Overview of the DUNE Phase-II Program

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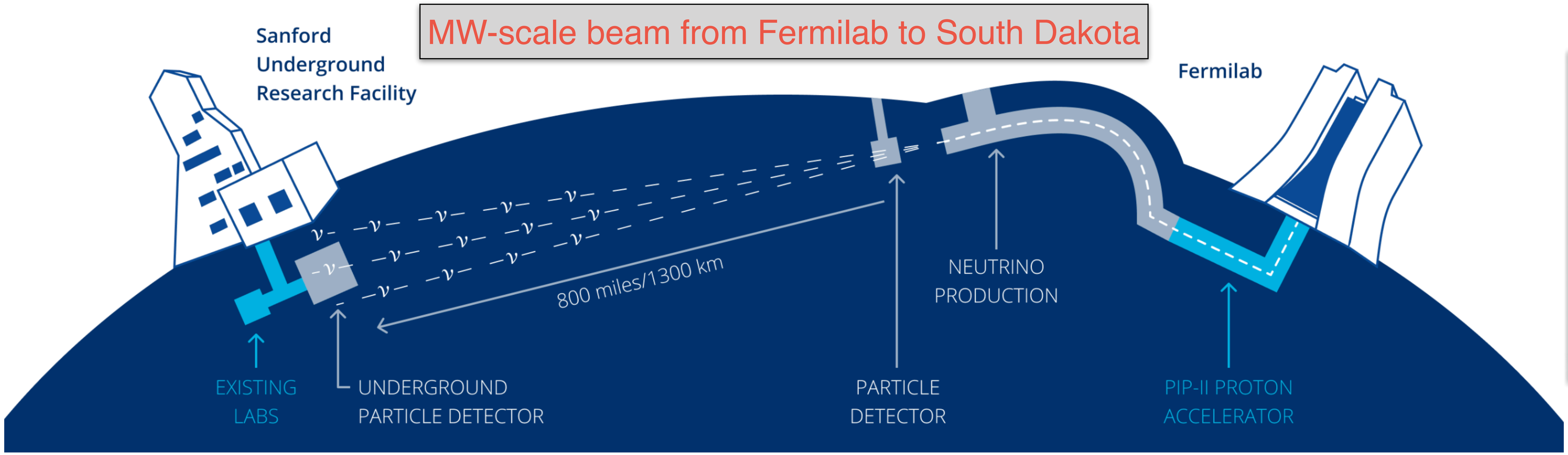
(On behalf of the DUNE Collaboration)

Conference on Science at the Sanford Underground Research Facility (CoSSURF)
SD Mines, May 16, 2024

The Deep Underground Neutrino Experiment (DUNE)



1400+ Collaborators
35+ Countries
200+ Institutes

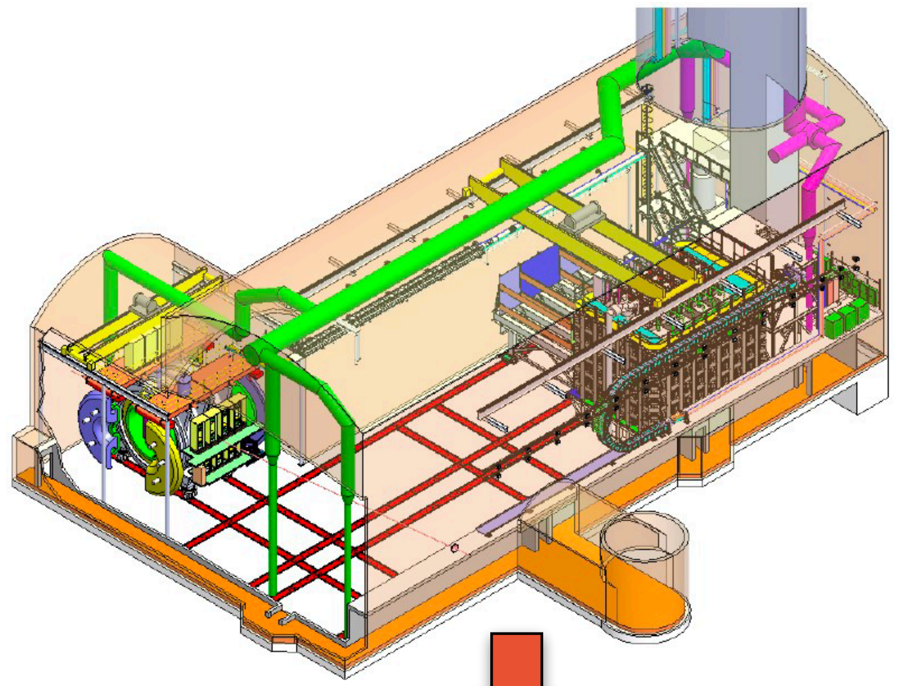
- A massive (70-kt total mass liquid argon equivalent) far detector a mile underground at Sanford Underground Research Facility (SURF)
- A capable near detector at Fermilab comprising of multiple technologies
- Far and Near site facilities and beam provided by the Long Baseline Neutrino Facility (LBNF)
- ***Rich physics program:*** Charge-Parity (CP) Violation, mass ordering, precision measurement of oscillation parameters, neutrino astrophysics, and Beyond the Standard Model (BSM) physics

