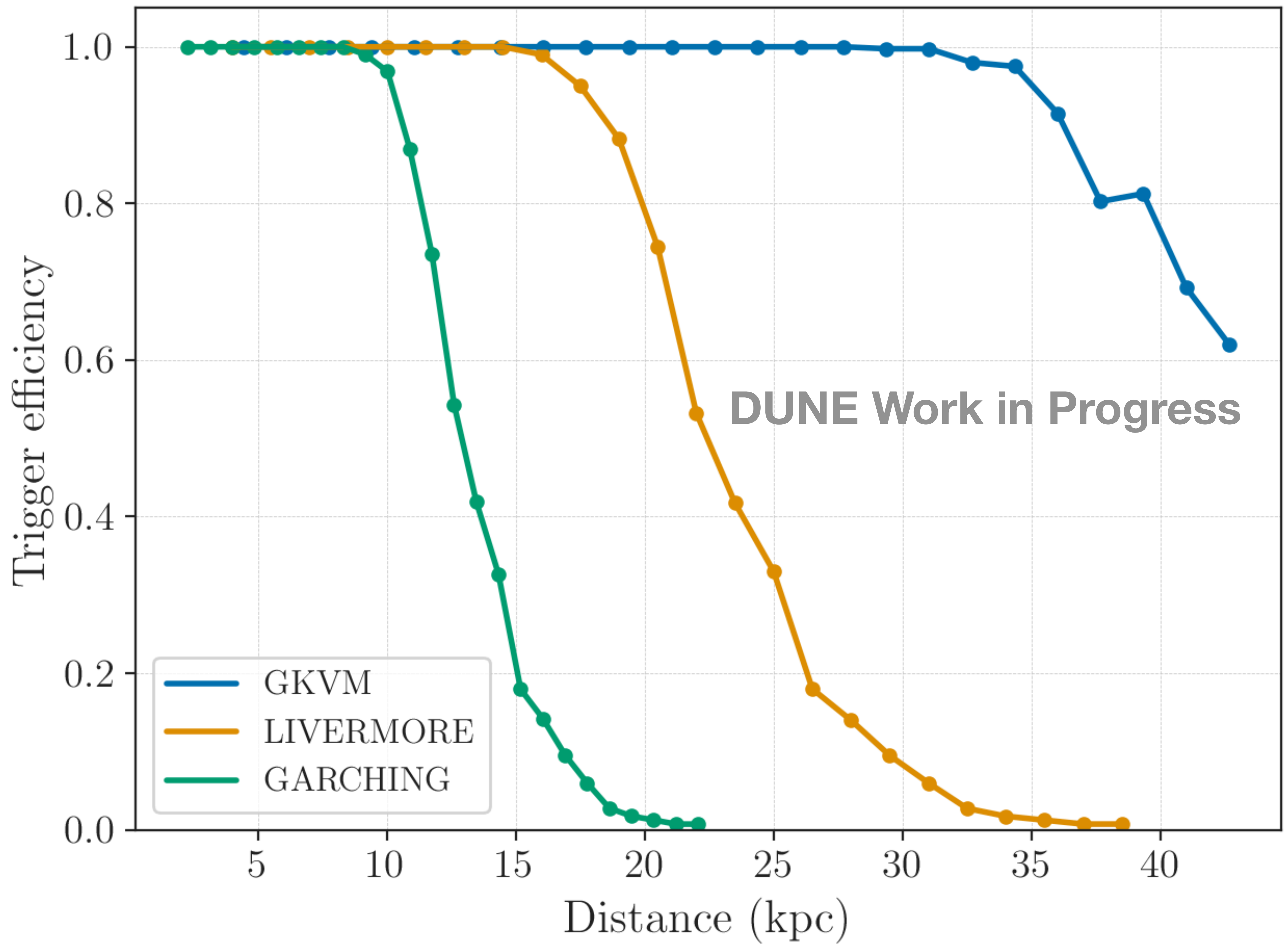
New trigger results (Preliminary)



	10 kpc	15 kpc	20 kpc	95% thresh
Livermore	1	0.997	0.791	18.61 kpc
Garching	0.969	0.212	0.014	10.63 kpc
GKVM	1	1	1	36.34 kpc

Trigger efficiencies (computational graph 10 kt)

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2. Supernova neutrino burst trigger
3. **Prospects**

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Prospects

- **Study the trigger efficiency for a complete set of scenarios:**
  - Different detector technologies (HD vs. VD) with the newer background models and geometries being developed.
  - Different DAQ thresholds (possible lower thresholds vs. the current 15 ADC counts).
  - Limited background scenarios.
  - Understand the algorithm’s robustness to small changes in the models and the light simulation.

Summary

- Detecting and studying the neutrino flux from a core-collapse supernova will give us important information related to both particle physics and astrophysics, including unique phenomena like neutrino self-interactions.
- DUNE will be uniquely sensitive to the ν_e charged current interaction channel among present and future neutrino detectors.
- Current results find DUNE's current PDS trigger sensitivity to a core-collapse supernova to be in the 10-30 kpc range. The precise value is highly dependent on the chosen supernova neutrino burst model.

Thank you for listening!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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XX International Workshop on Neutrino Telescopes

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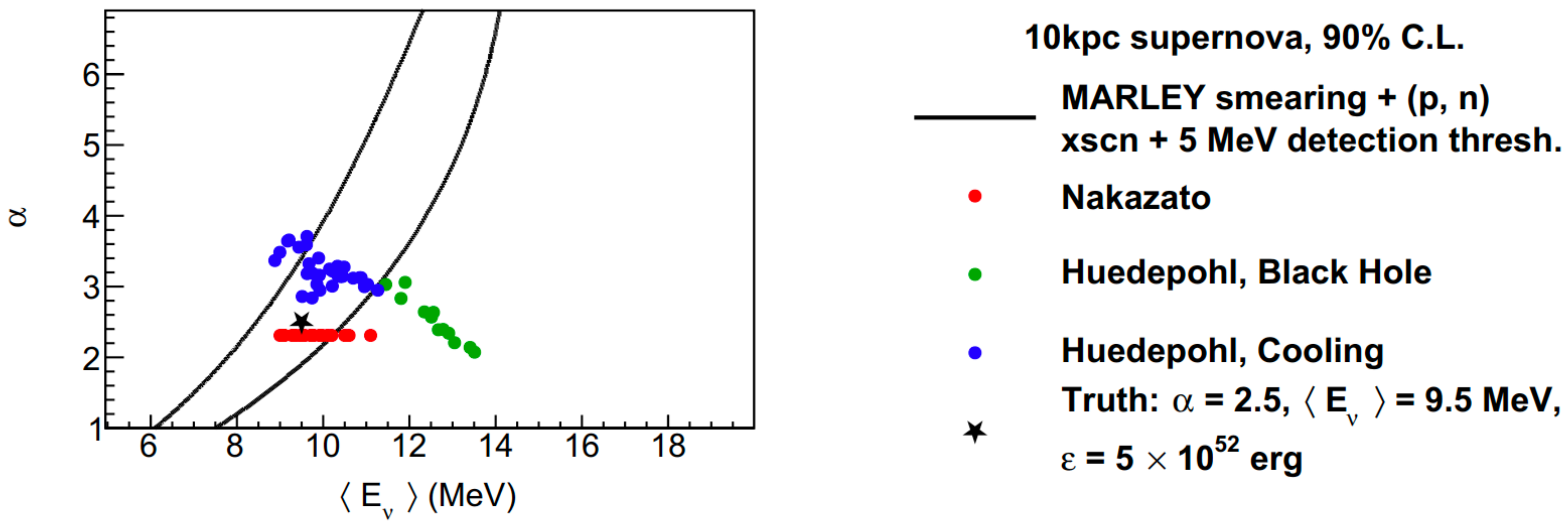
Physics: astrophysics of core collapse

