The DUNE Science program

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Supernova physics at DUNE, Virginia Tech, March 11-12th 2016

v1

What is DUNE ?

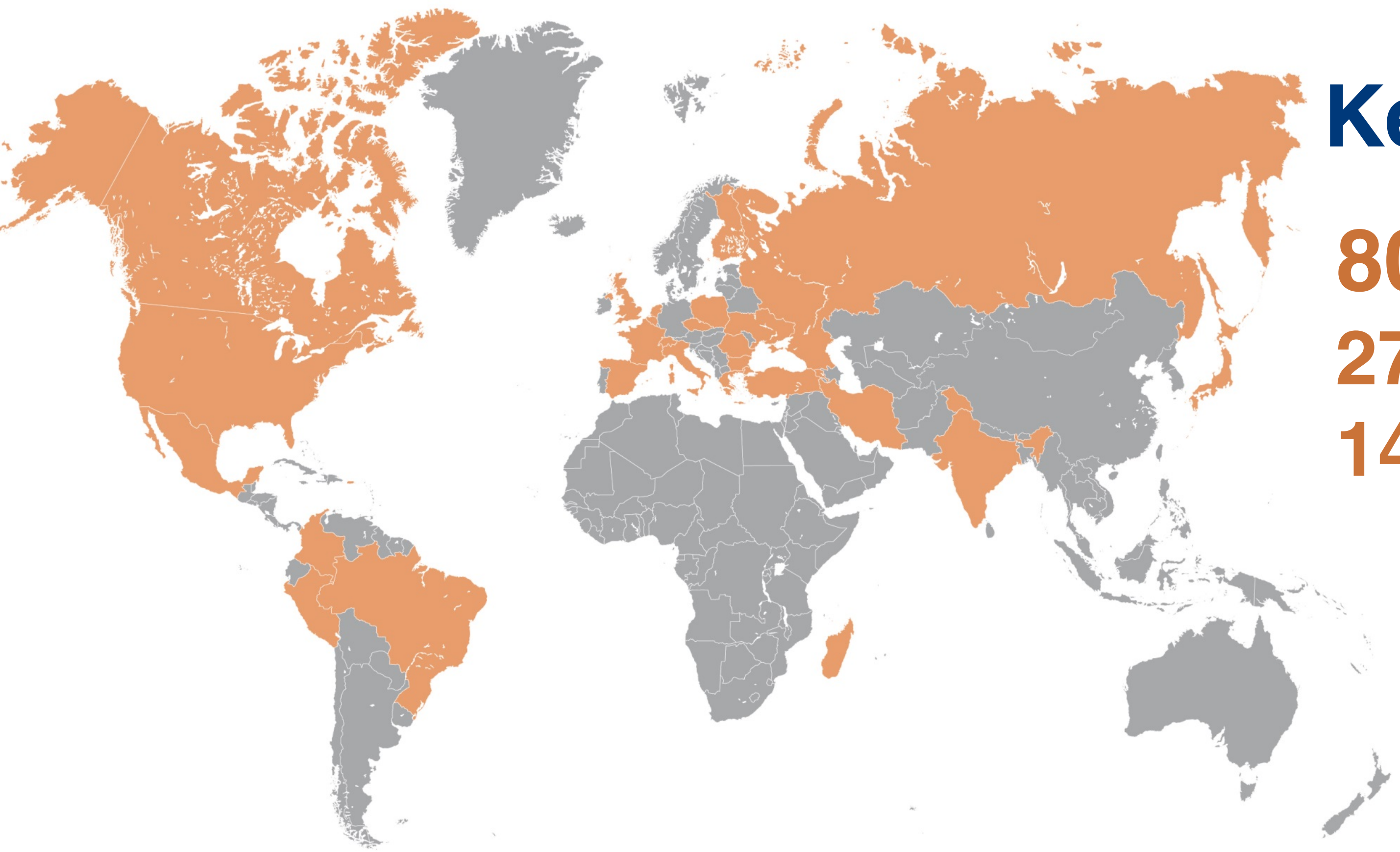
A rapidly evolving international scientific collaboration merging strengths and expertise from all previous efforts (LBNE, LBNO, others), built around the organisation model successfully implemented at the LHC

- First formal collaboration meeting **April 16th - 18th 2015**
- Conceptual Design Report (4 volumes) **June 2015**
- Passed DOE CD-1 Review **July 2015**
- Second collaboration meeting **September 2nd - 5th 2015**
- DOE CD-3a Review **December 2015 → CD3a will trigger FS excavation**
- Third collaboration meeting UTA, Texas January 12th - 15th 2016
- Fourth collaboration meeting SDSMT, South Dakota May 2016
- **Collaboration meetings at FNAL (Sep 16) & CERN (Jan 2017)**

Photo taken during 2nd Collaboration meeting

The DUNE Collaboration

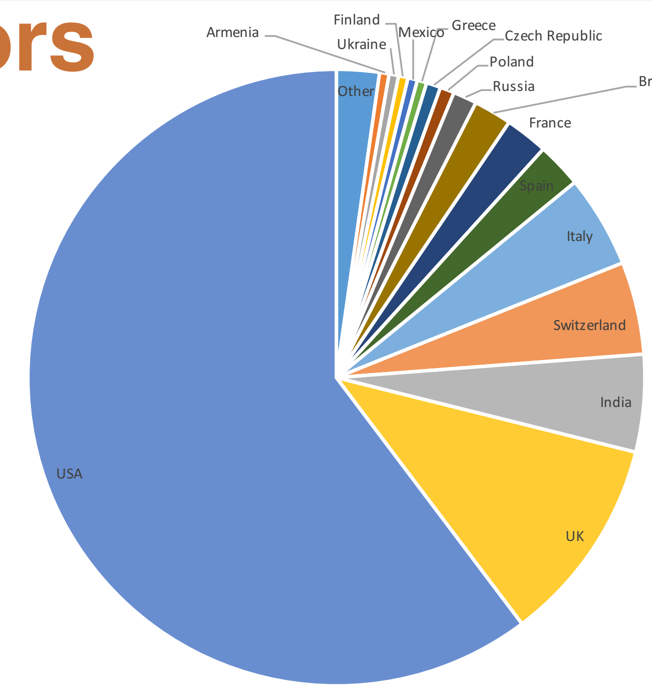
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Keeps growing:

805 Collaborators
27 Nations
146 institutions

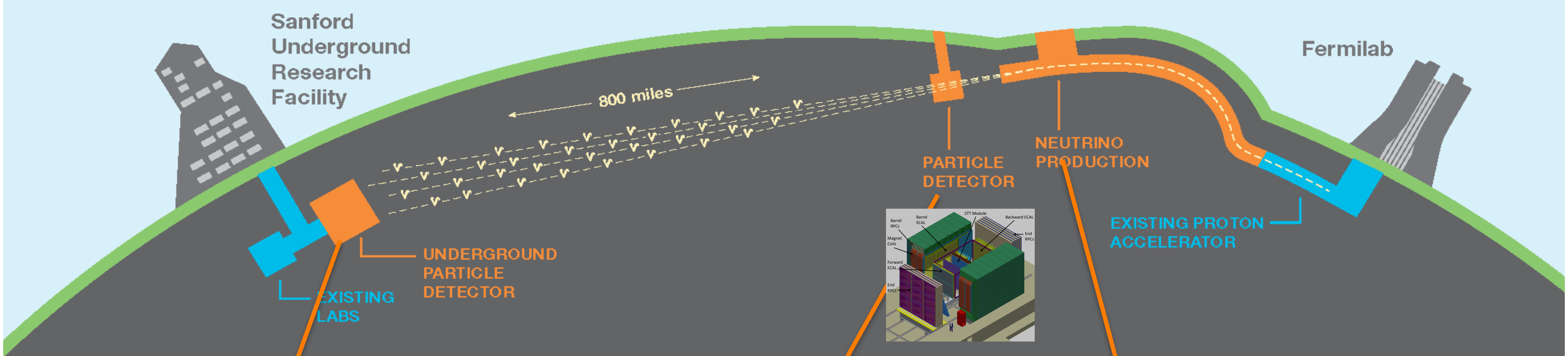
Greece and Finland recently joined

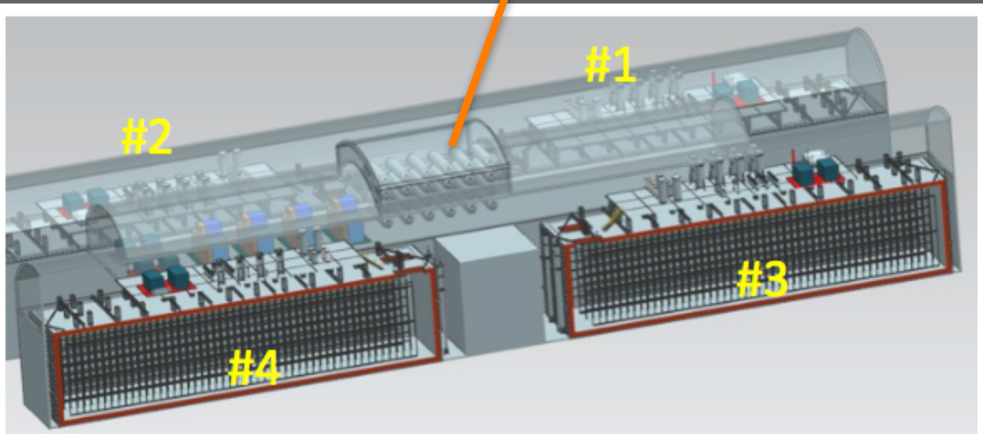


Armenia Yerevan Inst. for Theoretical Physics and Modeling
Belgium Univ. de Liege
Brazil Univ. Federal do ABC; Univ. Federal de Alfenas em Poços de Caldas; Univ. de Campinas; Univ. Estadual de Feira de Santana; Univ. Federal de Goias; Observatorio Nacional
Bulgaria Univ. of Sofia
Canada York University
Colombia Univ. del Atlantico
Czech Republic Charles University, Prague; Czech Technical University, Prague; Institute of Physics ASCR, Prague
France Lab. d'Annecy-le-Vieux de Phys. des Particules; Inst. de Physique Nucleaire de Lvon: APC-Paris: CEA/Sacla
Finland Jyväskylä
Greece Athens
India Aligarh Muslim University; Banaras Hindu University; Bhabha Atomic Research Center; Univ. of Delhi; Indian Inst. of Technology, Guwahati; Harish-Chandra Research Institute; Indian Inst. of Technology, Hyderabad; Univ. of Hyderabad; Univ. of Jammu; Jawaharlal Nehru University; Koneru Lakshmaiah; Univ. of Lucknow; Panjab University; Punjab Agri. University; Variable Energy Cyclotron Centre
Iran Inst. for Research in Fundamental Sciences
Italy Lab. Nazionali del Gran Sasso, Assergi; Univ. di Catania; Gran Sasso Science Institute; Univ. di Milano; INFN Sezione di Milano Bicocca; INFN Sezione di Napoli; Univ. of Padova; Univ. of Pavia, INFN Sezione di Pavia; CNI Pisa; Univ. di Pisa
Japan KEK; Kavli IPMU, Univ. of Tokyo
Madagascar Univ. of Antananarivo
Mexico Univ. de Colima; CINVESTAV
Netherlands NIKHEF
Peru PUCP
Poland Inst. of Nuclear Physics, Krakow; National Centre for Nuclear Research, Warsaw; Univ. of Warsaw; Wroclaw University
Romania Horia Hulubei National Institute
Russia Inst. for Nuclear Research, Moscow
Spain Inst. de Fisica d'Altas Energias, Barcelona; CIEMAT; Inst. de Fisica Corpuscular, Madrid
Switzerland Univ. of Bern; CERN; ETH Zurich
Turkey TUBITAK Space Technologies Research Institute
Ukraine Kyiv National University
United Kingdom Univ. of Cambridge; Univ. of Durham; Univ. of Huddersfield; Imperial College of Science, Tech. & Medicine; Lancaster University; Univ. of Liverpool; University College London; Univ. of Manchester; Univ. of Oxford; STFC Rutherford Appleton Laboratory; Univ. of Sheffield; Univ. of Sussex; Univ. of Warwick
USA Univ. of Alabama; Argonne National Lab; Boston University; Brookhaven National Lab; Univ. of California, Berkeley; Univ. of California, Davis; Univ. of California, Irvine; Univ. of California, Los Angeles; California Inst. of Technology; Univ. of Chicago; Univ. of Cincinnati; Univ. of Colorado; Colorado State University; Columbia University; Cornell University; Dakota State University; Drexel University; Duke University; Fermi National Accelerator Lab; Univ. of Hawaii; Univ. of Houston; Idaho State University; Illinois Institute of Technology; Indiana University; Iowa State University; Kansas State University; Lawrence Berkeley National Lab; Los Alamos National Lab; Louisiana State University; Univ. of Maryland; Massachusetts Institute of Technology; Michigan State University; Univ. of Minnesota; Univ. of Minnesota (Duluth); Univ. of New Mexico; Northwestern University; Univ. of Notre Dame; Ohio State University; Oregon State University; Pacific Northwest National Lab; Univ. of Pennsylvania; Pennsylvania State University; Univ. of Pittsburgh; Princeton University; Univ. of Puerto Rico; Univ. of Rochester; SLAC National Accelerator Lab; Univ. of South Carolina; Univ. of South Dakota; South Dakota School of Mines and Technology; South Dakota Science And Technology Authority; South Dakota State University; Southern Methodist University; Stanford University; Stony Brook University; Syracuse University; Univ. of Tennessee; Univ. of Texas at Arlington; Univ. of Texas at Austin; Tufts University; Virginia Tech; Wichita State University; College of William and Mary; Univ. of Wisconsin; Yale University

