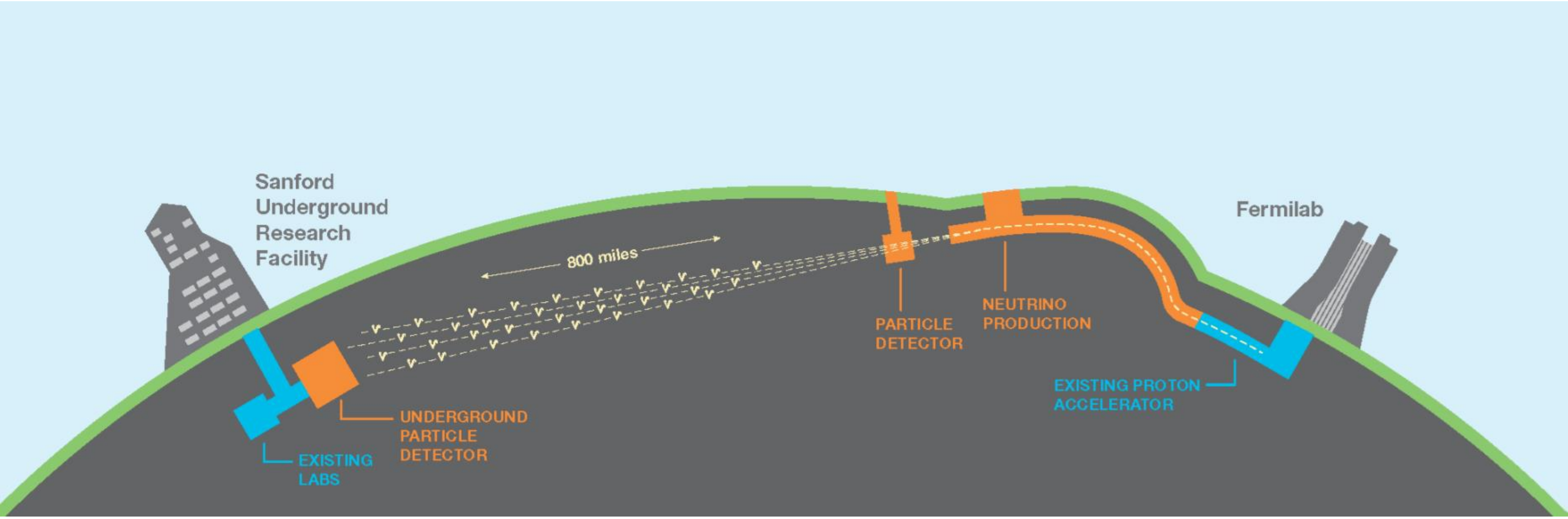
Supernova neutrinos in DUNE

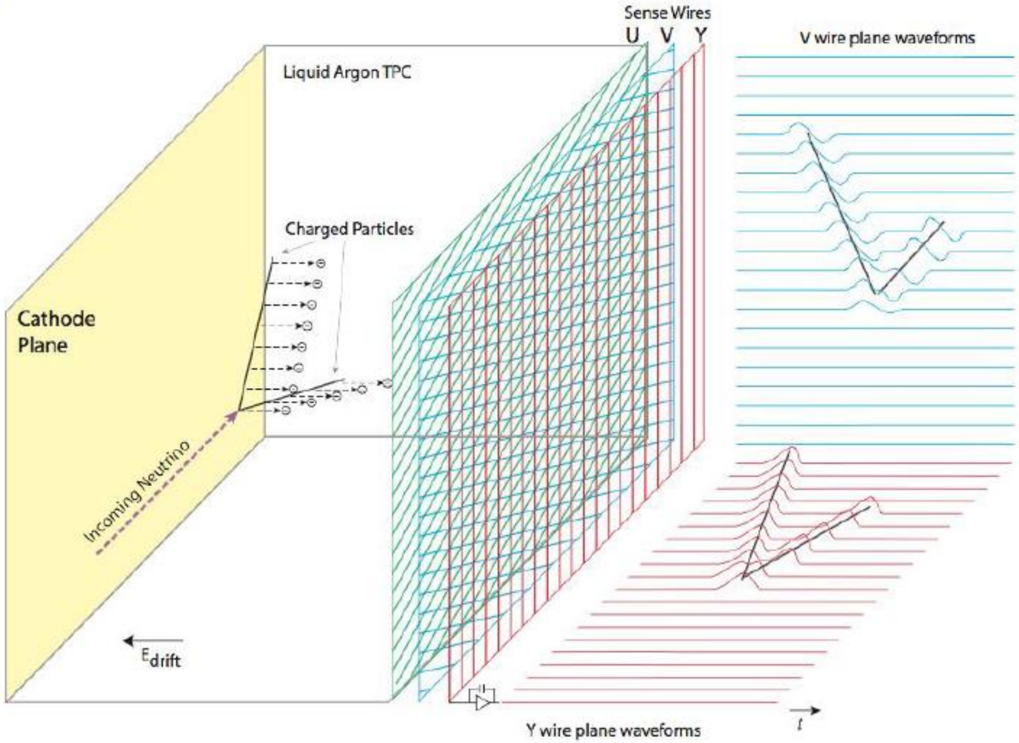
Dan Pershey
NPN: astrophysical neutrinos – SLAC
Jul 12, 2023

The Deep Underground Neutrino Experiment



- 4 x 10 kton (fiducial) liquid argon time projection chamber (LAr TPC) modules
- DUNE will further constrain neutrino oscillation parameters including the CP-violating phase angle
  - Measured using a high-purity $\nu_\mu/\bar{\nu}_\mu$ beam produced at Fermilab
- Huge size and 4300 mwe overburden makes DUNE ideal for searching for rare astroparticle phenomena

LAr TPC design



Neutrino experiments using LAr TPC's with data:

LArIAT
ArgoNeuT
MicroBooNE
ICARUS
ProtoDUNE

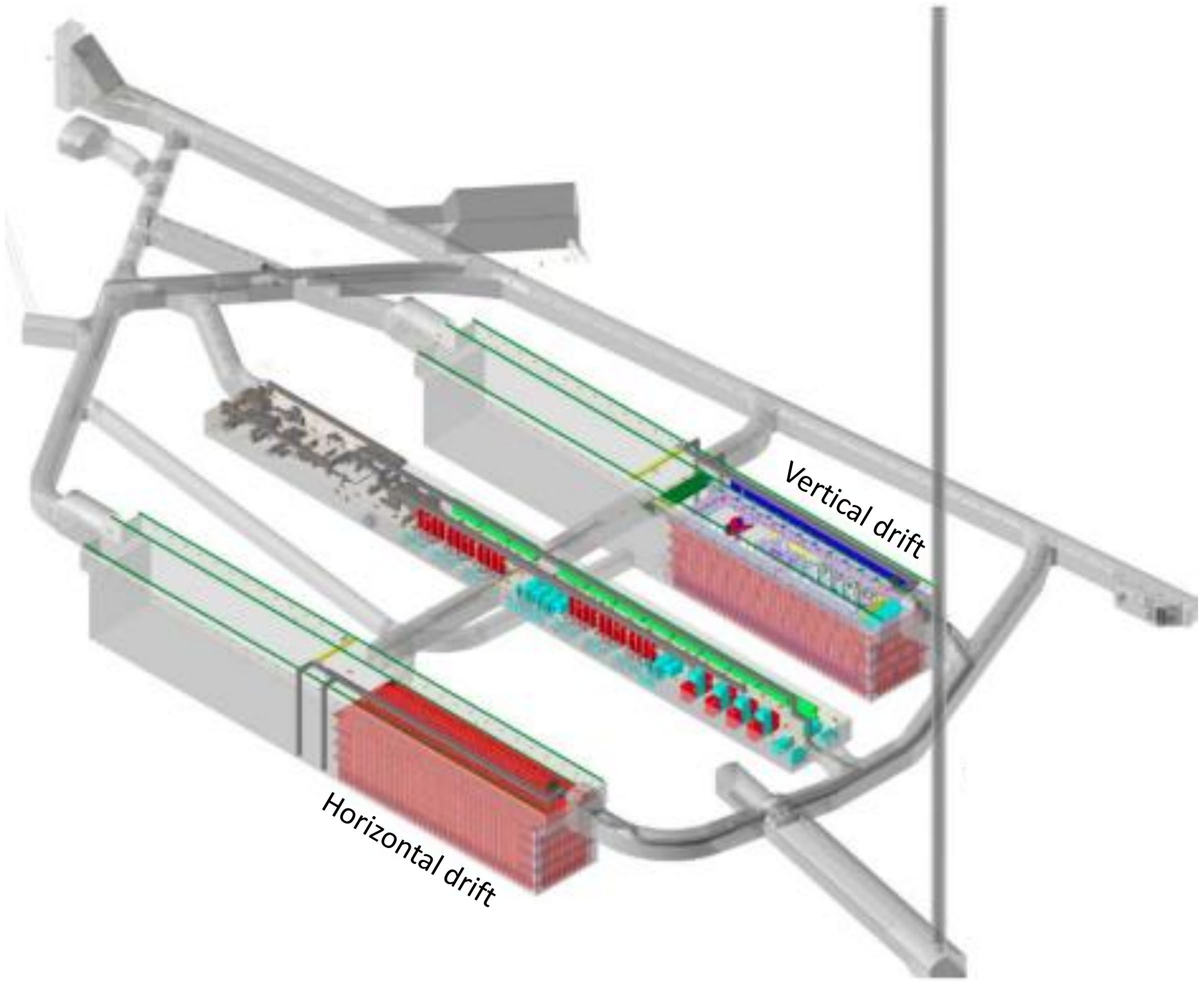
- In a noble gas, ionization charge is not re-absorbed in the medium
- An applied electric field drifts this charge to a planar readout
  - We will build three consecutive planes of readout wires with 0.5 cm spacing, oriented on different axes for two-dimensional reconstruction
- The depth in the detector is determined by photon-detection system
- Resolution is sub-cm in each dimension for an entire 10 kton module

DUNE phase I

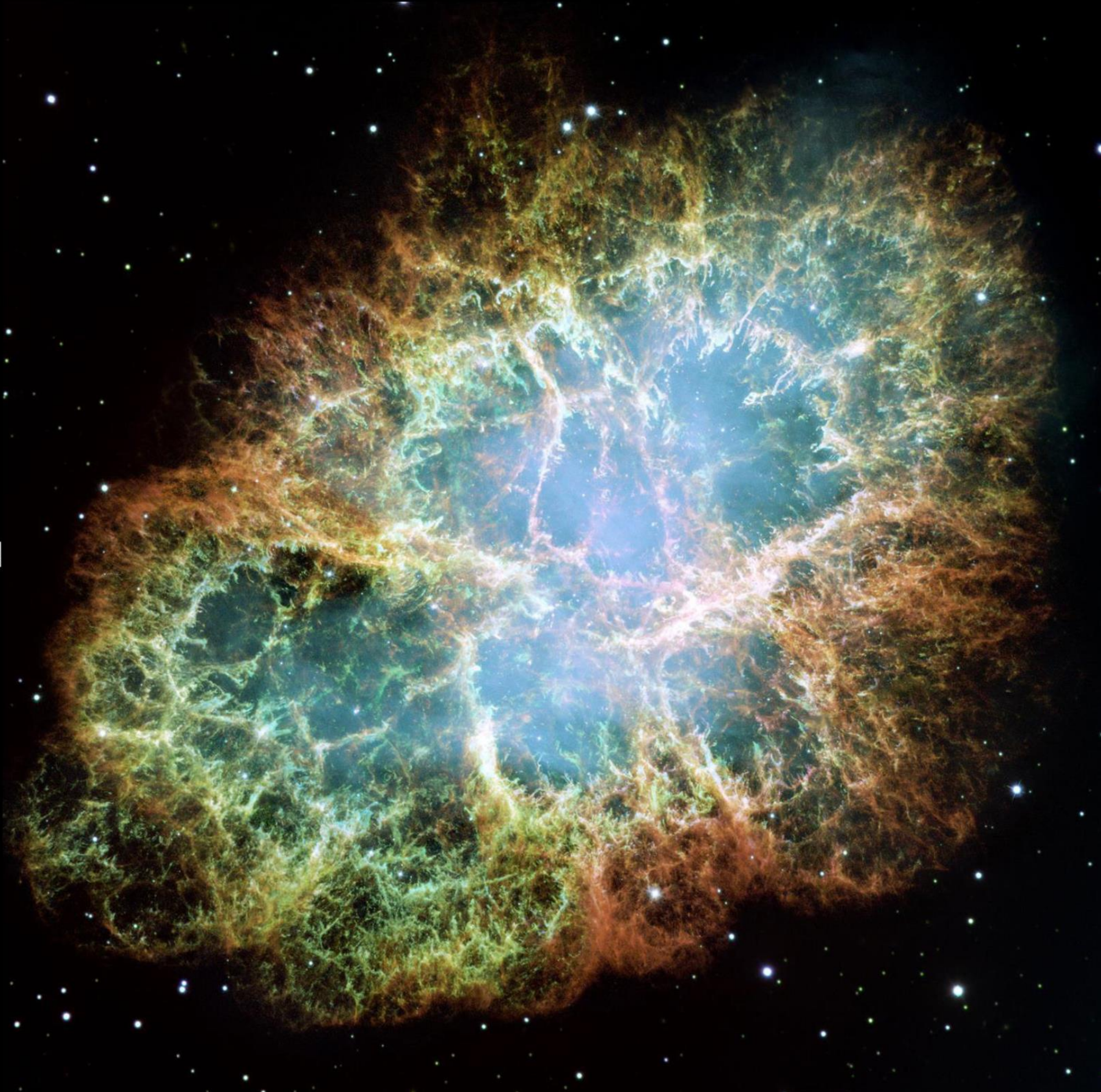
DUNE construction separated into two phases

