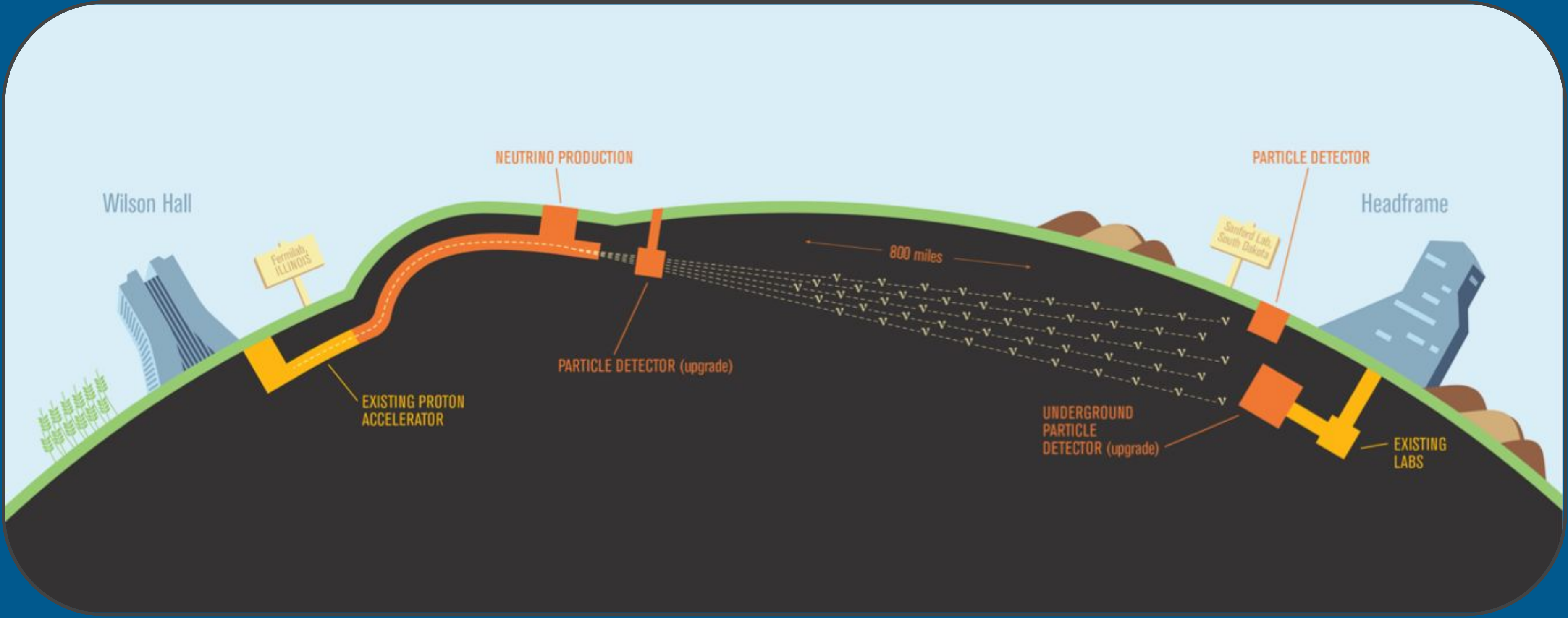
The Deep Underground Neutrino Experiment

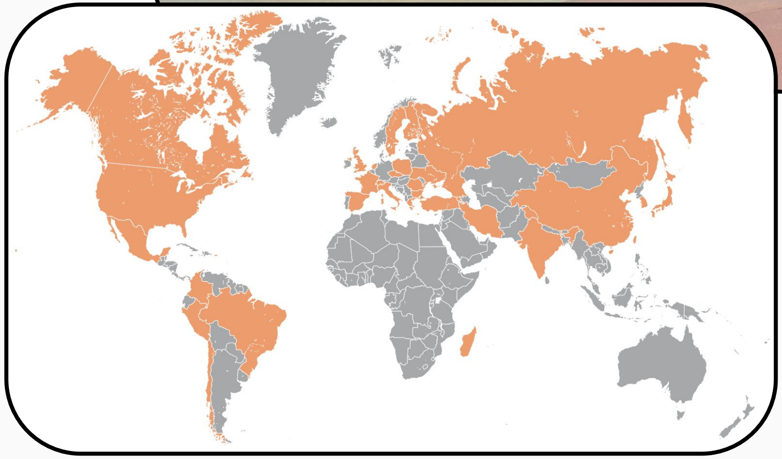
Matt Bass - University of Oxford

XVII International Workshop on Neutrino Telescopes



- Will measure ν_e appearance and ν_μ disappearance in a wideband ν beam at a 1300 km baseline
- Access to CP violation, mass hierarchy, and neutrino mixing parameters in a single experiment
- Large, underground detector also gives access to nucleon decay, supernova burst ν, and other interesting physics

DUNE Overview

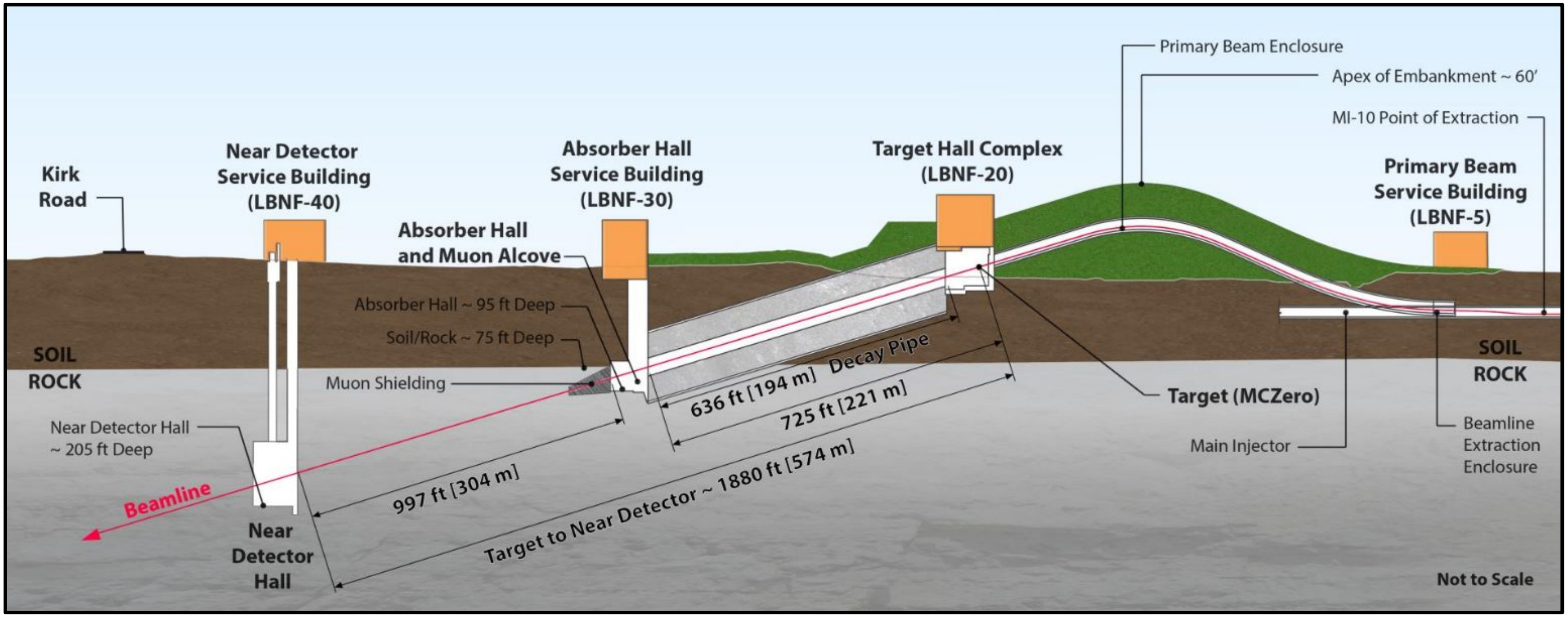


~1000 collaborators from 160 institutions in 30 nations

DUNE Collaboration

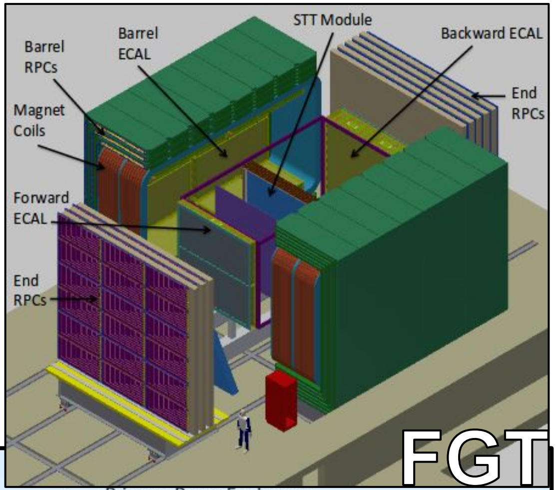
Beam

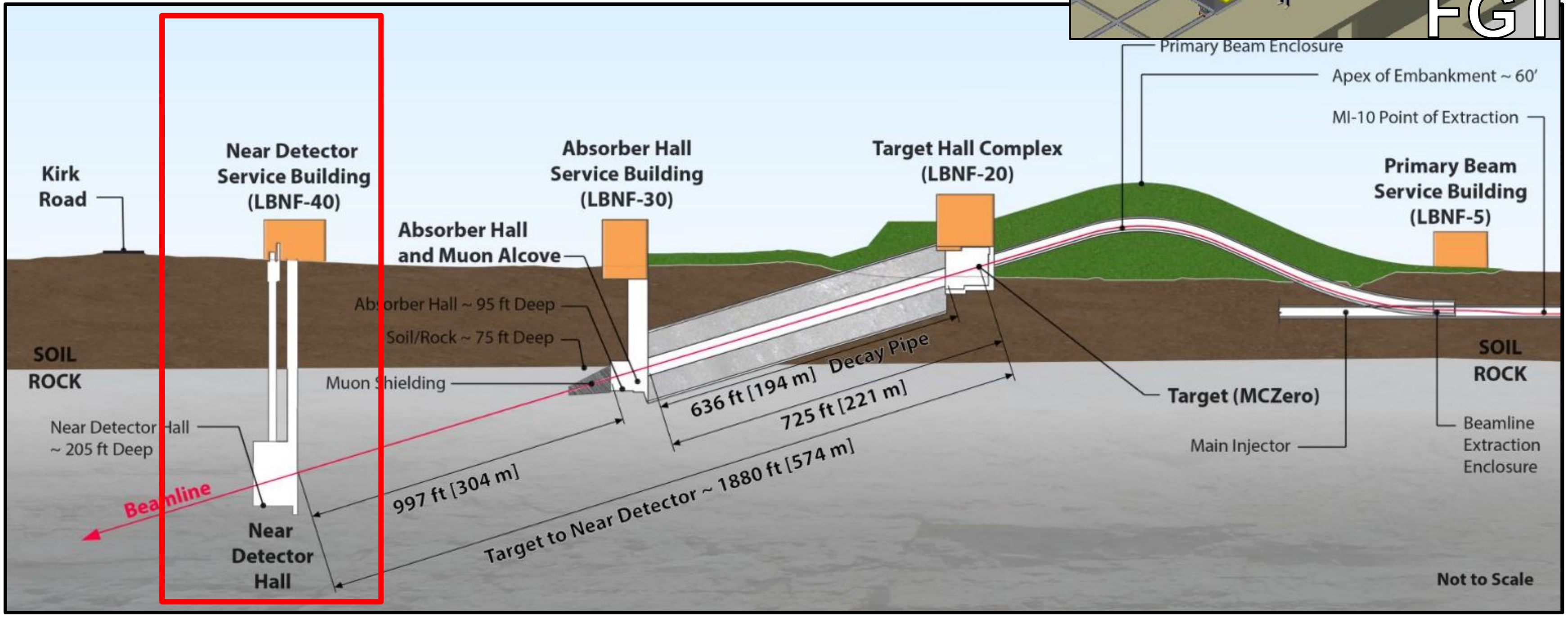
- **LBNF Neutrino Beam** (Long Baseline Neutrino Facility):
  - DOE/Fermilab hosted project with international participation
  - LBNF houses, and delivers beam to, detectors built by DUNE collaboration
- Horn-focused beam line similar to NuMI beam line
  - 60-120 GeV **protons** from Fermilab's Main Injector
  - 200 m decay pipe at ~5.8° pitch, angled at South Dakota (Sanford Underground Research Facility - **SURF**)
  - Initial **power**: 1.2 MW (@120 GeV); plan to upgrade to 2.4 MW
  - **Beam design** has been optimized for oscillation sensitivity



