The DUNE Phase II Far Detector

Technology & Physics Prospects

Anyssa Navrer-Agasson, for the DUNE Collaboration
(a.navrer-agasson@imperial.ac.uk)

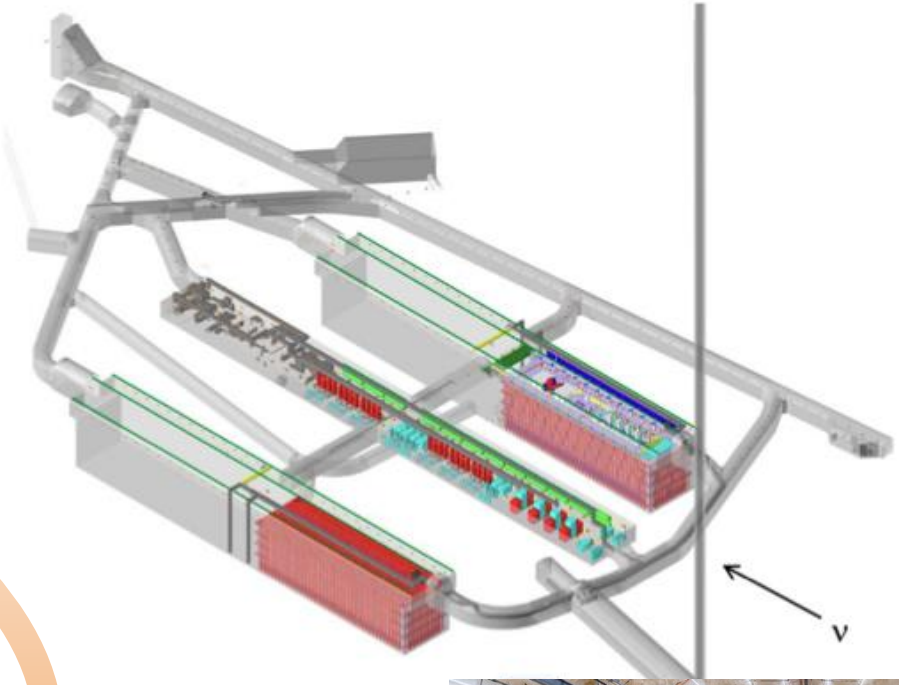
NNN 2026 – Seoul, South Korea
29th October 2026

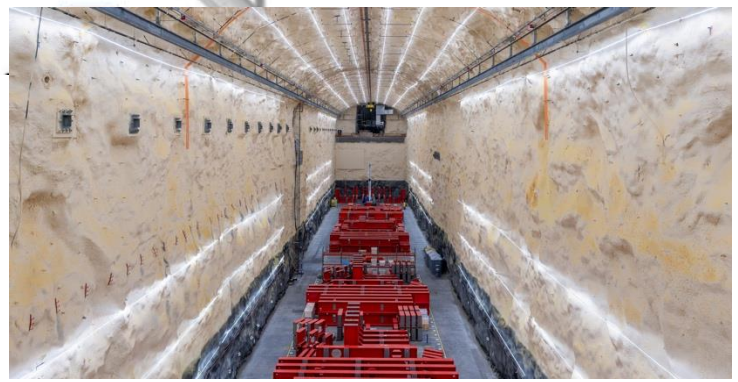
IMPERIAL DUNE

Phases of DUNE

Phase I

- 1.2 MW beam
- Near Detector Complex:
  - ND-LAr, TMS, SAND
- Two far detector modules (> 20 kt target mass)
  - FD1: Vertical Drift
  - FD2: Horizontal drift

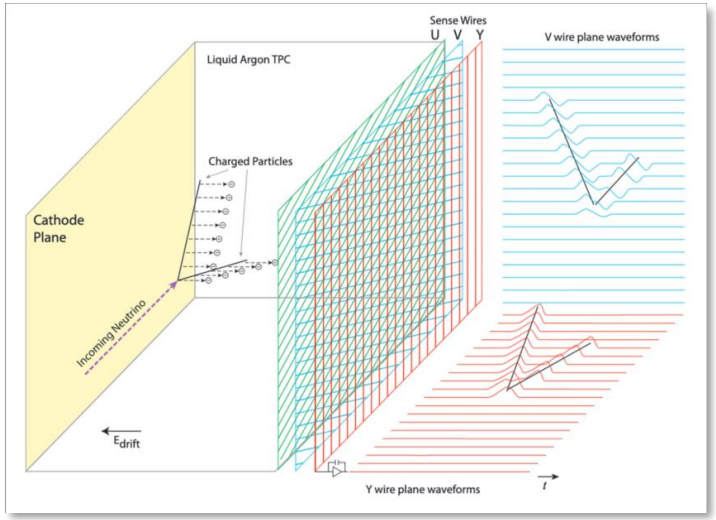




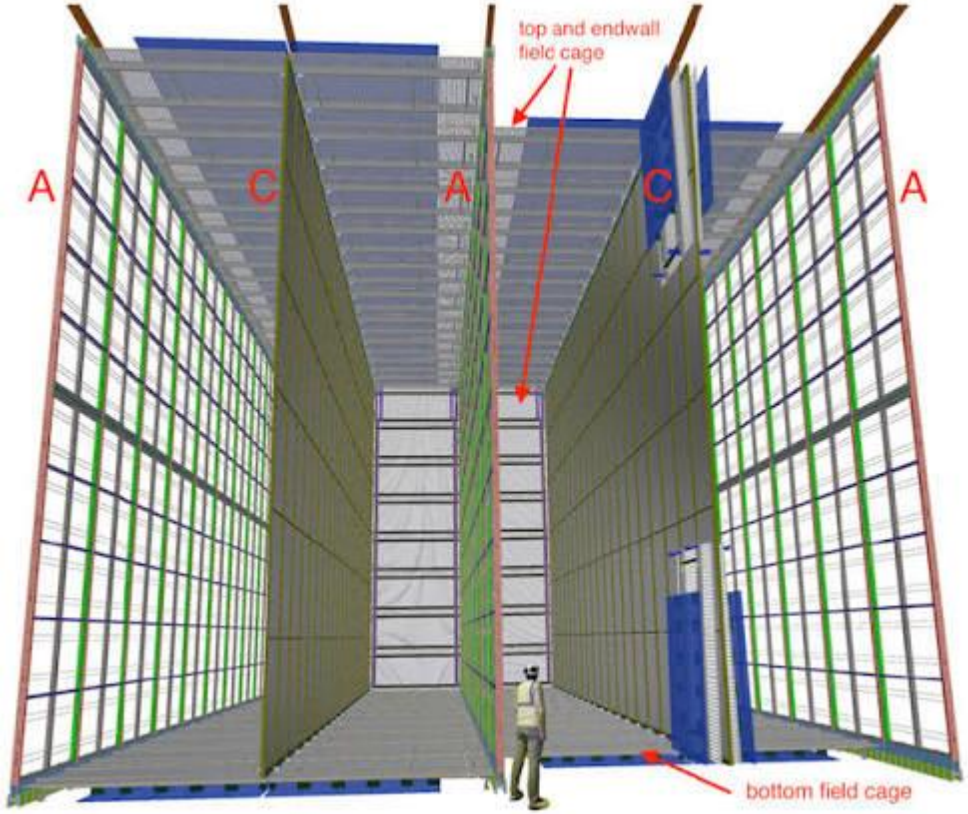
Excavation of the caverns is complete!!

