Supernova and solar neutrino searches at DUNE

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Ciemat
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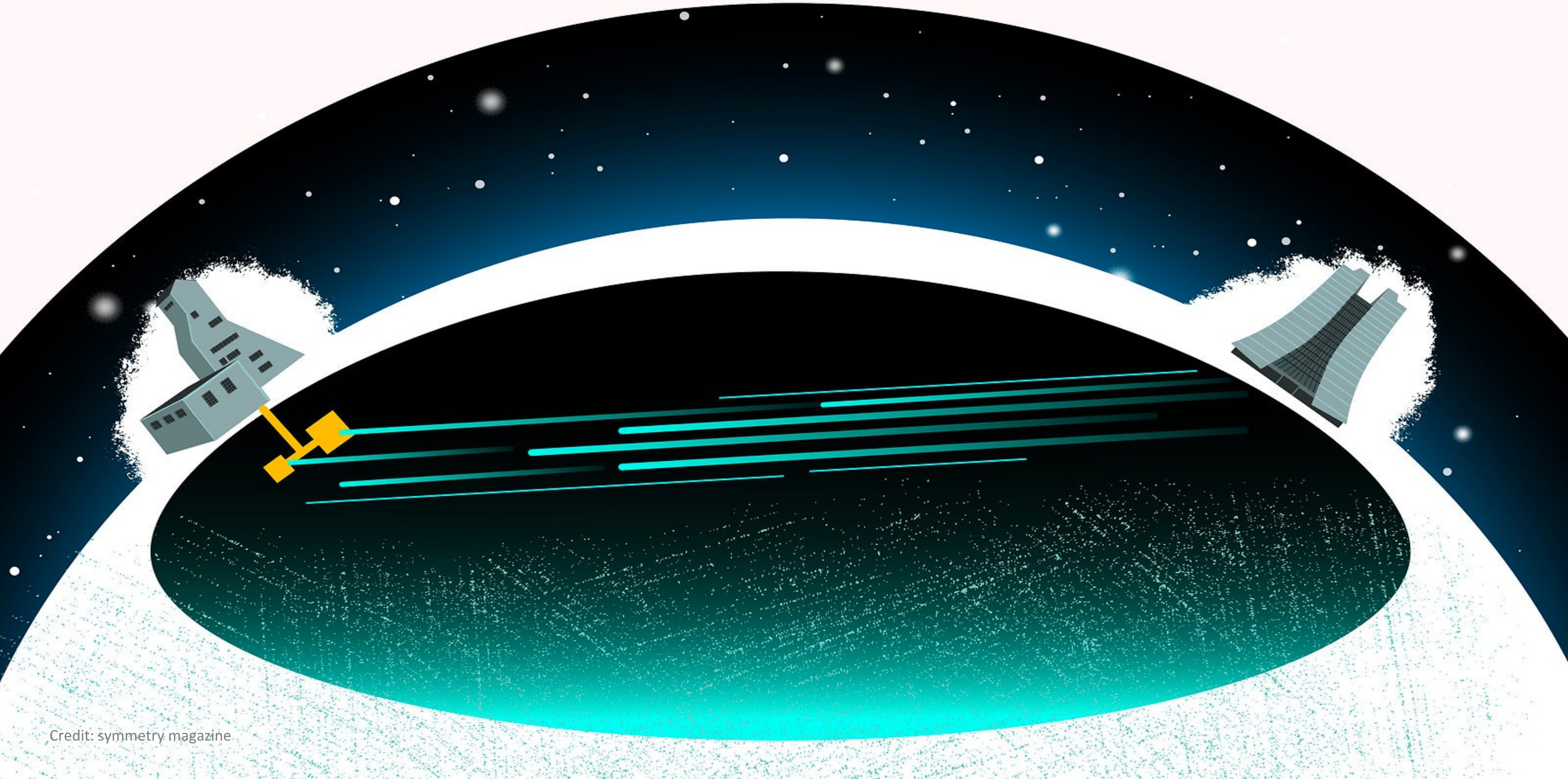
The Deep Underground Neutrino Experiment (DUNE)

