Queen Mary
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DUNE: now and in the future

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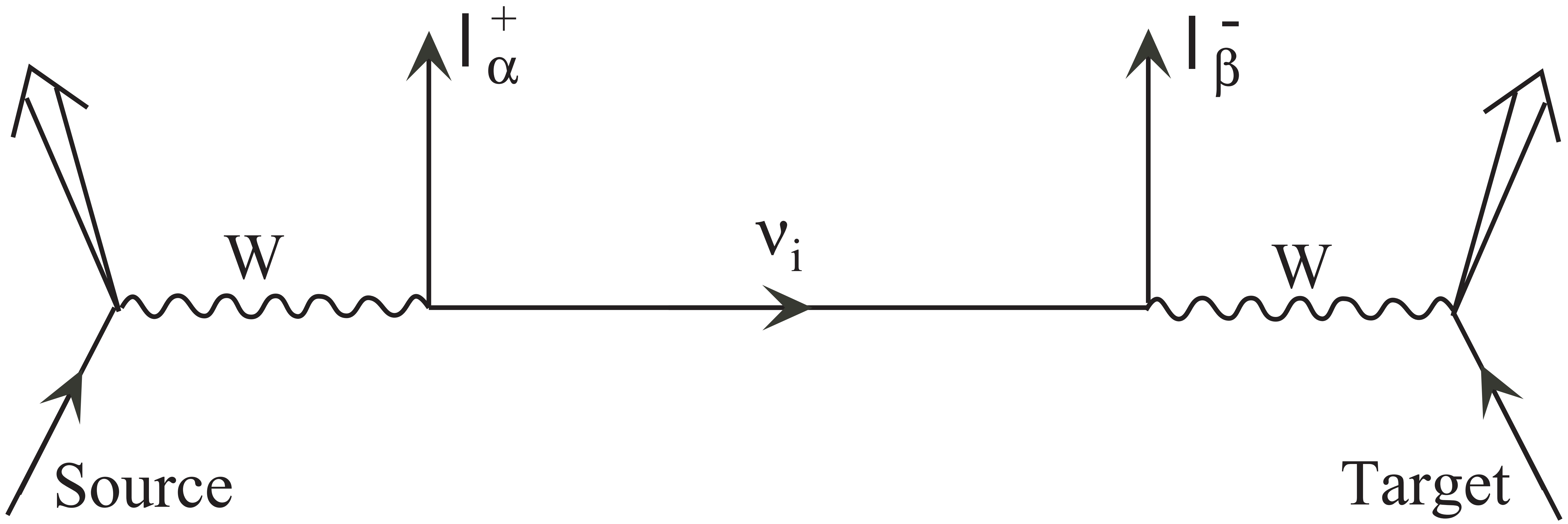
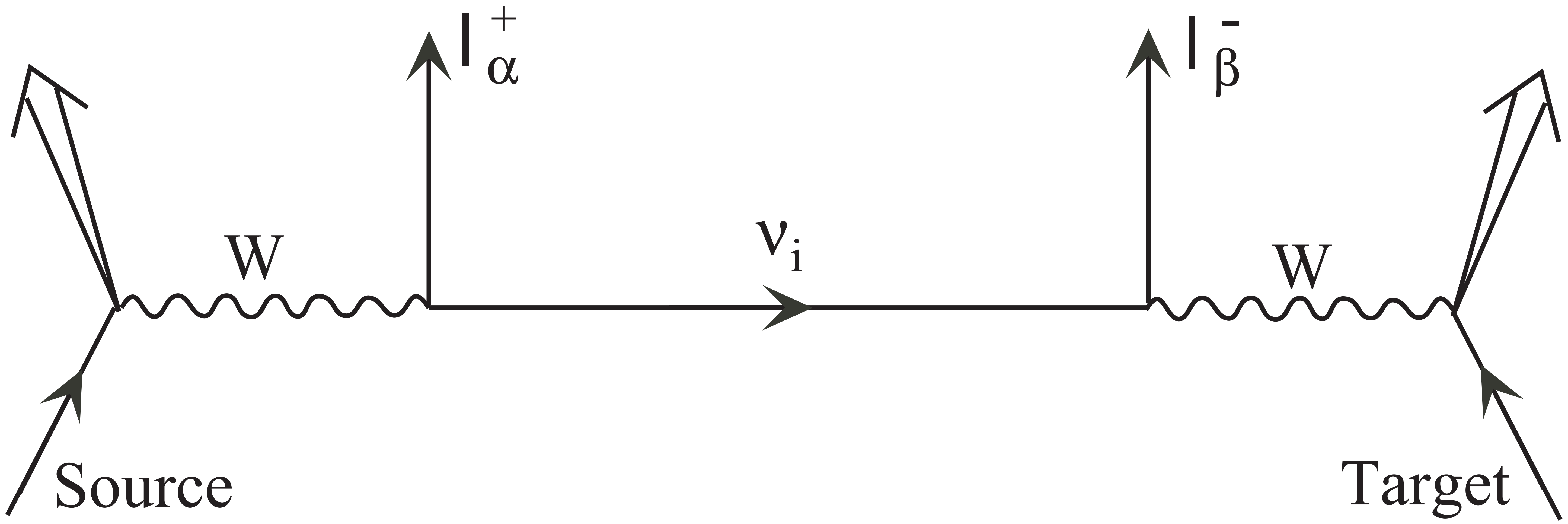
ECFA 2024, University of Durham, IPPP

Neutrino flavour oscillations: questions?



2015
Nobel Prize in Physics

Neutrino flavour oscillations: questions?



2015
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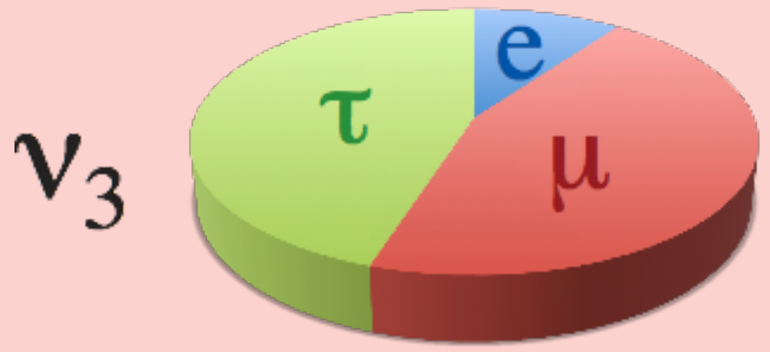
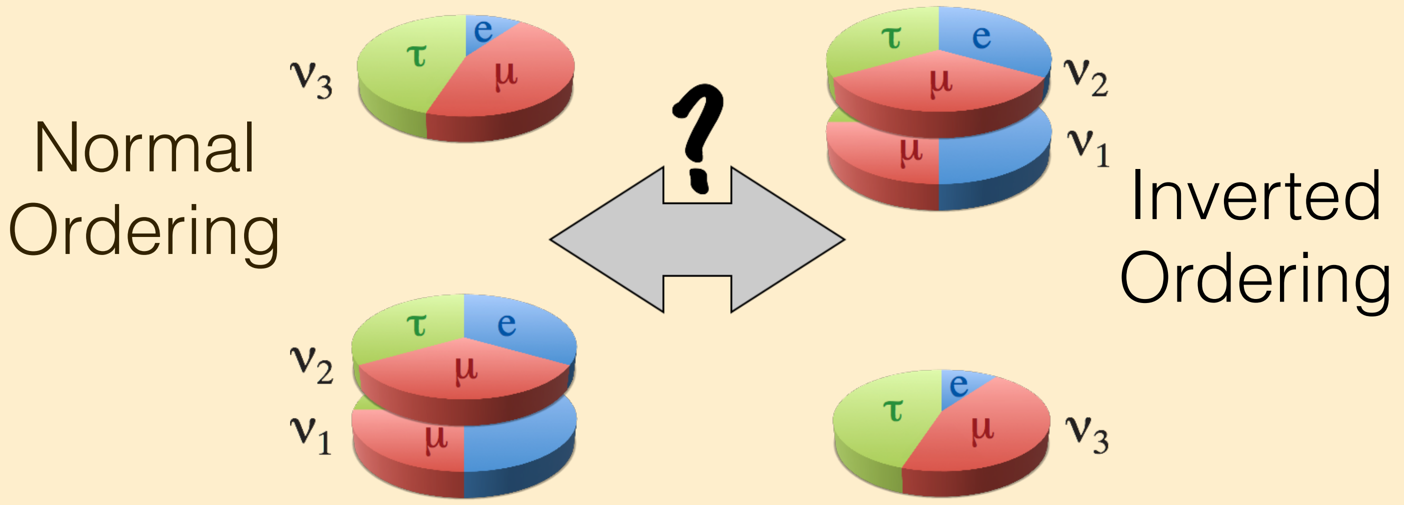
How much do neutrinos mix?



Jargon alert:
is θ_{23} maximal? Upper/Lower octant?

Which is the lightest neutrino?

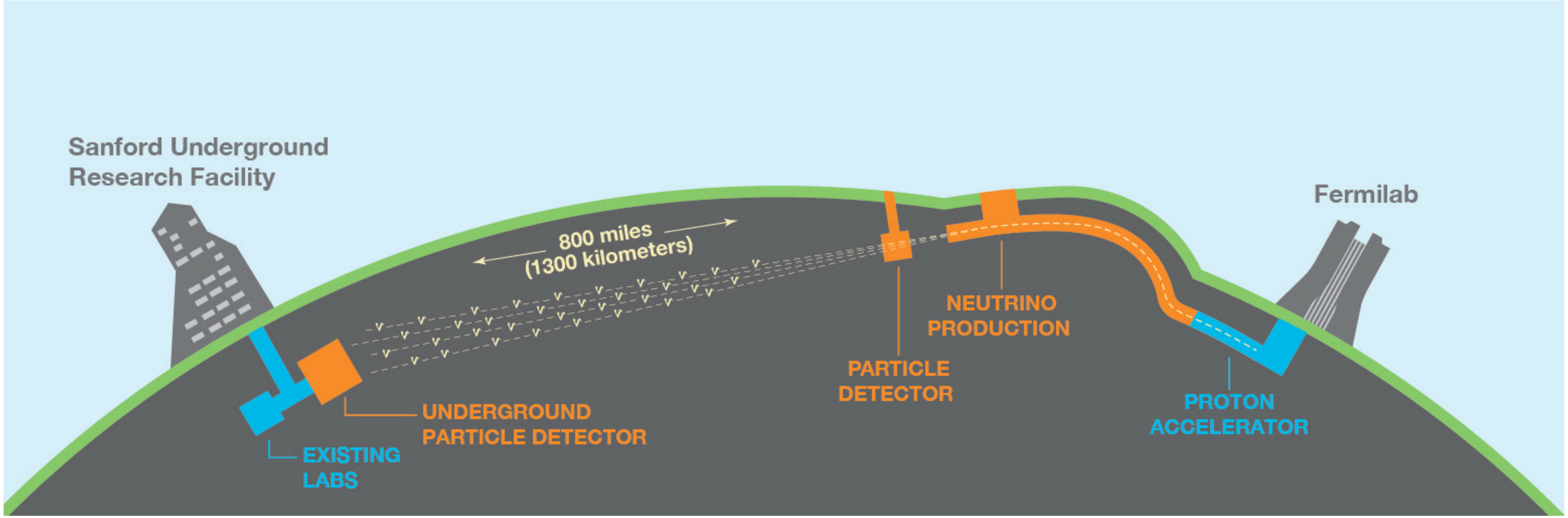


Jargon alert: is $\Delta m^2_{32} \lessgtr 0$?

Do neutrinos and antineutrinos oscillate in the same way?

Jargon alert: is $\delta_{CP} \neq 0$?

DUNE: Physics Goals



Discovery sensitivity to CP violation, mass ordering, and θ_{23} octant.

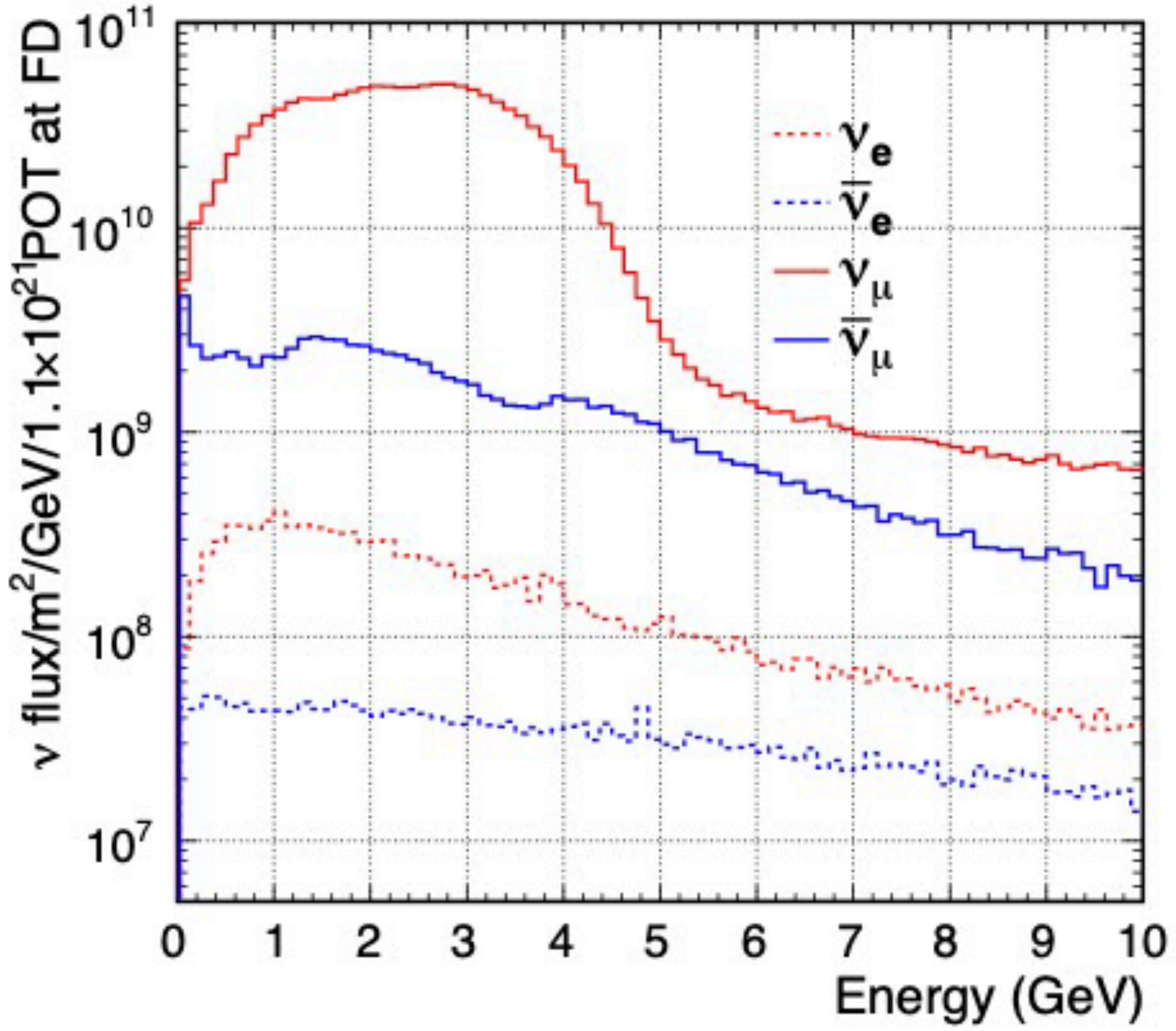
High-precision measurements of Δm^2_{32}, δ_{CP}, θ_{23}, θ_{13} in a single experiment.

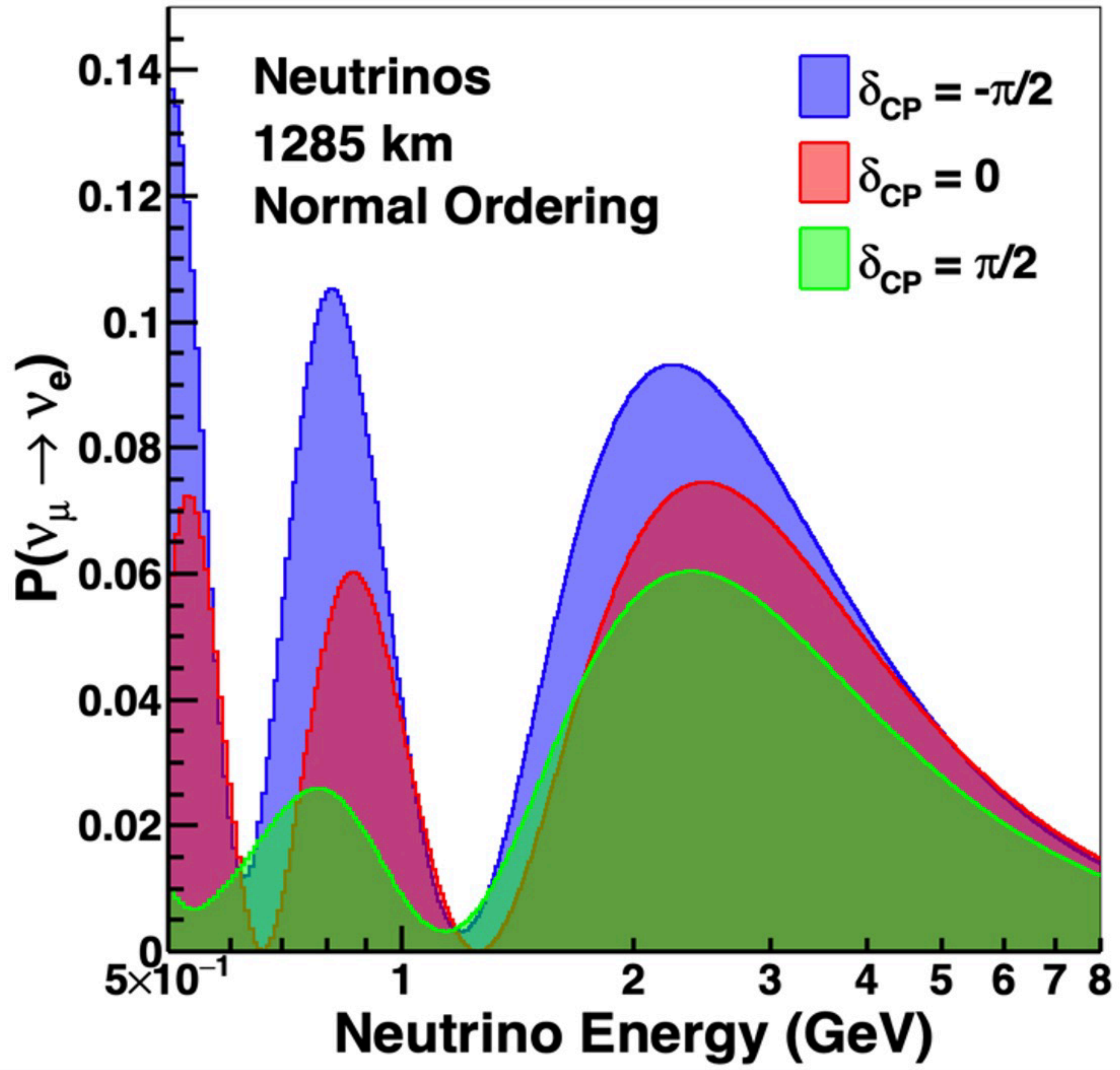
Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst.

Low backgrounds for sensitivity to BSM including baryon number violation.

