Core-Collapse Supernovae Burst Neutrinos in DUNE

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Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

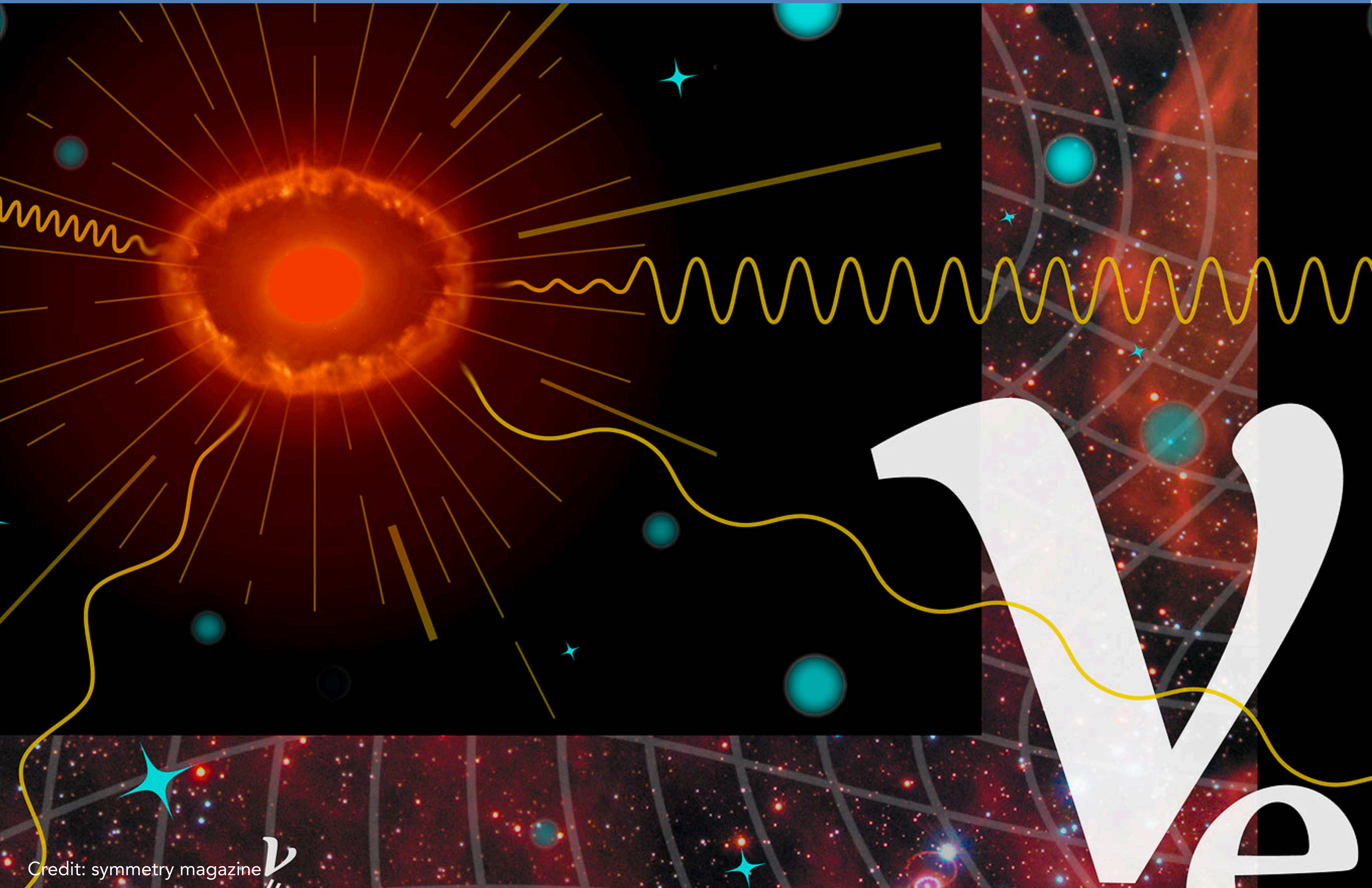
DUNE

Outline

- Supernova neutrino burst
- The DUNE detector
- Low energy events in DUNE
- What can we learn?

Core-collapse supernova burst

Supernova neutrino burst



Credit: symmetry magazine

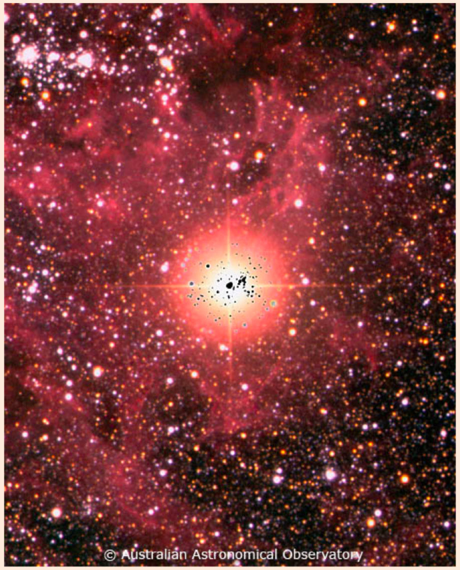
Core Collapse Supernovae

- Core-collapse supernovae are a huge source of neutrinos of all flavors
- Neutrino emission lasts ~10 sec
- Expected 1-3 SN/century in our Galaxy (d ~10 kpc)
- SuperNova Early Warning System (SNEWS)

Measurement of the ν energy spectra, flavor composition and time distributions from SN will provide information about:

- **Supernova physics**: Core collapse mechanism, SN evolution in time, cooling of the proto-neutron star, nucleosynthesis of heavy nuclei, black hole formation
- **Neutrino (other particle physics):** ν flavor transformation in SN core and/or in Earth, collective effects, neutrino absolute mass, other neutrino properties (sterile neutrinos, magnetic moments, extra dimensions…)