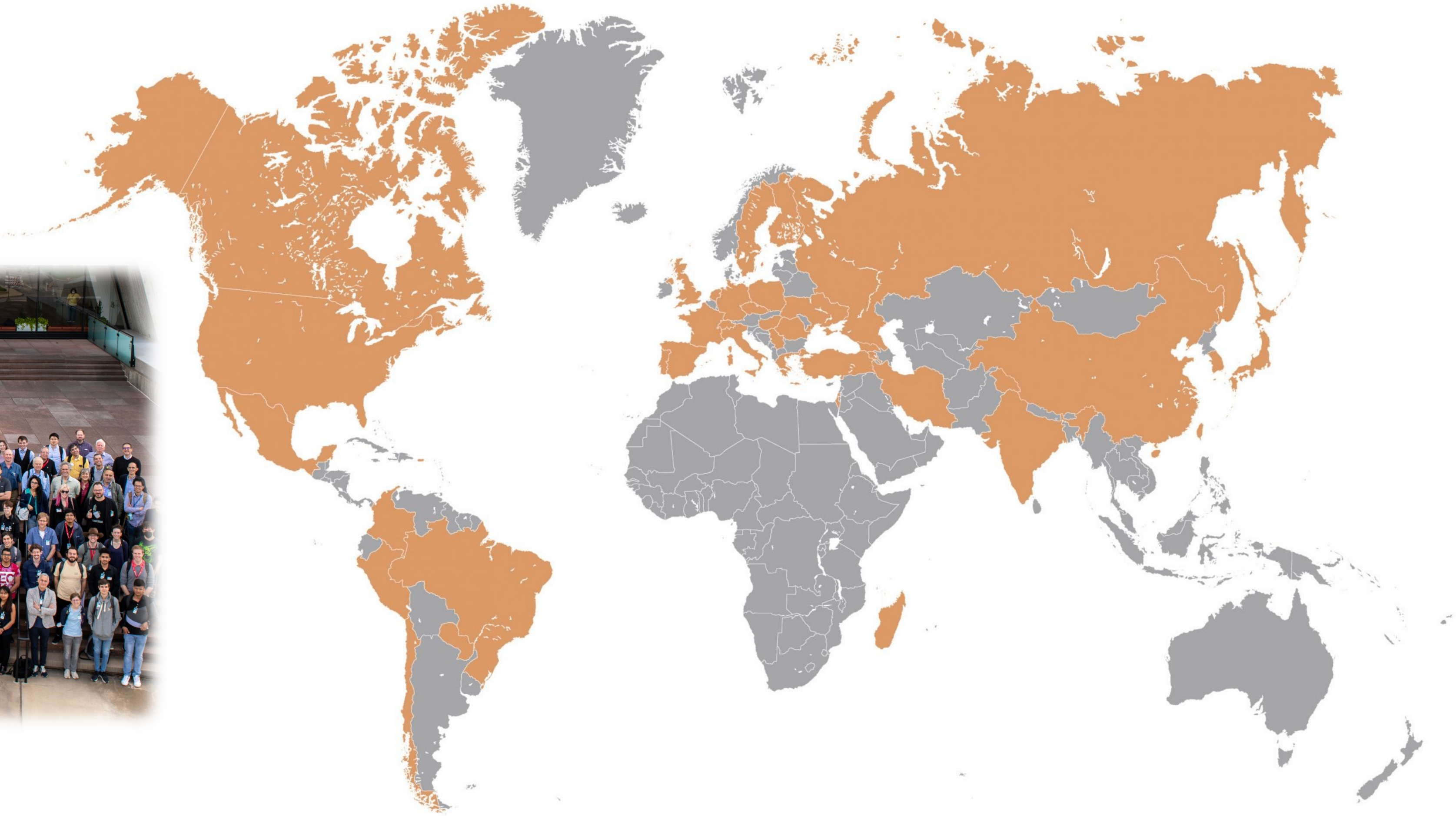


Credit: symmetry magazine

The DUNE Collaboration

~1400 collaborators from
~200 institutions in
>30 countries + CERN

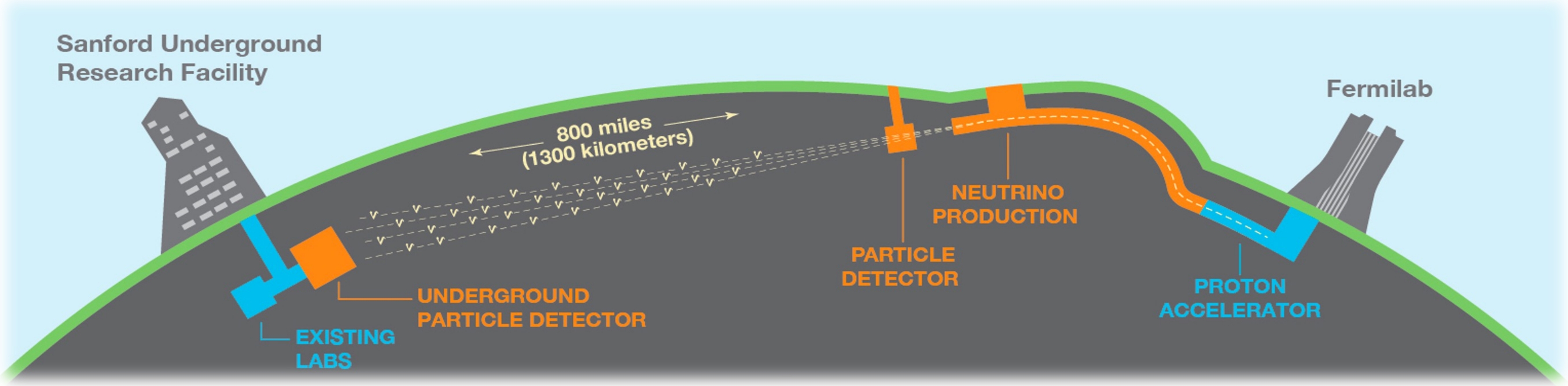
DUNE Collaboration Meeting,
Fermilab, May 2022



Deep Underground Neutrino Experiment (DUNE)

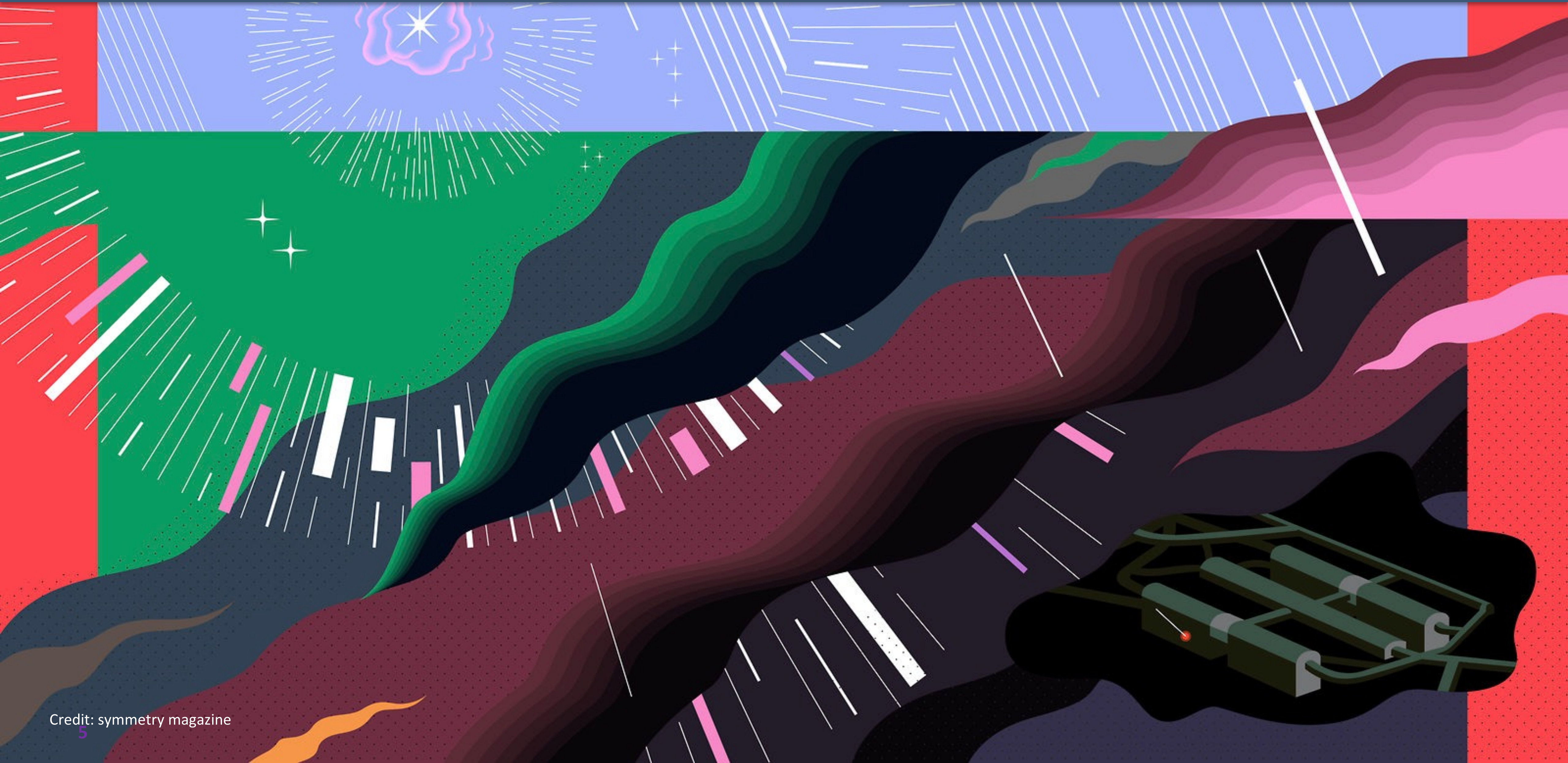
Main DUNE physics goals:

- Precise measurement of neutrino oscillation parameters (mass ordering, δ_{CP}) EPJC 80 (2020) 978
- **Detection of low energy neutrinos from a supernova and the sun** EPJC 81 (2021) 322
- Searches for physics beyond the Standard Model EPJC 81 (2021) 423



- New neutrino (ν_μ or $\overline{\nu}_\mu$) 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

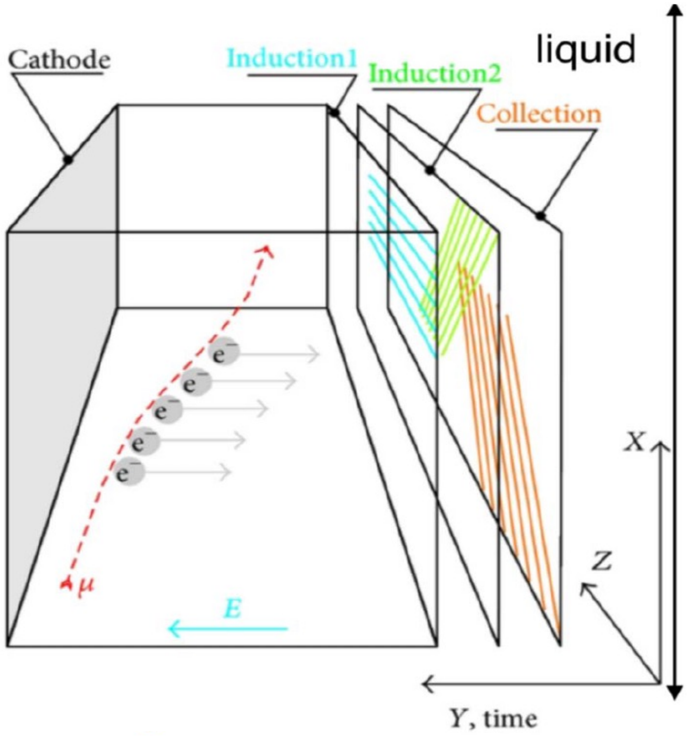
DUNE Far Detector



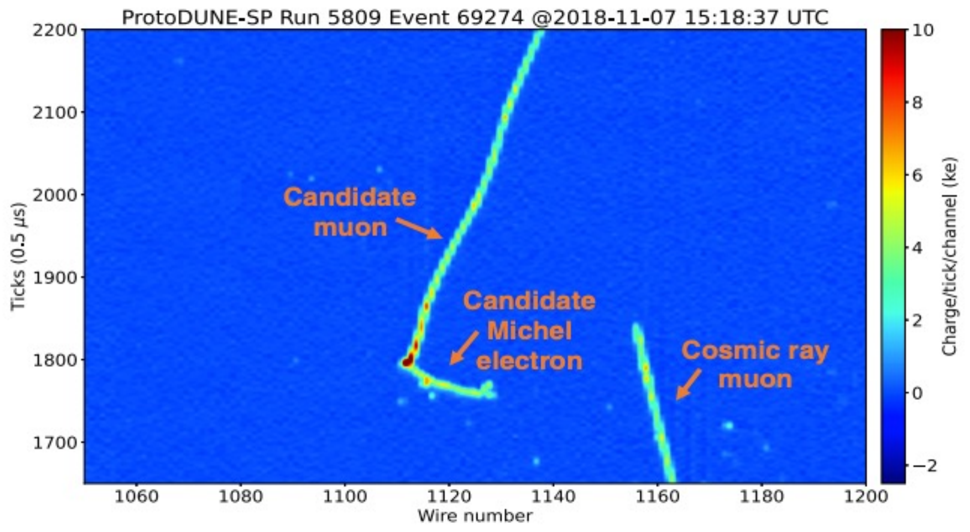
Credit: symmetry magazine

LAr TPC technology

- 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.