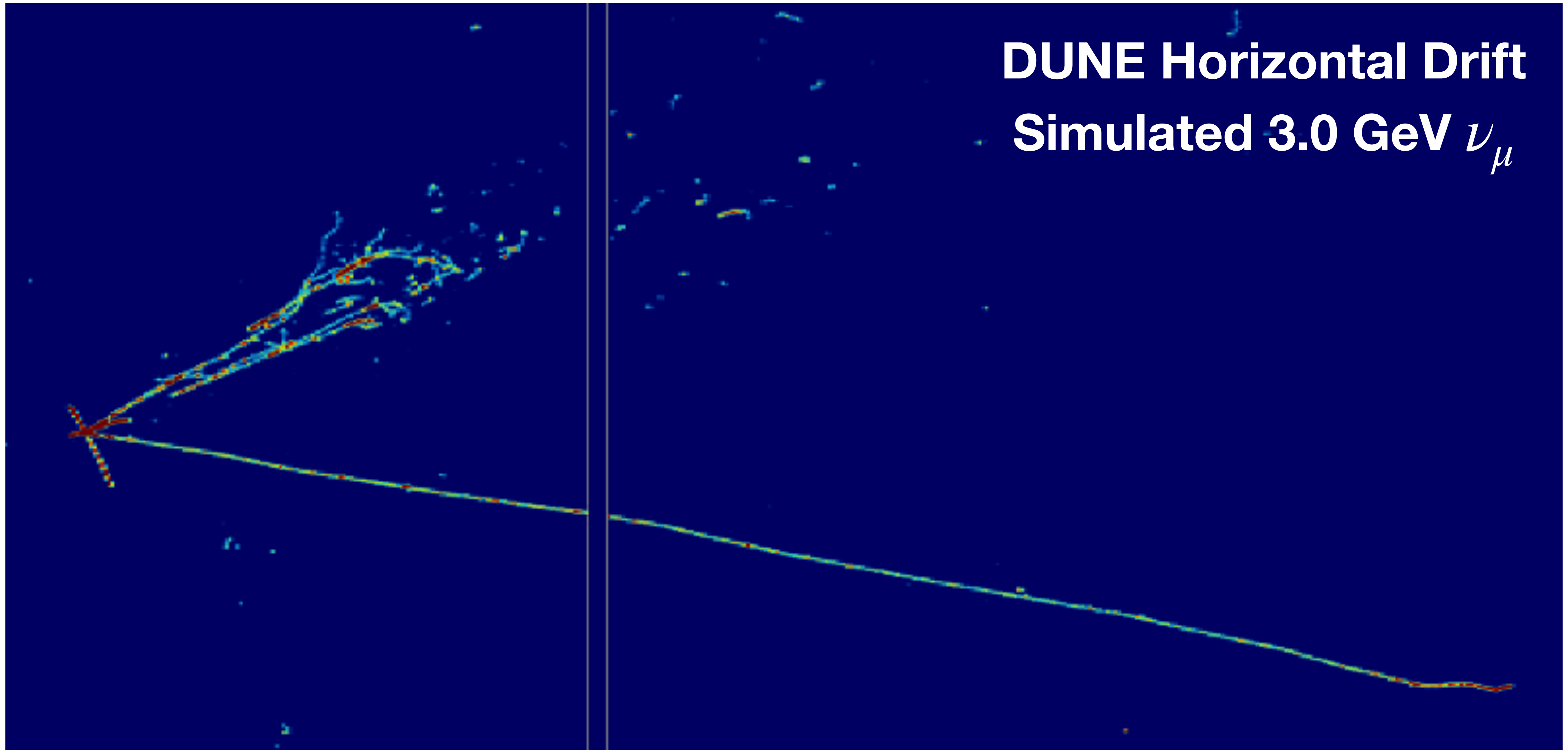
LBNF beamline: world-leading intensity

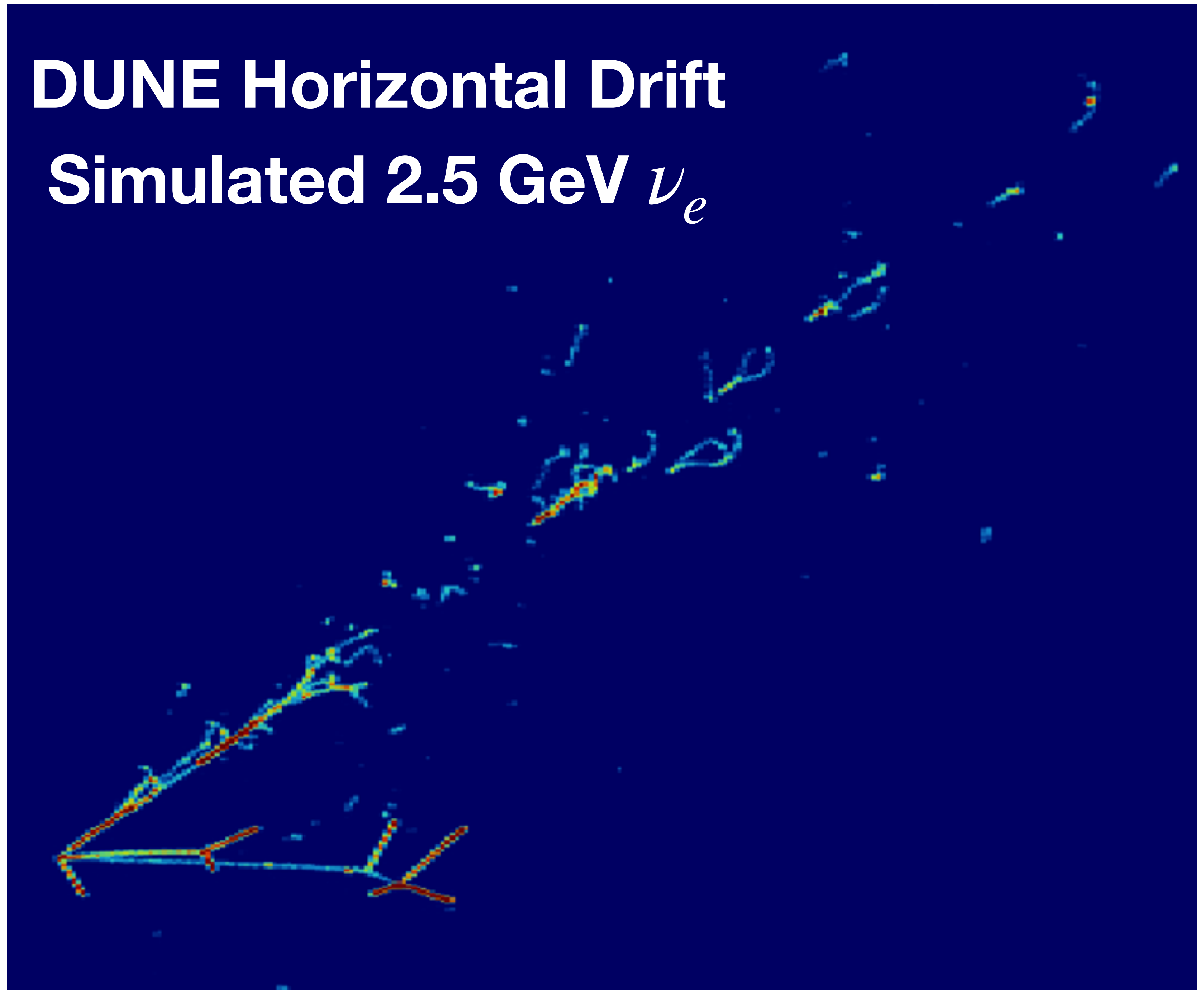
- Upgrade enables >2MW beam by ~doubling frequency of spills, and can be achieved before operations begin
- The long baseline + wideband beam provide unique ability to measure neutrino and antineutrino oscillations as a function of L/E - over more than a full oscillation period
- Does the three-flavor model describe the data?
    - If yes: measure the mixing angles, mass splittings, and CP phase
    - If no: characterize the new physics
- Need for a global program: different energies, matter effects, systematics, etc





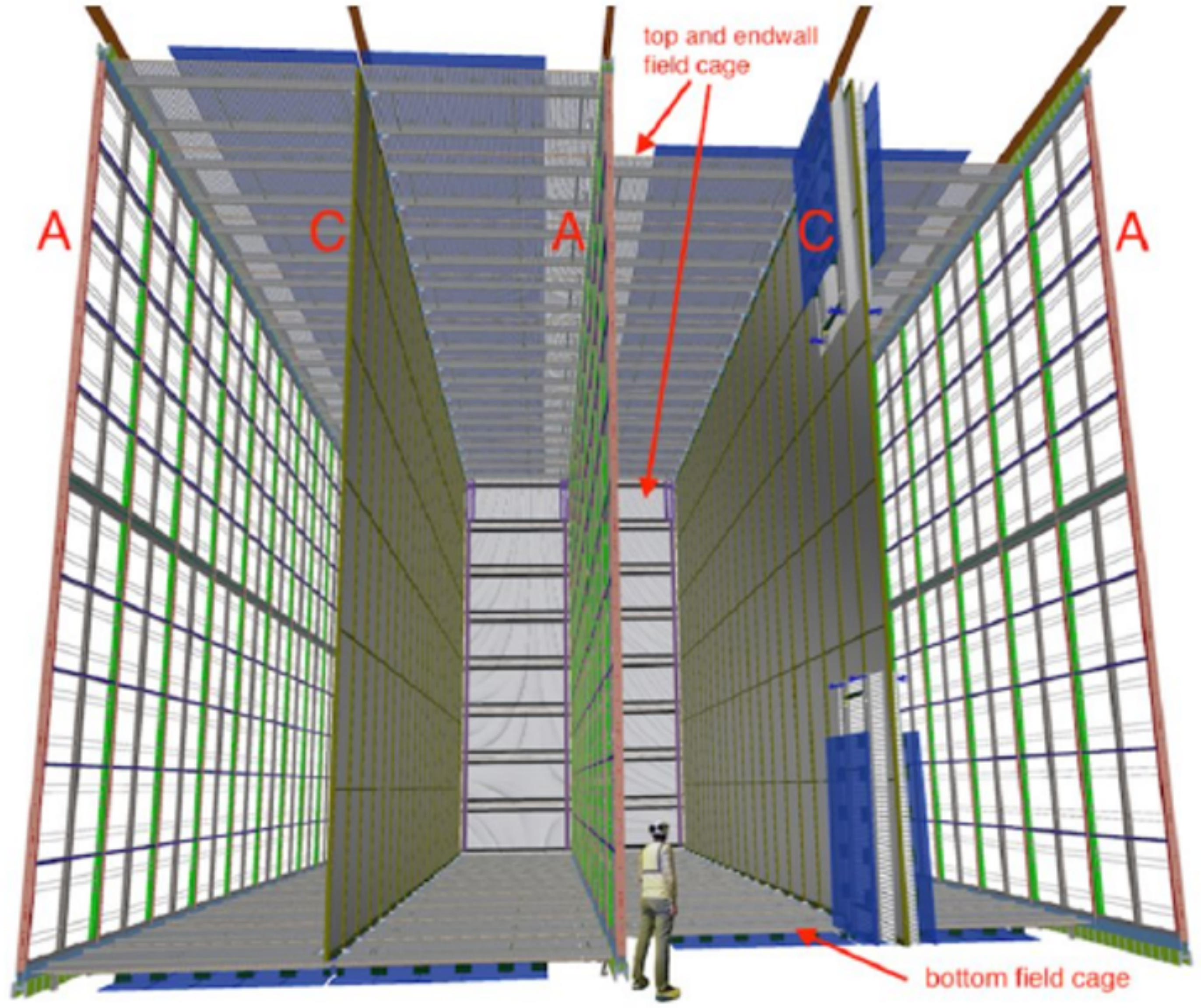
LArTPC: flavor & energy reco over a broad range of topologies



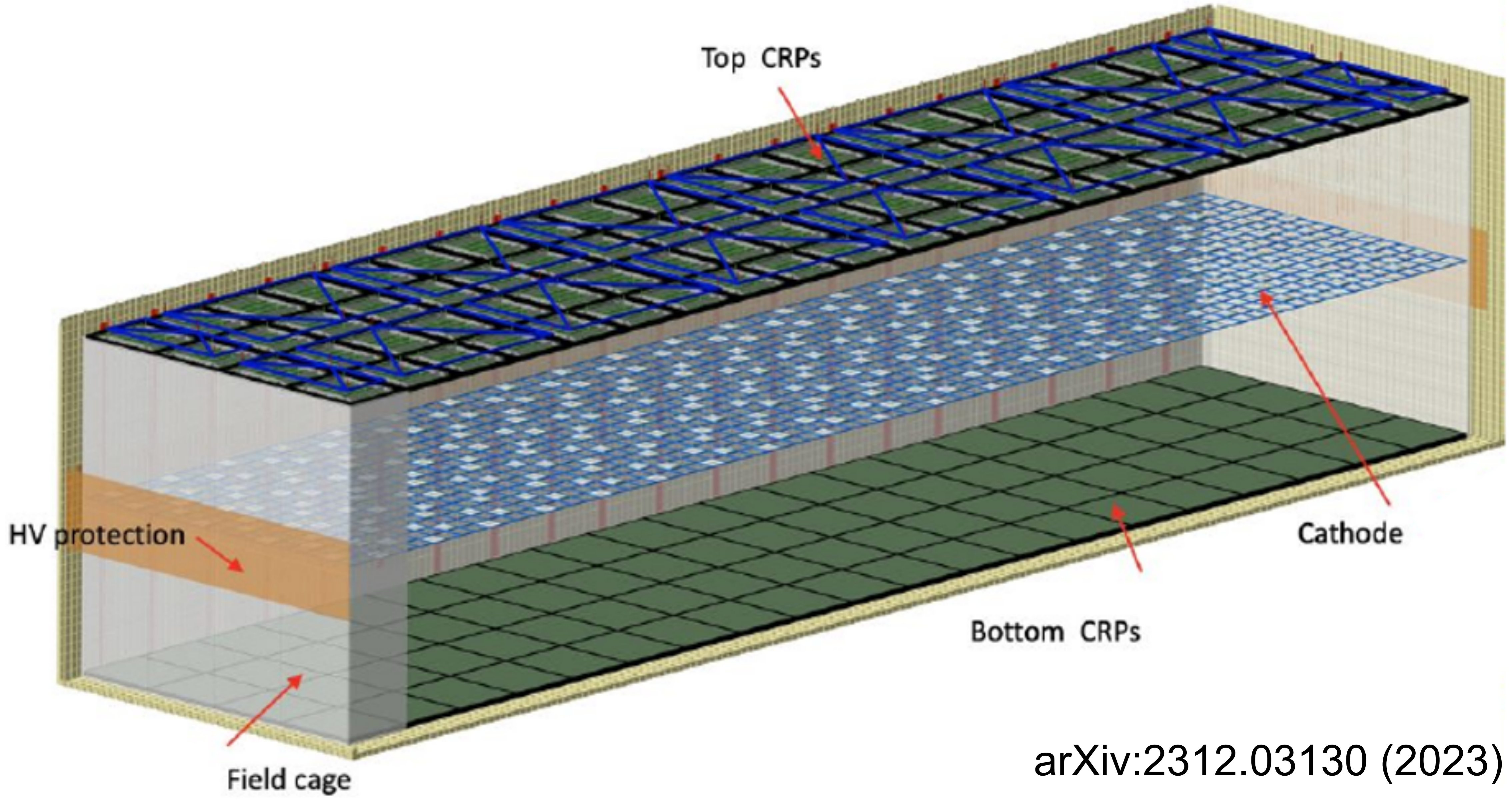


- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ and e/γ separation

Far Detector: two readout technologies



JINST 15 T08010 (2020)

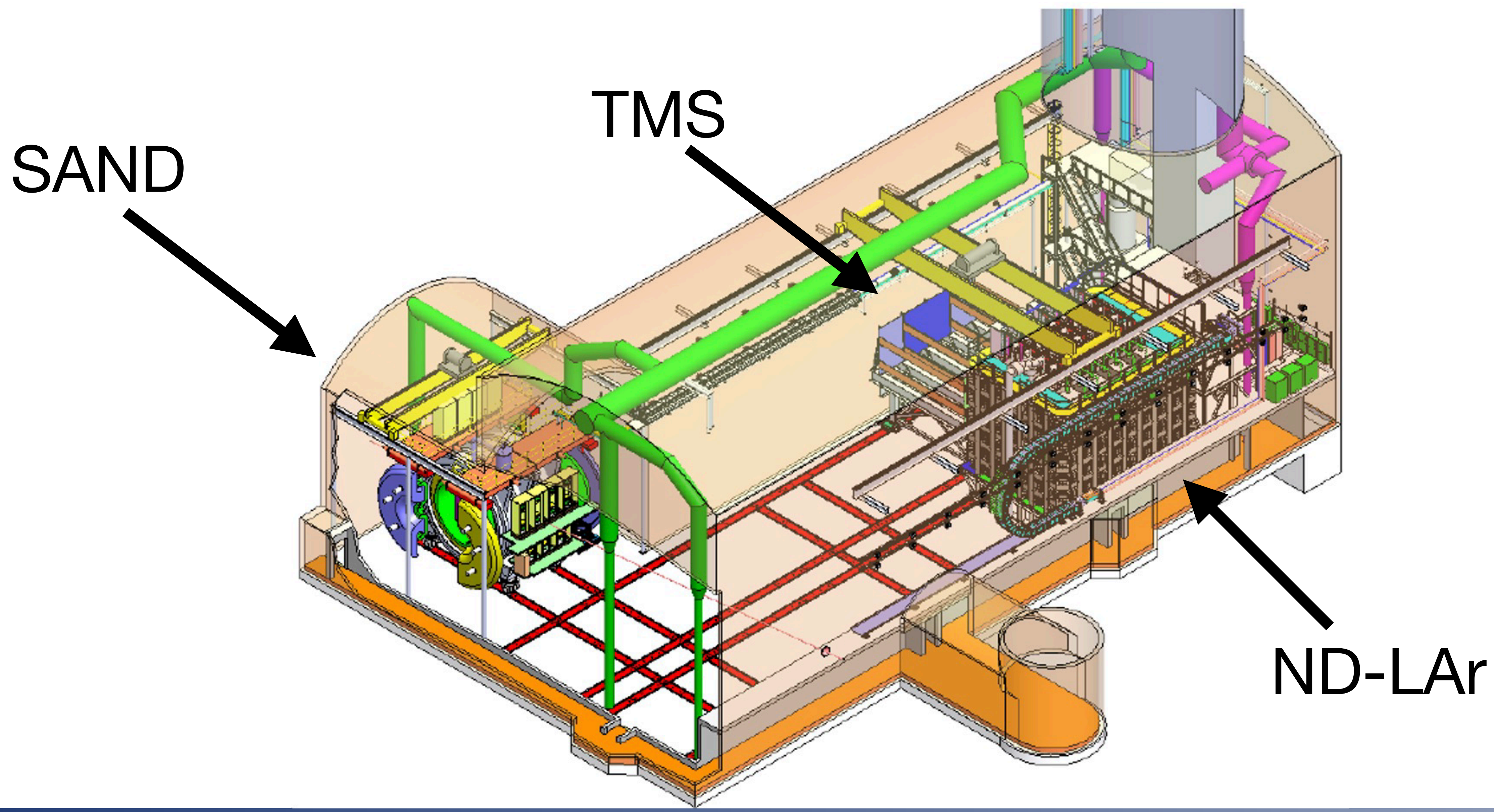


arXiv:2312.03130 (2023)

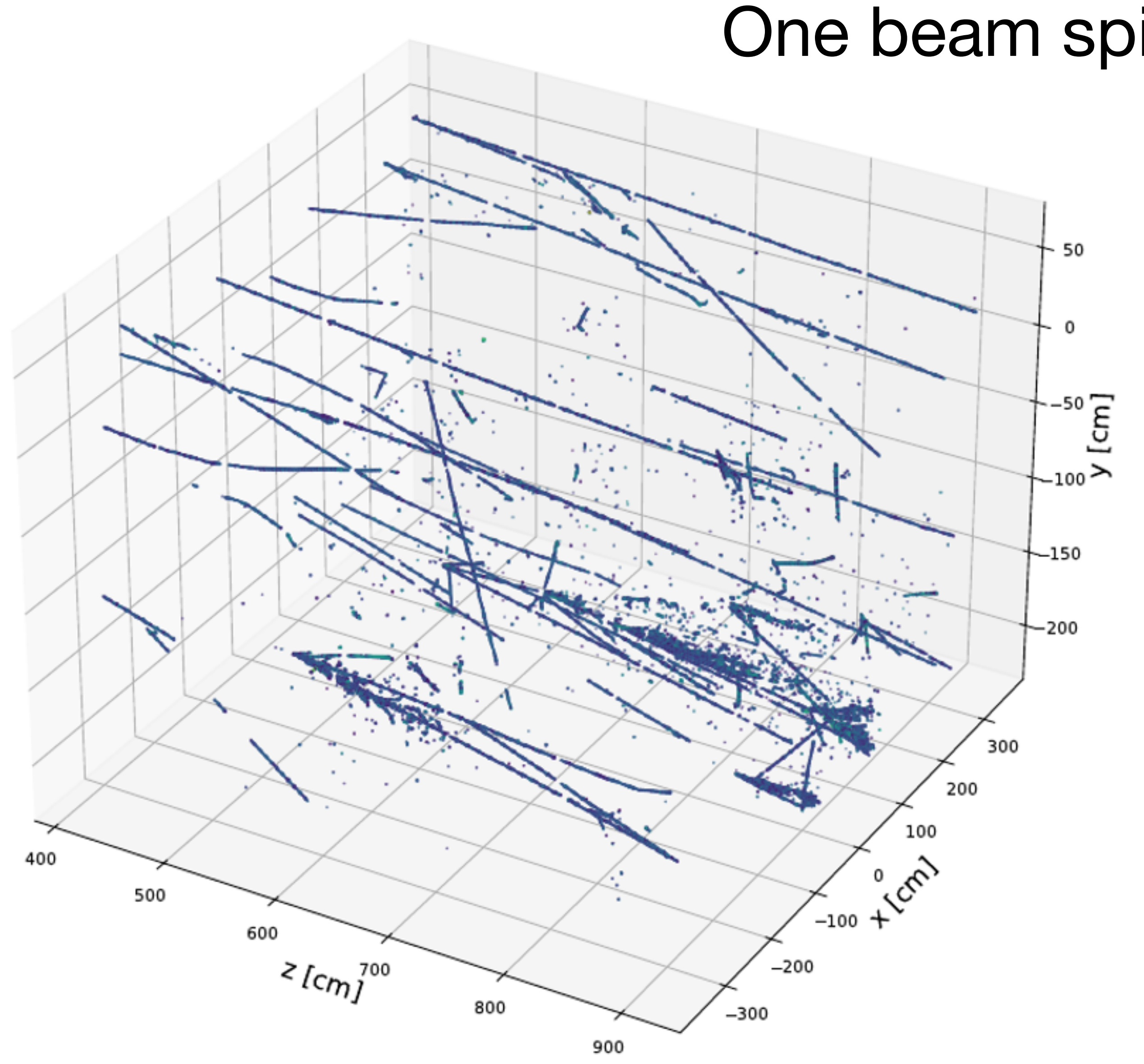
- Horizontal drift (HD, left) using wire readout planes, four drift regions
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for modules 3 and 4