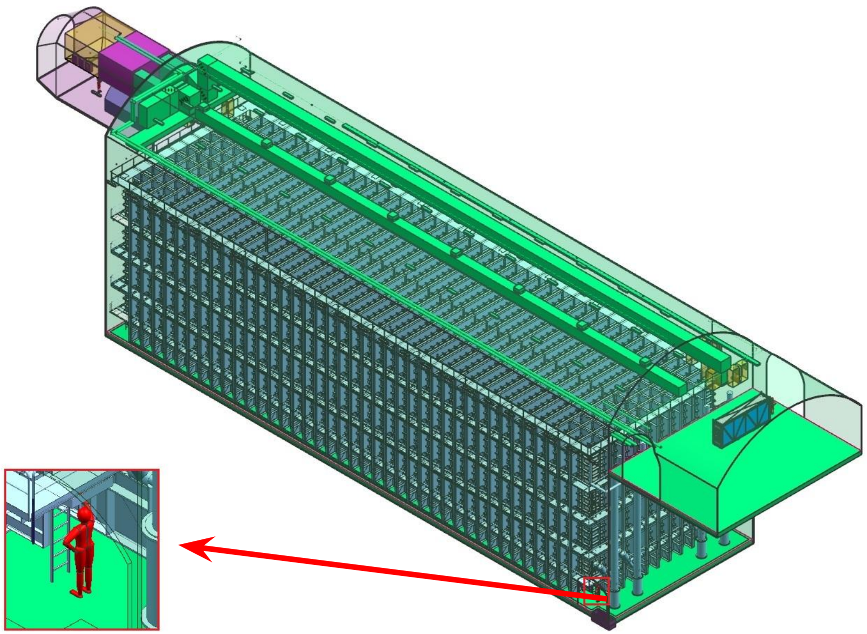
Near Detector

- DUNE will also have a **near detector**
  - Constrain systematic uncertainties in oscillation measurements
  - Precisely measure initial fluxes of neutrinos in the beam
  - Measure multiple neutrino cross sections
- Multiple **designs** under consideration
  - Liquid Argon TPC
  - High Pressure Gas Argon TPC
  - Fined-grained straw-tube tracker
  - Hybrid designs

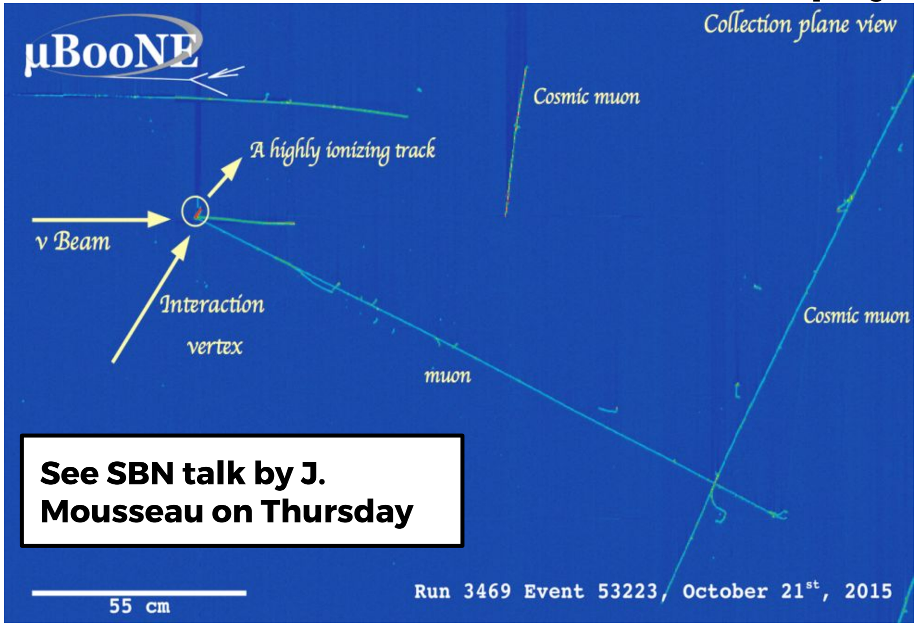




Far Detector

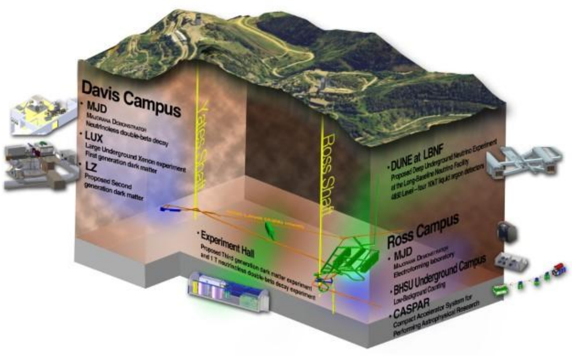


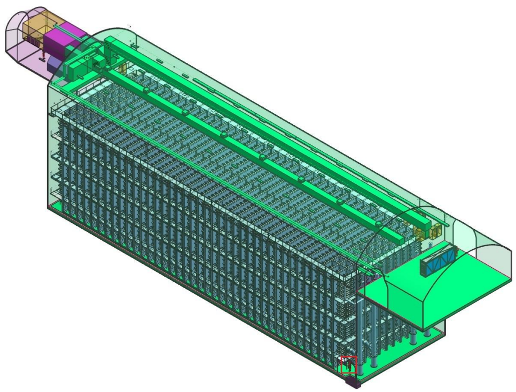
MicroBooNE LArTPC Event Display



- **40-kt** (fiducial) liquid argon TPC (**LArTPC**) at 4850L of SURF
- Four **10-kt** (fiducial) modules
- First module will be a **single phase LArTPC**
- Modules installed in **stages**; modules not necessarily identical
- Photon detection system

DUNE Timeline





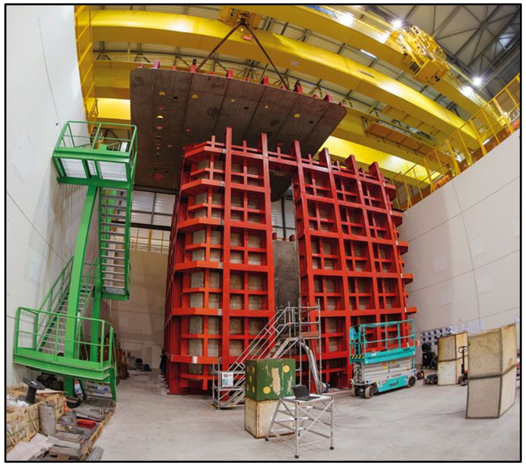
2017: Far Site Construction Begins

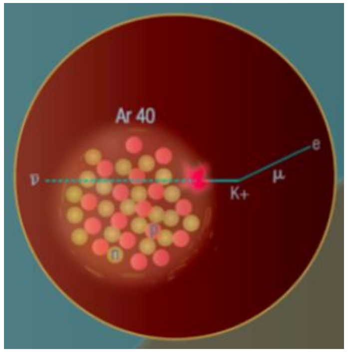
2018: protoDUNEs at CERN

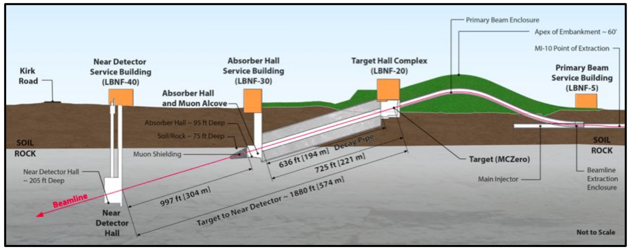
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available







DUNE Physics Program

Long-baseline Oscillation Physics

Nucleon Decay

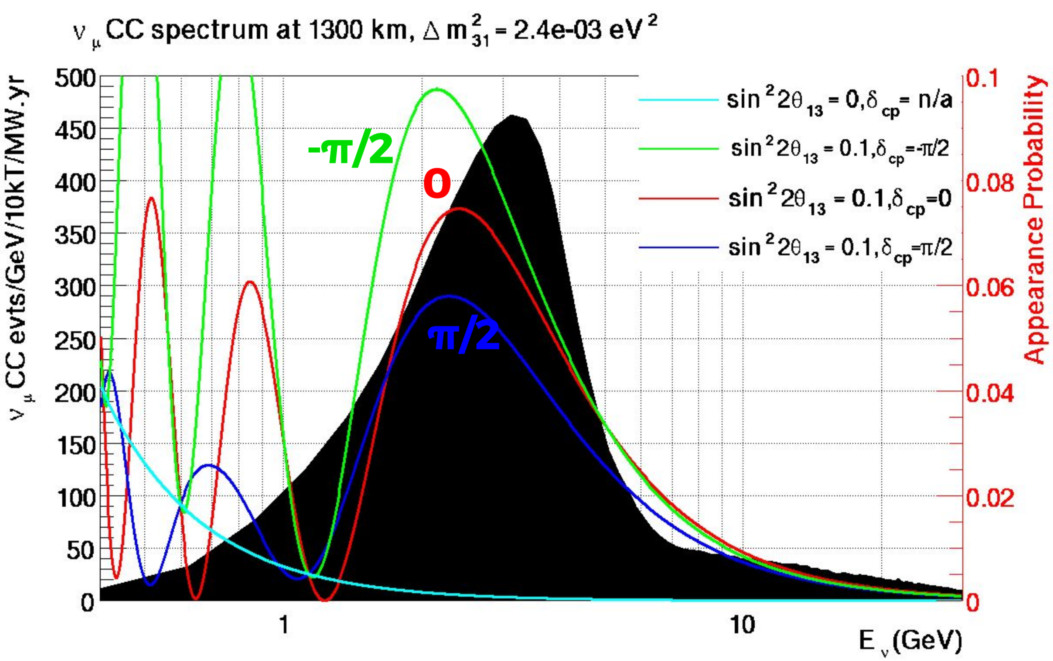
Supernova Burst ν

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



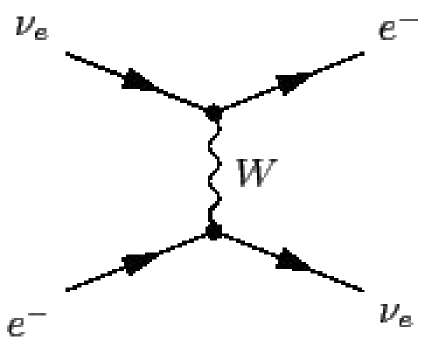
Large value of **$\sin^2(2\theta_{13})$** allows **significant ν_e appearance sample**

ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and **matter effects**

Measure all four in a single experiment!

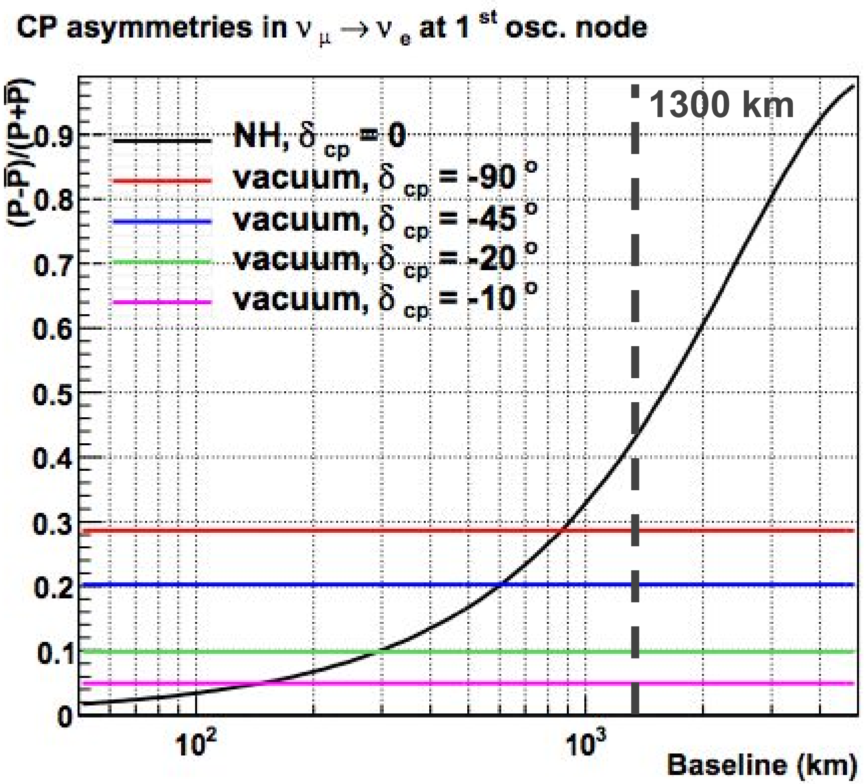
Matter & CP Asymmetry

Charged-current coherent forward scattering on electrons:



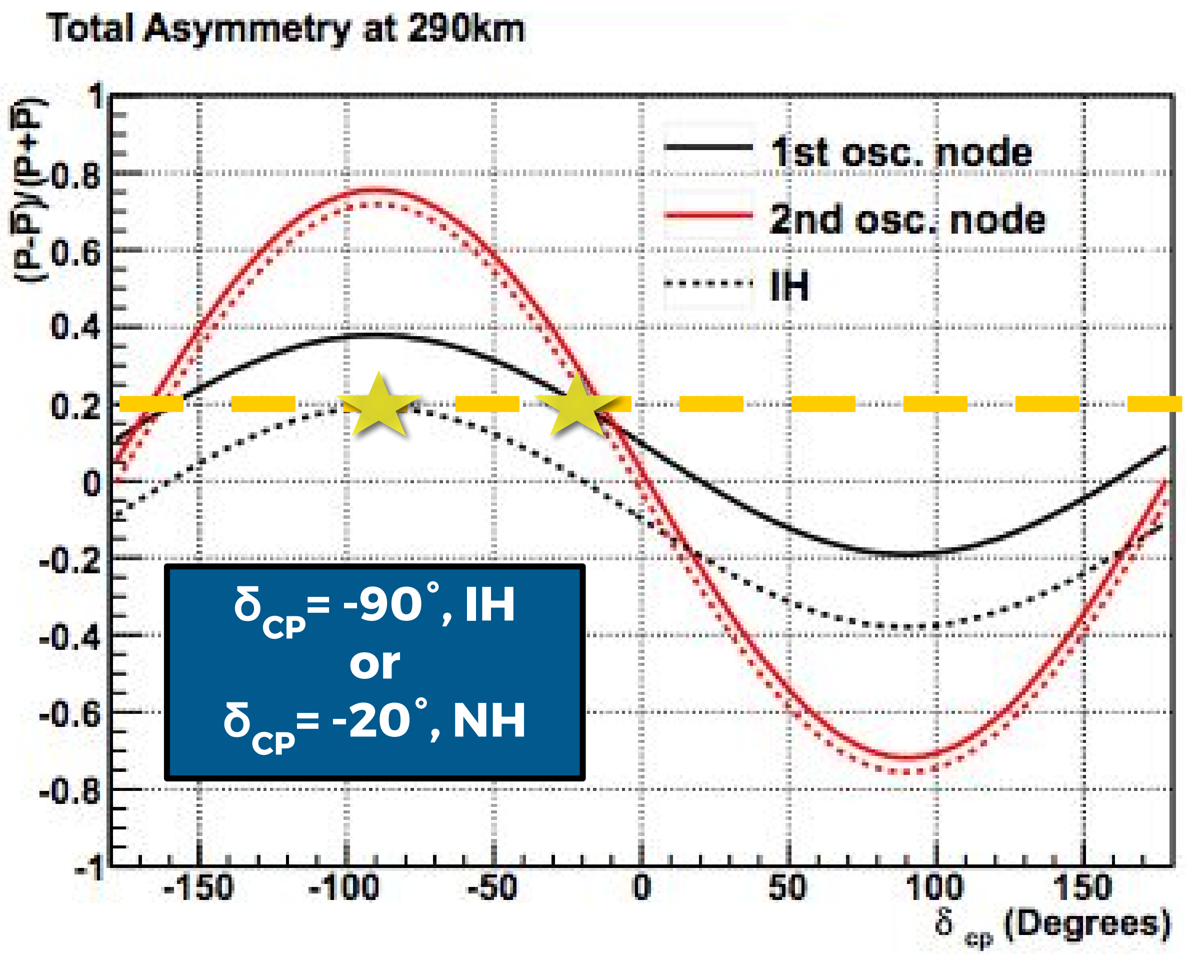
This **CC process** occurs for ν_e only; ν_μ and ν_τ have only NC interactions with electrons

In the Normal Hierarchy (NH), the matter effect **increases** appearance probability for neutrinos and **suppresses** it for antineutrinos



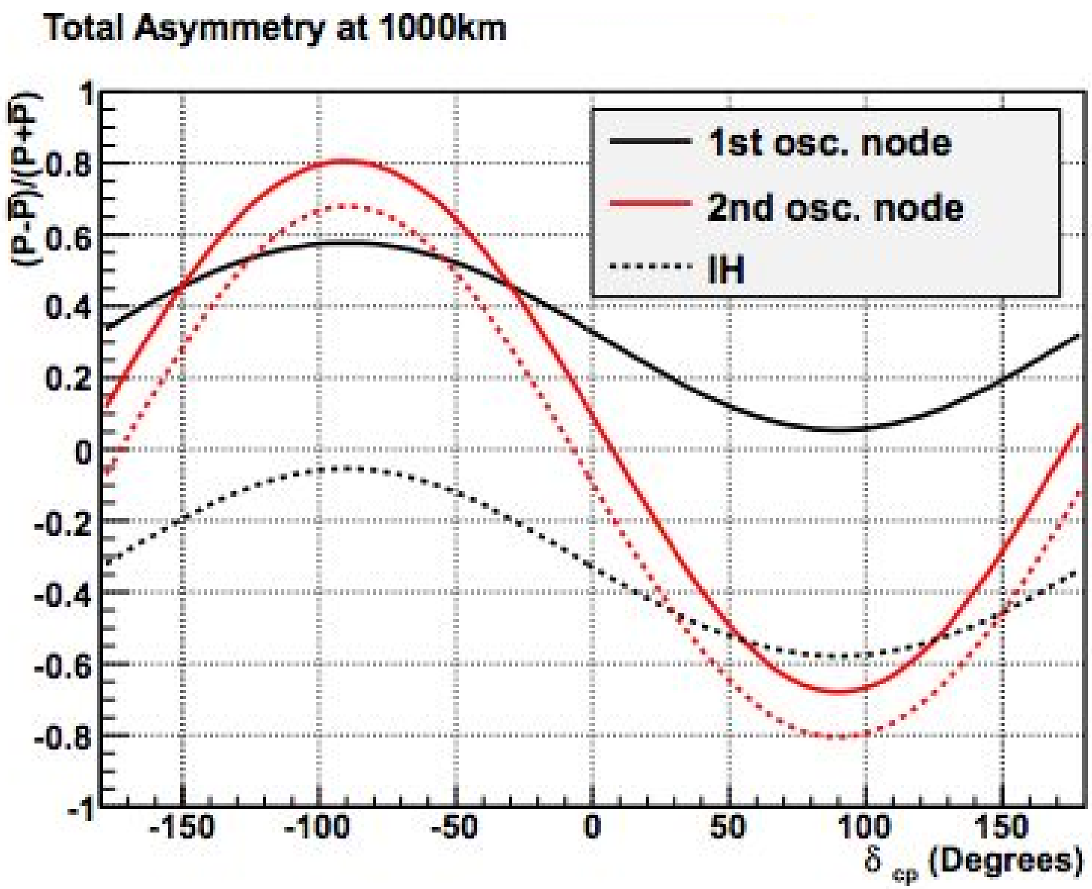
Matter asymmetry very important for long-baseline experiments!

Matter & CP Asymmetry



Degeneracy between CP and matter asymmetry for 1st oscillation node at short baseline

Matter & CP Asymmetry

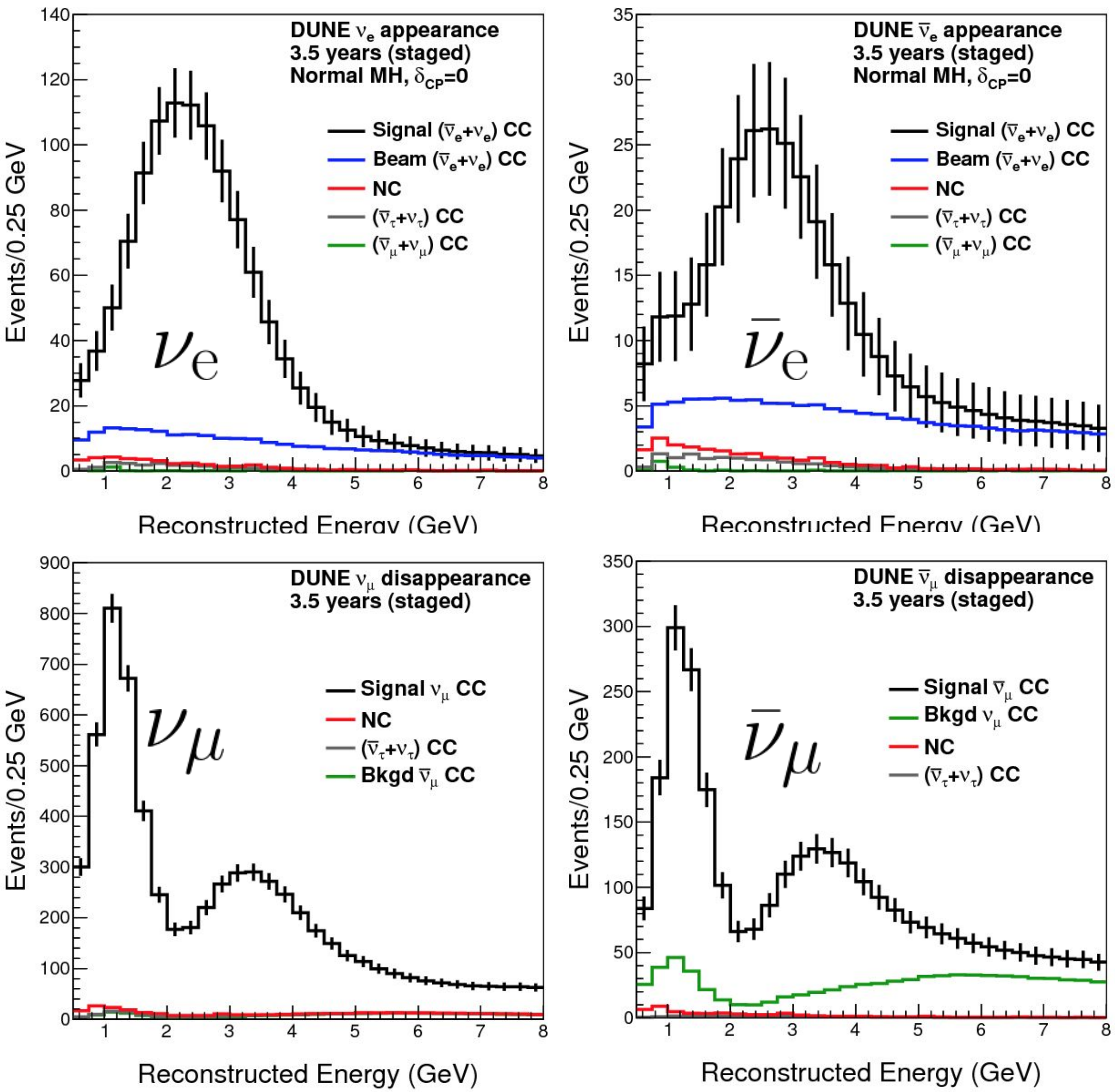


Baseline Optimization Study arXiv:1311.0212

Longer baseline **breaks degeneracy** between CP and matter asymmetry. Optimal baseline: ~1300 km

Wideband beam also helps break degeneracy.

Oscillation Sensitivity Overview



- GLoBES-based **simultaneous fit** to four FD samples
- Optimized **beam**-line
- **GENIE** event generator
- Reconstructed spectra predicted using expected **detector response** parameterized at the single particle level
- Order 1000 ν_e **appearance** events in ~7 years of equal running in neutrino and antineutrino mode
- Normalization **systematics** on signal & backgrounds
- GLoBES **configurations** arXiv:1606.09550

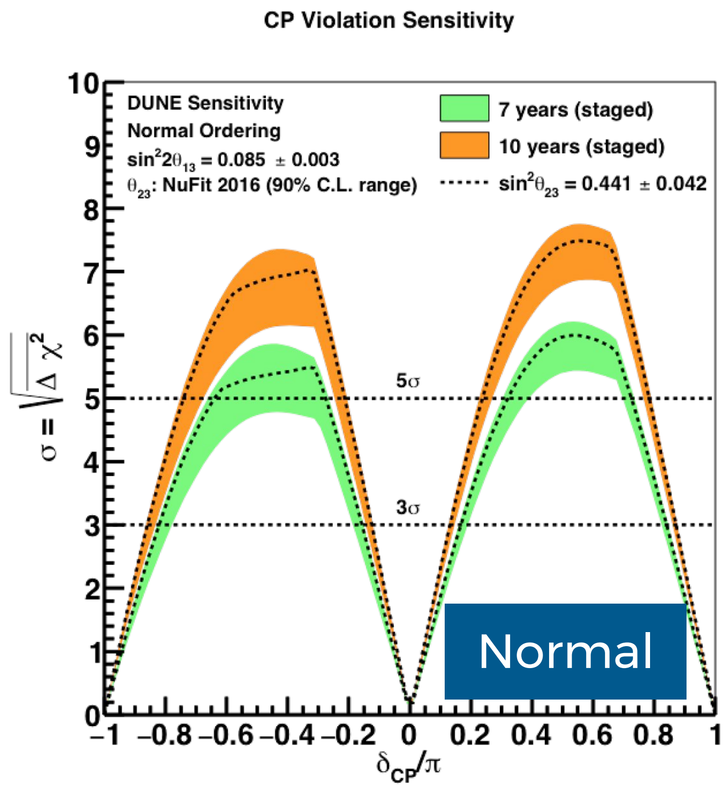
Staging

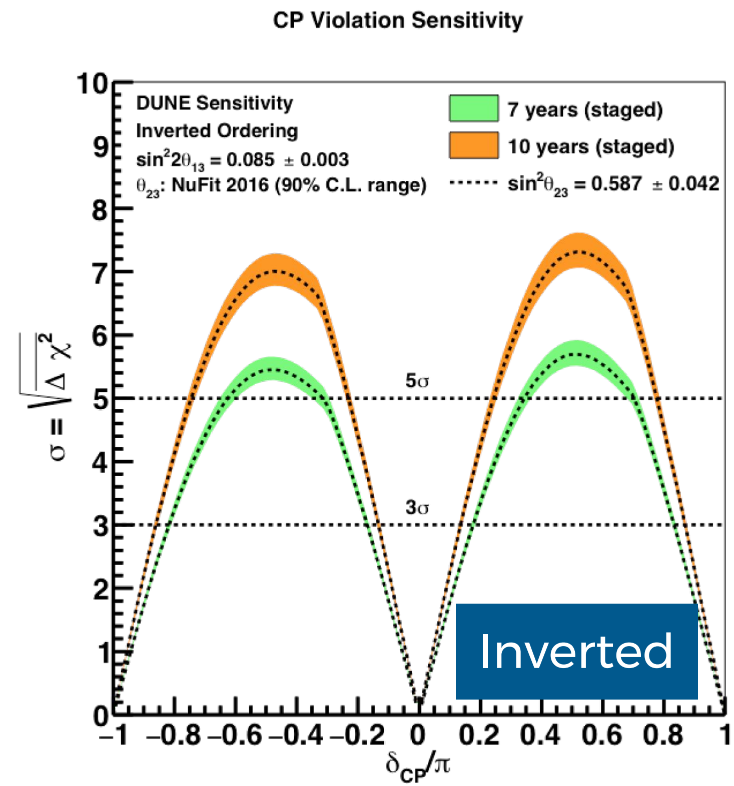
Experiment will be built in **stages**, so our oscillation sensitivities reflect this **staging plan**:

- **Year 1 (2026)**: 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- **Year 2 (2027)**: 30-kt FD
- **Year 4 (2029)**: 40-kt FD and improved ND constraints
- **Year 7 (2032)**: upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	**Exposure (Years)**
171	5
300	**7**
556	**10**
984	15

CP Violation Sensitivity

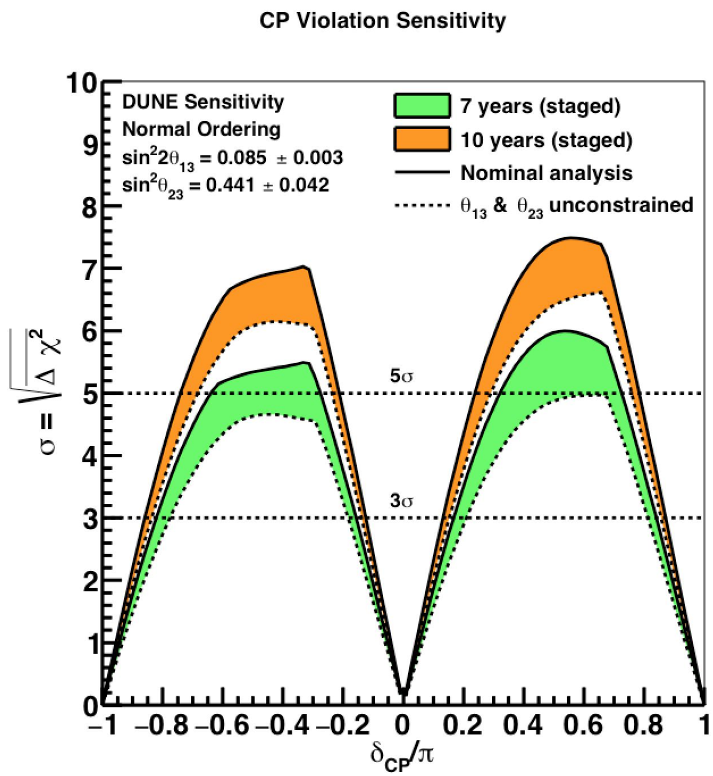




Width of band corresponds to 90% CL variations in value of θ_{23} based on NuFit 2016 fit values

Includes normalization **systematics** and results are **profiled** over oscillation parameter uncertainties, MH, and octant

CP Violation Sensitivity

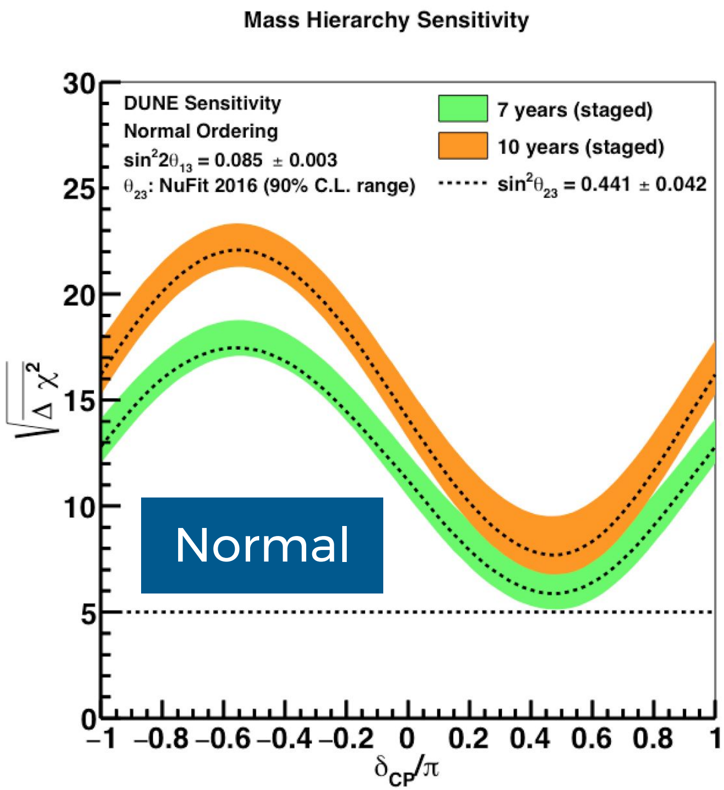


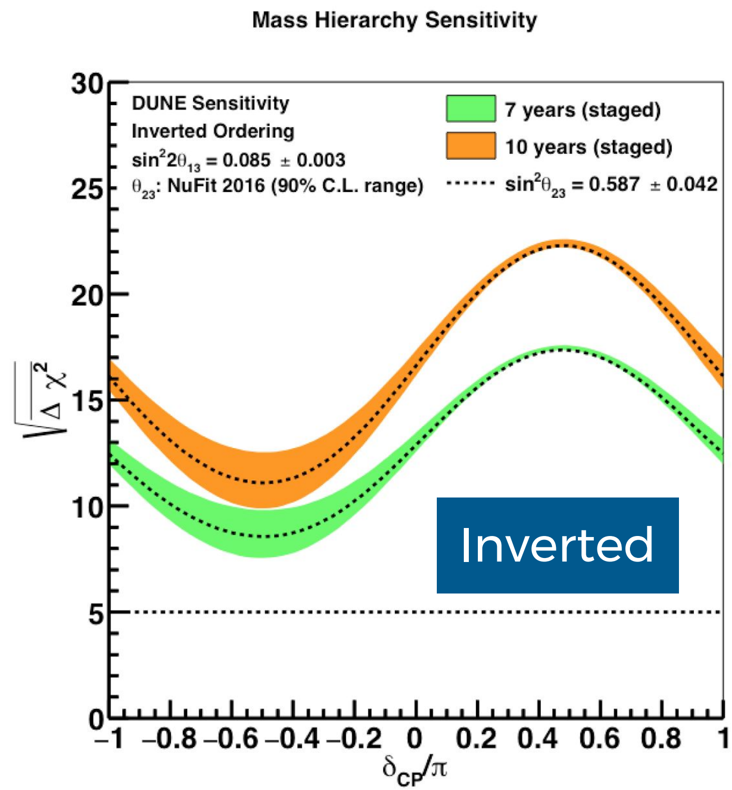
Top of band: Nominal analysis including external constraints

Bottom of band: θ_{13} and θ_{23} constraints removed

DUNE has sensitivity to measure all three oscillation parameters (θ_{13}, θ_{23}, δ_{CP}) and matter effects in a **single experiment**!

Mass Hierarchy Sensitivity





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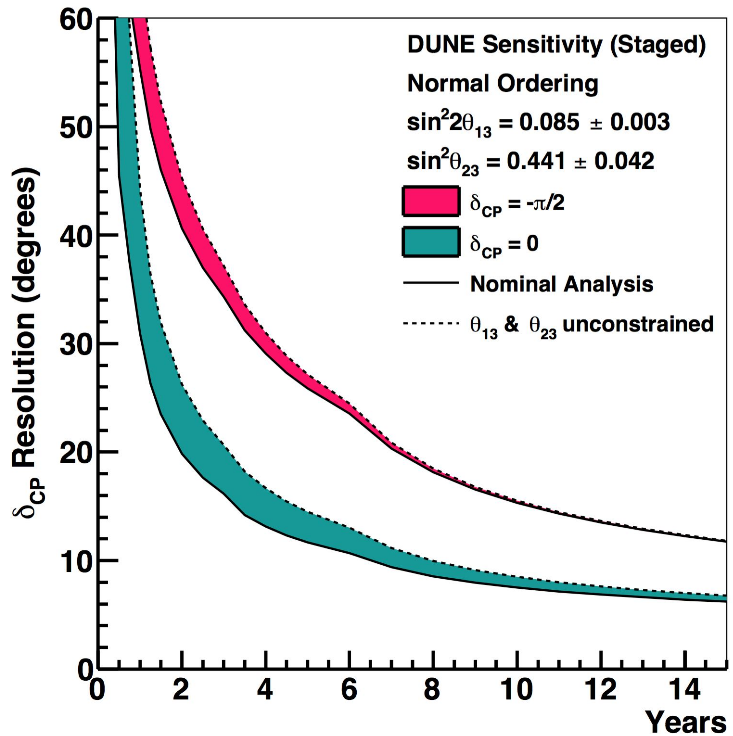
Includes normalization **systematics** and results are **profiled** over oscillation parameter uncertainties and octant

δ_{CP} Resolution

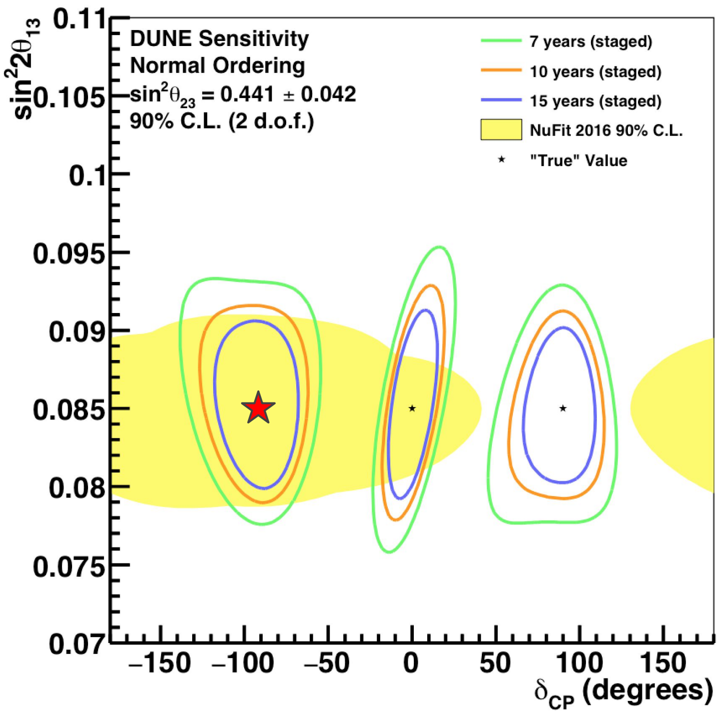


Top of band: Nominal analysis including external constraints

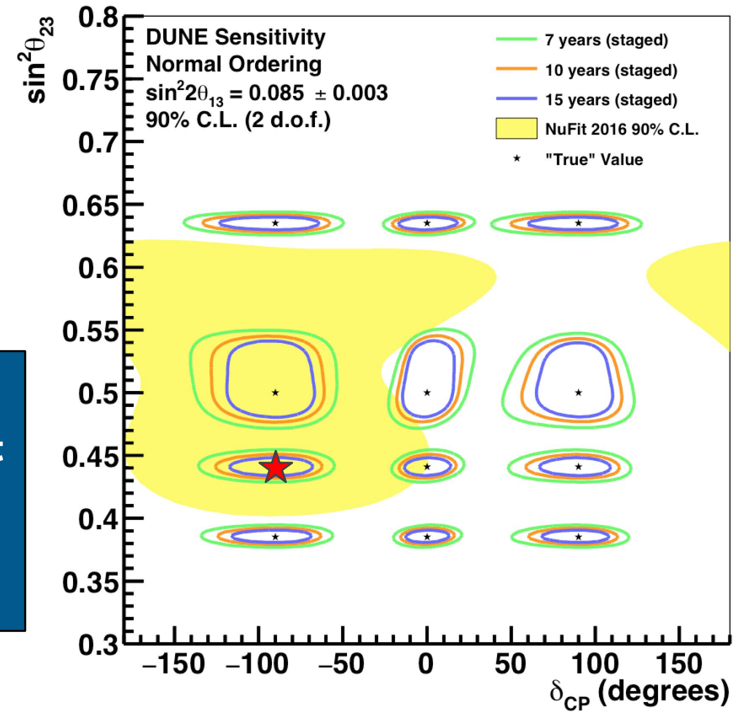
Bottom of band: θ_{13} and θ_{23} constraints removed