DUNE FD – Horizontal Drift

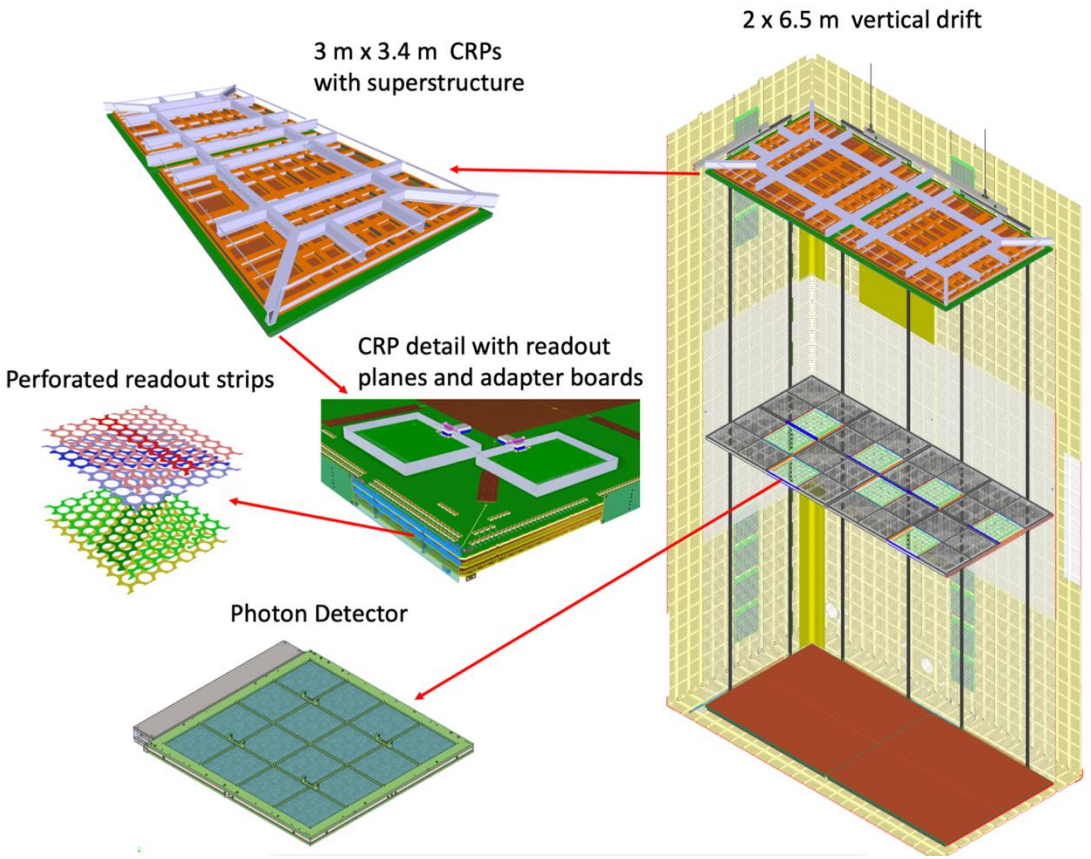
- Relies on long established technology
  - Wire-based charge readout: Anode Plane Assemblies (APAs)
  - X-ARAPUCAs for photon detection (more details in Maritza's talk right after mine)
- Four 3.6m drift sections



Cross-section of DUNE FD-HD

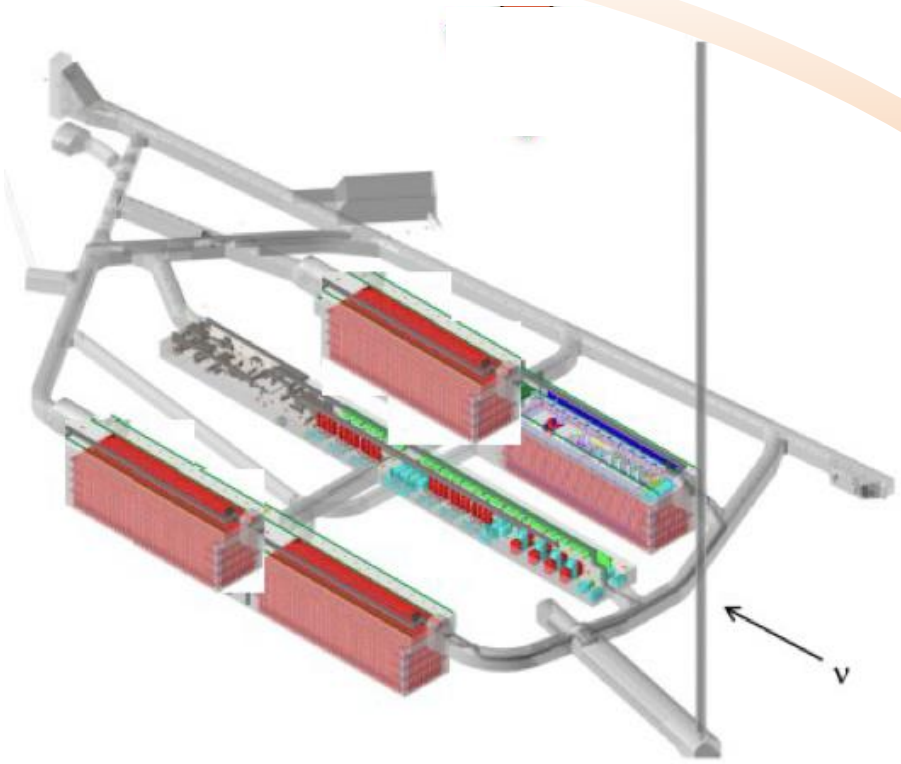


DUNE FD – Vertical Drift



- Cathode at mid-height, two anode planes (top & bottom)
- Longer drift distance 6.5m
- Charge Readout Planes (perforated PCBs) instead of APAs
- X-ARAPUCA photon detectors

Phases of DUNE



NB: Excavated caverns include space for Phase-II detectors

Phase II

- Enhanced beam (up to 2.3 MW)
- More Capable Near Detector (MCND)
- Two additional far detector modules (FD3 & FD4)
  - > 40 kt target mass
  - Designs not fixed

Phases of DUNE

Phase I

- 1.2 MW beam
- Near Detector Complex:
  - ND-LAr, TMS, SAND
- Two far detector modules (> 20 kt target mass)
  - FD1: Vertical Drift
  - FD2: Horizontal drift

Additional Mass

Reduced systematics

Extend DUNE's Physics Reach

Phase II

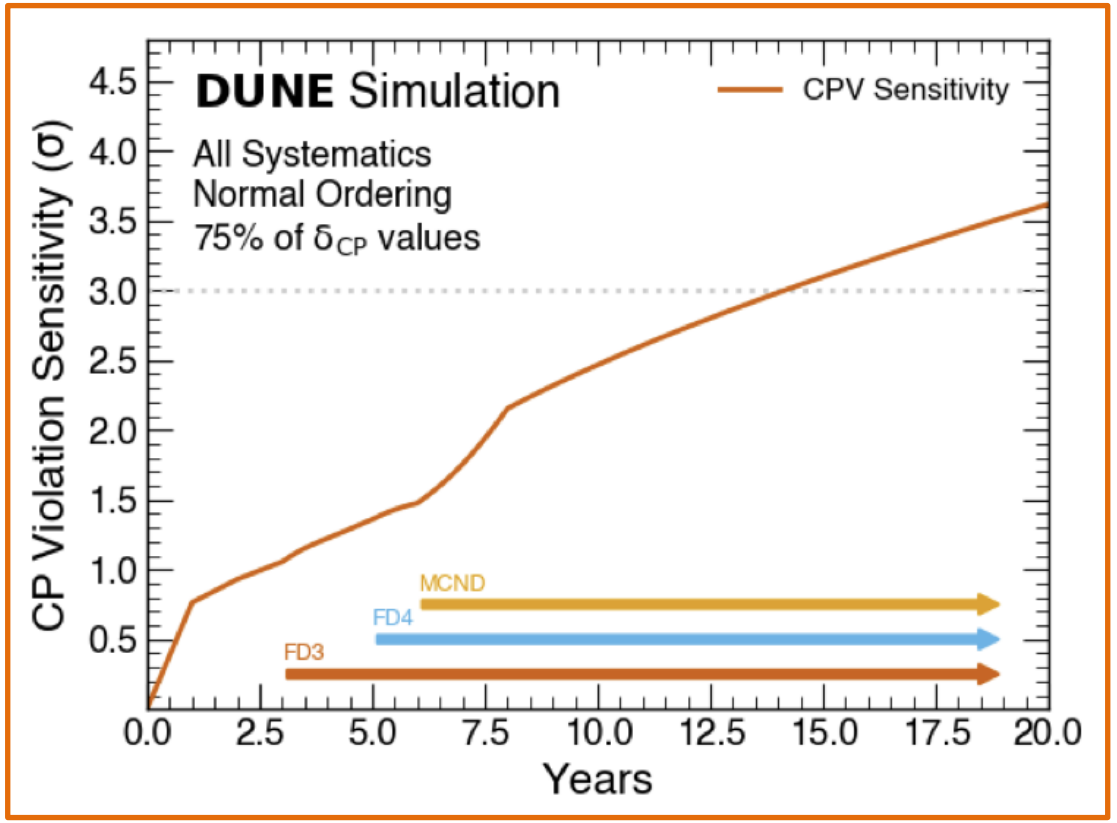
- Enhanced beam (up to 2.3 MW)
- More Capable Near Detector (MCND)
- Two additional far detector modules (FD3 & FD4)
  - > 40 kt target mass
  - Designs not fixed

The Physics of DUNE

DUNE Phase II White Paper
JINST **19** P12005 (2024)

Long-baseline oscillations

- High-precision measurements of oscillation parameters
- Establish CP violation over a broad range of possible δ_{CP} values