SN1987A



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

SN neutrino emission

Infall | Neutronization | Accretion | Cooling

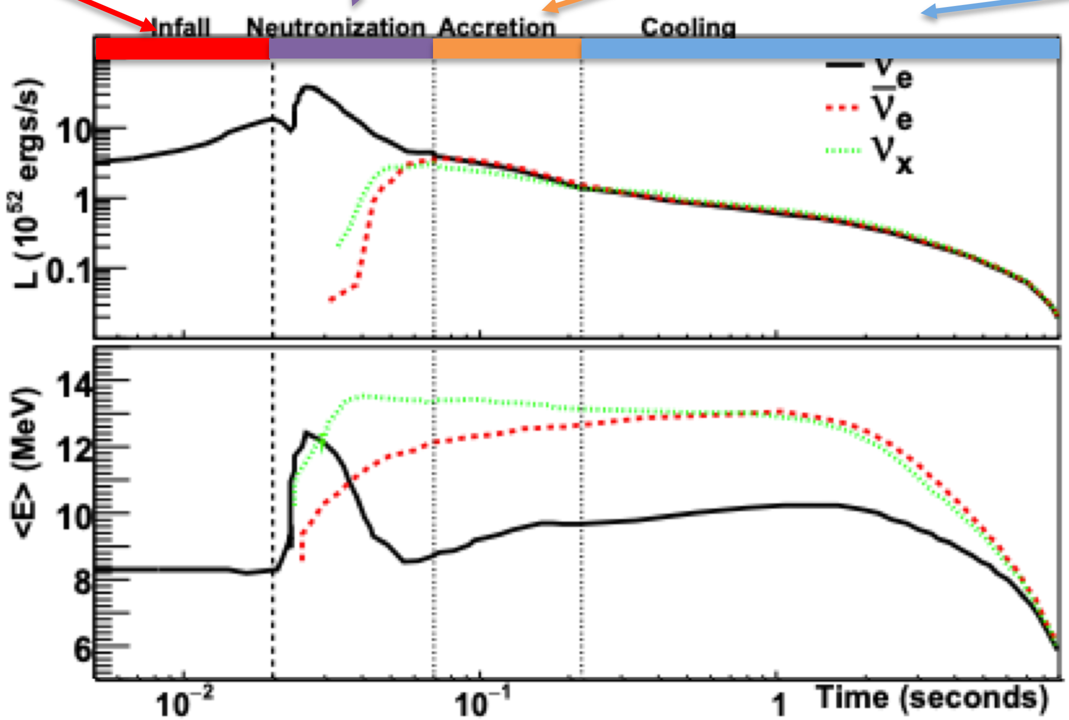
Core collapses, and a shock wave is formed. The medium is opaque even for neutrinos.

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

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

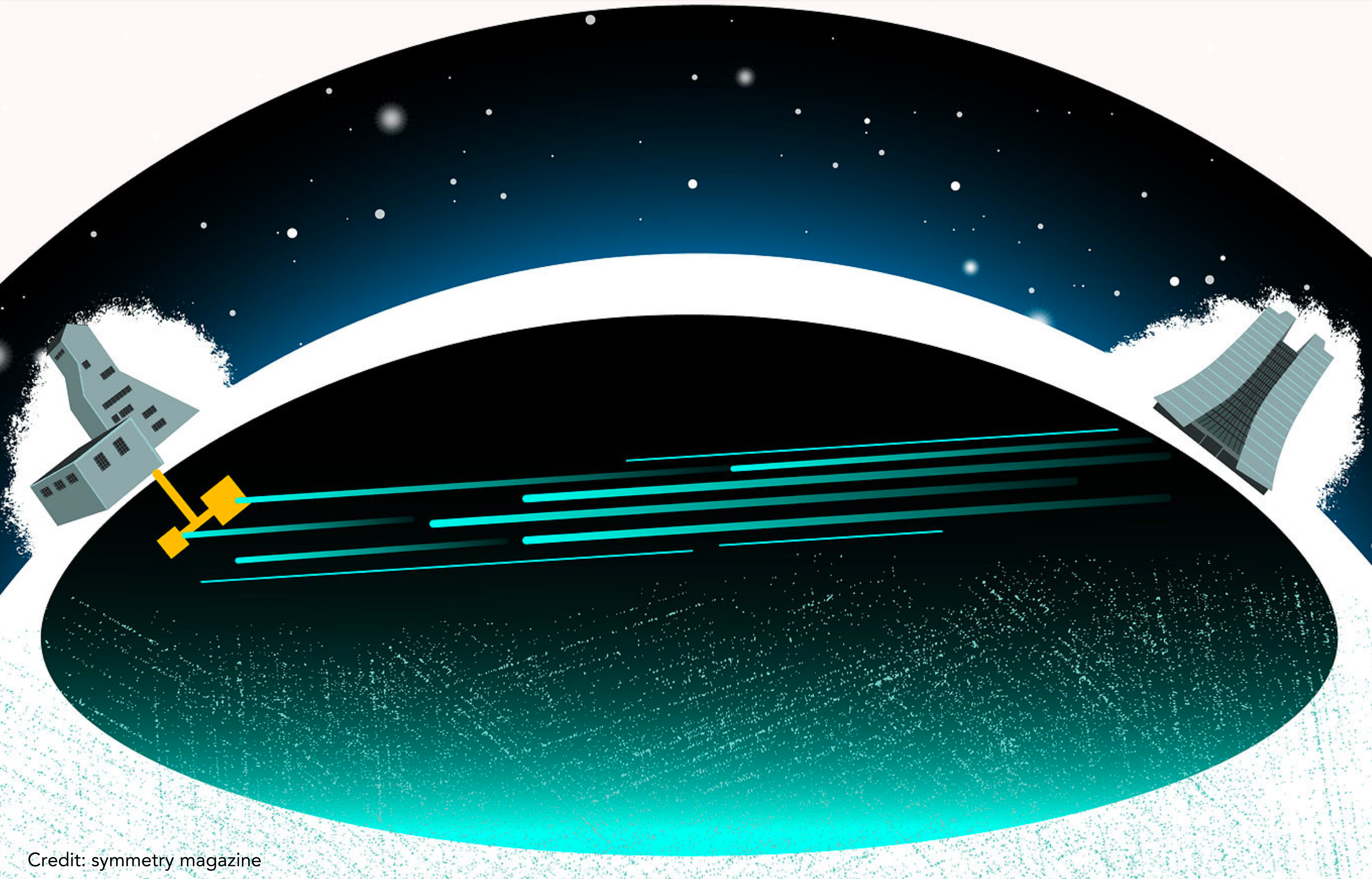
(~10s) main part of the signal, the proto-neutron star sheds its trapped energy.