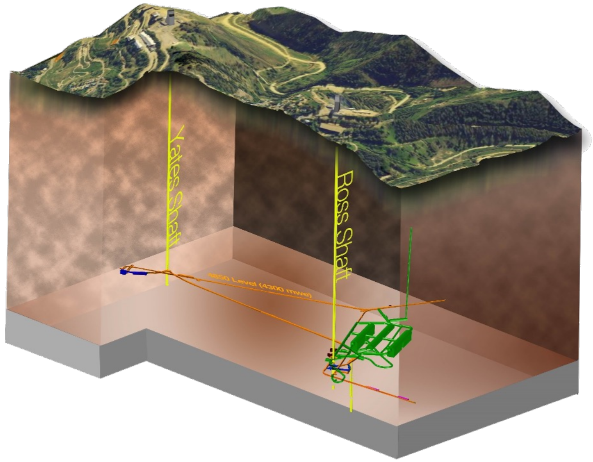
- Excellent **3D imaging** – few mm scale over large volume detector.
- Excellent energy measurement. capability – **totally active calorimeter.**
- **Particle ID** by dE/dx, range, event topology.

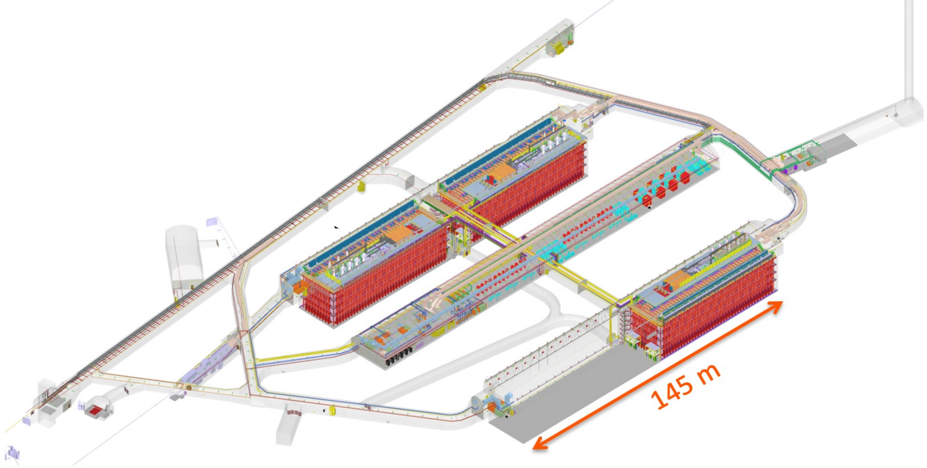


Michel e- candidate observed in ProtoDUNE-SP data.

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-1 horizontal drift (HD)
- FD-2 vertical drift (VD)

Phase II:

- Possibility of a module with enhanced low energy physics capabilities

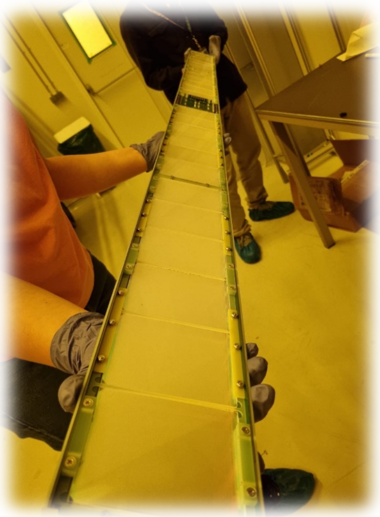
ProtoDUNEs

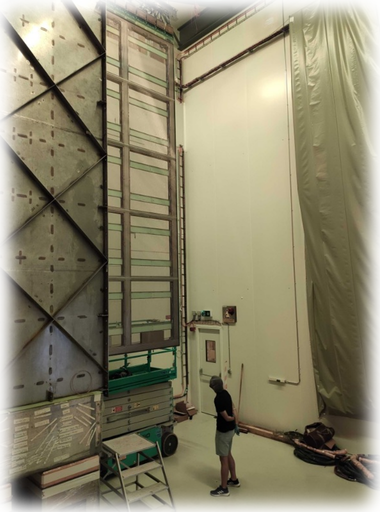
Construction and operation of 1 kton-scale prototypes at CERN, critical to demonstrate viability of technology

DUNE Far Detector 1

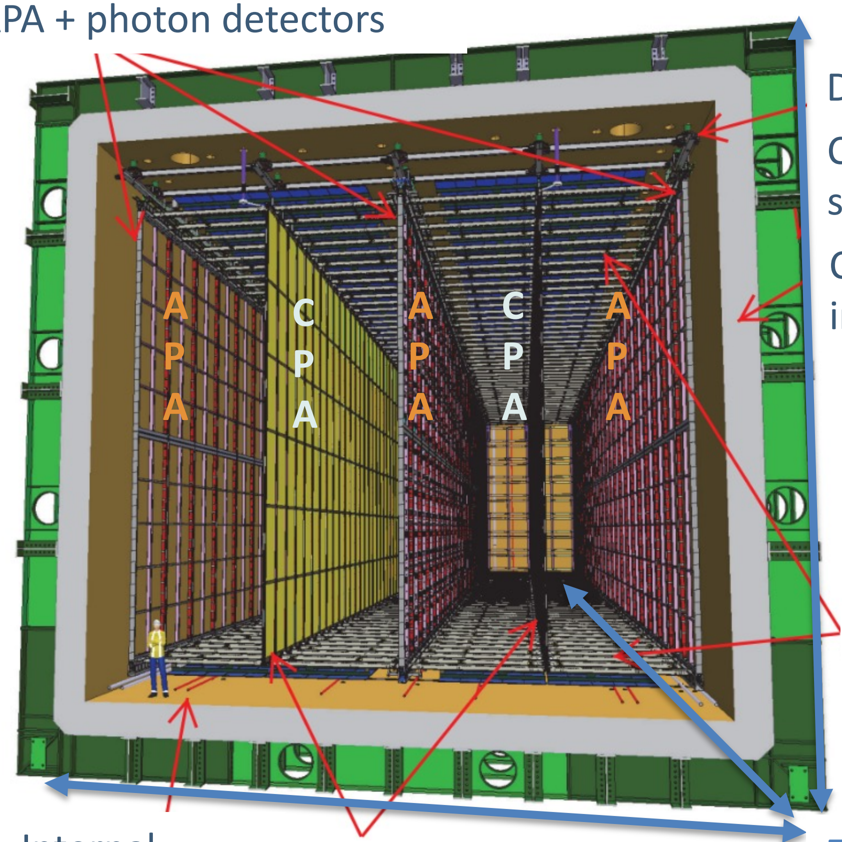
Horizontal drift

- **3.6 m horizontal drift**
- Anode and Cathode Plane Assemblies (**APA,CPA**)
- **Charge collected** on 3 views, pitch 5 mm
- **Photon detectors**:
  X-ARAPUCA light guides + SiPM, embedded in APAs





