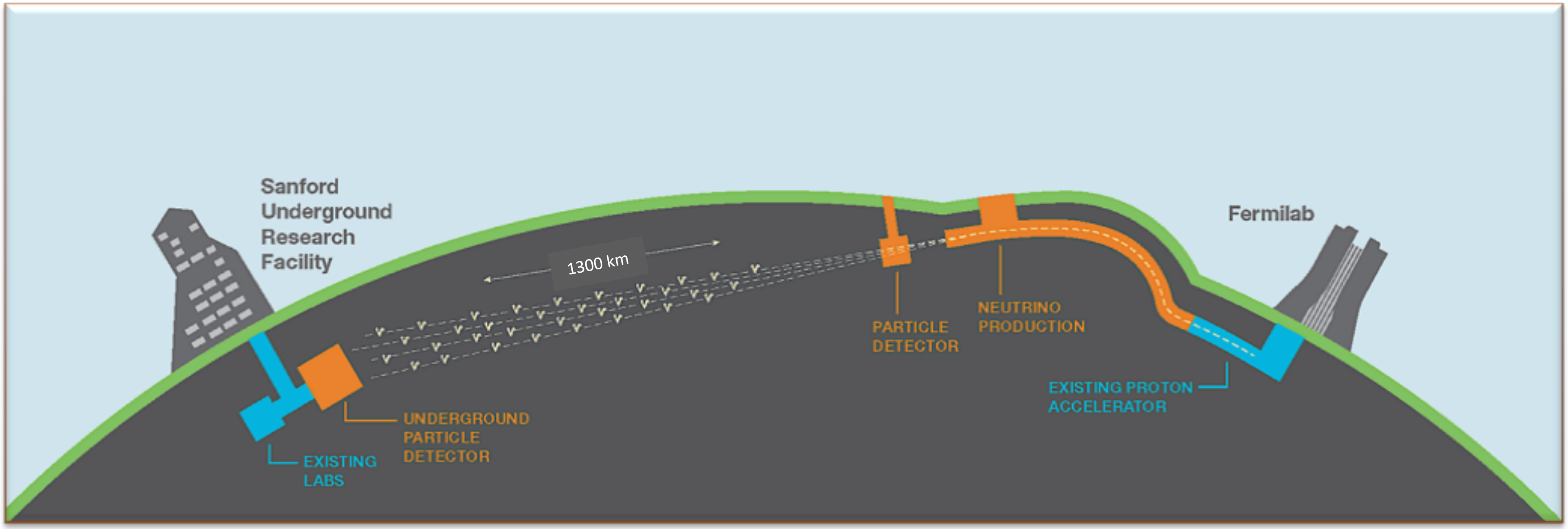
DUNE and the LBNF

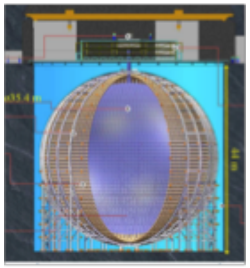


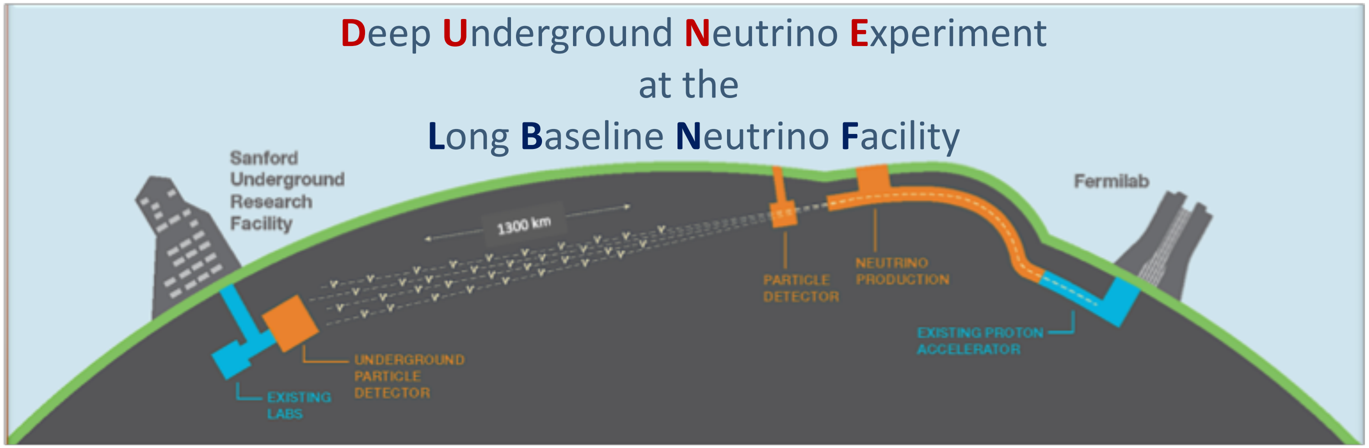
Bob Svoboda
University of California, Davis
for the DUNE Collaboration

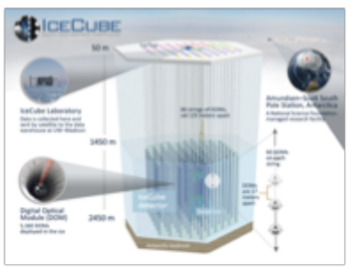
UCDAVIS UNIVERSITY OF CALIFORNIA

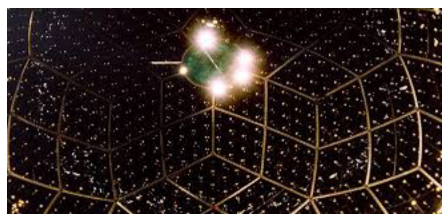
DUNE

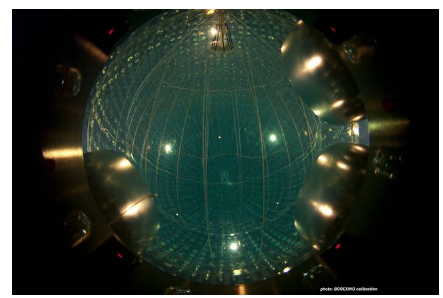
Global effort to use neutrinos to understand the universe

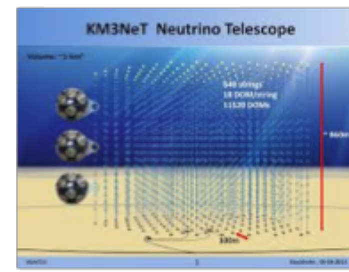


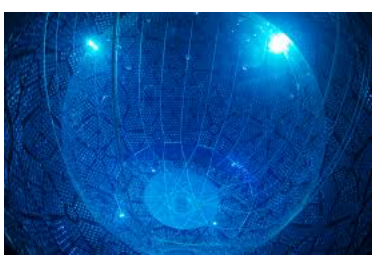


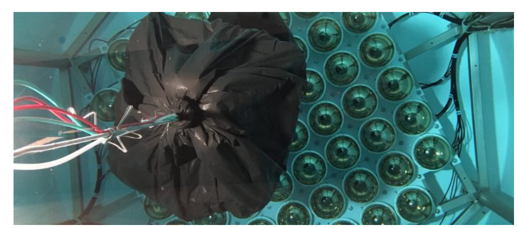


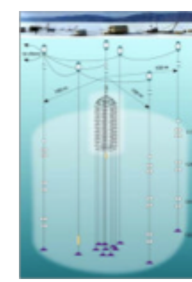










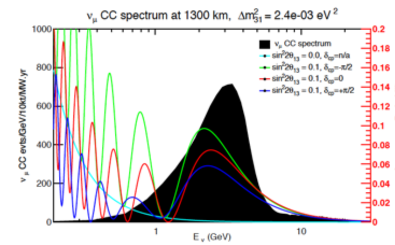


DUNE Collaboration

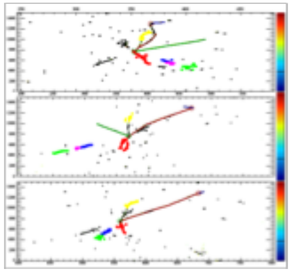
1180 collaborators from 177 institutions in 31 countries
628 faculty/scientists, 199 postdocs, 119 engineers, 234 PhD students

R.Svoboda, UC Davis

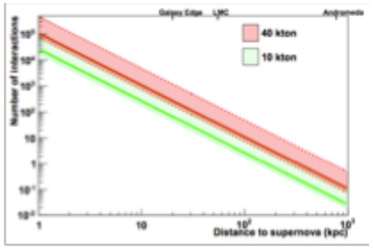
DUNE Primary Science Goals



- Testing the Neutrino Three-Flavor Paradigm
  - CP Violation
  - Mass Ordering
  - Precision Oscillation Measurements



- Baryon Number Violation and Grand Unification
  - Nucleon Decay
  - Neutron/Anti-Neutron Oscillation

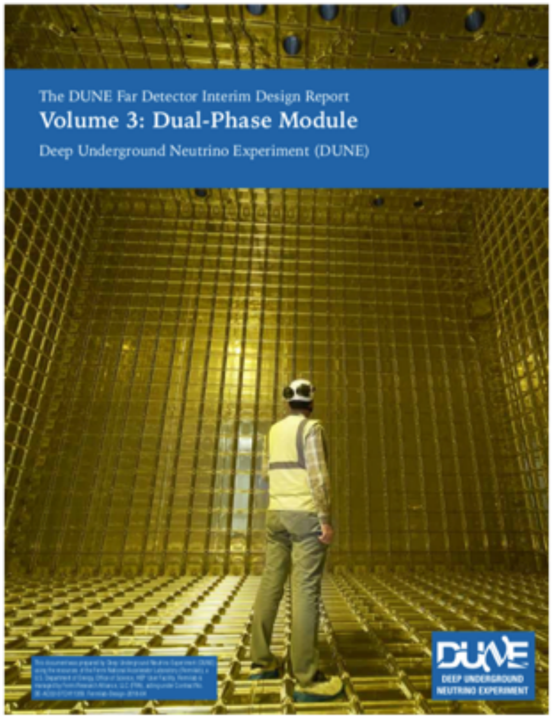


- Neutrino Astrophysics
  - Supernova Burst Neutrinos

Interim Design Report – July 2018

https://arxiv.org/abs/1807.10334

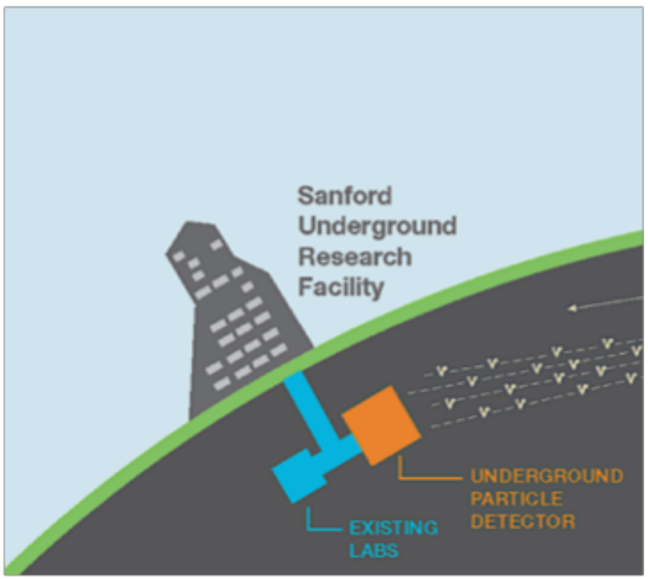
https://arxiv.org/abs/1807.10327



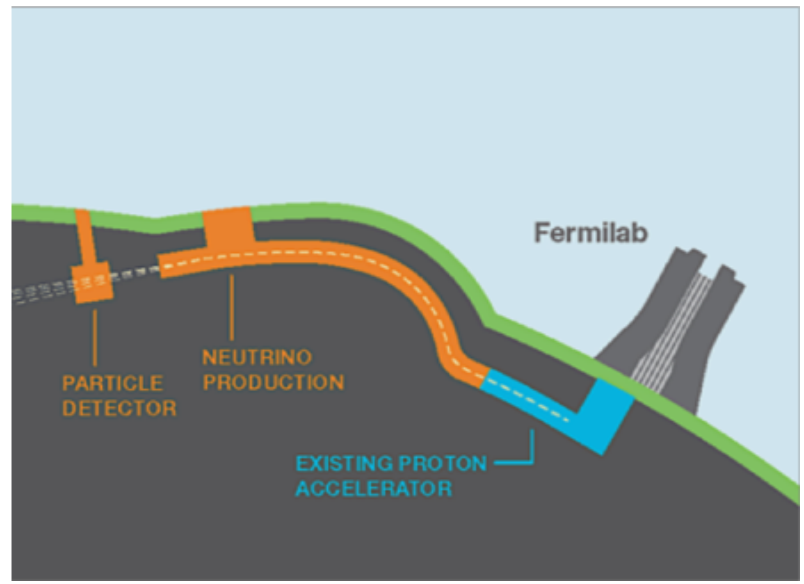
https://arxiv.org/abs/1807.10340

- Will be superseded by Technical Design Report summer 2019

Long-Baseline Neutrino Facility

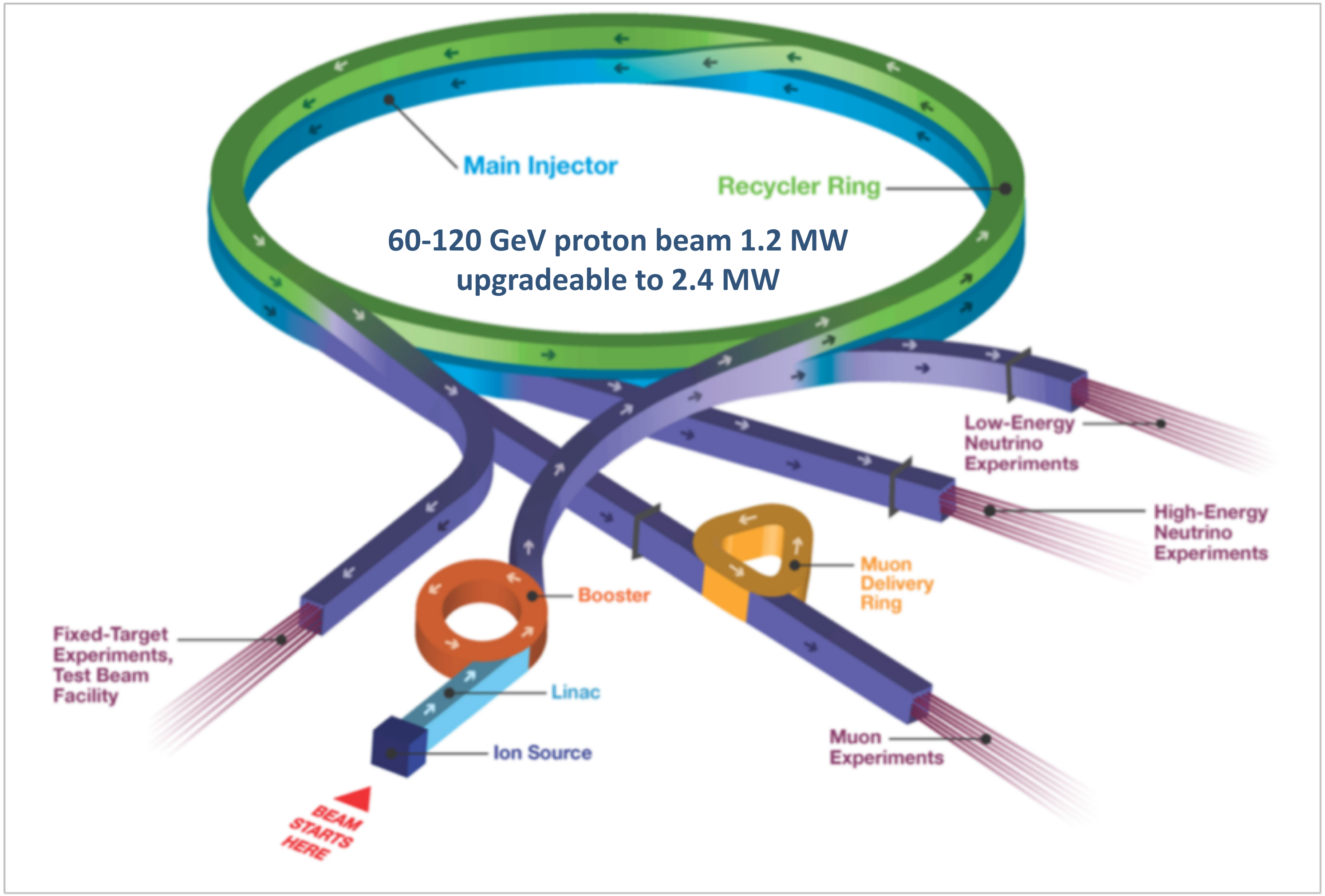


Far Detector Underground Laboratory at SURF



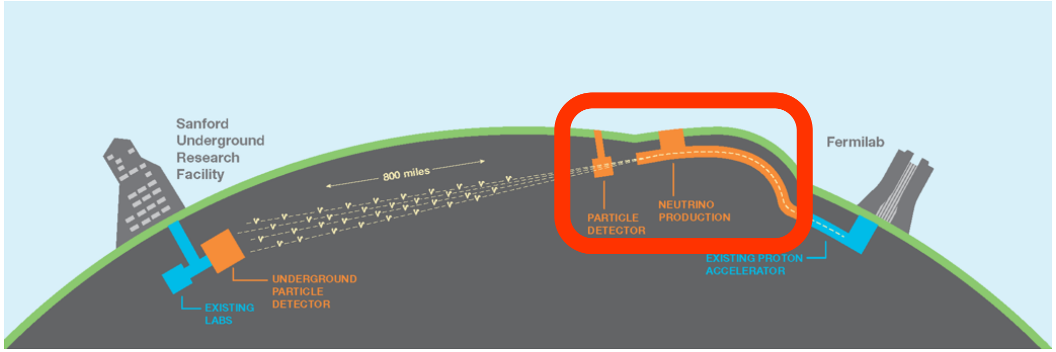
Neutrino Beam Source

Fermilab Accelerator Complex Upgrades

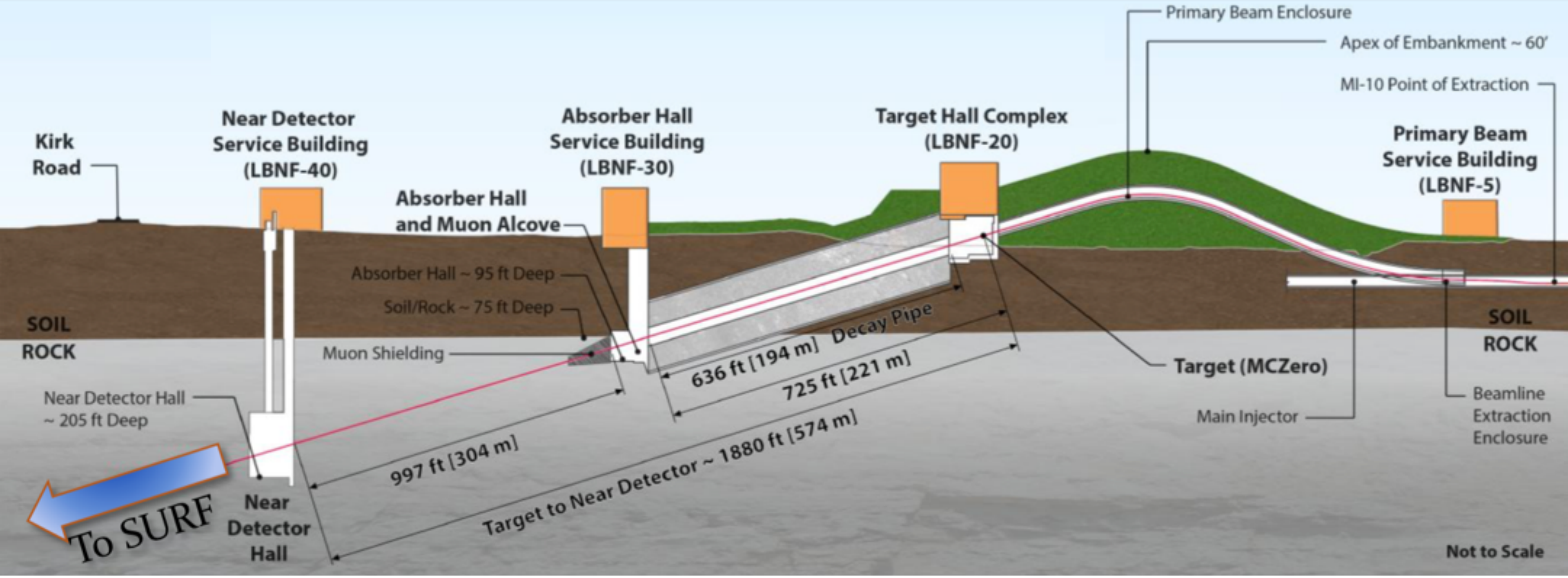


- PIP-II upgrade planning now underway. 1.2 MW to be operational by 2026
- upgradable to 2.4 MW with PIP-III

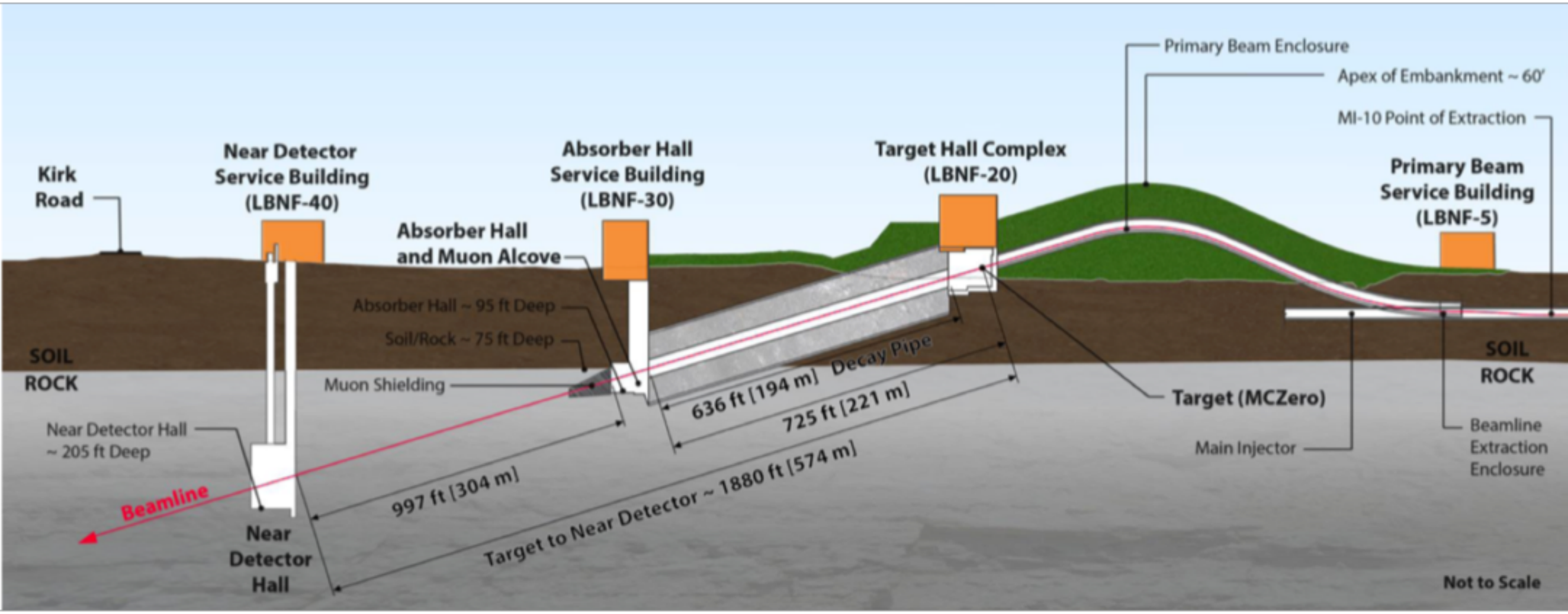
LBNF Neutrino Source and Near Detectors



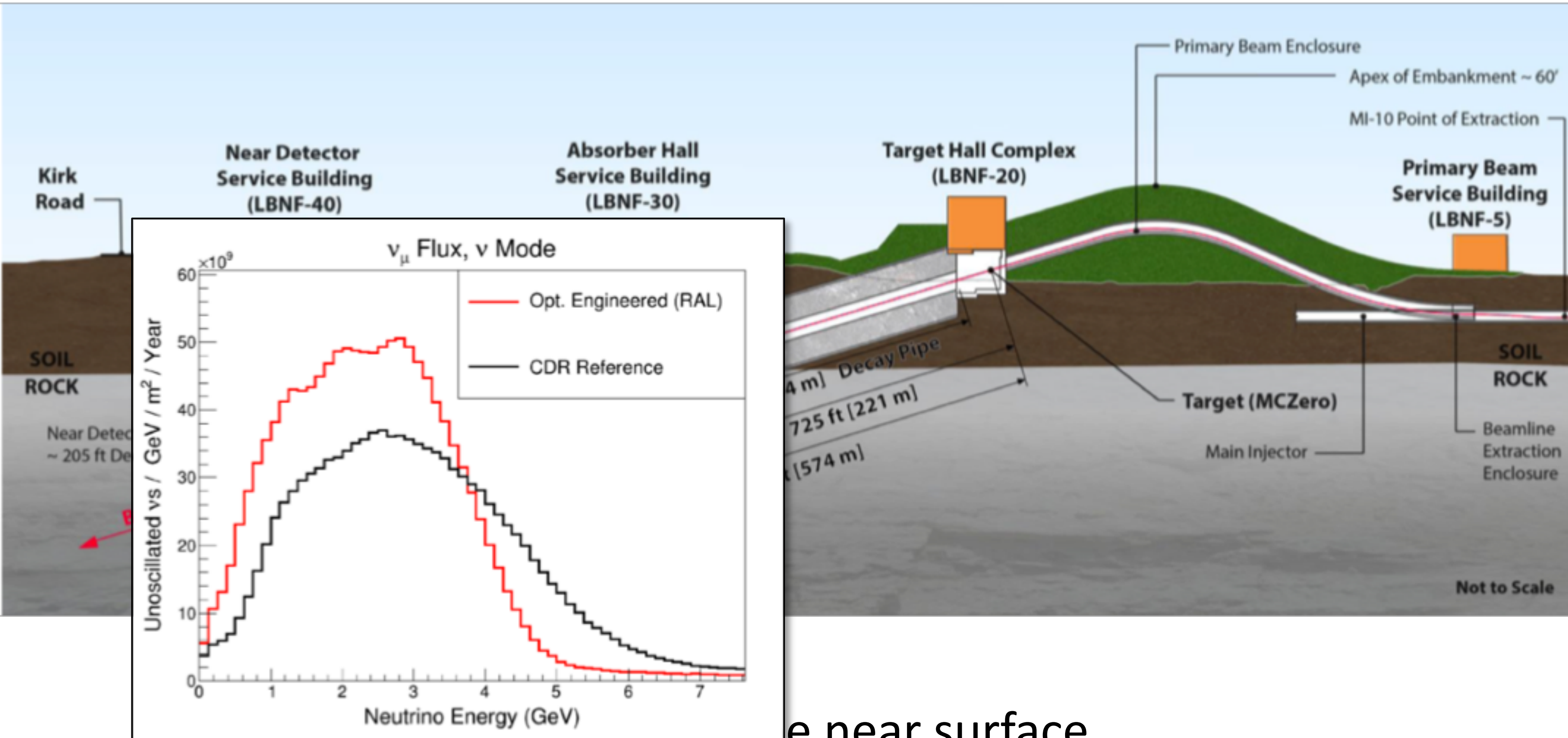
Near Detectors | **LBNF Neutrino beam-line**