LBNF/DUNE Overview

"Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF" (arXiv:1512.06148)





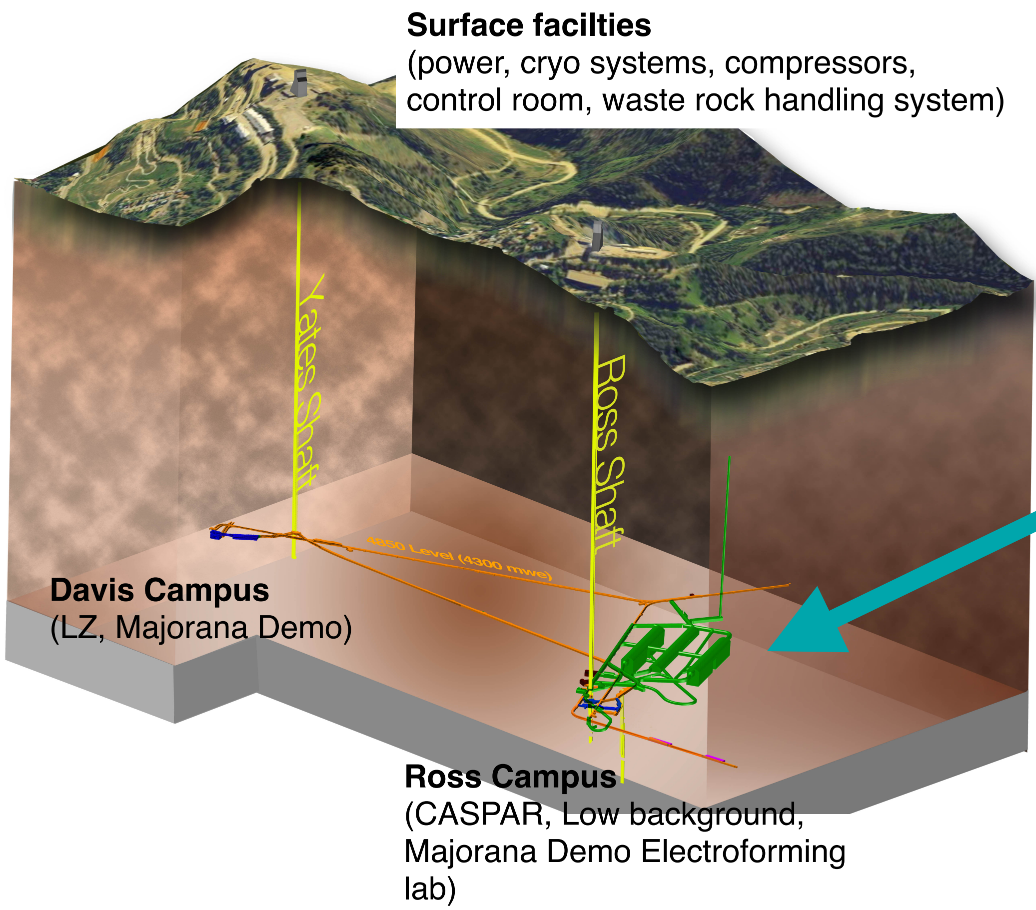
high precision
near detector complex

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

"Conceptual Design Report Volume 4: The DUNE Detectors at LBNF" (arXiv:1601.02984)

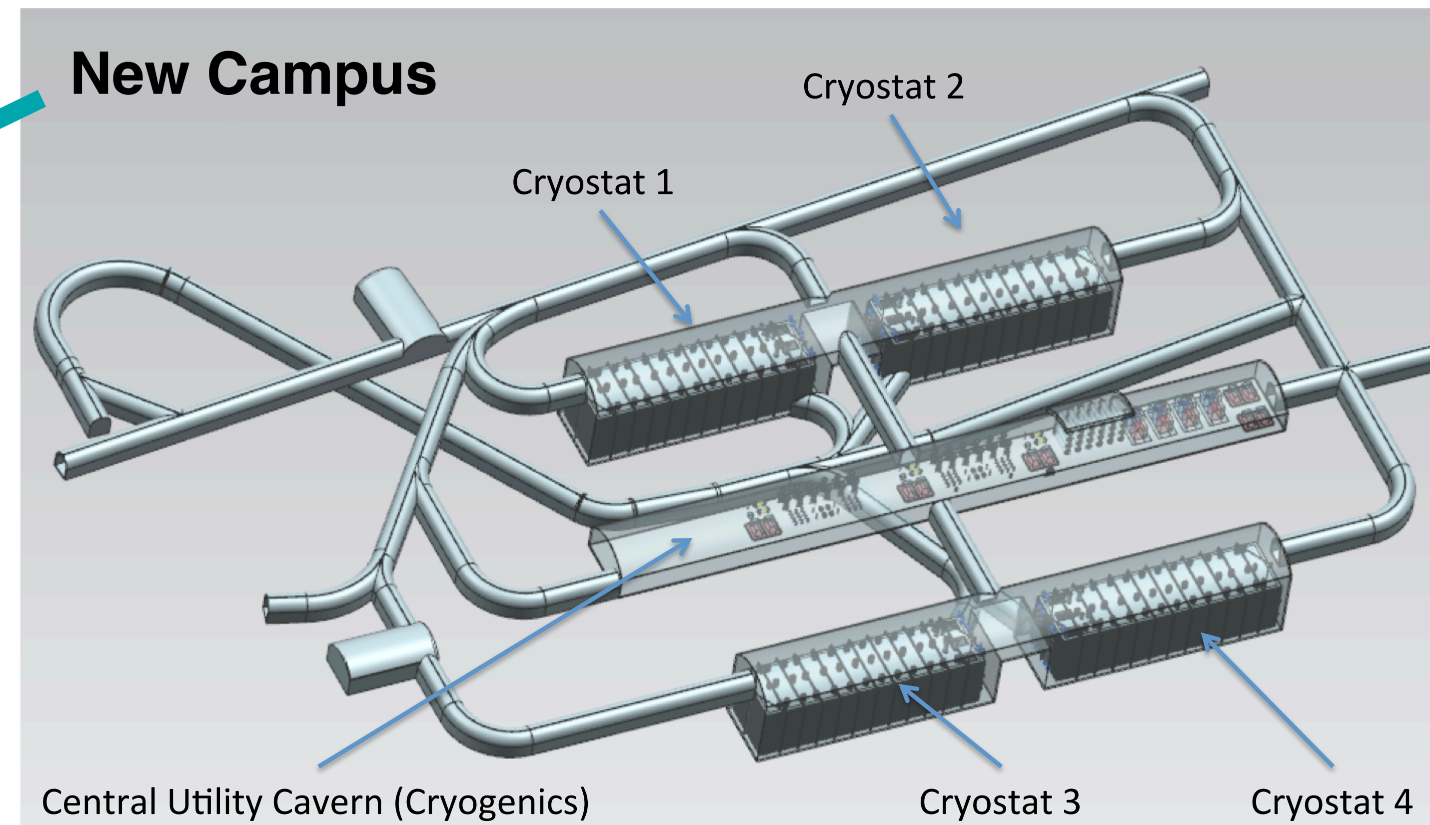
LBNF/DUNE Far Site @ SURF



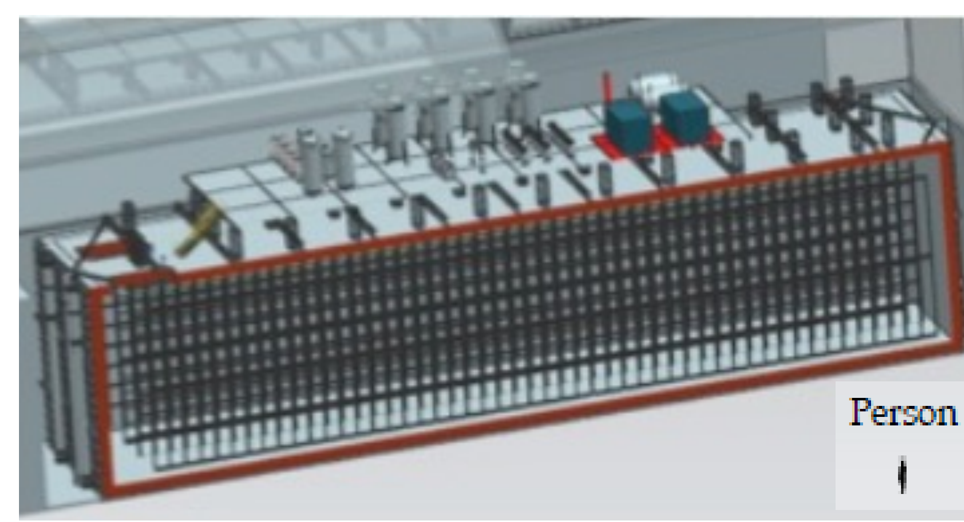
Sanford Underground Research Facility

http://sanfordlab.org

4850L Facilities (4300 mwe)



- Two parallel caverns each with two 10 kton detectors
- Separate cavern for utilities and cryogenics
- Four membrane tanks each 62m(L) x 14m(w) x 15m(h) with steel-frame exoskeleton designed by CERN
- Cryogenic system (w/ LAr purification) designed by joint FNAL and CERN
- Four independent and not necessary exactly identical 10 kton fiducial LAr TPCs. Two operating by 2026.



DUNE Far Detector choice

Far detector is a 40 kt (fiducial mass) liquid argon TPC, a design optimized for:

- Pattern recognition
- Energy measurement
- Particle ID

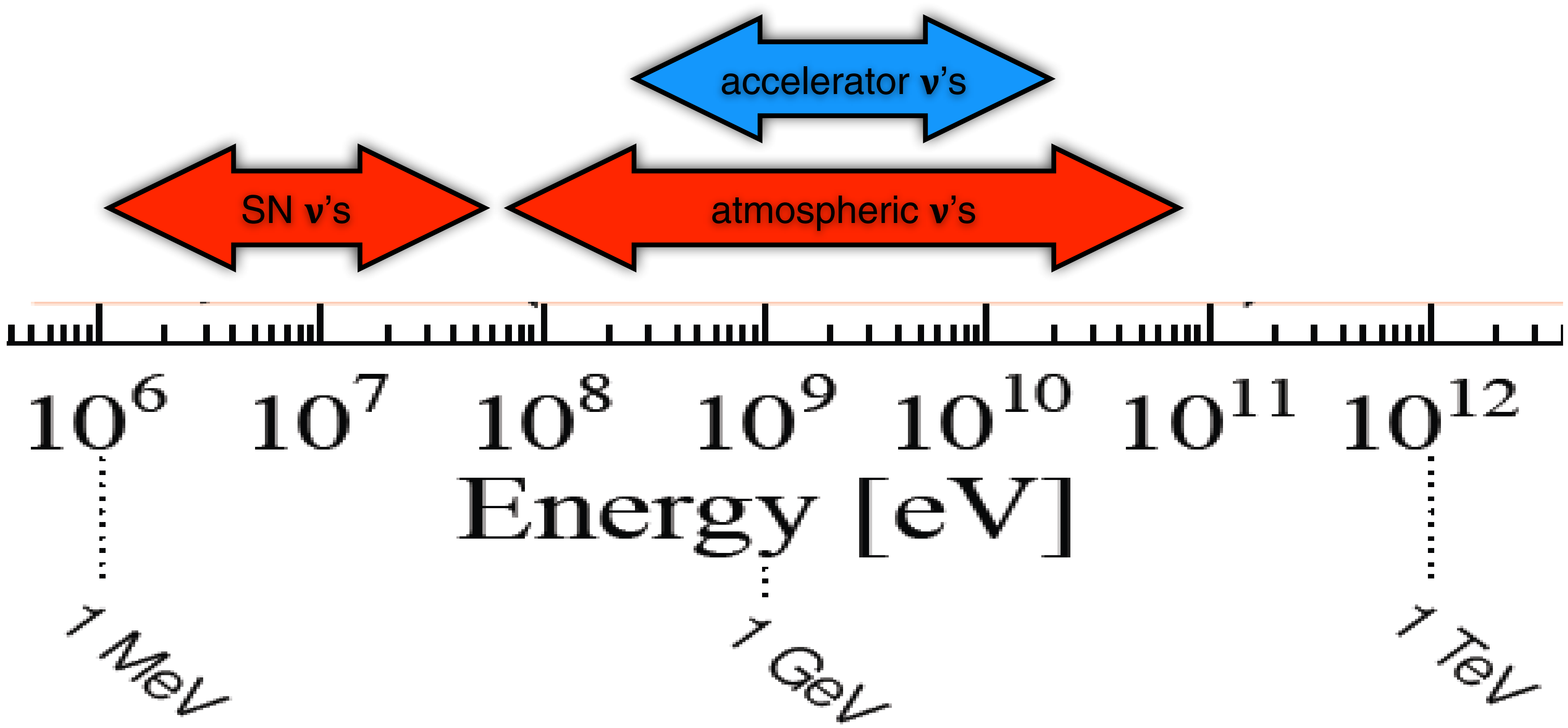
in energy range: few MeV – few GeV

LBNE
LBNO

LAr-TPC

LAr-TPC Far Detector technology gives:

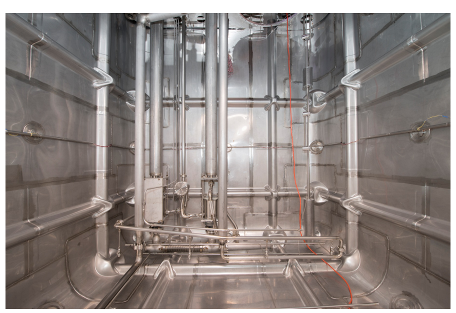
- Exquisite imaging capability in 3D
  - ~ few mm scale over large volume detector
- Excellent energy measurement capability:
  - totally active calorimeter
- Particle ID by dE/dx, range, event topology ,….



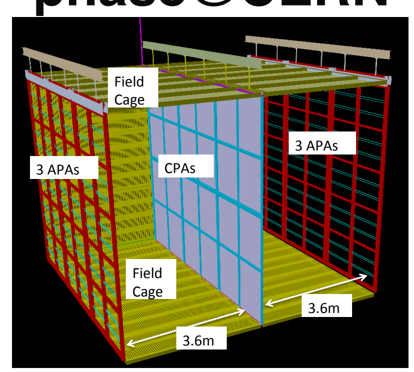
Far Detector Prototyping Program

- Basic technology demonstrated by ICARUS, ArgoNEUT/LArIAT, MicroBooNE, WA105 but **DUNE scale is very different** (each module is 40x ICARUS) and different in many details → **need strong prototyping!**
- DUNE has well-developed plans for a series of detector prototypes that will provide input to the process leading to the final design(s) for the DUNE far detector modules.
- **ProtoDUNE single- and dual-phase 300 tons prototypes to operate in 2018.**

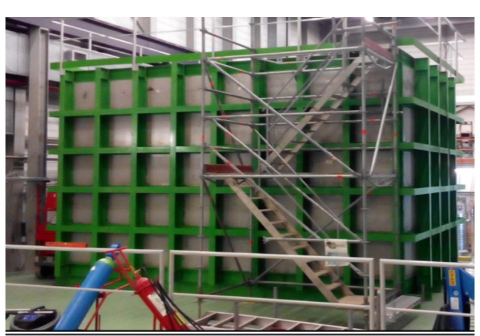
35T @ FNAL



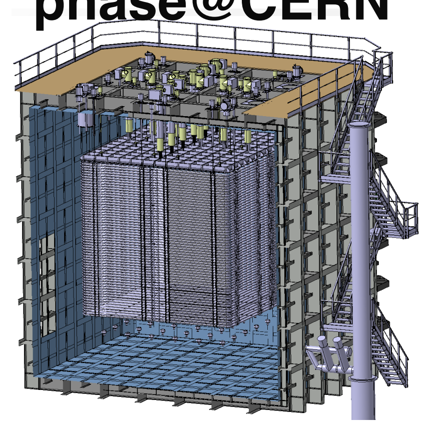
protoDUNE single phase@CERN



WA105 3x1x1@CERN



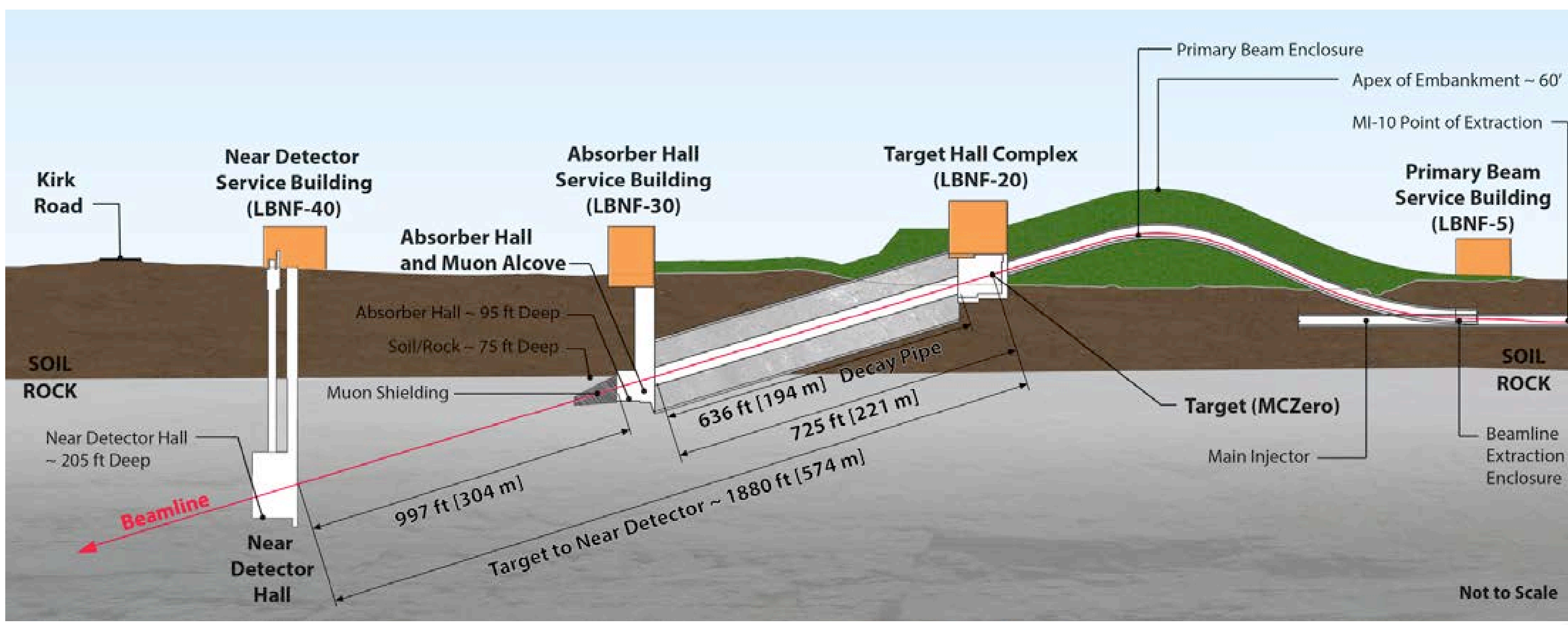
protoDUNE dual phase@CERN

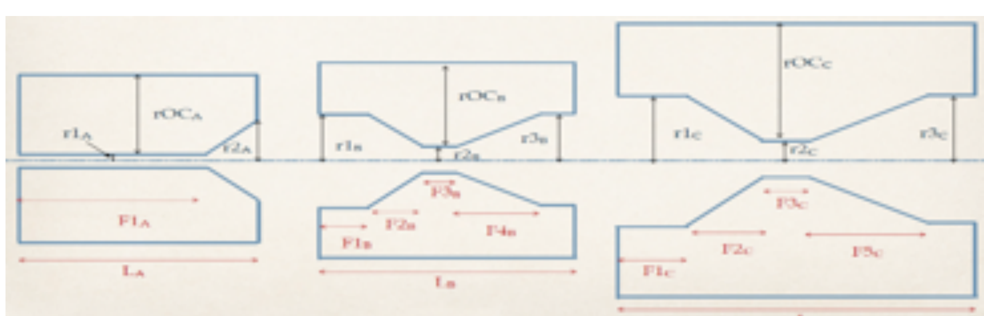


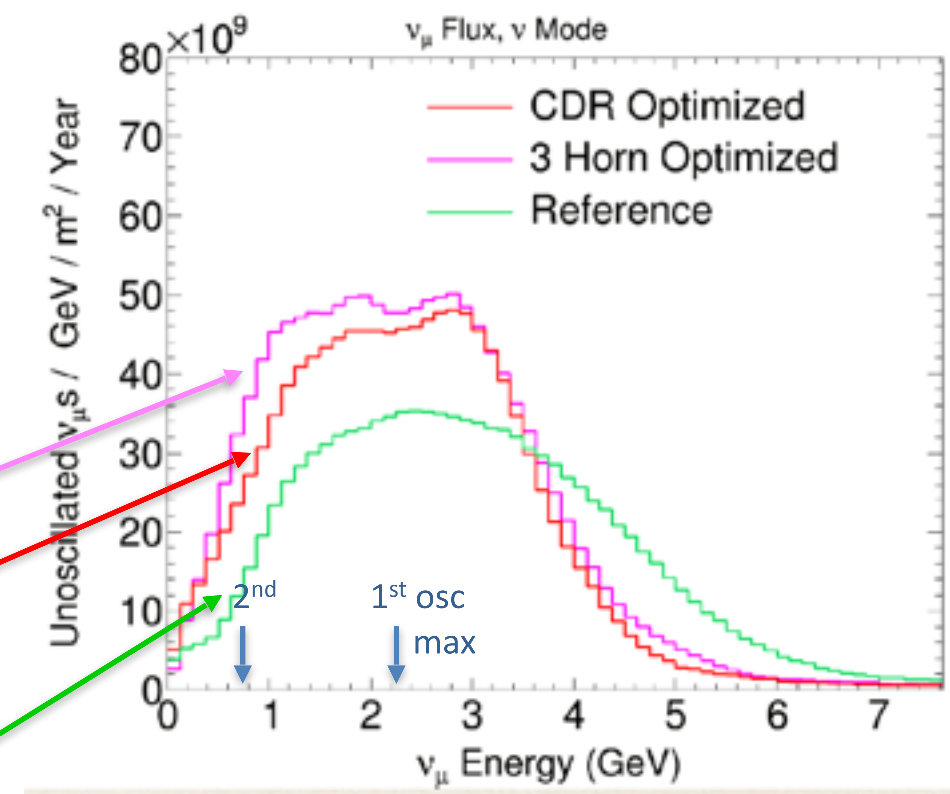
- *Mitigation of risks associated with current detector designs*
- *Establishment of construction facilities required for full-scale production of detector components*
- *Early detection of potential issues with construction methods and detector performance*
- *Provide required calibration of detector response to particle interactions in charged particle test beams*

LBNF neutrino beam

- **Primary 60-120 GeV proton beam** extracted from FNAL Main Injector
- Initial **≈1.2 MW beam power** upgradable to **≈2.4 MW** utilising improvements from PIP-II
- **Near detector hall @ 574 m**
- Fermilab-based design with input and ideas from the full international DUNE Collaboration





