Detecting supernova neutrinos at SNO+

Sammy Valder

Supernova Neutrinos in the Multi-Messenger Era

07/04/2022

UNIVERSITY
OF SUSSEX

Introduction

In this talk:

- SNO+ Experiment
- How do supernova neutrinos interact with SNO+?
- Backgrounds
- How do we detect supernova neutrinos?
- Outline of potential physics we can learn

SNO+ Experiment

- Upgrade from Sudbury Neutrino Experiment (SNO) which won the Nobel Prize in Physics in 2015
  https://www.nobelprize.org/uploads/2018/06/mcdonald-lecture-slides.pdf

- Housed in SNOLAB, Sudbury, Canada

- Multi-purpose neutrino experiment

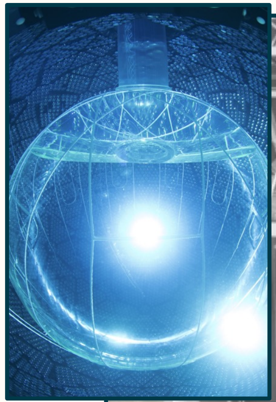
  - Primary research goal is neutrinoless double-beta decay ($0\nu\beta\beta$).

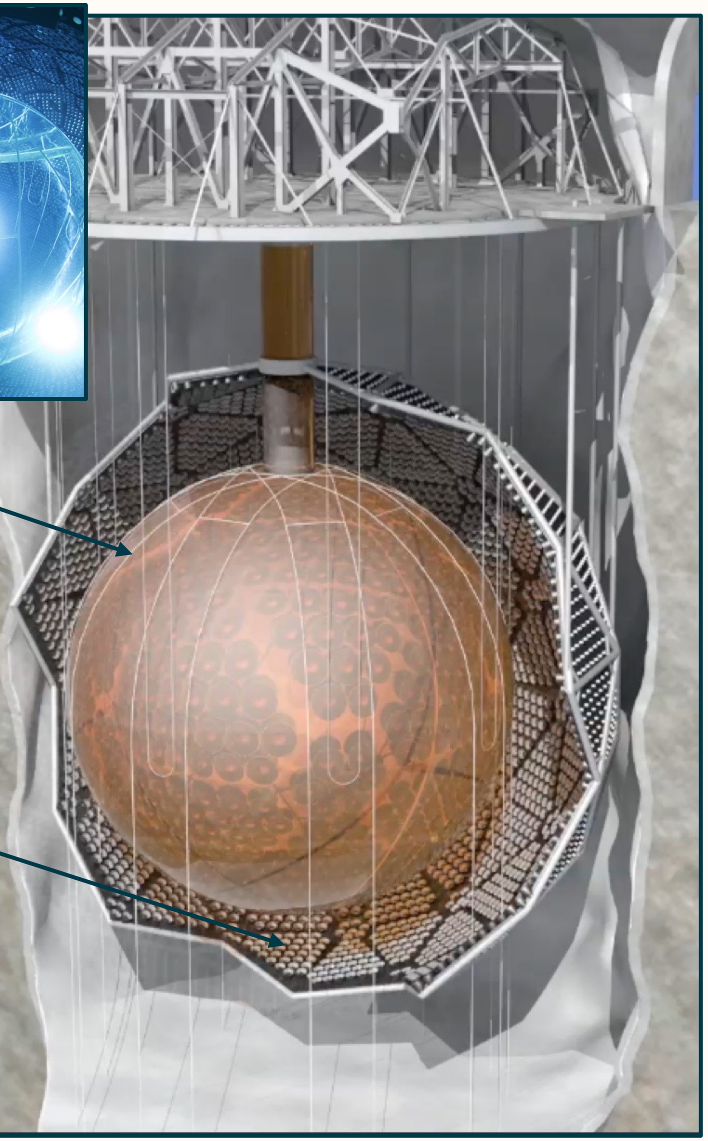
  - Broad physics program includes, solar and reactor neutrino oscillations, geoneutrinos and ***supernova neutrino detection***, nucleon decay, and dark matter detection

- Albanese, V., et al. "The SNO+ experiment." *Journal of Instrumentation* 16.08 (2021): P08059 https://arxiv.org/abs/2104.11687

SNO+ Detector

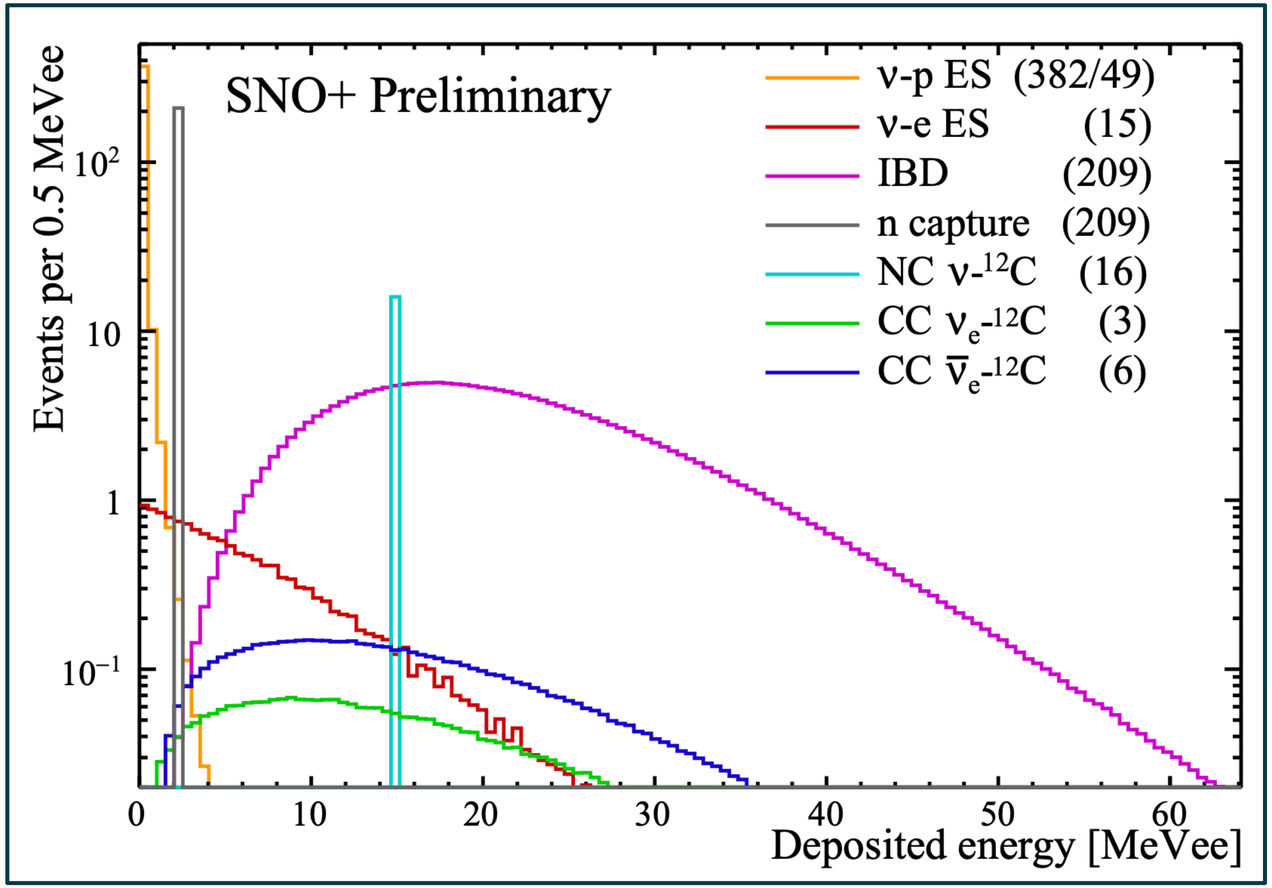
- 2 km underground, ~6000 MWE
- 12 m diameter Acrylic Vessel (AV):
  - Filled with 780 tonnes of liquid scintillator:
    - LAB + [target of] 2 g/L PPO
    - To be loaded with ^{130}Te for double beta decay studies
- Surrounded by 7 kT of external ultra-pure water
- Viewed by ~9300 (8”) PMTs mounted on a 17 m diameter PMT support structure (PSUP)
- AV is now full filled with liquid scintillator. Currently loading PPO, planned to start adding ^{130}Te at the end of 2022



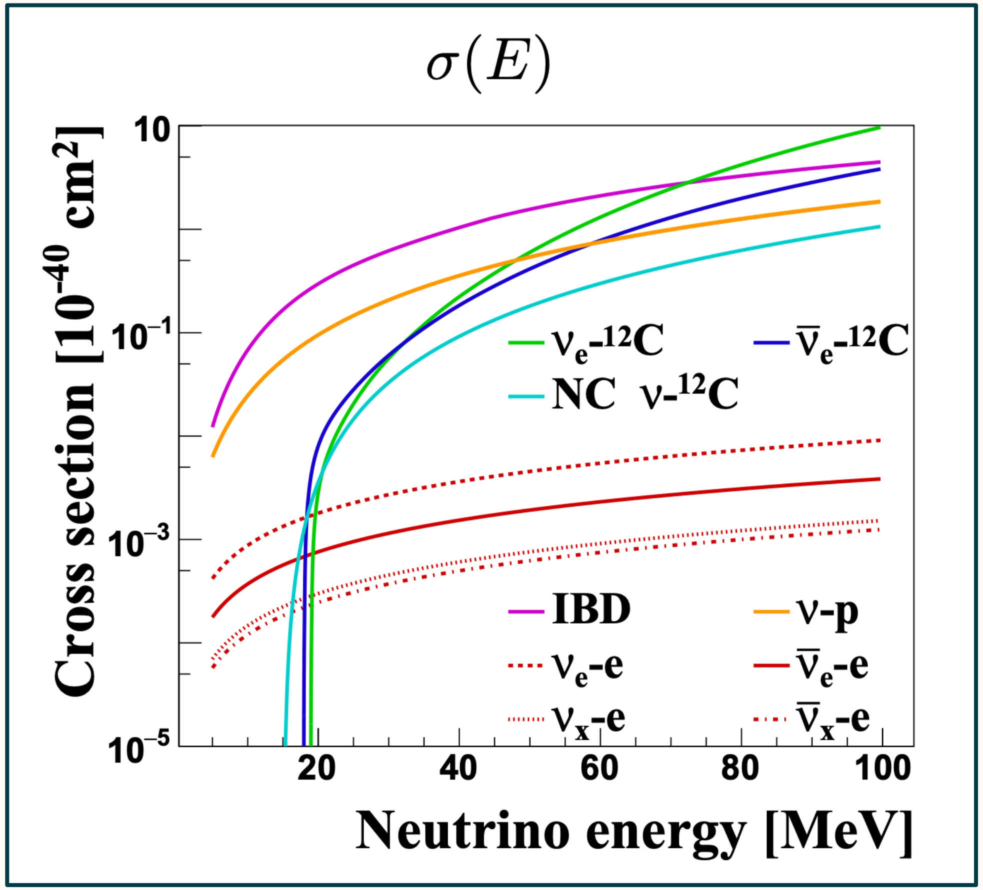


Interaction Channels

Supernova neutrino interaction channels available to SNO+ *inside* the AV

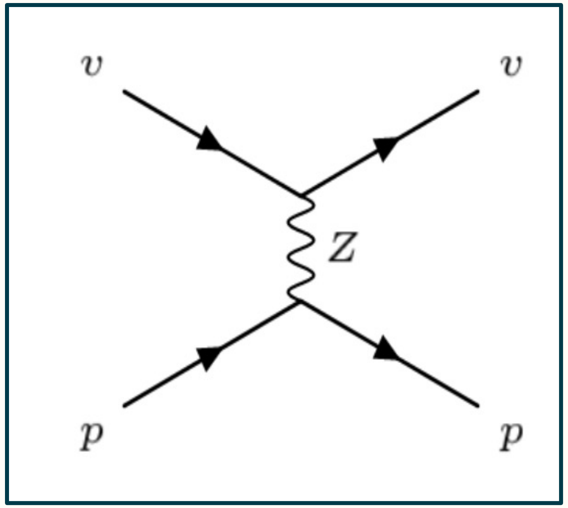


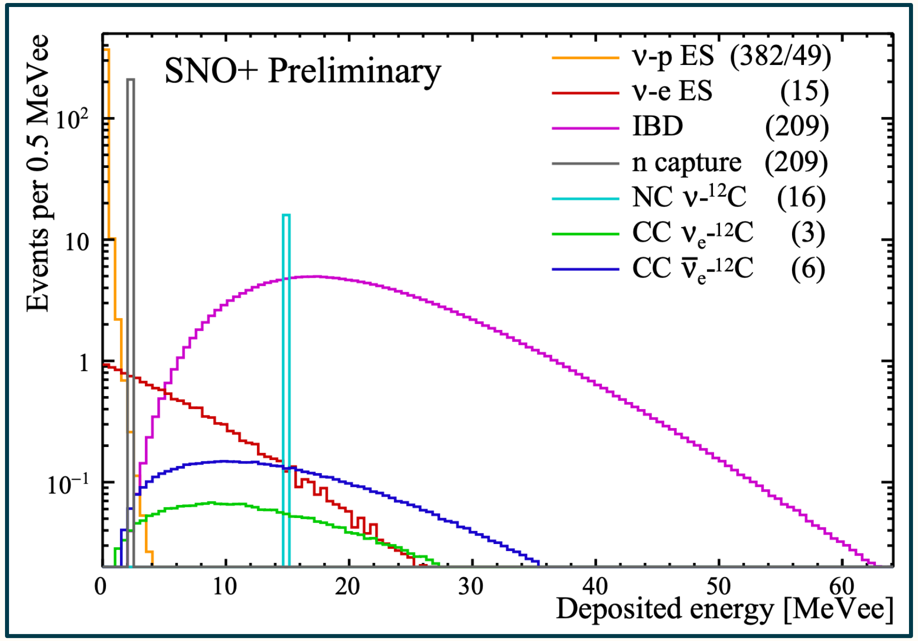
Cross-sections of interaction channels available to SNO+ *inside* the AV



