Towards the Deep Underground Neutrino Experiment (DUNE)

Paul de Jong
Universiteit van Amsterdam

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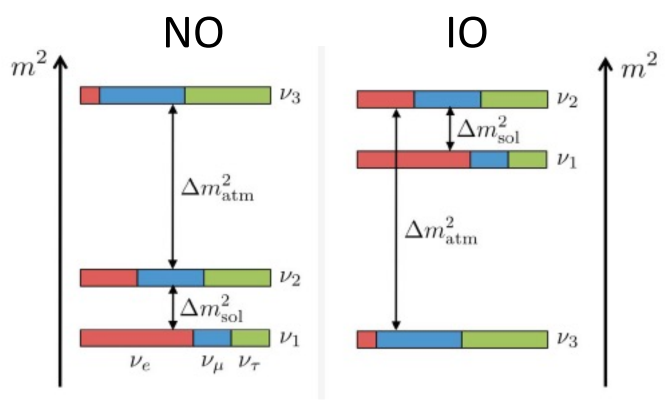
Oscillations with accelerator neutrinos

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

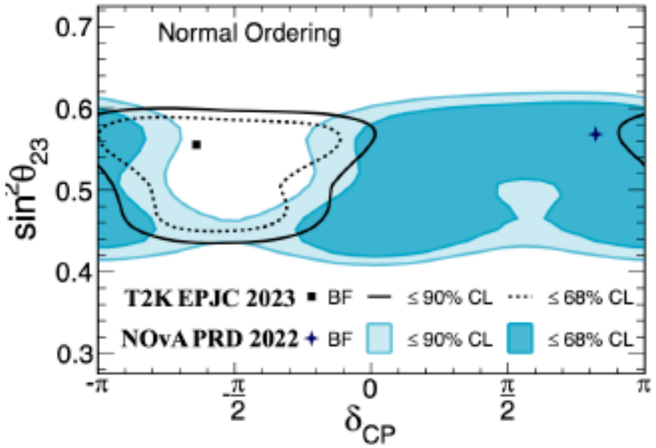


Long-baseline oscillations with accelerator neutrinos: sensitivity to θ_{23}, δ_{CP}, mass ordering, new physics.
Fewer neutrinos than neutrino telescopes, but more control over beam, in particular ν vs $\bar{\nu}$

Testing CP-violation in the neutrino sector is top priority in neutrino physics.