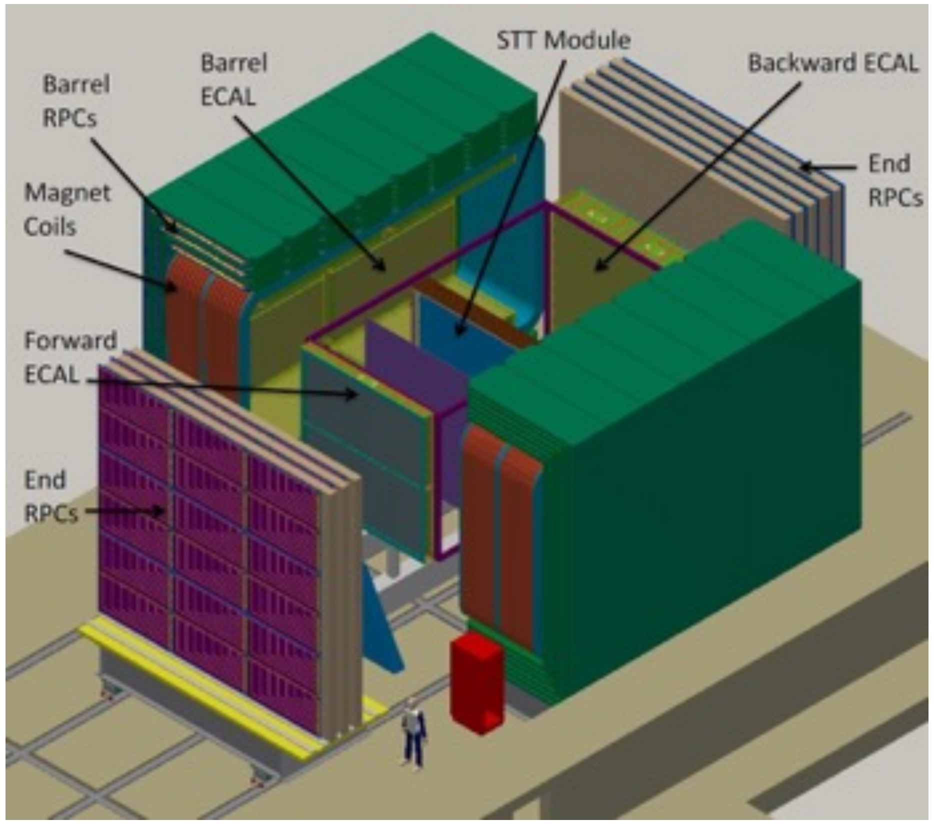


3-horn system,
CDR "Optimized" Design,
and the well-known NuMI-like Reference Design

Neutrino energy (GeV)

➡ CP sensitivity optimisation maximises lower energies

DUNE Near Detector



NOMAD-inspired Fine-Grained Tracker

- **It consists of:**
  - Central straw-tube tracking system with embedded nuclear targets
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems
- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program

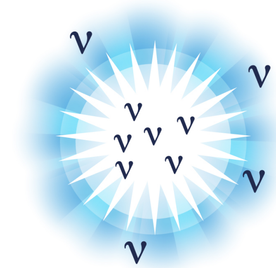
Will result in unprecedented samples of ν interactions

- >100 million nu&antinu-interactions over a wide range of energies:
  - Strong constraints on systematics for LBL physics
  - The ND samples will represent a huge scientific opportunity, e.g.
    - Inclusive & exclusive ν cross section measurements
    - Studies of nuclear effects, FSI etc.
    - Measurements of the structure of nucleons
    - Neutrino-based electroweak theory measurements

DUNE primary science program

Focus on fundamental open questions in particle physics and astroparticle physics – aim for discoveries:

- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
    - "*Our best bet for explaining why there is matter in the universe*"
  - Neutrino Mass Hierarchy
    - "*Guaranteed determination of MH (>5sigmas)*"
  - Precision Oscillation Physics & testing the 3-flavor paradigm



- **2) Nucleon Decay**
  - Predicted in beyond the Standard Model theories
    - "*Probe the unification of the fundamental forces*"

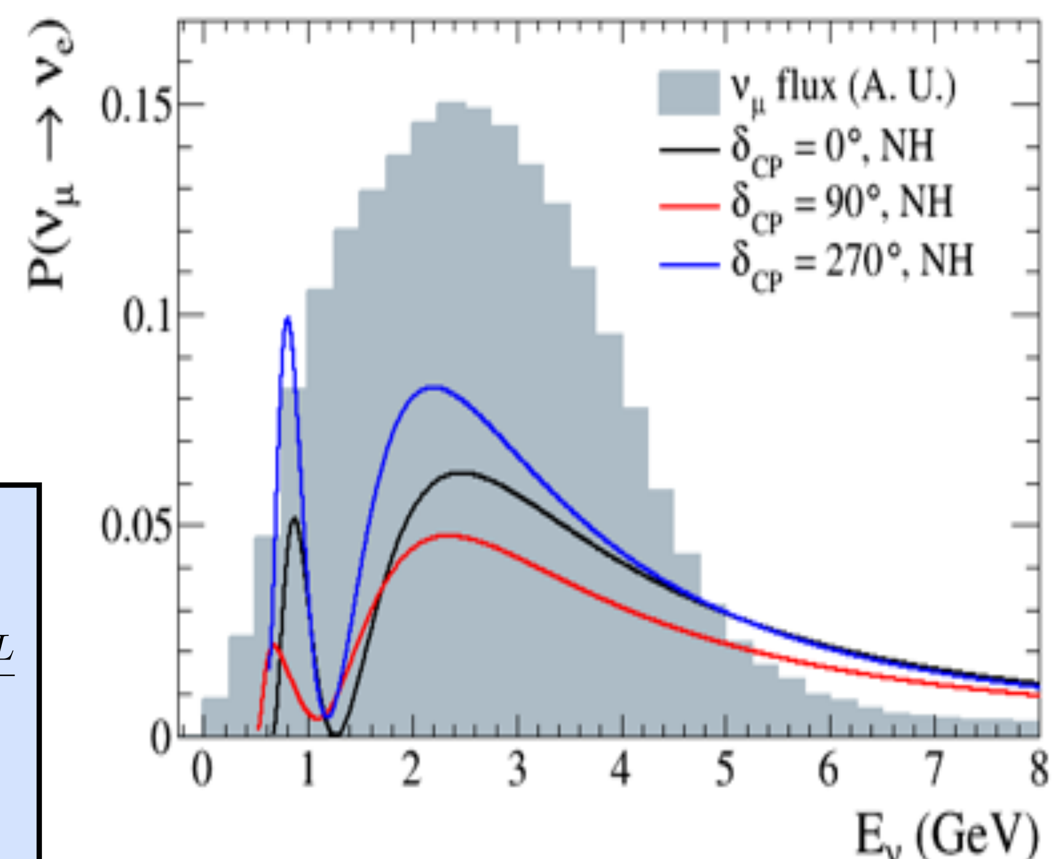
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, unique sensitivity to ν_e
    - *"Information on neutron star or even black-hole formation"*

DUNE - Primary Science Programme

1. **Long baseline neutrino oscillations**
   - Precise measurement of the L/E behaviour for neutrinos and antineutrinos at L>1000 km
     $\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$ with $\mathcal{A}_{CP} \propto L/E$; $\mathcal{A}_{Matter} \propto L \times E$
   - **High discovery potential** for **leptonic CPV** and **guaranteed determination of MH**; test of 3-ν flavour oscillation paradigm; determine the sector of Θ_{23}
   - Complete knowledge of PMNS matrix by precisely determining all parameters including CP-phase. Fundamental parameters of the SM → CKM and PMNS matrices to shed light on the **flavour problem**.

- **DUNE measures the energy dependence of electron-appearance and muon-disappearance oscillation probabilities, independently for neutrinos and antineutrinos**
- **High neutrino beam power and near + far detectors provide precise measurements with high statistics and low systematics**
  - **E.g. Appearance probability for neutrinos**

$$P(\nu_\mu \to \nu_e; L) \simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2} \cdot 2(1-2s_{13}^2)\right\} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$+ c_{13}^2 s_{13} s_{23} \left\{-\frac{aL}{E} s_{13} s_{23}(1-2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12}(-s_{13}s_{23}s_{12} + c_\delta c_{23} c_{12})\right\} \sin \frac{\delta m_{31}^2 L}{2E}$$
$$- 4\frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}} \frac{E}{\mathrm{GeV}}$$



Aim for discovery!

DUNE - Primary Science Programme

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Matter terms~a

CP-even

L/E dependence

CP-odd~sinδ$_{CP}$

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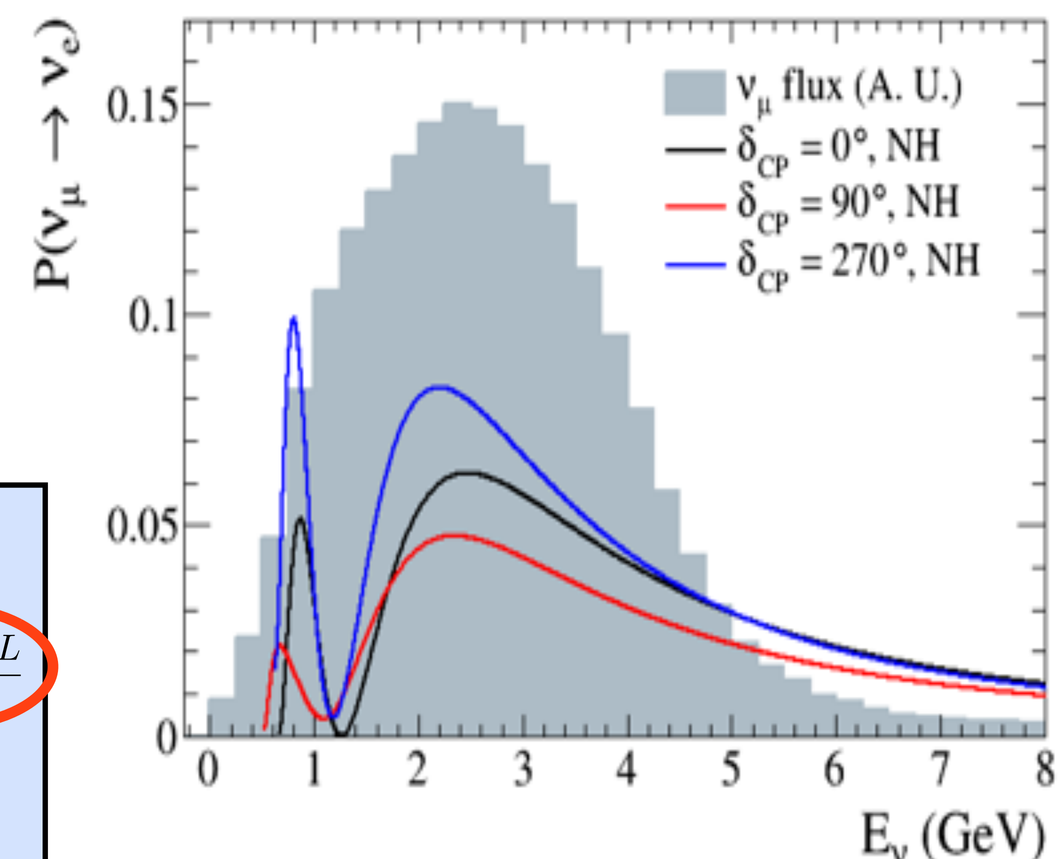
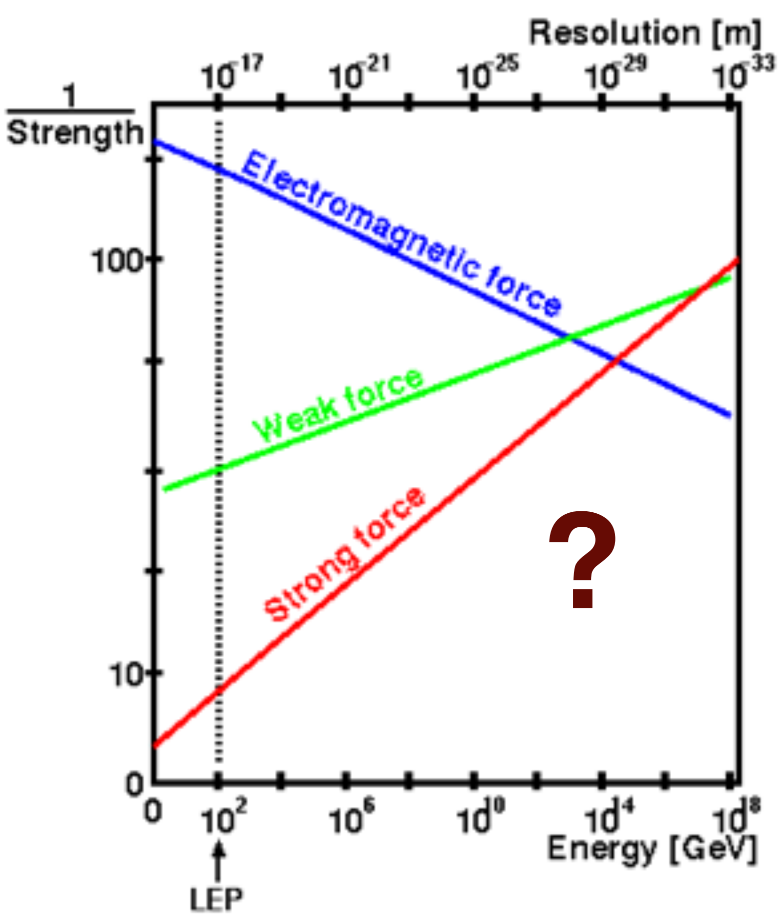


Aim for discovery!

