Physics at Future Neutrino Facilities

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Outline

- Physics at Long-Baseline Neutrino Facility (LBNF) with DUNE
- Cross-sectional neutrino measurements at FNAL: CAPTAIN-MINERVA
- Short Baseline Neutrino (SBN) program at Fermilab
- Physics at J-PARC facilities with HyperK experiment (Japan)
- Physics at J-PARC facilities with T2K extended (Japan)
- Bringing accelerators to detectors and physics prospects: “compact” high power proton cyclotrons for DAEδalus and IsoDAR.
- Neutrino Factory, MOMENT for high precision CPV phase measurements
- Summary and outlook

Future Neutrino Facilities Support Comprehensive Science Program

- Remarkable opportunities for major scientific discoveries:
  - **Leptonic CP violation phase measurement**
  - **Determination of neutrino mass hierarchy**
  - **Proton decay**
  - **Detection of galactic-core supernovae neutrinos**
  - **Searches for sterile neutrinos**

- Many other important topics:
  - Neutrino beam physics:
    - Determination of the θ_{23} octant
    - Precision measurement of neutrino oscillation parameters
    - Precision tests of 3 flavor neutrino model
    - Tests of neutrino NSI (Non-Standard Interactions)
    - Interaction cross-section measurements

  - Synergic scientific program in precision neutrino and weak interactions physics

Long Baseline Neutrino Facility (LBNF) and DUNE

Completing The Three Neutrino Mixing Model

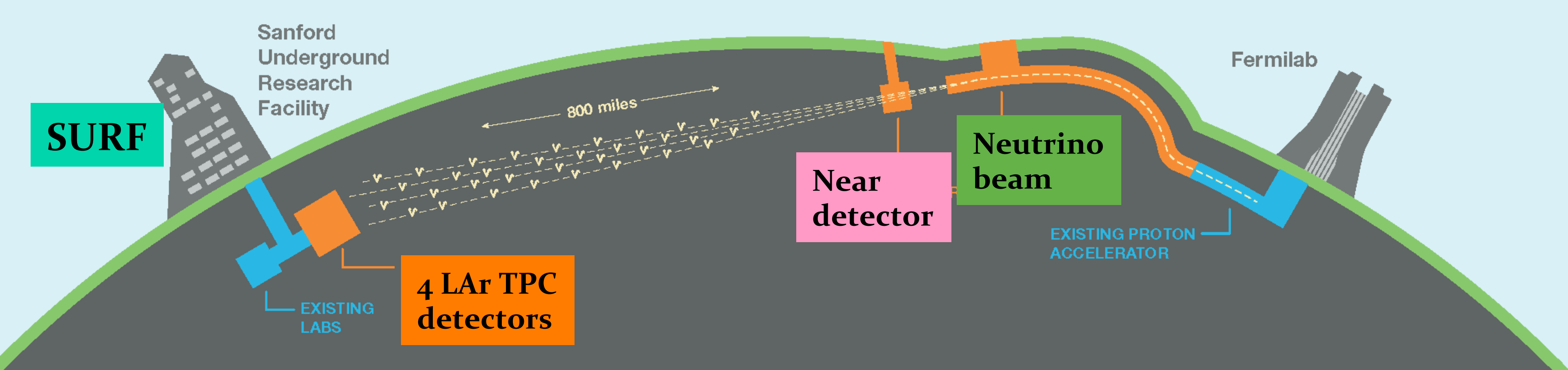
DUNE and LBNF

Deep Underground Neutrino Experiment (DUNE) consists of:
- 4 LAr TPC (Time Projection Chamber) detectors at SURF with 40 kton (fiducial) LAr TPC at 4850 ft depth
- Near Detector complex
- International science collaboration

LBNF will provide **wide-band neutrino beam** to DUNE. Unprecedented beam power up to date

1.2 MW (2026) → 2.4 MW (II phase)

Send ν_μ beam from Fermi Lab (FNAL) to Far Detector (FD) 1300 km away at SURF.
Run in both ν and anti-ν mode.
DUNE will detect disappearance of ν_μ and appearance of ν_e at FD to fulfill science goals.

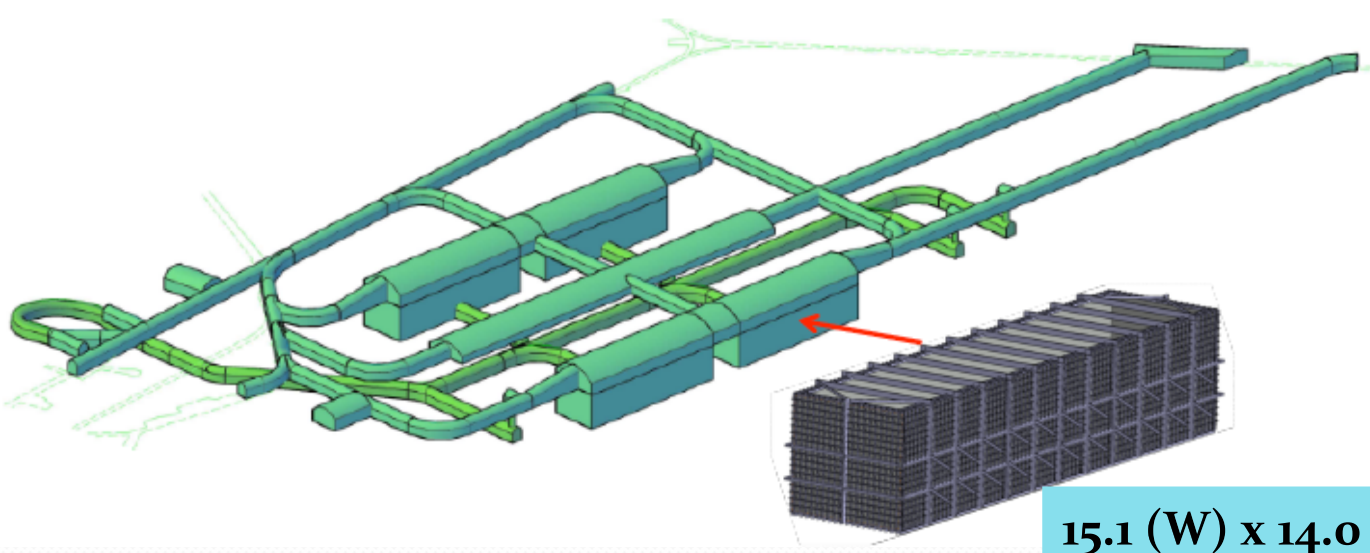


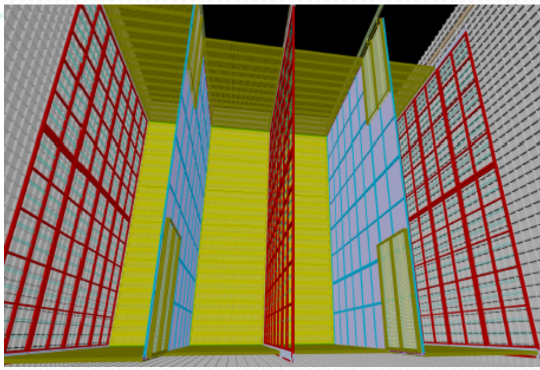
LBNF IS MORE THAN JUST A BEAM

- What does it take for LBNF to support DUNE's elaborate program?
  - Major partners: FNAL, CERN and SURF
  - Construction and maintenance of underground and surface facilities at SURF, capable of hosting a 4-module LAr TPCs with over 70 kton LAr.
  - Cryostats, refrigeration and purification systems to operate the detectors
  - A high-power, wide-band, tunable, neutrino beam at FNAL
  - Underground and surface facilities at FNAL hosting near detector and potentially other neutrino experiments

LBNF Hosting Far Detector at SURF

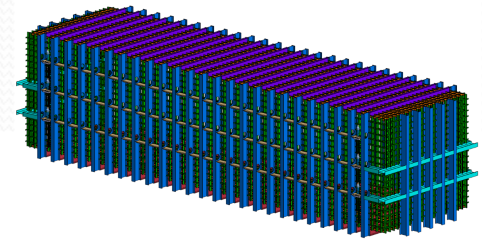
- First 10 kton module – single phase LAr TPC (follow previously developed concept design for LBNE).
- Built-in flexibility to accommodate all detector needs, independent of design.
- Follow-up modules may be single or dual phase, depending on performance of large scale single and dual phase prototypes.
- Both single and dual phase prototypes will be tested at CERN ~2018.





15.1 (W) x 14.0 (H) x 62 (L) m³

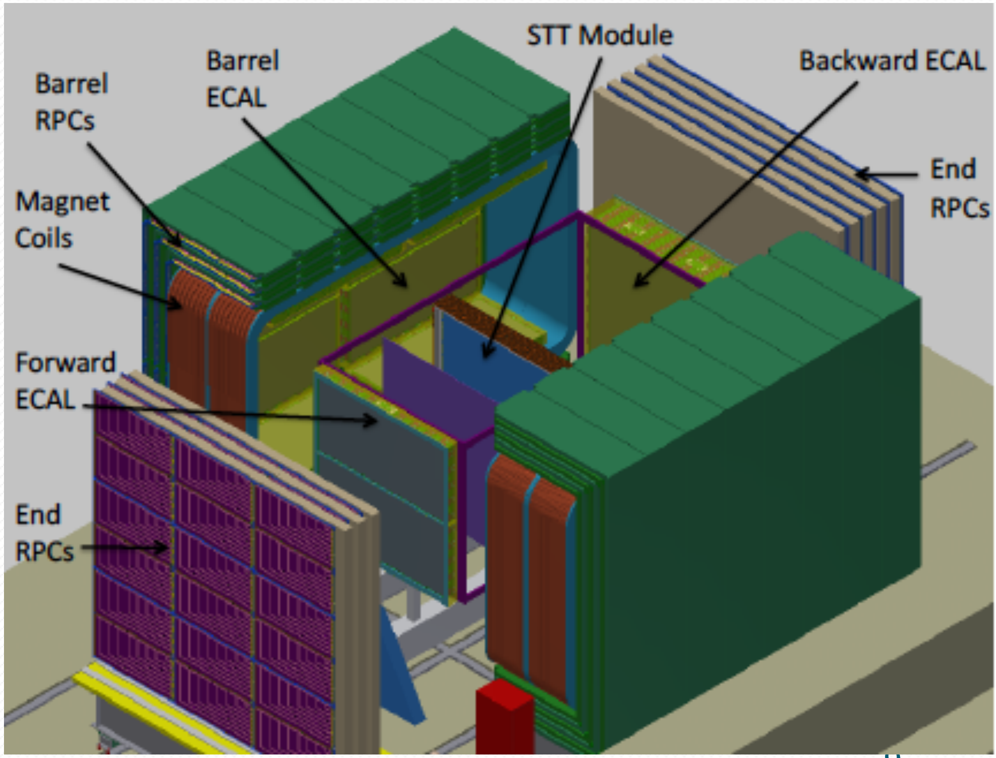
Scale of a single cryostat housing 17.5 kton LAr TPC



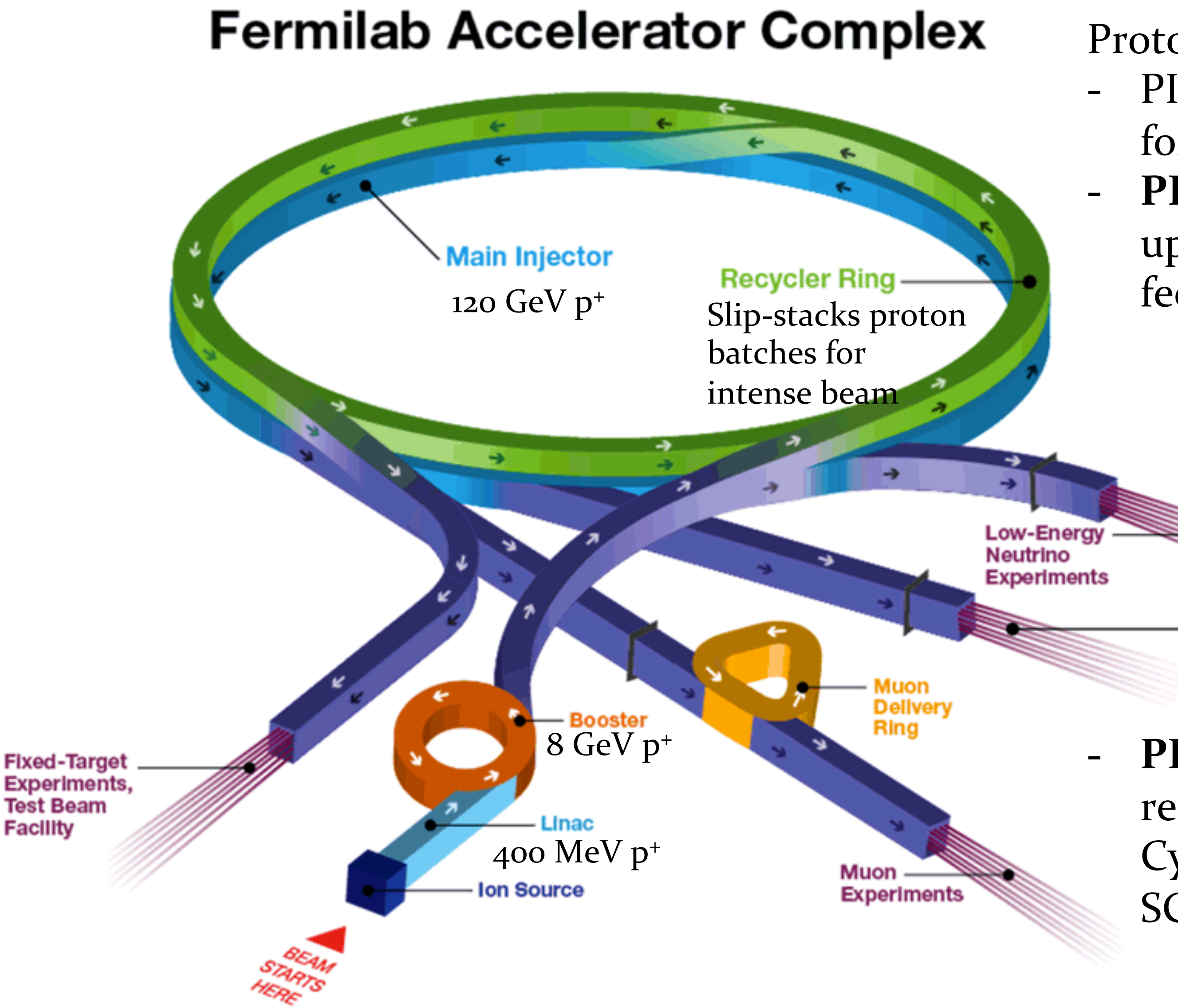
7 story
building 156 at CERN

Near detector

- Monitors initial neutrino beam
- Fine grain tracker magnetized neutrino detector (design based on success of NOMAD and T2K ND).
- Includes muon detectors in absorber hall.
- ND design will undergo detailed analysis and optimization
LAr TPC or high pressure gaseous Ar TPC may be added for direct comparison with FD.

