Low-Energy Physics Opportunities with DUNE

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Snowmass CSS
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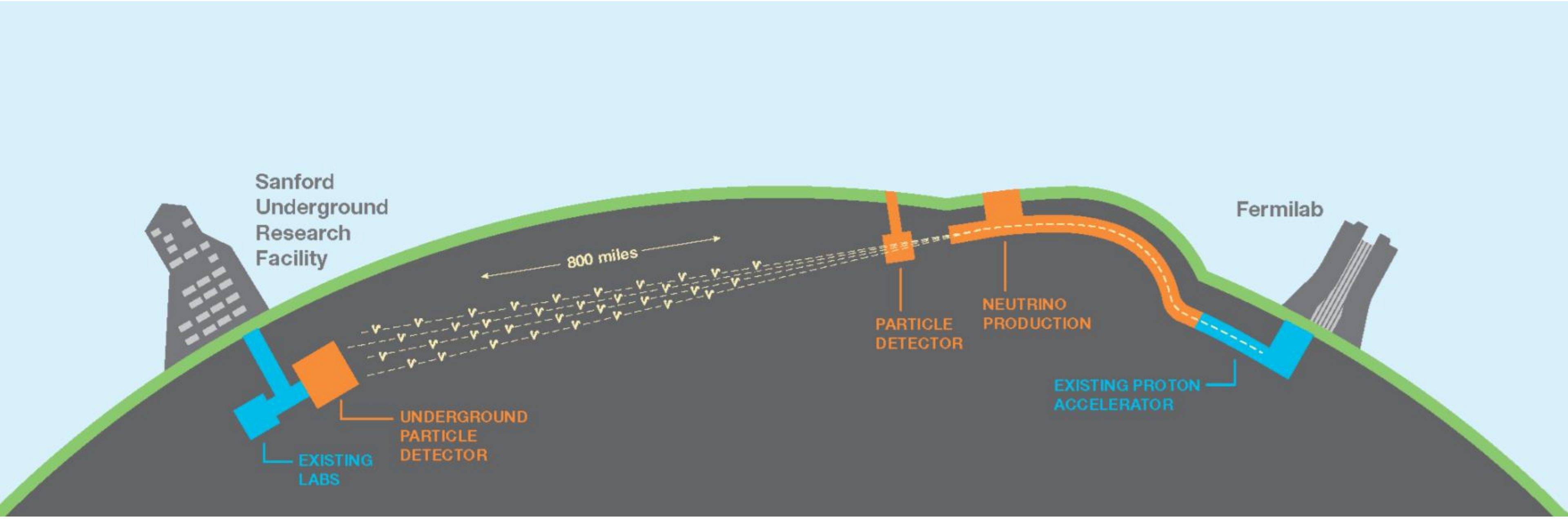
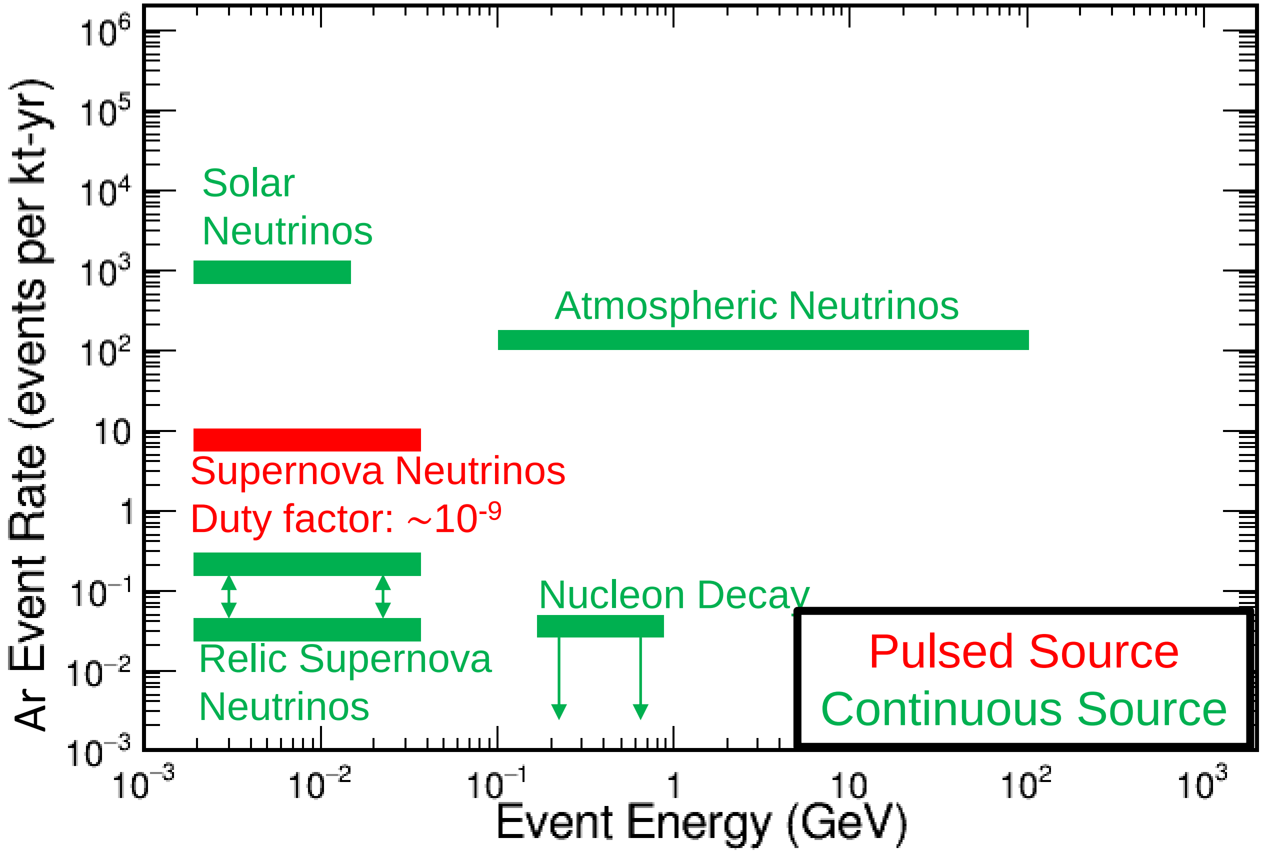
The Deep Underground Neutrino Experiment



- Large, 40 kton (fiducial) mass with 4300 mwe overburdern makes DUNE ideal for searching for rare astroparticle phenomena
  - Assume in this talk a DUNE with four liquid argon 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

