Supernova neutrinos in the DUNE experiment

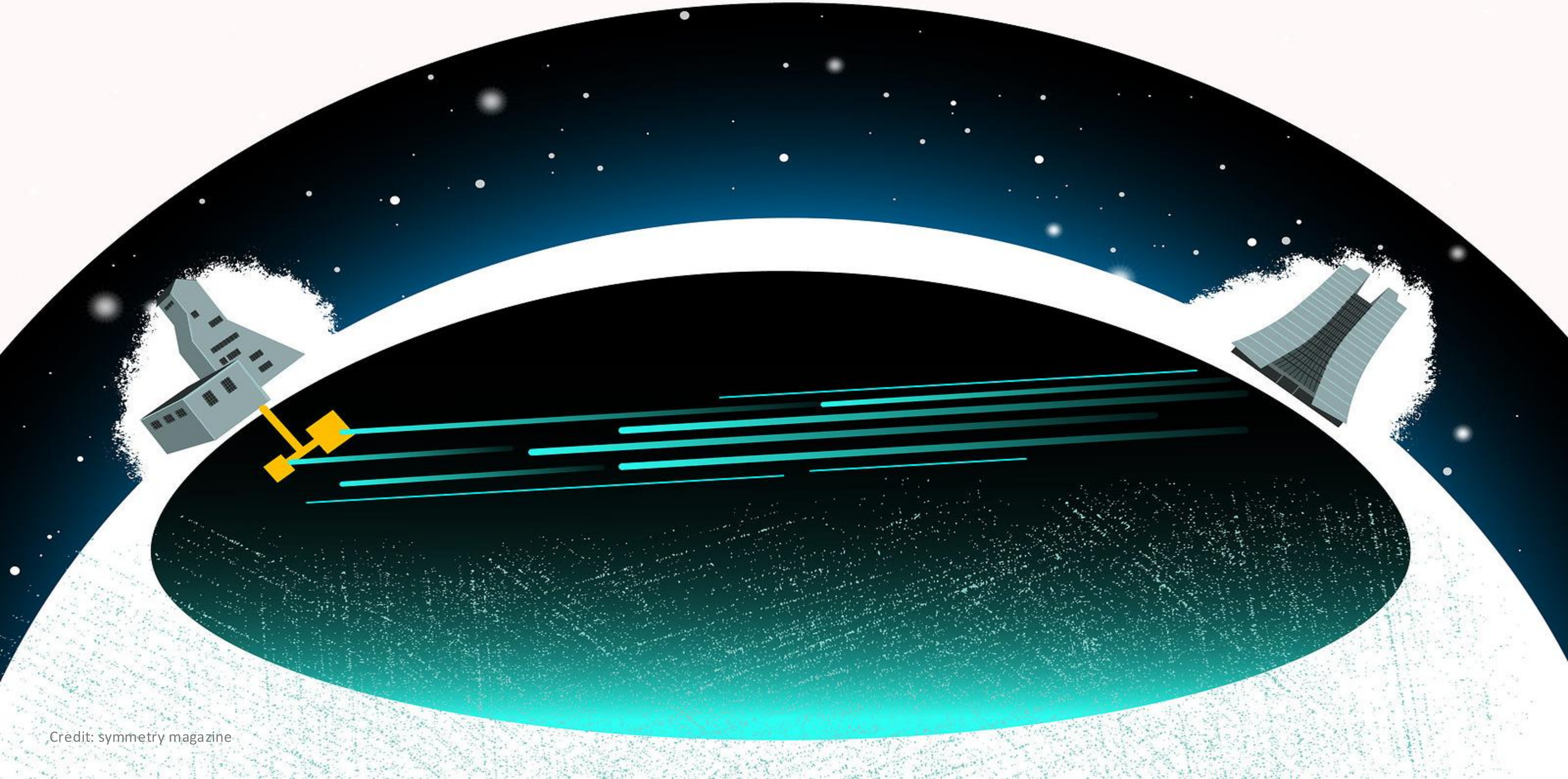
Clara Cuesta (CIEMAT) on behalf of the DUNE Collaboration

NuFact 2025

September 2nd, 2025

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
BBVA Foundation
DUNE

The Deep Underground Neutrino Experiment (DUNE)



Credit: symmetry magazine

The DUNE Collaboration

~1400 collaborators from
~200 institutions in
>35 countries + CERN

DUNE plenary talk by P. Granger tomorrow

DUNE Collaboration Meeting,
Fermilab (USA),
May 2025

Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:

- Precise measurement of neutrino oscillation parameters (mass ordering, δ_{CP})
- **Detection of low energy neutrinos from a supernova and the sun**
- Searches for physics beyond the Standard Model

EPJC 80 (2020) 978
EPJC 81 (2021) 322
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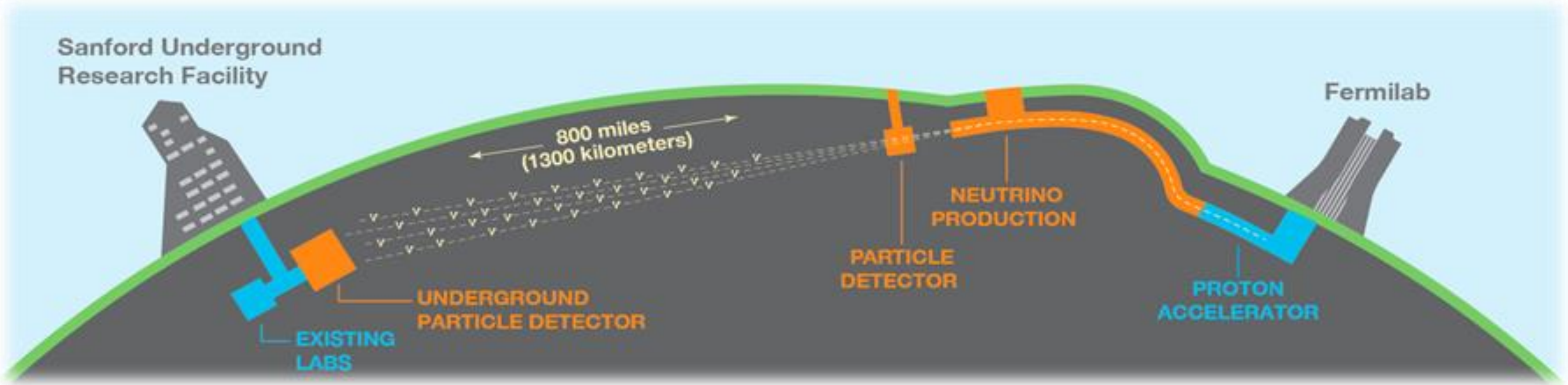
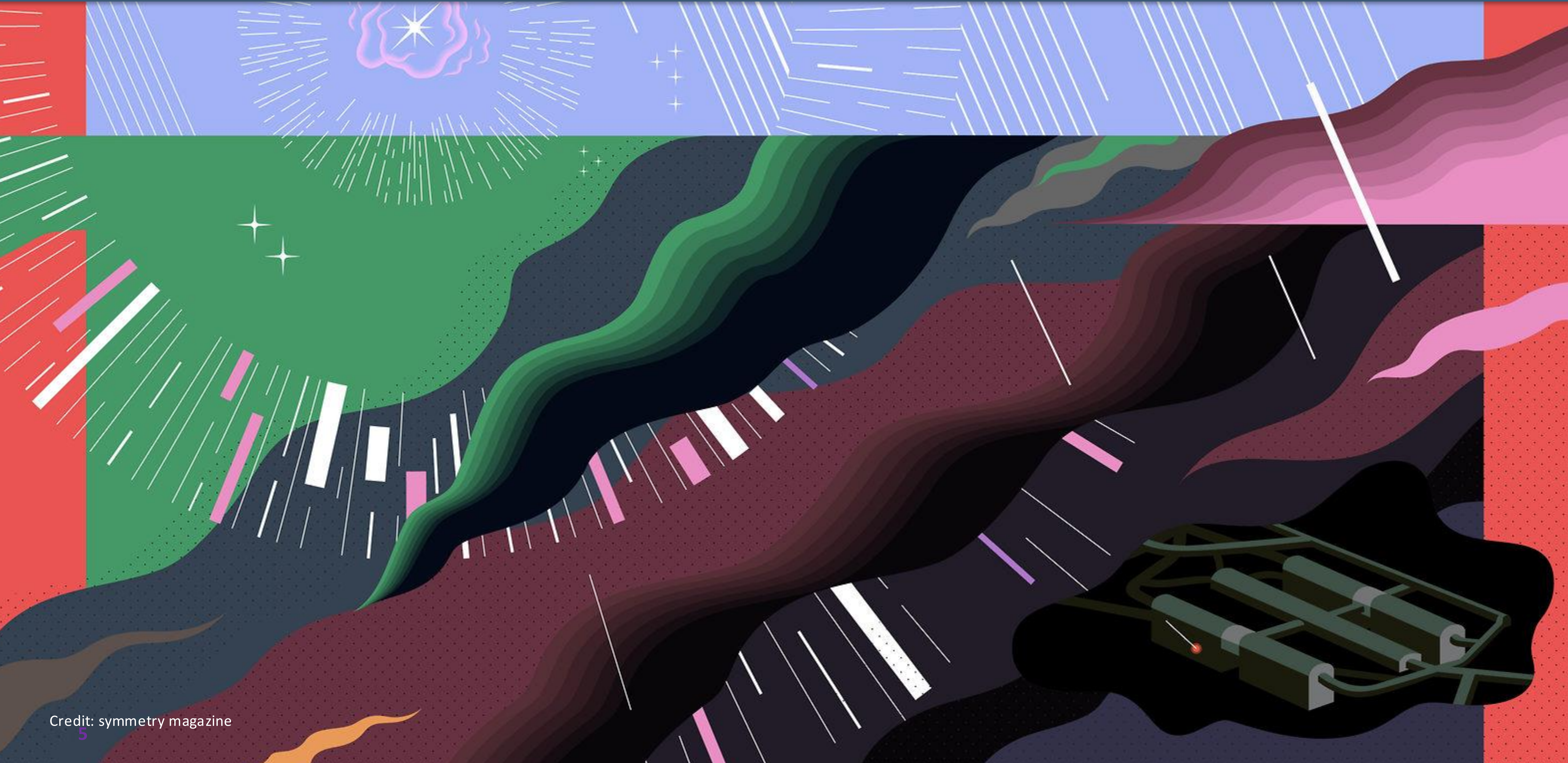


