Supernova and Solar Neutrinos with DUNE

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For the DUNE Collaboration

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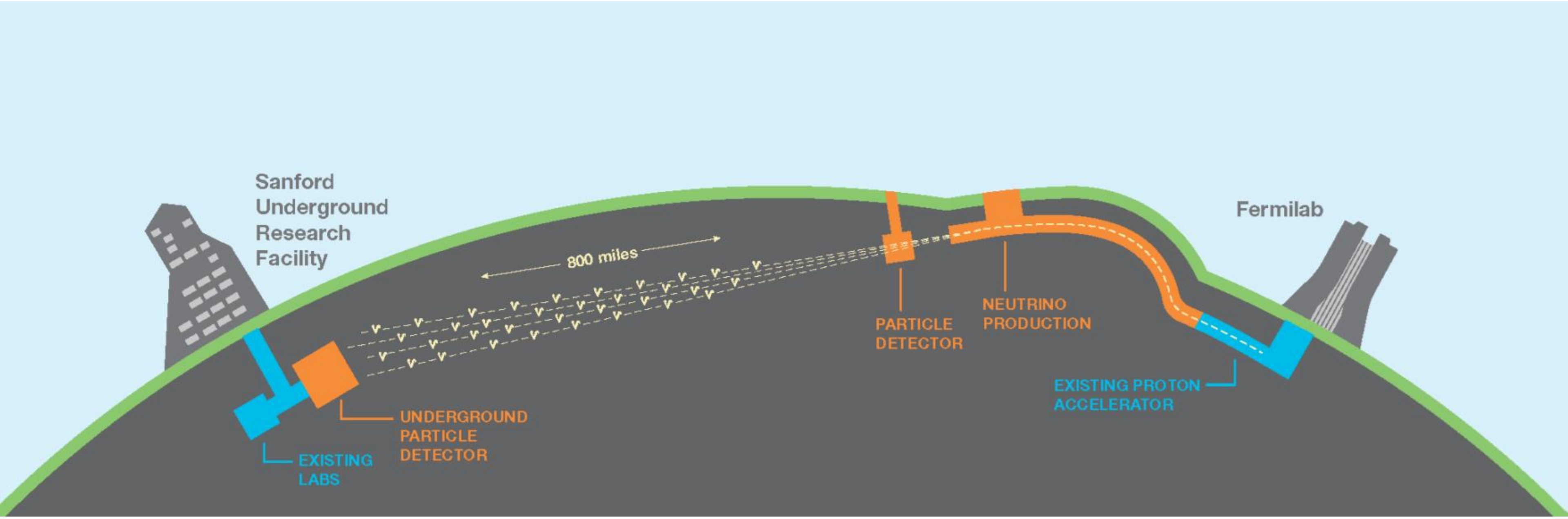
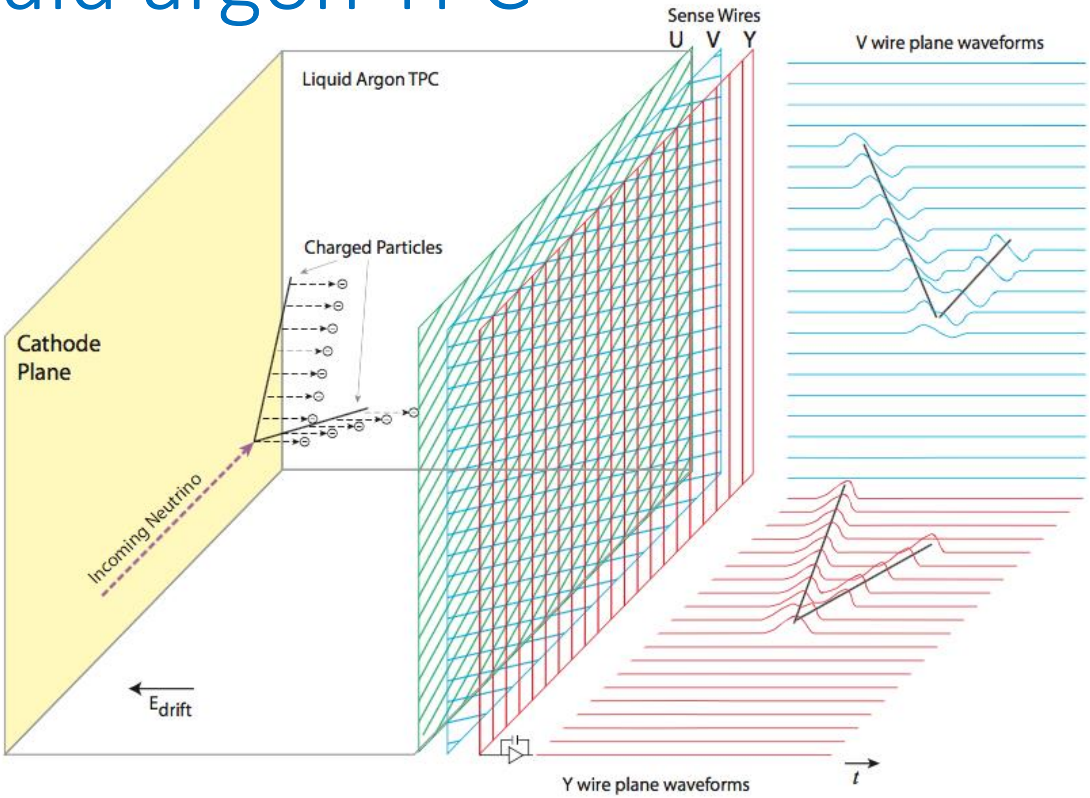
The Deep Underground Neutrino Experiment



- 40 kton (fiducial) liquid argon time projection chamber (LAr TPC)
- 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