Slight tension T2K & NOvA for NO

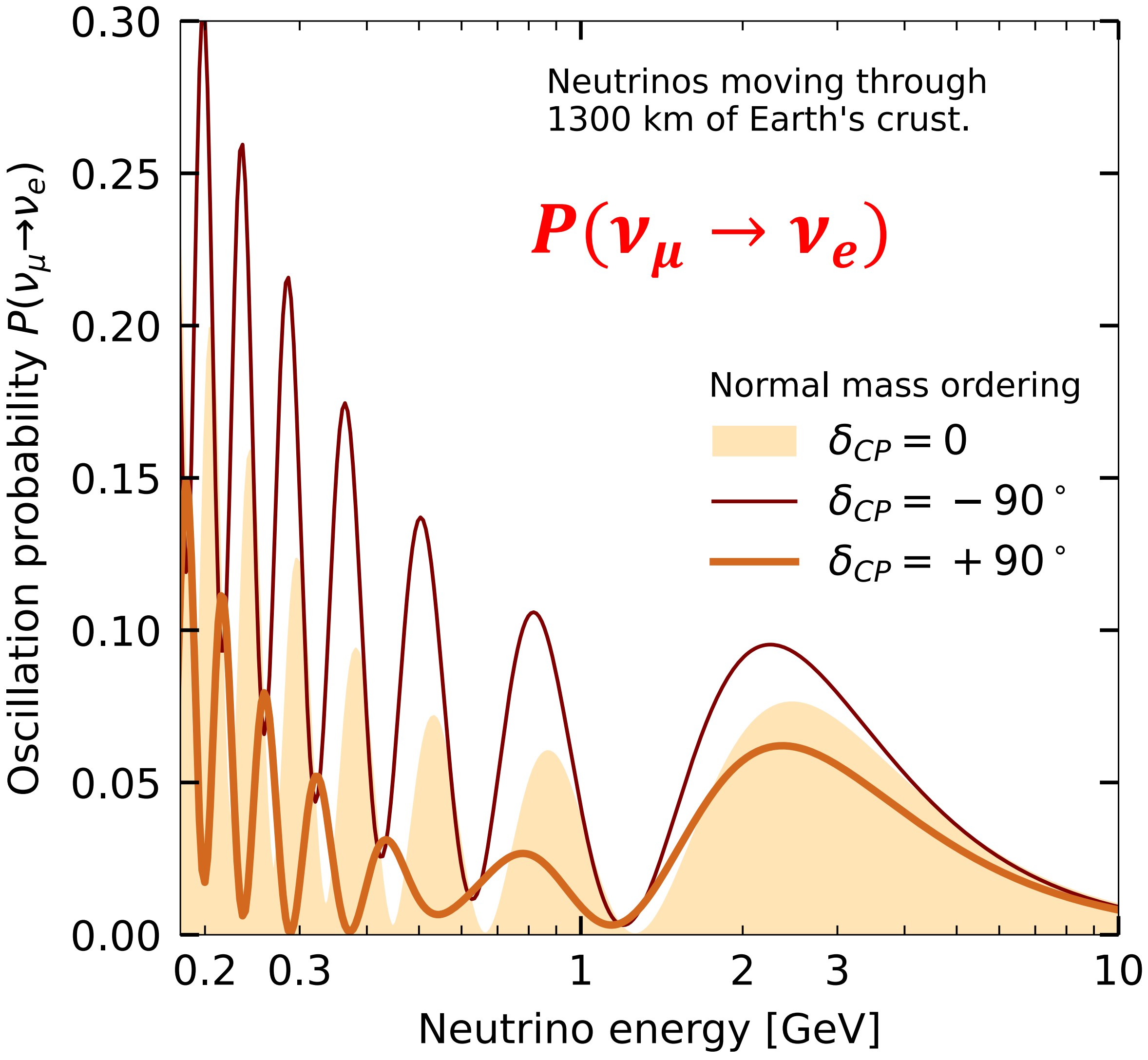
Current experiments: T2K, NOvA

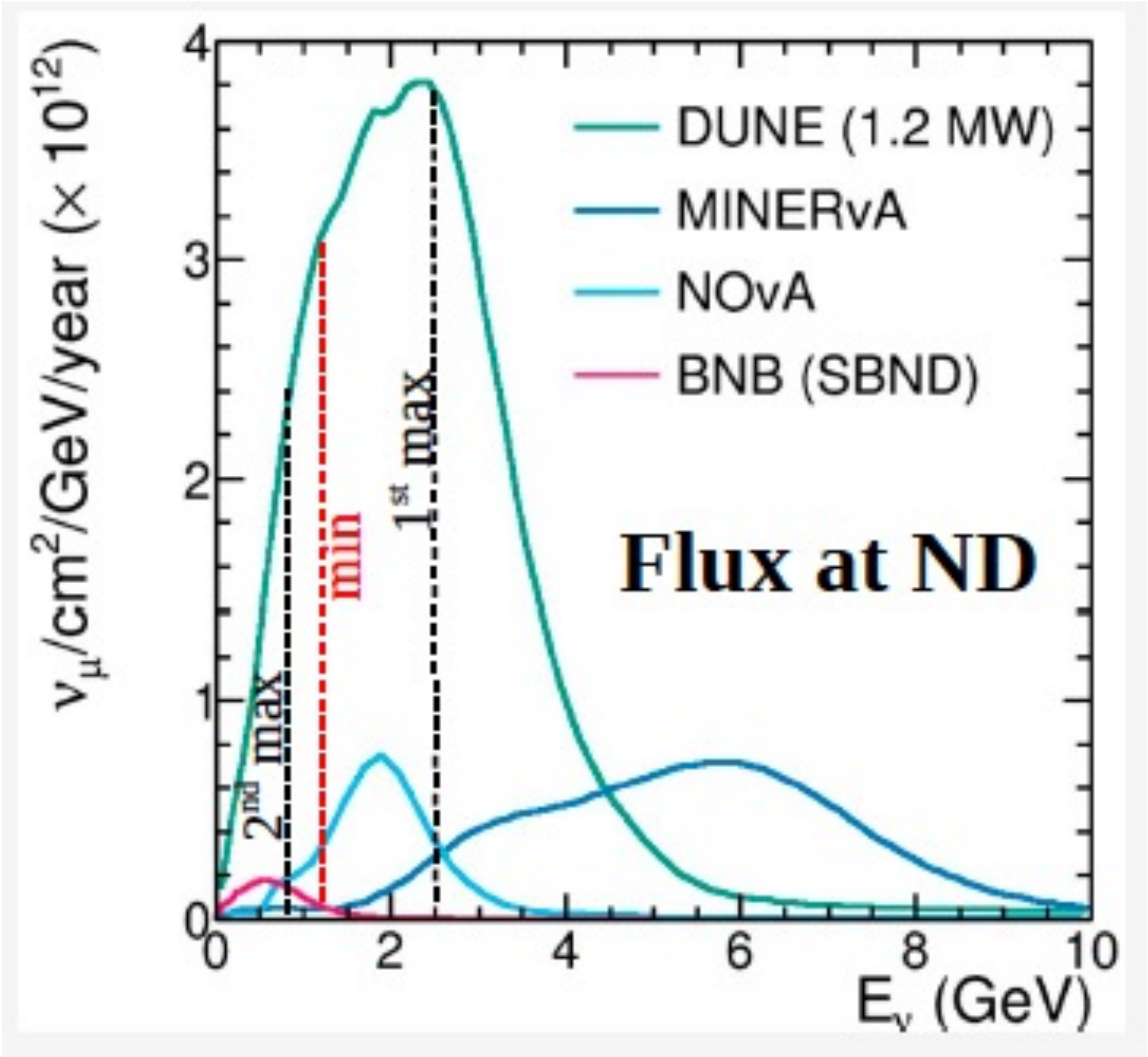


Weak sensitivity to δ_{CP}
Tension between results T2K, NOvA

Next generation: HyperK, DUNE

Oscillation probabilities and the DUNE wideband beam

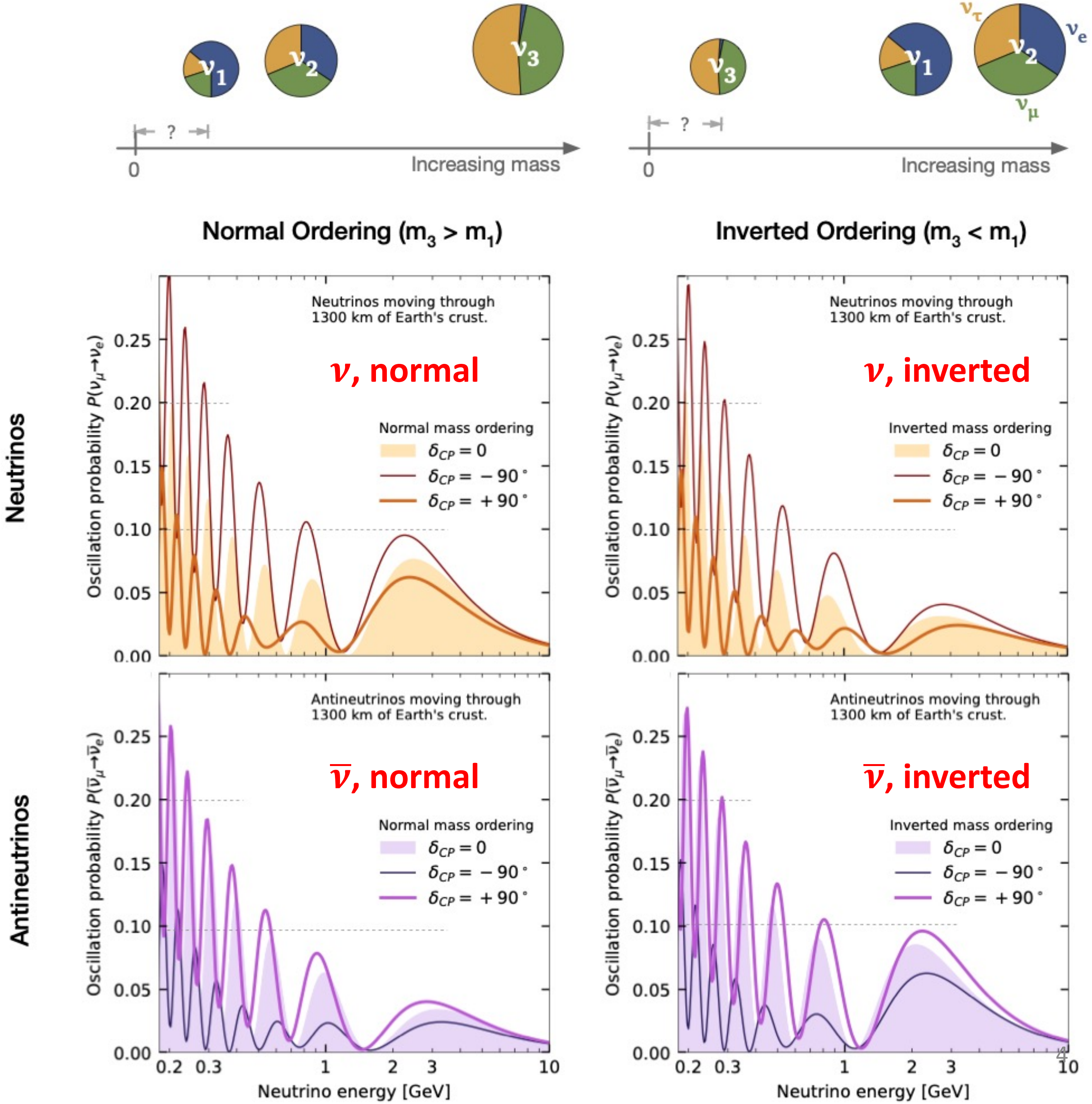




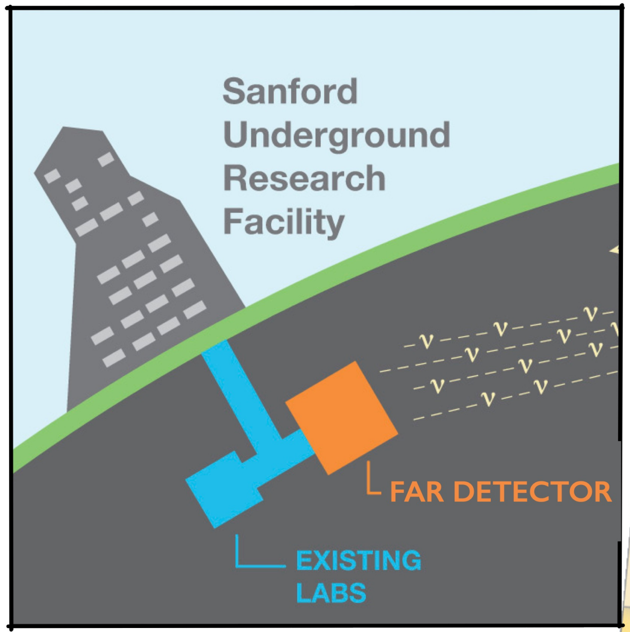
Oscillation probabilities

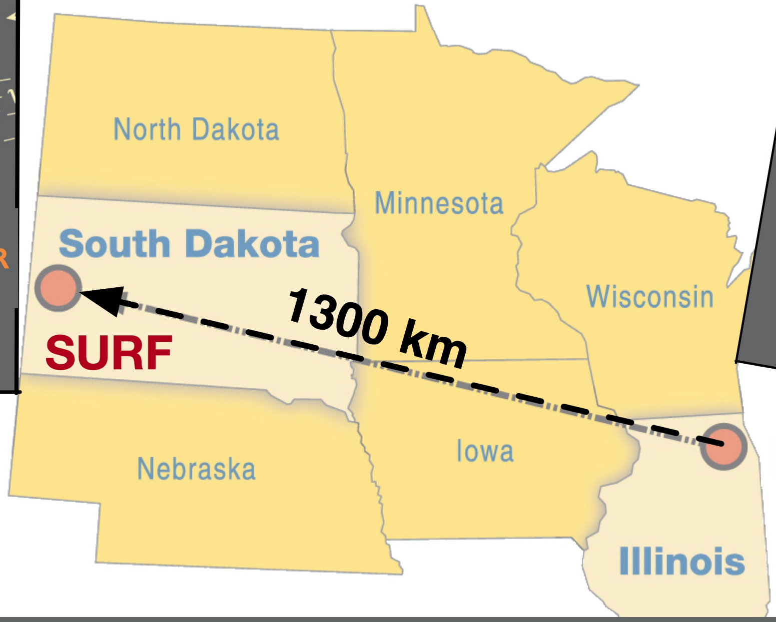
By using 1st and 2nd oscillation maximum, DUNE can disentangle neutrino mass ordering and CP-violation effects, in one expt. (Assuming SM, 3 generations)

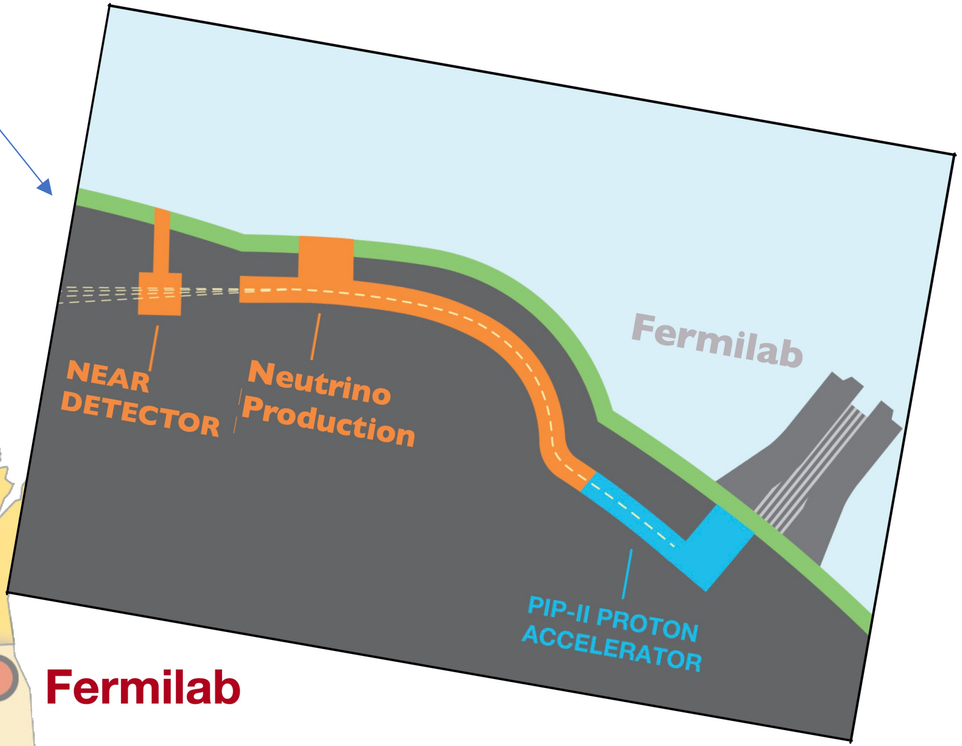
If data cannot be fitted:
new physics?
(Sterile ν, BSM interactions)



Far Away (So Close)