R.Svoboda, UC Davis

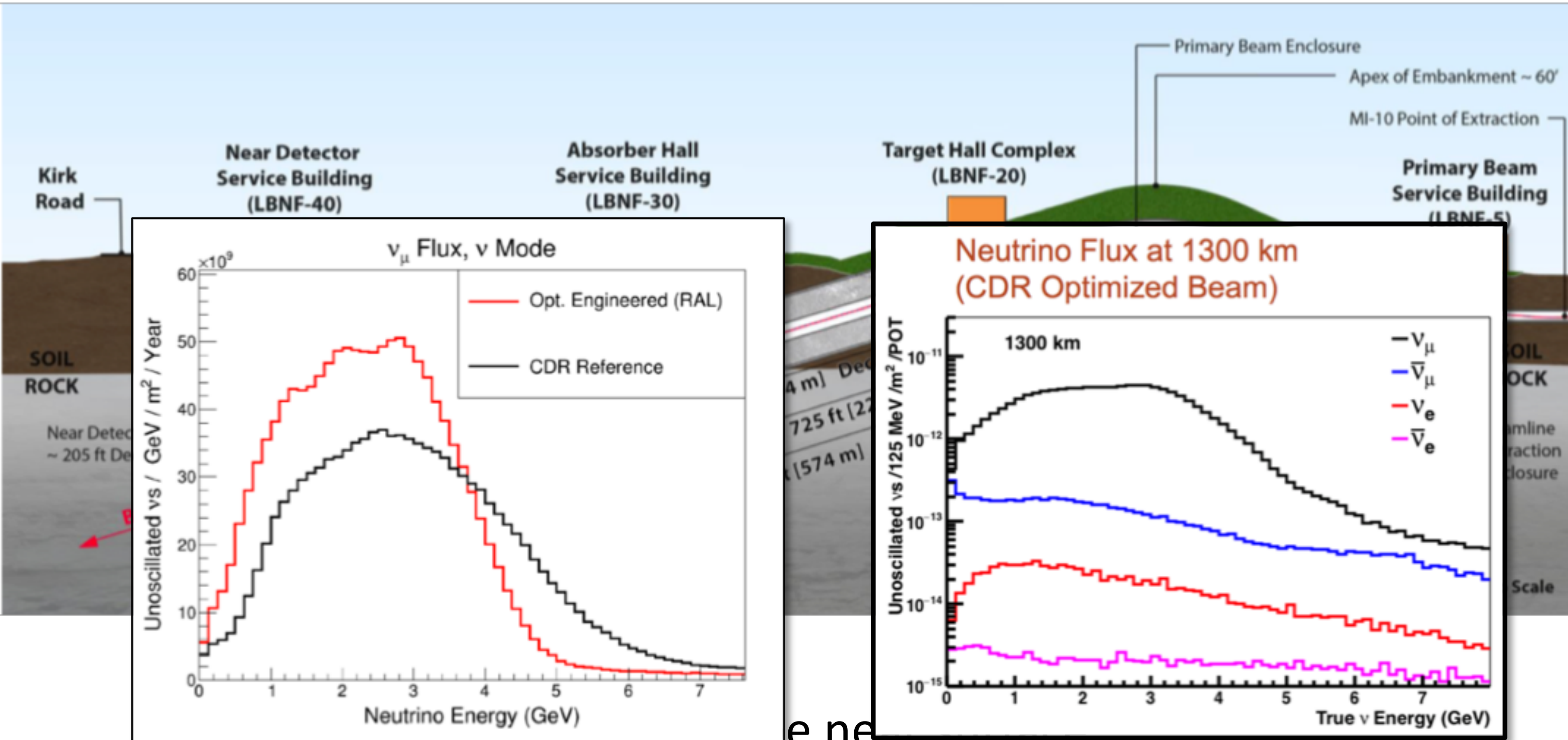


- Hill allows target hall to be near surface
- Decay Pipe 194 m long 4 m diameter He-filled
- Broad Band Beam allows access to wide L/E range
- Beam redesigned for lower energy and higher flux



e near surface

- Decay Pipe 194 m long 4 m diameter He-filled
- Broad Band Beam allows access to wide L/E range
- Beam redesigned for lower energy and higher flux

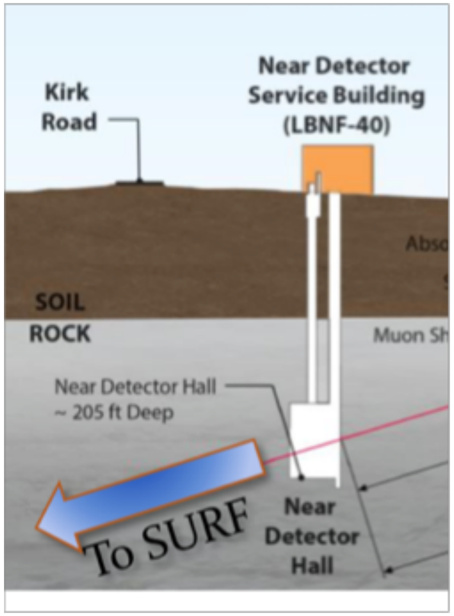


- Decay Pipe 194 m long 4 m diameter He-filled
- Broad Band Beam allows access to wide L/E range
- Beam redesigned for lower energy and higher flux

The Near Detector

- Constrain systematic uncertainties for long baseline oscillation analysis
- Also enables high precision neutrino interaction physics

- Current Concept is an integrated system composed of multiple detectors
  - Highly segmented Liquid Argon Time Projection Chamber (~75 t)
  - Magnetized multi-purpose tracker w/ High Pressure Ar-CH_4 TPC (~1 t) surrounded by electromagnetic calorimeter and muon tagger
  - Magnetized 3D scintillator tracker (~6 t)



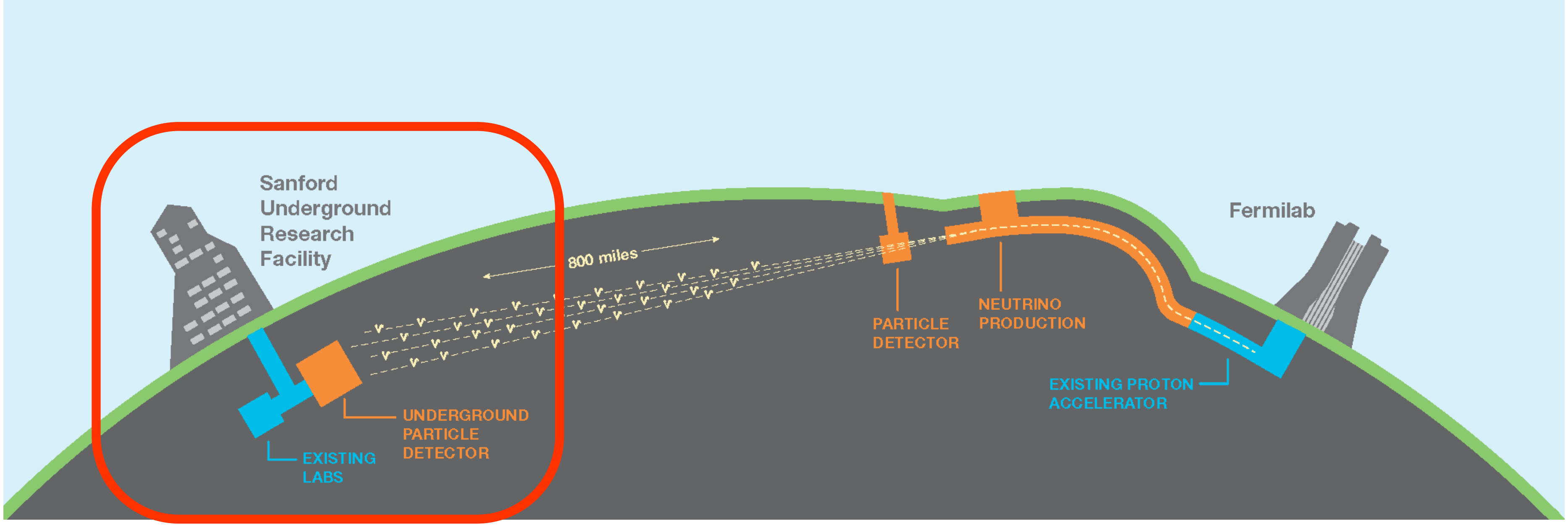
- Capability for the LArTPC to be moveable off axis is being investigated

- ND Conceptual Design Report (CDR) planned for 2019

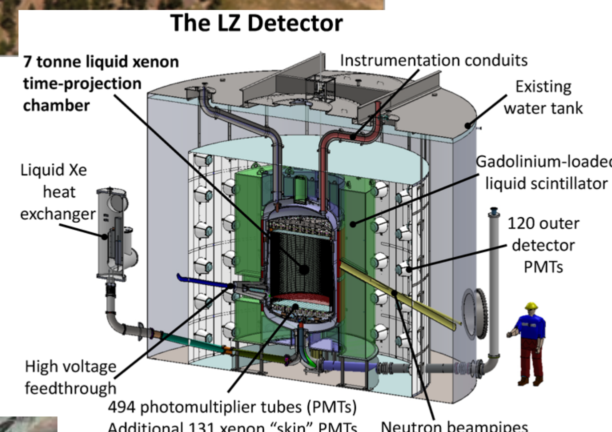
Sanford Undergrounds Research Facility (SURF)

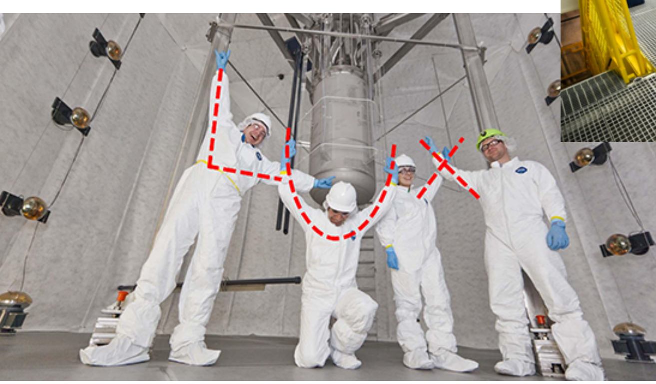
https://sanfordlab.org/

1300 km away from Fermilab

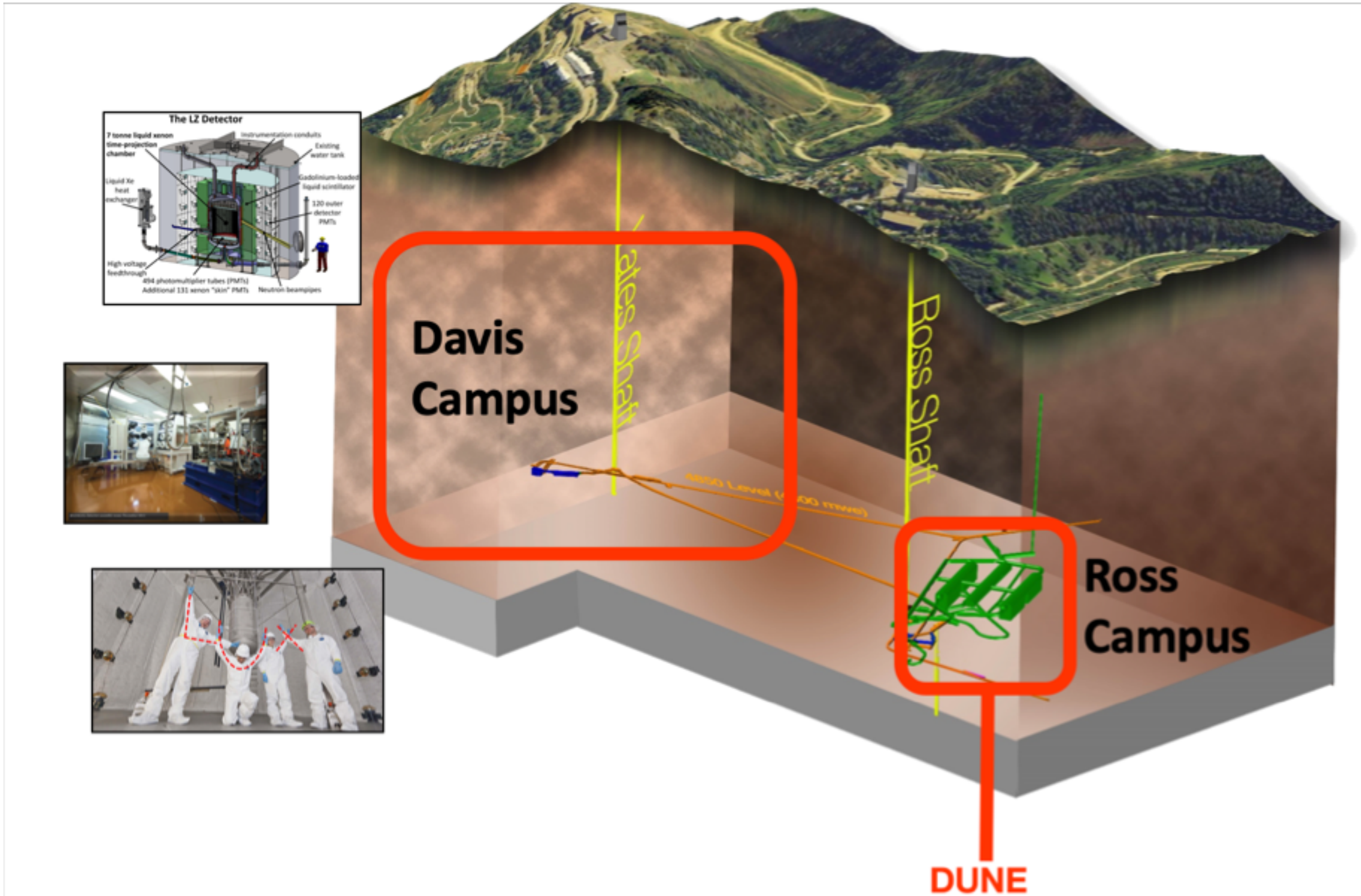


Sanford Underground Research Facility (SURF)





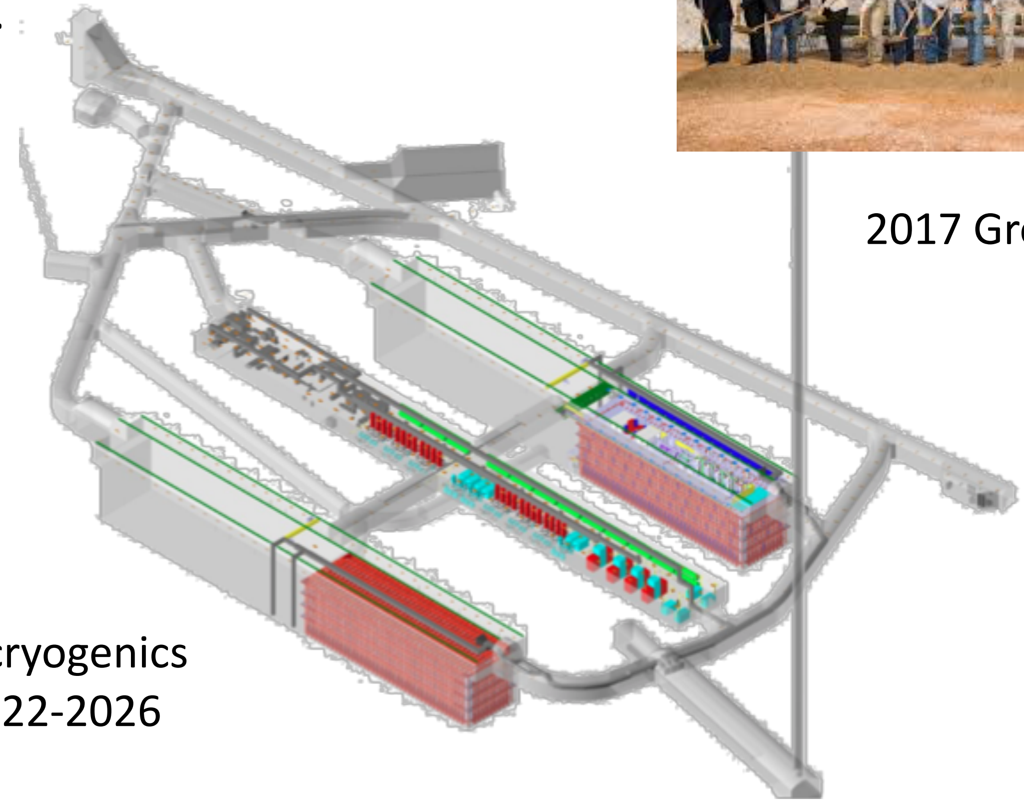
Sanford Underground Research Facility (SURF)



LBNF Experimental Halls at SURF

Four experimental halls and a central utility drift now under construction.

2017 Groundbreaking

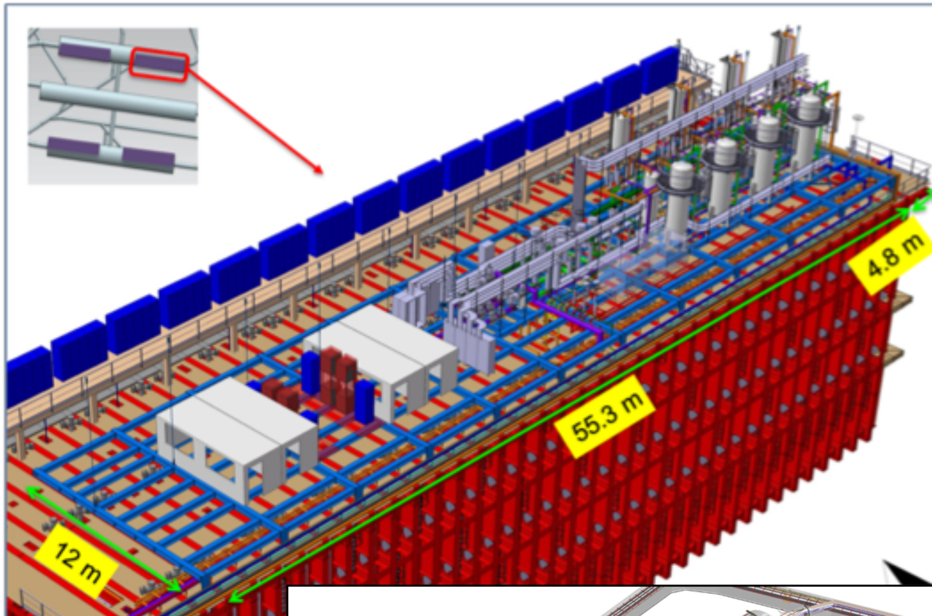


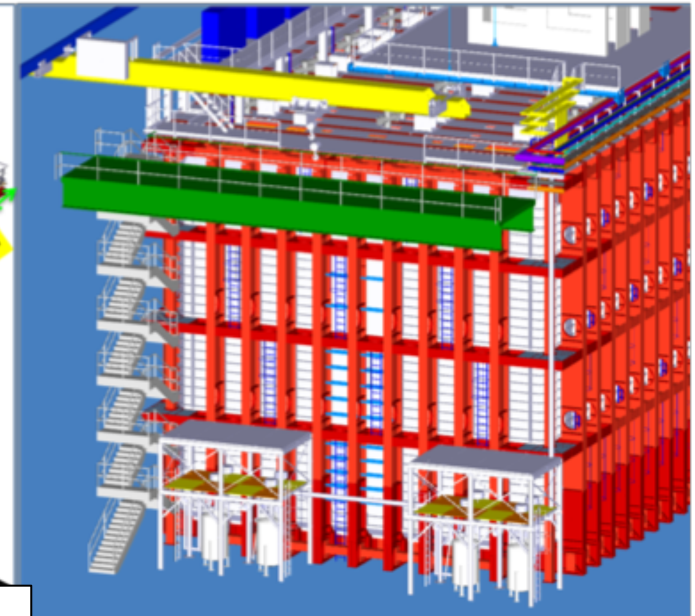
Cryostat and cryogenics installation 2022-2026

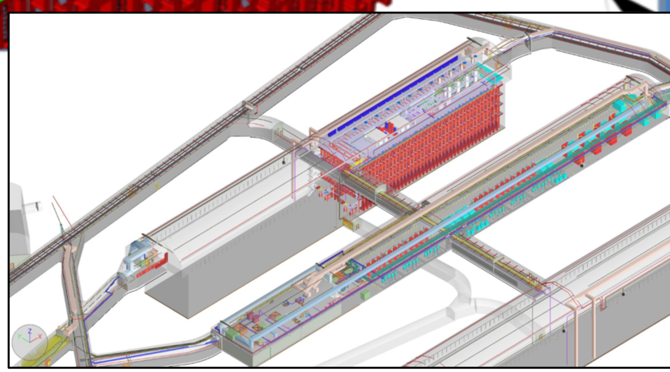
Anticipated ready for first detector installation mid-2024

DUNE Far Detector

Basic module is a 10 kt fiducial mass (17 kt total) liquid argon TPC







Designed and engineered by CERN

DUNE Cryostats

ProtoDUNE-SP Cryostat

The DUNE far detectors will use Time Projection Chambers installed in large commercial-scale cryostats used for LNG transport