- New neutrino (ν_μ or $\bar{\nu}_\mu$) beam facility at Fermilab (LBNF), US.
- Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints. Instruments 5 (2021) 31
- **Far detector** composed by 4 x 17 kton liquid argon time-projection chambers (LArTPC) modules deep underground at SURF (Lead, SD, 1300 km baseline). JINST 15 (2020) T08008 JINST 15 (2020) T08010

DUNE Far Detector

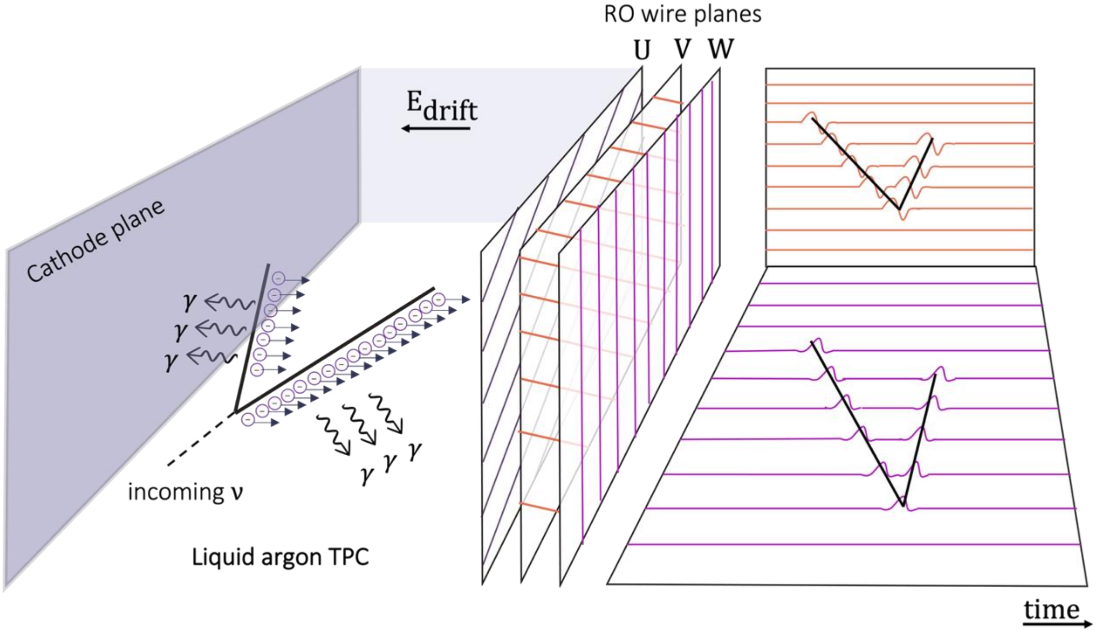


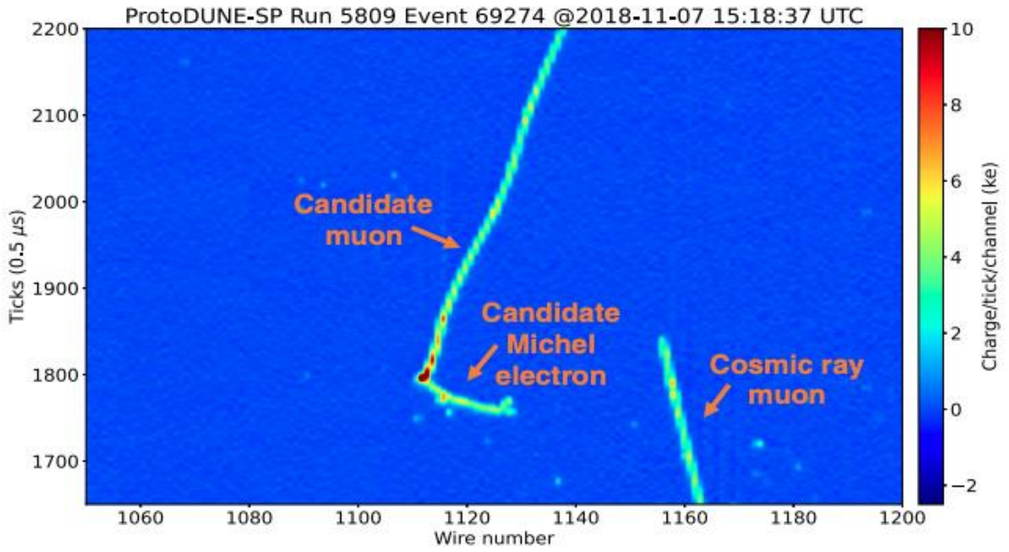
Credit: symmetry magazine

LAr TPC technology

[PRD 107 (2023) 092012](#)

- Liquid argon is inert, dense and naturally abundant.
- Strong electric field applied across the TPC to collect e^- produced by energy loss.
- LAr is transparent to its own scintillation VUV light which can be used as an internal trigger and for complementary calorimetry measurement.



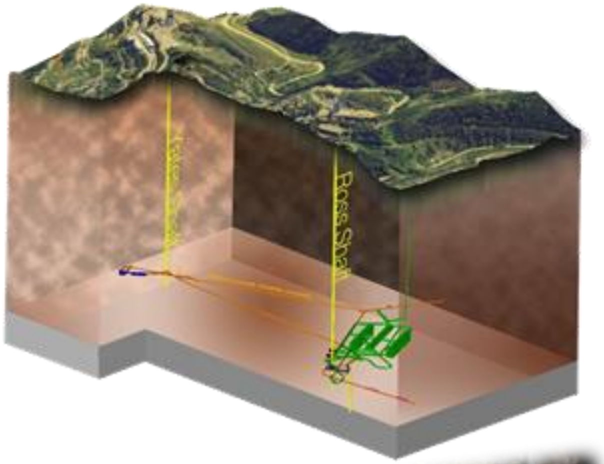


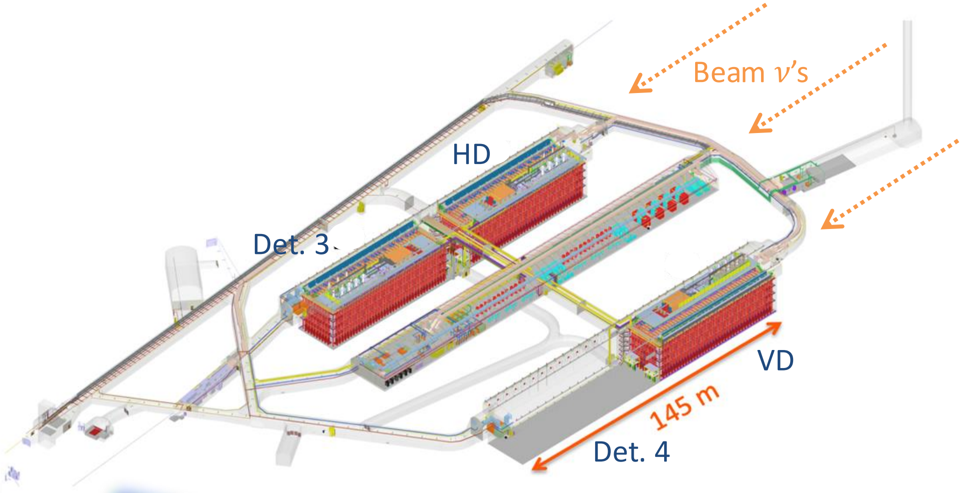
Michel e- candidate observed in ProtoDUNE-SP data.

- Excellent **3D imaging** – few mm scale over large volume detector.
- Excellent energy measurement. capability – **totally active calorimeter.**
- **Particle ID** by dE/dx, range, event topology.

DUNE Far Detector

Located 1.48 km underground at Sanford Underground Research Facility in Lead, South Dakota (USA)





Four 17-kt LAr TPC modules

Phase I:

- FD vertical drift (VD)
- FD horizontal drift (HD)

Phase II:

- Possibility of a module with enhanced low energy physics capabilities

ProtoDUNEs

Construction and operation of 1 kton-scale prototypes at CERN, critical to demonstrate viability of technology

Low energy events in DUNE

Credit: symmetry magazine

Low energy events in LAr

Solar neutrinos in DUNE talk by A. Lopez Moreno

The DUNE FD is sensitive to ν's produced by the Sun and in core-collapse supernovae with **E ~5-100 MeV**.

