DUNE Low Energy Physics with Solar and Supernova Neutrinos

Gleb Sinev on behalf of DUNE Collaboration

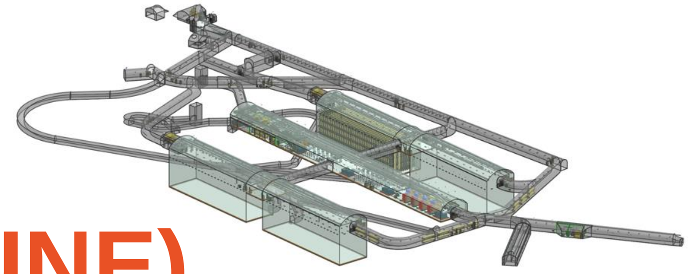
CoSSURF 2024

May 16, 2024

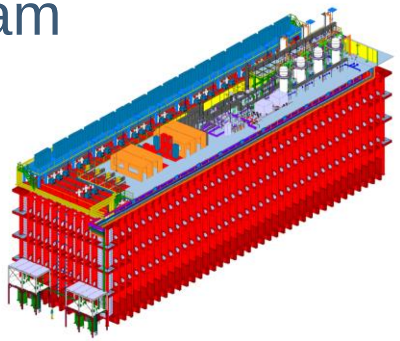
Outline

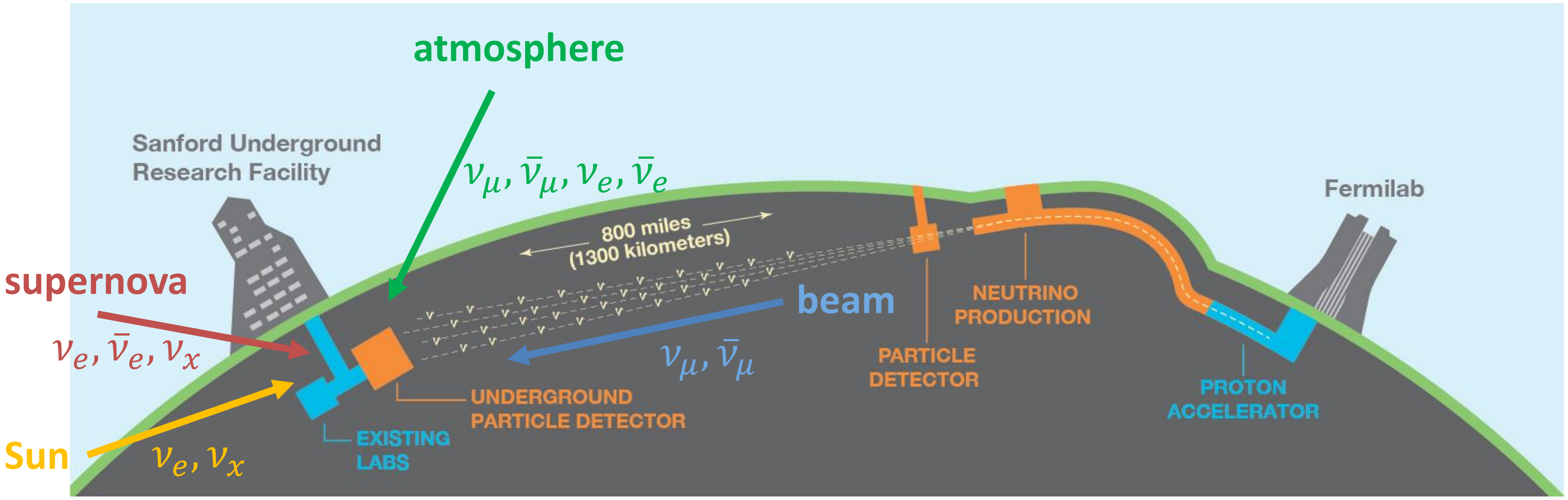
- Deep Underground Neutrino Experiment
- Low-energy neutrino interactions
- Supernova neutrinos
- Solar neutrinos
- Low-Background Module
- Conclusions

Deep Underground Neutrino Experiment (DUNE)

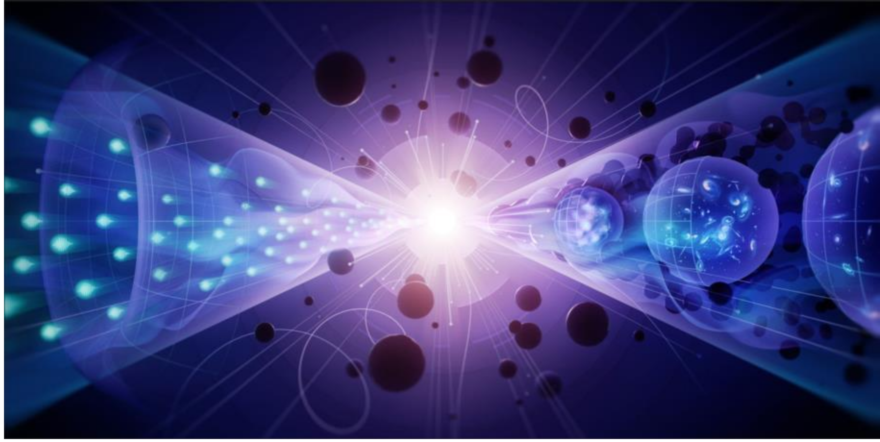


- 1.2 MW (upgradeable to 2.4 MW) LBNF neutrino beam
- Near Detector (ND) complex with multiple detectors
- Far Detector (FD): 4 modules, 70 kt liquid Ar total
  - 1 mile underground at SURF, excavation completed





P5 report



https://www.usparticlephysics.org/2023-p5-report/assets/images/hero-full.jpg

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We reaffirm the previous P5 recommendations on major initiatives:

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos. Knowledge of this fundamental property is a crucial input to cosmology and nuclear science (*elucidate the mysteries of neutrinos*, section 3.1).

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).