Reach **~7° (16°) resolution** in **10 years** for **δ_{cp}=0° (-90°)**

2-D Parameter Sensitivity



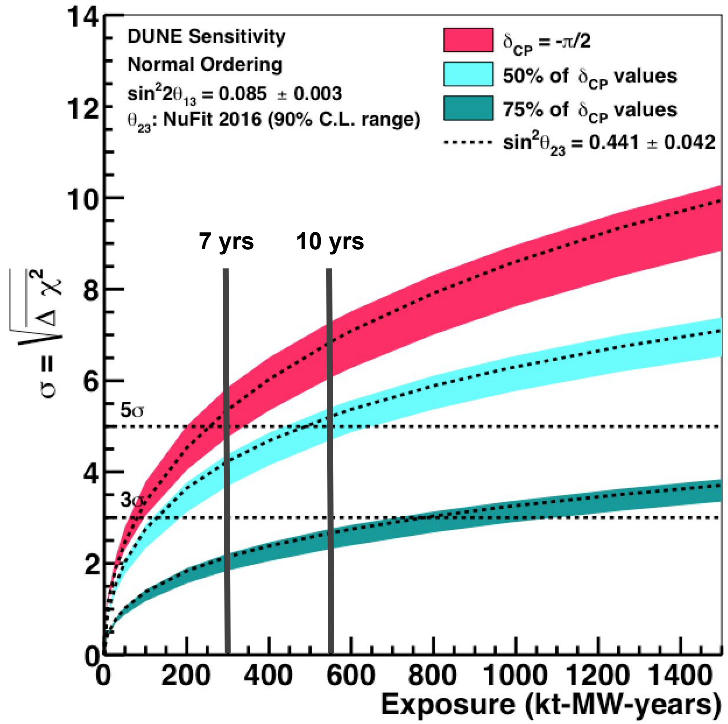
Near NuFit 2016 Best-fit



Yellow regions represent **90% CL contours** from NuFit 2016

Significant **improvements** on oscillation parameter constraints

CP Violation Sensitivity vs Time



Width of **band** corresponds to 90% CL variations in value of $\boldsymbol{\theta_{23}}$.

δ_{cp}=-π/2 or 50%, 75% of δ_{cp} values covered at indicated significance

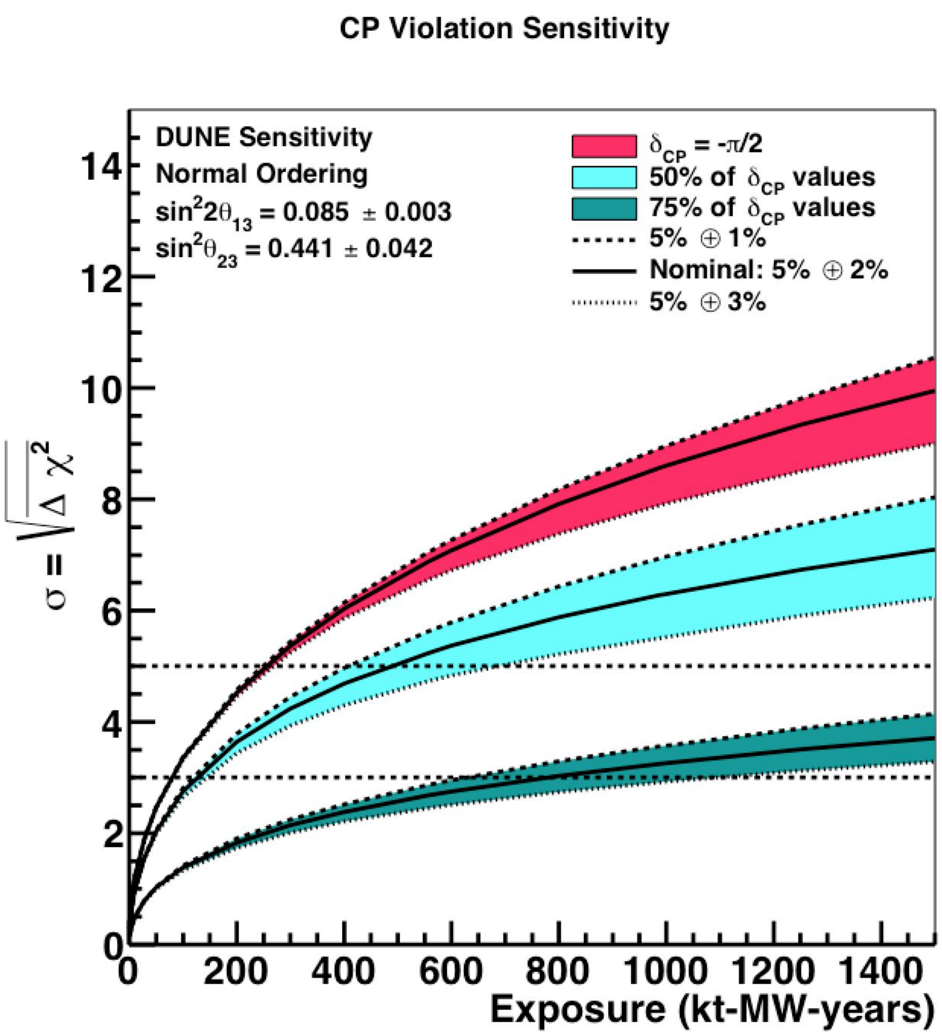
Sensitivity vs Time

DUNE CDR

Physics milestone	Exposure kt · MW · year (optimized beam)	
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	45	1 yrs
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	60	
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	100	2 yrs
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	210	
MH at 5σ (worst point)	230	5 yrs
10° resolution ($\delta_{\rm CP} = 0$)	290	
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	320	7 yrs
CPV at 5σ 50% of $\delta_{\rm CP}$	550	
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	850	
CPV at 3σ 75% of $\delta_{\rm CP}$	850	

Interesting **measurements** will be made **throughout** the DUNE beam-physics program

Systematics

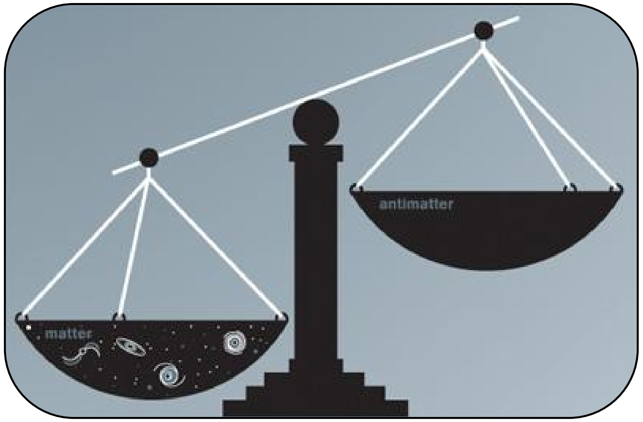


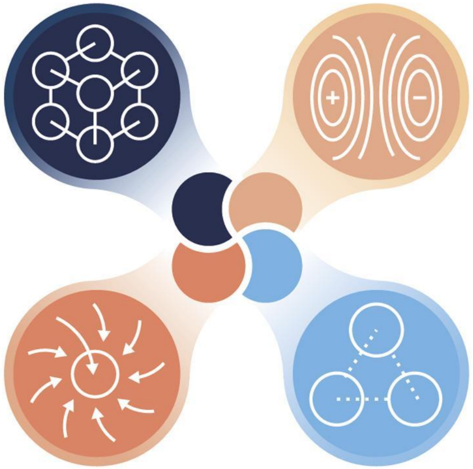
- CPV measurement **statistically limited** for ~100 kt-MW-years
- Sensitivities are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using **uncorrelated signal & background normalization** uncertainties.
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$
  - $\nu_e = \bar{\nu}_e = 2\%$
- Uncertainty in ν_e appearance sample normalization must be ~5% ⊕ 2% to discover CPV in a timely manner
- **Near detector** designed to meet these standards

Proton Decay

- Test of **fundamental symmetries**
  - Matter-antimatter asymmetry requires baryon number non-conservation (Sakharov)
  - Baryon number conservation is observed, so far, but there is no known reason why this must be so

- Well-motivated Grand Unification Theory models suggest **proton decay** may exist and be observable
  - GUTs make specific predictions about proton decay modes and branching fractions that can be tested in DUNE



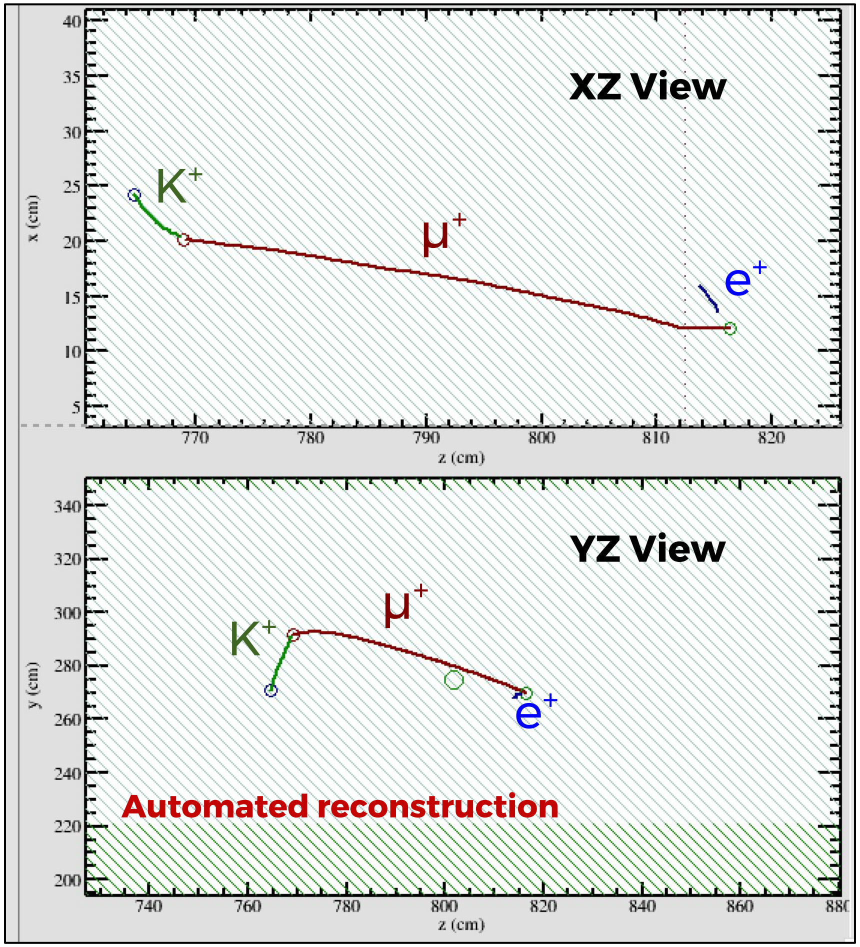


Sensitivity to Nucleon Decay

Detector requirements

- **Low background rate**
  - Cosmogenic background (primarily entering neutral kaons and neutrons) reduced by deep underground location
  - Atmospheric neutrinos also a source of background
- **High signal efficiency**
  - Precision tracking in LArTPC especially effective for modes with kaons, neutrinos, or complex final state
- **Large exposure** (detector mass × time)
  - 40-kt detector expected to run for 20+ years

Simulated $p \rightarrow \bar{\nu}K^+$ event:



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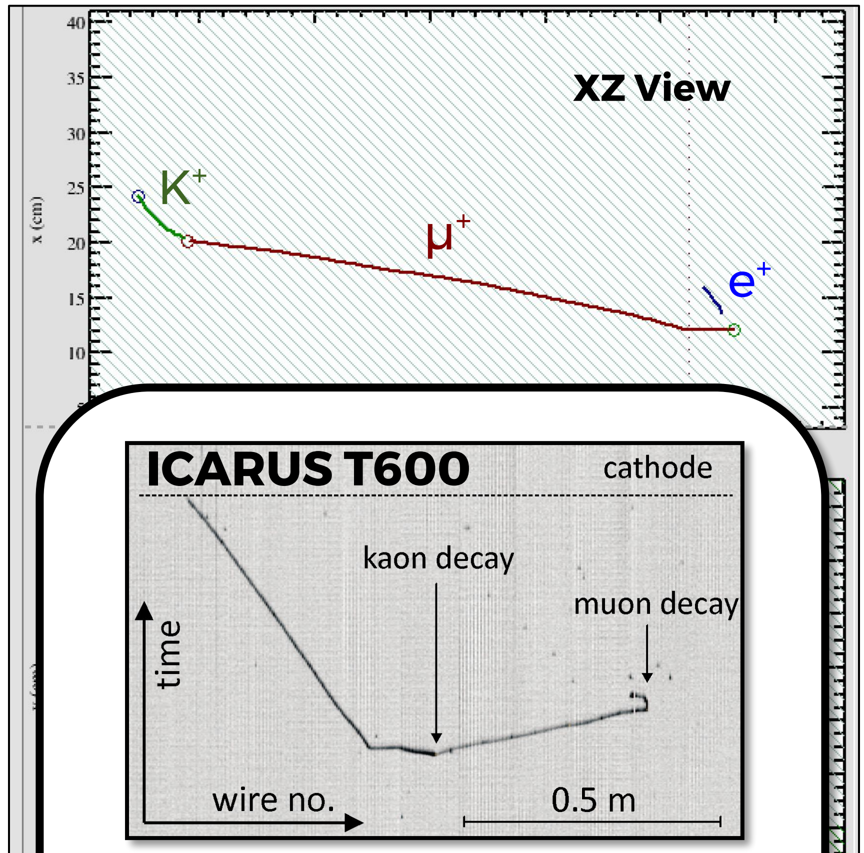
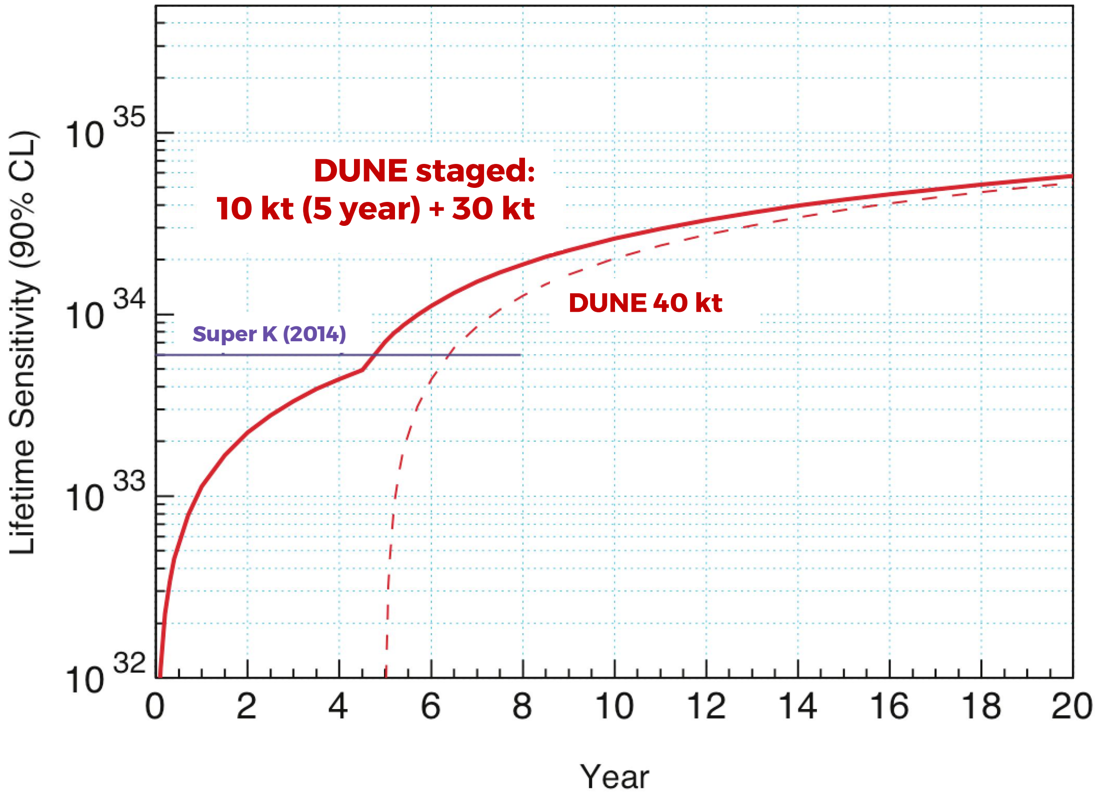


ICARUS T600 data kaon decay candidate (cosmogenic)
arXiv:1210.5089

Sensitivity for $p \rightarrow \bar{\nu}K^+$



$p \rightarrow \bar{\nu}K^+$ in DUNE:

- ~97% signal efficiency
- ~1 background event/Mt-year

SuperK result:
Phys. Rev. D 90, 072005 (2014)

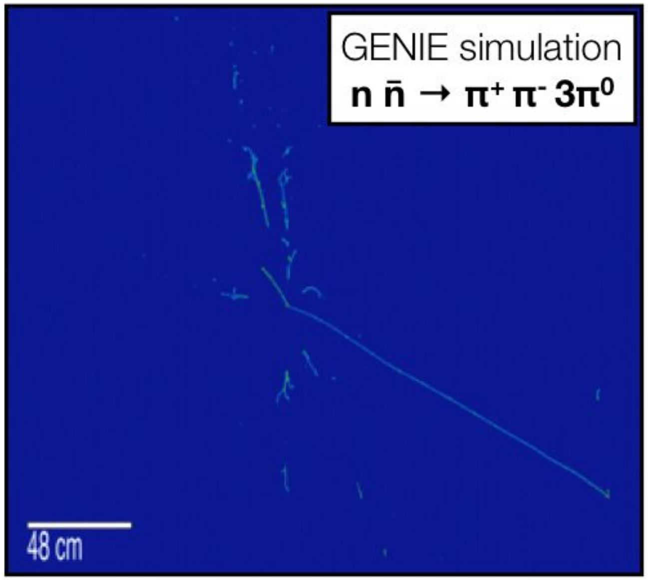
A **low-background** mode with **high** detection **efficiency**

DUNE will do well in decay modes with kaons, and modes with neutrinos or with complicated topologies.

Neutron-Antineutron Oscillation

- Beyond SM (**|ΔB=2|**) process, sibling to proton decay
- Current limit ***τ* > 2.7 x 10^{8} s** (90% CL) from SuperK; Phys. Rev. D 91, 072006 (2015)
- Signature in LArTPC is **spherical cascade of pions** with total E ~= 2 GeV & p < ~300 MeV
- Potential for **improvement** in DUNE:
  - Large exposure
  - Good spatial resolution
  - Improved particle ID
  - Low background rate

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	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%



Neutrinos from Stellar Core Collapse

- More than **99%** of energy in supernova burst is emitted in the form of **neutrinos** with energy $\mathcal{O}$(10 MeV)
- Basic physical model of SNB understood and confirmed by observation of **SN1987a** but many details remain to be understood
- High-statistics observation of SNB neutrinos, with sensitivity to flavor components, interesting for **astrophysics** and **neutrino physics**

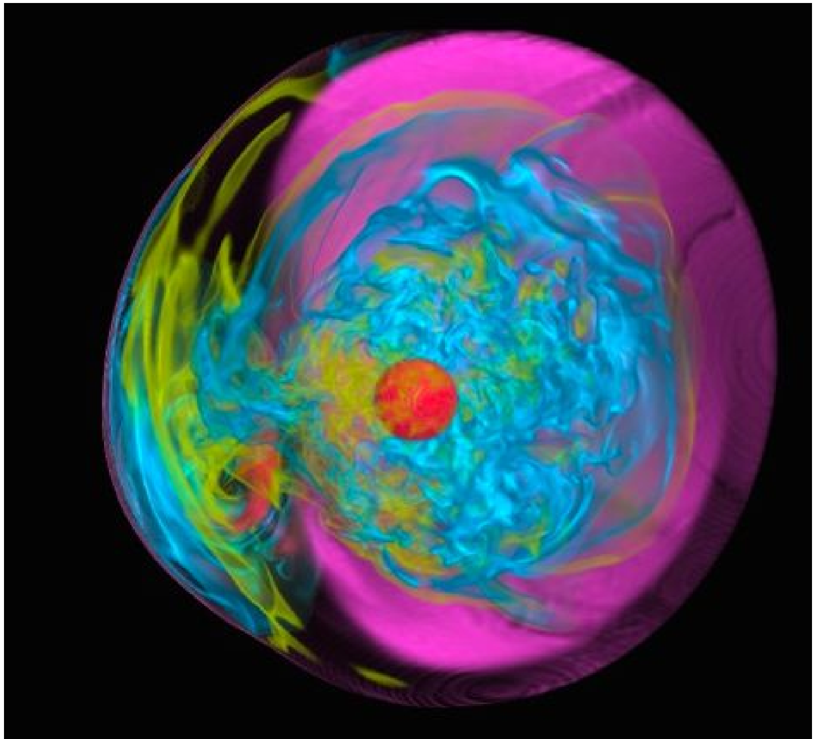
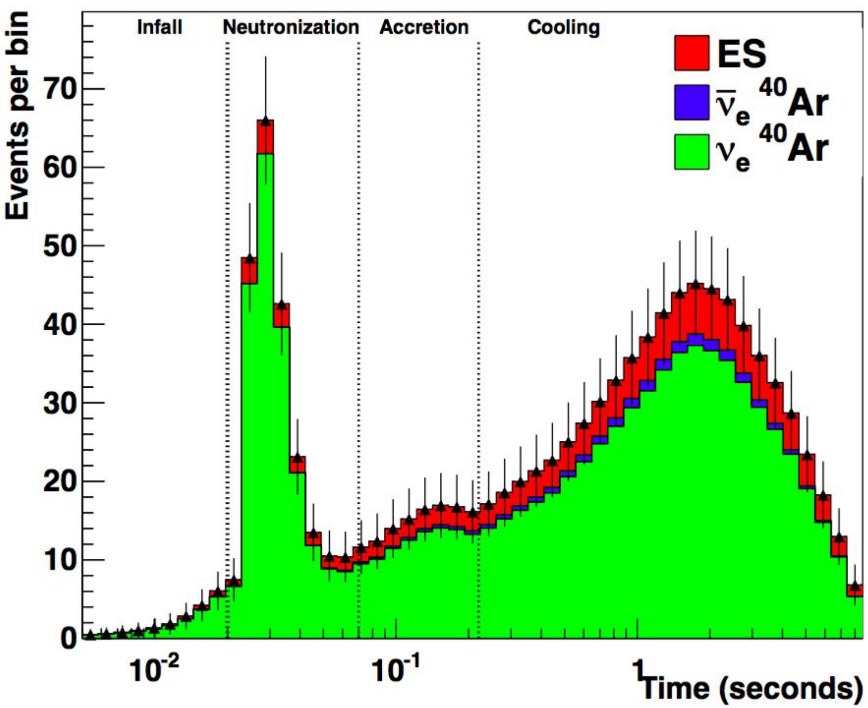


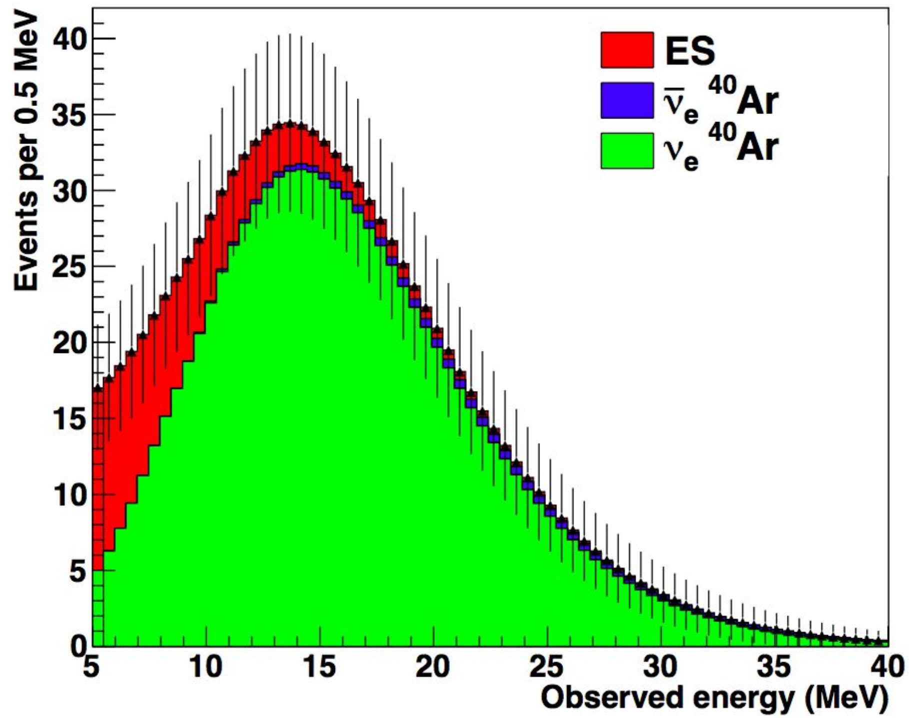
Image credit: A. Mezzacappa

Supernova Signal in DUNE

Flavor composition as function of time:



Energy spectra integrated over time:



For 40-kt LArTPC, SNB @ 10 kpc, "Garching" model (Significant variation among models)

Electron flavour is dominant. Allows mapping of the neutronization burst at the beginning of the signal.