X-ARAPUCA installation in APA at ProtoDUNE-HD

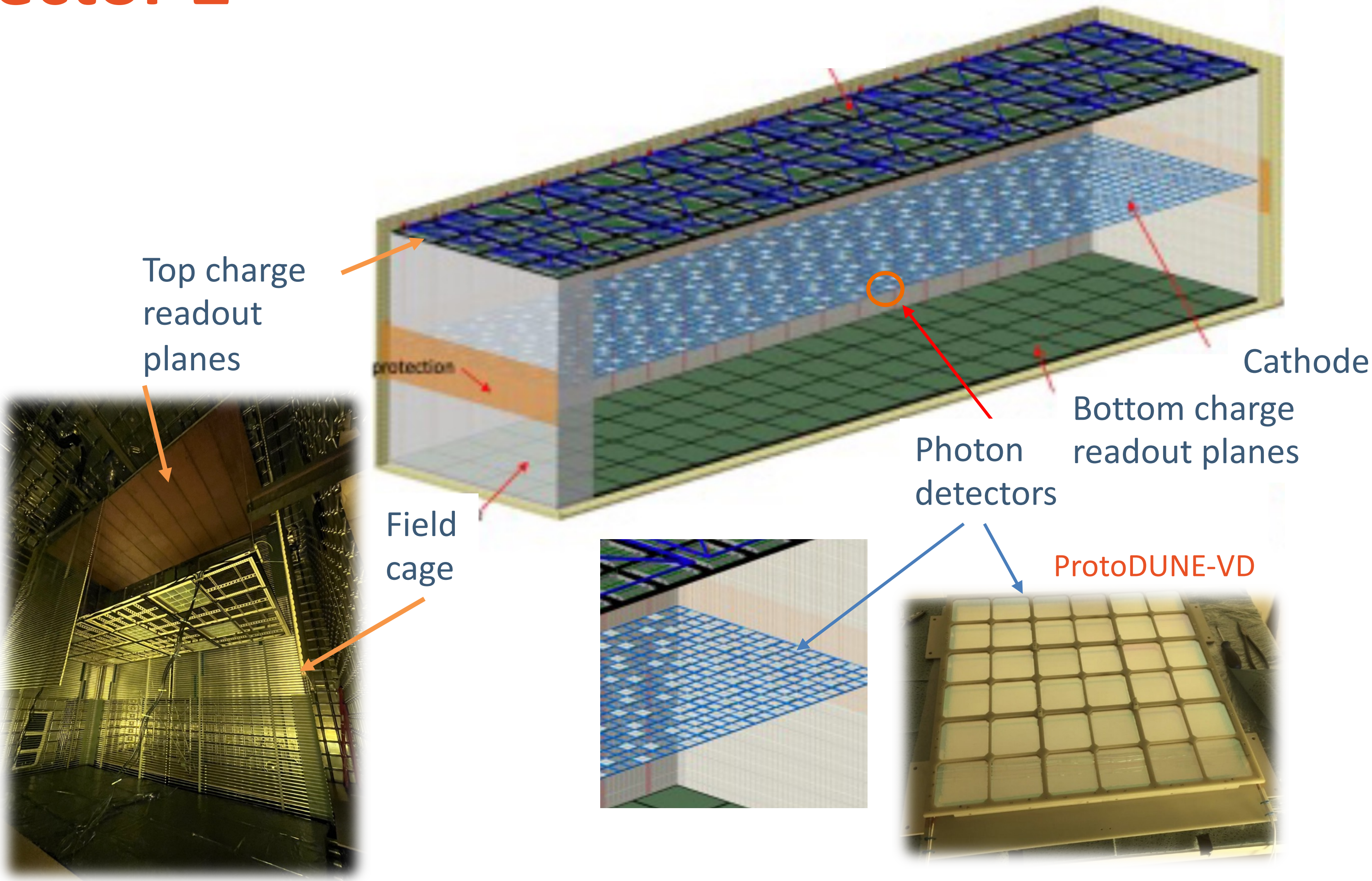


JINST 15 (2020) T08008
JINST 15 (2020) T08010

DUNE Far Detector 2

Vertical drift

- Novel technology with **6-m vertical drift** that maximizes active volume.
- **Printed Circuit Board**-based readout scheme makes detector assembly much simpler.
- **Photodetection system** deployed (X-ARAPUCA) on the central cathode plane + cryostat walls.
- LAr doped with Xe.
-



ProtoDUNE-VD

Low energy events in DUNE

Credit: symmetry magazine

Low energy interactions in LAr

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

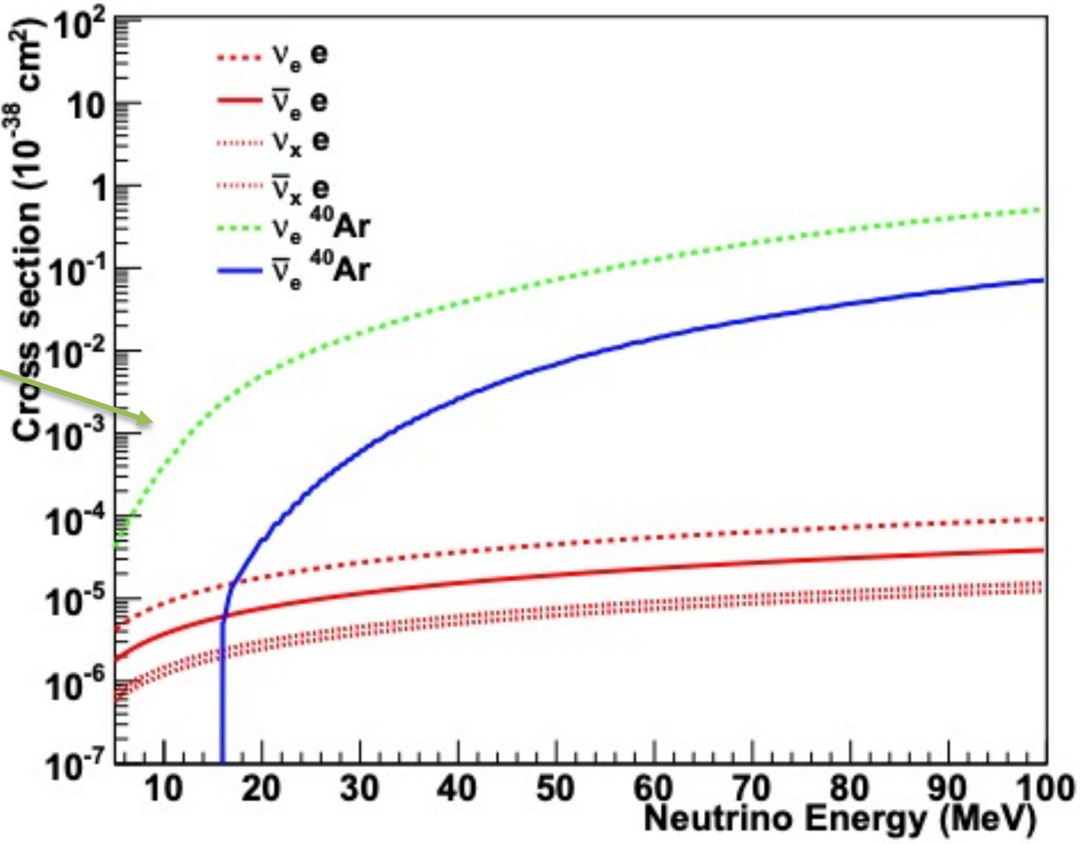
   $\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$

2. Elastic scattering on electrons (ES)

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

3. Neutral current (NC) interactions on Ar

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



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

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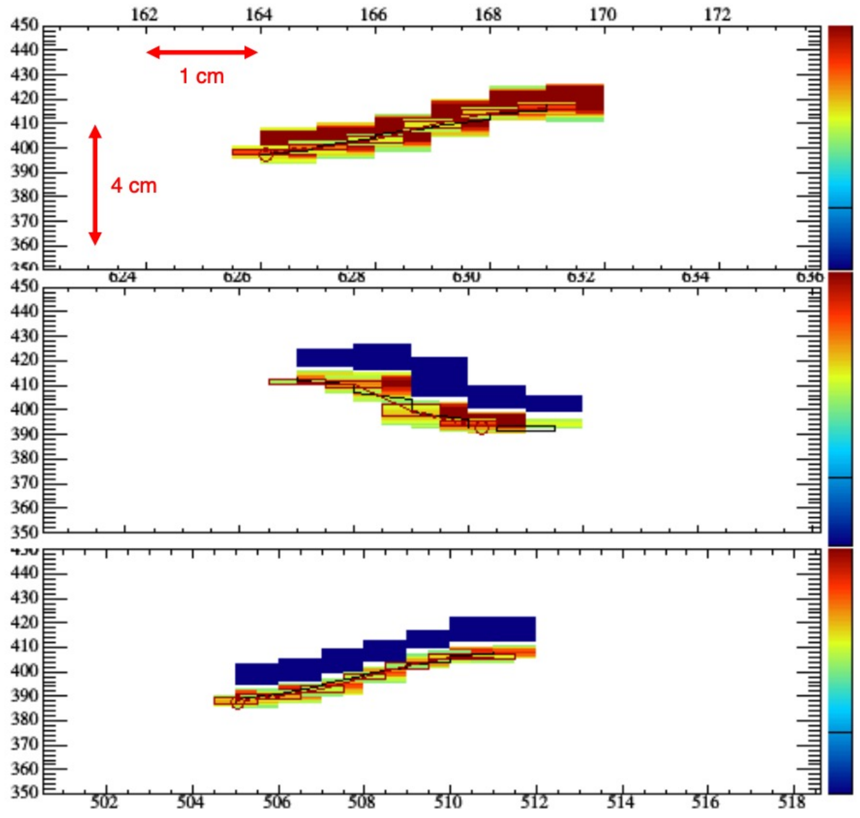
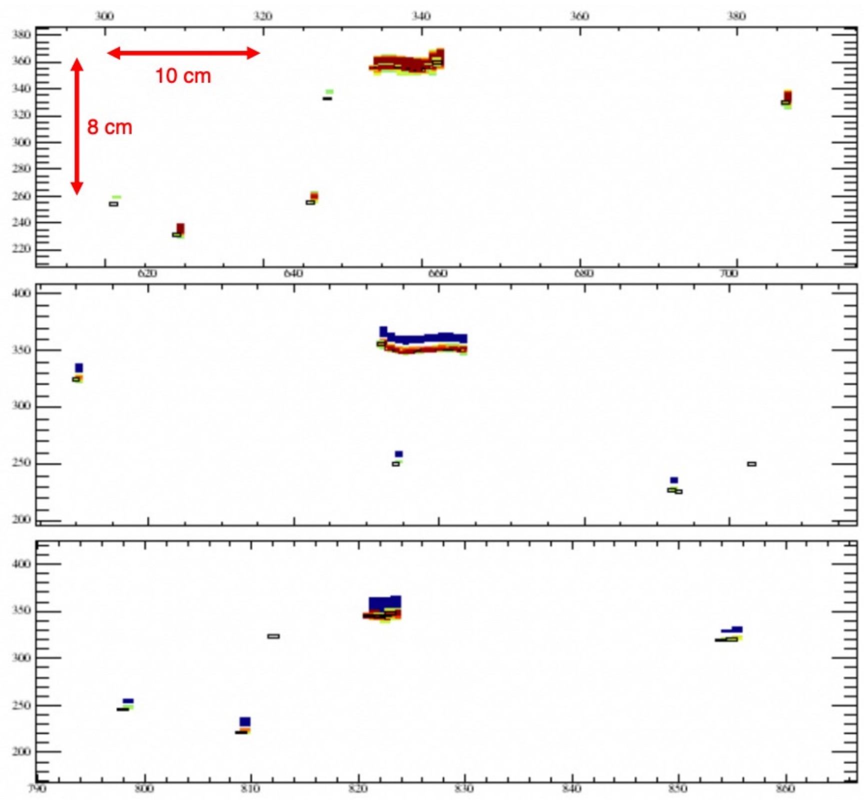
Low energy event simulation and reconstruction in DUNE

