Searches for Neutron-Antineutron Oscillations in the Deep Underground Neutrino Experiment

By Joshua L. Barrow

jbarrow3@vols.utk.edu

For the DUNE Collaboration

at the *Meeting of the American Physical Society's Division of Particles and Fields*, August 3rd, 2017

This research is funded by Department of Energy-High Energy Physics Grant DE-SC0014558

THE UNIVERSITY OF TENNESSEE KNOXVILLE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Motivations for Experimental Detection of $n \to \bar{n}$ Oscillations

- Any matter-antimatter asymmetry created by $(B-L)$ conserving BSM interactions is thought to be erased during the **e**lectro**w**eak (EW) phase transition
  - Sphaleron "washes out" effectively all asymmetry
  - Thus, **solely** $\Delta(B-L)=0$ would not be a permissible explanation of baryogenesis
- Some models DO violate $\Delta(B-L)$ …
  - These could be $\Delta B=1$, like $N \to lepton$, **violating** $(B-L)$: $n \to e^-\pi^+$

    …rather than $N \to antilepton$ **conserving** $(B-L)$: $p \to e^+\pi^0$
  - …or, $\Delta B=2$ processes, **like neutron-antineutron ($n \to \bar{n}$) oscillations**
  - These probe BSM physics above LHC
  - A "post-sphaleron" baryogenesis (PSB) [Babu, Mohapatra,… 2013]
- Observation of oscillation would be a spectacular discovery
  - Could explain the BAU (then make ~unobservable leptogenesis irrelevant)
  - …or rule out PSB

Phenomenology of $n \rightarrow \bar{n}$

- Can search for such oscillations in both free beam and bound nuclei experiments
  - Free Oscillation:

$$P_{free} \sim \left(\frac{t_{experiment}}{\tau_{n\rightarrow\bar{n}}}\right)^2$$

  - However, the bound oscillation is suppressed in nuclei, such as in O:

$$\tau_A = \frac{\Delta V_{n \text{ vs. } \bar{n}}}{\hbar} \tau_{n\rightarrow\bar{n}}^2 = R\tau_{n\rightarrow\bar{n}}^2$$

where $R \sim 5 \cdot 10^{22} s^{-1}$ from prediction by Friedman and Gal, and

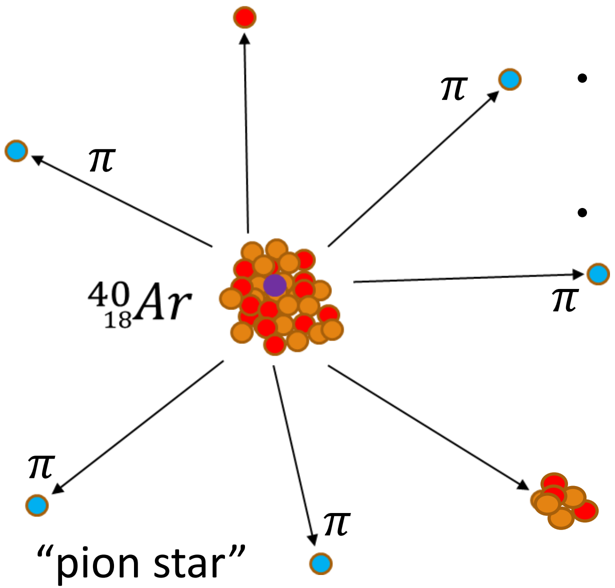
$$P_A = e^{-\frac{t_{experiment}}{\tau_A}}$$

which represents nucleon decay/nuclear lifetime-like experiment

Signal Comparison

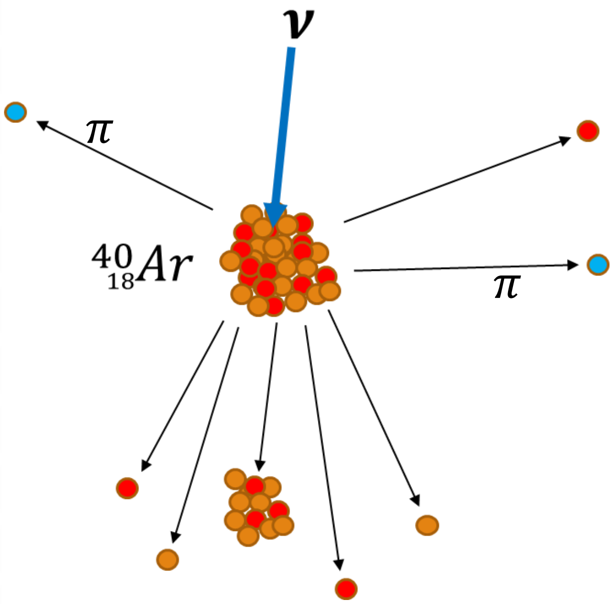
$n \rightarrow \bar{n}$ vs. Atmospheric Neutrino