Proton Scattering

- Few MeV protons are invisible in water Cherenkov detectors, but is possible to see them in liquid scintillator → available to SNO+
- Neutral current (NC) interaction → sensitive to all neutrino flavours
- Proton recoil spectrum provides spectral information about incoming neutrino → measure neutrino energy
- Difficult to detect
- Signal will be quenched in the detector
  - 382 events predicted†, 49 events above a 200 keV threshold* after proton quenching
  - Second largest SN signal in SNO+



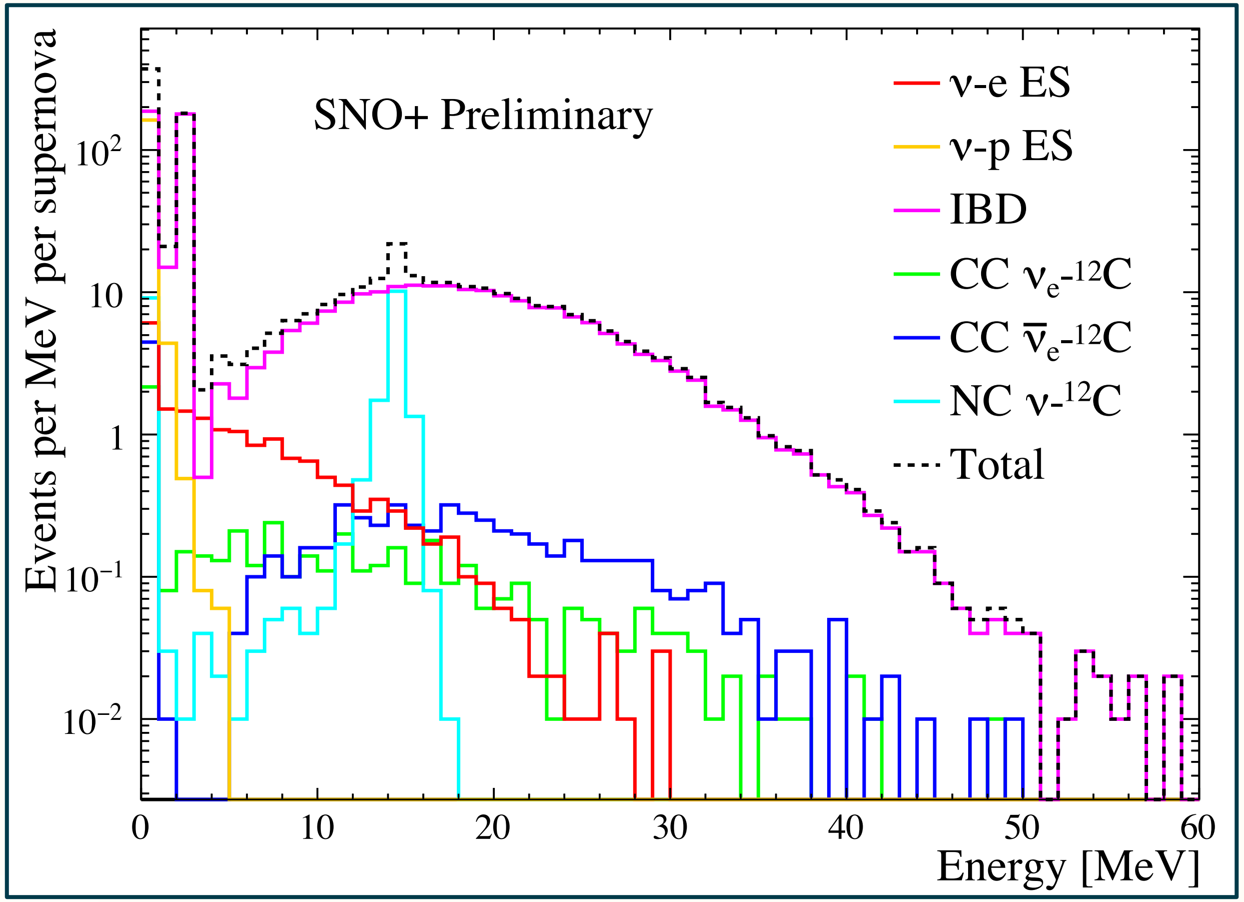


† $27 M_\odot$ progenitor CCSN with LS220 equation-of-state, 10 kpc away

* This threshold has since been dropped to 100 keV for SNO+

Event Generation

- SNO+ recently integrated with sntools[1] to simulate supernova neutrinos in the detector
- Generated events for 100 supernovae – renormalise to predict sensitivity per example[2] supernova
- Run through detector simulation to include energy smearing and reconstruction
- Can measure NC ν-^{12}C through 15.1 MeV excitation
- Have sensitivity to ν-p elastic (NC) scattering which is unique to liquid scintillators
    - Proton recoil spectrum can also give information about incoming ν energy

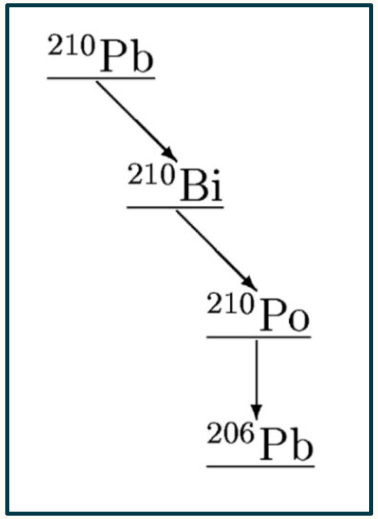


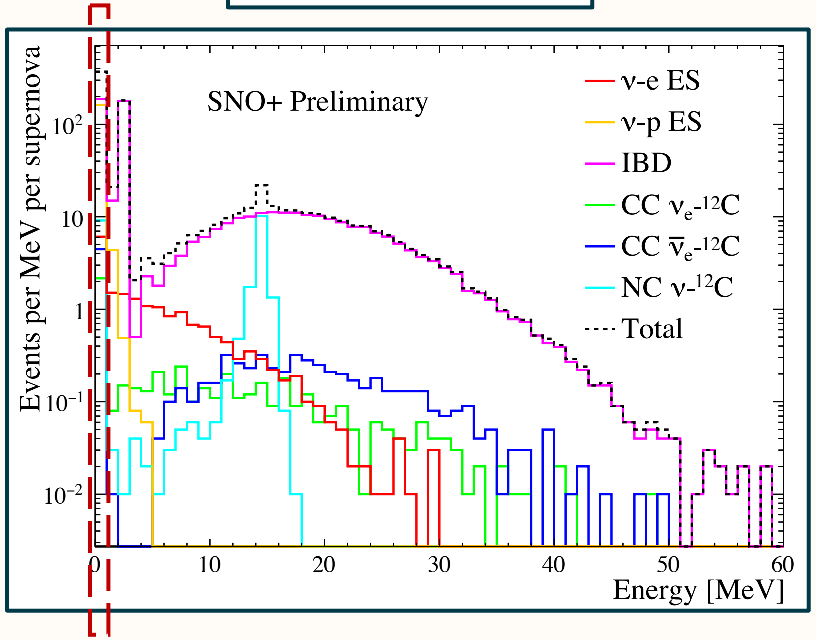
[1] Migenda et al., (2021). sntools: An event generator for supernova burst neutrinos. Journal of Open Source Software, 6(60), 2877, https://doi.org/10.21105/joss.02877

[2] A. Mirizzi et al. Rivista del Nuovo Cimento Vol. 39 N. 1-2 (2016)

[with 27$M_\odot$ progenitor CCSN with LS220 equation-of-state, at 10 kpc]

Backgrounds

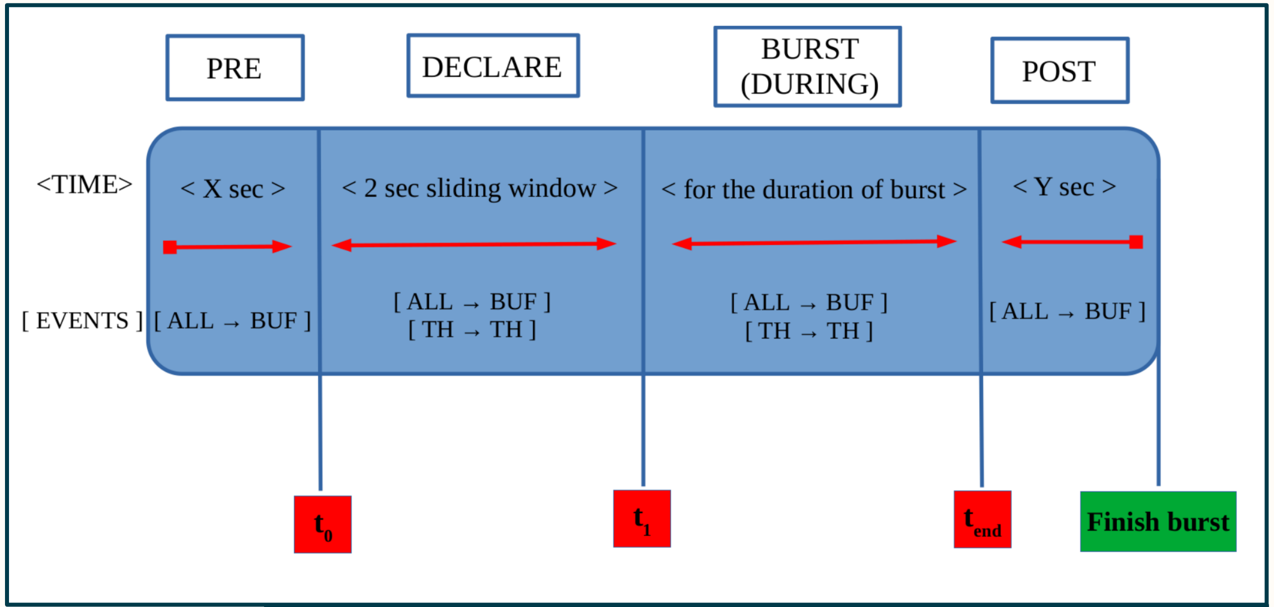




- Two main sources:
  - Intrinsic background from scintillator
  - Background from AV
- Only relevant in low energy regions < 1 MeV
  - Only affects ν-p and neutron scattering
- IBD signal is essentially background free due to neutron tagging
- Very low background likely for NC ν-^{12}C peak
- External backgrounds from other detector objects (PMTs, ropes, external water) are negligible for 5 m fiducial volume
- Re-evaluation of key backgrounds due in the near future

Burst Detection

- Looking for bursts of multiple coincident events above an energy threshold lasting $\mathcal{O}(10)$s long
- Three levels:
  - Level 1: Detect/define the bursts
  - Level 2: Analyse default observables
  - Level 3: Data cleaning
- Almost in real-time: 1-2 s latency to builder, < 30 s to analyse
- Four different buffers → allows for customisation/tuning
- Run in circular buffers to deal with boundaries
- Alarms when SN-like signal is detected:
  - Tuneable threshold values aim for ~ 1 alarm per month
- Supernova shifters on-call 24/7 for burst monitoring