Focus on low-energy physics

Astroparticle events in underground detectors

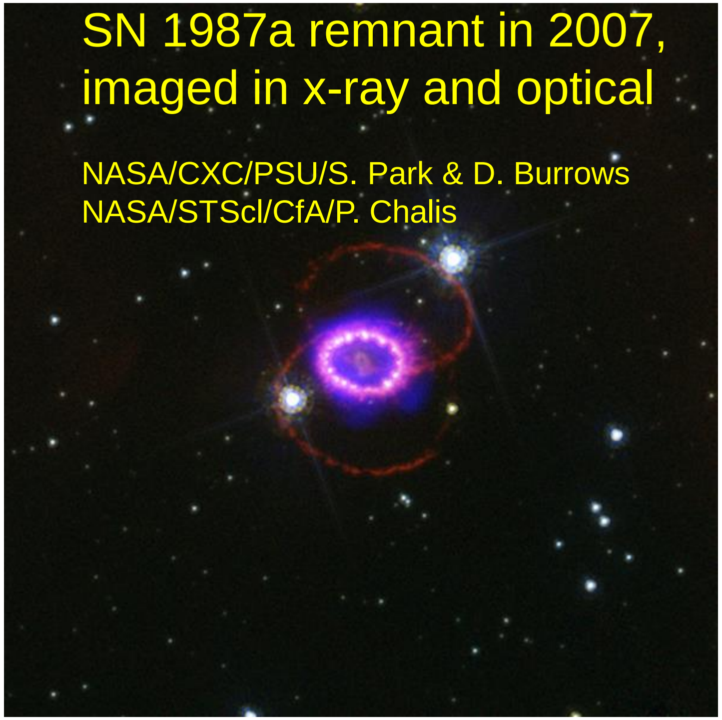


- As DUNE is an underground experiment, potential for astroparticle measurements spanning several orders of magnitude of energy and event rate
- Understanding the < 100 MeV-scale astrophysical neutrino flux a primary physics driver for the DUNE experiment

A core-collapse supernova

- When a star collapses, it releases its gravitational binding energy (~10^{53} ergs)
  - as neutrinos (99%)
  - as light (0.01%)
  - as KE of ejected matter (1%)
- Burst of neutrinos lasts ≈ 10 seconds
- 1-3 such events in our galaxy per century

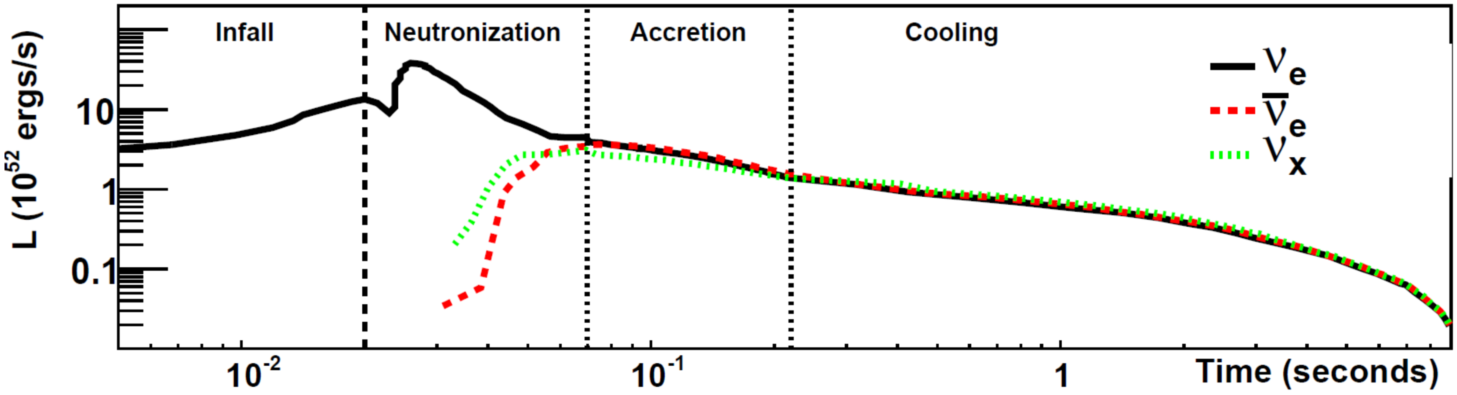
- A single event would teach us:
- Astrophysics
  - Core-collapse mechanism, neutronization rate, neutrino diffusion, black hole formation, nuclear density in neutron star
- Particle physics
  - Neutrino magnetic moment, absolute mass, oscillations, sterile neutrinos