- Study of the SN explosion mechanism.
- SN neutrino burst in coincidence with gravitational waves and as an early warning to astronomers.
- Long-timescale sensitivity search (i.e. SNB background) can provide limits on the SN core-collapse rate.
- **Supernova spectral parameter fit:**

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

At any given time, the energy spectrum of SN neutrinos is given approximately by the above.
Goal: find the evolution of luminosity *N*, *<E>* and pinching parameter α with time.



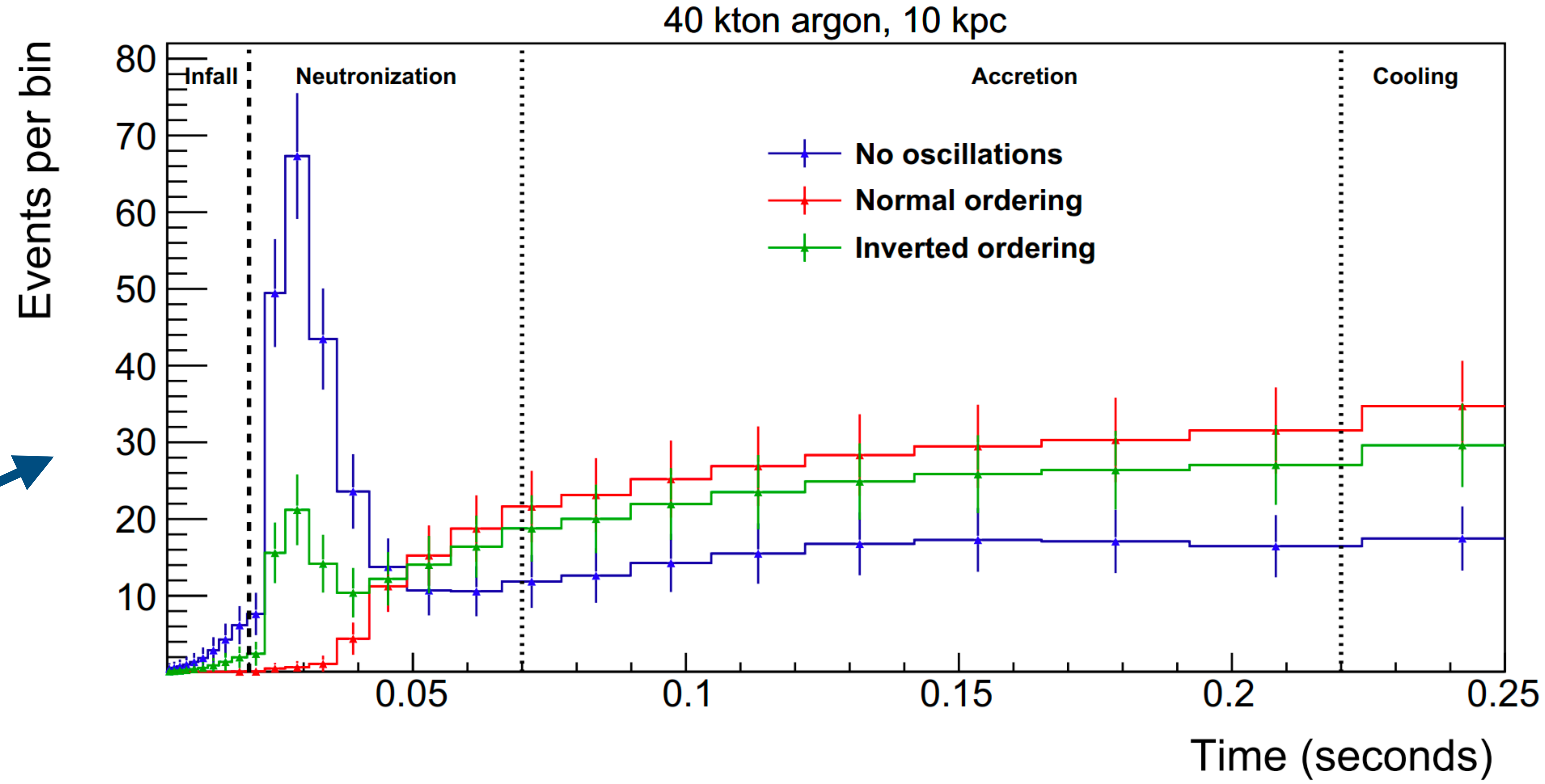
Physics: neutrino and particle physics

- **Flavor transition physics.** Search for signatures left by flavor transitions in early and late stages of the core collapse, where there are great theoretical uncertainties.

- **Neutrino-neutrino scattering.** The initial stages of a CC SN are dense enough for coherent scattering of neutrinos from each other —> oscillations characterized by collective models.

