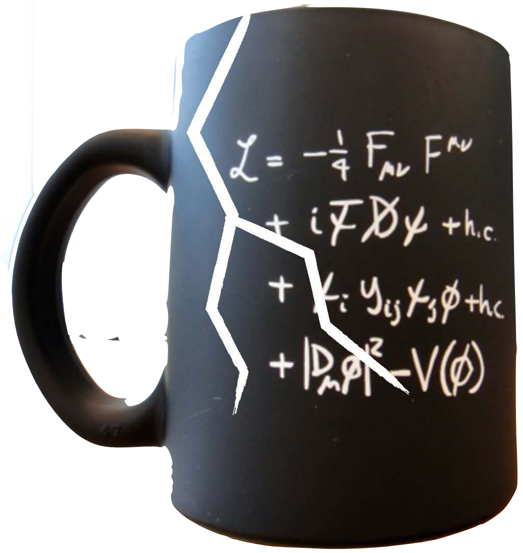


Beyond the Standard Model Physics Opportunities with DUNE

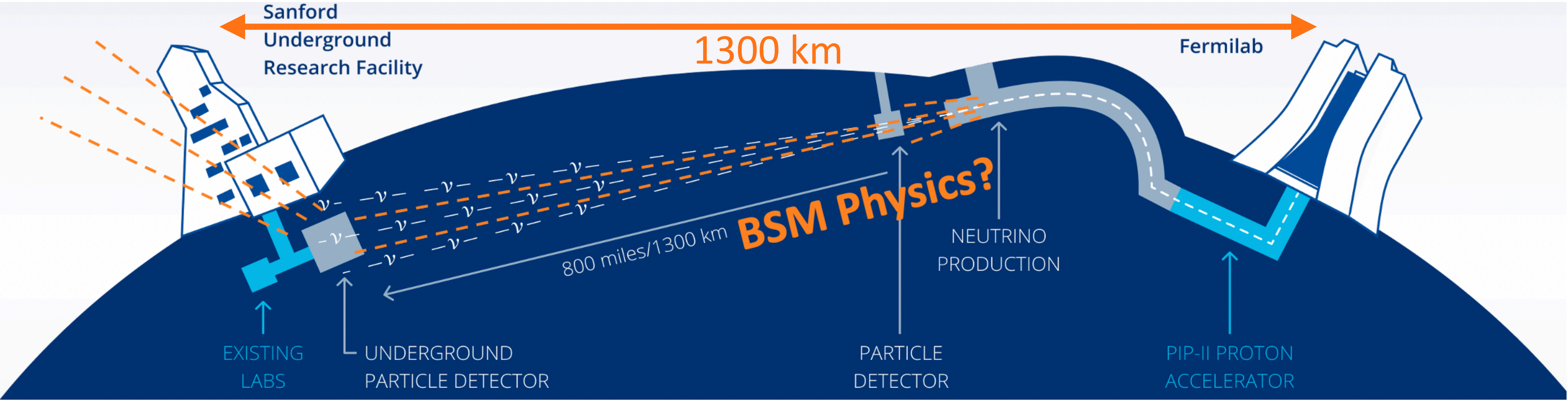
Alex Sousa
University of Cincinnati
for the DUNE Collaboration

COMHEP

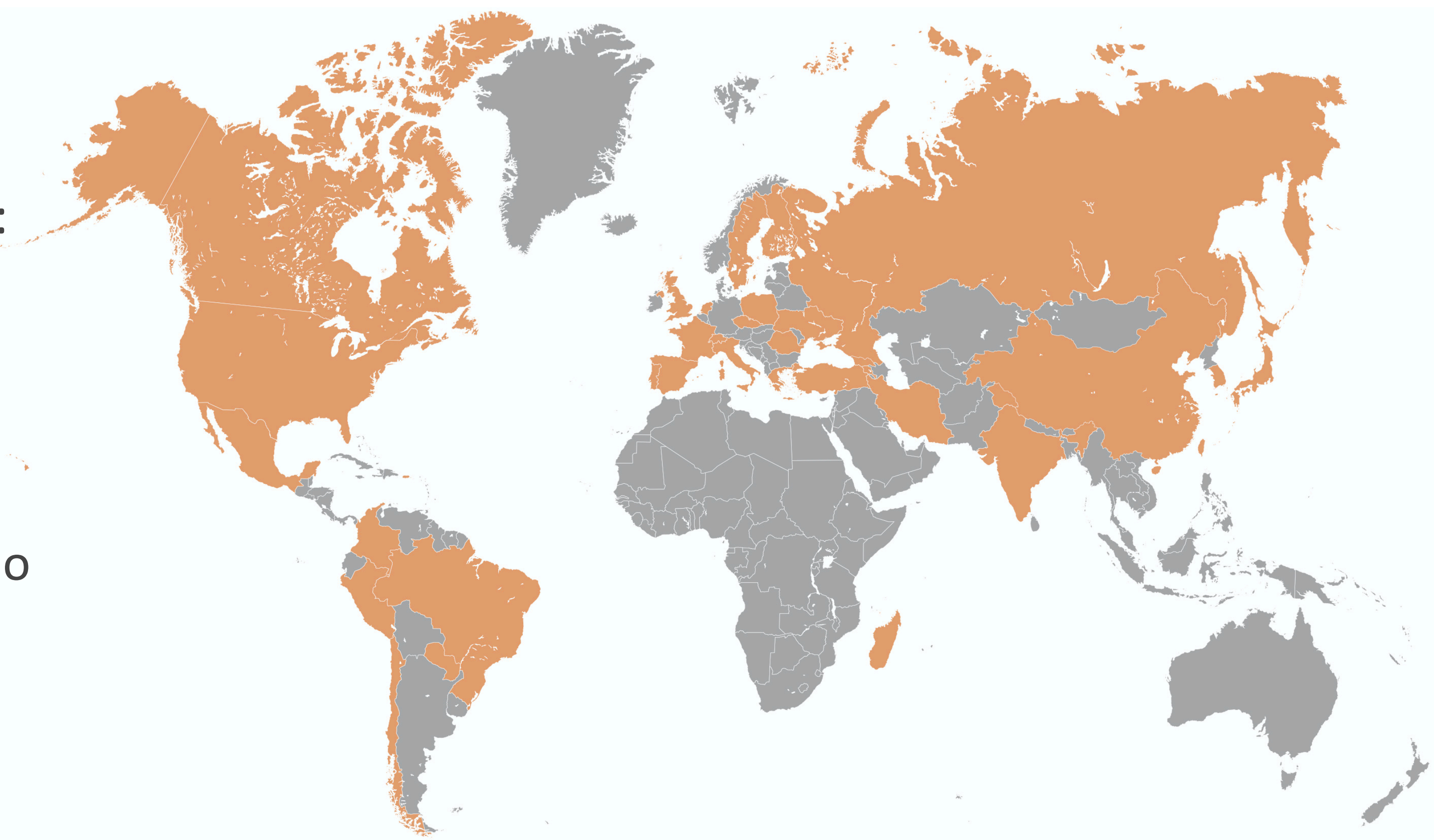
5th Colombian Meeting on High Energy Physics
December 3, 2020

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The DUNE Experiment



- Rich Physics program with primary goals:
  - Probe leptonic CP violation and determine neutrino mass ordering
  - High-precision measurements of neutrino mixing parameters
  - Supernova neutrinos and other neutrino astrophysics
  - Nucleon decay and other searches for BSM Physics



1263 collaborators from 211 institutions in 34 nations

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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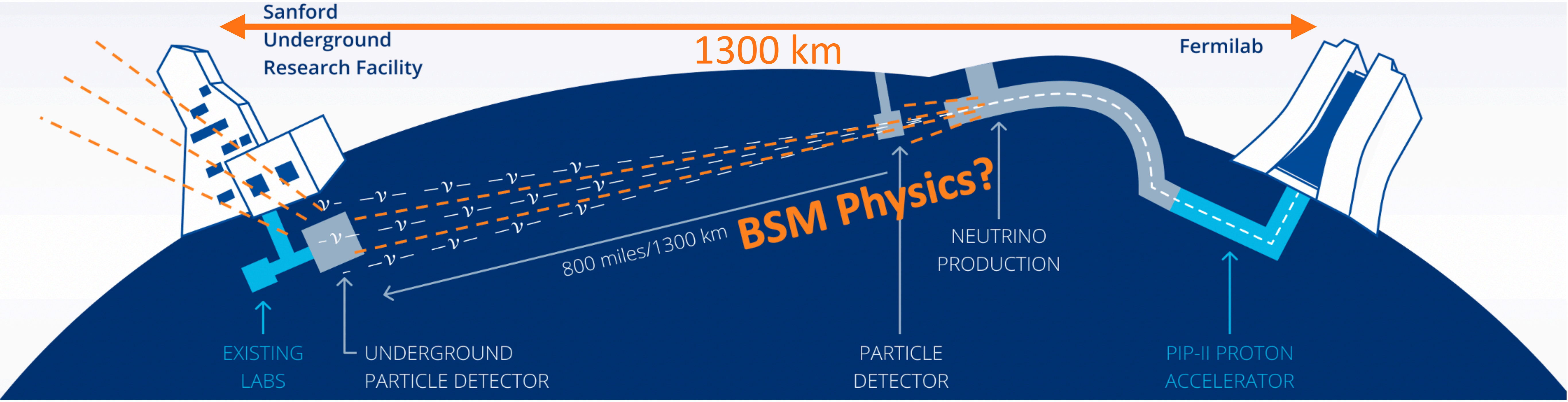

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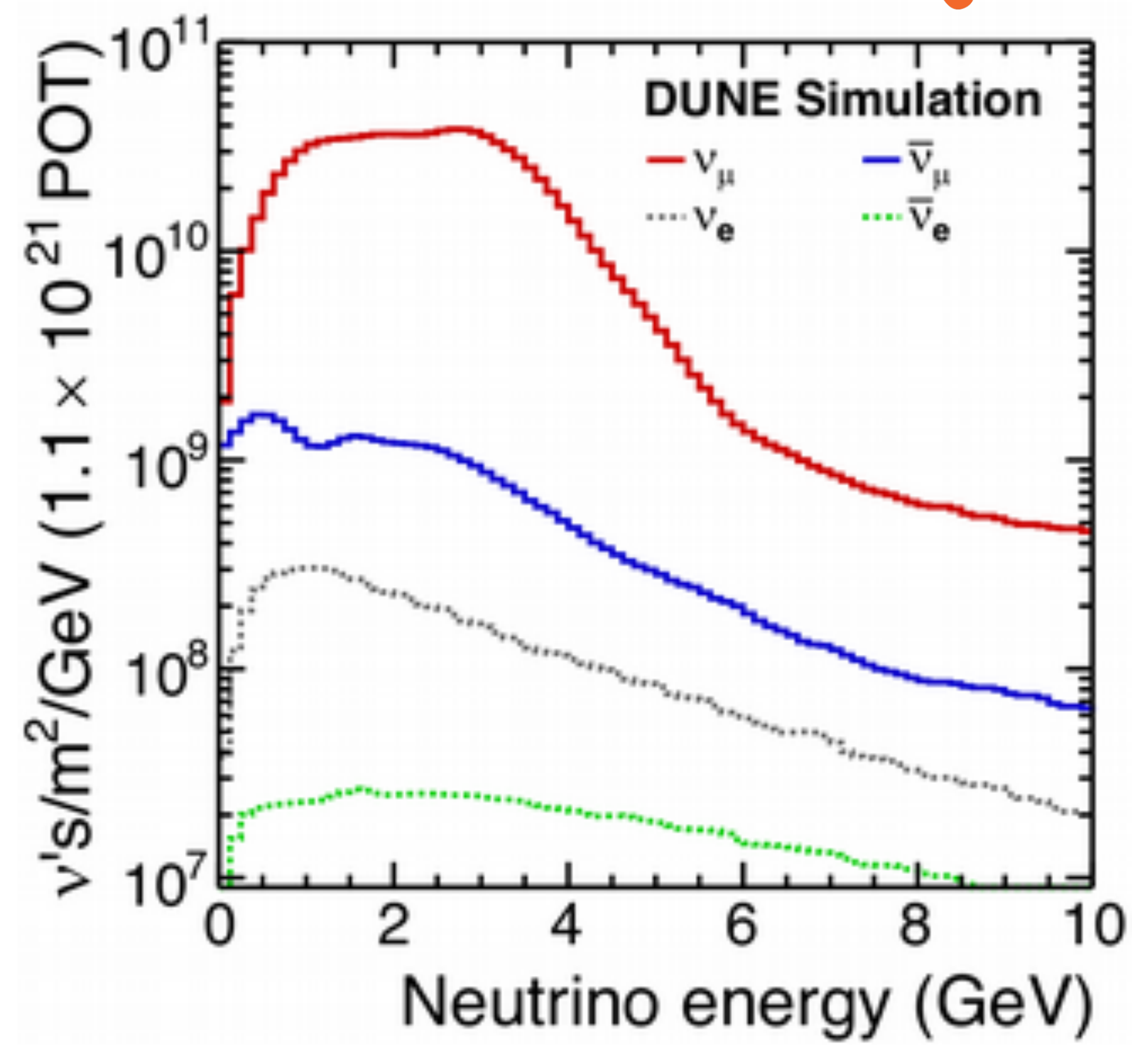
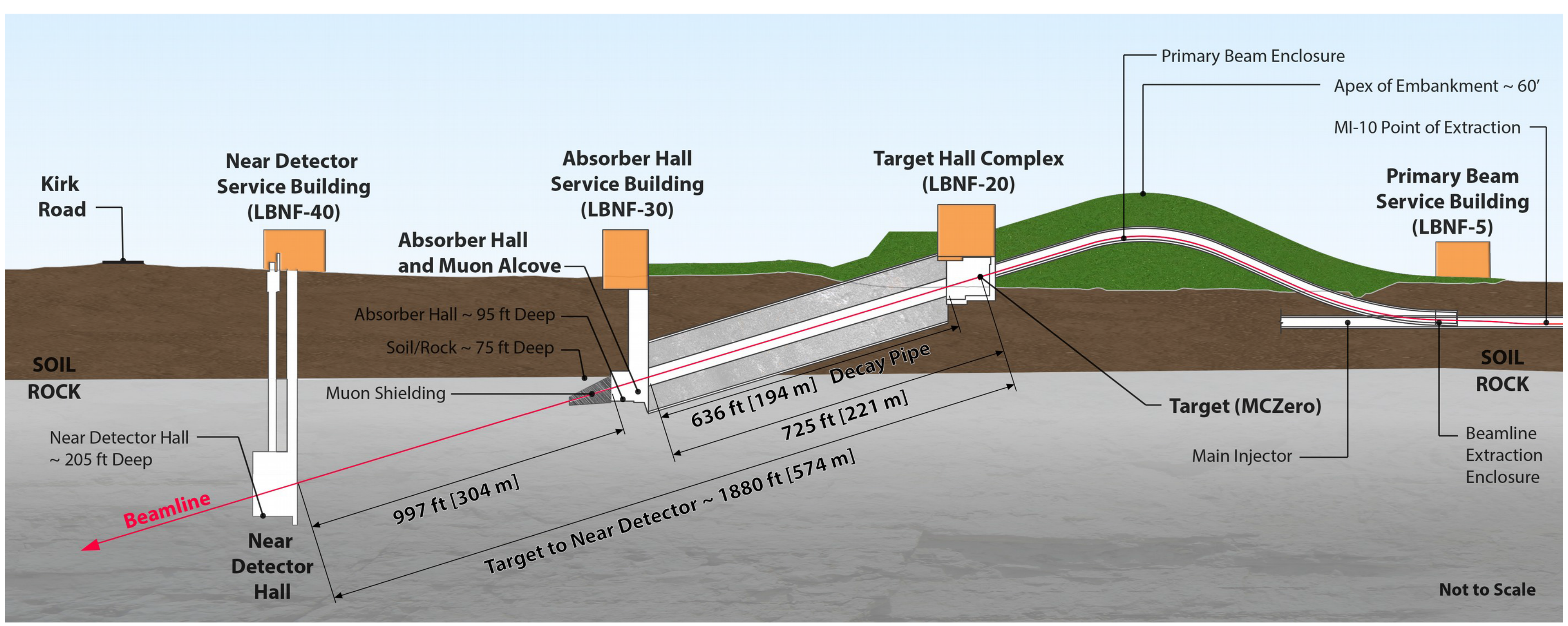
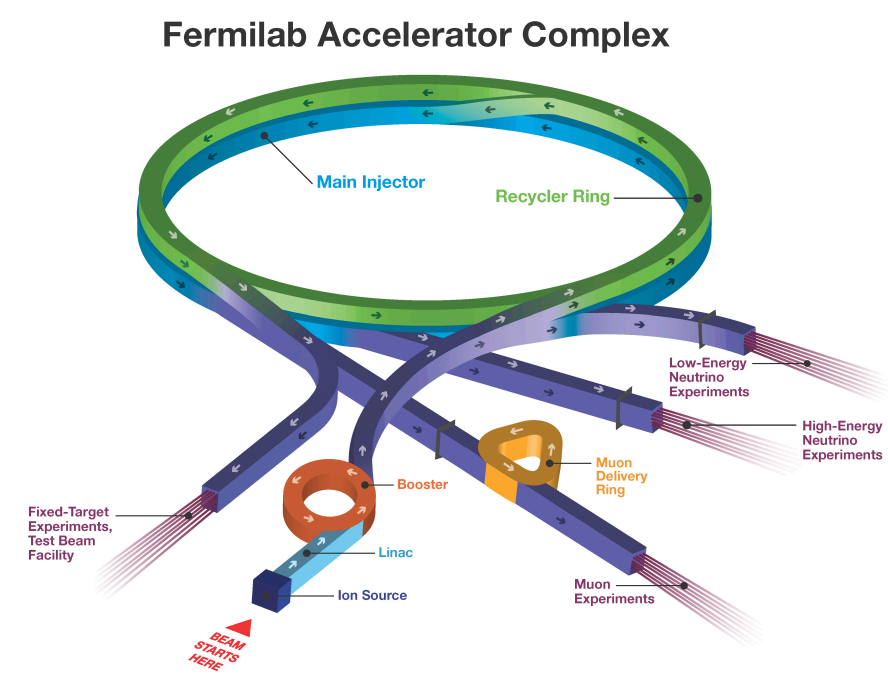
The LBNF Beamline