- **MARLEY simulates** tens-of-MeV ν-nucleus interactions in LAr
- **Reconstruction**: **LArSoft** to identify interaction channel, ν flavor in CC events & incoming ν momentum

ν-e^- ES event *(10.25 MeV e^-)*



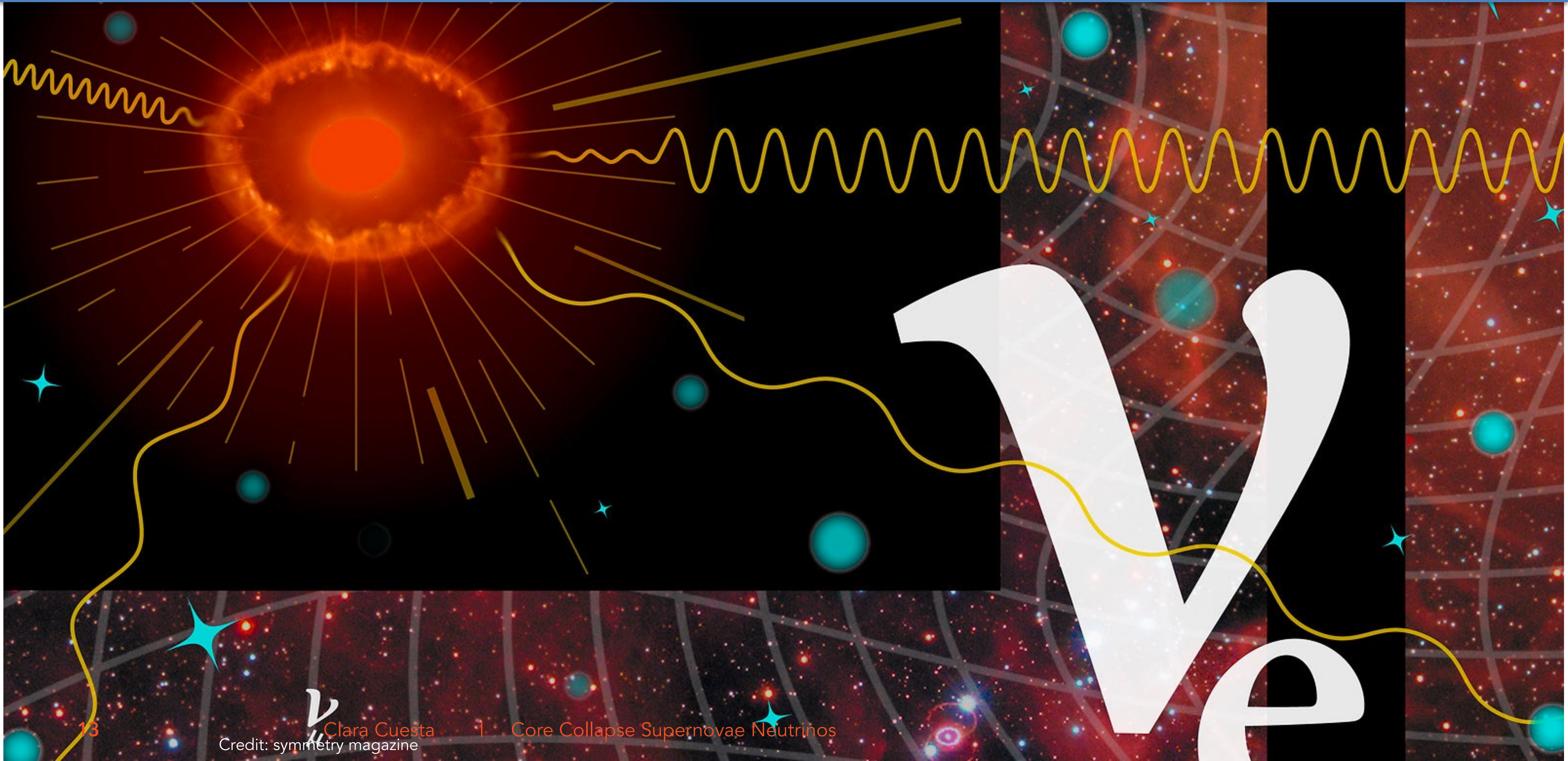
ν_eCC event *(20.25 MeV ν)*



VD and HD technologies are studied

[EPJC 81 (2021) 423]

Supernova neutrino burst



Credit: symmetry magazine

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.