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

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

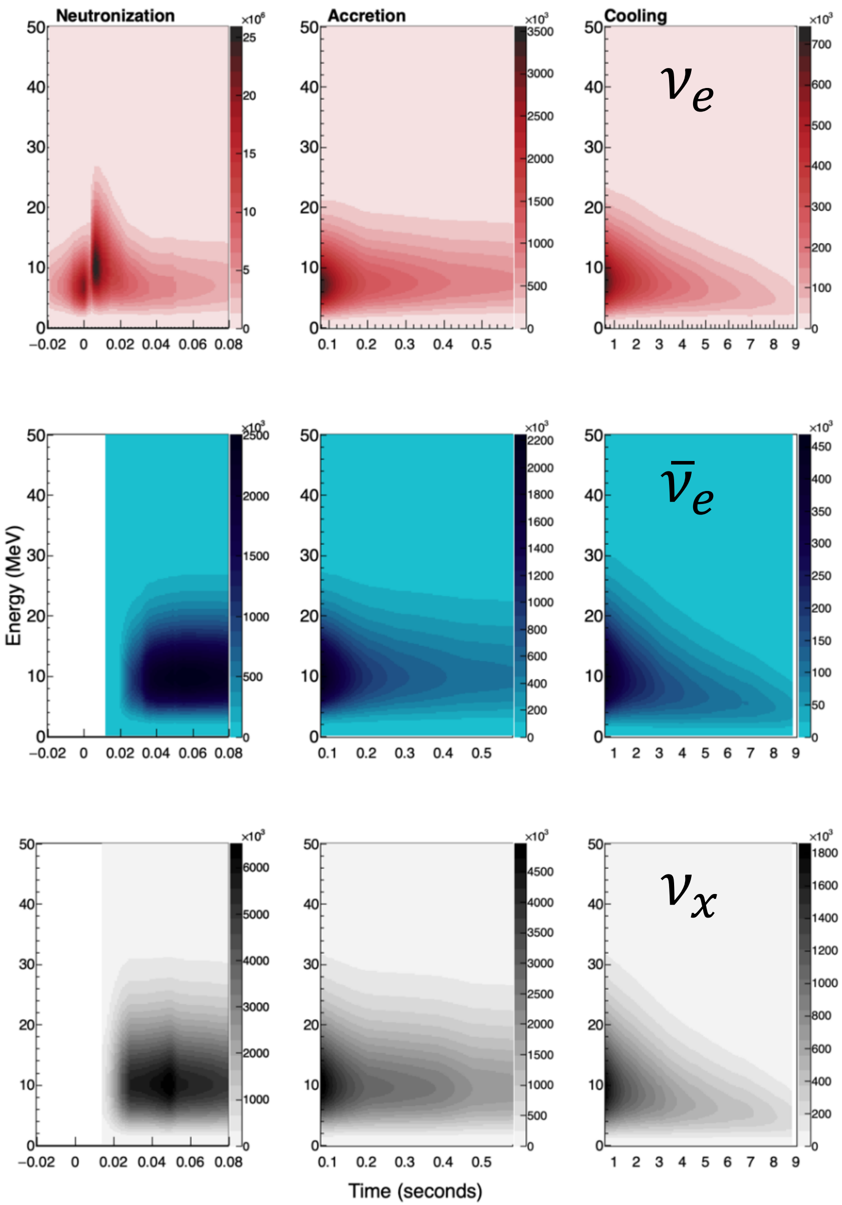
Neutrinos emission in a supernova



- 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



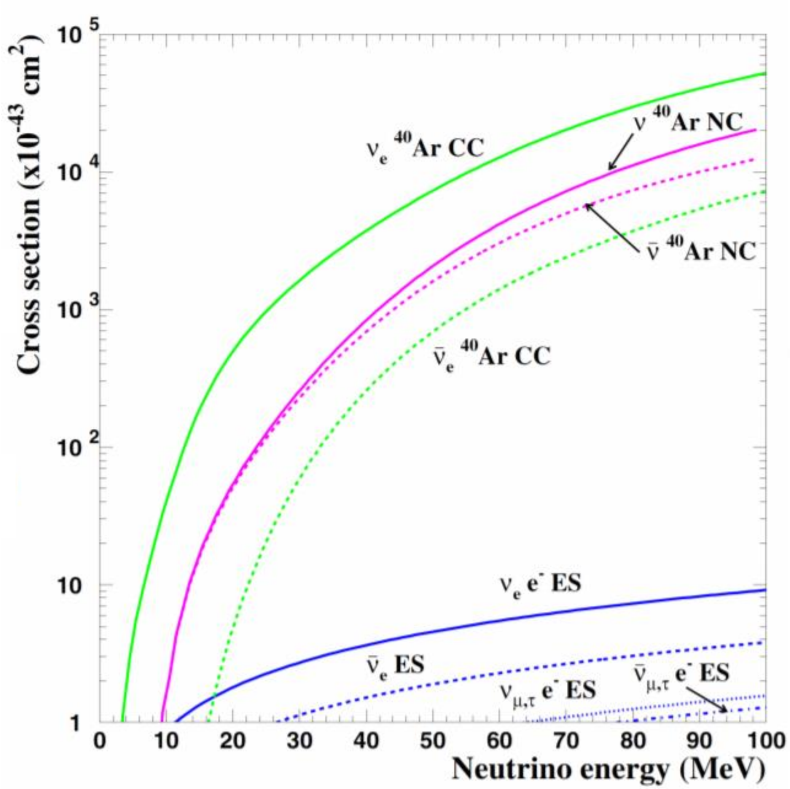
- We observe a flux depending on three variables – energy, time, and flavor
- Beyond precise reconstruction of kinematics, we must probe all flavors to fully understand the core collapse
  - ν_e – observe neutronization
  - ν_e + $\bar{\nu}_e$ CC – good for calorimetry
  - ν_x NC – no oscillation ambiguity

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)

Interaction channels in argon



- Charged current interactions on Ar sensitive only to ν_e flux
  - $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ — $E_\nu > 1.5$ MeV
  - $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ — $E_\nu > 7.5$ MeV
- Neutral current interactions on Ar
  - $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$
  - $\bar{\nu}_x + {}^{40}Ar \rightarrow \bar{\nu}_x + {}^{40}Ar^*$
  - } $E_\nu > 1.5$ MeV
- Neutrino scattering off electrons
  - $\nu_x + e^- \rightarrow \nu_x + e^-$
  - $\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$

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

ν-e 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

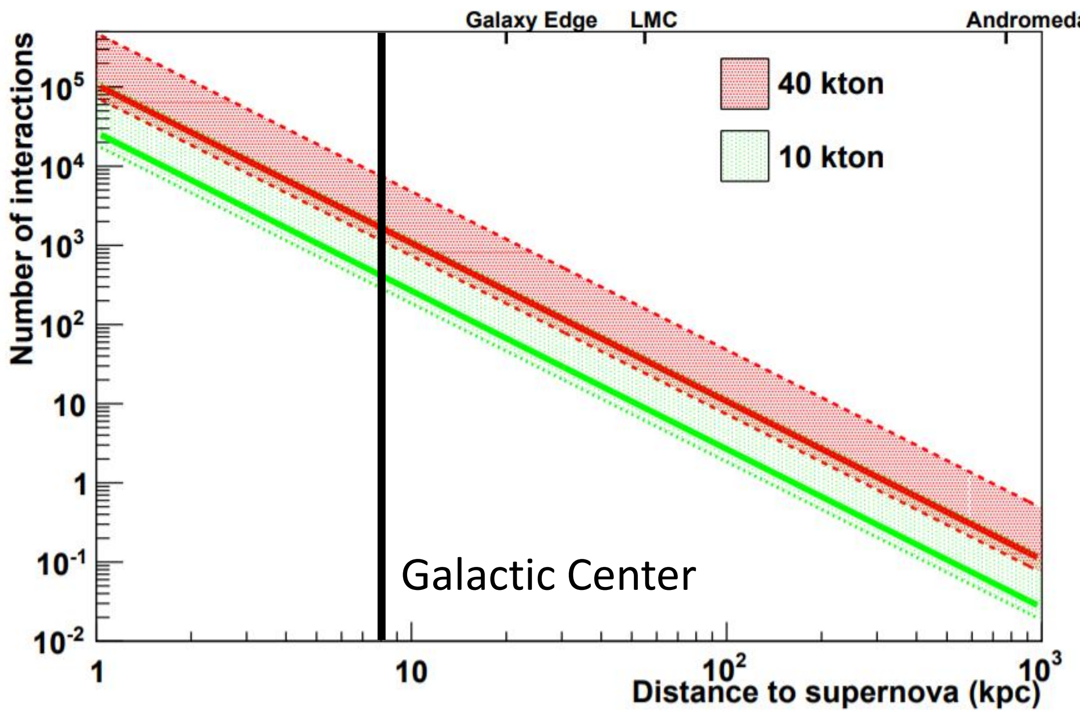
Channel	Events "GKVM" model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

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

But there are large theoretical uncertainties on the total rate
Solid: Garching model[1]

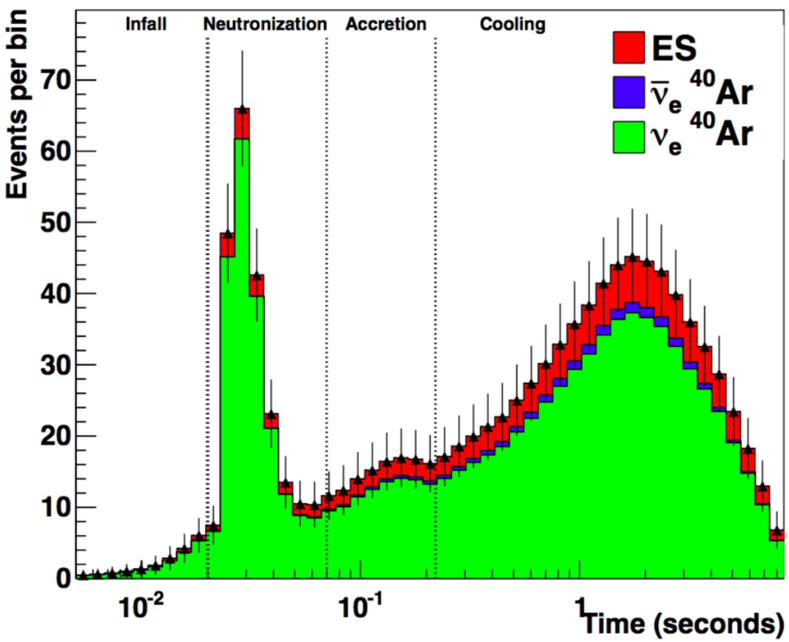
Would see few thousand events from galactic star or several dozen events from the LMC for efficient triggering