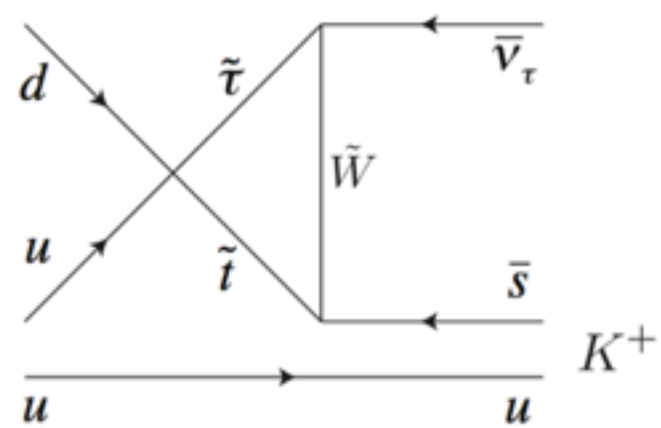
DUNE - Primary Science Programme

2. Nucleon Decay (and atmospheric neutrinos)

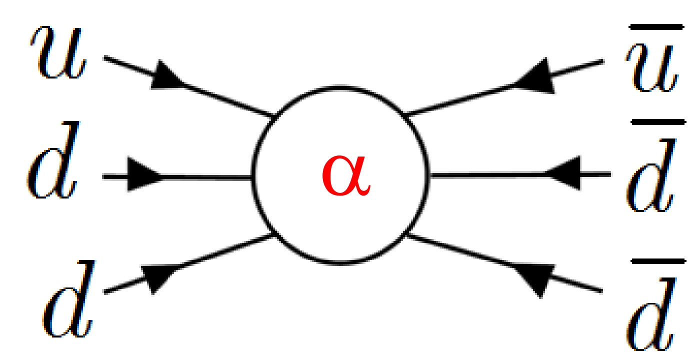
- EW+QCD are all local-gauge QFT with similar structure → GUT ? many hints exist in favour (high energy behaviour of couplings; $Q_e = -Q_p$, neutrino masses, …) but the **missing link** is the **direct observation of a nucleon decay**.
- Measurements of branching ratios inform GUT models (SUSY, non-SUSY).
- Signatures of annihilations from n-nbar oscillations can also be searched for.
- DUNE provides a generational advance in atmospheric neutrino detection and study.



SUSY dim-5



n-nbar oscillations



A discovery would be monumental !

DUNE - Primary Science Programme

3. **Neutrino astrophysics, including supernova detection**
   - SN burst to verify models of stars' explosions; but also neutrino physics
   - Measurement of the **neutrino energy spectra**, **time distributions** and **flavor composition** with **large statistics** from SN will provide information about:
     - Supernova physics:
       - Core collapse mechanism
       - Supernova evolution in time
       - Cooling of the proto-neutron star
       - Nucleosynthesis of heavy nuclei
       - Black hole formation
     - Neutrino flavour transformation and propagation physics:
       - Flavor transformation in SN core has rich physics affected by my phenomena, such as matter & collective effects, sterile neutrinos and in general neutrino properties (e.g. anomalous magnetic moment)
     - Early alert for astronomers

SN detection provides unique and broad science opportunities !

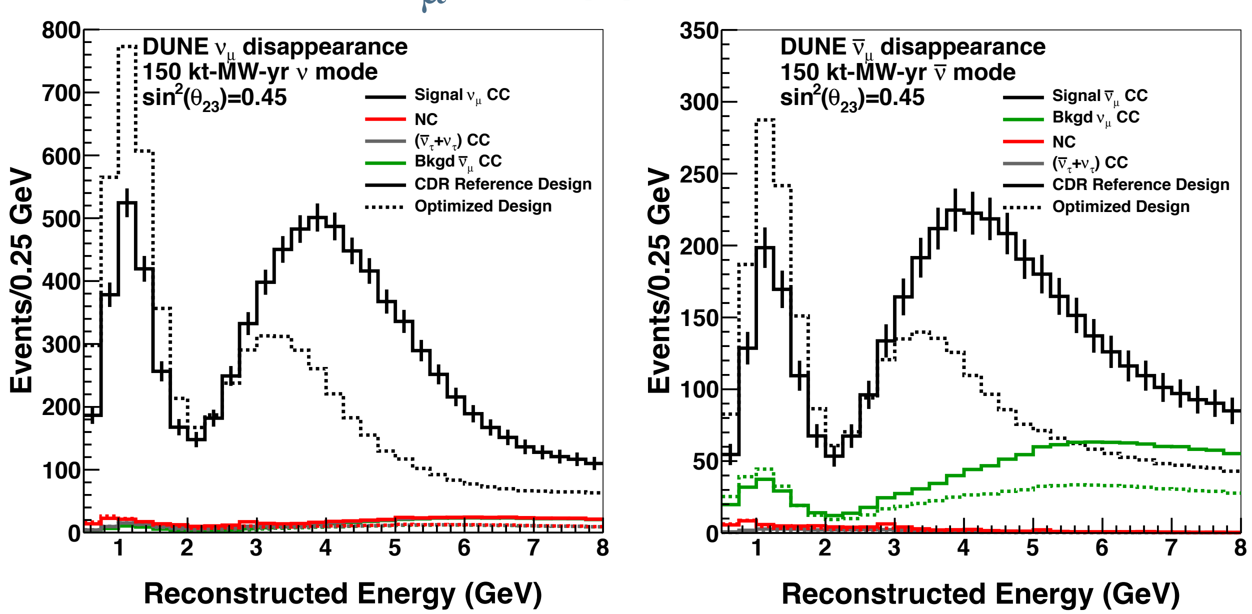
LBL oscillation strategy

Measure neutrino spectra at 1300 km in a wide-band beam

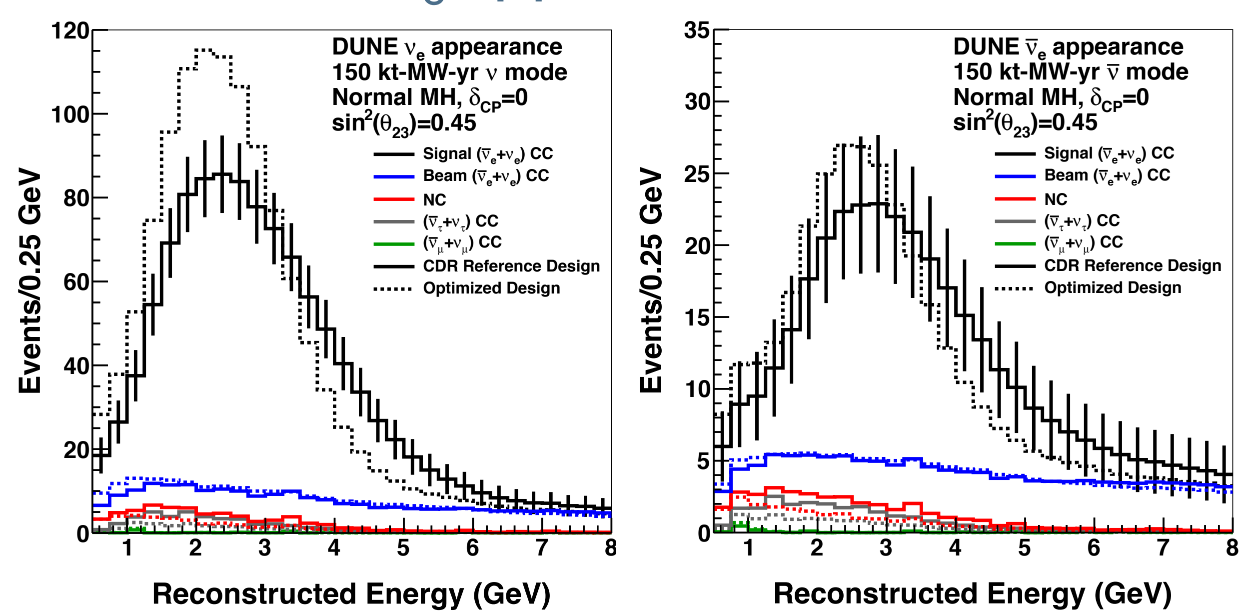
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Study $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) and $\nu_\mu \to \nu_x$ ($\bar{\nu}_\mu \to \bar{\nu}_x$) over range of energies
    - MH & CPV effects are separable

Systematic errors to be negligible compared to statistical power reached over lifetime of experiment

ν_μ disappearance



ν_e appearance



LBL oscillation strategy (II)

CPV & MH : Systematic errors presented in CDR

After fits to both near and far detector data and all external constraints.

Signal: **5%** (abs. $\nu\mu$ norm.) $\oplus$ **2%** (νe norm.) for both neutrinos and antineutrinos sample

Background processes:

From CDR Volume 2 "Physics":

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

External experimental and theoretical input (nu cross-sections, hadroproduction, detector test beams, SBN) and DUNE ND important ingredients to achieve these levels.

LBL science discovery potential

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year**
- e.g. in best-case scenario for MH :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

DUNE 40 kton * 1.2 MW beam
≈ 50 kt.MW.year per year

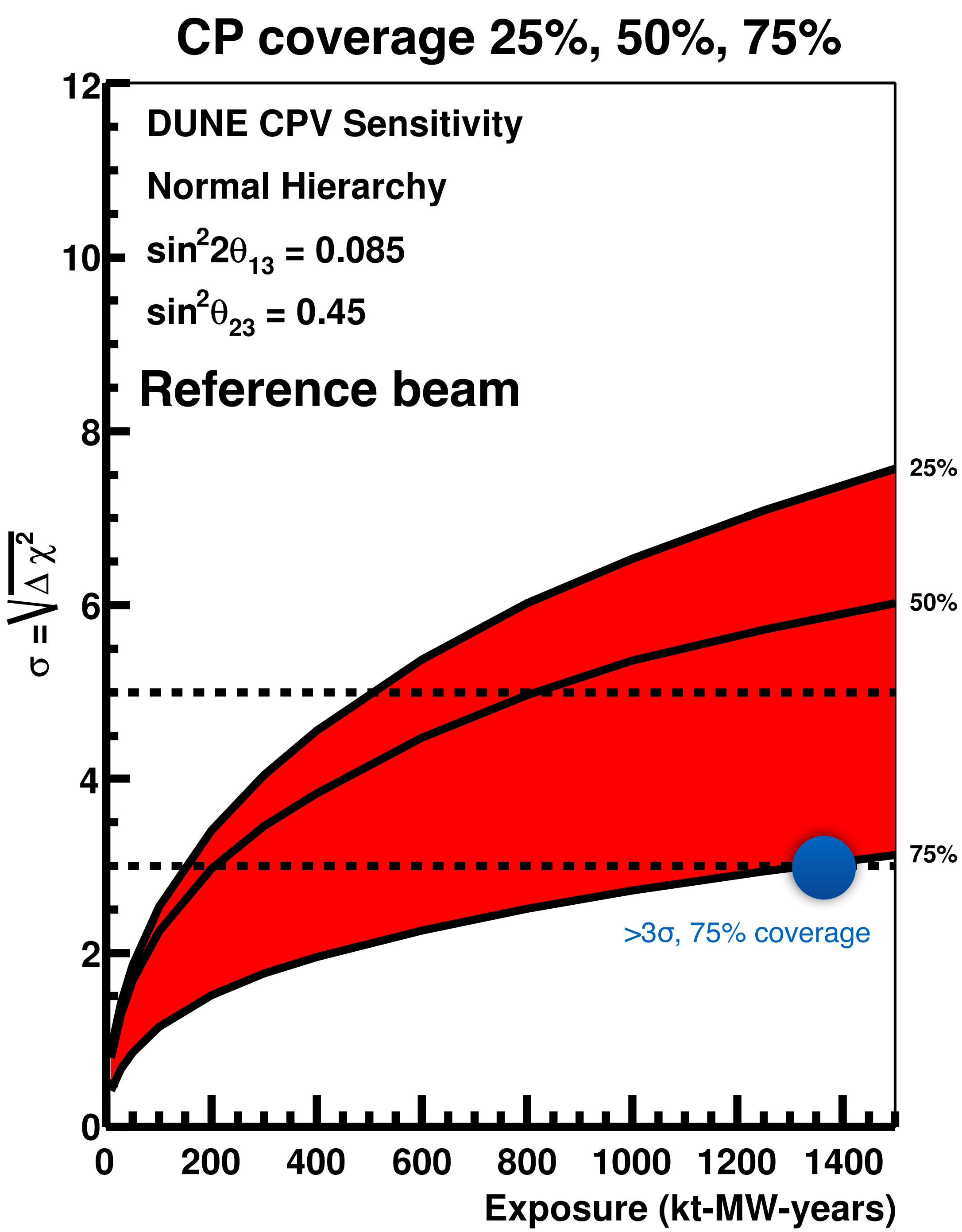
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