DUNE Design: Systematics constraints for precision physics

- Main purpose: enable prediction of Far Detector reconstructed spectra
- Movable detector system: LArTPC with muon spectrometer
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed Eν in Far Detector



One beam spill at ND-LAr



DUNE Plans and Installation

Phase I

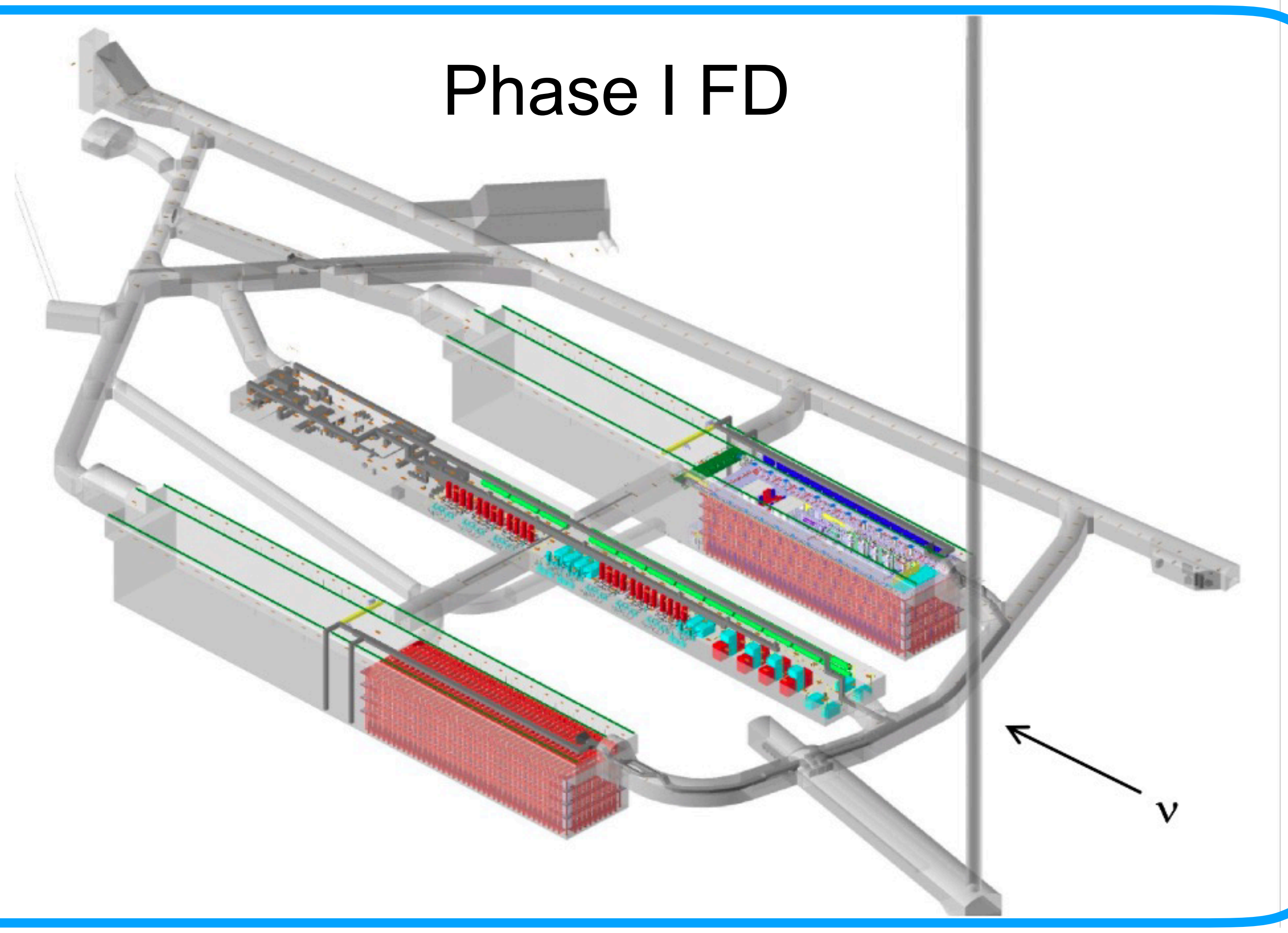
Ramp to 1.2 MW beam intensity

Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.

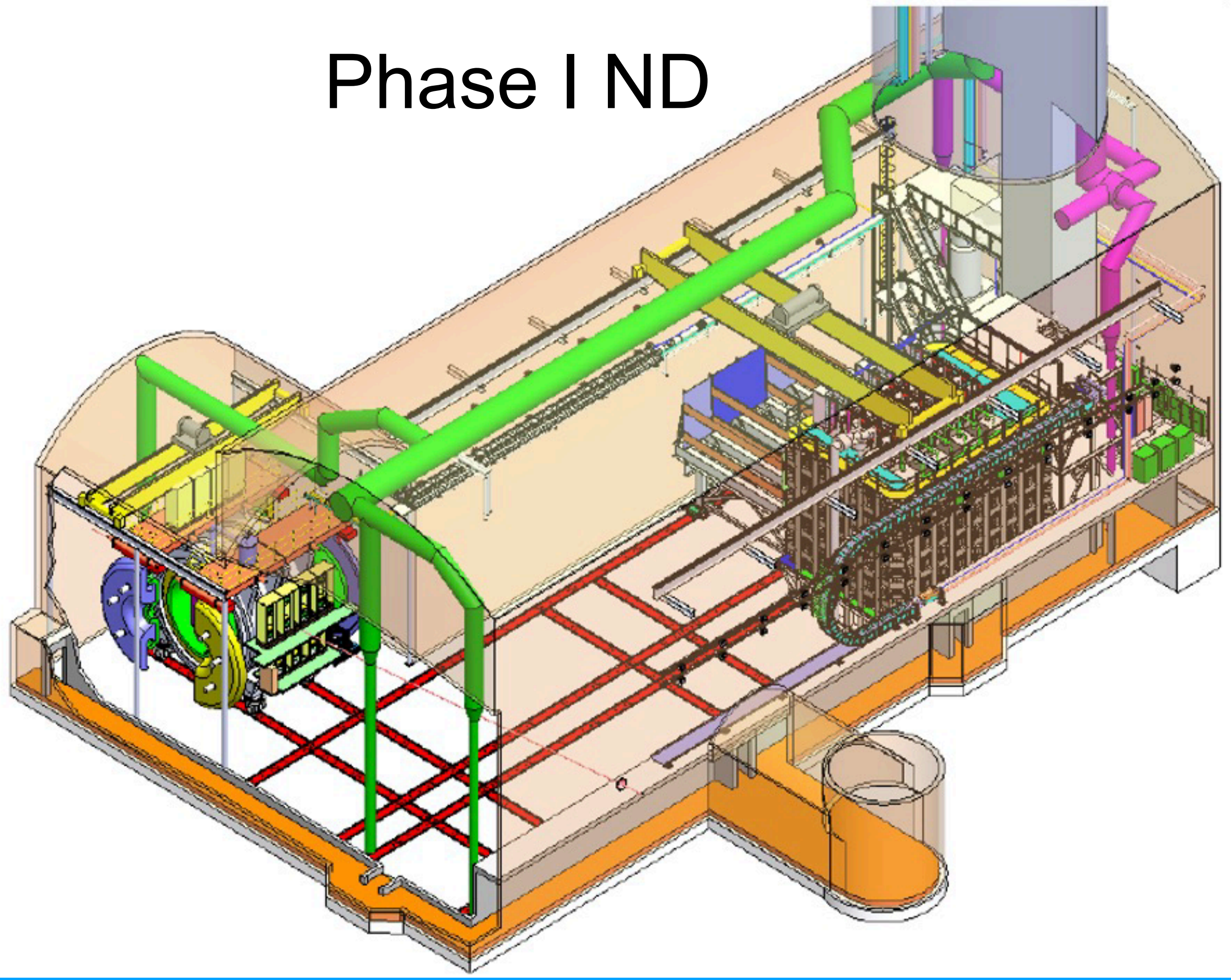
Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND.

Moveable to enable PRISM.

Phase I FD



Phase I ND



DUNE Plans and Installation

Phase I

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Phase II

Proton beam increase to 2.4 MW

Four FD modules (3 LAr TPCs + 1 new tech)

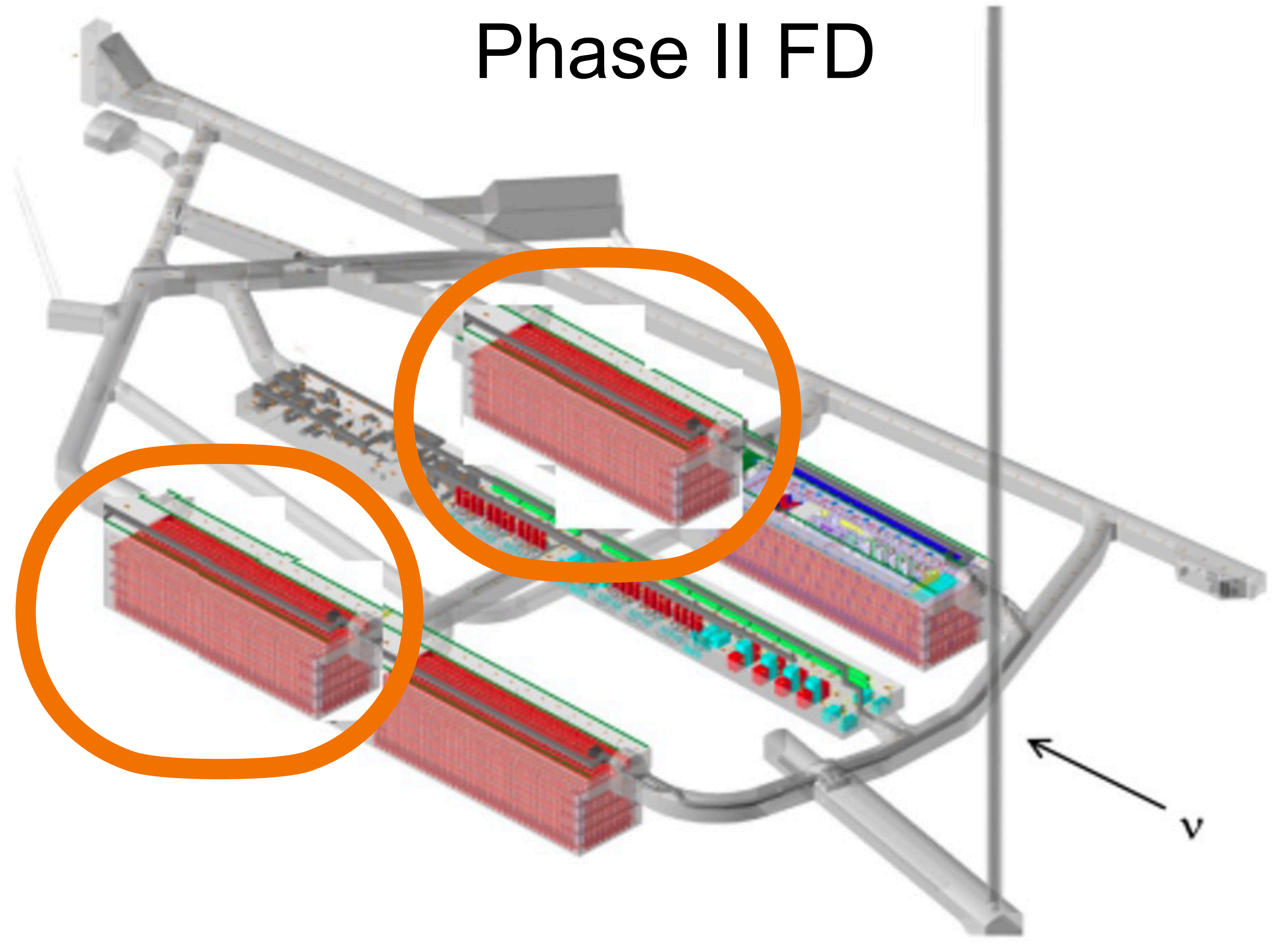
TMS Upgraded to a More Capable Near Detector (MCND)

This has been fully endorsed by P5

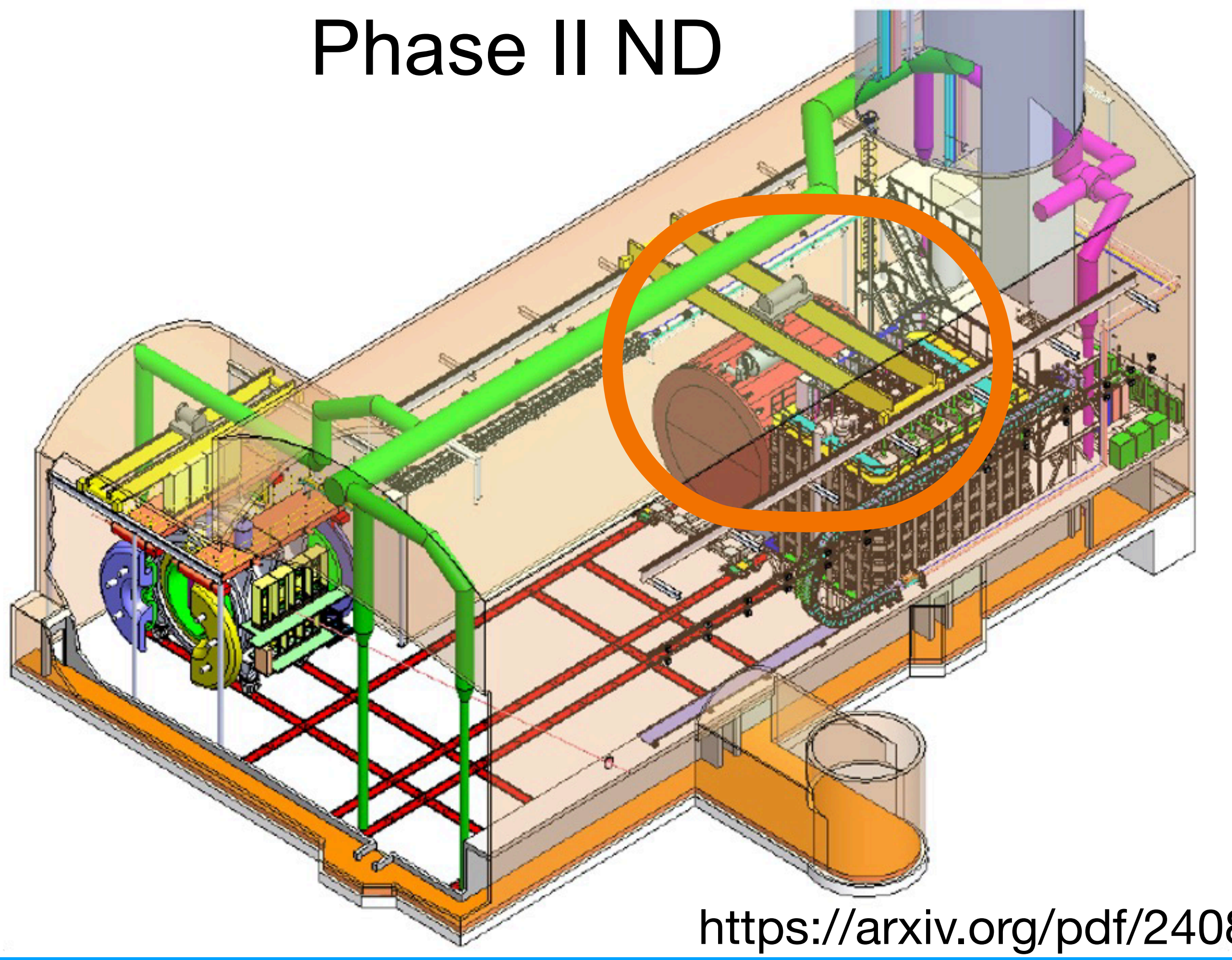
LBNF was built for the full programme (Phase I+II)

Resources and funding are still tbd but a first very positive message is that US-DOE has committed to contribute at a significant level.

Phase II FD



Phase II ND



https://arxiv.org/pdf/2408.12725

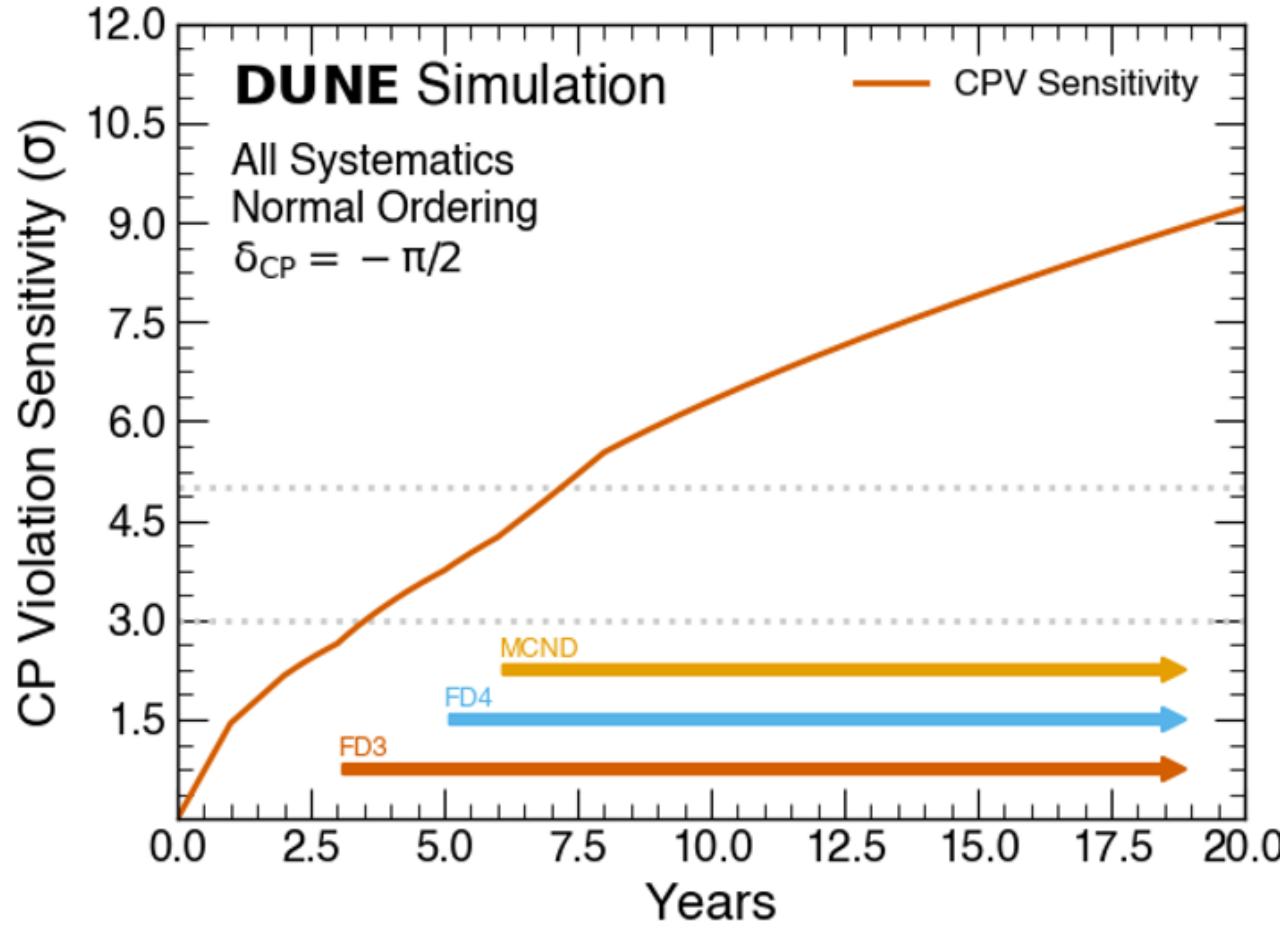
Timelines

Phase I

- **FD cavern excavation complete!**
- FY29: Start science w/ FD-VD
- FY30: FD-HD fully operational
- FY31: Start beam-based science (1.1-1.6MW)!