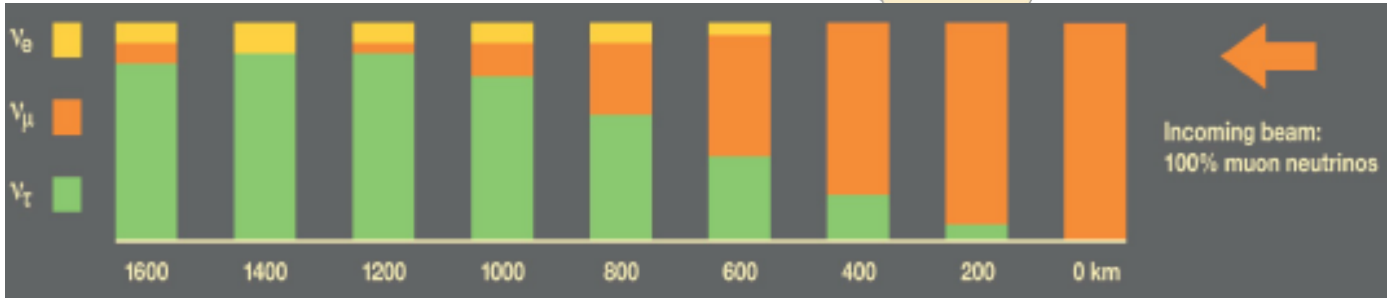




4 x 17 kton LAr detector
1500 m underground

New PIP-II accelerator

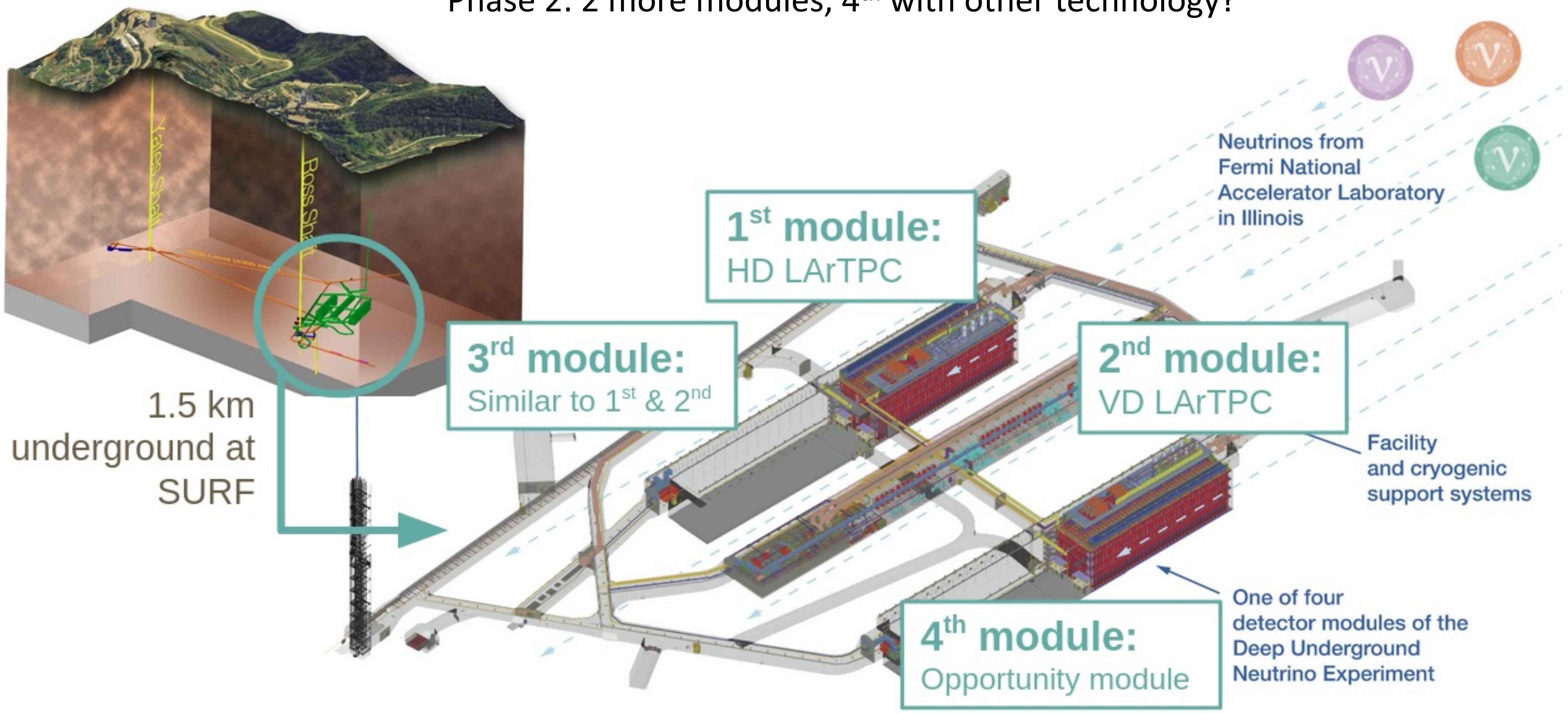
1.2 MW proton beam
to be upgraded to 2 MW



oscillations of a muon neutrino beam

Far site: Sanford Underground Research Facility, Lead, South Dakota

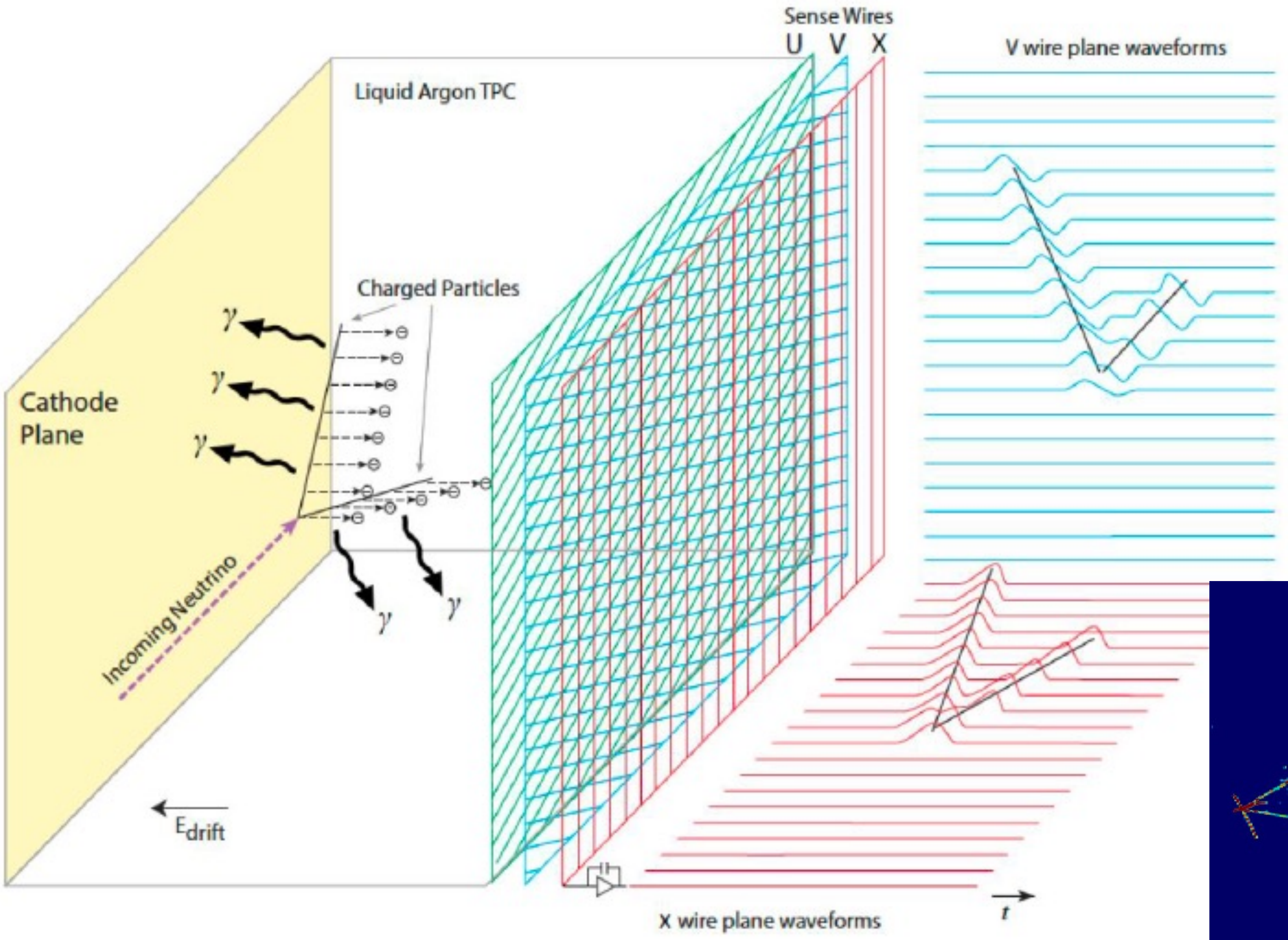
Phase 1: at least 2 modules
Phase 2: 2 more modules, 4^{th} with other technology?

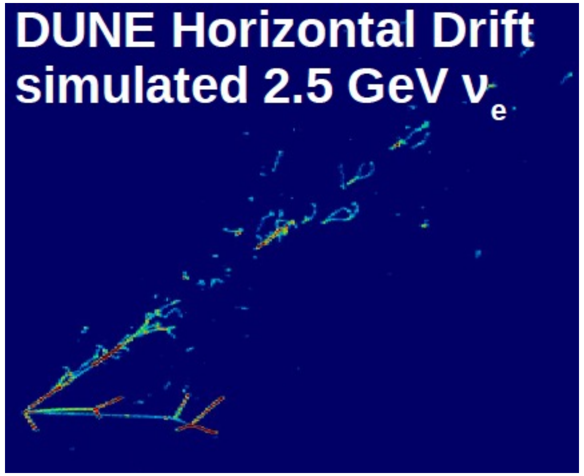


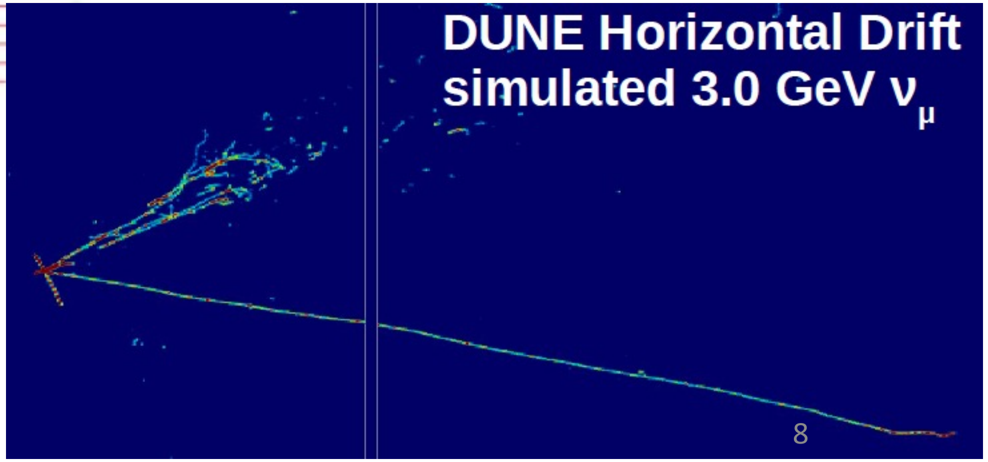
DUNE Far Site: excavation and infrastructure