Phase I
1x horizontal drift module
1x vertical drift module

Phase II:
R&D work underway to determine technology



Supernova neutrinos



Crab nebula, remnant of supernova recorded in 1054

A core-collapse supernova

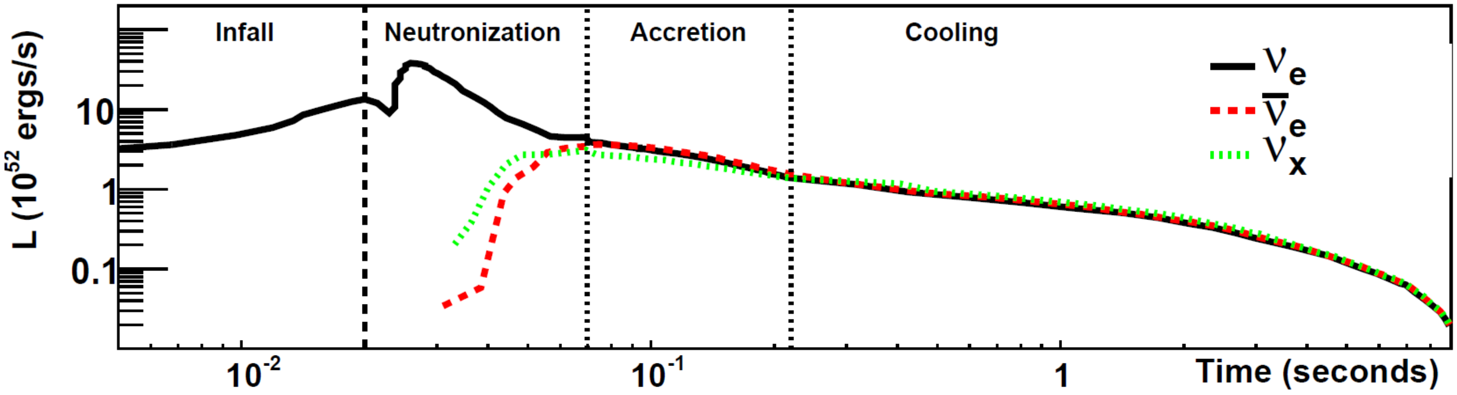
- When a massive star runs of fusable material, it releases 99% of its gravitational potential energy as a bright flash of $\sim 10^{58}$ neutrinos
- Burst lasts for several seconds and is observable from across the galaxy
- 1-3 supernovae expected / century

- A single event would teach us:
- Astrophysics
  - Core-collapse mechanism, neutronization rate, neutrino diffusion, blackhole formation, nuclear density in neutron star
- Particle physics
  - Neutrino magnetic moment, absolute mass, oscillations, sterile neutrinos, axions, dark matter

A burst of neutrinos was observed in supernova 1987a, associated with the death of a star in the Large Magellanic Cloud

$\approx 20\ \bar{\nu}_e$ interactions between Kamiokande, IMB, and Baksan

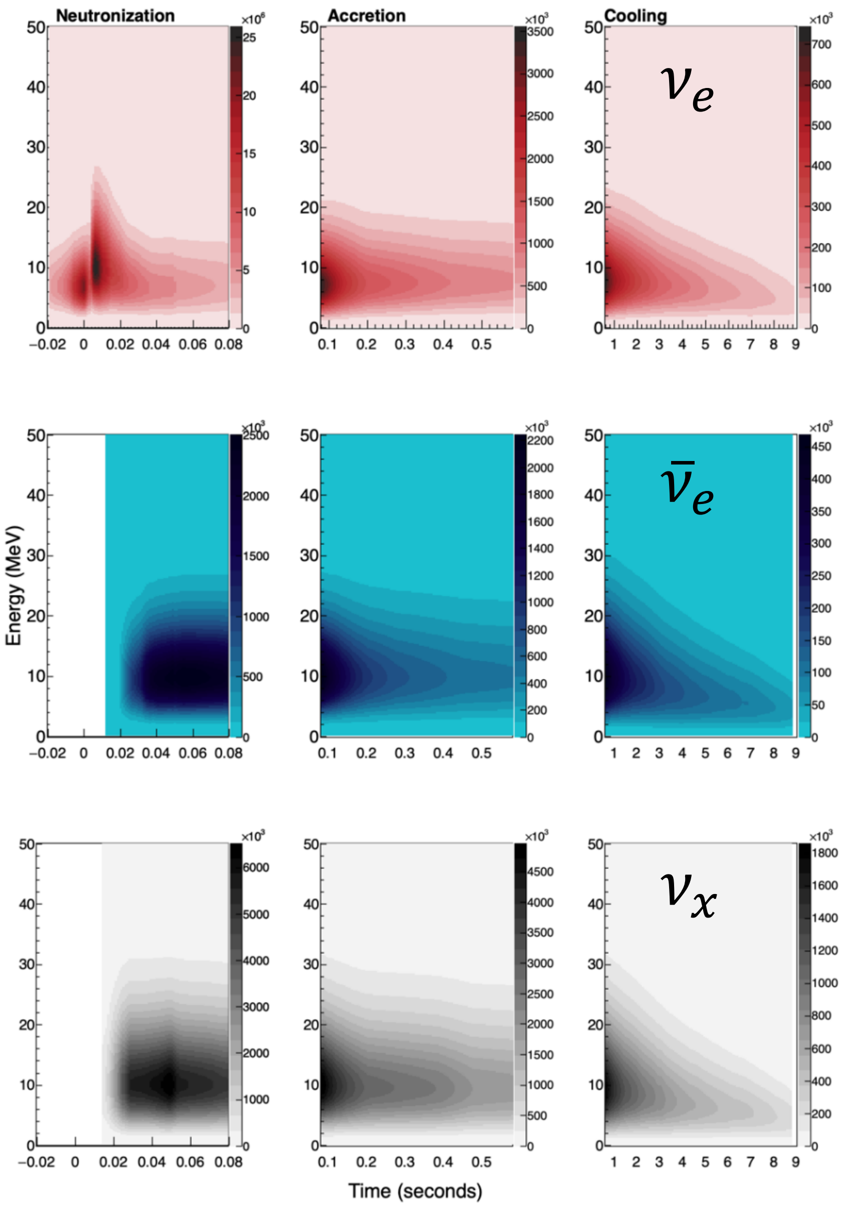
Neutrinos emission in a supernova



- After a heavy star exhausts its supply of fusible nuclei within its core, it releases neutrinos in three discernable epochs during a supernova
  - 1. Neutronization through electron capture in the core gives a short-lived, intense flash of ν_e
  - 2. Neutrino production then dominated by matter falling into the core
  - 3. Emission then slowly cools as neutrinos diffuse

- DUNE expects to see several thousand events from a galactic supernova to test time/energy profiles

Goal: determine the neutrino flux



- Include neutrinos in multi-messenger observation of collapse and measure the differential flux
- Beyond precise reconstruction of kinematics, we must probe all flavors to fully understand the core collapse
  - ν_e – observe neutronization
  - $\nu_e + \bar{\nu}_e$ CC – good for calorimetry
  - ν_x NC – no oscillation ambiguity

DUNE uniquely sensitive to ν_e component!

	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

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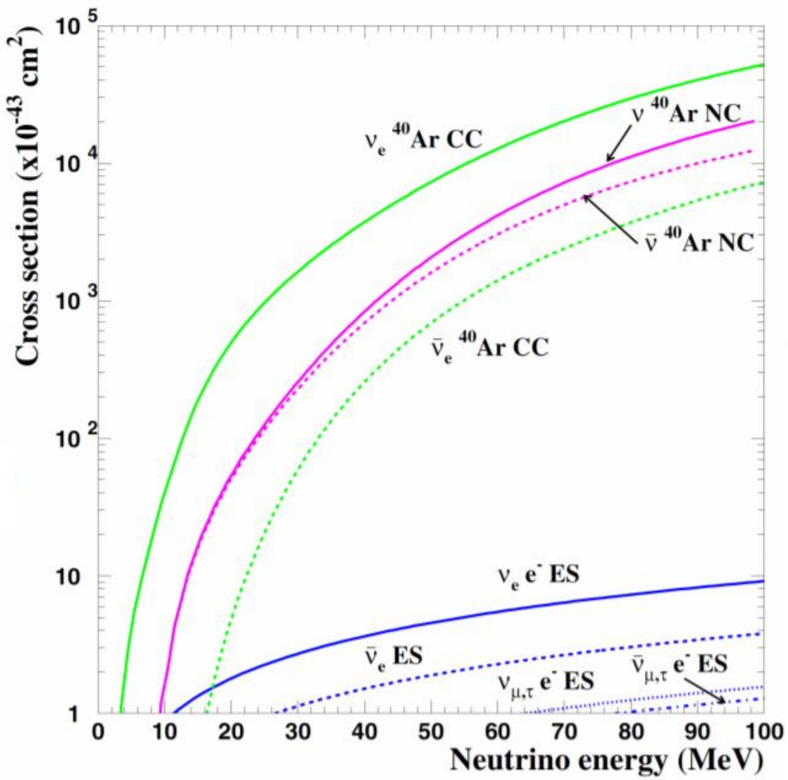
Interaction channels in argon



- Charged current (CC) interactions on Ar sensitive only to ν_e flux

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

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

- Neutral current interactions on Ar

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

$$\bar{\nu}_x + {}^{40}Ar \rightarrow \bar{\nu}_x + {}^{40}Ar^*$$

- Neutrino scattering off electrons (ES)

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

$$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$$

Sub-cm spatial resolution allows for event-by-event categorization by interaction type

NC events create a cloud of deexcitation gamma blips

CC events give an electron in a deexcitation cloud

ES scatters produce a lone electron pointing away from the supernova

Supernova events at DUNE

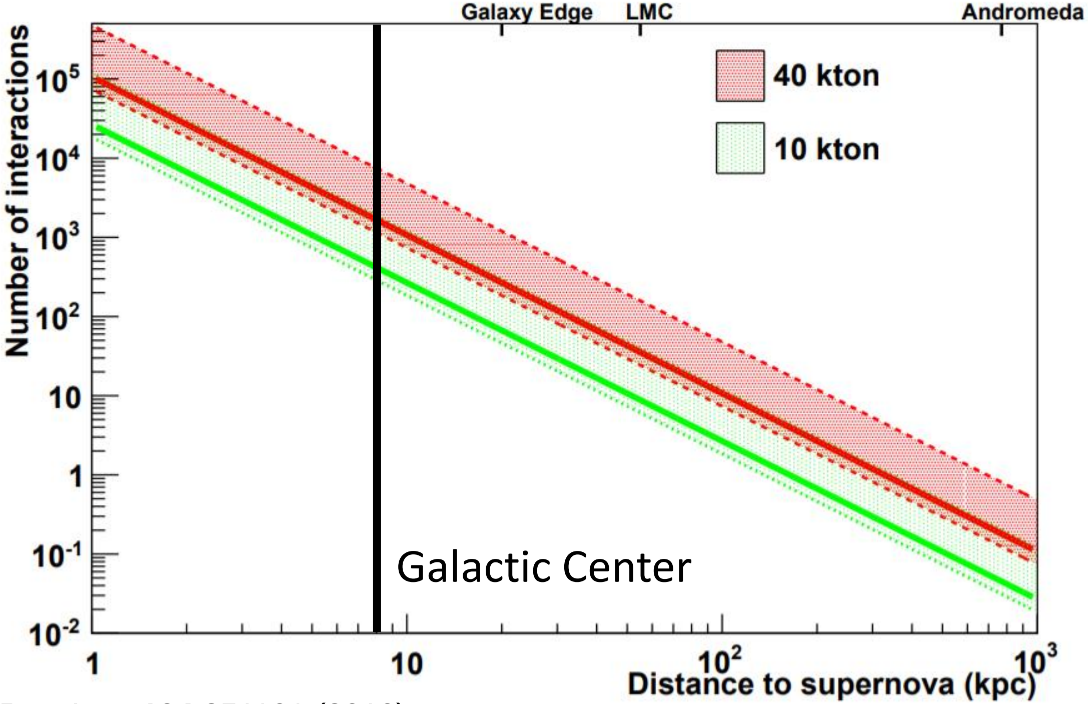
- For a typical galactic supernova (originating 10 kpc away), we expect ≈4000 neutrinos in 40 kton of argon

Channel	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

Most sensitive to the ν_e flux
Unique aspect of argon detectors!