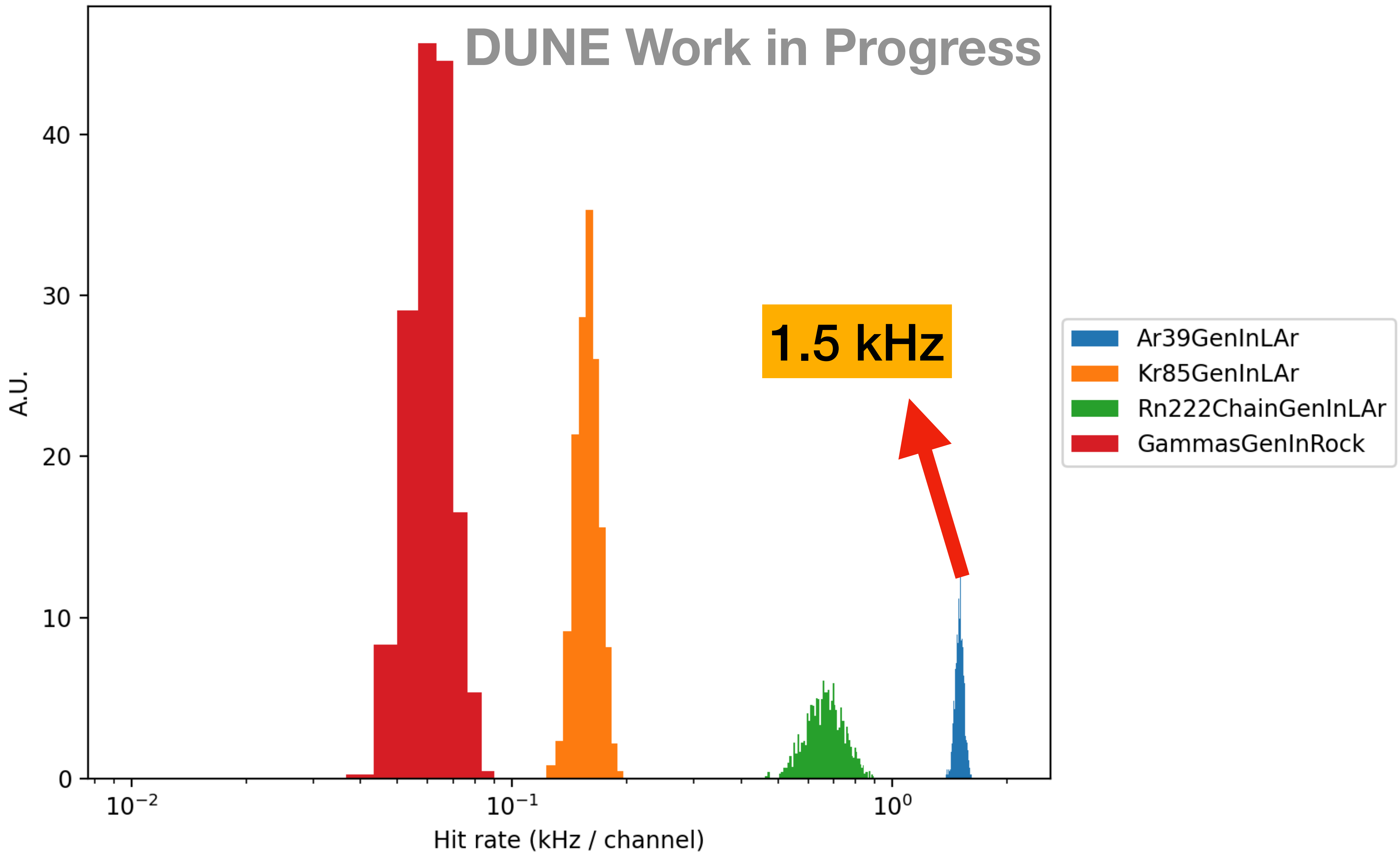
- Neutrino mass ordering effects.

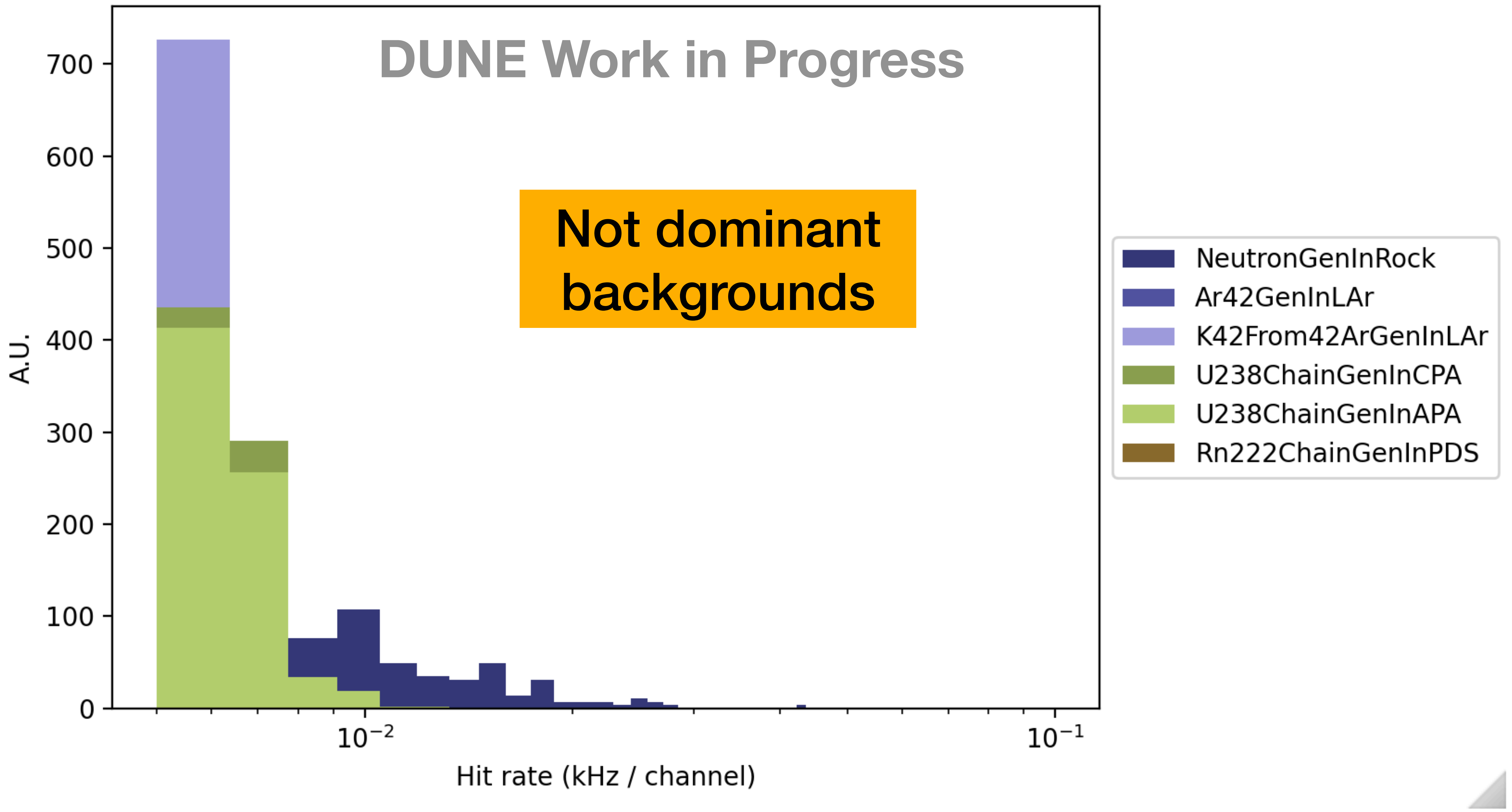
- Searches for new physics (of course).