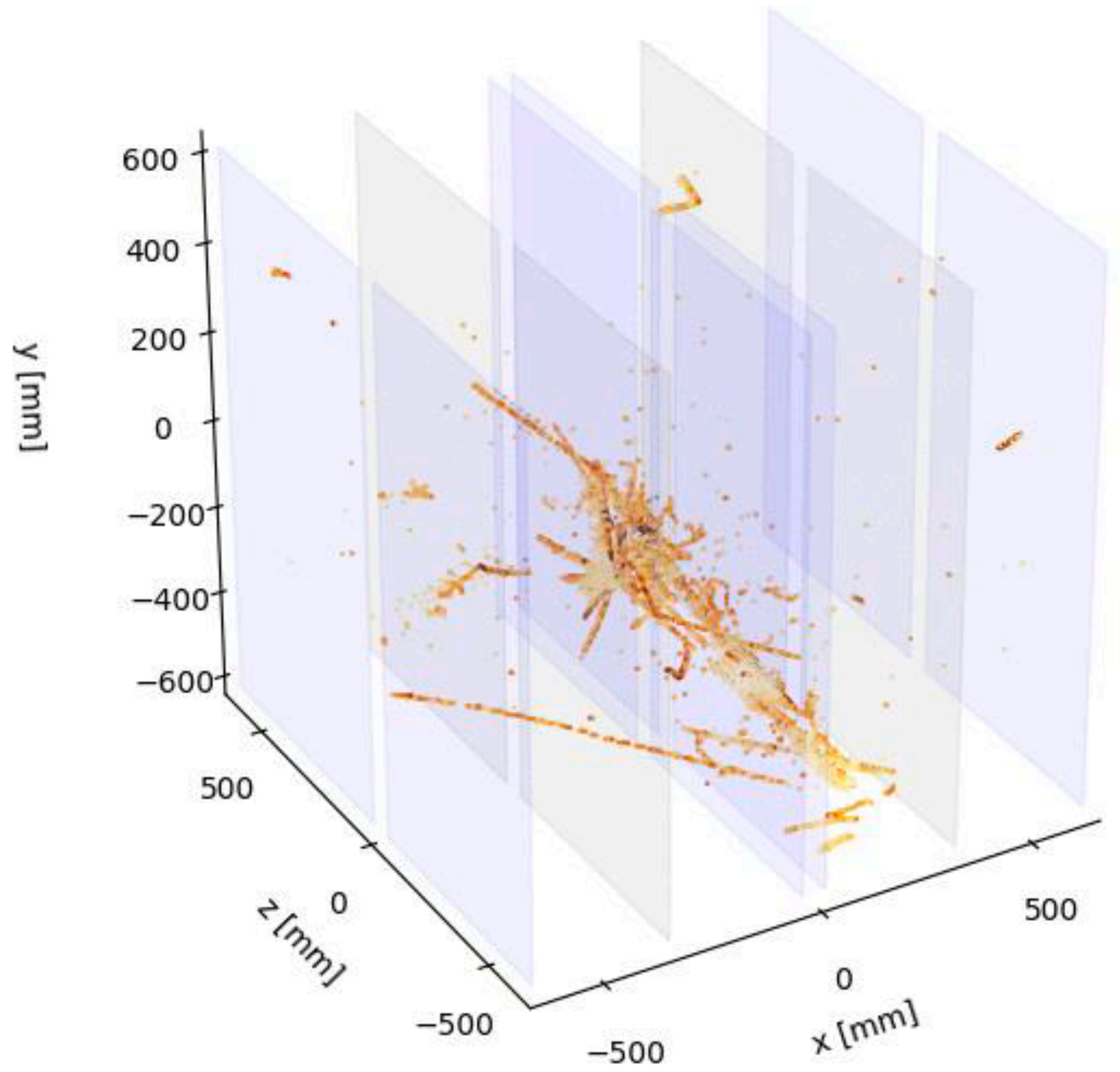
Phase II

- Year 4: FD3 fully operational
- Year 6: FD4 fully operational
- Year 7: More Capable Near Detector fully operational
- Beam ramp up to 2.3MW in 15 years

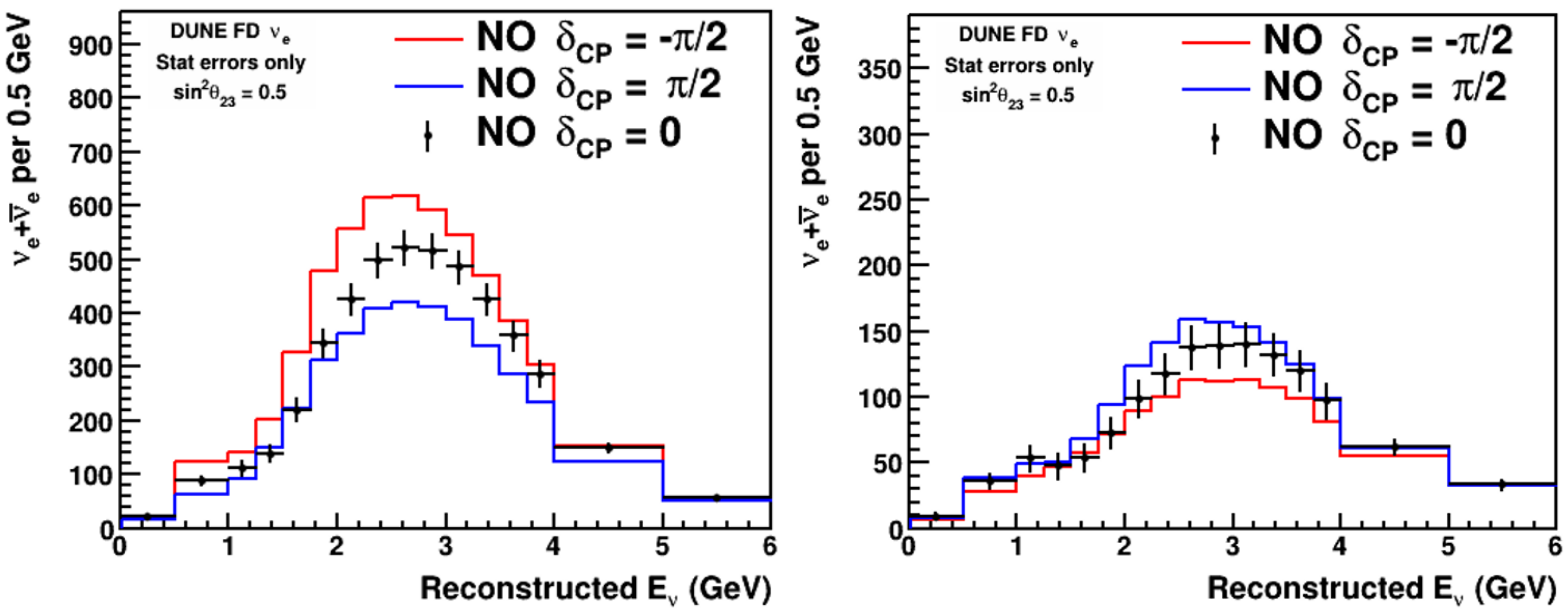


Prototypes

- FD prototypes operating at CERN (ProtoDUNEs-2)
    - HD collected beam over the summer
    - VD commissioning in the autumn
- ND-LAr 2x2 demonstrator (modular liquid argon TPC) is operating in antineutrino beam at Fermilab
    - Took 6 days of data before summer shutdown and will resume data taking once NuMI is back.

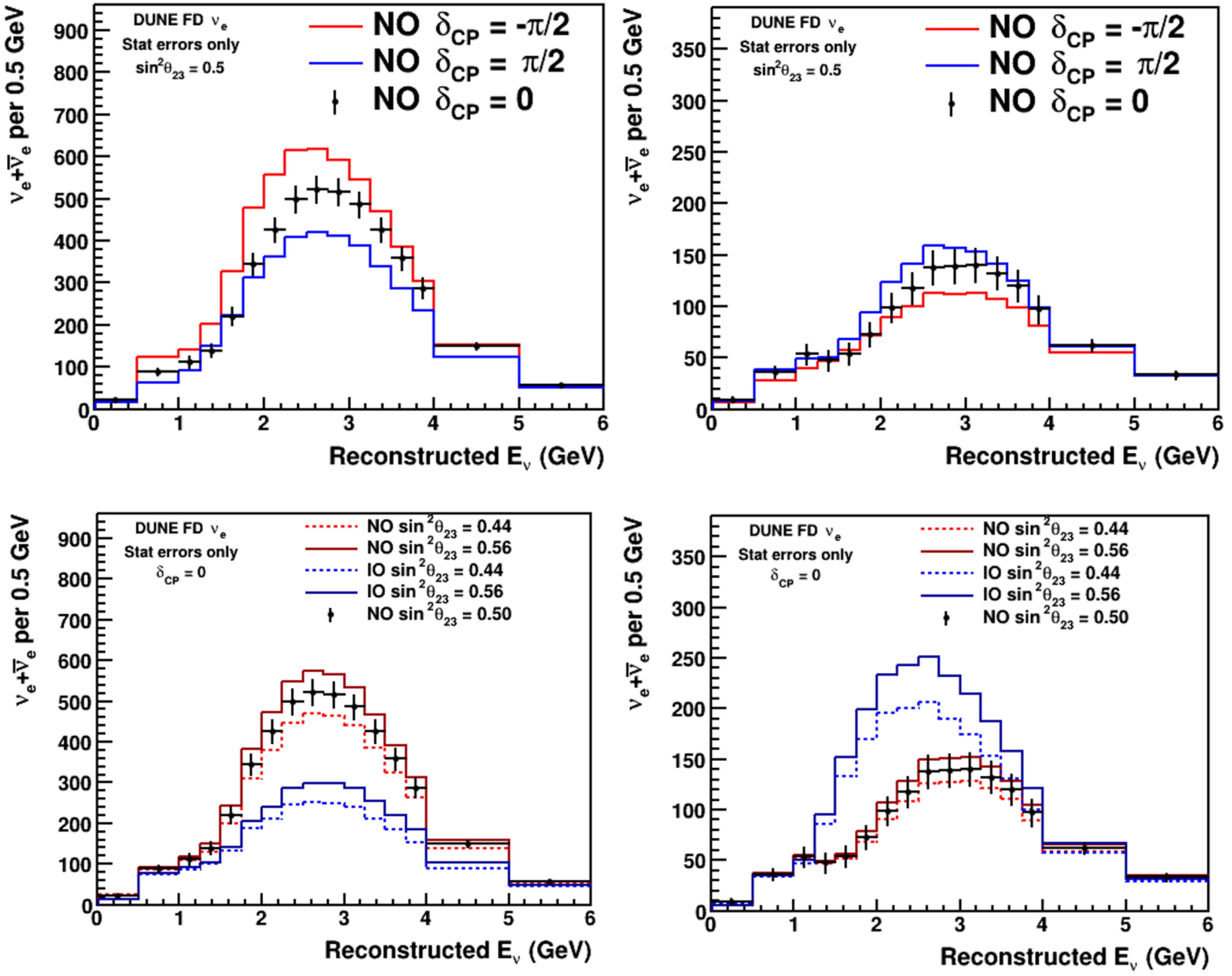


FD spectra are sensitive to CP violation



- If δ_{CP} ~ -π/2, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance

FD spectra are sensitive to CP violation

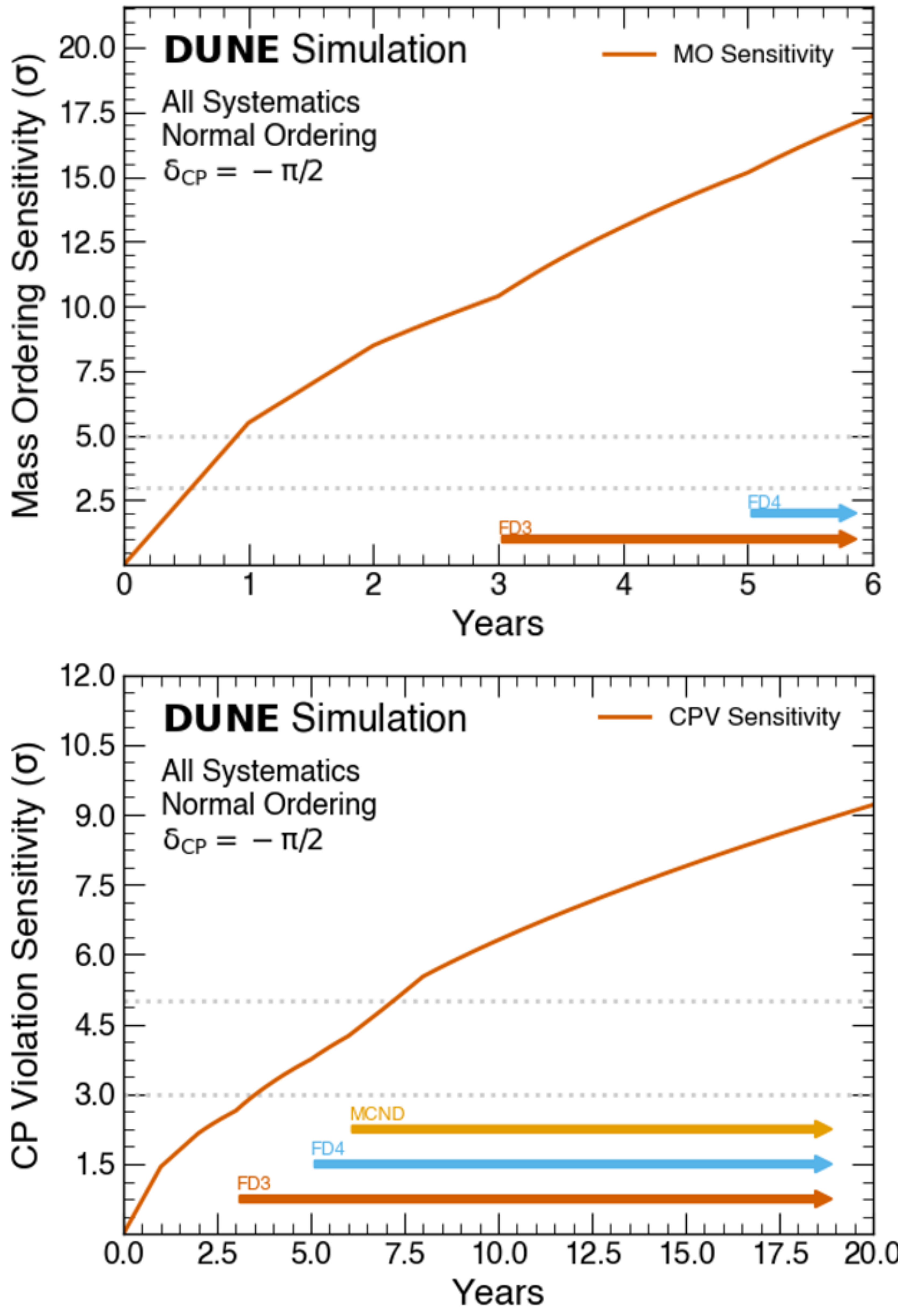


- If δ_{CP} ~ -π/2, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- If the mass ordering is normal, DUNE will measure a much larger enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies
- If new physics is present, there may be no combination of MO, δ_{CP}, and θ_{23} that fits data

Eur. Phys. J. C 80, 978 (2020)

MO and CPV - if nature is kind

- For best-case oscillation scenarios, DUNE has
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years