Focus on astroparticle measurements today

Liquid argon TPC

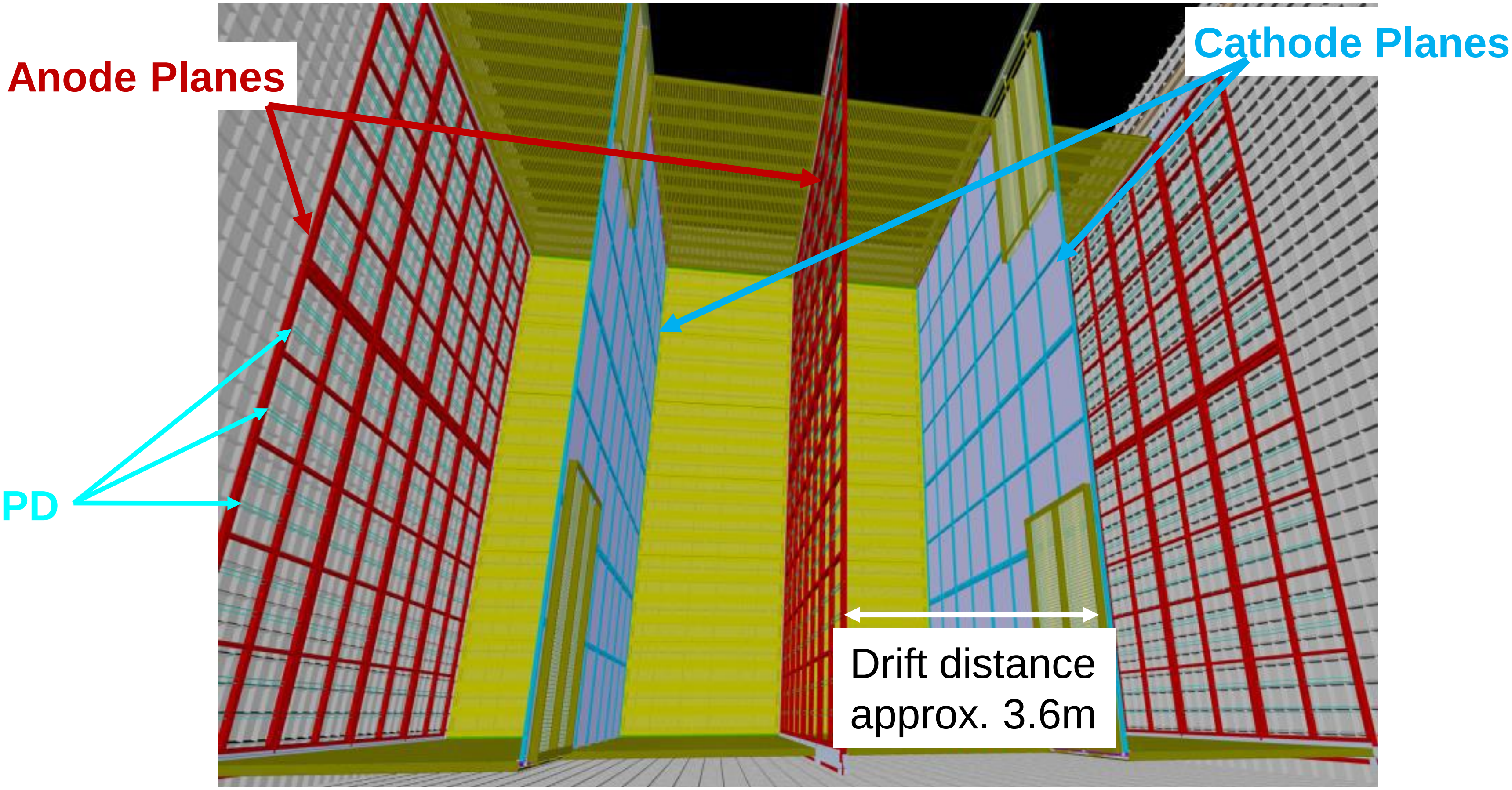


Neutrino experiments using LAr TPC's with data:

LArIAT
ArgoNeuT
MicroBooNE
ICARUS
ProtoDUNE-SP

- 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 the electron drift-time
- Resolution is sub-cm in each dimension for an entire 10 kton module

DUNE photon detection system (PDS)

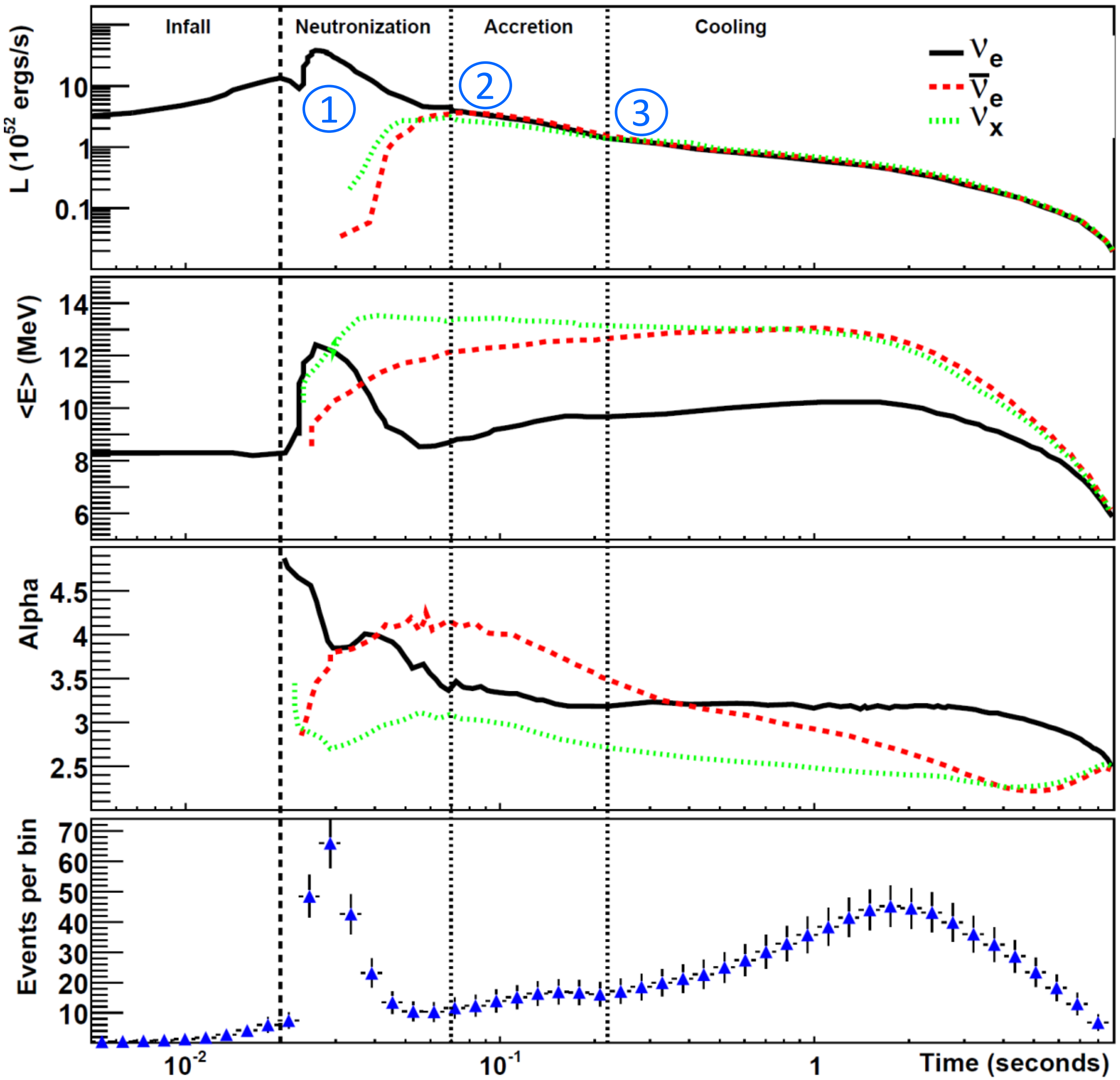


- Unfortunately, A LAr TPC can not determine the interaction time, t_0
- We will implement a PDS to determine event timing from an optical flash
  - Argon also has a naturally high scintillation yield, ≈40000 photons / MeV
- PD design uses a wave-guide read by a SiPM designed specifically for DUNE