Event generation: backgrounds

Three main backgrounds (in terms of hit rate) are: Ar39 in LAr, Rn222 in LAr and Kr85 in LAr, followed by cavern gammas.





Algorithm: clustering

The optimal cluster parameters found (including the BDT) for Livermore and Garching models and used in the TDR where:

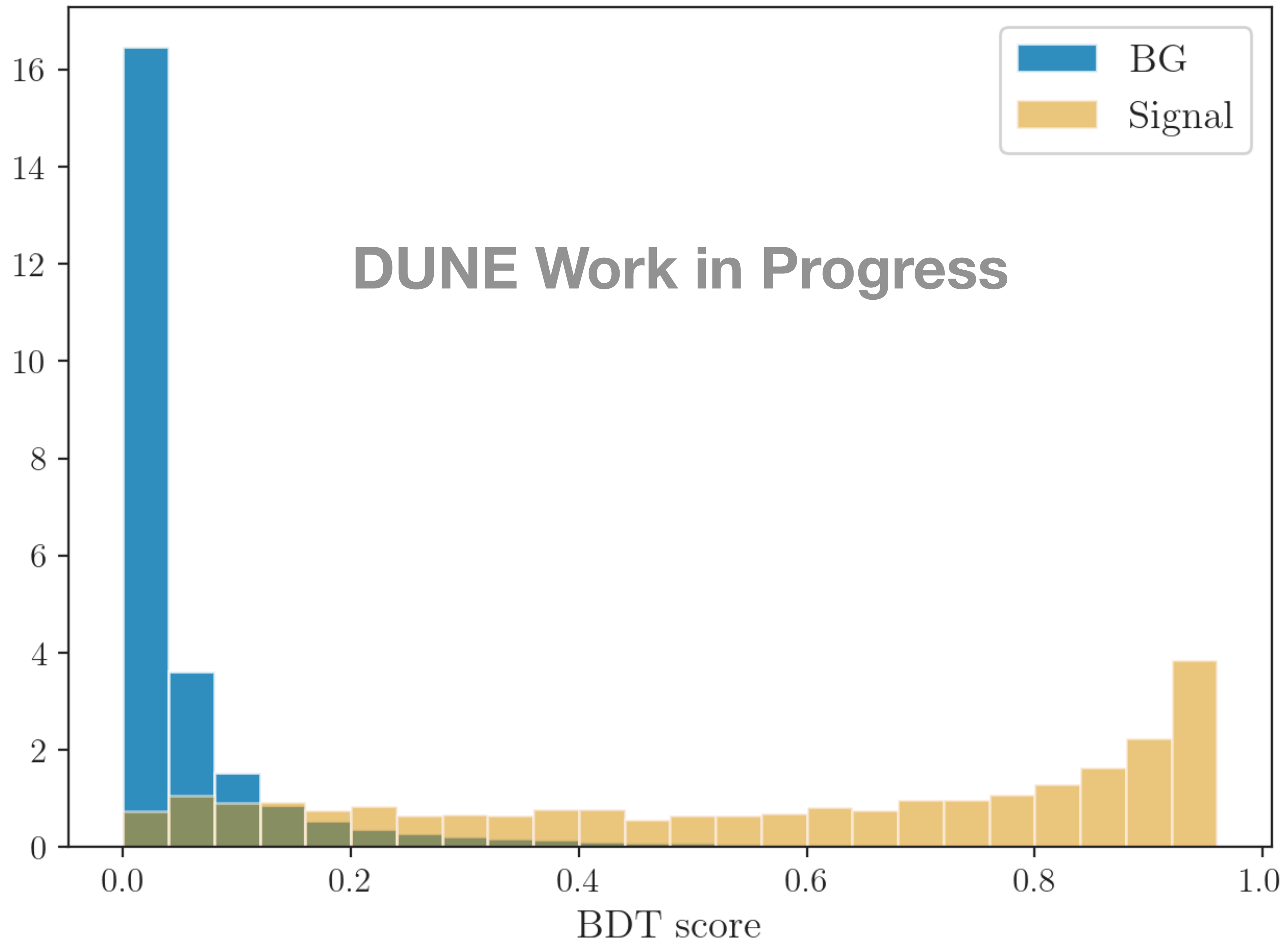
- Maximum cluster duration: **190 us**
- Maximum time difference between consecutive hits: **110 us**
- Maximum spatial distance between neighbouring optical channels detecting the hits: **270 cm**
- Minimum hit multiplicity: **9**