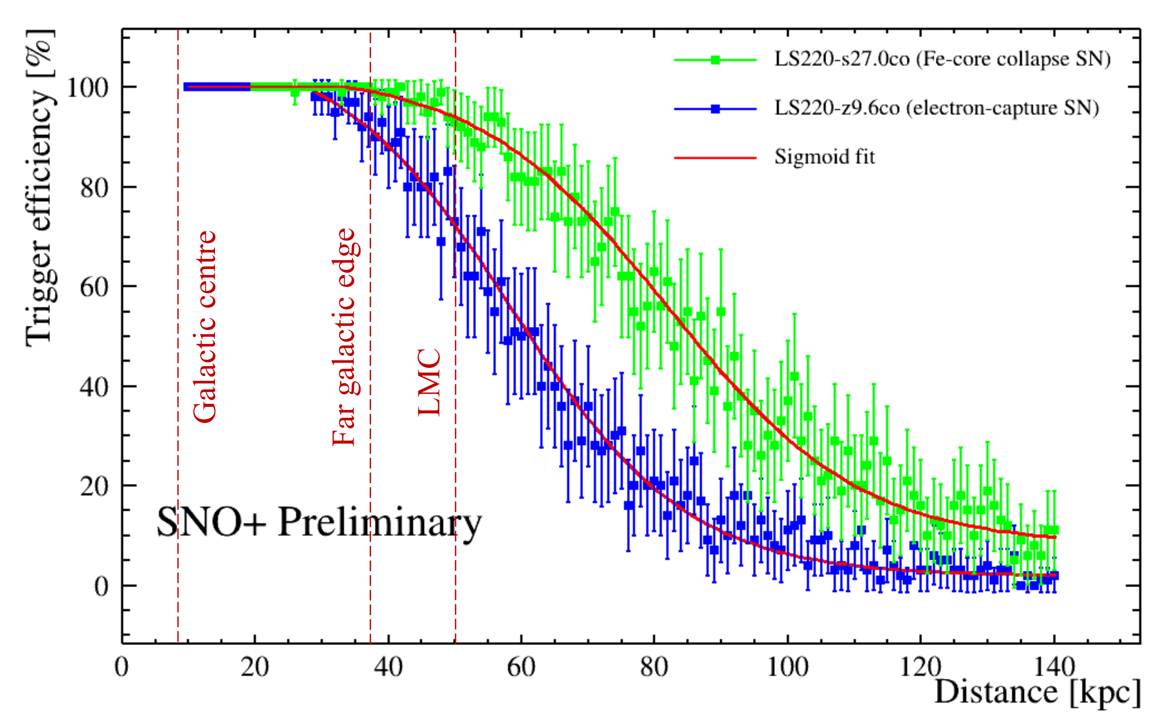


M. Rigan, IoP HEPP, APP & NP Annual Conference 2021

SNO+ has recently integrated with SNEWS test channel, work ongoing for SNEWS2

https://snews.bnl.gov/ https://snews2.org/

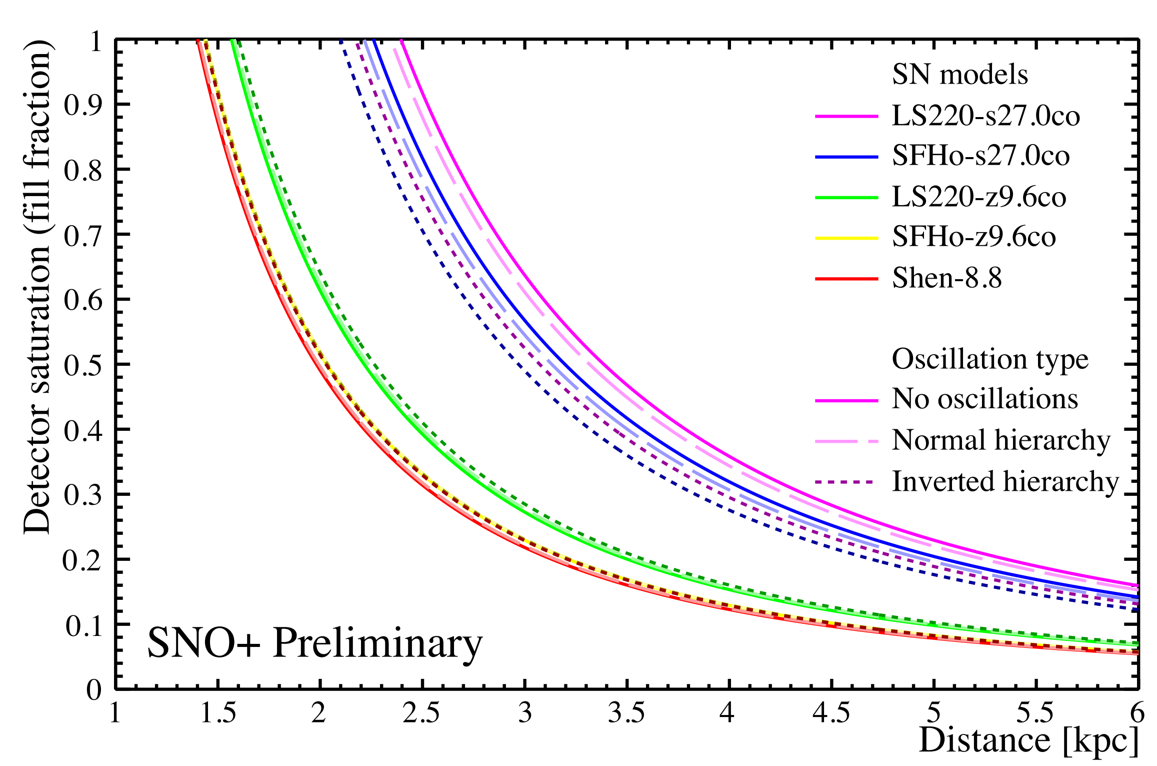
Detection Efficiency



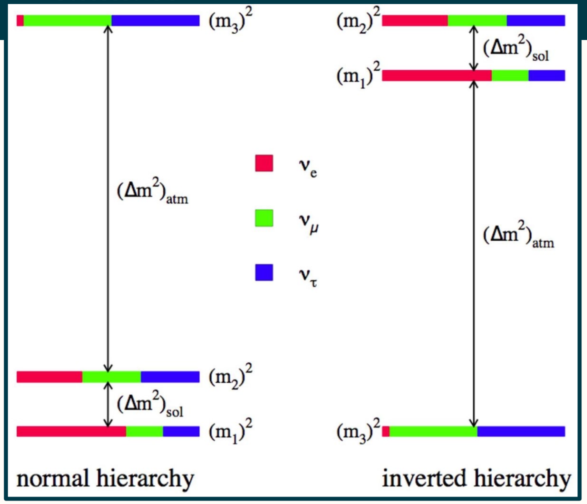
Burst trigger efficiency as a function of supernova distance

Some astronomical features are shown for context

Detector [DAQ] saturation as a function of supernova distance



Physics Program

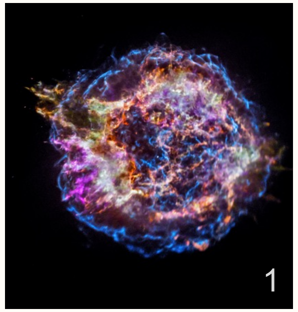


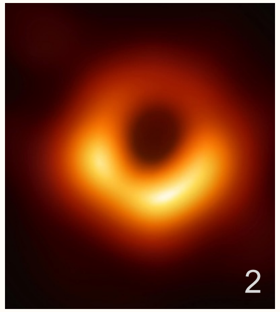
Neutrino Physics:

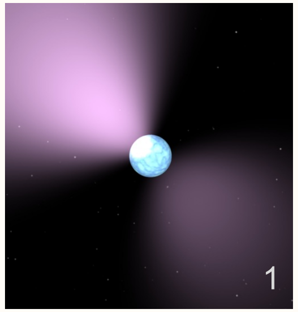
- Large source of neutrinos between 1 – 60 MeV
- Measurement of neutrino mass hierarchy through looking at beginning of the burst
- Other BSM physics, e.g. sterile neutrino search, self-interactions, neutrino mixing in dense environments, limits on ν mass/charge/magnetic moment
    - Potentially a method to distinguish Dirac vs Majorana neutrinos!

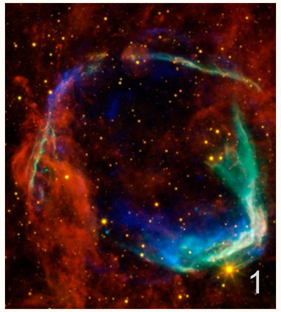
Supernova Physics:

- Supernova explosion mechanisms
- Neutron star properties
- Black hole formation → improvements to stellar evolution models



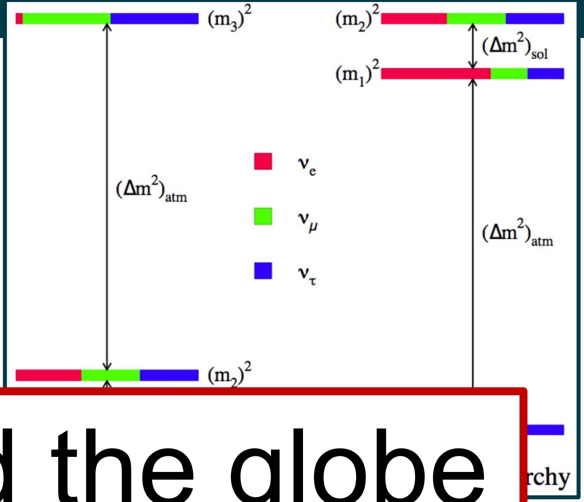






[1]*Credit NASA: https://nasa.gov* ; [2]*Credit: Event Horizon Telescope collaboration et al.*

Physics Program



Neutrino Physics:

- Large source of neutrinos between 1 – 60 MeV
- Measurement of neutrino mass hierarchy through looking at beginning of the burst
- Oth
  mix
  -

Supernova

Lots of neutrino detectors around the globe with complimentary techniques observing the same SN!

- Supernova explosion mechanisms
- Neutron star properties
- Black hole formation → improvements to stellar evolution models

[1]Credit NASA: https://nasa.gov ; [2]Credit: Event Horizon Telescope collaboration et al.

Summary

- SNO+ is now filled with liquid scintillator → gives greater sensitivity to supernovae and access to new interaction channels
- The expected supernova signal at SNO+ is well understood
- SNO+ is a low background detector → supernova backgrounds are only prevalent < 1 MeV
- The SNO+ burst trigger is operational and has been running now for ~ 2 years
- SNO+ has excellent detection efficiency of supernova within our galaxy
- SNO+ has recently joined SNEWS, and work is in progress to integrate into SNEWS2
- Broad neutrino and astrophysical physics programs with SNO+ sensitivities to be explored

Supernova neutrinos at DUNE

Sammy Valder
for the DUNE collaboration

Supernova Neutrinos in the Multi-Messenger Era

07-04-2022

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITY OF SUSSEX

This talk

In this talk:

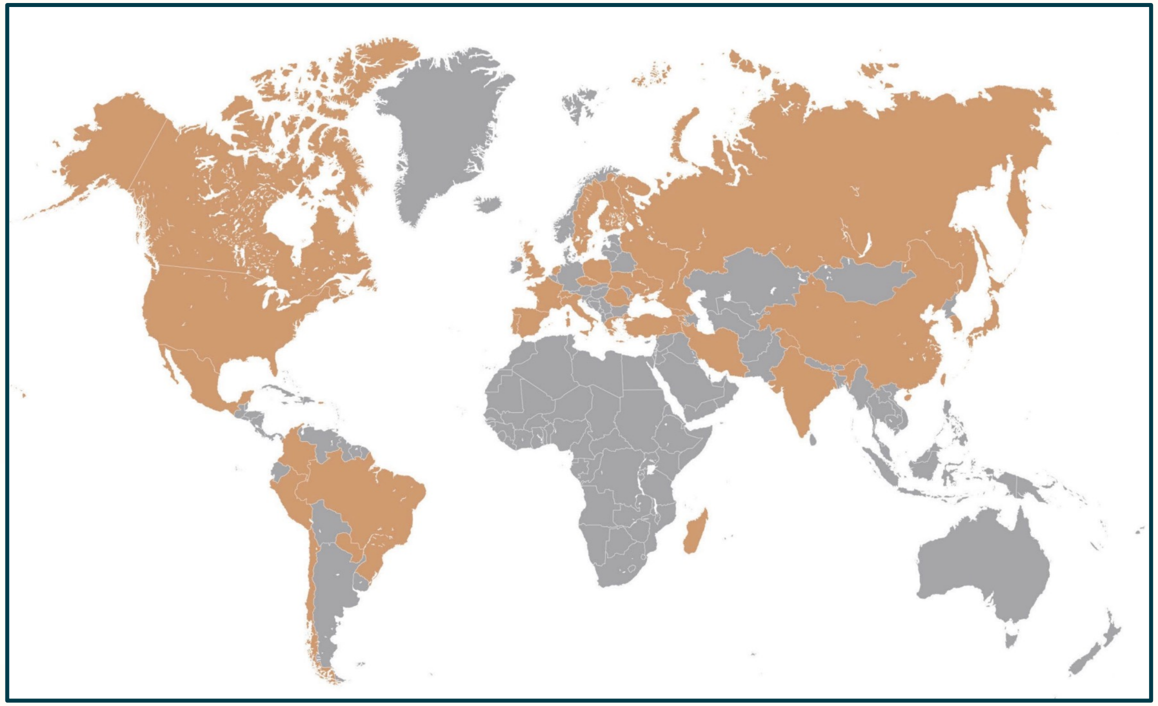
- Deep Underground Neutrino Experiment (DUNE)
- Liquid Argon TPCs
- Liquid Argon Interaction Modes at DUNE
- How many supernova neutrinos will DUNE detect?
- Backgrounds
- Burst Trigger
- Pointing Studies
- Potential Physics Programme

UNIVERSITY OF SUSSEX

DUNE Collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- **1350+ Collaborators**
- **200+ Institutions**
- **30+ Countries + CERN**

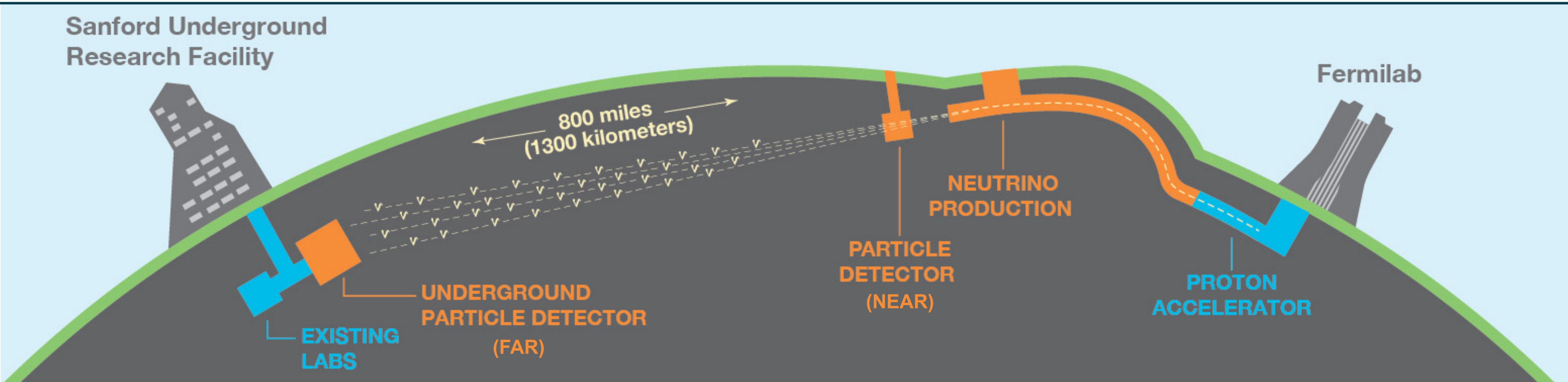


International flagship neutrino experiment

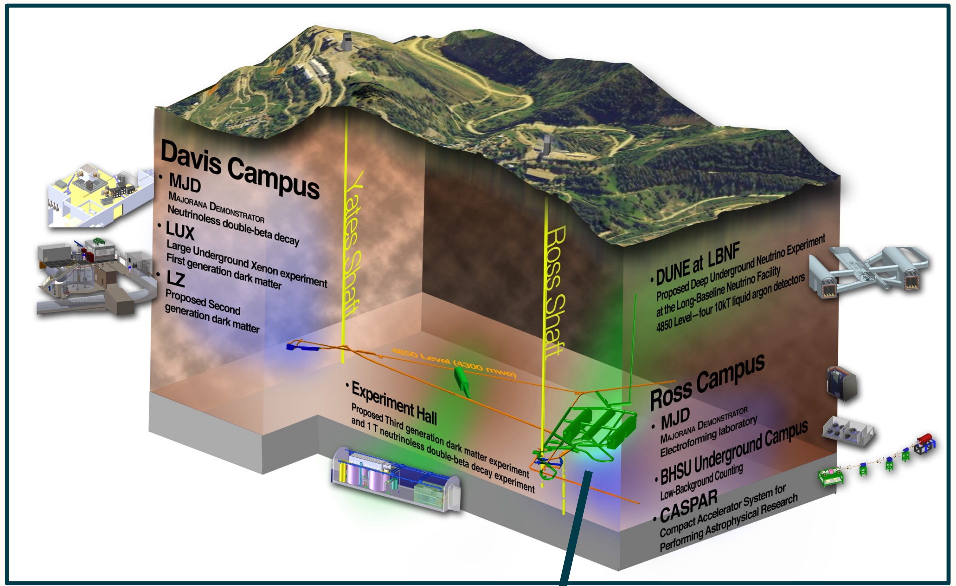
- High intensity neutrino beam (1.2 MW → Up to 2.4 MW)
- 1300 km baseline, with on-axis detector
- Four large-volume detector modules (17 kt), 1.5 km underground
- Multiple complimentary near detectors providing unprecedented control on systematic uncertainties

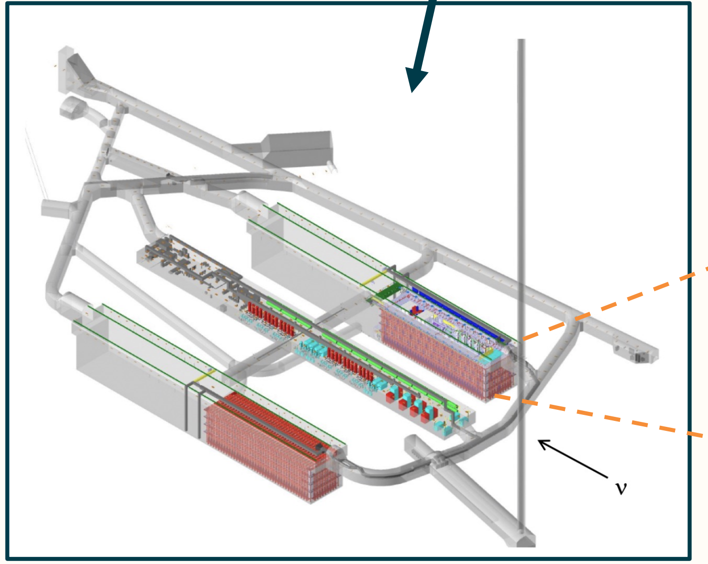
Rich physics programme

- Neutrino oscillations: mass-ordering, CP-violation, neutrino mixing parameters
- **Core-Collapse Supernova (CCSN) neutrinos**
- Nucleon Decay
- Plus many other topics (e.g. neutrino interaction physics, atmospheric neutrinos, sterile neutrinos, WIMP searches etc.)

