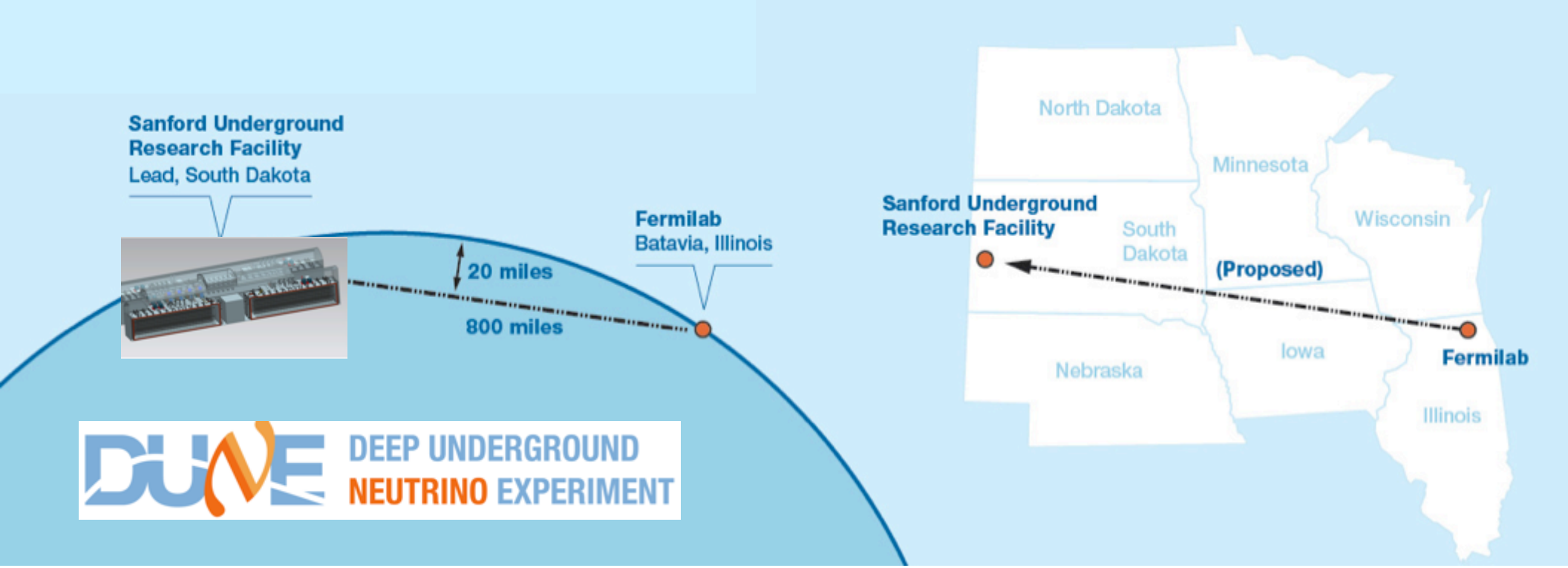


DUNE: the Physics Potential of a Large, Underground, Liquid Argon Neutrino Detector