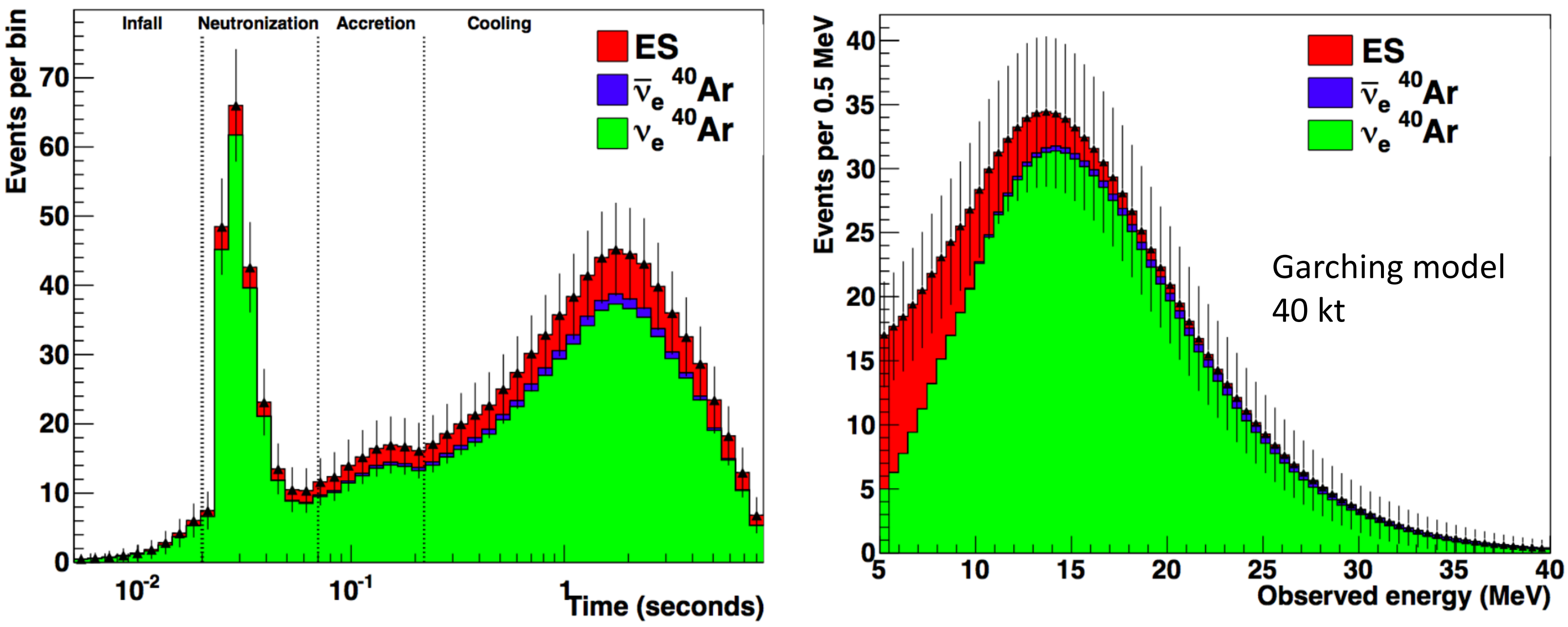
Hundreds-thousands of events for galactic core collapse

Current effort within DUNE exploring machine learning techniques to improve triggering capabilities



[1]Huedepol, Müller, Janka, Marek, and Raffelt, *Phys. Rev. Lett.* **104** 251101 (2010)

Expected spectrum of events



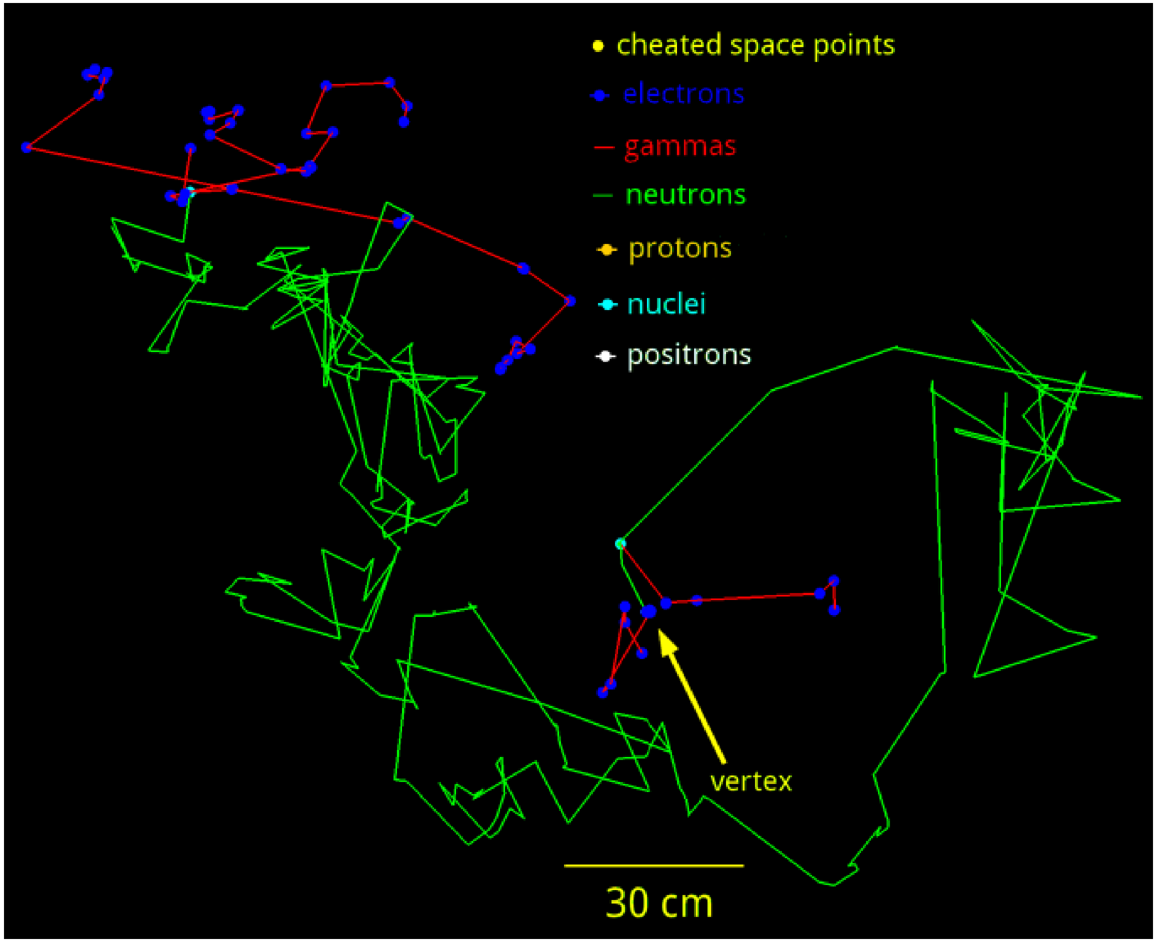
- We are most sensitive to the ν_e CC interaction – but we will observe others
  - Unique to DUNE, other detectors largely sensitive to anti-ν_e from IBD
- We can further exploit the reconstruction capabilities of the DUNE TPC to separate the flavors

Simulating neutrino interactions with MARLEY

- DUNE is a fine-grained tracking detector: need precise understanding of event hit topology for low-energy events that can be complicated
- Use MARLEY event generator (Steven Gardiner, https://www.marleygen.org/)

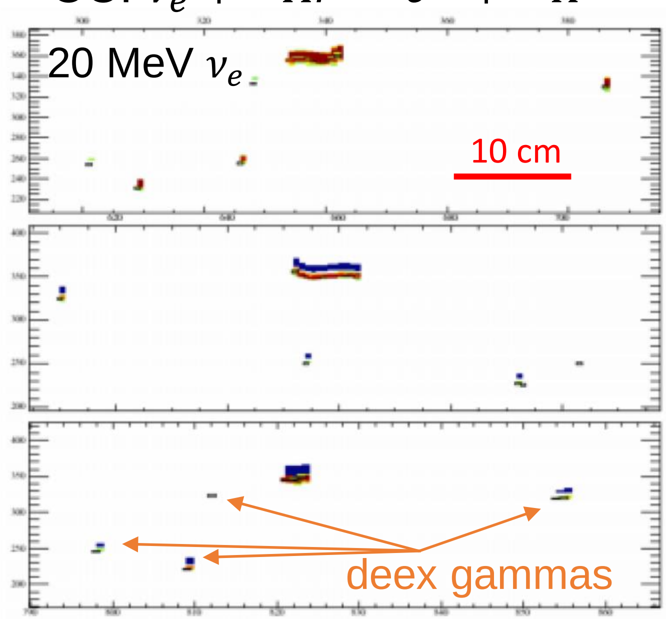
Neutrino energy: 16.3 MeV

Charge depositions
Electron: 4.5 MeV
neutron (captures): 7.6 MeV
^{39}K: 68 keV

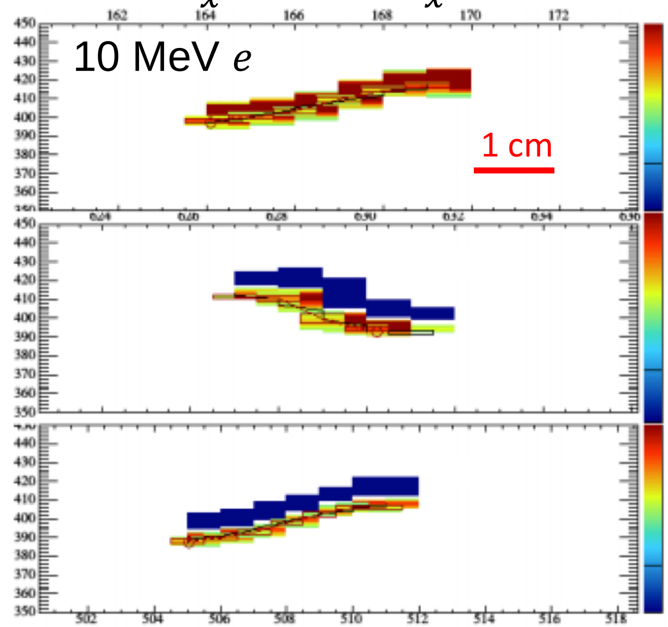


Event topologies in DUNE

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

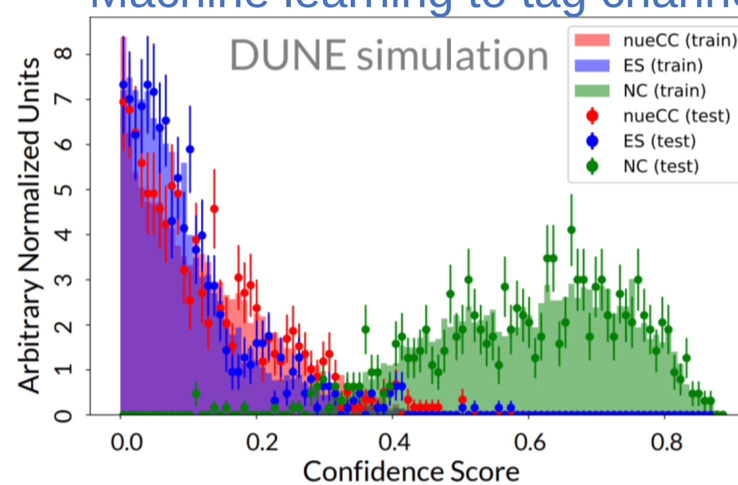


ES: $\nu_x + e^- \rightarrow \nu_x + e^-$



- Precision tracking of particles in TPC
  - Electron track visible in CC and ES
  - Comptons from deexcitation gammas show up as small blips surrounding electron track
- Can discriminate between channels based on deexcitation gammas

Machine learning to tag channels



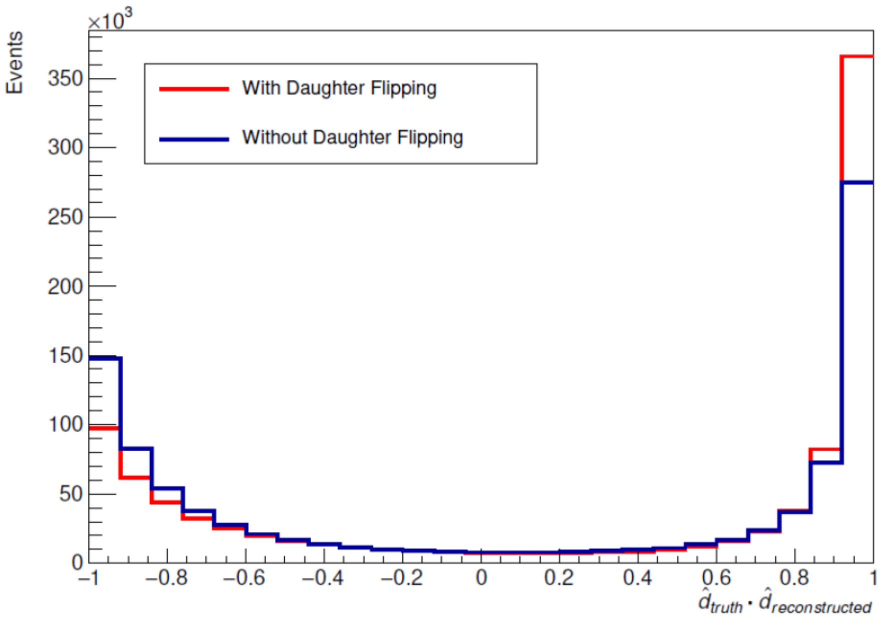
Predicting supernova direction with DUNE