The Physics of DUNE

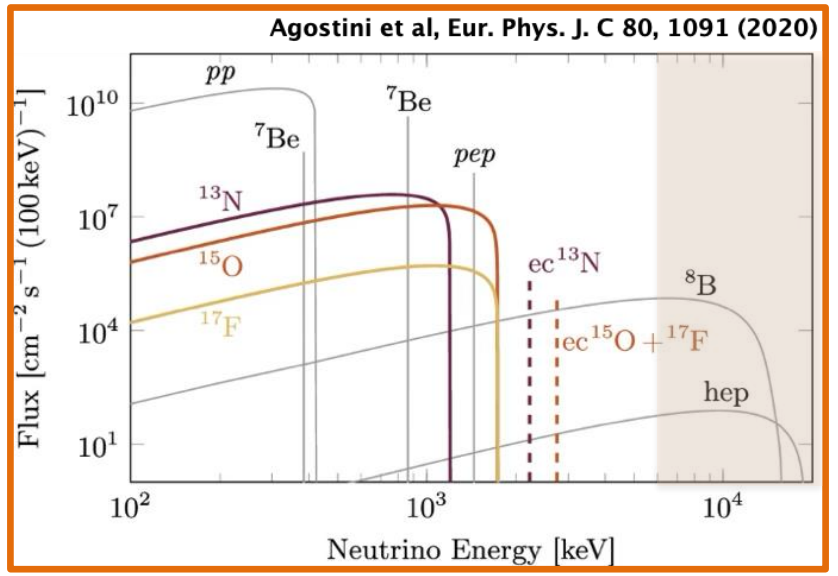
DUNE Phase II White Paper
JINST **19** P12005 (2024)

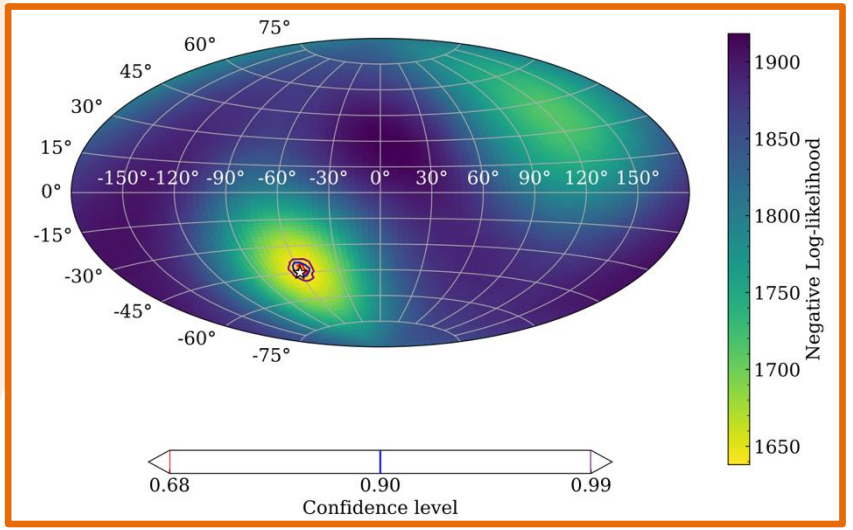
Long-baseline oscillations

- High-precision measurements of oscillation parameters
- Establish CP violation over a broad range of possible δ_{CP} values

Low-energy physics

- Solar neutrinos
- Supernova core collapse bursts
- Diffuse supernova neutrino background



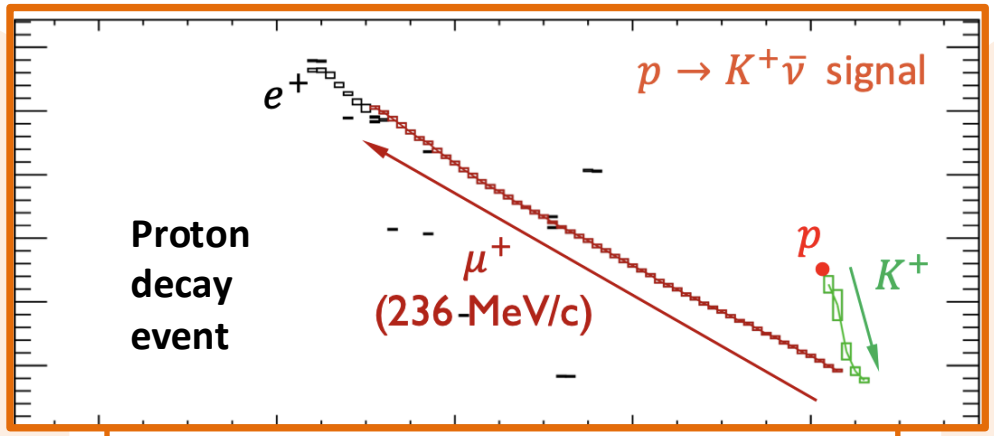


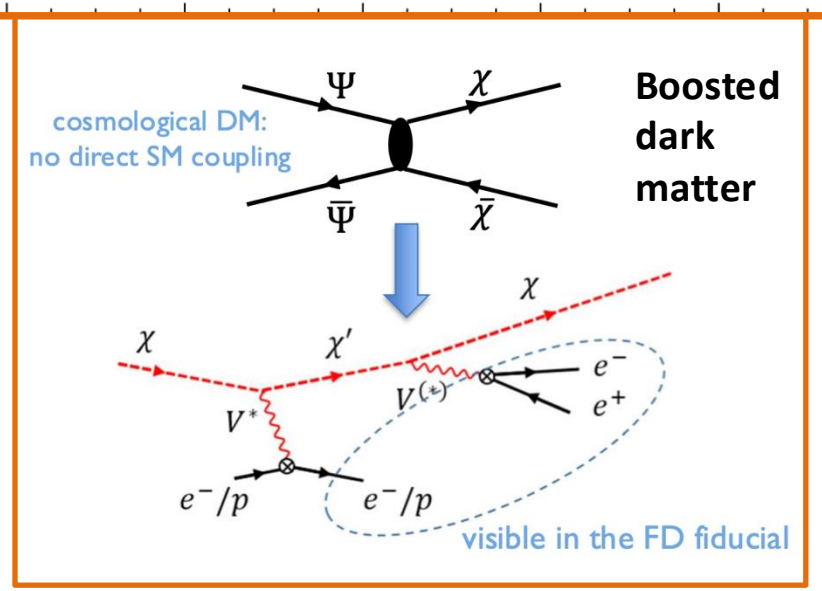
The Physics of DUNE

DUNE Phase II White Paper
JINST **19** P12005 (2024)

Long-baseline oscillations

- High-precision measurements of oscillation parameters
- Establish CP violation over a broad range of possible δ_{CP} values





Beyond Standard Model

- Proton decay
- Dark matter searches
- Nonstandard interactions

Extending the Physics of DUNE

Challenges

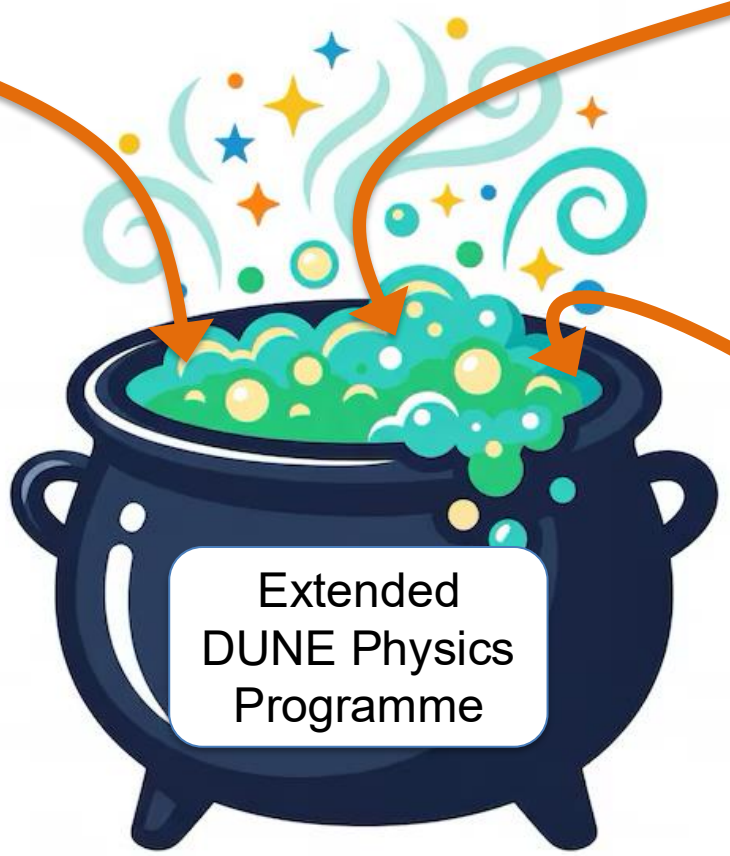
- Low energy physics:
  - Low threshold required
  - Radiological backgrounds
  - Improved triggering
  - Enhanced light yield and charge-light matching
- Non-beam physics:
  - Continuous readout = high data rate