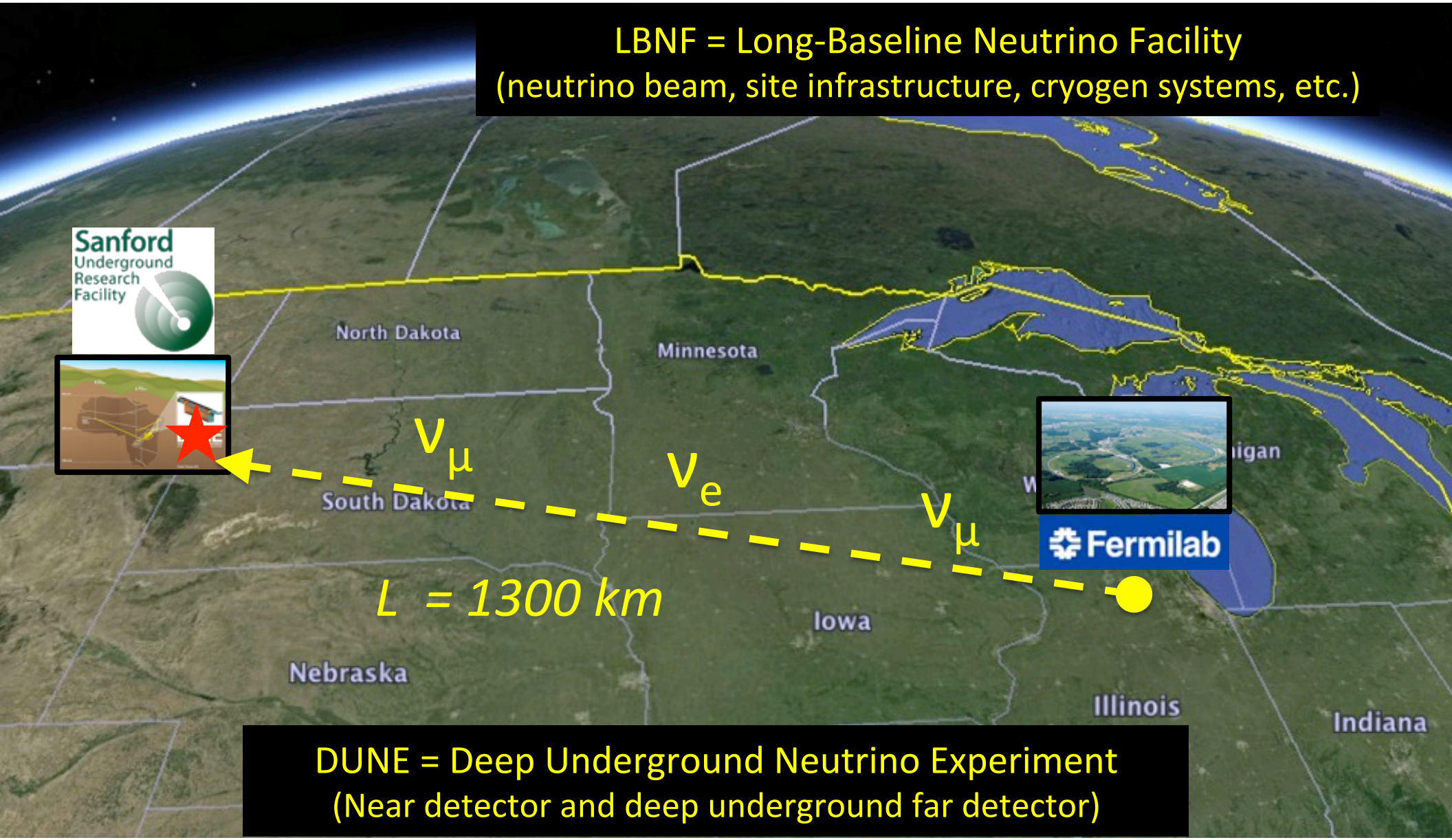
Christopher Grant, UC Davis

- On behalf of the DUNE Collaboration -

DPF 2015 - University of Michigan – Ann Arbor, MI

August 4, 2015

DUNE and LBNF



Project Overview

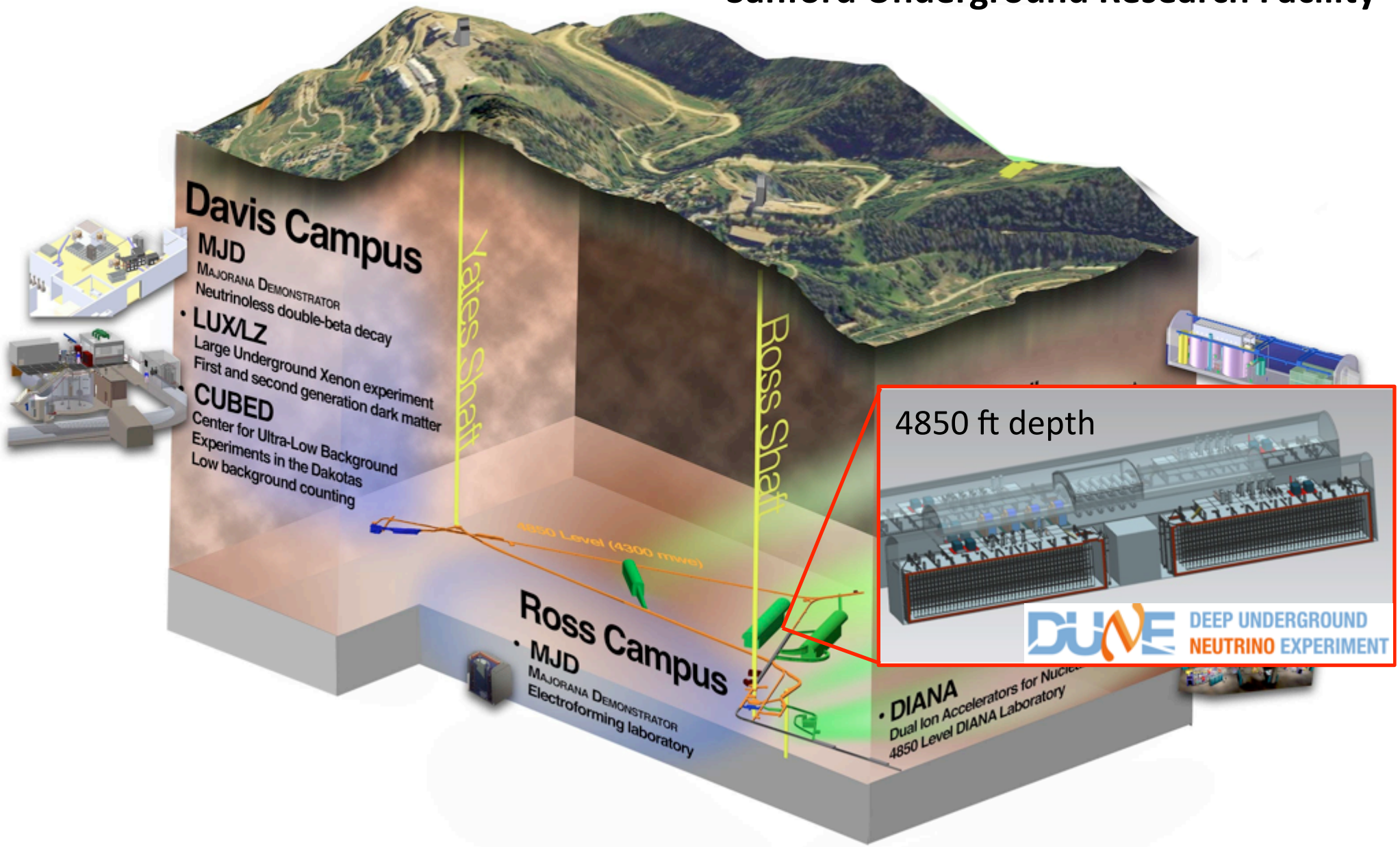
In the scope of the **2014 P5 report**, the international neutrino community aims to do the following with DUNE/LBNF:

- Exposure of at least 120 kt•W•year by 2035
- 1.2 MW beam power, upgradeable to a few MW power
- Underground far detector with at least 40 kt liquid argon fiducial volume
- Demonstrated capability to search for supernova bursts
- Demonstrated capability to search for proton decay with significant improvement over current bounds on the proton lifetime

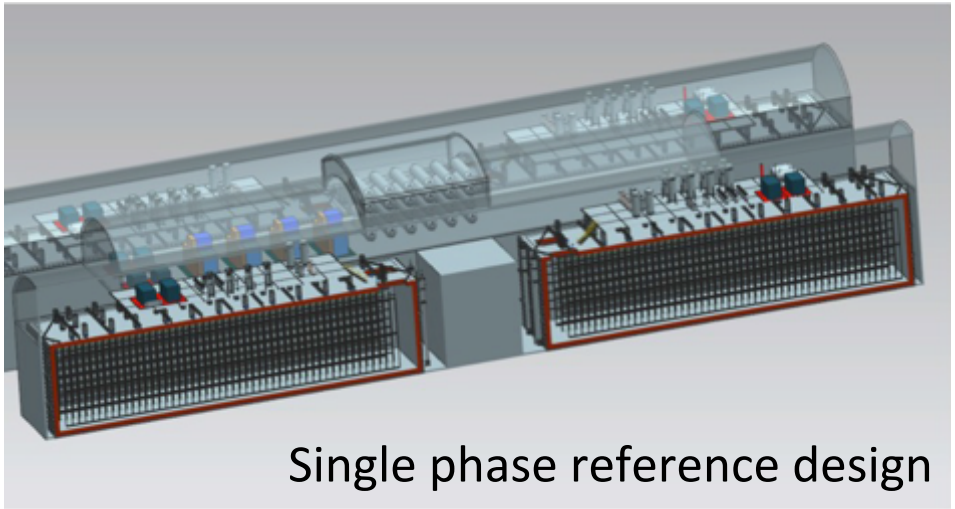
DUNE will be equipped for underground physics

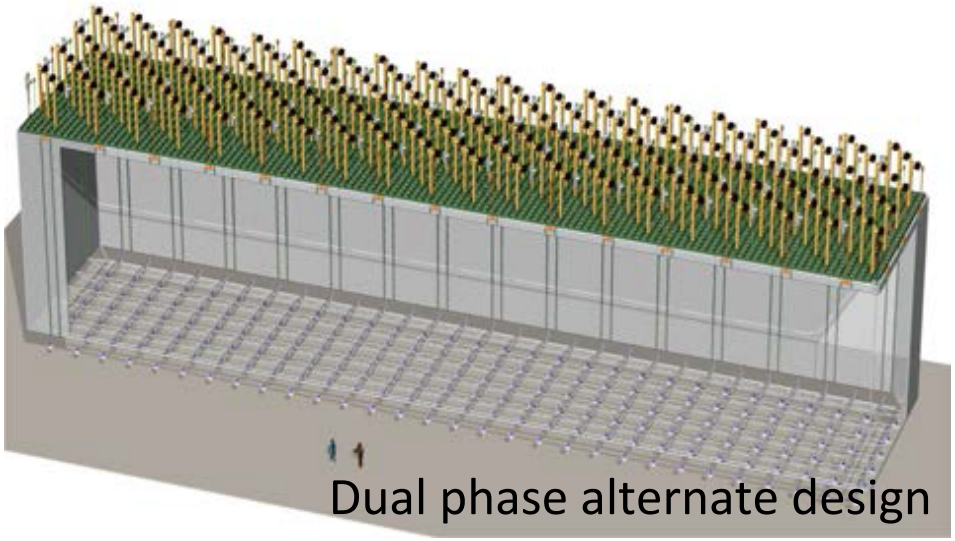
DUNE Far Detector at SURF

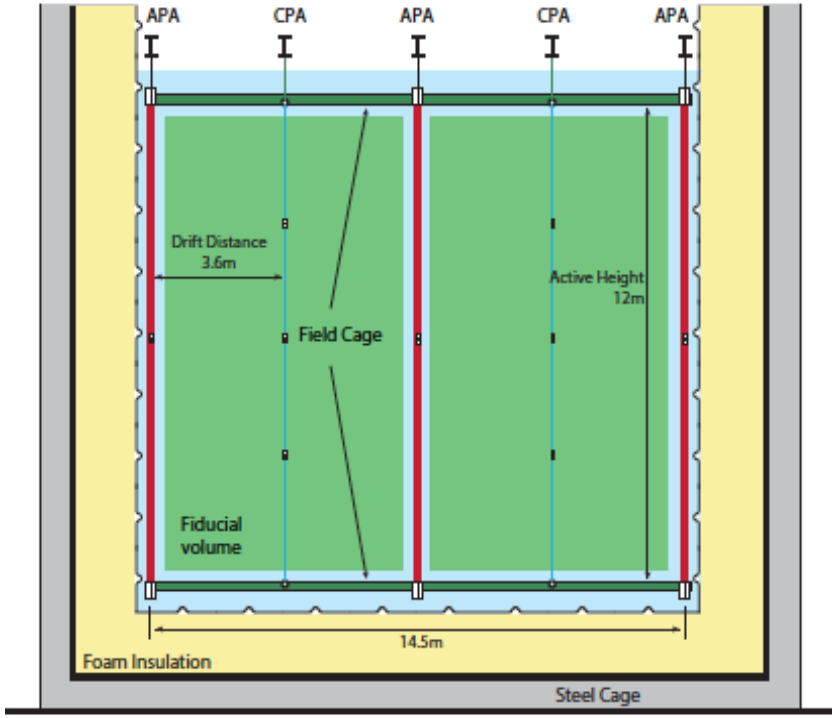
Sanford Underground Research Facility

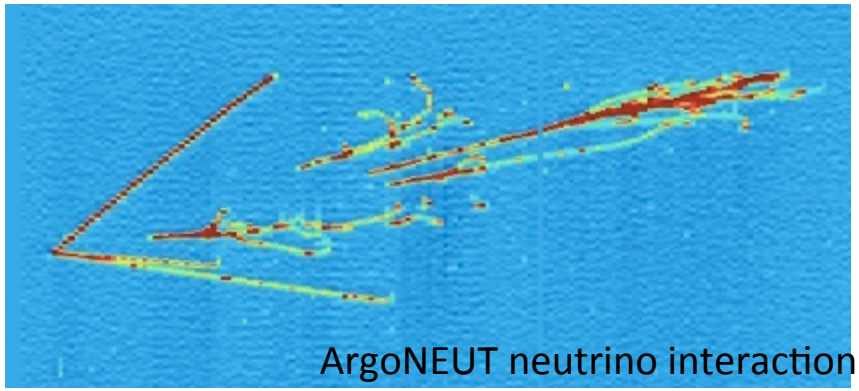


Far Detector Reference Design


Single phase reference design


Dual phase alternate design




ArgoNEUT neutrino interaction

Two detector designs are being explored in parallel. Both will have the ability to detect scintillation light. Construction of four 10-kt modules will be phased over several years time.