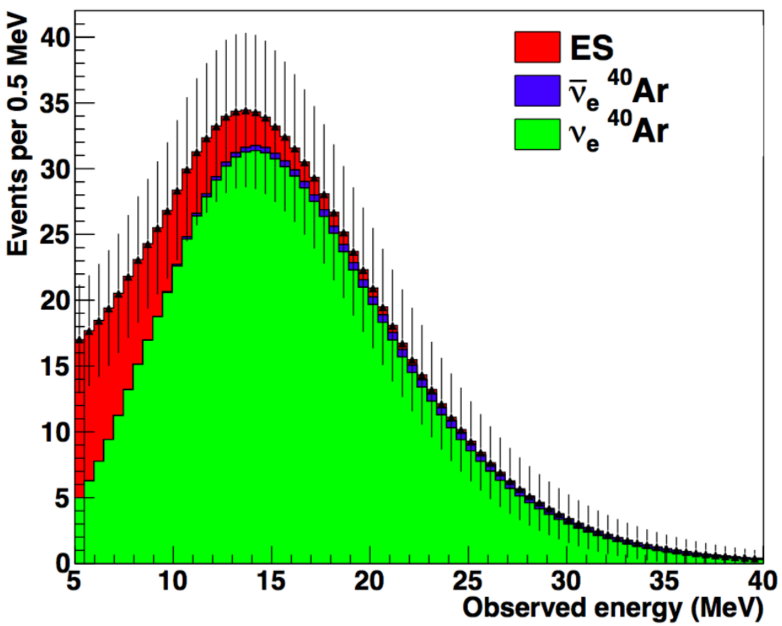
Andromeda supernova would produce ≈ 1 event



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

Expected spectrum of events



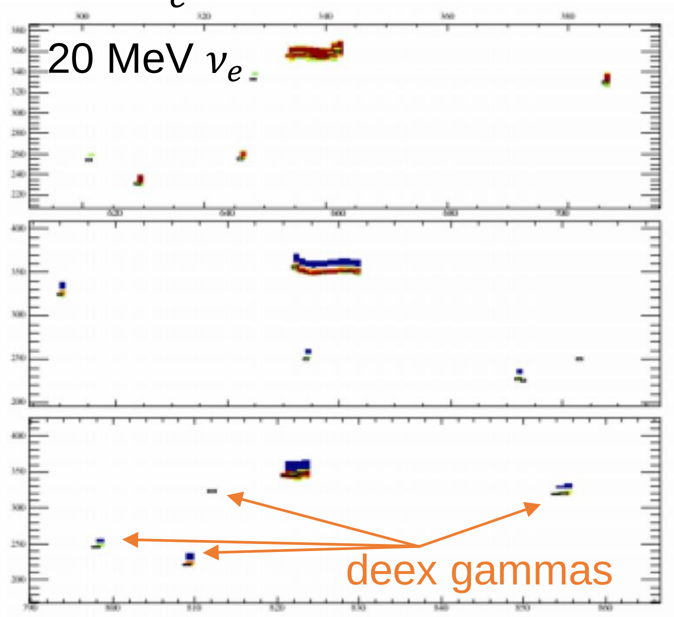


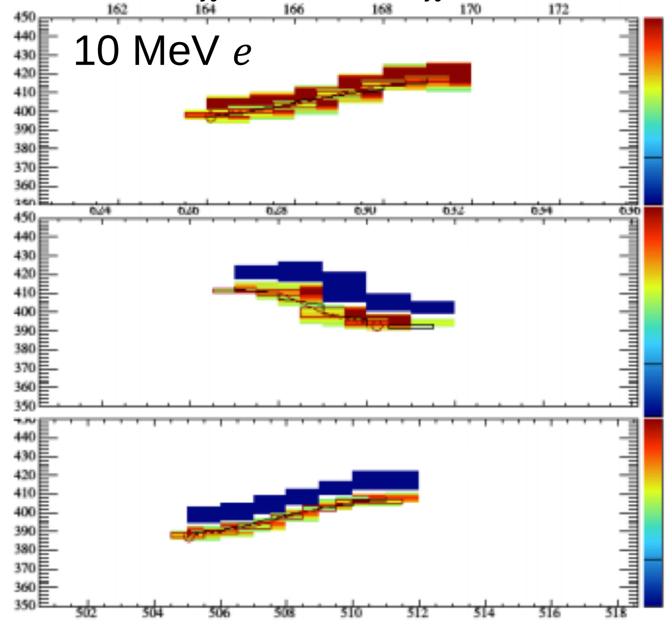
- We are most sensitive to the ν_e CC interaction – but we will observe others
  - Unique to DUNE, other detectors largely sensitive to anti-ν_e from IBD
- We can further exploit the reconstruction capabilities of the DUNE TPC to separate the flavors

Isolating interaction channels in DUNE

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

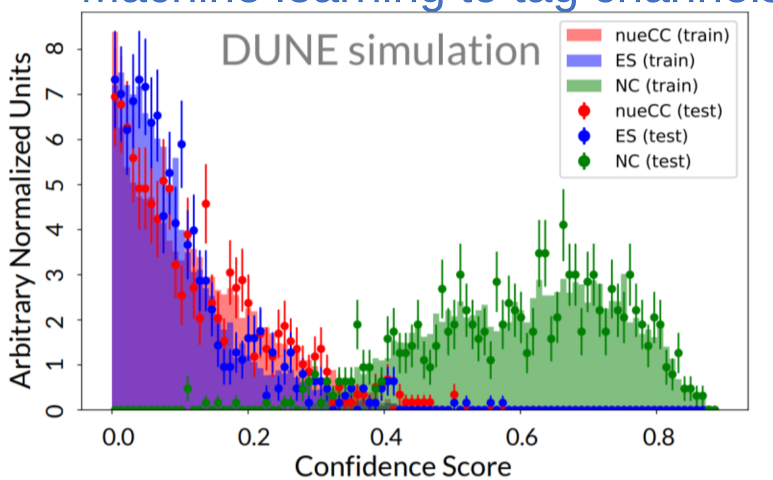
ES: $\nu_x + e^- \rightarrow \nu_x + e^-$





- 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



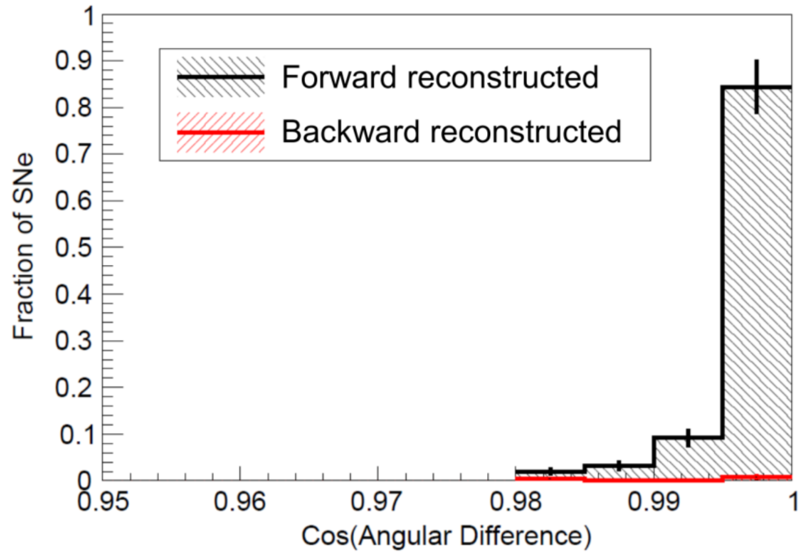
Predicting supernova direction with DUNE