- The new LBNF (**L**ong-**B**aseline **N**eutrino **F**acility) neutrino beam will use 60-120 GeV protons from Fermilab's Main Injector
- Initial nominal power of 1.2 MW (~10^{21} protons-on-target/year), upgradeable to > 2 MW
- Can run in Neutrino (FHC) and Antineutrino (RHC) modes by switching polarity of magnetic horns
- Wideband beam enables use of second osc. maximum and enhances probing of new BSM phenomena

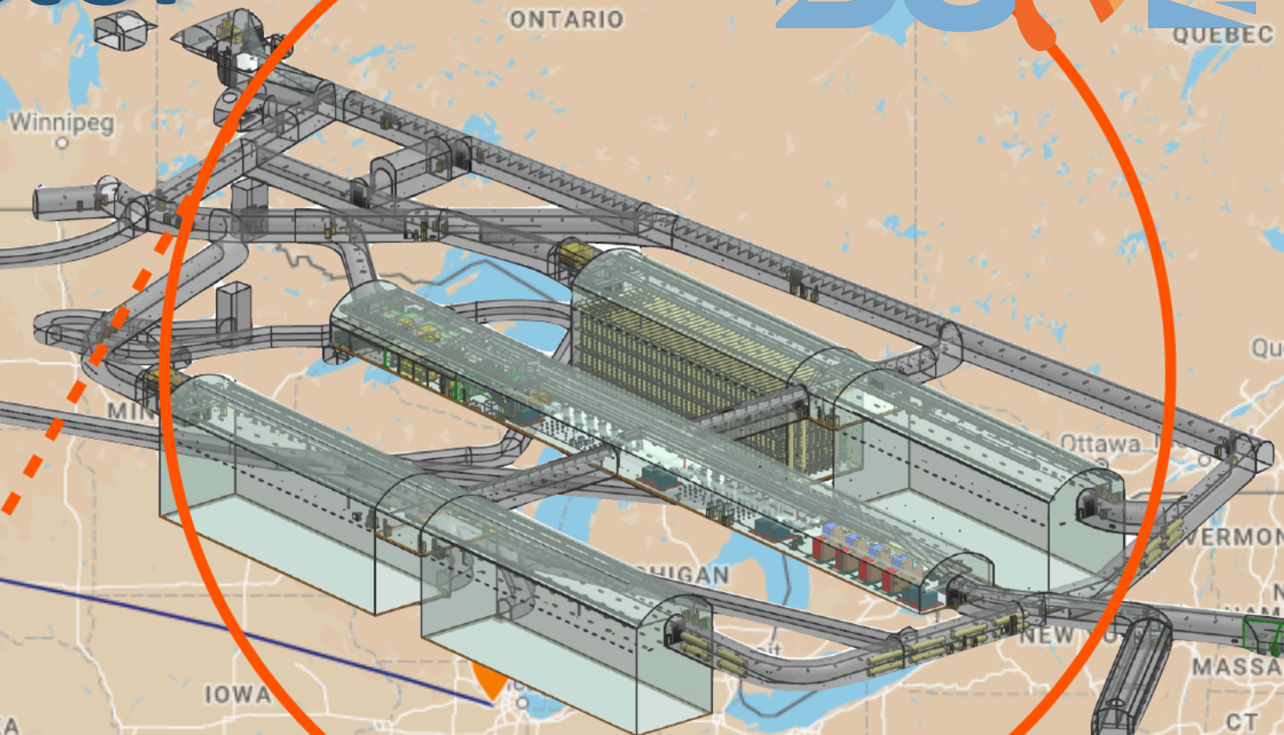


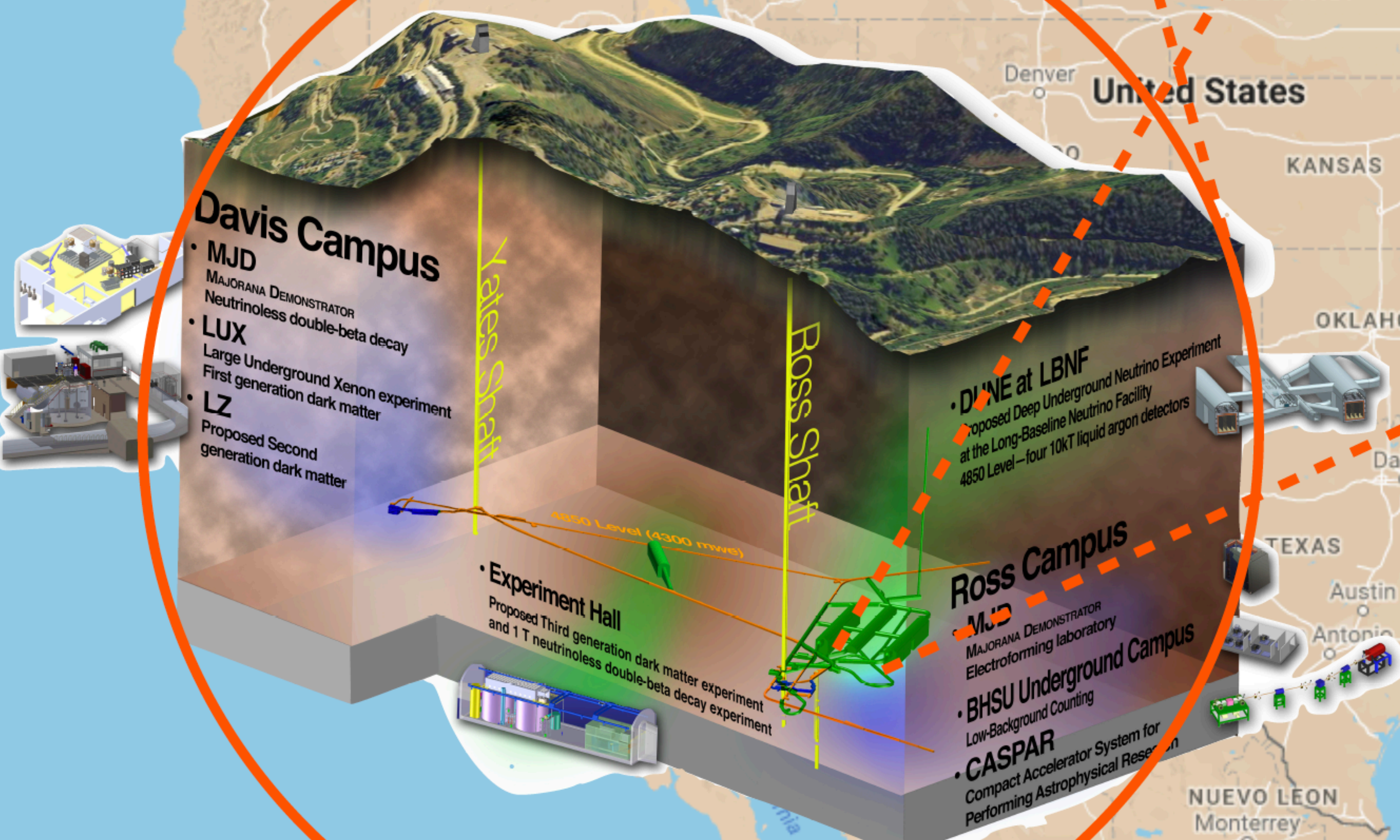




Far Detector

- Located 4850 ft (1500 m) underground at SURF, enables low-energy and atmospheric neutrino physics
- Four 17 kton (10 kton fiducial) LArTPC modules, with single and dual phase detector designs





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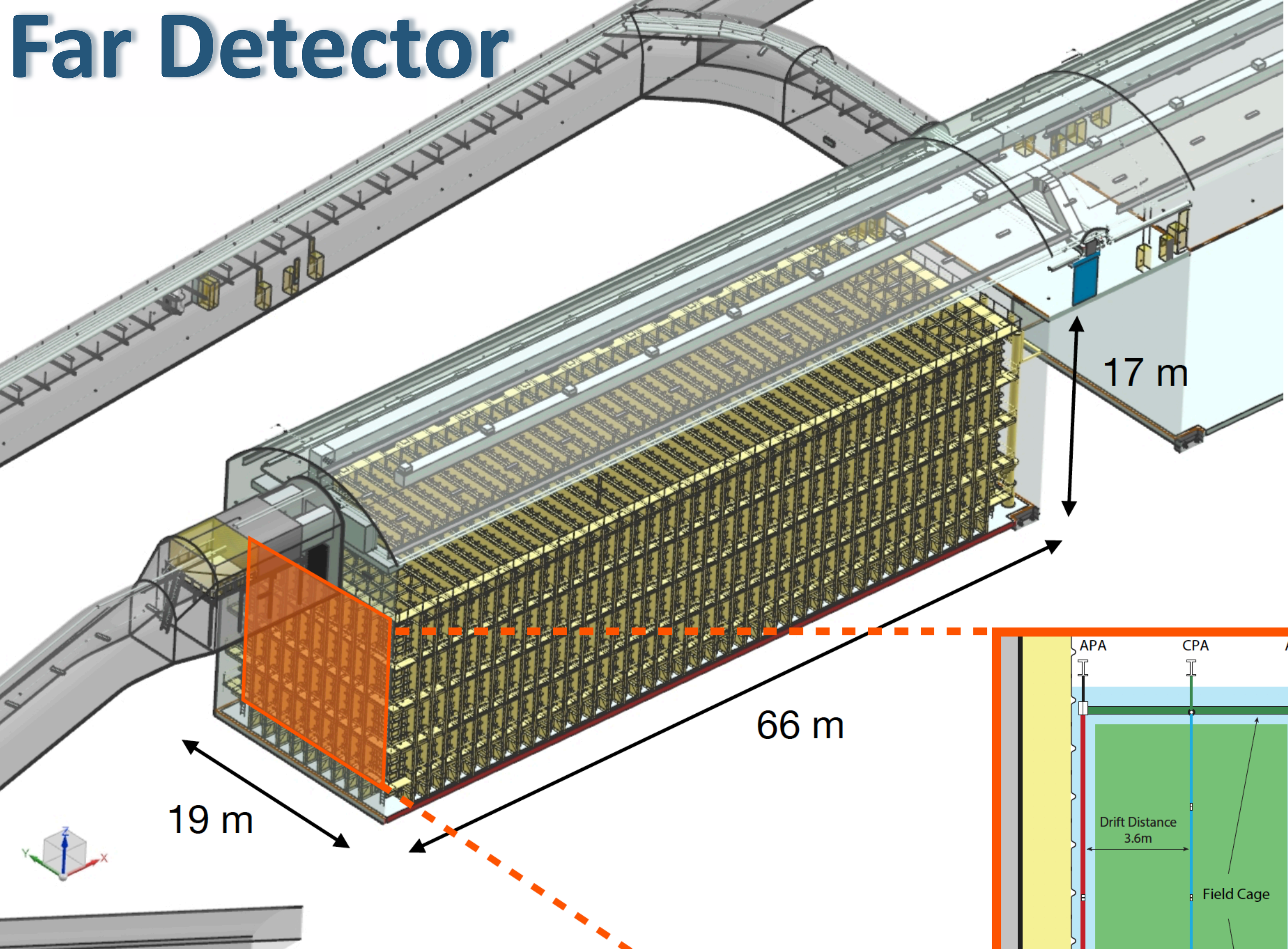
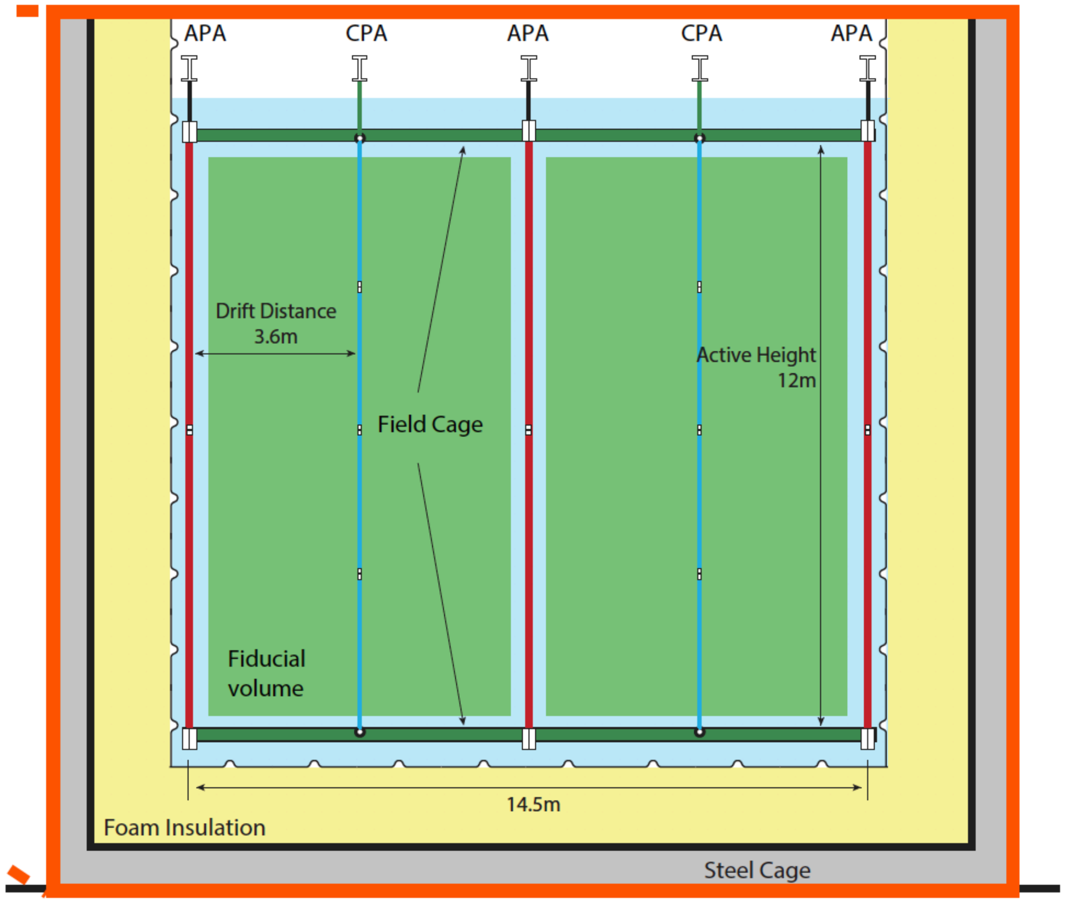
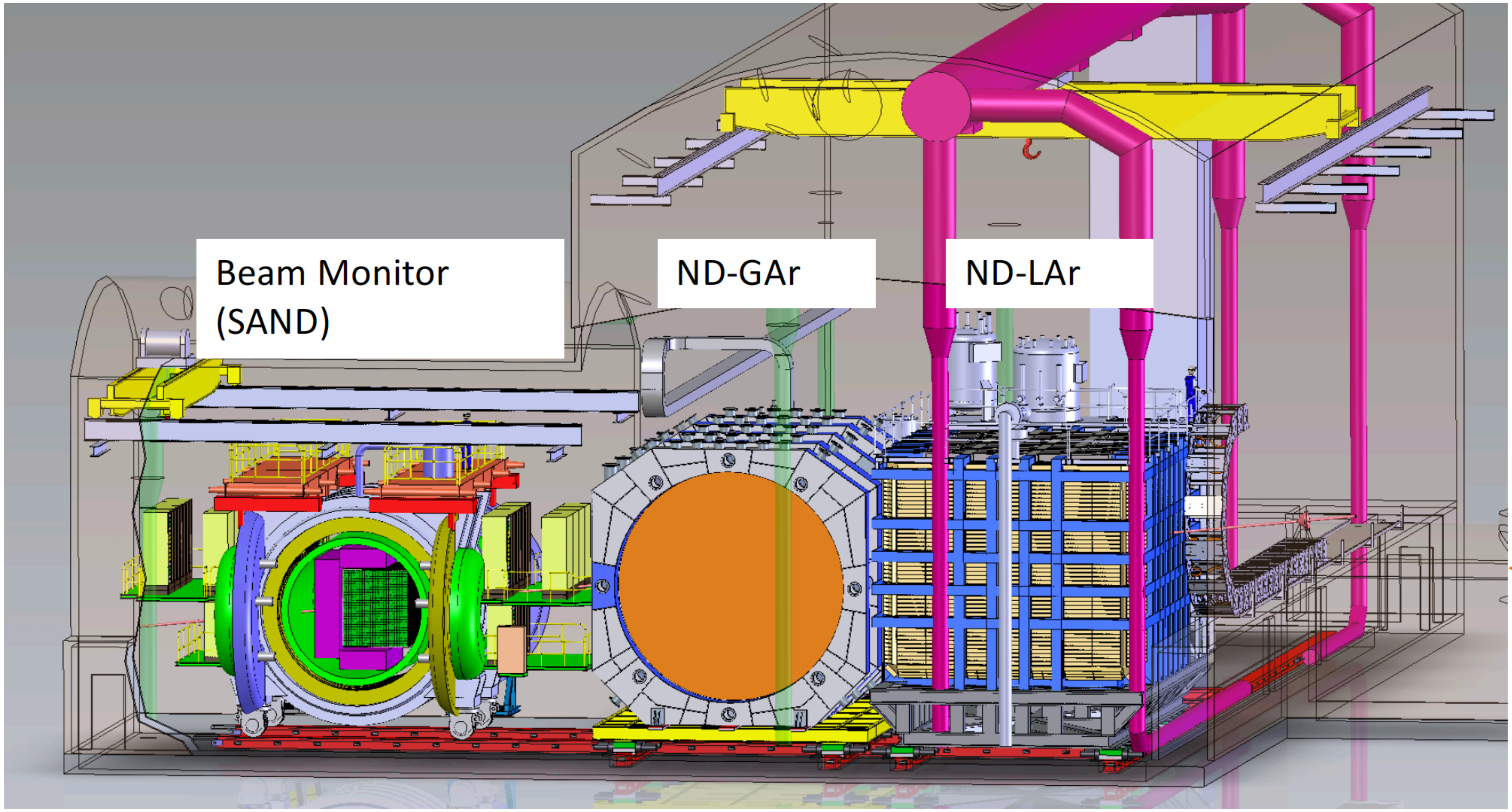




- Single-phase 17 kton (10 kton fiducial) LArTPC module
- Far site pre-excavation underway since 2017
- Cavern excavation will require moving 800 000 tons of rock to surface!