Liquid Argon Time Projection Chamber

3D-tracking
Reconstruction of all charged particles
dE/dx measurement, particle id







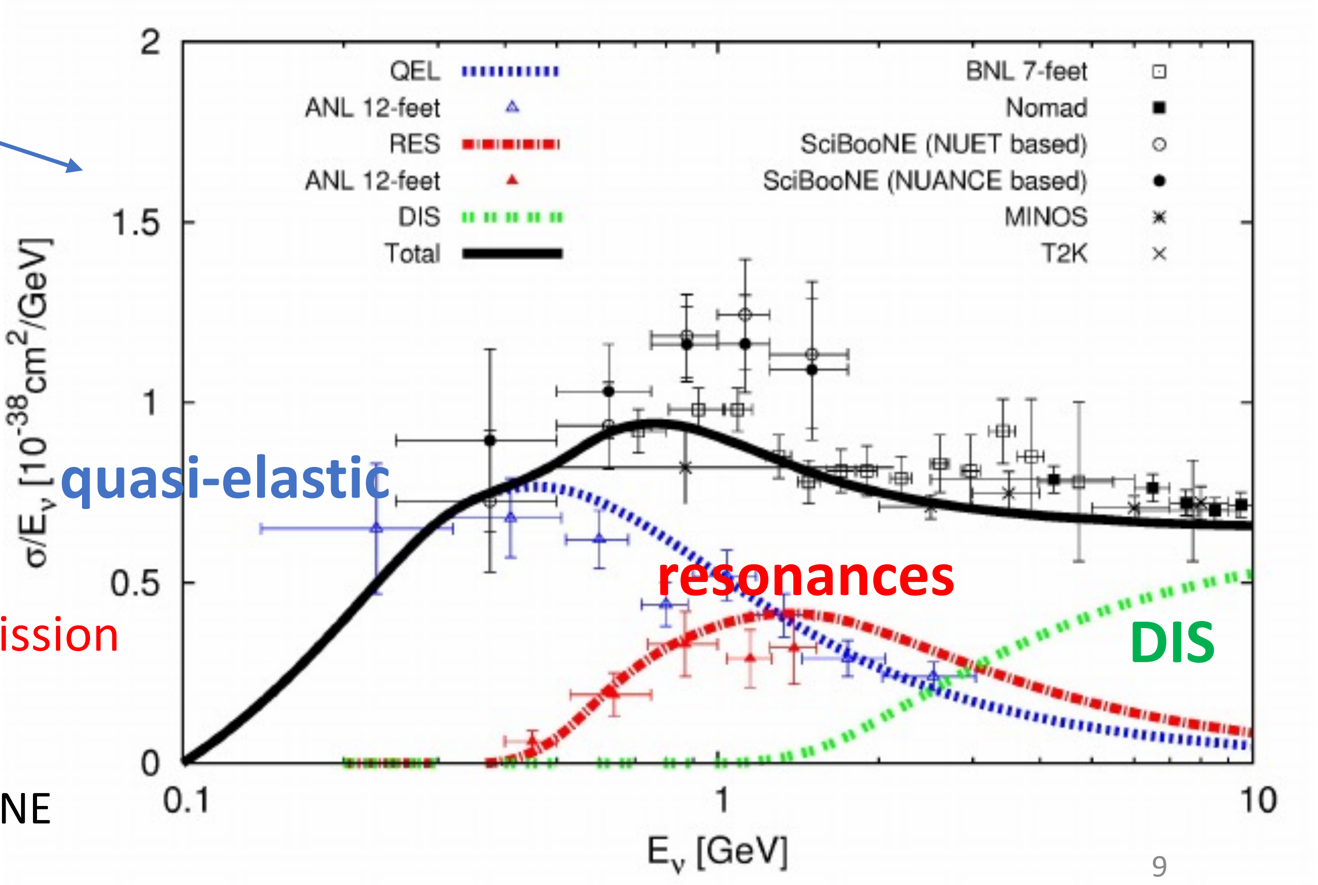
Challenges

Or: what could possibly go wrong?

- detector technology and scale of the experiment
- neutrino cross section systematics
- beam uncertainties

Prototype: **ProtoDUNE**

Near Detector at Fermilab site



quasi-elastic: Ar nucleus recoils

resonances: nucleus excited, decays via p, $\pi^{\pm}, \pi^{0}$ emission

DIS: deep inelastic scattering, nucleus breaks up

input from ArgoNeuT, MicroBoone, Minerva, T2K, ProtoDUNE

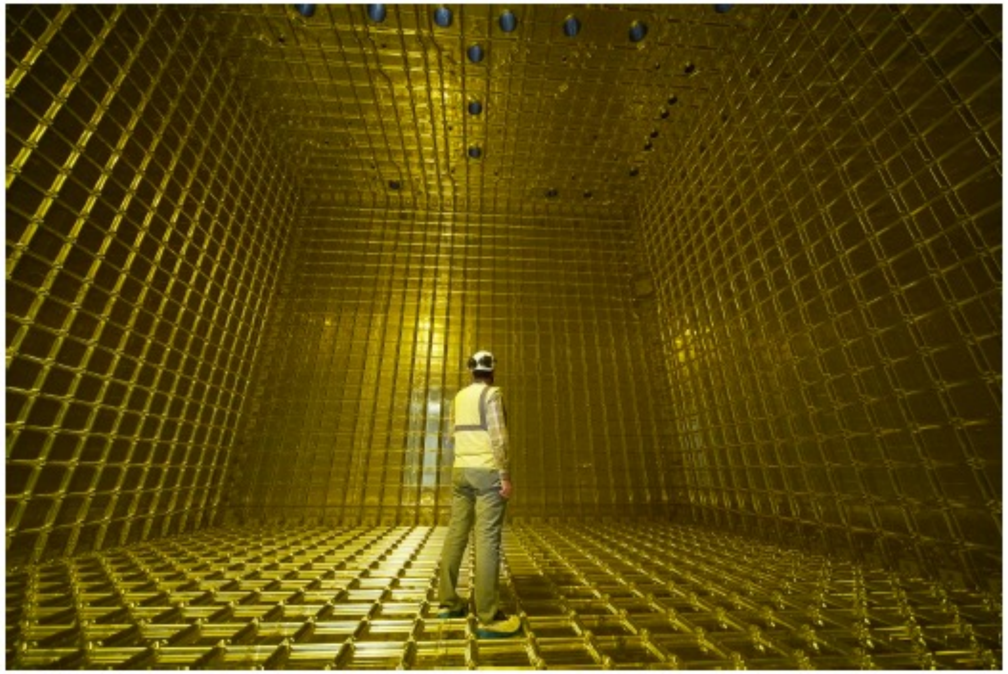
ProtoDUNE

CERN North Area

- Actually 2 ProtoDUNEs, 6x6x6 meter, each 800 ton LAr
- NP4 took beam data in 2018, NP2 took cosmics data
- Different technologies