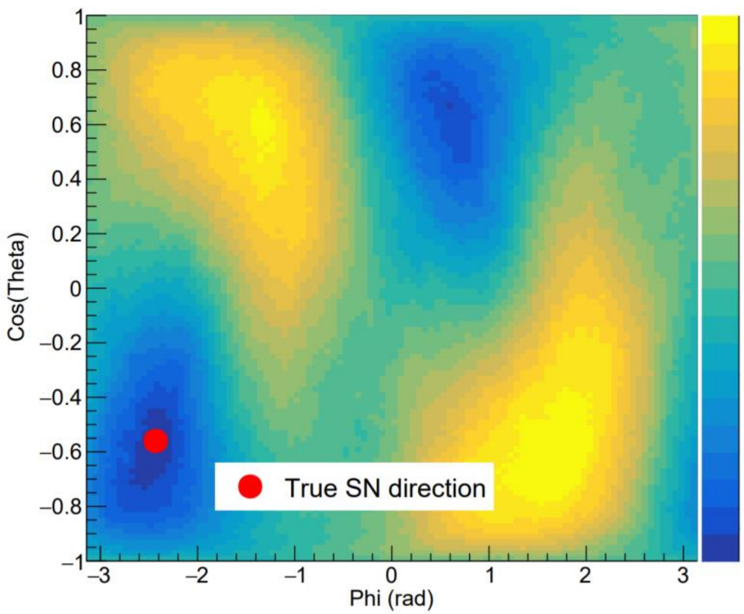
1987 supernova, Anglo-Australian Observatory

- 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

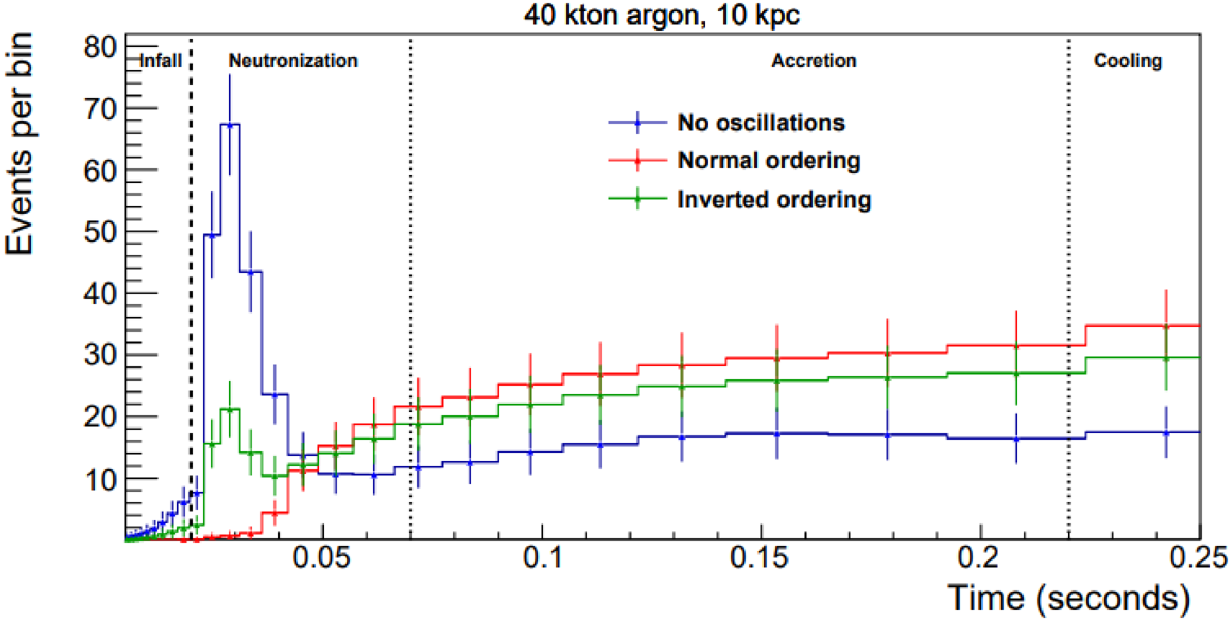
- Simulated supernova at 10 kpc with the Garching model
  - 260 $\nu - e$ scattering events
    - Low-Q^2 → great pointing
  - 3350 ν_e CC events
    - ≈ isotropic





- 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 ≈ 4.5 deg

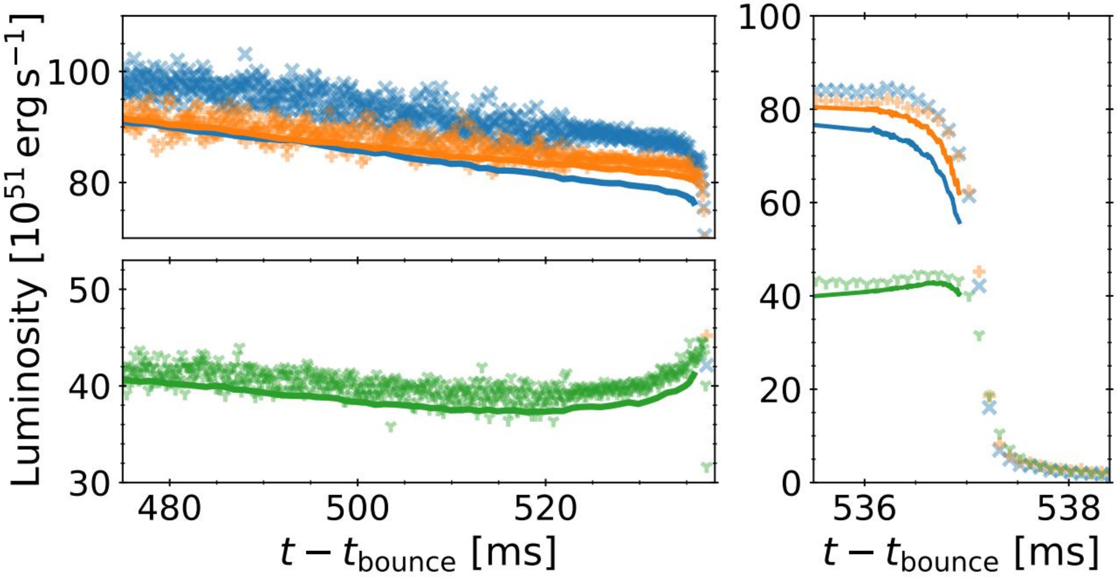
Observing the neutronization burst



- 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

Gullin, O'Connor, Wang, Tseng, *Astrophys. J.* **926** 212 (2022)



- The neutrino signal can discriminate between neutron star and black hole forming supernova
- During black hole formation, an event horizon is created about 0.5s after the start of the collapse quickly quenching the neutrino flux
- Subsequent tail of neutrino flux arising from neutrino scattering between source and Earth