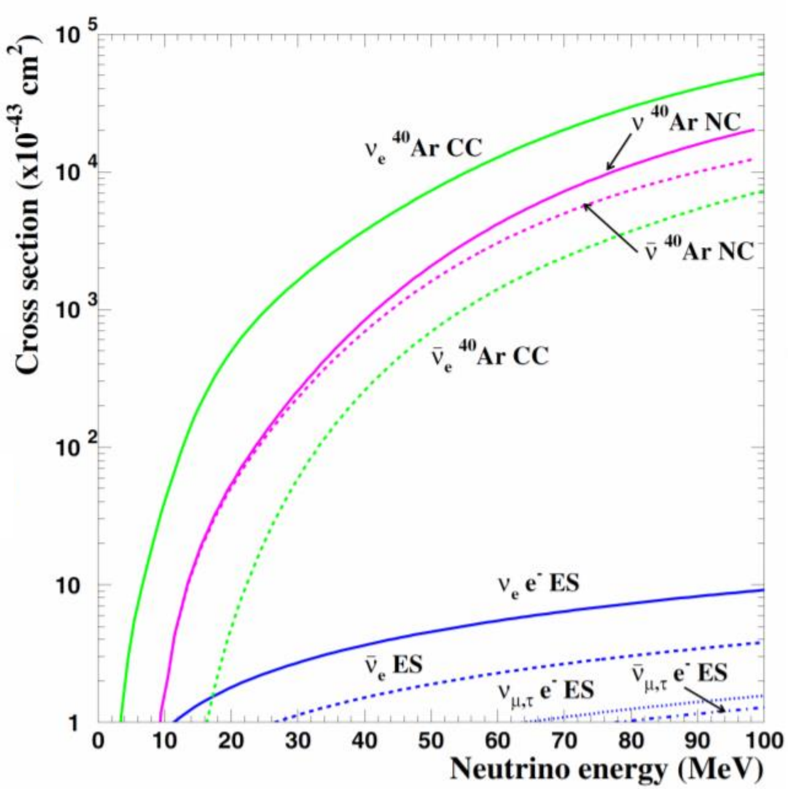
Neutrino production in supernovae

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



Supernova signals 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

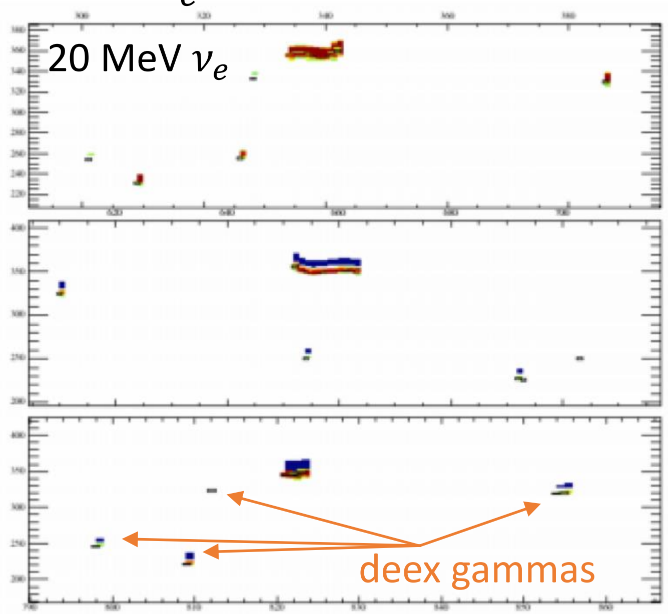
NC events create a cloud of deexcitation gamma blips

CC events give an electron in a deexcitation cloud

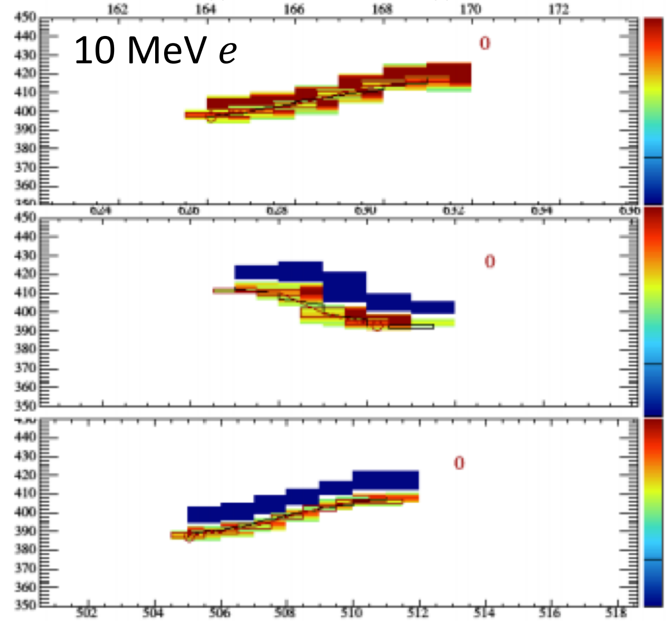
ν-e scatters produce a lone electron pointing away from the supernova

Supernova events in DUNE

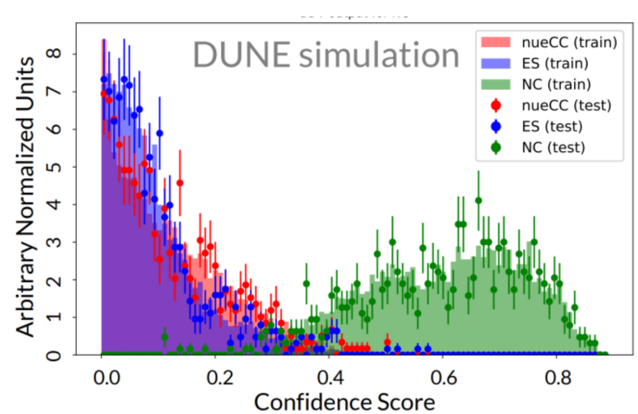
CC: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