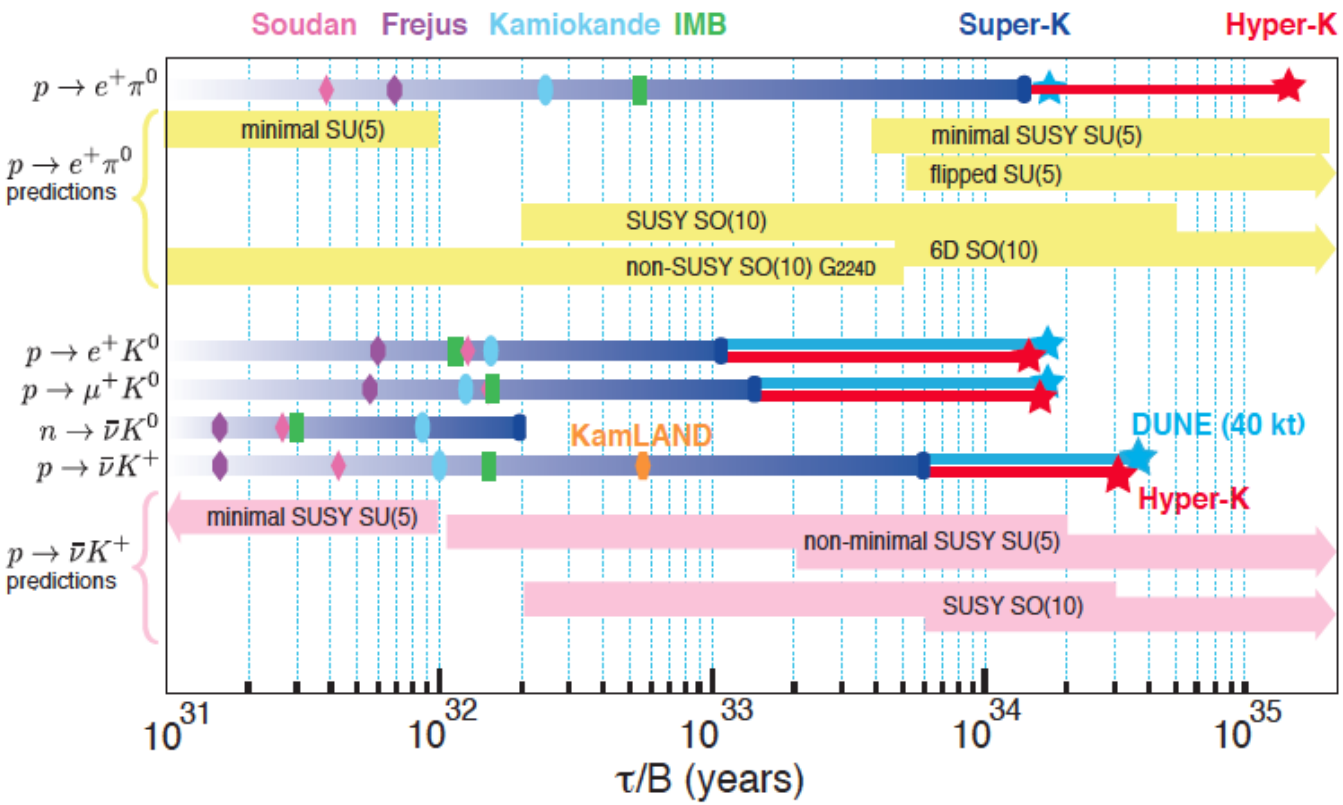
Underground Physics Opportunities

With 40 kt of liquid argon at 4850 ft underground, there is significant potential for the following:

- **Nucleon decay**
- **Atmospheric neutrinos**
- **Supernova burst neutrinos**

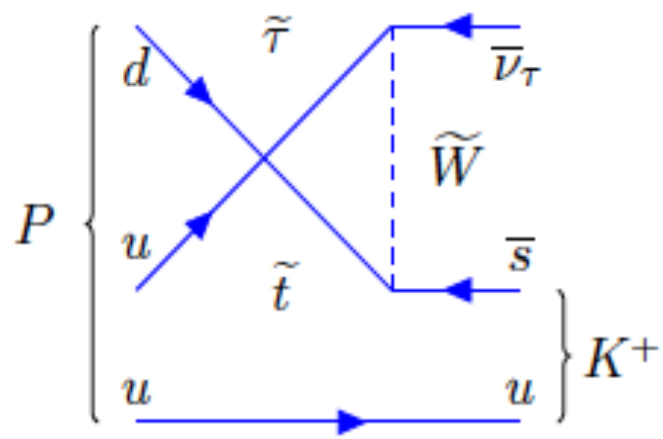
Other physics involving solar neutrinos, diffuse supernova background neutrinos, indirect dark matter searches are also being studied

Nucleon Decay Physics



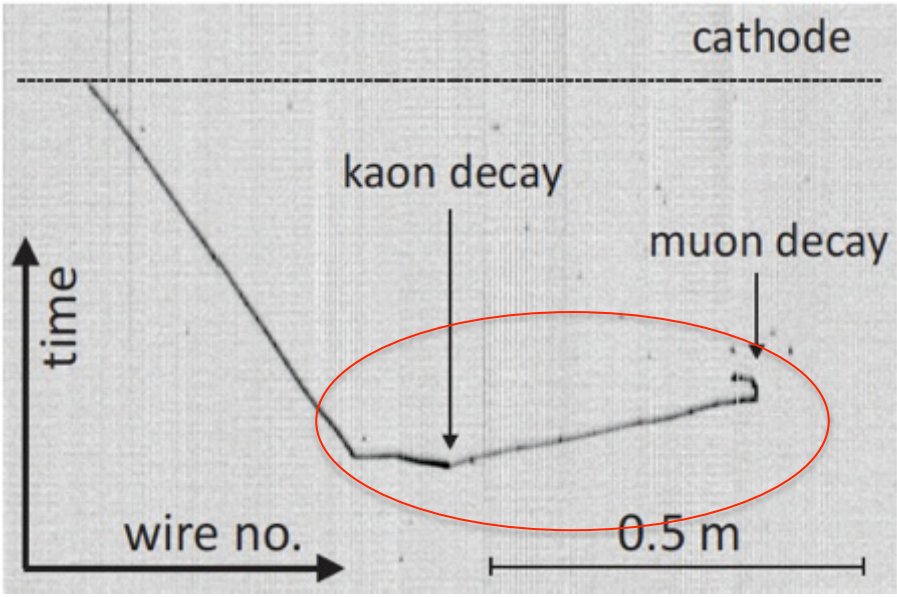
Where does the matter-antimatter asymmetry come from? Baryon number should be violated, ie. nucleon decay. GUT's allow B number violation and give predictions for the lifetimes of nucleon decay.

Some supersymmetric GUT models favor modes with kaons produced in the final state. DUNE has enhanced capability for detecting these modes, compared to water Cherenkov detectors.