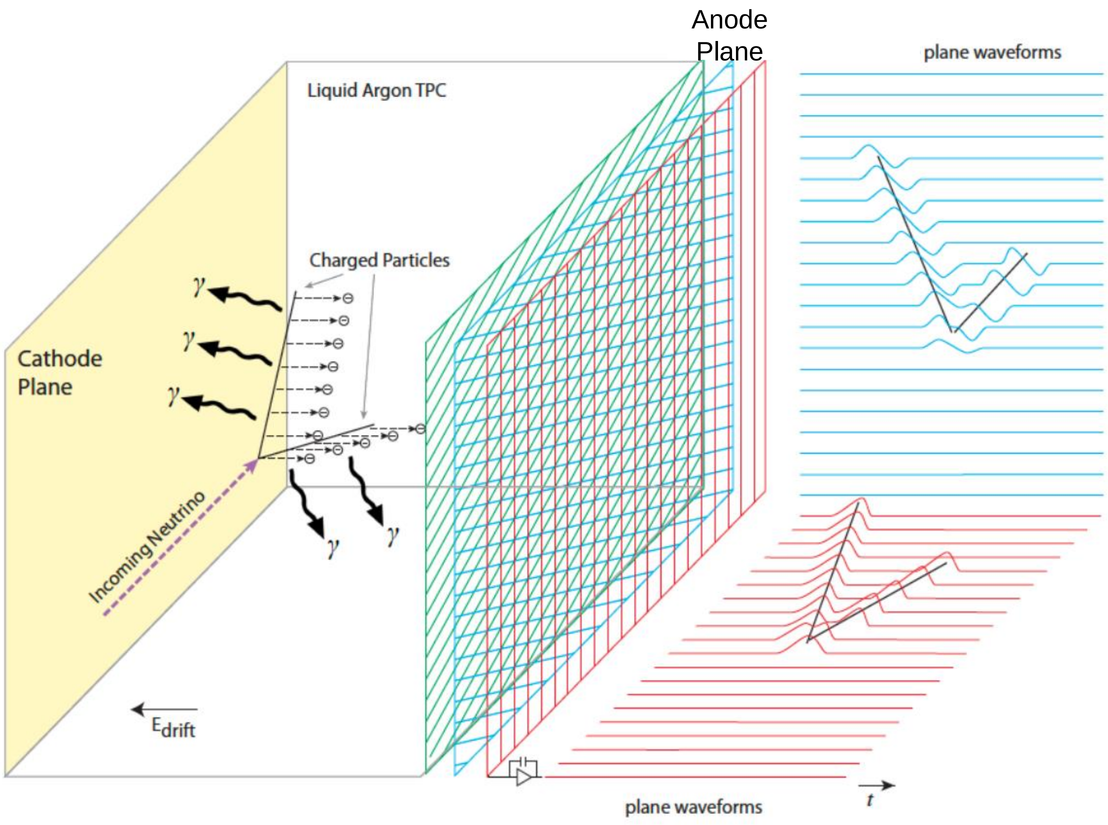
Strong endorsement!

https://www.usparticlephysics.org/2023-p5-report/full-list-of-recommendations

Particle detection in LArTPC

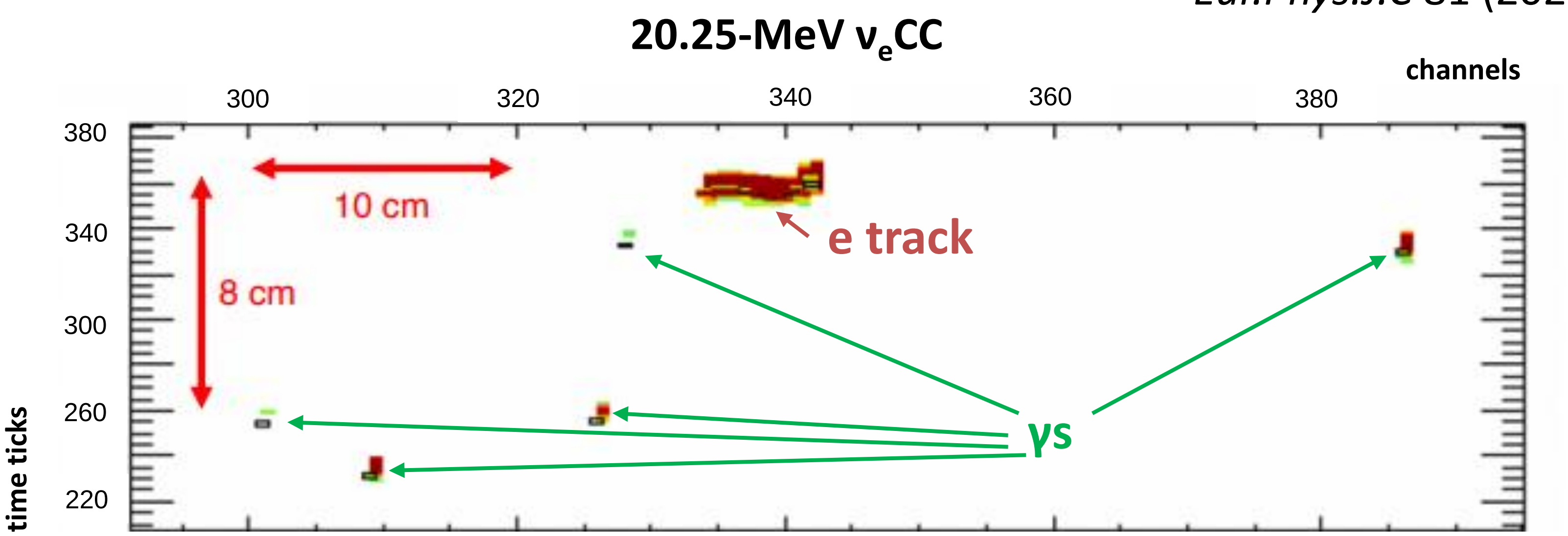
- Neutrinos interact in argon, produce charged particles
- Argon scintillates, light is quickly detected by photon detectors
- Charged particles ionize argon, electrons slowly drift to anode
- Anode is instrumented (readout wires/strips)
  - Combining with light, reconstruct 3D events

DUNE uses Liquid-Argon Time-Projection Chamber (LArTPC) as detector technology



Low-energy ν event in DUNE

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



Simulation with MARLEY ([Comput. Phys. Commun. 269, 108123](), [arXiv:2101.11867 [nucl-th]]())

- Low-energy neutrino events typically leave several-cm **track** (over several channels) in TPC
- Primary track may be surrounded by deexcitation particles that increase event size to tens of cm (**γs**) or even m (ns)
- Radiological backgrounds make reconstruction challenging

Low-energy ν interactions in Ar

- Charged current (CC)
  - $\nu_e + {}^{40}_{18}Ar \rightarrow {}^{40}_{19}K^* + e^-$
    - Dominant channel
  - $\bar{\nu}_e + {}^{40}_{18}Ar \rightarrow {}^{40}_{17}Cl^* + e^+$
- Neutral Current (NC)

  $\nu_x + {}^{40}_{18}Ar \rightarrow {}^{40}_{18}Ar^* + \nu_x$
- Elastic scattering (ES)