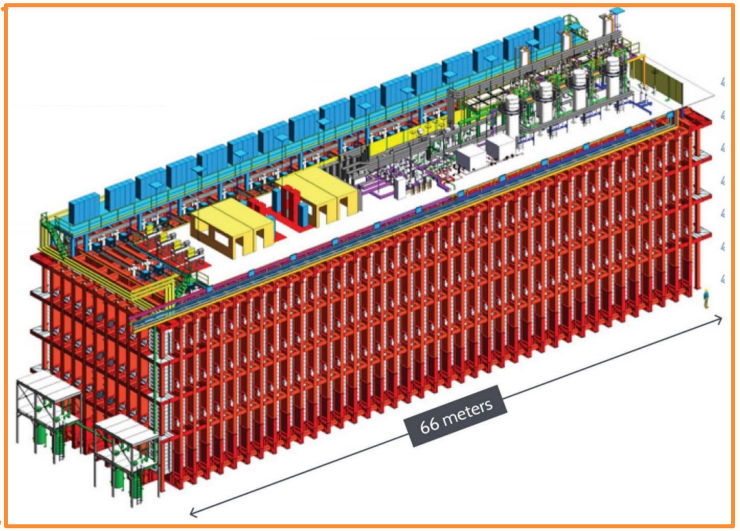


DUNE Far detector

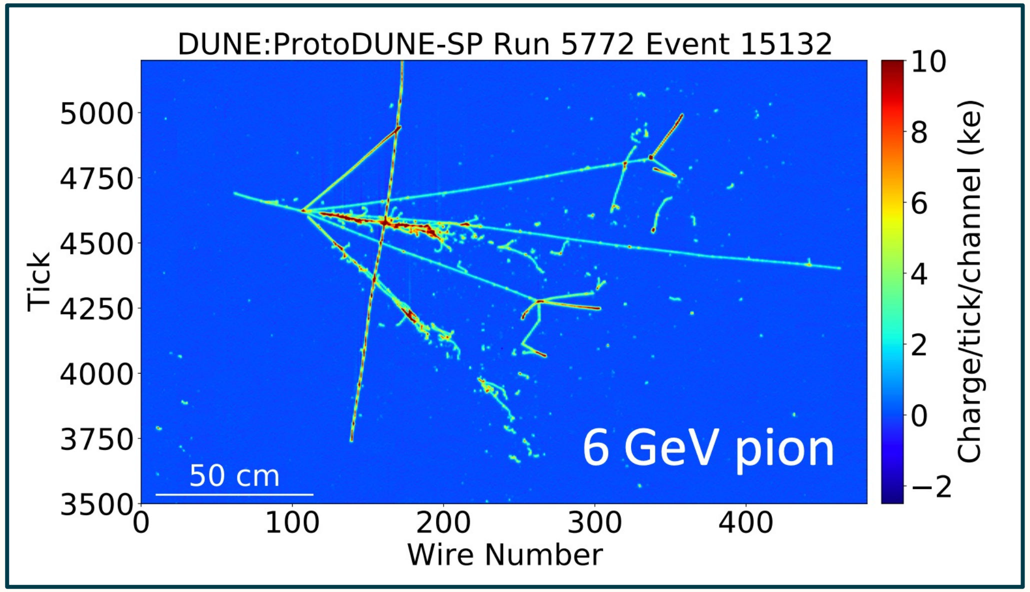


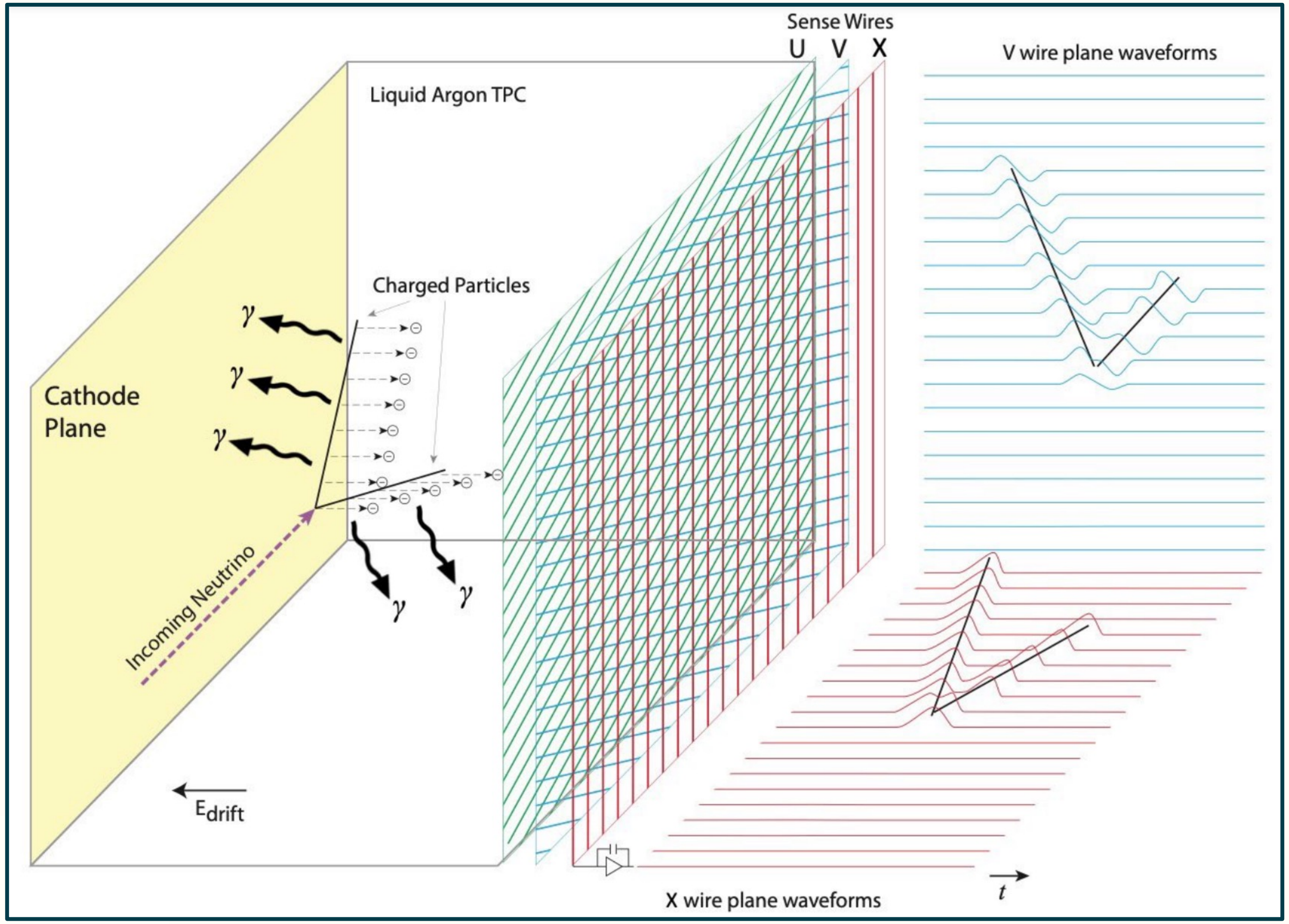


- Four 17 kt modules:
  - Module 1, 2, and 3: **Liquid Argon TPC**
  - Module 4: **Module of Opportunity**
- Module 1 technology: 3.6 m horizontal drift with vertical anode and cathode planes and photon detector
- Module 2 technology: 6.5 m vertical drift with horizontal PCB anode and cathode planes and photon detector



Liquid Argon TPC





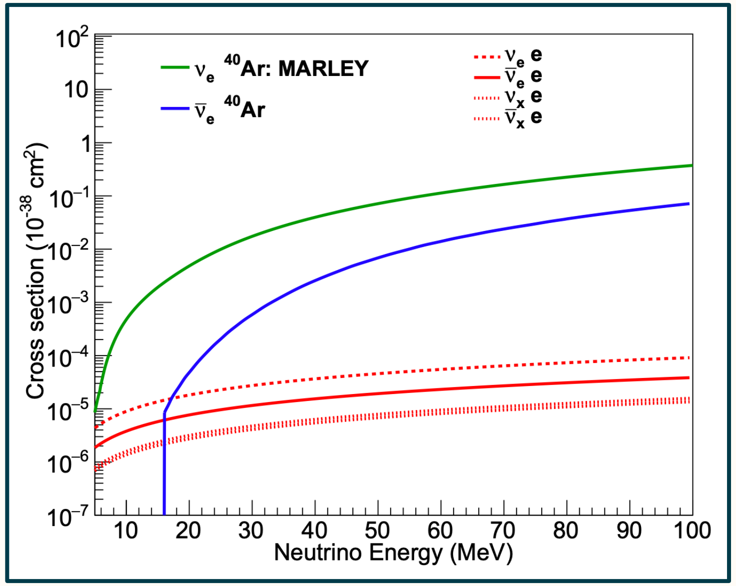
- Primary detector technology for DUNE
  - Detailed images of events
  - Excellent spatial and calorimetric resolutions

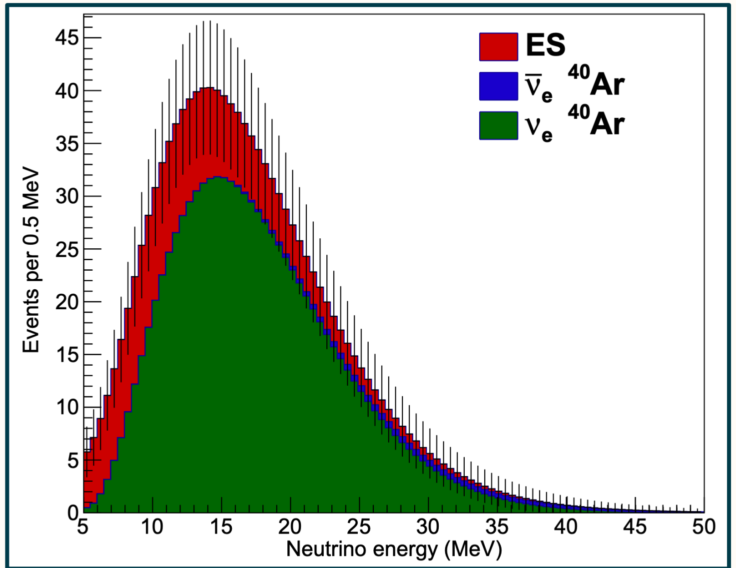
Interaction Channels

- Liquid argon has particular sensitivity to the ν_e component of the SN neutrino burst
- Dominant interaction ν_e-CC-^{40}Ar :

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

- Additional channels:
  - $\overline{\nu}_e$-CC-^{40}Ar
  - electron elastic scattering (ES)
- NC interactions on ^{40}Ar have not yet been fully studied → large systematic uncertainties
  - Although potentially has 9.8 MeV photon signature that could be measured through e^+e^- pair production



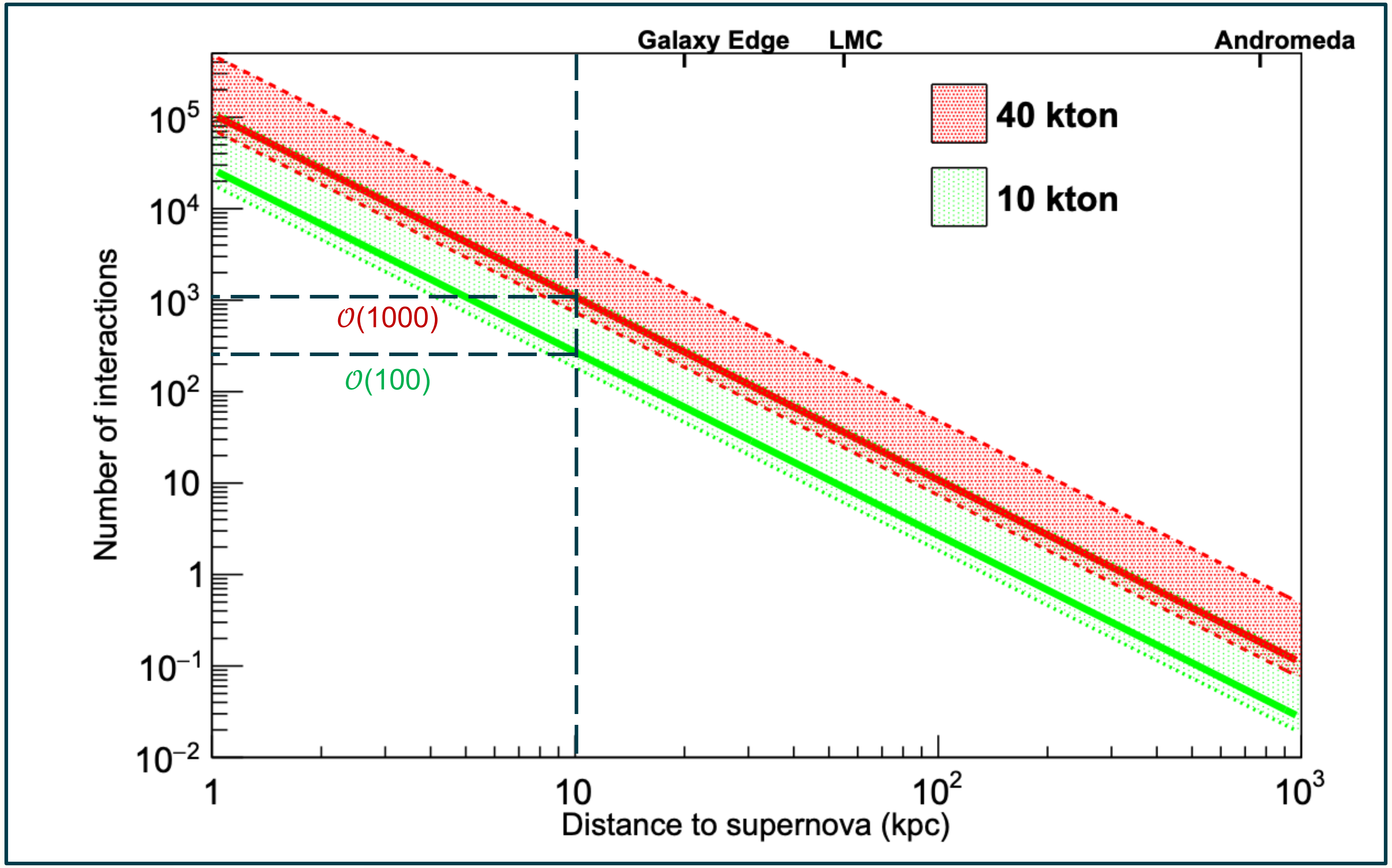


Eur. Phys. J. C 81 (2021) 5, 423

How Many SN Neutrinos?

- Expected number of supernova neutrino interactions as a function of supernova distance
- Shown for 40 kt and 10 kt interaction volumes
- Bands refer to uncertainties in supernova models with different average neutrino energies, $\langle E_\nu \rangle$, and pinching parameters, α :
  - Upper limit → $\langle E_\nu \rangle$ = 12 MeV, and α = 2
  - Lower limit → $\langle E_\nu \rangle$ = 8 MeV, and α = 6

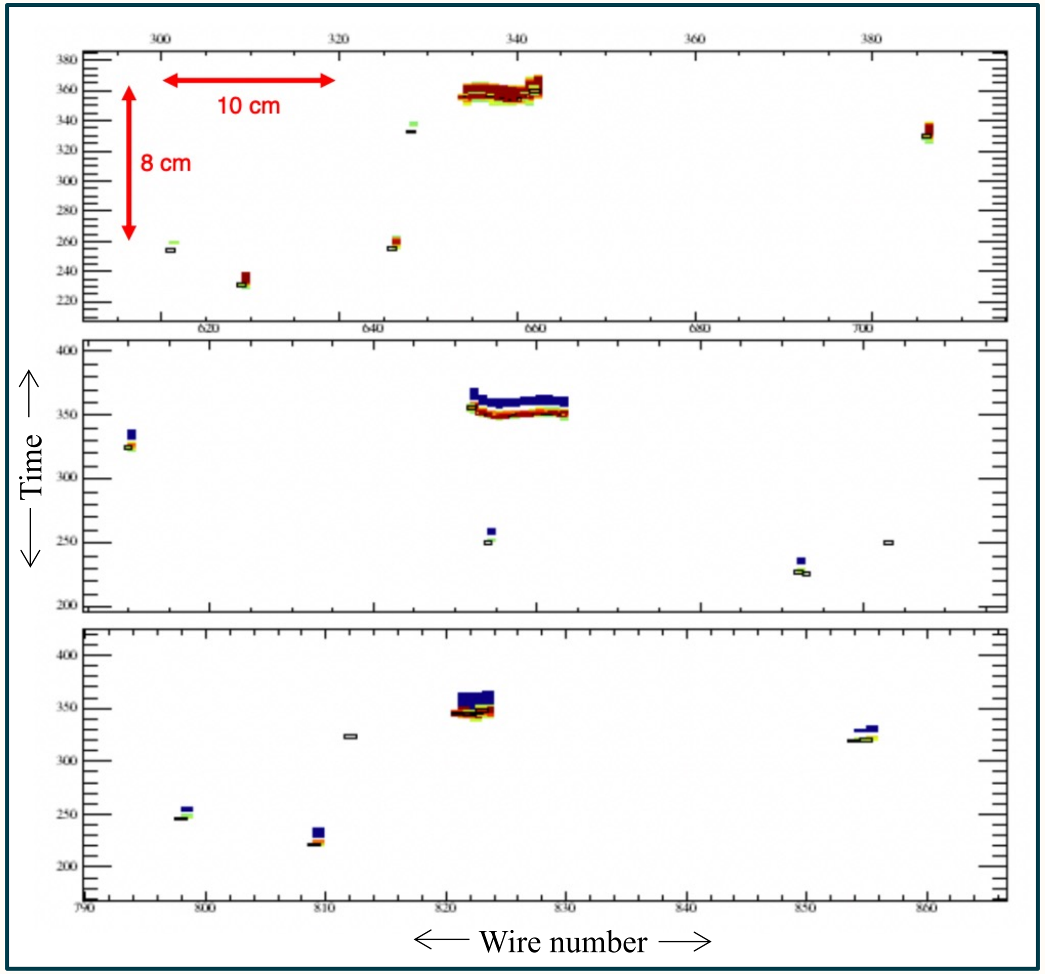
Eur. Phys. J. C 81 (2021) 5, 423



Backgrounds

- Events at [relatively] low energy for DUNE → smaller tracks
- Understanding radiological and cosmological backgrounds is important
- Dominant radiological background is from ^{39}**Ar** with β-decays at a rate of ~ 1 Bq/litre, with an end point < 1 MeV
- Preliminary studies suggest backgrounds will have very minor effect on reconstruction of triggered burst events
- Future studies: effects of backgrounds on DAQ and triggers
- Low background module white paper: *arXiv:2203.08821*