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.

DUNE

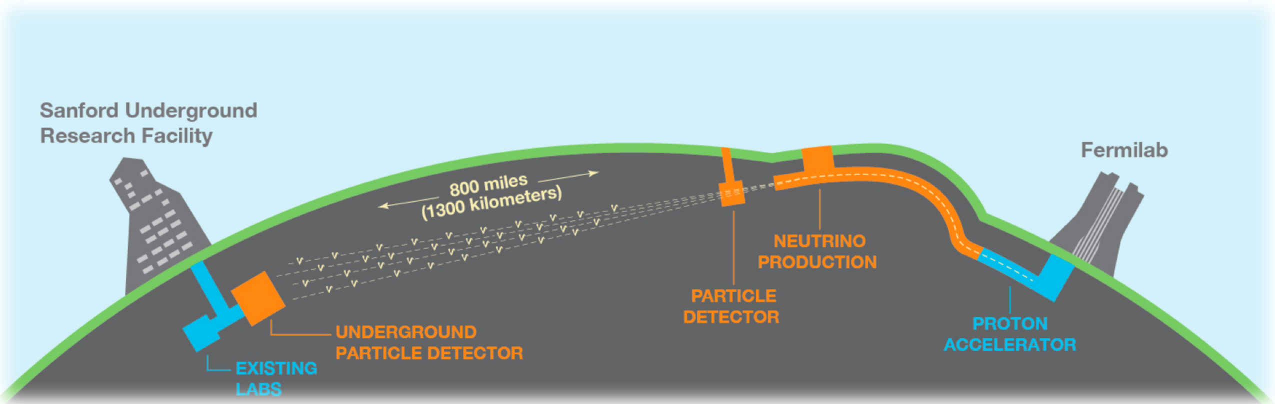


Credit: symmetry magazine

DUNE

DUNE aims at answering fundamental questions related to:

- The matter-antimatter asymmetry - neutrino oscillations & mass ordering
- The Grand Unification of forces - nucleon decay searches
- **The supernova explosion mechanism - supernova neutrino detection**

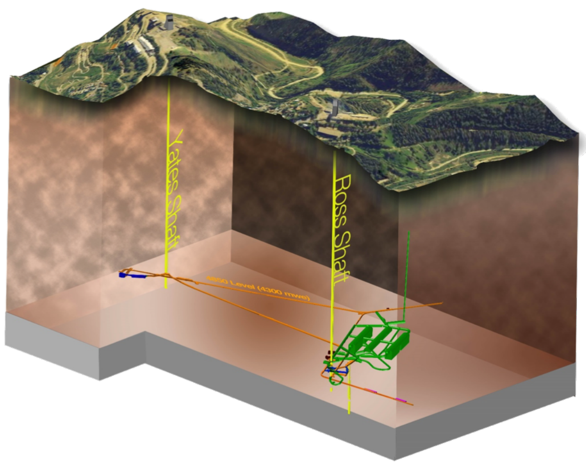


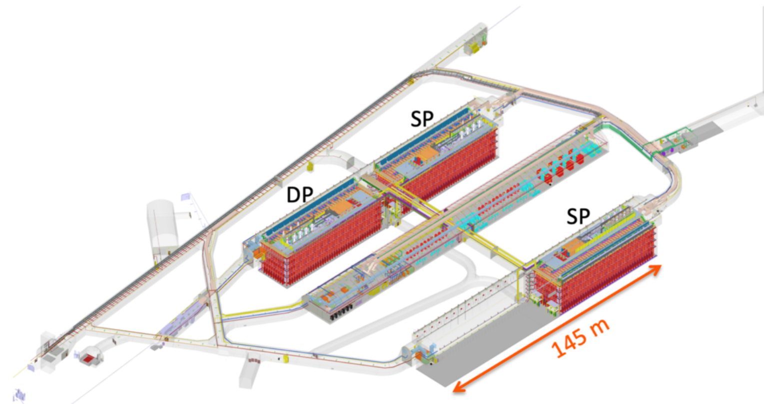
- New neutrino (ν_μ or $\overline{\nu}_\mu$) beam facility at Fermilab (LBNF), US
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints
- 4 x 10 kton (fiducial) LArTPC modules (single and/or dual-phase) deep underground at SURF (Lead, SD, 1300 km baseline)

TDR v1 arXiv:2002.02967

Far Detector

Located 1.48 km underground at Sanford Underground Research Facility in Lead, SD, US





Four 10-kt fiducial LAr TPC modules

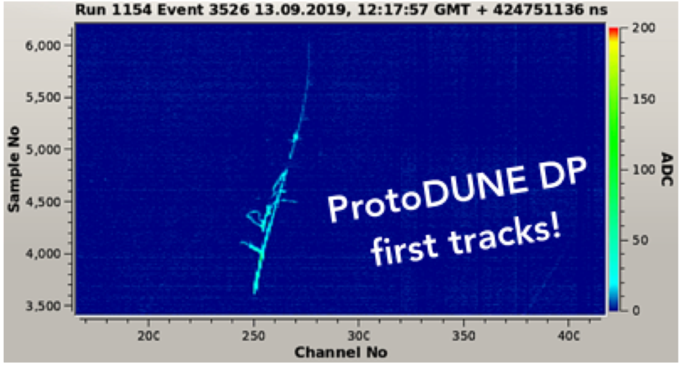
"2+1+1" model:
- 2 modules Single Phase
- 1 Dual-Phase module
- 1 "opportunity" module