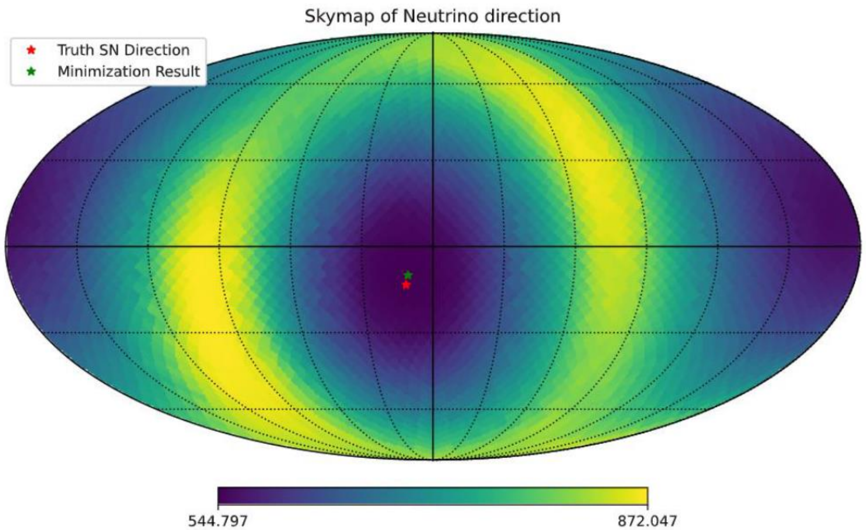
1987 supernova, Anglo-Australian Observatory

- Studying the light signal from the supernova also interesting from the beginning of the collapse through several months after explosion
- The neutrino burst arrives at Earth ≈hour before light so we can warn optical astronomers of an event and indicate source location
  - Neutrino signal facilitates multi-messenger study of supernovae

Pinpointing a supernova with DUNE data

- Simulated supernova at 10 kpc with the GKVM model
  - 260 ES scattering events
    - Low-Q^2 $\rightarrow$ great pointing
  - Forward/backward ambiguity in track reconstruction solved by "daughter flipping"

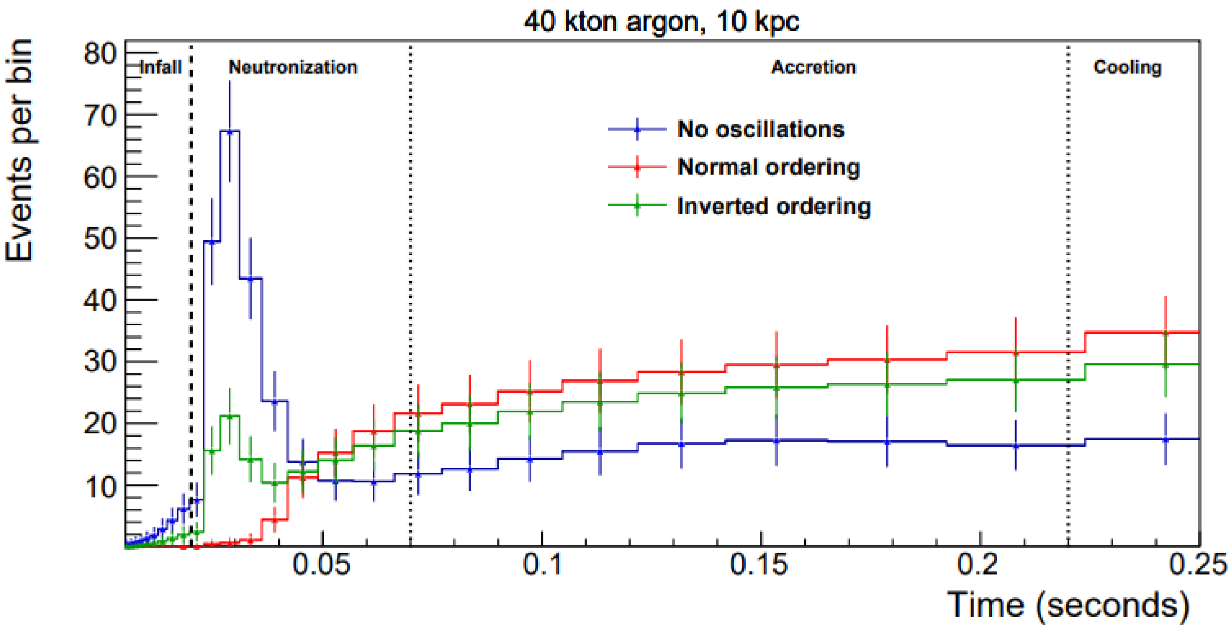




- TPC allows flavor discrimination so the ν_e CC component can be mitigated
- Exploiting the directionality of $\nu - e$ scattering events, we can determine the direction of the supernova to $\approx$ 4.5 deg

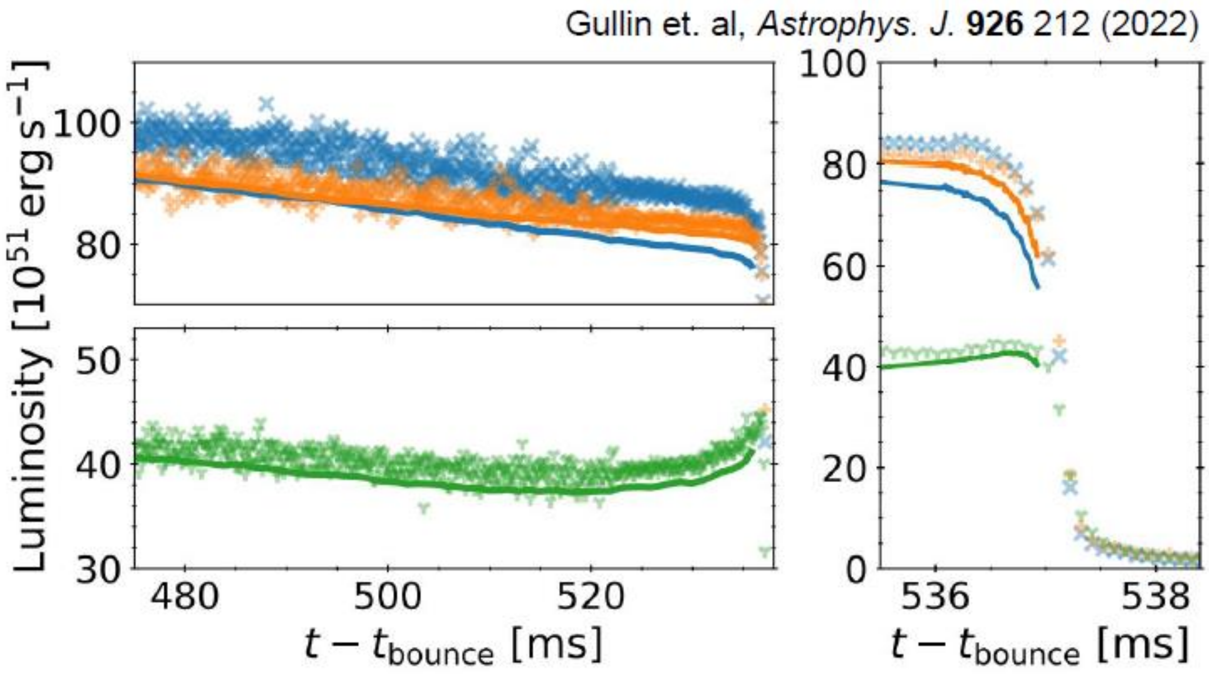
Paper in preparation!

Observing the neutronization burst



- An intense flux ν_e of is produced from neutronization early in the collapse – DUNE can uniquely search for this peak due to dominant ν_e CC sensitivity
- But, the ν_e content from neutronization depends on several unknowns
  - Neutrino mass ordering
  - Collective oscillations from ν-ν scattering
  - Underlying model – physics uncertainties in core collapse
- Observing neutrino flux with multiple flavors is only way to probe physics

Detecting black hole formation



- The neutrino signal can discriminate between neutron star and black hole forming supernovae
- During black hole formation, an event horizon is created ~ 100 ms after the start of the collapse which quickly quenches the neutrino flux
- Neutrino signal may be only indication of supernova – light may wink out

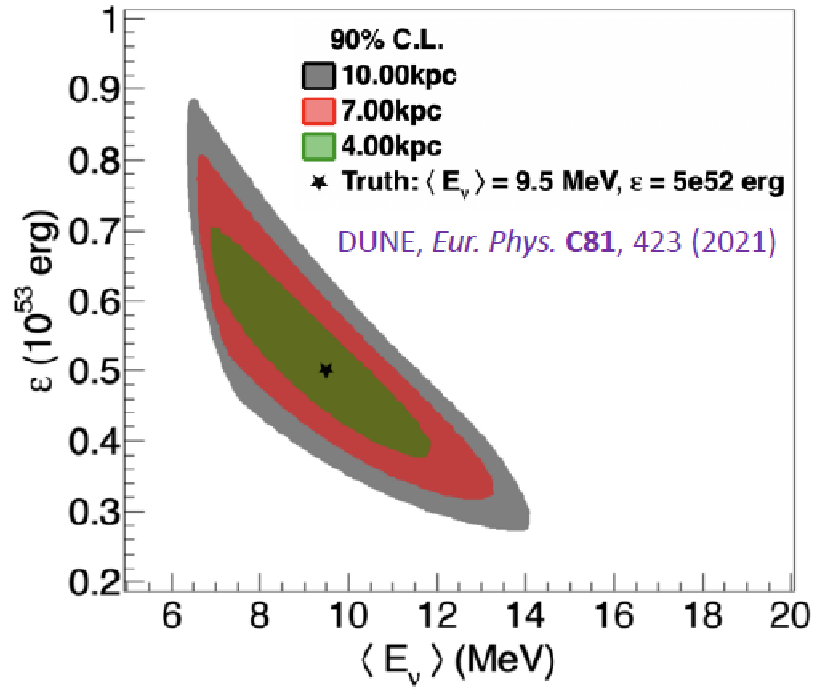
Testing astrophysical models with ν spectrum

- Energy transport models in supernovae give a wide range of predicted neutrino spectra observed by DUNE
- General "pinched thermal flux" shape is sufficient to describe flux predicted by these models but with different parameters

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

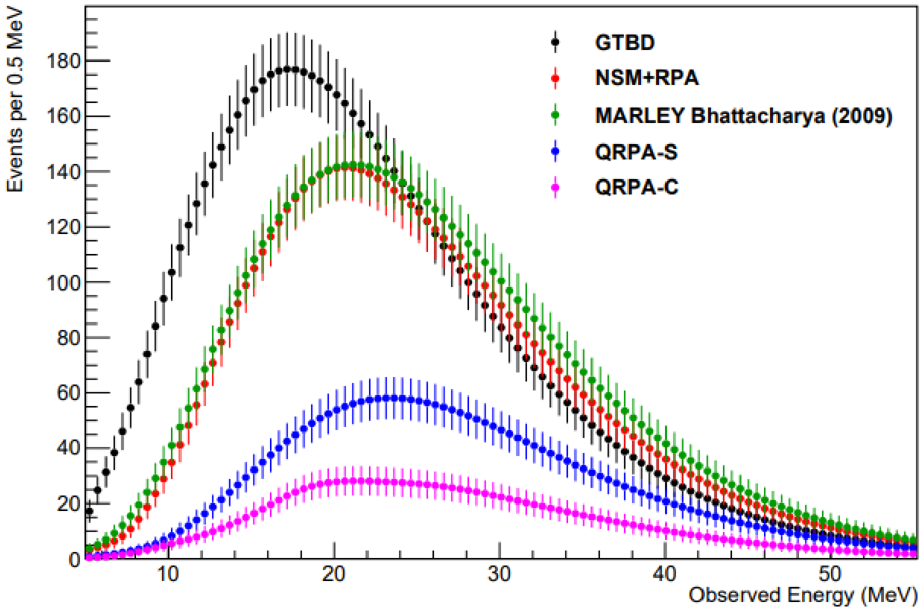
Different for each flavor – DUNE needed to test ν_e!