1. Charged-current (CC) interaction on Ar

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

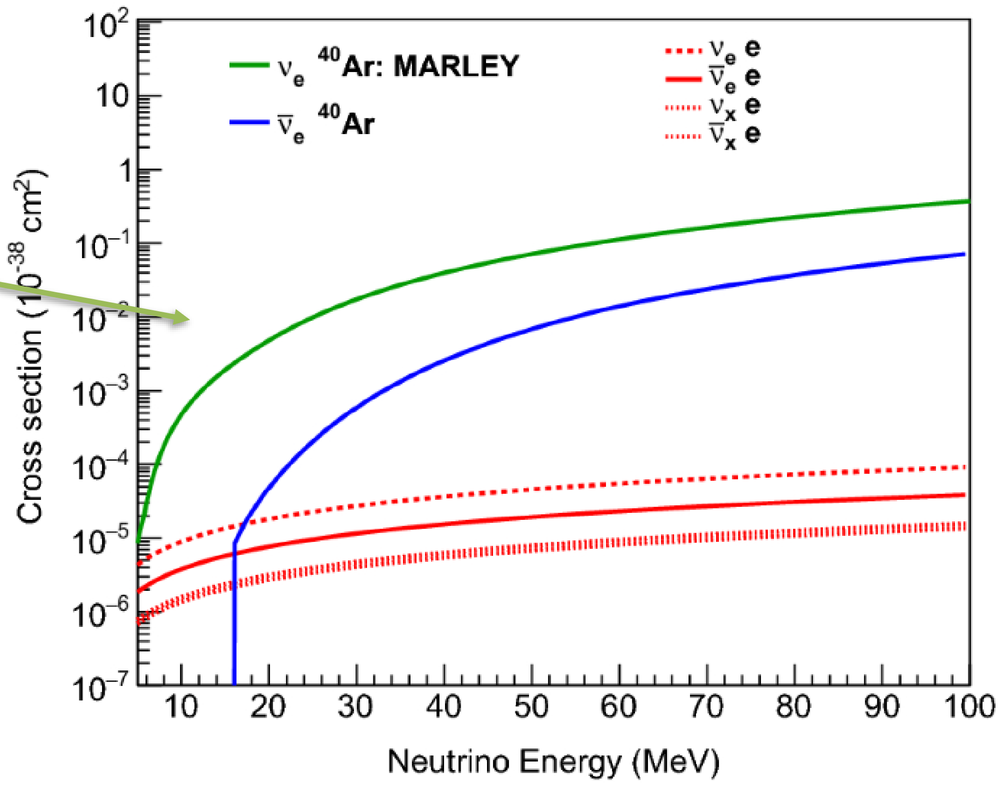
   $\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$

2. Elastic scattering on electrons (ES)

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

3. Neutral current (NC) interactions on Ar

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



Large theoretical uncertainties on $\sigma(E_\nu)$, while DUNE requires $\sigma(E_\nu) < 5\%$ uncertainty for supernova neutrino spectral parameter fitting. A direct measurement of low-energy ν_e-Ar scattering would be invaluable.

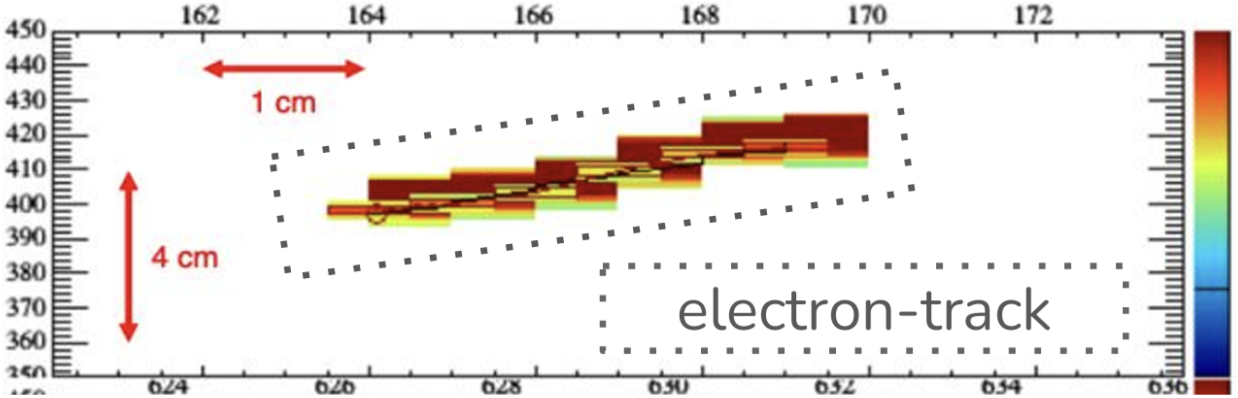
PRD 107 (2023) 112012

Low energy events in LAr

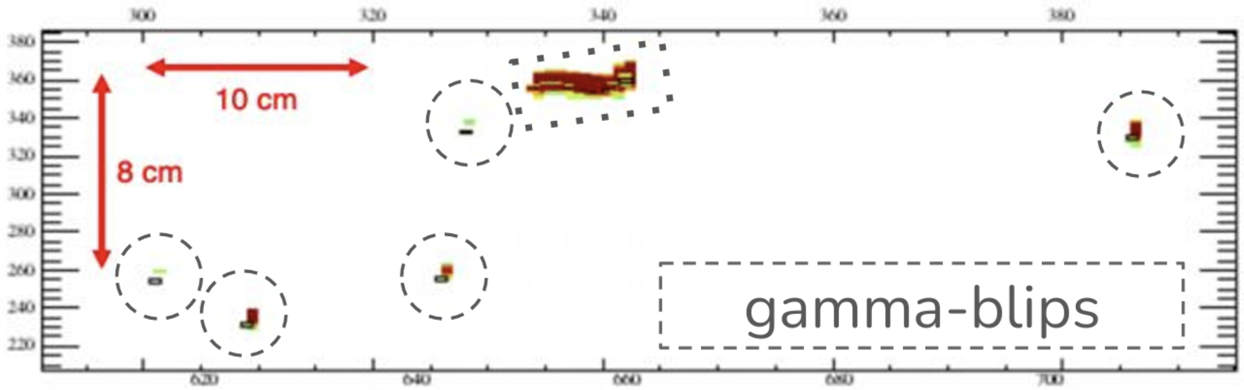
In the predominant channels (CC & ES), the topology is a short electron track (few cm) that can be accompanied (CC) or not (ES) from nuclear de-excitation gamma-blips.

Possibility to separate the various channels by a classification of the associated photons from the K, Cl or Ar deexcitation (specific lines for CC and NC) or by the absence of photons (ES)

ν-e^- ES event (10.25 MeV e^-)



ν_eCC event (20.25 MeV ν)



DUNE simulation of low energy events

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Low energy event simulation in DUNE

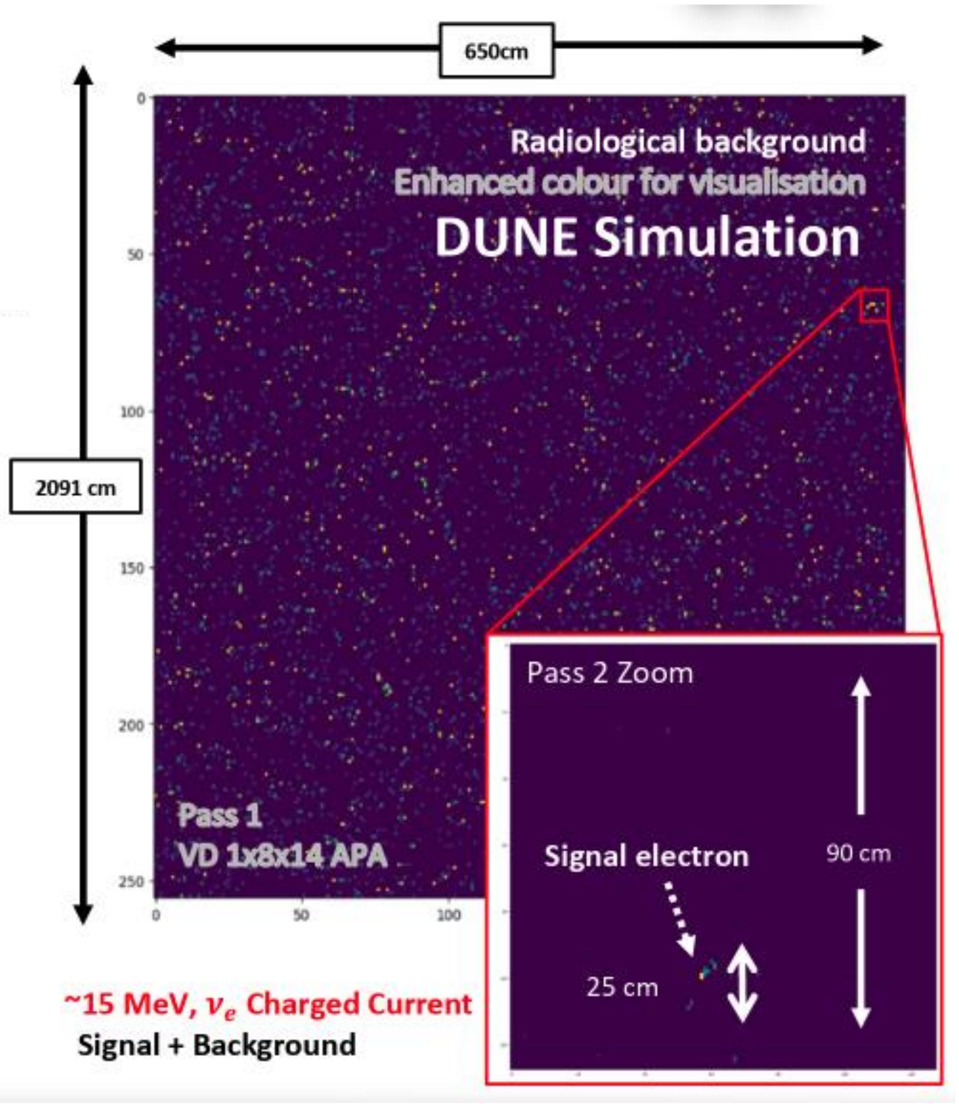
Supernova neutrinos: MARLEY simulates tens-of-MeV ν-nucleus interactions in LAr.