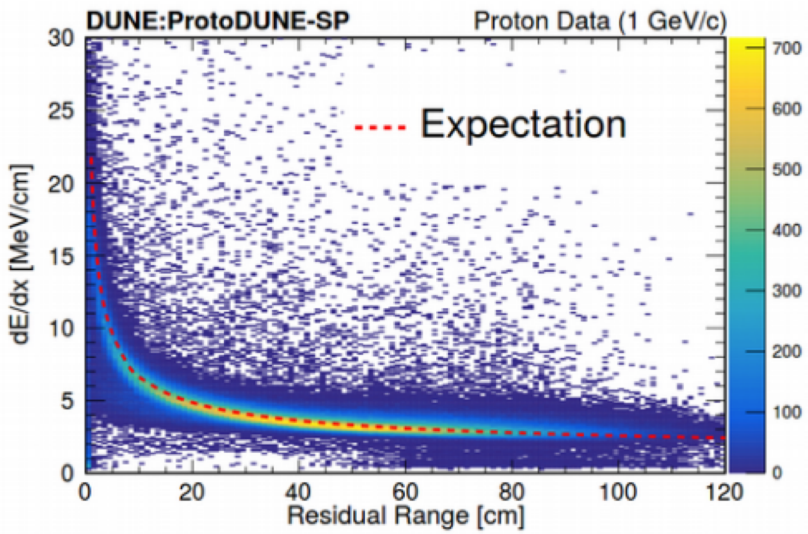
ProtoDUNEs

Construction and operation of 1 kton-scale SP and DP prototypes at CERN from 2018, critical to demonstrate viability of technology

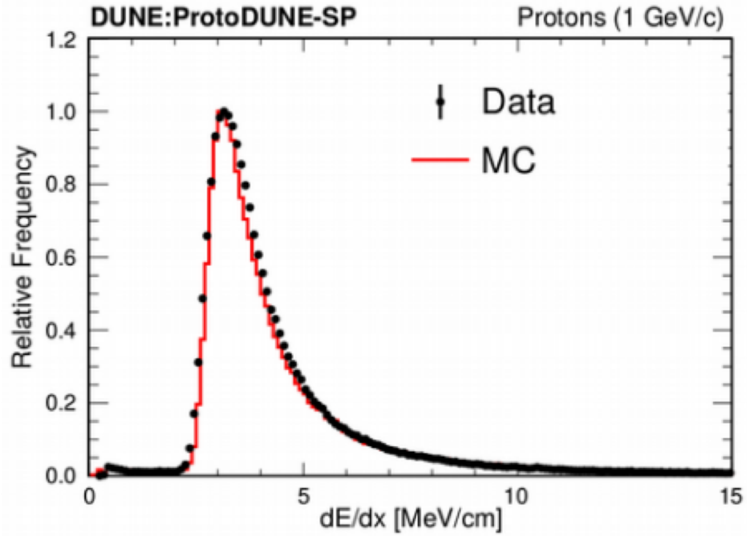
LAr TPC technology

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





dE/dx vs. residual range for 1 GeV protons (data)

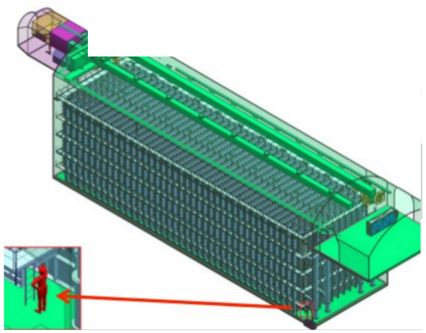


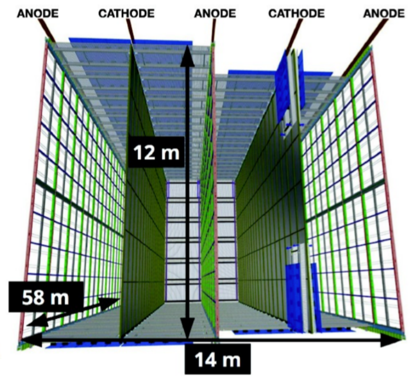
dE/dx distribution of 1 GeV protons (data vs. MC)

arXiv:2007.06722

Far Detector

Single Phase

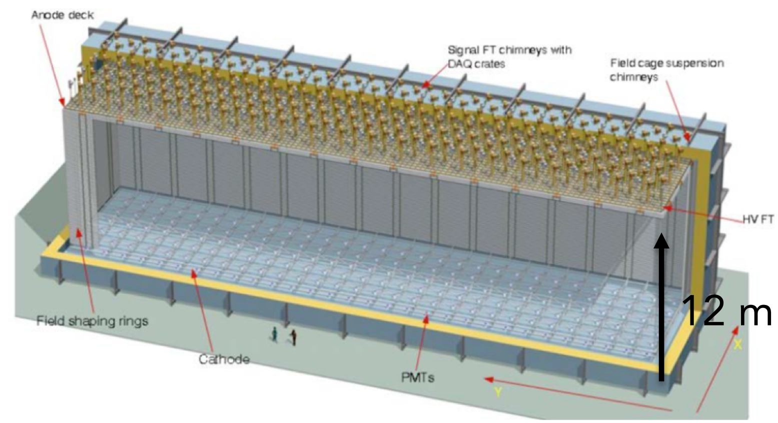




- 3.6 m horizontal **drift**
- Anode wires immersed in LAr vertical
- Anode and Cathode Plane Assemblies (**APA,CPA**)
- **Charge collected** on 3 views, pitch 5 mm
- **Photon detectors:** ARAPUCA light traps + SiPM, embedded in APAs