$n \rightarrow \bar{n}$ Annihilation and Knockouts

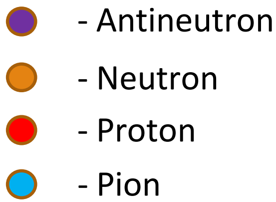


- Noncontinuous energy spectrum
- Generally a ~spherical topology
- Low momentum due only to Fermi motion

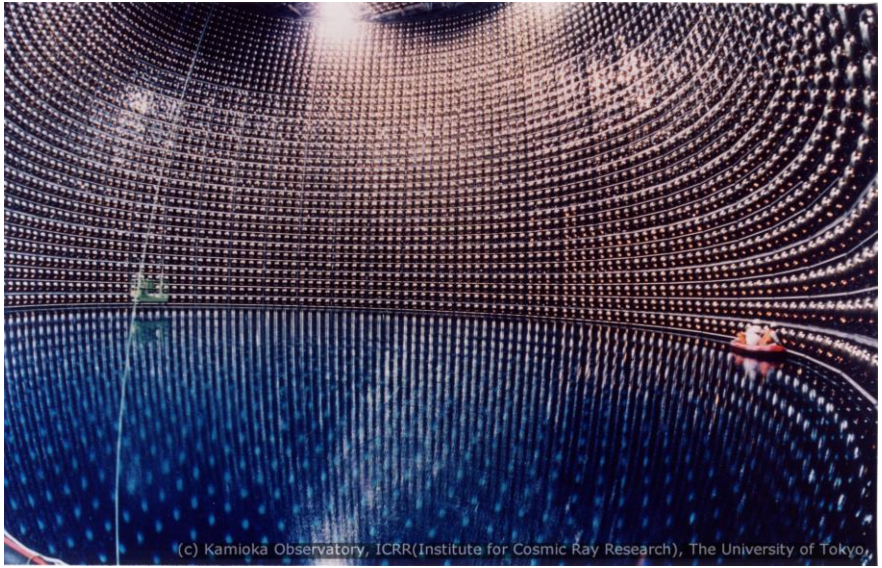
Neutral Current Atmospheric ν



- Continuous energy spectrum
- Generally a ~correlated topology
- Large range of total momentum