Nucleon Decay in Liquid Argon

Collection plane of the ICARUS T600 detector



Cosmogenic induced kaon decay candidate as seen in ICARUS:

$$K \rightarrow \mu\nu_\mu$$

$$\mu \rightarrow e\nu_e\nu_\mu$$

Proton decay will produce a single p = 340 MeV K^+

Sources of backgrounds for the Kaon channels

Background Source	Mitigation Strategy
Internal cosmic ray spallation	Energy threshold
External cosmogenic K^+ production	Depth, fiducialization
External cosmogenic K^0 production +internal charge-exchange to K^+	Cuts on other secondaries
Atmospheric ν $\Delta S = 0$ processes	Cut on associated strange baryon
Atmospheric ν $\Delta S = 1$ processes	Cabibbo-suppressed, lepton ID
Atmospheric ν with π mis-ID	dE/dx discrimination, 236 MeV muon track
Reconstruction pathologies	dE/dx profiles vs track length

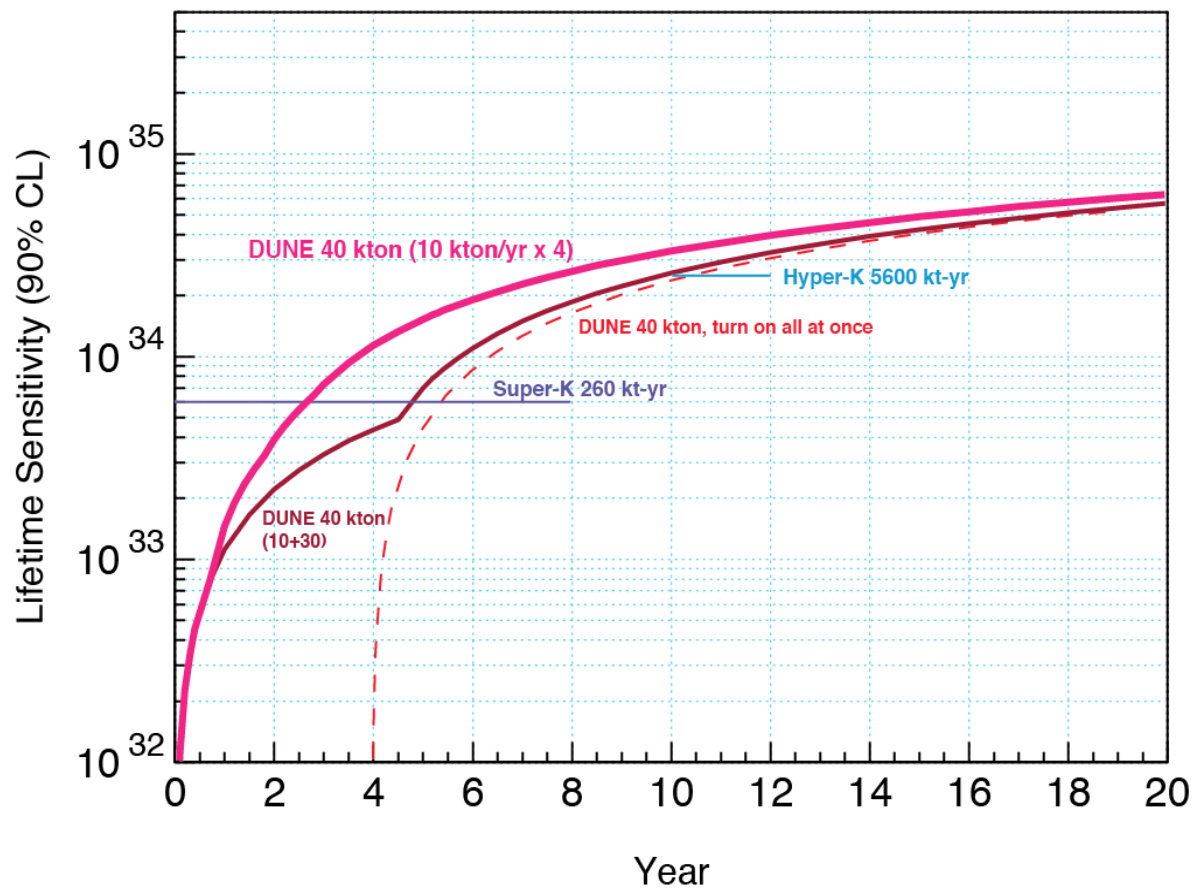
Backgrounds come from cosmic-rays and atmospheric neutrinos. Cosmic-rays mainly reduced by depth. Use energy threshold cut and strict PID (dE/dx) to tag final state baryons from atmospheric neutrinos – containment of final state particles is key.

Expected Sensitivity to Nucleon Decay

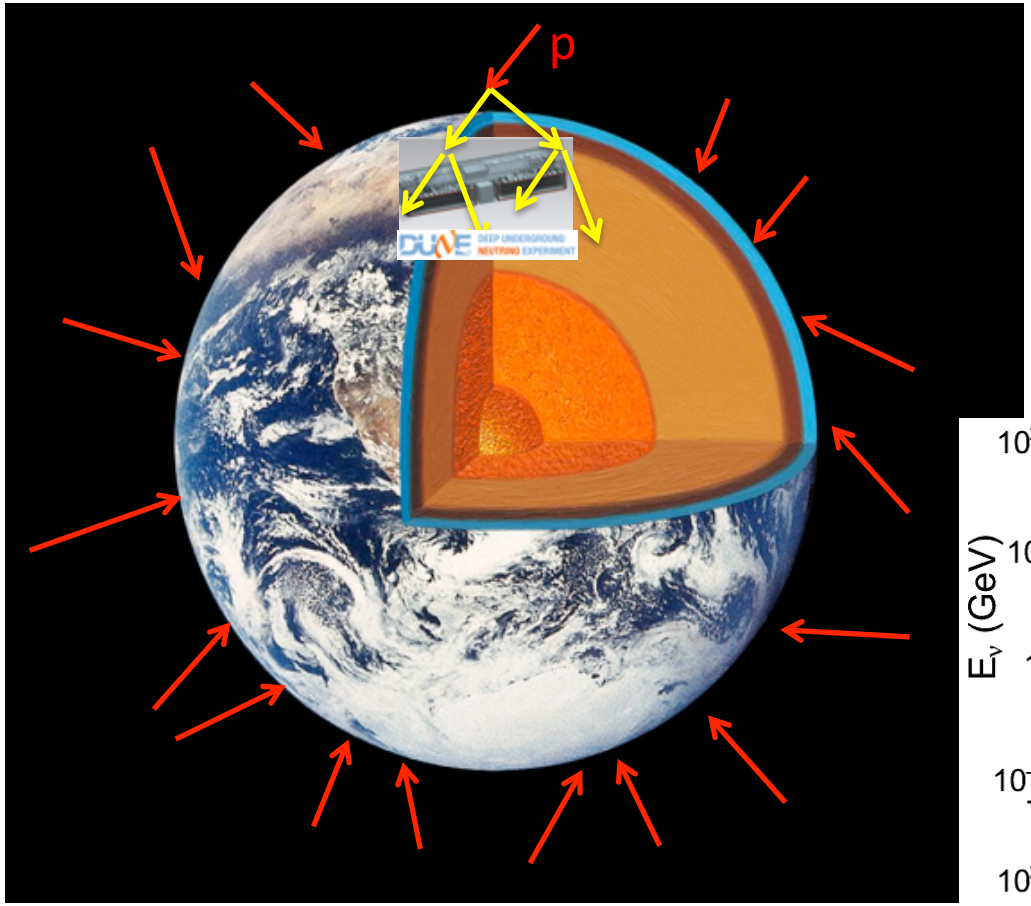
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

Background event rates are listed in events / (Mt•year) for the nucleon decay channels of interest.