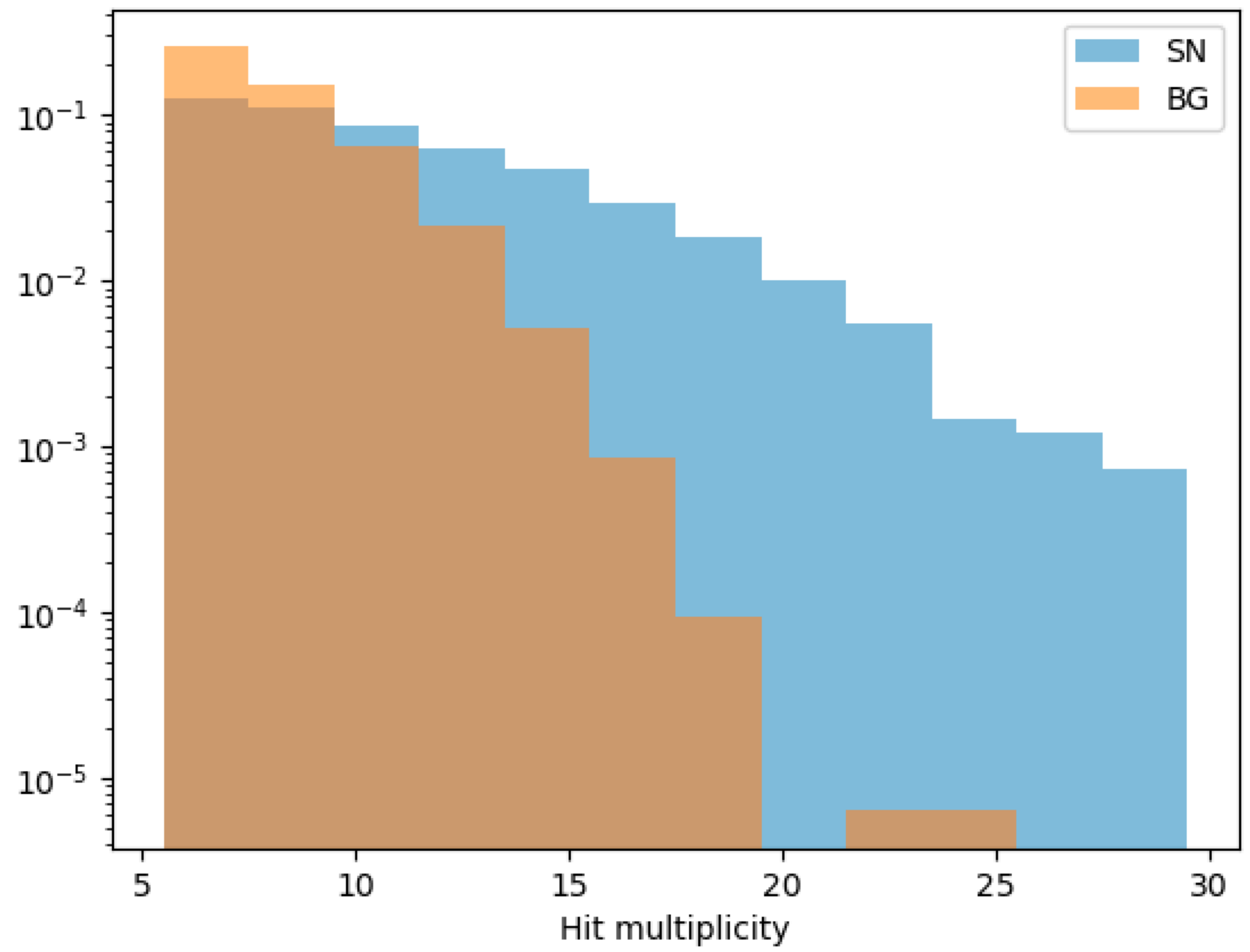
We can also find the optimal clustering parameters *without* using the BDT. In this case the search was less exhaustive, but we find:

- Maximum cluster duration: **250 us**
- Maximum time difference between consecutive hits: **170 us**
- Maximum spatial distance between neighbouring optical channels detecting the hits: **400 cm**
- Minimum hit multiplicity: **9**

Algorithm: BDT

- We obtain a great discrimination between signal and background clusters!
- Need to take into account that not all SN events deposit visible light.





Hit multiplicity per cluster distributions for supernova and background events

TPC Trigger results (VD TDR Dec 22)

Livermore model

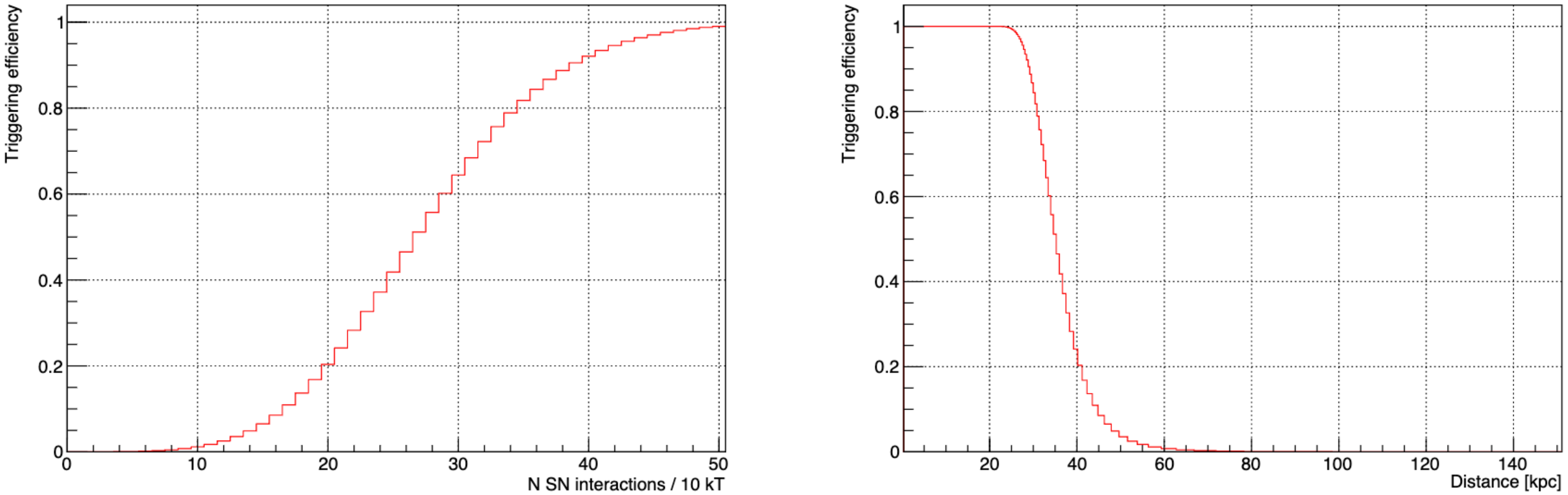
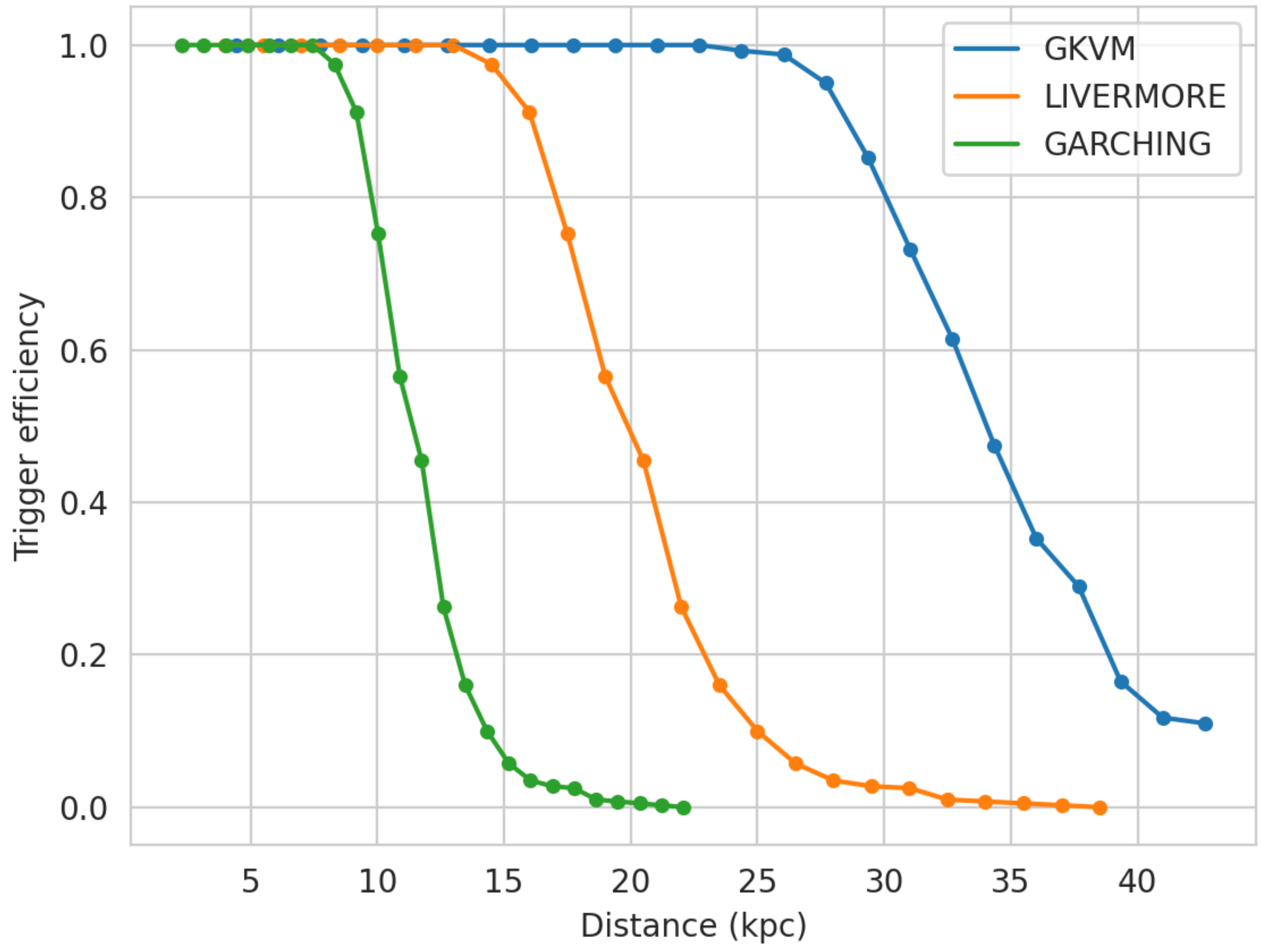