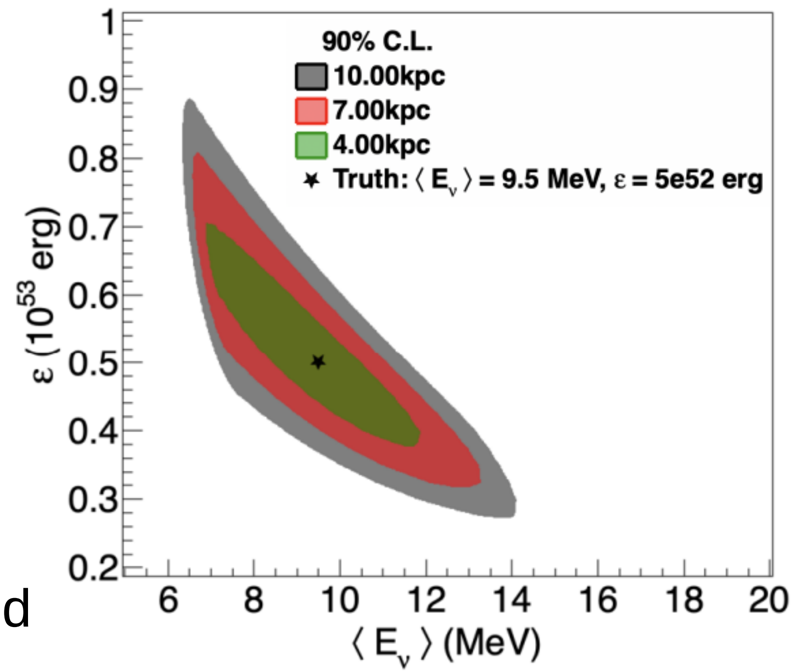
Testing astrophysical models with ν spectrum

- 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

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

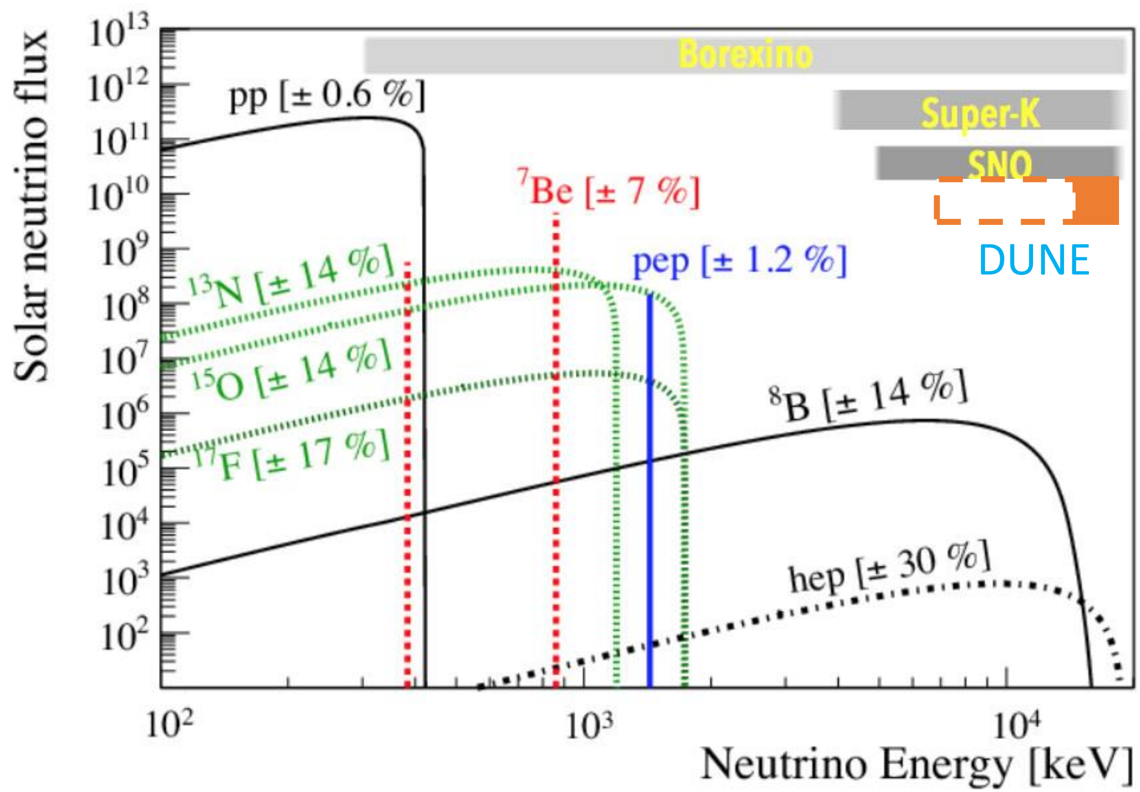
Different for each flavor – DUNE needed to test ν_e!

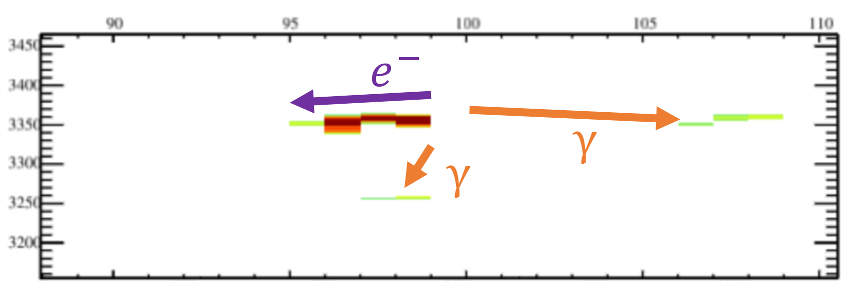
- DUNE can constrain the three relevant parameters
- Provides a test of these supernova transport models
- A measurement at 10 kpc would constrain current models
  - Current understanding of neutrino scattering model limits constraint – theory and experimental input needed



Neutrinos produced in solar fusion

- The sun produces a large flux of neutrinos which may interact in DUNE
- Dominant interaction channel is CC
- Threshold set by large background rate at several MeV
- ^{8}B and hep fluxes are observable