TDR v4 arXiv:2002.03010

Dual Phase



- 12 m vertical **drift**
- Ionization e- extracted from LAr to gas
- Signal amplified in GAr by Large Electron Multiplier (**LEM**)
- **Charge collected** on 2 views, pitch 3 mm
- **Photon detectors:** PMTs below the cathode

IDR v3: arXiv:1807.10340

Low energy events in DUNE

Credit: symmetry magazine

Supernova neutrino signal in LAr

1. Charged-current (CC) interaction on Ar

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

Dominant interaction

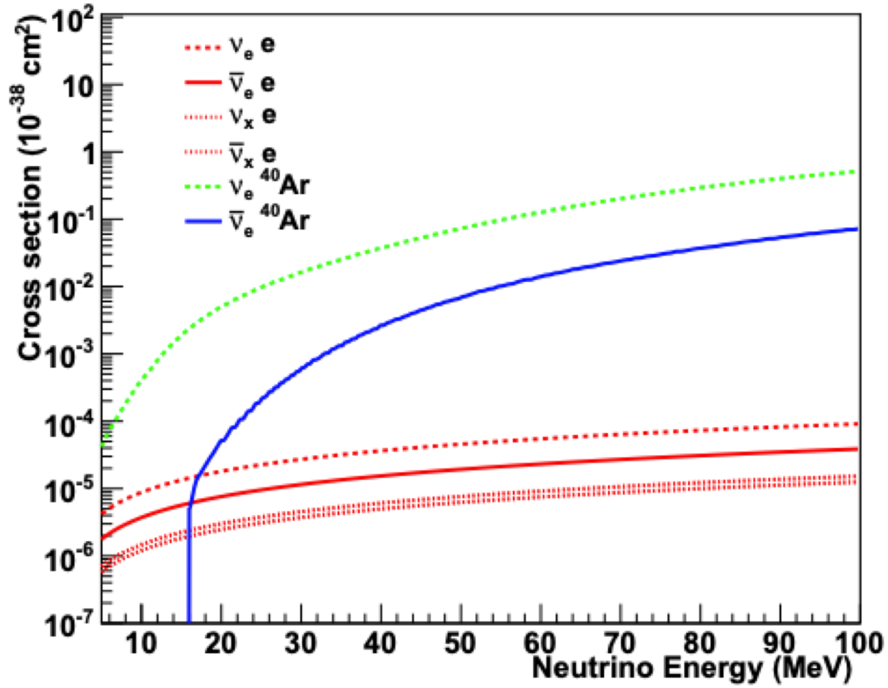
$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

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)

SN Event simulation and reconstruction in DUNE

MARLEY simulates tens-of-MeV ν-nucleus interactions in LAr

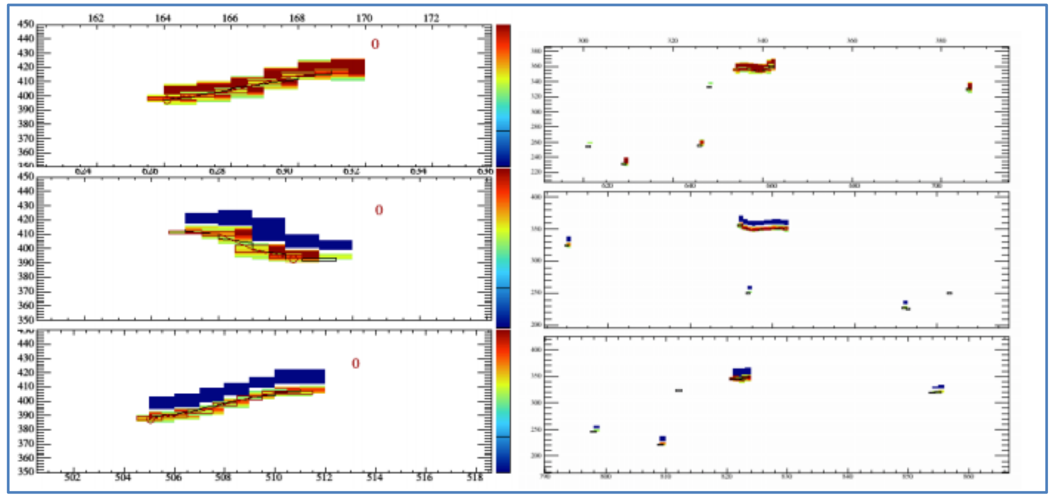
Reconstruction: **LArSoft** to identify interaction channel, ν flavor in CC events, & incoming neutrino 4-momentum

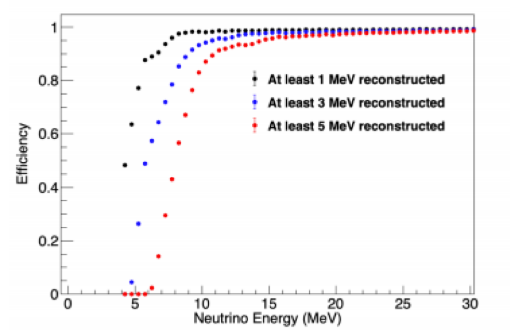
SNOwGLoBES: computation tool of the predicted event rate from a SNB

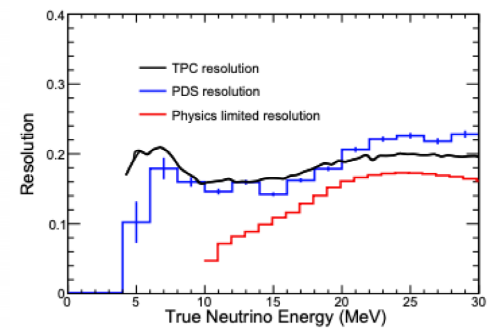
Backgrounds will have a minor impact on reconstruction, but can affect triggering