  $\nu_x + e \rightarrow \nu_x + e$

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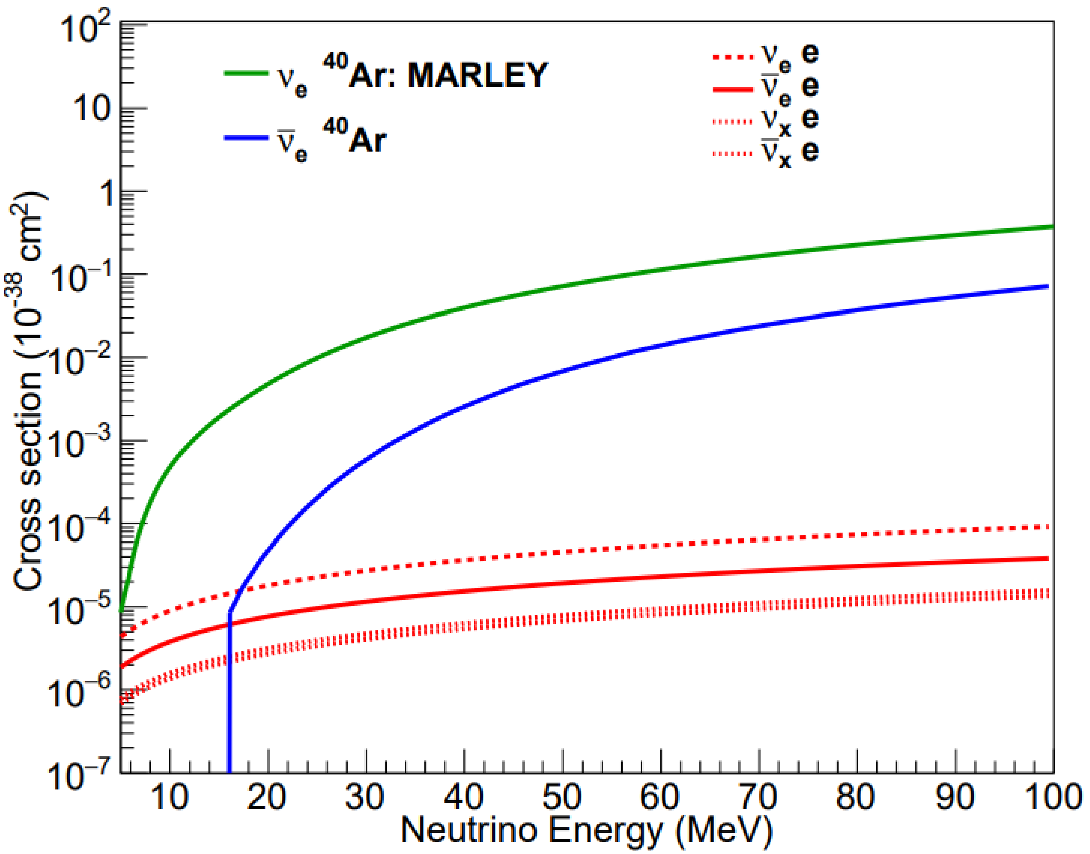
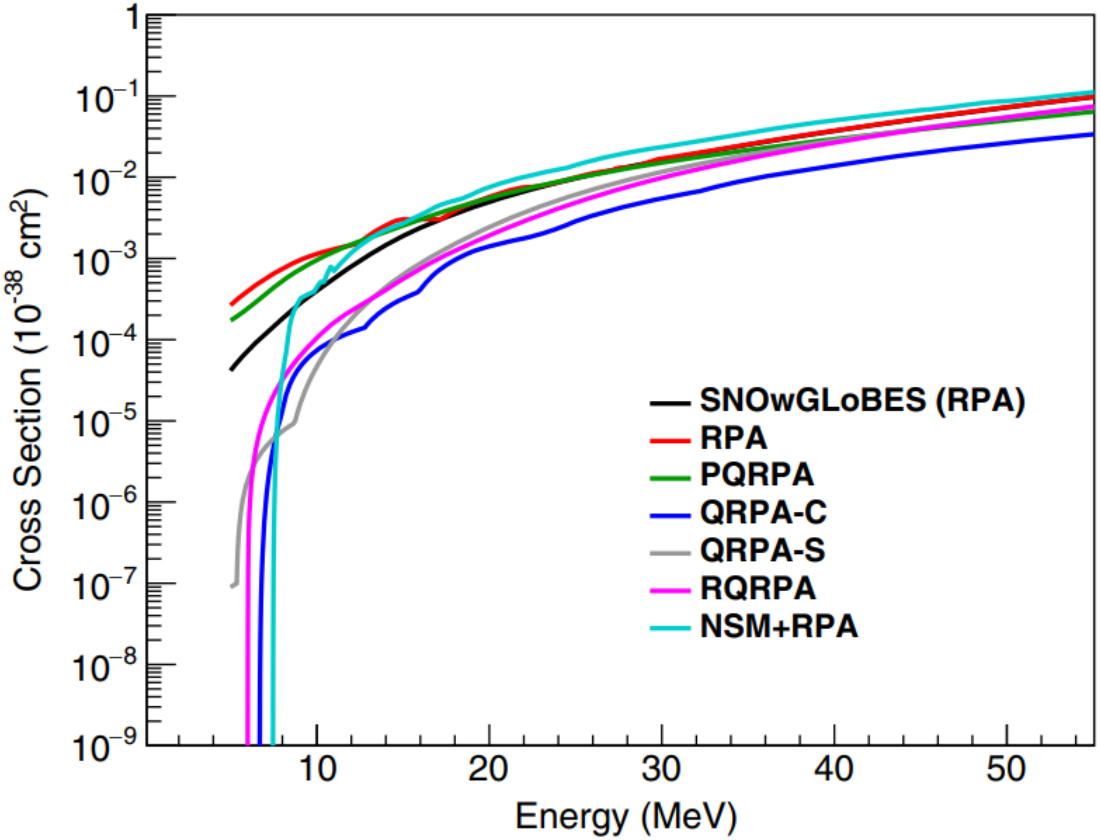


Uncertainty in interactions

Phys. Rev. D 107, 112012 (2023)

- Models disagree by ~order of magnitude on cross sections of ν_eCC interactions
- May significantly affect low-energy studies in DUNE
- Need measurements