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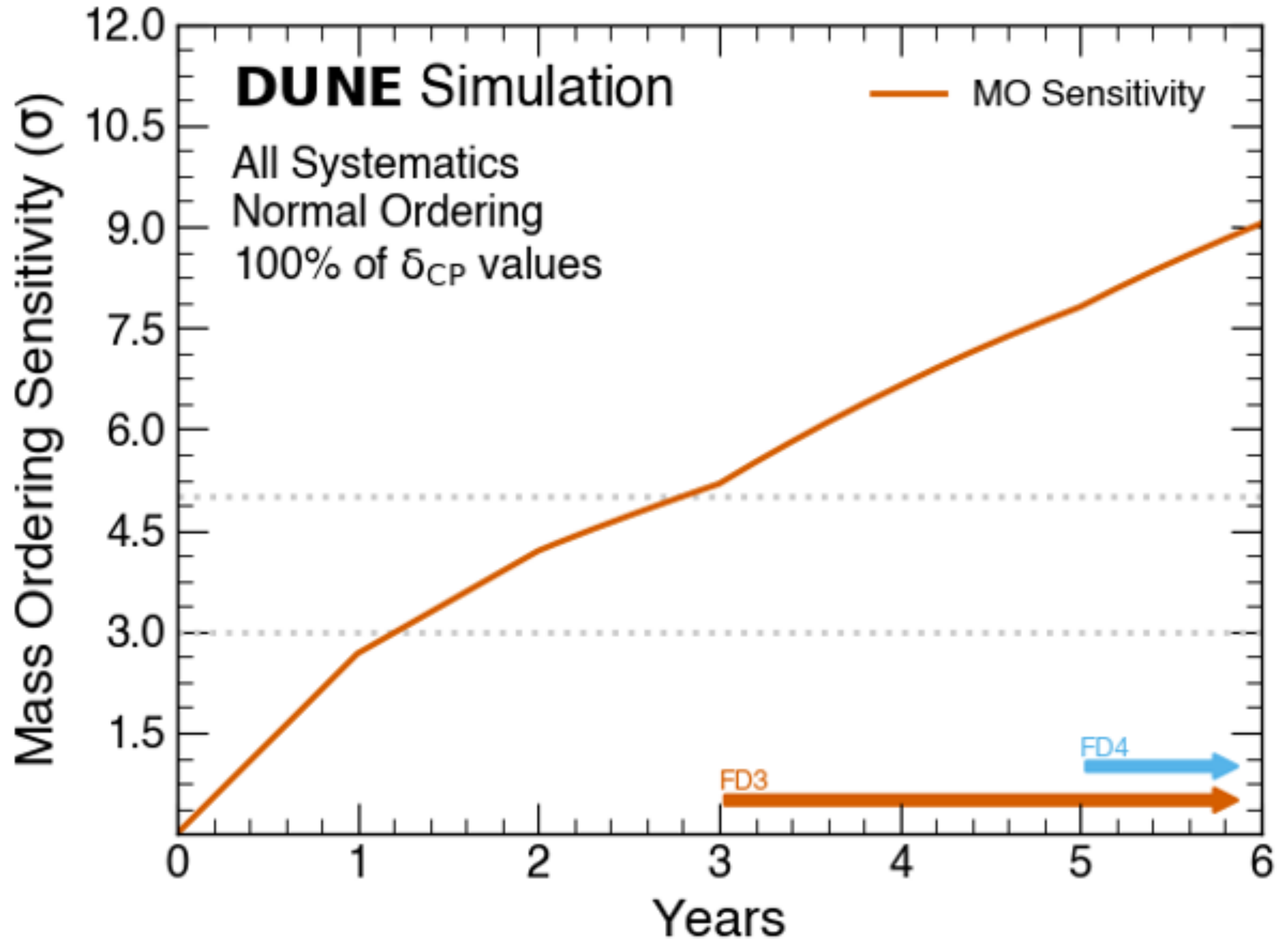
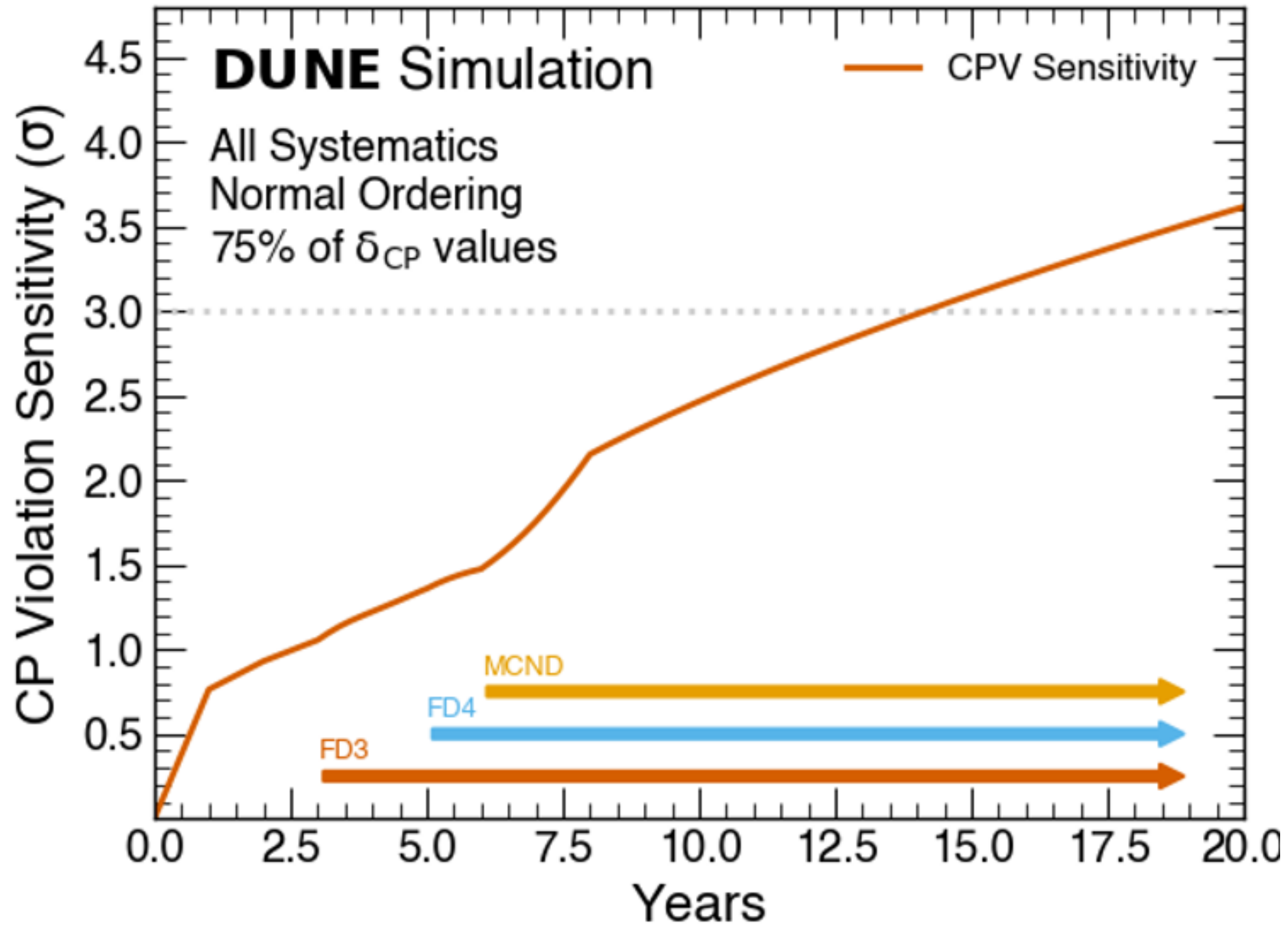
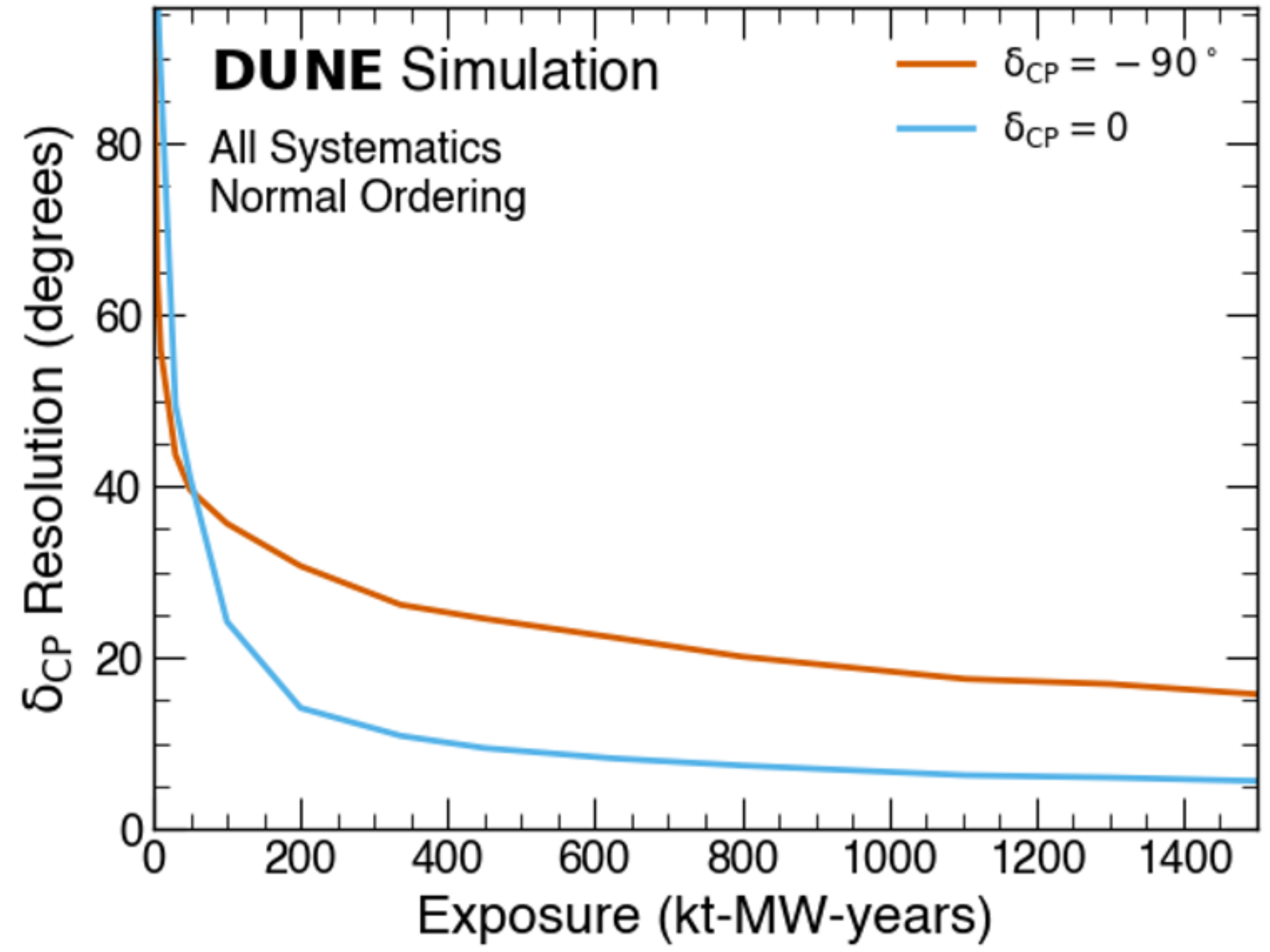
MO and CPV - if nature is unkind

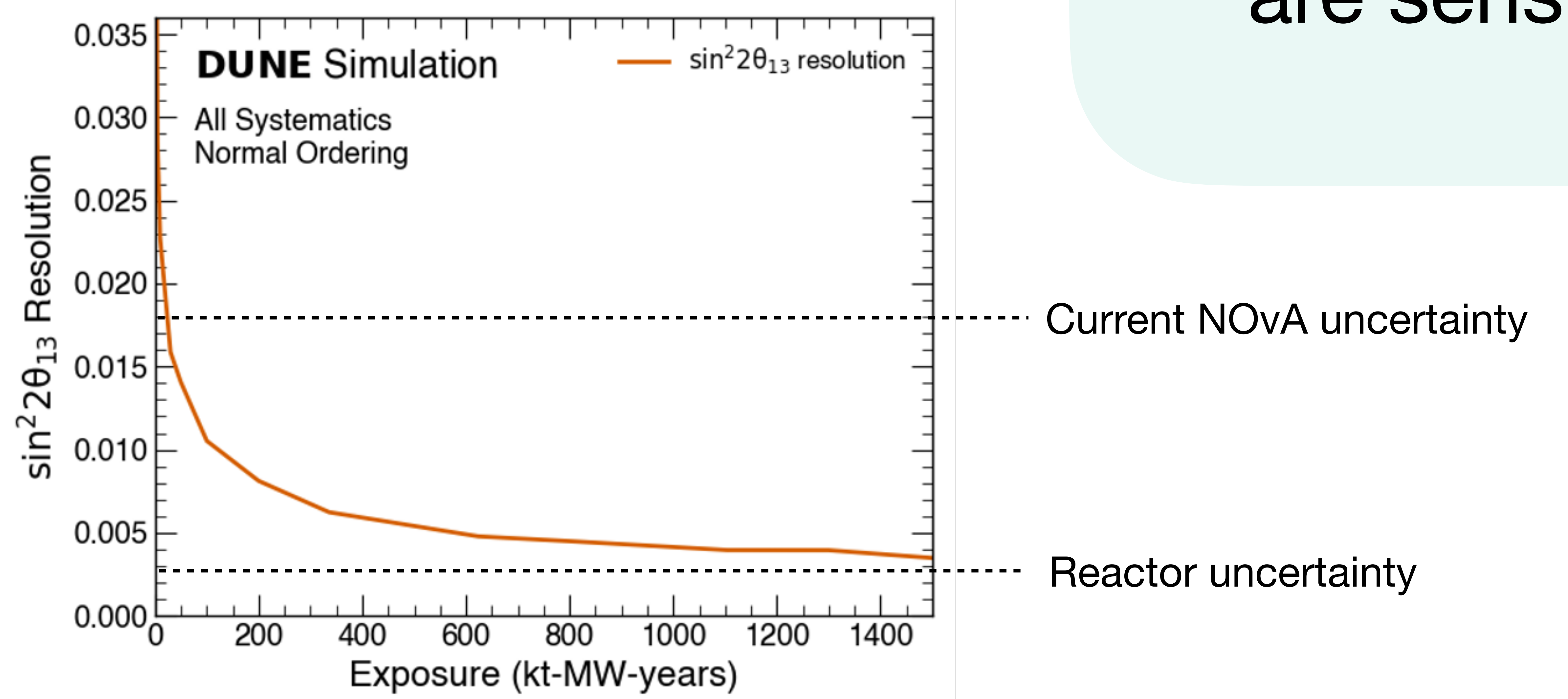
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ
- Arrows indicate assumed staging scenario





Precision measurements of 3-flavor parameters





- Ultimate precision 6-16° in δ_{CP}
- World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2_{32} → comparisons with reactor measurements are sensitive to new physics

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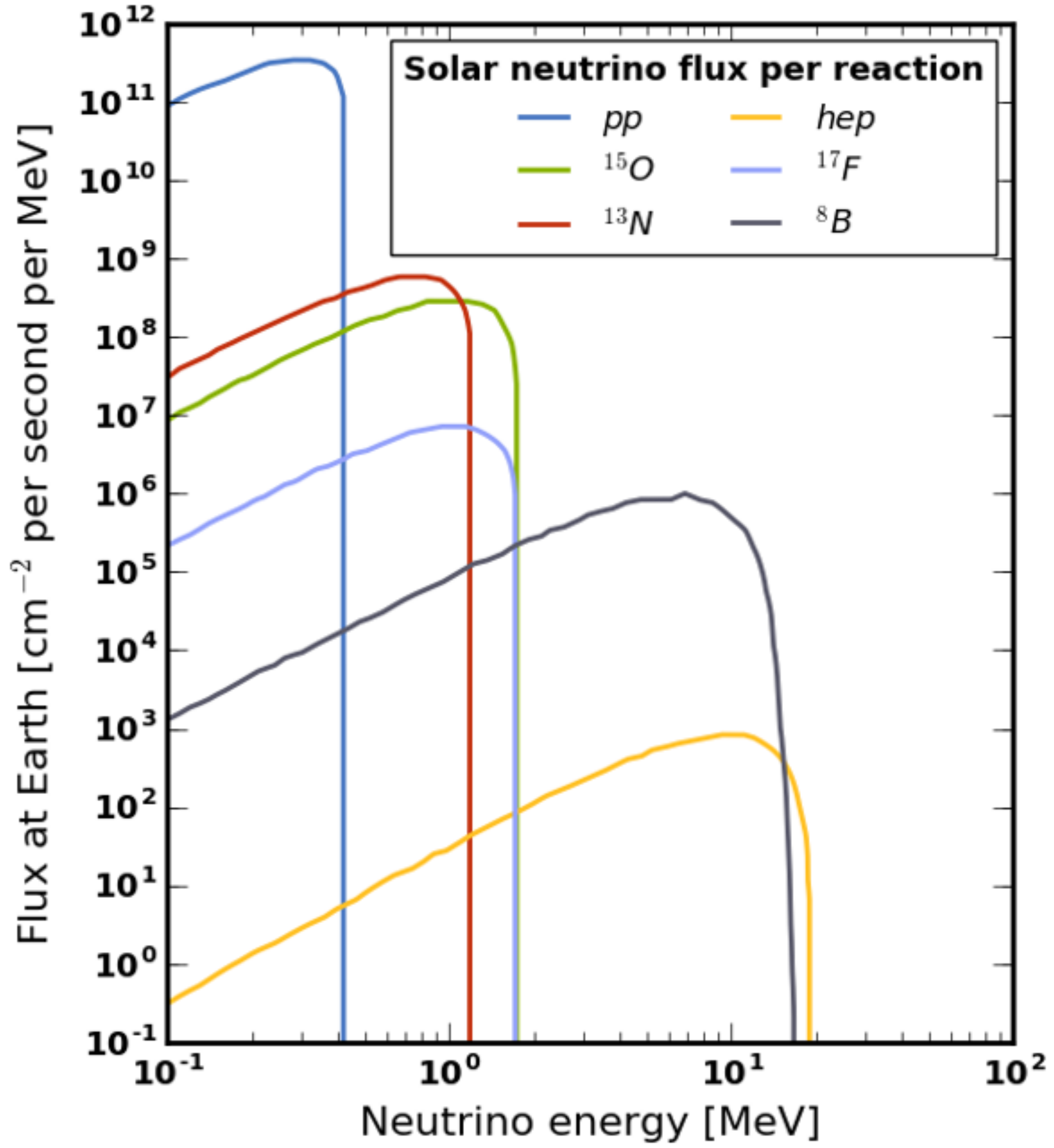
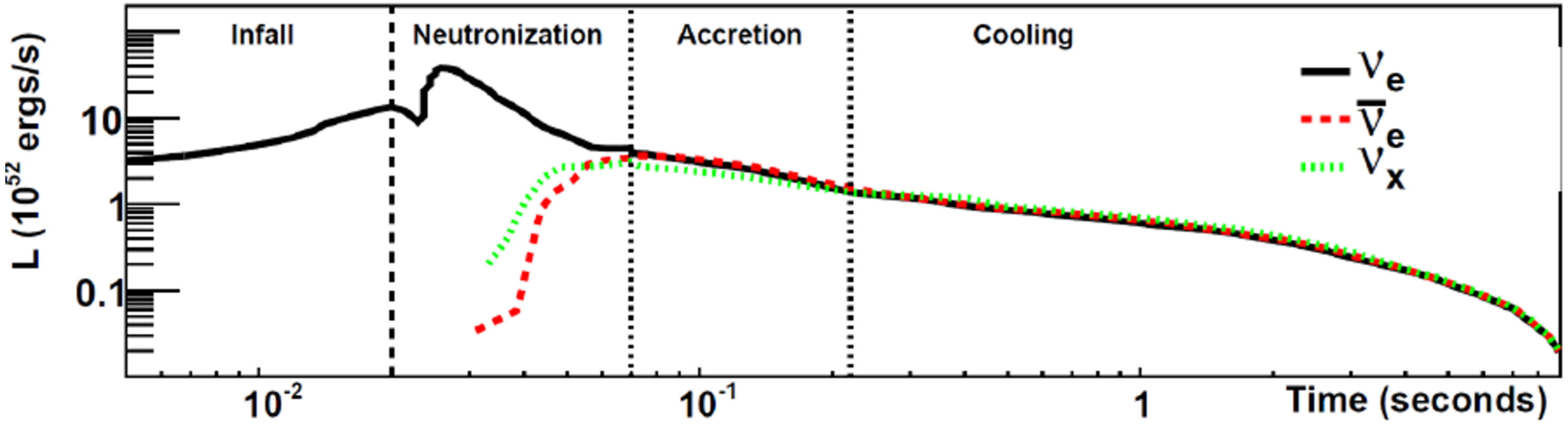
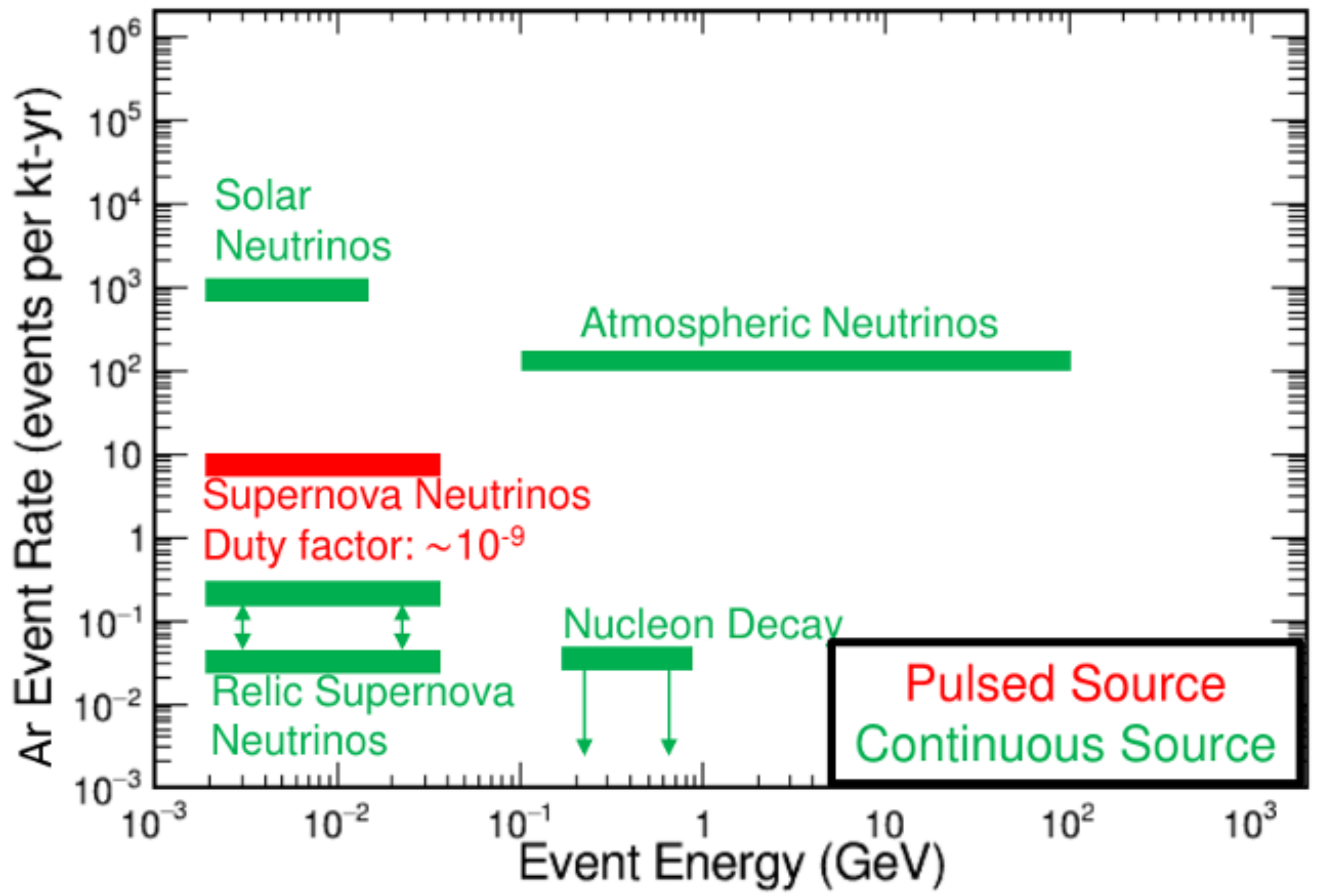
Additional Neutrino Physics

- DUNE FD will observe atmospheric, solar, and supernova neutrinos
- Argon target gives unique sensitivity to MeV-scale electron neutrinos
  - $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ ($E_\nu >$ 1.5 MeV)
  - $\nu_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ ($E_\nu >$ 7.5 MeV)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
- Highly complementary to other experiments (Hyper-K, JUNO) that predominantly see $\bar{\nu}_e$ via IBD