Figure 1.6: SNB triggering efficiency using the TPC signal. Left: In terms of the real number of interactions. Right: Converted to the distance from an SNB.

PDS Trigger results (VD TDR Dec 22)

Comparing several SN models:

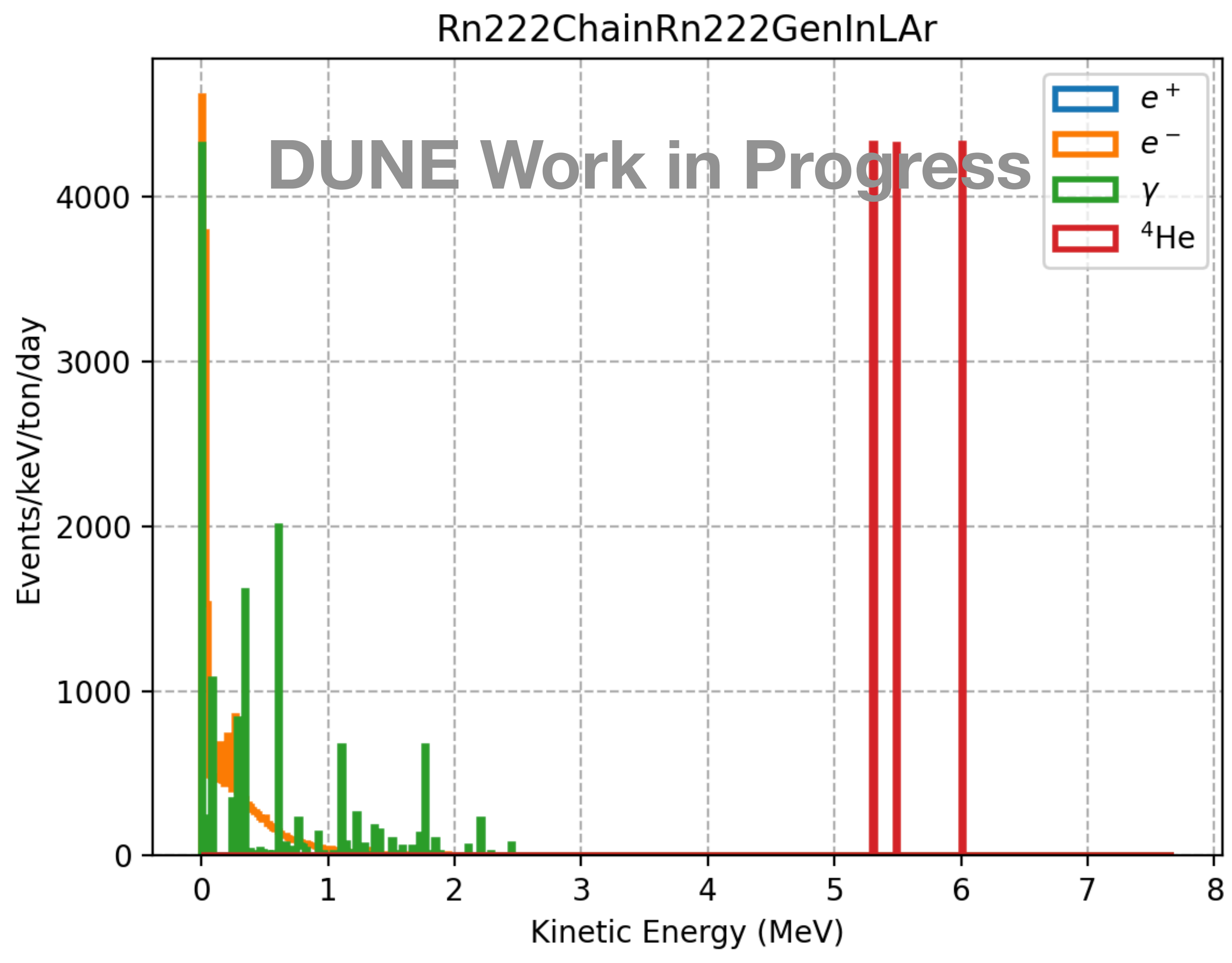


	10 kpc	15 kpc	20 kpc	95% thresh
Livermore	1	0.954	0.492	16.12 kpc
Garching	0.758	0.066	0.006	9.24 kpc
GKVM	1	1	1	28.56 kpc