- DUNE can constrain these three relevant parameters
- Provides a test of these supernova transport models
- A measurement at 10 kpc would constrain current understanding
  - Current understanding of neutrino scattering model limits constraint – theory and experimental input needed



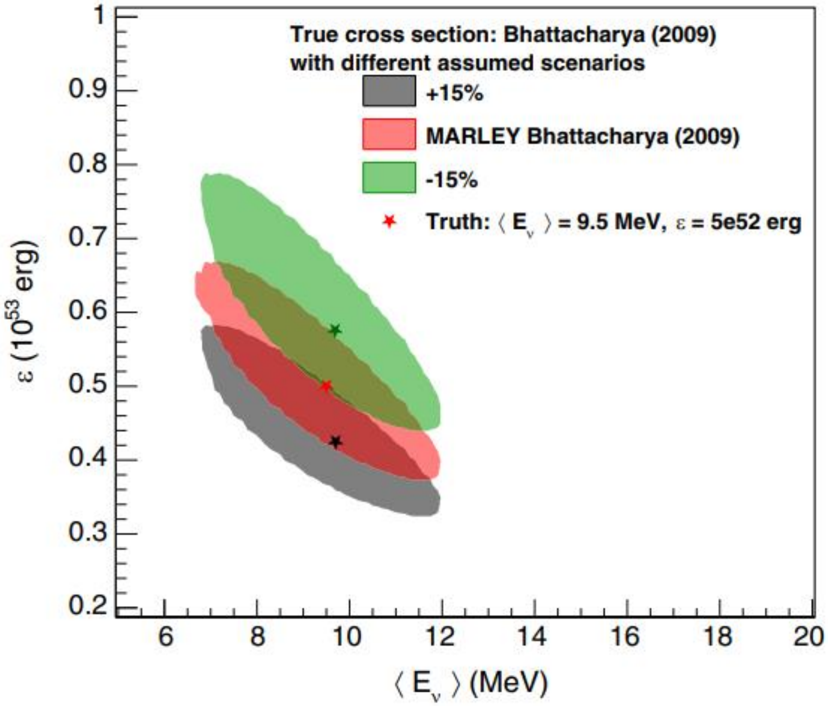
Warning: cross section uncertainties

DUNE, PRD 107 112012



- The ν_e CC cross section on argon is only known to an order of magnitude
- Must understand before next core collapse supernova!

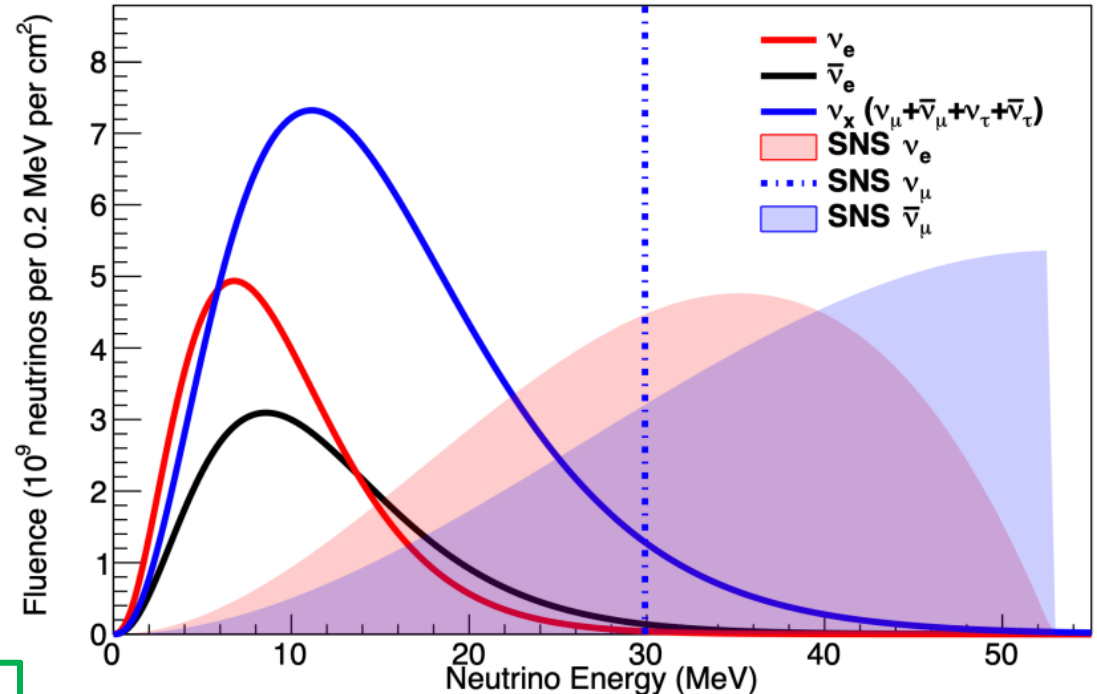
≈ 15% benchmark for cross section normalization



Measurement with stopped pion sources

Aside: separate from DUNE!

- π⁺ decay at rest (πDAR): convenient terrestrial neutrino source in same energy regime as a supernova
- Multiple flavors – can test ν_e CC and NC cross sections



πDAR source @ Oak Ridge National Lab

Spallation neutron source currently supporting πDAR neutrino program

1.4 MW beam of 1.0 GeV protons incident on Hg target at 60 Hz

Large flux!

≈ 2e12 ν_e / cm^2 / day

≈ 1 ν_e CC / 180 kg argon / day @ 28 m

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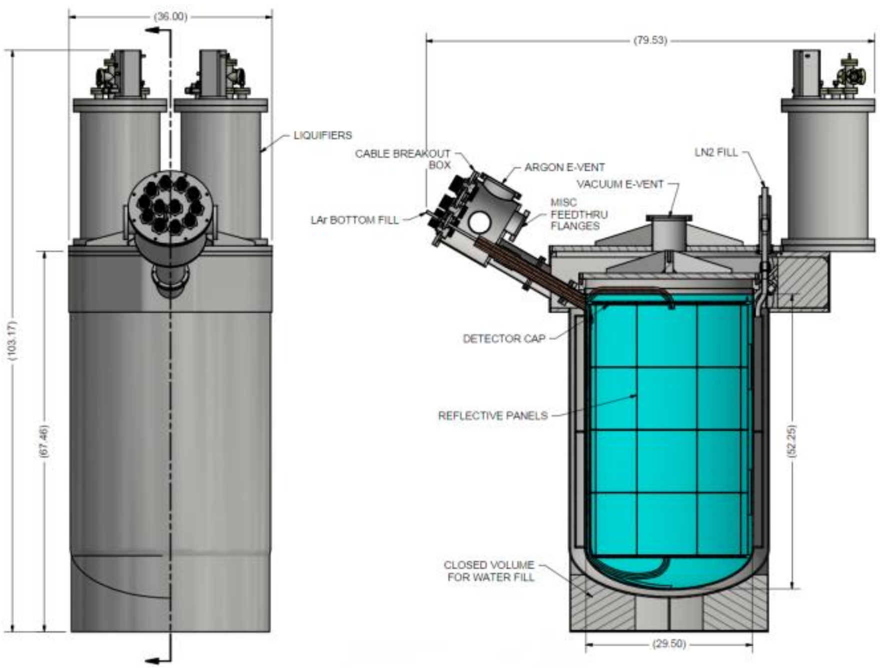
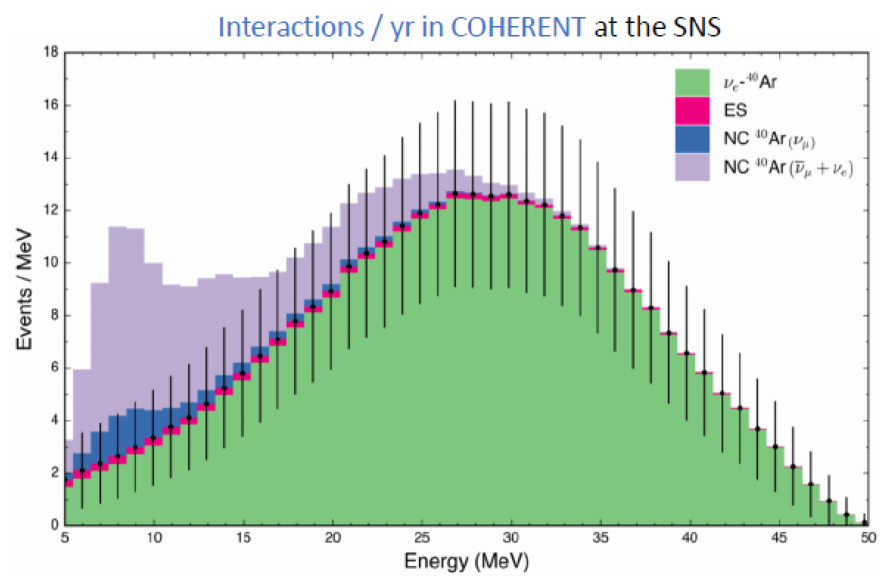
COHERENT argon program

Aside: separate from DUNE!

- 24-kg scintillation calorimeter argon prototype detector running at SNS since 2017
  - First measurement of coherent neutrino-nucleus scattering (*PRL* **126** 012002)
  - Calibration for CC constraint underway
- Currently constructing upgraded 610-kg fiducial argon detector which will be deployed in 2024 and record ≈ 400 inelastic neutrino interactions in the supernova region of interest





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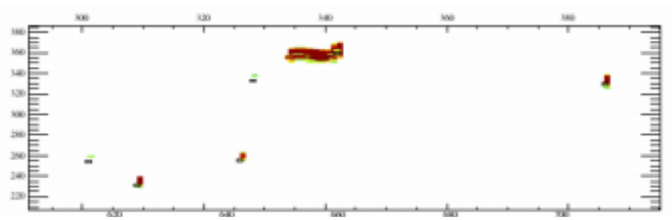
New ideas: bringing a TPC to the SNS

Aside: separate from DUNE!

Motivation: low-energy neutrino topology complicated in DUNE, measure electron and deexcitation cascade with similar resolution



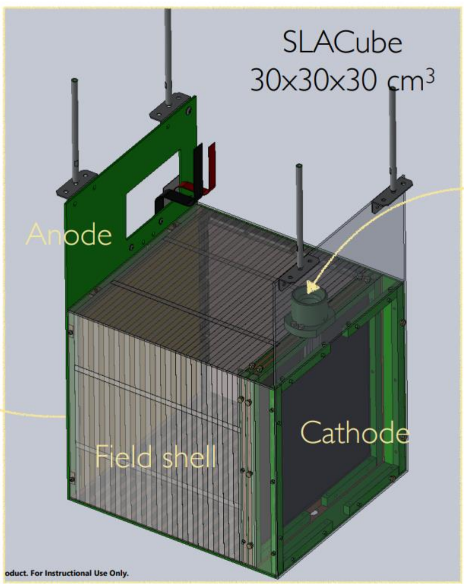
A TPC installed at the SNS would be very beneficial for DUNE's low-energy program

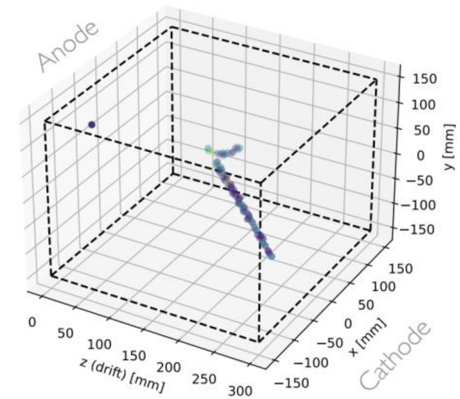
Potential testing in a neutrino beam for TPC R&D relevant for DUNE program

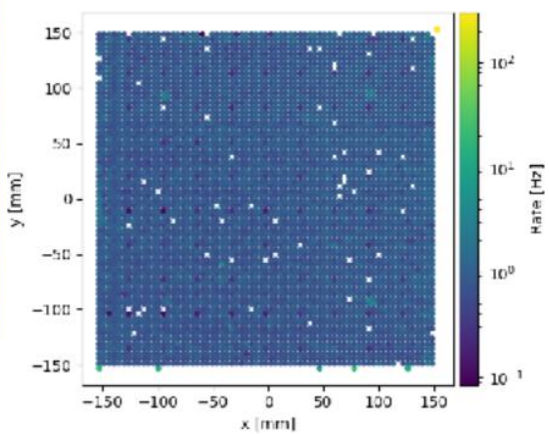
See Yun-Tse Tsai, SN neutrino workshop [here on indico]

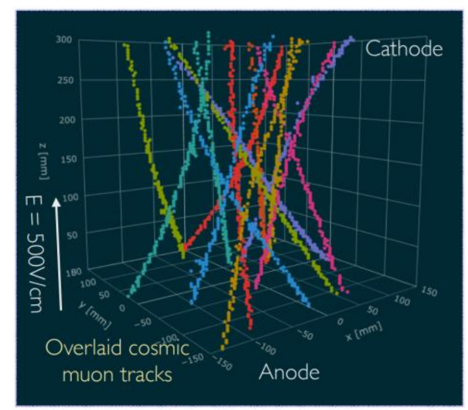
38 kg TPC built and operated at SLAC

Other TPC R&D possible









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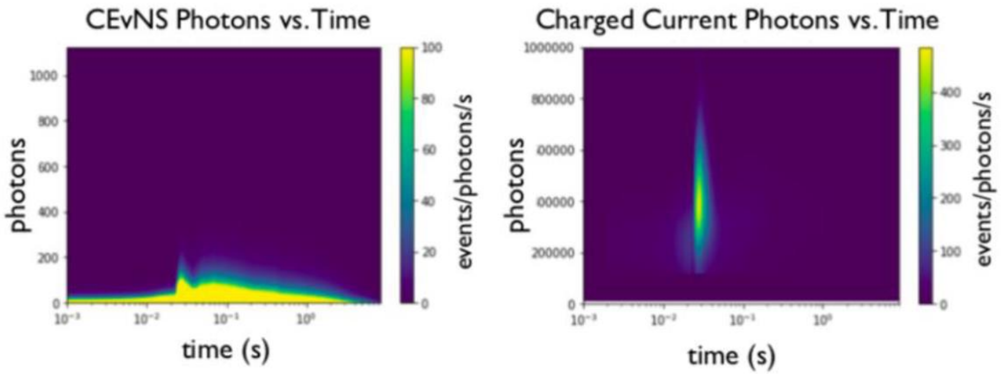
New ideas: measuring NC with CEvNS glow