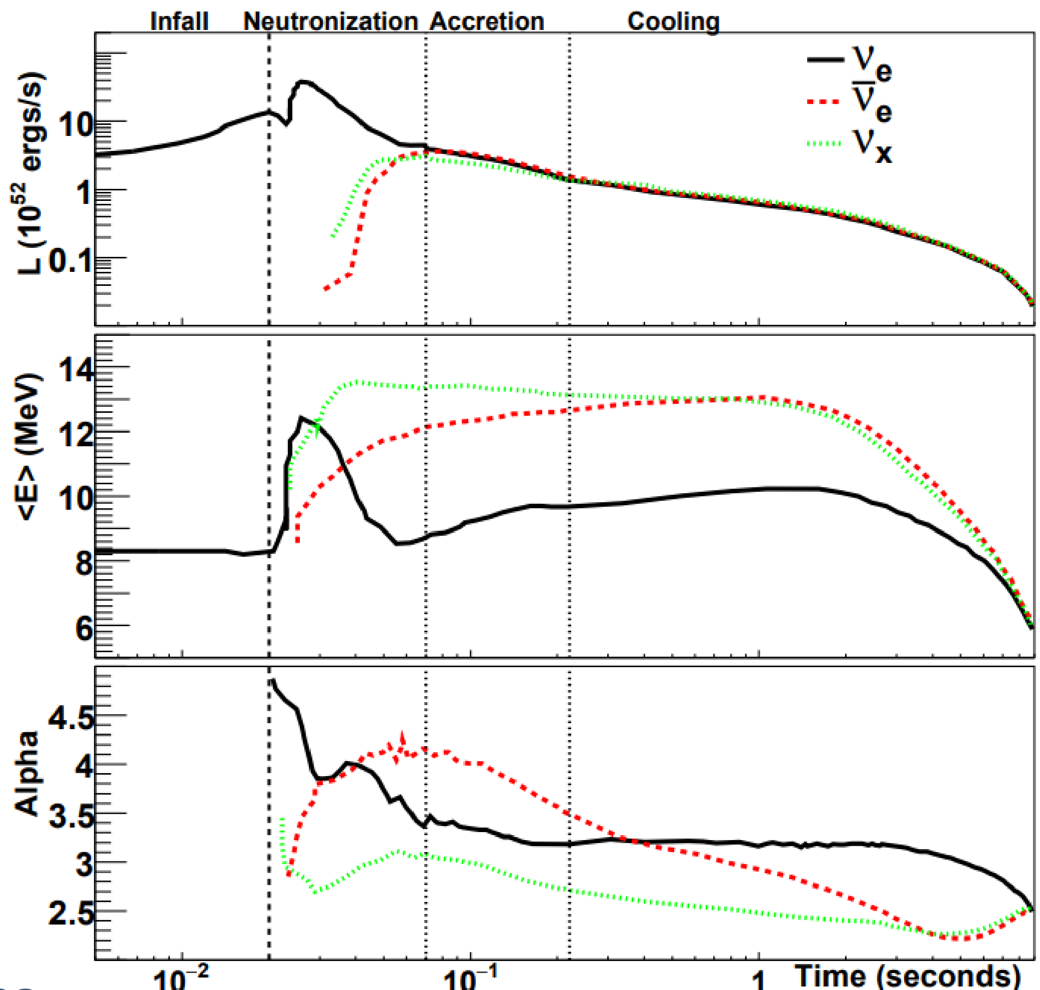


SOUTH DAKOTA MINES

Supernova neutrinos

- Neutrinos produced from core-collapse supernova burst (SNB)
- Neutrinos from only one supernova have been detected: SN 1987A
  - ~2 dozen neutrinos
- Time and energy distributions will carry information about supernova physics
  - May also help us understand neutrino physics

Garching model



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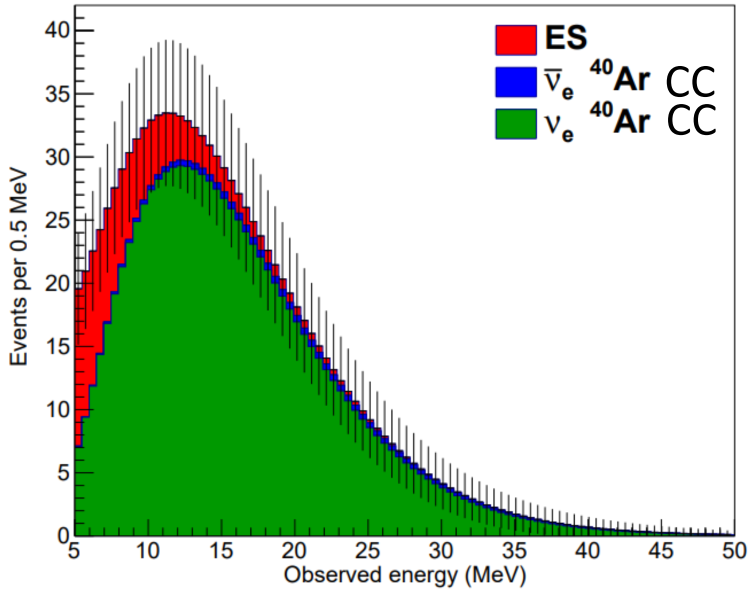
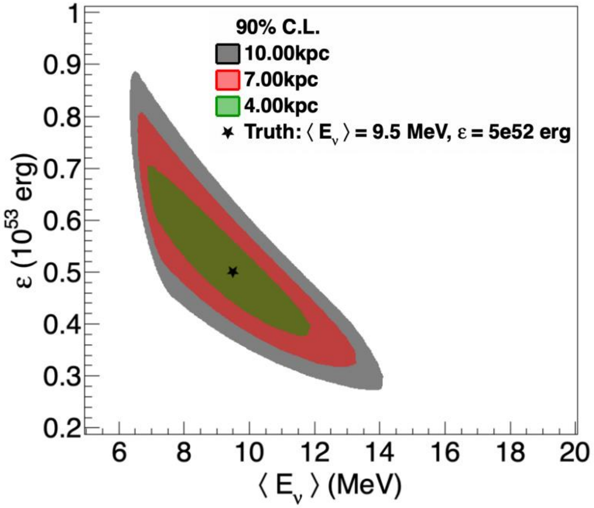
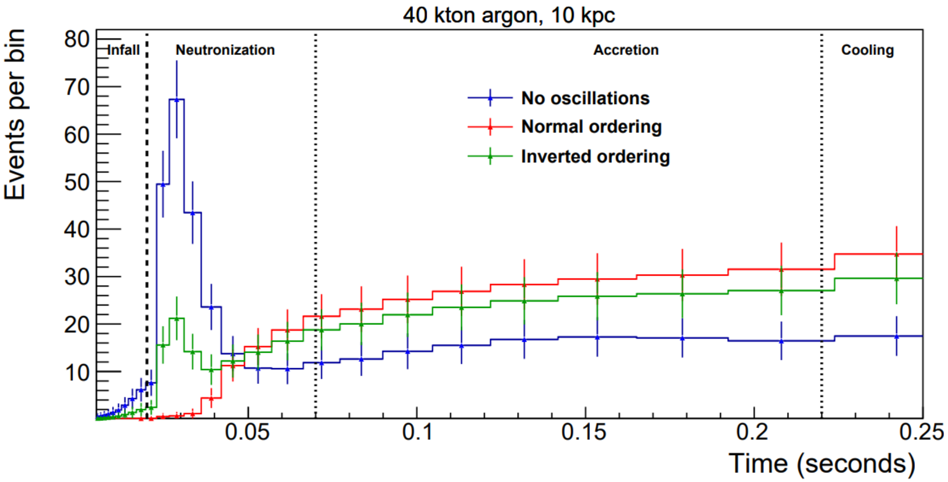
Supernova neutrinos in DUNE