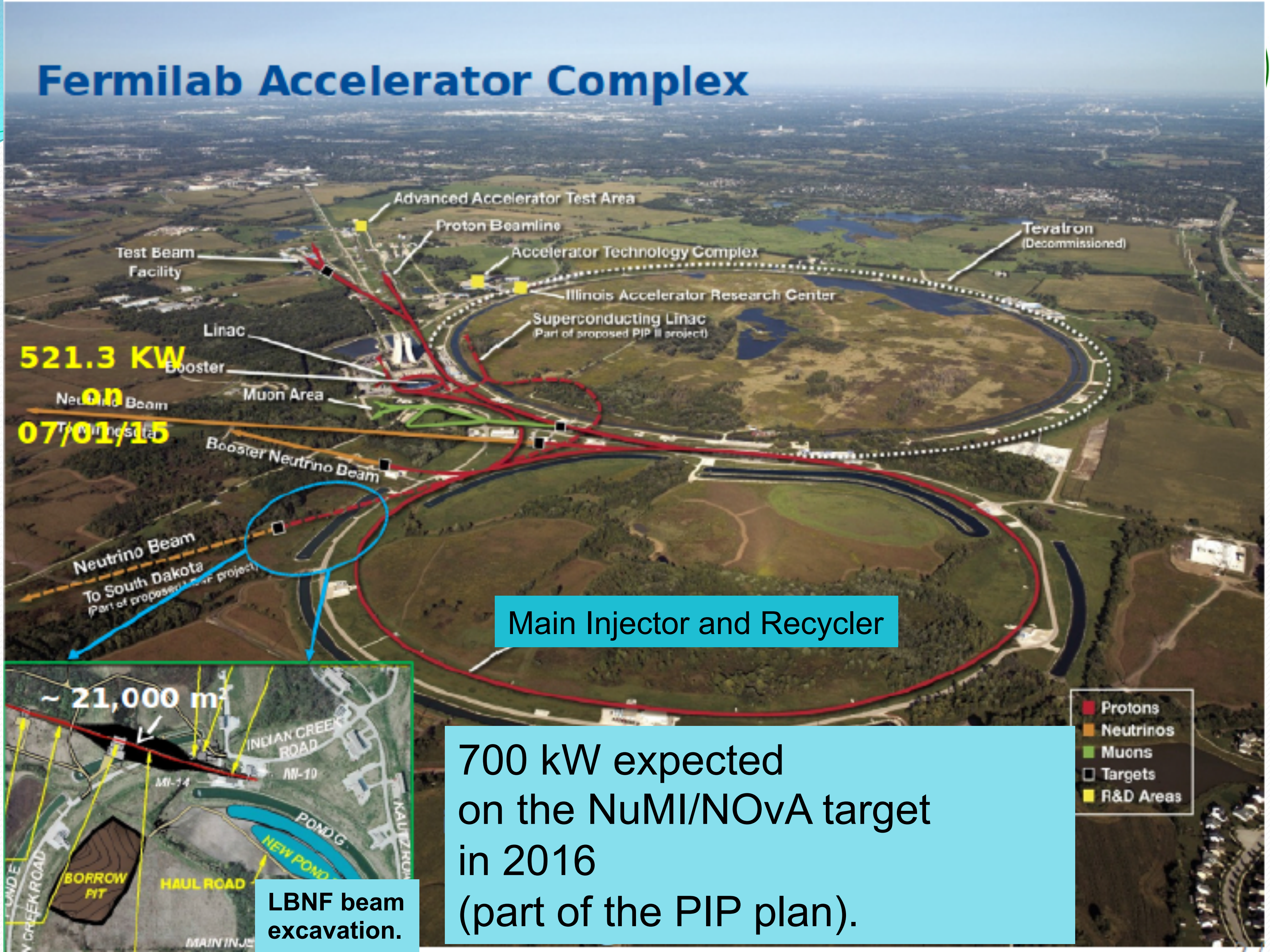


Toward the world most intense neutrino beam



Proton Improvement Plan PIP

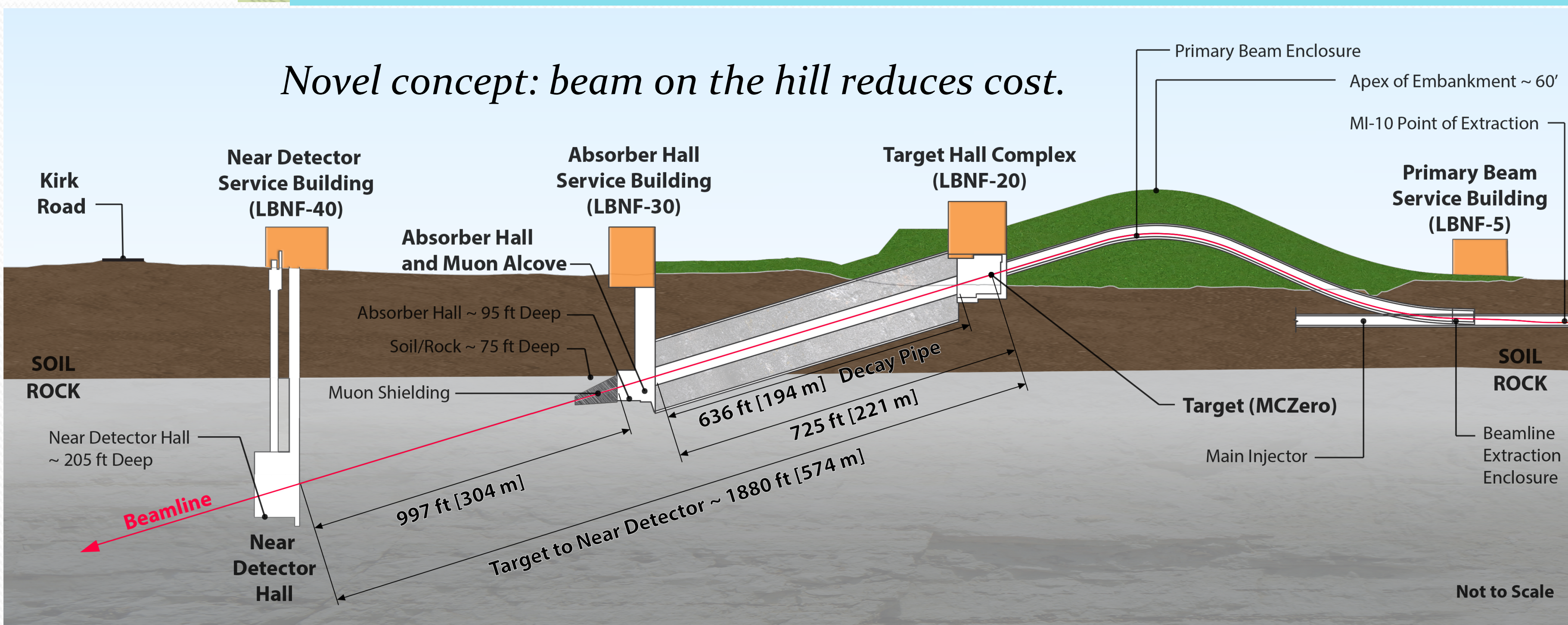
- PIP - current beam upgrades for NOVA (700 kW)
- **PIP-II – by 2026** replacing upstream portion of Linac feeding into 8 GeV Booster.
  - 1.03 MW at 60 GeV
  - 1.07 MW at 80 GeV
  - 1.20 MW at 120 GeV
- **PIP-III in R&D phase**: replace Booster with Rapid Cycling Synchrotron (RCS) or SC Linac.
  - > 2.0 MW at 60 GeV
  - > 2.4 MW at 120 GeV


Fermilab Accelerator Complex
Advanced Accelerator Test Area
Proton Beamline
Test Beam Facility
Accelerator Technology Complex
Tevatron (Decommissioned)
Illinois Accelerator Research Center
Superconducting Linac (Part of proposed PIP II project)
Linac
521.3 KW on 07/01/15
Booster
Muon Area
Booster Neutrino Beam
Neutrino Beam To South Dakota
Main Injector and Recycler
~ 21,000 m²
INDIAN CREEK ROAD
MI-14
MI-10
POND G
NEW POND
BORROW PIT
HAUL ROAD
LBNF beam excavation.
700 kW expected
on the NuMI/NOvA target
in 2016
(part of the PIP plan).
Protons
Neutrinos
Muons
Targets
R&D Areas

The LBNF Beamline

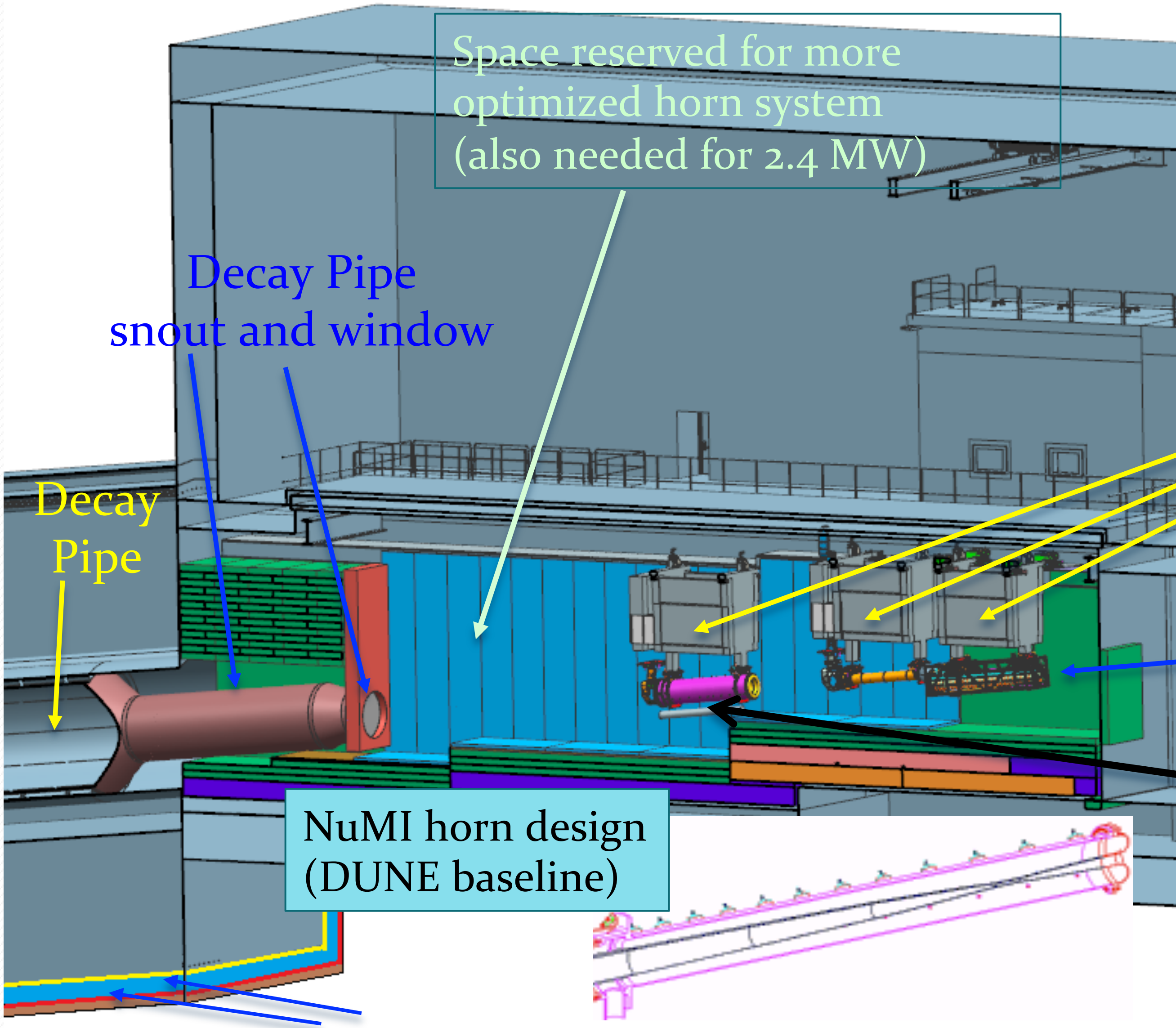
- Primary proton beamline: extracts 60, 100, 120 GeV protons.

Novel concept: beam on the hill reduces cost.

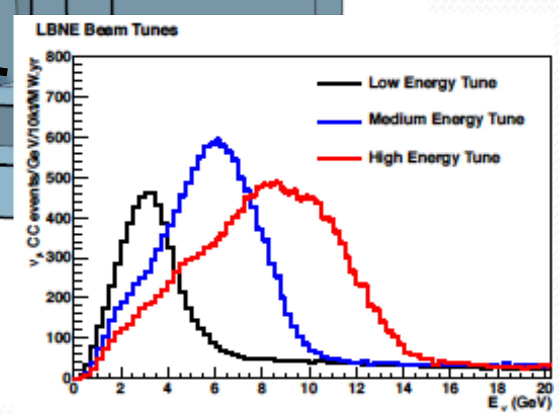


The LBNF Beamline

- Well developed conceptual design relies on upgraded tunable NUMI focusing.



multi-ply geosynthetic barriers, separated by a drainage layer



LBNF: Preparing for 2.4 MW beam

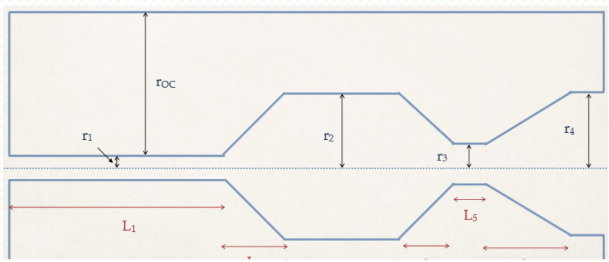
- Expensive systems already designed for 2.4 MW, as later replacements are prohibitively expensive:
  - Size of enclosures (primary proton beamline, target chase, target hall, decay pipe, absorber hall)
  - Radiological shielding of enclosures
  - Primary Beamline components
  - Target chase cooling panels
  - Decay pipe and its cooling
  - Beam absorber
  - Remote handling equipment
  - Radioactive water piping
  - Horn support structures designed to last for a lifetime of the facility

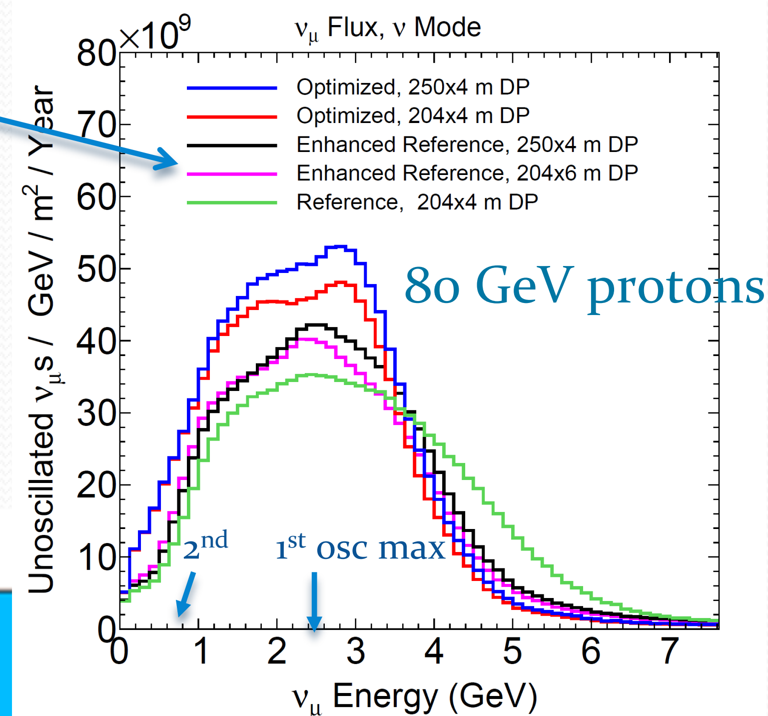
  - New horn design and target needed; subject to R&D.

Optimizing the Focusing System

- Based on genetic algorithm developed for LBNO.
- Vary: proton energy 60-120 GeV, horn shape/size/current/position, target size/shape/position/materials, decay pipe length/diameter.