Radiological background: Full background model developed

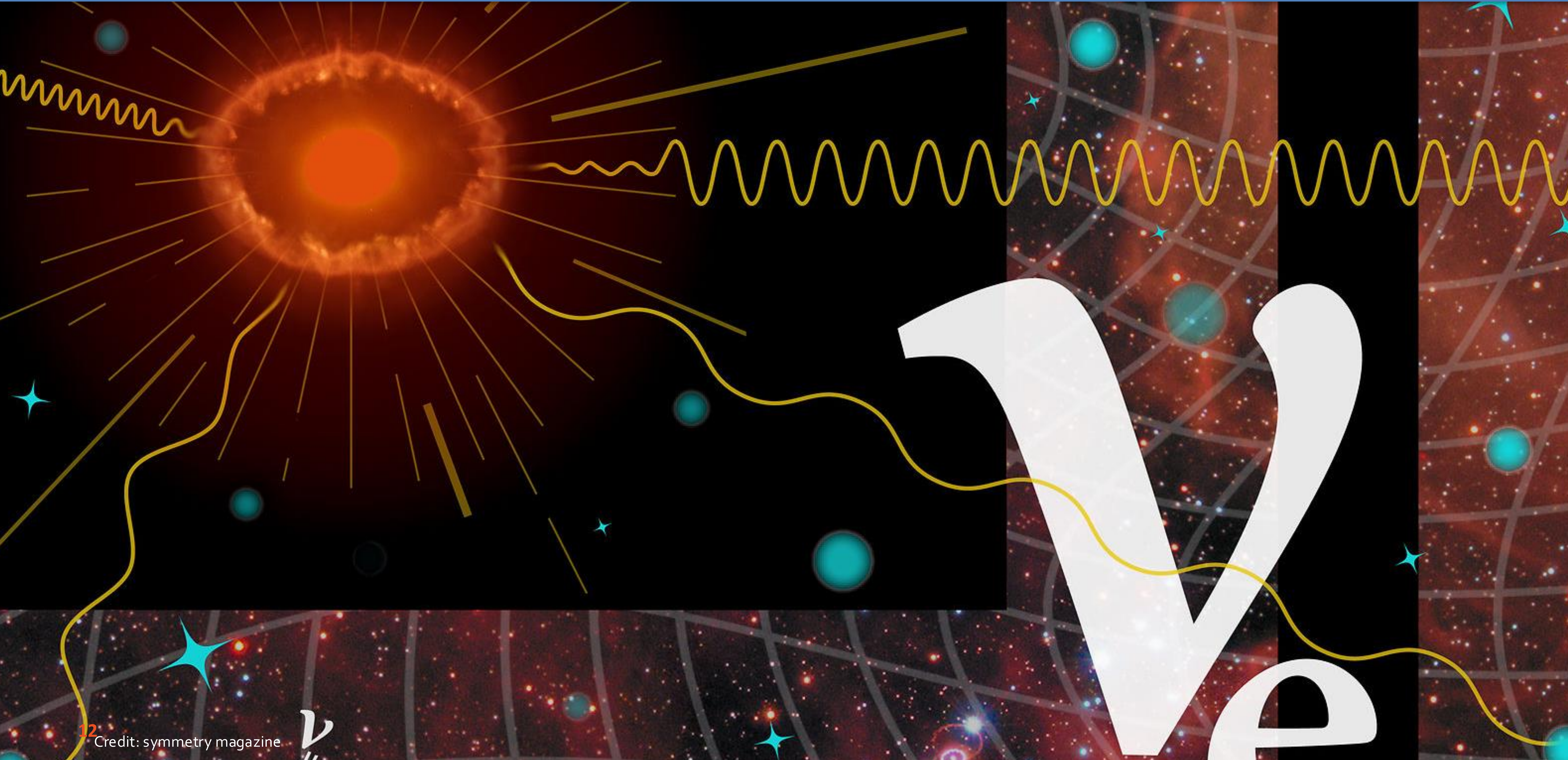
- LAr bulk contributions (^{39}Ar, ^{85}Kr, ^{42}Ar) and isotopes with ion drifting towards cathode.
- Internal contributions inside FD-HD and FD-VD cryostats: cathode, anode, and photon detection system
- External contributions from cavern neutrons, cavern gammas, cavern gammas from neutron capture in the cavern and cryostat, and cryostat foam gammas.

Impact of radiological backgrounds mitigated:

- Fiducialize to identify SN activity regions, small volumes.
- Some backgrounds are localized near cryostat walls (neutrons, gammas) or detectors.
- Precise background characterization in the first period of data taking and periodically.



Supernova neutrino burst



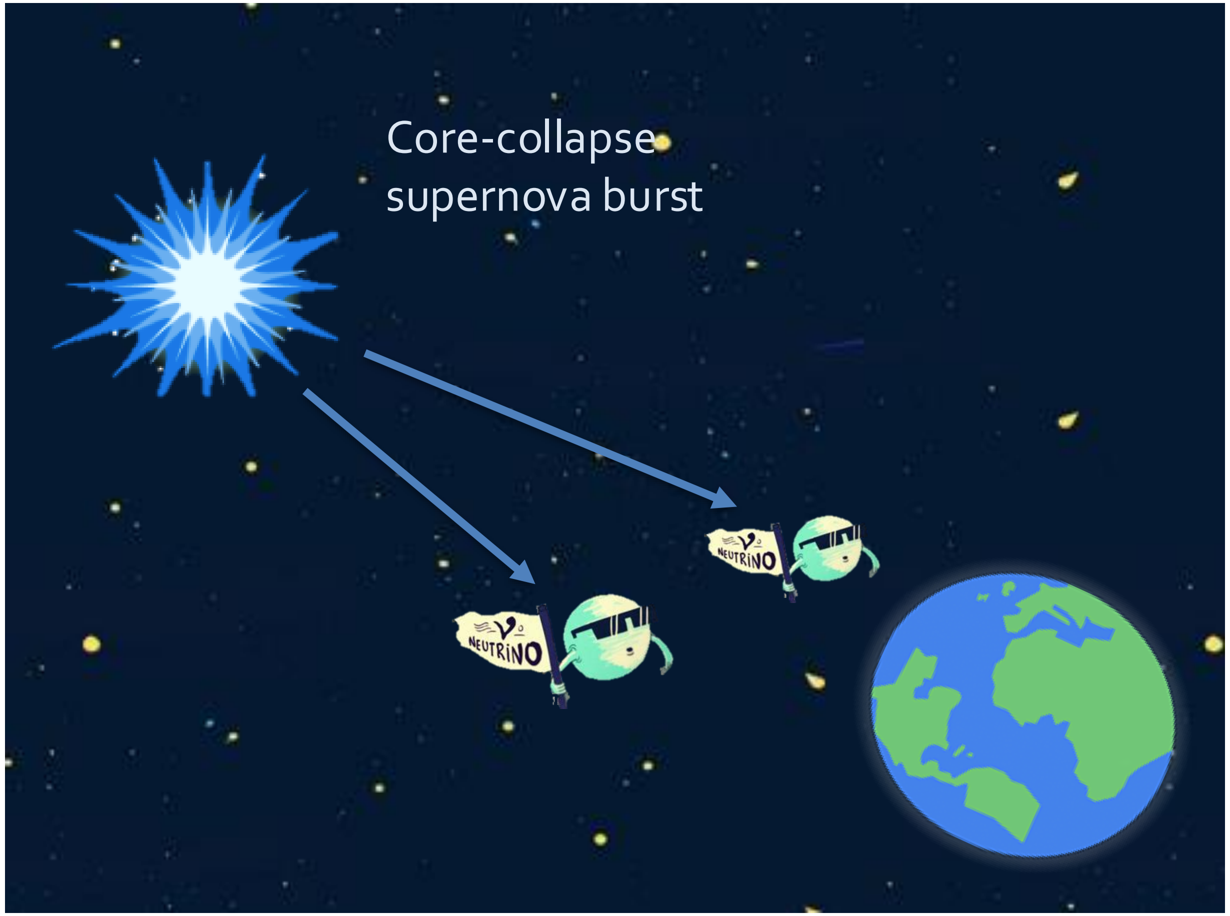
Credit: symmetry magazine

Supernova neutrinos

- **Core-collapse supernova (SN)** are a huge source of ν's:
  - **>99%** of the energy is carried by the ν's.
  - ν's emitted in **all flavors.**
  - **1-3 SN/century** in our Galaxy (10 kpc).
  - ν emission lasts **~10 sec**.
  - **~1-30 MeV** energy range.

SN1987A

- ~25 neutrinos detected in Kamiokande, IMB, Baksan
- Confirmed baseline model
- Beginning of neutrino & multi-messenger astronomy



- **Diffuse supernova background** (DSNB), accumulated ν flux from all past SN are not detected yet.

Supernova neutrino emission

Infall

Core collapses, and a shock wave is formed. The medium is opaque even for neutrinos.

Neutronization

Primarily ν_e escape, as messengers of the shock front breaking.

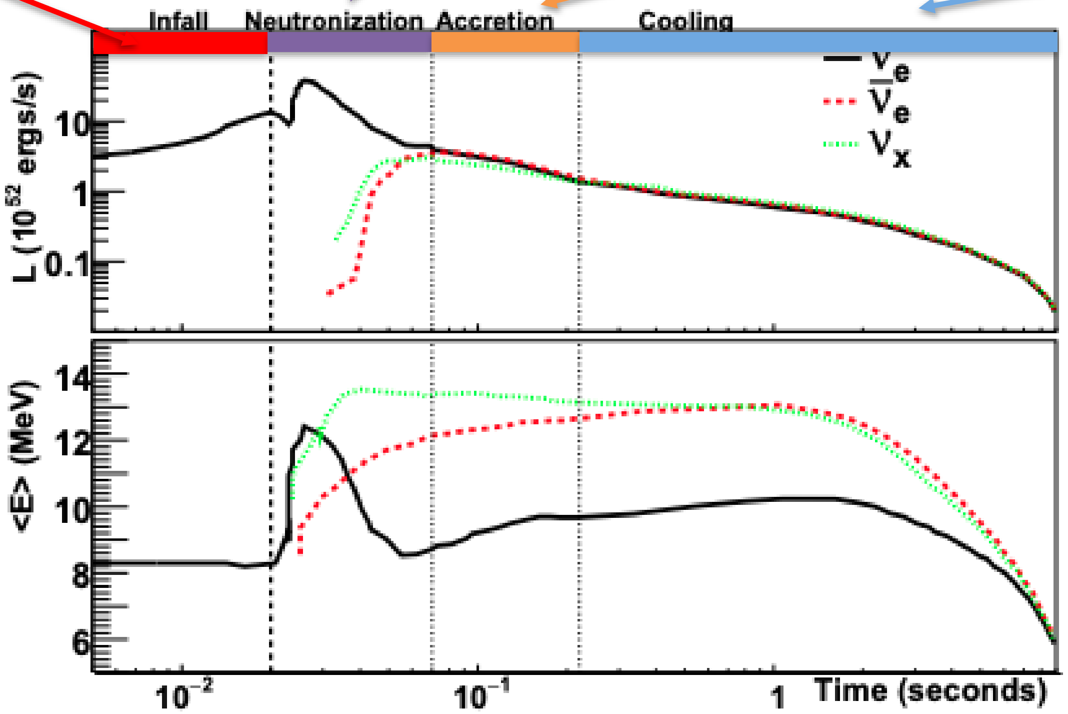
Accretion

(<1s) ν's powered by infalling matter.