Extending the Physics of DUNE

Improved Charge Readout

Increased Photon Detector Coverage

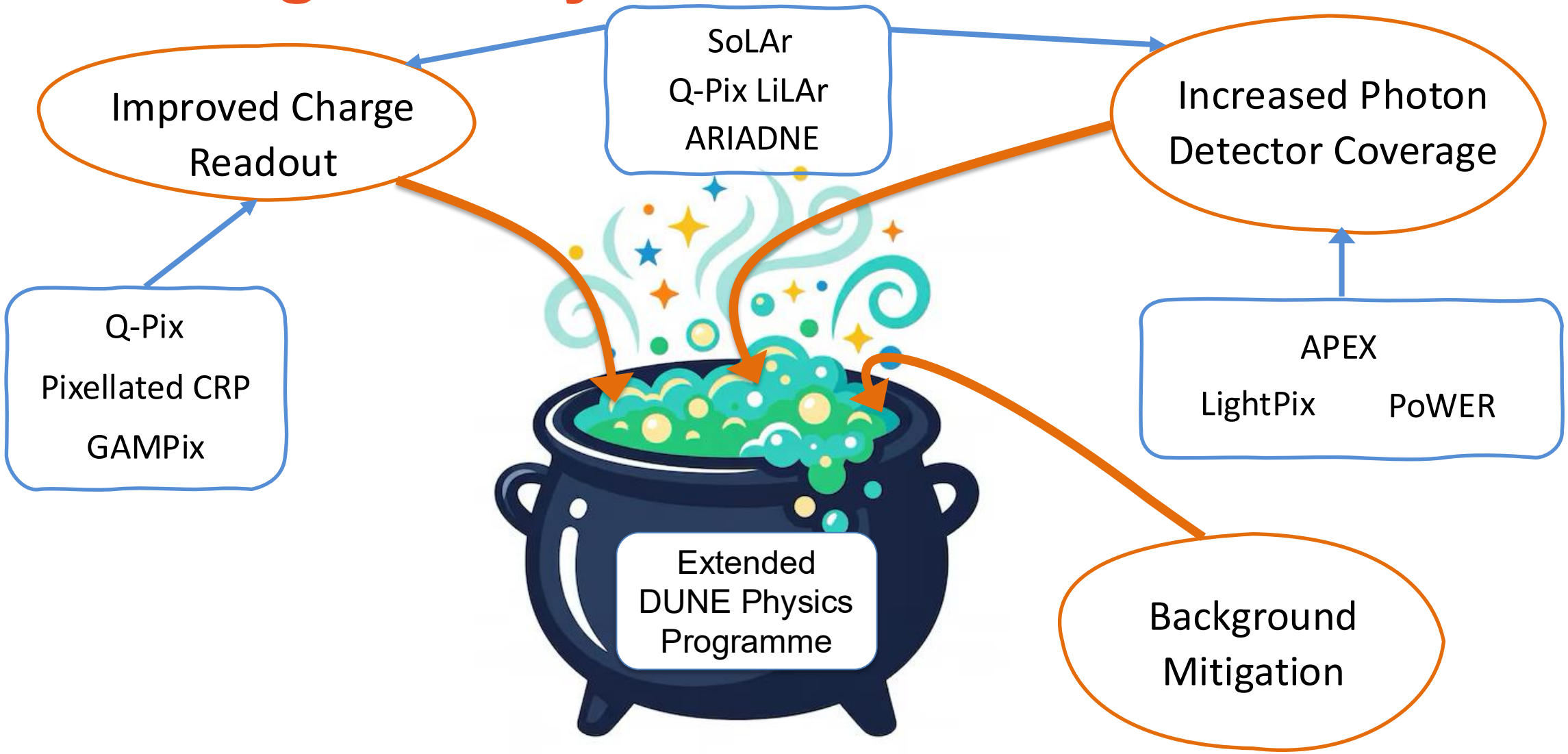


Background Mitigation

Challenges

- Low energy physics:
  - Low threshold required
  - Radiological backgrounds
  - Improved triggering
  - Enhanced light yield and charge-light matching
- Non-beam physics:
  - Continuous readout = high data rate

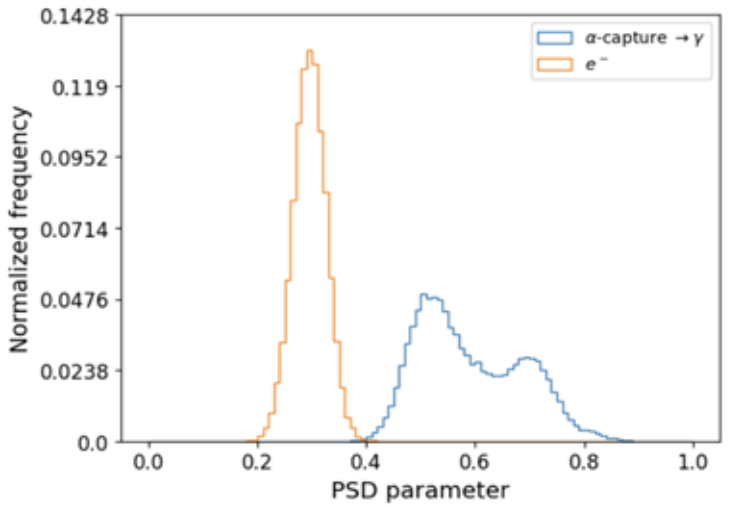
Extending the Physics of DUNE



Improved Photon Detectors

- Improve matching of charge-light information
  - Better t_0 determination and event fiducialisation
- Enables precision light-based (and charge plus light-based) calorimetry, at both MeV-scale and GeV-scale energies
- Background mitigation through pulse-shape discrimination

Pulse-shape discrimination with Q-Pix

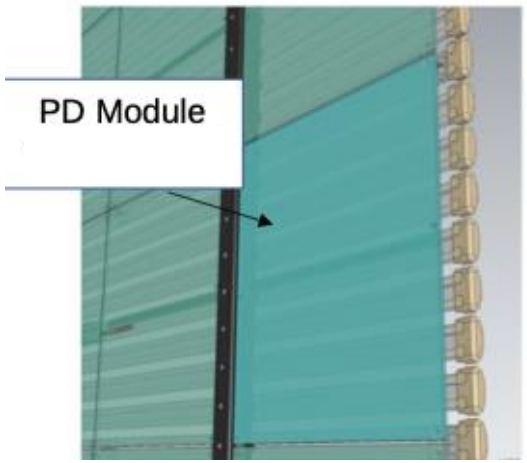


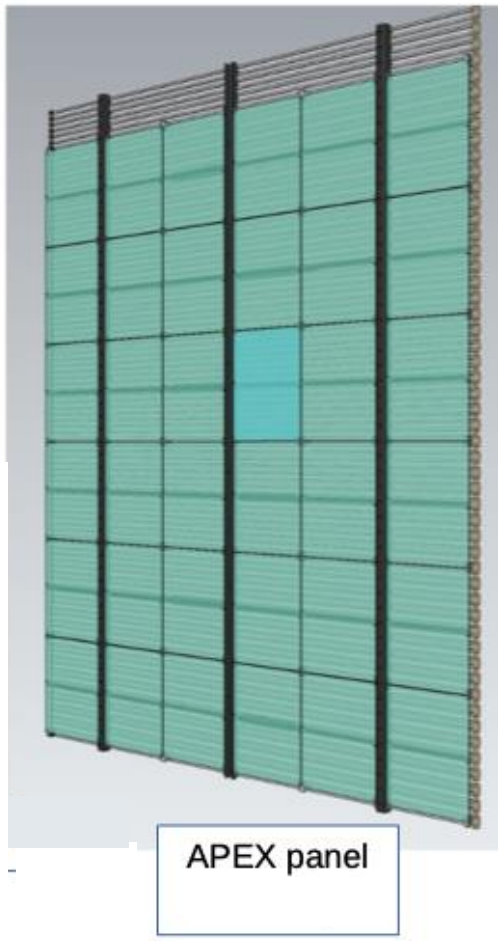
Phys. Rev. D 112, 092009 (2025)

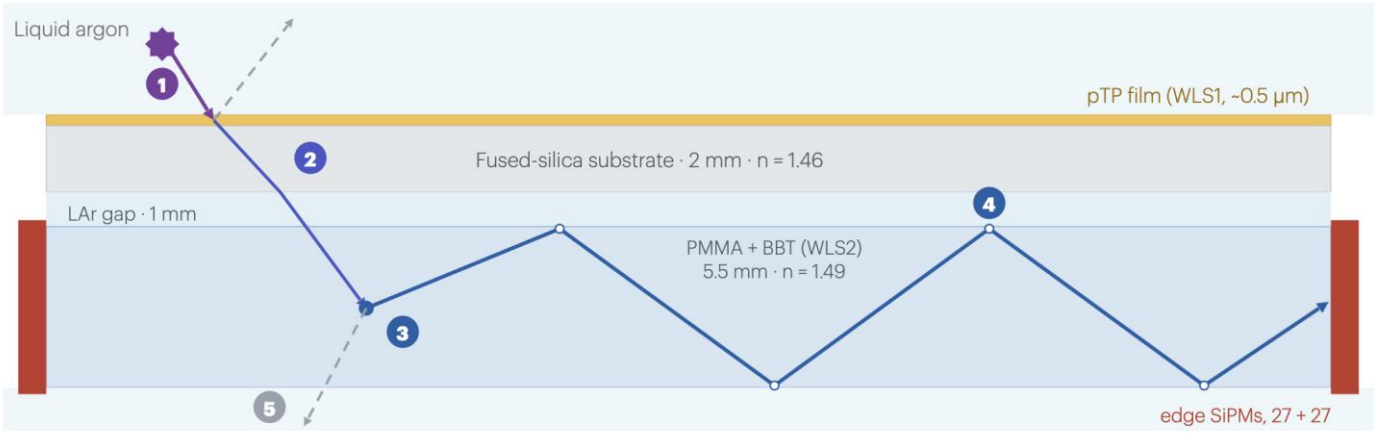
Improved Photon Detectors

APEX

- Based on DELTA light-trapping mechanism
- APEX panels covering the entire field cage:
  - ~60% photon detector coverage
- Enhanced light yield and uniformity of PDS response