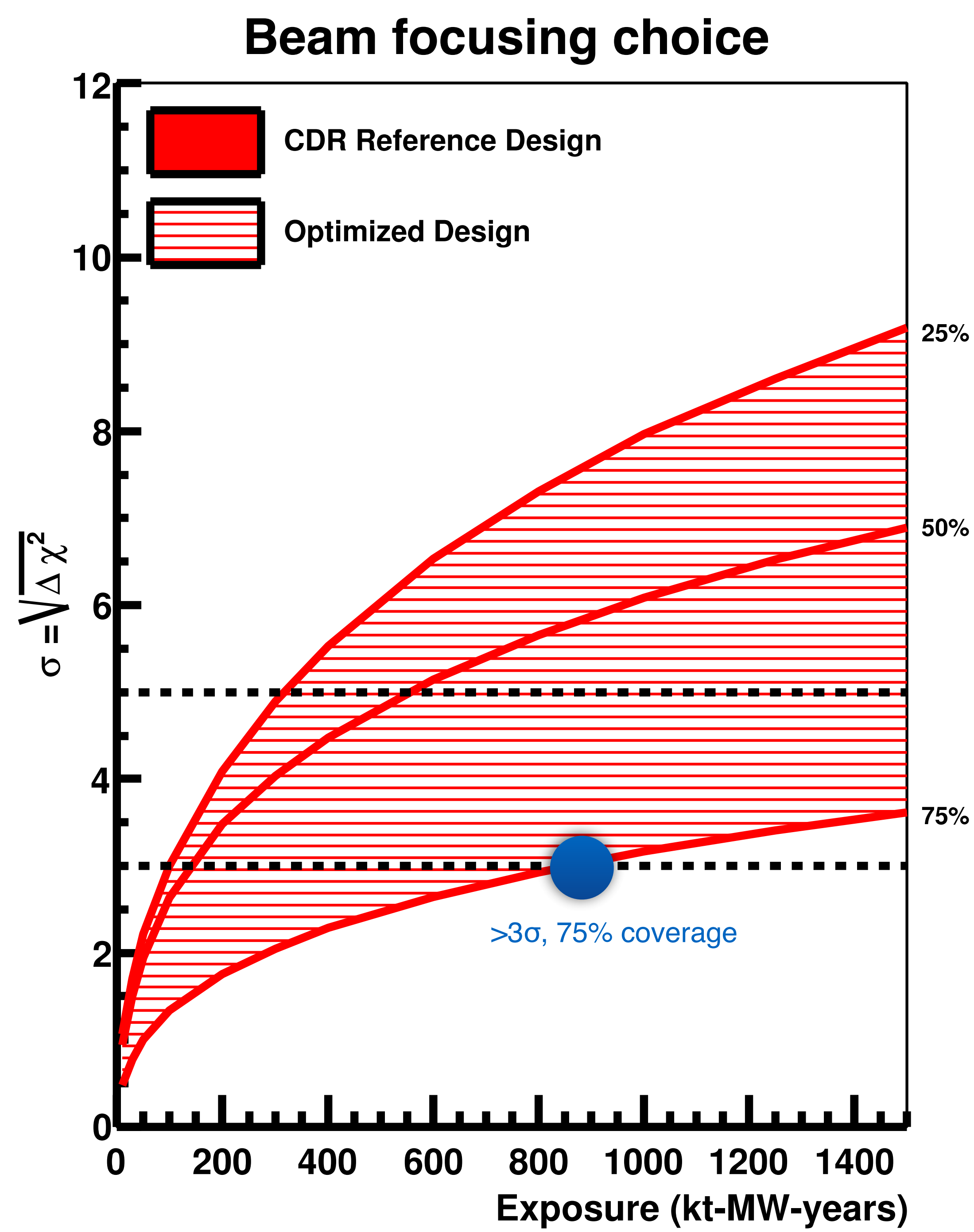
5σ CPV Discovery

Opportunities for early discoveries !

CPV sensitivity

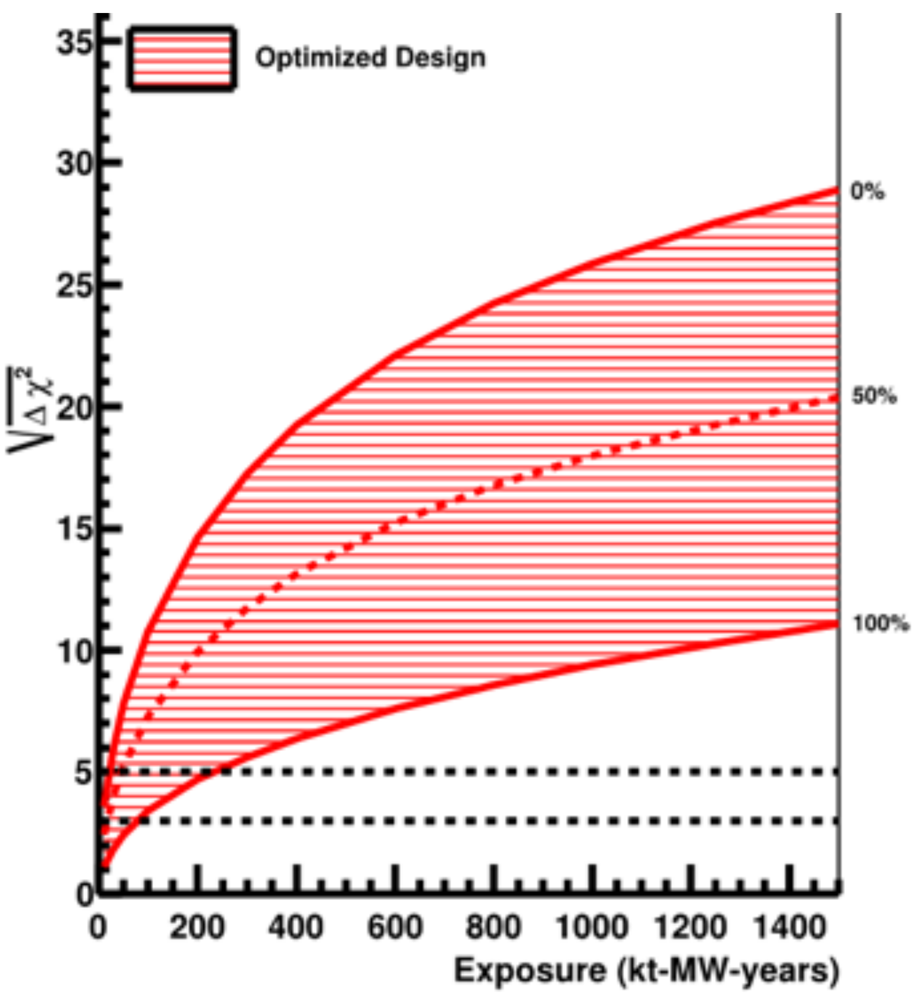
- Sensitivities depend on multiple factors:
  - CPV parameter δ, other mixing angles e.g. θ_{23}
  - Beam spectrum, …