Cooling

(~10s) main part of the signal, the proto-neutron star sheds its trapped energy.

For a supernova at 10 kpc from Earth.

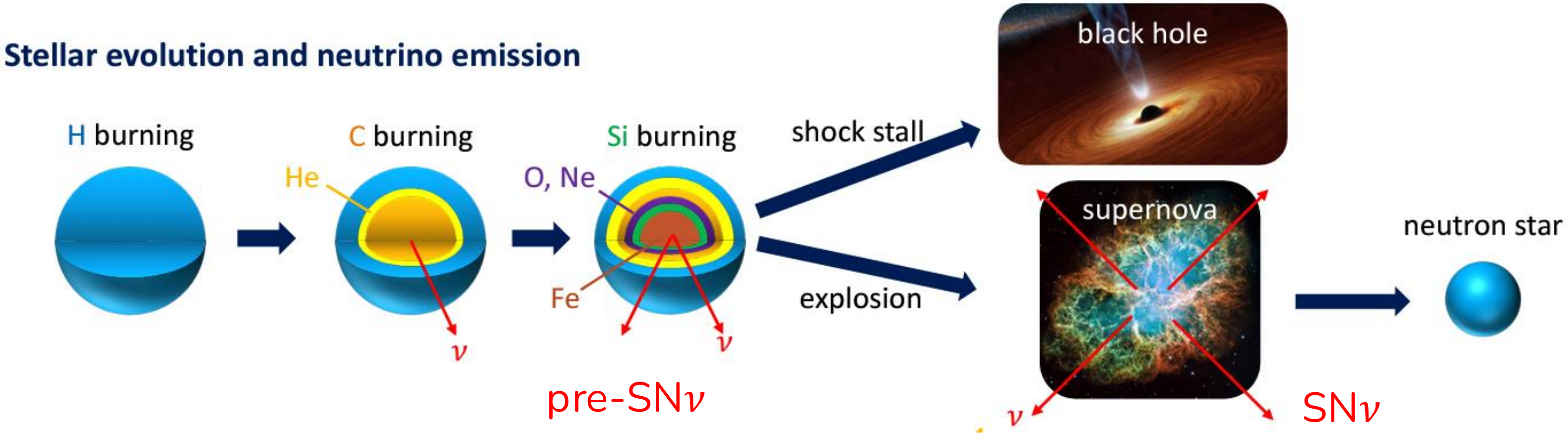


A lot of information about the supernova in this profile:
flavor content and spectra of the ν's emitted change throughout these phases, and the supernova's evolution can be followed with the ν signal.

Why do we look for SN neutrinos?

Astrophysics of core collapse

- ν's will bring the insight to confirm the **SN explosion mechanism:**
  - ν_e from neutronization burst, but flavor transition effects observable.
  - Formation of a black hole would cause a sharp signal cutoff.
  - Shock wave effects would cause a time dependent change in flavor.
  - Standing accretion shock instability (SASI), would give a flavor-dependent flux modulation.
  - Turbulence effects would cause flavor-dependent spectral modification as a function of time.
- SN ν burst in coincidence with **gravitational waves.**
- SN ν burst as **early warning to astronomers.**
- **Long-timescale sensitivity** search without burst will provide limits on the SN core-collapse rate.

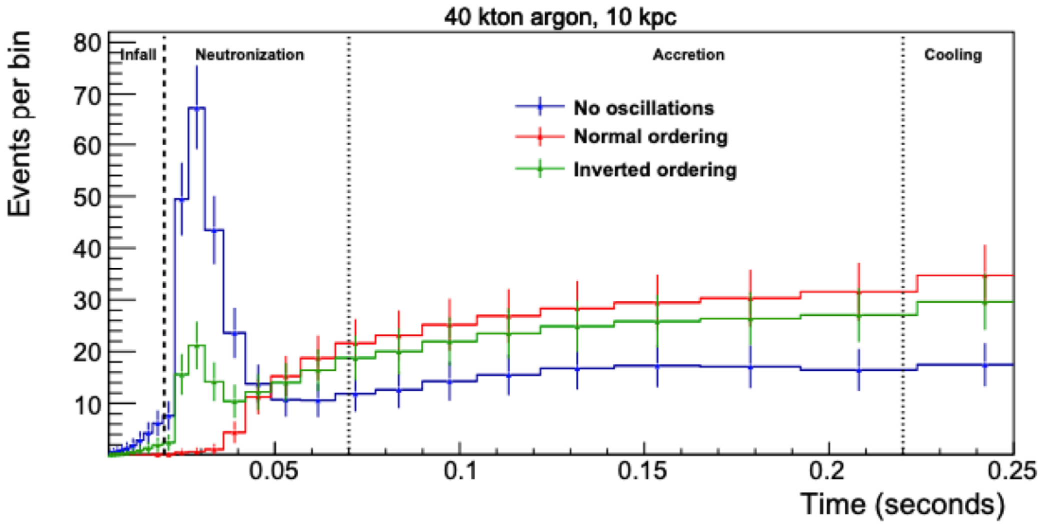


From M. Eizuka, SNvD 2023@LNGS

Why do we look for SN neutrinos?

Neutrinos and particle physics

- Core-collapse SN is a system to search for **new physics:** Goldstone bosons, neutrino magnetic moments, dark photons, unparticles, and extra-dimensional gauge bosons.
- Study **neutrino-neutrino interactions** experimentally, complex coherent scattering on neutrinos off each other. Oscillations characterized by collective modes as interactions couple ν's and $\bar{\nu}$'s of different flavor and energies.
- Possible to constraint **absolute neutrino** mass. *PRL 129 (2022) 121802*
- **Neutrino mass ordering** affects the specific flavor composition, different models under study.



Example of how mass ordering can affect the event rate in DUNE.

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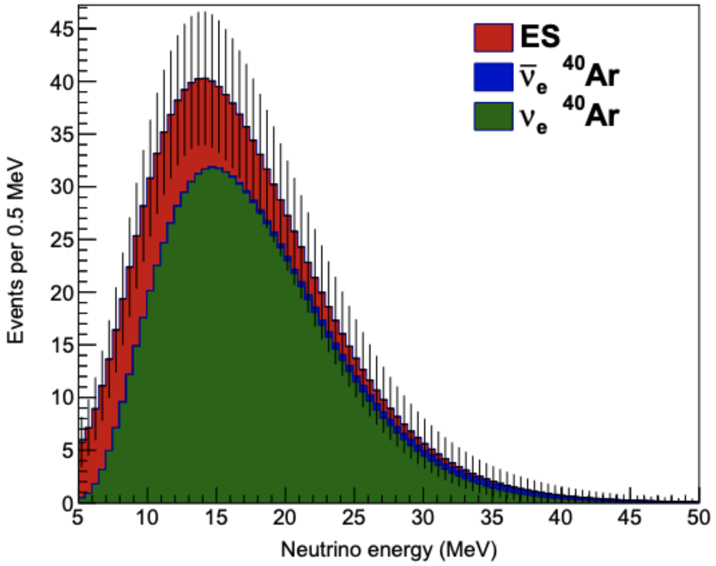
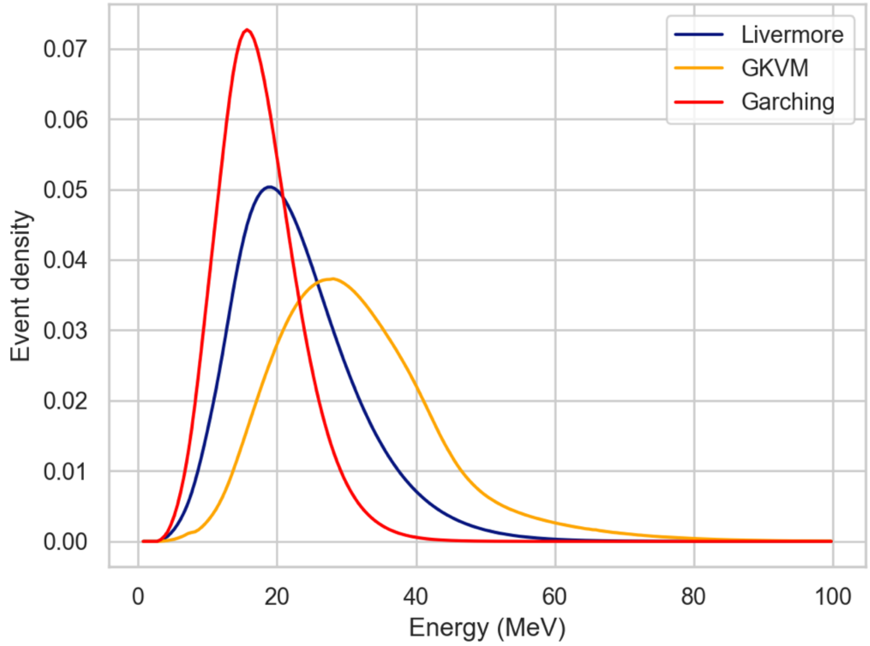
Expected Supernova burst signal in DUNE

Expected ν events for different SN models :



40 kton LAr,
10 kpc SN
"Garching model"

ve CC events with arbitrary normalization.



40 kton LAr, 10 kpc SN

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

ν_e flavor dominates.