Near Detector Complex



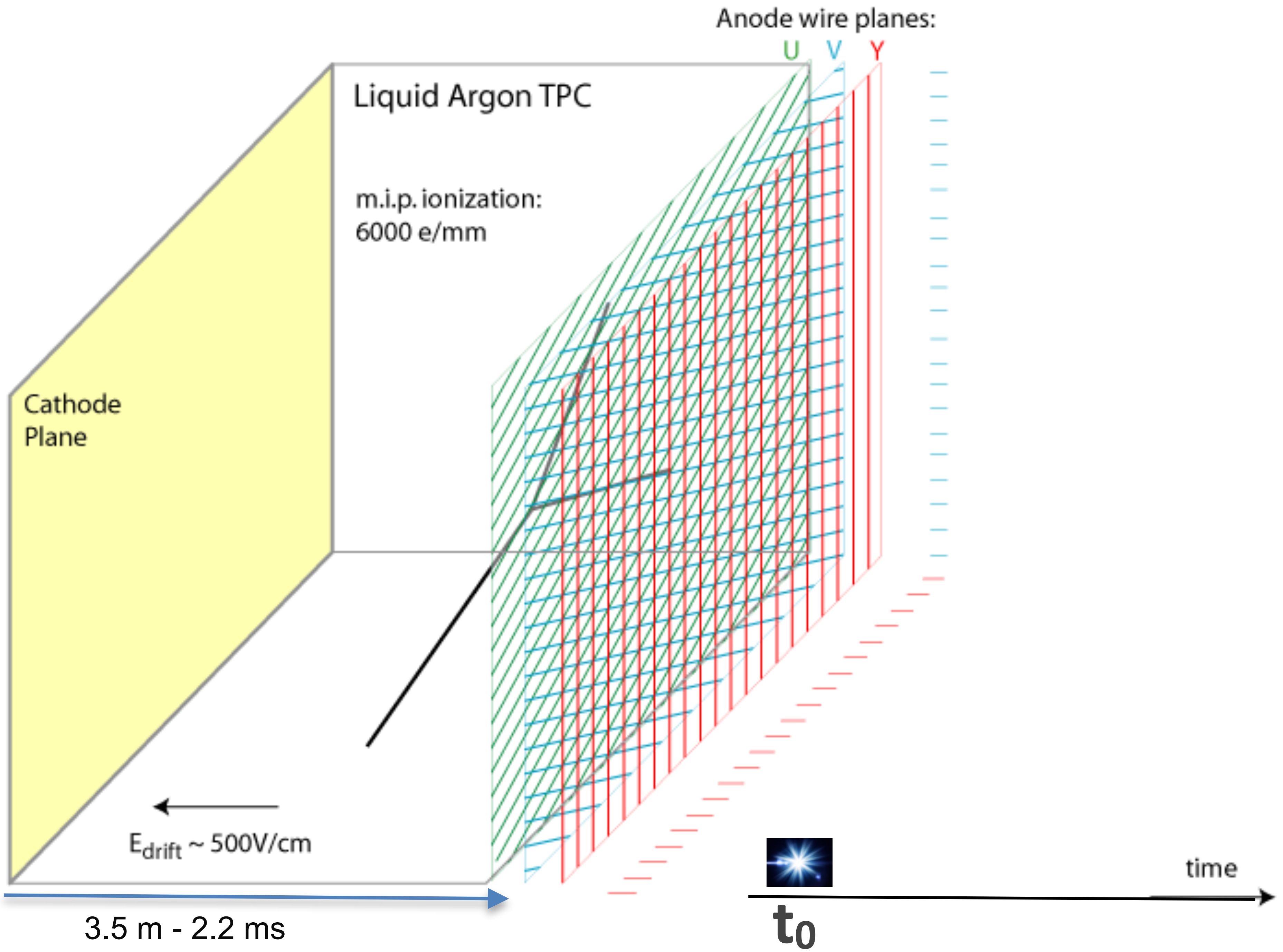
Neutrino Beam

- Located 574 m downstream of production target
- ND-LAr: modular, pixelated LArTPC
  - Acts as primary target and is most similar to FD (both contain LAr)
- ND-GAr: high-pressure GArTPC surrounded by ECAL and magnet
  - Constrains nuclear interaction model; muon spectrometer
- SAND: tracker surrounded by ECAL and magnet
  - On-axis monitor of beam spectrum

- ND-LAr/ND-GAr can move off-axis (DUNE-PRISM)
- $\mathcal{O}$(10 million/year) neutrino interactions will enable rich non-oscillation physics program

LArTPC Detector Technology

- Liquid Argon Time Projection Chambers
  - Critical to have ultra-high LAr purity, and a uniform and stable electric field



- Energy release from charged particles in LAr:
  - free electron charge (TPC)
  - scintillation light (PD)
- Photon detection for triggering and t_0 determination

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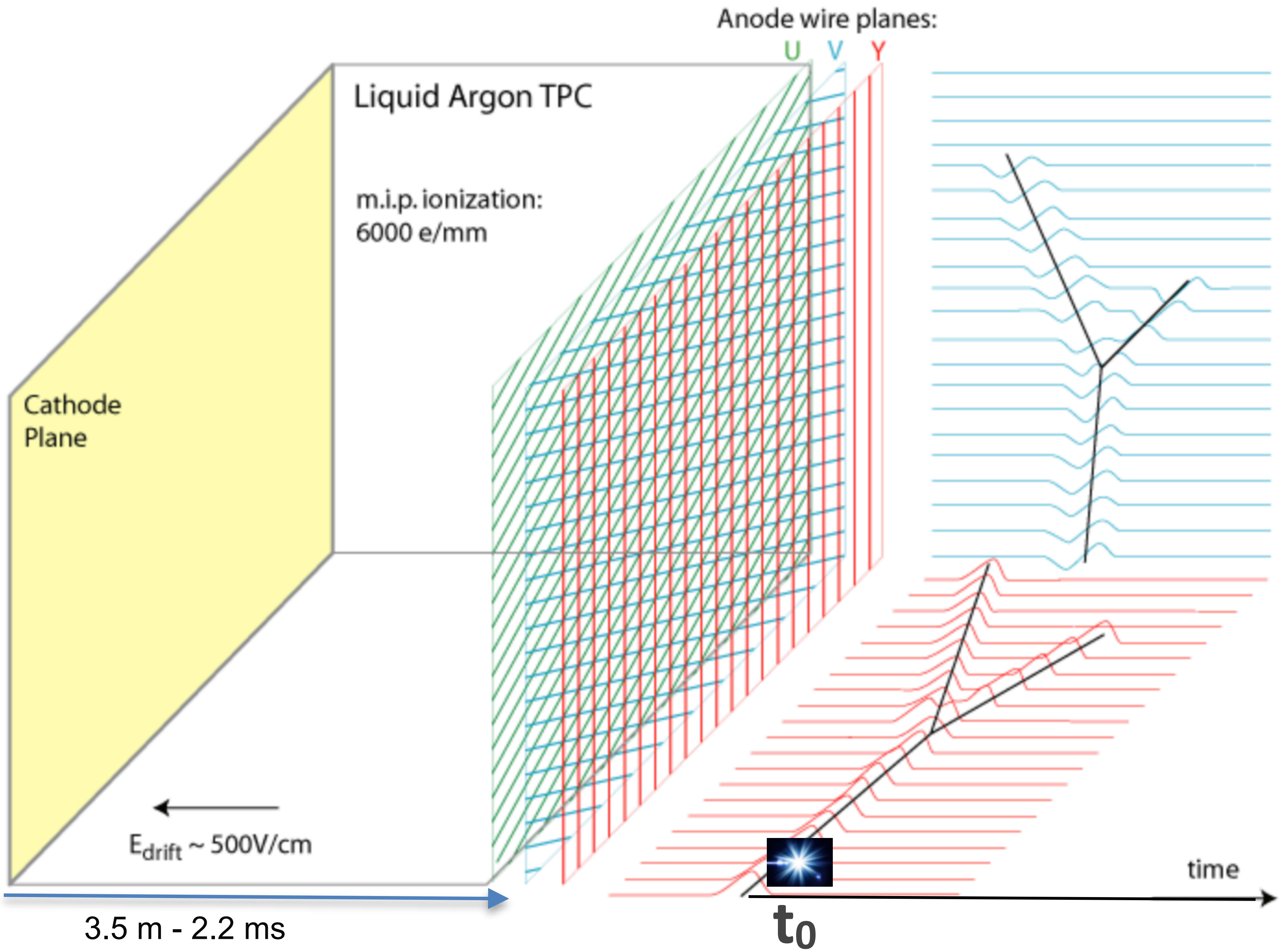

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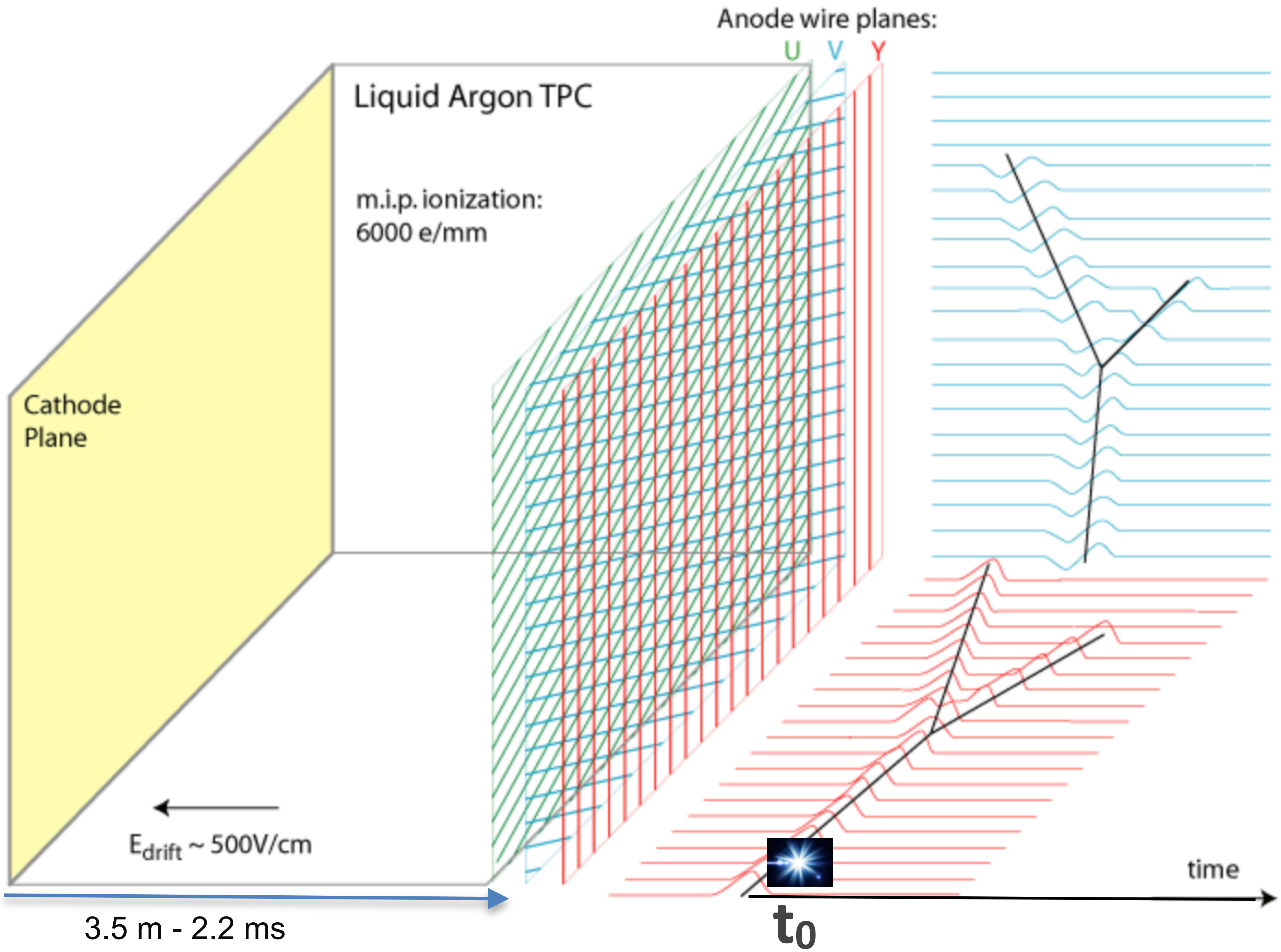
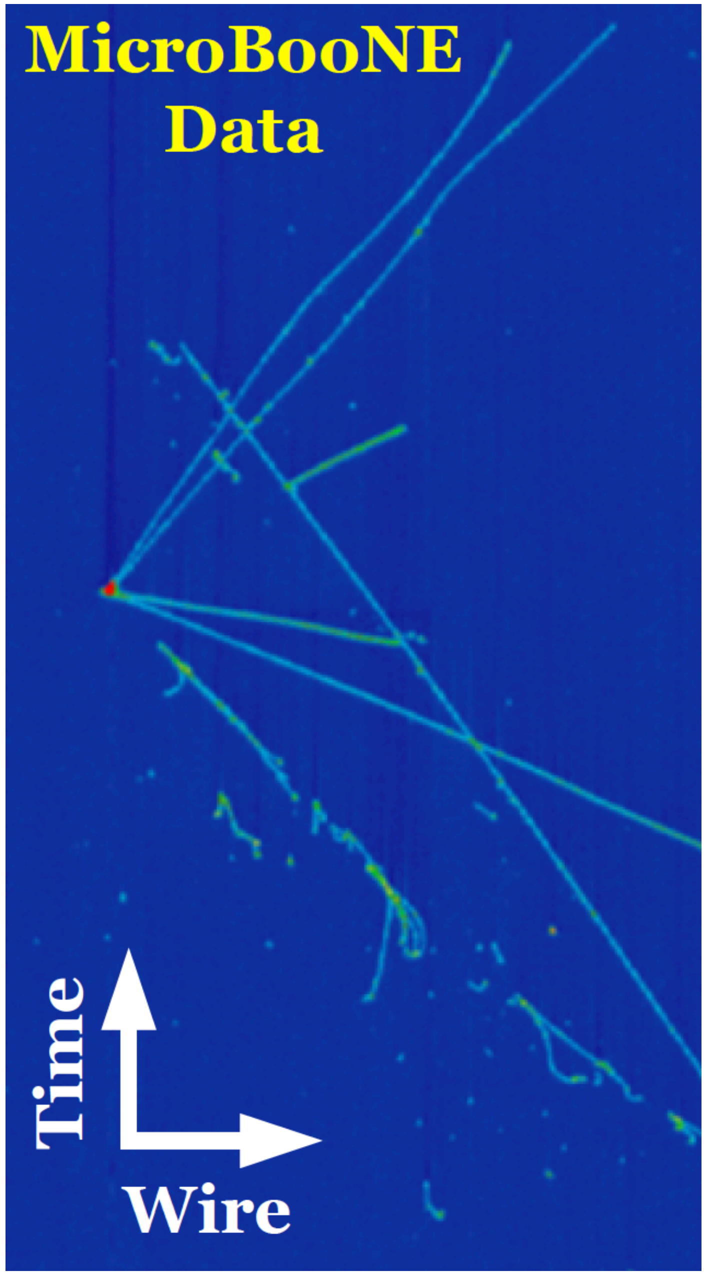
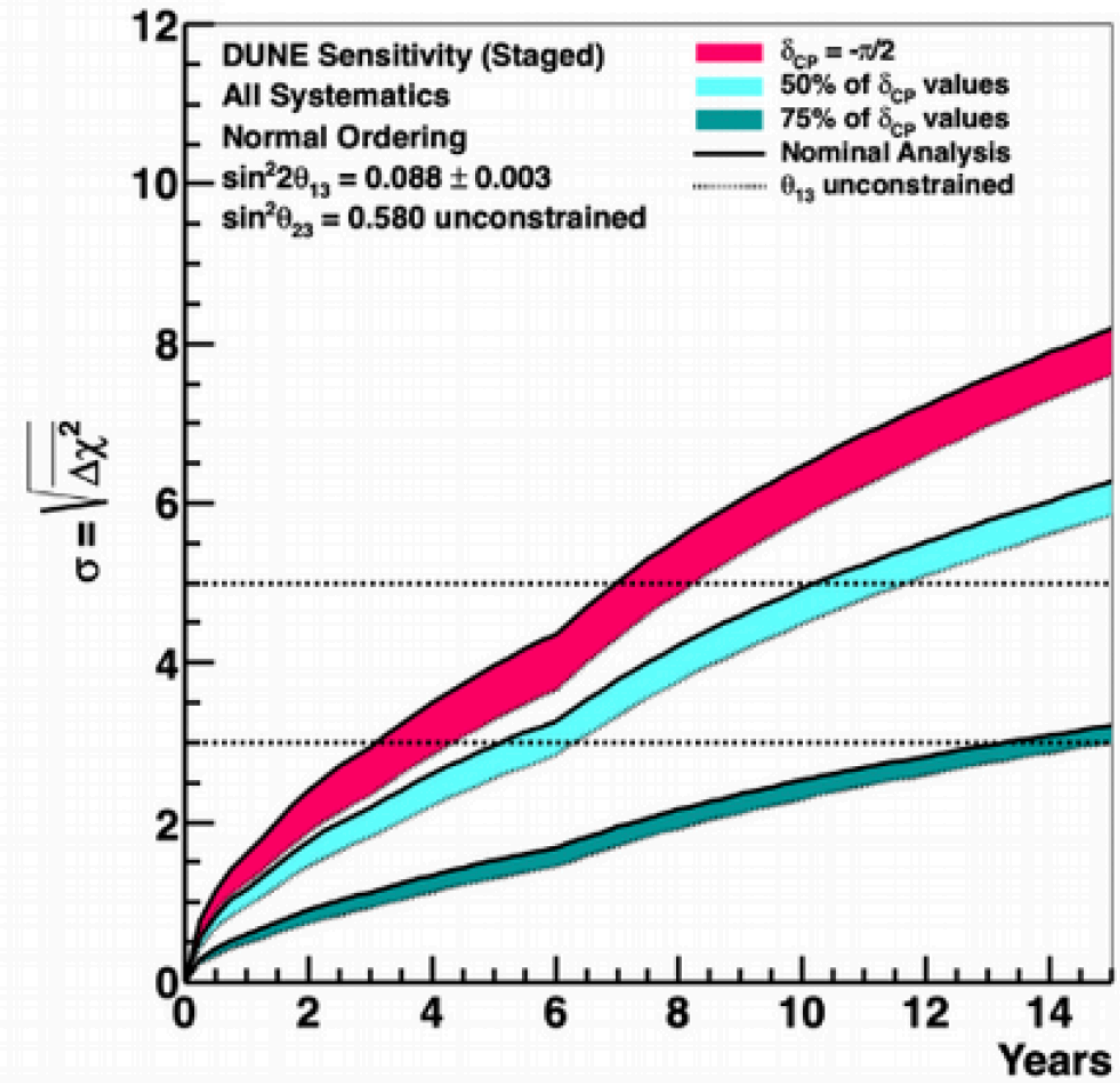