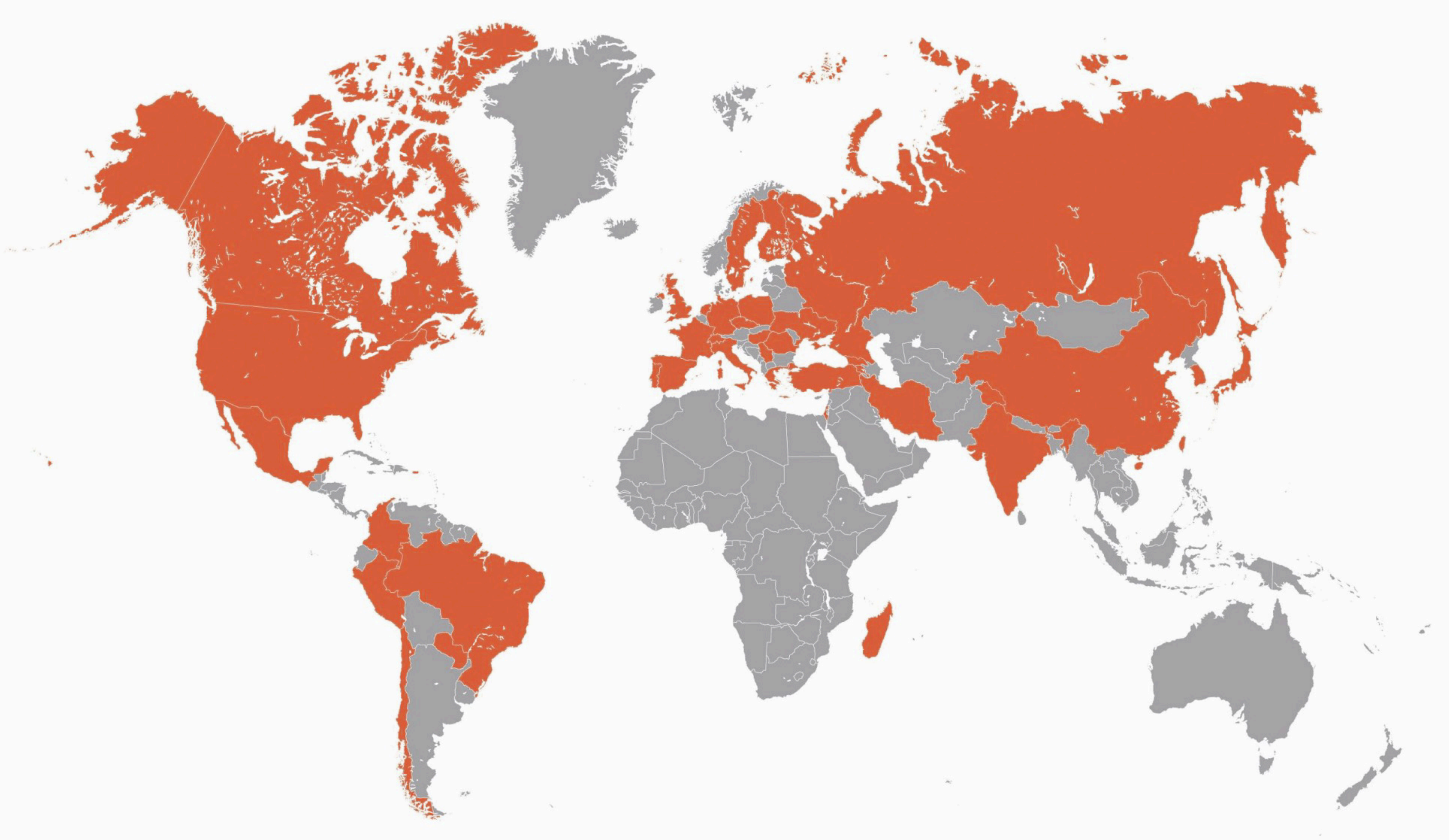






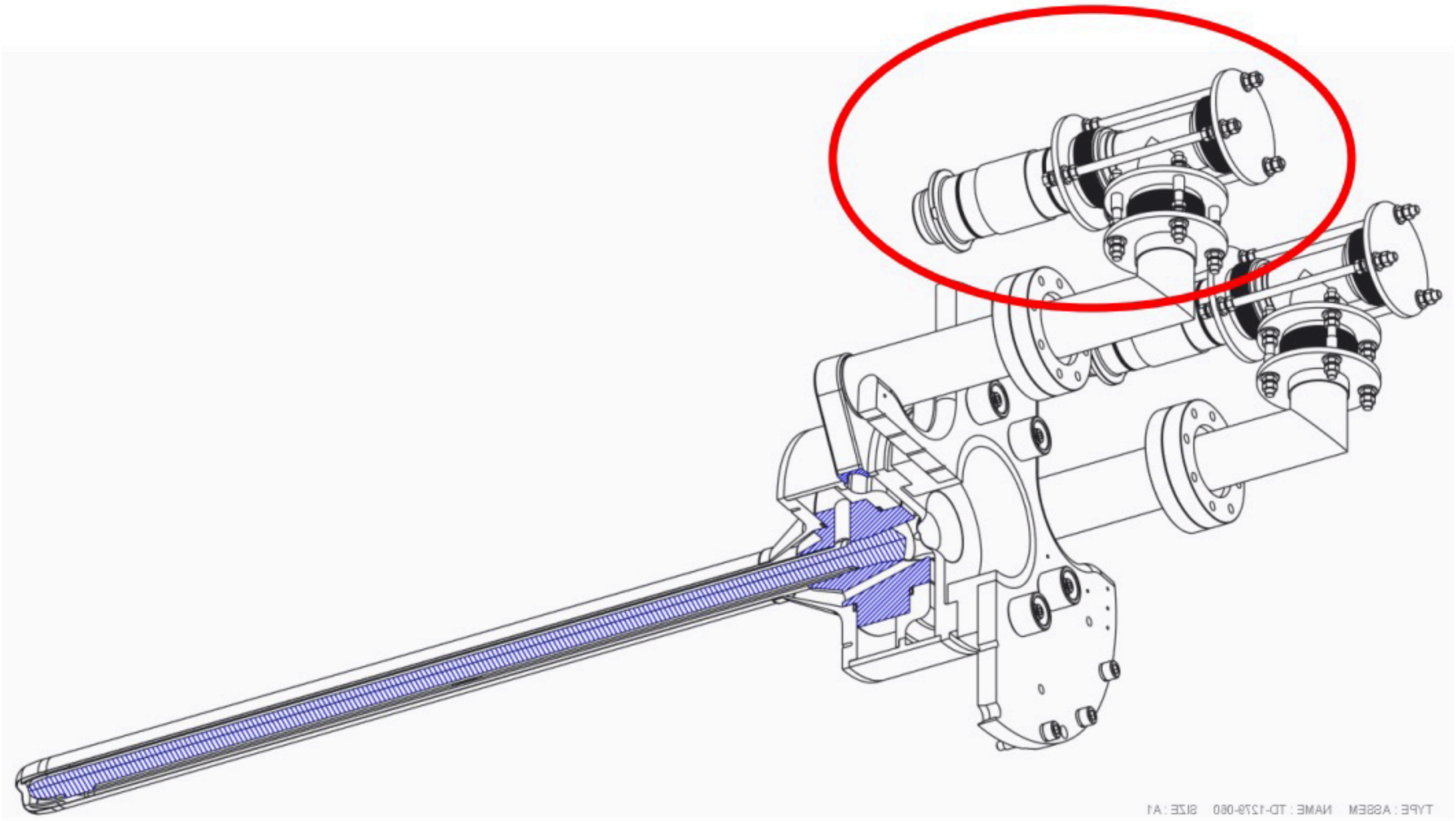
DUNE Collaboration

- DUNE is an international collaboration of 1400 scientists and engineers from 37 countries + CERN (and counting)
- UK:
  - ~140 collaborators
  - Contributed 2 Spokes, Leads in all relevant Consortia, Resource Board Chair, ProtoDUNE coordinator, several working groups conveners, and more.



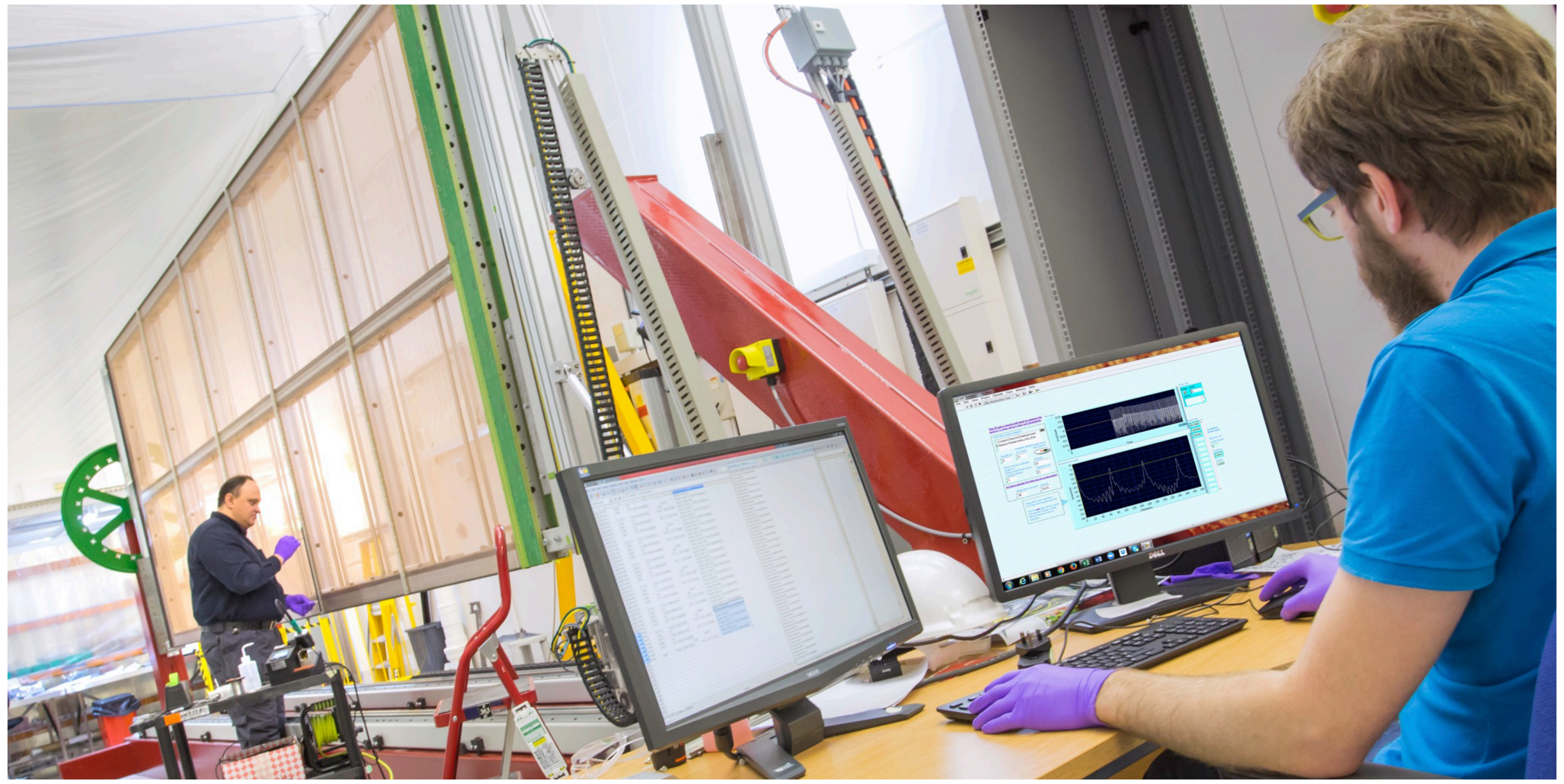
UK leadership in LBNF

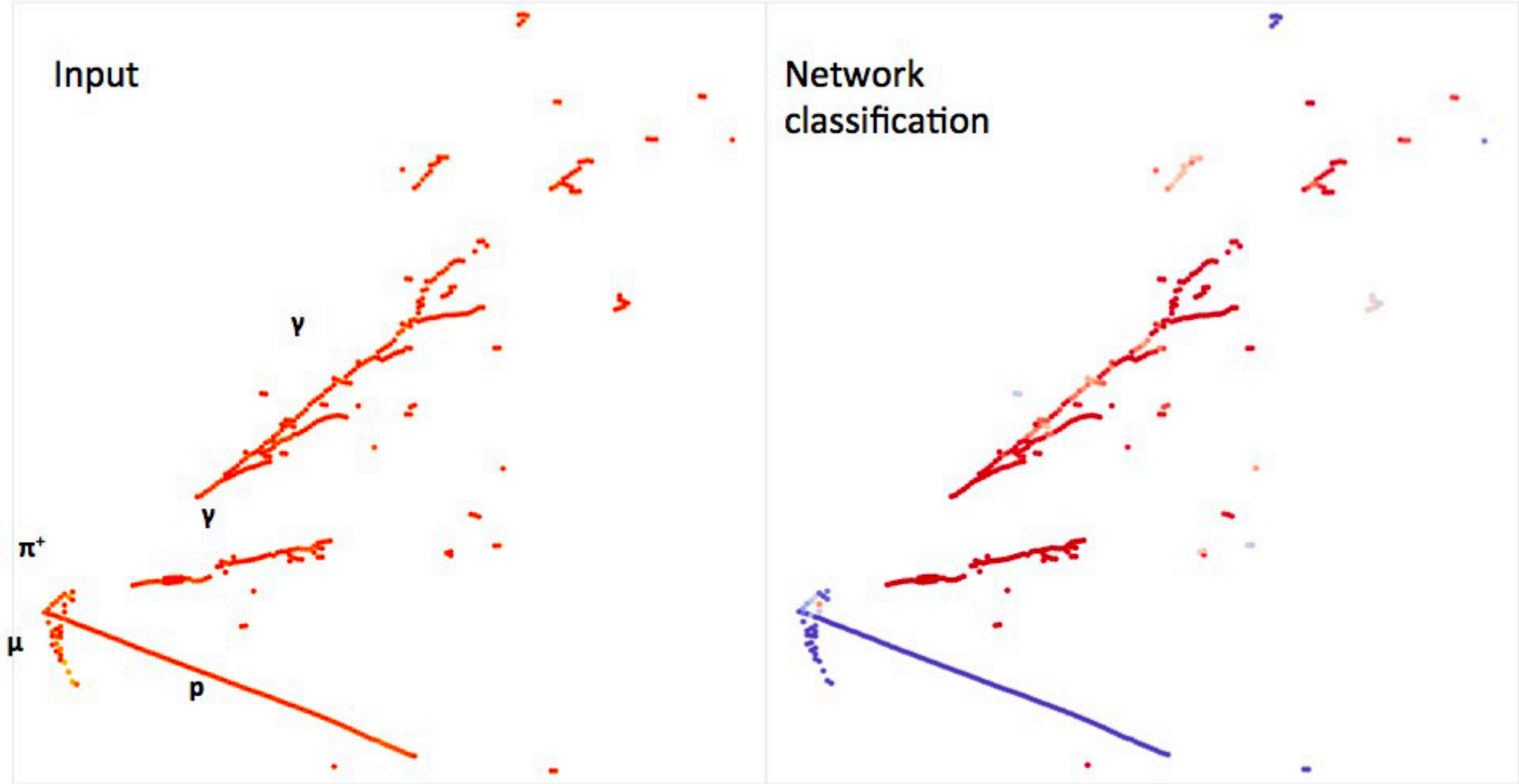
- Daresbury and RAL are world centres of accelerator expertise
- **PIP-II:** Producing RF cavities for the PIP-II upgrade for the LBNF 1.2 MW beam and eventual 2.4 MW goal
- **LBNF Target:** supply 1.2 MW helium-cooled graphite target plus associated infrastructure



UK leadership in DUNE

- Building the majority of readout planes (137 **APAs**) for the horizontal drift FD - Major construction factory at Daresbury.
- Providing the **DAQ** for the first two FD and ND.
- Delivering LAr **reconstruction software** for the FD and **distributed computing** contributions.
- Additional contributions from fellowships funding in the ND simulation and reconstruction, and neutrino oscillation analysis.
- Phase-II
    - Currently, strong UK R&D contributions to FD4 and NDGAr, and overall leadership of Phase II effort.
    - A proposal to prototype FD4 technology in Boulby currently with STFC.





Conclusion

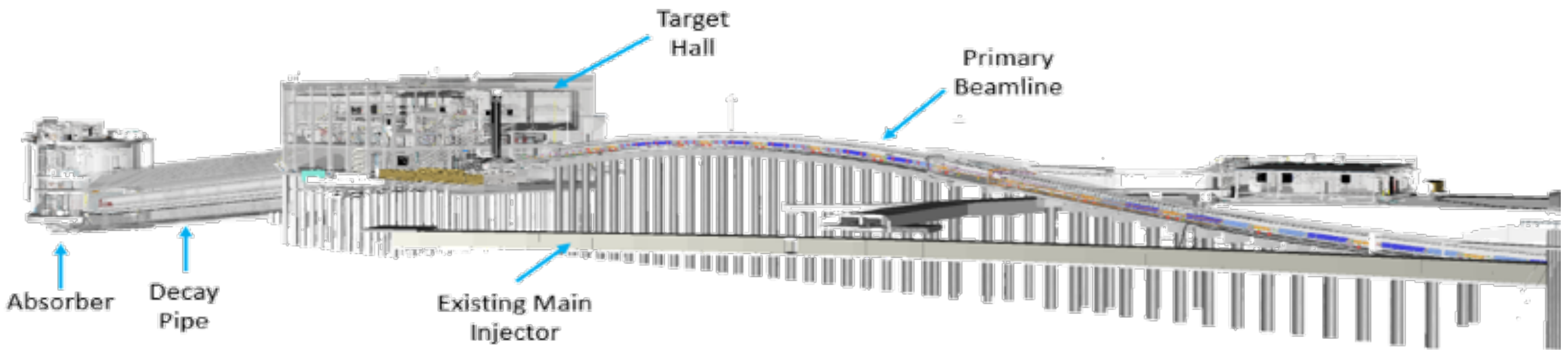
- DUNE is a long-baseline oscillation experiment and neutrino observatory
- Unique and complementary reach in oscillations, MeV-scale neutrinos, and BSM searches
- DUNE has an active prototyping program, with excavation complete and components under construction → start of science in this decade
- The UK has strong leadership in LBNF and DUNE projects.

Thank you!