Super-Kamiokande $n \rightarrow \bar{n}$ in $^{16}_{8}O$

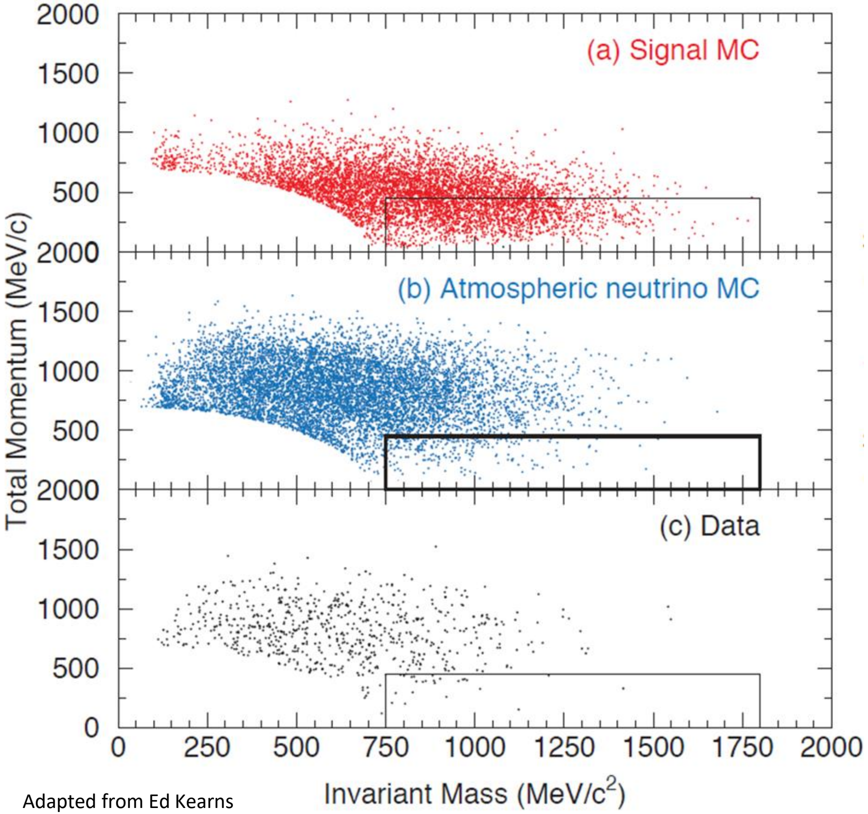


$\bar{n} + p$		$\bar{n} + n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

Based on antiproton annihilation data

*These values are slightly changed within the $^{40}_{18}Ar$

Simulations and Experimental Results in Super-Kamiokande (2015)



Adapted from Ed Kearns

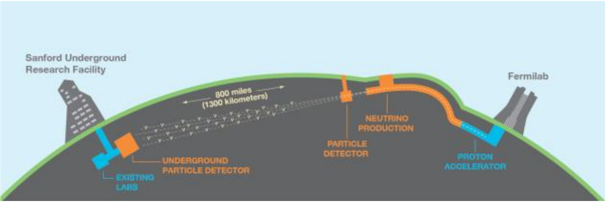
24 candidate events were observed

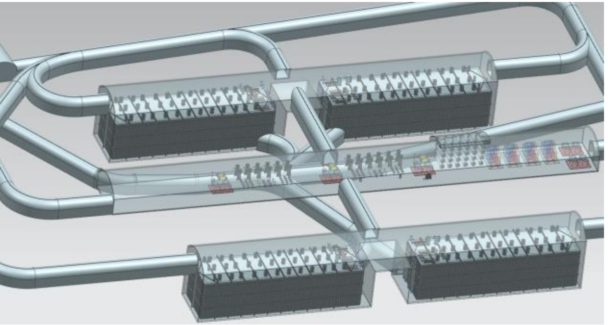
- Expected atmospheric ν background was 24.1 events
  - Box size due to optimization of **S/B**
  - $\boldsymbol{\tau_A \geq 1.89 \times 10^{32} years \rightarrow \tau_{n-\bar{n}} \geq 2.7 \times 10^8\ s}$
- High thresholds and nuclear absorption within Cherenkov detectors (decreases invariant mass)

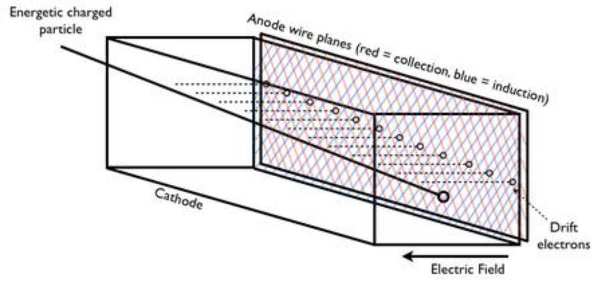
DUNE LArTPCs offer…

- Low thresholds, good PID through $\frac{dE}{dx}$, but also suffer from absorption
- Similar MCs and analysis is currently being pursued in DUNE

The Deep Underground Neutrino Experiment and Proposed $n \to \bar{n}$ Search





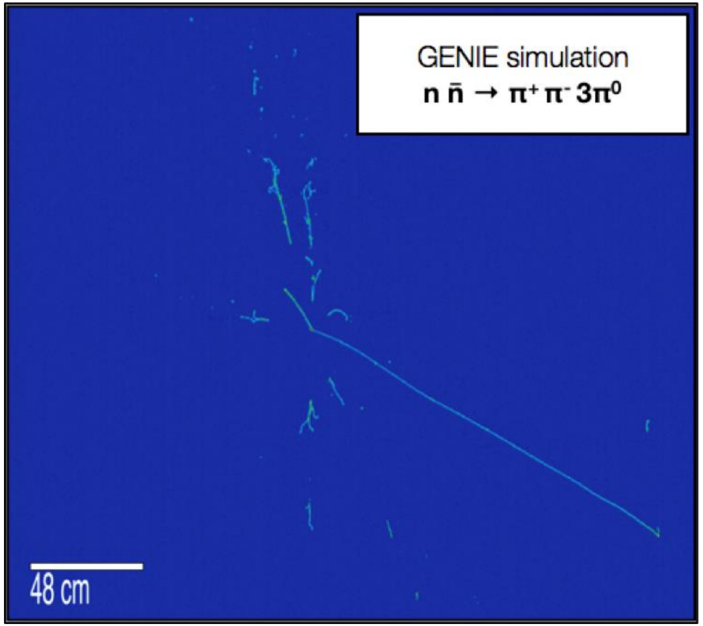


- **DUNE** international collaboration of 950+
  - Partnership of Fermilab and LBNF
  - Will construct world’s most intense ν beam
  - The far detector will utilize LArTPCs
  - **Fiducial volume** of ~40 kilotons
- LArTPC’s superior tracking and PID capabilities enable background reduction
  - Is background-free/quasi-free $n \to \bar{n}$ search possible?
    - The real question we need to answer…