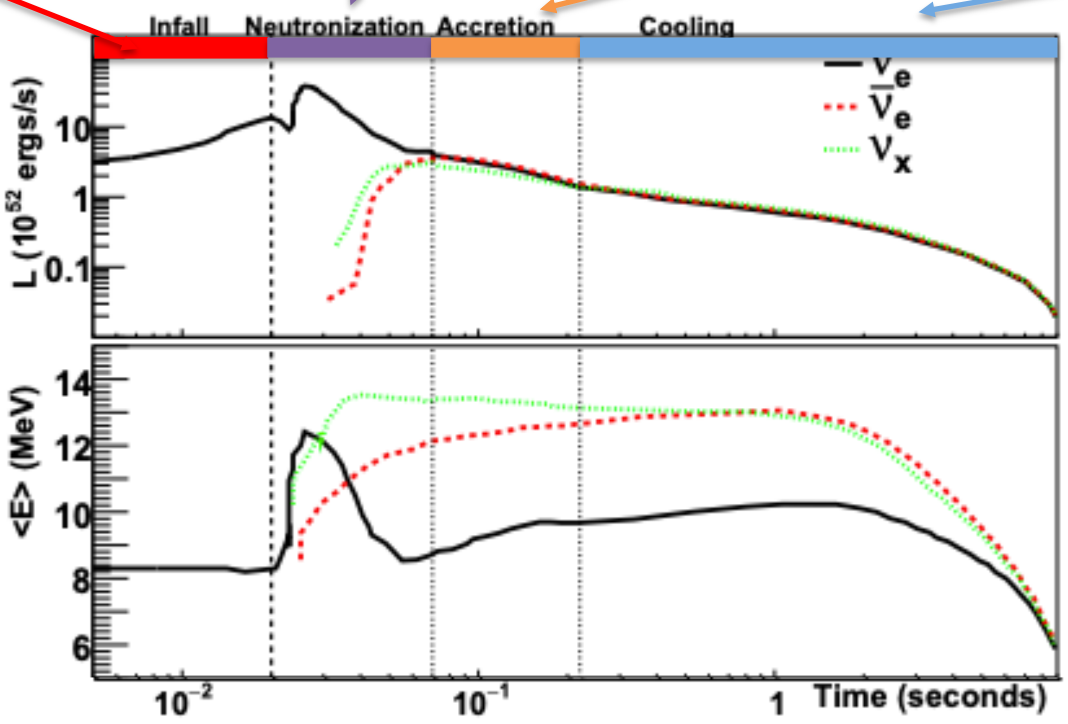
Accretion

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

Cooling

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

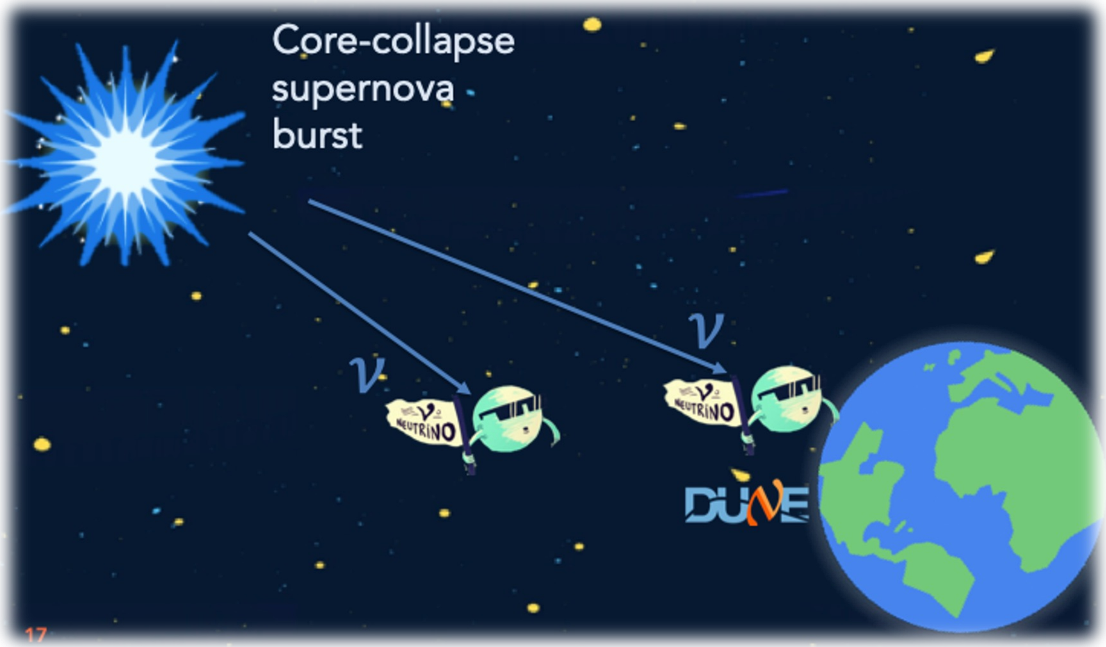
For a supernova at 10 kpc from Earth.

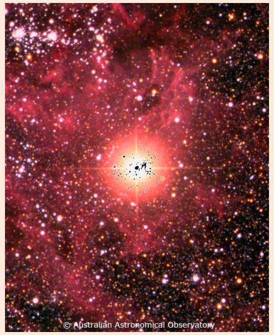


A lot of information about the supernova in this profile: flavor content and spectra of the ν's emitted change throughout these phases, and the supernova's evolution can be followed with the ν signal.

Supernova neutrinos

- **Core-collapse supernovae** are a huge source of ν's of all flavors in ~10 sec.
  - 1-3 SN/century in our Galaxy (10 kpc).
  - DUNE will participate in SuperNova Early Warning System (SNEWS).
  - Measurement of the SN ν's will provide information about:
    - **Supernova physics**: Core collapse mechanism, SN evolution in time, black hole formation.
    - **Neutrino physics:** ν flavor transformation, ν absolute mass, other ν properties (sterile ν's, magnetic moments, extra dimensions…).
- **Diffuse background supernova ν's** are also potentially detectable.

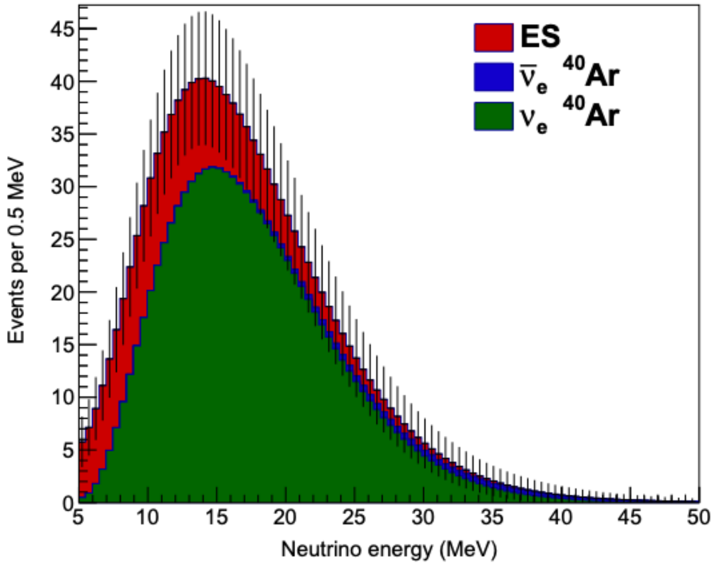




SN1987A
- ~25 neutrinos detected in Kamiokande, IMB, Baksan
- Confirmed baseline model
- Beginning of neutrino & multi-messenger astronomy

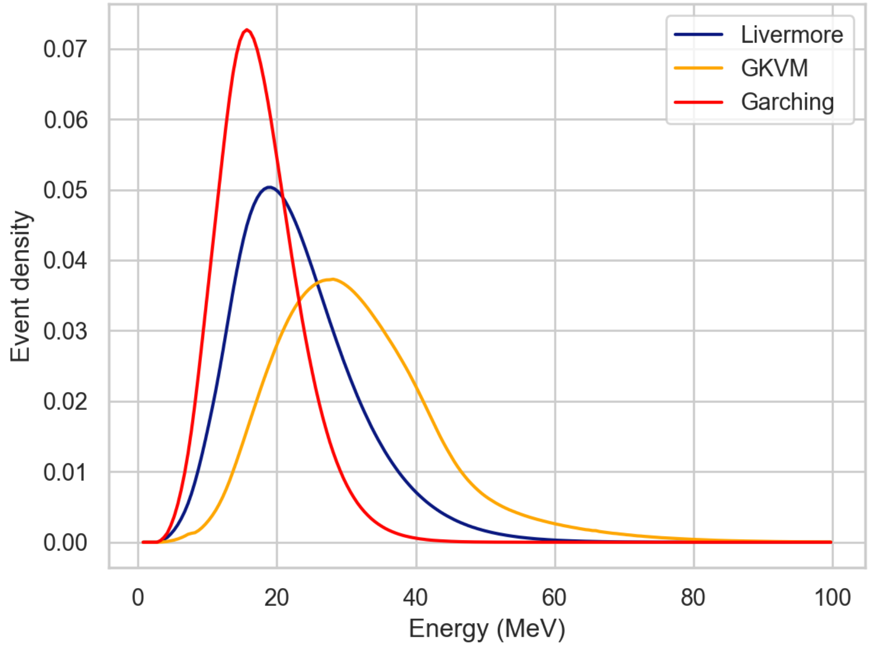
Expected Supernova burst signal in DUNE

SNOwGLoBEs computation of 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
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

ν_e flavor dominates.