- Supernova neutrinos will also make CEvNS, but each scatter is below threshold
- High cross section compensates – about 12% of scintillation from CEvNS
  - ≈100x as many CEvNS compared to CC from cross section
  - ≈6x as many CEvNS compared to CC from using all flavors in flux
  - ≈0.001x as much visible energy per event (10 keV vs 10 MeV)
  - ≈0.2x quenching for nuclear recoils

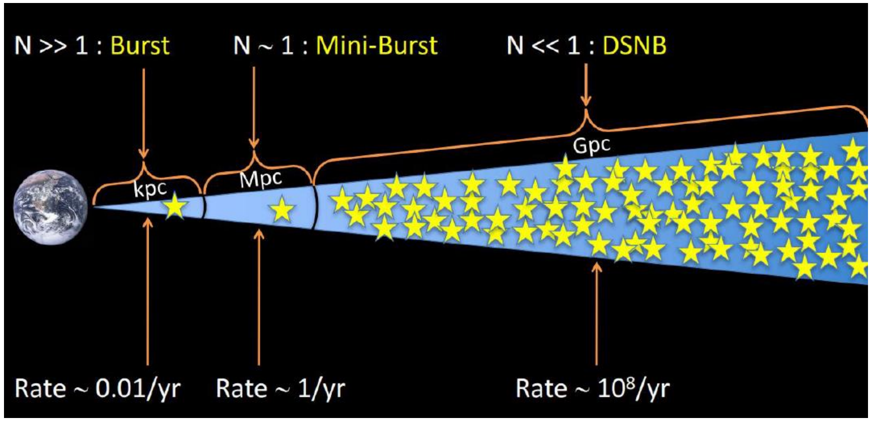
- CC scintillation comes in bright flashes, we can look for the bulk evidence of CEvNS from the supernova flux by looking at low scintillation level events
- CEvNS is NC – so sensitive to all flavors and gives DUNE access to the ν_x flavor



A. Major and K. Scholberg, Preliminary

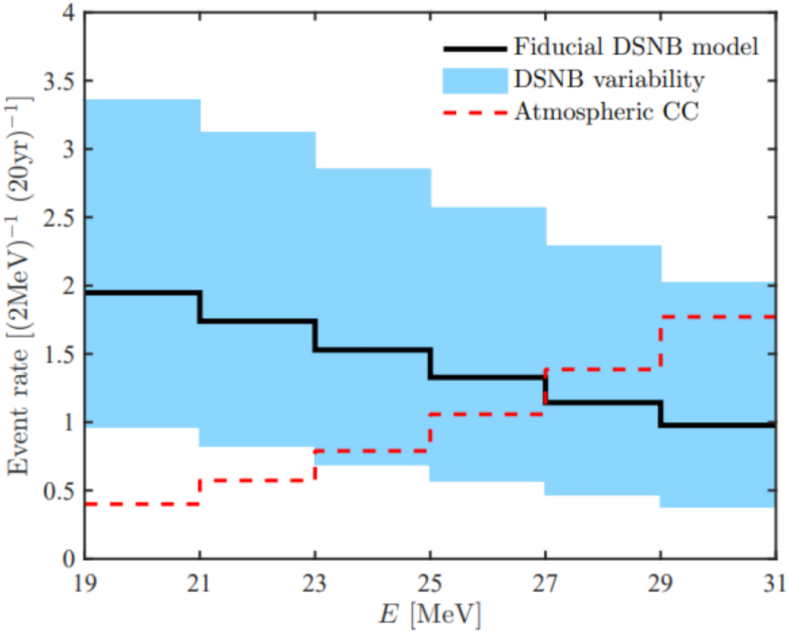
New ideas: searching for the DSNB

The neutrino flux from a supernova depends on distance, $\propto 1/r^2$. But, further from Earth, the density of stars increases $\propto r^2$. Two effects cancel out and the total flux of supernova events sums up to a finite contribution up to Gpc scales



Guaranteed signal! No waiting for burst

Moller et al., *J. Cosmo. And Astro. Phys.* **05**, 066 (2018)



- Measurement gives information on typical supernova spectrum and measures the fraction of supernovae that make black holes

Density of supernova events (/Mpc³/s)

Inflation effects

$$\frac{d\Phi}{dE} = \int_0^{z_{max}} R_{SN}(z) \times \frac{dN(E'_\nu)}{dE'_\nu}(1+z) \times \left| c\frac{dt}{dz} \right| dz$$

Neutrino spectrum released by supernova (redshifted)

- DUNE has unique sensitivity to the neutrino component, but sensitivity is meager

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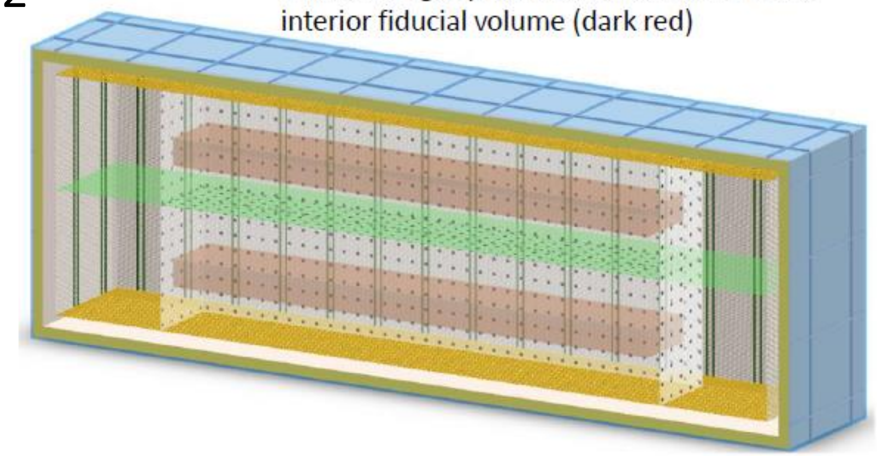
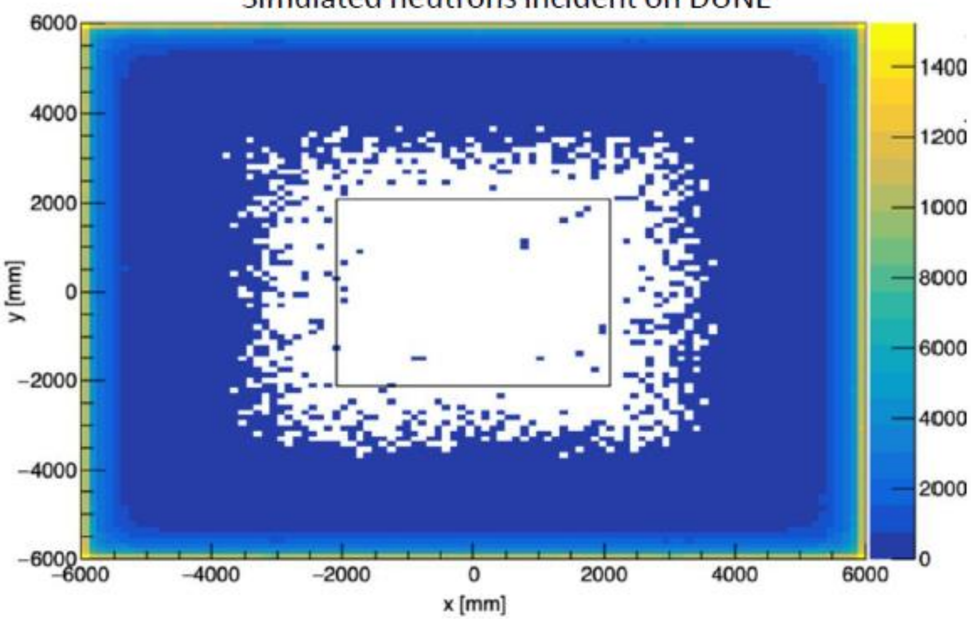
Re-imagining DUNE's role in the cosmic frontier

- Investment in a DUNE Module of Opportunity would be game-changing for low-energy physics
- Low-background module: *J Phys G* **50** 060502
  - Rate reduced by passive shielding
  - Increased photodetector coverage
  - Heavy fiducialization
  - Argon depleted of ^{39}Ar

DUNE low-background module concept
Increased SiPM (black dots) coverage on interior of acrylic vessel (white) forming volume of increased light yield which contains a 1-3 kt interior fiducial volume (dark red)



Simulated neutrons incident on DUNE



Potential for 100-keV thresholds would turn DUNE into a kt-scale powerhouse

All this possible without losing sensitivity to neutrino mixing parameters

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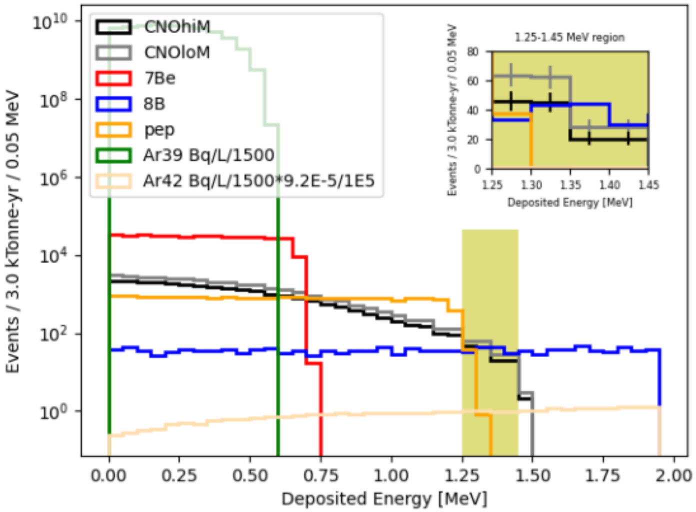
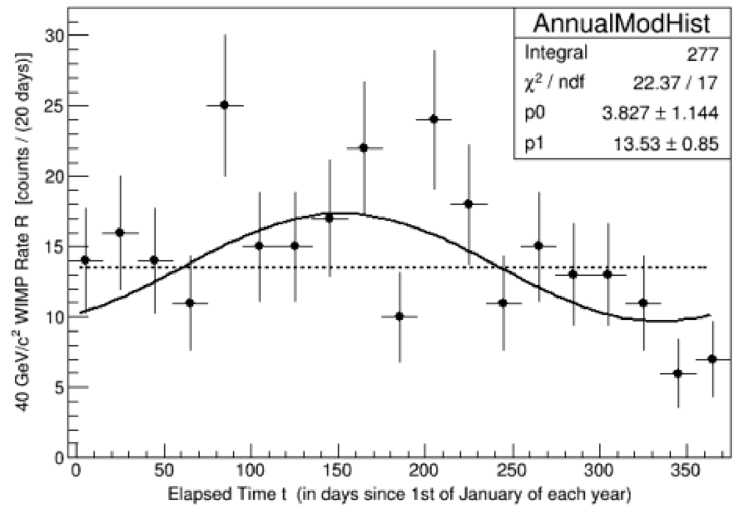
Physics with a low-background module