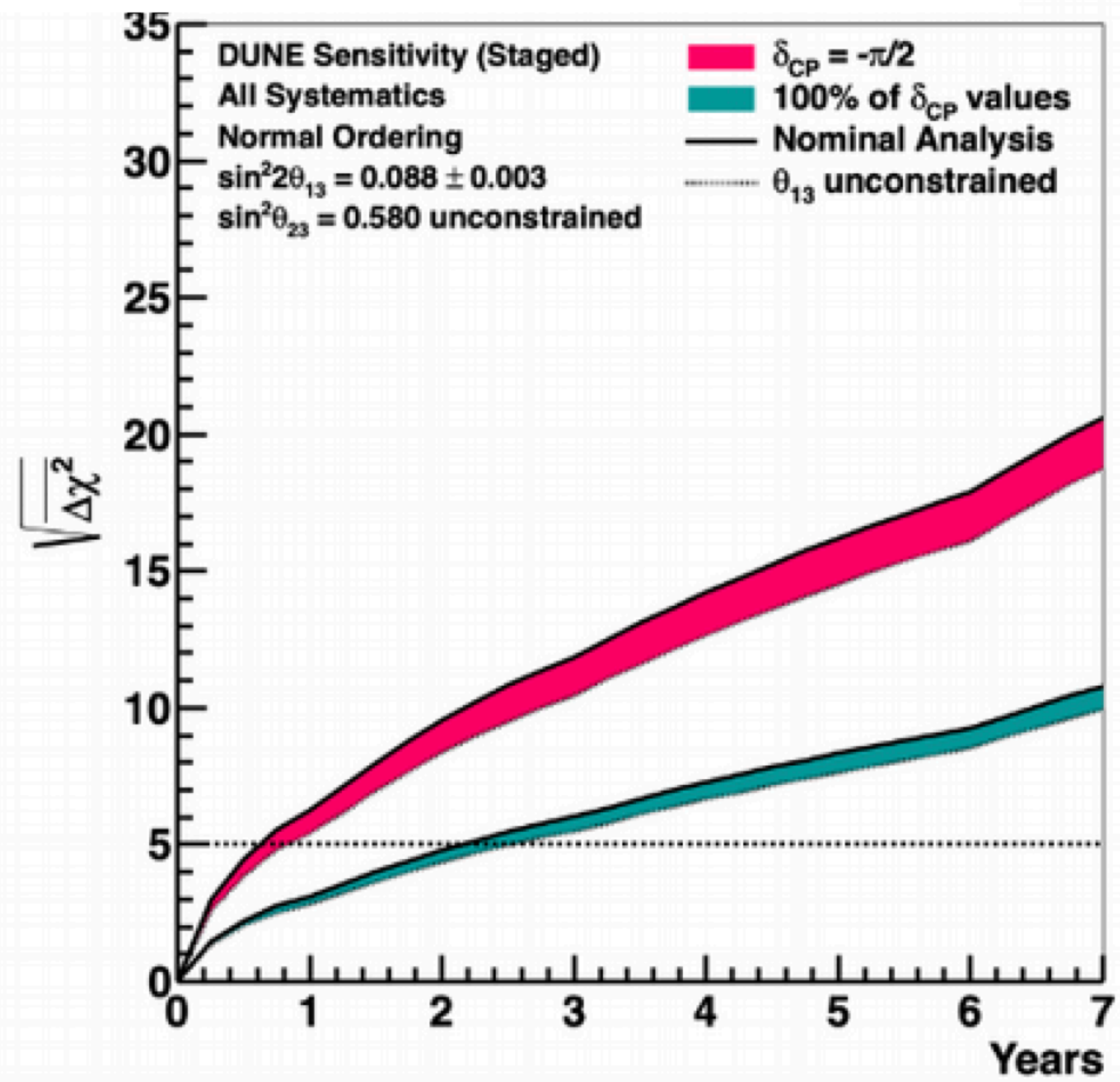


Std. Osc. Sensitivities Over Time

CP Violation Sensitivity



Mass Ordering Sensitivity



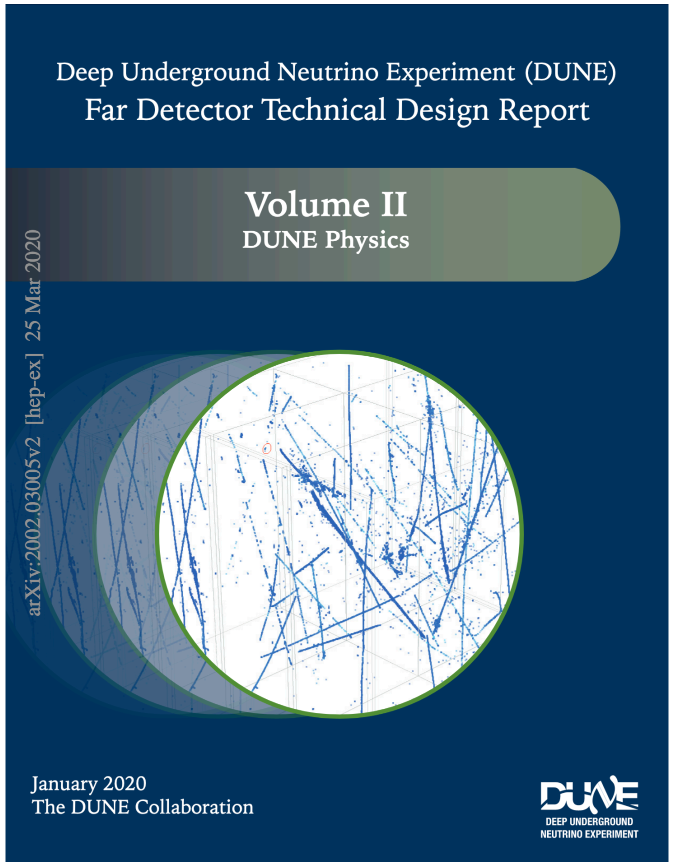
- CP violation discovery if true $\delta_{CP} = -\pi/2$ in ~7 years (staged)
- CP violation discovery for 50% of true δ_{CP} values in ~10 years
- Unambiguous determination of neutrino mass ordering within first few years

BSM Physics Topics Being Studied

- Non-standard short-baseline and long-baseline oscillation phenomena
  - Mixing with light sterile neutrinos
  - Large extra-dimensions
  - Non-standard neutrino interactions
  - CPT violation
  - Non-unitarity of the mixing matrix*

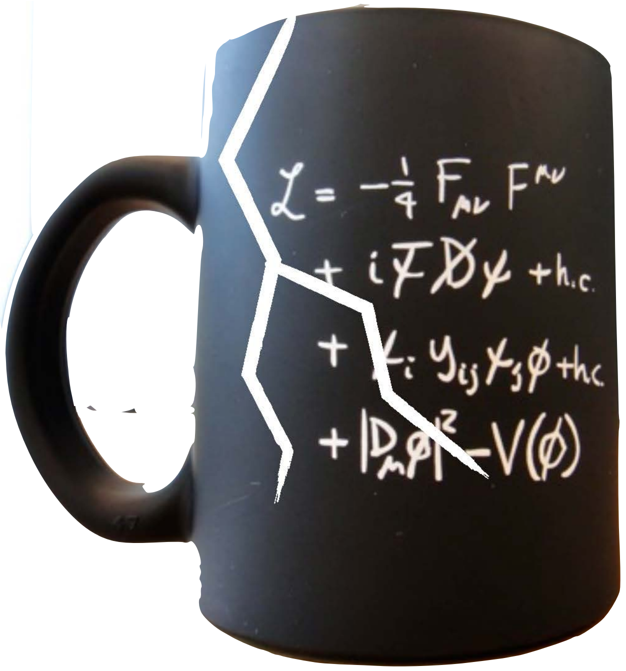
- Searches for new phenomena/particles at the ND
  - Low-mass dark matter
  - Neutrino trident interactions
  - Heavy neutral leptons

- Searches for new phenomena at the FD benefitting from its large mass and resolution
  - ν_τ physics
  - Inelastic boosted dark matter from the galactic core
  - Boosted dark matter from the Sun*
  - Nucleon decay*



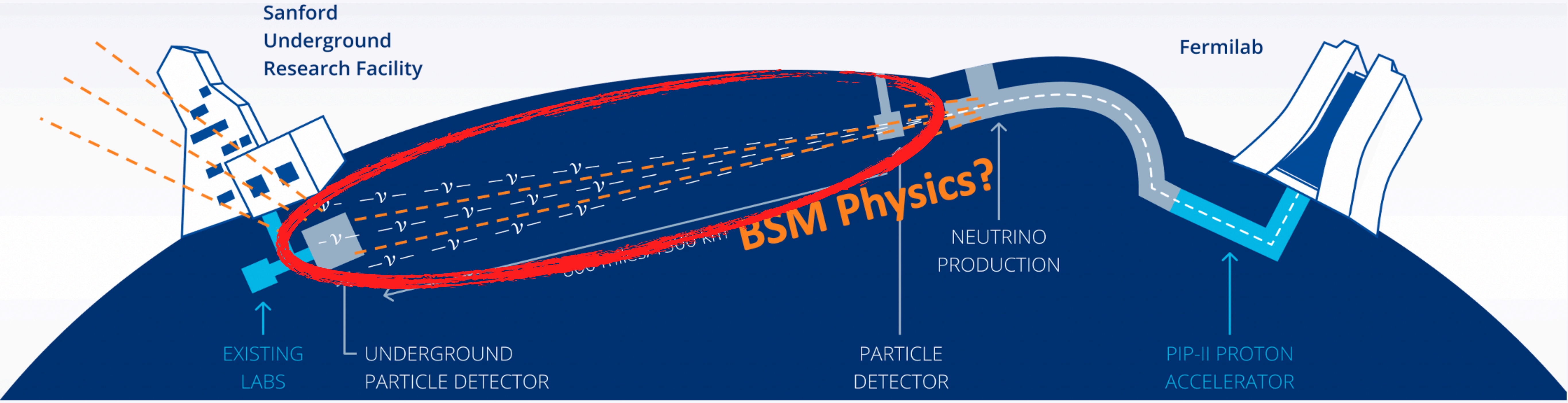
[Far Detector Technical Design Report]

[DUNE BSM Paper, arXiv:2002.03005, submitted to EPJ C]



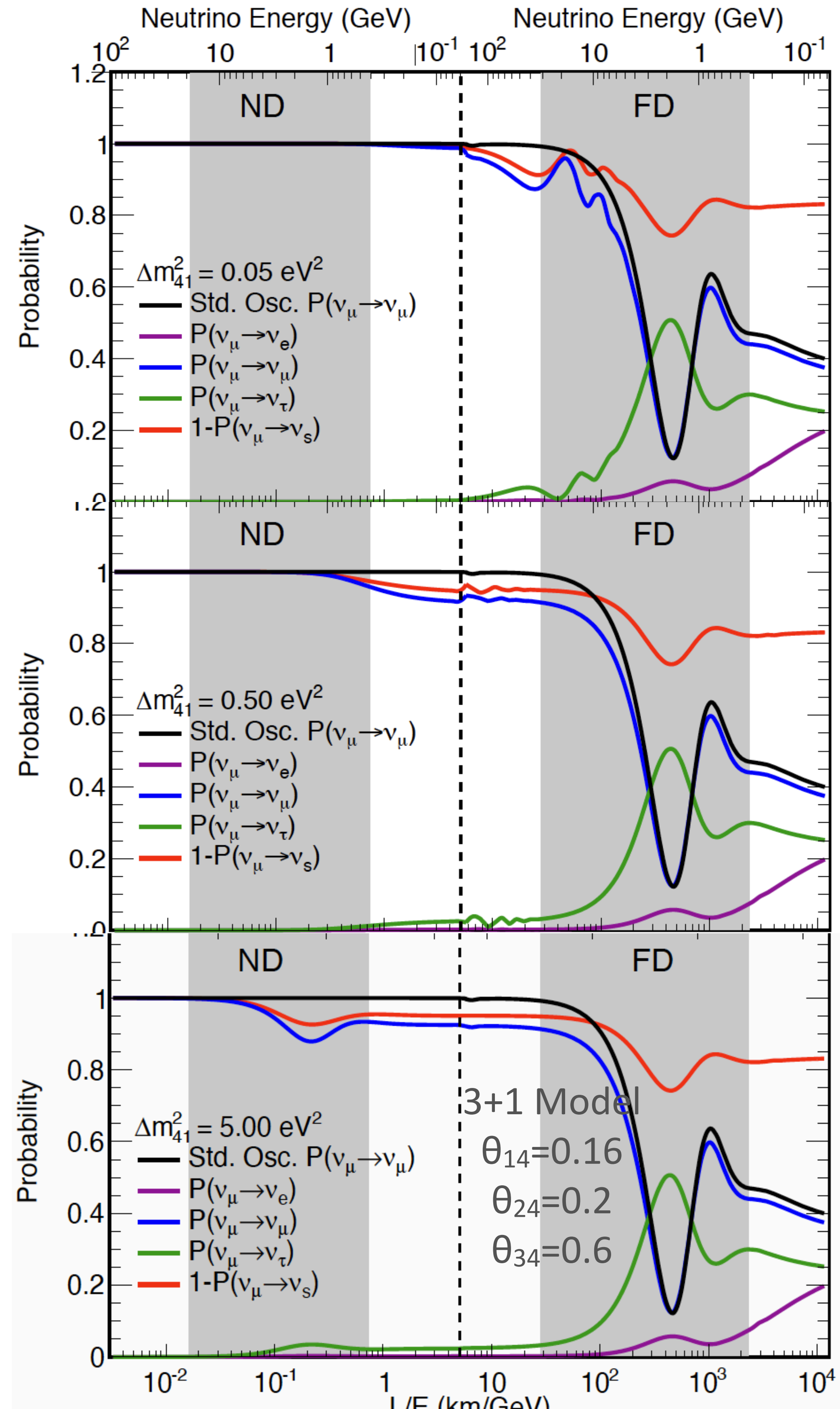
*Not discussed in this talk

Non-standard SBL and LBL neutrino oscillations



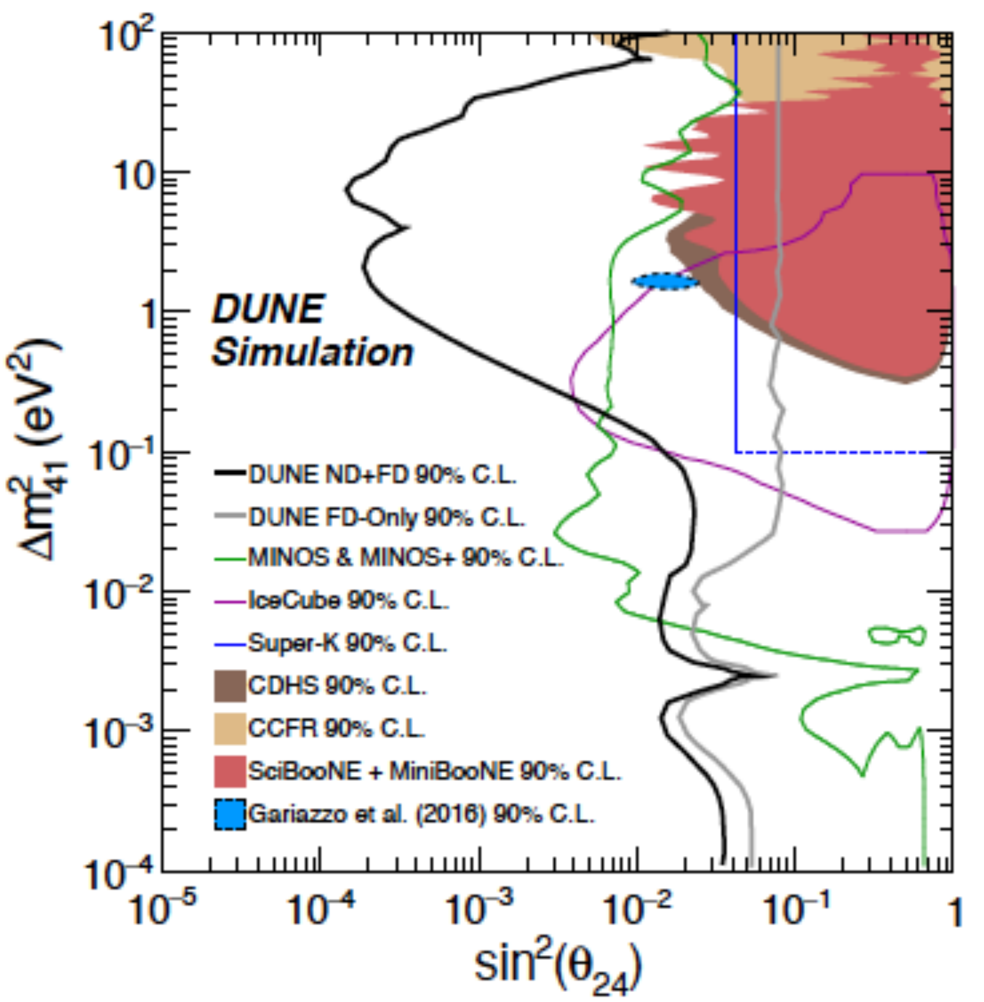
Light Sterile Neutrinos

- Oscillations between active and new light sterile neutrino states would distort standard oscillation probabilities
  - DUNE will be sensitive to this effect through the combined analysis of the ν_μ and ν_e spectra from both the near and far detectors.
  - DUNE may also probe nonstandard ν_τ appearance in the near detector or use the atmospheric sample from the far detector.