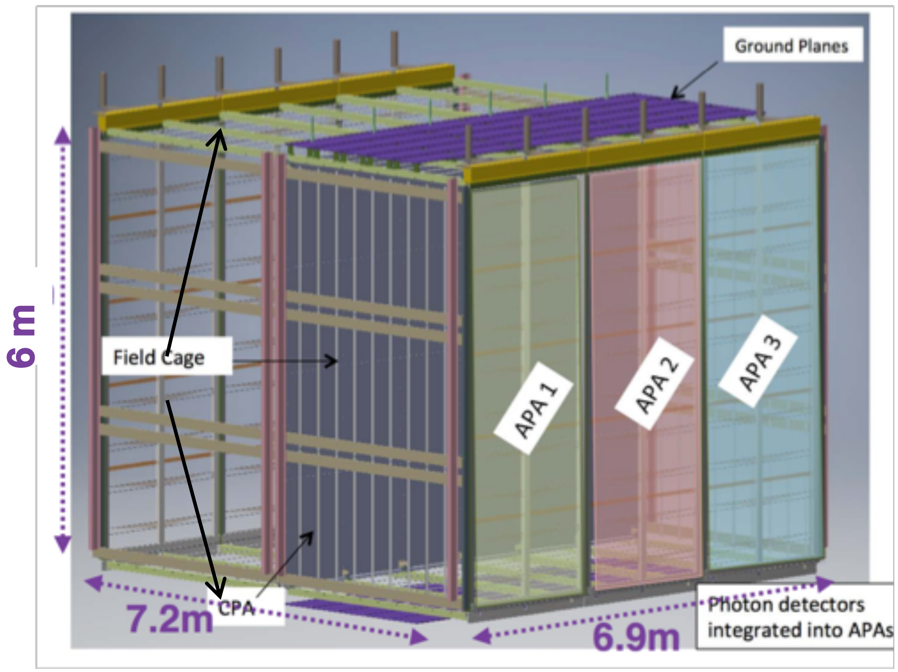
Commercial LNG Cryostat

DUNE Far Detector: Two LAr TPC Approaches

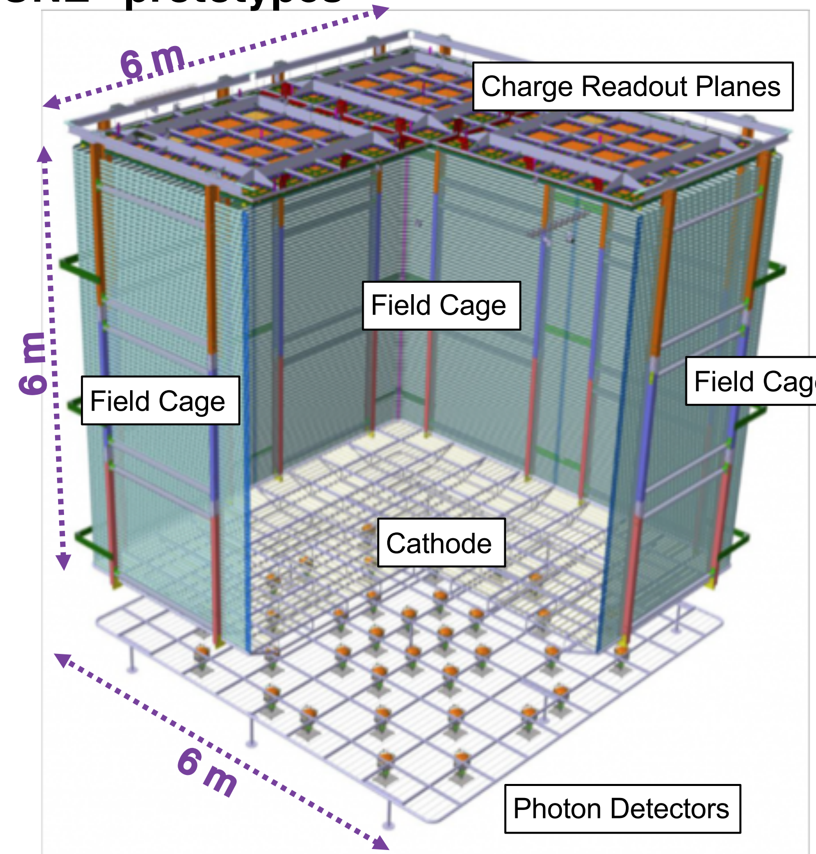
Single-Phase
3.6-m horizontal drift in liquid
-> readout in liquid

Dual-Phase
12-m vertical drift in liquid
-> extraction to readout in gas

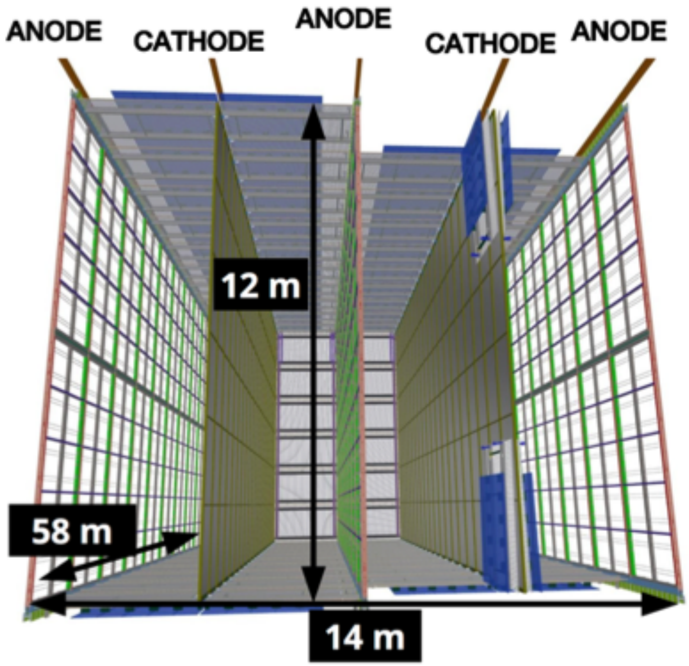
Large-scale "ProtoDUNE" prototypes



APA = Anode Plane Assembly   CPA = Cathode Plane Assembly



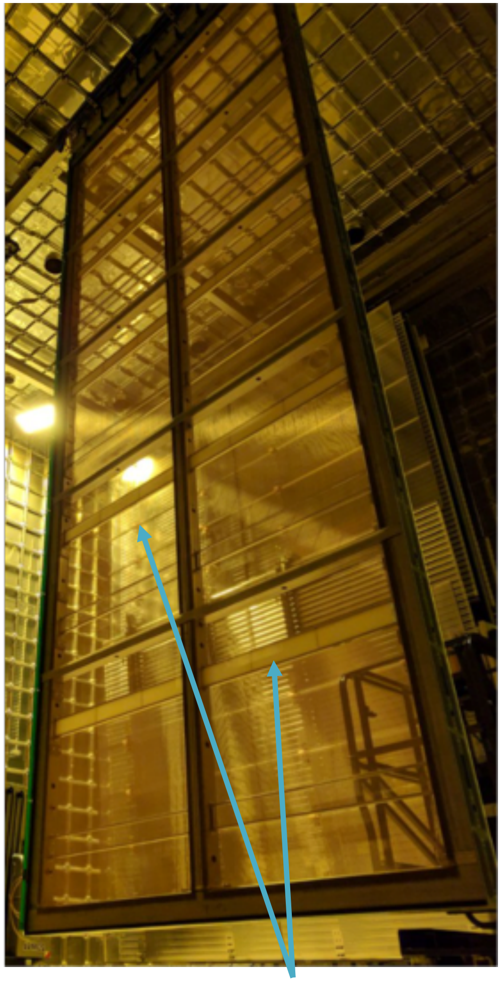
Single Phase TPC Module



- Based on ICARUS design except “wrapped” anode planes sensitive from both sides (X, U, V, G planes)
- Anode Plane Assembly (APA): 6 m x 2.8 m; 150 APAs per 17 kt module
  - 3520 wires/APA; 2560 readout channels/APA
- Deadtime-less readout for SNB with 100 sec buffer

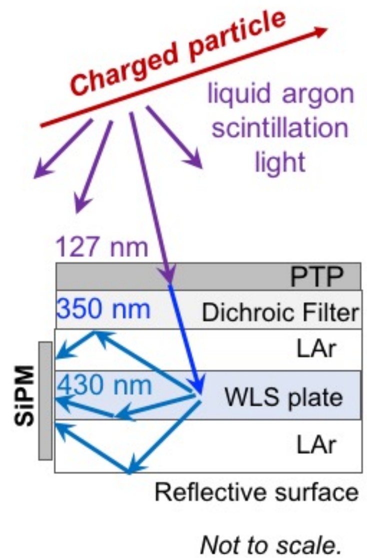
Single Phase Module – Photon Detectors

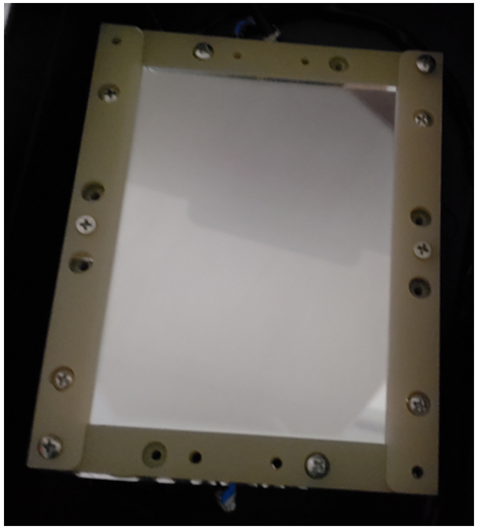
- Determination of T0 for correction for electron capture along the drift direction is important for energy calibration, tracking, and non-beam physics triggers
- Measure event energy in scintillation photons as cross-check to TPC or improve the resolution significantly since ionization and scintillation are anti-correlated
- Complementary trigger for SNB
- Challenge: Need to be embedded within the ~5cm space between anode planes



Photon detector embedded in the anode planes

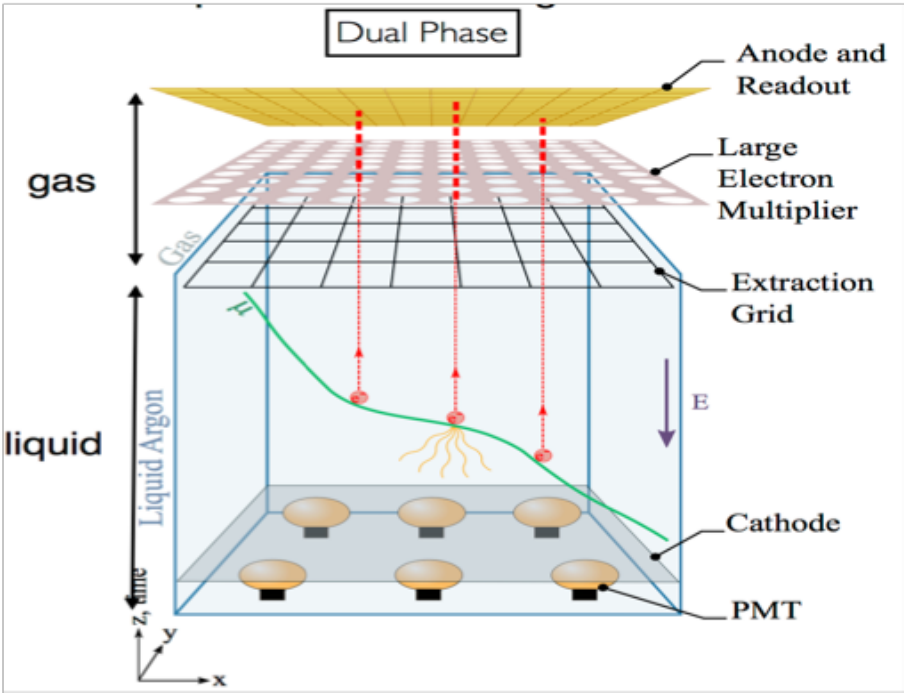
SP Photon Detector – X-ARAPUCA

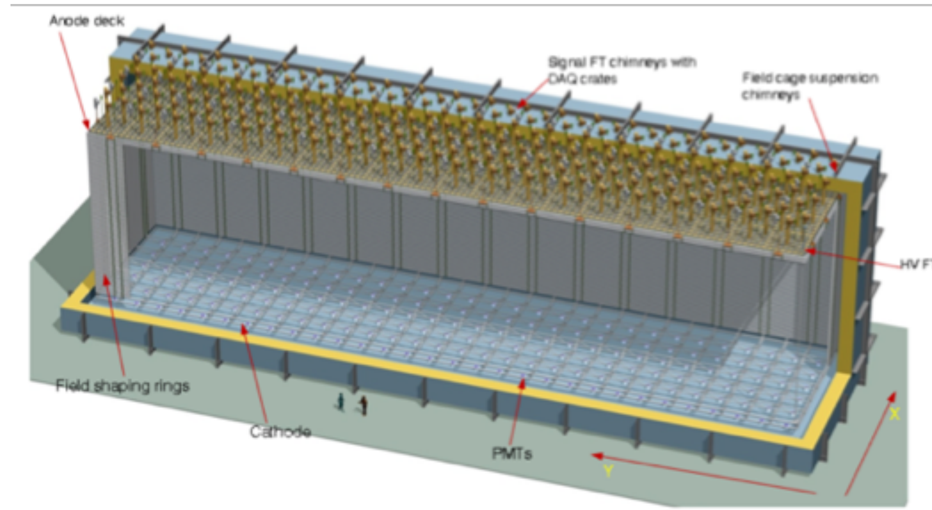




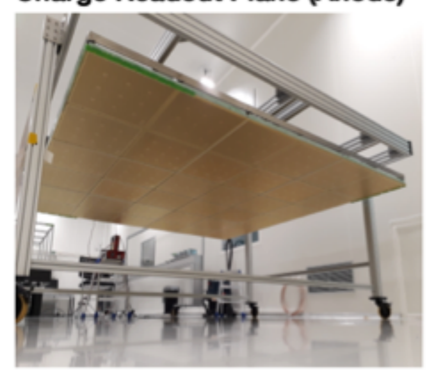
- X-ARAPUCA: Wavelength shifters and “light-trap” concept with dichroic filters
- 3.5% photon detection efficiency achieved for incident 127 nm scintillation light
- Each PD module has 4 optically isolated supercells (48.8 cm x 10 cm) each with 48 ganged 6 mm x 6mm silicon photomultipliers (SiPMs)
- Each PD module ~equivalent to about 3 coated 8” PMTs
- 6000 PD signals (288,000 SiPMs) per 17 kt far detector module

Dual Phase TPC Module



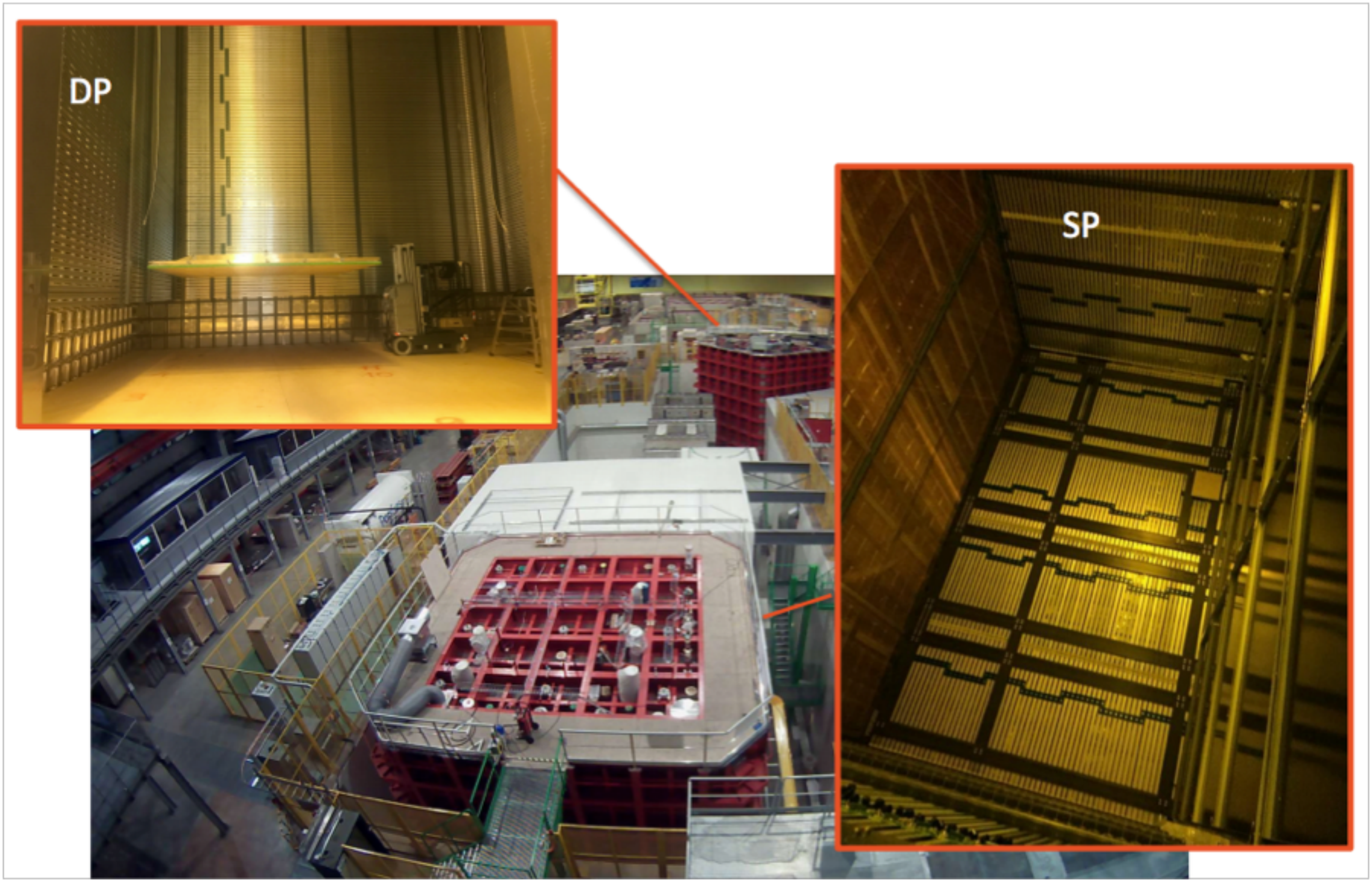


Charge Readout Plane (Anode)

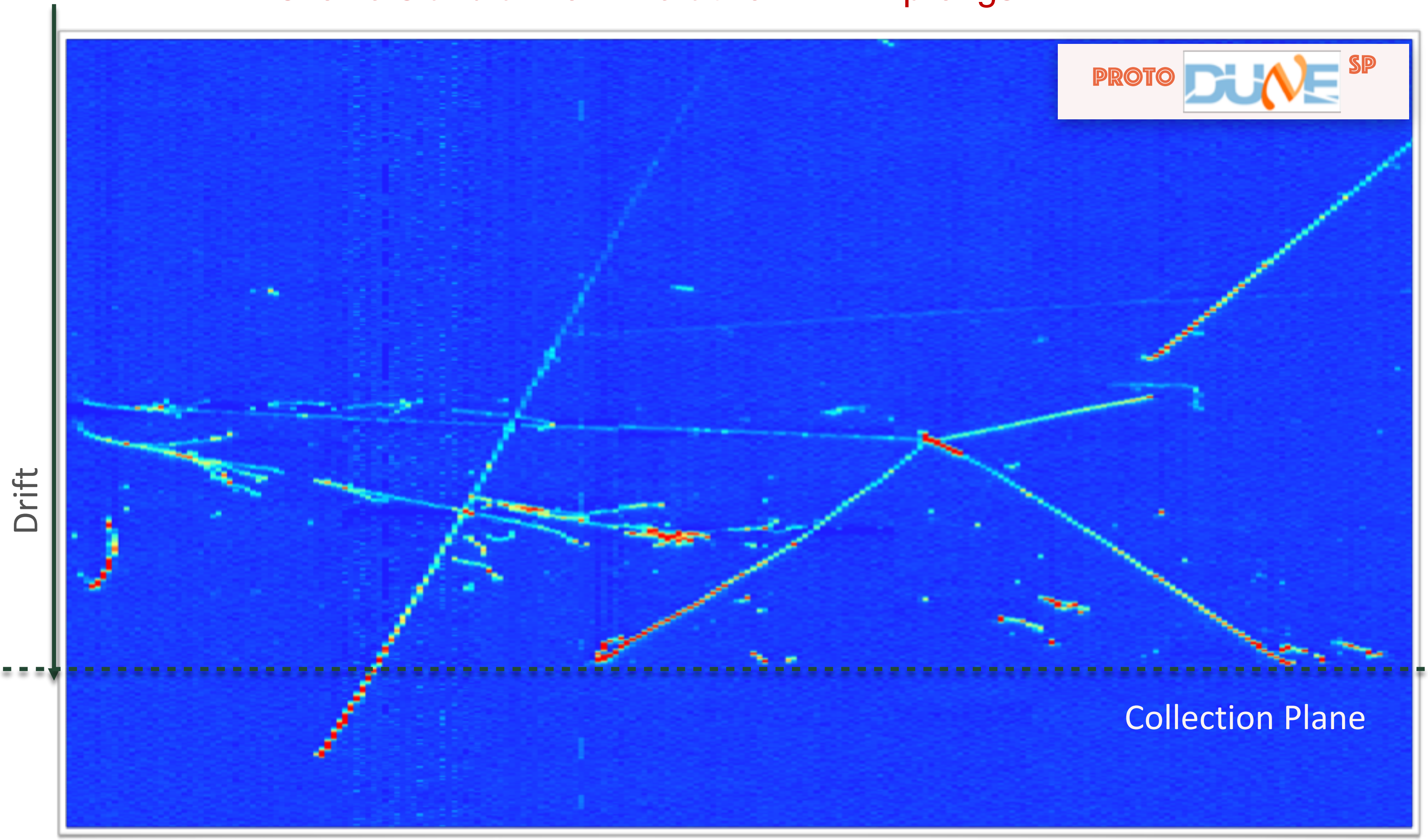


- Single homogeneous LAr drift volume
- Signal amplification in the gas phase leads to improved signal/noise
- 600,000 volts between cathode and anode
- Photosensors under semi-transparent cathode grid

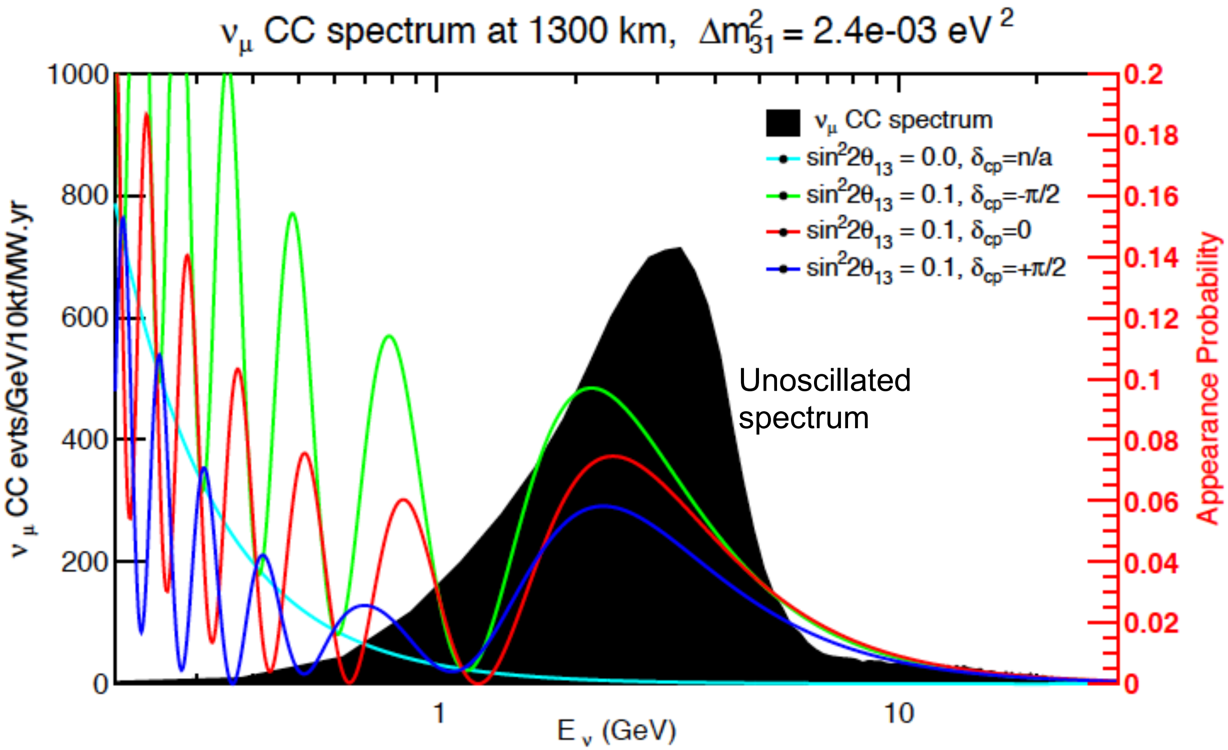
Large-Scale Prototypes: ProtoDUNE



2 EM showers and a Pion Interaction with 4 prongs

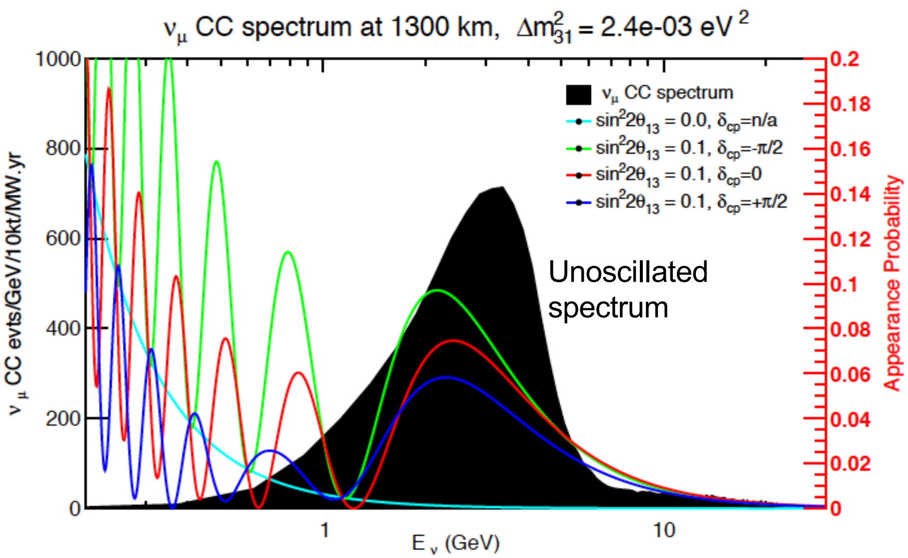


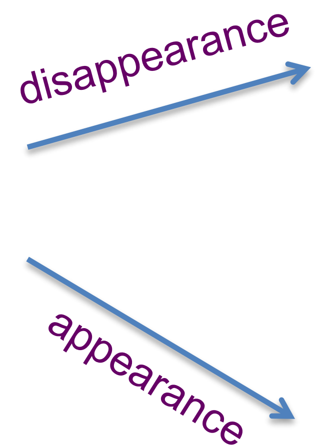
Testing the Neutrino Three-Flavor Paradigm