BACK UP

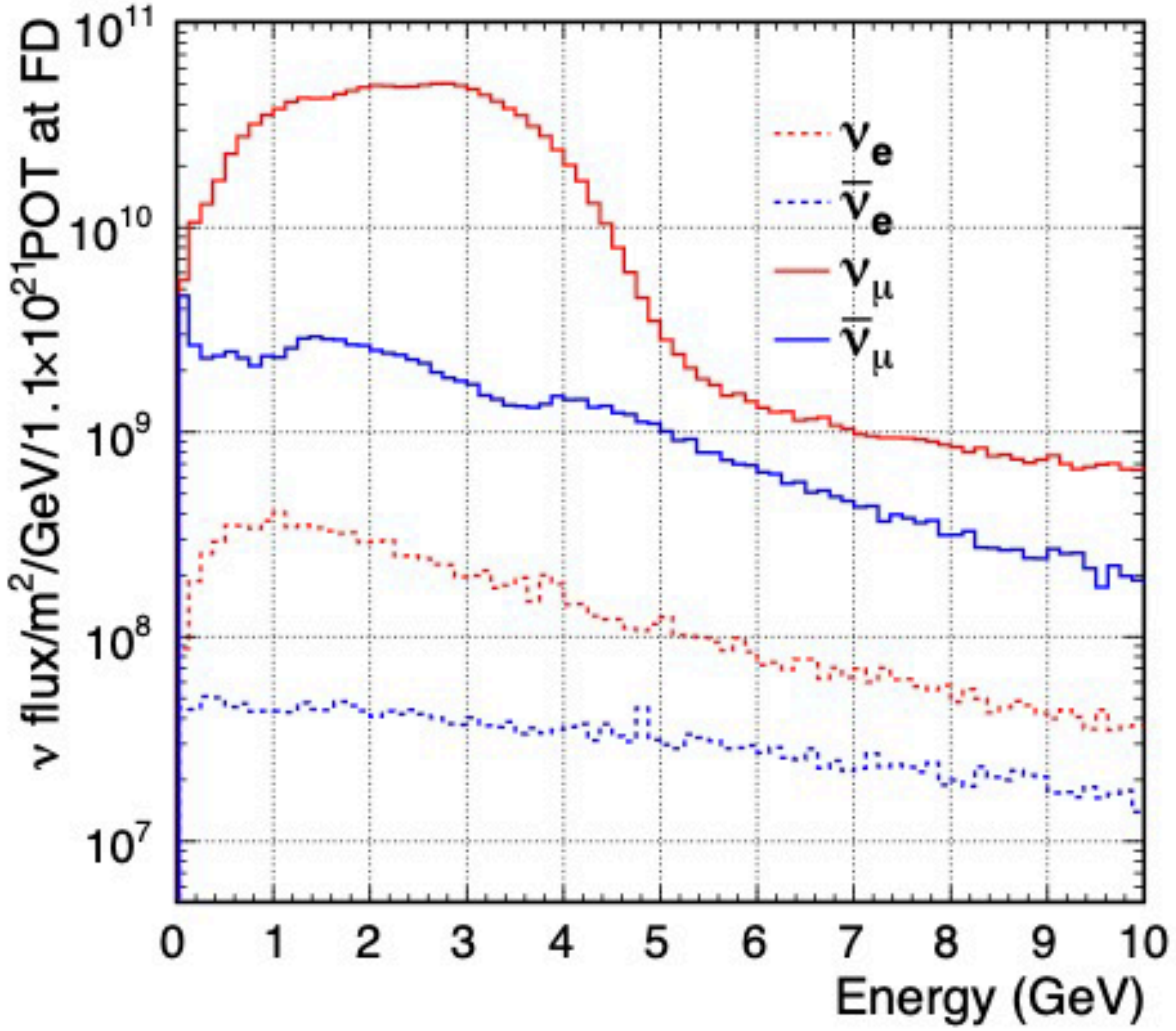
A broad physics programme:

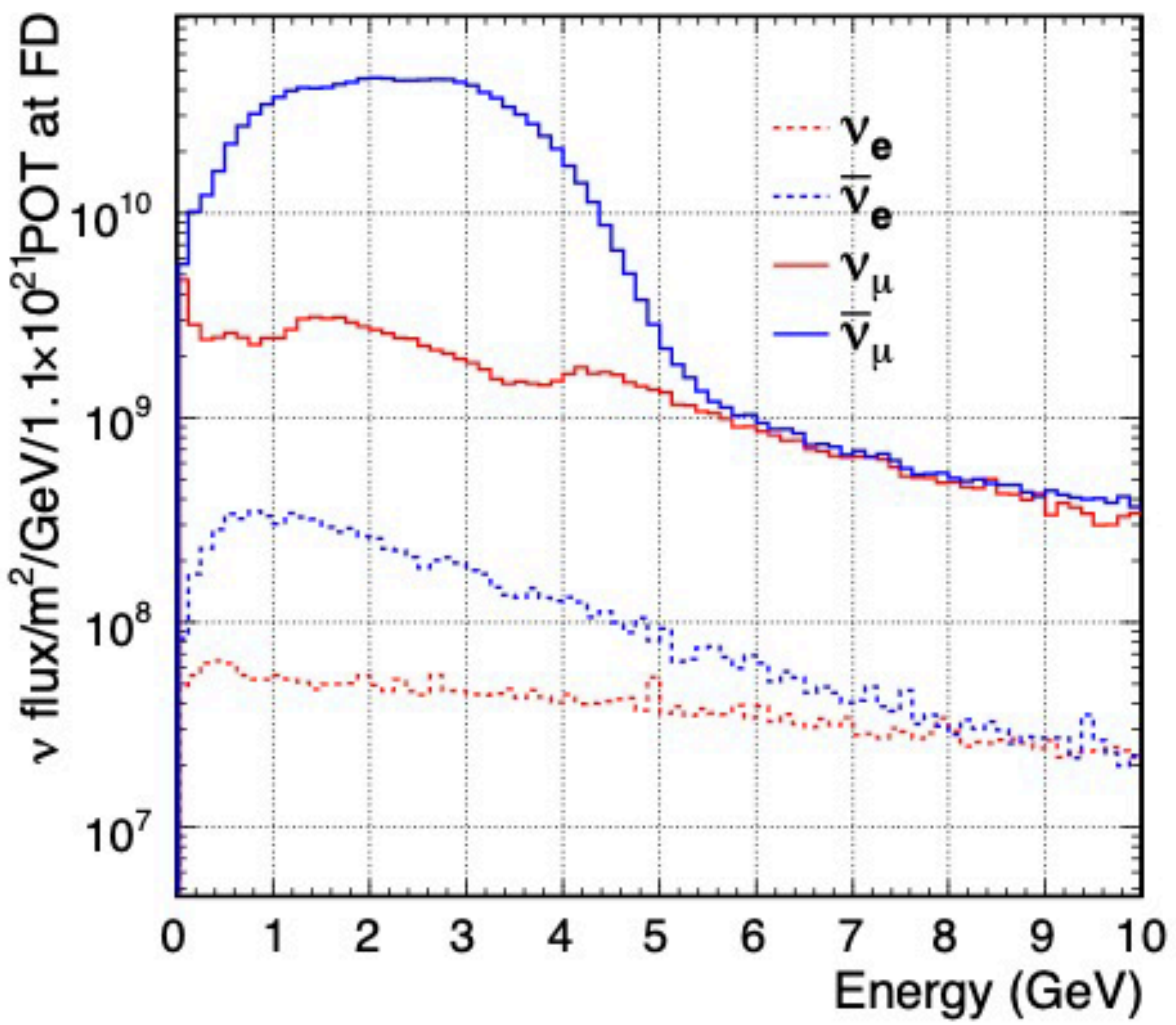
- Large, sensitive underground detectors are excellent to:
  - Observe supernova burst neutrinos
  - Measure solar and atmospheric neutrinos
  - Search for new physics (nucleon decays, cosmogenic dark matter, etc.)
- Intense beams with capable near detectors are excellent to:
  - Search for new physics produced in the beamline
  - Search for new physics in rare interactions (i.e. neutrino tridents)



DUNE Design: Wideband Beam

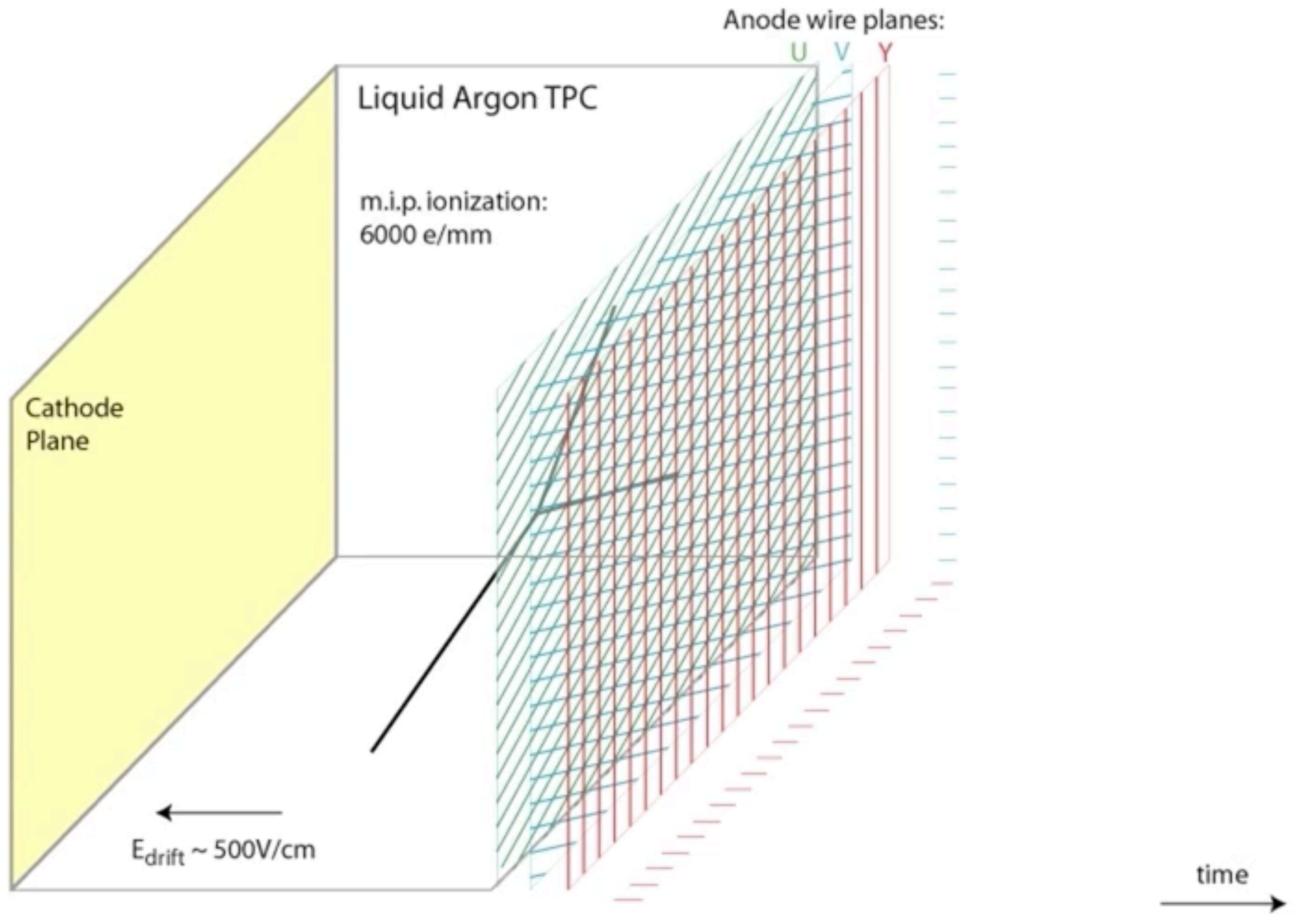
- The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0-5+ GeV
- Simulated neutrino fluxes at the far detector are shown below.





Liquid argon TPC

- Argon is a noble element -> small electronegativity
- Liquid argon ~ 1000 times more dense than gas Argon -> increase likelihood of neutrino interactions
- Relatively inexpensive



Animation by Bo You (BNL)

PMNS Parametrisation - 3 flavours

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$

θ_{ij} : the mixing angles

δ : CP-violating phase

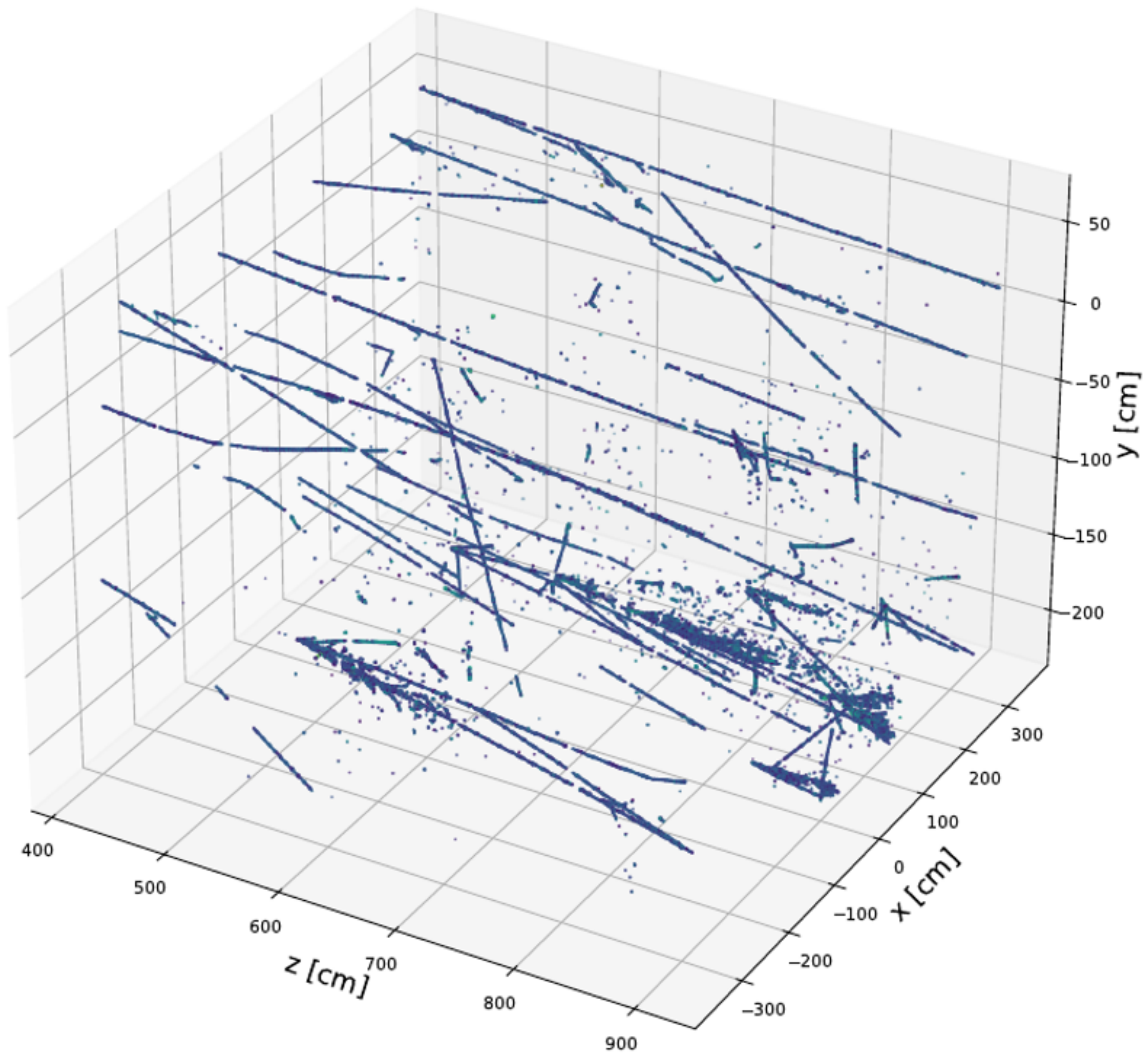
α, β : Majorana phases

Atmospheric	"Reactor/LBL"	Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

Unique challenge for ND: pile-up

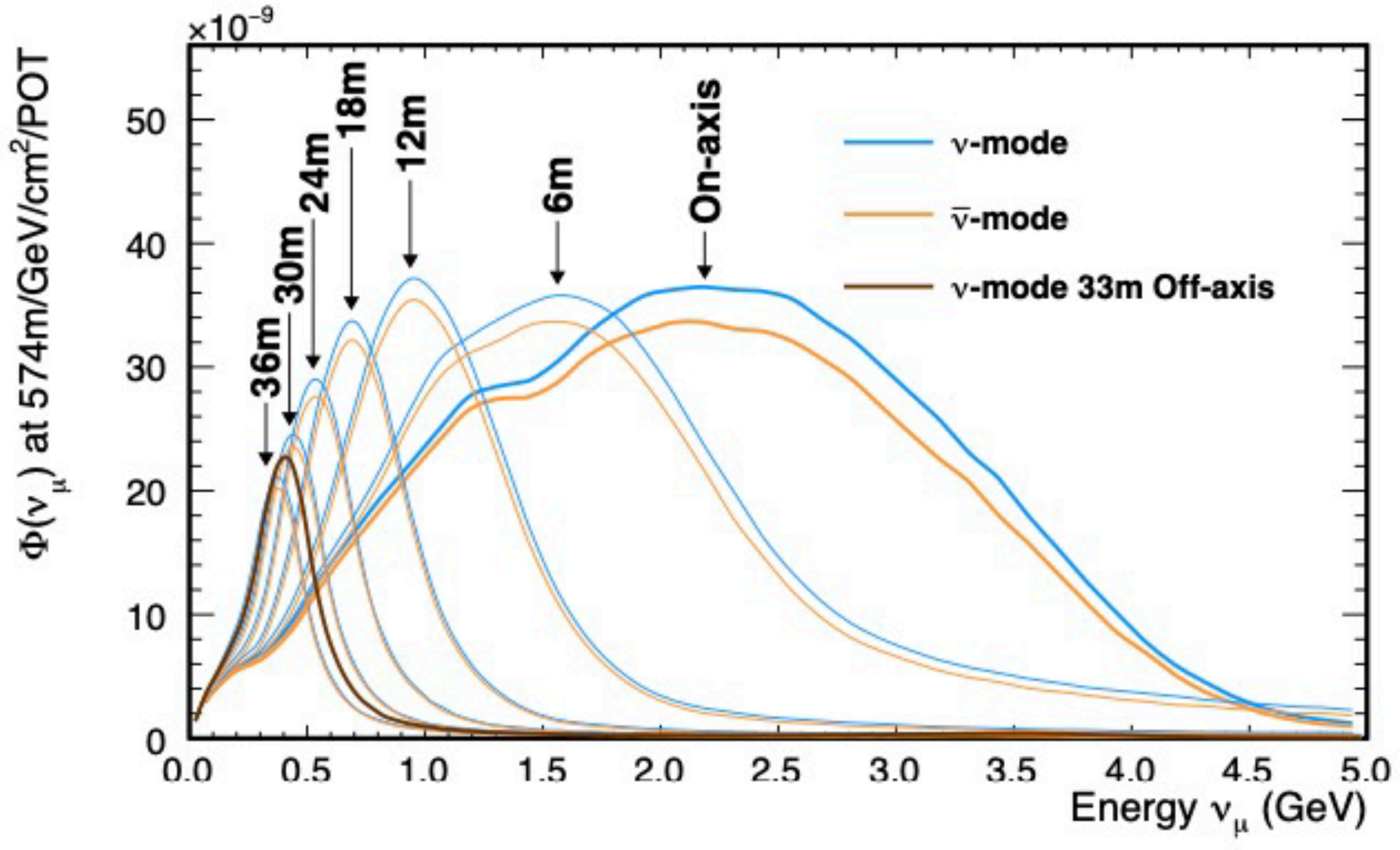
- Neutrino pile-up: very high rate at near site motivates pixelated readout and optical modularity
- Pixel readout: Natively 3D information in raw data, for resolving activity that would overlap in 2D projections
- Optical modularity: For charge-light matching, to allow association of detached energy (e.g. from neutrons)

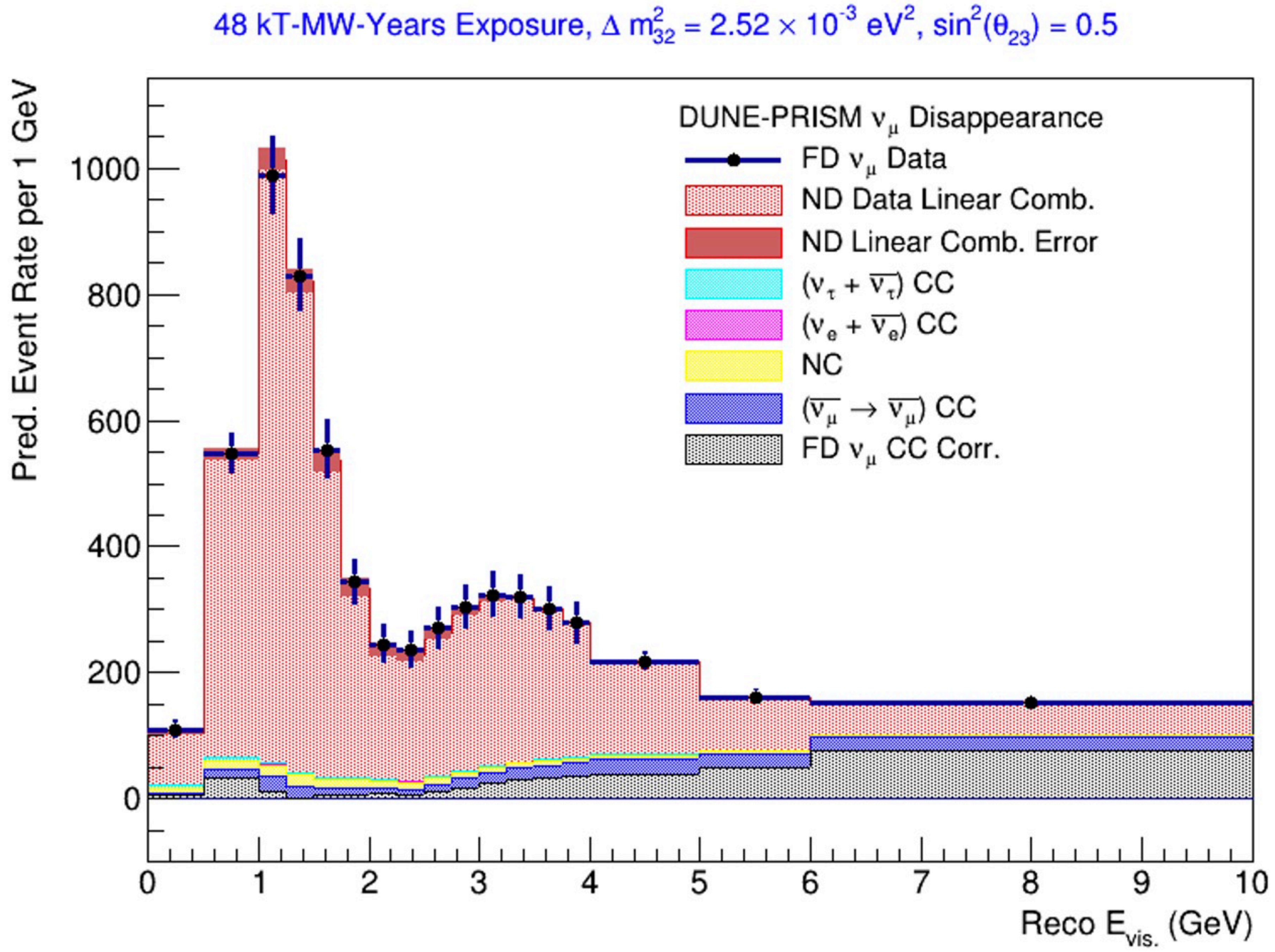
One beam spill at ND-LAr



DUNE Design: PRISM

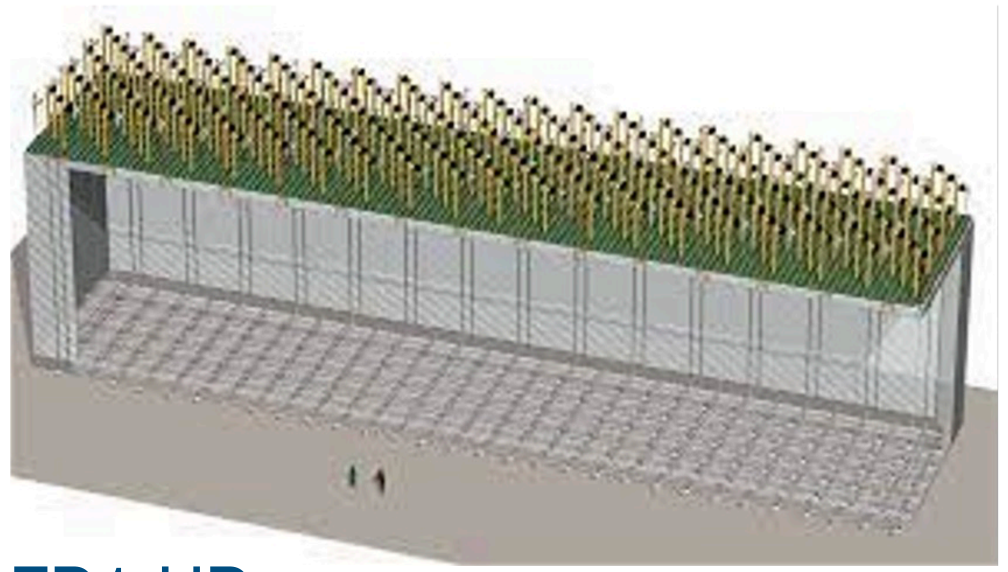
- ND-LAr + Spectrometer can be moved off-axis to enhance flux at lower energies.
- These samples allow one to build a linear combination to match FD oscillated specta and build analysis with minimal interaction modelling.