DUNE only future prospect for a large, cleanly tagged SN ν_e sample

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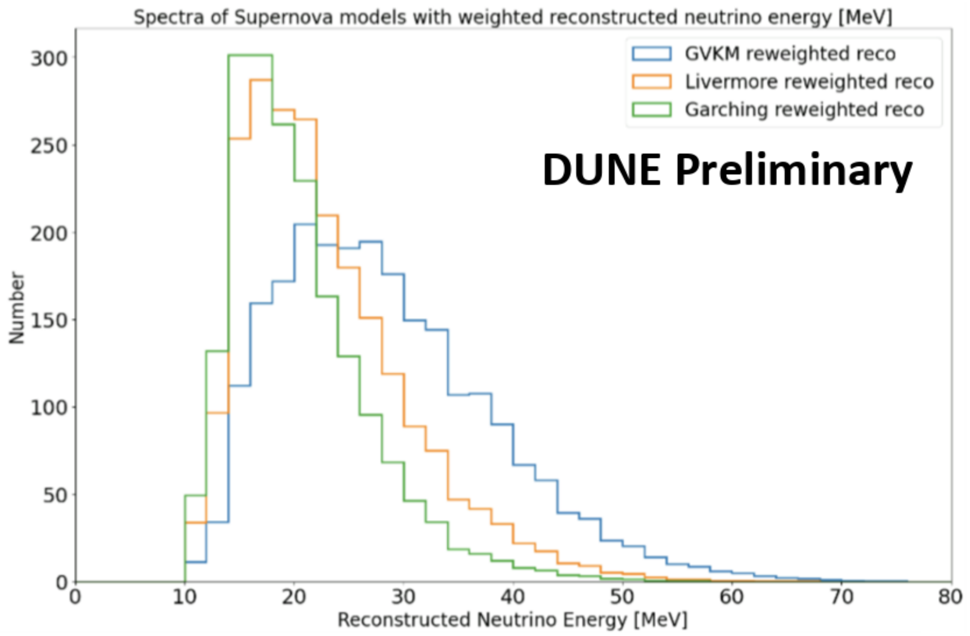
Core-collapse supernova neutrinos in DUNE

Goals

1. **Measurement of neutrino energy spectra, flavor composition, and time distributions.**
   - Complementary flavor sensitivity with other multi-kt detectors.
   - Channel tagging based on nuclear deexcitation activity (CC – ν_e, ES - ν_x).
   - Precise calorimetry taking advantage of dominant CC channel. → Developed dedicated low energy reconstruction tools for DUNE.



SN ν energy spectra expected in DUNE with reconstructed energy

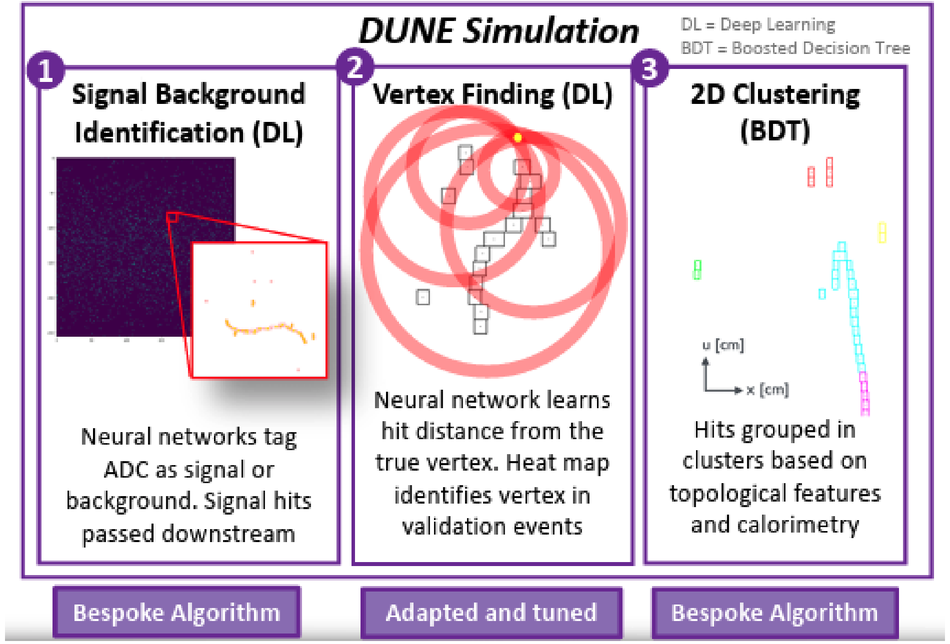
2. **Trigger** on the supernova burst and participate in SNEWS to provide the astronomical community with a prompt alert of an imminent Galactic core-collapse event.

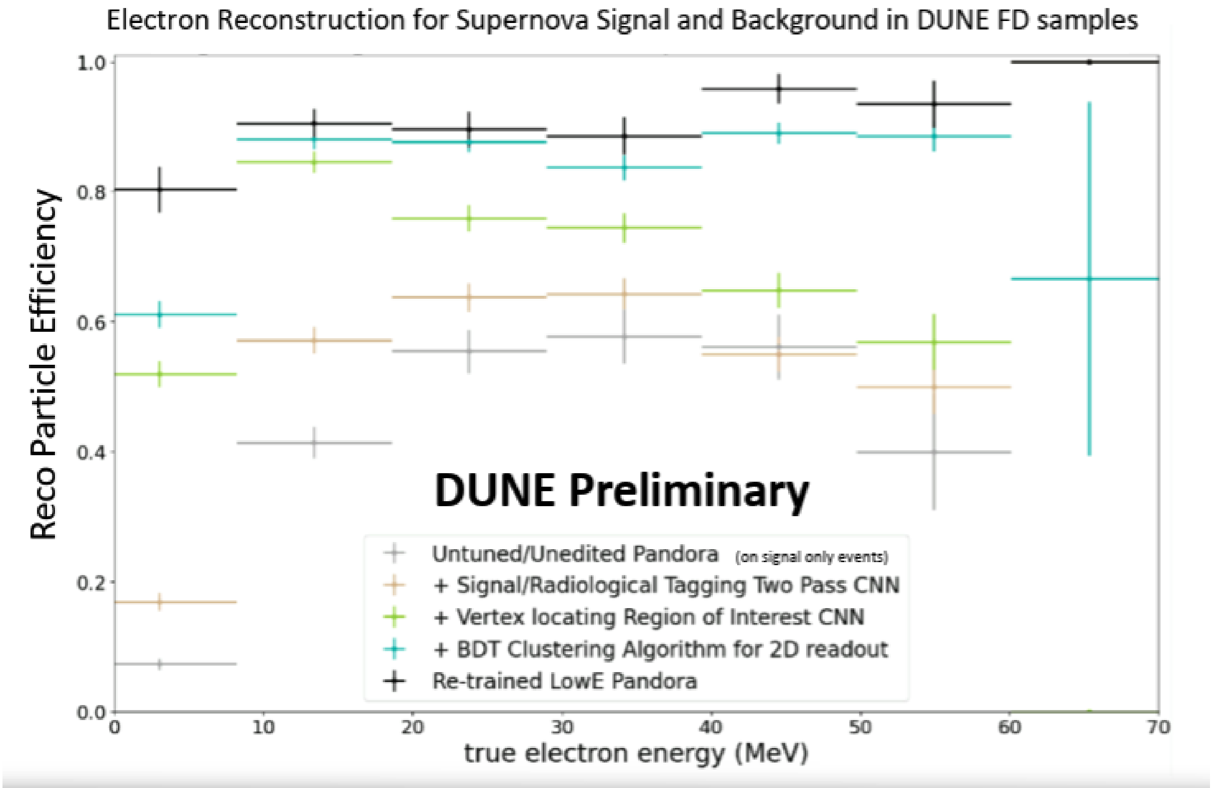
3. **Supernova pointing** to determine the direction of the stellar core collapse via neutrino emission, which is crucial for the identification of the progenitor and enabling multi-messenger follow-up observations.

Low energy event reconstruction in DUNE

Dedicated development for **low energy reconstruction** focusing on topologies different to e.g. accelerator beam neutrinos reconstruction.

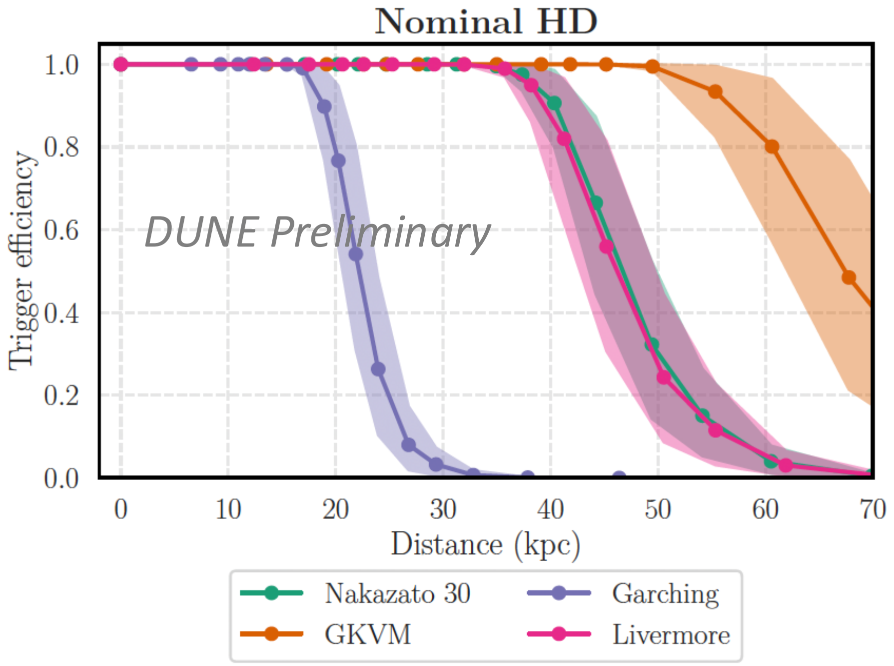
Pandora: multi-algorithm pattern recognition reconstruction chain tuned for low energy events.