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



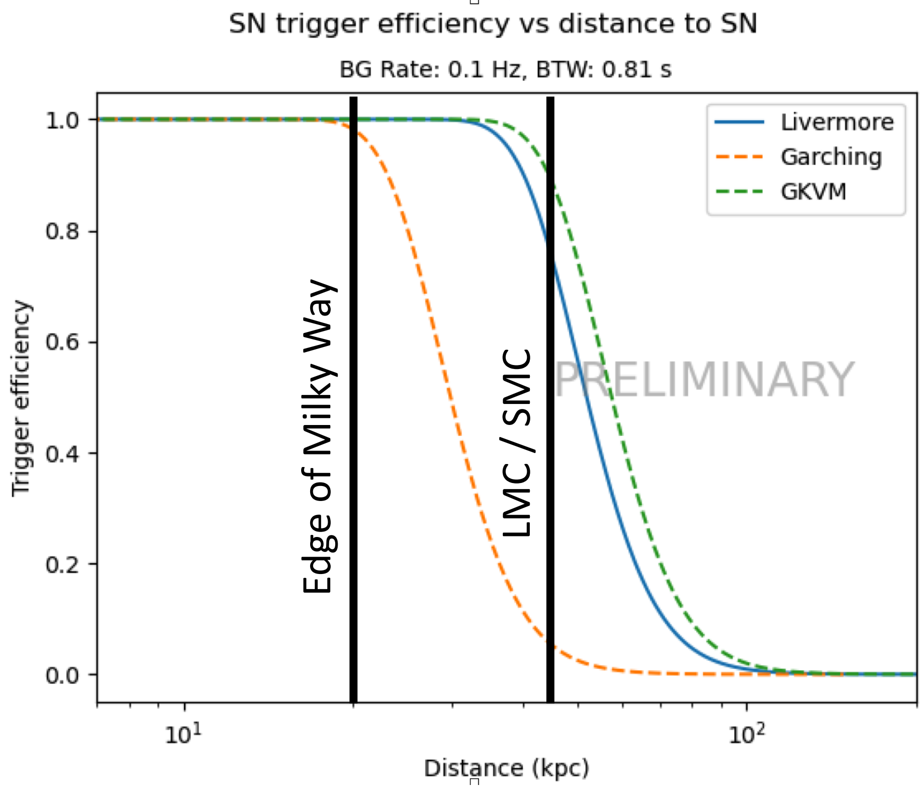
- Precision tracking of particles in TPC
  - Electron track visible in CC and ES
  - Comptons from deexcitation gammas show up as small blips surrounding electron track
- Can discriminate between channels based on deexcitation gammas



Reco label

True label	CC	ES
CC	97	3
ES	20	78

DUNE triggering on a supernova



- Trigger on an increased number of observed clusters in the TPC
  - Very little reconstruction, done fast online
- With a selected background rate of 0.1 Hz, we can trigger on any supernova in the Milky Way with < 1 false trigger / month

Supernova events at DUNE

- For a 10 kpc supernova, 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

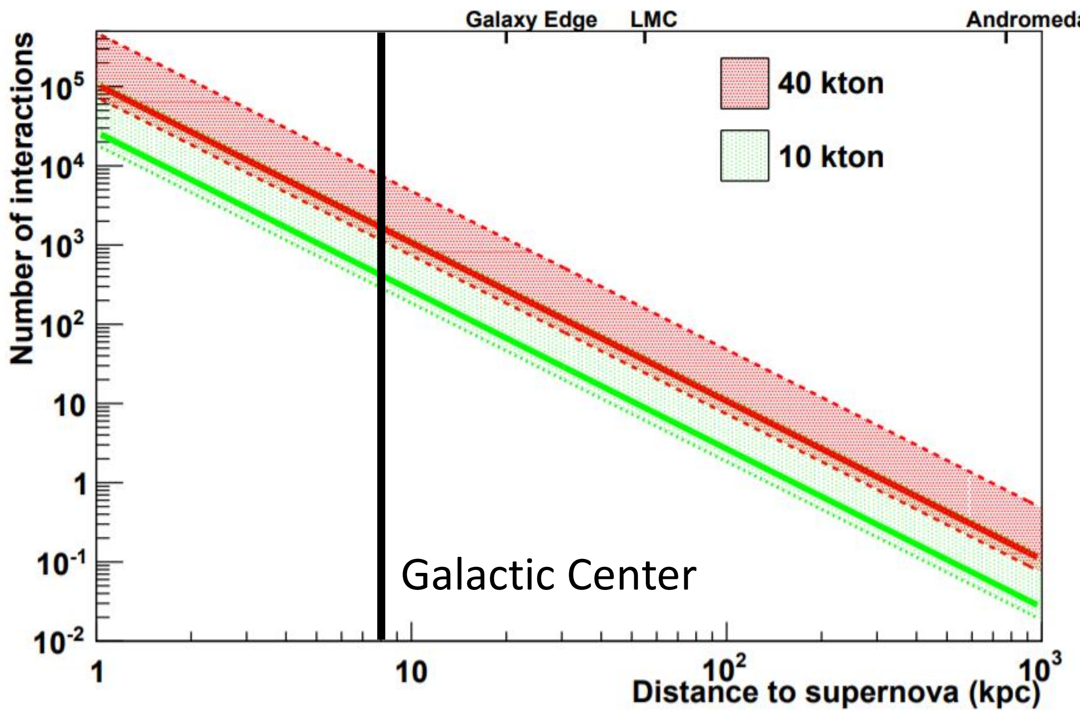
Most sensitive to the ν_e flux
Unique aspect of argon detectors!

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

Andromeda supernova would produce ≈1 event, lost in noise



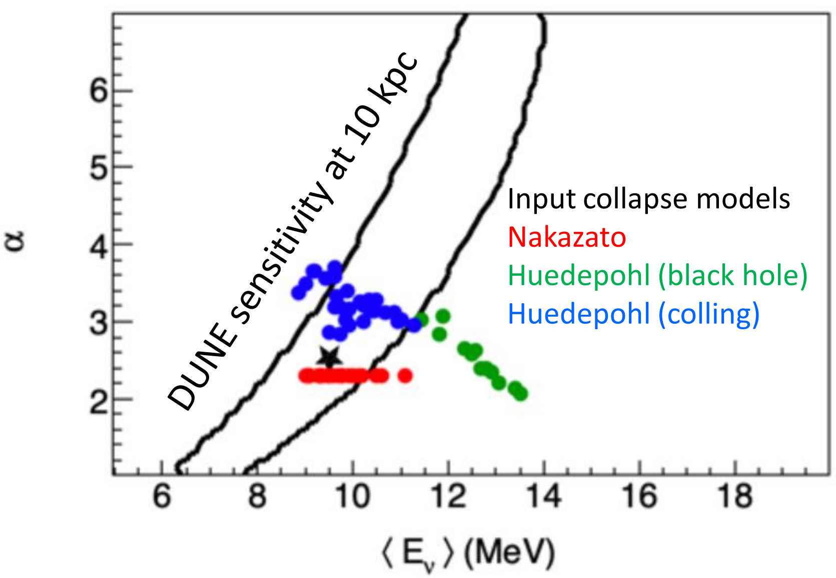
[1]Huedepol, Müller, Janka, Marek, Raffelt; PRL104 (2010) 251101