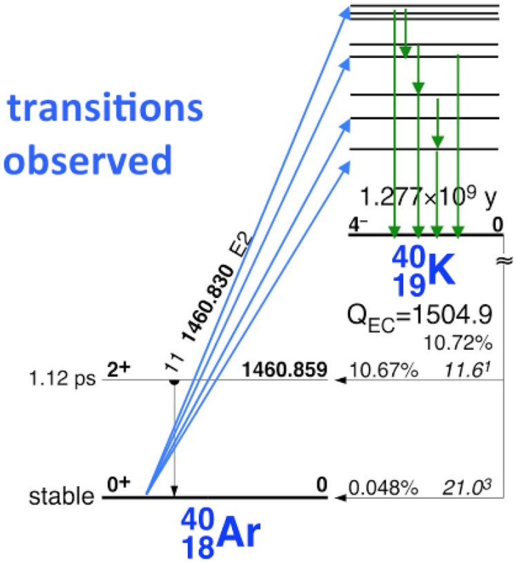
SN Neutrino Detection

Charged-current absorption:

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

At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)



Transition levels are determined by observing de-excitations (γ's and nucleons)

Transitions to particle-unbound levels occur with many competing de-excitation channels

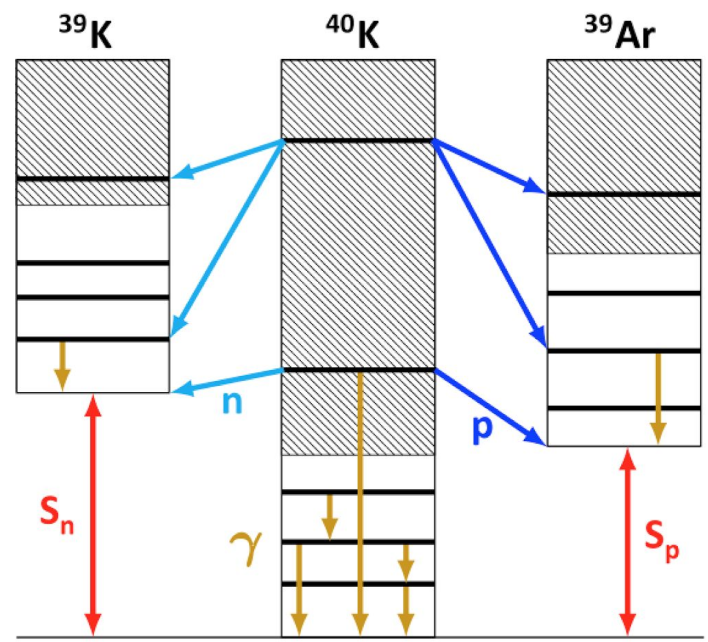
Large uncertainties in nuclear data and models complicate energy reconstruction

Reconstructing true neutrino energy:

Q is determined by measuring de-excitation gammas and nucleons

Outgoing e- Energy | Energy donated to transition | Recoil Energy of Nucleus (negligible)

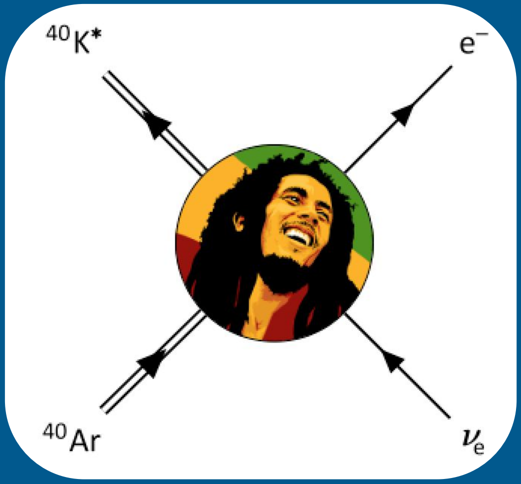
$$E_\nu = E_e + Q + K_{\text{recoil}}$$



SNB Neutrino Simulation

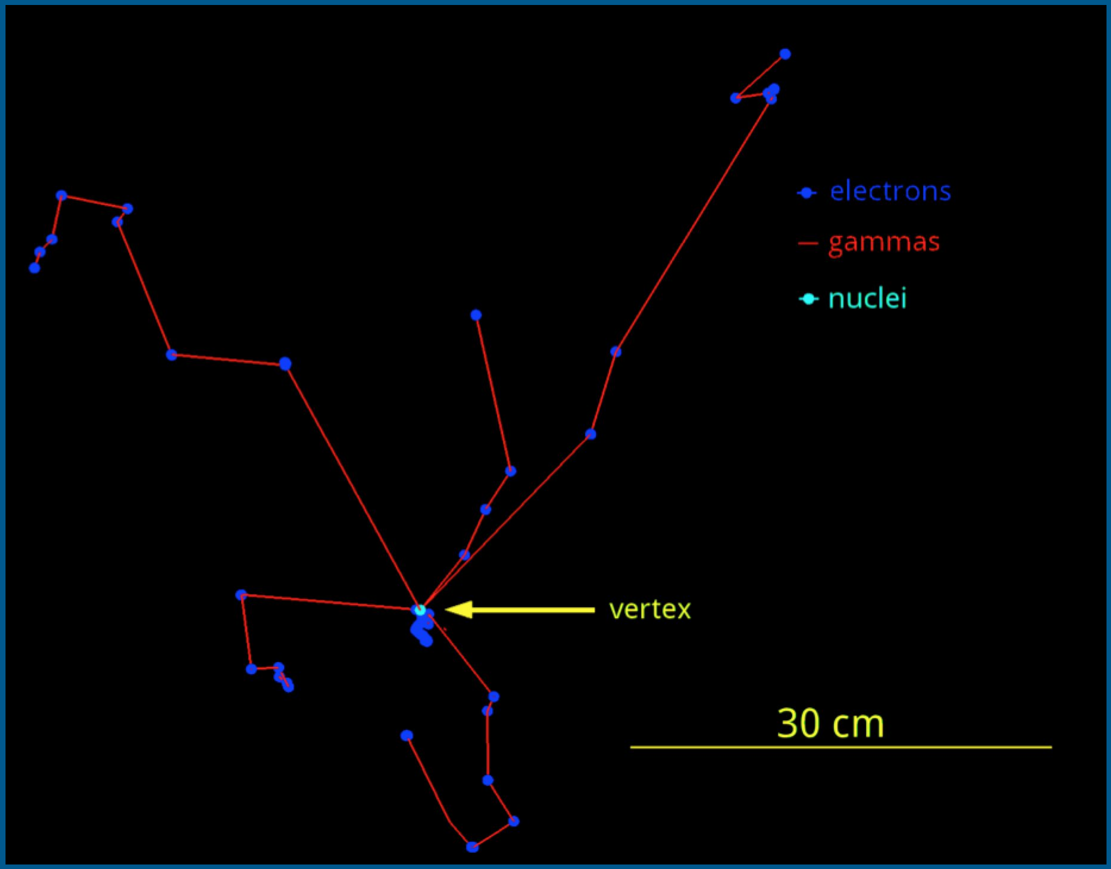
LArSoft: A multi-experiment LArTPC simulation package

Contributed to and used by DUNE collaborators



MARLEY: Model of Argon Reaction Low-Energy Yields
An event generator for supernova neutrinos in liquid argon

Simulated charged-current supernova ν_e event:



Charged-current absorption:

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

Summary

- DUNE has a **broad physics program**
  - CP Violation, mass hierarchy, neutrino oscillation parameters, and other LBL physics
  - Nucleon decay
  - Supernova burst ν
  - **More!** (BSM, NSI, Sterile, Atmospheric ν, dark matter)
- DUNE will **determine the MH** and can **measure CPV at 5σ**
  - Wideband-beam, 1300 km baseline, and 40 kt, deep-underground LArTPC enable this physics reach
  - Beam characterized and interaction systematics will be constrained by a **near detector**
- **Excavation** at SURF (far-site) starting soon, **stay tuned**!

Extra Slides

Oscillation Fit Parameters

Oscillation fits assume NuFit 2016 parameters

For 1σ uncertainty in DUNE sensitivity calculations, we take 1/6 of the ±3σ range, to account for non-Gaussian PDFs in NuFit.

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

What's in NuFit 2016?

Solar experiments

- Chlorine total rate [3], 1 data point.
- Gallex & GNO total rates [4], 2 data points.
- SAGE total rate [5], 1 data point.
- SK1 full energy and zenith spectrum [6], 44 data points.
- SK2 full energy and day/night spectrum [7], 33 data points.
- SK3 full energy and day/night spectrum [8], 42 data points.

⇒ SK4 2055-day energy and day/night spectrum [9], 46 data points.
- SNO combined analysis [10], 7 data points.
- Borexino Phase-I 740.7-day low-energy data [11], 33 data points.
- Borexino Phase-I 246-day high-energy data [12], 6 data points.

⇒ Borexino Phase-II 408-day low-energy data [13], 42 data points.

Atmospheric experiments

- SK1–4 (including SK4 1775-day) combined data [14], 70 data points.

⇒ IceCube/DeepCore 3-year data [15, 16], 64 data points.

Reactor experiments

- KamLAND combined DS1 & DS2 spectrum [17], 17 data points.
- CHOOZ energy spectrum [18], 14 data points.
- Palo-Verde total rate [19], 1 data point.

⇒ Double-Chooz FD-I (461 days) and FD-II (212 days) spectra [20], 54 data points.
- Daya-Bay 621-day spectrum [21], 36 data points.
- Reno 800-day near & far total rates [22], 2 data points (with free normalization).
- SBL reactor data (including Daya-Bay total flux at near detector), 77 data points [21, 23].

Accelerator experiments

- MINOS 10.71×10^{20} pot ν_μ-disappearance data [24], 39 data points.
- MINOS 3.36×10^{20} pot $\bar{\nu}_\mu$-disappearance data [24], 14 data points.
- MINOS 10.6×10^{20} pot ν_e-appearance data [25], 5 data points.
- MINOS 3.3×10^{20} pot $\bar{\nu}_e$-appearance data [25], 5 data points.
- T2K 6.57×10^{20} pot ν_μ-disappearance data [26], 16 data points.
- T2K 6.57×10^{20} pot ν_e-appearance data [27], 5 data points.

⇒ T2K 4.01×10^{20} pot $\bar{\nu}_\mu$-disappearance data [28, 29], 63 data points.

⇒ T2K 4.01×10^{20} pot $\bar{\nu}_e$-appearance data [30], 1 data point.

⇒ NOνA 2.74×10^{20} pot ν_μ-disappearance data [31], 18 data points.

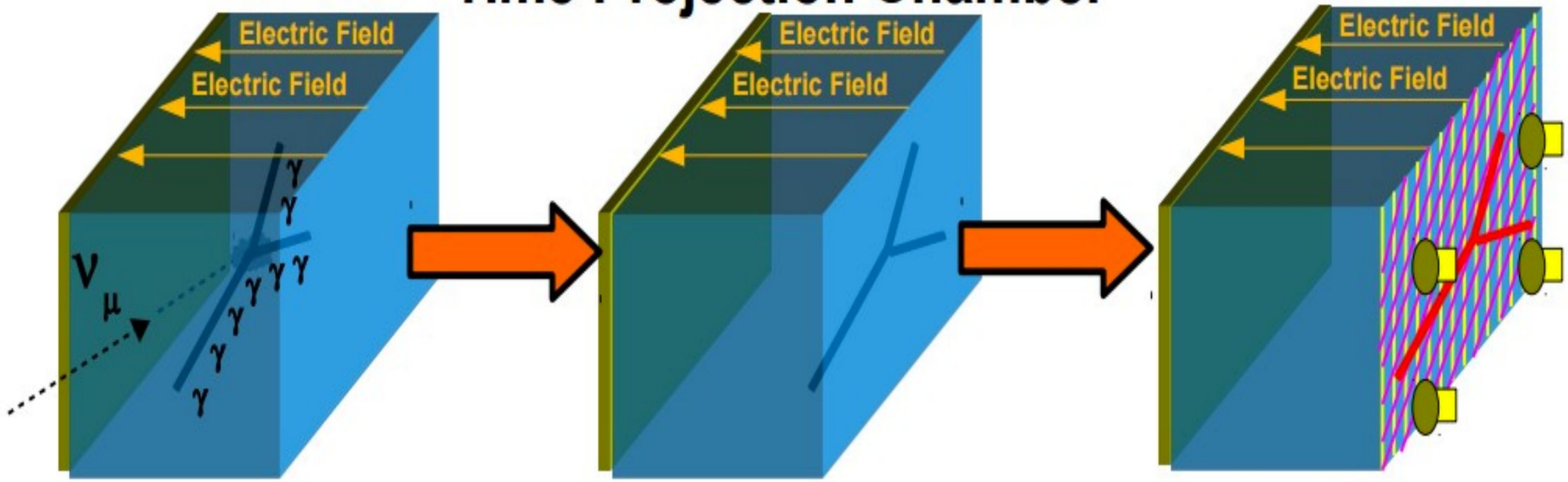
⇒ NOνA 2.74×10^{20} pot ν_e-appearance data [32], 1 data point (both LEM and LID).