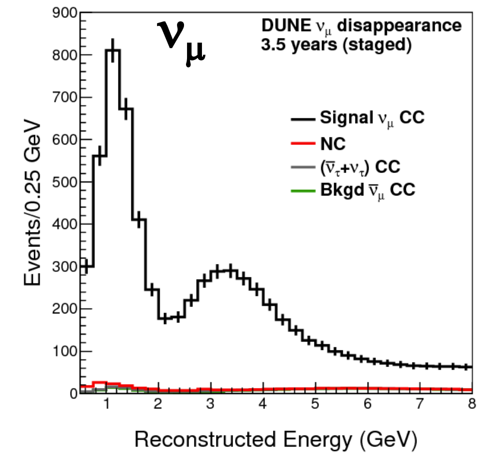


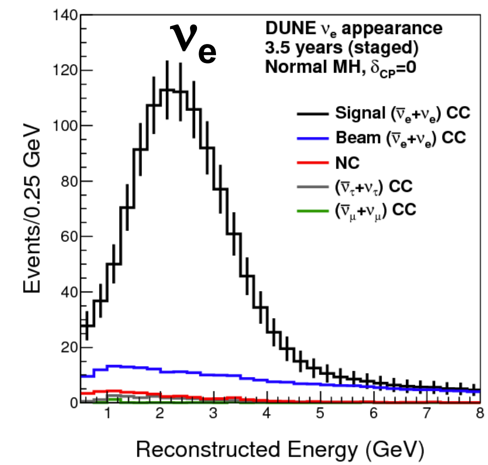
- Oscillation probability depends on the ratio of distance travelled (L) and neutrino energy (E): L/E
- Lines shows ν_e appearance probability for a pure ν_μ beam for L = 1300 km for three values of CP violating phase δ_{CP}
- Filled in curve shows ν_μ energy spectrum at L if there were no oscillations

Experimental Method





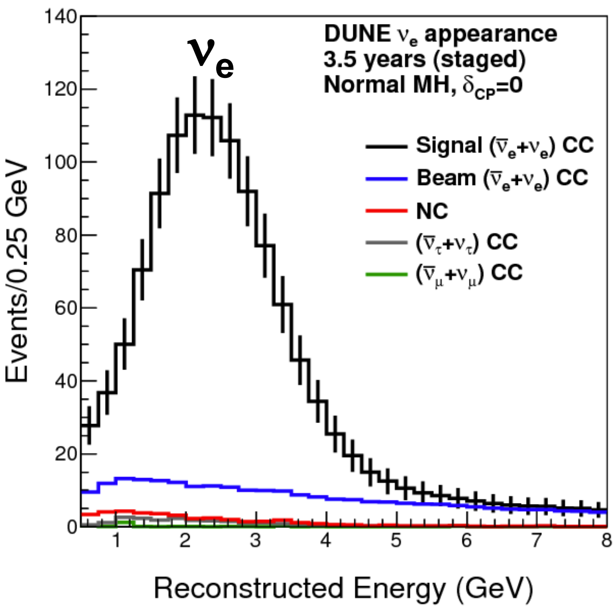




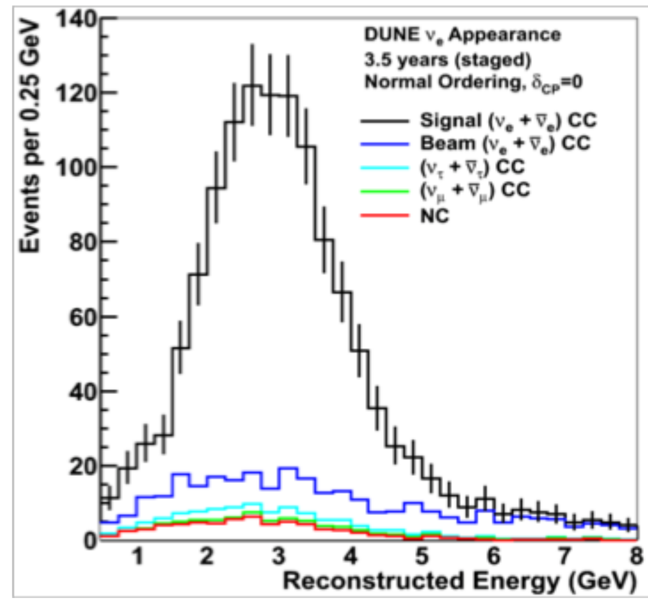
- Produce a pure on-axis ν_μ beam with spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- Do the same with anti-neutrinos
- **Fit all four spectra simultaneously**
- DUNE optimized the choice of beam and distance to have sensitivity to CP violation, CP phase, neutrino mass ordering, and other oscillation parameters ***in the same experiment***

Improving Our Tools

Conceptual Design Report (2016):
Parametrized detector response and estimated efficiency



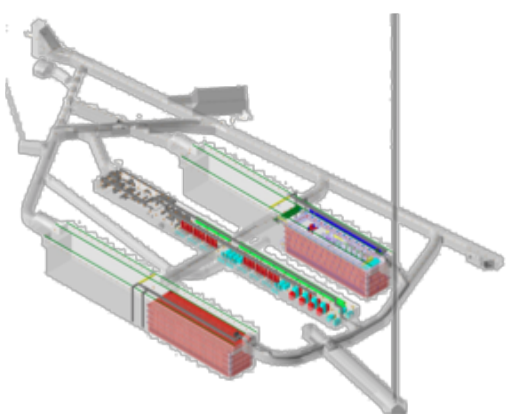
Technical Design Report (2019):
Full reconstruction chain and CVN selection



- Sensitivity from MC-based analysis with full reconstruction chain similar/better than in Conceptual Design Report (CDR)
- Sensitivity plots will be updated for the TDR (early 2019)

DUNE Staging Scenario

- Year 1: 20 kt far detector fiducial mass, 1.2 MW, 80 GeV proton beam and initial Near Detector
- Year 2: addition of 3rd detector for total mass of 30 kt
- Year 4: addition of 4th detector for total mass of 40 kt, final Near Detector
- Year 7: beam upgrade to 2.4 MW



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

DUNE CDR Systematics

Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

Spectral uncertainty not included in this treatment.

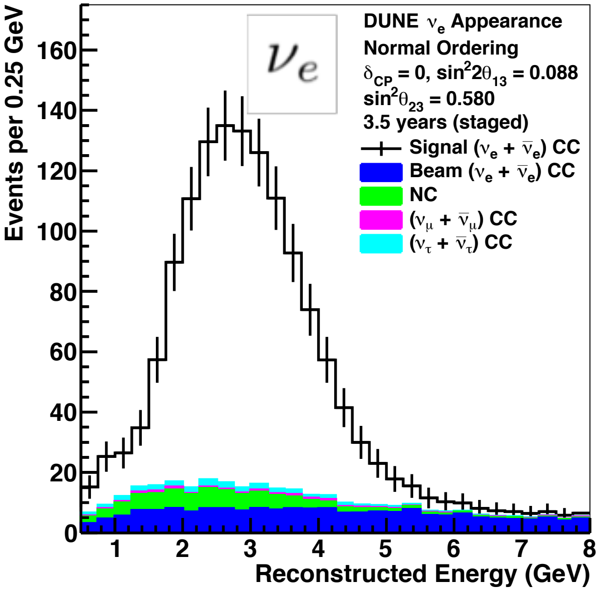
Signal normalization uncertainties are treated as *uncorrelated* among the modes ($\nu_{e,}$ $\nu_{e,}$ $\nu_{\mu,}$ ν_{μ}) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied.

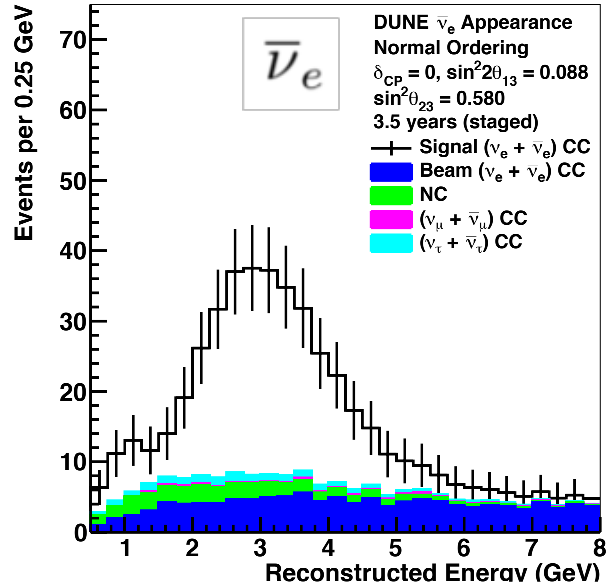
$\nu_{\mu} = \nu_{\mu} = 5\%$ → Flux uncertainty after ND constraint

$\nu_{e} = \nu_{e} = 2\%$ → Residual uncertainty after ν_{μ} and $\nu/\bar{\nu}$ constraint

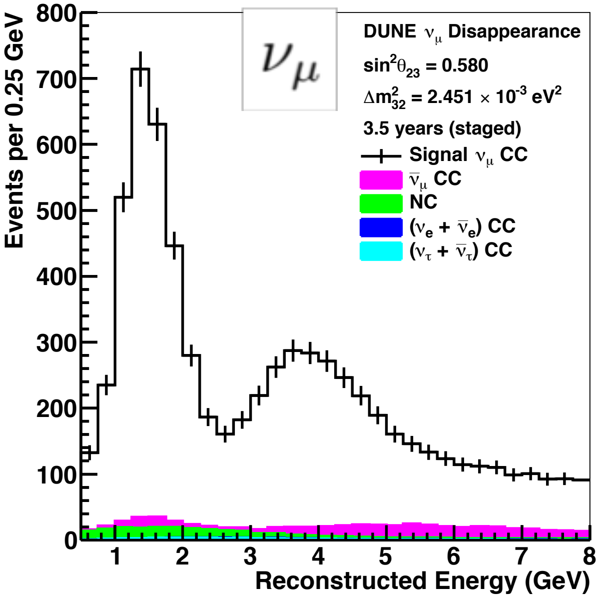
Oscillation parameter central values and uncertainties are taken from NuFit 2016 (arXiv:1611.01514). Parameters are allowed to vary constrained by 1/6 of the $\pm 3\sigma$ range in the global fit.

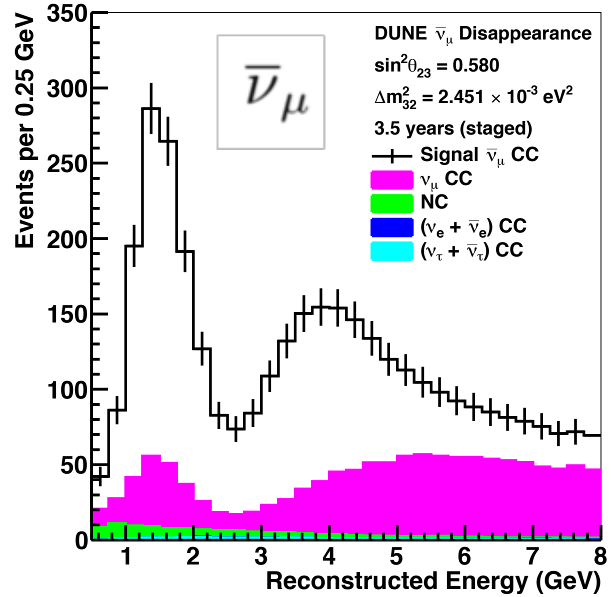
Will be updated soon in Preliminary Design Report





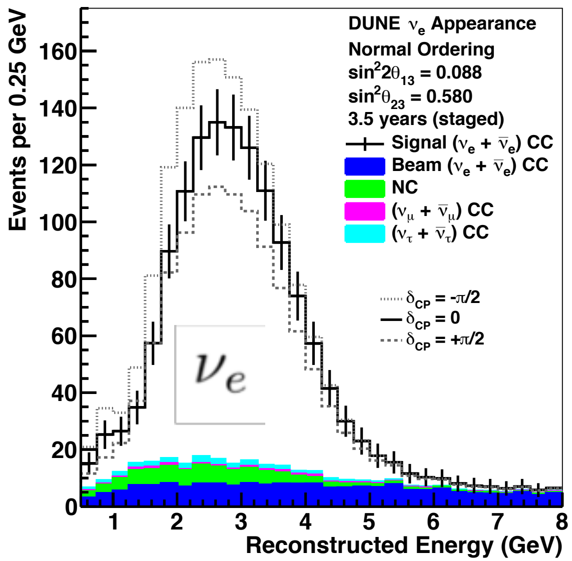
- 3.5 years staged scenario
- CVN event selection
- Normal ordering
- NuFit4.0 parameters
- $\delta_{cp} = 0$
- PID cut

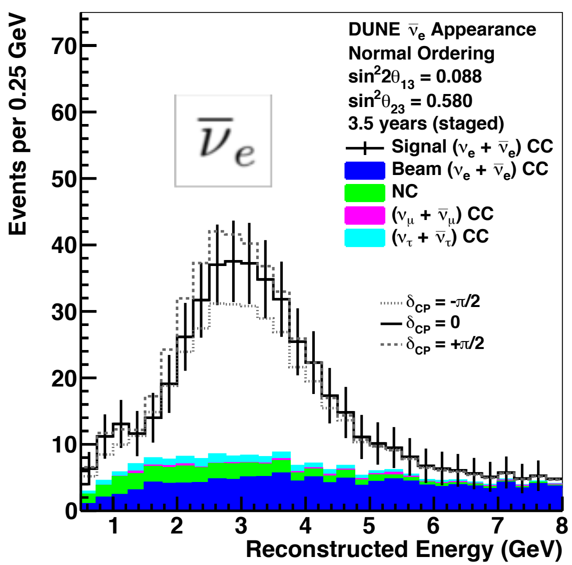




Broad Spectrum allows effective use of spectral information

Large Matter Effect





- 3.5 years staged scenario
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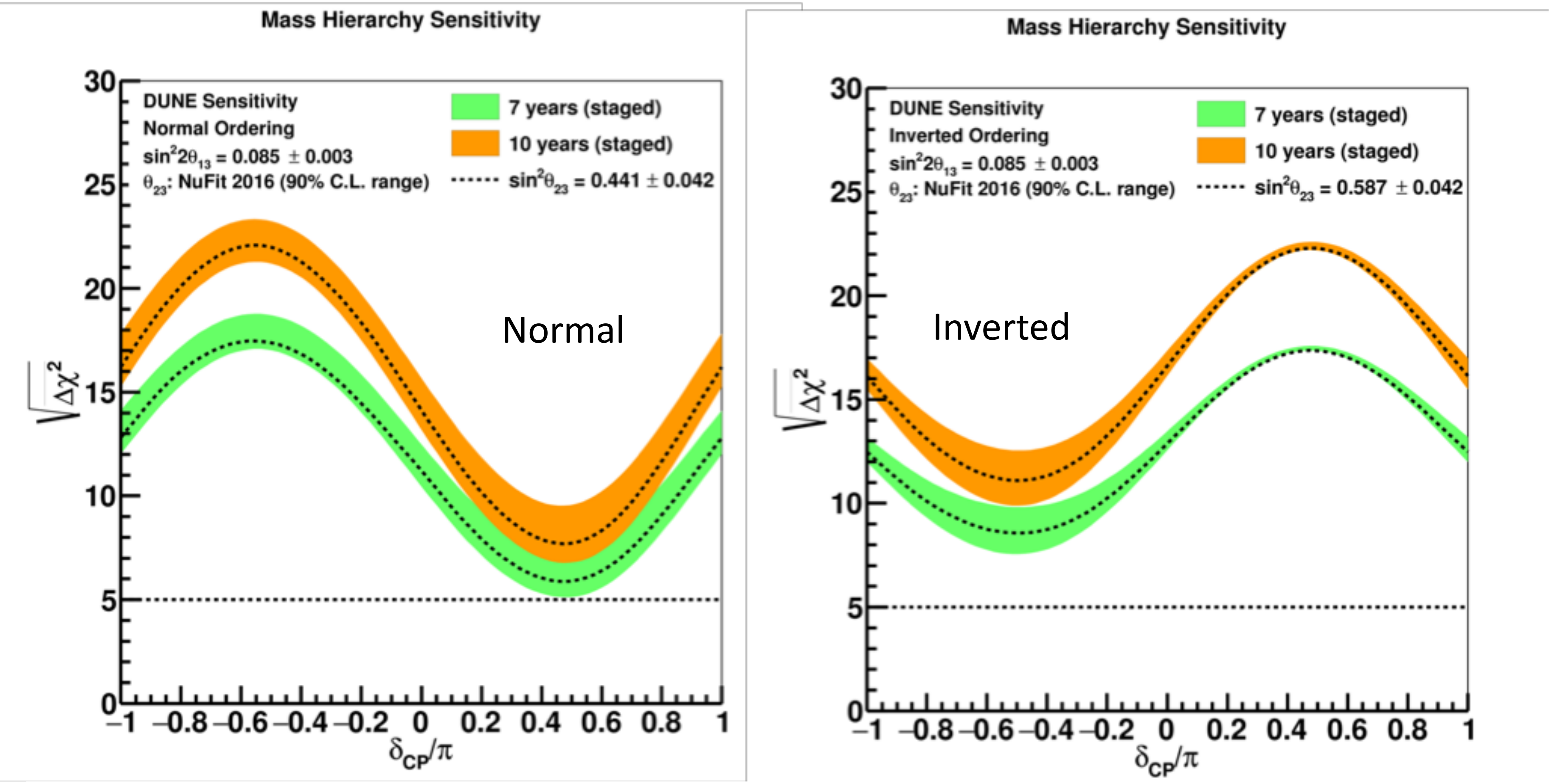
Broad Spectrum allows effective use of spectral information

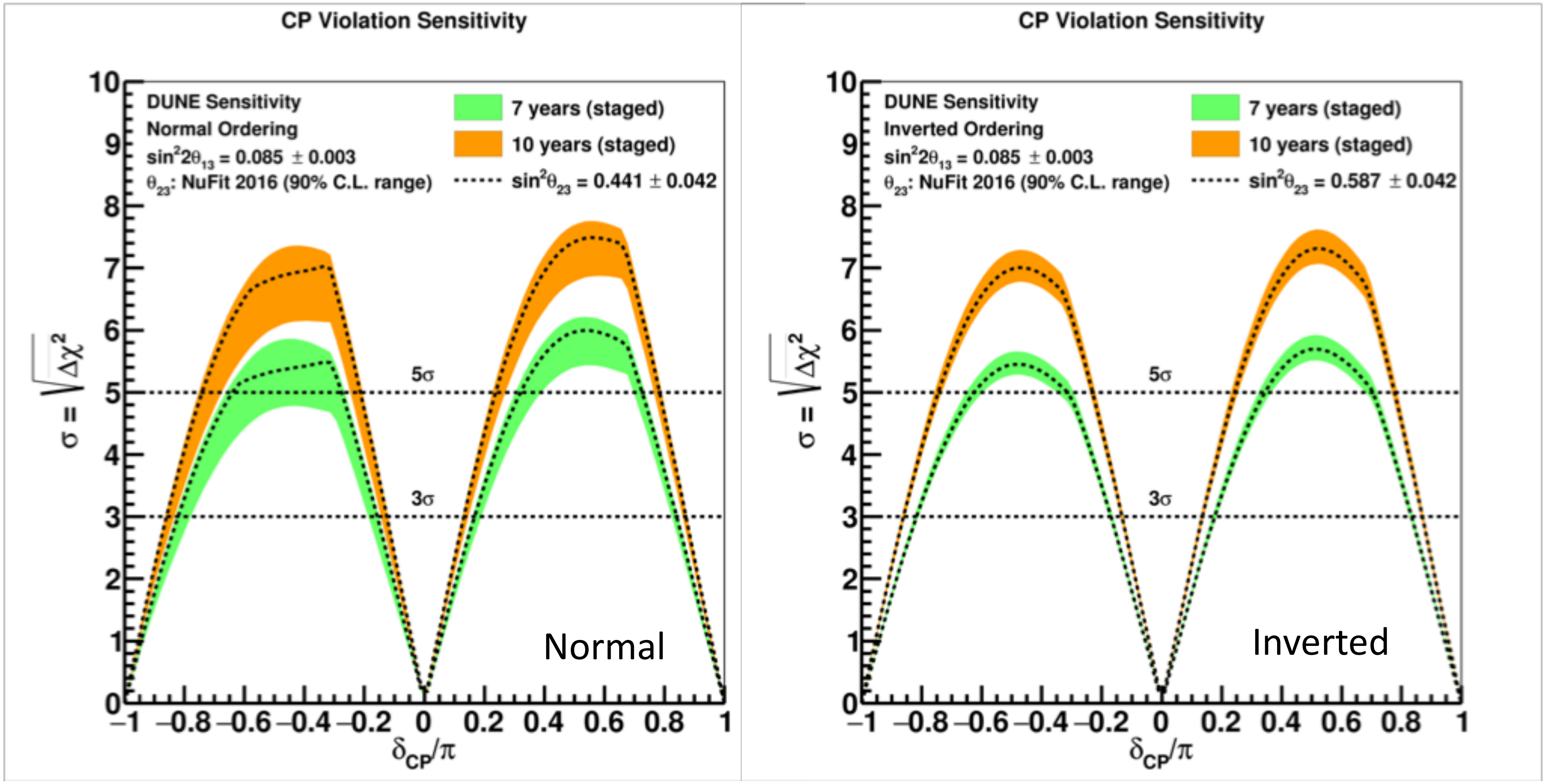
Large Matter Effect

Mass Ordering Determination



- Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range (www.nu-fit.org)
- Assumes equal running in neutrino and antineutrino mode
- Includes simple normalization systematics and oscillation parameter variations