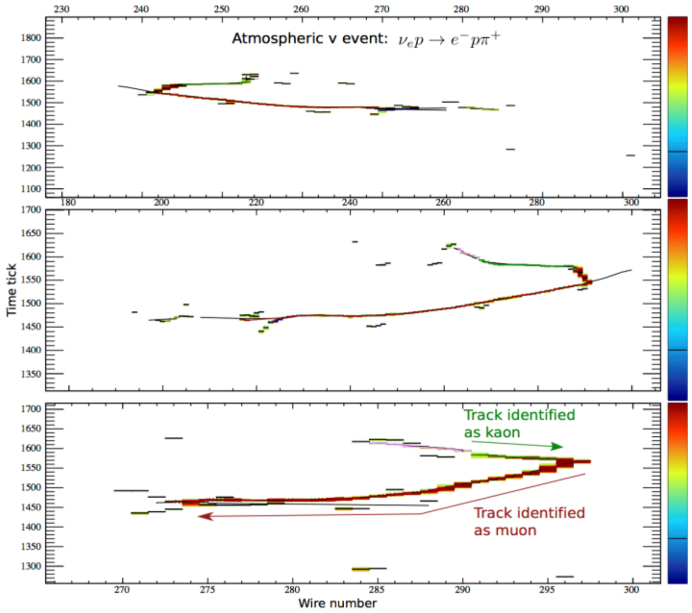
Events in LArTPC's (MC Simulations)

Simulated $n \rightarrow \bar{n}$ oscillation event in liquid argon, using the GENIE 2.12 event generator. The 6 showers from the decays of $3\pi^0$'s are clearly seen, as well as two tracks from the two charged pions. The distinctive spherical topology makes these events easily identifiable by eye, and work is underway to develop event selection criteria using DUNE reconstruction and particle ID algorithms.