- Most interactions will be ν_eCC
- Depending on neutrino oscillations, neutronization burst may be clearly observable or not present at all
- Fitting energy spectrum may help narrow down supernova models





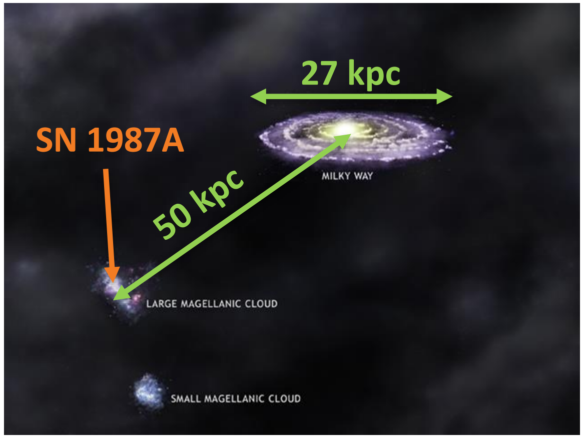


Supernova neutrinos in DUNE

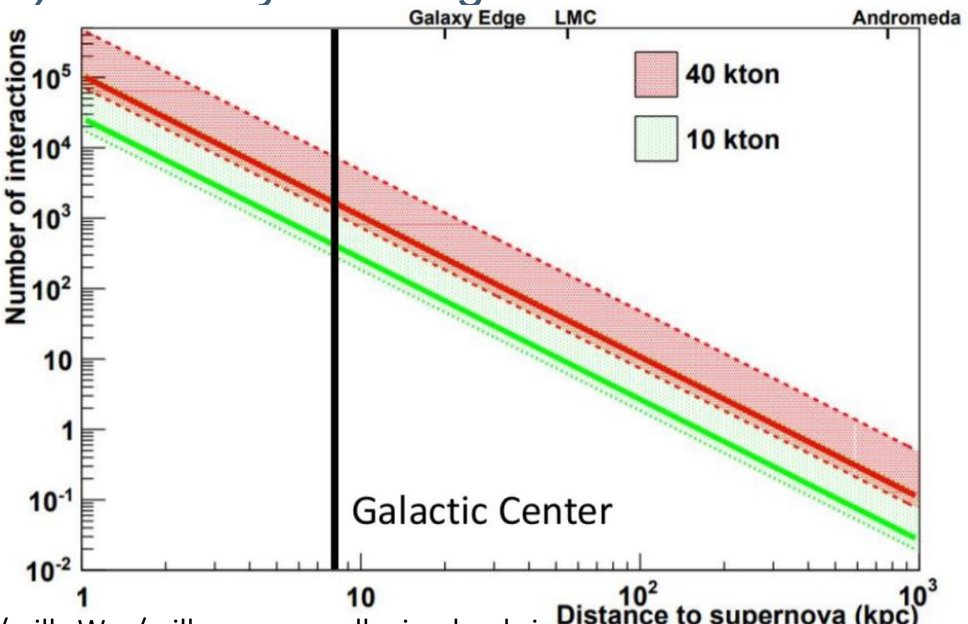
Mostly ν_eCC, unique to DUNE/LAr detectors!

- Expect to detect 1,000s of neutrinos from supernova close to Milky Way center
  - On order of 1 event from Andromeda
  - Many more than were detected from SN 1987A
  - Possibility of pointing (res. of ~5°) and early warning
    - Provide input for SNEWS

New J. Phys. 23 031201 (2021)



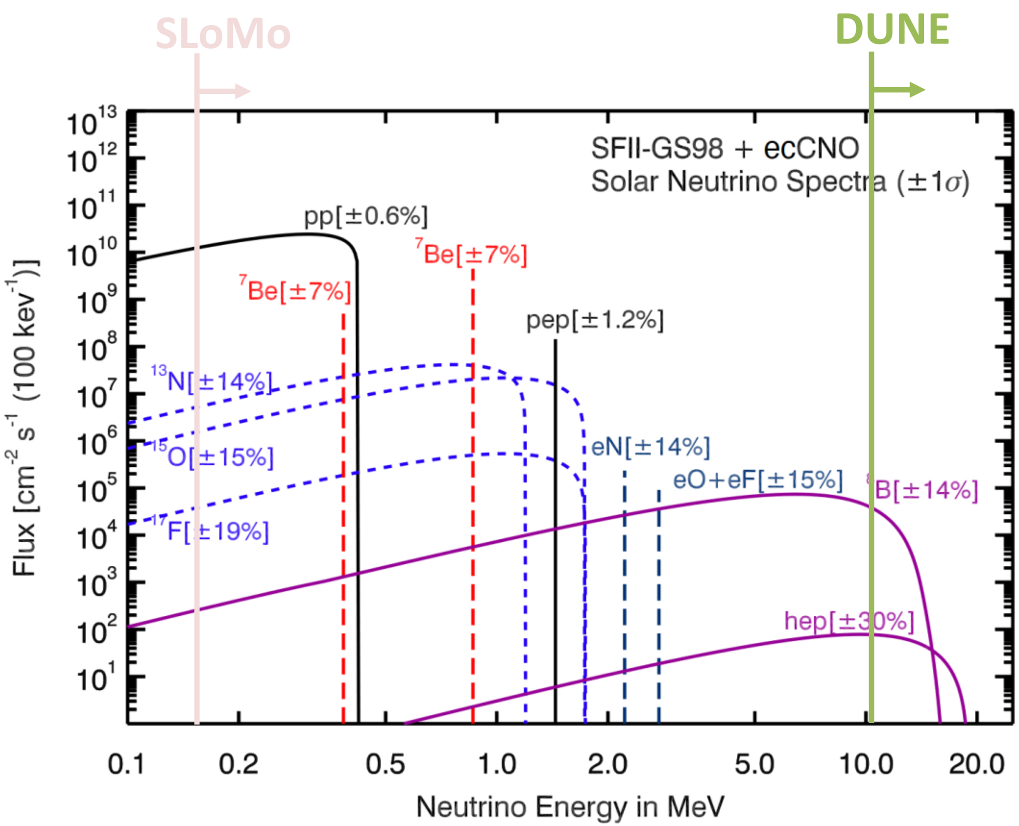
https://www.chandra.cfa.harvard.edu/graphics/resources/illustrations/milkyWay/milkyway_magellanic_clouds.jpg