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

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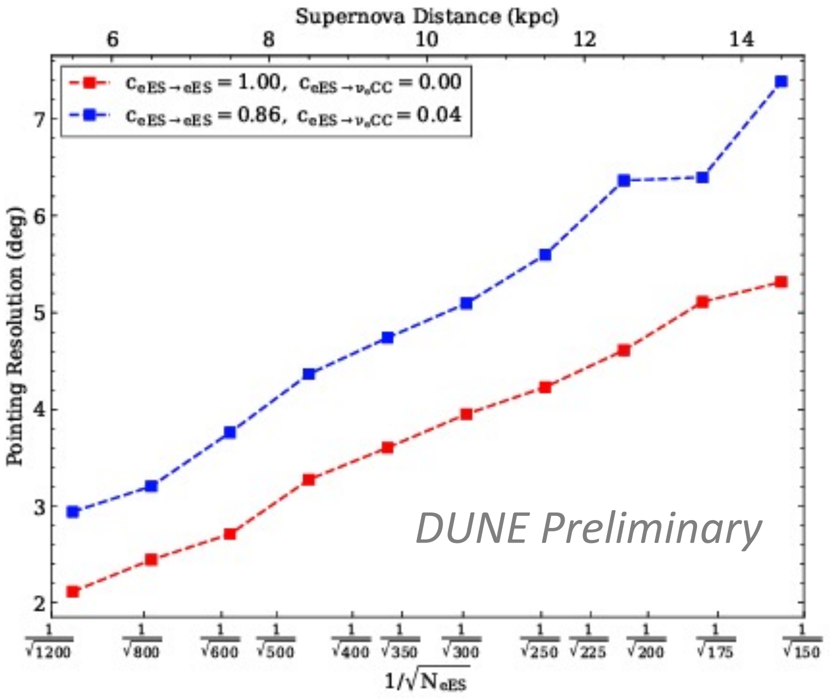
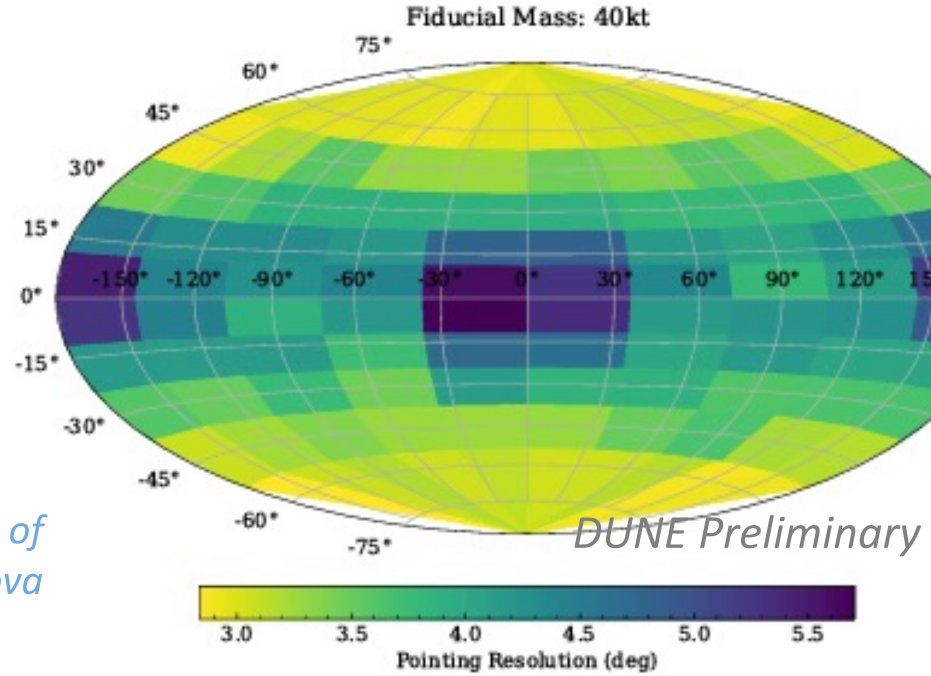
Expected Supernova burst signal in DUNE

- New study on burst pointing resolution
- Simulated supernova at 10 kpc with the GKVM model
- TPC allows flavor discrimination so the ν_e CC component can be mitigated



Burst pointing resolution vs. detected eES events

vs. direction of supernova

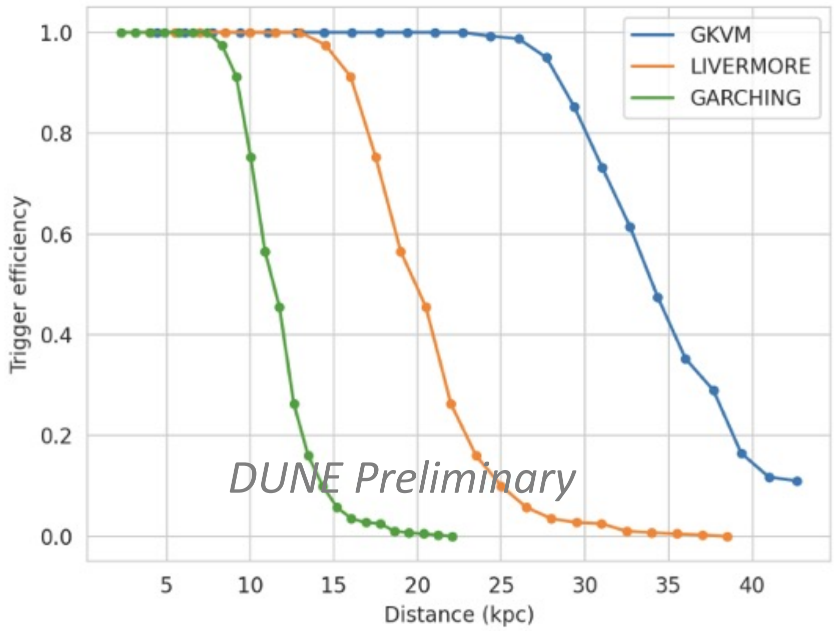


- Exploiting the directionality of $\nu{-}e$ scattering events, we can determine the direction of the supernova to ≈ 4.5 deg

Paper in preparation!

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)



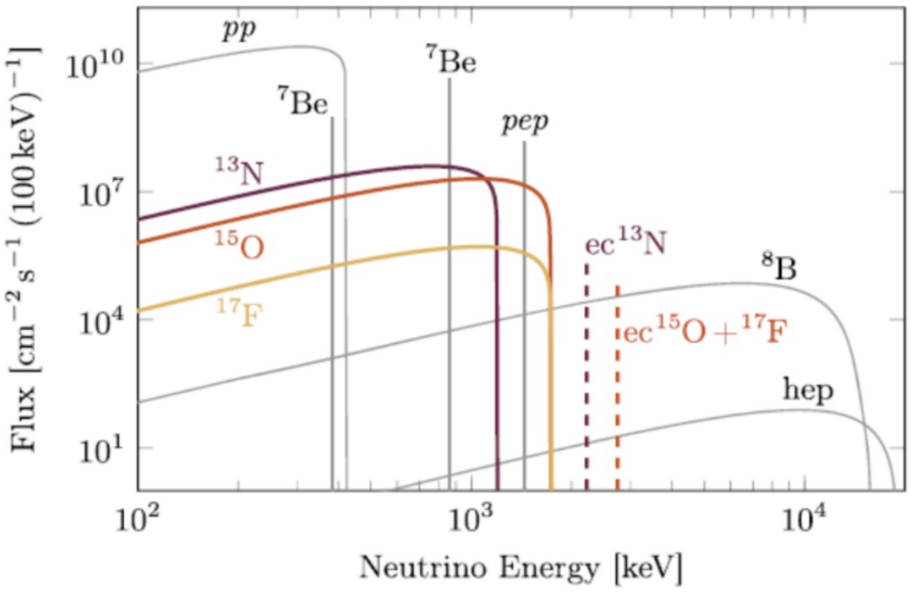
Example: Photon detection system.

- 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).

Backgrounds will have a minor impact on reconstruction, but can affect triggering