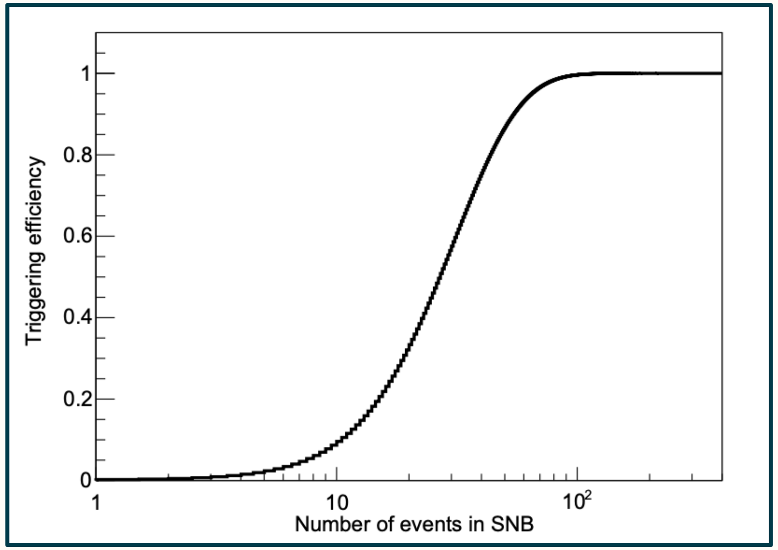
Eur. Phys. J. C 81 (2021) 5, 423

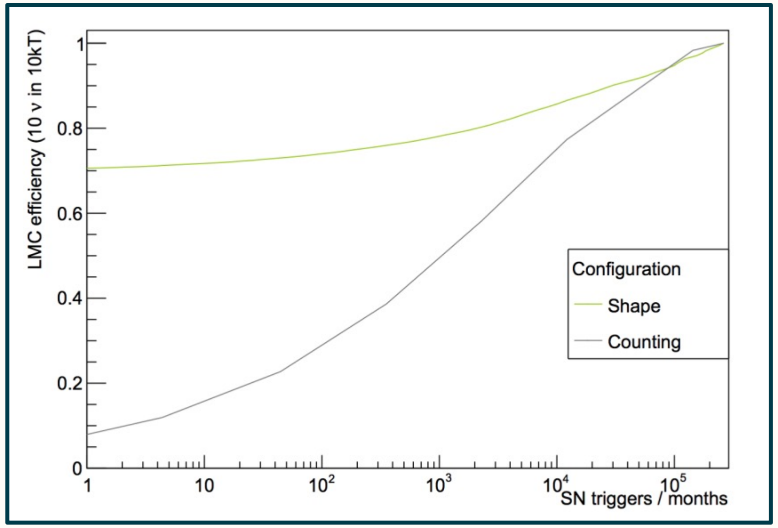


SN neutrino tracks are smaller and can be mimicked by radiological backgrounds

- Triggering utilises both TPC and photon detection, and exploits coincidences of multiple signals of a typical SN burst length
- Preliminary trigger system has been developed
  - Future trigger system is being developed [at Sussex]
- Aiming for fake trigger rate of 1 per month
- Optical trigger searches for PMT hits, and clusters based on hits combined together using space/time information
- TPC trigger selected charge deposits on per wire basis to create trigger primitives → these are then correlated in time and channel space
  - Multiplicity based trigger yields good efficiency to galactic edge, whilst keep fake trigger rate down
- Energy-weighting can significantly increase trigger efficiency → 100% to galactic edge, 70% at the LMC

Eur. Phys. J. C 81 (2021) 5, 423



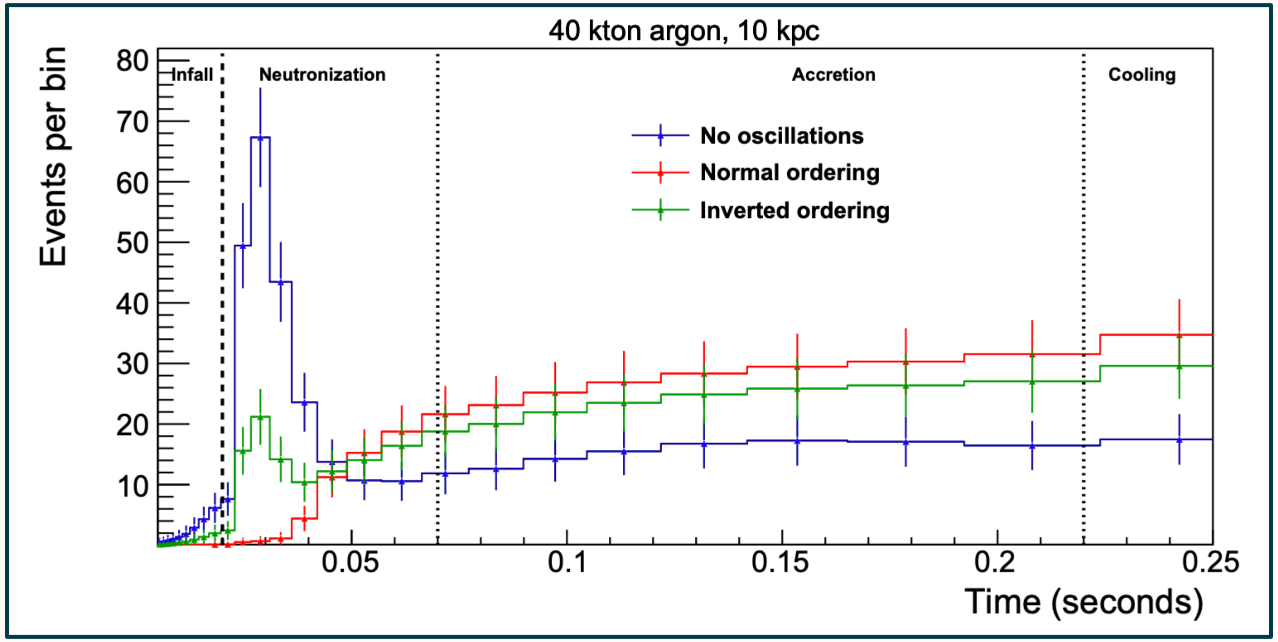


Pointing

- Studies are ongoing to determine and improve DUNE's pointing resolution for supernovae
- Supernova neutrinos are simulated and reconstructed with different interaction topologies included, over clean and background included samples
- Daughter tracks have been used to flip parent track direction when ambiguity is present
- Likelihood function determines supernova direction from all electron directions and energies
- Pointing resolution from electron scattering events with noise and radiological backgrounds is estimated to currently be 11.1 degrees for a SN at 10 kpc
- Detailed discussion available here: *A.J. Roeth, "Supernova Neutrino Pointing with DUNE", ICHEP 2020*

- DUNE has strong sensitivity to neutronization burst
- Unique sensitivity to electron neutrinos
  - Could yield sensitivity to **neutrino mass hierarchy**
- Neutrino mixing from spectra:
  - Flavour conversion in SN/Earth
  - Collective effects
- Other neutrino physics: e.g. sterile neutrinos, self interactions, limits on absolute ν mass/charge/magnetic moment, etc.
- **Supernova physics:** stellar evolution, explosion mechanisms, BH formations, etc.

Eur. Phys. J. C 81 (2021) 5, 423



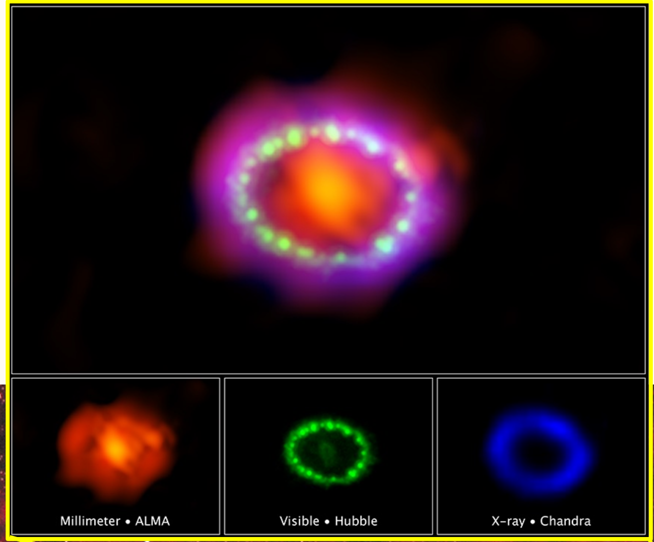
Summary

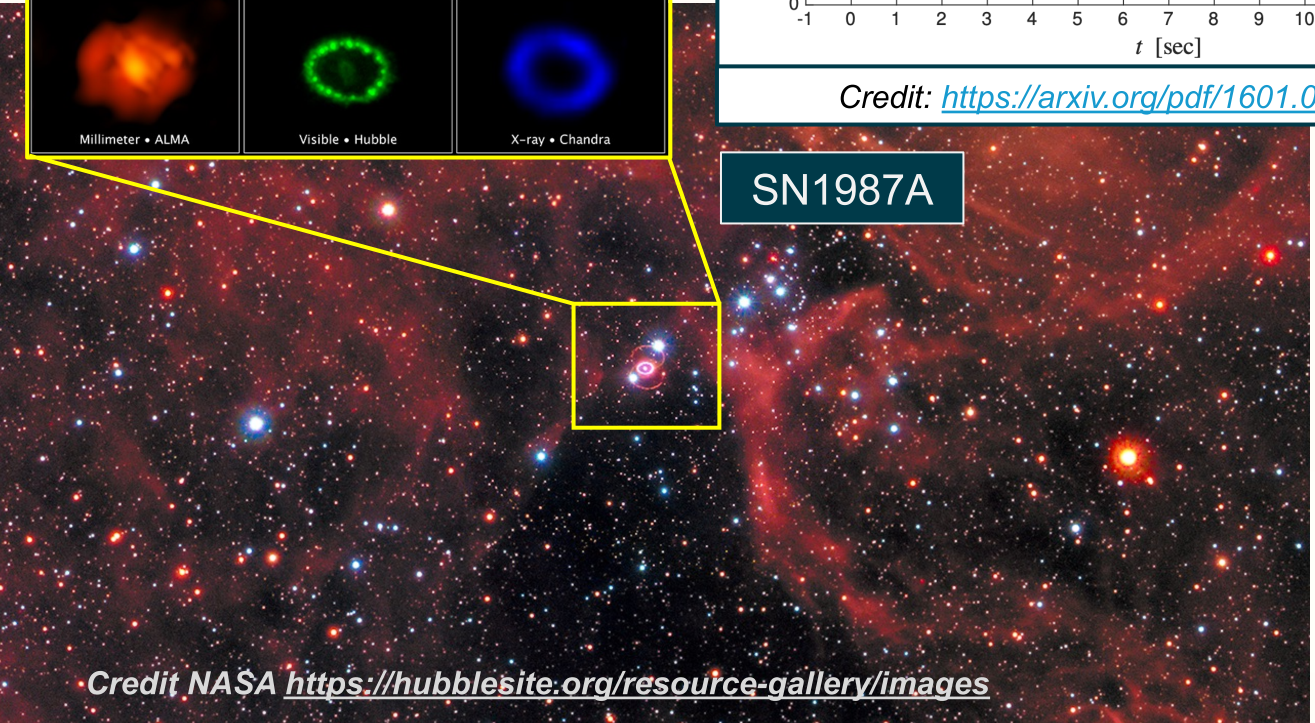
- DUNE is a next generation neutrino experiment
- Up to 40kT fiducial mass of liquid Argon which provides unique SN neutrino interaction channels
  - DUNE has unique sensitivity to electron neutrinos
  - Possible NC interaction mode could be tagged and is being looked at in the future
- $\mathcal{O}(10^3)$ supernova neutrinos are expected to be measured at DUNE
- Preliminary SN burst trigger has been created for both photon detection and TPCs
  - Future development of the burst trigger is underway at University of Sussex
- Studies are ongoing to determine and improve DUNE's pointing resolution for supernovae
- Through the neutronization burst, DUNE may have sensitivity to constrain the neutrino mass ordering through SN neutrinos