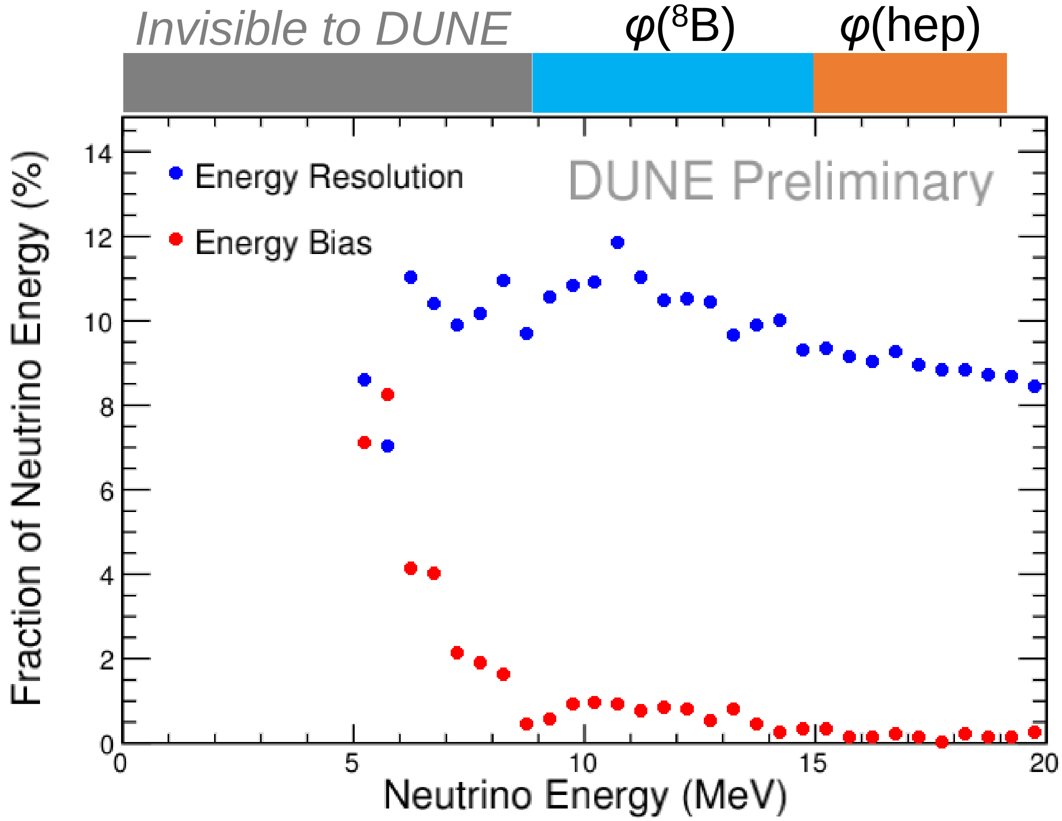




$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

CC channel dominates signal: leaves a ≈10 MeV electron and gamma cascade in detector

Reconstructing solar neutrinos



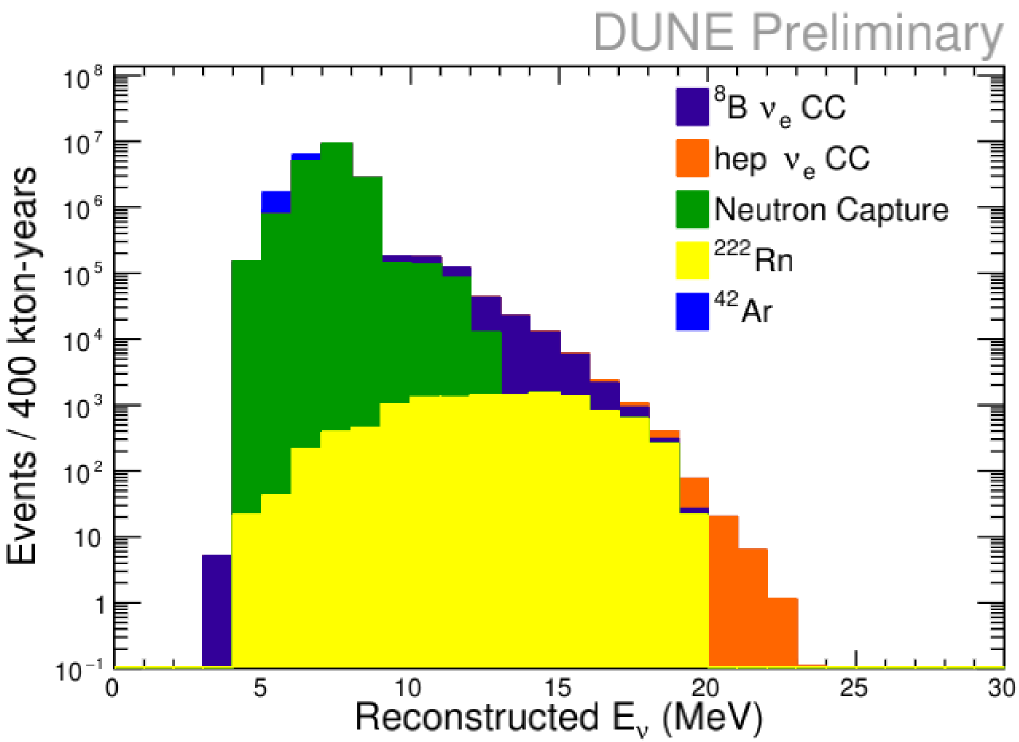
- ❑ Reconstruct events calorimetrically – sum all energy deposited in electron track and gamma cascade blips
  - PDS gives t_0 for electron lifetime correction and fiducialization
- ❑ We achieve 9-12% resolution on neutrino energy throughout the solar energy range