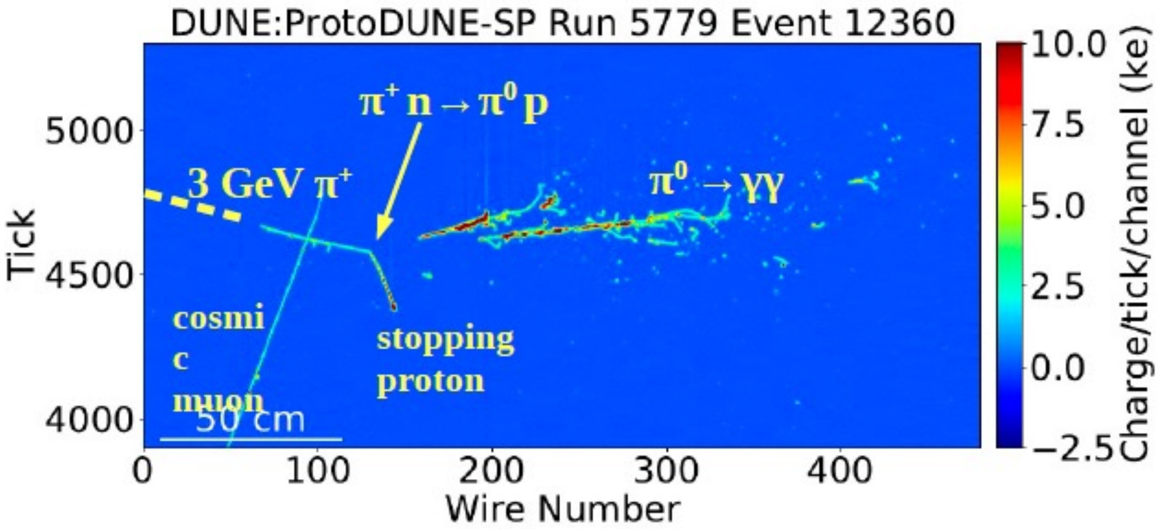
Nikhef contributed to DAQ for NP4

Inside of the ProtoDUNE Neutrino Platform 2 cryostat



Neutrino Platform 2

Neutrino Platform 4



p, e, μ, π beam

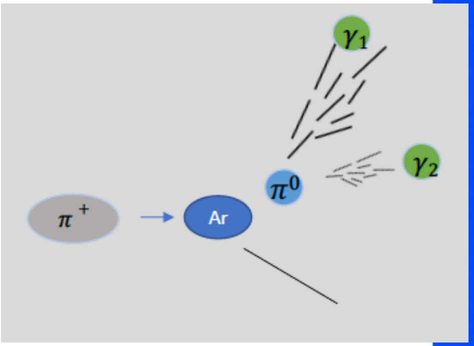
ProtoDUNE detector performance

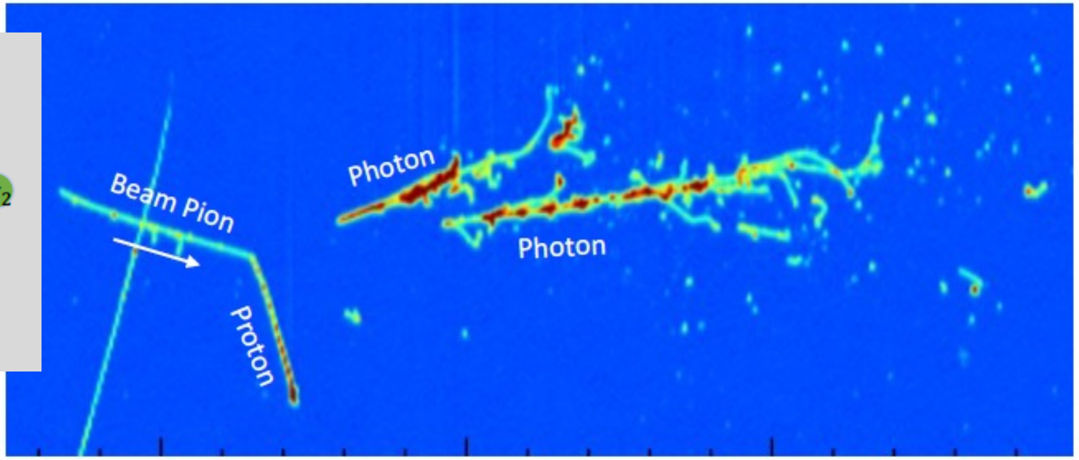
Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE Noise Signal-to-noise ⟨SNR⟩	 (C) 550 e, (I) 650 e ENC (raw) (C) 48.7, (I) 21.2 (w/CNR)	 < 1000 e ENC
CE dead channels	0.2%	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)
PDS time resolution	14 ns	< 100 ns

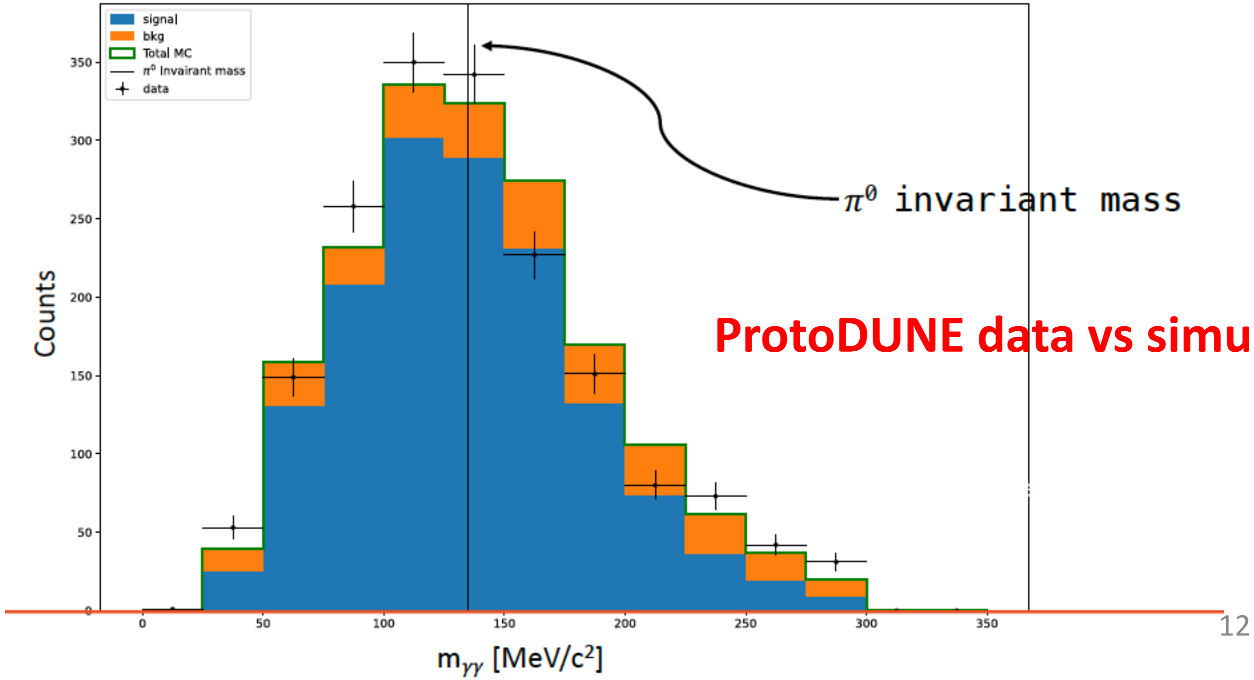
A second run of (slightly) modified detectors takes place in 2024, starting now!

ProtoDUNE analysis

π^0 reconstruction: energy scale, e-π separation, cross-section

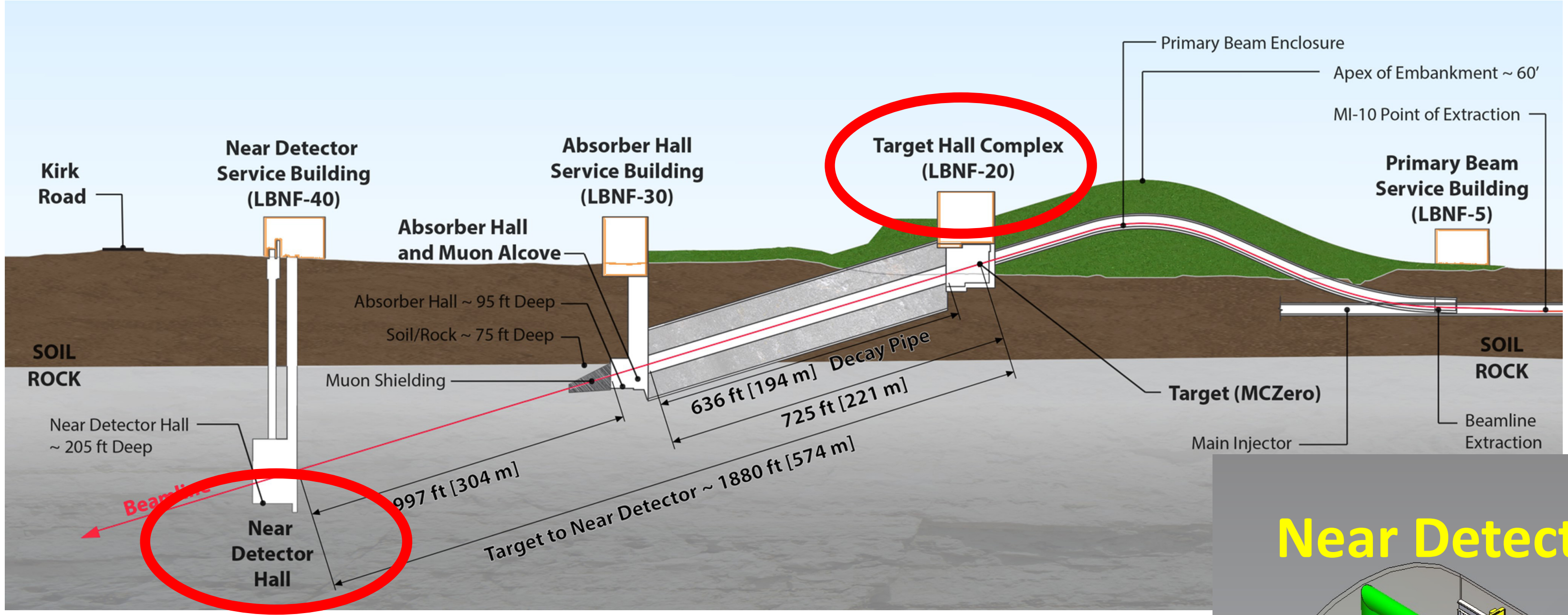






ProtoDUNE data vs simulation

Characterizing the beam: Near Detector



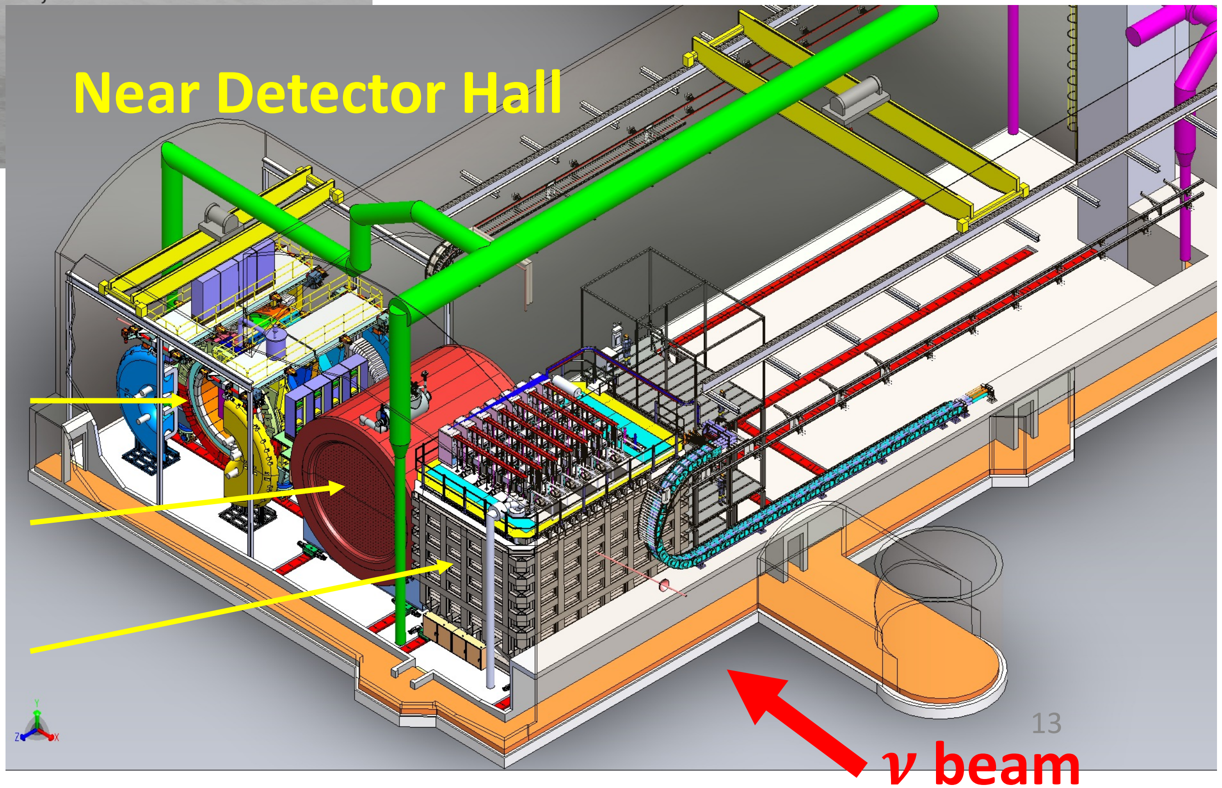
Near Detector, 574 meter from target, 60 m underground