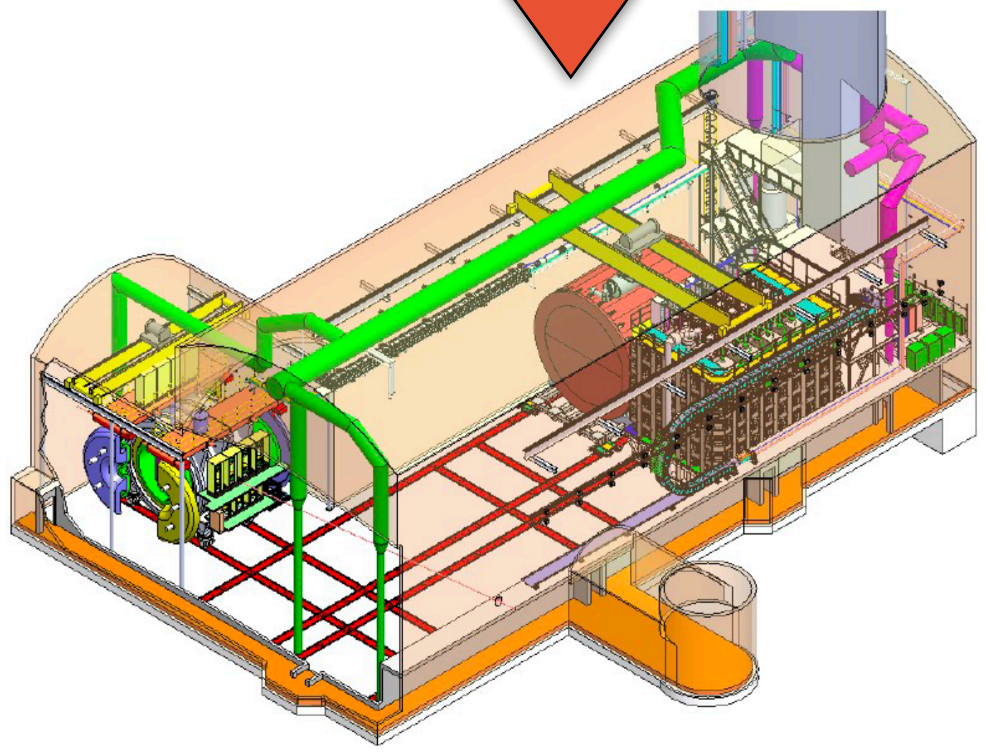
Underground Facility at SURF

- *The DUNE far detector will be located a mile underground at SURF*
- *Excavation of the underground spaces began in 2021*
- *Some 800,000 tonnes of rock have been excavated and transported to the surface.*
- *As of January 2024, excavation of the massive underground caverns at SURF complete!*

DUNE will be Built in Two Phases

Near Detector (ND)