Solar neutrinos

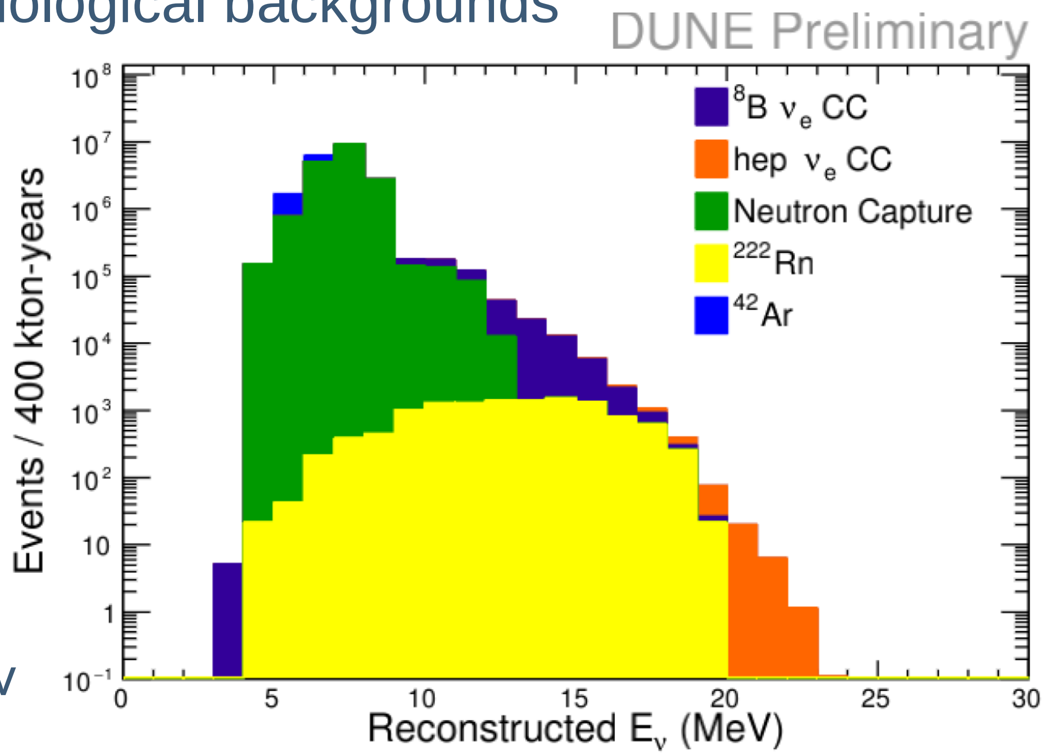
- ν_e neutrinos produced in nuclear reactions in Sun
- Different reactions produce components with different spectra and intensity

https://pdg.lbl.gov/2023/reviews/rpp2023-rev-neutrino-mixing.pdf



Solar neutrinos in DUNE

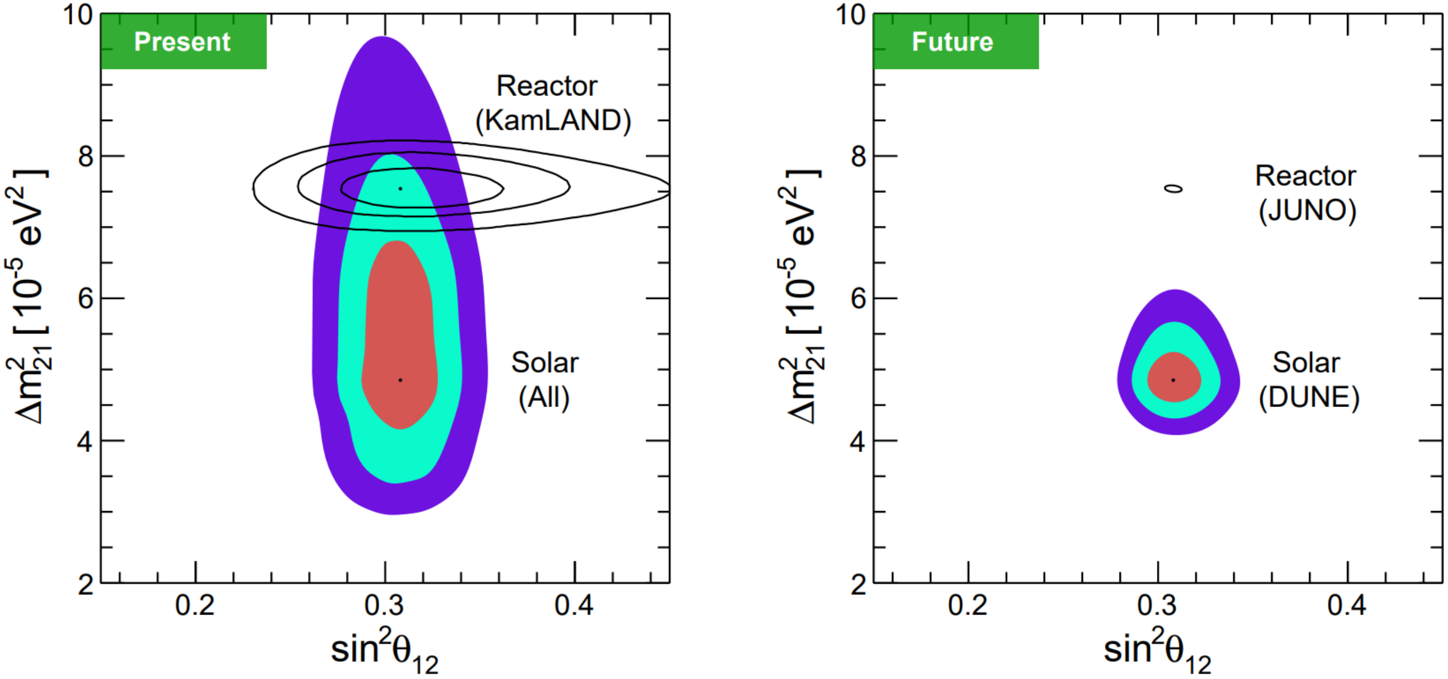
- DUNE will observe thousands of solar neutrinos/year
- Challenge is to mitigate radiological backgrounds to not drown signal
- Currently expect threshold ~9 MeV visible energy
- ^{8}B and hep neutrinos will be detectable
  - hep neutrinos have not been observed
  - No rad background for hep ν
- Possible to study oscillations