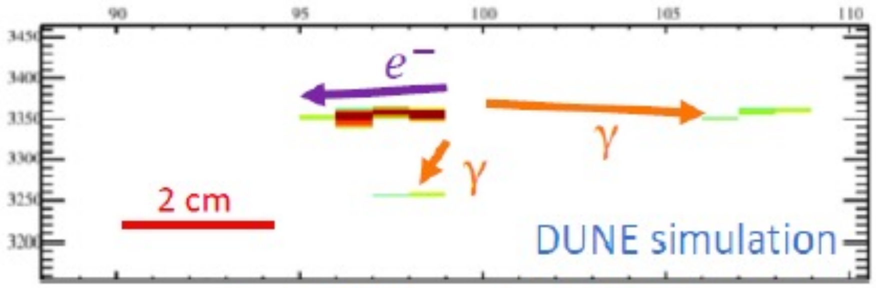
Solar neutrinos

Solar neutrinos in DUNE



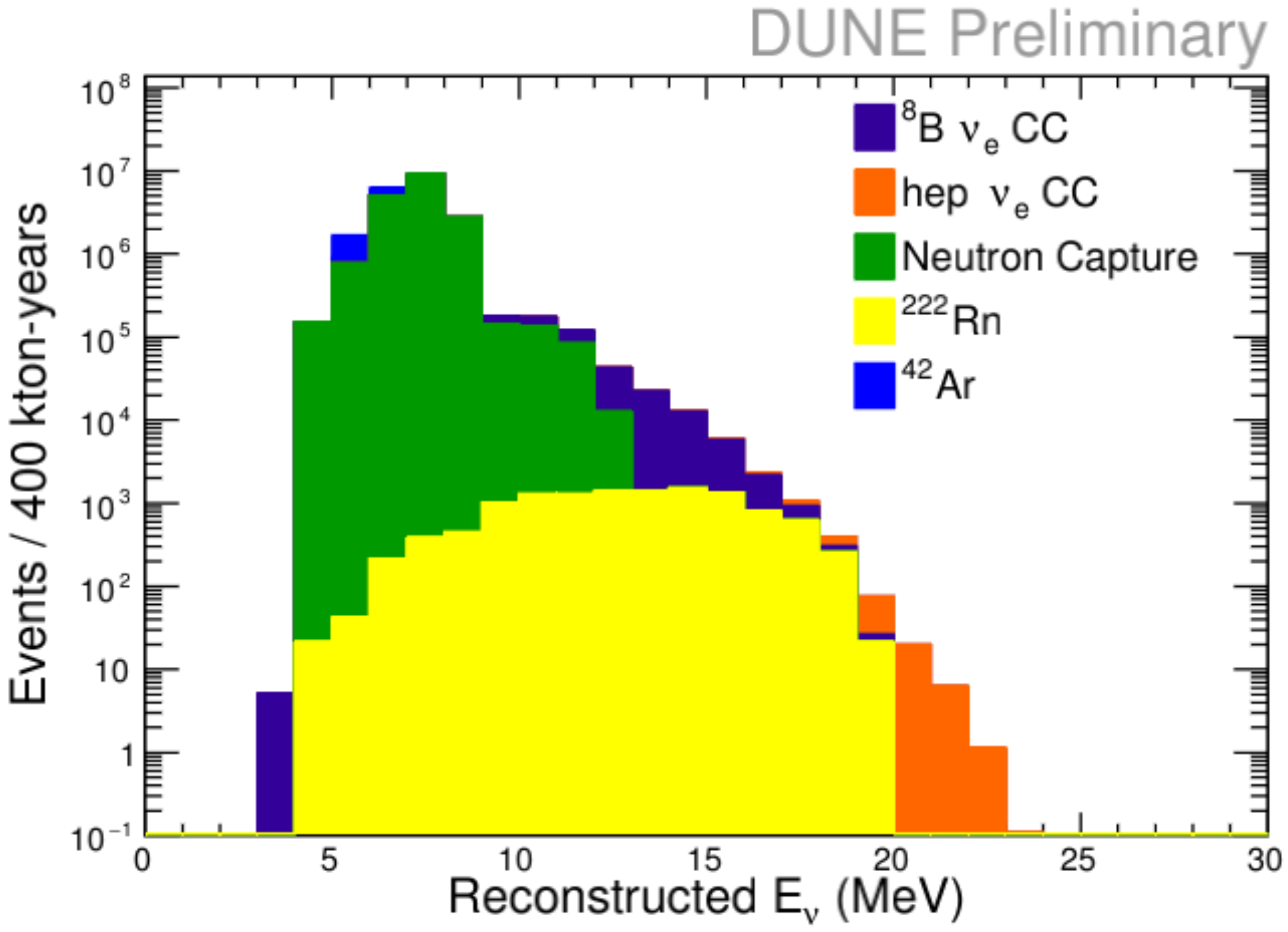
- The sun produces a large flux of neutrinos with may interact in DUNE.
- ^{8}B and hep fluxes are detectable:
  - ^{8}B flux used to extract the solar neutrino oscillation parameters).
  - Neutrinos from hep fusion: ^{3}He + p $\longrightarrow$ ^{4}He + e$^+$ + ν_e have not been observed yet.

- Dominant interaction channel is CC.
- Signal leaves an e- track + gamma cascade in TPC + scintillation light
- Need to trigger and identify



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

Solar neutrinos in DUNE



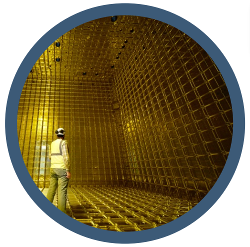
- DUNE will record an enormous amount of solar neutrinos → several events/day/kt.
- Backgrounds are very important. Neutron capture dominates (9 MeV analysis threshold).
- Discovery potential for hep neutrinos in DUNE!
- Precision of neutrino mixing and fluxes.
- DUNE has favorable sensitivity for measuring Δm^2_{21}.
- **On-going full DUNE study.**

Conclusions

Conclusions

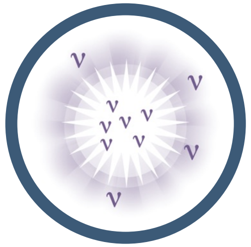
DUNE

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 particular 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 preliminary physics and astrophysics sensitivity studies.



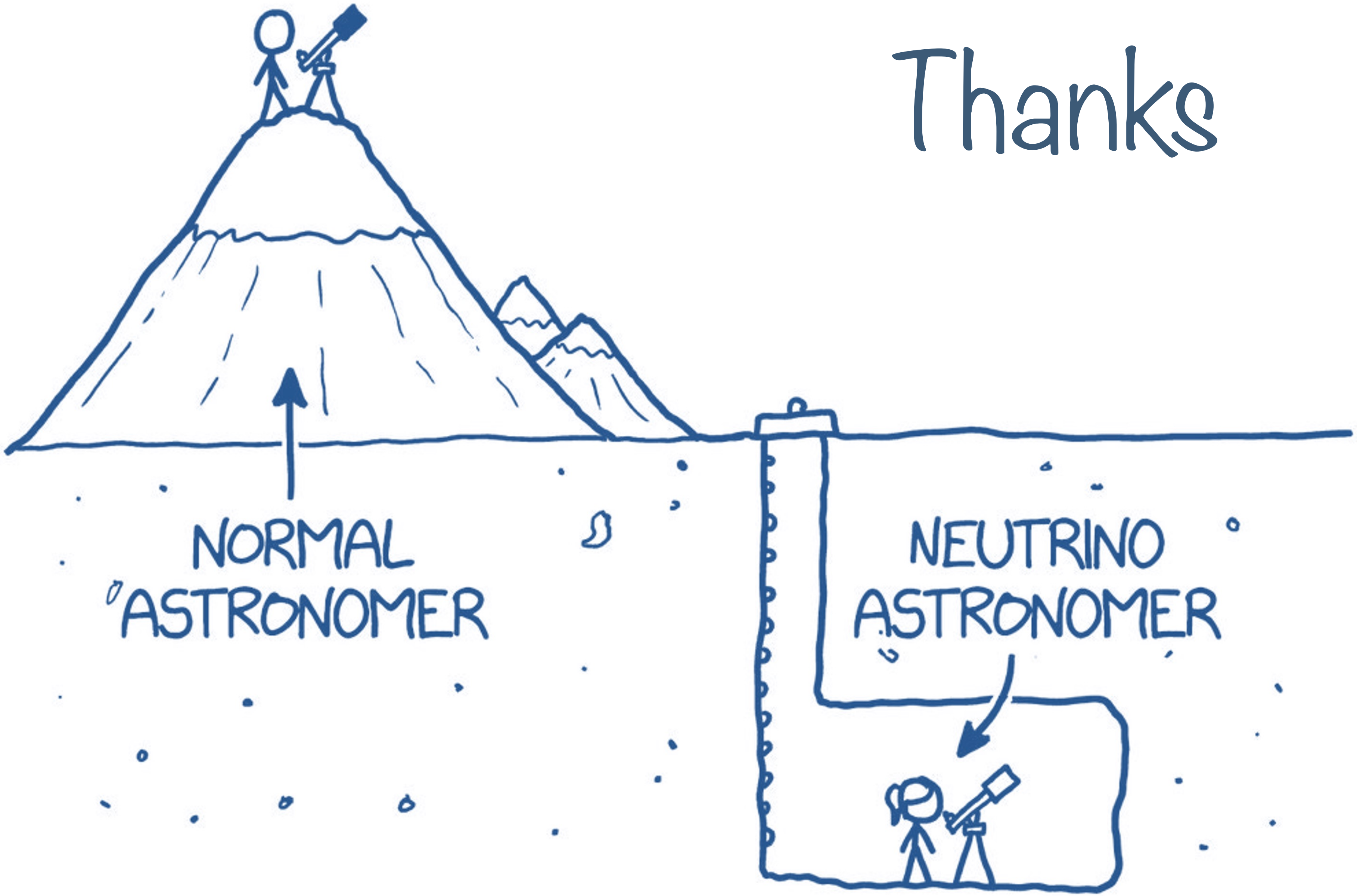
SUPERNOVA NEUTRINOS

DUNE will have good sensitivity to the entire Milky Way, and possibly beyond, depending on the neutrino luminosity of the core-collapse supernova. The observation of a burst will also enable sensitivity to neutrino mass ordering, and potentially many other topics.

SOLAR NEUTRINOS

There is discovery potential for hep neutrinos in DUNE and perform a precision measurement of neutrino mixing and fluxes.

Thanks



Credit: Randall Munroe