Enhanced design: thinner and shorter cylindrical Be target, 25 cm upstream of the 1st horn



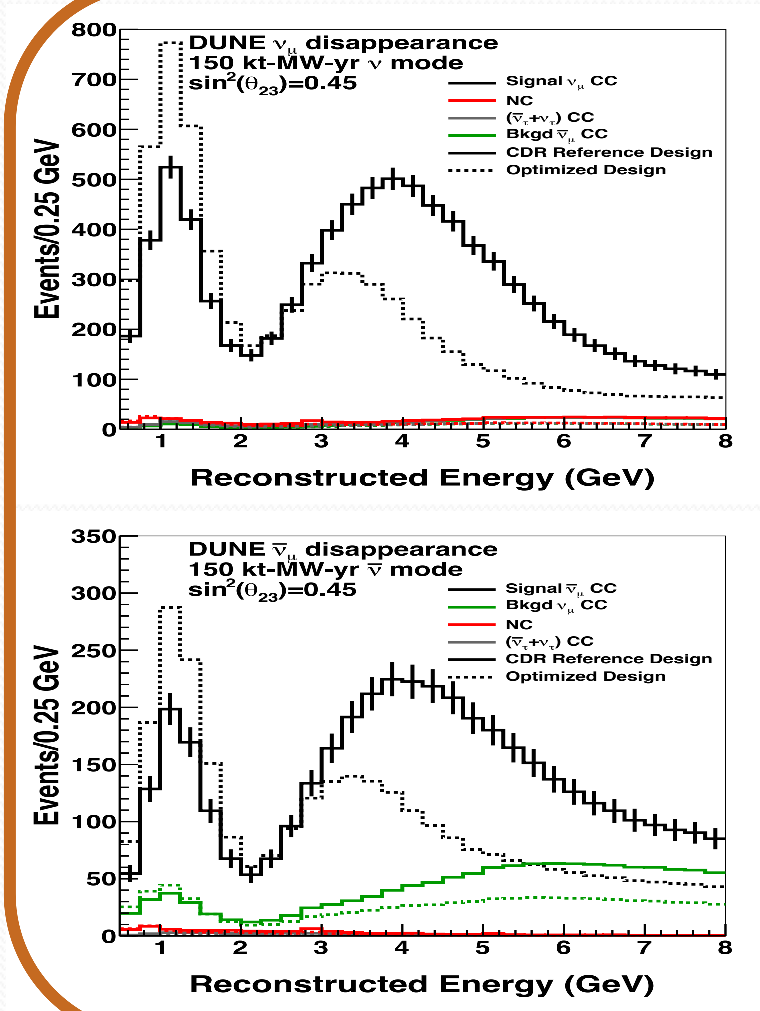


Neutrino spectra in DUNE

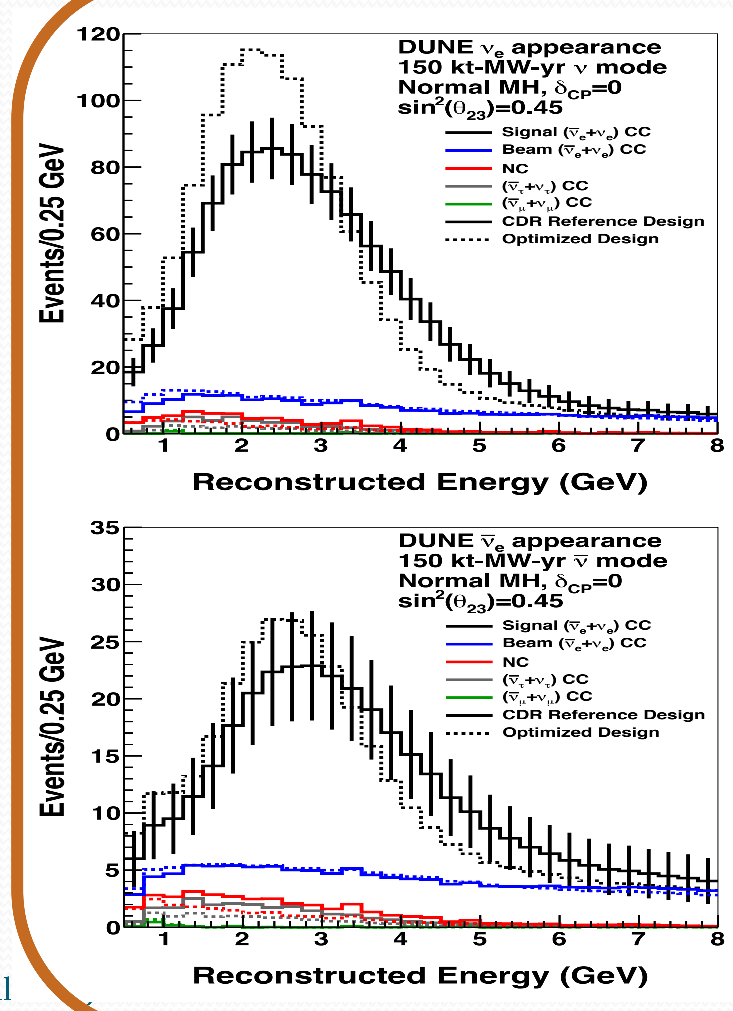
Long baseline: Matter effects are large ~ 40%

Wide-band beam: Measure ν_e appearance and ν_μ disappearance over range of energies

MH & CPV effects are separable



ν_μ / $\bar{\nu}_\mu$ disappearance



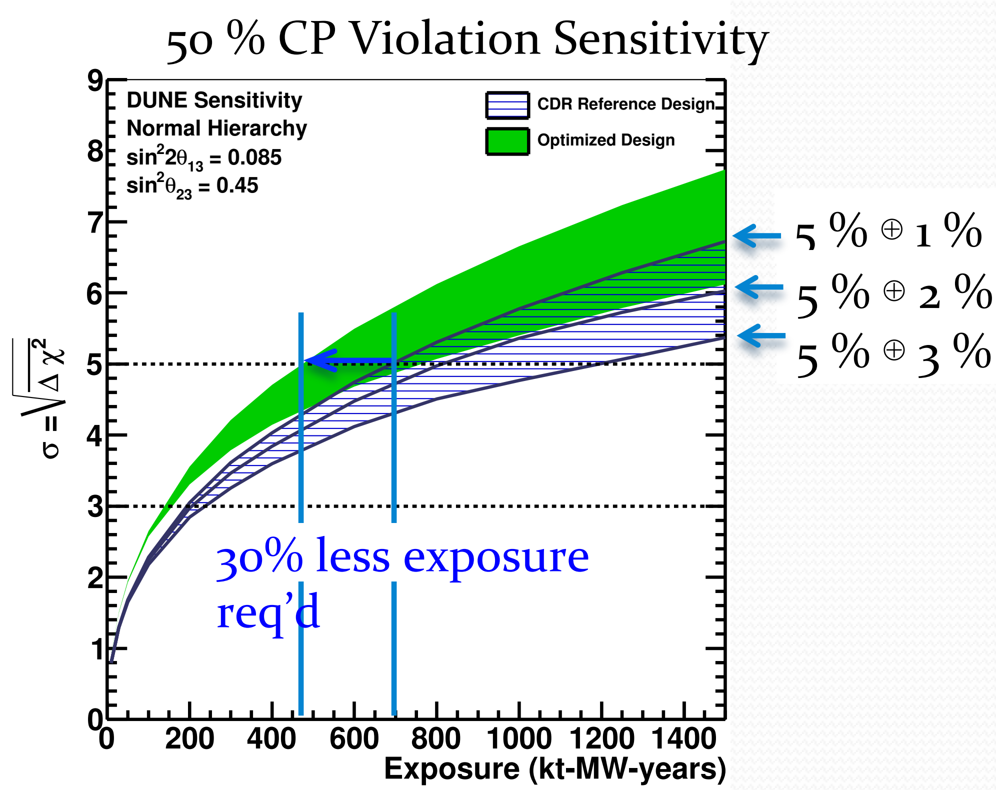
ν_e / $\bar{\nu}_e$ appearance

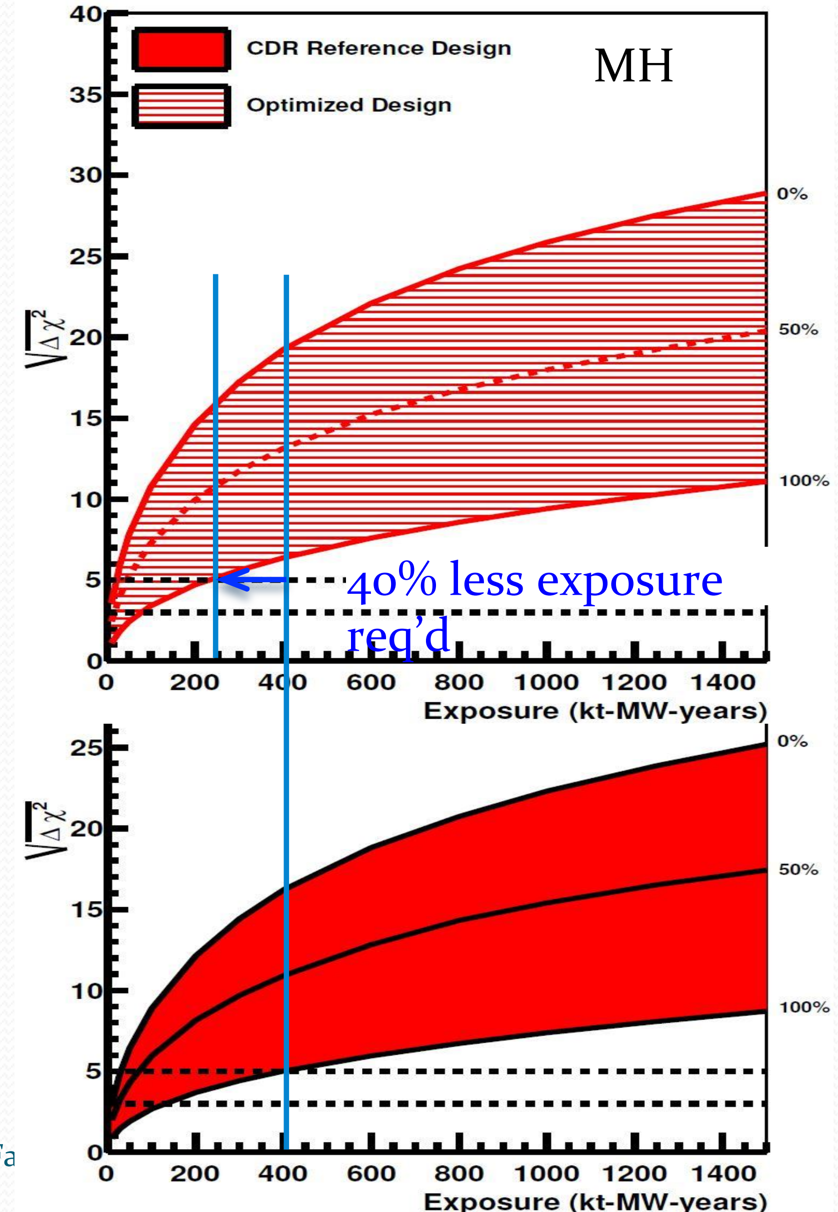
DUNE: normalization uncertainties

- Fit to ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$ powerful
  - Near detector constrains flux
- Estimation of systematics:
  - Oscillation parameters:
    - Constrain from DUNE data
  - Flux:
    - Normalization and shape
  - Cross sections: ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$
  - Nuclear effects:
    - Initial and final state effects
  - Detector response:
    - Energy reconstruction