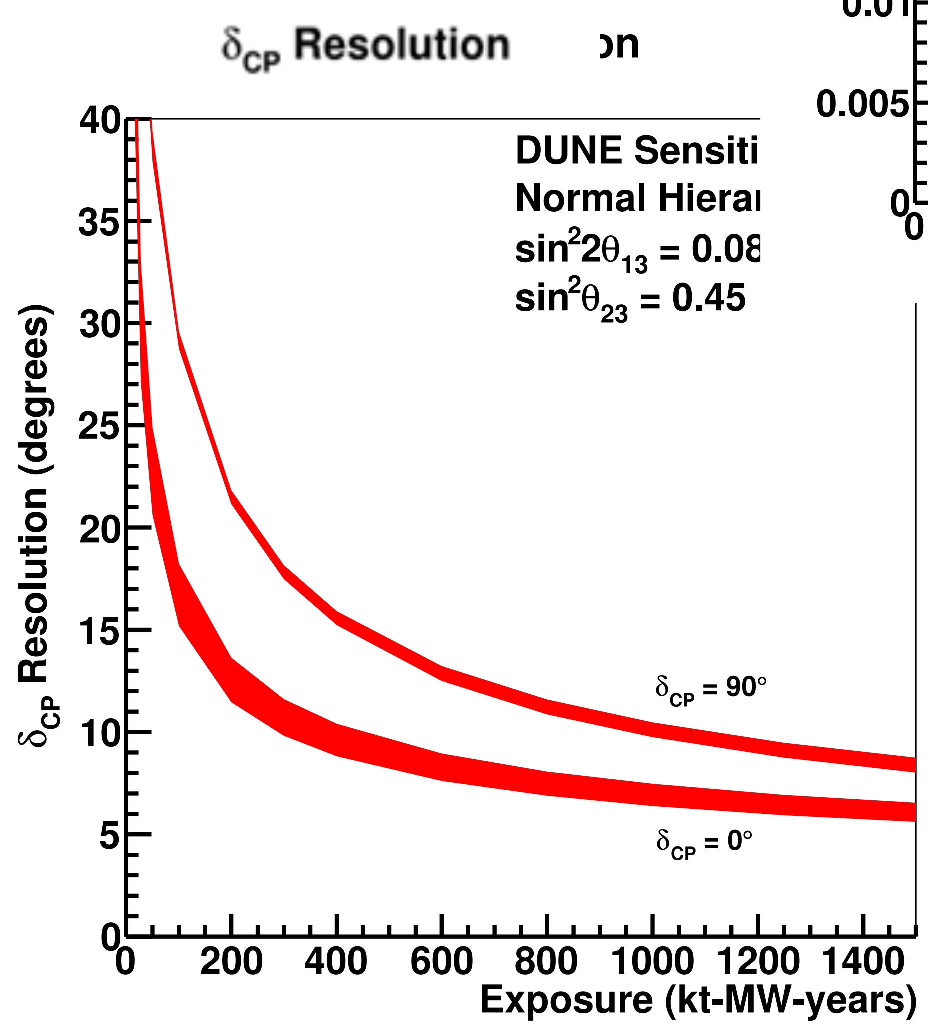


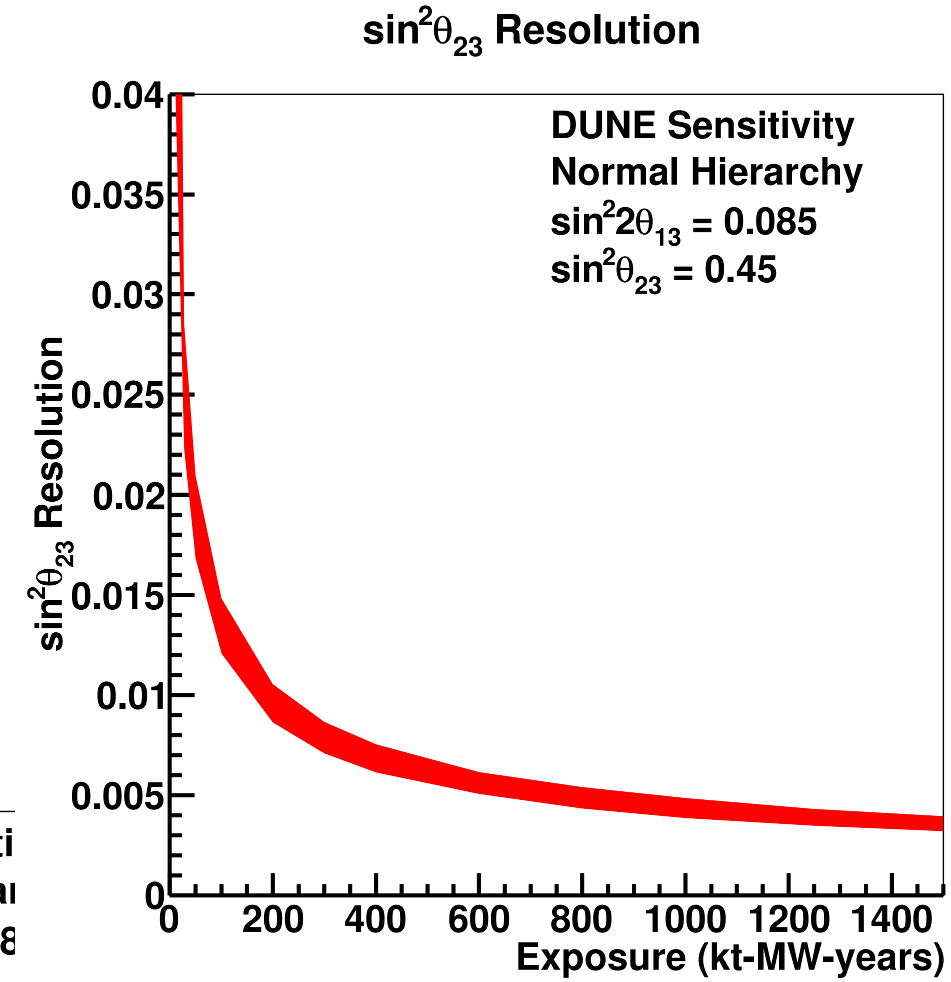


MH, δ_{CP} and $\sin^2\theta_{23}$ Sensitivities

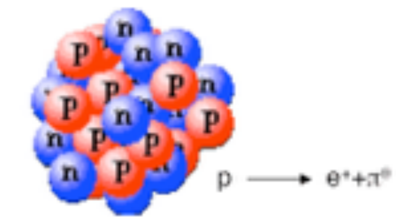
Mass hierarchy coverage







Nucleon decay searches in DUNE



DUNE provides a generational advance in detection method:

Exploit tracking and calorimetry for unbiased, exclusive final state reconstruction of decay products with precise kinematics, low thresholds (no Cherenkov threshold)

For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

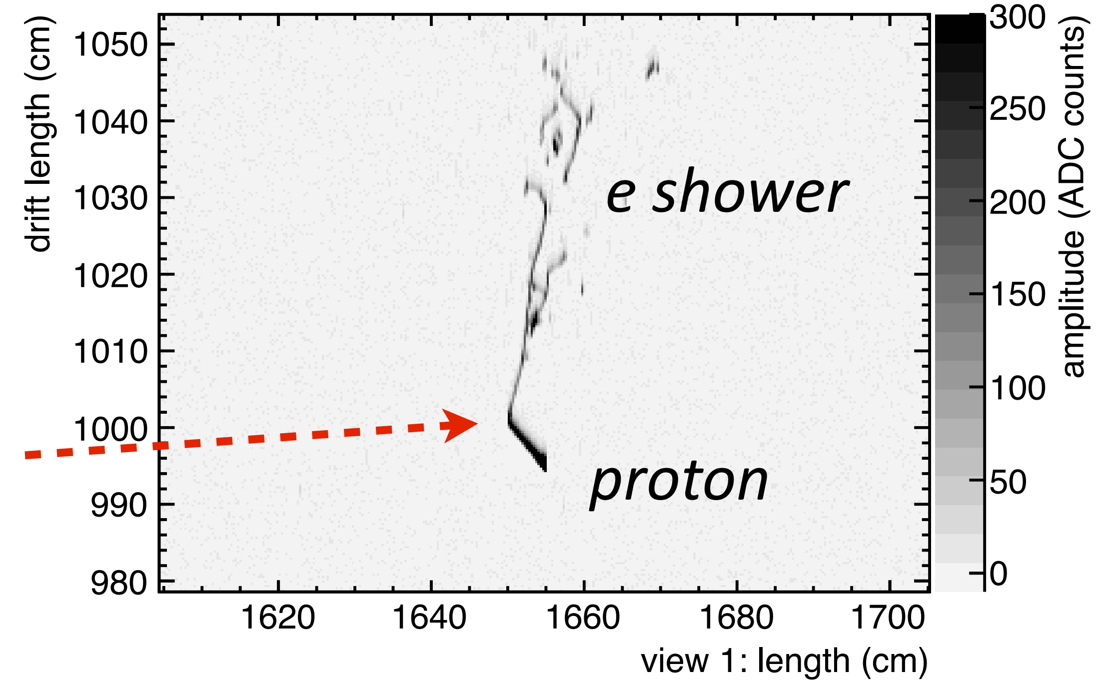
Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	**$>3\times10^{34}$ yrs**
$p \to e^+\gamma$, $p \to \mu^+\gamma$	**$>3\times10^{34}$ yrs**
$p \to \mu^-\pi^+K^+$	**$>3\times10^{34}$ yrs**
$n \to e^-K^+$	**$>3\times10^{34}$ yrs**
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$ yrs
$p \to \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \to e^+\pi^-$	$>0.8\times10^{34}$ yrs

- **Phenomenology is rich and there are many possible decay modes (≈90 identified)**
  - **Proton decay modes**
  - **Neutron decay modes**
  - **n-nbar oscillation modes**
- **Backgrounds can be calculated using atmospheric neutrino samples and estimated using side-bands**
- **Efficiencies involving π's in the final states are affected by nuclear uncertainties but constrained by neutrino cross-section measurements**
- **With LAr imaging & excellent kinematics, we find a ≈linear sensitivity improvement with exposure until 1000 kton×year… or 25 years of DUNE…**

Atmospheric neutrinos in DUNE

Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline beam**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)

Low energy neutrinos in DUNE

hep-ph/0307222; JCAP 10 (2003) 009; JCAP 08 (2004) 001

- Elastic scattering (ES) on electrons

$\nu + e^- \rightarrow \nu + e^-$

- Charged-current (CC) interactions on Ar

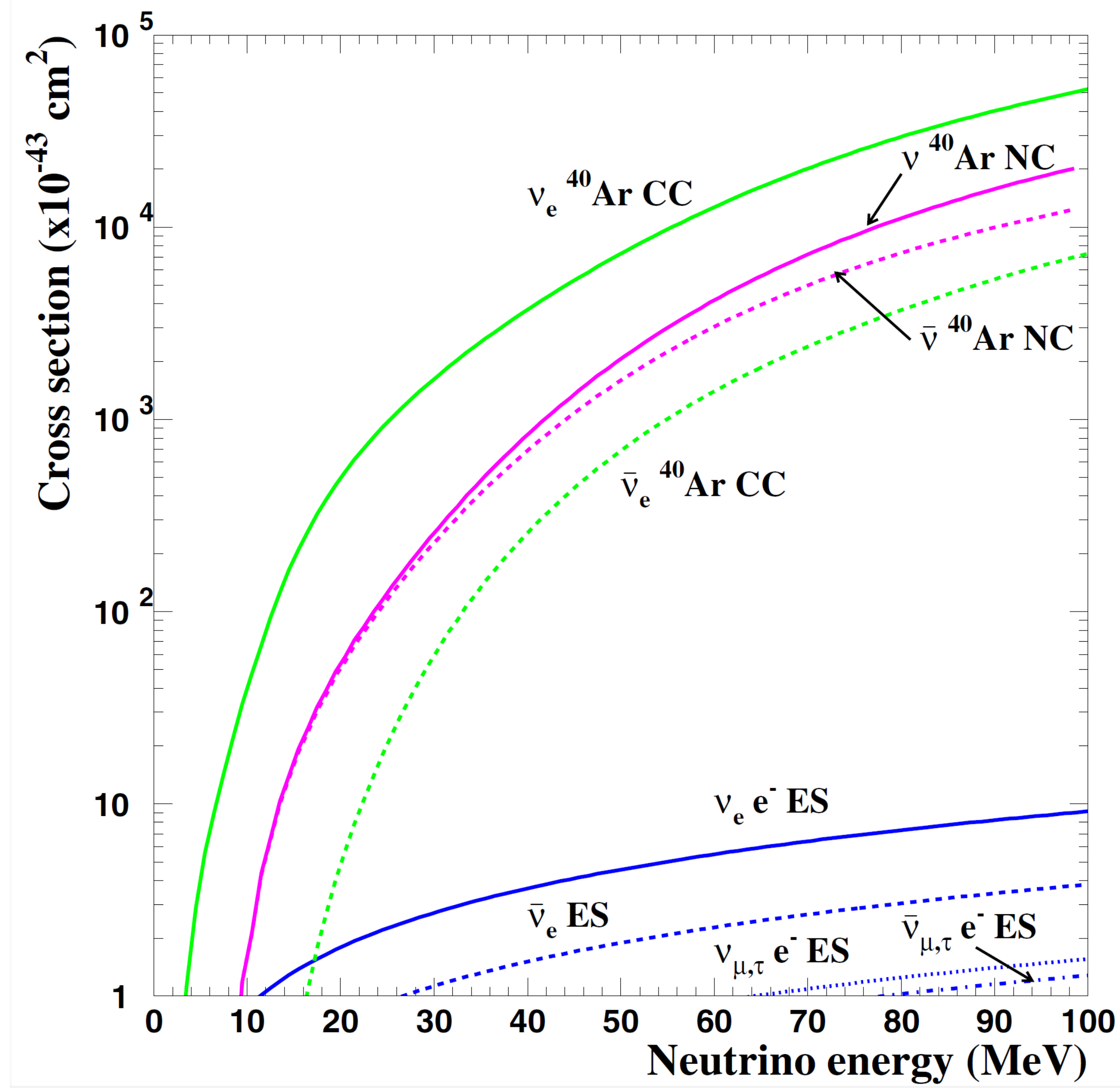
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ | $E\nu_e > 1.5$ MeV

$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$ | $E\bar{\nu}_e > 7.48$ MeV

- Neutral current (NC) interactions on Ar

$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$ | $E\nu > 1.46$ MeV

SN ν cross sections on Ar



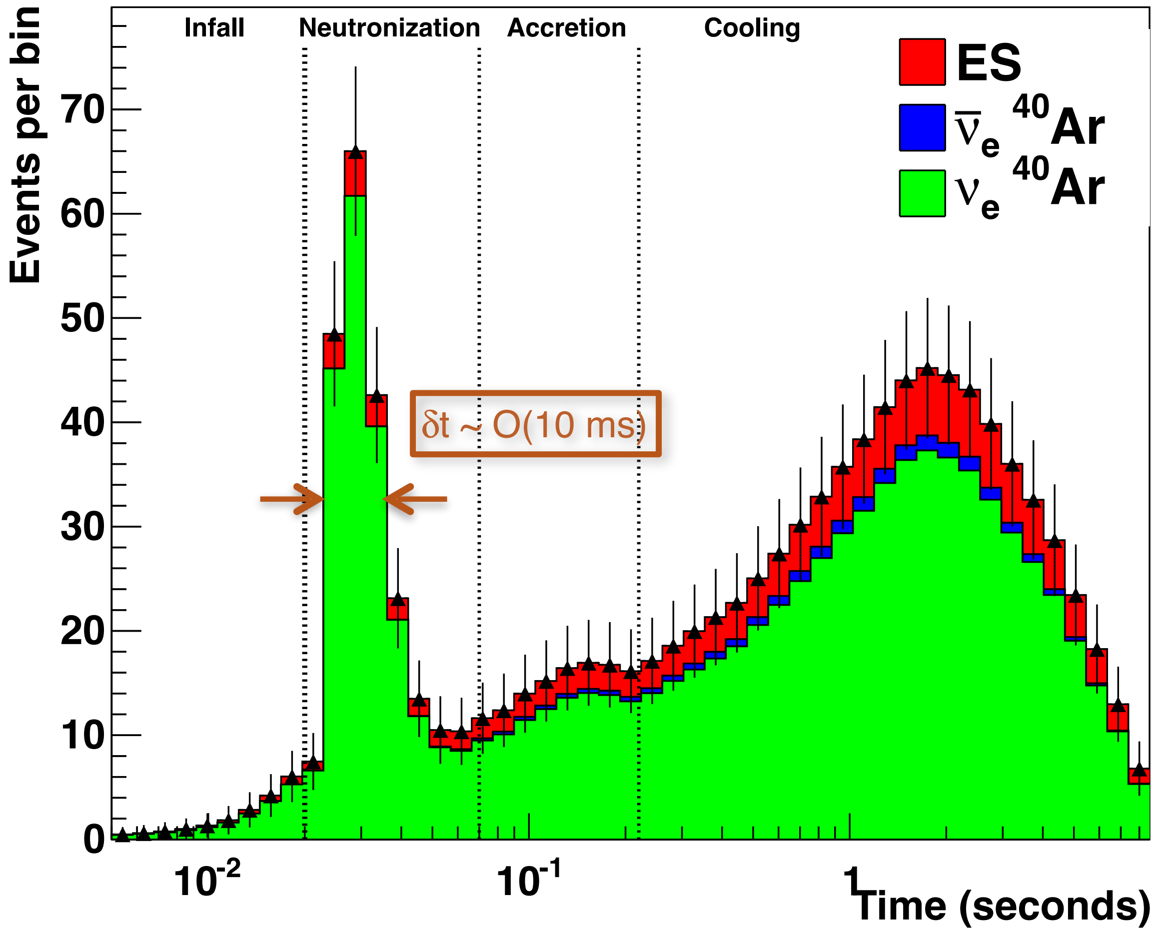
Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)