CP Violation Sensitivity



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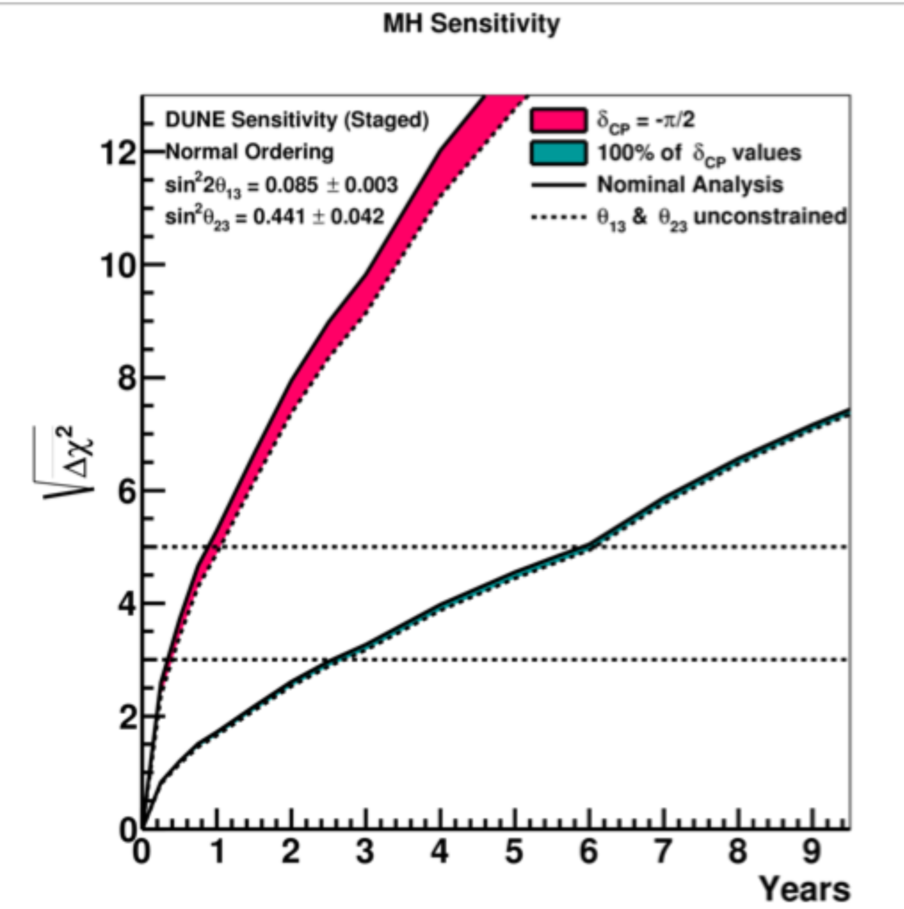
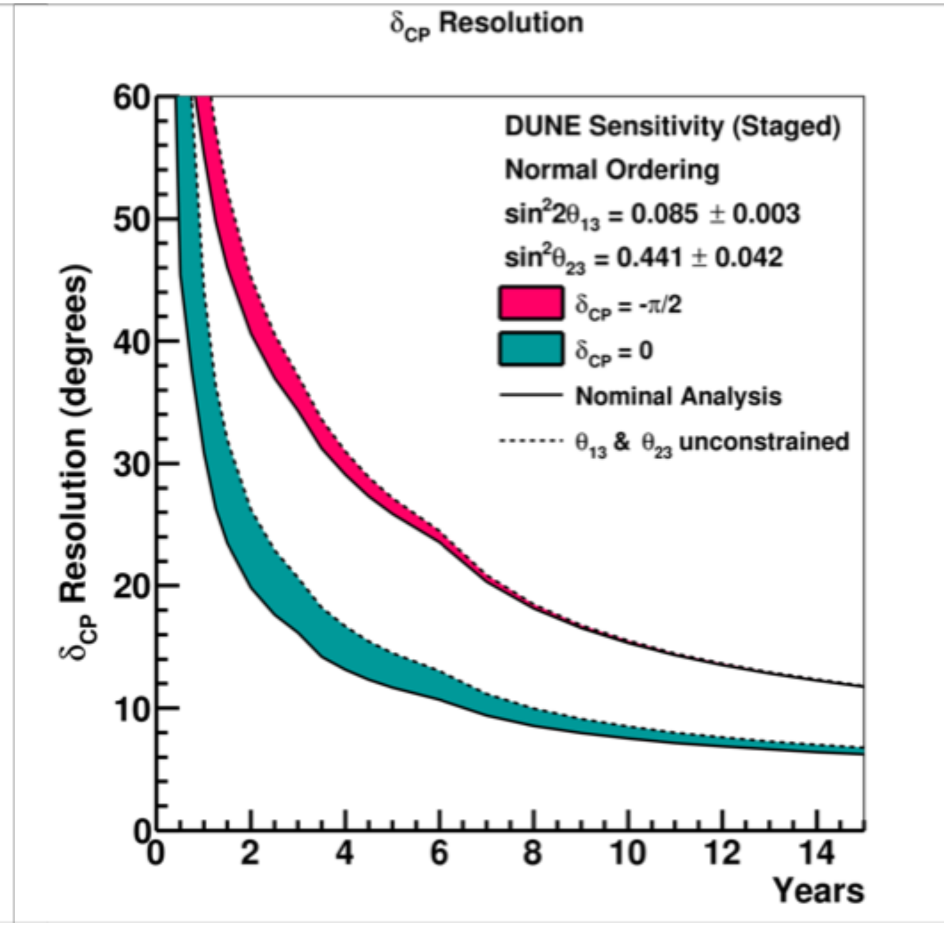
- Assumes equal running in neutrino and antineutrino mode
- Includes simple normalization systematics and oscillation parameter variations

DUNE Only Sensitivity



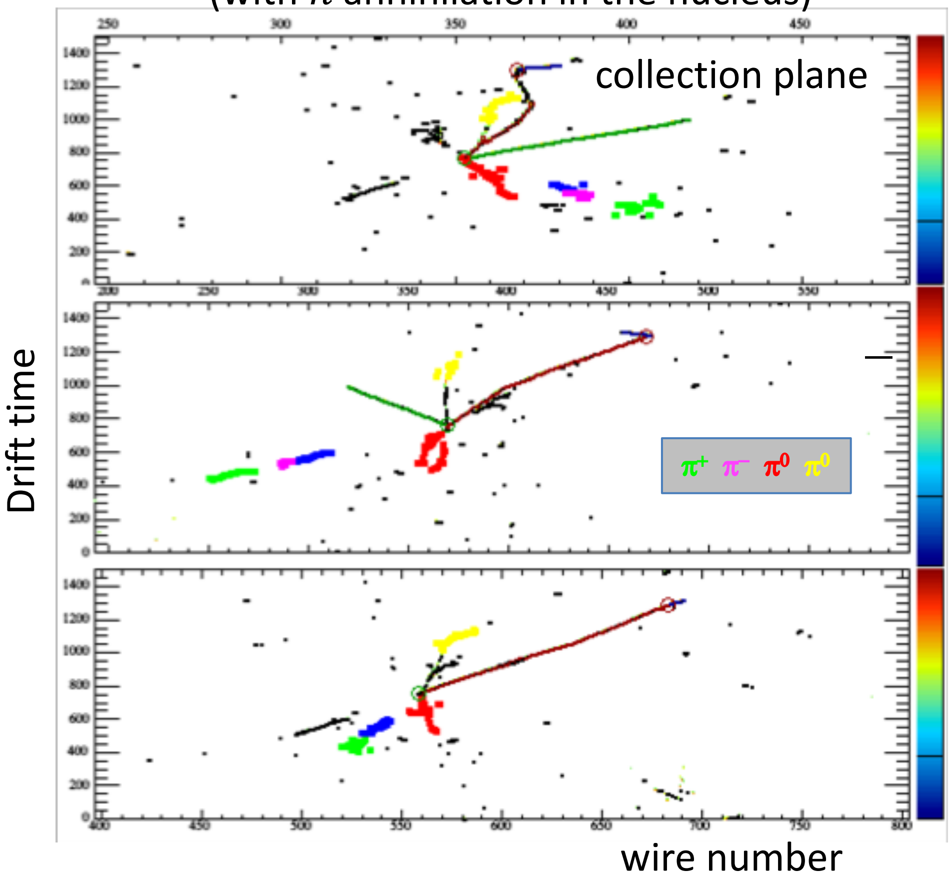


- Width of band indicates variation between using external constraints and a “DUNE-only” analysis
- Assumes equal running in neutrino and antineutrino mode
- Includes simple normalization systematics and oscillation parameter variations

Baryon Number Violation

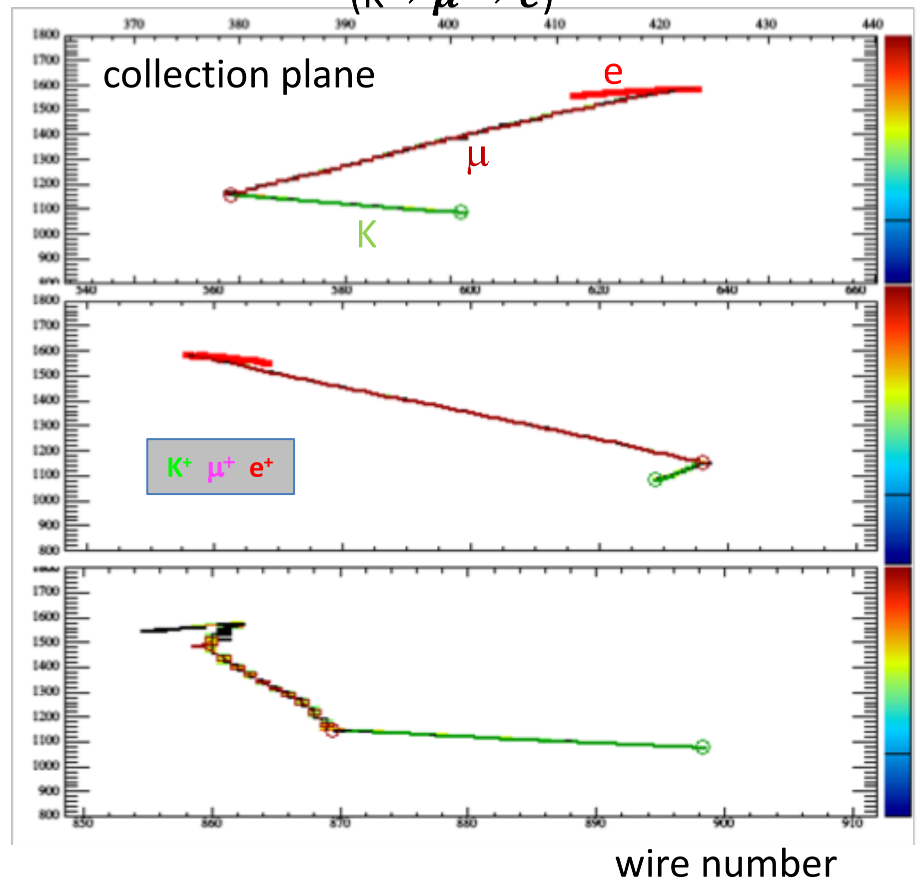
$n - \bar{n}$ oscillation

(with $\bar{n}$ annihilation in the nucleus)



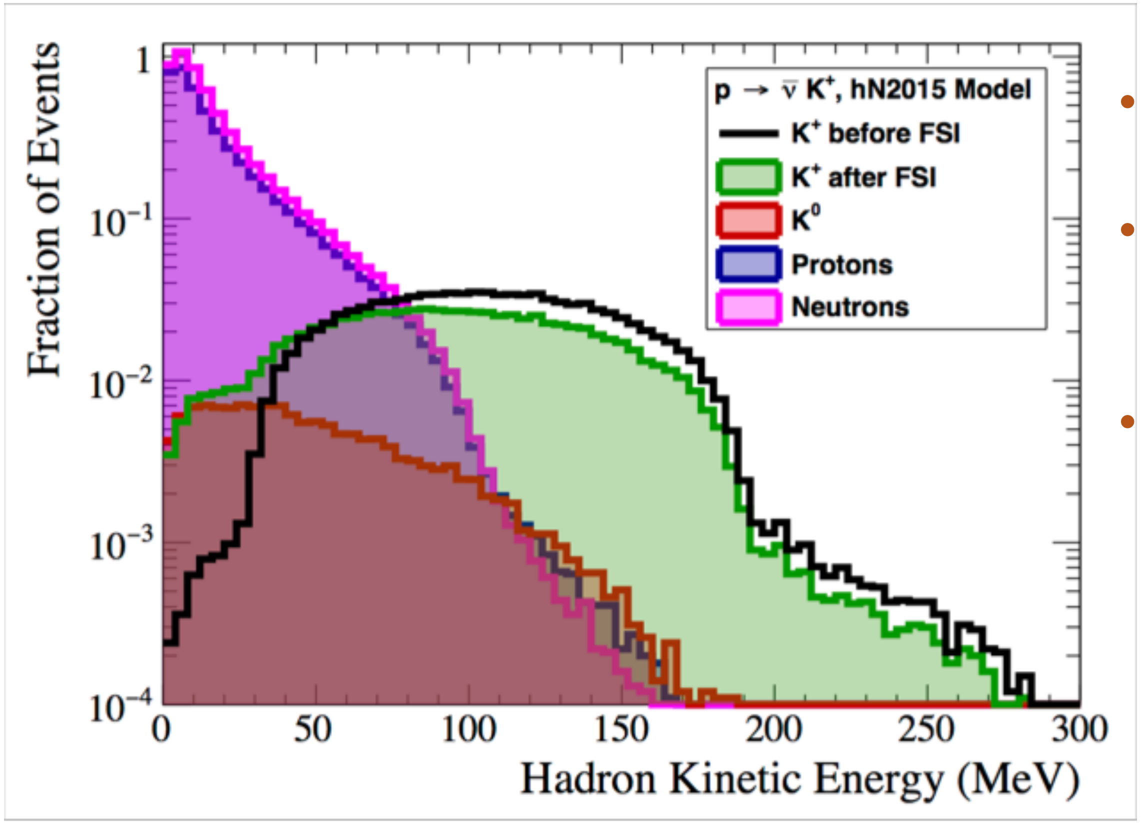
$p \to \bar{\nu} K$

(K$\to \mu \to e$)



- Full simulation and reconstruction
- Updated efficiency and sensitivity in the upcoming Technical Design Report

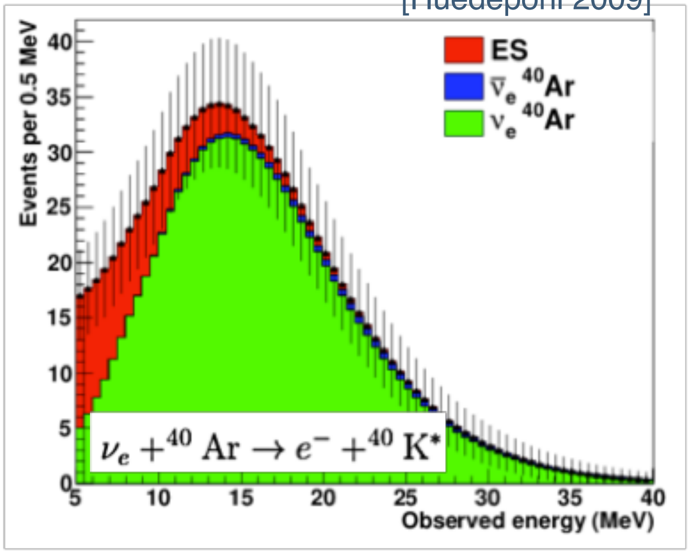
Nucleon Decay Example: $p \rightarrow \bar{\nu} K^+$



- Effects of FSI on K^+ are being updated for the TDR
- GENIE hN2015 intranuclear hadron transport model shown on the left has updated
- About 6% of the FS K^+ are above the expected threshold of 30 MeV

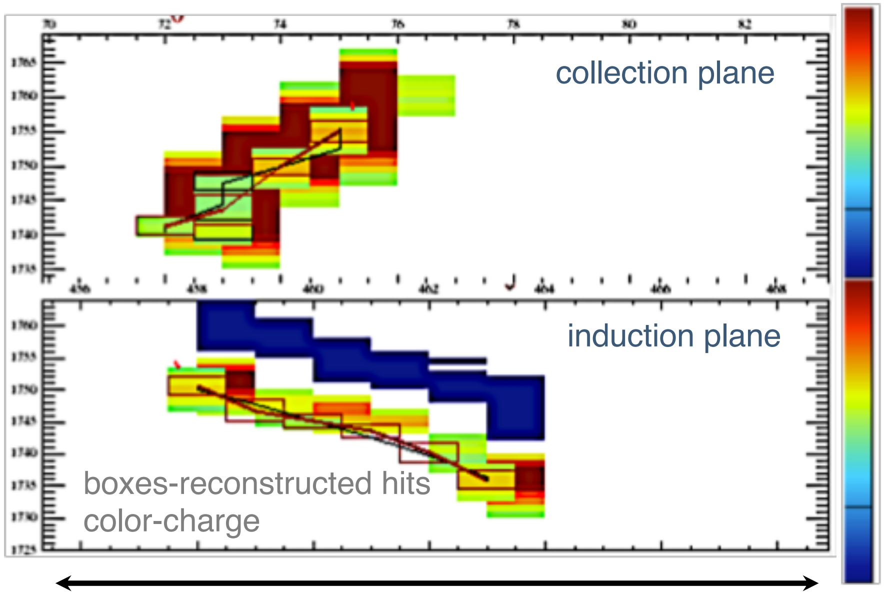
Supernova Burst/Low Energy Neutrinos

[Huedepohl 2009]



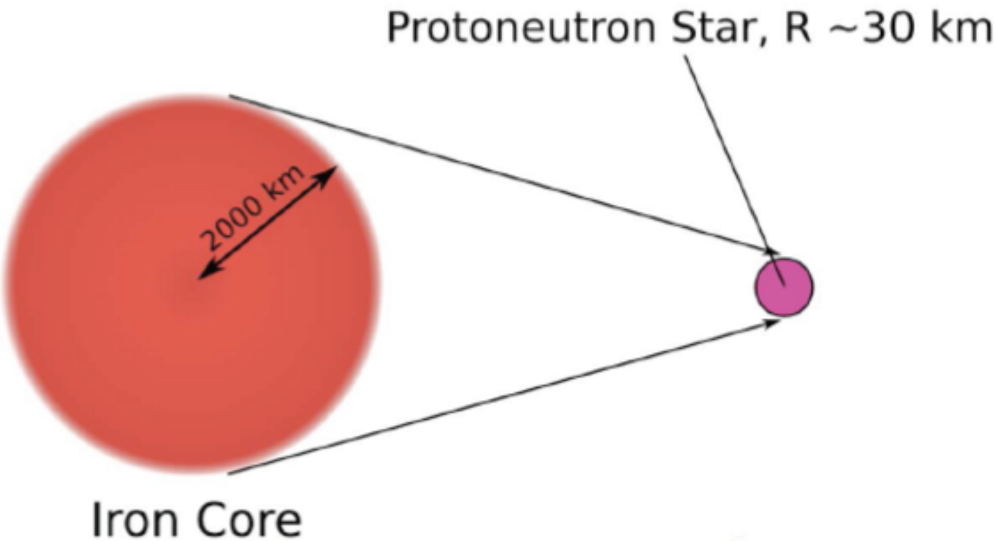
Event spectrum from electron-capture SN at 10 kpc in 40-kt LArTPC

10.25 MeV electron

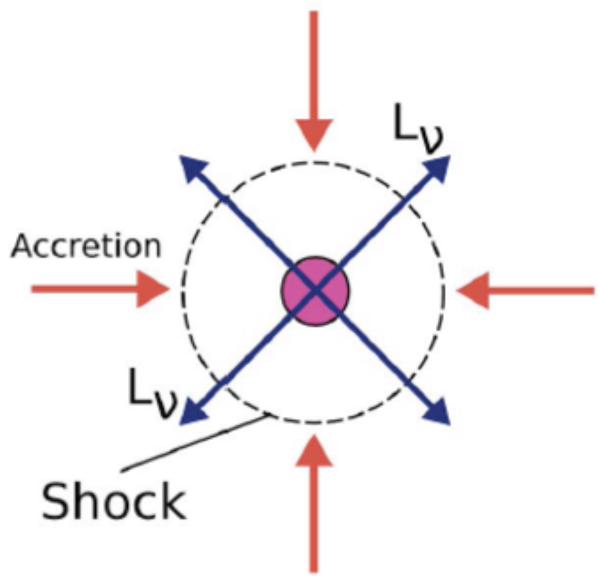


6.5 cm

- Tracks only a few centimeters long
- Full simulation and reconstruction tools developed
- Event-by-event energy reconstruction possible
- Pointing a possible using elastic scattering (ES) from electrons
- Triggering understood for SNB but a challenge for solar neutrinos



Reviews:
Bethe'90
Janka+'12



Nuclear equation of state (EOS) stiffens at nuclear density.

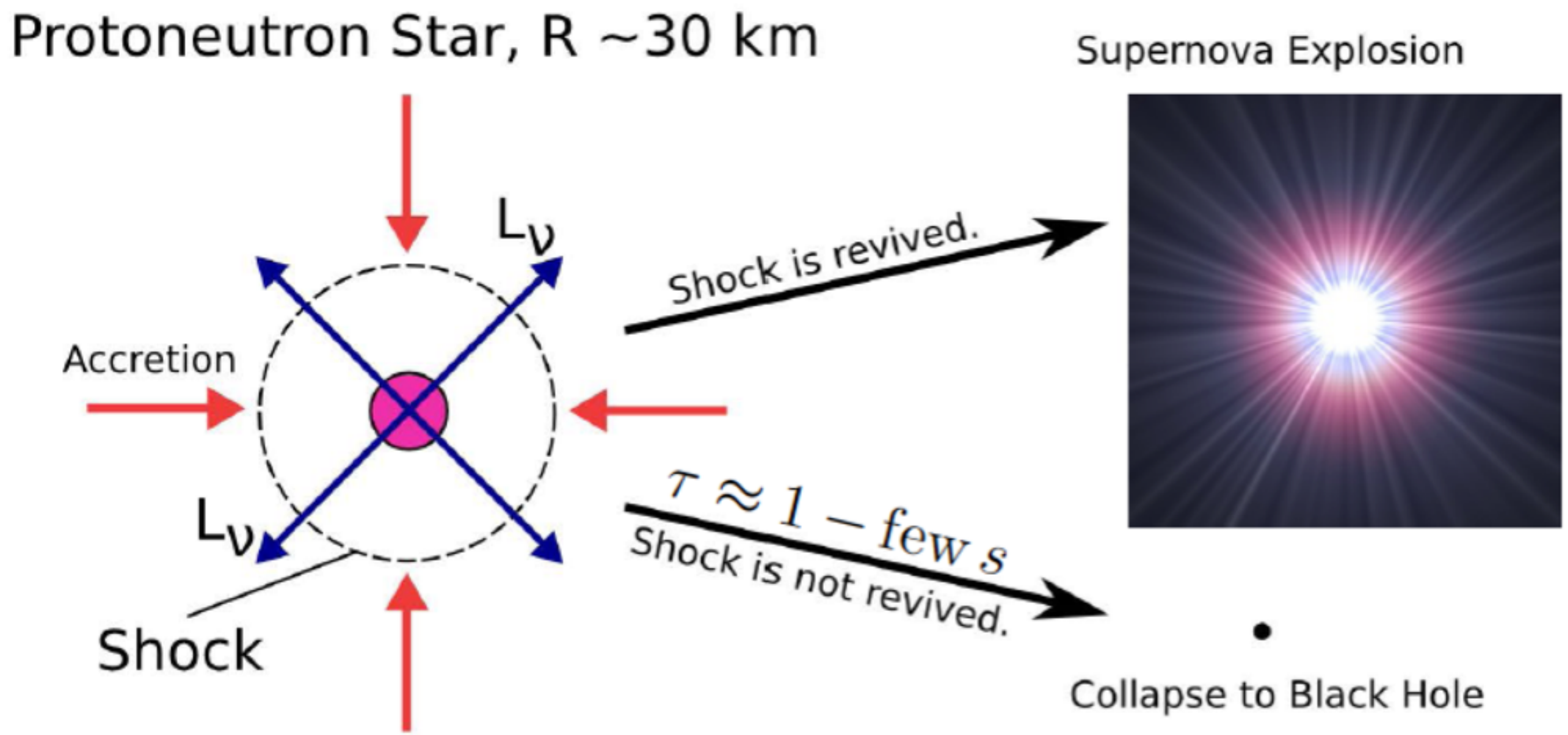
Inner core (~0.5 M_{Sun})
-> protoneutron star core.
Shock wave formed.

Outer core accretes onto shock & protoneutron star with O(1) $M_\odot$/s.