Solar neutrino oscillations

- DUNE has potential to use solar neutrinos to improve knowledge of oscillations parameters, as well as to probe beyond-standard-model physics

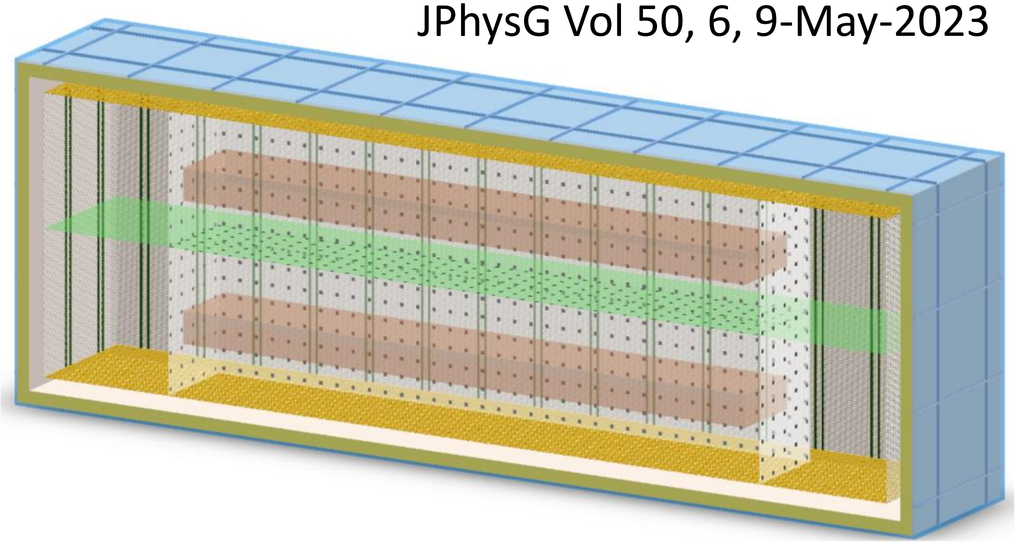
F. Capozzi, S.W. Li, G. Zhu, J.F. Beacom, Phys. Rev. Lett. 123, 131803 (2019)



Low-background module (SLoMo)

- SURF Low Background Module
  - One concept for Module of Opportunity
  - Improved capabilities for low-energy studies
- Significant reduction of radiological backgrounds
  - 3 kt of radiopure underground argon
  - constructed out of radiopure materials
  - water shielding
- better light coverage

T. Bezerra et al.
JPhysG Vol 50, 6, 9-May-2023



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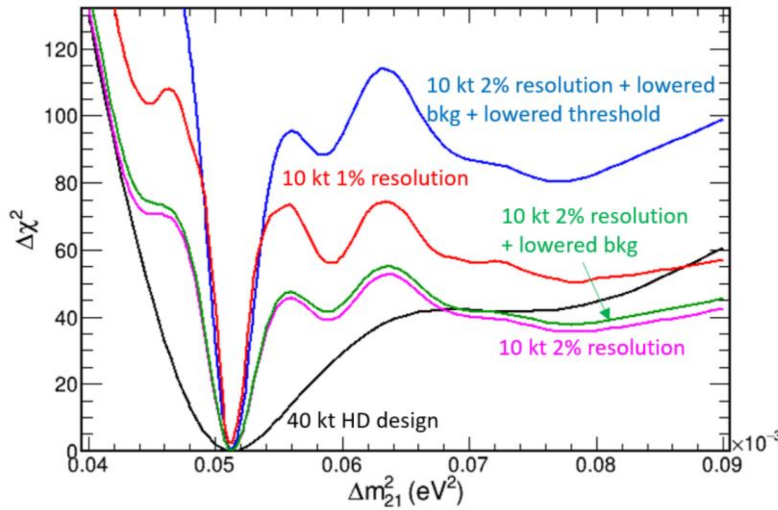
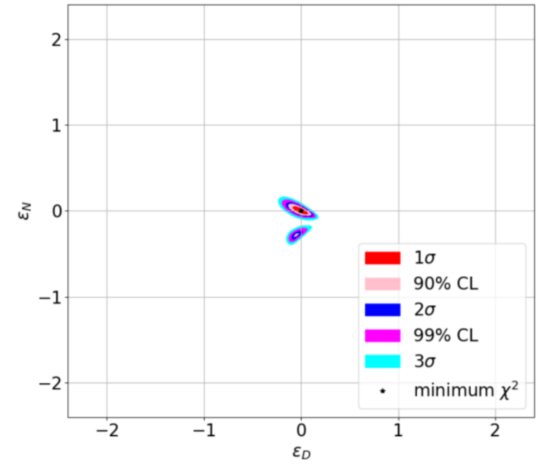
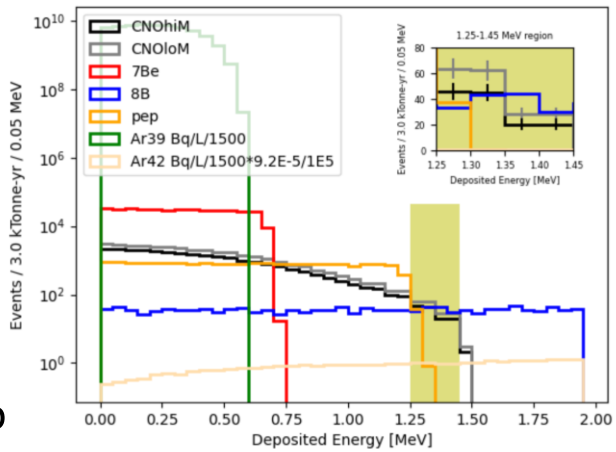
Physics with SLoMo