Supernova burst neutrinos

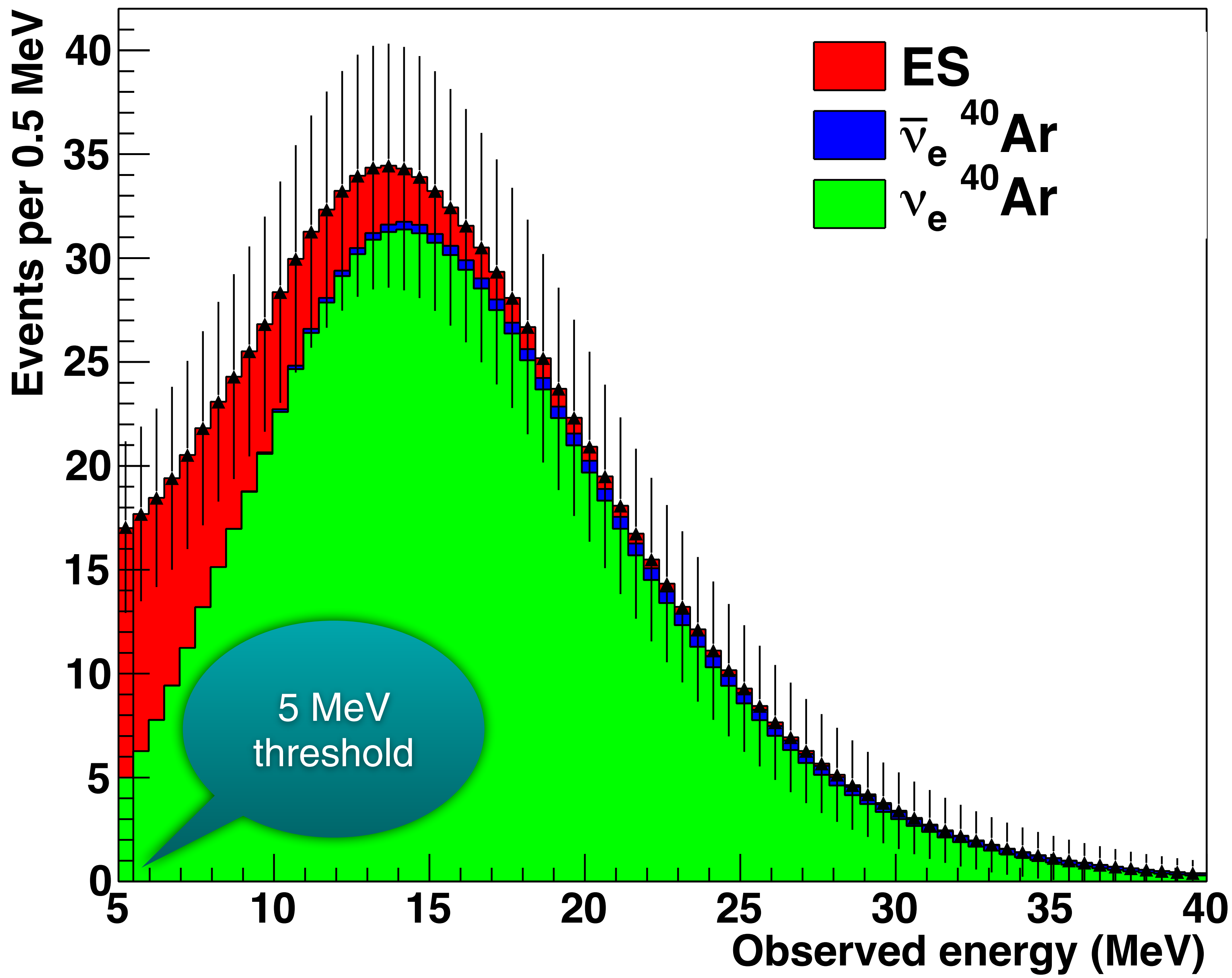
Expected event rates for 40 kton and SN at the distance of 10 kpc : (no oscillations included!)

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

- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Peak of neutronization (osc?)
- Combined analysis of all reaction modes – can NC reaction be observed ?
- Oscillation (both standard and collective) will potentially have a large effect
- Neutrino abs. mass via TOF

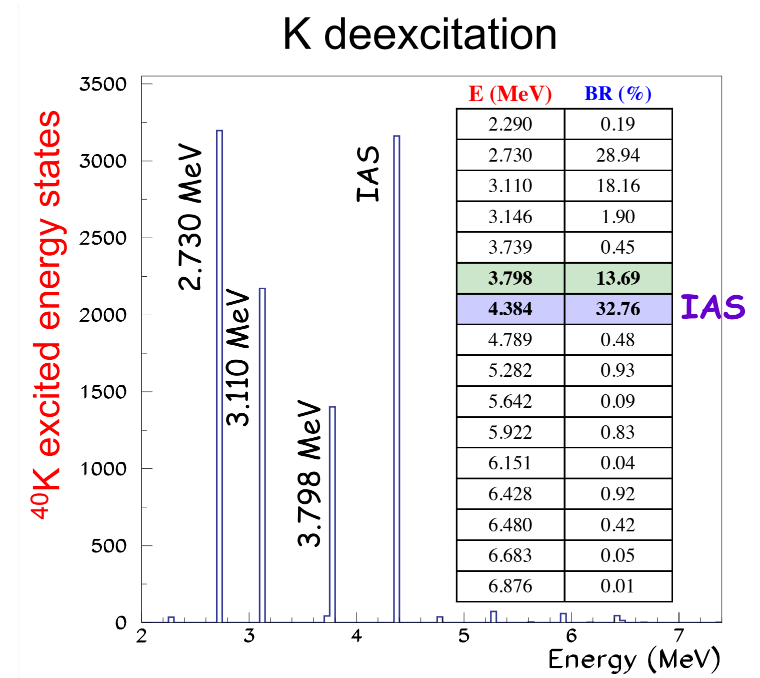


Energy spectrum



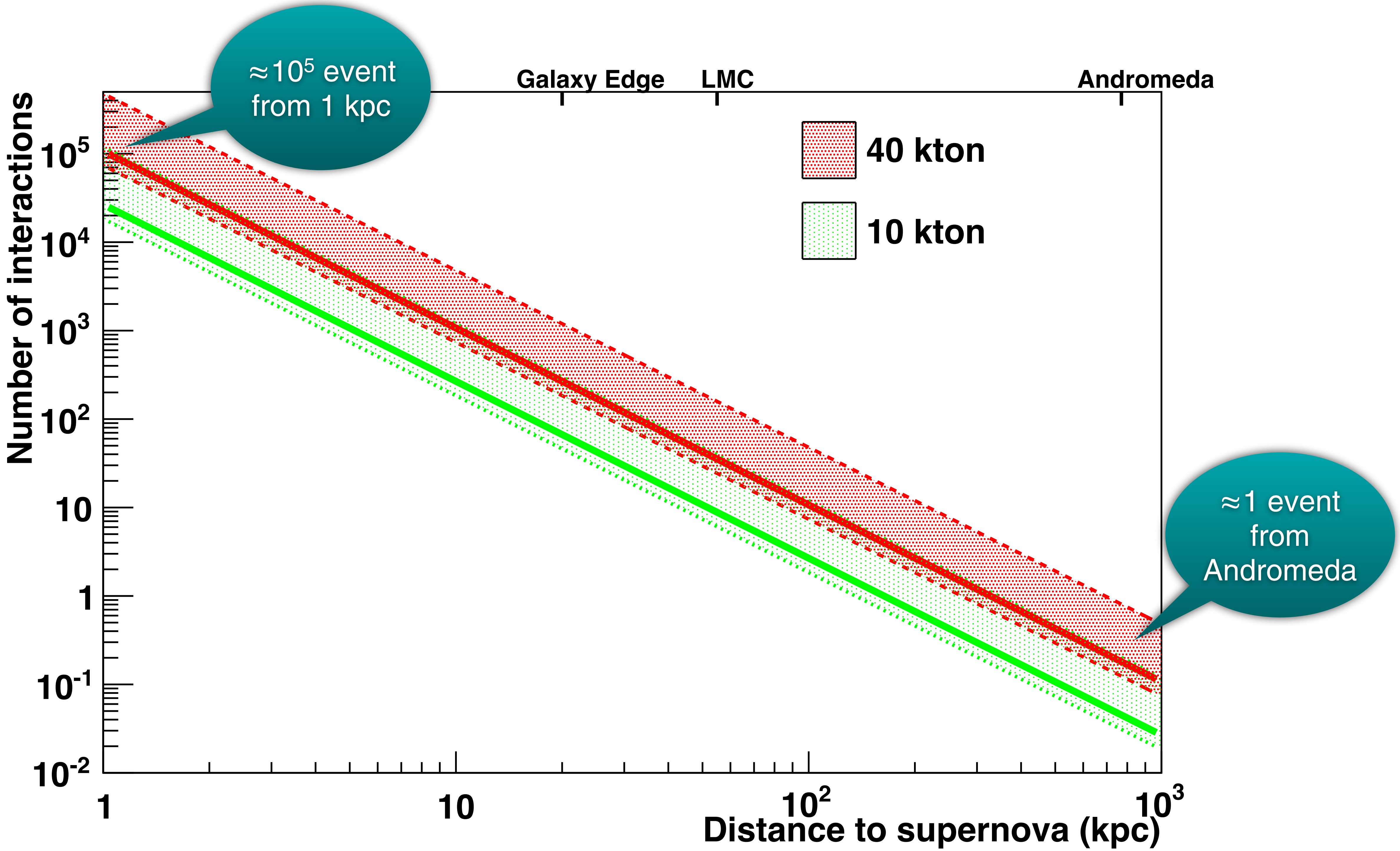
- Spectrum calculated with SNoWGloBES

- Spectrum assumes final state energy is fully reconstructed
- Neutrino flavour classification assumes detection of **deexcitations photons**



- Measurement campaigns of low energy cross-section on Argon needed to exploit statistical power of SN event burst.

Events vs distance



- Band represents range of models (factor of ~10 in rate)
- Solid line: “Garching” model (Raffelt et al., PRL104, p. 251101, 2010)

Summary

- LBNF/DUNE will be a game-changing program in neutrino physics and astro-particle physics
  - Definitive 5σ determination of MH
  - Broad exploration of leptonic CPV with significant prospects for discovery
  - Precisely test 3-flavor oscillation paradigm
  - Extend sensitivity to nucleon decay
  - Unique measurements of supernova neutrinos (if one should occur in the lifetime of the experiment)
  - Generational advance in precision neutrino physics at the near site
- A strong world-wide collaboration has formed to build the experiment
  - LAr TPC Far Detector,
  - Fine-Grained Tracker Near Detector
  - MW-class Neutrino Beam
- The LBNF/DUNE Project is advancing quickly. We look forward to further exploring and expanding the DUNE science.

Backup