SAND detector (magnet and calorimeter from KLOE)

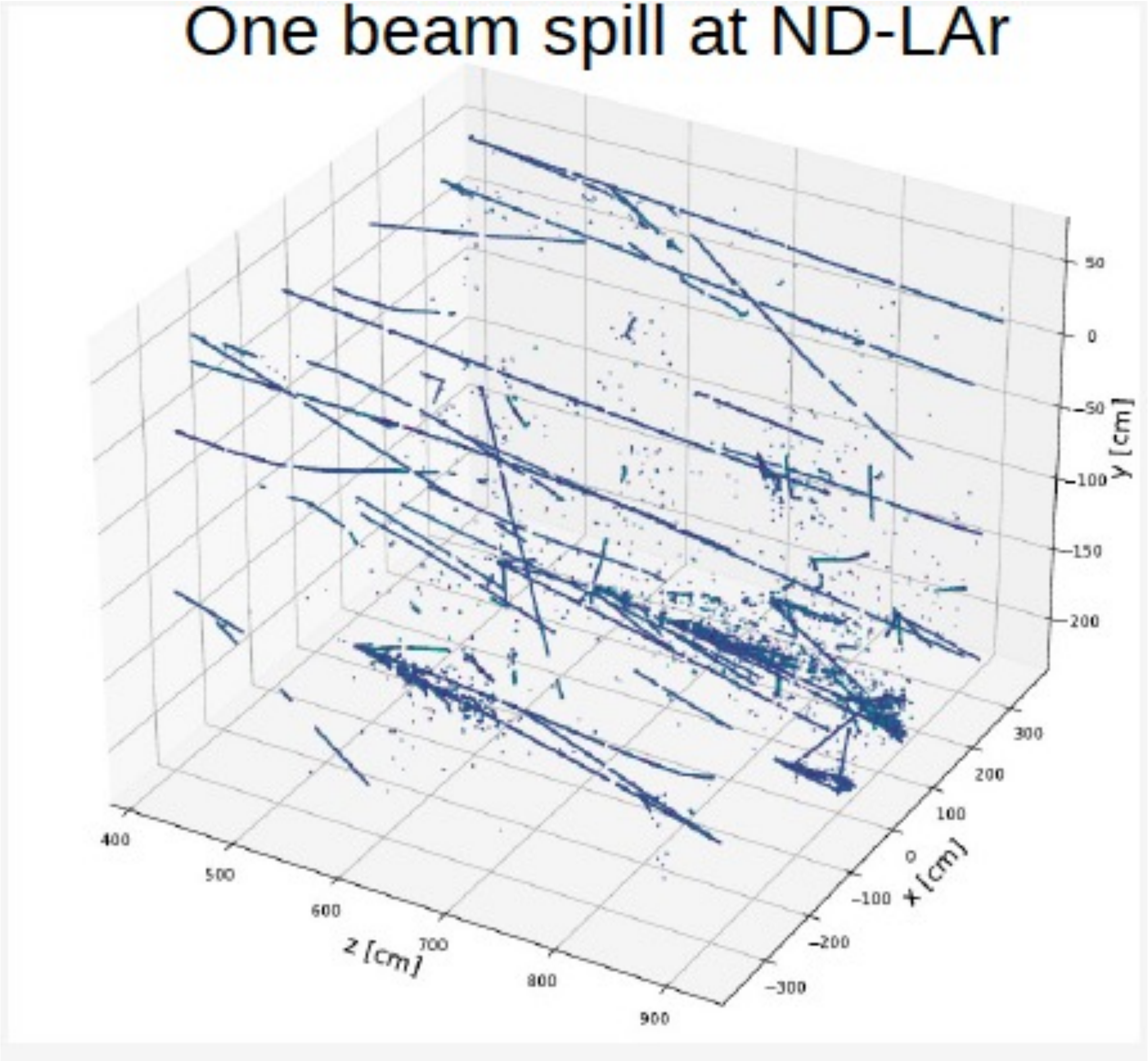
Movable
on-axis/off-axis
→ beam profile,
energy dependence

Muon spectrometer

ND-LAr: modular liquid argon TPC



The challenge of the Near Detector



Beam spill lasts 10 μs, and repeats at 1 Hz

Maximum drift time of electrons: 300 μs

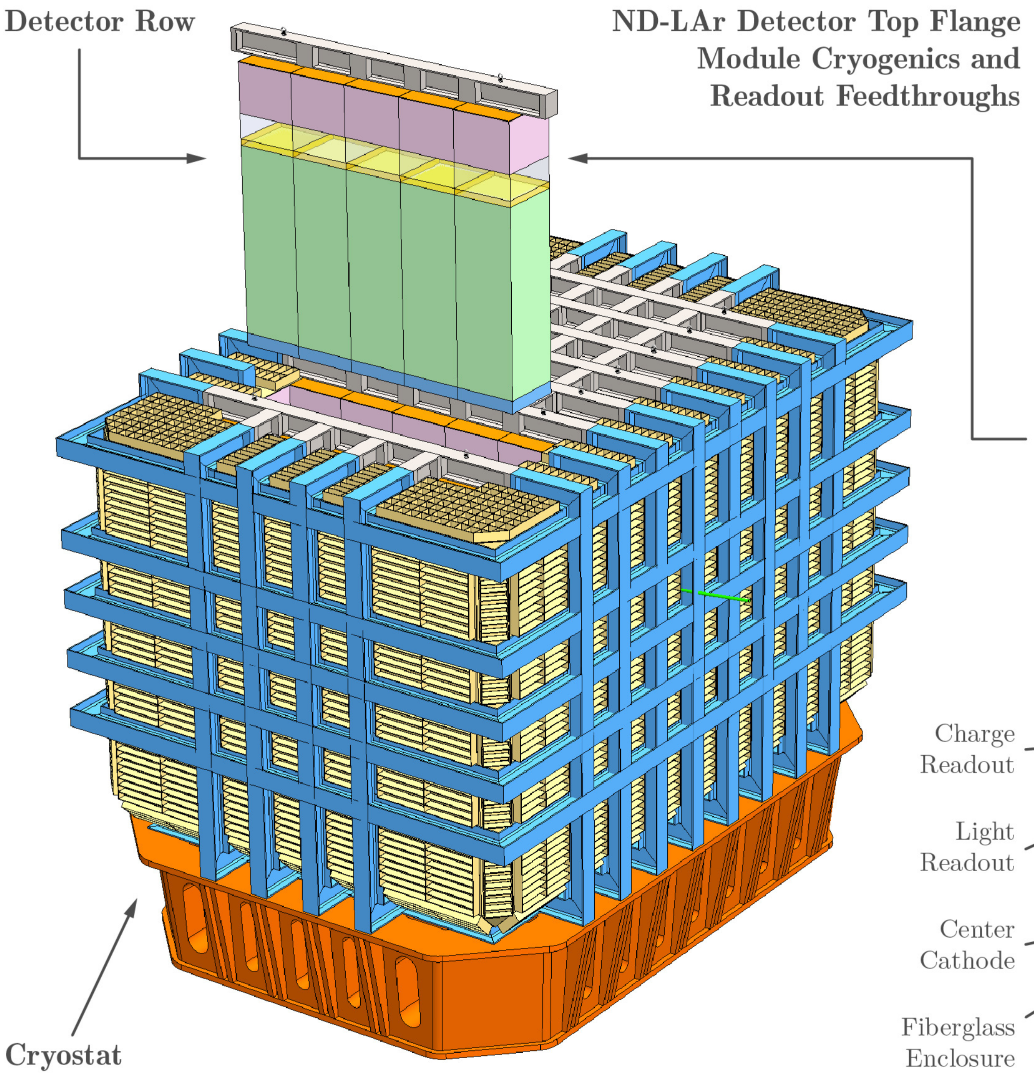
Every spill: up to 50 interactions
(neutrinos in LAr and in rock leading to muons)

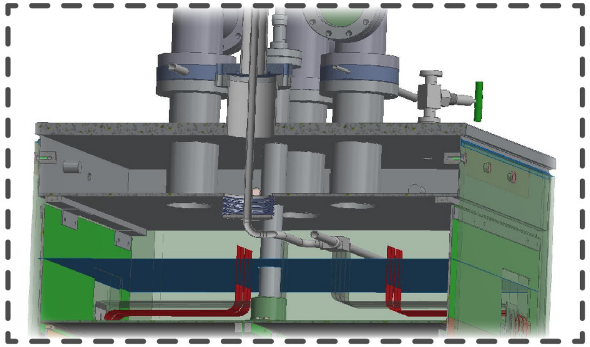
Disentangle interactions:

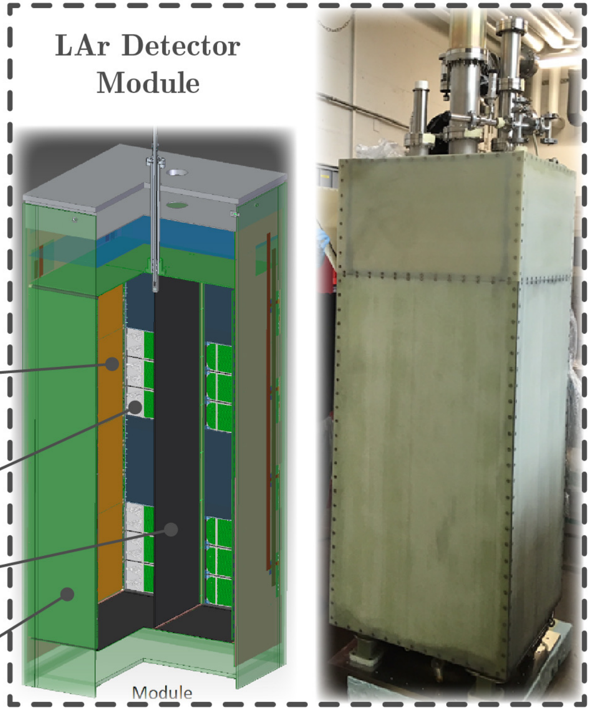
- make small light-tight compartments
- scintillation light determines event time
- match scintillation light and charge

(But also: unprecedented event sample for physics!)