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

DUNE: CPV and MH sensitivity

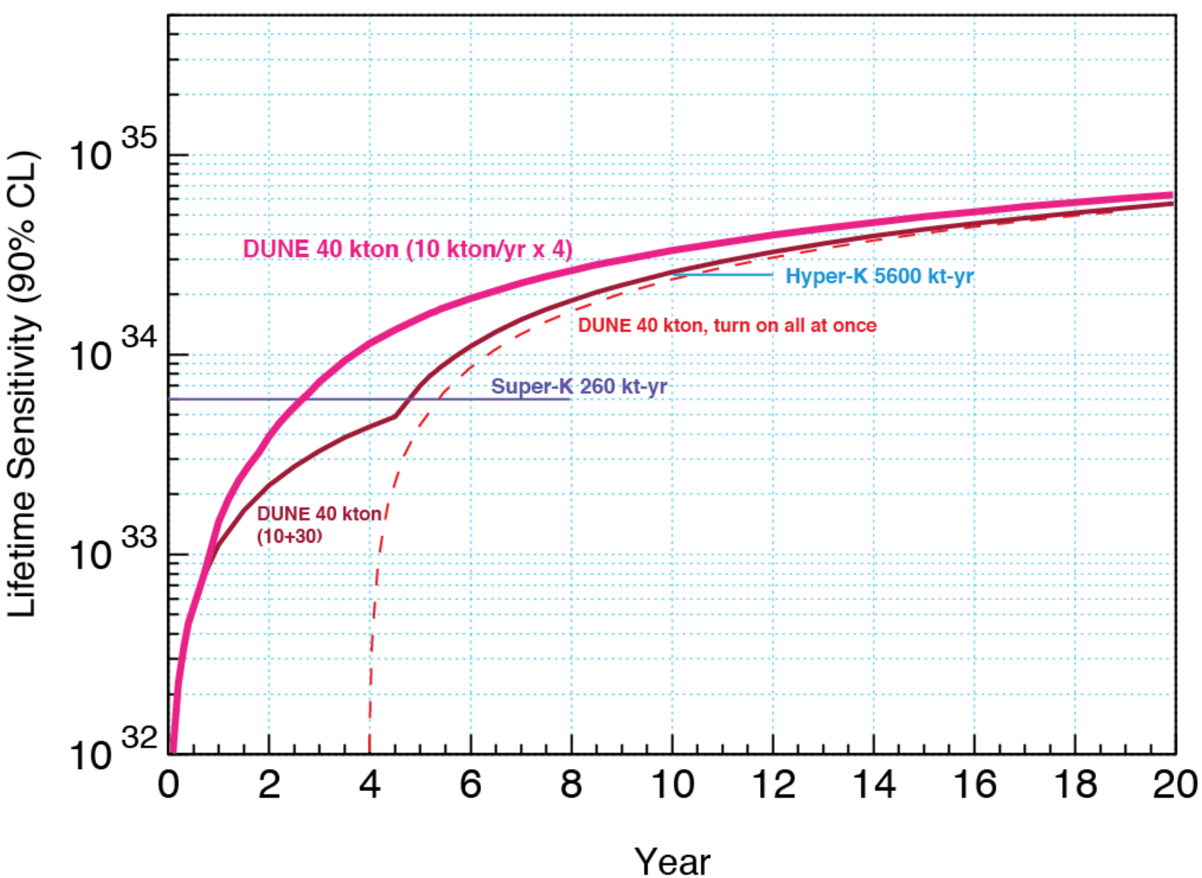




Proton Decay Sensitivity

$p \to K \nu$

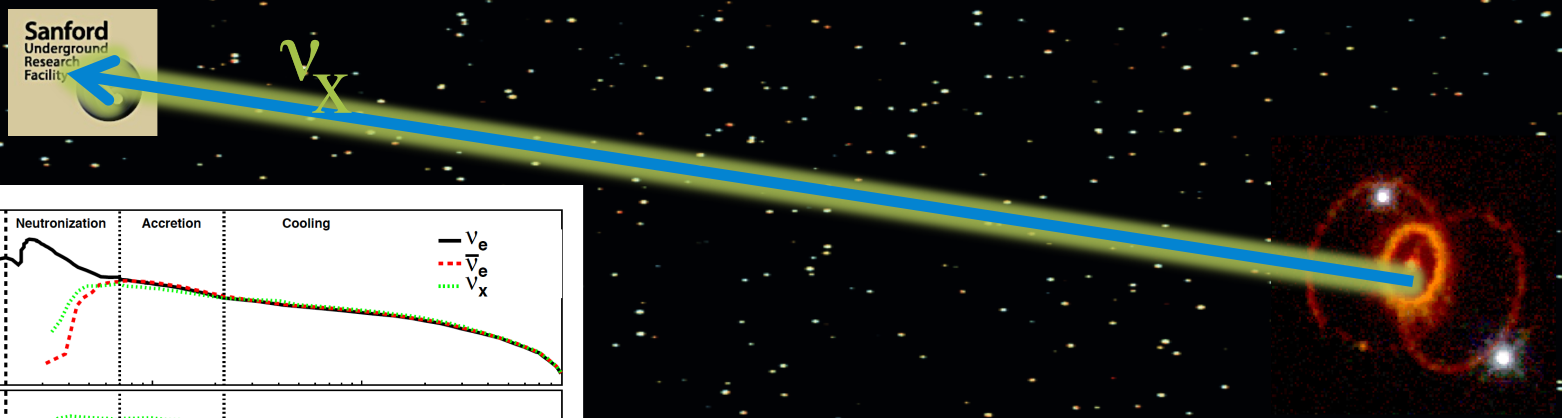
DUNE for various staging assumptions

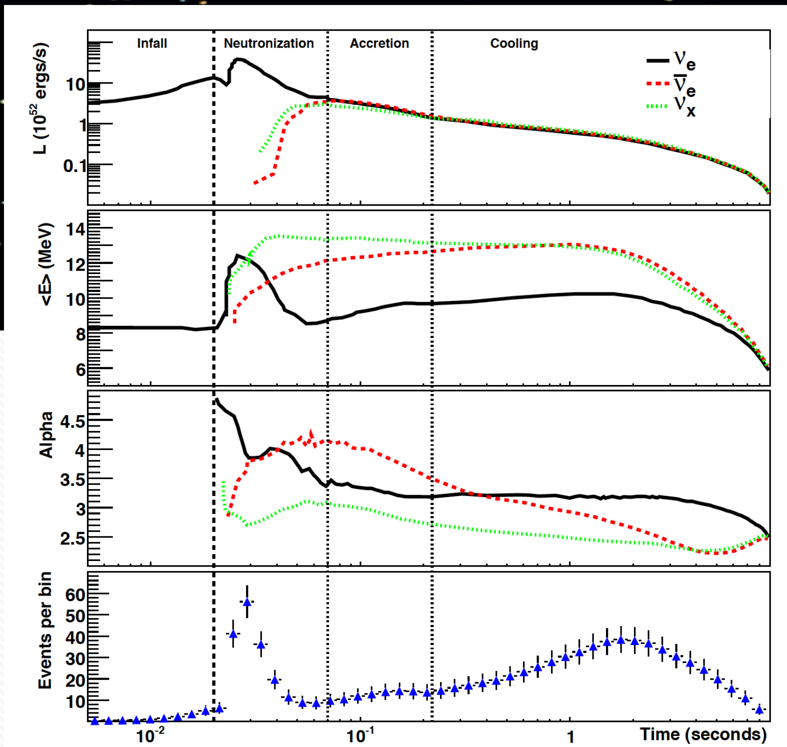


Super-nova neutrino detection

- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos.
- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3500 neutrinos in 40kt DUNE for SN@10 kpc
- Unique sensitivity through

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

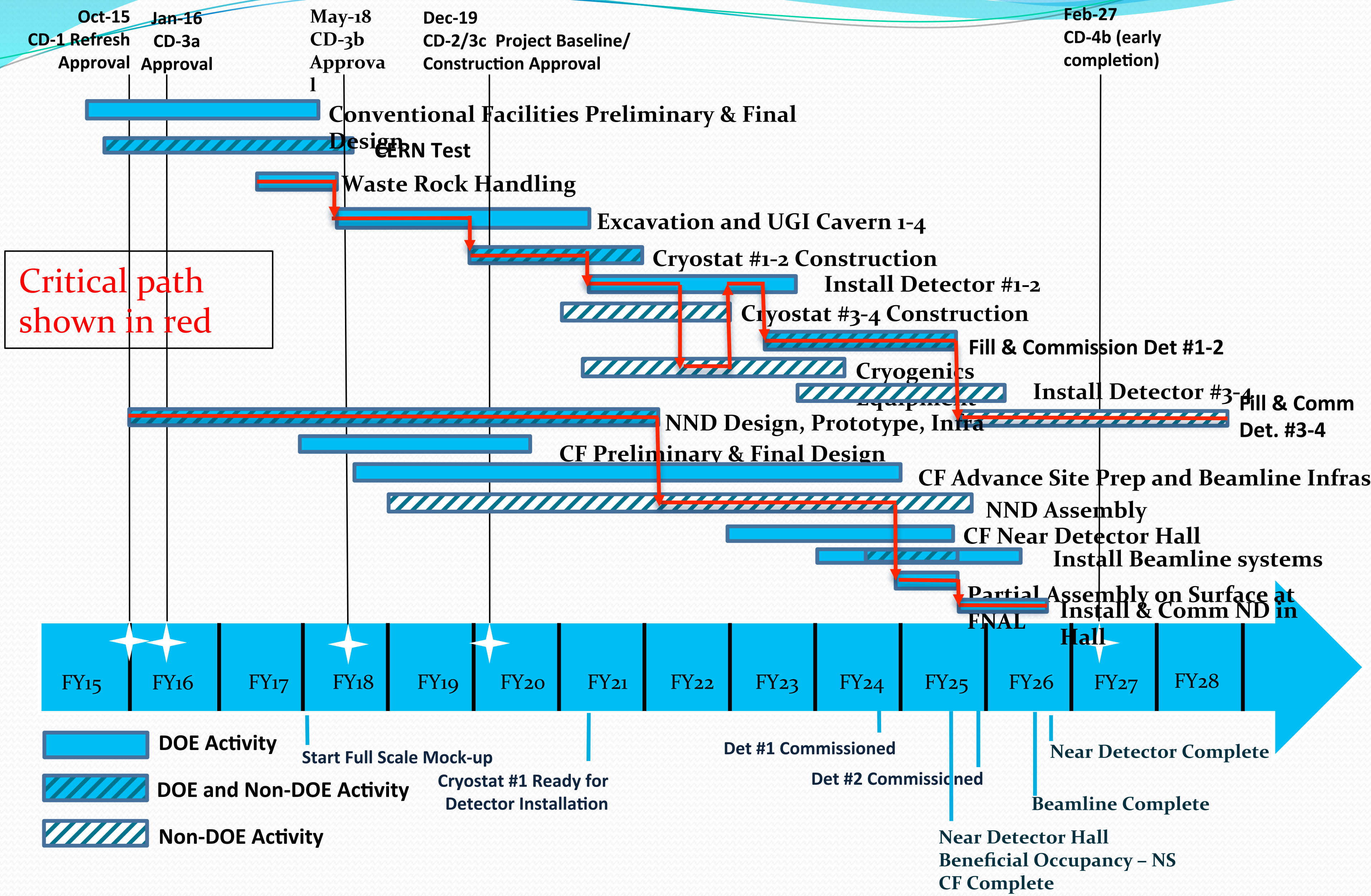




Complex relation between neutrino dynamics in supernovae and detector observables – affected by self-interaction, oscillations and mass.

Major effort underway to understand the model dependences.

LBNF/DUNE Schedule Summary Overview

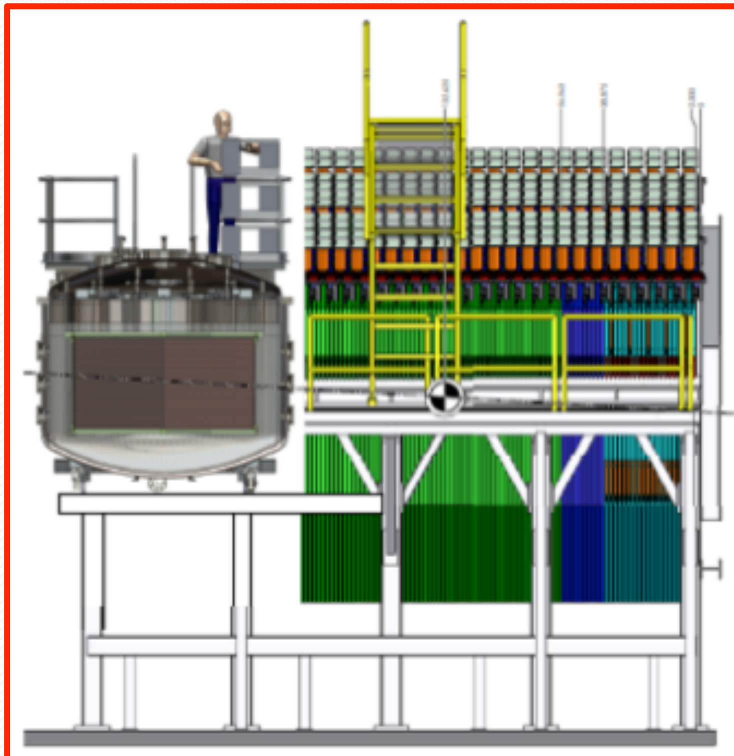


CAPTAIN – MINERVA in NuMI Beam at FNAL

Precisely Measuring Neutrino Interaction Cross-sections

CAPTAIN-MINERVA

- 5 T, LAr TPC in front of MINERvA
  - In NuMI beam: $2 < E < 10$ GeV
  - Powerful magnetic detector
- Measurement program:
  - Cross sections:
    - Cross-section ratio: Ar to C
      - Allows constraint of models
  - Particle Id and event reconstruction
  - 2-year run gives substantial samples
- Gained Stage I approval in 2015
- Start 2017

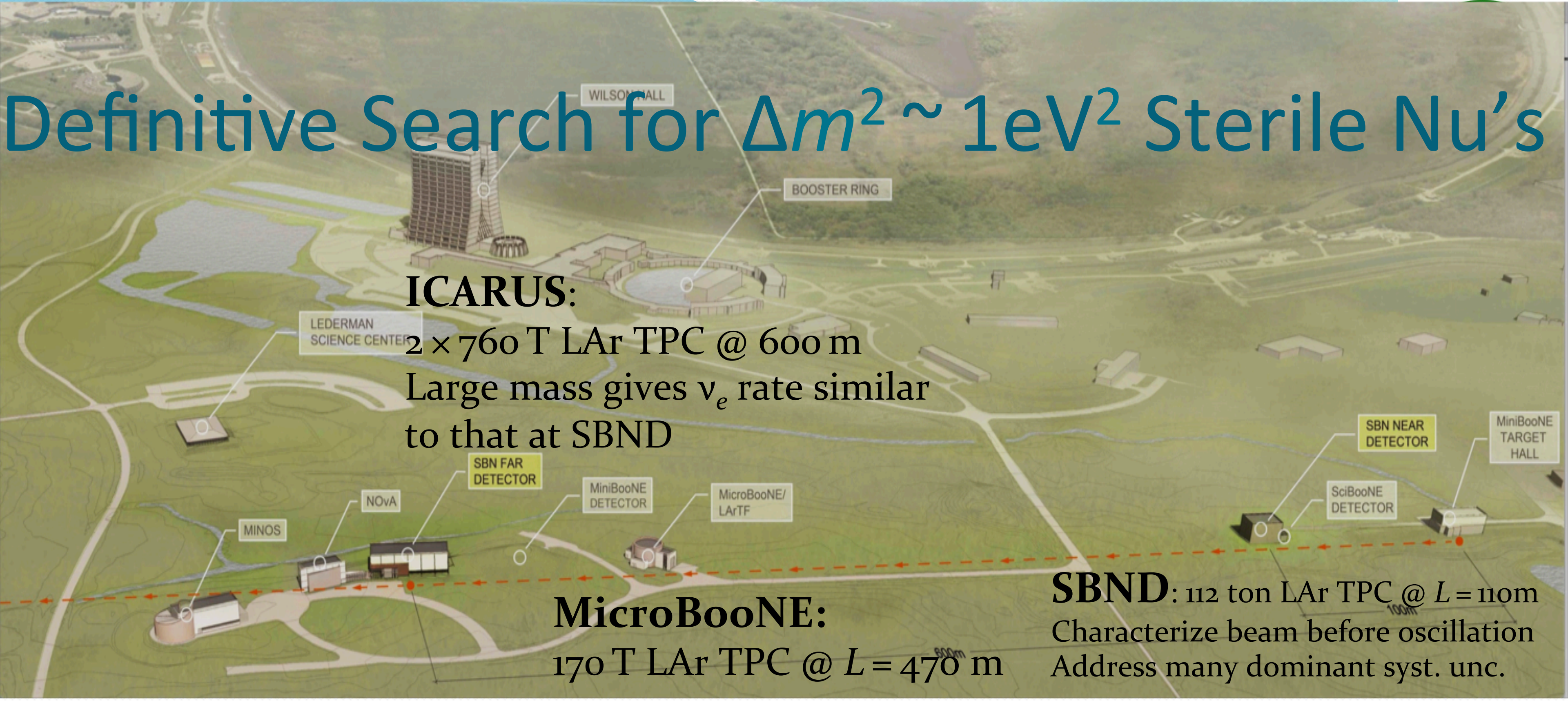


	Events w/ reco μ	Events w/ reco μ and charge
CCQE-like	916k	784k
$CC1\pi^{\pm}$	1953k	966k
$CC1\pi^{0}$	1553k	597k

Short Baseline Neutrino (SBN) program at FNAL

Sterile Neutrino Investigation

Definitive Search for $\Delta m^2 \sim 1\text{eV}^2$ Sterile Nu's

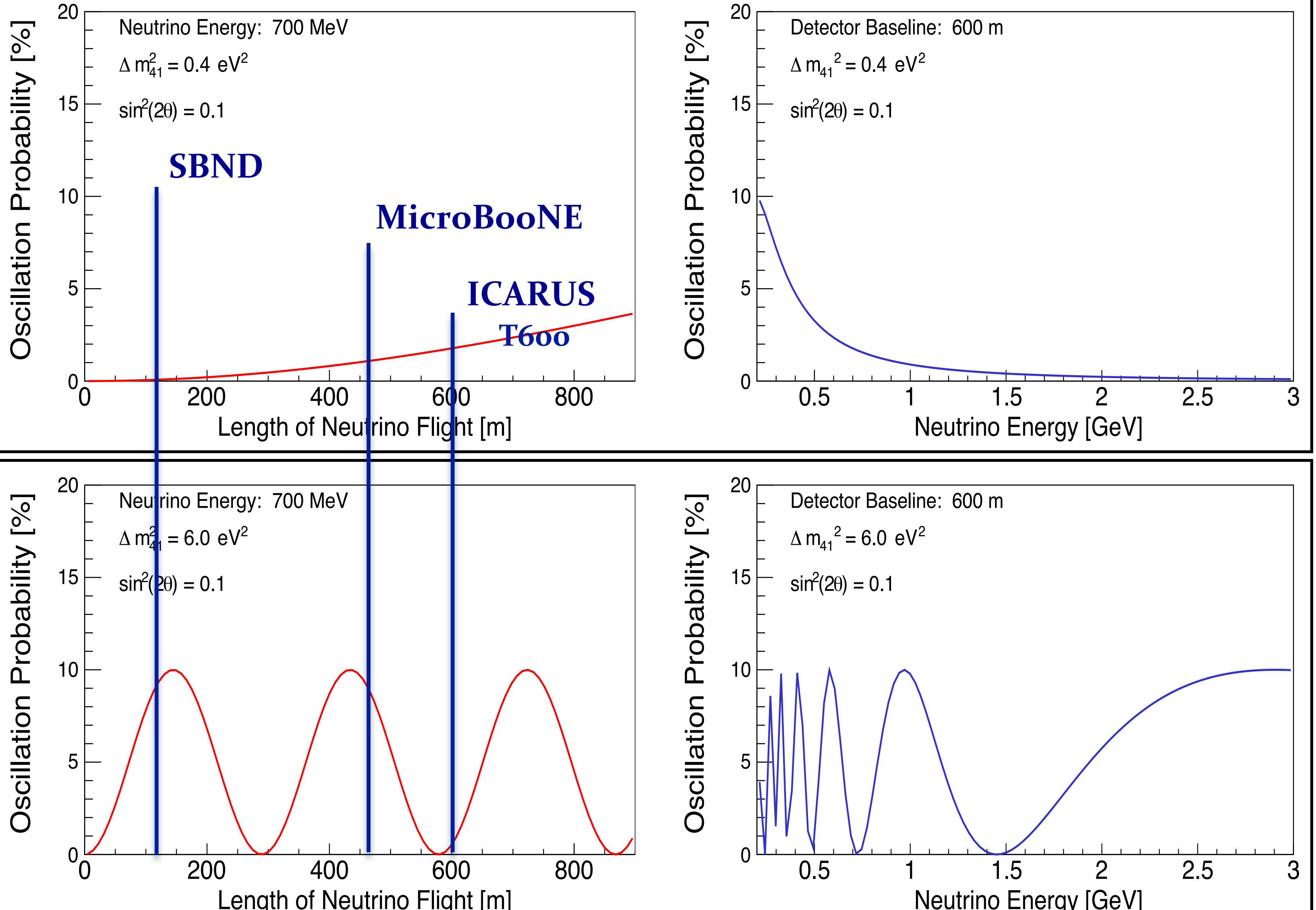


ICARUS:
2×760 T LAr TPC @ 600 m
Large mass gives ν_e rate similar to that at SBND

