Low-Energy Physics Opportunities with DUNE

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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
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 ($\sim 10^{53}$ ergs)
  - as neutrinos (99%)
  - as light (0.01%)
  - as KE of ejected matter (1%)

- Burst of neutrinos lasts $\approx 10$ 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

$\approx 20 \bar{\nu}_e$ 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 $\nu_e$
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
  - $\nu_e$ – observe neutronization
  - $\nu_e + \bar{\nu}_e$ CC – good for calorimetry
  - $\nu_\chi$ NC – no oscillation ambiguity

DUNE uniquely sensitive to $\nu_e$ component!

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
<th>$\nu_\chi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUNE</td>
<td>89%</td>
<td>4%</td>
<td>7%</td>
</tr>
<tr>
<td>SK$^1$</td>
<td>10%</td>
<td>87%</td>
<td>3%</td>
</tr>
<tr>
<td>JUNO$^2$</td>
<td>1%</td>
<td>72%</td>
<td>27%</td>
</tr>
</tbody>
</table>

Interaction channels in argon

- **Charged current interactions on Ar** sensitive only to $\nu_e$ flux
  
  \[
  \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \quad \text{E}_\nu > 1.5 \text{ MeV}
  \]
  \[
  \bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}^* \quad \text{E}_\nu > 7.5 \text{ MeV}
  \]

- **Neutral current interactions on Ar**
  
  \[
  \nu_x + ^{40}\text{Ar} \rightarrow \nu_x + ^{40}\text{Ar}^* \quad \text{E}_\nu > 1.5 \text{ MeV}
  \]
  \[
  \bar{\nu}_x + ^{40}\text{Ar} \rightarrow \bar{\nu}_x + ^{40}\text{Ar}^* \]

- **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
- $\nu$-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 \( \approx 4000 \) neutrinos in 40 kton of argon.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events “GKVM” model</th>
</tr>
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<tbody>
<tr>
<td>( \nu_e + ^{40} \text{Ar} \rightarrow e^- + ^{40} \text{K}^* )</td>
<td>3350</td>
</tr>
<tr>
<td>( \bar{\nu}_e + ^{40} \text{Ar} \rightarrow e^+ + ^{40} \text{Cl}^* )</td>
<td>160</td>
</tr>
<tr>
<td>( \nu_x + e^- \rightarrow \nu_x + e^- )</td>
<td>260</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3770</strong></td>
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Most sensitive to the \( \nu_e \) 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 \( \approx 1 \) event

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Expected spectrum of events

- We are most sensitive to the $\nu_e$ CC interaction – but we will observe others
  - Unique to DUNE, other detectors largely sensitive to anti-$\nu_e$ 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 $\approx$ 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-$Q^2 \rightarrow$ great pointing
  - 3350 $\nu_e$ CC events
    - $\approx$ isotropic

- TPC allows flavor discrimination so the $\nu_e$ 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
Observing the neutronization burst

- An intense flux $\nu_e$ of is produced from neutronization early in the collapse – DUNE can uniquely search for this peak due to dominant $\nu_e$ CC sensitivity

- But, the $\nu_e$ content from neutronization depends on several unknowns
  - Neutrino mass ordering
  - Collective oscillations from $\nu$-$\nu$ 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 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 $\nu$ 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

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

- 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

Different for each flavor – DUNE needed to test $\nu_e$!
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
- $^8\text{B}$ and hep fluxes are observable

CC channel dominates signal: leaves a $\approx 10$ MeV electron and gamma cascade in detector

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

<table>
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<th>Bkg</th>
<th>Rate</th>
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<tr>
<td>$^{40}$Ar(n,y)</td>
<td>44 / t-yr</td>
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<td>0.62 / t-yr</td>
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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

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**Graph:**

- Events / 400 kton-years vs. Reconstructed $E_\nu$ (MeV)
- $^8$B $\nu_e$ CC
- hep $\nu_e$ CC
- Neutron Capture
- $^{222}$Rn
- $^{42}$Ar
Future sensitivity to solar oscillations

- DUNE has favorable sensitivity for measuring $\Delta m_{21}^2$ from day/night effect – a partial regeneration of the $\nu_e$ 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 $5\sigma$
- DUNE working to publish our own sensitivity calculation

![Graph showing sensitivity to solar oscillations with DUNE compared to other experiments.](image)
Future topics for DUNE engagement

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

- “CEvNS glow” from supernova neutrinos
  - CEvNS – low energy but huge interaction rate
  - Visible from increased PDS activity
  - NC process sensitive to $\nu_x$!

- 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 mixing parameters, DUNE will provide large datasets of astrophysical neutrinos.
- Argon detectors uniquely sensitive to $\nu_e$ 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.
- 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.