- Improved measurement of solar neutrino-oscillation parameters
- Studying non-standard neutrino oscillations with solar neutrinos
- Measuring CNO solar neutrinos
- Detecting CEvNS from SNB neutrinos
- Other topics
  - Dark matter including seasonal variations
  - Neutrinoless double-beta decay





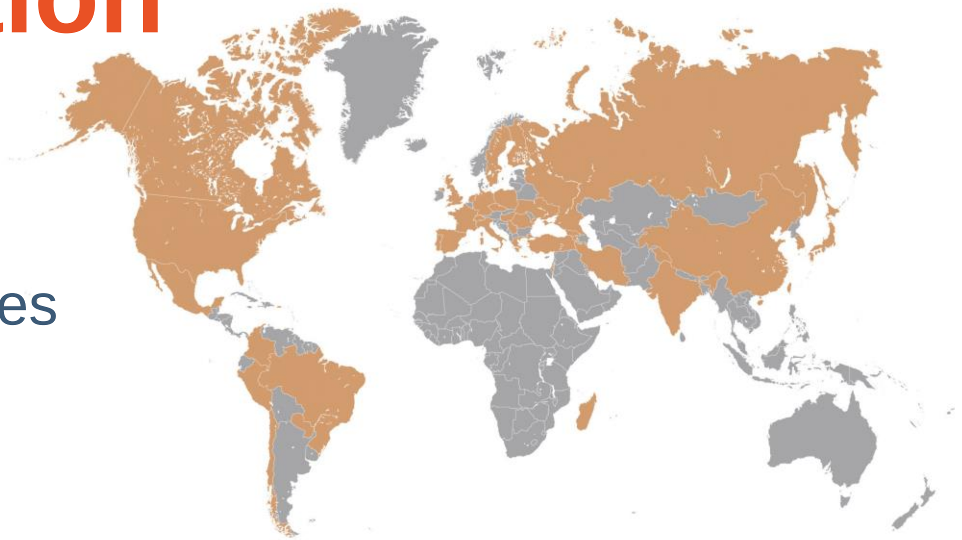
A. Mastbaum, F. Psihas, J. Zennamo
PhysRevD 106, 092002 (2022)

Conclusions

- DUNE has potential to become powerful tool to study low-energy neutrino physics
  - Large-size LArTPC is suited for detection of supernova and solar neutrinos
  - Radiological-background mitigation is important for reaching this goal
  - SLoMo as Module of Opportunity may significantly improve its capabilities

DUNE Collaboration

- 1,400+ people from
  200+ institutions in 30+ countries



DUNE Collaboration meeting at CERN, 2024

T. Bezerra et al.
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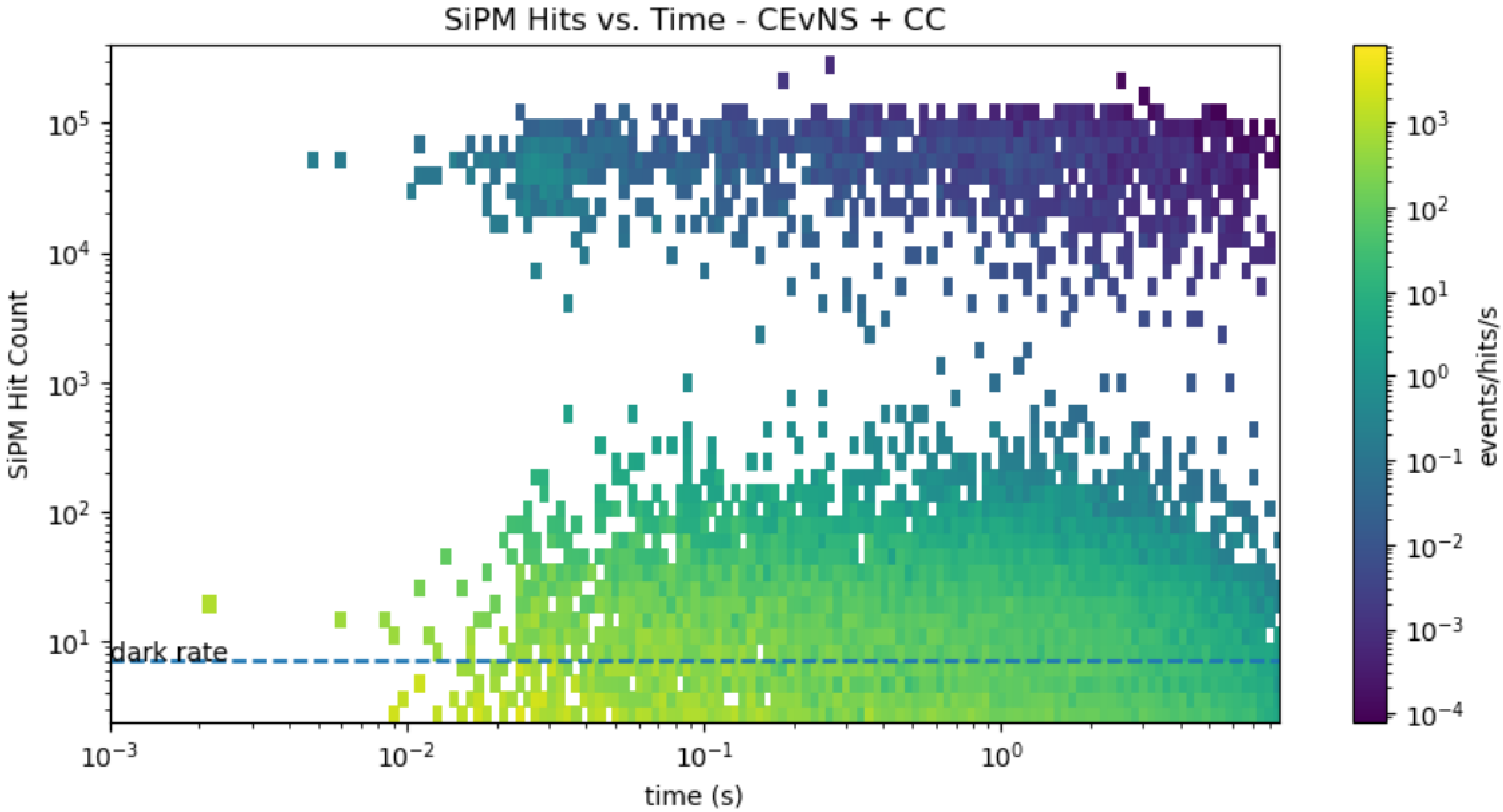
SNB CEvNS glow in SLoMo



SLoMo supernova reach