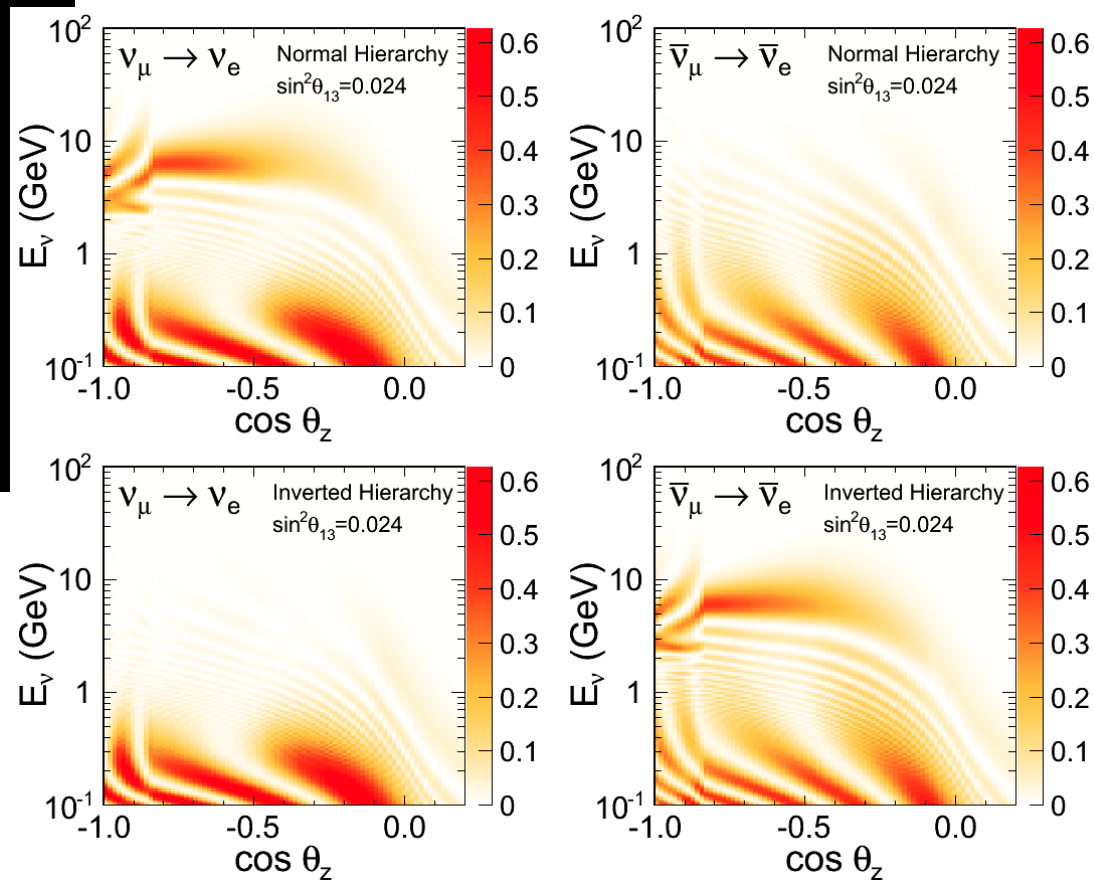
DUNE sensitivity depends on the phasing of the experiment. For a 20 year exposure with a 40 kt mass, upper limits on the proton lifetime will improve by an order of magnitude over limits set by Super-K for a 260 kt•year exposure.



Oscillation Studies with Atmospheric Neutrinos



The MSW resonance inside the Earth affects electron neutrinos of several GeV energy. Compare the effect on neutrinos and anti-neutrinos using statistical discrimination of event tagging features like p-recoil and decay electrons (nu or anti-nu?):



Oscillation parameters can be measured using atmospheric neutrinos (propagating through Earth) which cover a wide range of L/E.

Normal Hierarchy $\to \nu_e$ resonance
Inverted Hierarchy $\to \overline{\nu}_e$ resonance

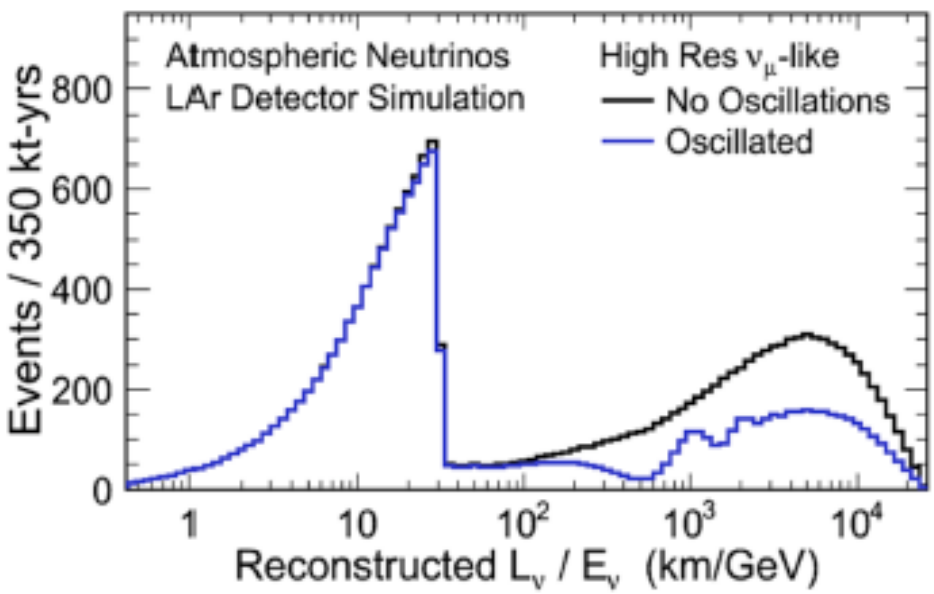
Oscillation Structure from MSW Effect

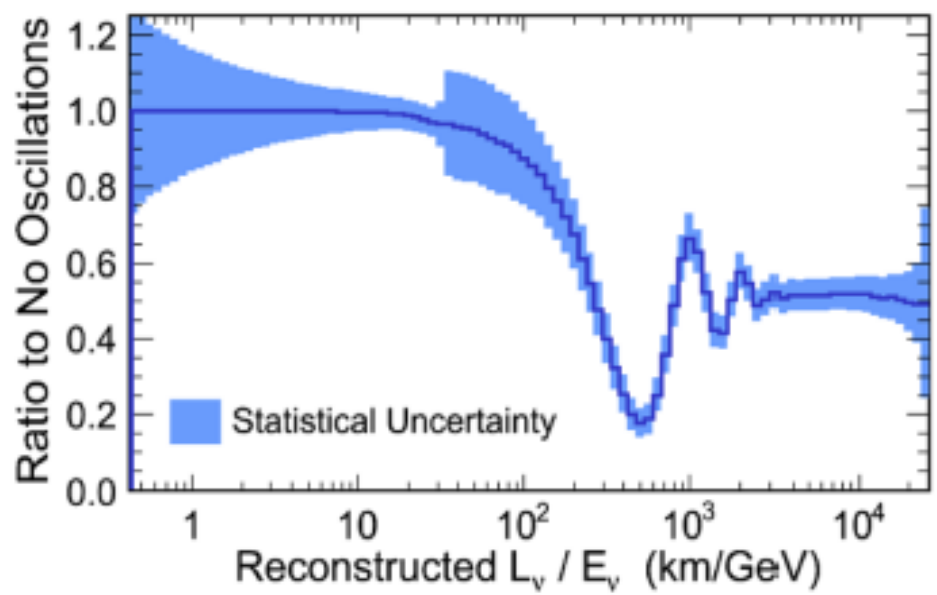
Summary of atmospheric neutrino interactions in DUNE (from detector simulation + GENIE). Relies on selecting high-resolution (energy and angle) events.

Expected sample for 350 kt-yr exposure

Sample	Event Rate
fully contained electron-like sample	14,053
fully contained muon-like sample	20,853
partially contained muon-like sample	6,871

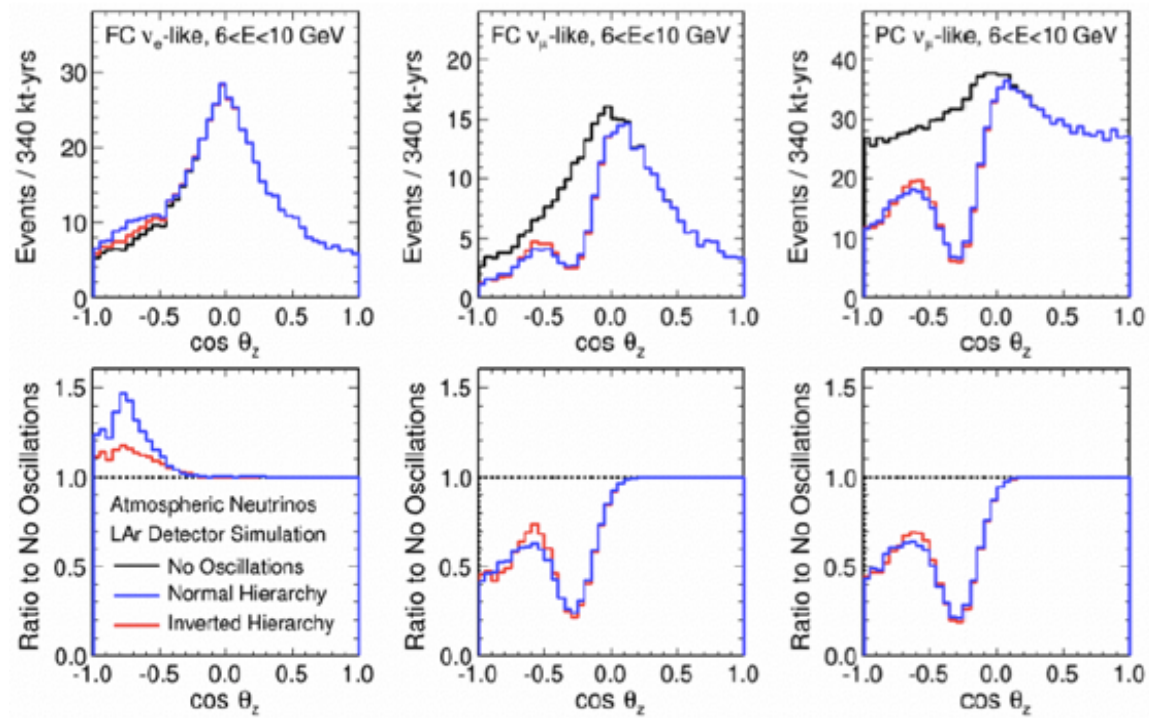
L/E distributions for a 350 kt•year exposure with ratio of oscillated and no oscillations – structure is very well-defined. Events from each containment sample are binned by energy and angle for oscillation analysis.