Testing astrophysical models with ν spectrum

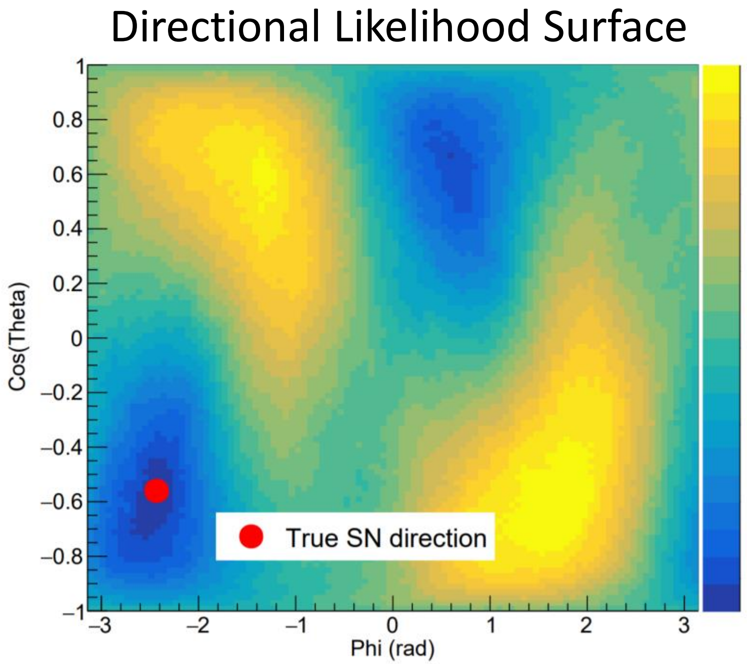
- Energy transport models in supernovae give a wide range of predicted neutrino spectra observed by DUNE
- General “pinched thermal flux” shape is sufficient to describe flux predicted by these models

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

- DUNE can constrain the three relevant parameters
- Provides a test of these supernova transport models
- A measurement at 10 kpc would constrain current models

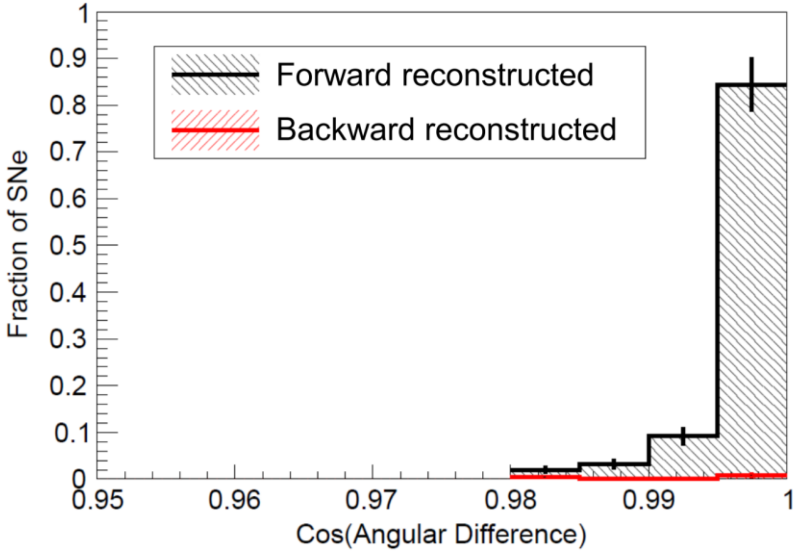


Supernova early detection



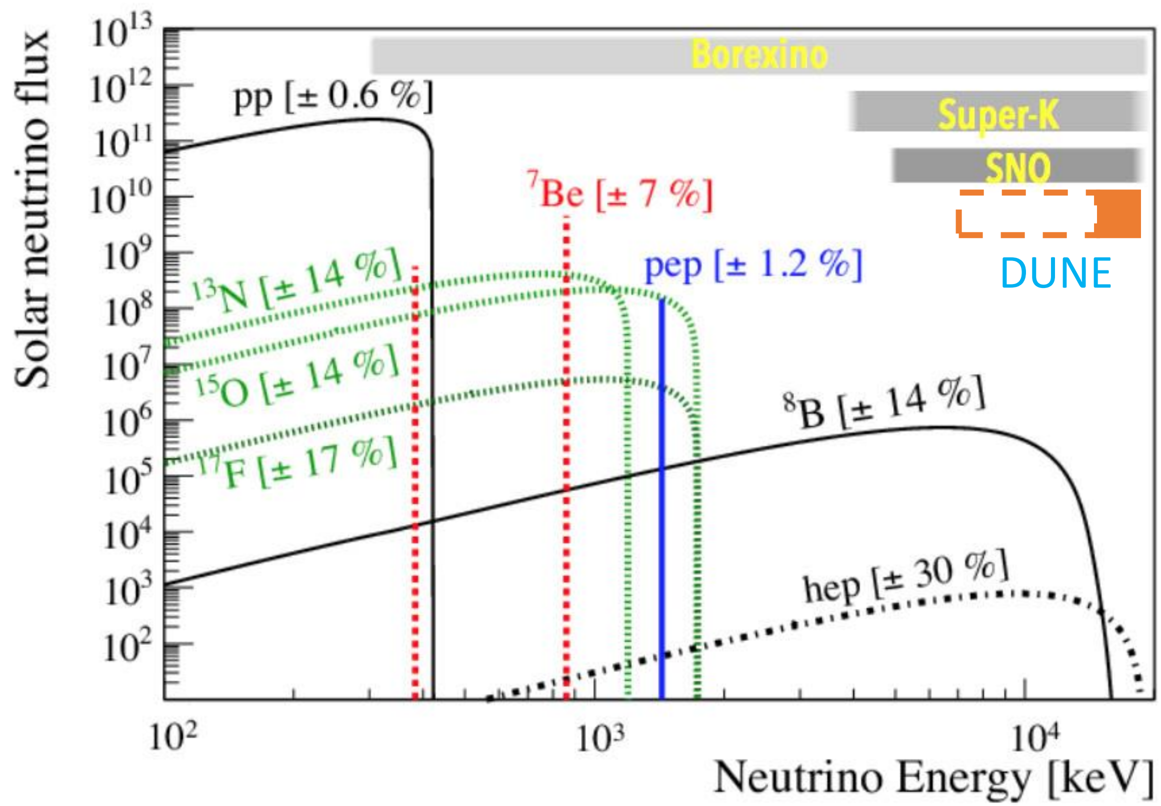
- Neutrinos signal arrives a few hours ahead of light signals from supernova
- DUNE (and others) can estimate where in the sky the burst originated
- Will inform astronomers where to point telescopes to observe the light signal
- Multi-messenger astronomy