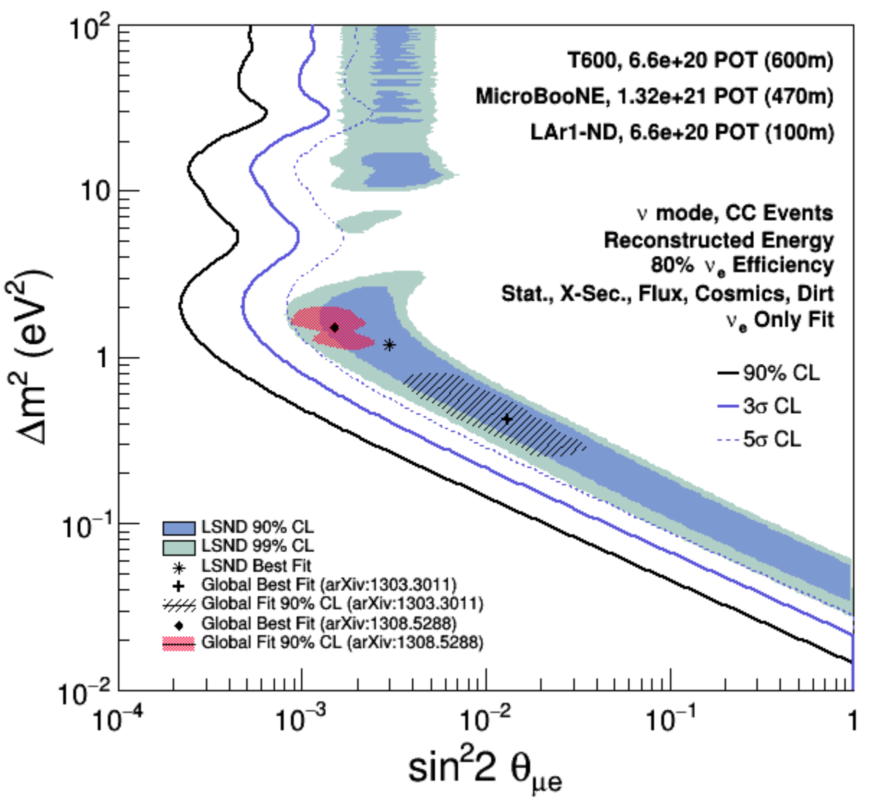
MicroBooNE:
170 T LAr TPC @ $L = 470$ m

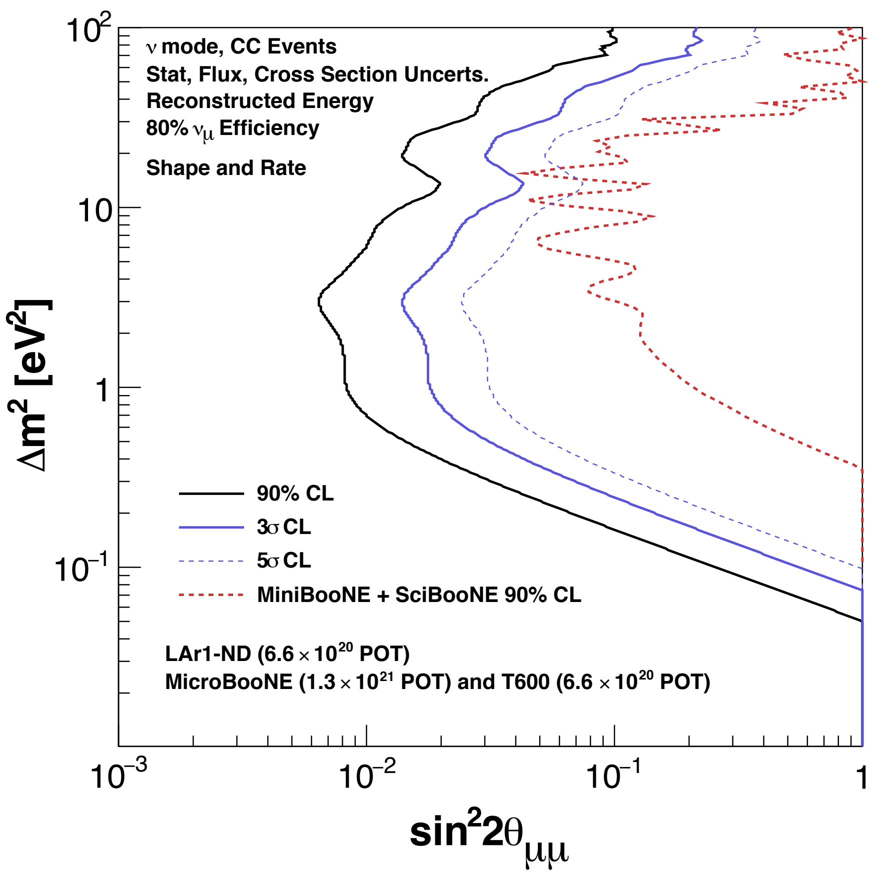
SBND: 112 ton LAr TPC @ $L = 110$m
Characterize beam before oscillation
Address many dominant syst. unc.

- Exploit *L*, *E* and *L*/*E* modulation; detectors at three baselines
- Appearance, $\nu_\mu \rightarrow \nu_e$, *and*, disappearance, $\nu_e \rightarrow \nu_X$
  - Exploit 3 LAr detectors; minimise inter-detector systematics
- Robustly address backgrounds and uncertainties:
  - ν_e contamination in FNAL Booster Neutrino Beam,...


Neutrino Energy: 700 MeV
$\Delta m^2_{41} = 0.4\ eV^2$
$sin^2(2\theta) = 0.1$
SBND
MicroBooNE
ICARUS
T600
Oscillation Probability [%]
Length of Neutrino Flight [m]
Detector Baseline: 600 m
$\Delta m_{41}{}^2 = 0.4\ eV^2$
$sin^2(2\theta) = 0.1$
Neutrino Energy [GeV]
Neutrino Energy: 700 MeV
$\Delta m^2_{41} = 6.0\ eV^2$
$sin^2(2\theta) = 0.1$
Oscillation Probability [%]
Length of Neutrino Flight [m]
Detector Baseline: 600 m
$\Delta m_{41}{}^2 = 6.0\ eV^2$
$sin^2(2\theta) = 0.1$
Neutrino Energy [GeV]

SBN sensitivity



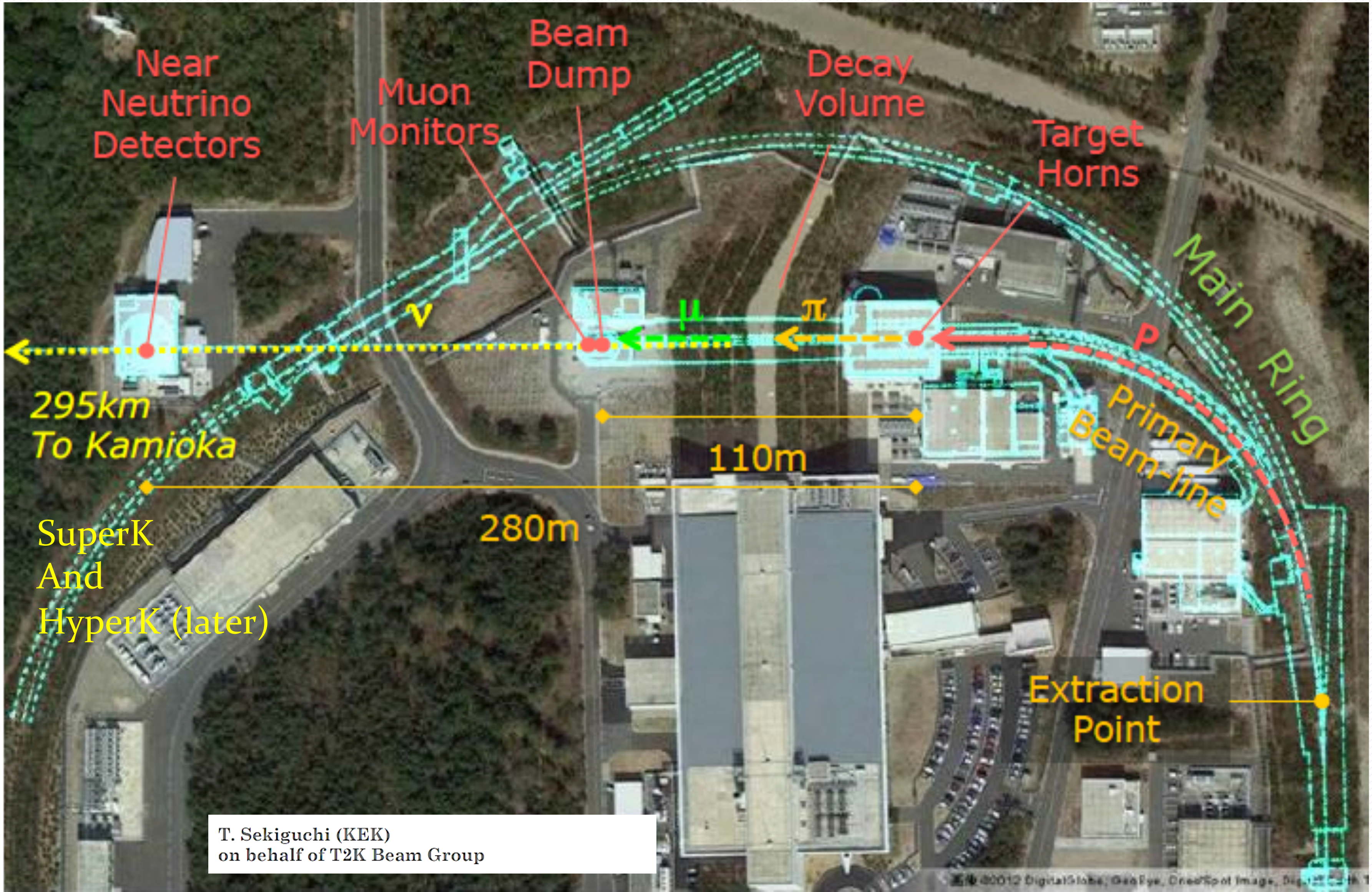


- Region of interest can be addressed at 5σ
- Run start in 2018

Physics at Japan Proton Accelerator Research Complex J-PARC with HyperK and T2K-extended

Completing the three neutrino standard model

J-PARC for T2K and HyperK



Tokai to Hyper-Kamiokande

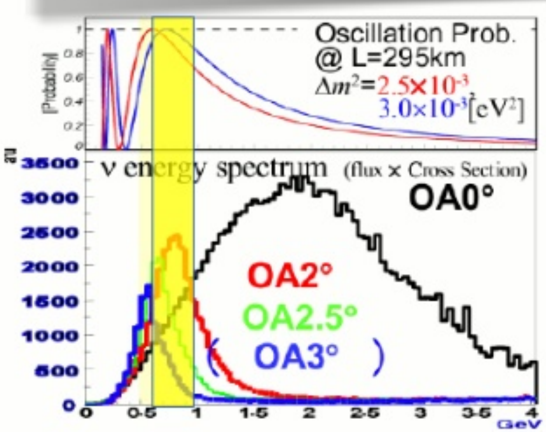
F. Di Lodovico,
Future Nu in J WS

Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power 750kW, 2.5° off-axis angle.

Same strategy as for T2K

T. Sekiguchi (KEK)
on behalf of T2K Beam Group

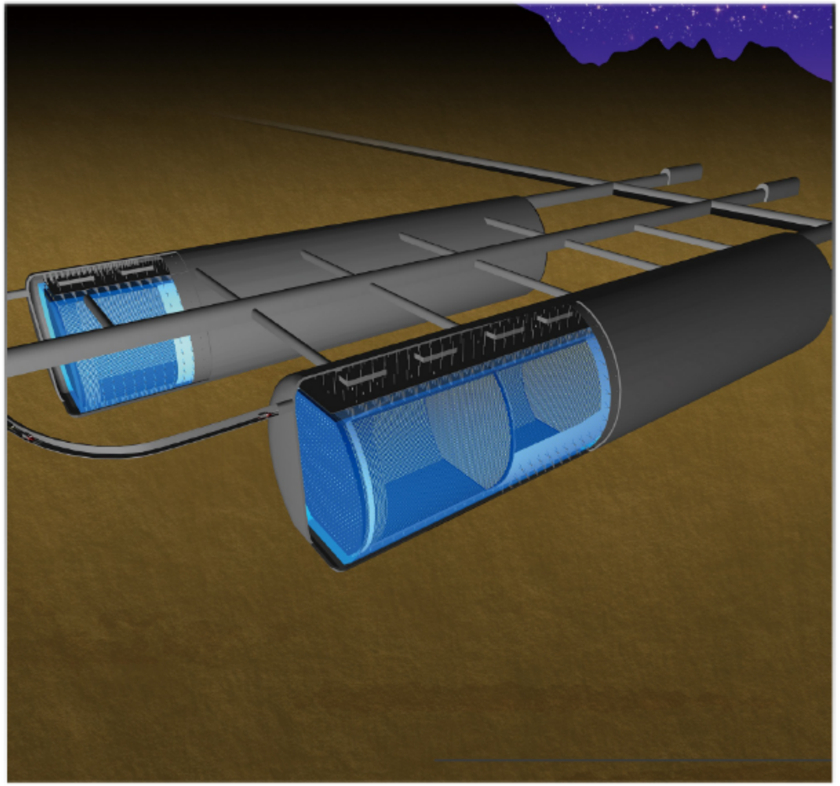
Near Detectors



- Narrow-band beam at ~600MeV at 2.5° off-axis
- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pure ν_μ beam with ~1% ν_e contamination

Hyper-Kamiokande

- Next-generation gigantic multi-purpose detector
  - Water Cherenkov technology
  - 560kt fiducial mass
  - 20% photo-coverage with 99k 20-inch PMTs
- Physics
  - Neutrino oscillation
    - Accelerator based LBL
    - Atmospheric nu
    - Solar nu
    - ..
  - Proton decay
  - Astrophysics neutrinos
    - Supernova, SRN, dark matter, etc