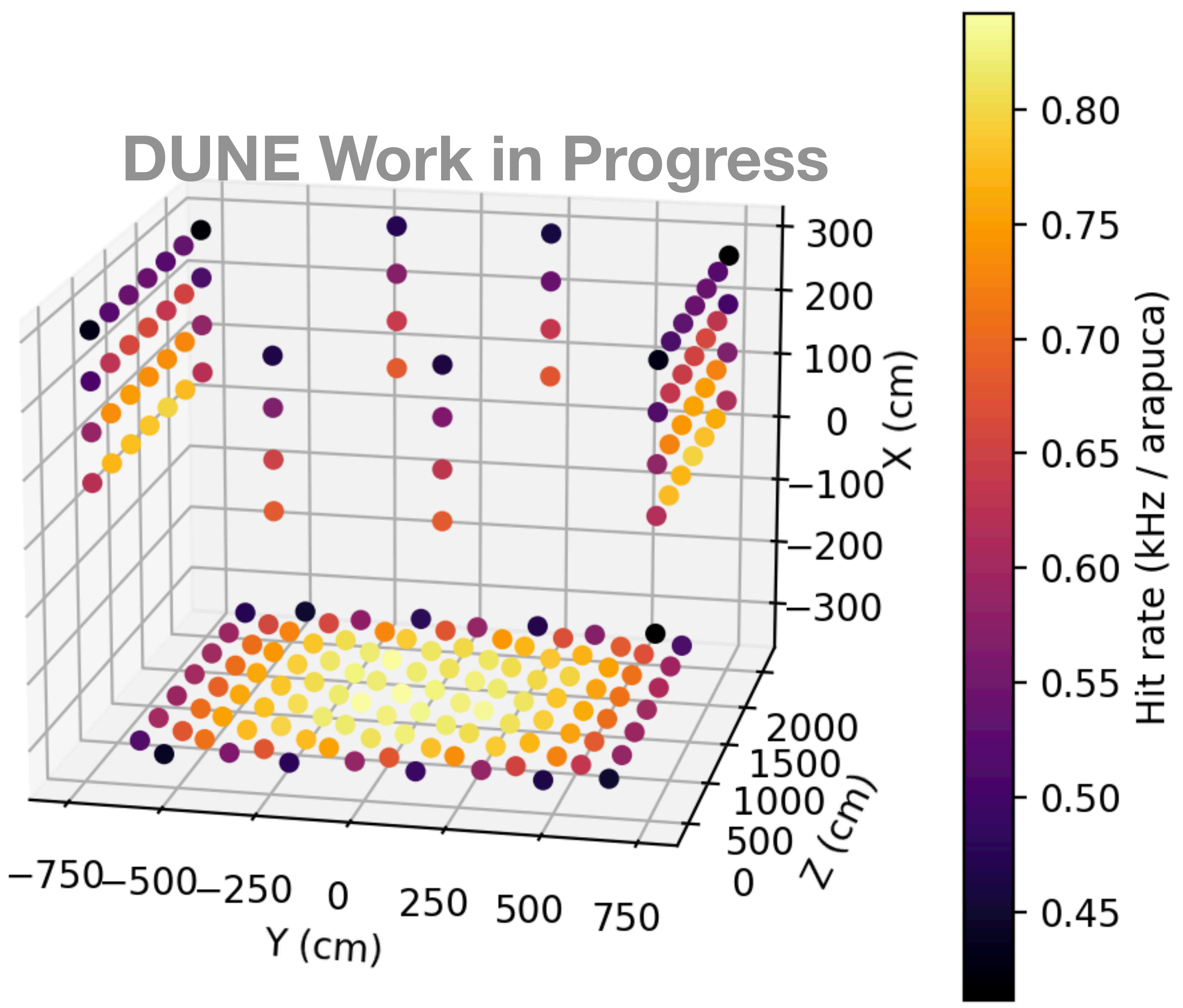
Trigger efficiencies (12 kt active volume)

Background characterization

- Checks that backgrounds are correctly generated and propagated through the detector (some problems with cavern gammas)



Rn222 decay chain energy distribution (truth)