Cross-section between the two instrumented edges · not to scale (thickness ×10, pTP film enlarged)

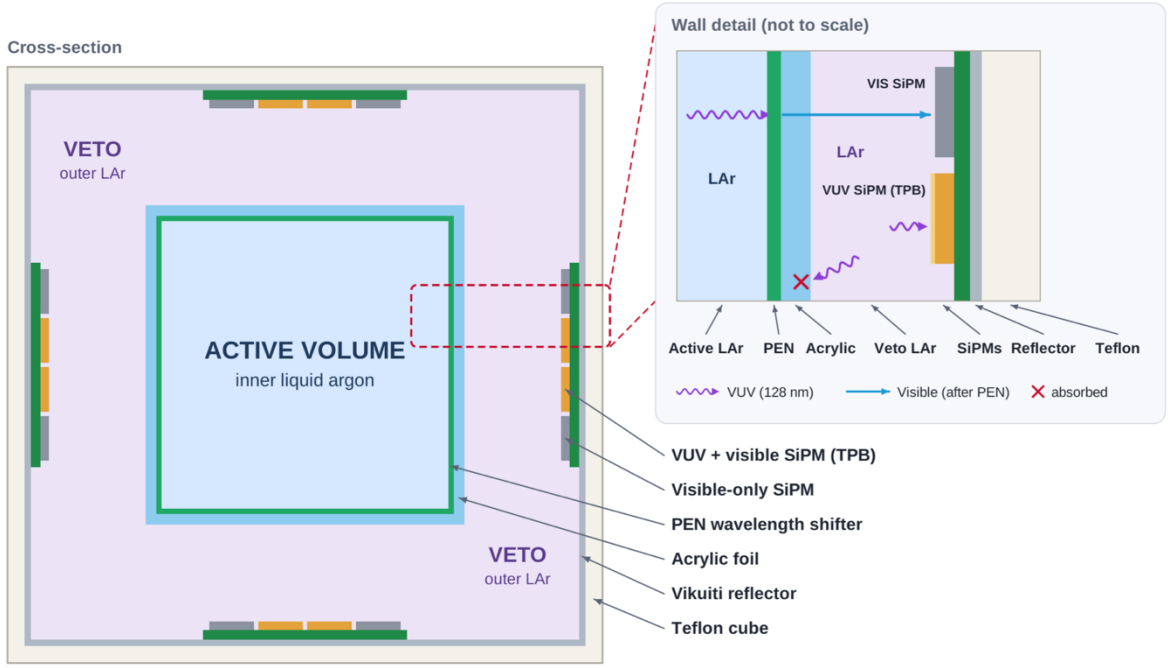
Improved Photon Detectors

PoWER

- Increase light collection by using reflector and wavelength shifter coatings
- Active LAr veto with VUV and VUV+ visible SiPMs

- Light from veto region events not wavelength shifted:
  - Higher UV fraction in total number of photons
  - Additional background rejection tool

- Application to DUNE:
  - Field cage covered with a wavelength shifter (PEN)
  - Cryostat membrane coated with a reflector



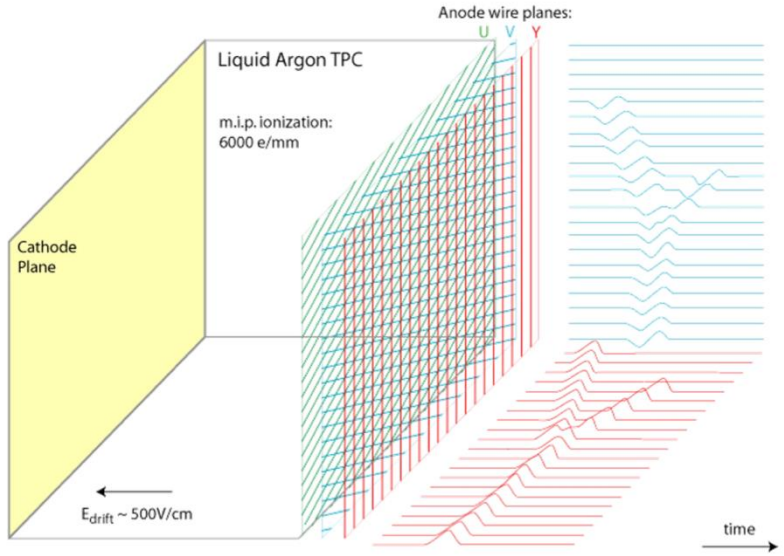
Proof of concept PoWER detector

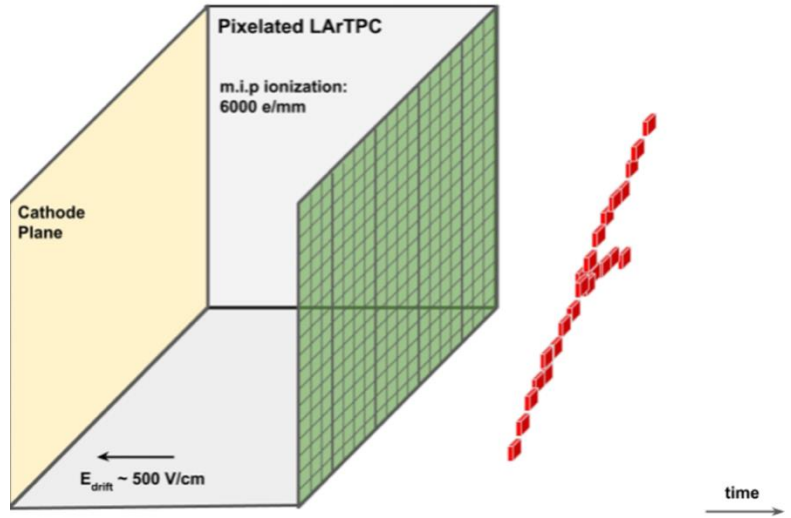
3D Charge Readout

- Native 3D readouts reduce ambiguities and errors compared to 2D readouts
  - Better handling of high-multiplicity interactions
  - Removal of pathological directions in reconstruction performance

- Pixels provide reduced data rates and better triggering schemes for non-beam physics

- Closer to ND-LAr design
  - Minimises uncertainties on near-to-far extrapolations