-> **Shock stalls at ~100 km, must be "revived" to drive explosion.**

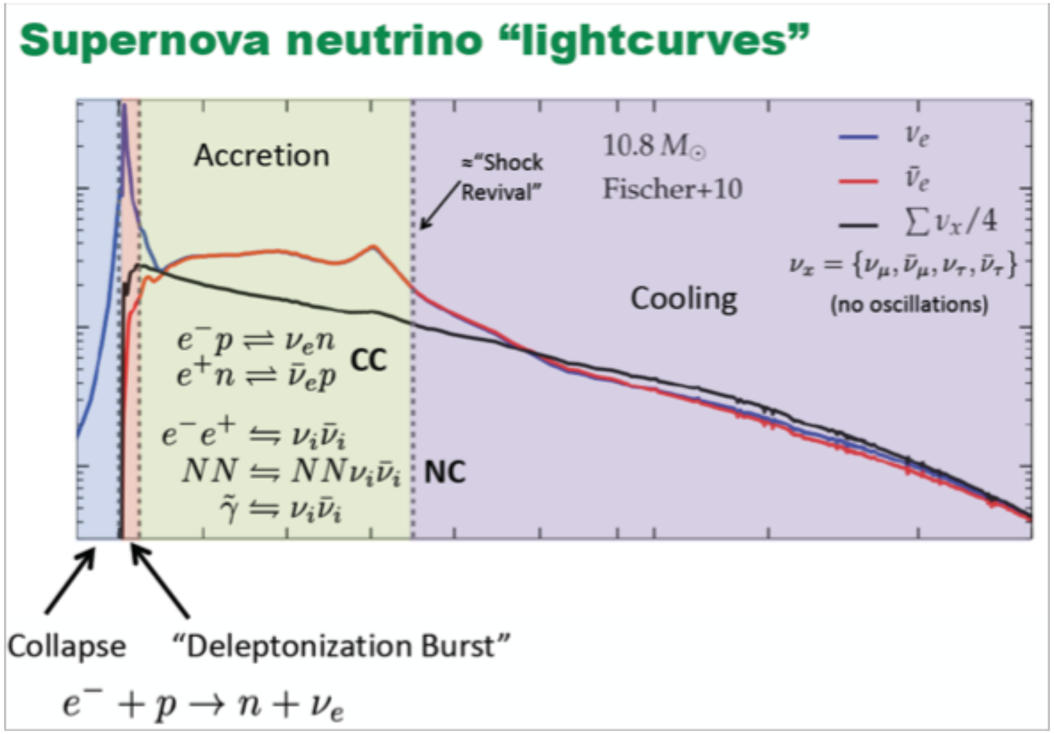
Courtesy C. Ott, Caltech

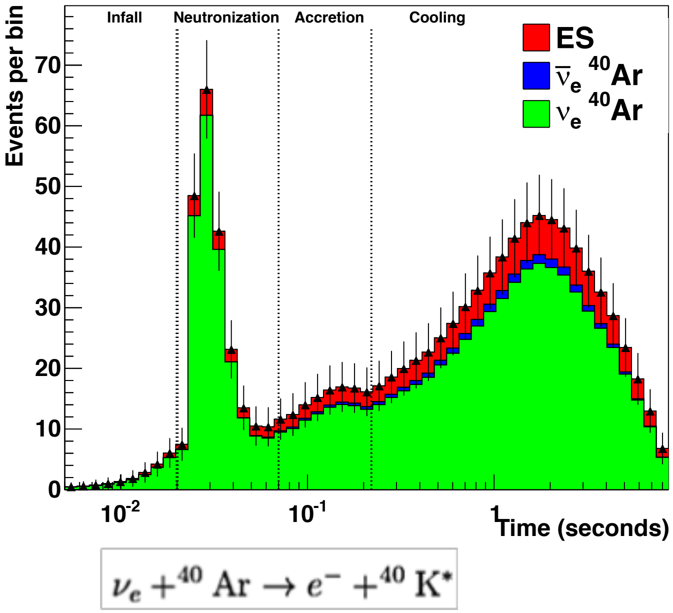
“Postbounce” Evolution



Courtesy C. Ott, Caltech

Supernova Burst/Low Energy Neutrinos





Due to the sensitivity to ν_e DUNE has excellent sensitivity to the collapse and accretion stages of the collapse.

But how well do we understand the cross-section?

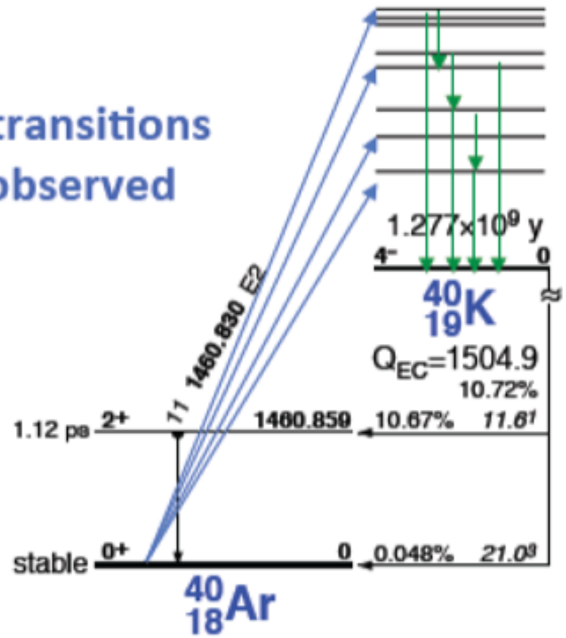
Supernova neutrino detection in liquid argon

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)
- Compton scatters above some threshold, so detector will never observe total energy

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)

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

Uncertainties in the cross-section:

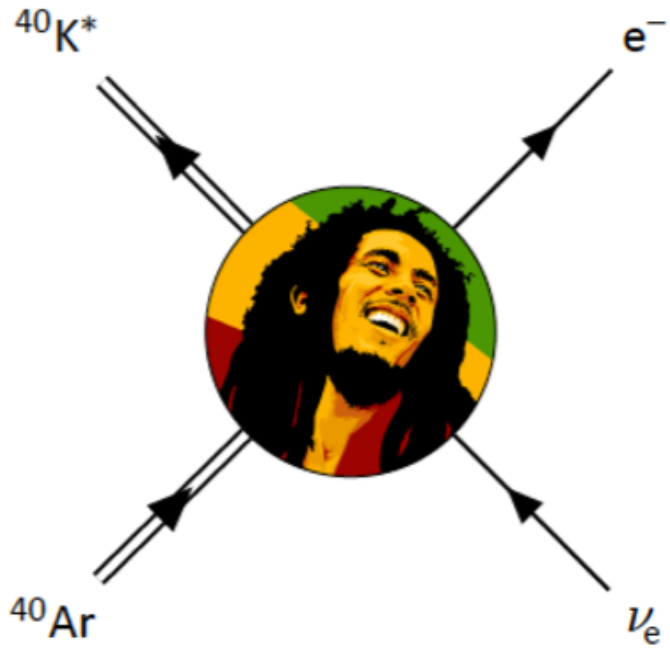
Need to measure the transition intensities

$$\sigma(E_\nu) = \frac{G_F^2 \cos^2(\theta_{ud})}{\pi\hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(GT) + B_i(F)]$$

MARLEY: Model of Argon Reaction Low-Energy Yields

- **Goal:** determine whether "every little thing gonna be all right" for SN neutrino physics in LArTPCs

- Event generator for SN ν on ^{40}Ar
- Modern C++, mostly from scratch
- No required external dependencies
- Current version focuses on generating ν_eArCC events
- Additional reactions can be added in upcoming versions
- Reaction data can also be added for other nuclear targets



Gardiner and Svoboda, 2016

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya, A. García, and N. I. Kaloskamis*
University of Notre Dame, Notre Dame, Indiana 46556

E. G. Adelberger and H. E. Swanson
University of Washington, Seattle, Washington 98195

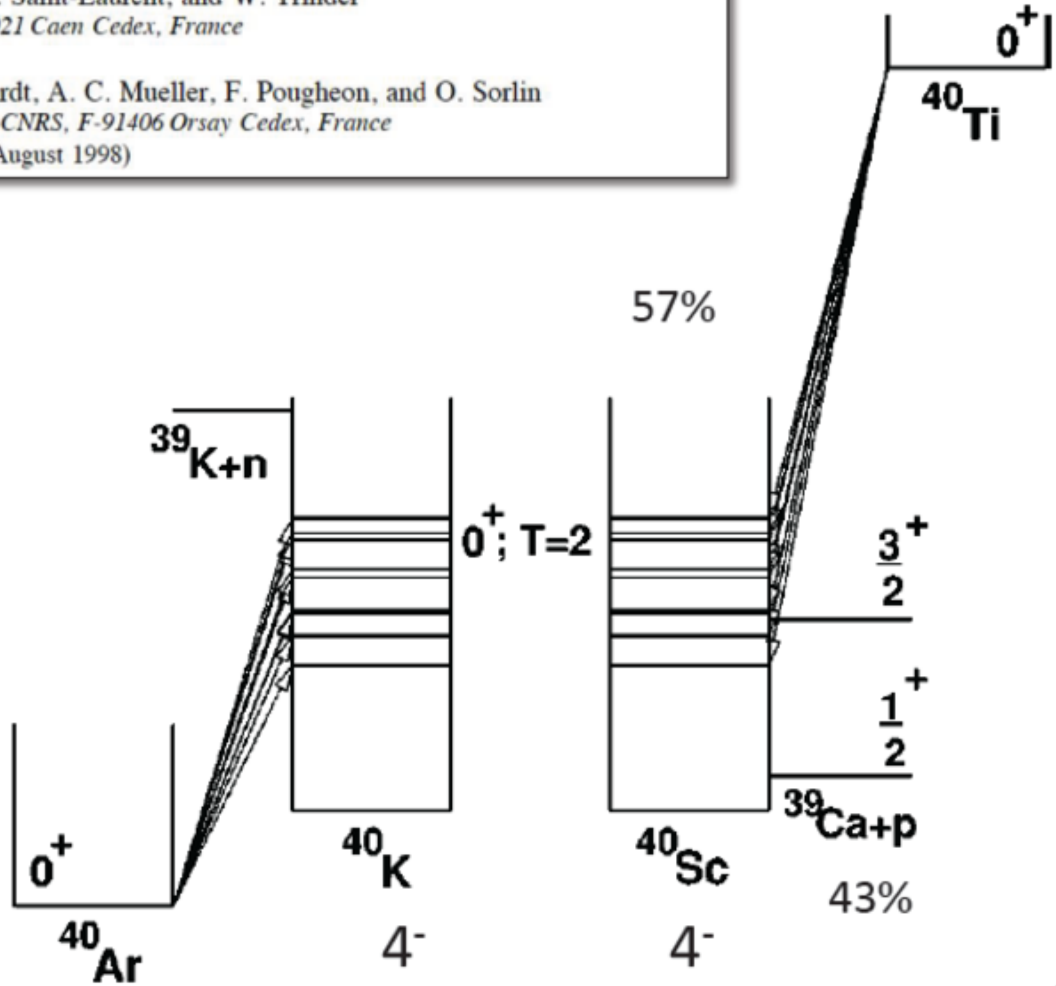
R. Anne, M. Lewitowicz, M. G. Saint-Laurent, and W. Trinder
GANIL, BP 5027, F-14021 Caen Cedex, France

C. Donzaud, D. Guillemaud-Mueller, S. Leenhardt, A. C. Mueller, F. Pougheon, and O. Sorlin
Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
(Received 4 August 1998)

Make 40-Ti via heavy ions on a thin, heavy target (e.g. Cr on Ni). Embed ions in silicon detector.

Use TOF and dE/dx to separate 40-Ti out from ion "soup"

Observe beta decay to 40-Sc excited states, which decay via delayed proton emission

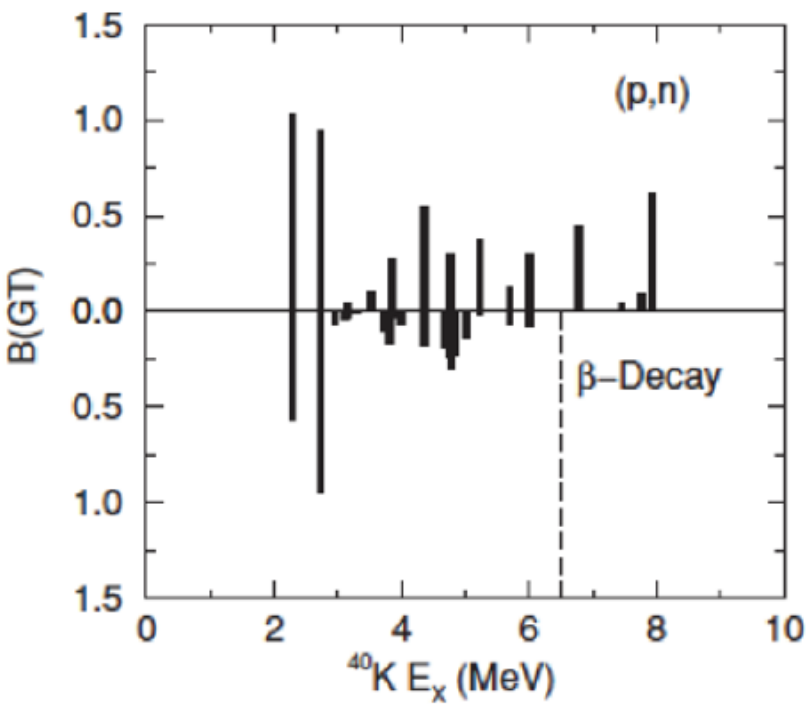


(p,n) data

PHYSICAL REVIEW C 80, 055501 (2009)

Weak-interaction strength from charge-exchange reactions versus β decay in the $A = 40$ isoquintet

M. Bhattacharya,[1,2,*] C. D. Goodman,[2] and A. García[3]

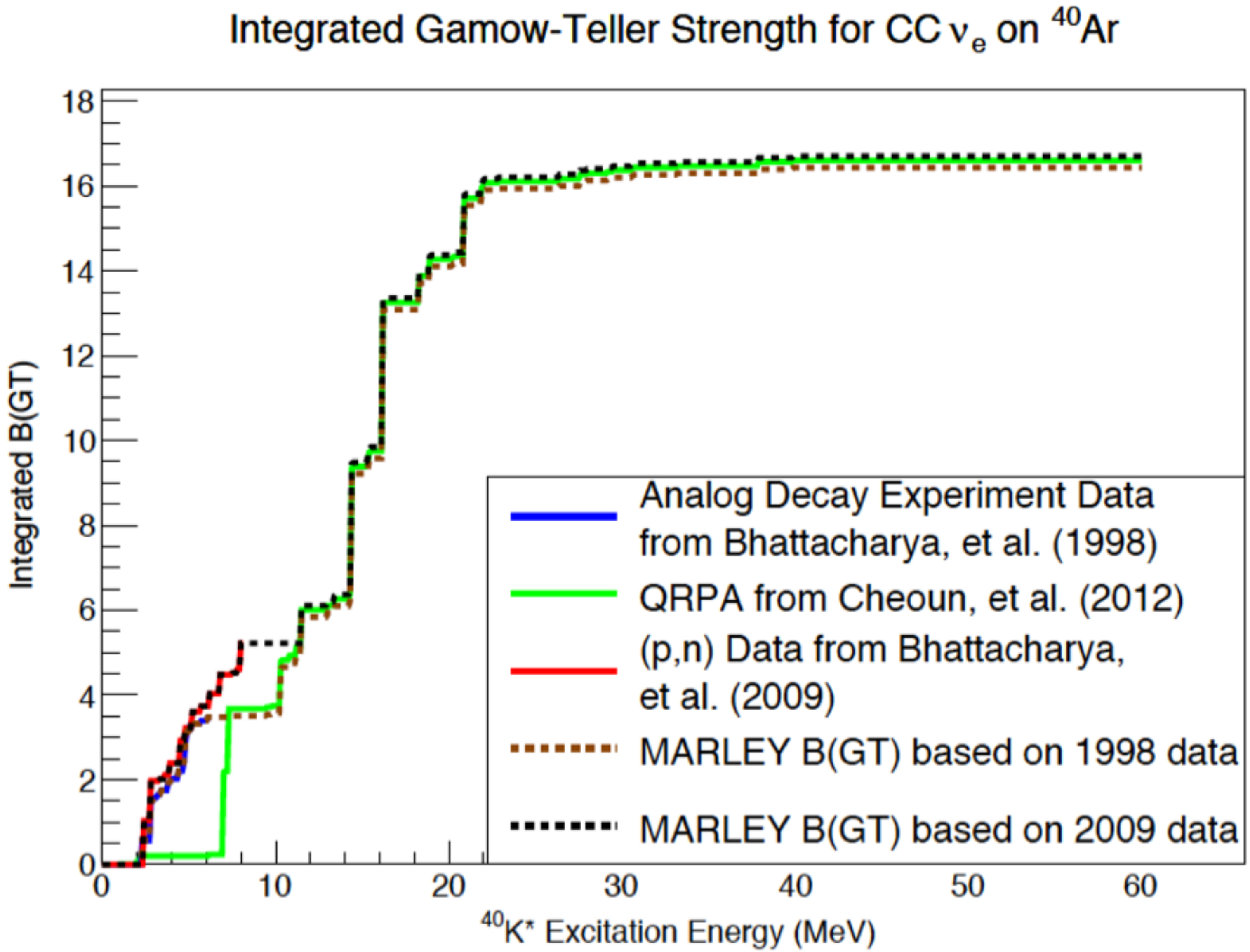


One can measure GT strength via very forward (p,n) scattering.

Comparison of B(GT) obtained from (p,n) [top] and 40-Ti [bottom]

This leads to differences in cross-section and final states.

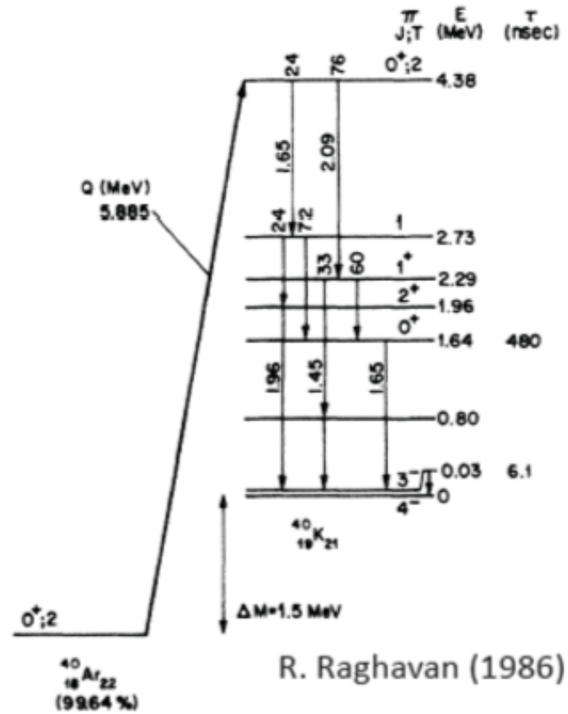
Combining results from these three sources gives us a useful first-pass B(GT) dataset



MARLEY nuclear de-excitation model

- If the residual nucleus is in a bound state, the GENERATOR consults its STRUCTUREDATABASE to see if γ-ray data are available.
  - If so, a DECAYSCHEME is used to repeatedly sample gammas down to the ground state
  - If not, MARLEY uses the same γ-ray model as for unbound states

- The discrete level data to use are specified in a CONFIGURATIONFILE
- MARLEY uses the same structure data format as the TALYS nuclear code
- **Recommended level data:** TALYS-1.6
  - based on ENSDF and RIPL-3 experimental databases
  - fills in missing pieces with theory
  - GPL-licensed
  - subset available now at http://www.marleygen.org



R. Raghavan (1986)

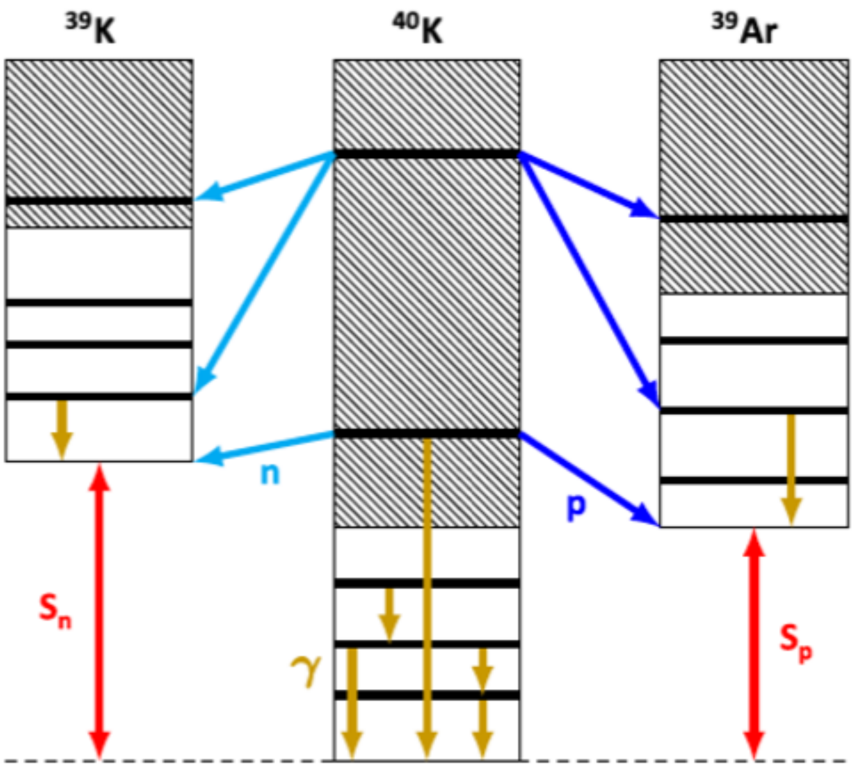
FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.

MARLEY nuclear de-excitation model

- If the residual nucleus is in an unbound state, a HAUSERFESHBACHDECAY object computes partial decay widths and samples an EXITCHANNEL
- The EXITCHANNEL handles a binary decay of the nucleus
- If excitation energy remains in the new nucleus, another bound or unbound de-excitation step is simulated as appropriate

Hauser-Feshbach statistical model

- Assumes that the ν reaction forms a compound nucleus
- Partial decay widths depend on
  - initial level E_x and J^π
  - discrete levels (DECAYSCHEME)
  - continuum level density (LEVELDENSITYMODEL)
  - transmission coefficients (OPTICALMODEL, GAMMASTRENGTHFUNCTIONMODEL)



MARLEY simulations can already help us better understand the ν_e signal

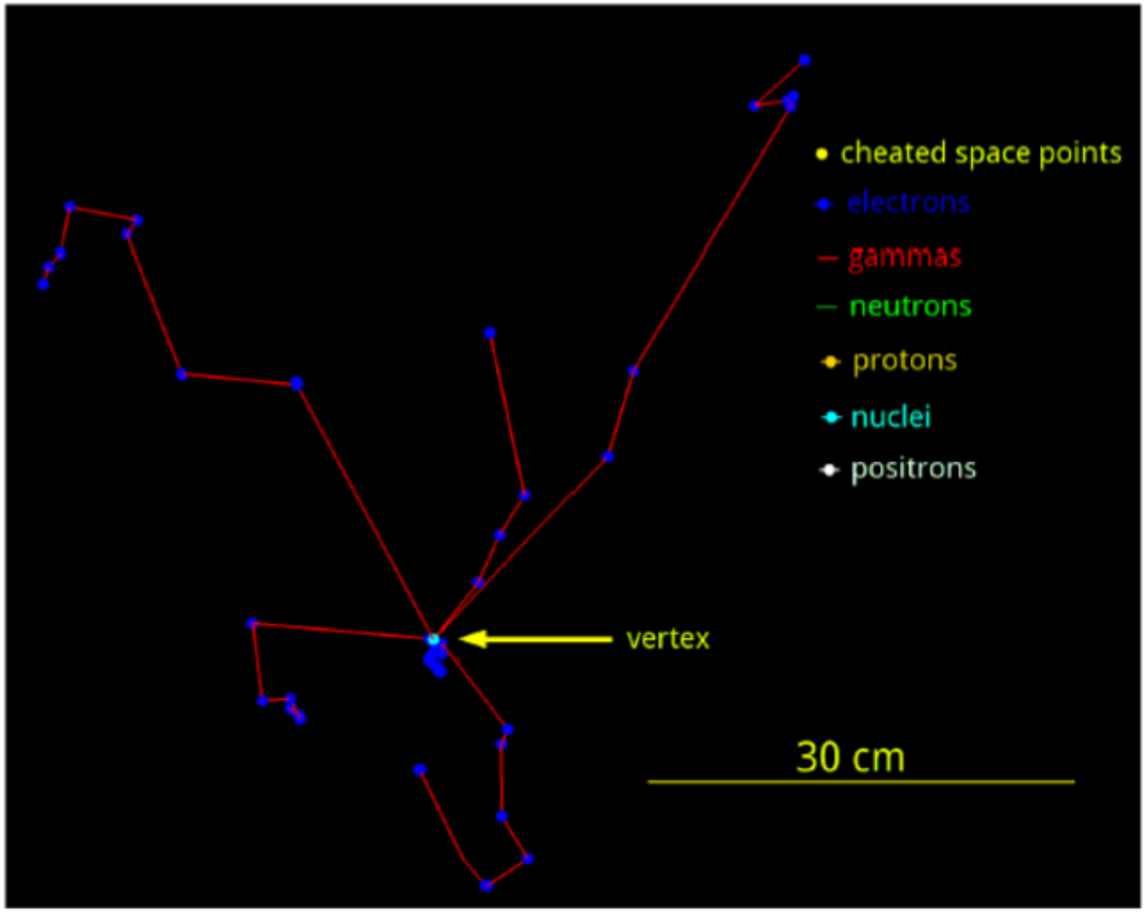
T=3.5 MeV FD Spectrum

BR(%)	Event Type	Average Fraction of Final-State KE e^-	γ	n	p
82.5%	e^- + γs only	75.6%	24.4%	0%	0%
15.9%	single n	67.3%	16.2%	16.0%	0%
1.4%	single p	54.0%	14.1%	0%	31.0%
0.2%	other	44.7%	14.1%	1.5%	2.6%
100%	all events	73.9%	22.9%	2.5%	0.4%