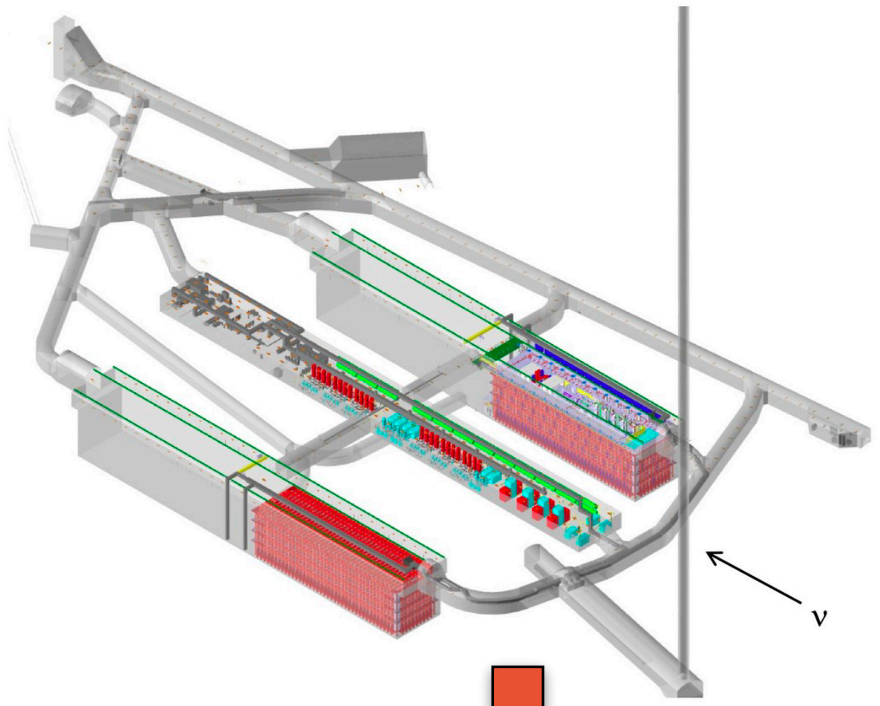
Phase I

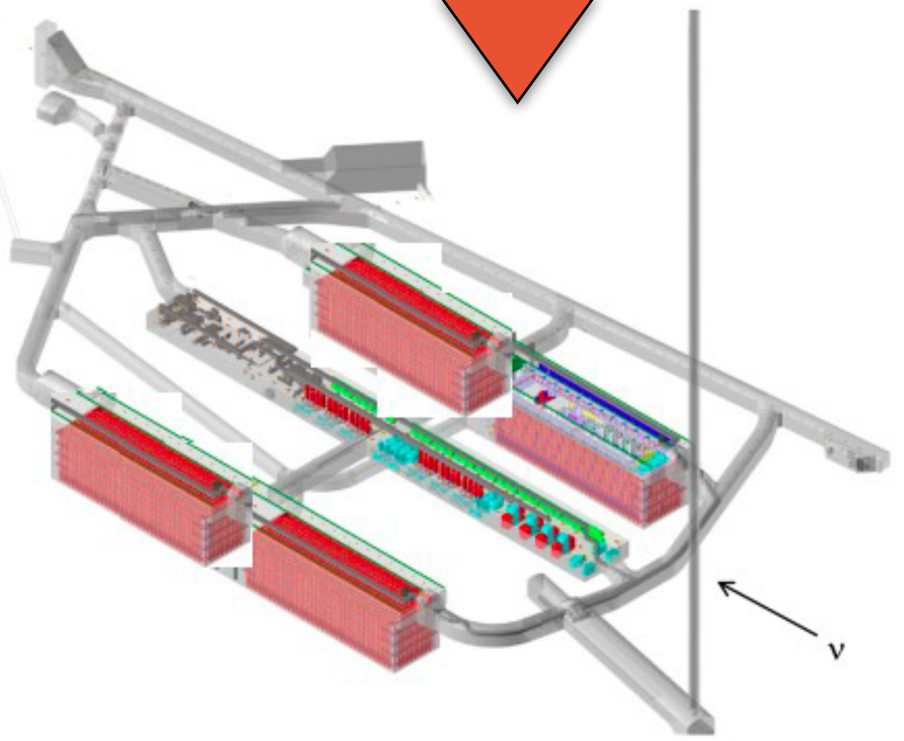
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

Phase II

- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)

Far Detector (FD)





LArTPC: *Liquid Argon Time Projection Chamber*
ND-LAr: *Liquid argon-based ND*
TMS: *Temporary Muon Spectrometer*
SAND: *System for on-axis ND*
MCND: *More Capable ND*
ND-GAr: *Gaseous argon-based ND*
PRISM: *movable ND capability for off-axis beam measurements*
PIP-II: *Proton Improvement Plan-II*
ACE: *Accelerator Complex Evolution at Fermilab*

Parameter	Phase-I	Phase-II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	>2 MW	FD statistics
ND configuration	ND-LAr, TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