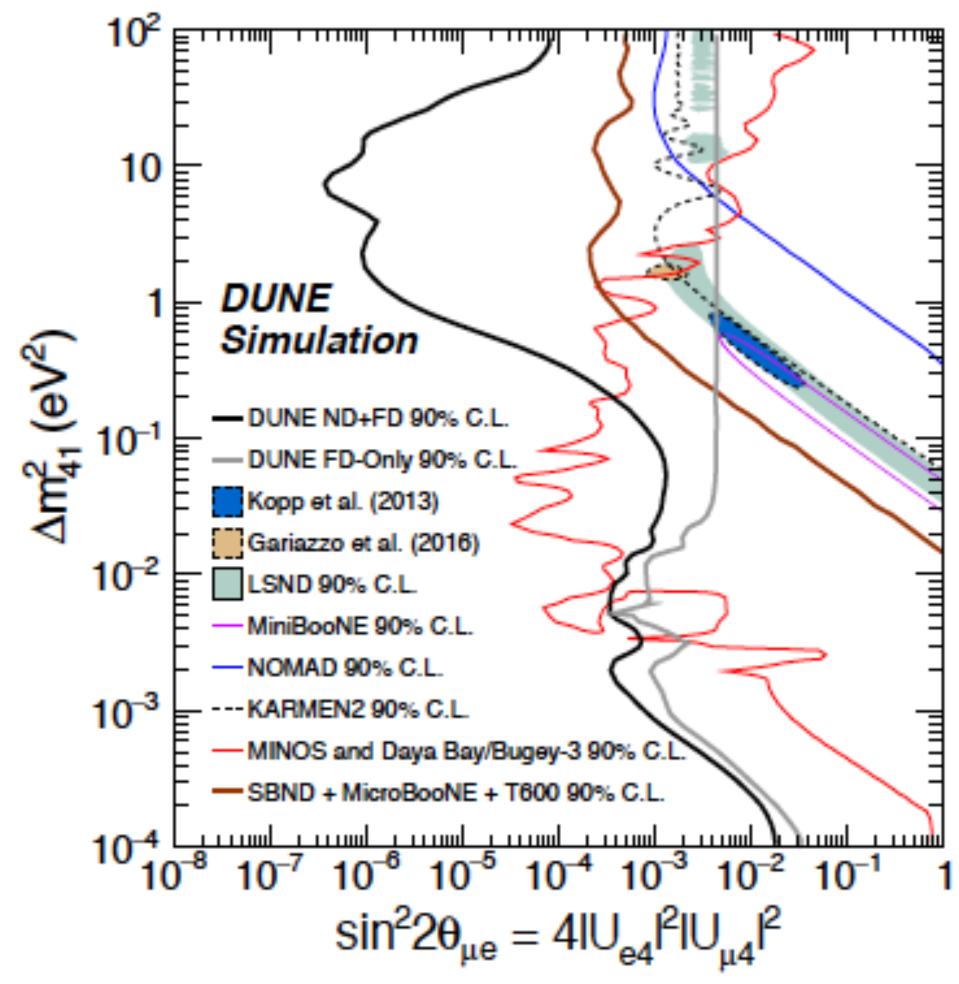


- Plots show distortions of standard oscillation probabilities for different values of Δm^2_{41}
  - **Small Δm^2_{41}**: slow oscillations visible at FD only
  - **Intermediate Δm^2_{41}**: rapid oscillations average out at FD but still not visible at ND
  - **Large Δm^2_{41}**: oscillations average out at FD and distortions are visible at the ND

Light Sterile Neutrino Sensitivities



ν_μ Disappearance



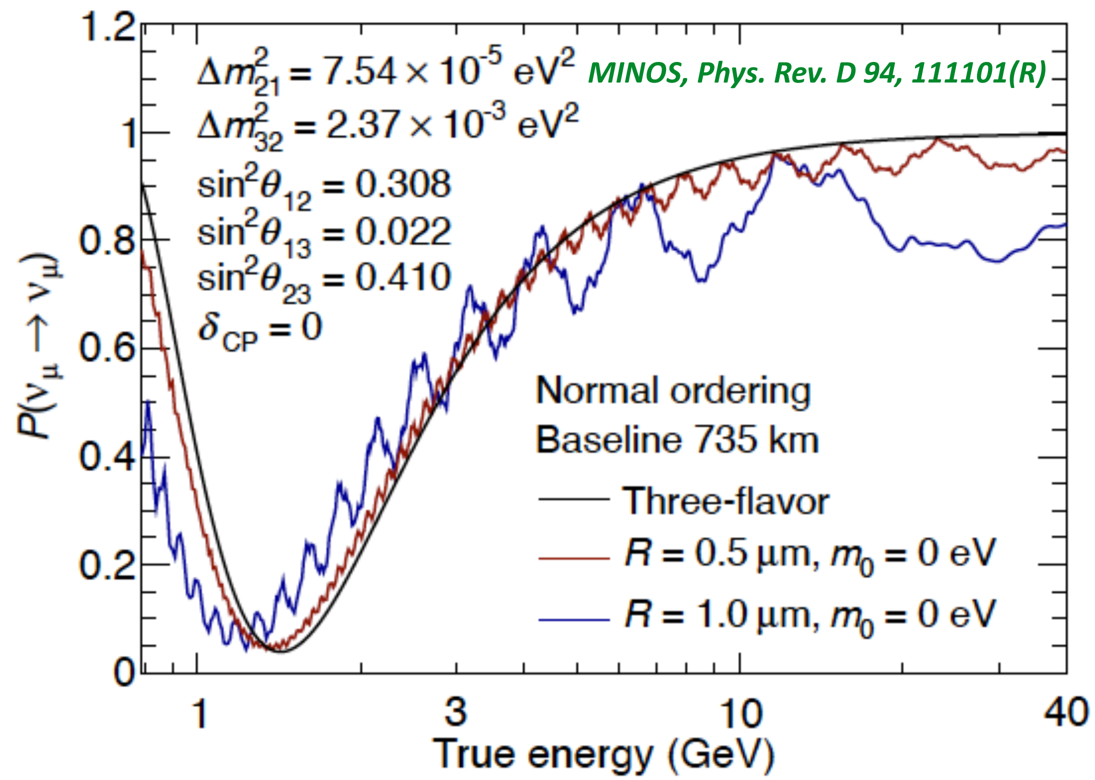
ν_e Appearance

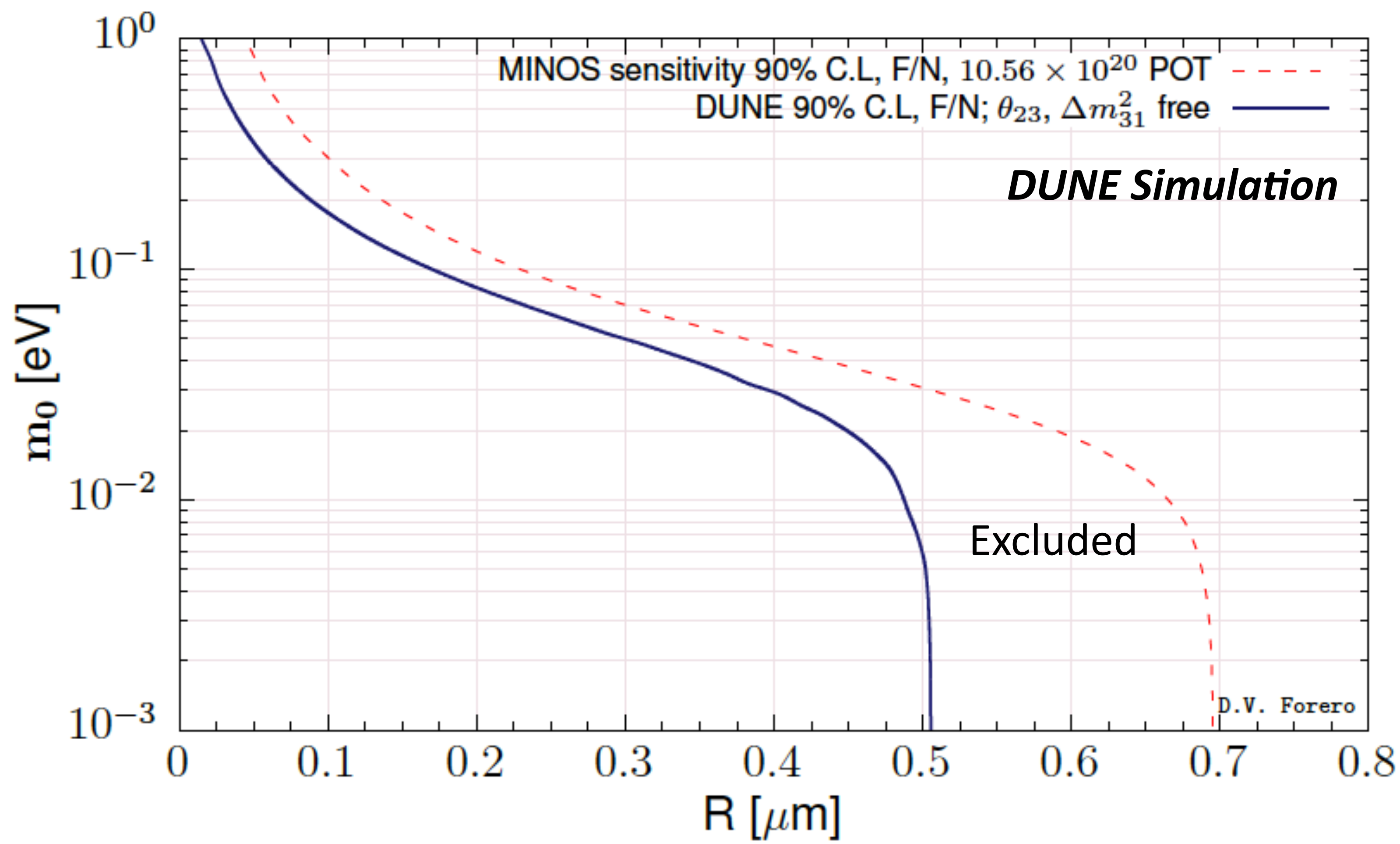
- Assuming 300 kton.MW.year exposure (staged 7 year running) for 3+1 model with simultaneous oscillations in ND and FD implemented in GloBES
  - On its own, DUNE can probe the sterile mixing parameter space at the same level or better than present and future experiments

	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
DUNE Best-Case	1.8°	15.0°	0.001	0.067
DUNE Worst-Case	15.1°	25.5°	0.068	0.186
NOvA	20.8°	31.2°	0.126	0.268
MINOS/MINOS+	4.4°	23.6°	0.006	0.16
Super–Kamiokande	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

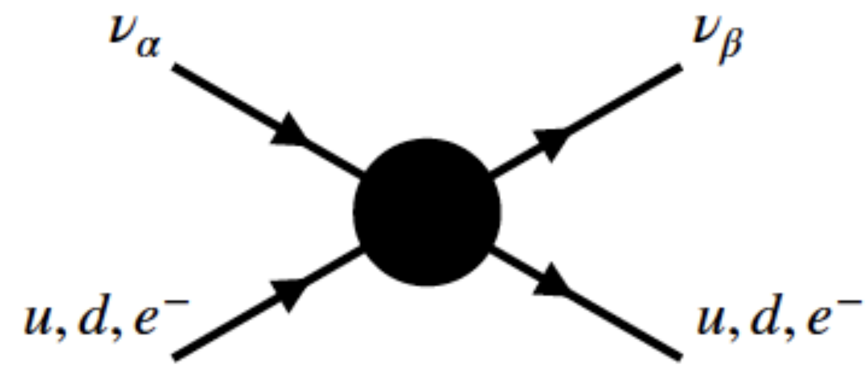
Large Extra-Dimensions

- Large Extra-Dimensions can be probed through distortions of 3-flavor oscillation pattern caused by mixing of neutrinos with Kaluza-Klein modes
  - For ADD model [*Phys.Lett. B 429, 263-272 (1998)*], assuming one large extra-dimension in the bulk, Kaluza-Klein (KK) modes in 3+1 brane behave like sterile neutrinos
  - Showing DUNE sensitivity compared to MINOS published results





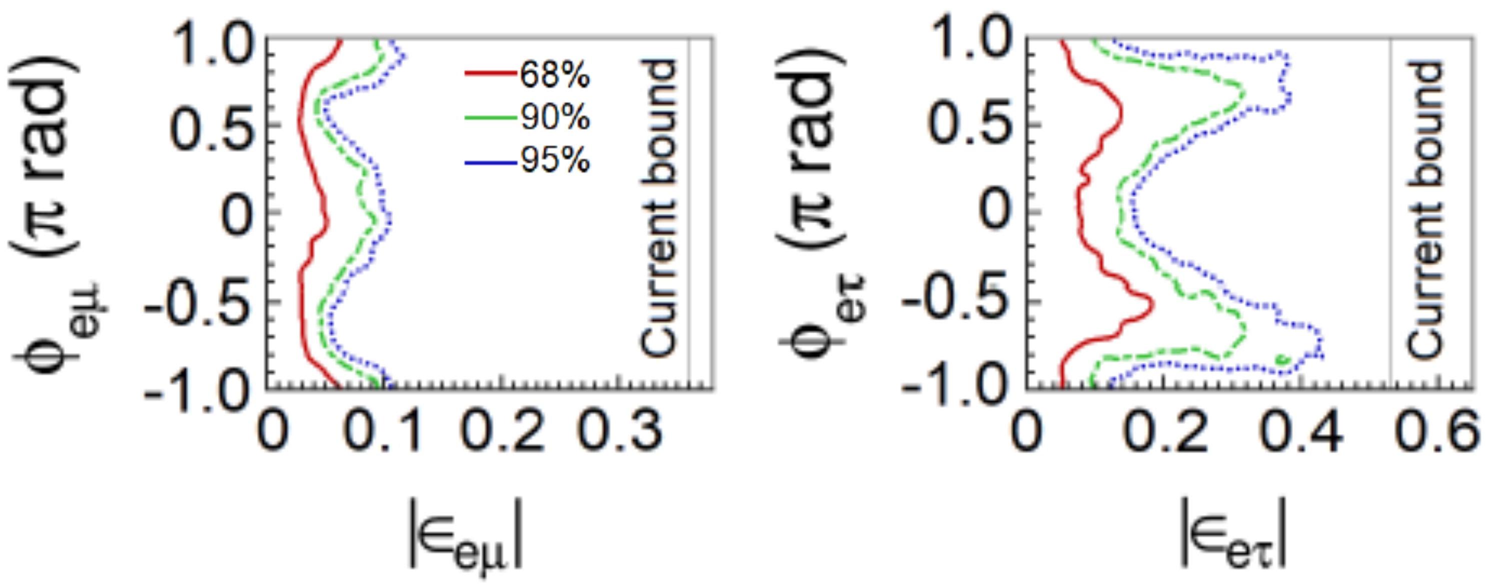
Non-Standard Neutrino Interactions



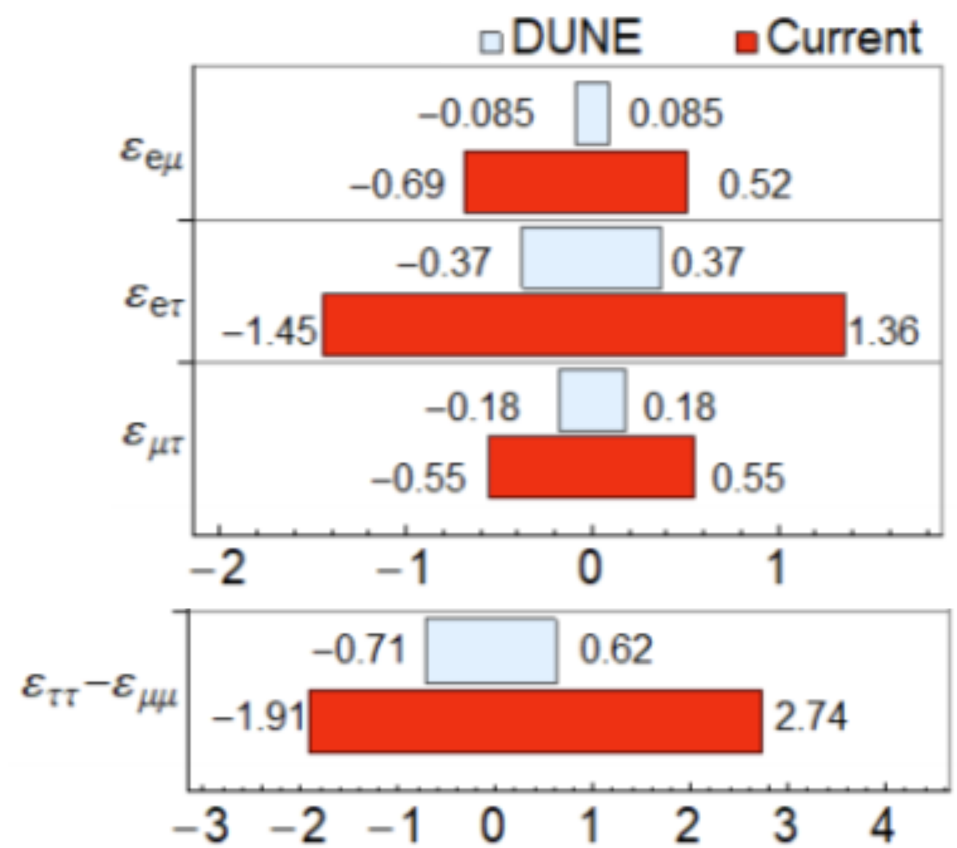
- Neutral-current non-standard interactions in propagation can be described as new contributions to the MSW effect:

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}\,, \quad \tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

- DUNE may improve current constraints on $|\epsilon_{e\tau}|$ and $|\epsilon_{e\mu}|$ by at least a factor of 2



- Allowed regions for an exposure of 300kt.MW.year
Current bounds are taken from [arXiv:1307.3092]



- 90% C.L. 1D DUNE constraints compared with current constrains in [arXiv:1710.09360]

CPT Symmetry Violation

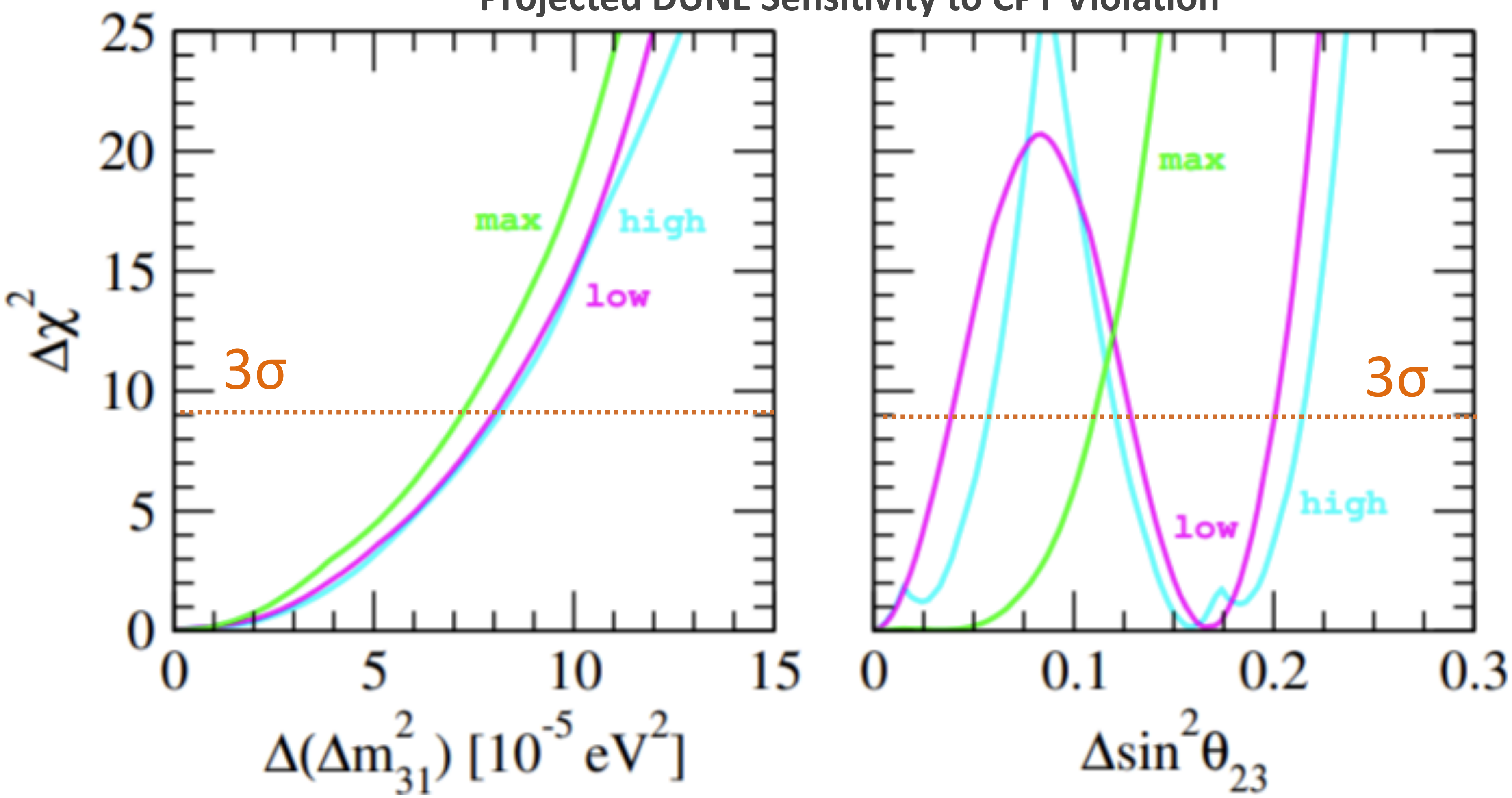
- CPT violation in the neutrino sector can be probed by separately measuring neutrino and antineutrino disappearance between ND and FD.

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow \text{CP violation}$$

$$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow \text{CPT violation}$$

- Projected sensitivity of DUNE to CPT violation for an exposure of 300kt.MW.year and different values of the θ_{23} mixing angle: maximal mixing (green), lower octant (magenta), and upper octant (blue).

Projected DUNE Sensitivity to CPT Violation

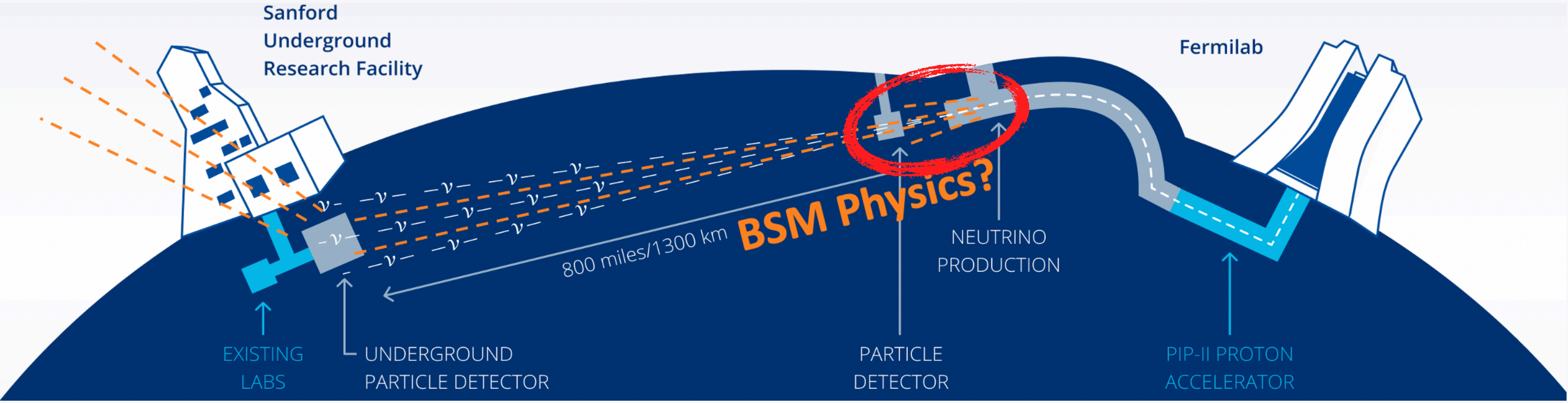


Parameter	Value
Δm^2_{21}	7.56×10^{-5}eV^2
Δm^2_{31}	2.55×10^{-3}eV^2
$\sin^2\theta_{12}$	0.321
$\sin^2\theta_{23}$	0.43, 0.50, 0.60
$\sin^2\theta_{13}$	0.02155
δ	1.50π

arXiv:1712.01714

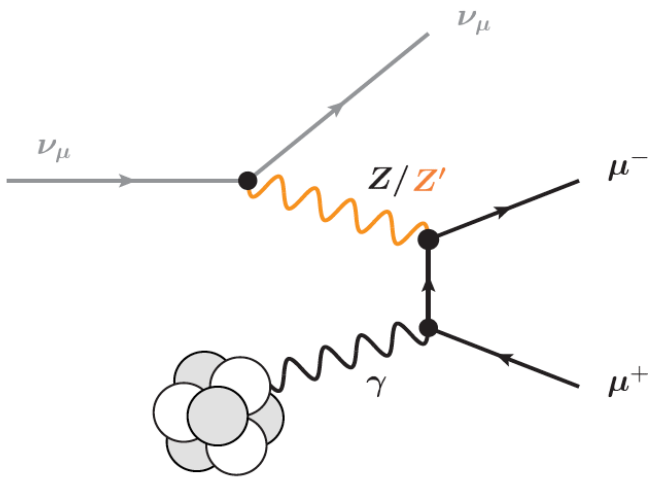
- DUNE can improve current limit on $\Delta(\Delta m^2_{31})$ by one order of magnitude: $\Delta(\Delta m^2_{31}) < 8.1\times10^{-5}$ eV^2

New Physics at the Near Detector



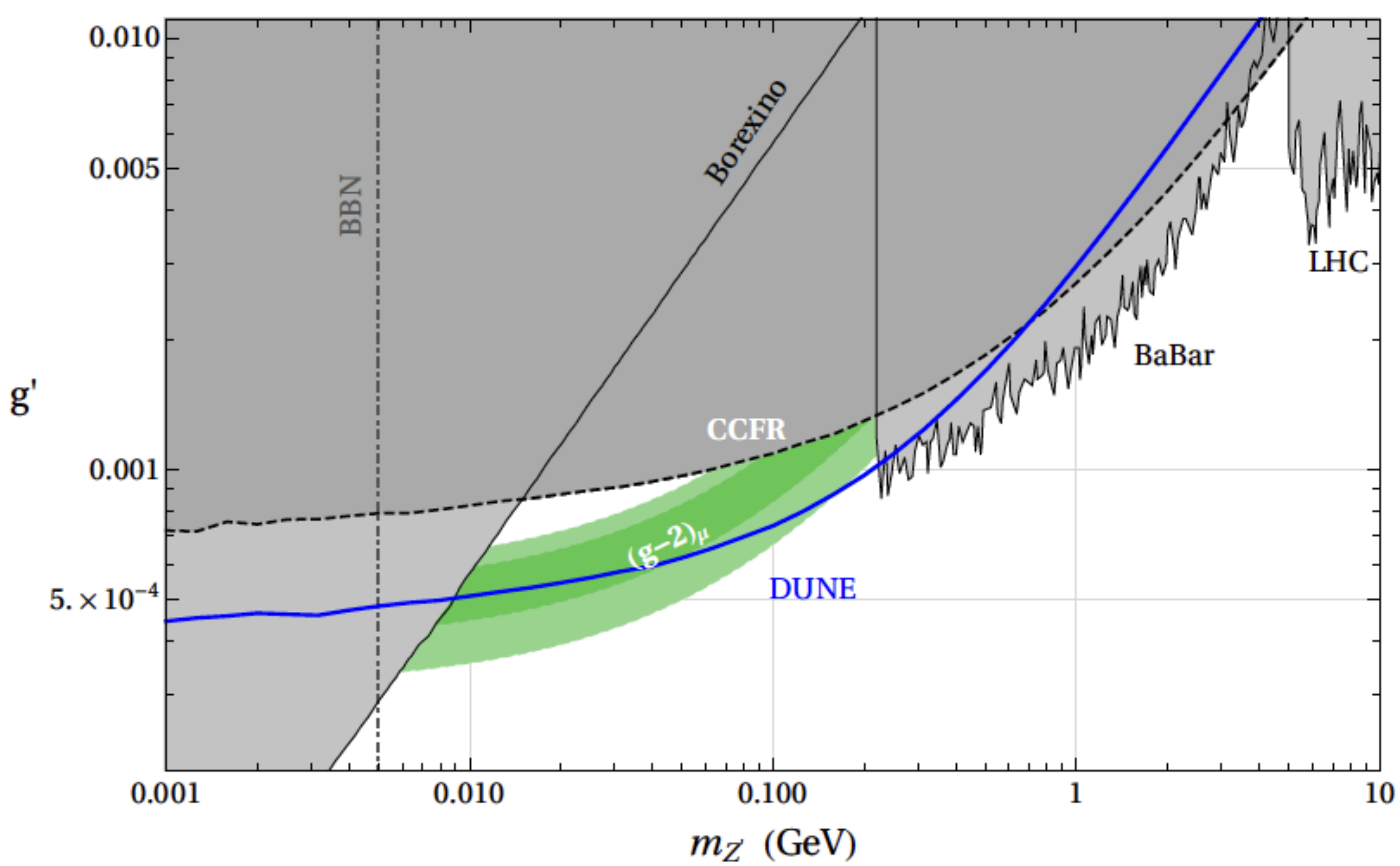
Neutrino Tridents at the ND

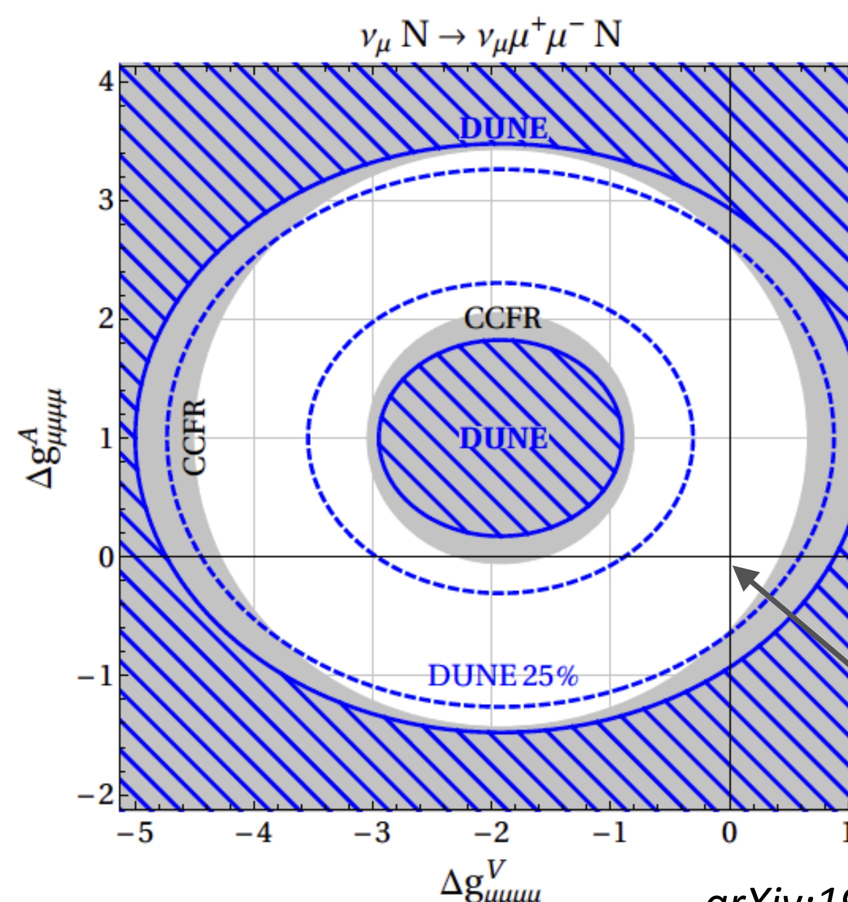
- Rare SM process. Has been observed with measured cross section in good agreement with SM



$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\rm exp}}{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\rm SM}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$

- Departure from SM prediction can be evidence for new physics: DUNE can be sensitive to the existence of light vector mediators, *e.g.* Z', which could explain $(g-2)_\mu$ anomaly
- May be improved further with Machine-learning-based event selection