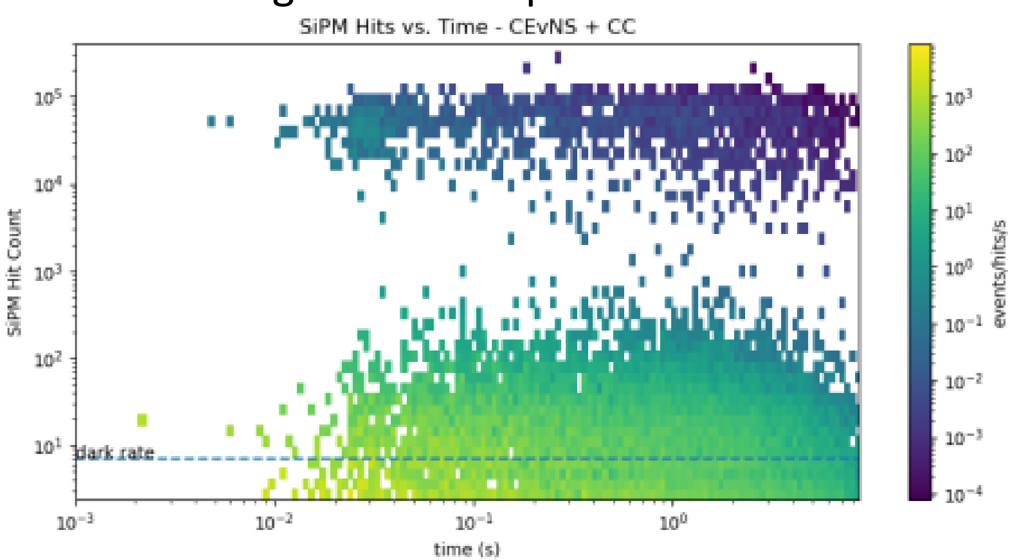
Solar CNO neutrinos + metalicity



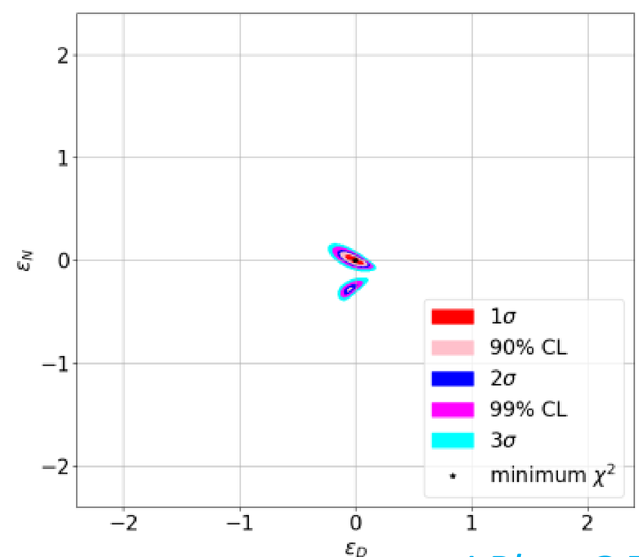
DM + annual modulation



NC CEvNS glow from supernova



Solar non-standard matter effects



J Phys G **50** 060502

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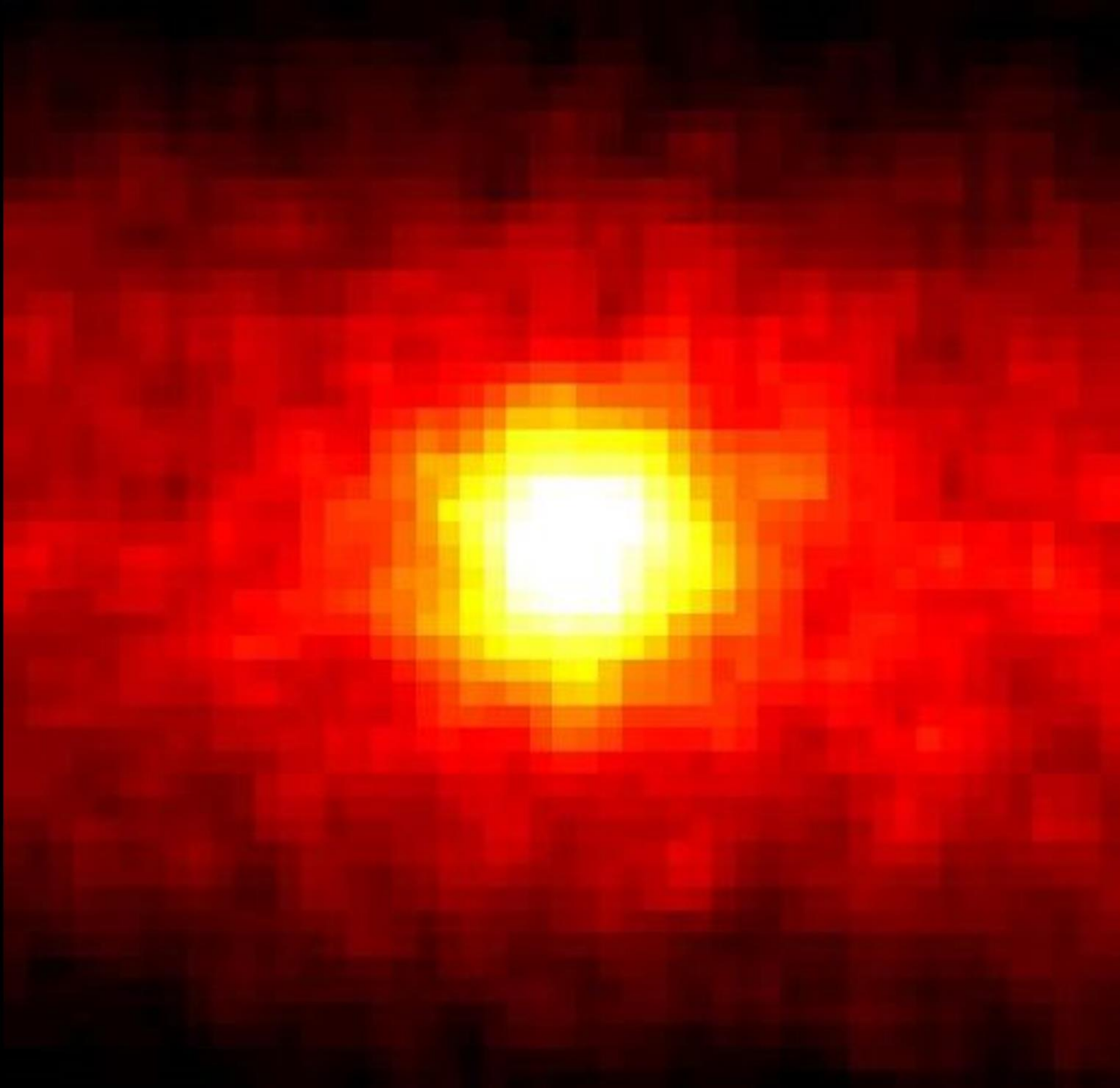
Solar neutrinos

First photo of the sun taken from below a mountain –SK collaboration



Discovering solar neutrinos

- Neutrino astronomy was born with Ray Davis and the Homestake experiment – discovery of solar neutrinos (starting 1967)
  - Observed $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ radiochemically by isolating dozens of individual argon atoms and observing subsequent decays
- Confirmed fusion was the source of energy for stars, but found solar ν_μ flux was only about 1/3 of expectations from the standard solar model

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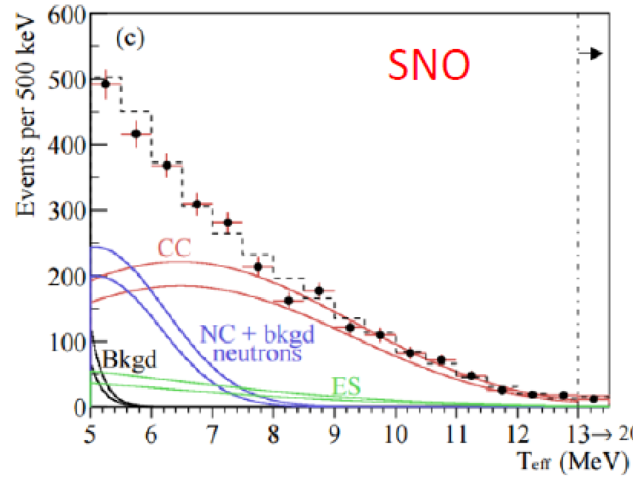
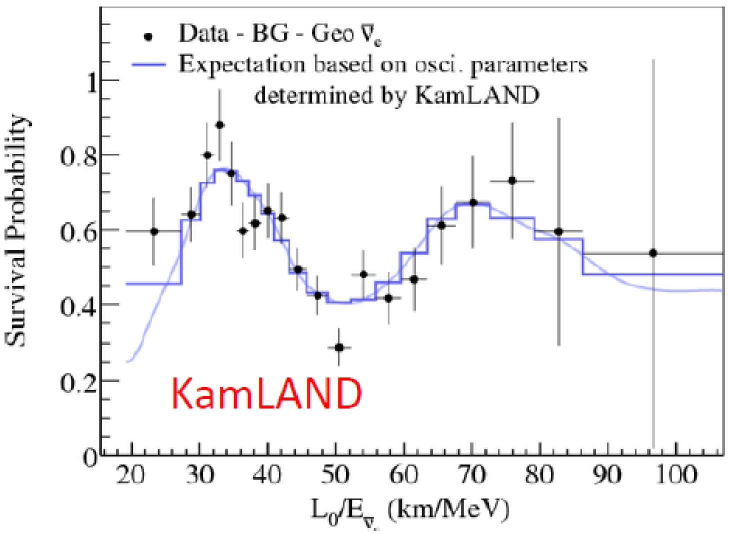
Neutrino oscillations with solar neutrinos

Davis measured a low because of flavor transitions as they travel from the sun – neutrino oscillations

SNO solidified oscillation hypothesis by simultaneously measuring CC/NC/ES components





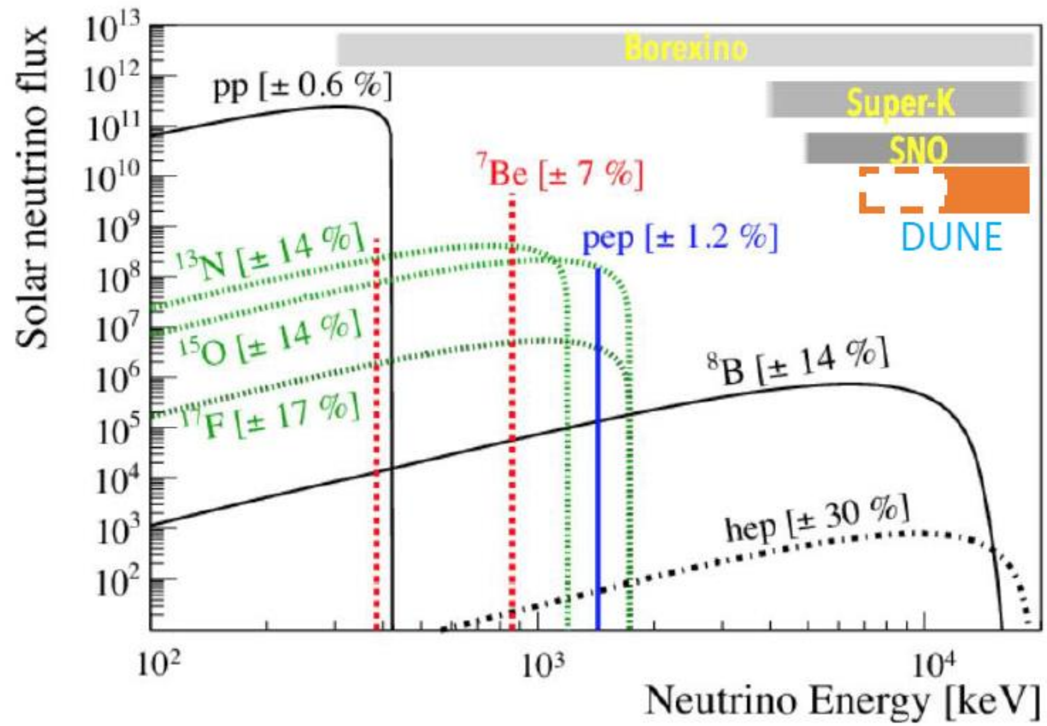
KamLAND: measured oscillations using neutrinos from multiple reactors with similar baselines

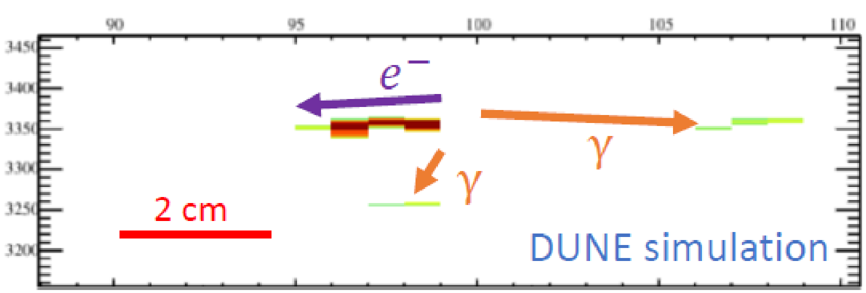
Test of neutrino oscillations in a laboratory setting that confirmed L/E dependence

- Both solar and terrestrial reactor experiments observe neutrino oscillations, but disagree on the value of the mass splitting by $\approx 1.5\ \sigma$
- May point to new physics such as matter effects from BSM neutrino interactions in the sun and should be tested with next-generation experiments

Neutrinos produced in solar fusion

- The sun produces a large flux of neutrinos which may interact in DUNE
- Thresholds set by large background rate at several MeV (mostly neutron captures)
- 8B and hep fluxes are observable





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

In DUNE, CC channel dominates signal: leaving a ≈10 MeV electron and gamma cascade in detector

Precision energy reconstruction!