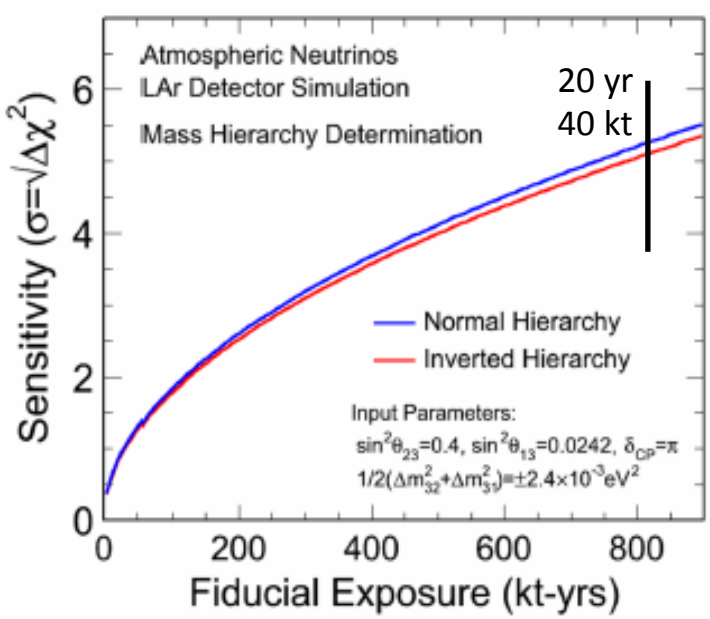


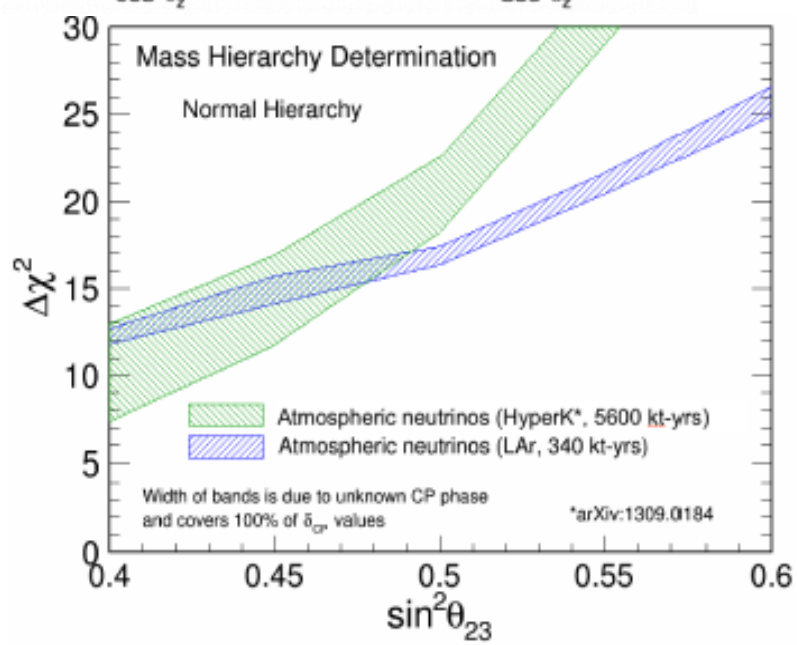
Atmospheric Neutrino Sensitivity to Mass Hierarchy

Relies mainly on electron neutrino appearance and muon neutrino disappearance. Differences between hierarchies appear when compared to 'no-oscillation' scenario. **Unlike beam analysis, mass hierarchy sensitivity is essentially independent of δ_{CP}.**

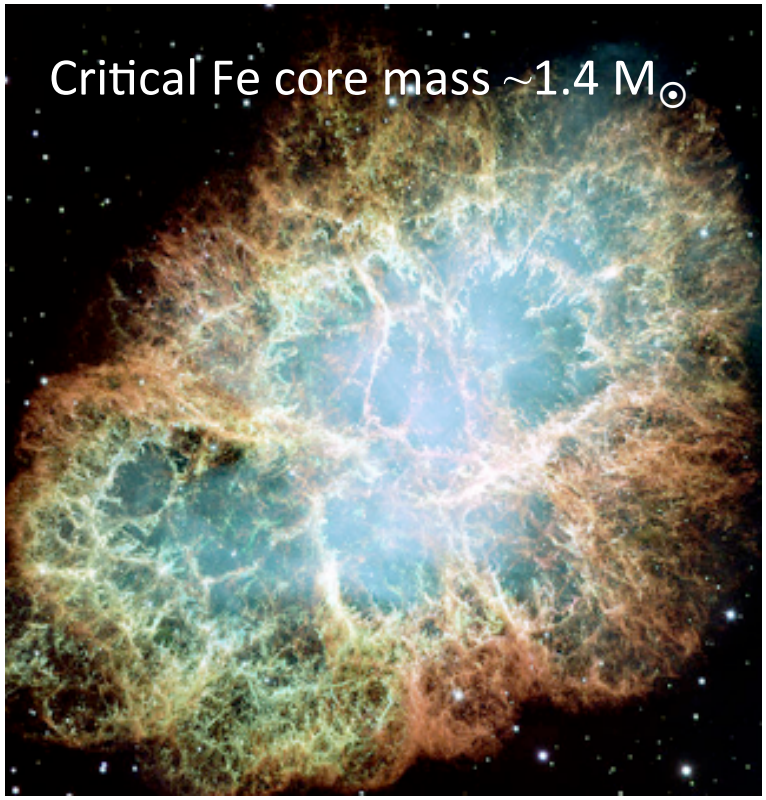


Sensitivity of 40 kt DUNE is comparable to Hyper-K due to better angular and energy resolution of a LArTPC.