Courtesy S. Gardiner

Example e⁻ + γs Only Event (true trajectories)

- E_ν = 16.1 MeV
- e^- deposited 10.2 MeV
- γs deposited 4.3 MeV
- ^{40}K deposited 3.7 keV
- Total visible energy:
  14.5 MeV
- Visible energy sphere radius:
  48.4 cm
- Electrons are nearly always easy to see
- Gammas leave "blips" plus pair production tracks at high energy



Example e^- + γs Only Event (cheated reco)

- E_ν = 16.1 MeV
- e^- deposited 10.2 MeV
- γs deposited 4.3 MeV
- ^{40}K deposited 3.7 keV
- Total visible energy:
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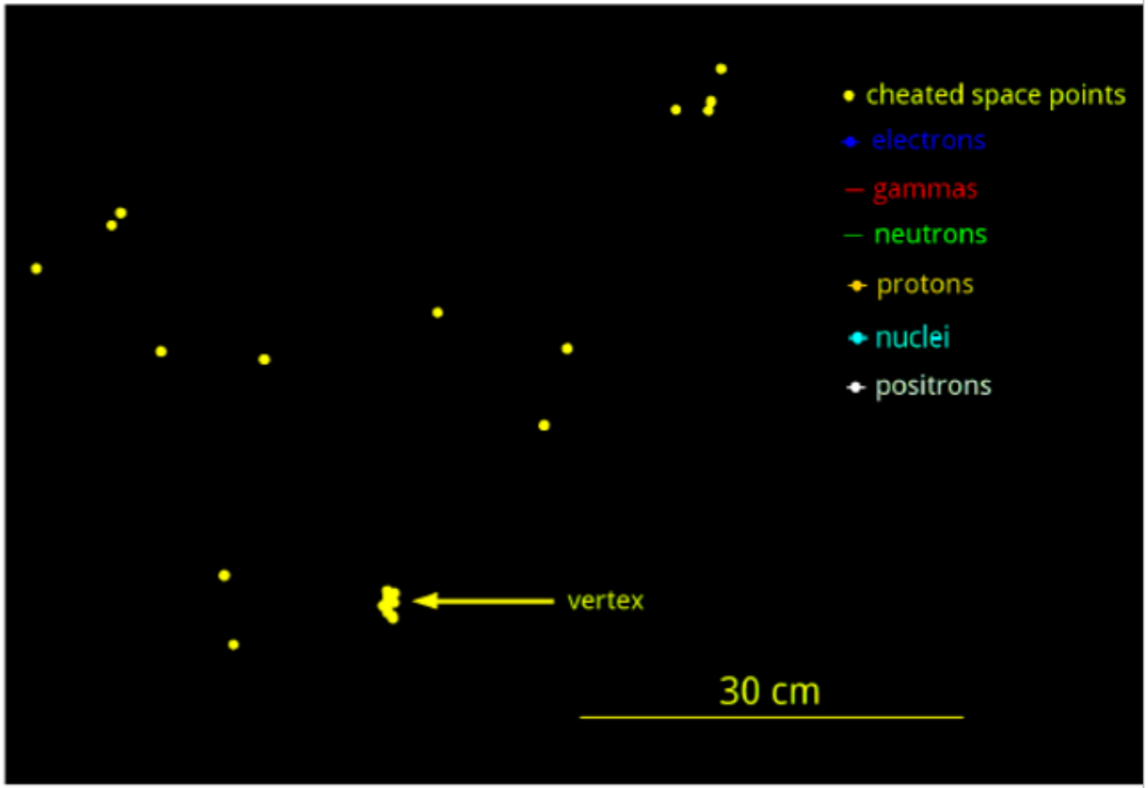
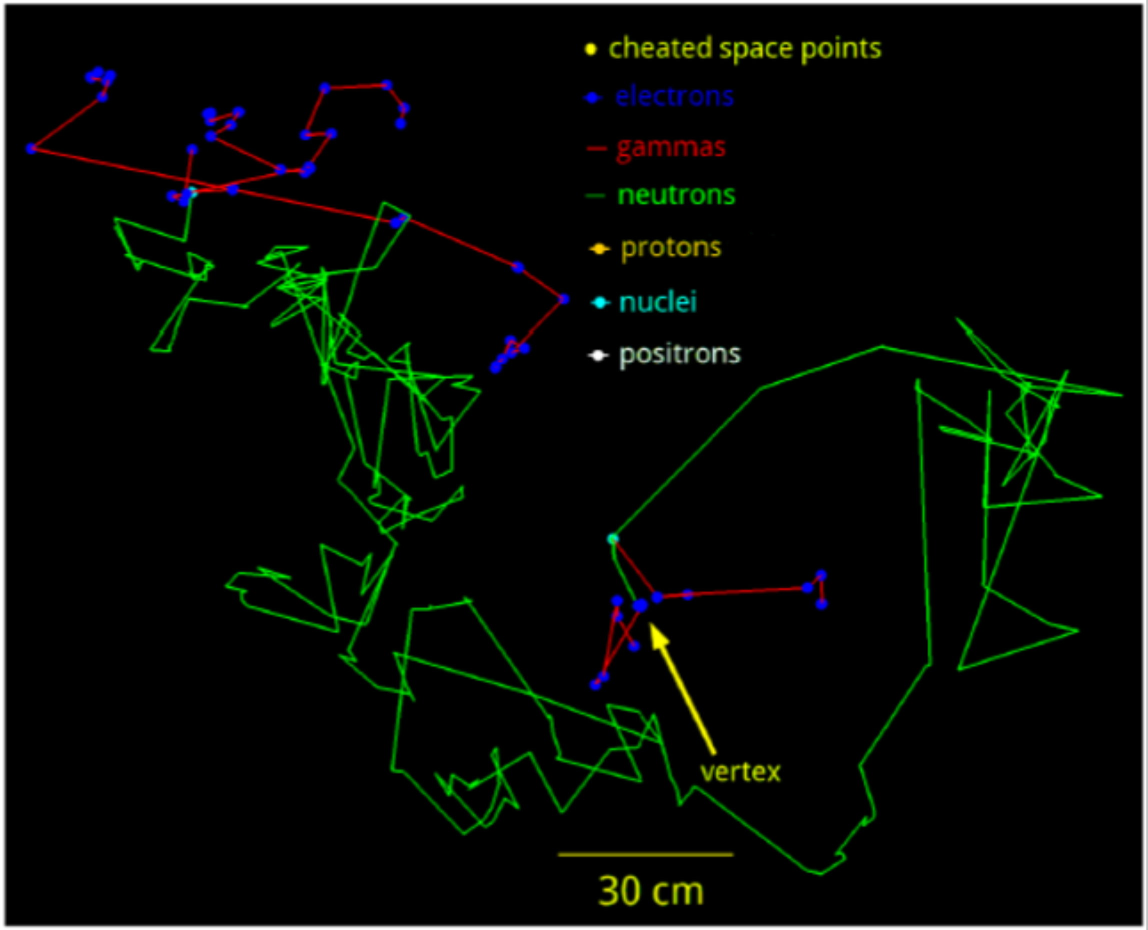


Example neutron event (true trajectories)

- E_ν = 16.3 MeV
- e^- deposited 4.5 MeV
- No primary γs from vertex
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- Total visible energy:

  12.2 MeV
- Visible energy sphere radius:

  1.44 m
- Neutrons bounce around for a long time!



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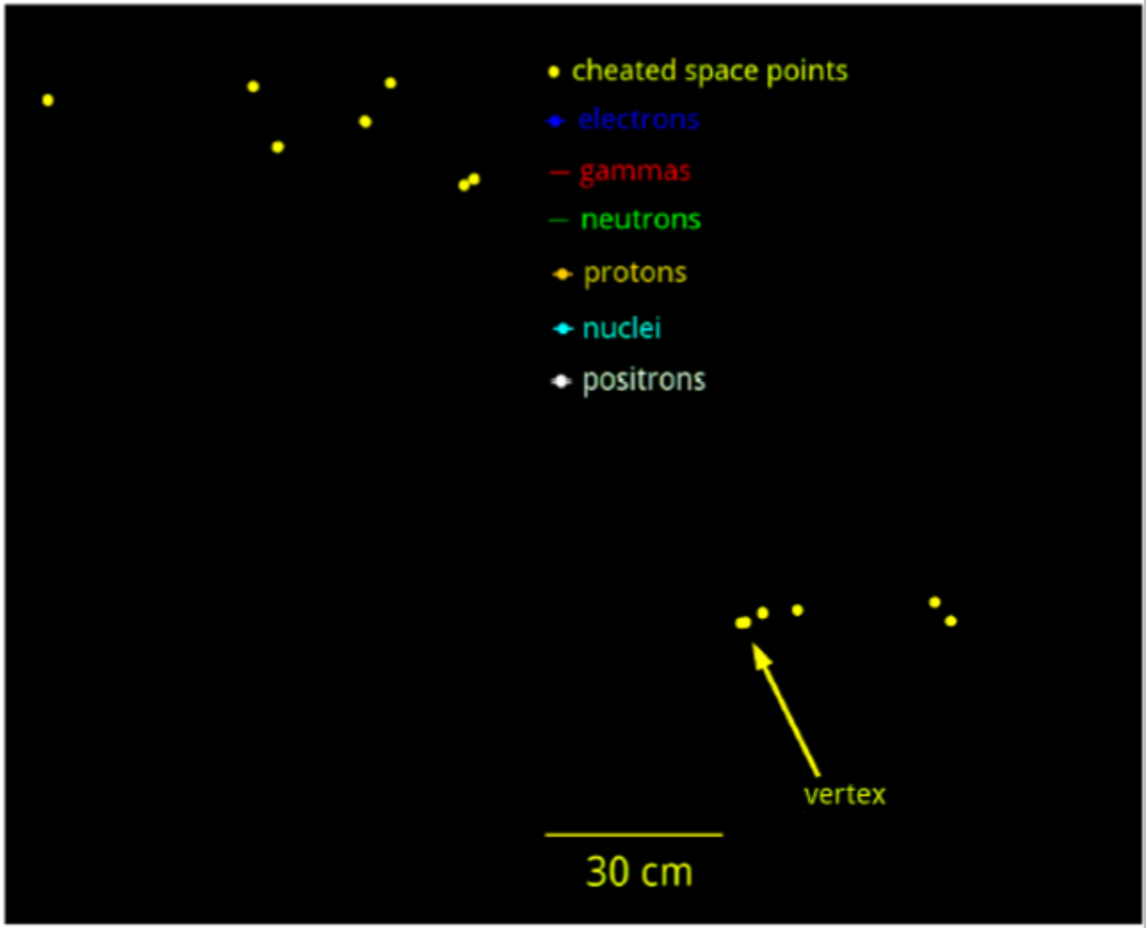
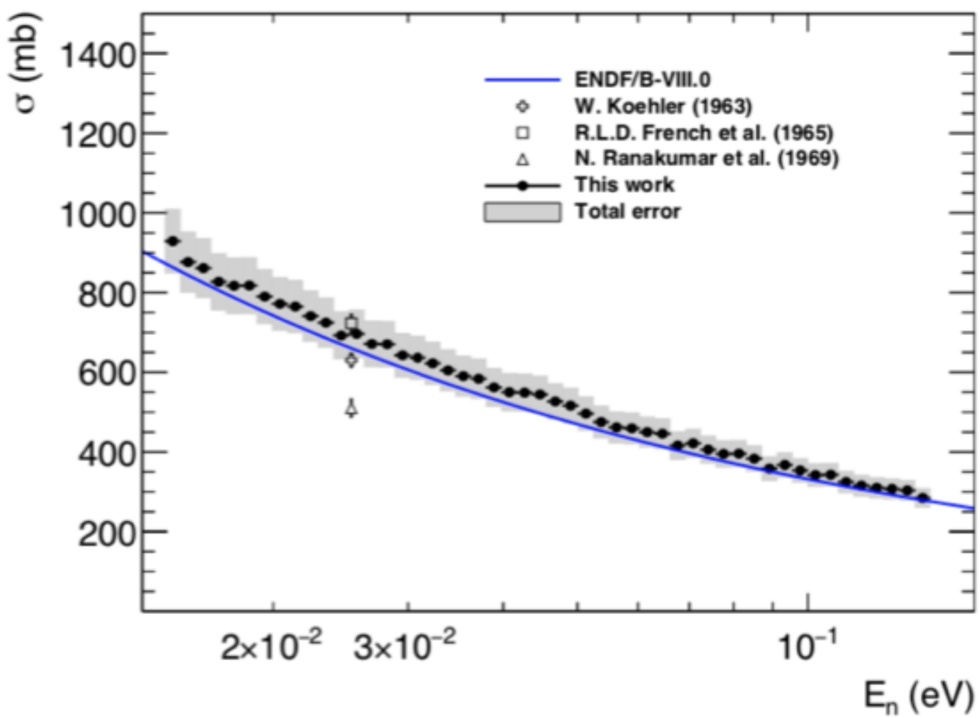
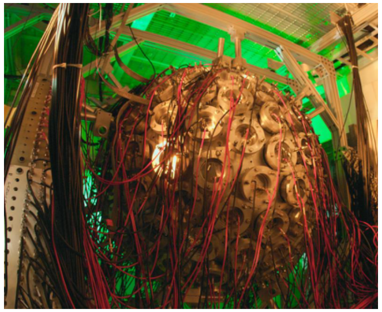


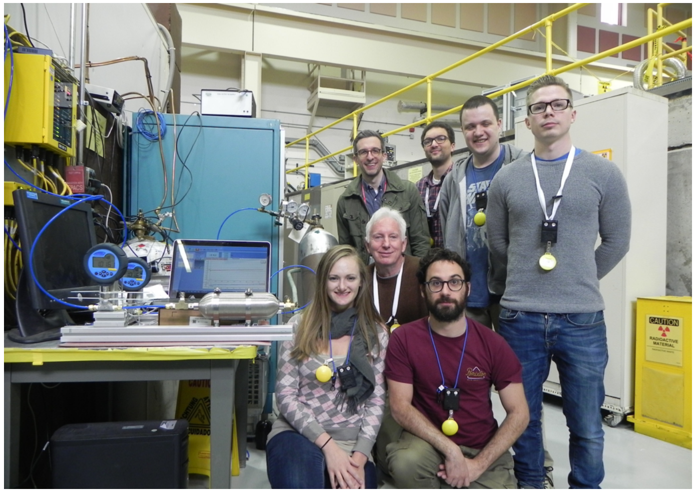
Neutron measurements supporting DUNE

Argon **C**apture **E**xperiment at **D**ANCE





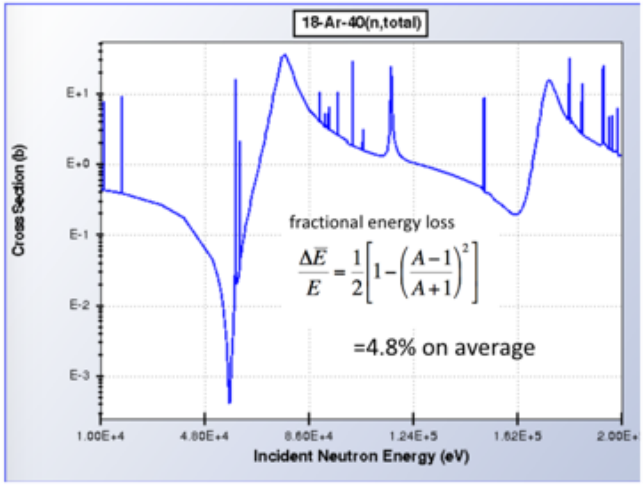
ACED



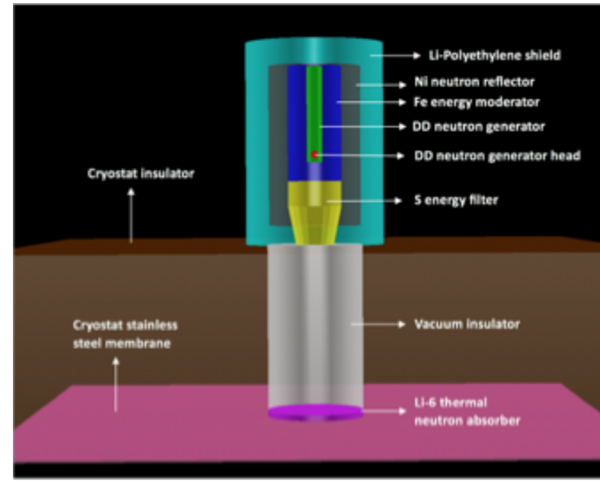
first differential measurement of the neutron capture cross section on argon

Fischer, et al., 2019

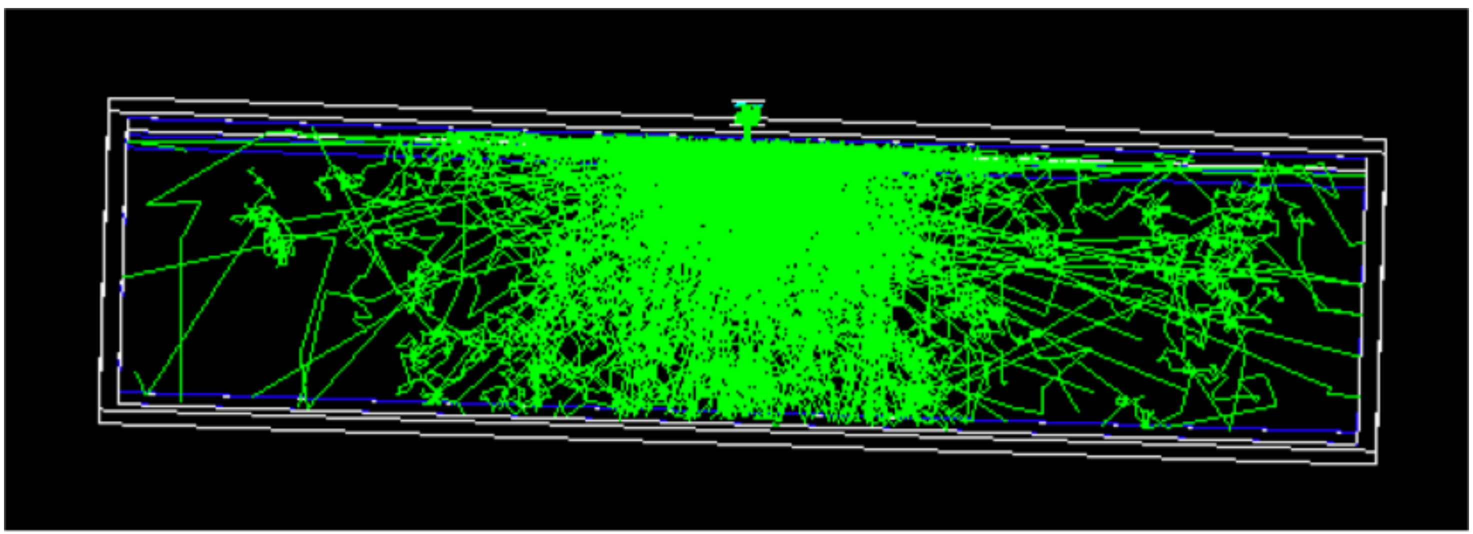
Pulsed Neutron Source (PNS) Calibration



Neutron scattering resonance structure in 40-Ar may have a significant anti-resonance at 57 keV that could be used for energy calibration



Proposed Pulsed Neutron Source (PNS) calibration device for DUNE

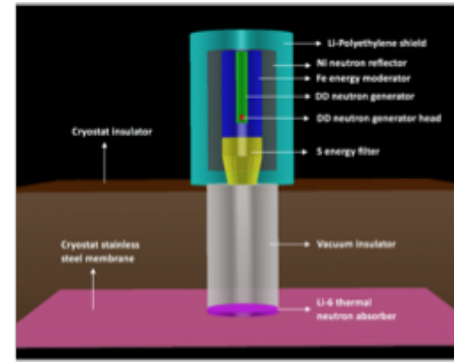


One DD generator could cover half the DUNE detector with “standard candle” neutron captures…

If the anti-resonance actually exists

Neutron measurements supporting DUNE

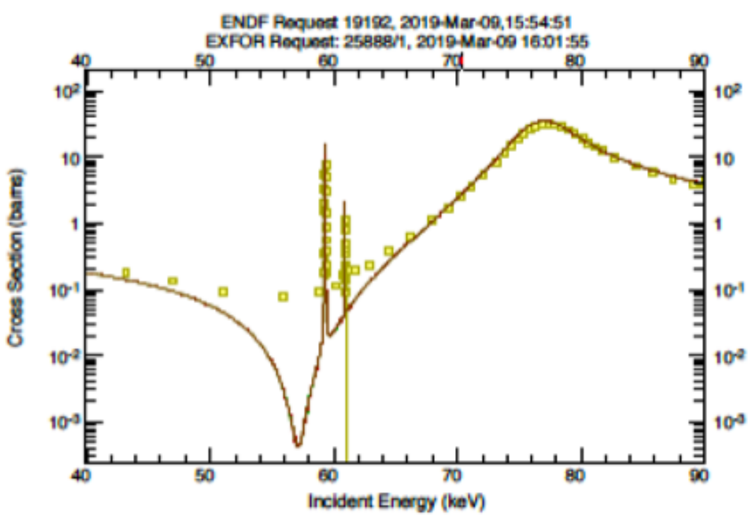
Argon **R**esonant **T**ransport **I**nteraction **E**xperiment



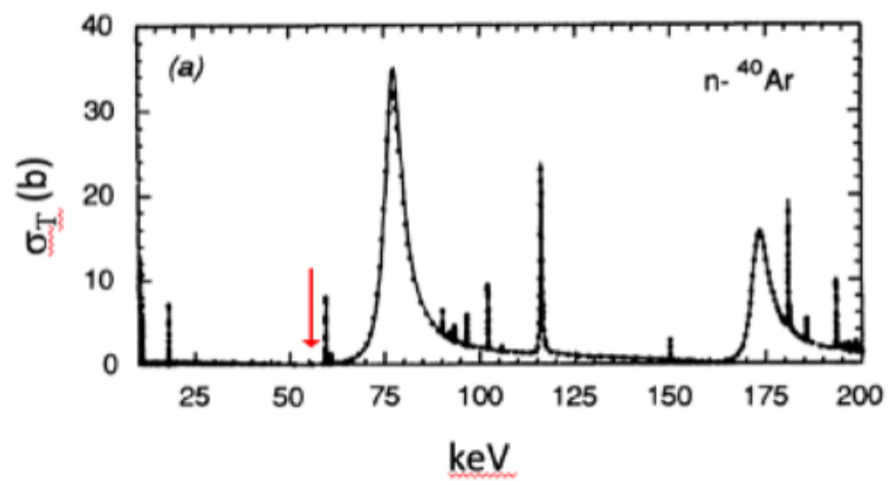
Proposed measurement of 57 keV neutron anti-resonance in 40-Ar at LANSCE. Important for calibration, reconstruction, and simulations in liquid argon

ARTIE

One previous experiment did not see the anti-resonance, but may not have been sensitive…

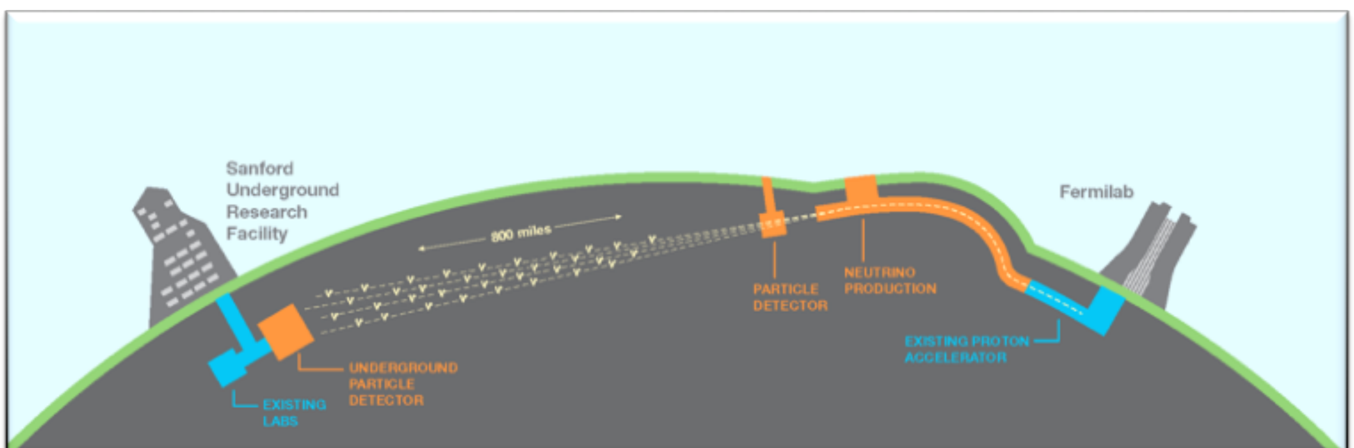


R.R. Winters, R.F. Carlton, C.H. Johnson, N.W. Hill, and M.R. Lacerna, Phys. Rev. C 43 492 (1991)