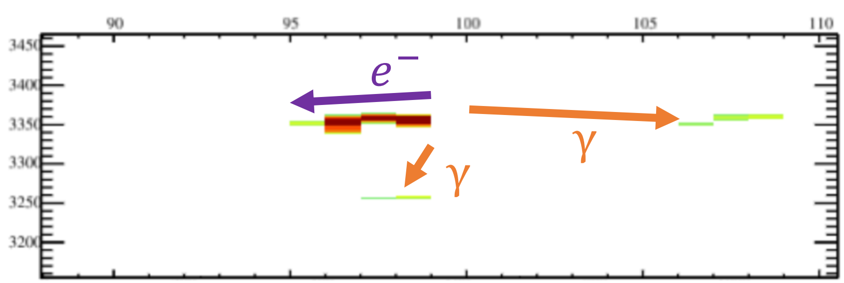
- Simulated supernova at 10 kpc
  - 260 $\nu - e$ scattering events
    - Low-Q^2 $\rightarrow$ great pointing
  - 3350 ν_e CC events
    - Exploit angular prediction of xsec
- 4.5 degree pointing resolution



Solar neutrinos in DUNE

- 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

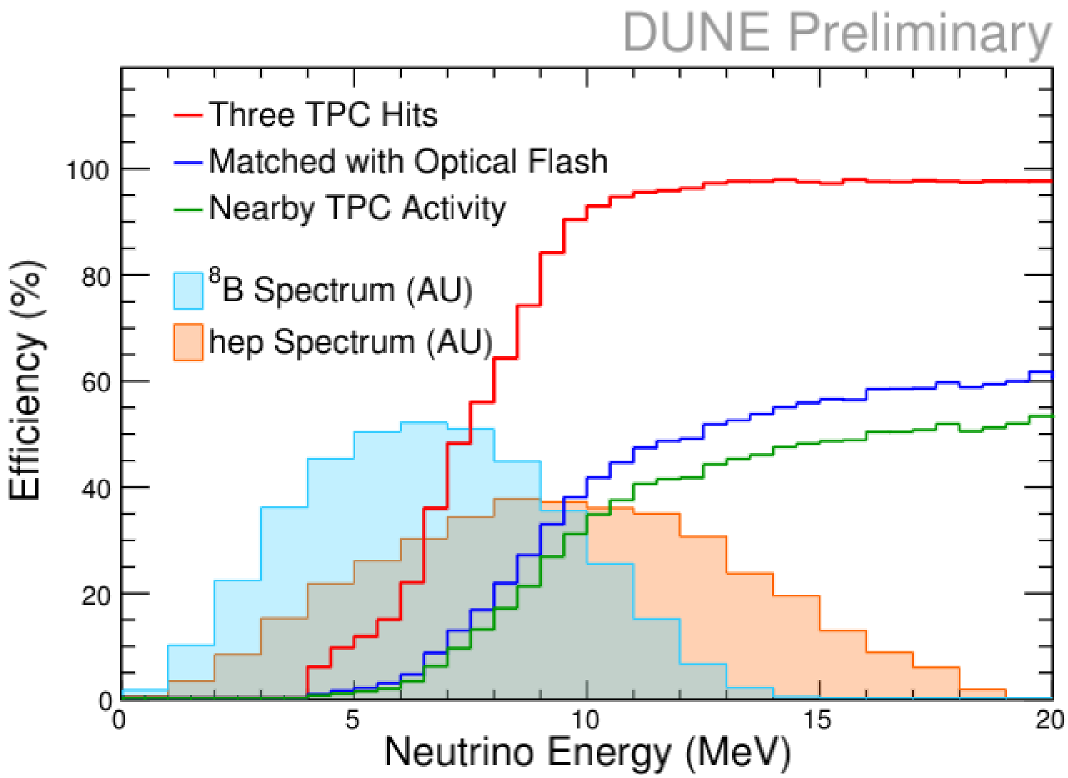




$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

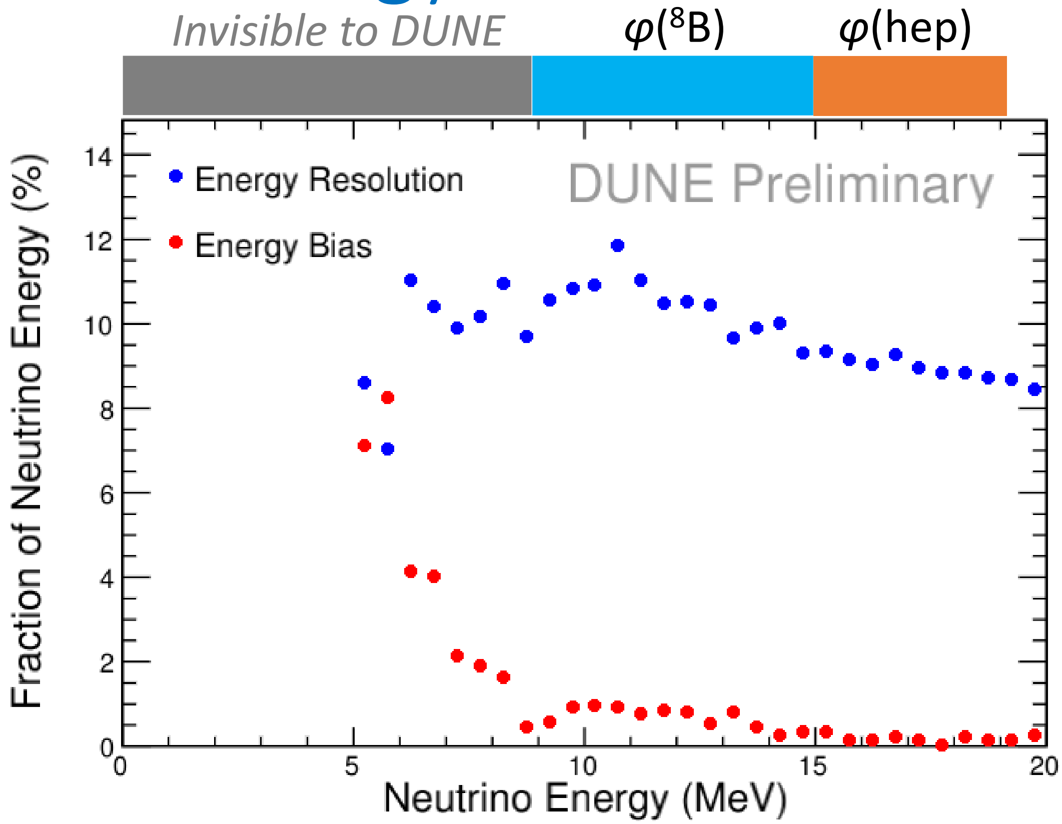
- Signal leaves a ≈10 MeV electron and gamma cascade in detector
- Need to trigger and identify