$n \rightarrow \bar{n}$



Atmospheric ν

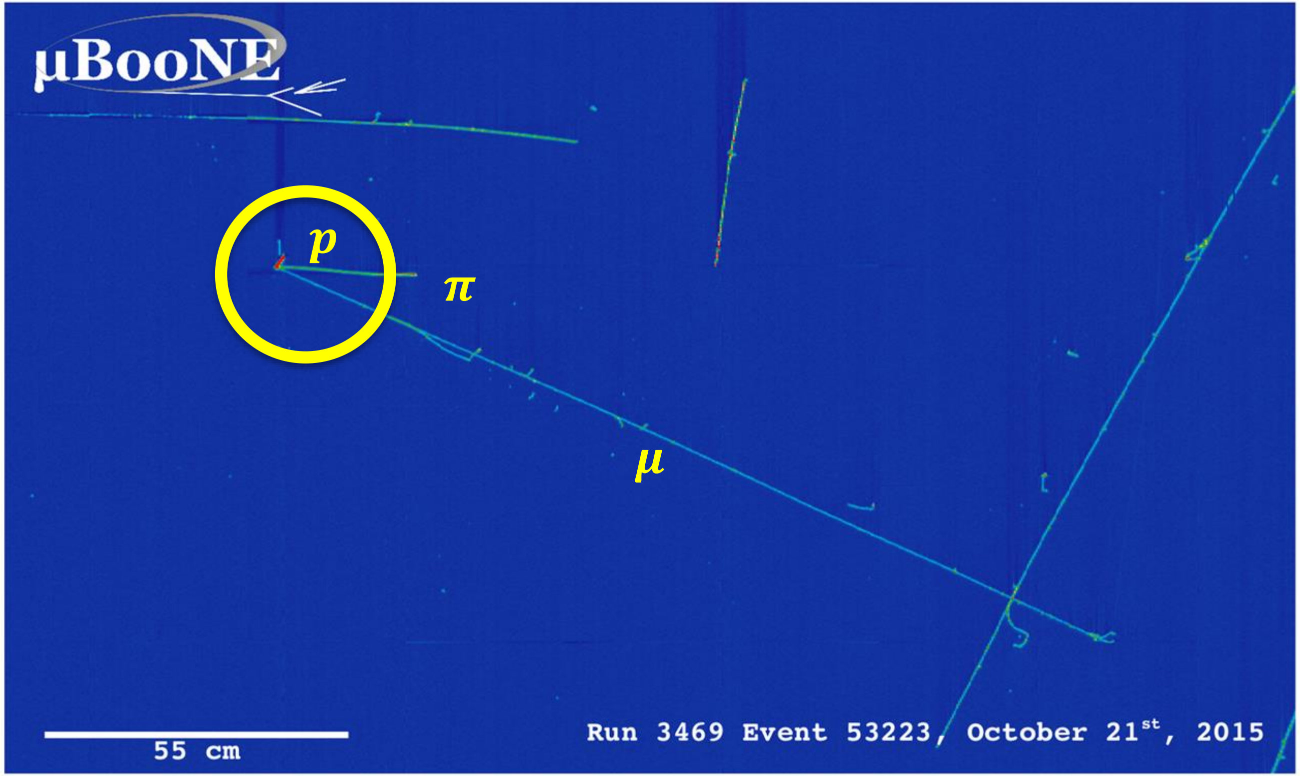


Time vs. wire view of the same charged current resonant pion production, $\nu p \rightarrow e^- p \pi^+$, atmospheric neutrino event that passed selection cuts for $p \rightarrow \bar{\nu} K^+$, which was shown in other figures as ortho-3D view. Here, the three panels are the collection and two induction planes. In this view it is more clear why the event was incorrectly reconstructed, and therefore passed the signal selection cuts for $p \rightarrow \bar{\nu} K^+$. The three panels correspond to the three wire readout planes (one collection plane, two induction planes).

Excellence of LArTPCs—See MicroBooNE

An example charged current ν event in MicroBooNE

REAL DATA!



Proton reconstruction is an important step for DUNE in nucleon decay searches; SK will soon add gadolinium to their WCD to track neutrons!

LArTPC and WC Comparisons

Liquid Argon Time Projection Chambers

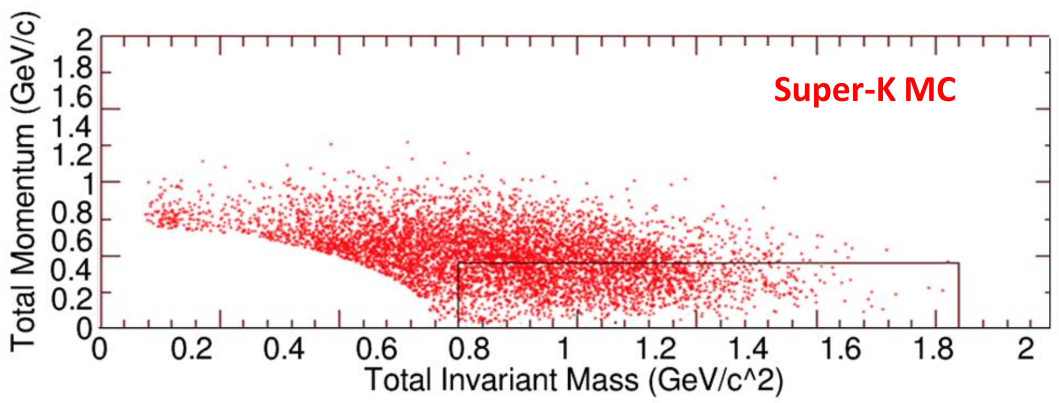
1. **Lower kinetic energy** thresholds on charged particles
   - $\sim 10\ MeV$ threshold for $\pi^{\pm}$
   - **$21\ MeV$ threshold for p** [ArgoNeuT]
2. Excellent track resolution and reconstruction
   - PID and $\frac{dE}{dx}$ information
3. Detail allows $e\ \mathrm{vs.}\ \gamma$ separation
   - Important to reject CC events for $n \rightarrow \bar{n}$
4. Developing technology