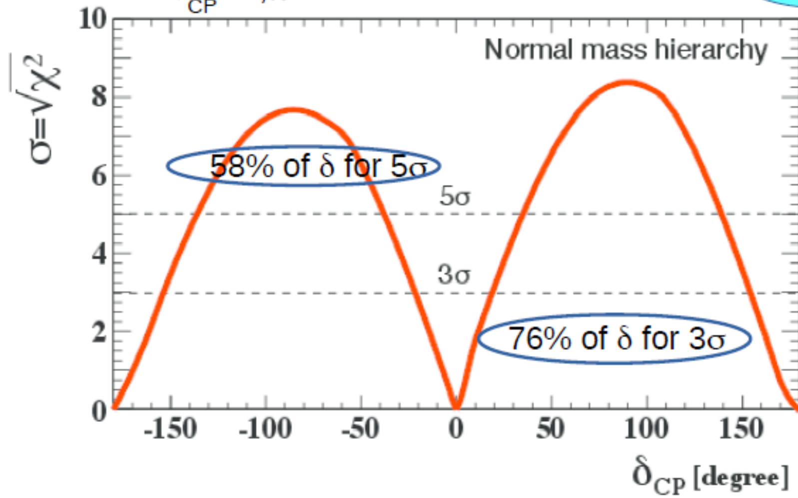


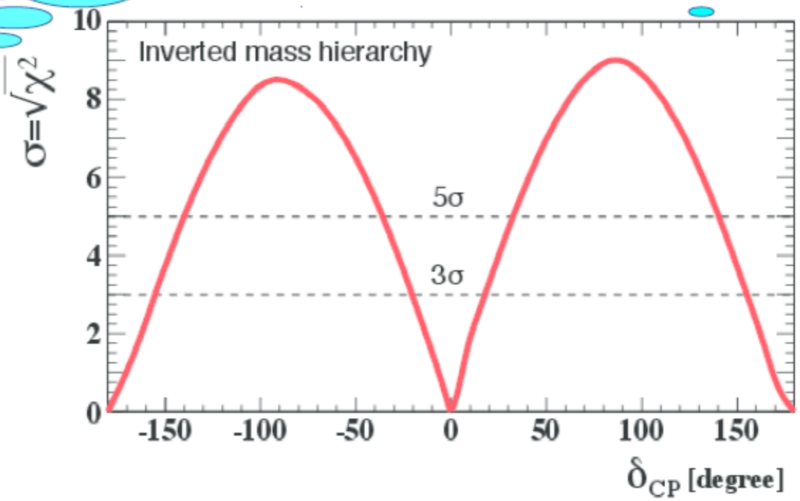
Hyper-K Sensitivity to δ_{CP}

Will improved with updated errors

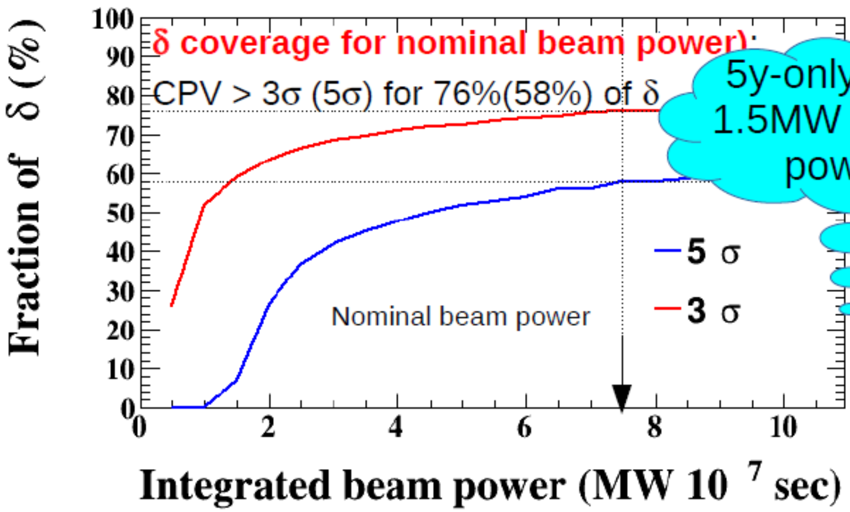
Assume MH is known

CPV discovery sensitivity
to $\delta_{CP}=0,\pi$ w/ MH known



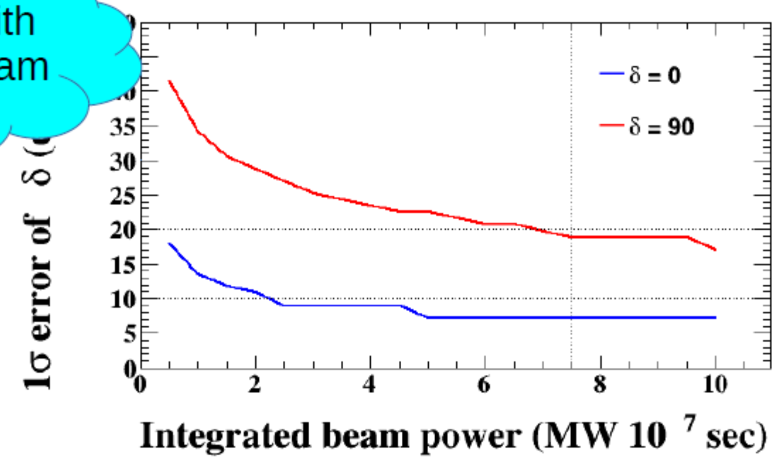


Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ



5y-only with 1.5MW beam power

1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)



Beamline

J-PARC High Intensity Neutrino Beam

T. Sekiguchi (KEK)
on behalf of T2K Beam Group

Design Philosophy of Neutrino Beamline

- **Tolerance for high power beam**
  - All beamline components designed for 750 kW beam
  - Equipments that cannot be replaceable after irradiation are designed for 3 or 4 MW beam.
- **Remote maintenance**
  - Secondary beamline equipments are highly irradiated with more than 1 Sv/h.
  - Beamline components inside Target Station can be replaceable remotely.

10 Year Term Plan of Beam Power Improvement

- **Design beam power = 750 kW**
  - Will be achieved in 2018
  - Beam power over 750 kW is recently being considered.
- **Aim for 1.3 MW beam by 2026**
  - Proton intensity = **3.2×10^{14} protons/pulse**.
  - Repetition cycle = **1.16 sec.** with new MR power supplies.
- **Can our beamline accommodate to 1.3 MW beam?**

Beam Power	# of protons/pulse	Rep. rate
350 kW (achieved)	1.8×10^{14}	2.48 sec
750 kW (proposed) [original plan]	2.0×10^{14} [3.3×10^{14}]	1.30 sec. [2.10 sec.]
1.3 MW (proposed)	3.2×10^{14}	1.16 sec.

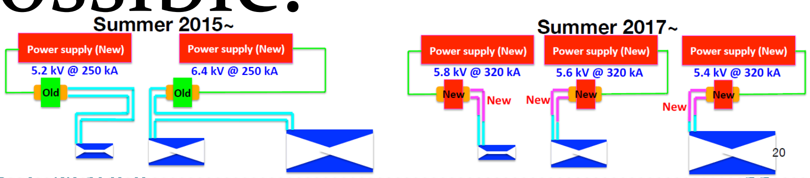
Yes, it is possible.

Prospect for Hardware Upgrade

- **Cooling capacity**
  - Apparatuses themselves can withstand 1.3 MW beam.
  - Improvement of flow rate both for water and helium circulations is needed.
    - Replacement with larger pumps
    - Replacement with larger-size plumbing
    - ⇒ These will be feasible but need 1 year for modification.
- **Radiation**
  - Radioactive air
    - Reinforcement of air-tightness ⇒ 1.3 MW can be manageable.
  - Radioactive water disposal
    - Enlargement of dilution tank
      - Modification of existing tank ⇒ ~1.3MW
      - New facility building for water disposal ⇒ 2MW
        - 2 years for construction (no beam stop needed)

Horn Operation Improvement

- **Operation status**
  - 250 kA operation for physics data taking since 2010.
    - Mainly due to refurbishment of old K2K PS (rated 250 kA).
  - Currently, operated with 2.48 s cycle.
    - 1.3 s for 750 kW (not operated with the existing PS)
- **3 PS configuration for 320 kA and 1 Hz operation**
  - New power supply developed (2 PS's already produced).
  - Also, low impedance striplines newly developed.
- **Timeline**
  - Production of the last PS, transformers, part of striplines
  - Aim to start 320 kA operation from summer 2017.



In the Meantime – T2K extended

T2K - Extended

- Neutrino community initiated work to propose "extended T2K"

- Interconnect "desert" between T2K/NOVA and DUNE/HK era

- Make full use of present existing facilities with modest upgrades
  J-PARC MR upgrade → possibility up to ~1.3MW operation
~$2e^{22}$ pot by around 2026 before HK/DUNE start operating

- Another ~50% increase of effective statistics by
  1) Horn current 250kA → 320kA
  2) analysis improvements

GOALS for T2K extended:

- Extract best possible/most precise physics outputs
- Provide learning ground for next generation experiment
- Realize >1 MW high power stable beam operation (acc/beamline)
- Systematic errors down to a few %

T. Sekiguchi (KEK)
on behalf of T2K Beam Group

Compact Cyclotrons for Precision Neutrino Measurements

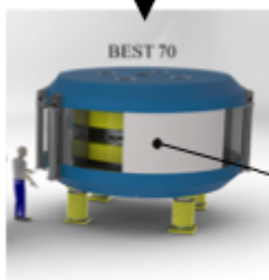
Bringing accelerators to detectors

DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System

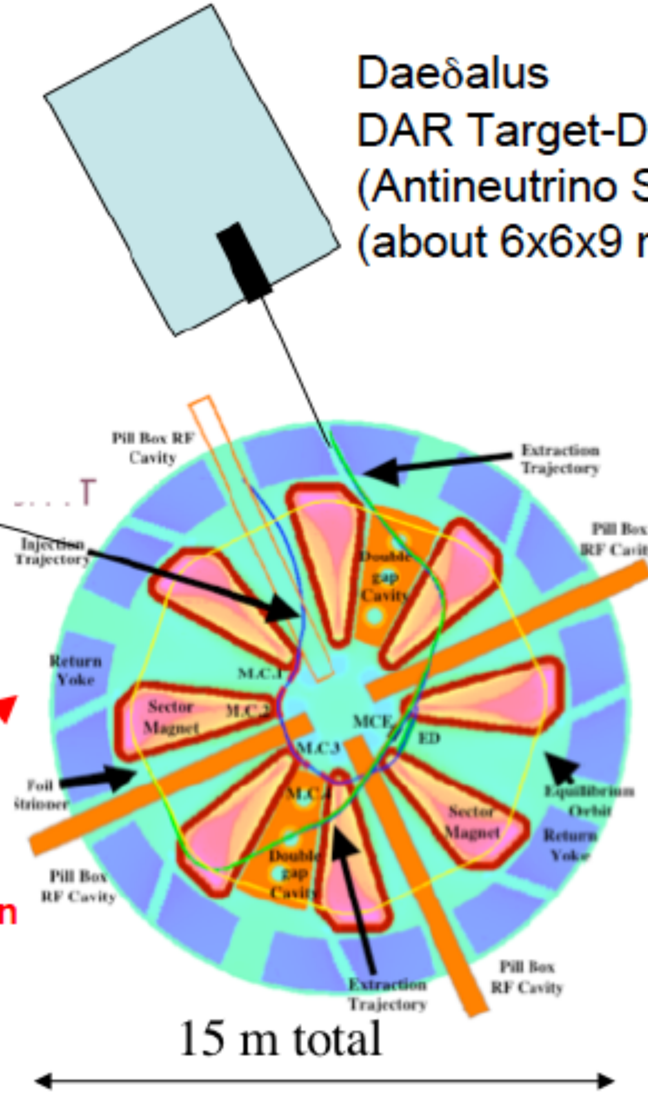
H_2^+ Ion Source

IsoDAR 60 MeV Cyclotron

Injector Cyclotron (Resistive)



Daeδalus DAR Target-Dump (Antineutrino Source) (about 6x6x9 m^3)

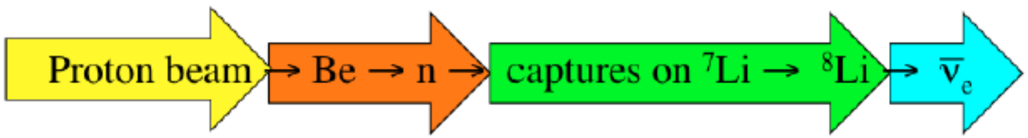


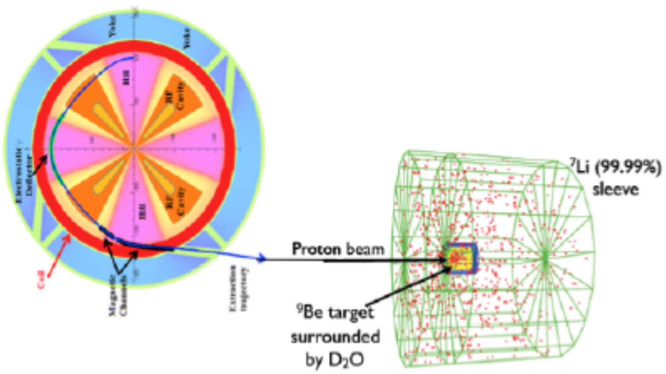
800 MeV Ring Cyclotron (Superconducting)

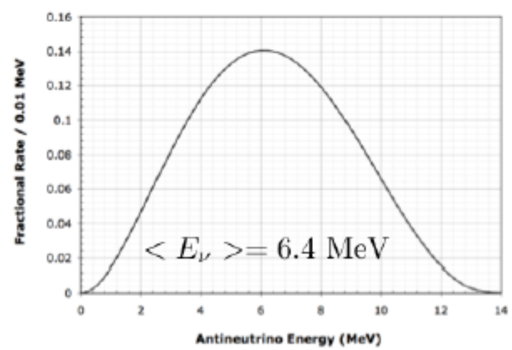
Multimegawat Daeδalus Cyclotron for Neutrino Physics

arXiv:1207.4895

IsoDAR – very short baseline search for sterile neutrinos



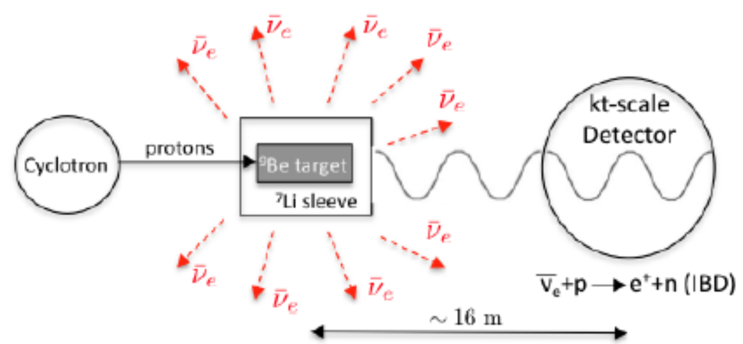




5 mA H_2^+ @ 60 MeV/n
(600 kW proton beam)

$^8\text{Li} \rightarrow ^8\text{Be} + e^- + \bar{\nu}_e$

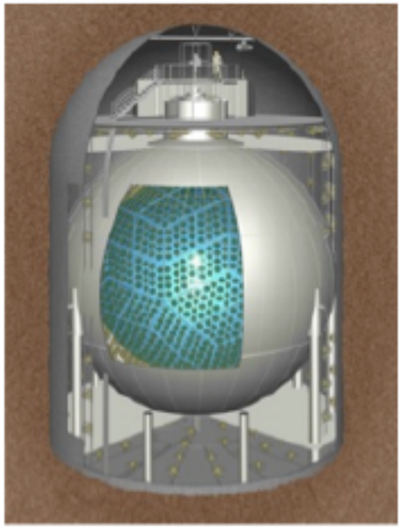
Produces 1.29×10^{23} $\bar{\nu}_e$ in
5 years (with 90% duty factor)



Where Can IsoDAR Run?