ND-LAr TPC

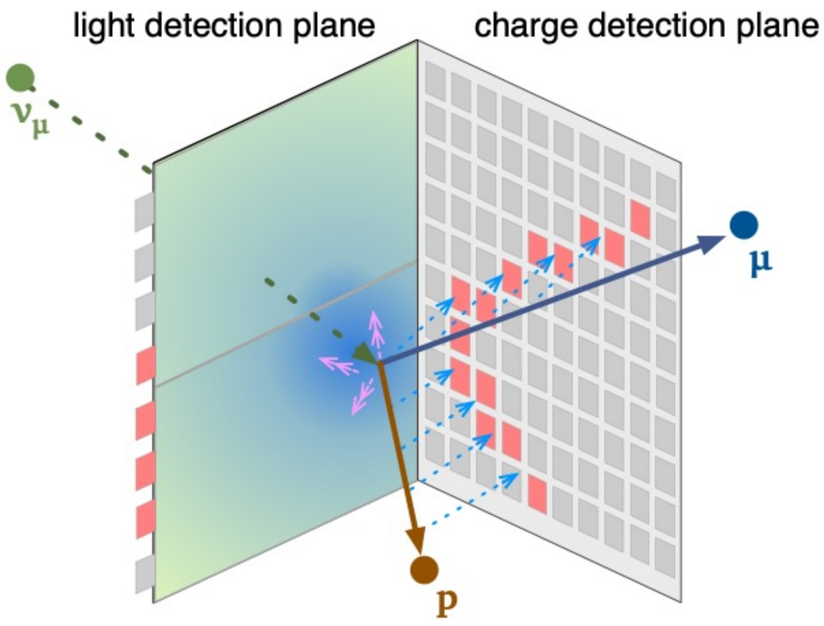




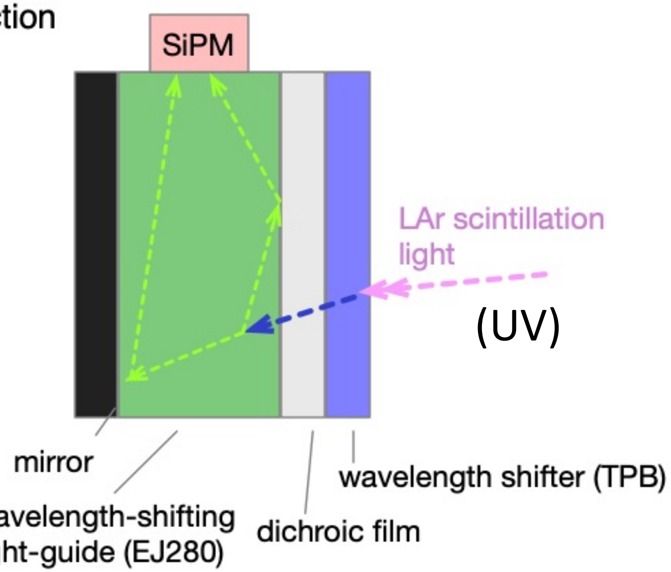


7 rows of 5 modules each

1 x 1 x 3 meter



light detection plane
cross section



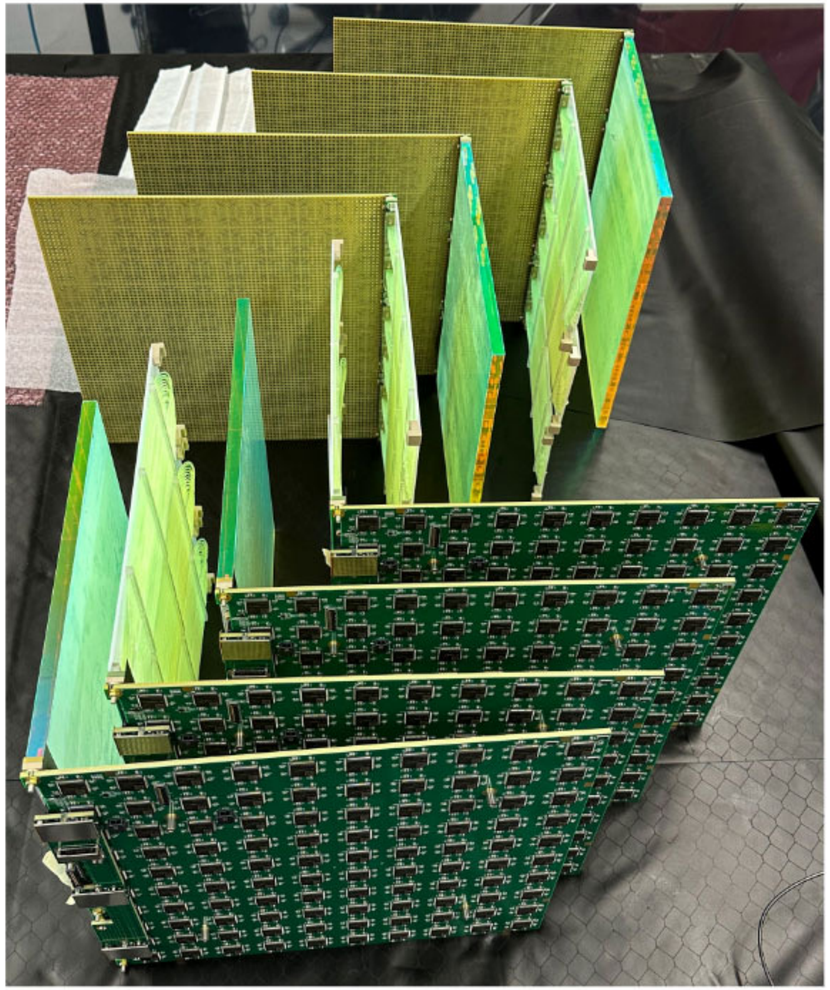
The 2x2 Prototype

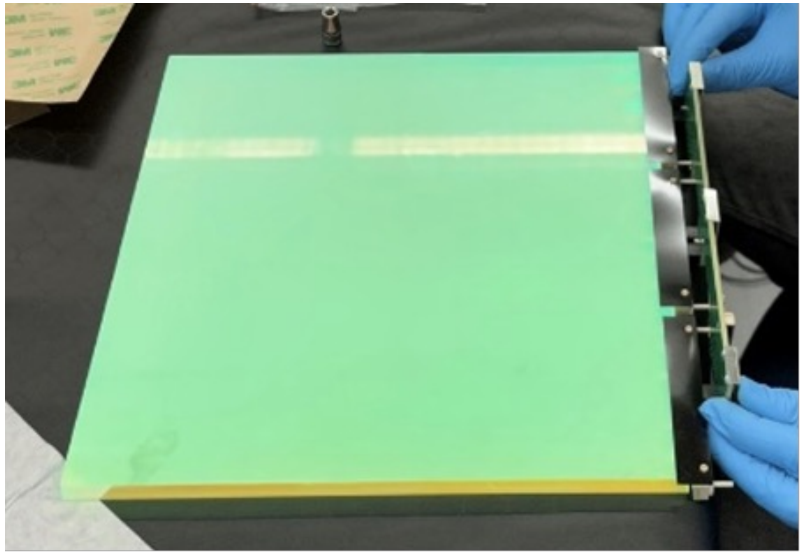
Currently in the NuMi neutrino beam at Fermilab

Marjolein van Nuland-Troost

Nikhef plans

Light detection system for ND-LAr modules (with U. Bern)





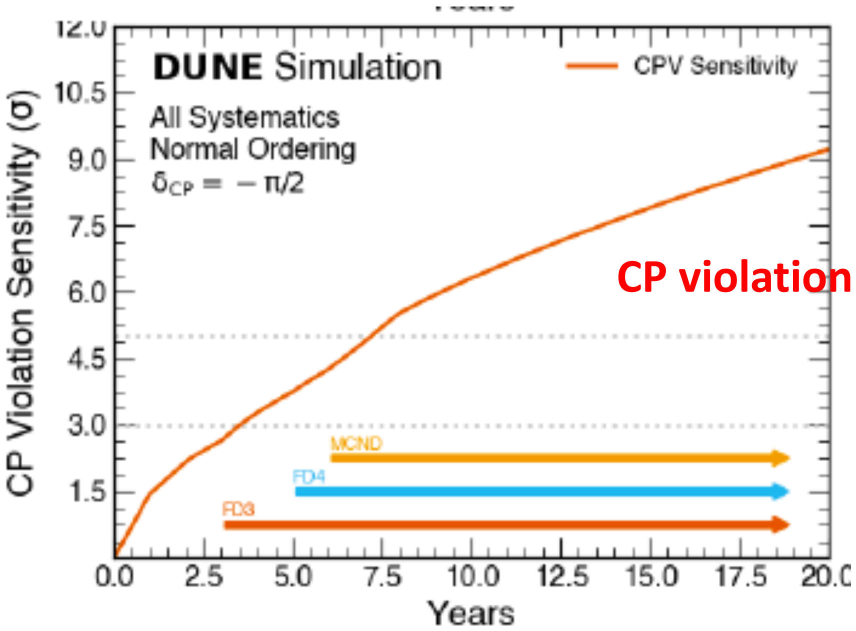
Light collectors SiPM Preamps	}	cold
Cabling		
Amplifiers TDCs	}	warm