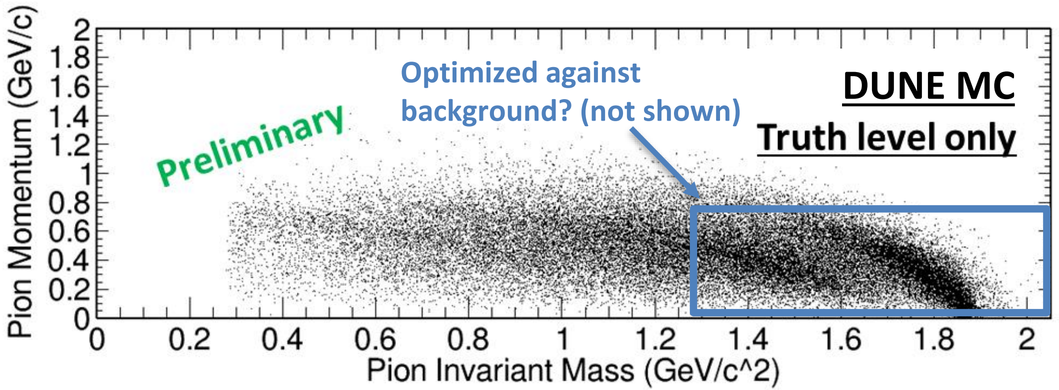
Water Cherenkov Detectors

1. Moderate kinetic energy thresholds on charged particles
   - $\sim 100\ MeV$ threshold for $\pi^{\pm}$
   - $\sim 1\ GeV$ threshold for p
2. Low cost, and low atomic number
3. Vertex reconstruction can suffer due to multi-prong topology and multiple scattering
4. Battle tested technology

Final States for $n - \bar{n}$:

DUNE v. Super-Kamiokande MC Simulations





MC: $n - \bar{n}$ for O-16 from Super-Kamiokande

- Requires two+ rings (particles)
- Includes detector effects
  - Moderate to high kinetic energy cuts
- Uncertainties due to transport through the nucleus
  - Quantifiable
- Study is quite background limited
  - **Efficiency of ~12%**
  - **Best background rejection is boxed region**
  - **24.1 background events expected in experiment**

MC: $n - \bar{n}$ for Ar-40 for DUNE (truth level only)

- Two+ $\pi^{\pm,0}$ (no requirements on other final state particles)
- **REQUIRE LOW THRESHOLDS**
  - 25+ MeV KE for each $\pi^{\pm}$
  - Threshold approximation for a good track length
  - Assume 100% π^0 reconstruction
- Uncertainties due to transport through the nucleus
  - Currently quantifiable?
- **Best background rejection box? Backgroundless?**
  - ***Can* be higher efficiency (~45% shown here)**
  - **Lowest number of background events?**

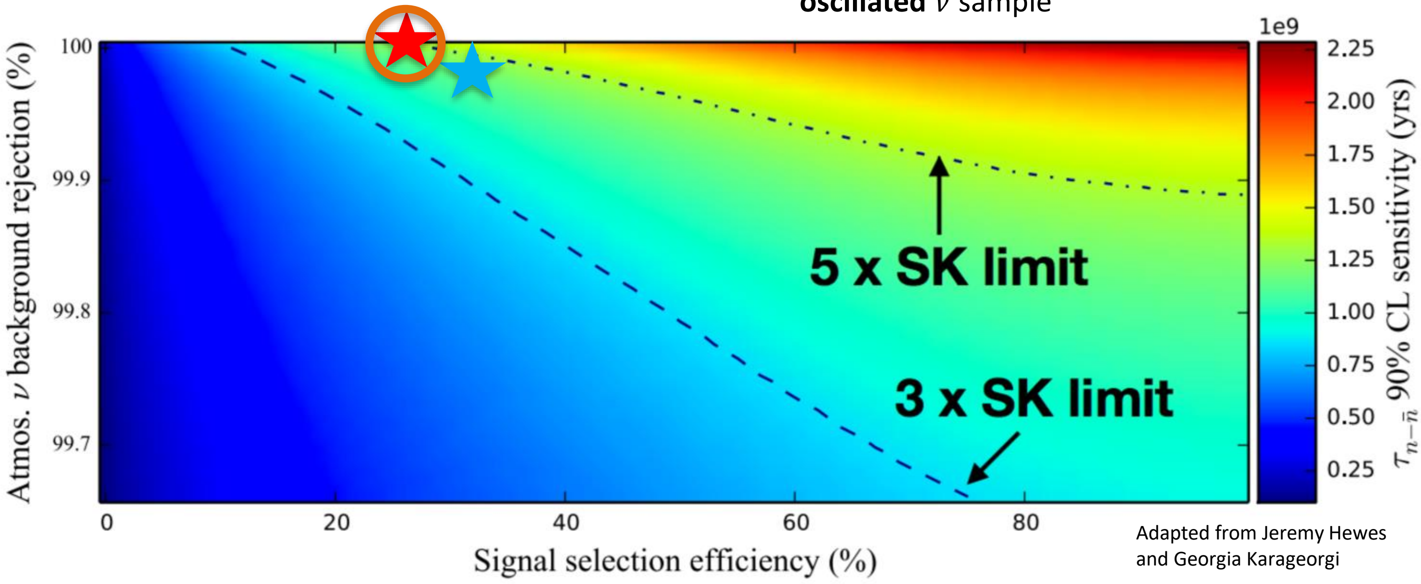
Lower limits? Elimination of background?