ν-e^- ES event (10.25 MeV e^-)

ν_eCC event (20.25 MeV ν)







TDR v2 arXiv:2002.03005
Paper under preparation

Expected SNB signal in DUNE

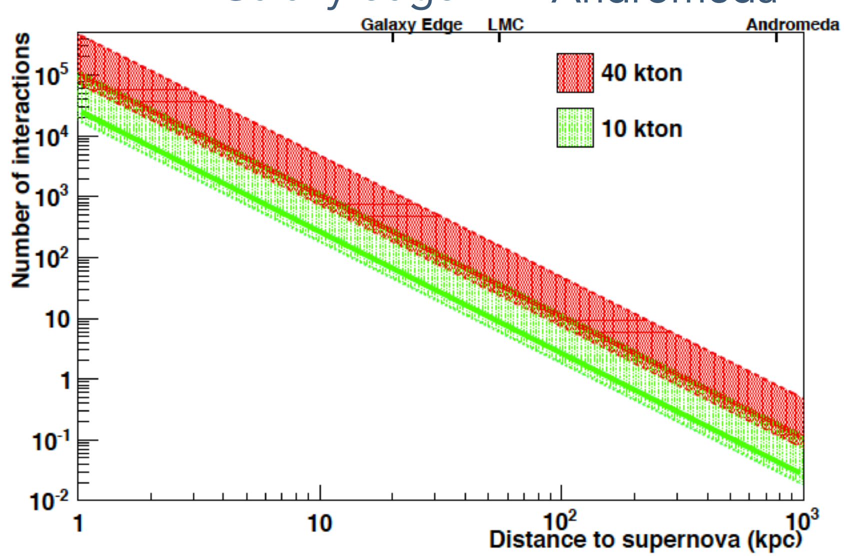
Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$	2720	3350
$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

ν_e flavor dominates.

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

Number of SN ν interactions scales with mass and inverse square of distance

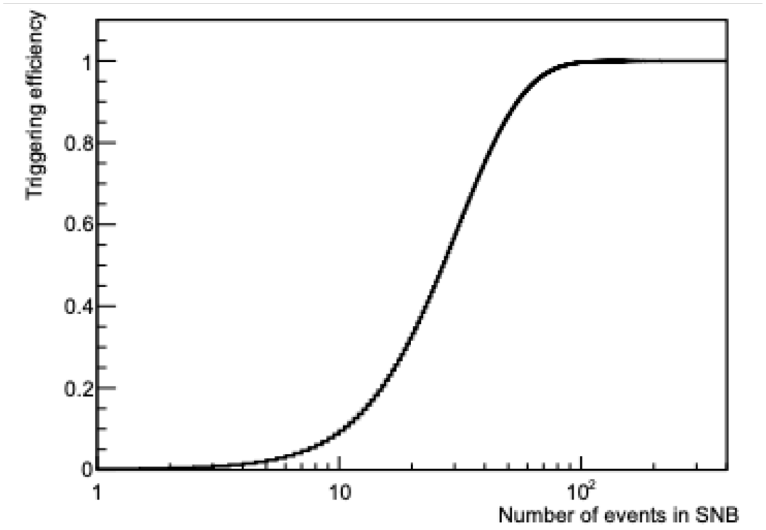
Galaxy edge Andromeda



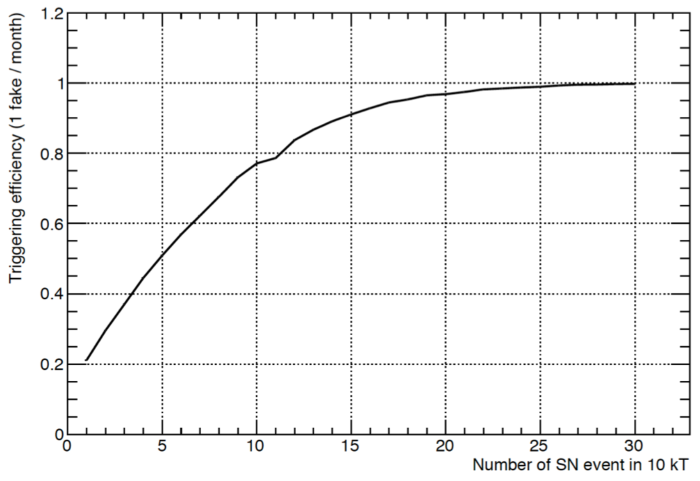
DUNE SN burst event triggering

- Trigger scheme: time coincidence of multiple signals over a timescale matching the SN luminosity evolution
- Redundant and highly efficient triggering scheme under development
- Preliminary trigger designs with maximum fake trigger rate (1/month)