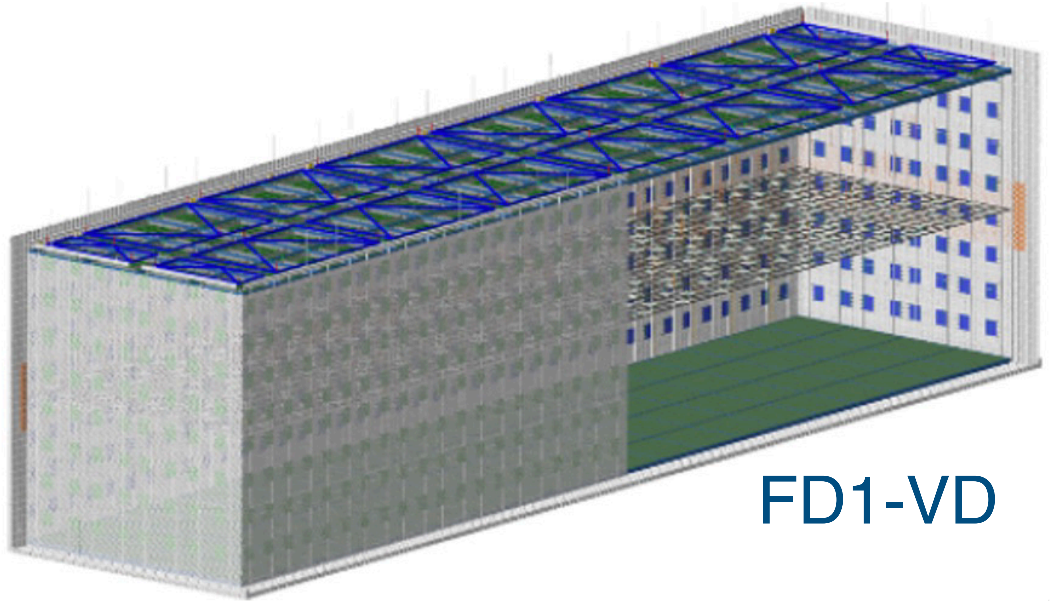


DUNE Design: Precision Reco

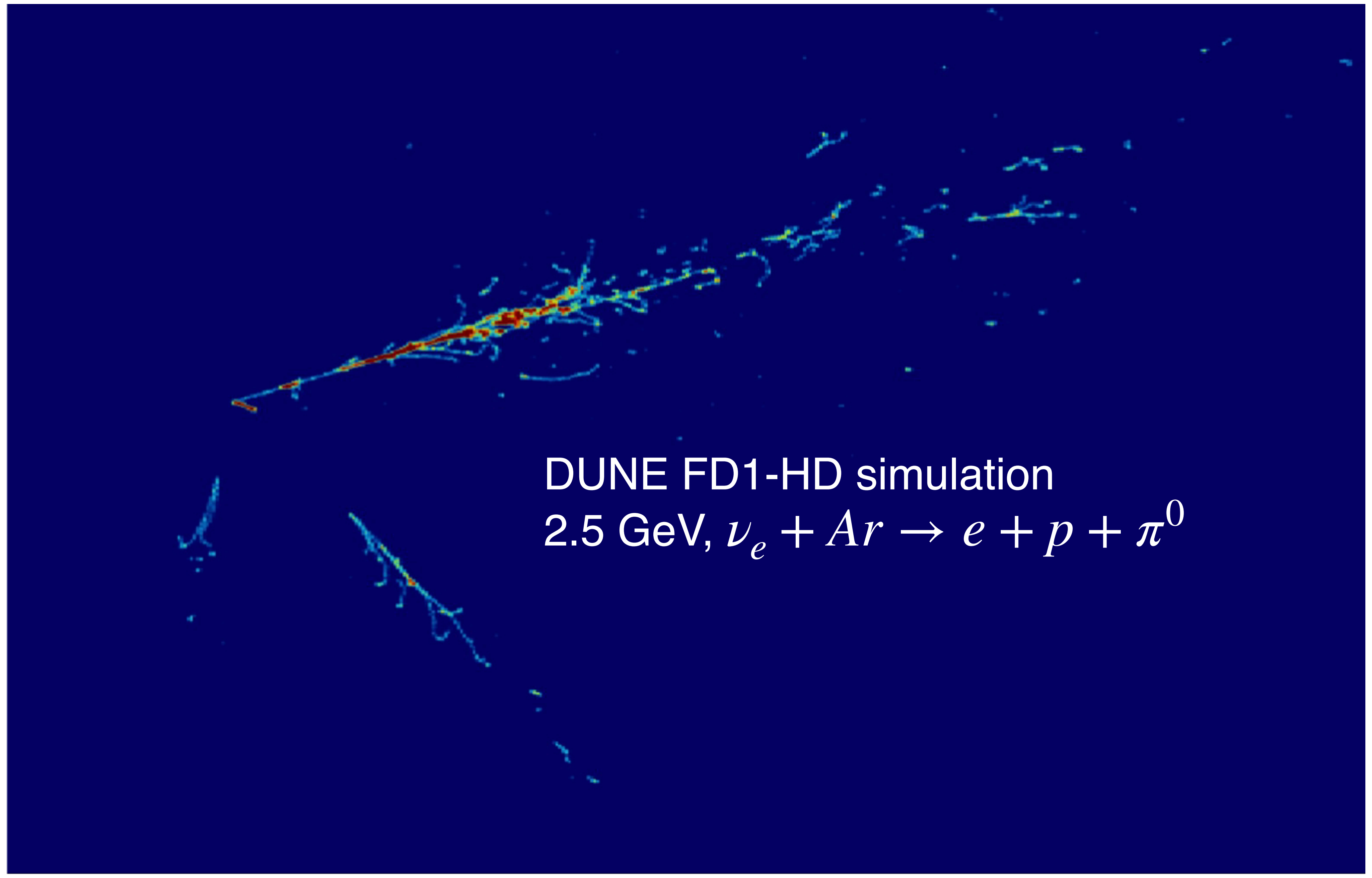
- The far detector must be able to identify flavour and reconstruct neutrino energy over the broad range over energies and interaction topologies provided by the beam.
- LAr TPC technologies fulfil both and scales to very large detector mass.
- DUNE will use a combination of horizontal drift and vertical drift modules.



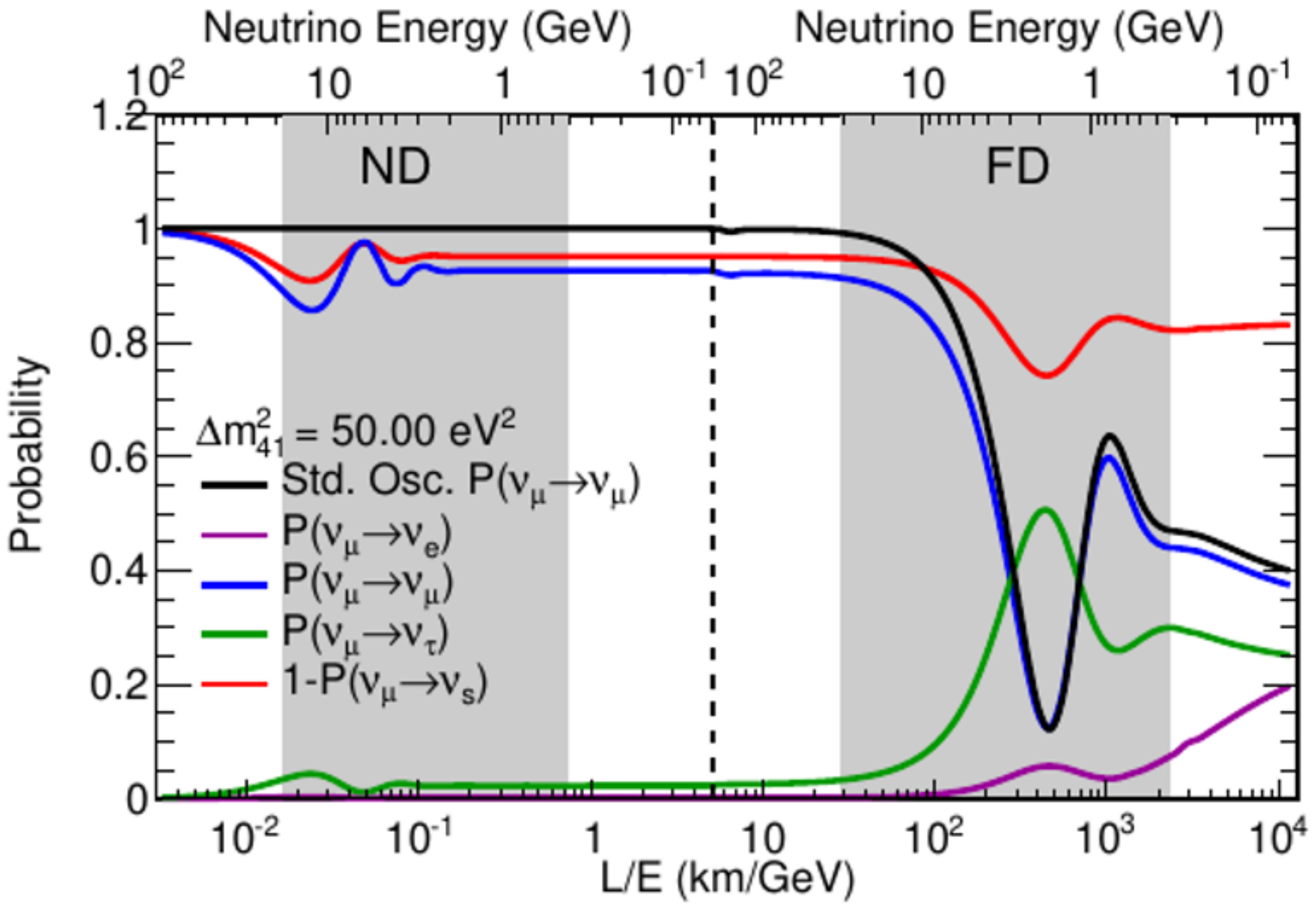
FD1-HD



FD1-VD



Beyond 3 flavours



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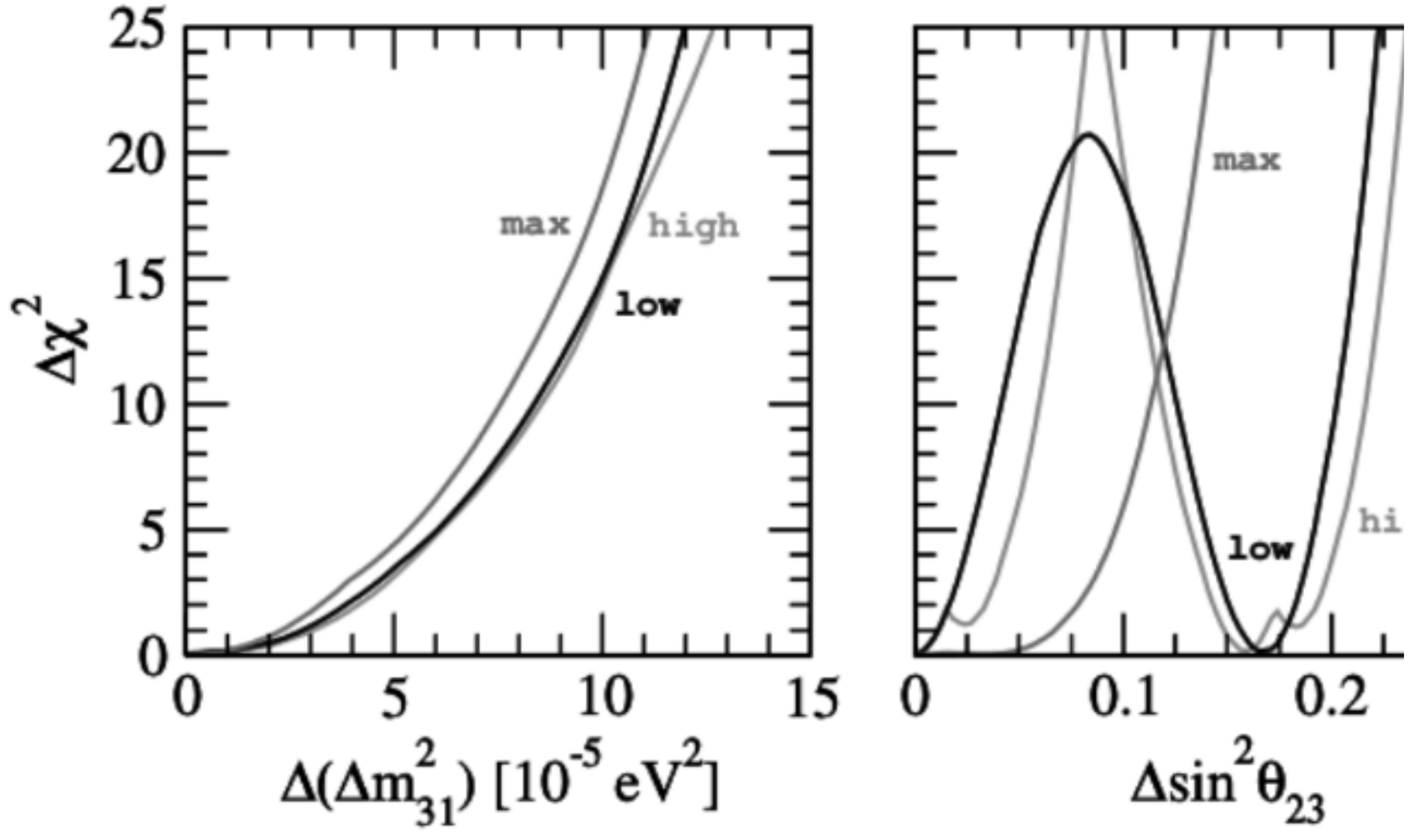

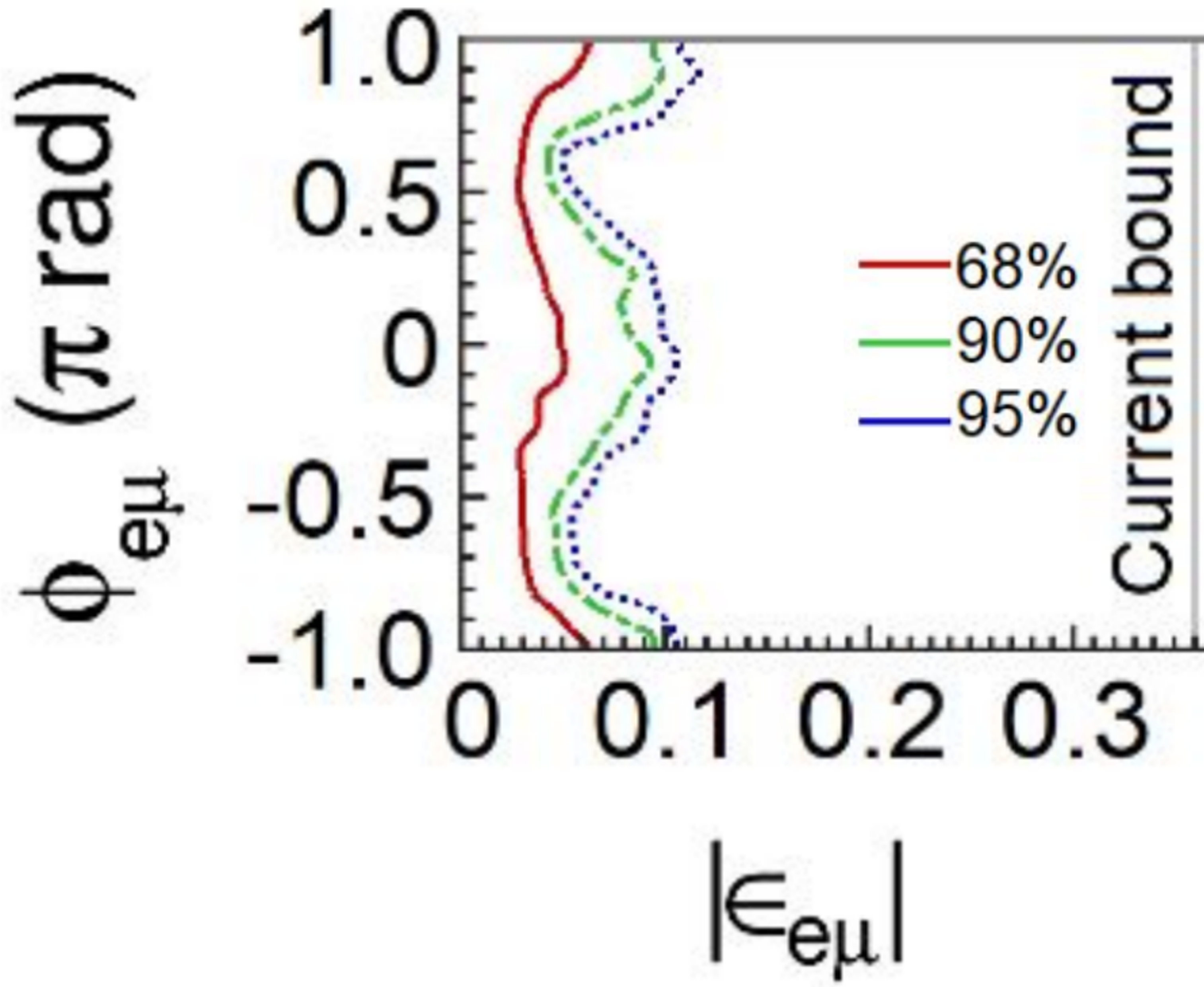

- Broad range of L/E at ND and FD → search for non-SM oscillations
- High statistics neutrino and antineutrino measurements → search for CPT violation
- Very large matter effect → uniquely sensitive to some NSI