Solar neutrinos in DUNE

- Solar ^{8}B + hep flux is enormous – 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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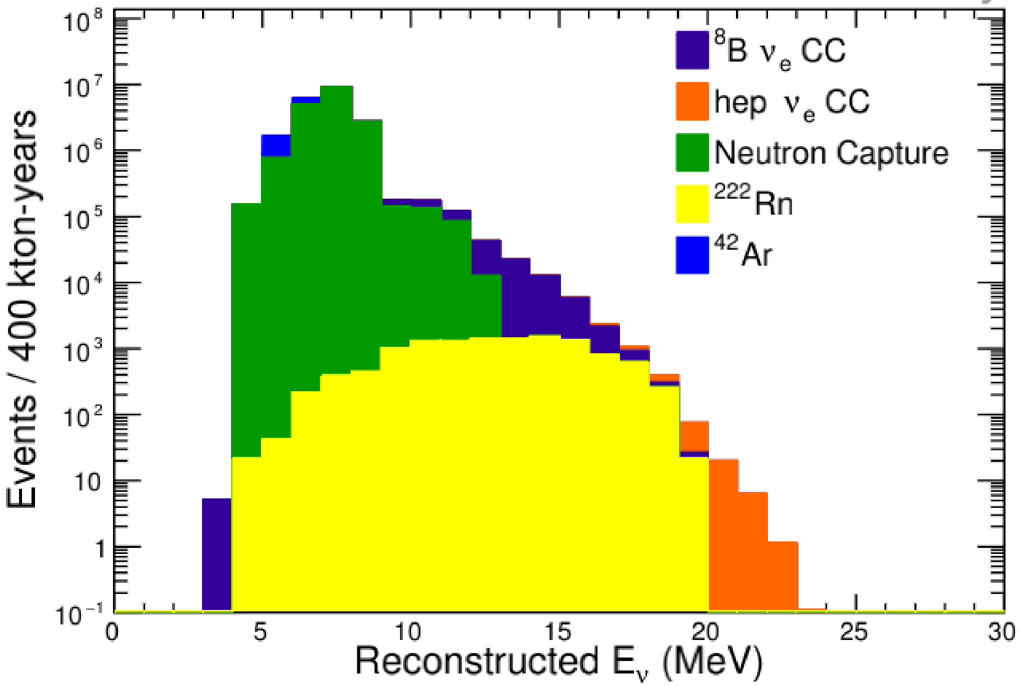
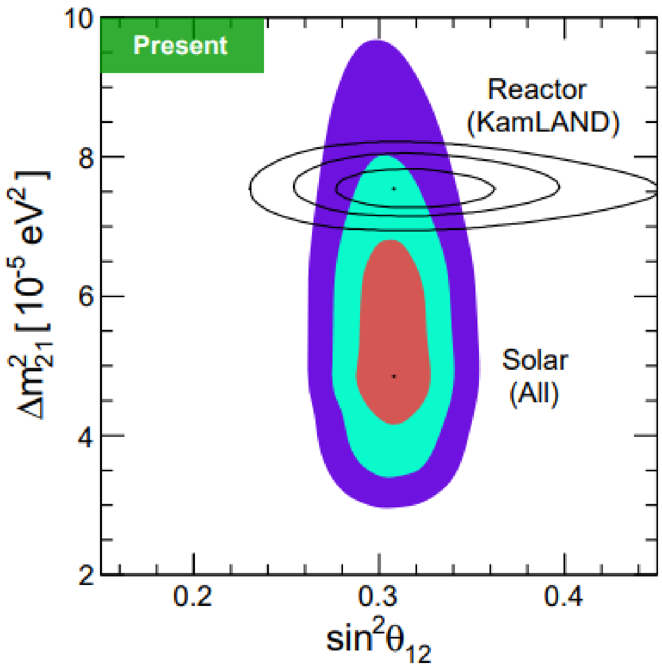
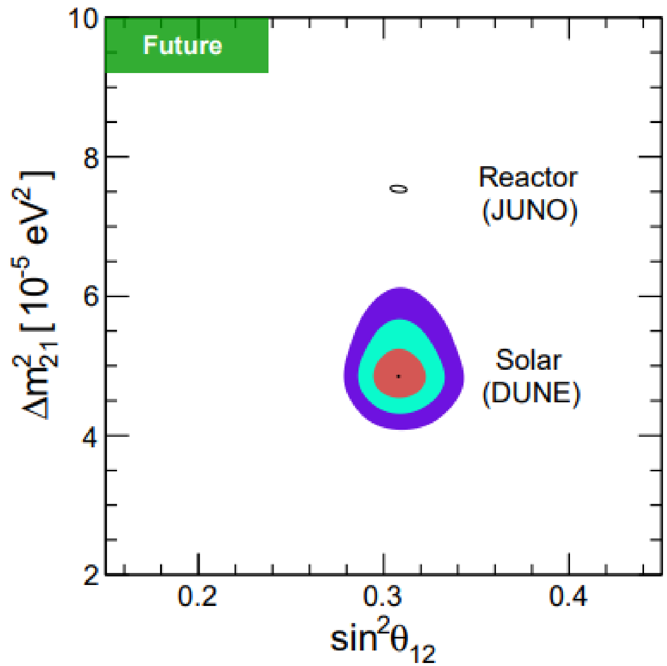
- DUNE will measure the yet-unobserved hep flux
  - $^{3}He + p$ fusion
  - Low flux, high energy
- 5σ discovery within first 20 kt-yrs of exposure



Future sensitivity to solar oscillations

Capozzi et al., PRL **123** 131803

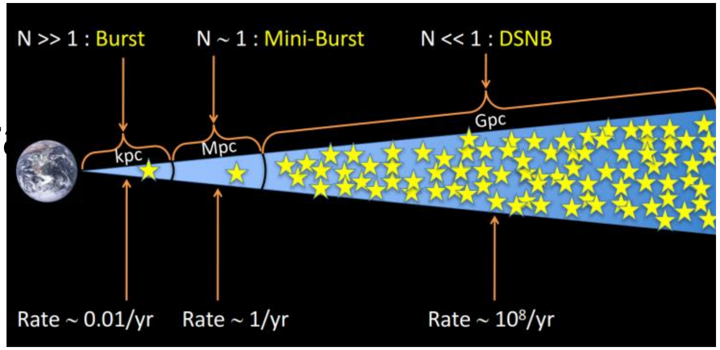




- DUNE has favorable sensitivity for measuring Δm^2_{21} from day/night effect – a partial regeneration of the ν_e flux due to matter effects in Earth
  - With these parameters, DUNE will measure all neutrino mixing parameters
- May push current tension between SK/SNO and KamLAND to 5σ
- DUNE working to publish our own sensitivity calculation

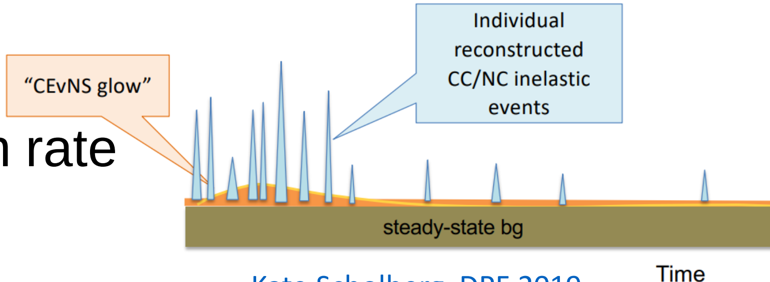
Future topics for DUNE engagement

- Diffuse supernova neutrinos
  - Galactic supernovae: huge event rate but r
  - Can search for steady stream of neutrinos produced by high rate of far-off supernova
  - Meager but unique sensitivity to ν_e flux



John Beacom, TAUP 2011

- "CEvNS glow" from supernova neutrinos
  - CEvNS – low energy but huge interaction rate
  - Visible from increased PDS activity
  - NC process sensitive to ν_x!



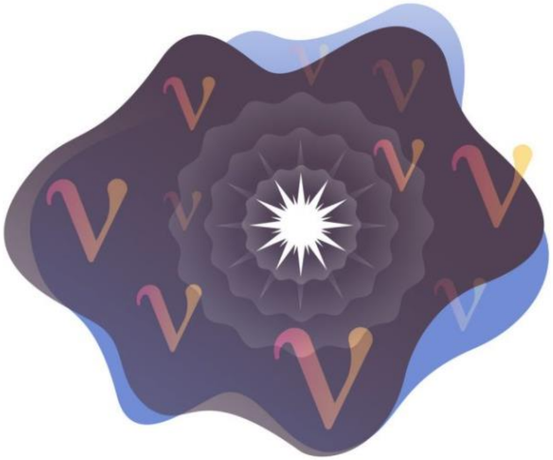
Kate Scholberg, DPF 2019

- And searches for new physics and better understanding of astrophysics
  - Neutrino properties: neutrino decay, magnetic moment, dark photons …
  - Astrophysics: SASI, properties of quark matter, shock wave …

Re-imagining DUNE's role in the cosmic frontier

- Investment in a DUNE Module of Opportunity would be game-changing for low-energy physics
- Extent of program limited by background rates
  - Rate reduced for LAr TPC by shielding, increased photodetector coverage, fiducialization, and ^{39}Ar depleted argon
- Potential for 100-keV thresholds would turn DUNE into a kt-scale powerhouse
  - Dark matter searches + angular modulation
  - $0\nu\beta\beta$ searches
  - Much better resolution of CEvNS glow from reduced ^{39}Ar decay
  - Improved solar neutrino measurements
- All this possible without losing sensitivity to neutrino mixing parameters

Summary



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

- Large physics potential early in the experiment's running – discovery of hep solar neutrinos and 100s-1000s of events from any galactic supernova with just 10 kt of argon even before arrival of the first beam pulse

DEEP UNDERGROUND
NEUTRINO EXPERIMENT