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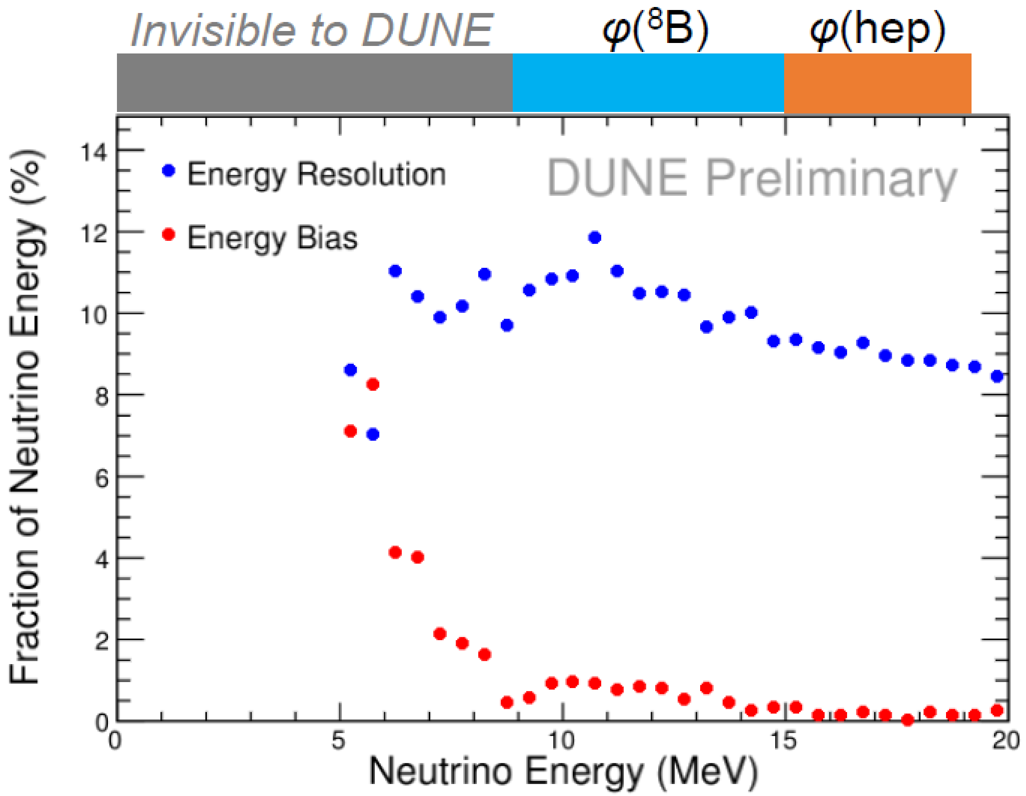
Reconstructing solar neutrinos



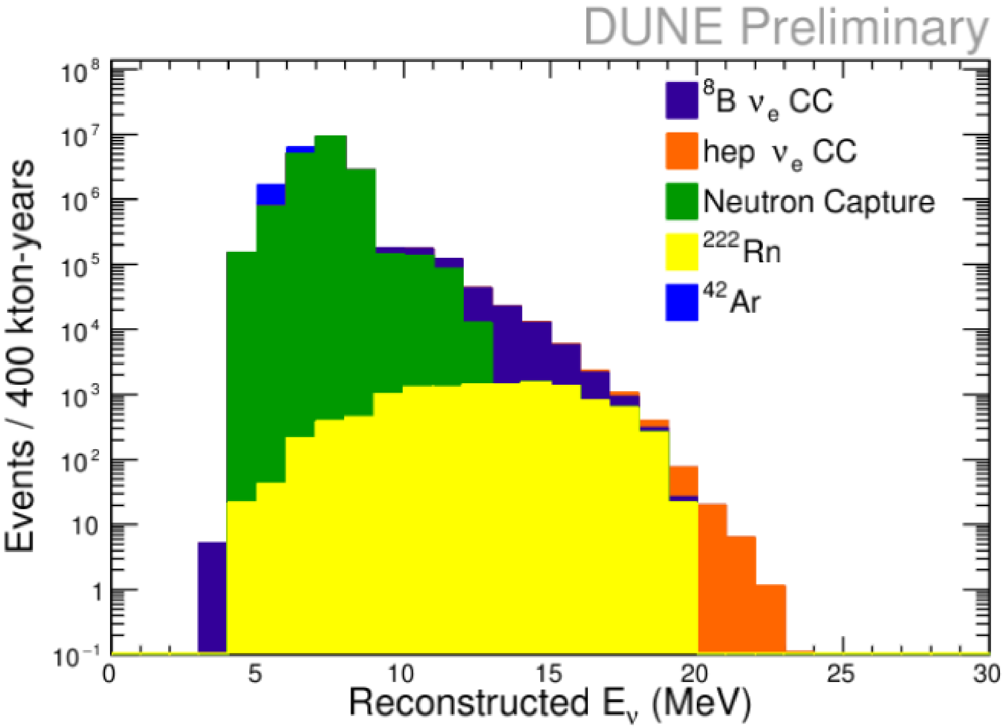
- Reconstruct events calorimetrically – sum all energy deposited in electron tracks and gamma cascade blips
  - PDS gives t_0 for electron lifetime correction and fidicialziation
- We achieve 9-12% resolution on neutrino energy throughout the solar energy range

Solar neutrinos in DUNE

- Solar ^{8}B flux is enormous – high signal yield of several tagged events / day / kt

- But also huge background rate, we need to understand what energy range to study
  - Neutron capture drowns events below 9 MeV

Bkg	Rate
$^{40}Ar(n,\gamma)$	44 / t-yr
$^{36}Ar(n,\gamma)$	0.62 / t-yr
$^{40}Ar(\alpha,\gamma)$	0.051 / t-yr



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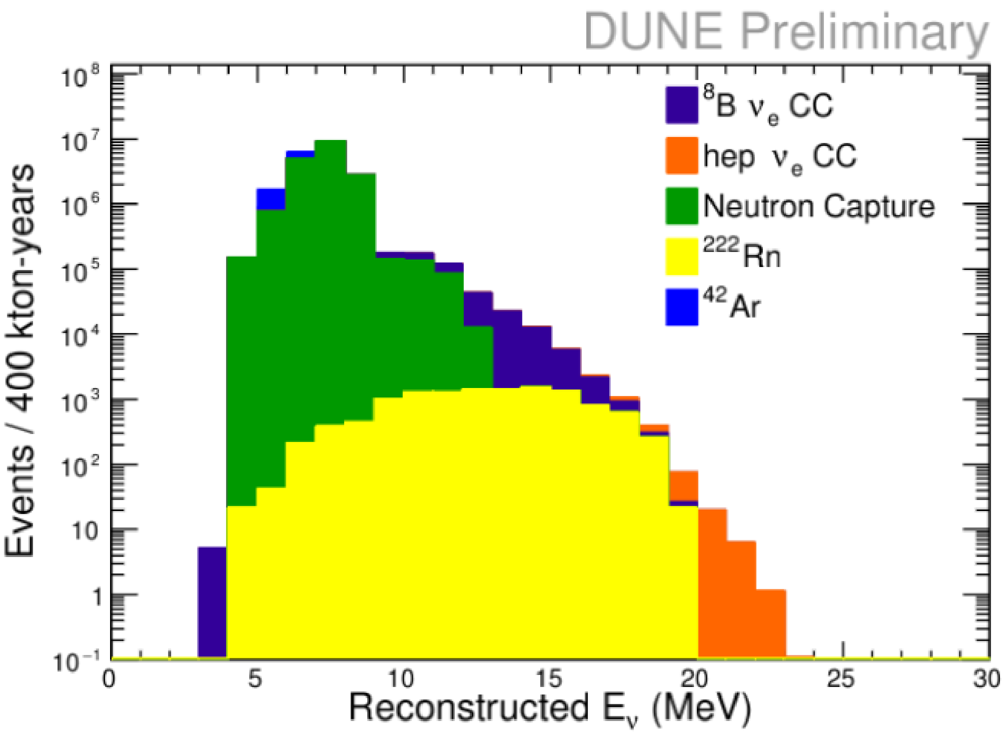
- DUNE will measure the yet-unobserved hep flux
  - 3He + p fusion
  - Low flux, high energy
- 5σ discovery within first 20 kt-yrs of exposure
- Unique measurement for DUNE achieved early in detector running



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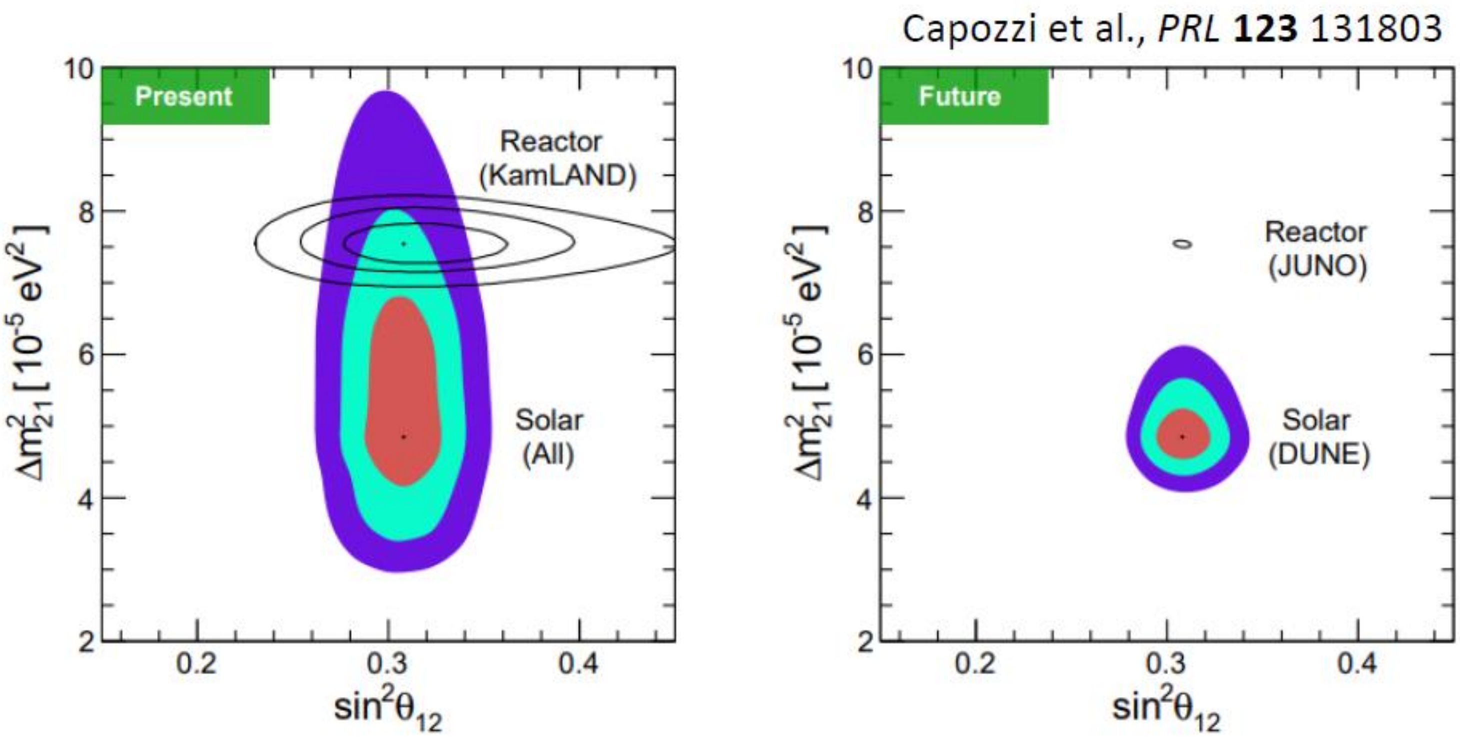
Next-generation sensitivity to solar oscillations



- DUNE has favorable sensitivity for measuring Δm^2_{21} through day/night effect – a partial regeneration of the ν_e flux due to matter effects in Earth
  - With these parameters, DUNE will measure all neutrino mixing parameters
- May push current tension between SK/SNO and KamLAND to > 5 σ and determine Δm^2_{21} measurement to as good as 1%

See Gleb Sinev's talk for more

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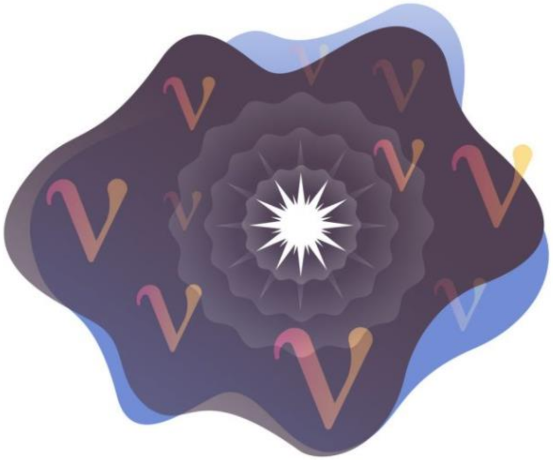
Summary

- Beyond precision measurements of neutrino mixing parameters, DUNE will provide large datasets of astrophysical neutrinos
- Argon detectors uniquely sensitive to ν_e flux which facilitates studies of physics not accessible with other detection technologies
- Large mass and excellent tracking allows efficient reconstruction and channel selection
- Further understand neutrino properties from solar spectra and oscillations



DEEP UNDERGROUND NEUTRINO EXPERIMENT