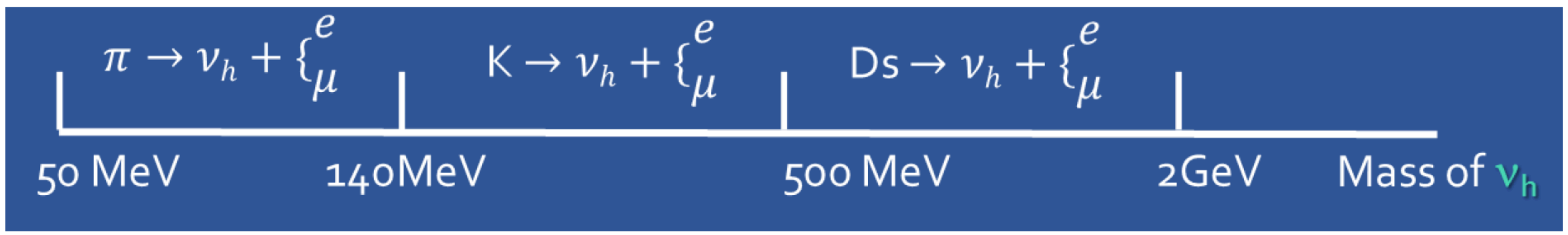


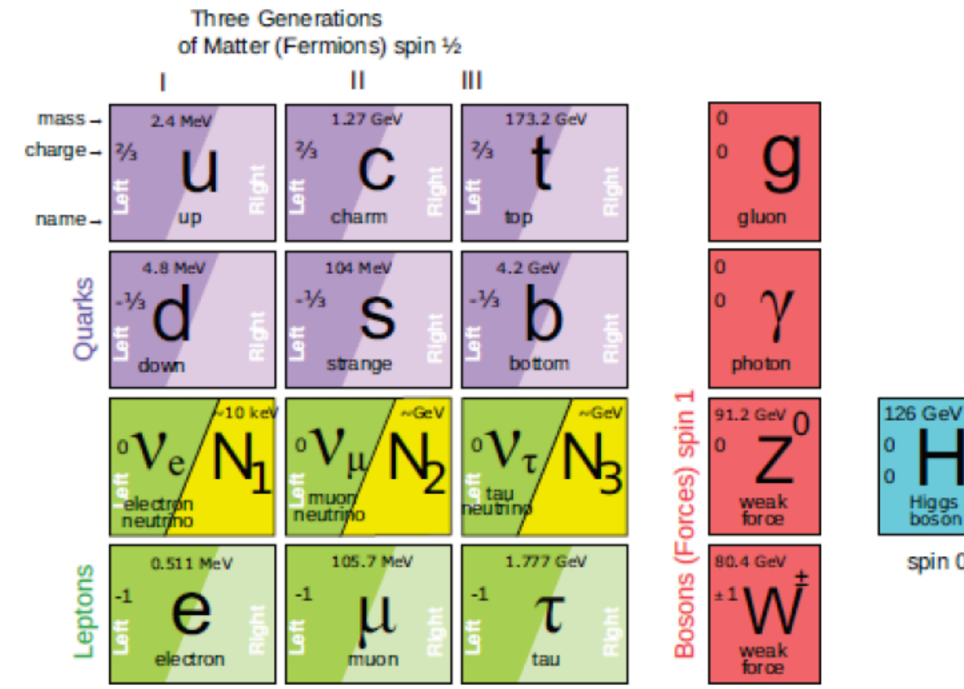


arXiv:1902.06765

Heavy Neutral Leptons at the ND

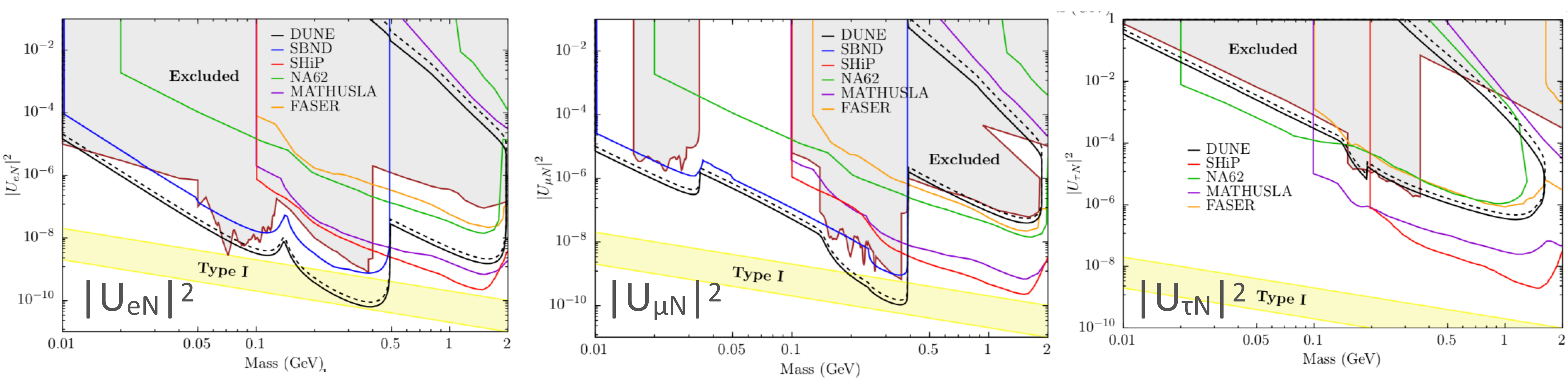
- Right-handed partners singlets N=3 extension of the SM
- May be created by meson decays in the LBNF beam





- Showing DUNE's 90% CL sensitivity to mixing between the active neutrinos and HNLs over a HNL mass range of 10 MeV to 2 GeV

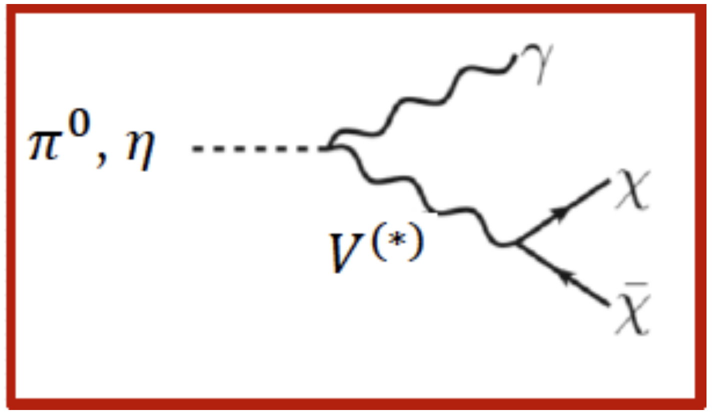
arXiv:1905.00284



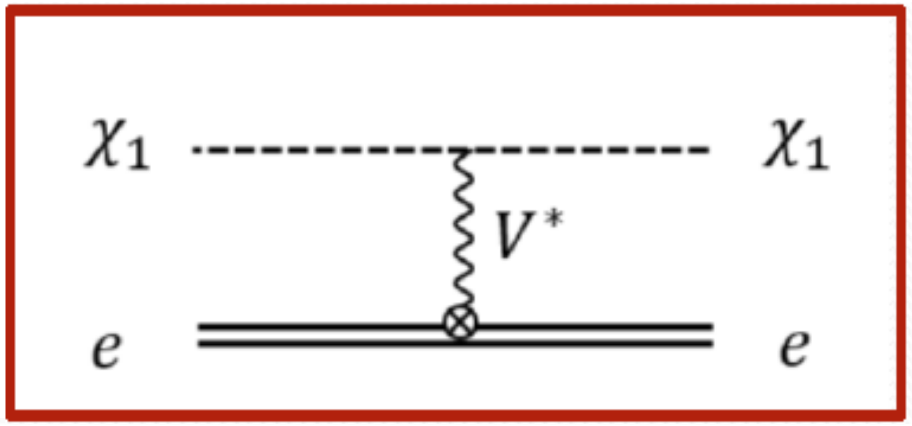
- DUNE will improve on present experimental limits and be competitive with proposed new efforts measure HNLs

Low-Mass Dark Matter at the ND

- Production of low-mass dark matter in the LBNF beam is possible through π^0, η decays into a dark photon V

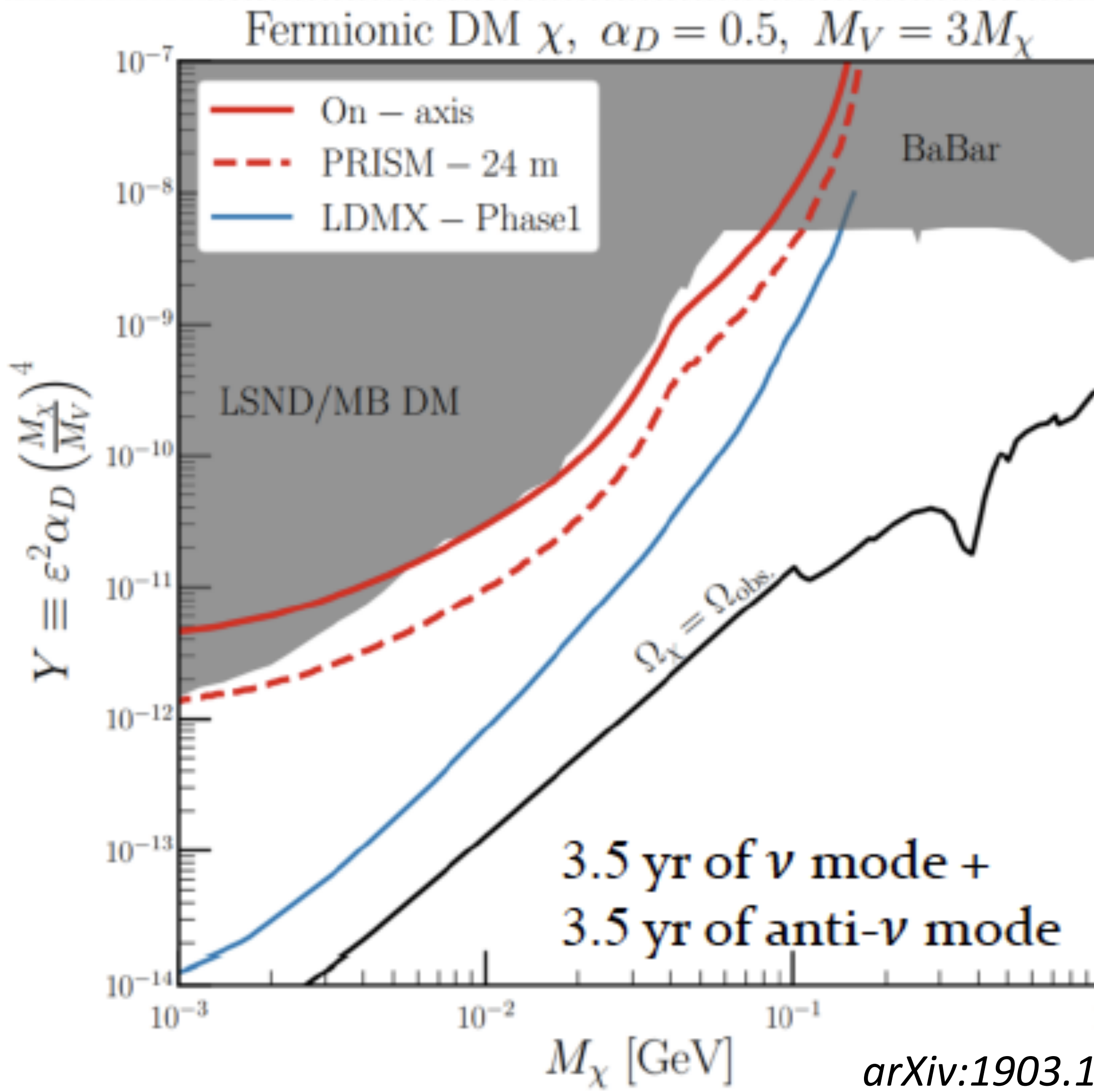


- Considering dark matter elastically interacting with electrons in the ND



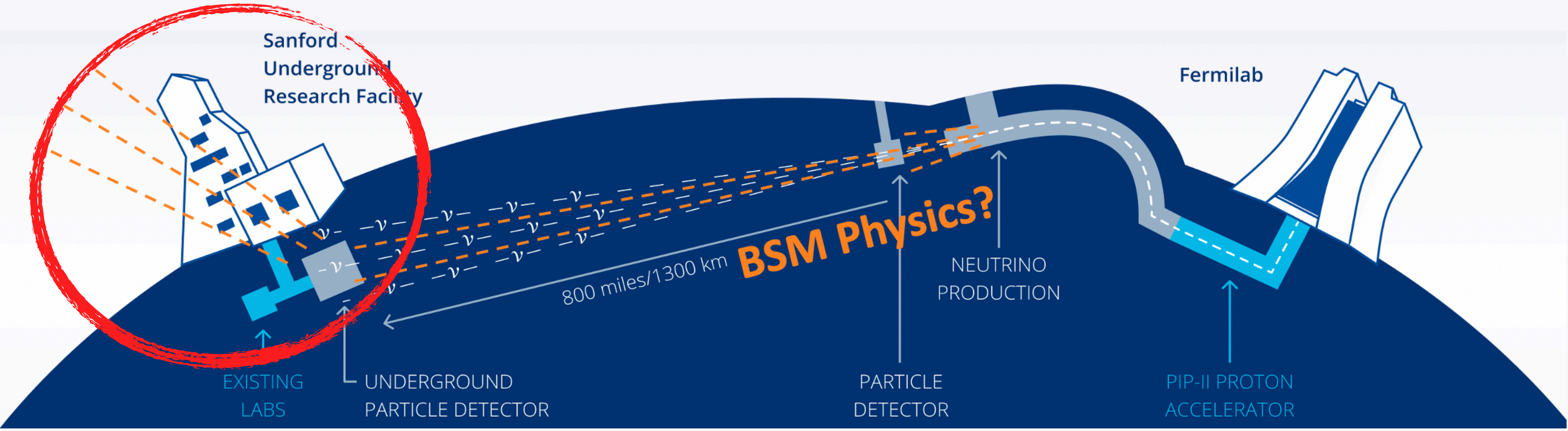
- Showing sensitivity (90% CL) of DUNE for a 7-year (50% neutrino beam, 50% antineutrino) run.

- The main background (neutrino-electron scattering) can be suppressed by taking data with ND off-axis (DUNE-PRISM)