Triggering solar events in DUNE



- ❑ Both TPC and PDS activity required to trigger a solar neutrino
  - Observable electron track in TPC
  - Associated gamma cascade in TPC
  - Coincident activity in PDS required for vertexing and background control

Solar neutrino energy resolution



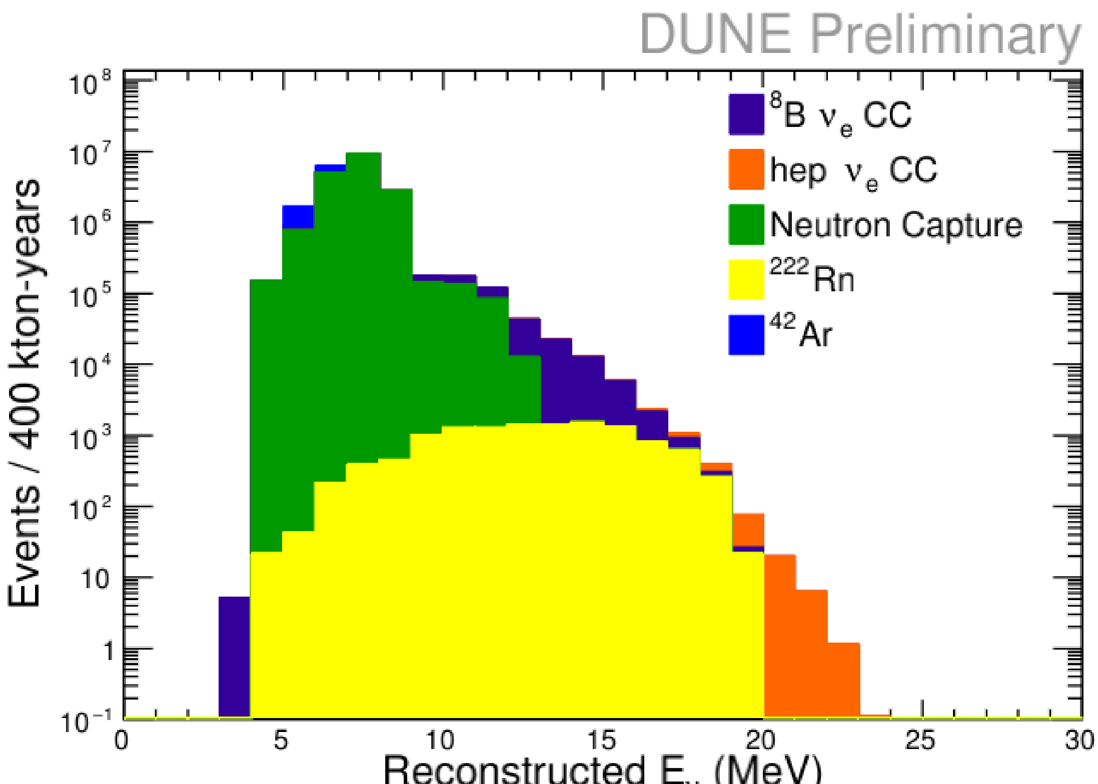
- ❑ Reconstruct events calorimetrically – sum all energy deposited in electron track and gamma cascade blips
  - PDS gives t_0 for electron lifetime correction and fiducialization
- ❑ We achieve 9-12% resolution on neutrino energy throughout the solar energy range

Solar neutrinos in DUNE

- Solar 8B + hep flux is enormous – expect several tagged events / day / kt
- Backgrounds very important when studying solar neutrinos
  - Mostly neutron capture events affect us – only events > 9 MeV are resolvable

Solar events do not arrive as a burst – backgrounds are very important!

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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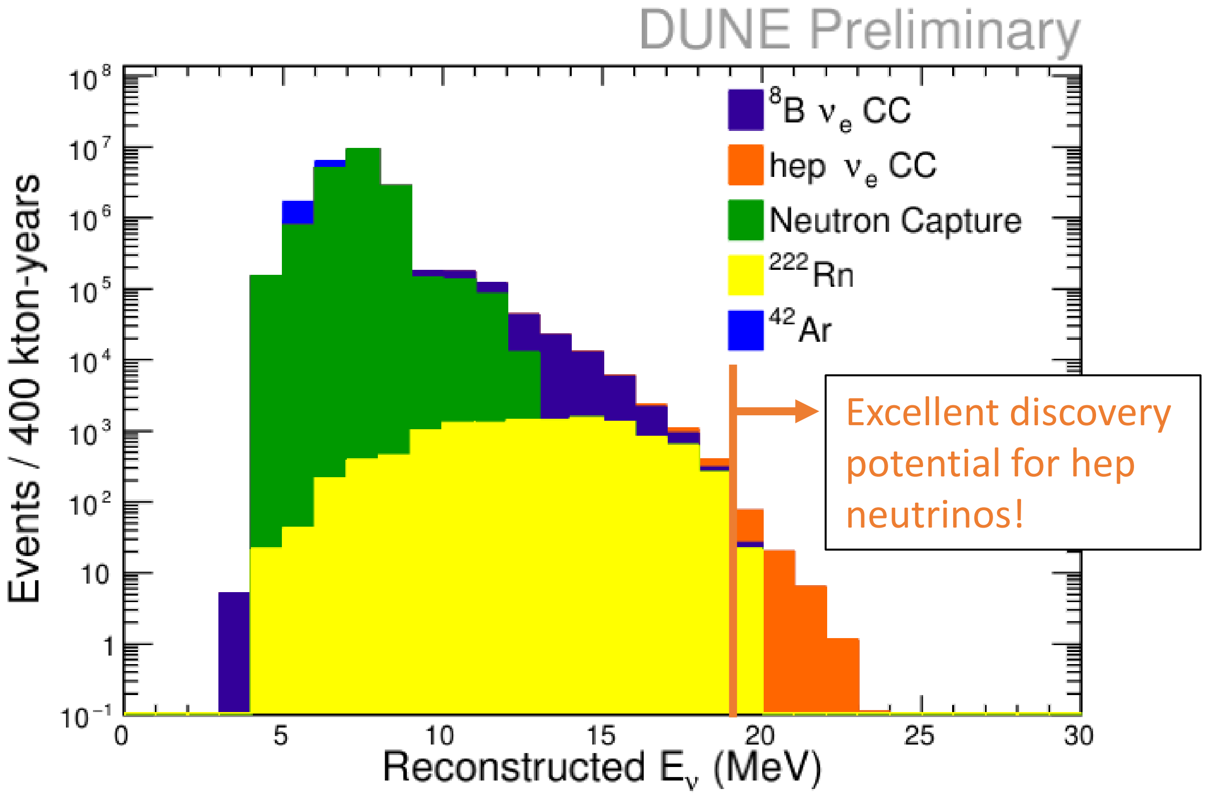
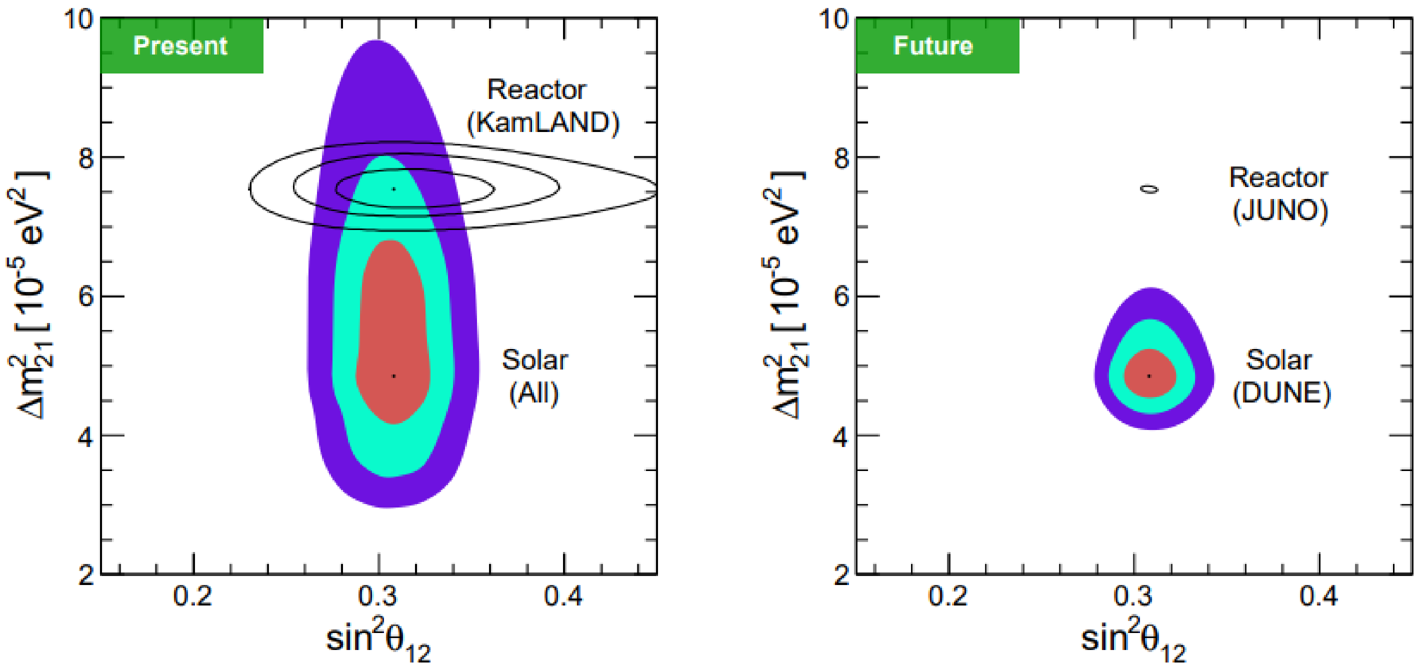