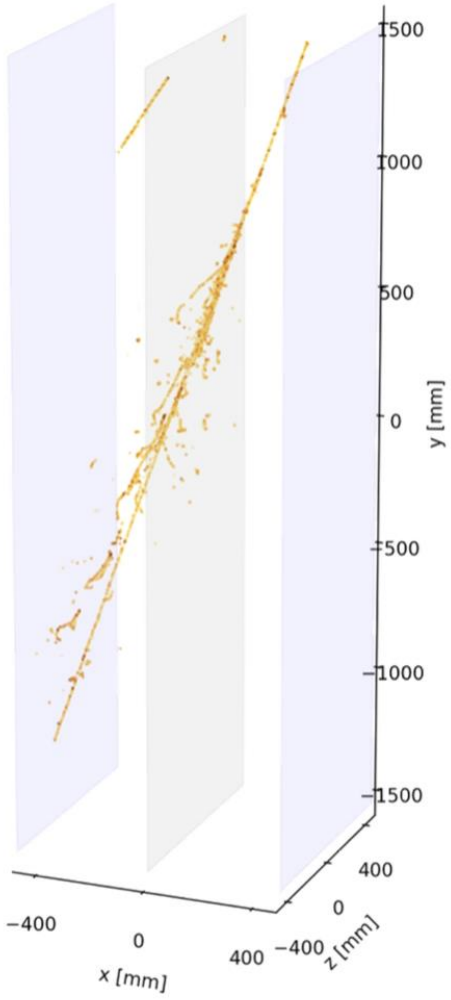


3D Charge Readout

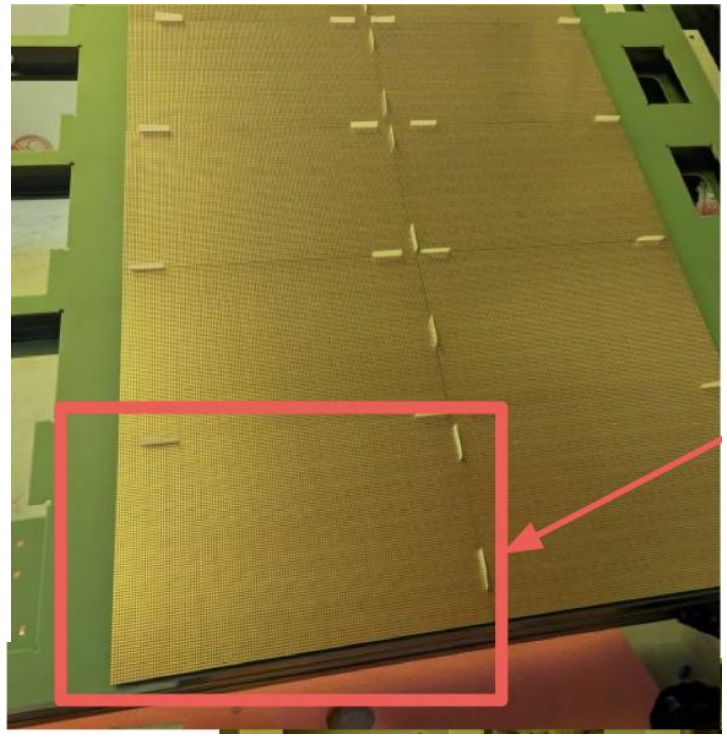
Pixellated CRP

- Use FD-VD mechanical structure, but replace strip CRPs with pixel tiles

- Making use of the LArPix ASICs developed for DUNE ND-LAr
  - Already demonstrated operations of $\mathcal{O}(10^5)$ pixels
  - Readily available
  - Need to validate scale-up from ND-LAr



Full-scale ND-LAr demonstrator
~ 410k pixels

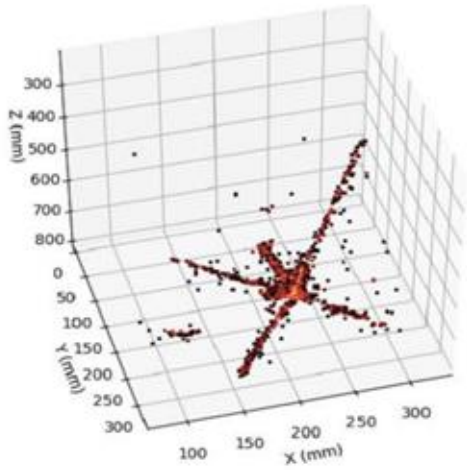


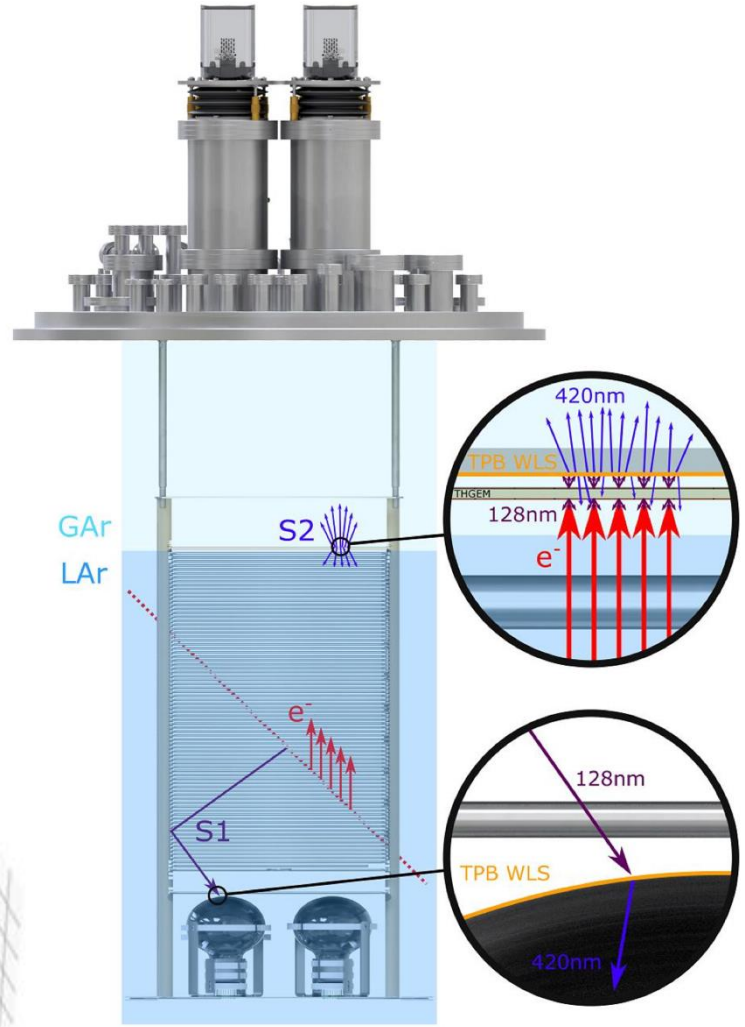
10-tile pCRP

3D Charge Readout

Optical charge readout: ARIADNE

- Dual-phase optical TPC
- THGEMs convert electrons into photons which are readout by TimePix cameras
- Excellent spatial resolution (~1 mm/pixel)
- Only pixels with hits are saved
- Easier maintenance (out-of-cryostat)
- Recent run in CERN ProtoDUNE CRP cold box





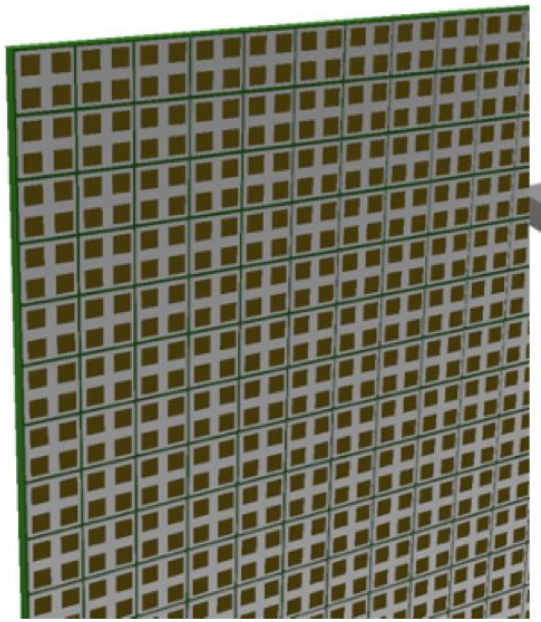
ARIADNE detection principle

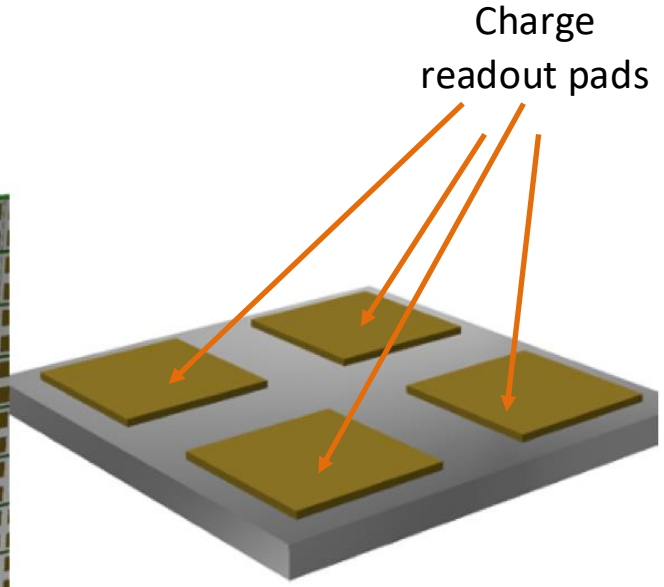
Integrated light & charge readout

SoLAr

- Monolithic all-silicon charge and light sensor
  - Photon detector tile with four embedded charge readout pads
  - Aims to achieve sub-10% energy resolution at solar neutrino energies

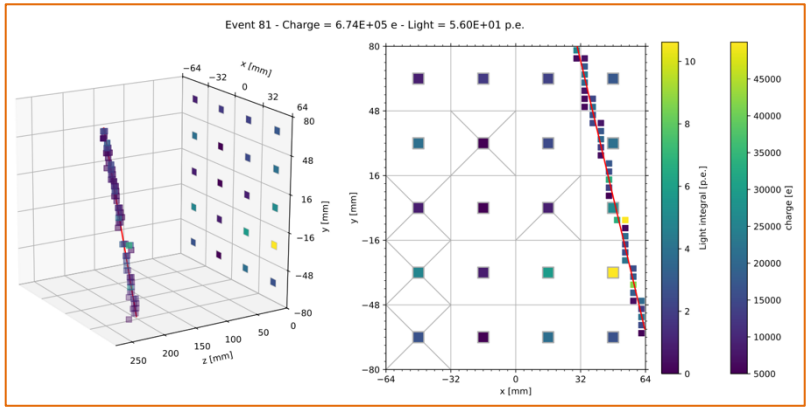
- Successful tests of light & charge combined anode using LArPix and SiPMs @ Bern