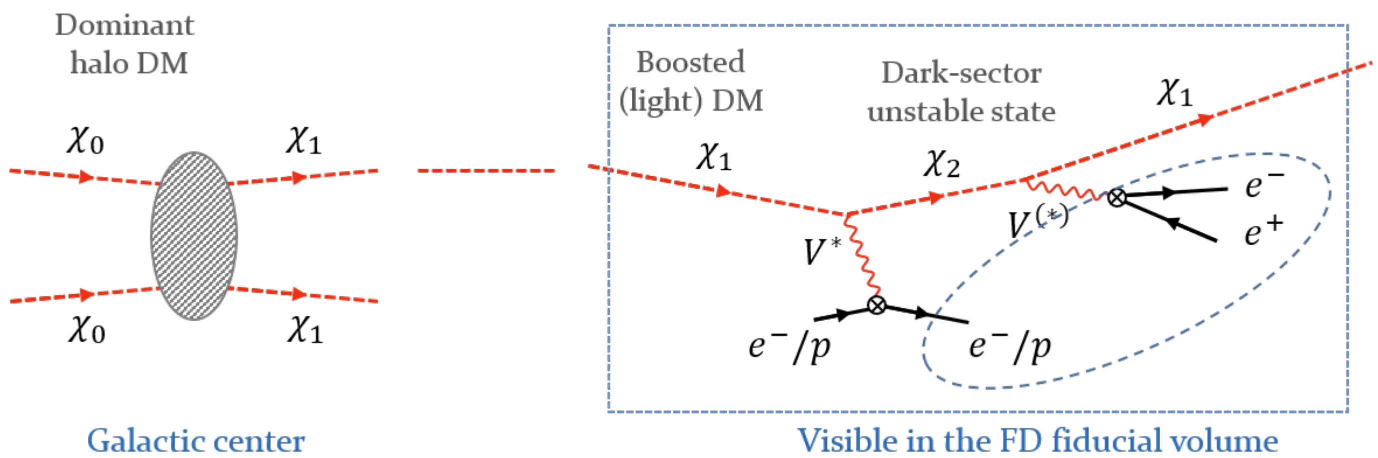
arXiv:1903.10505

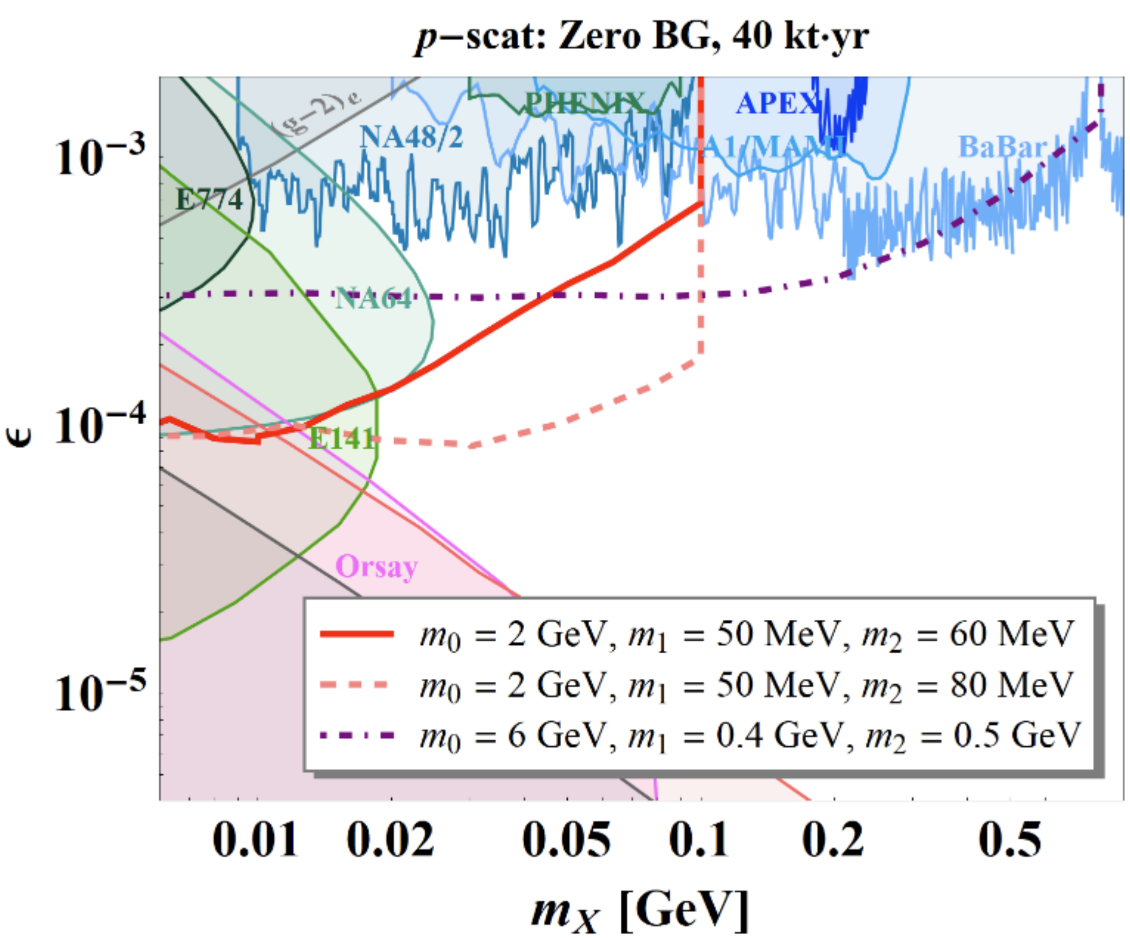
New Physics at the Far Detector

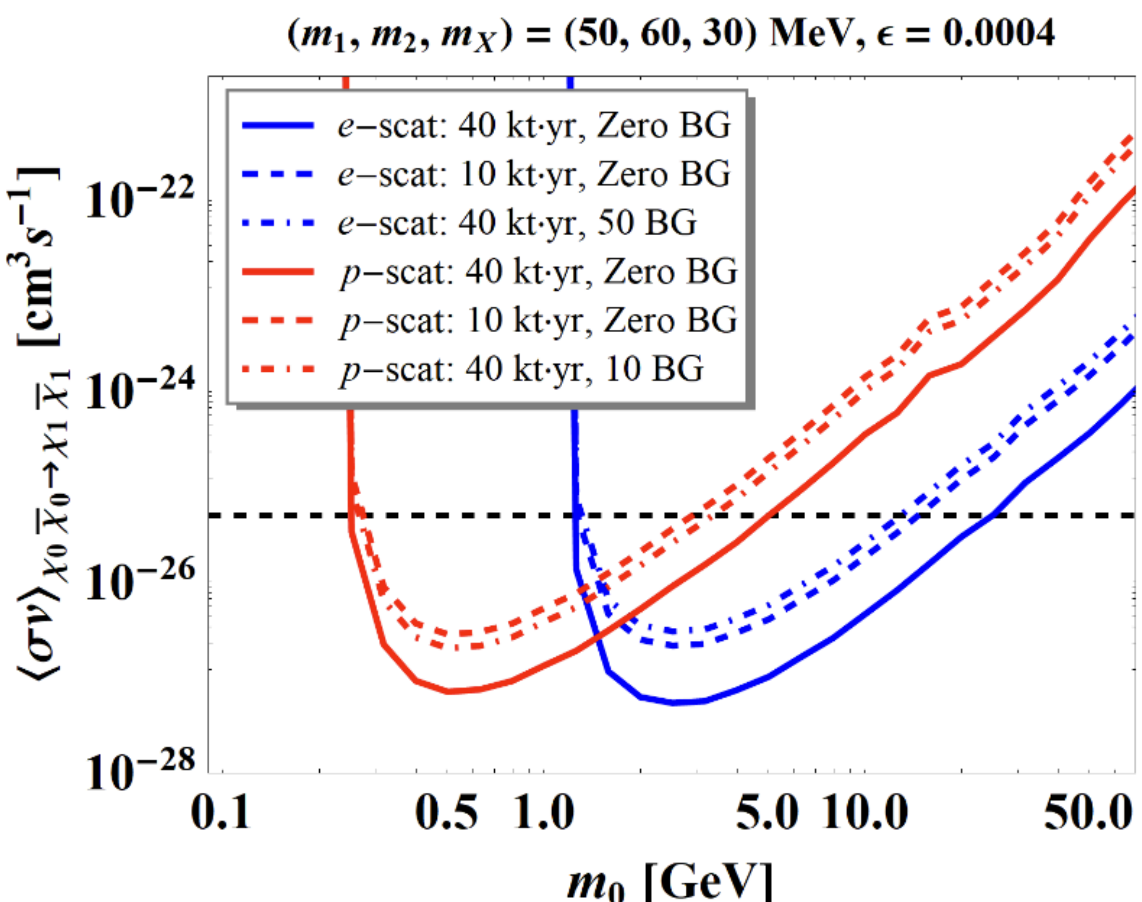


Inelastic Boosted Dark Matter

- The DUNE far detector modules, with a large fiducial mass of 40 kton and high tracking resolution, can be sensitive to boosted (light) dark matter signals with multiple particle tracks
  - *e.g.*, inelastic boosted dark matter from the galactic core [*arXiv: 1612.06867*]





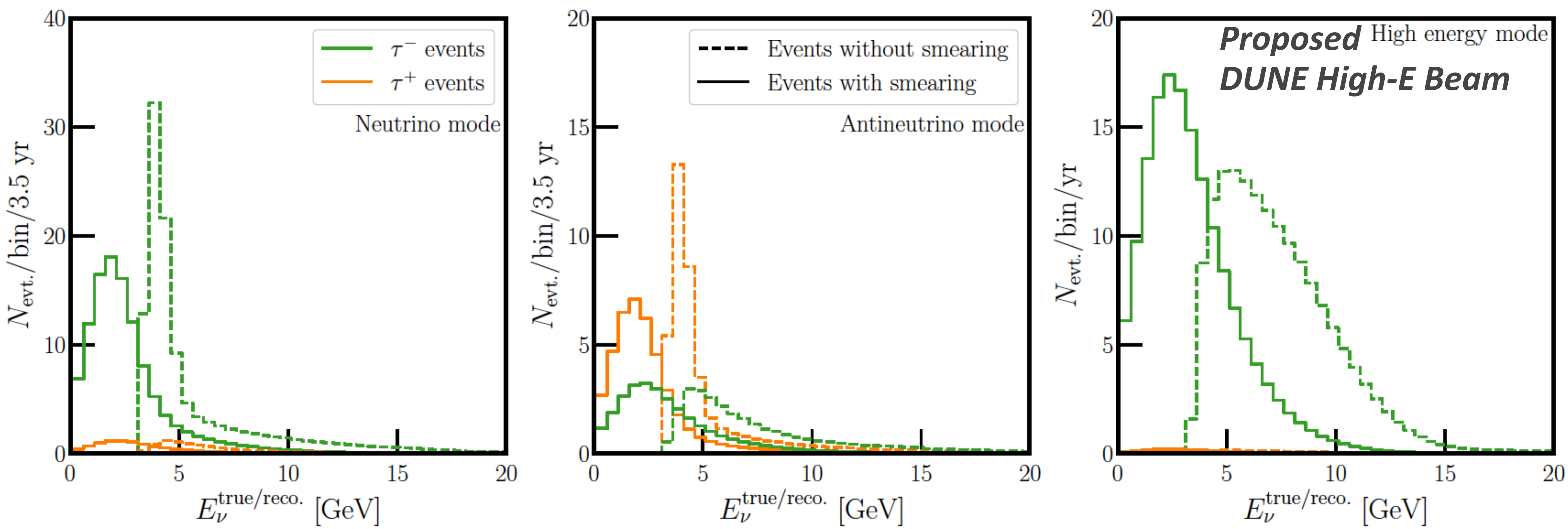


arXiv:2005.08979

BSM Opportunities with ν_τ

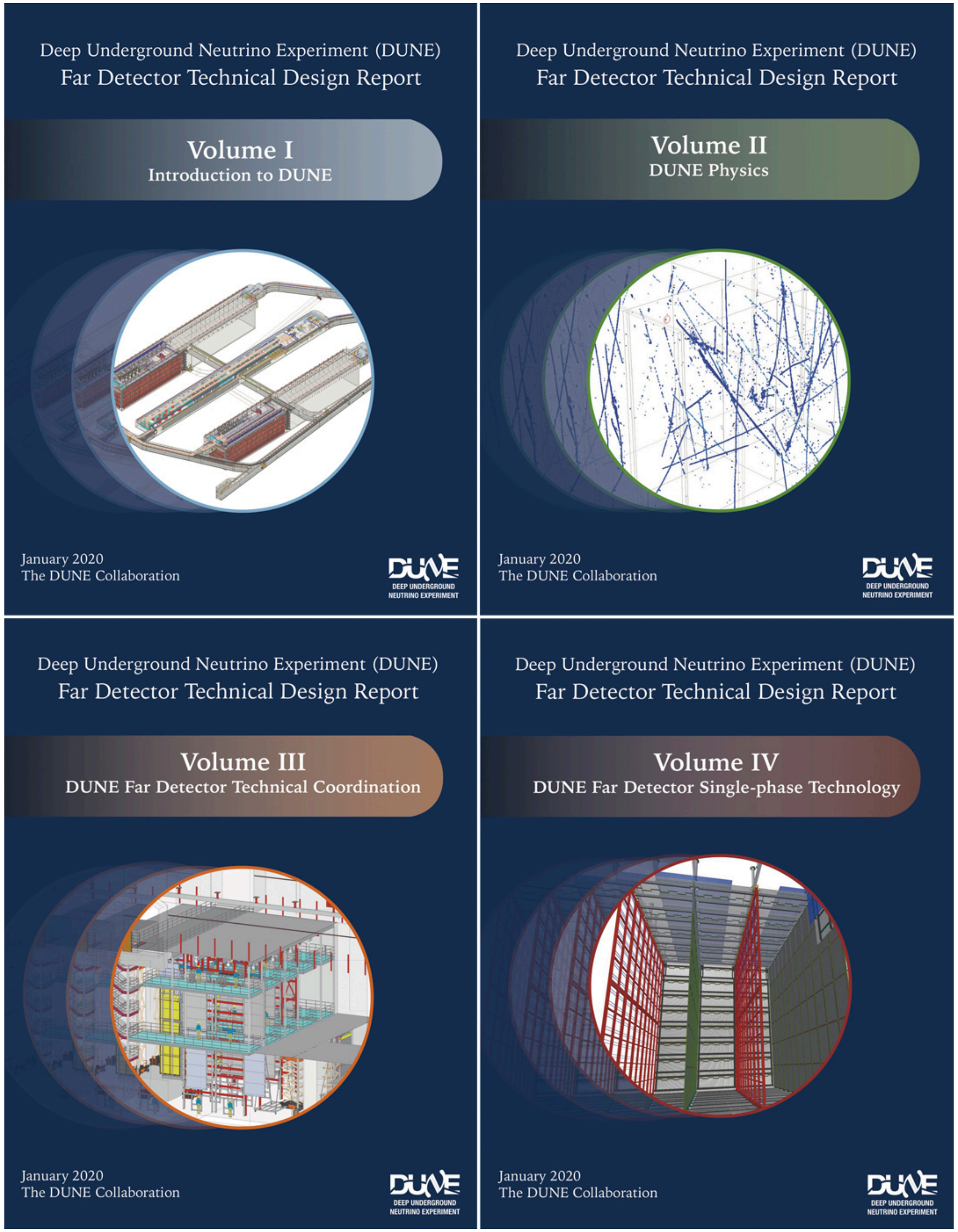
- Currently, almost all knowledge of the tau neutrino sector is taken from lepton universality for cross sections and unitarity of the PMNS neutrino mixing matrix
- Tau neutrinos are challenging to select and reconstruct, but they could provide valuable complementary information for BSM physics searches.
- Beam event statistics (for flat efficiency of 30%):
  - Low-E Beam: ~130 ν_τ CC/year; ~30 $\bar{\nu}_\tau$ CC/year
  - High-E Beam: ~800 ν_τ CC/year
- Expect and additional ~70 ν_τ and $\bar{\nu}_\tau$ CC in atmospheric exposure of 350 kton.year
- If tau neutrinos can be selected and reconstructed, it is possible to go after a rich physics program
  - "unitarity triangle"-like test of ν oscillations
  - Heavy or light new neutrino states.
  - Non-standard neutral-current neutrino interactions.
  - Neutrino decay…

arXiv:1904.07265



DUNE Status and Plans

- Far site construction underway
- Near site preparation underway
- Prototypes:
  - protoDUNEs (large scale FD prototypes at CERN Neutrino Platform) have completed Run-I data taking
  - Plans for protoDUNE-ND and protoDUNE Run-II underway
- Far detector physics data expected in late 2020s
- Neutrino beam expected to be available on similar timescale
- Details of timeline will be finalized when project is baselined (expected 2021)
- Far Detector TDR published in January 2020; Near Detector TDR in preparation
  - Recommended reading for full details on DUNE BSM Physics prospects!

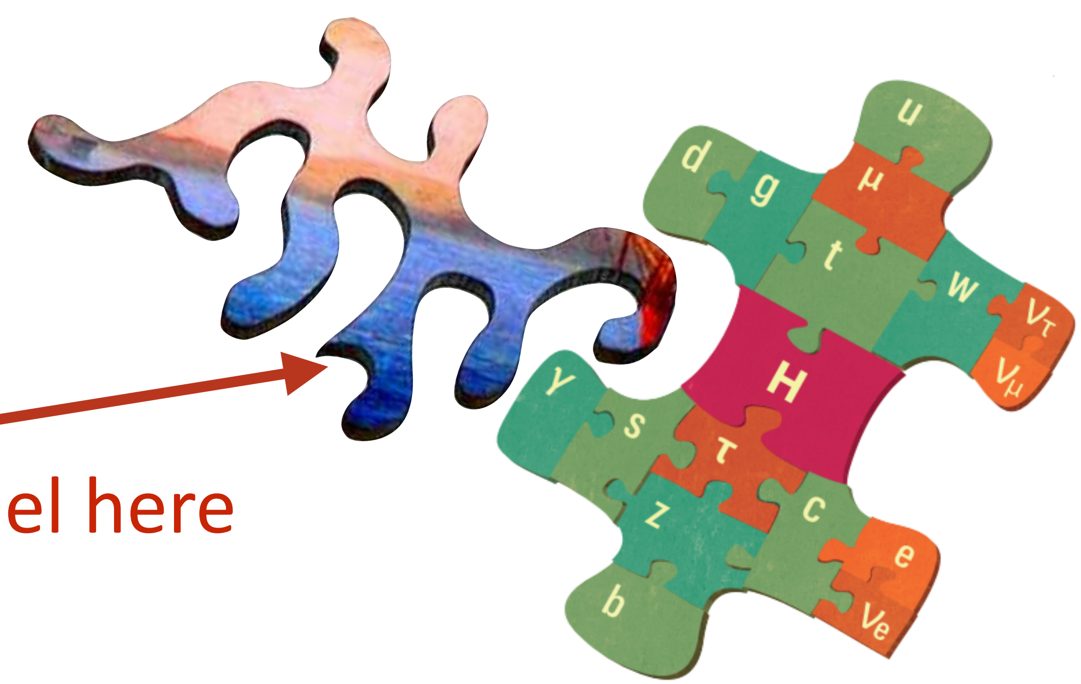


[DUNE Far Detector Technical Design Report]

[DUNE BSM Paper, arXiv:2002.03005, submitted to EPJ C]

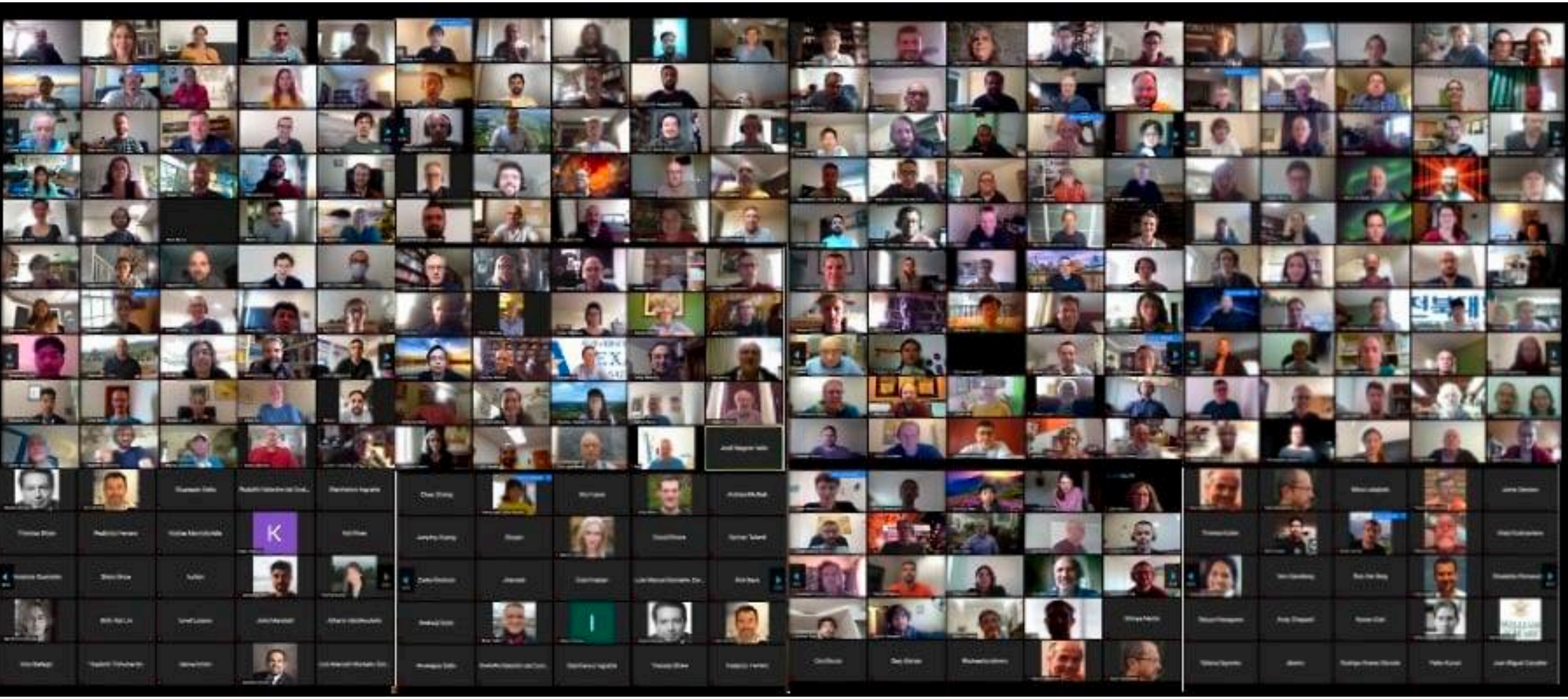
Summary and Outlook

- The highly-capable DUNE detectors and the powerful LBNF beam enable a very rich and diverse program for BSM Physics probes
- Exploration of these capabilities is a direct result from very productive collaborations between theorists/phenomenologists and experimentalists
- Look for further development of these results in the upcoming DUNE Near Detector Technical Design Report
- Currently working on adding further realism to existing studies and exploring some new scenarios - Your ideas are welcome!



Your favorite model here

DUNE Virtual Collaboration Meeting - Sept. 2020



Thank You!