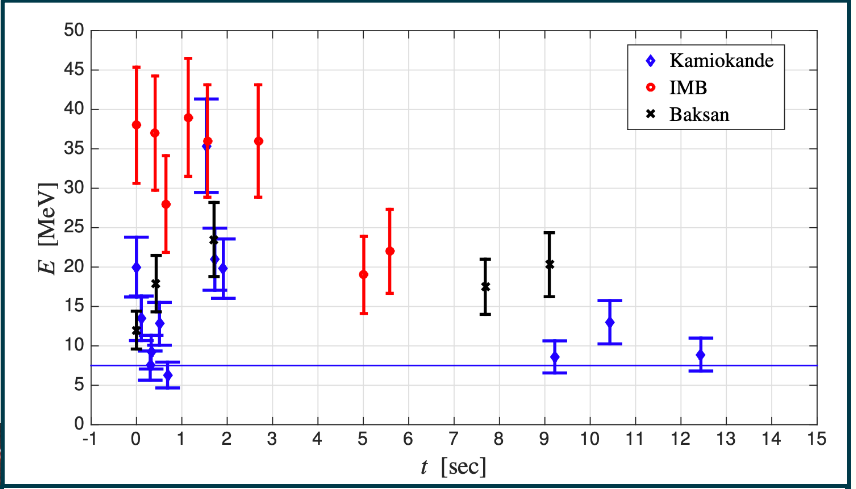
SNO+ Backups

UNIVERSITY
OF SUSSEX

Supernovae





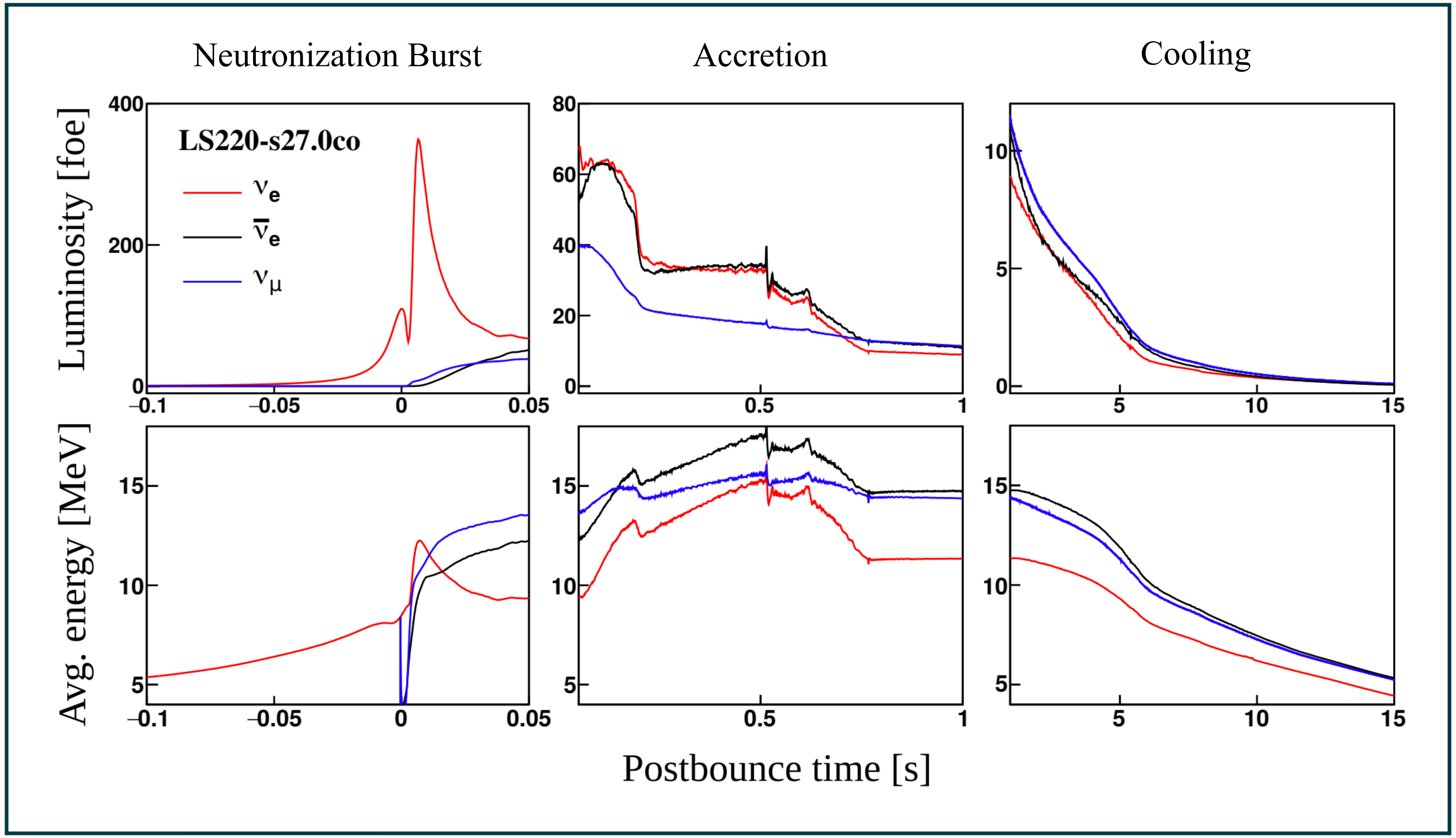


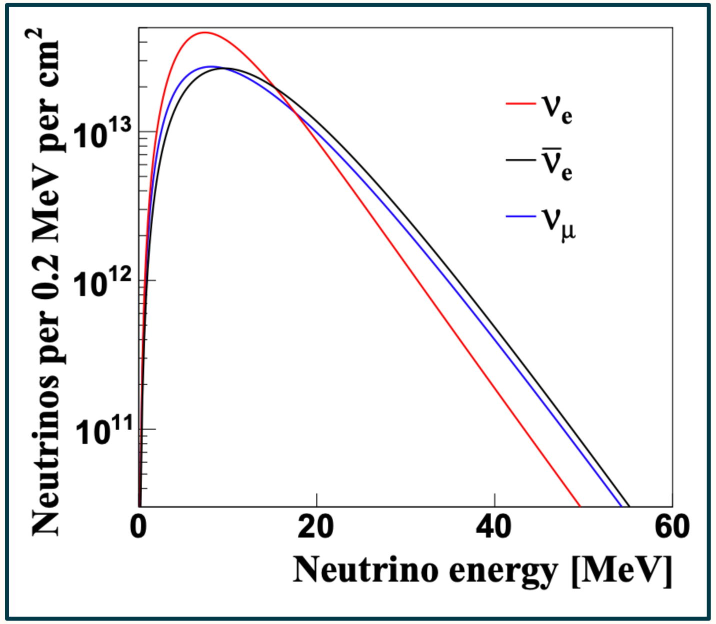
Credit: https://arxiv.org/pdf/1601.03422.pdf

- As a massive star approaches the end of its life will likely go **supernova (SN)**
- These are some of the most powerful and luminous phenomena known to the universe
- Extremely rare within our galaxy with 1.63 ± 0.46 CCSNs per century †
- $\mathcal{O}(10^{58})$ neutrinos emitted carrying 99% of the energy
- Last observed supernova neutrinos signal occurred in 1987 (SN1987A)
- Neutrino burst lasting ~ $\mathcal{O}$(10s)

† arXiv:2009.03438

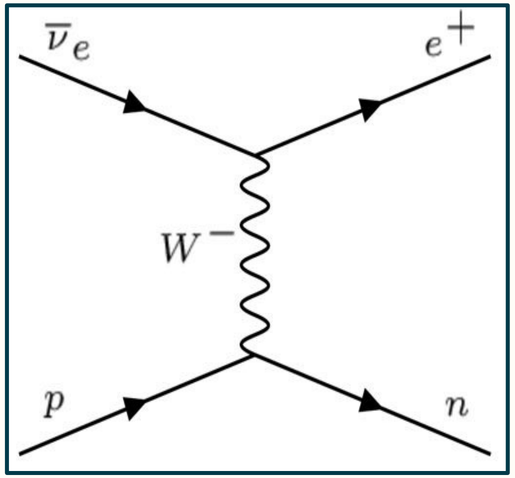
- The flux and average energy of (anti)neutrinos exiting the supernova (right). Flux and energy convolved (left).
- Separated into three CCSN phases:
  - Neutronization
  - Accretion
  - Cooling
- [1]LS220-s27.0co is shown and is the standard model used throughout this talk



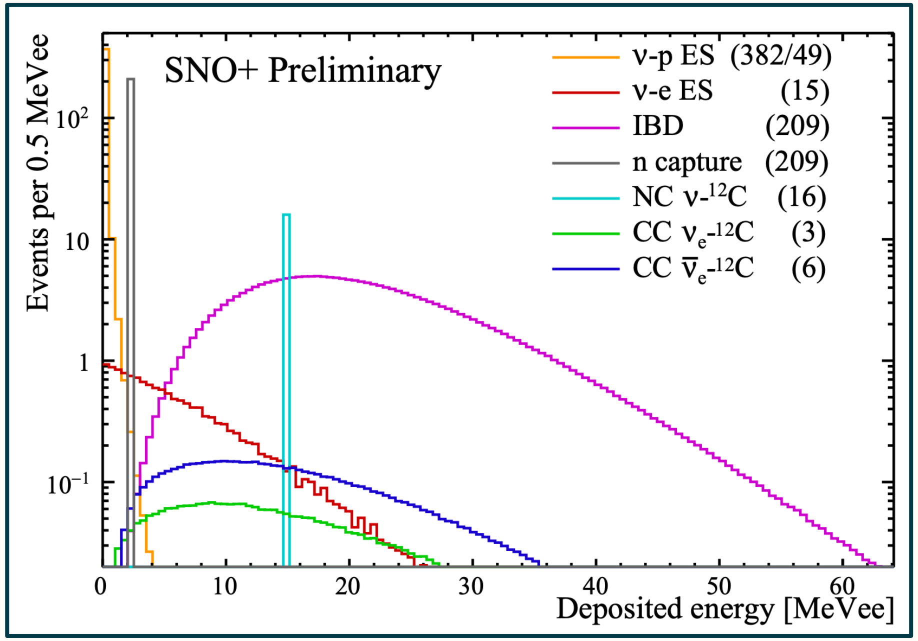


[1]Model provided by the Garching group, see: A. Mirizzi et al. Rivista del Nuovo Cimento Vol. 39 N. 1-2 (2016)

- Anti (electron)neutrino undergoes charged current (CC) interaction with proton to produce positron and neutron

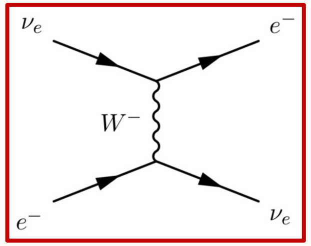


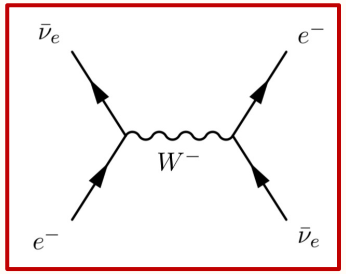
- Outgoing positron detected as spectrum
- Neutron capture on proton produces 2.2 MeV delayed photon
  - Easy to tag
- Largest signal from supernovae in SNO+
  - 209 events expected from example† SN at 10 kpc