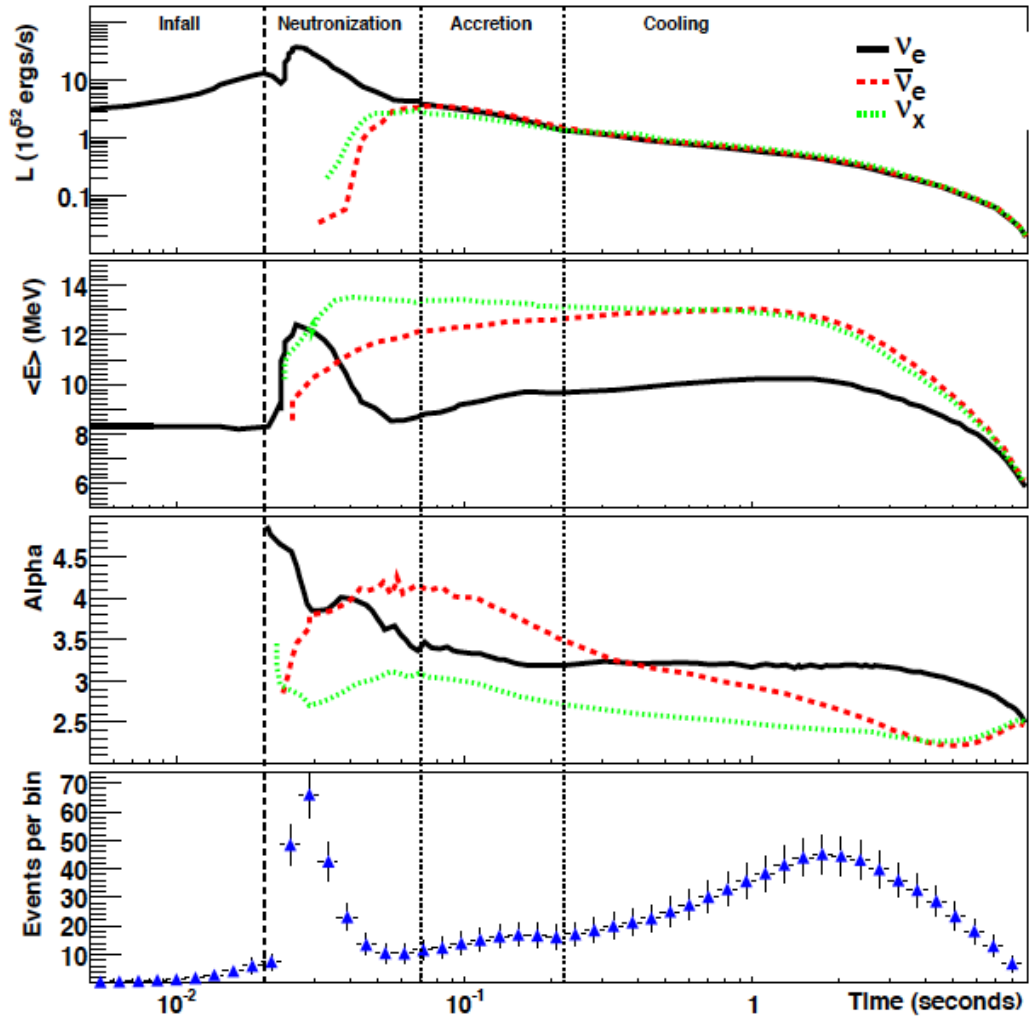


Supernova Burst Neutrinos



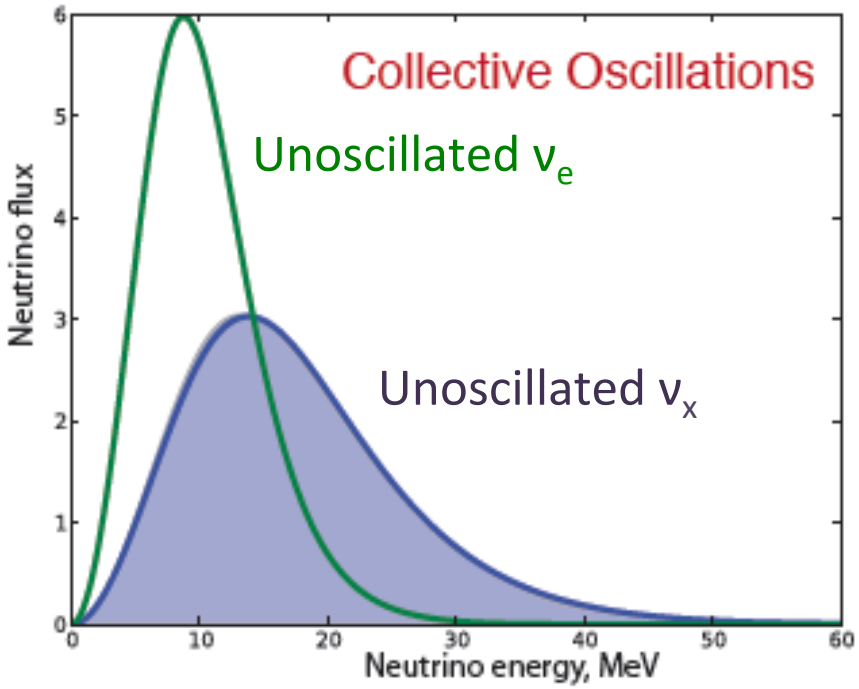
For core-collapse supernovae, about 99% of the gravitational binding energy is emitted in the form of neutrinos – on the order of 10^{58} over the course of the explosion!

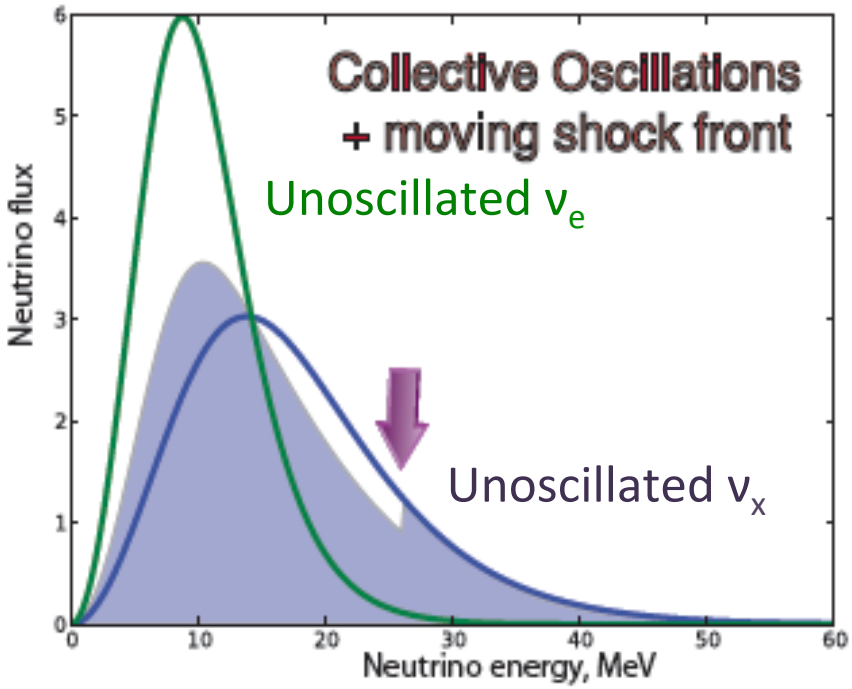
Below is the evolution of the burst for a specific flux model. Neutronization ($p + e^- \rightarrow n + \nu_e$) burst at early times is primarily electron flavor – only liquid argon detectors are sensitive to this component.



Supernova Neutrino Dynamics

Extreme conditions inside the supernova produce exotic effects, like neutrino-neutrino interactions, that are visible in the observed energy spectrum on Earth.





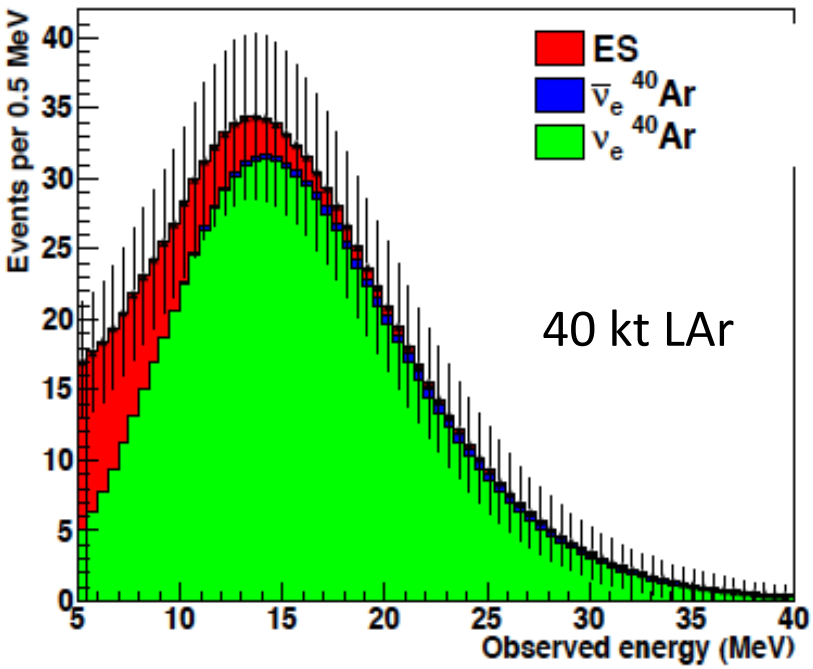
The ability to do physics with supernova neutrinos relies heavily on accurate reconstruction of the true neutrino energy. This is a non-trivial task.