- **Background suppression** in specific regions of ***pion momentum vs. invariant mass*** parameter spaces **looks promising**

- Optimization studies to come…

~27% Efficiency, 100% background rejection
Truth Level **ONLY**, Preliminary
Consider only 3+ Pions, 1+ Protons
Assume complete CC separation
Uses old, small, un-oscillated ν_μ and ν_e sample

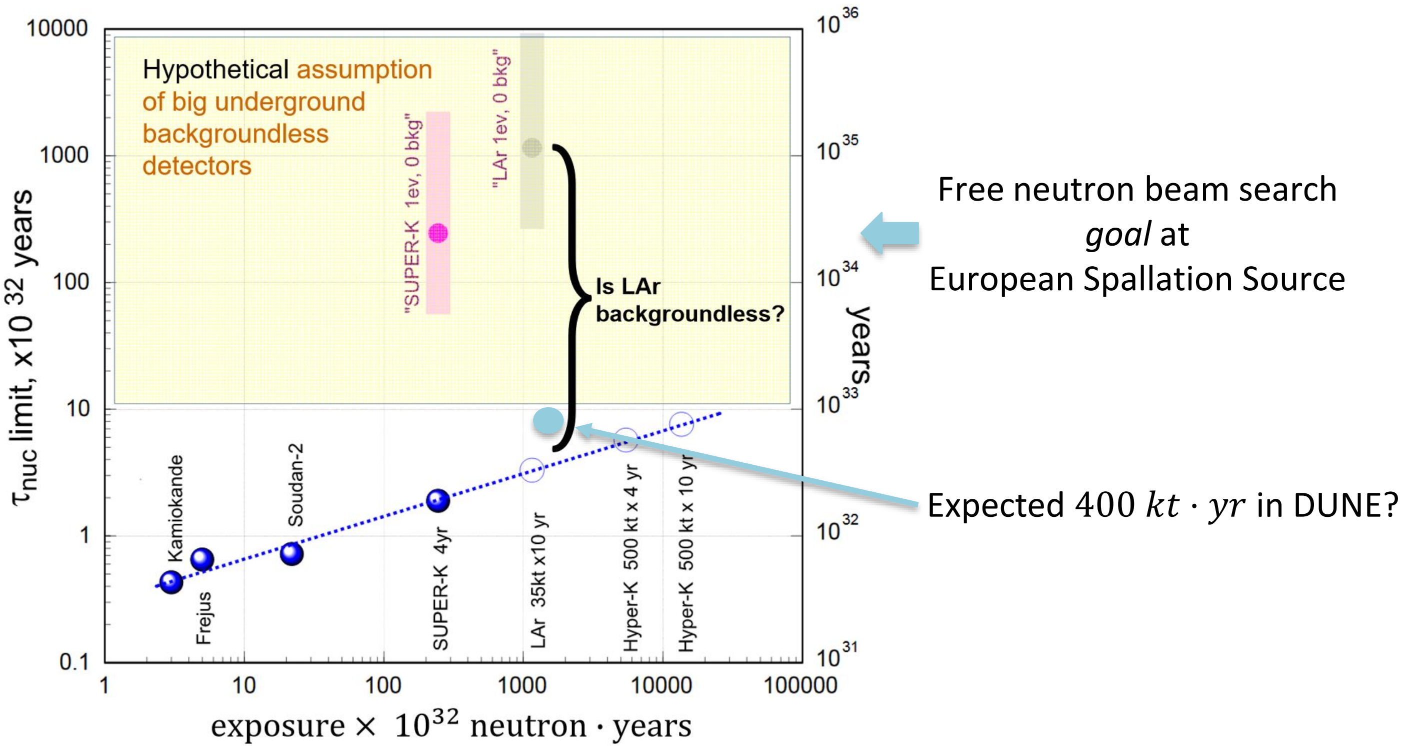
~32% Efficiency, 99.98% background rejection
Deconvolved, images processed
Uses Convolutional Neural Networks (in development)
Training/limits completed with fully simulated **oscillated** ν sample