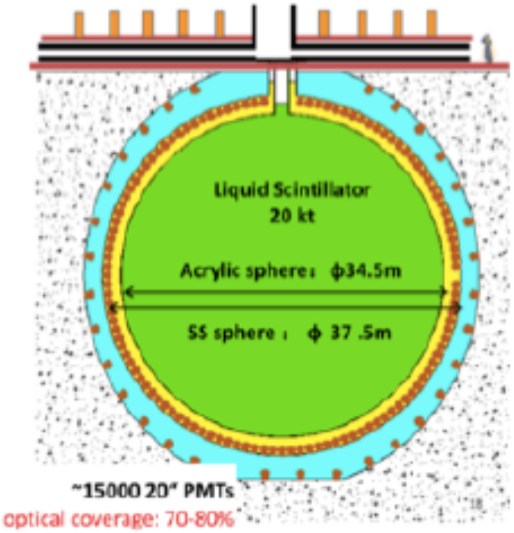
LENA

KamLAND

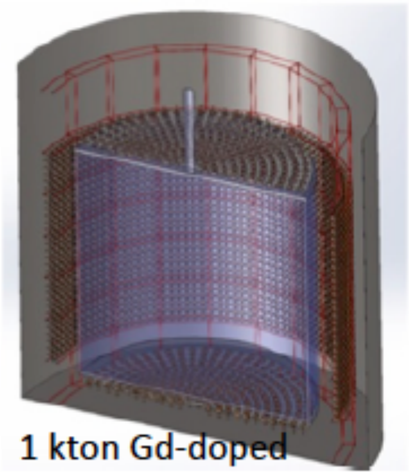


1 kton liquid scintillator

JUNO

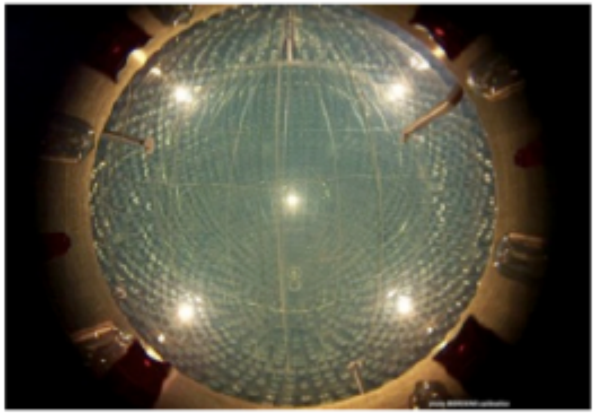


WATCHMAN

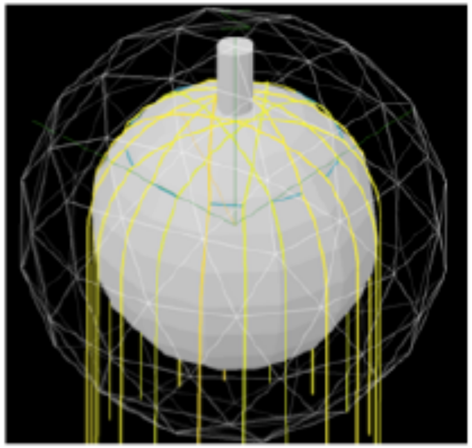


1 kton Gd-doped
water Cerenkov

Borexino

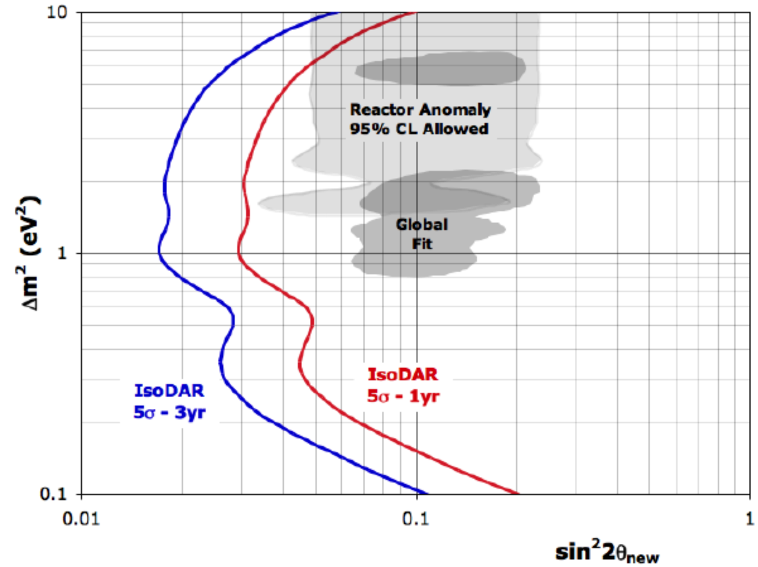


SNO+



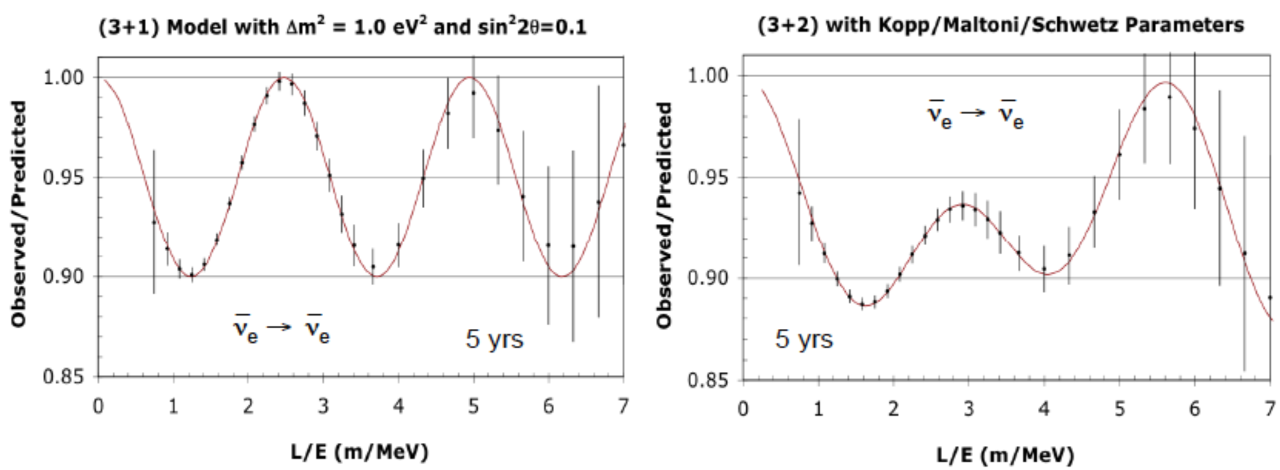
M. Shaevitz

IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



⇒ Global fit region can be ruled out at > 5σ in 4 months of running!

Observed/Predicted event ratio vs L/E including energy and position smearing



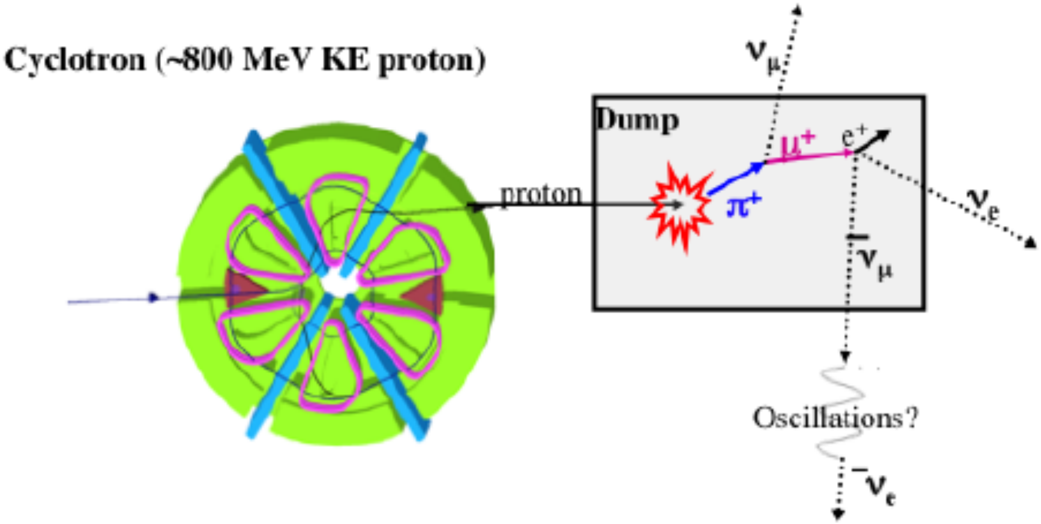
IsoDAR's high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models

M. Shaevitz

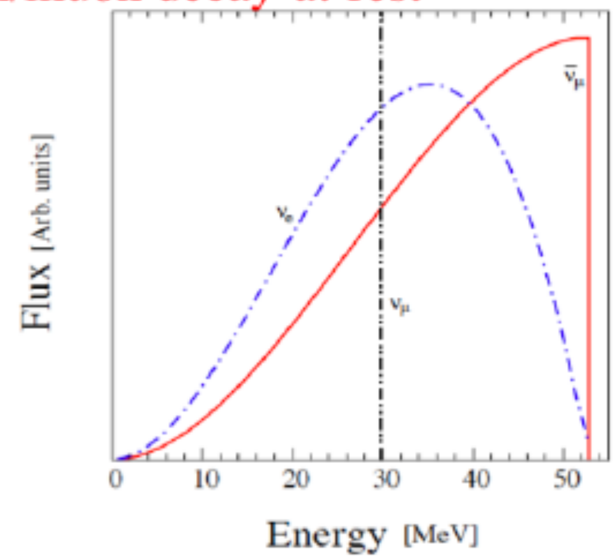
Daeδalus Setup:

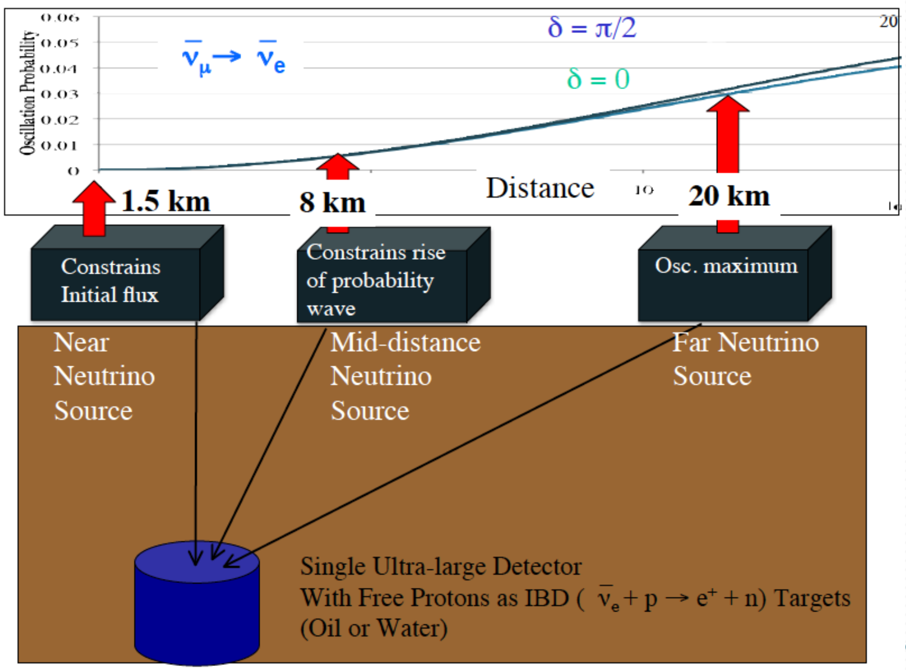
A new way to **search for CP violation** in the ν-sector

J.M Conrad and M. H. Shaevitz, PRL 104, 141802 (2010)

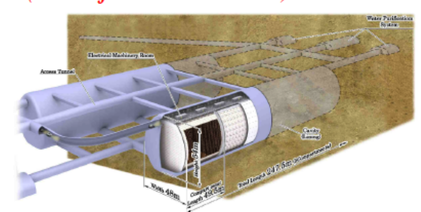


Pion/muon decay-at-rest

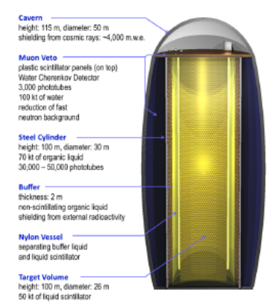


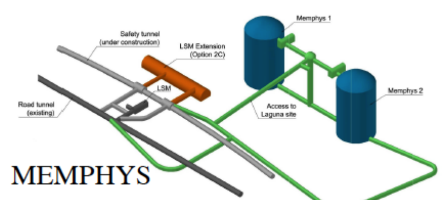


Hyper-K (or initially, Super-K)
(Focus for current studies)



LENA - Scintillator Dectector

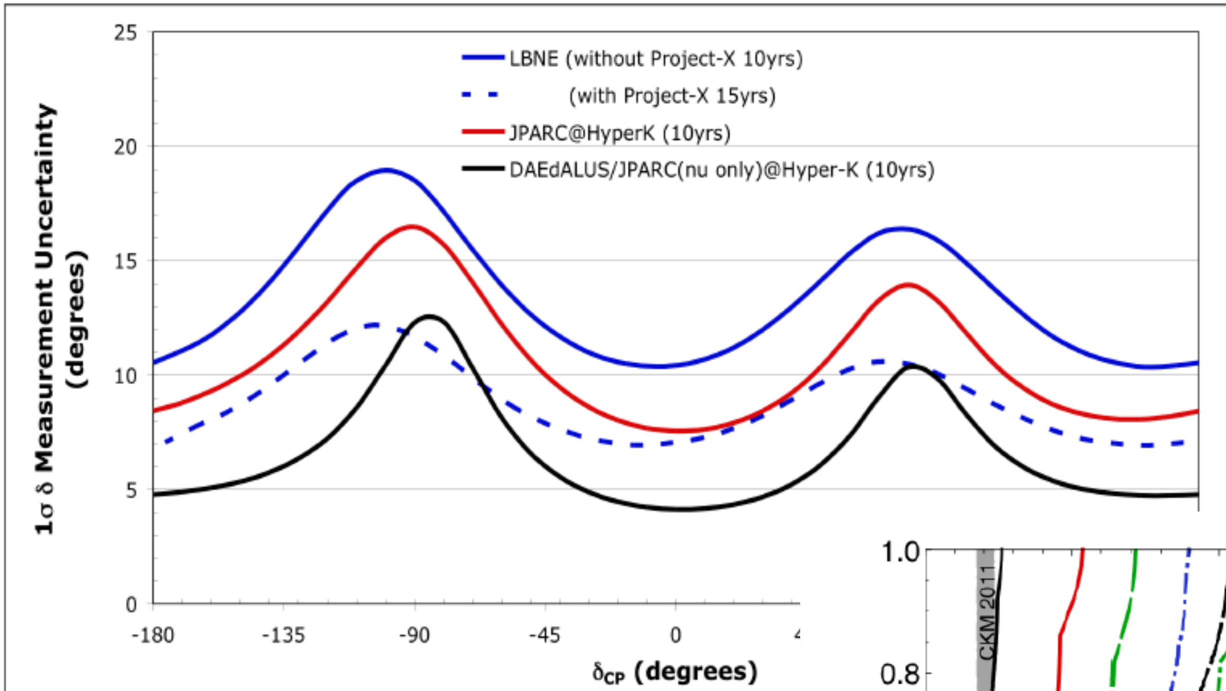


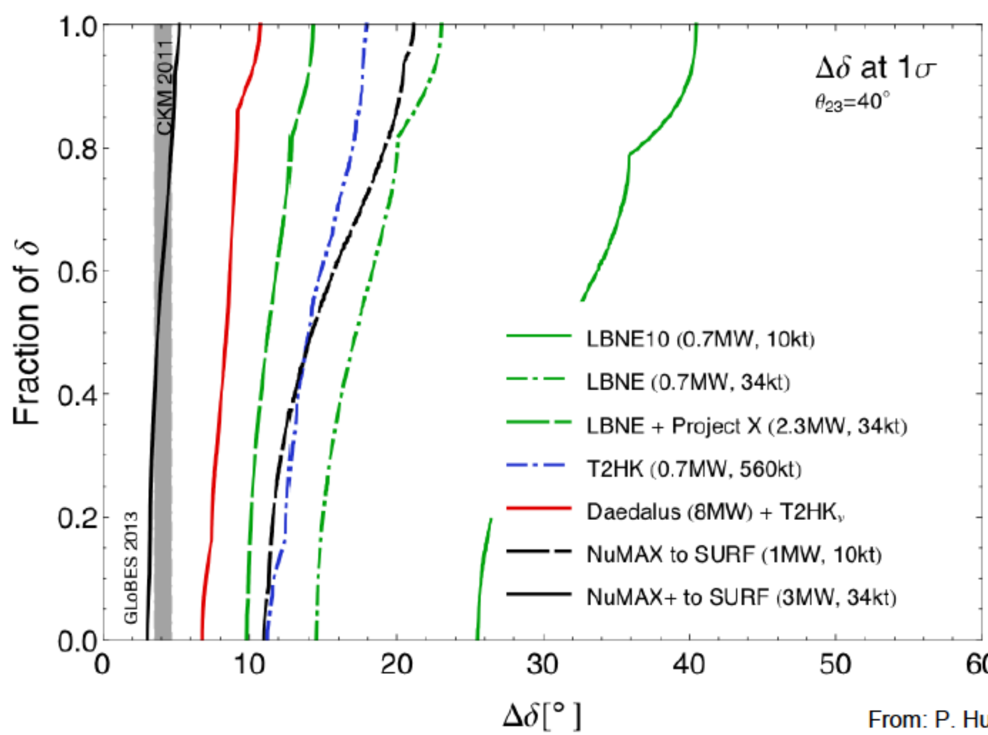


MEMPHYS

Detector needs to have free protons to capture neutrons from IBD ⇒ liquid argon is not an option