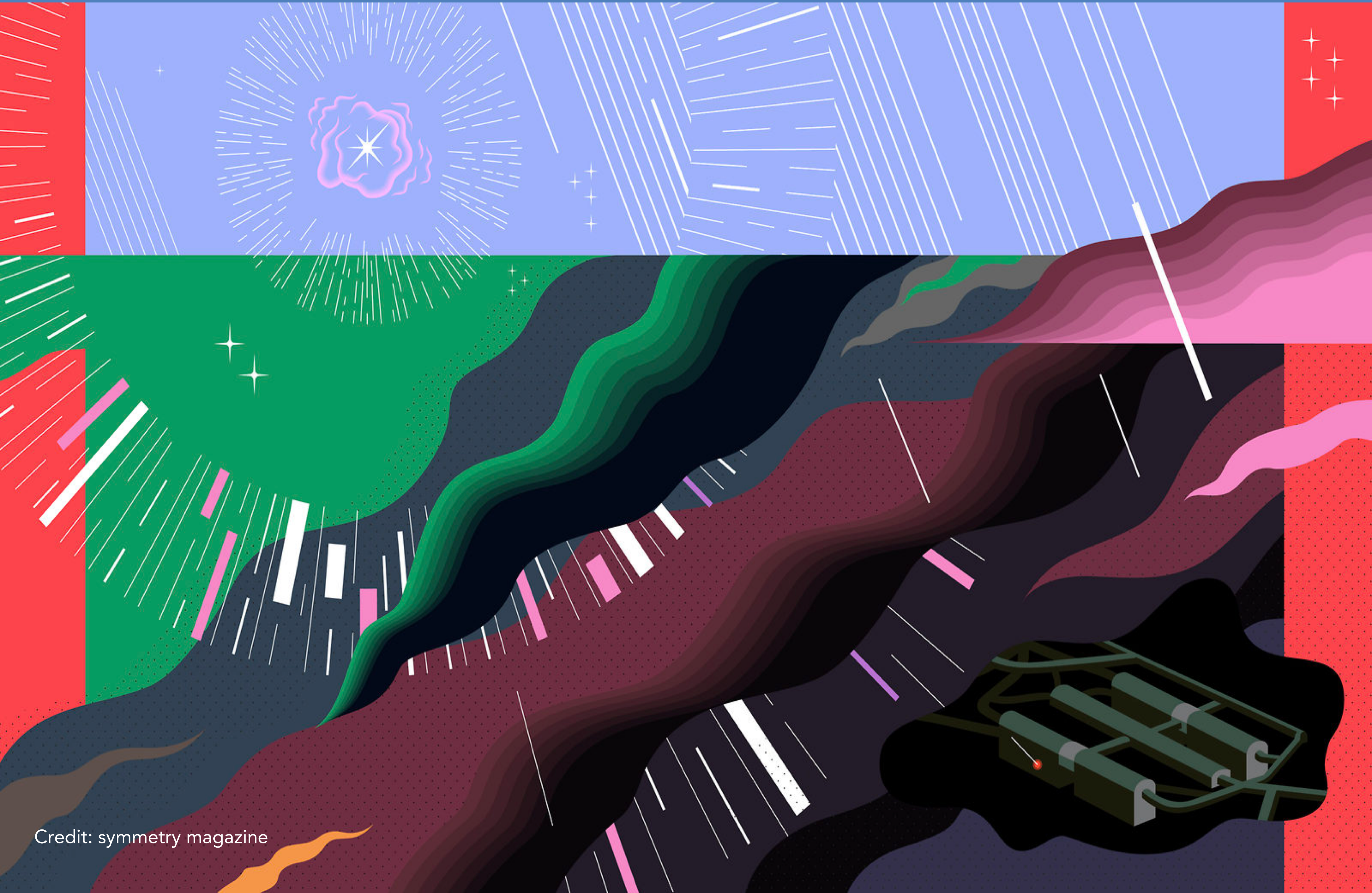
Photon detection system in dual-phase: Real time algorithm provides trigger primitives by searching for PMT hits and optical clusters (based on time/spatial information).



TPC: multiple coincidences in up to 10s, with multi-level data selection chain (per wire basis with a threshold-based hit finding).



What can we learn?



Credit: symmetry magazine

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

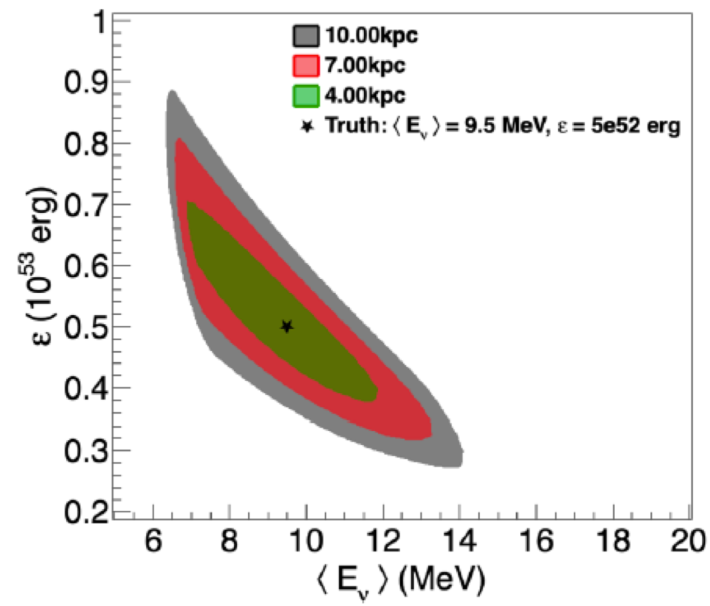
Astrophysics of core collapse

- **Supernova spectral parameter fits**
  - Fit to the SN spectral parameters

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

~ luminosity   'pinching' parameter

  - SNOwGLoBES to model signals described by the pinched-thermal form.
  - Focus on ν_e flux and ν_e-CC interactions.

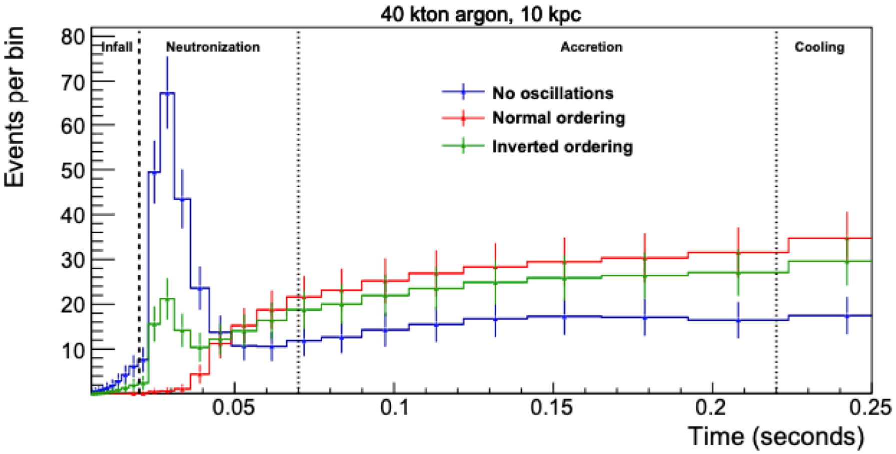


- **Effect of event timing.** Supernova-specific design considerations:
  - Interval between ν interactions is 0.5-1.7 ms (50 ms of a 10-kpc-distant SN)
  - SASI flavor oscillations (~10 ms)
  - ν trapping notch width 1-2 ms