DUNE Supernova burst event triggering

- It is essential to develop a redundant and highly efficient triggering scheme in DUNE.
- The trigger on a supernova neutrino burst can be done using either TPC or photon detection system information.
- Trigger scheme exploits the time coincidence of multiple signals over a timescale matching the supernova luminosity evolution.
- Preliminary trigger designs with maximum fake trigger rate (1/month).



Example: Photon detection system.

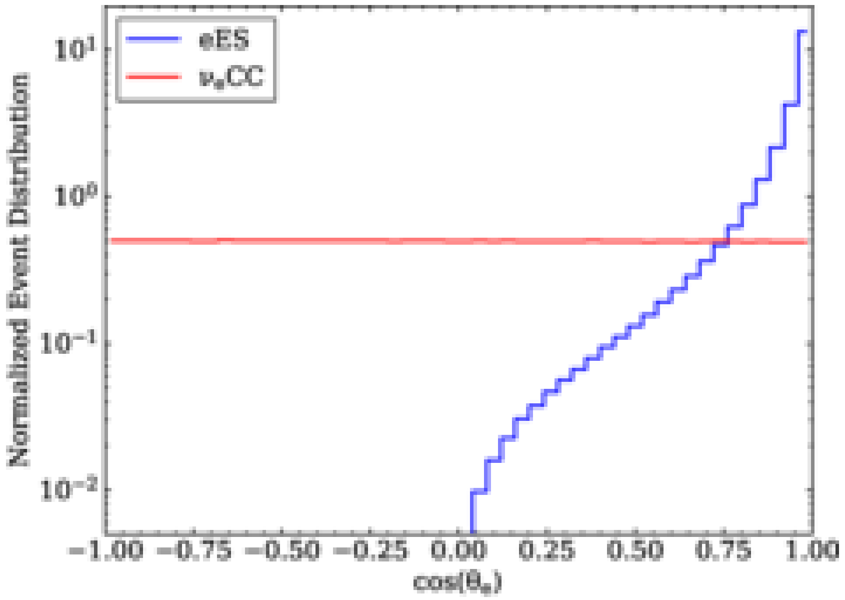
- Real time algorithm provides trigger primitives by searching for hits and optical clusters, based on time/spatial information.
- >90% efficiency on a SNB at a distance up to ≥20 kpc, so it would cover the entire Milky Way (model dependent).

Supernova pointing in DUNE

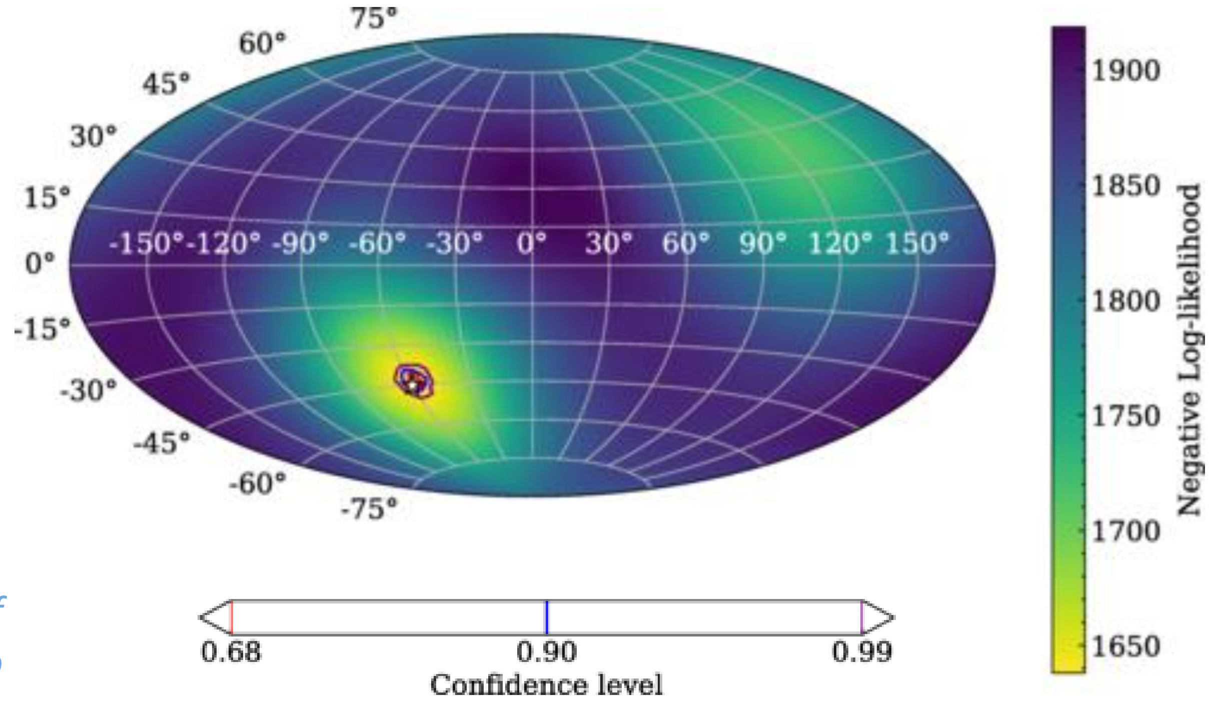
- From the correlation between the supernova neutrino and the outgoing primary electron of ES events during a burst, the SN direction can be determined.

[PRD 111 (2025) 092006](PRD 111 (2025) 092006)

- Simulated supernova at 10 kpc with the GKVM model with internal and detector backgrounds.
- TPC allows flavor discrimination so the ν_e CC component can be mitigated.

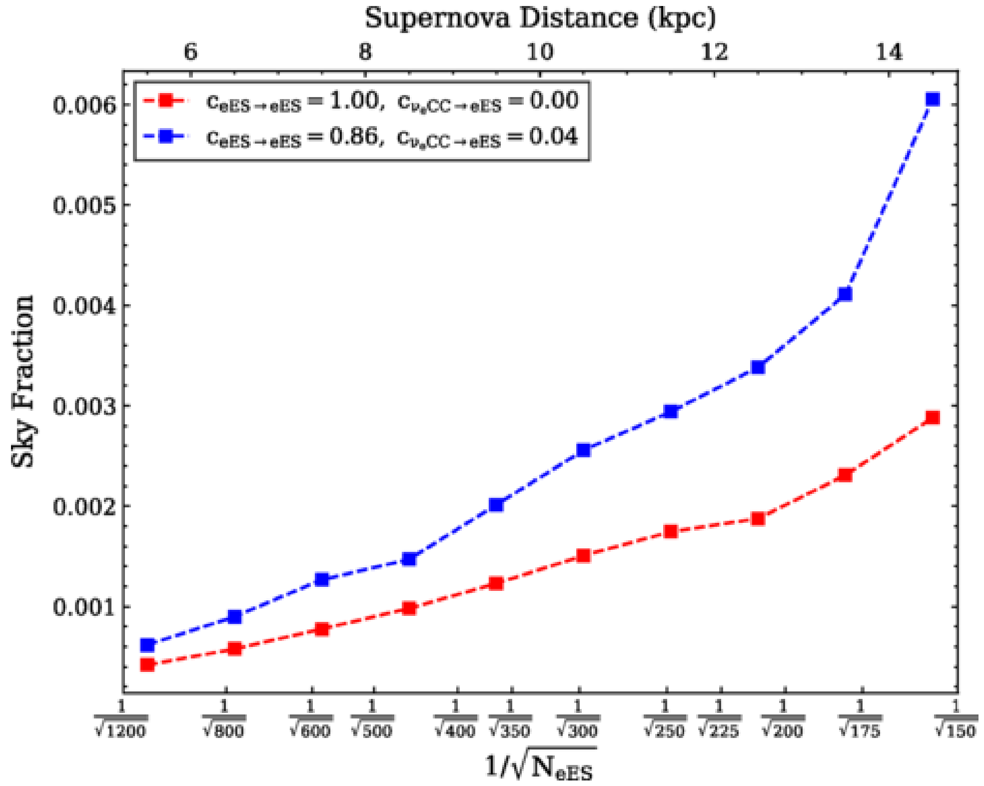


Distribution of the cosine of the scattering angle.