Future sensitivity to solar oscillations

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



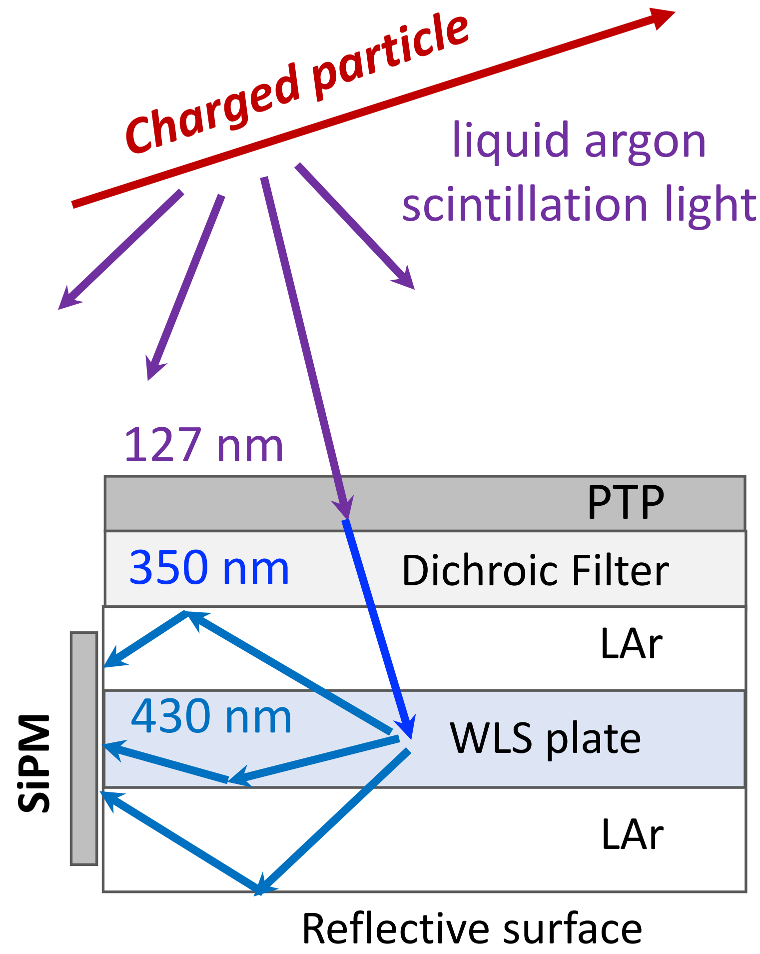
- DUNE has favorable sensitivity for measuring Δm^2_{21} largely from day/night effect – a partial regeneration of the ν_e flux due to matter effects in Earth
- May push current tension between SK/SNO and KamLAND to 5σ
- DUNE working to publish our own sensitivity calculation


ROBERT RATHBUN

Backup

Collecting Scintillation Light with the PDS

- ARAPUCA[1] photon detectors developed to enhance light yield in DUNE by trapping photons of a certain wavelength
- PD is coated in PTP which shifts photon wavelengths to 330-400 nm
- A dichroic filter just below is transparent to photons at wavelengths below 400 nm but reflective at longer wavelengths
- Below, a second wavelength shifter adjusts the wavelength to 430 nm
- Light is thus trapped between the dichroic filter and the reflective wall until captured by a SiPM



Not to scale.

[1]Marinho, Paulucci, Machado, Segreto; arXiv 1804.03764

Matching PDS and TPC Activity

- Both PDS and TPC hits will give information on the coordinates perpendicular to the drift direction

- Requiring a coincidence between the PDS flash and TPC positions will reduce the rate of uncorrelated background in the two systems
  - Vertex reconstruction is within 240 cm for PDS and TPC
  - The time of the PDS flash precedes TPC activity, with the time delay no more than one drift time