**Non-Argon options currently under consideration for Phase-II near and far detectors not listed*

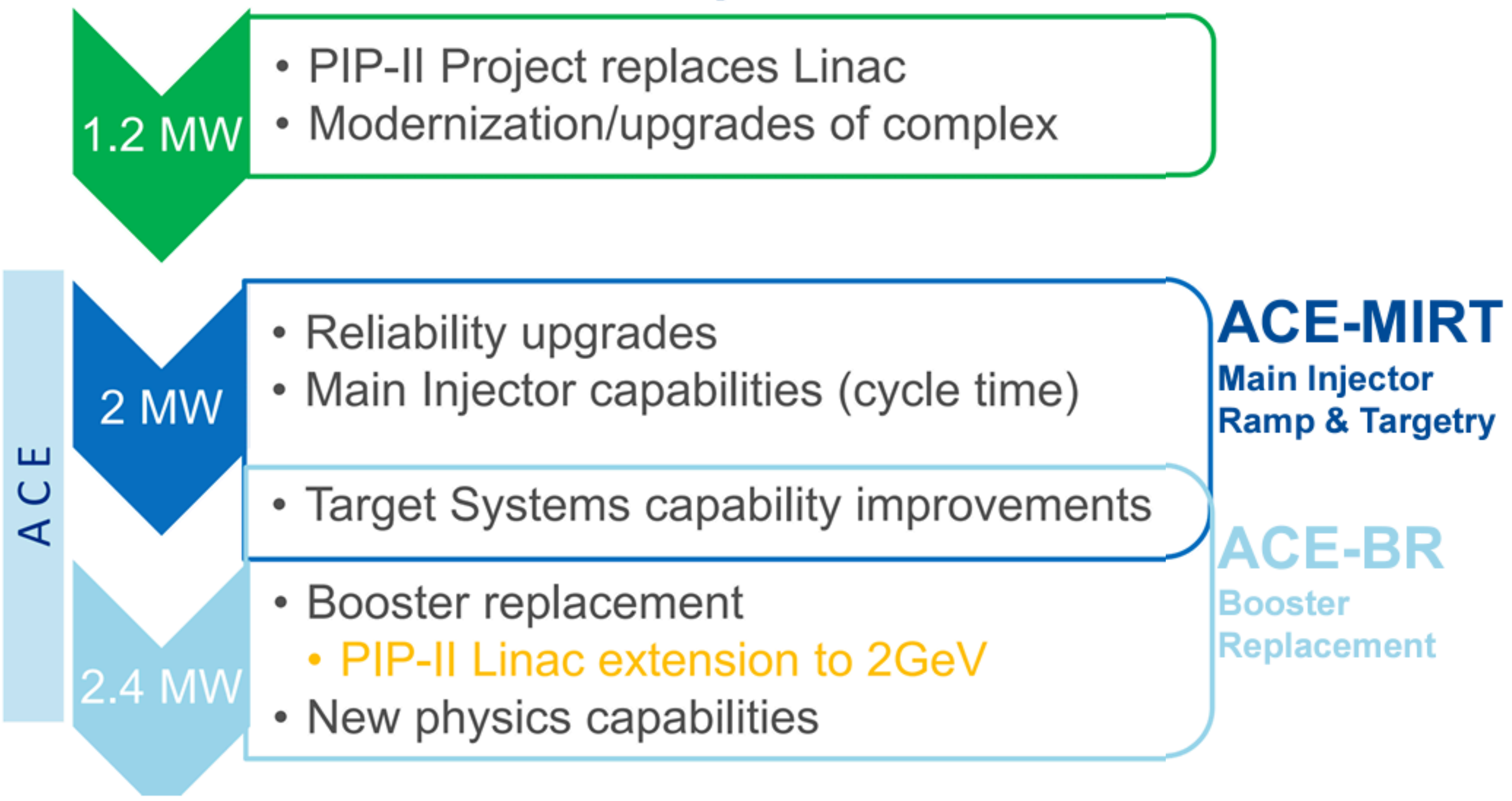
Accelerator Upgrades: PIP-II and ACE

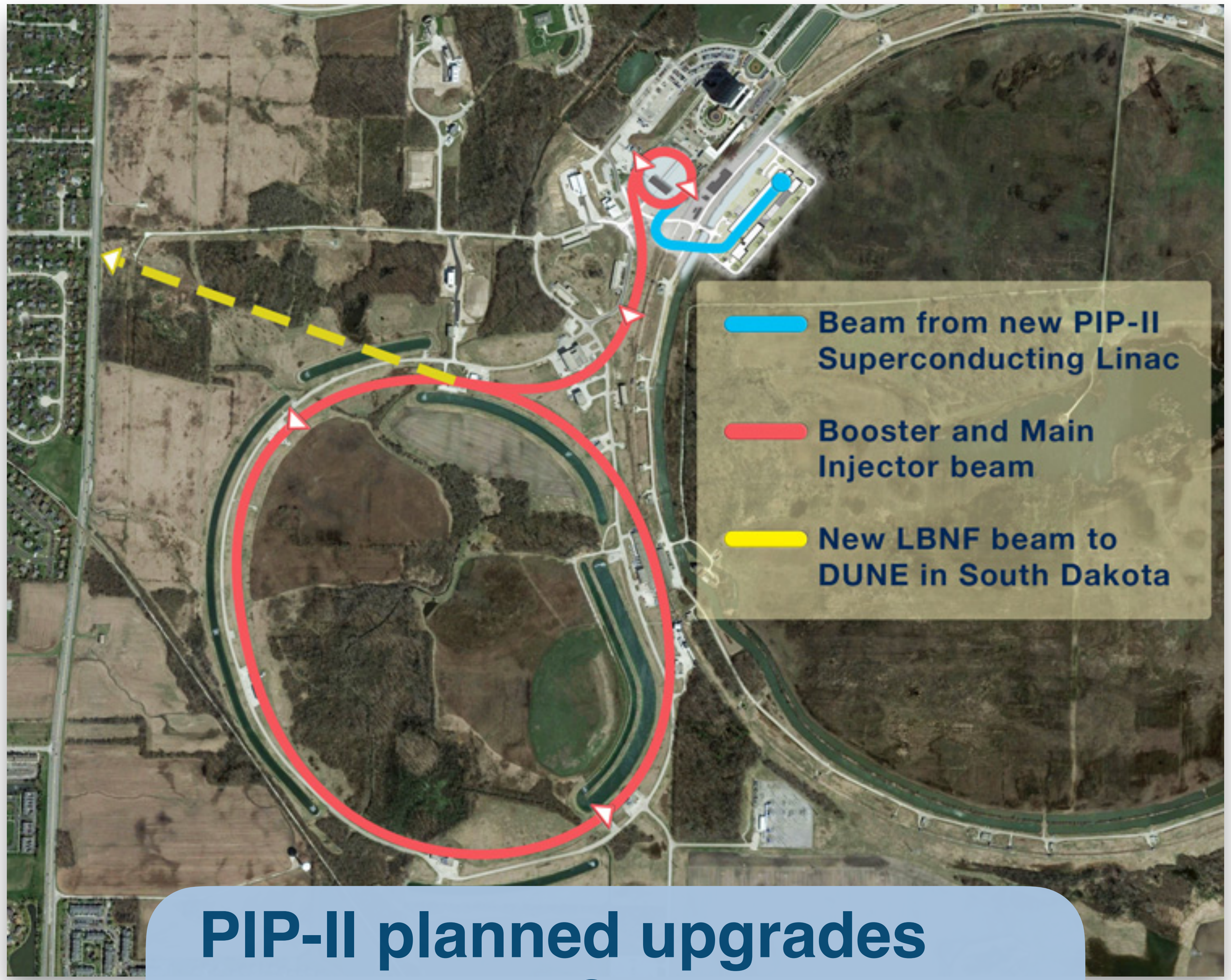
PIP-II

- New PIP-II linac (to be completed in 2029) provides beam for injection into Booster at energy increased to 800 MeV from present 400 MeV
- Proton flux at 8 GeV increases 2 times resulting in beam power from Main Injector up to 1.2 MW

ACE

- The Accelerator Complex Evolution (ACE) plan has two main components ACE-MIRT and ACE-BR to achieve greater than 2 MW beam power for DUNE





PIP-II planned upgrades
- 800 MeV LINAC
- LINAC to Booster Transfer line
- Upgraded Booster
- Upgraded Recycler and Main Injector
- Conventional Facilities

PIP-II creates a platform for next-generation upgrades

Phase-II Elements and Science Drivers

Elements

- **Beam**: 1.2 → > 2 MW beam power
- **FD**: Two additional modules FD3 and FD4 (total of 4 detectors; 70 kt total LAr-equivalent)
- **ND**: More capable ND (TMS → ND-GAr)