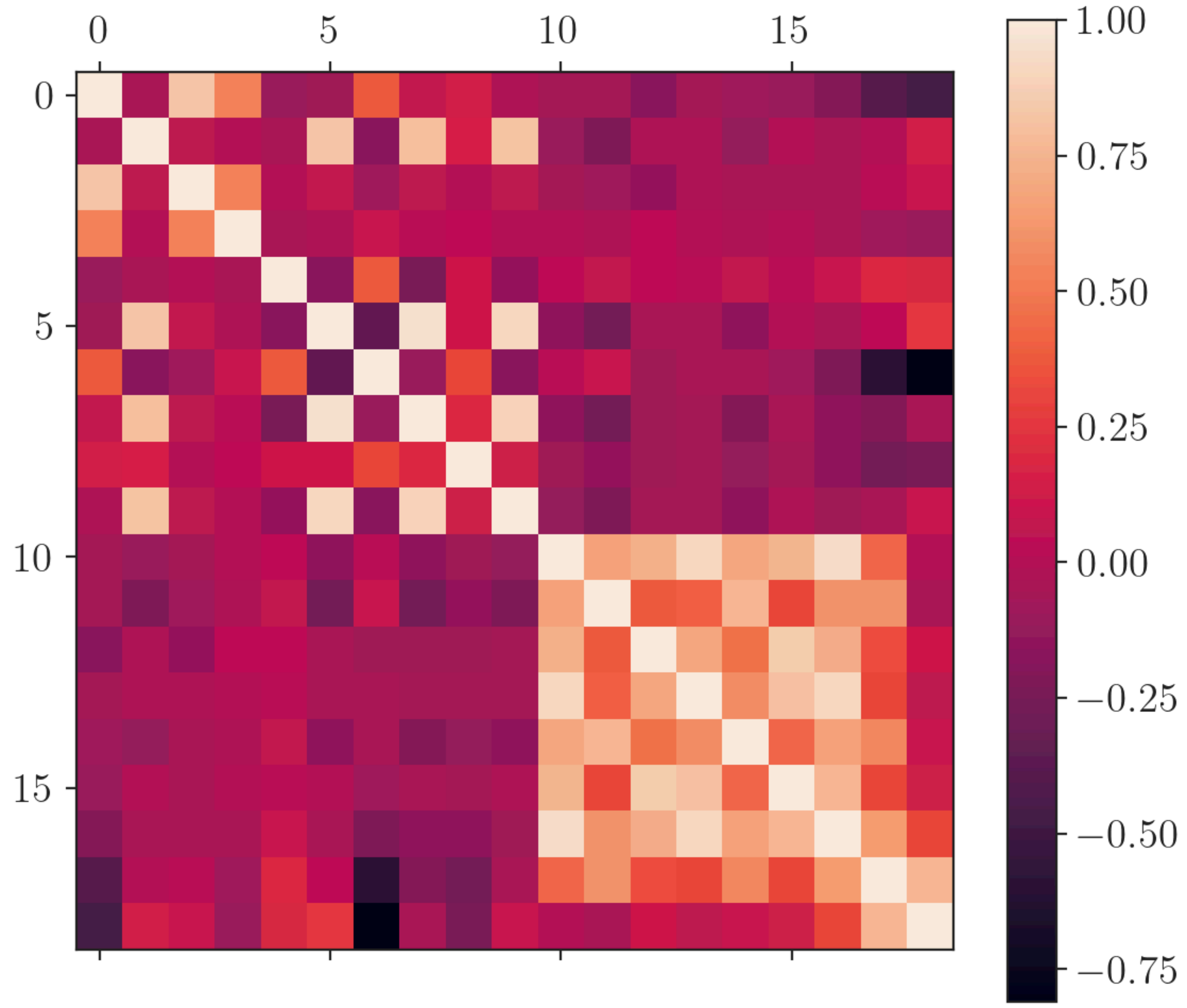


Hit rate received per X-ARAPUCA

- **New radiological model (decay0 v3) under development** by the DUNE Low Energy group (more accurate gamma and neutron simulation, and updated decay rates from the assays).

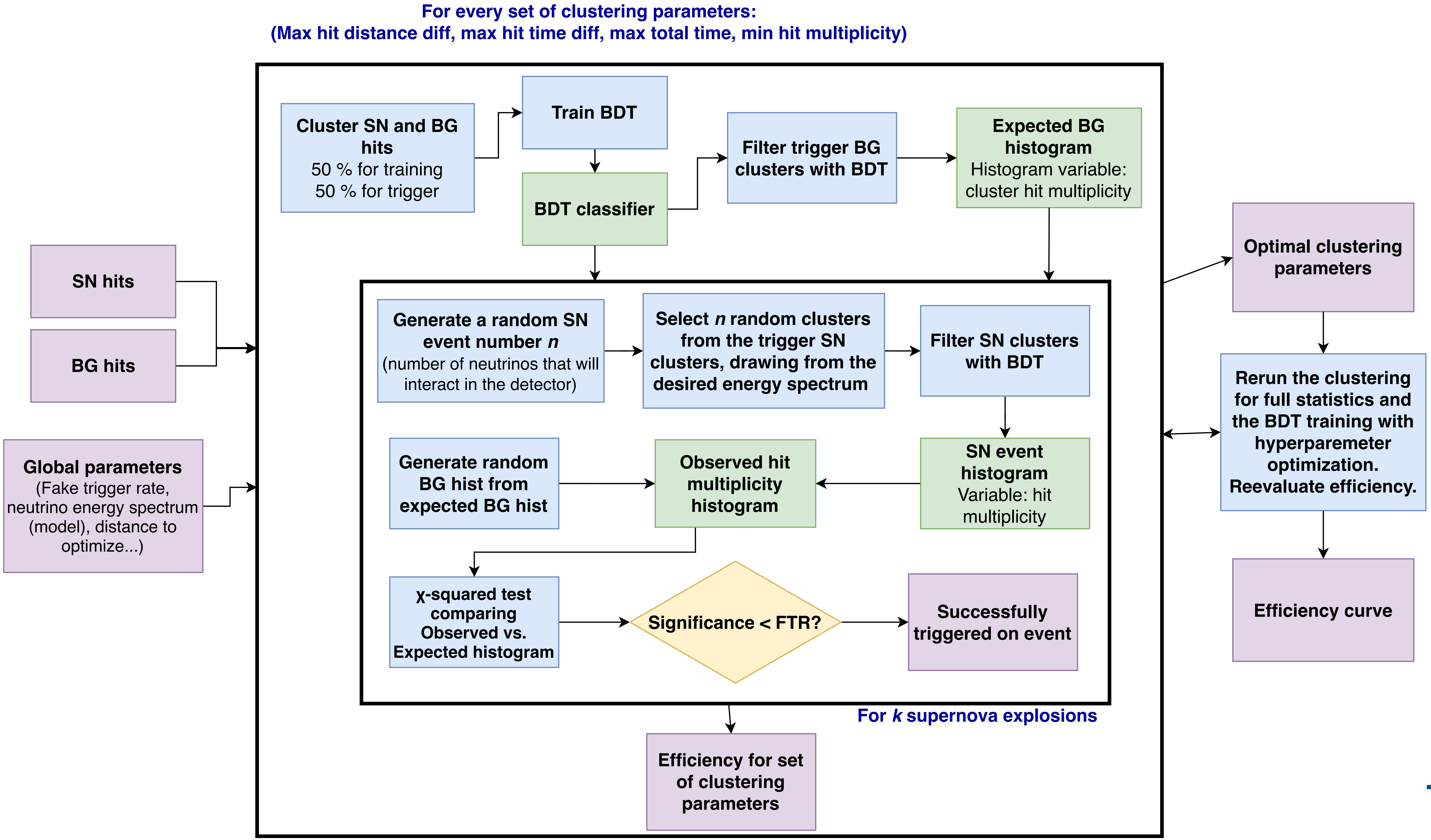
Prospects

- **BDT parameter importance and correlation:** Interest from the DAQ group on implementing the trigger algorithm without (or with a reduced version) of the BDT. And interesting from the physics point of view.



Correlation matrix of the BDT cluster parameters

- **MARLEY event generator.** MARLEY is missing interaction channels (NC, antineutrino) that could be very important for supernova triggering and for the posterior physics analysis. Also, it relies on a simplified cross section model that is inaccurate at higher energies (e.g. crucial for angular distribution and pointing). *Working on this!*


For every set of clustering parameters:
(Max hit distance diff, max hit time diff, max total time, min hit multiplicity)
Cluster SN and BG hits
50 % for training
50 % for trigger
Train BDT
BDT classifier
Filter trigger BG clusters with BDT
Expected BG histogram
Histogram variable: cluster hit multiplicity
SN hits
BG hits
Global parameters
(Fake trigger rate, neutrino energy spectrum (model), distance to optimize...)
Generate a random SN event number n
(number of neutrinos that will interact in the detector)
Select n random clusters from the trigger SN clusters, drawing from the desired energy spectrum
Filter SN clusters with BDT
Generate random BG hist from expected BG hist
Observed hit multiplicity histogram
SN event histogram
Variable: hit multiplicity
χ-squared test comparing Observed vs. Expected histogram
Significance < FTR?
Successfully triggered on event
For k supernova explosions
Efficiency for set of clustering parameters
Optimal clustering parameters
Rerun the clustering for full statistics and the BDT training with hyperparemeter optimization. Reevaluate efficiency.
Efficiency curve