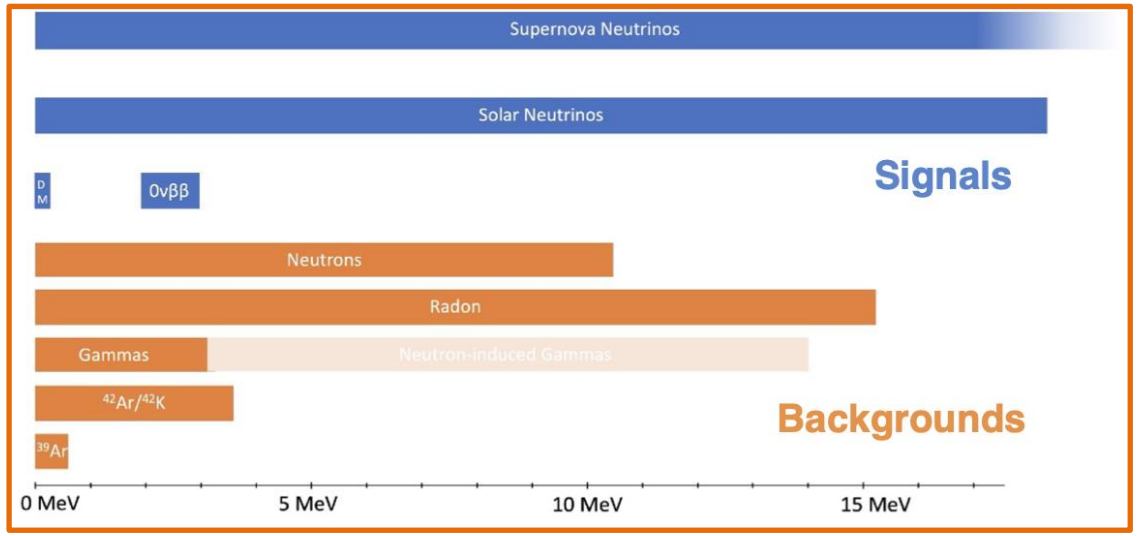
Photon
detection cell



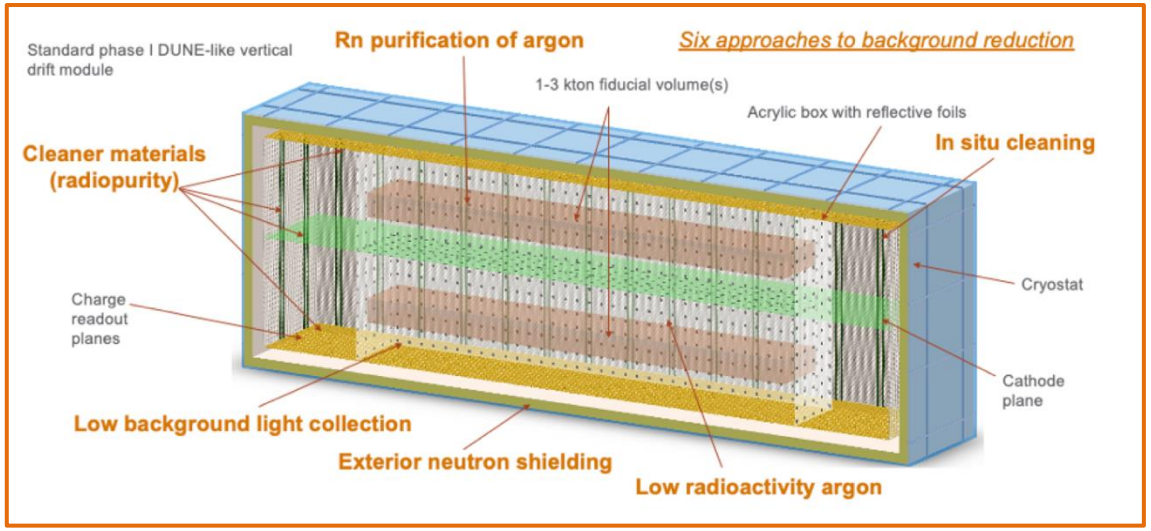


Background Mitigation

- Extending DUNE's physics to lower energies requires careful control of radiological backgrounds

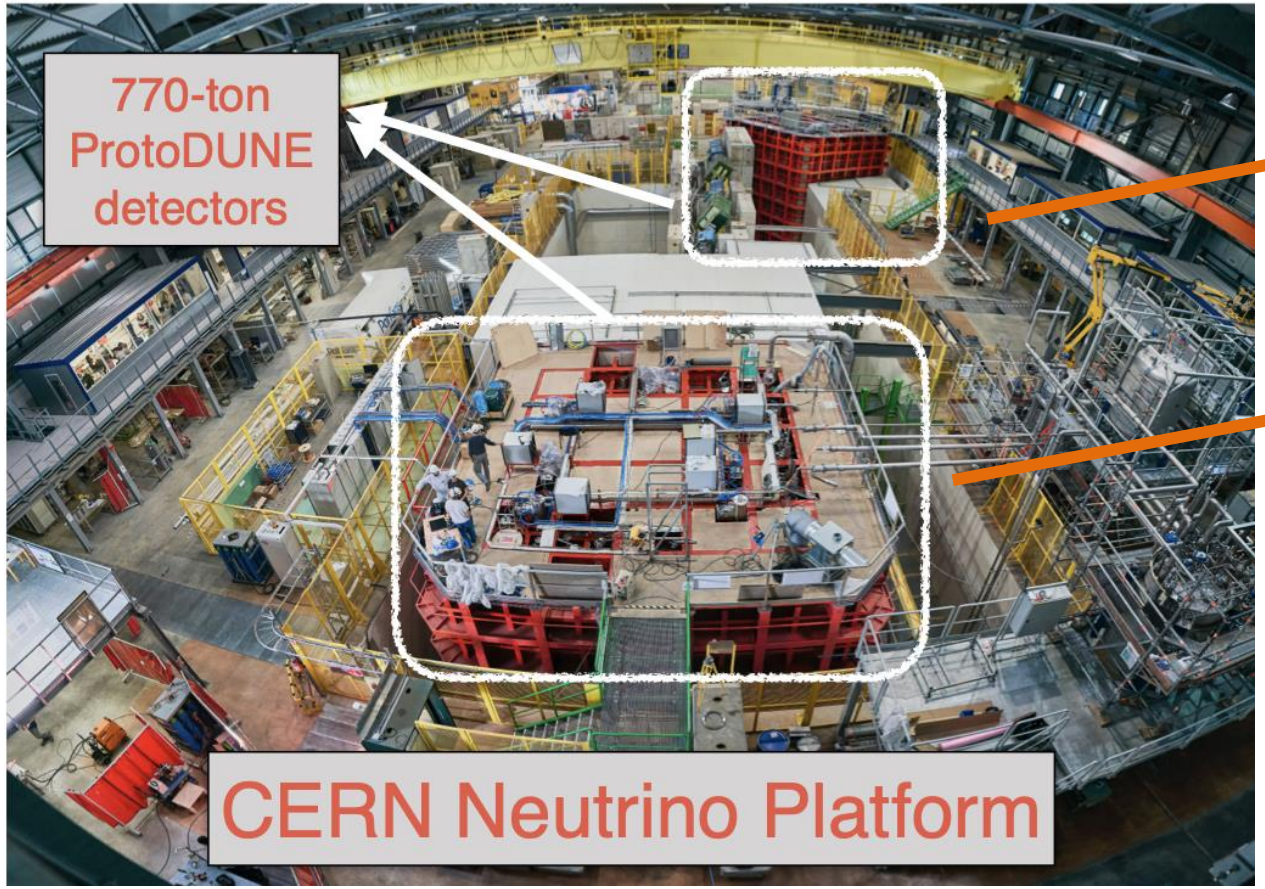


- Many avenues for mitigation:
  - Material choices
  - Passive shielding
  - Radon traps
  - Scintillation photons
  - Underground argon in an acrylic vessel (SloMo)