Timing resolution requirements in DUNE
- TPC: 0.6 ms
- Photon Detection system: $< 10\ \mu s$

Neutrino & 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).
- Energy-loss analysis using **total energy of the emitted neutrinos and cooling rate. Complementary** data of $\bar{\nu}_e$ from water Cherenkov detector and scintillator detectors.
- **Flavor transition physics** and its signatures: a lot to be understood in earlier and later periods.
- 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.
- **Neutrino mass ordering** affects the specific flavor composition, different models under study



Conclusions

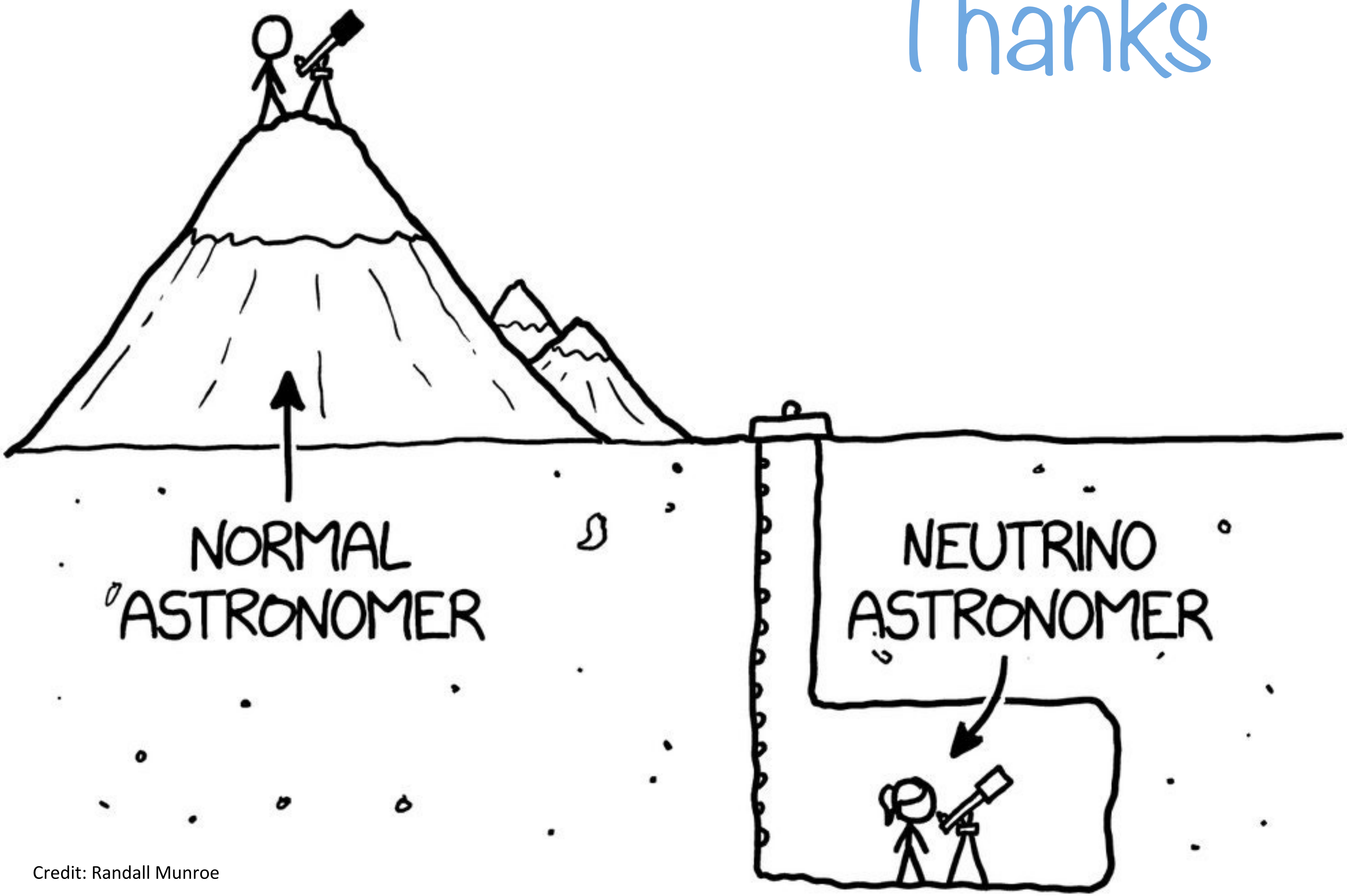
Credit: CERN

Conclusions

- DUNE experiment's sensitive to neutrinos with about 5 MeV up to several tens of MeV, the regime of relevance for core-collapse supernova burst neutrinos.
- This low-energy regime presents particular challenges for triggering and reconstruction. Backgrounds are expected to be relatively tractable during the few tens of second interval of a supernova burst.
- 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.
- DUNE will have good sensitivity to the entire Milky Way, and possibly beyond, depending on the neutrino luminosity of the core-collapse supernova.
- We expect a threshold turning on at about 5 MeV deposited energy, and an energy resolution between 10 and 20%. We expect good sensitivity to supernova ν_e spectral parameters.
- The observation of a burst will also enable sensitivity to neutrino mass ordering, collective effects, and potentially many other topics.

Next talk by AJ Roeth 'Supernova Neutrino Pointing with DUNE'

Thanks



Credit: Randall Munroe