Obtaining Physics from Detection

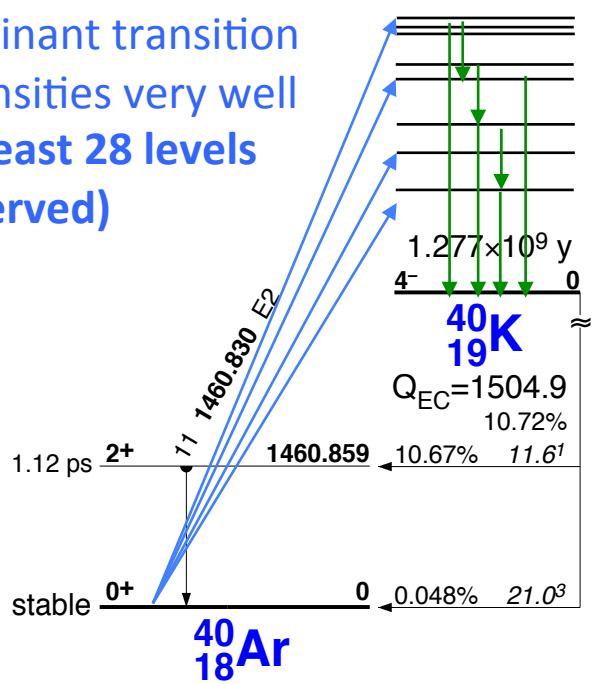
Reconstructing true neutrino energy:

Neutrino Energy — Outgoing Electron Energy — Q-value of Transition — Recoil Energy of Nucleus

CC reaction: $E_\nu = E_e + Q + K_{\text{recoil}}$



We need to know dominant transition intensities very well **(at least 28 levels observed)**



Also need to know all the de-excitation gammas and their branching fractions

Reaction Type	Events / 10 kt
(CC) $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	~700 [1]
(CC) $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	~60 [1]
(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$	~85 [1]
(NC) $\nu_x + {}^{40}\mathrm{Ar} \rightarrow \nu_x + {}^{40}\mathrm{Ar}^*$	~90 [2]

(SN at 10 kpc)

[1] K. Scholberg
[2] A. Hayes

Supernova Neutrino Detection Challenges

Key aspects that must be addressed for energy reconstruction:

- Need to develop accurate model of energy levels and gamma/nucleon evaporation for excited states $^{40}K^*$, $^{40}Cl^*$ and $^{40}Ar^*$

- Model needs to address both the ***bound and the unbound*** states of the final nucleus (QRPA for example)

- One such model is currently under development:

  ***MARLEY**: **M**odel of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields*

  (S. Gardiner, K. Bilton, C. Grant, R. Svoboda, E. Pantic)

- Small scale LAr TPC near a source of <60 MeV electron neutrinos needs to demonstrate that the model is correct (or fine-tune it)

  Example: CAPTAIN TPC (0.35 ton or 5 ton) near a source of electron neutrinos from muon decays at Fermilab

Conclusions

- DUNE, with 40 kt of LAr at a depth of 4850 ft, has significant potential for exciting underground physics. Greatest potential from the following: **nucleon decay**, **atmospheric neutrino oscillations**, and **SN burst neutrinos**

- **Nucleon decay sensitivity comes primarily in the form of modes with kaons, preferred by some SUSY GUT models**
  - Particle ID, dE/dx, threshold cuts are very important for tagging a single kaon and rejecting events from atmospheric neutrinos
  - Sensitivity to lifetime bounds can improve from $\sim 6 \times 10^{33}$ (SK) to $\sim 6 \times 10^{34}$ using these modes

- **Atmospheric neutrino oscillations provide complimentary physics to the beam source**
  - MSW effect in the Earth can be used to obtain information on the neutrino mass hierarchy

Conclusions

- Sensitivity to the mass hierarchy strongly depends on θ_{23} but not so much on the value of δ_{CP}

- **Supernova burst at 10 kpc will yield ~3000 electron neutrino CC interactions on ^{40}Ar in DUNE (40 kt). Neutrinos can provide us with information on the dynamics of the burst and other exotic phenomena**
  - Information comes from the SN neutrino energy, which needs to be accurately reconstructed
  - Complications arise in the energy reconstruction from lack of precision models of argon reactions at < 60 MeV and lack of direct measurements for comparison
  - Efforts are being made to study this problem with indirect beam sources and small-scale experiments

Thank you!

DUNE Collaboration at first meeting

Co-spokespersons

André Rubbia

Mark Thomson

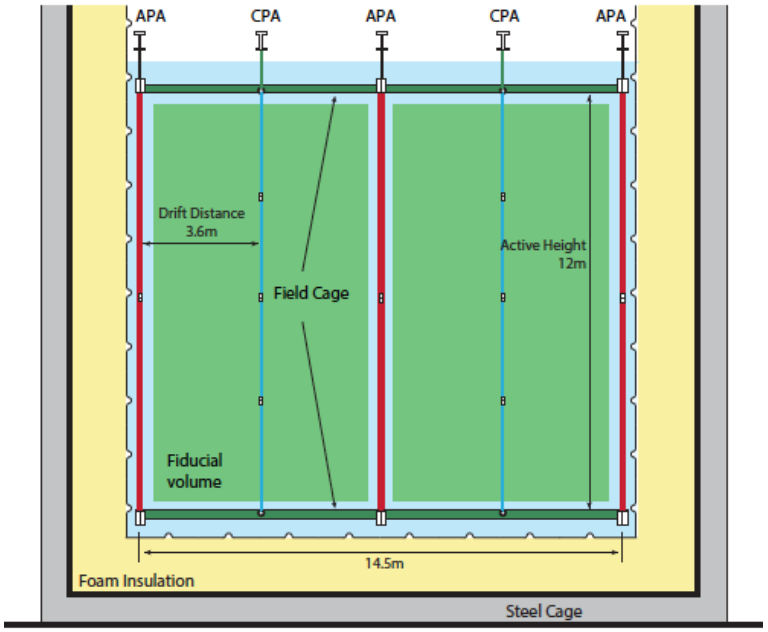
DUNE is a multi-national collaboration is made up of 144 institutions from 26 countries

Backup

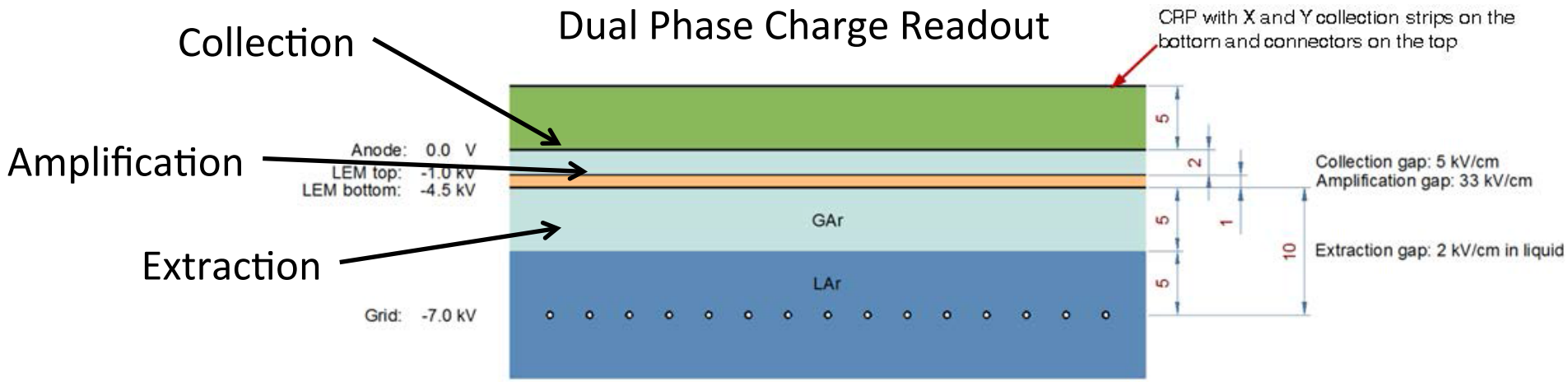
Single Phase TPC Concept

Parameter	Reference Performance	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio[1]	9:1	10:1 [6, 7][2]	9:1
Electron Lifetime	3 ms	> 15 ms [7]	> 3 ms
Uncertainty on Charge Loss due to Lifetime	$< 1\%$	$< 1\%$ [7]	$< 1\%$
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution[3]	(2.5,2.5,2.5) cm		(1.1,1.4,1.7) cm [8, 9]
$e-\gamma$ separation ϵ_e	0.9		0.9
$e-\gamma$ separation γ rejection	0.99		0.99
Multiple Scattering Resolution on muon momentum[4]	$\sim$18%	$\sim$18% [10, 11]	$\sim$18%
Electron Energy Scale Uncertainty	5%	2.2%[12]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\mathrm{MeV})}$ $\oplus 1\%$	$0.33/\sqrt{E(\mathrm{MeV})}$ [12] $+1\%$	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	1–5%		From LArIAT and CERN Prototype
Stub-Finding Efficiency[5]	90%		$> 90\%$

DUNE



Dual Phase TPC Concept



Comparing to single-phase design:

- Higher gain and larger S/N
- Larger fiducial volume
- Lower detection threshold
- 3 mm pitch in x and y readout
- Fewer readout channels: 154k vs 384k for single phase
- Absence of dead material in LAr volume