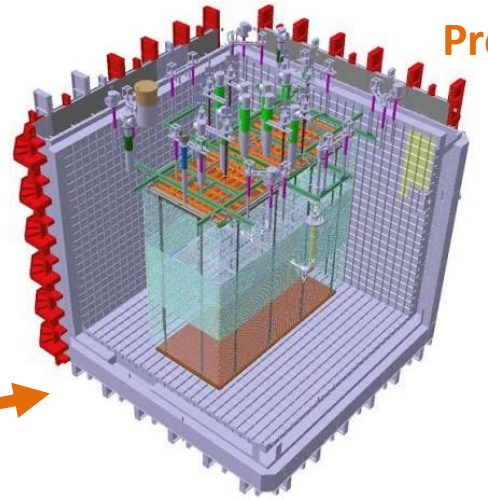


SloMo design

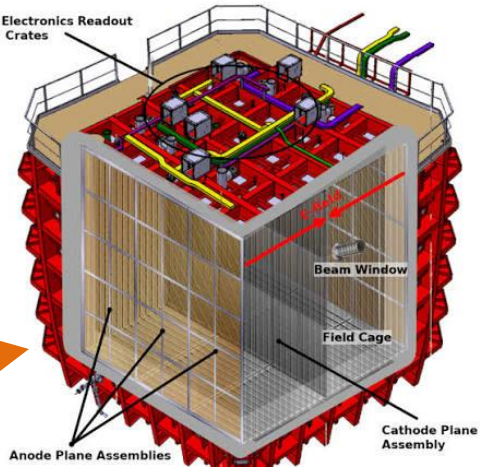
ProtoDUNE @ CERN



ProtoDUNE-VD



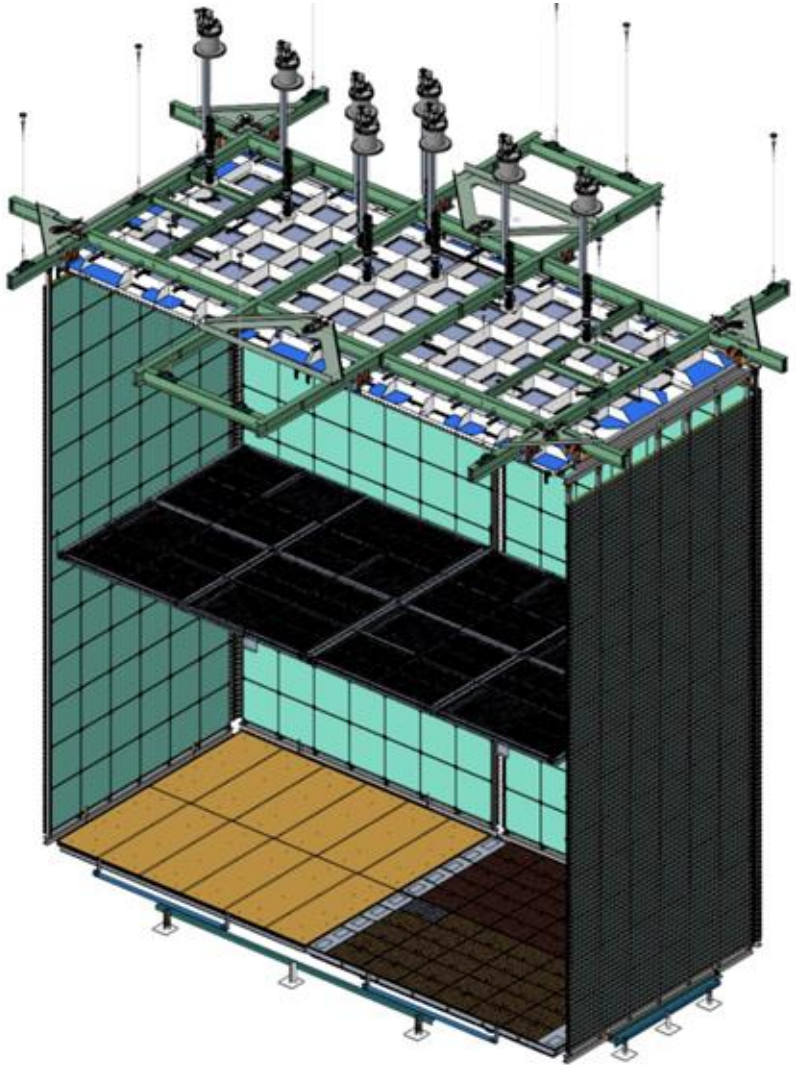
ProtoDUNE-HD



- Two large-scale prototype DUNE Far Detector Modules at CERN (HD and VD)
- Two successful runs
- Used to validate Phase-I technologies

ProtoDUNE-III @CERN

- Planned for ~2029
- Installed in the ProtoDUNE-VD cryostat
  - Based on vertical drift design
- Aims to bring together technologies developed for DUNE Phase-II
  - Improved CRP
  - Optical charge readout
  - Pixel charge readout
  - Integrated light & charge readout



Summary

- Phase II is an integral part of DUNE physics programme
  - Critical for oscillation programme
  - Allows to broaden DUNE's physics reach

- Staged approach offers opportunities for technology improvements
  - Very exciting time for DUNE R&D!
  - Many options being considered and prototyping efforts are underway

- Next major milestone: ProtoDUNE-III run at CERN
  - Will allow to test several readouts at the same time

DUNE Collaboration Meeting, Rapid City, SD
May 18-21, 2026



Backup

DUNE Phase II

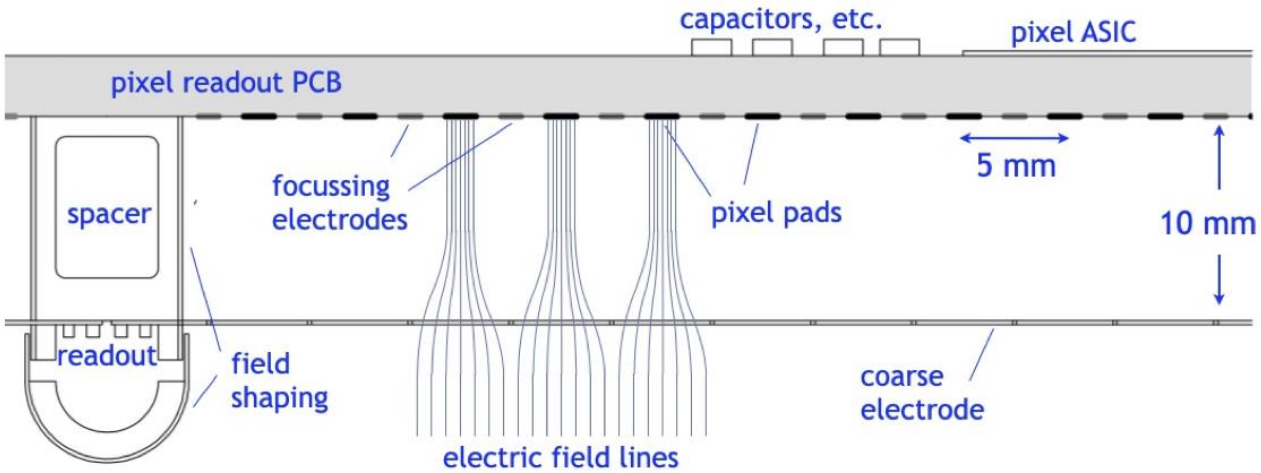
DUNE Phase II White Paper
JINST **19** P12005 (2024)

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (> 20 kt fiducial)	4 FD modules (> 40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	> 2 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

GAMPix

Grid-Activated Multi-scale PIXels

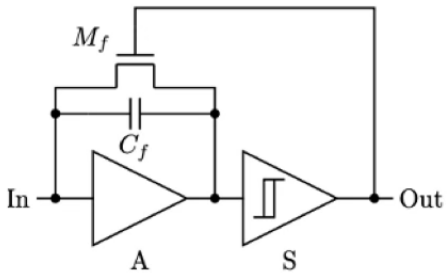
- Combines an external induction grid with a pulsed-power pixel plane
- Low power consumption
- Possible charge-only drift length measurement
- Low noise (50 e-/pixel)
  - Ideal for MeV-scale physics

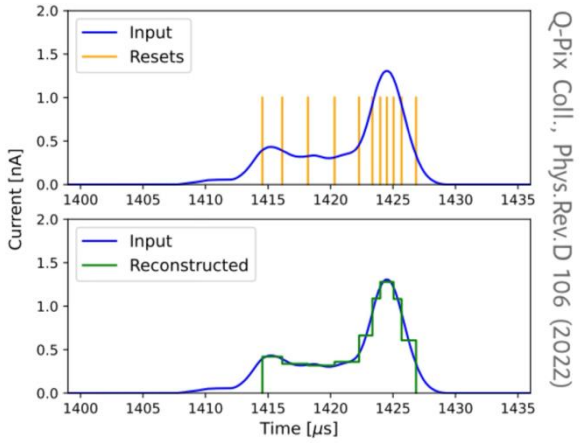


Q-Pix/Q-Pix LiLAr

Q-Pix

- Developed to solve the data rate issue of pixellated readouts
- Electronic principle of least action
- Saves time stamps instead of full waveforms





Q-Pix LiLAr

- Q-Pix charge readout with amorphous selenium coating
  - Photons converted into electrons
  - Charge pixel detects both ionization and converted