Most relevant data up to May 2016

See release notes

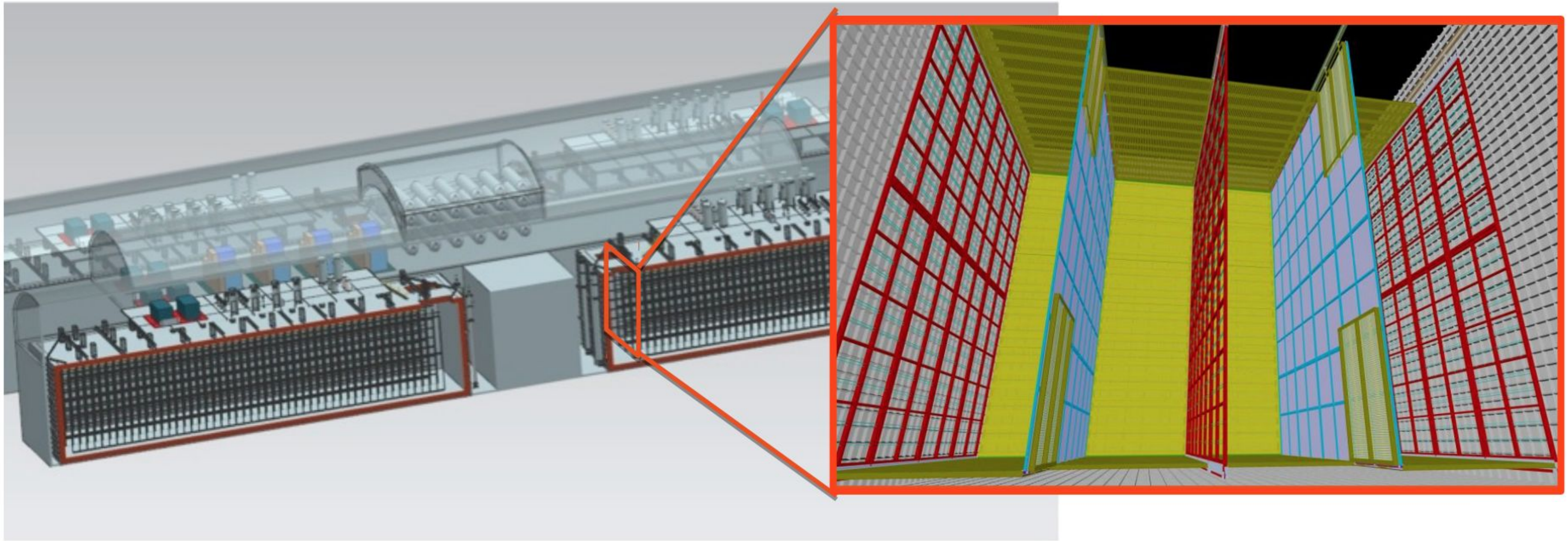
Credit: Jonathan Asaadi

Time Projection Chamber



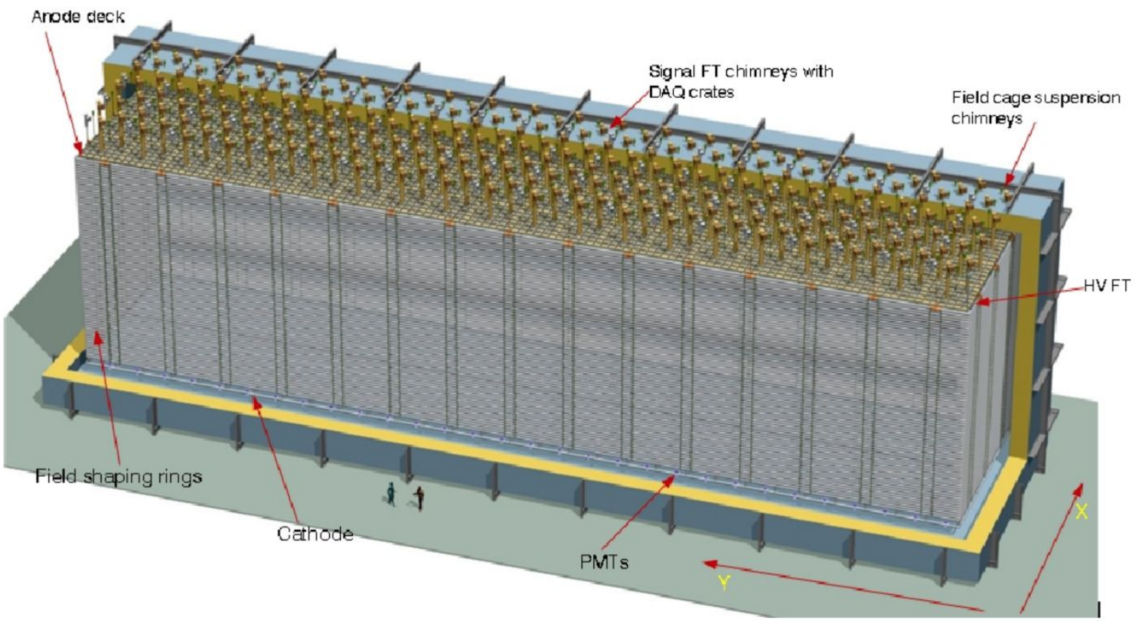
- **Electric field**, ~500 V/cm, is setup by **cathode plane**
- **Interactions** in **LAr** produce **ionization electrons** and photons
- Prompt **scintillation light** (128 nm) reaches the **PMTs** first
  - Wavelength shift (fibers, plates, coating on walls of TPC, etc) to readout in PMTs
- Due to **electric field**, electrons drift, at mm/us, to anode plane where they induce charge in the **induction planes** and are collected on the **collection plane**
  - No charge amplification -> charge readout is proportional to deposited energy
- This is the single phase approach

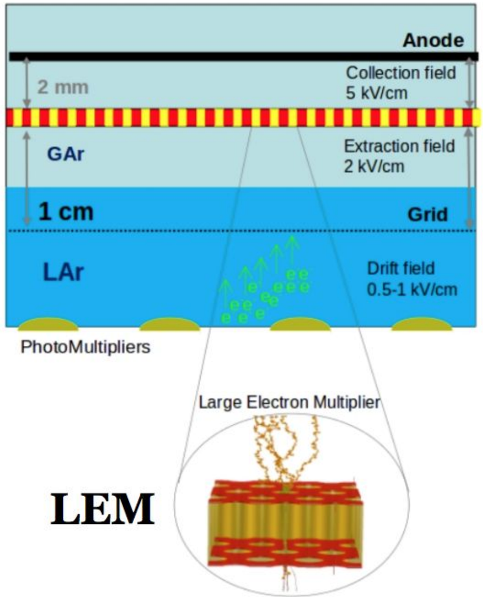
Far Detector: Single Phase



- **Single phase** FD based on LBNE modular drift cells
  - Suspended anode and cathode plane assemblies (APAs and CPAs)
  - 3.6 m drift with 500 V/cm E field
  - Cold digital electronics to reduce noise levels
- Three wire planes (two wrapped induction planes, one collection)
  - Wrapping reduces complexity and number of channels
  - Photon detector within APA frames

Far Detector: Dual Phase





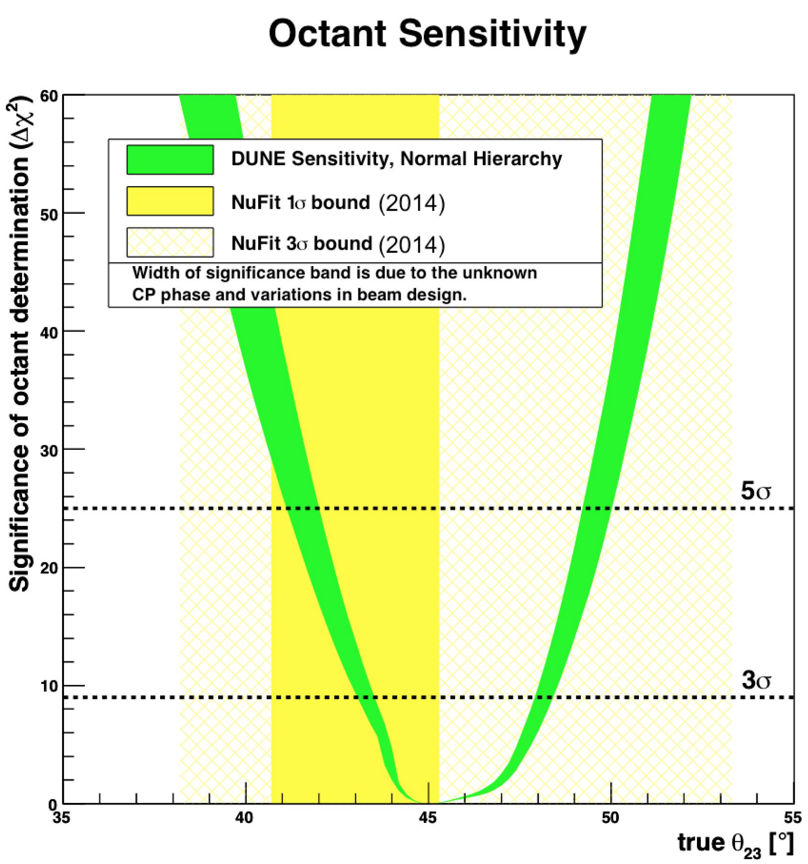
- **Dual phase** TPC inspired by LBNO FD design
  - 12 m vertical drift, 500 V/cm E field in LAr and GAr
  - Charge amplification via Large Electron Multiplier (LEM)
  - Partially cold electronics (accessible for maintenance)
- Readout is via two orthogonal, interleaved collection plane views
  - Excellent S/N via gain in GAr
- PMTs at bottom of cryostat

Nucleon decay channels

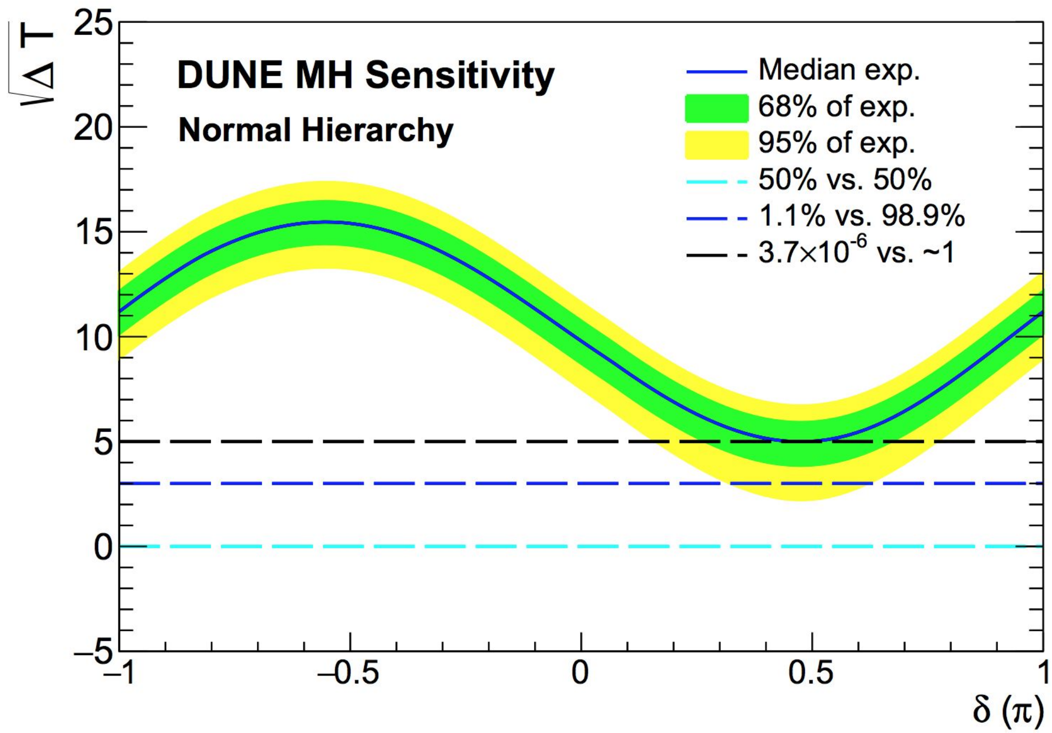
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

Efficiencies and background rates (events per Mt · year) for nucleon decay channels of interest for a large underground LArTPC, and comparison with water Cherenkov detector capabilities.

Octant Sensitivity



MH Statistics



The sensitivity, given by √ΔT =√Δχ2 for a typical experiment (solid blue line), is compared to the bands within which 68% (green) and 95% (yellow) of experiments are expected to fall due to statistical fluctuations. The solid blue line (representing a minimum significance of √T = 5 for 100% of δCP values) is the expected sensitivity in our standard treatment. The dashed lines show the values of the √ΔT metric an experiment must measure for the probability of determining the correct neutrino MH to be 50% (cyan), 98.9% (blue), or 1 to 3.7 × 10−6 (black). In the legend, the numbers corresponding to the dashed lines indicate [probability of determining MH incorrectly] vs. [probability of determining the MH correctly].

Other Physics

- DUNE will also make interesting measurements in:
  - Other LBL oscillation physics (BSM, NSI, Sterile)
  - Atmospheric neutrinos
  - Near detector measurements
  - Dark matter searches

Atmospheric ν event rates (350 kt.yr)

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