δ_{CP} Sensitivity Compared to Others



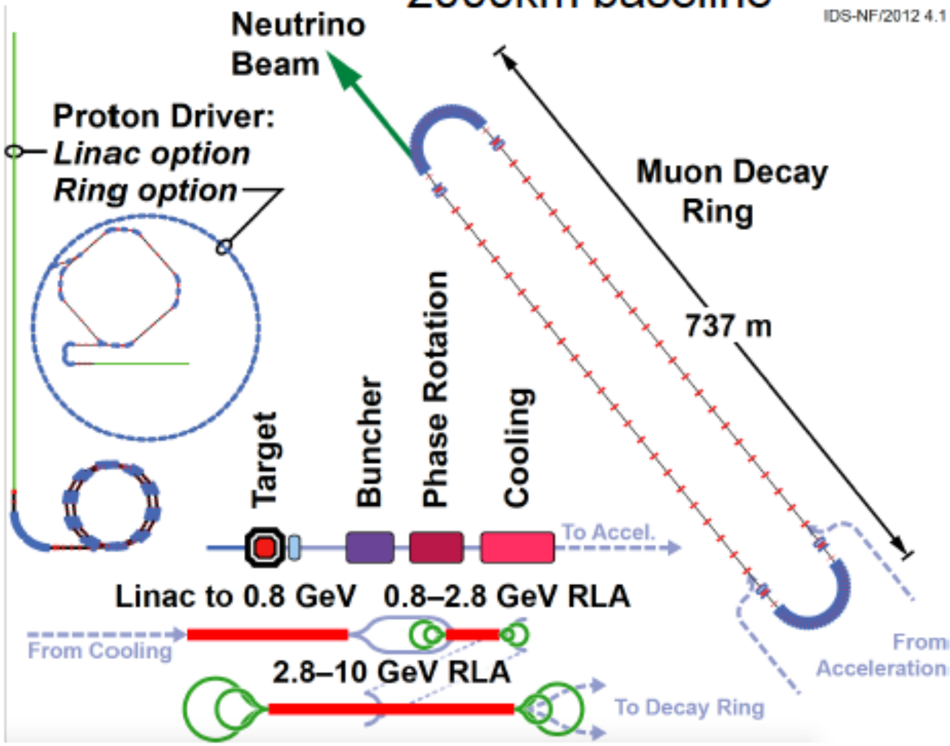


From: P. Huber
Globes 2013

Neutrino Factory Power: precision measurement of CPV phase and non-leading order effects

NuMAX - Neutrino Factory+, MOMENT

Neutrino Factory
IDS-NF



This is green-field design
Site specific: NuMAX @ Fermilab

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \; \nu_e$$
$$\mu^- \rightarrow e^- \nu_\mu \; \bar{\nu}_e$$

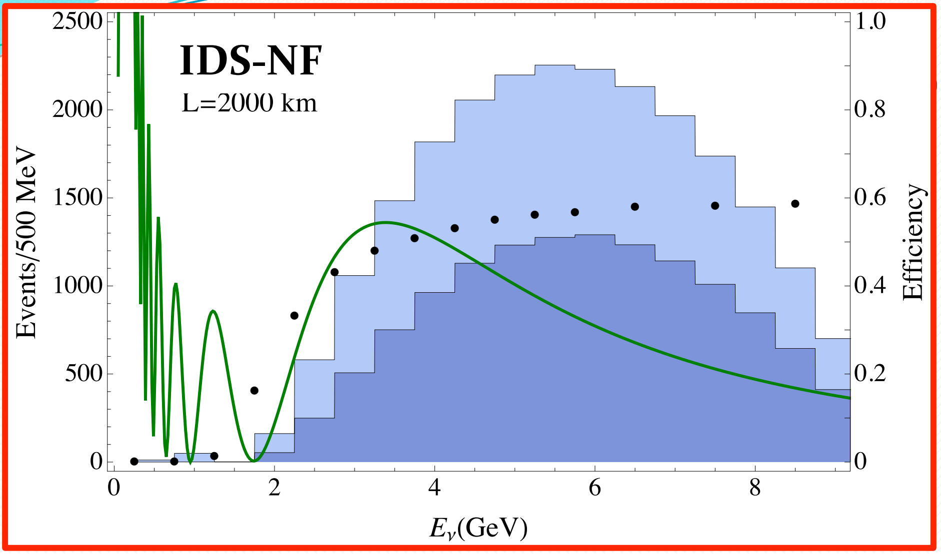
- Precisely known flux & composition
  - ν flux derived from instrumentation in D.R.
  - Many factors driving uncertainties in conventional ν beams, no longer relevant
    - Secondary particle production
      - Particle types, flux and energy distribution
    - Proton beam targeting stability
    - Target/horn stability
- Flux not dependent on desired ν energy
  - Small losses due to acceleration
  - Impossible now or ever with conventional ν beam
- Interestingly, NF can now be considered "technology-ready"
  - MERIT, MuCool, MICE, EMMA

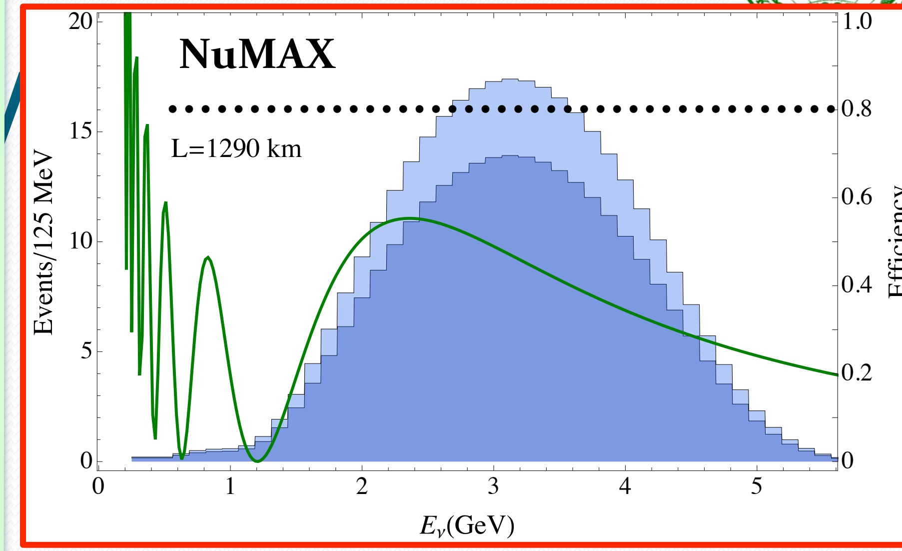
Oscillation channels at the NF

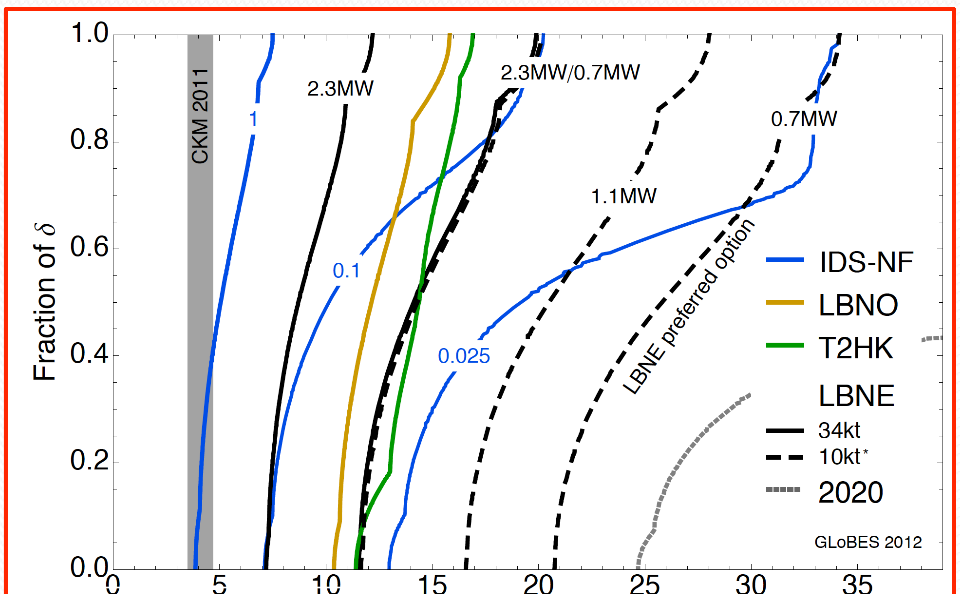
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

12 channels accessible
if E_ν is above the τ threshold

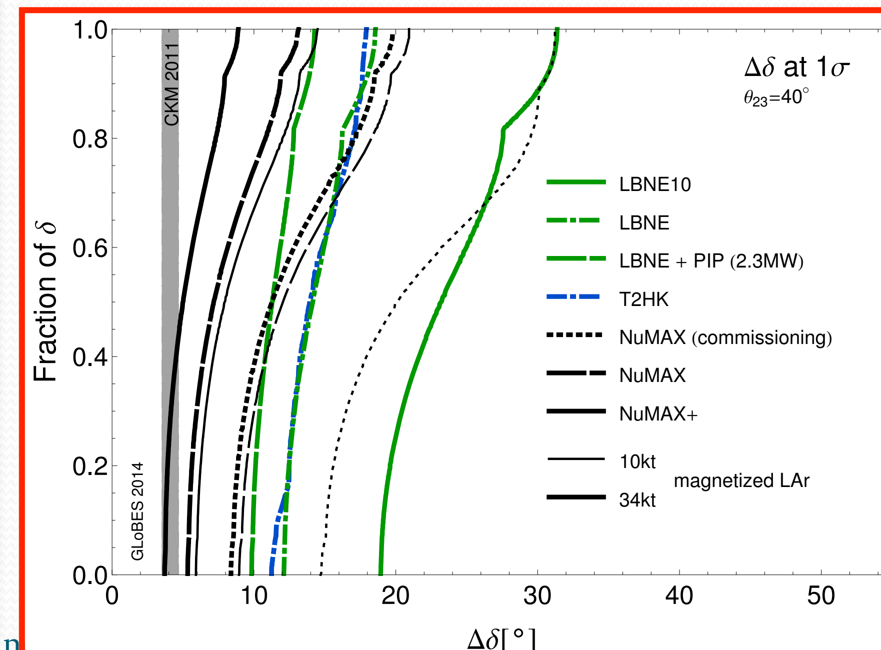
Precision on Delta Phase





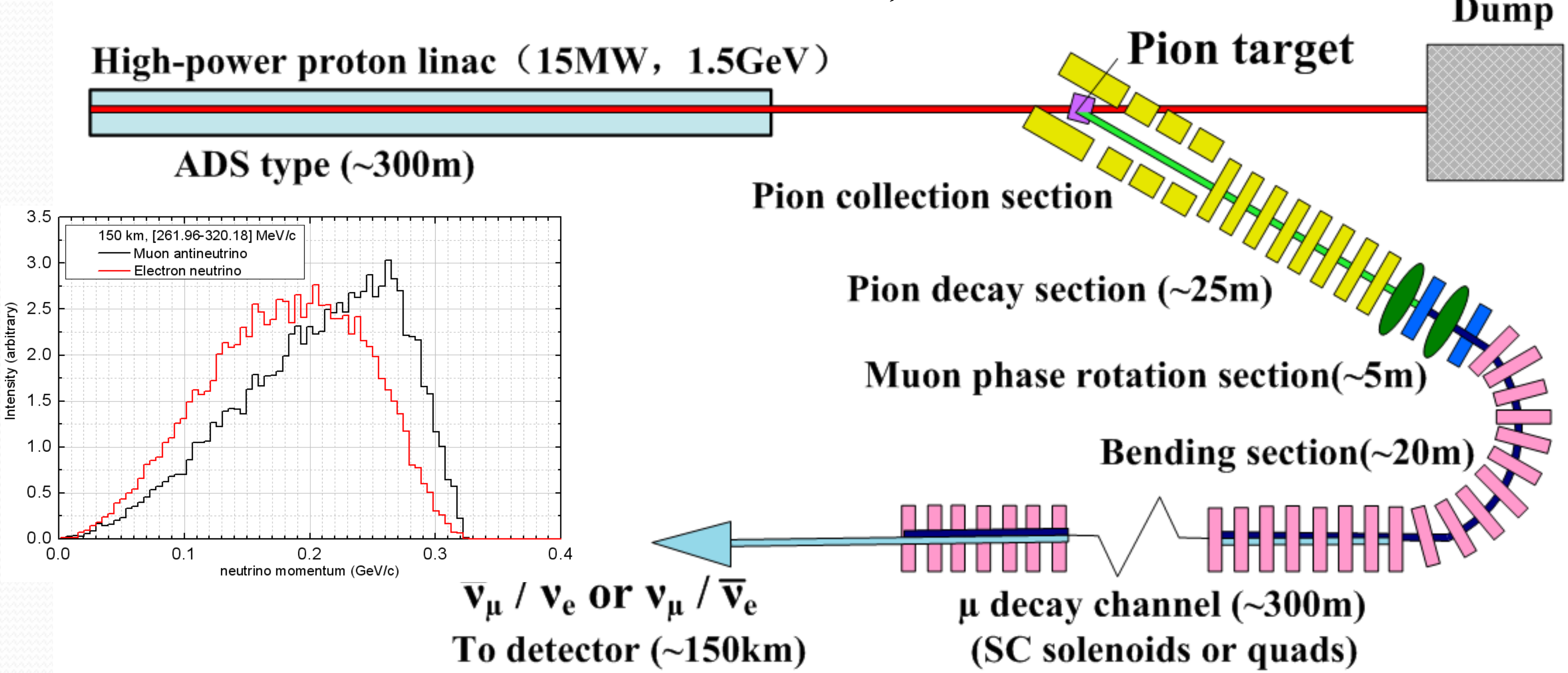


Coloma, Huber, Kopp, Winter
arXiv:1209.5973



MOMENT: A New Idea on ν Beam

Jingyu TANG and several talks in NuFact15,
Jun Cao



- Neutrinos from muon decay
- Proton LINAC for ADS ~15 MW
- Energy: 300 MeV/150 km
- Phys. Rev. STAB **17**, 090101 (2014)

Neutrinos after the target/ collection/decay similar to NuFact: ~ 10^{21} ν/year

Summary

- Future of the neutrino physics looks bright thanks to excellent progress of future neutrino facilities
- Measurement of CPV, MH, sterile neutrino searches, astrophysical nu's, precision oscillation physics and NSI are finally within reach
- Well defined, viable **plans and funding** in place toward MW beams at LBNF and J-PARC by 2026 toward exciting measurements to complete our understanding of 3-nu standard mixing model
- Neutrino Factories (NuMAX, IDS-NF), MOMENT will provide powerful beams needed for precision measurements of CPV phase and non-leading order effects beyond LBNF and J-PARC era
- Cyclotrons development provides promising complementarity for increased science impact for sterile neutrinos and CPV phase measurement, driven by the needs of the medical field.

Thank you!