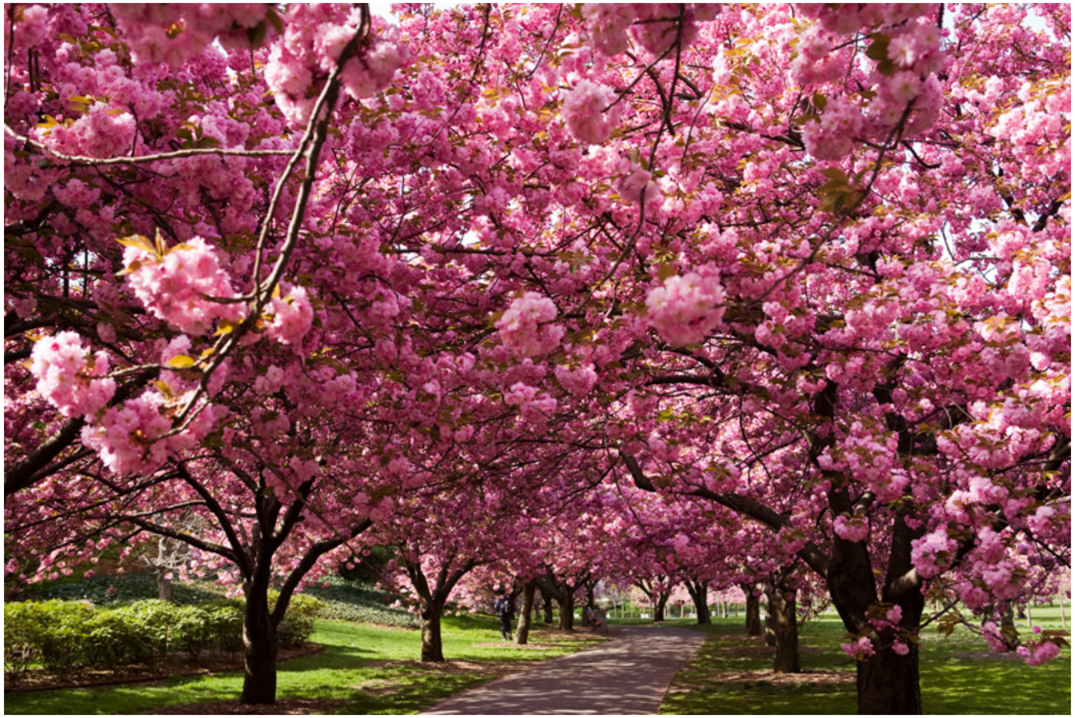


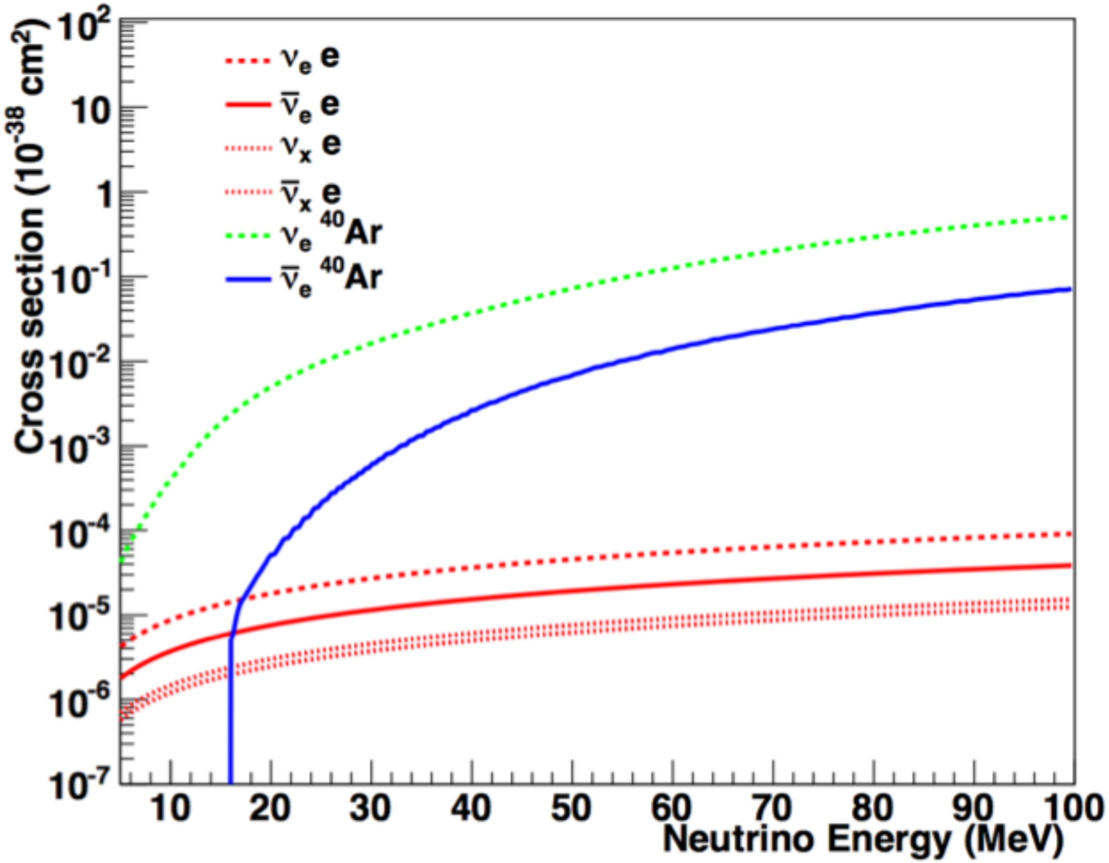
Summary

- LBNF is currently under construction, with detector cryostat installation to start in 2022. DUNE detector development is continuing, with the Technical Design Report (TDR) nearing completion
- Excellent sensitivity in CP violation parameter measurement, and neutrino Mass Ordering determination
- Supernova sensitivity especially promising given ν_e sensitivity. Work continuing on cross-section, triggering, and reconstruction



Thank you!



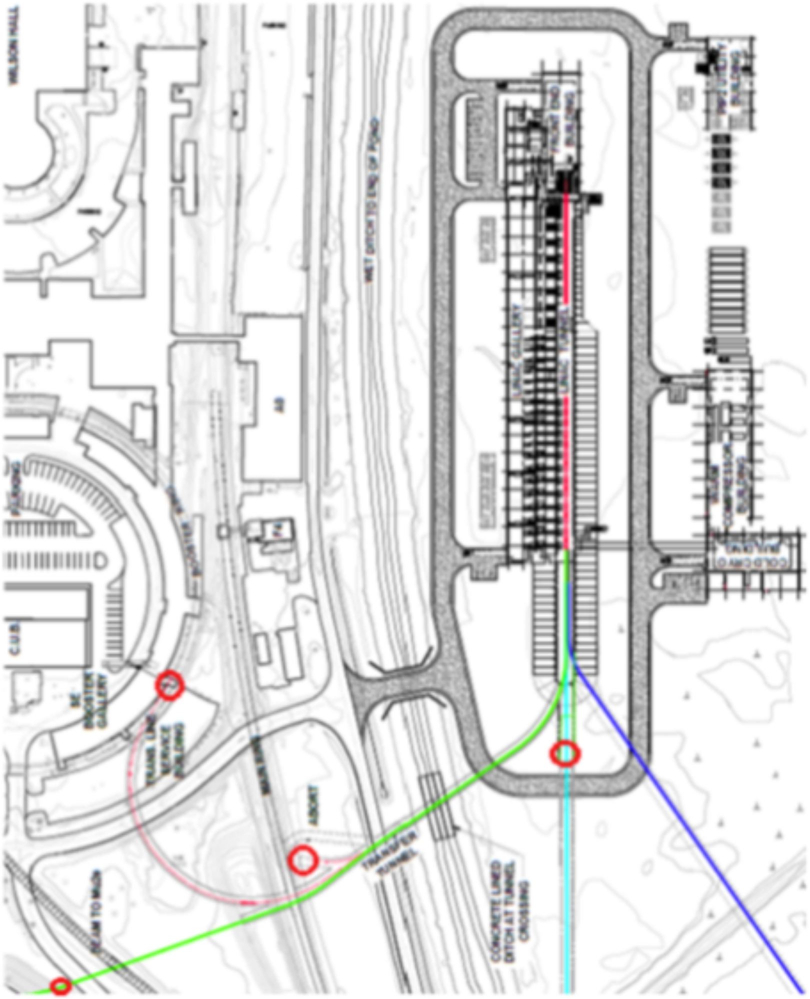


Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

PIP-II Summary

PIP-II Components

- 800 MeV linac
  - Warm Front End
  - SRF section
- Linac-to-Booster transfer line
  - 3-way beam split to: (1) Beam dump, (2) Booster & (3) Mu2e-II
- Upgraded Booster
  - 20 Hz, 800 MeV injection
    - New injection area
    - Resonant Magnet Upgrade
- Upgraded Recycler & MI
  - RF in both rings
- Conventional Facilities
  - Includes 2 empty slots at the linac end (L≈23 m)
  - Up to 1 GeV
- Cryogenic Plant



Beam Summary

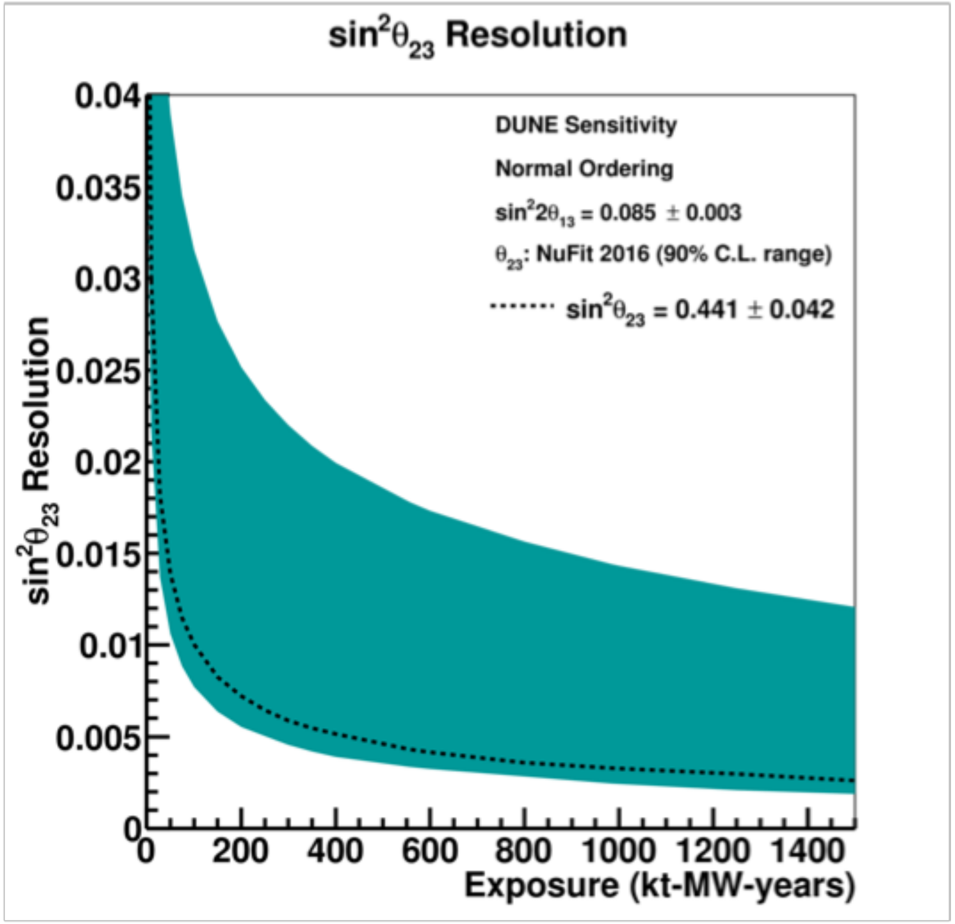
Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

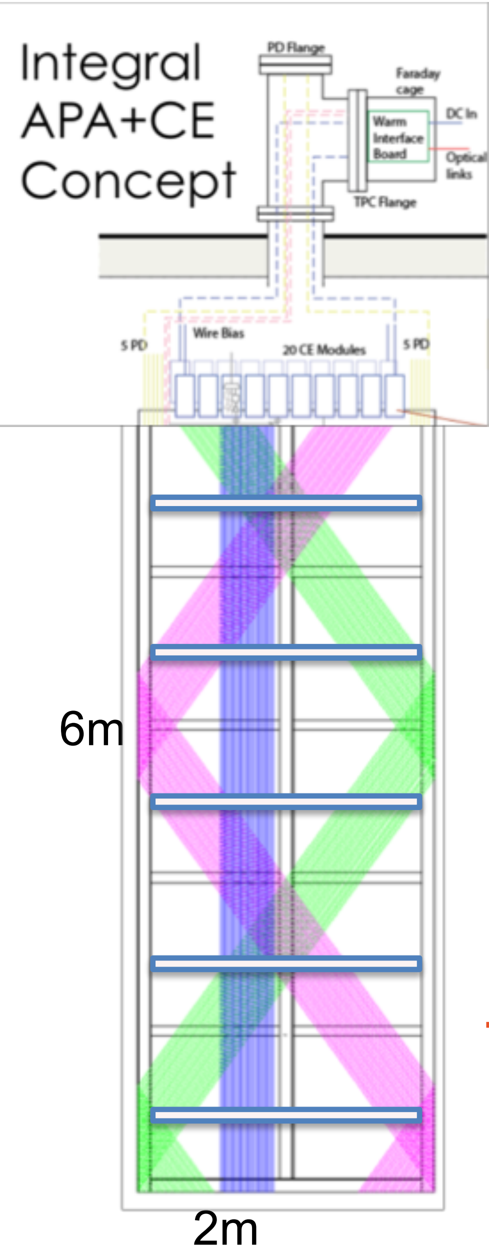
Atmospheric Neutrino Rate

Expected rate of neutrino interactions in ^{40}Ar for a 10 kton-year exposure.

10 kton-years	CC	NC	Total
ν_μ	1038	398	1436
$\bar{\nu}_\mu$	280	169	449
ν_e	597	206	83
$\bar{\nu}_e$	126	72	198
Total	2014	845	2886

θ_{23} Sensitivity





Core detector element: Anode Plane Assemblies (APA) with integrated Cold Electronics Boards and Ph.Detector modules

Each APA : 960 X, 800 V, 800 U, 960 G (un-instrumented) wires

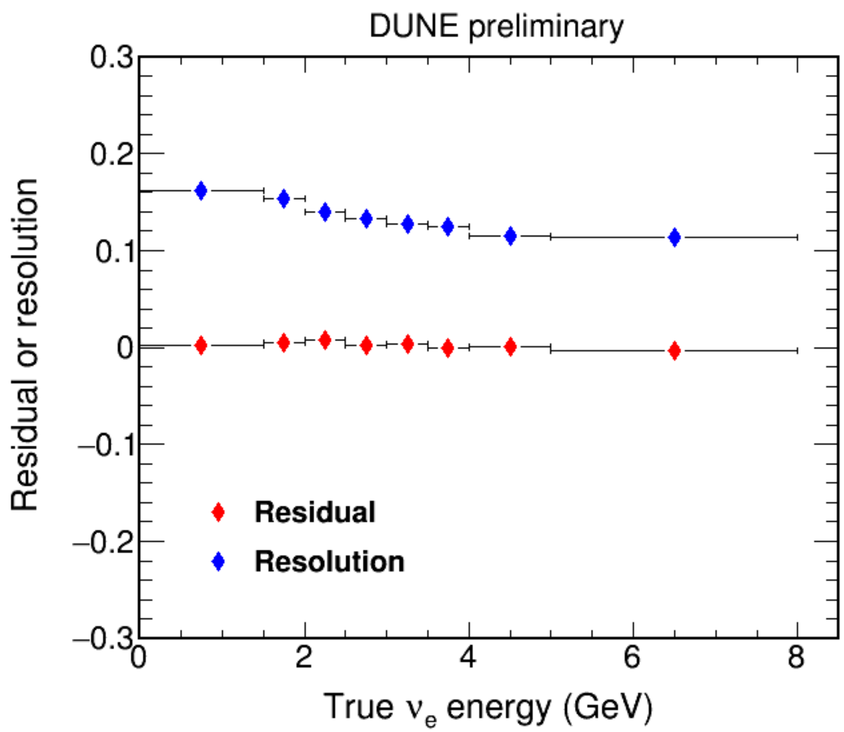
10 Photon Detectors are installed into each APA frame

20 ColdElectronics Boxes mounted onto the APA frame and connected to the wires - 2560 Channels-Wire

> The modular approach to detector construction enables the construction of detector elements to take place in parallel and at multiple sites.

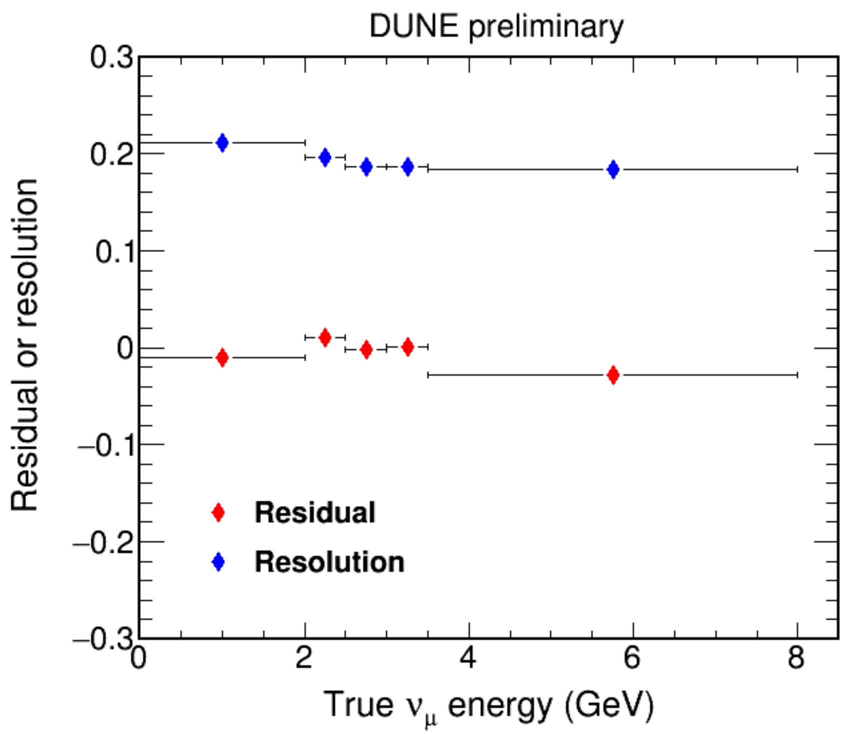
This will be an essential approach for the DUNE Far Detector

ν_e Energy Resolution



From simulations of contained CC interactions inside the FV after reconstruction

ν_μ Energy Resolution



From simulations of contained CC interactions inside the FV after reconstruction

DUNE CDR Detector Parameters

Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^\pm$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}[\mathrm{GeV}]$	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}[\mathrm{GeV}]$	5°
n	50 MeV	$40\%/\sqrt{E}[\mathrm{GeV}]$	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}[\mathrm{GeV}]$	5°

Will be updated soon with Preliminary Design results

DUNE CDR event rates

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

- 150 kt · MW · yr
- $\delta_{cp} = 0$

Will be updated soon with Preliminary Design results

DUNE CDR event rates

- $150\ \text{kt} \cdot \text{MW} \cdot \text{yr}$
- $\delta_{cp} = 0$

	CDR Reference Design	Optimized Design
ν mode ($150\ \text{kt} \cdot \text{MW} \cdot \text{year}$)		
ν_μ Signal	10842	7929
$\bar{\nu}_\mu$ CC Bkgd	958	511
NC Bkgd	88	76
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63	29
$\bar{\nu}$ mode ($150\ \text{kt} \cdot \text{MW} \cdot \text{year}$)		
$\bar{\nu}_\mu$ Signal	3754	2639
ν_μ CC Bkgd	2598	1525
NC Bkgd	50	41
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39	18

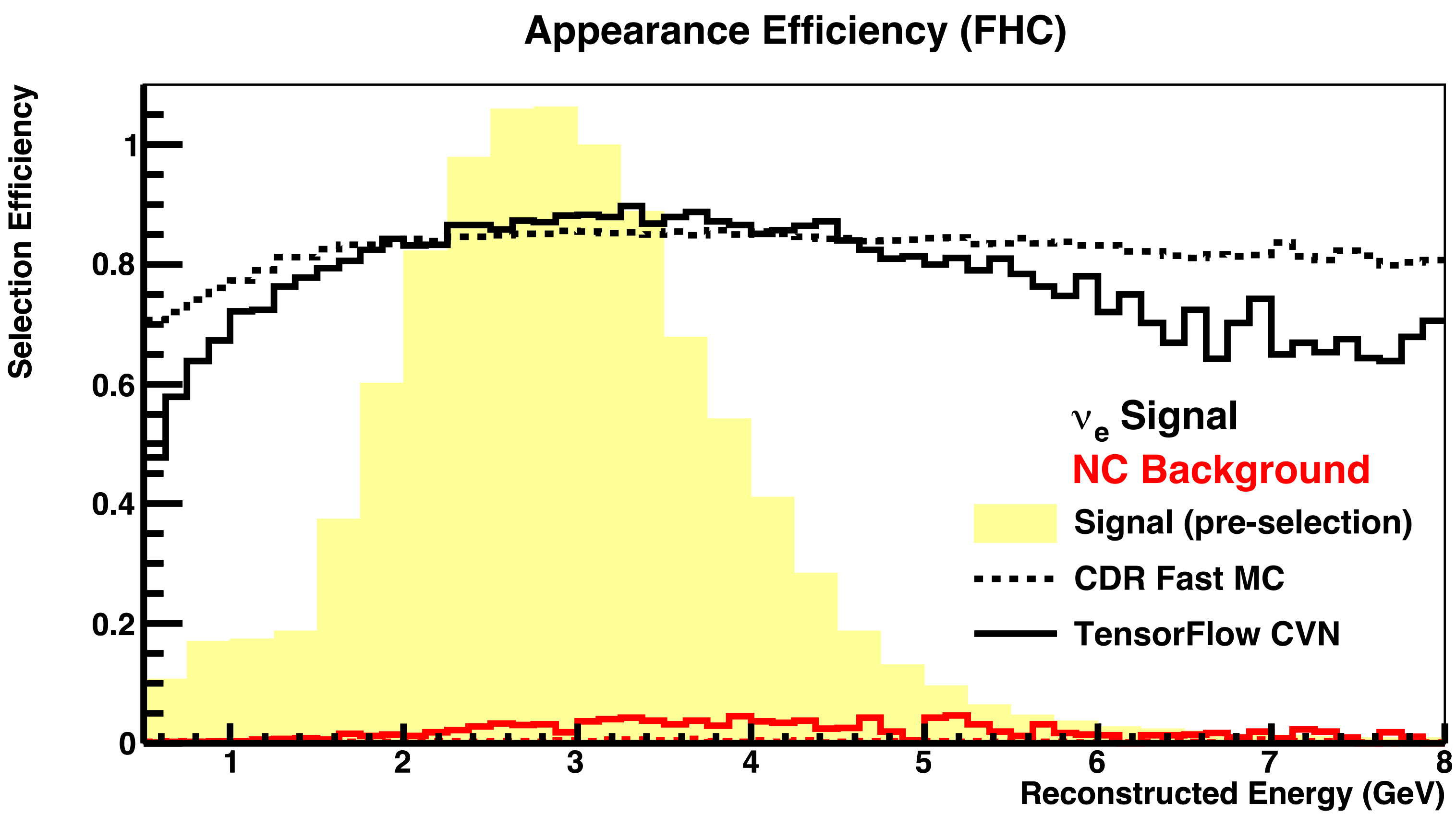
Will be updated soon with Preliminary Design results

DUNE CDR uncertainty budget

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	3.2%	2%	See "Flux Uncertainties" in Section 3.6.2
Interaction Model	2.7%	5.3%	$\sim 2\%$	See "Interaction Model Uncertainties" in Section 3.6.2
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in 5% ν_μ sample normalization uncertainty in DUNE 3-flavor fit.
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%	See "ν_e Energy-Scale Uncertainties" in Section3.6.2
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	6.8%	3.6 %	
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$	Residual ν_e uncertainty: 2%

Will be updated soon with Preliminary Design results

Selection Efficiency



CVN ν_e event selection efficiency similar to that from CDR Fast MC