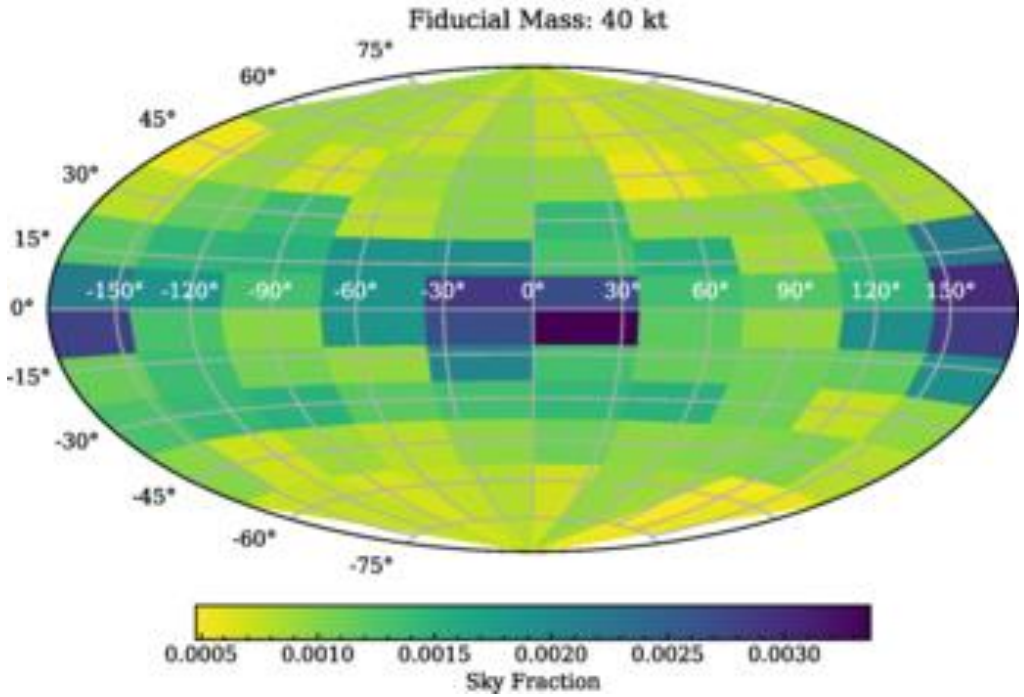
Example of directional map

Supernova pointing in DUNE

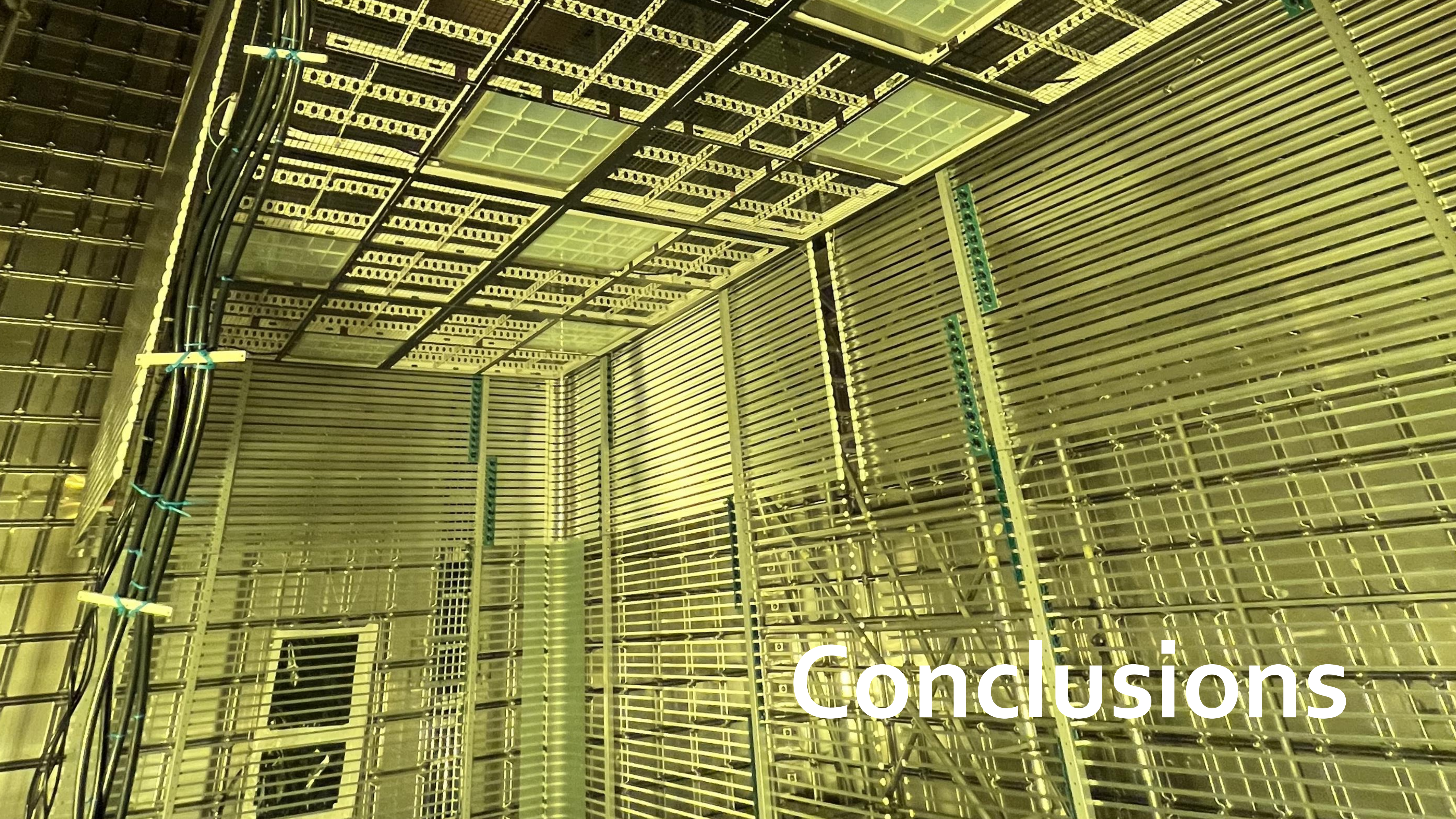


Burst pointing resolution vs. detected eES events (

vs. direction of supernova



With an assumed classification efficiency of 96%, the estimated pointing resolution is 4.3 degrees (with 40 kT LAr) for 68% of sky-coverage. *PRD 111 (2025) 092006*

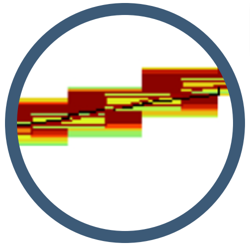

Conclusions

Conclusions

DUNE

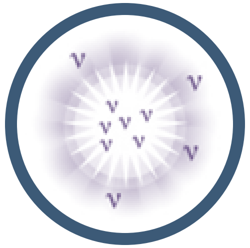
DUNE experiment is sensitive to neutrinos with about 5 MeV up to several tens of MeV, the regime of relevance for core-collapse supernova burst neutrinos and solar neutrinos.

LOW ENERGY EVENTS



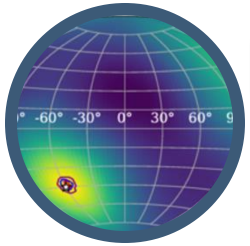
This low-energy regime presents challenges for triggering and reconstruction. DUNE's TPC and PDS systems will both provide information about these events, and we have developed software tools that enable triggering and energy reconstruction considering background contributions.

SUPERNOVA NEUTRINOS



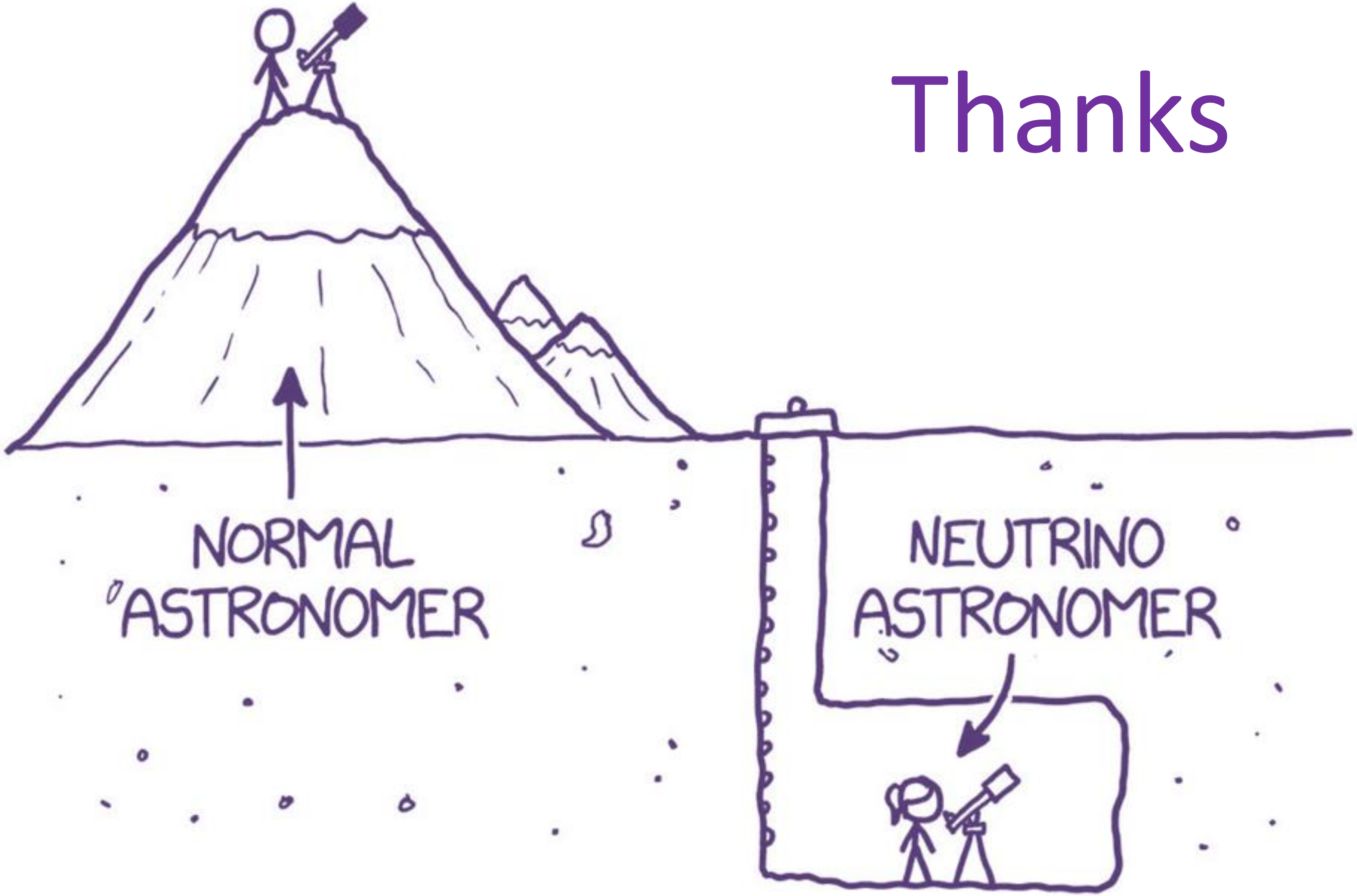
DUNE will have unique sensitivity to ν_e in the entire Milky Way, and possibly beyond, depending on the neutrino luminosity of the core-collapse supernova. The observation of a burst will provide information about the core-collapse supernova but also about particle physics.

SUPERNOVA POINTING



DUNE will be able to point towards the SN direction exploiting the directionality of $\nu - e$ scattering events, we can determine the direction of the supernova to <5 deg.

Thanks



Credit: Randall Munroe