+ software, analysis

35 modules, 8400 electronics channels

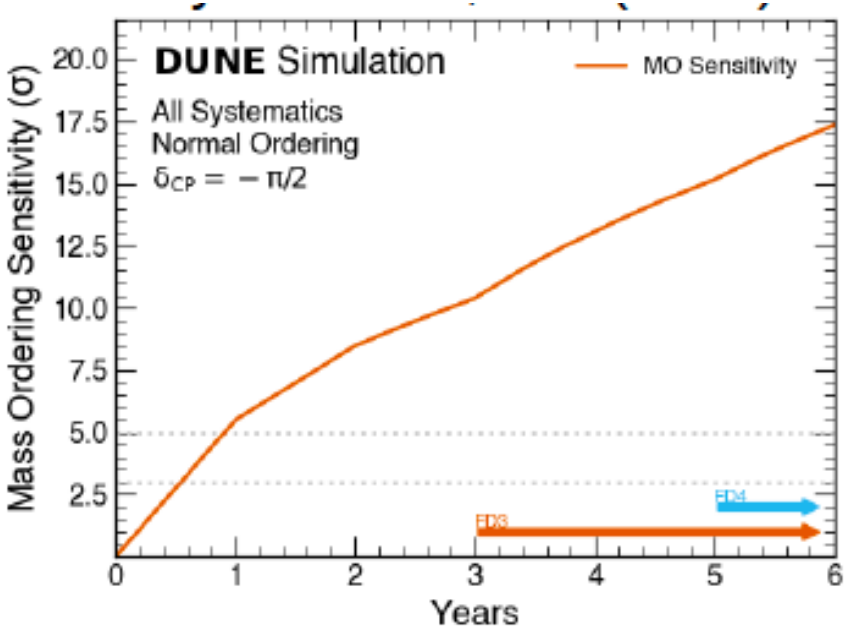
Physics expectations

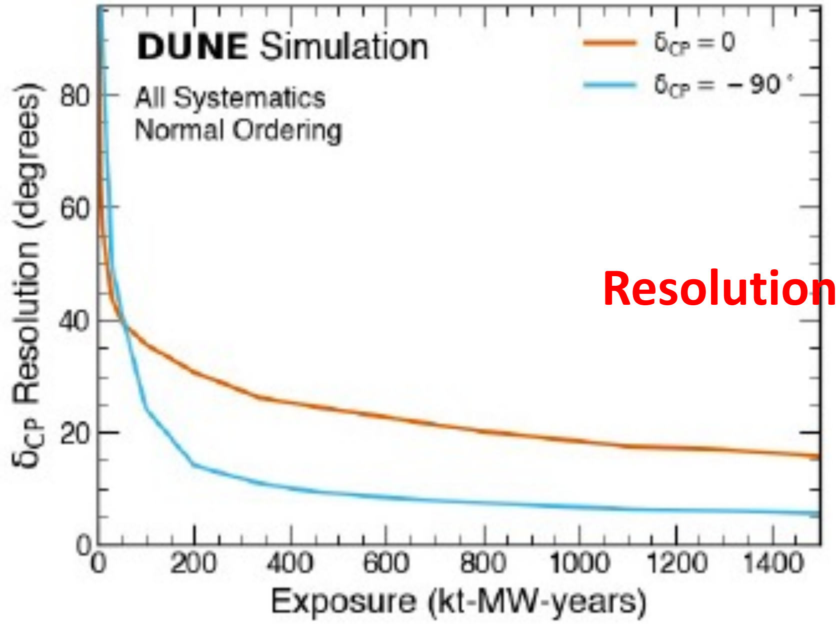
Assuming realistic detector staging and beam performance.



CP violation (max CPV, NO)

Mass ordering (in case of max CPV, NO)





Resolution on δ_{CP}

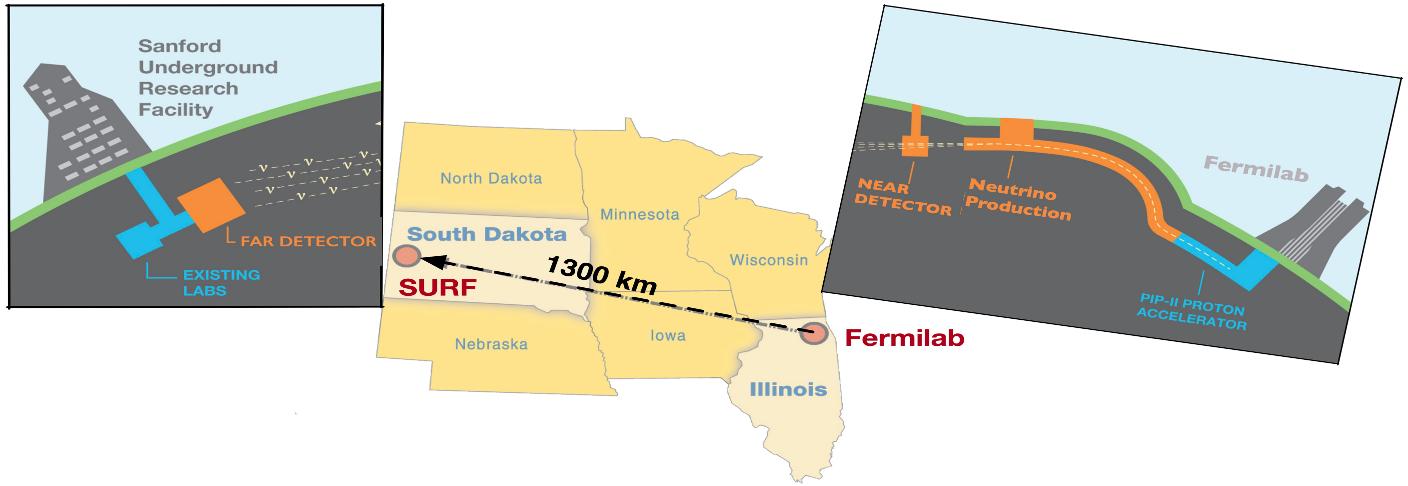
Timeline

Far Detector:

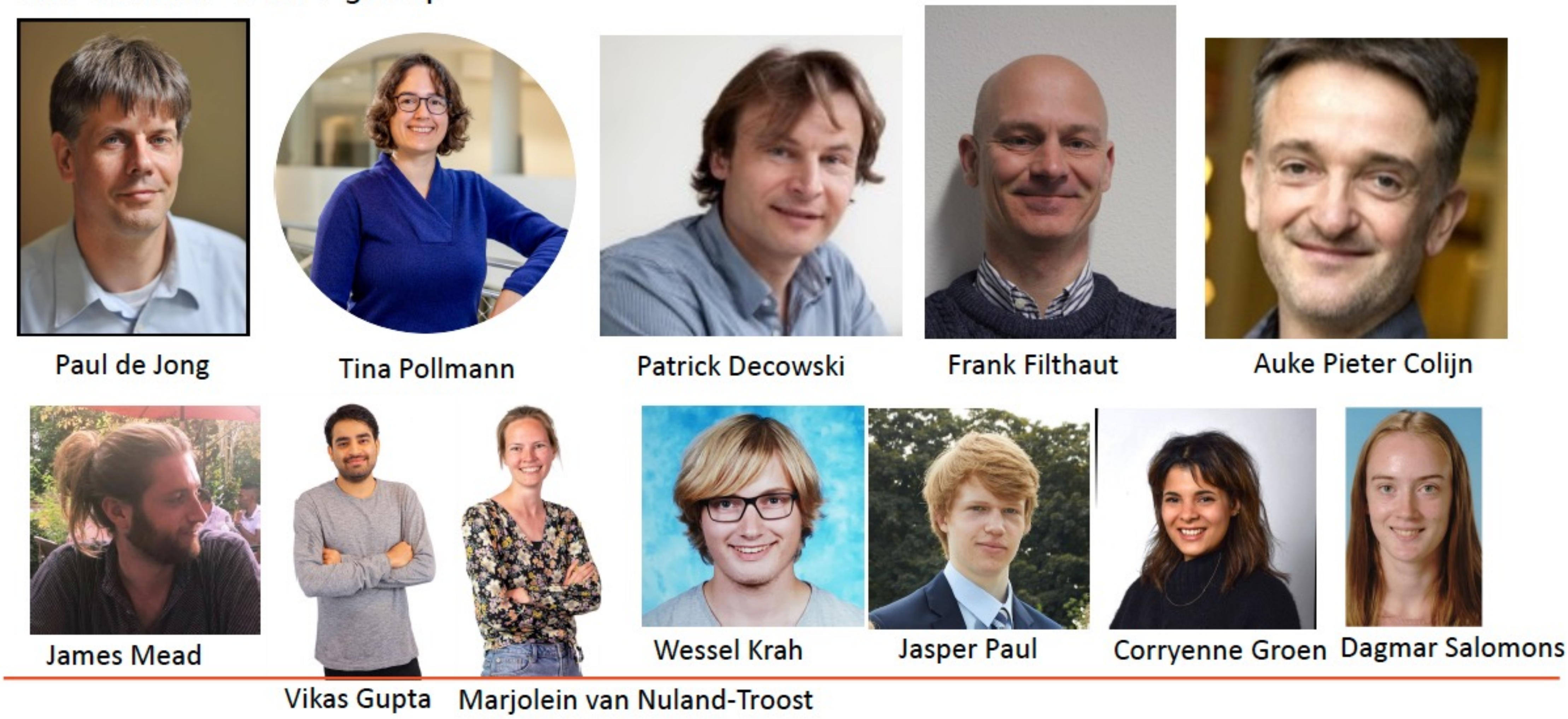
- 2024-2025: Infrastructure
- 2025-2026: Cryostats
- 2026-2027: First 2 modules
- 2028: fill with Ar and purify
- 2029: first data with atm. ν
- 2031: beam

Near Detector LAr:

- 2024-2025: 2x2 tests
- 2024: first full size demonstrator module
- 2026: first row of 5 modules
- 2028-2029: completion 35 modules
- 2029-2030: installation, commissioning
- 2031: beam



The Nikhef DUNE group



+Nikhef and RU electronic engineers