Adapted from Jeremy Hewes and Georgia Karageorgi

Prospect of Intranuclear $n \rightarrow \bar{n}$ Searches are Background Dependent

Adapted from
Y. Kamyshkov



24 candidate events in Super-K **might contain** several genuine $n - \bar{n}$ events…

Quasi-free/backgroundless detectors needed to explore bound $\tau_{n-\bar{n}} > \ 10^{33}$ years assuming only 1 event

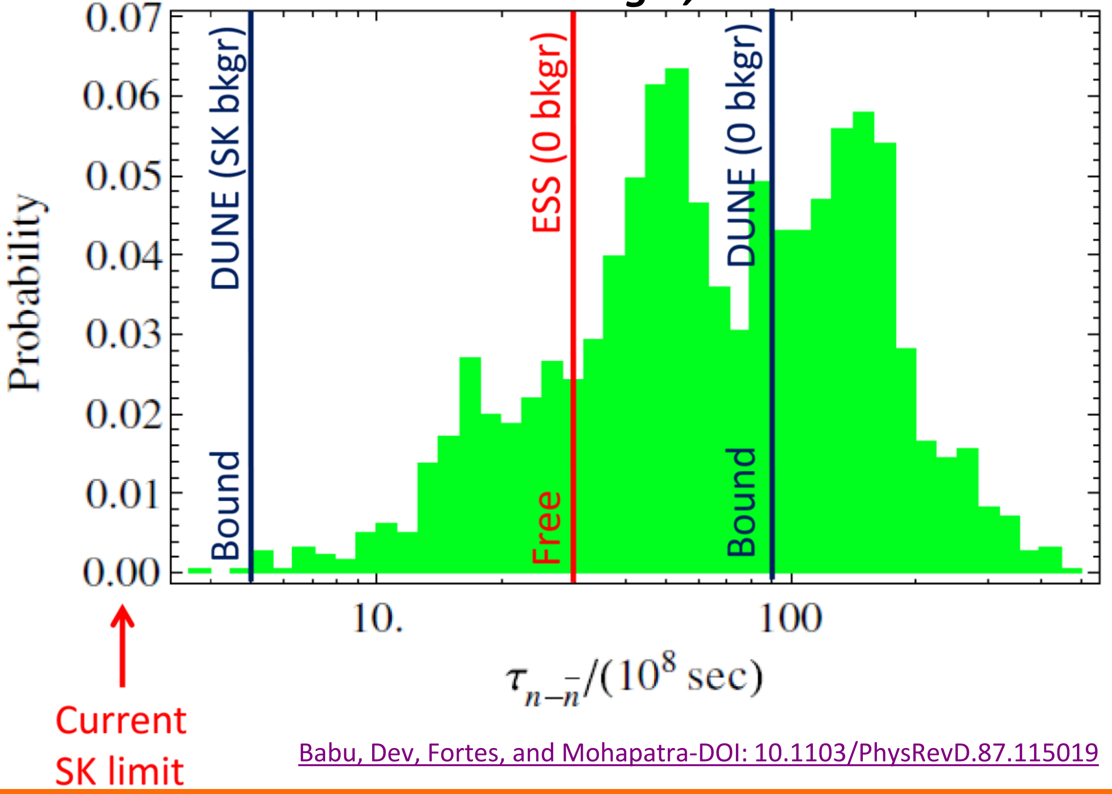
Whether atmospheric neutrinos and $n - \bar{n}$ signals can be separated in LAr detectors is an R&D issue for DUNE

Relations Between Theory and Experiment

2013 work by Mohapatra et al. on PSB produces a probability distribution of $\tau_{n\to\bar{n}}$

- Based on MC simulations of various parameters over plausible ranges in a non-SUSY BSM PSB
- Blue line shows horizontal beamline
  - **ESS**: 3-5 yrs exp. (claim to be backgroundless)
- Red lines show LArTPC
- Roughly coincides with ultimate $\tau_{n\to\bar{n}}$ goal
  - **DUNE**: 10 yrs exp.
  - Get to $\sim 1\times 10^{10}$s?
  - **Both assume no background**

Limits for *single, true events*



Babu, Dev, Fortes, and Mohapatra-DOI: 10.1103/PhysRevD.87.115019

Final Thoughts

- DUNE may provide better…
  - Background discrimination due to particle ID via $\frac{dE}{dx}$
  - Lower energy thresholds increase probability of $n \rightarrow \bar{n}$ detection
    - *Hope to* push background to zero (remains ultimate goal of research with LAr)
  - Low energy protons can now be included in analysis