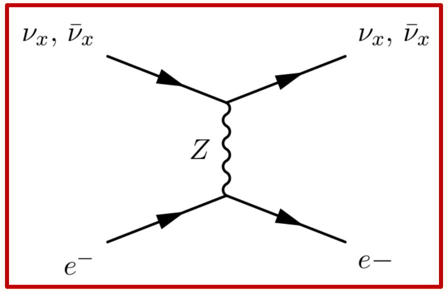


† $27M_\odot$ progenitor CCSN with LS220 equation-of-state

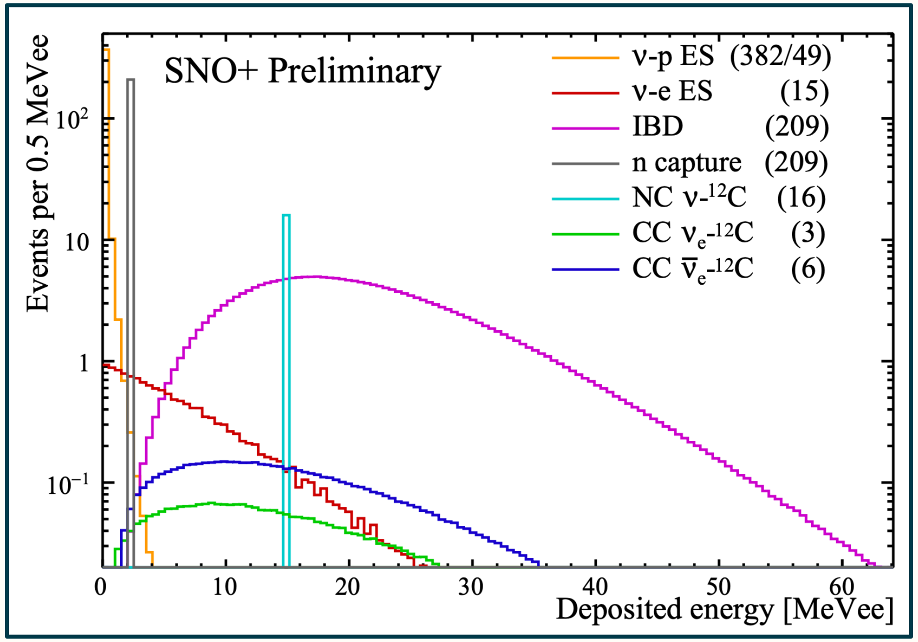
Other Interactions







- Flavour dependent cross-section
- ν_e and $\nu_e \rightarrow$ CC interactions
- $\nu_x \rightarrow$ NC interactions



$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N} + e^-$$

ν_e Charged Current on ^{12}C

$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+$$

$\bar{\nu}_e$ Charged Current on ^{12}C

$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$$

ν_x Neutral Current on ^{12}C

- Distinctive 15.1 MeV excitation
- Cross-section measured by Karmen

SNEWS and SNEWS2

Super**N**ova **E**arly **W**arning **S**ystem

Currently listed experiments (on SNEWS2 website):

Water Cherenkov

Super-Kamiokande, KM3NeT, and IceCube

Liquid Scintillator

SNO+, KamLAND, and NOvA

Lead

HALO

Dark Matter Detectors

XENONnT, LZ, and PandaX-4T

Also listed on SNEWS website:

Borexino, LVD, MiniBooNE, and Daya Bay

Quenching

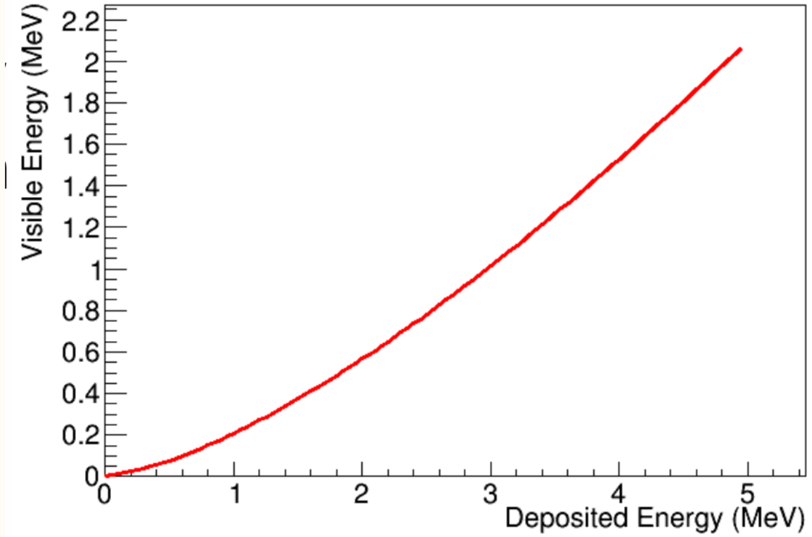
- Scintillator produces light via excitation and subsequent de-excitation.
- More ionising particles (protons) excite the particles such that less light is produced (Quenched)
- Modelled using Birks' Law
  - kB is Birks Constant which is material dependent
  - Has been measured for SNO+ scintillator

Observed energy

Deposited energy

$$\frac{d\epsilon}{dx} = \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

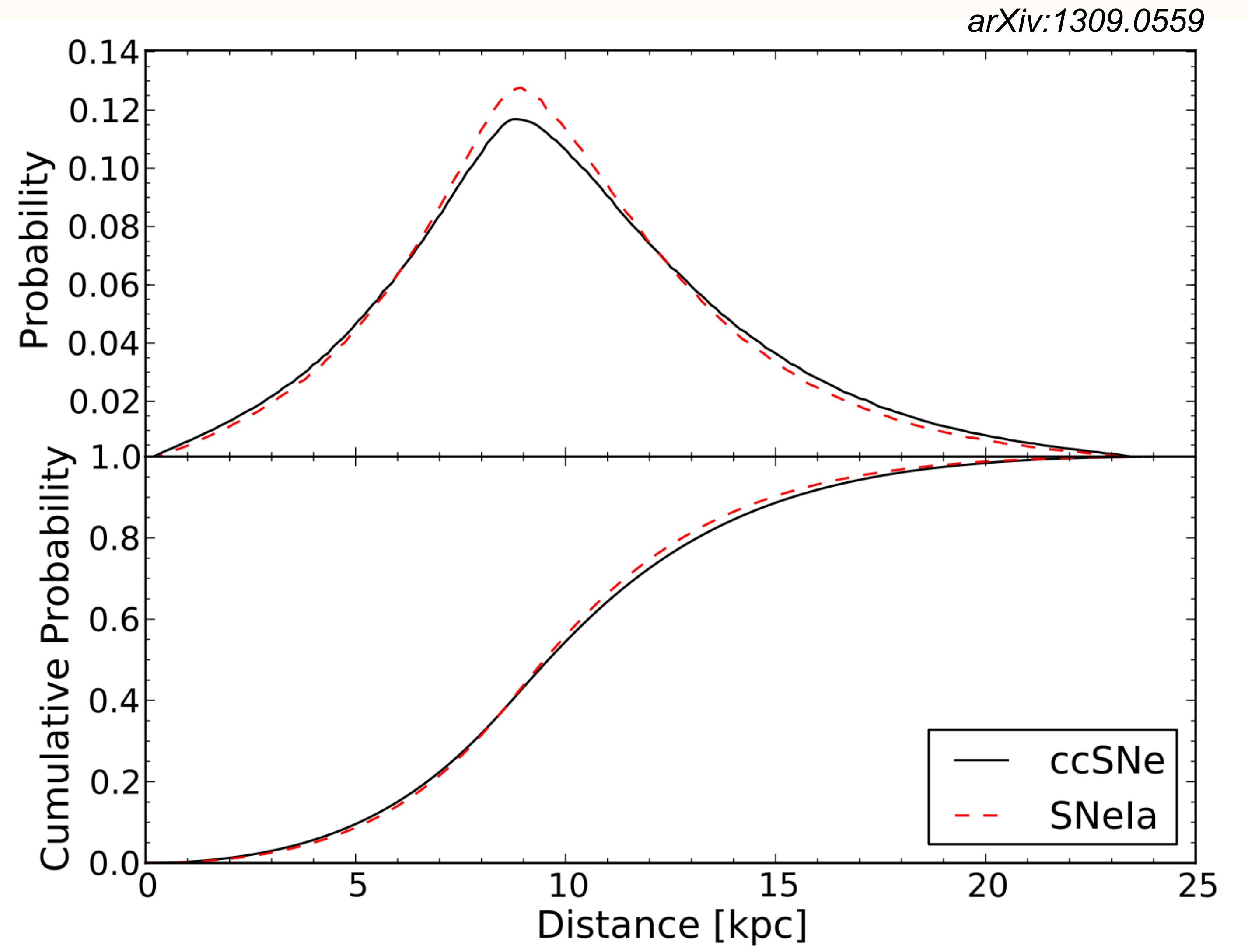
0.0096 ± 0.0003 for SNO+ scintillator



Proc. Phys. Soc. A64 (1951) 874-877

Arxiv:1301.6403

SN Probability



DUNE Backups

UNIVERSITY
OF SUSSEX

Event Visualisation

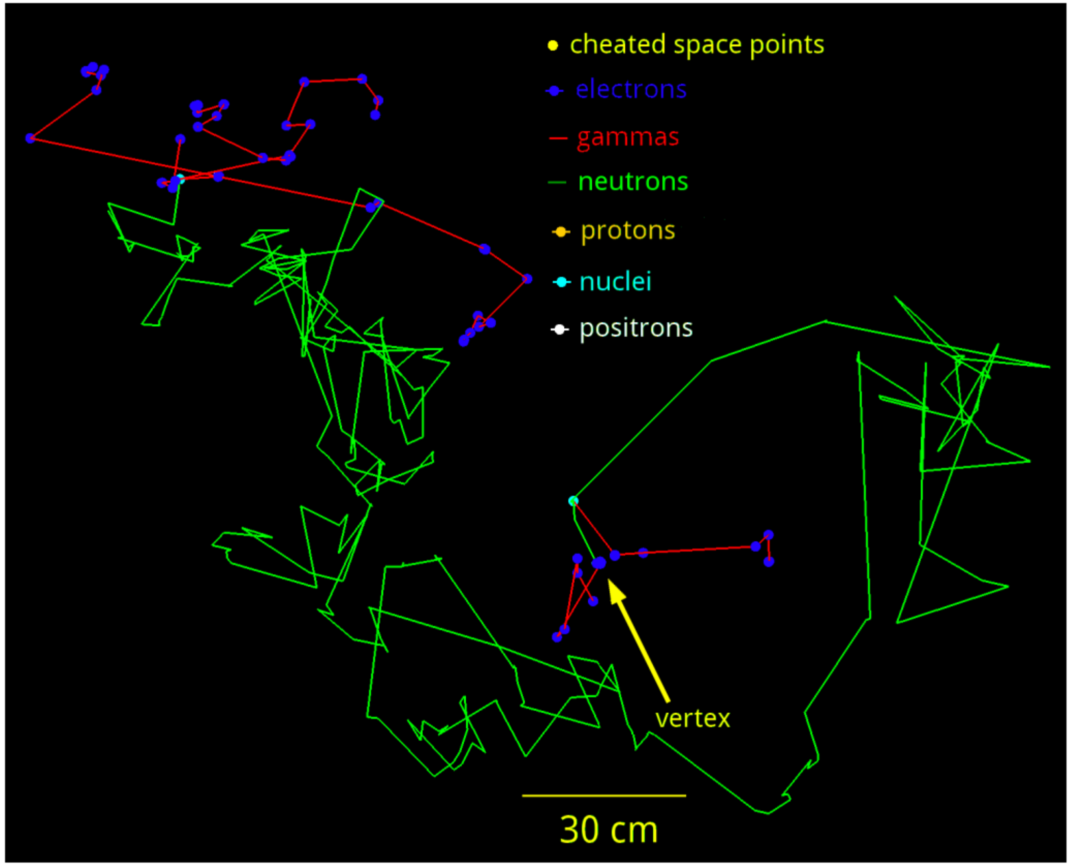


Fig. 5 Visualization of an example MARLEY ν_eCC event simulated in LArSoft, showing the trajectories and energy deposition points of the interaction products.