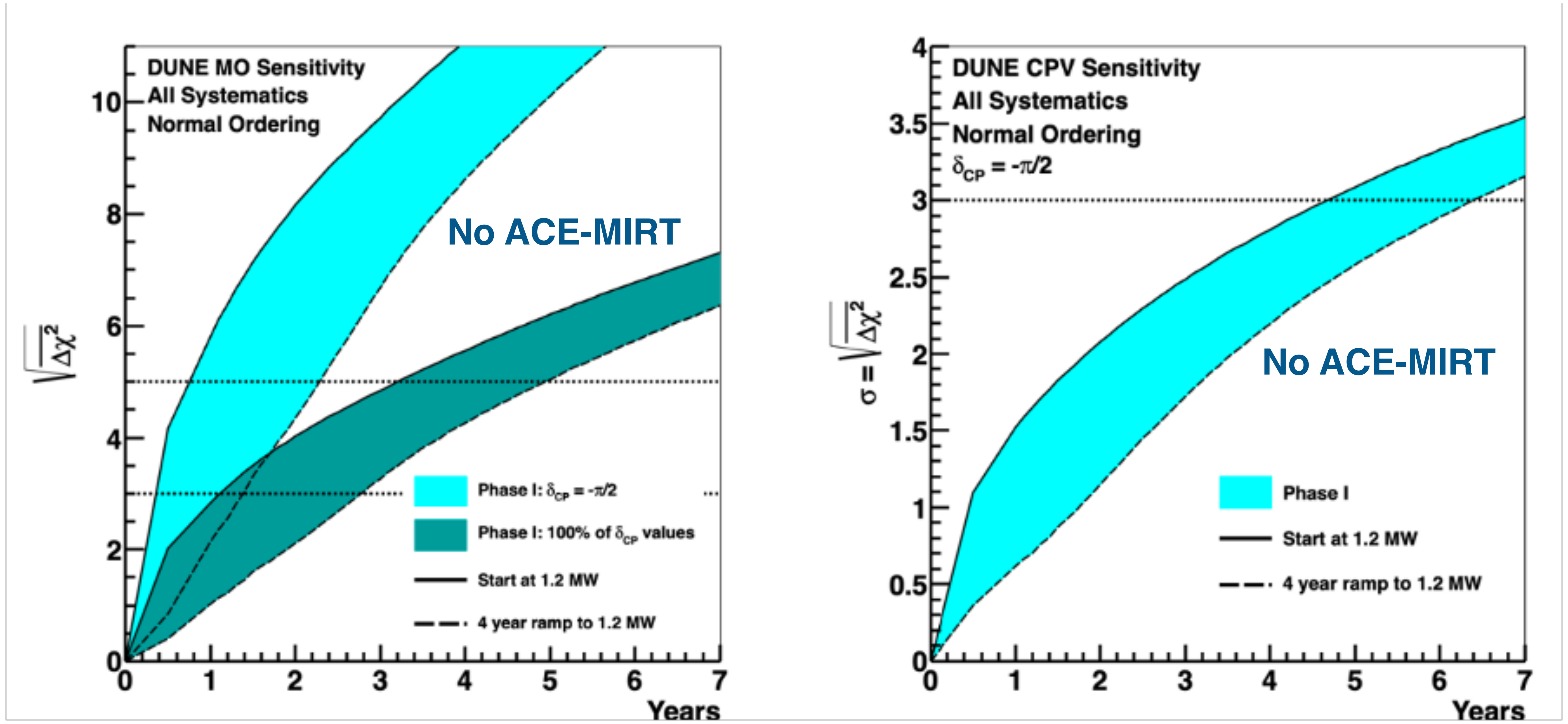
Science Drivers

- **Long-baseline Physics**: Phase I+II combined provide ultimate measurement of 3ν oscillation parameters (Δm^2_{32}, θ_{13}, θ_{23}, and δ_{CP}) with 600-1000 kt·MW·yr exposure and percent-level systematic uncertainties
- **Neutrino Astrophysics**: Expand MeV-scale neutrino astrophysics reach (e.g. supernova, solar neutrinos)
- **BSM Physics**: More sensitive searches for long-lived particle decays and tests of 3ν oscillation paradigm at ND and FD, and more

Long Baseline Physics with Phase-I

- In Phase I, DUNE can accumulate ~100 kt-MW-yr of data in 5 years. This is sufficient to
  - conclusively determine neutrino mass ordering at > 5σ significance, regardless of the true parameter values.
  - establish CP violation at 3σ if CP violation is nearly maximal ($\delta_{CP} \approx +/- \pi/2$)
- Early implementation of Fermilab accelerator upgrades can accumulate Phase-I statistics twice as fast

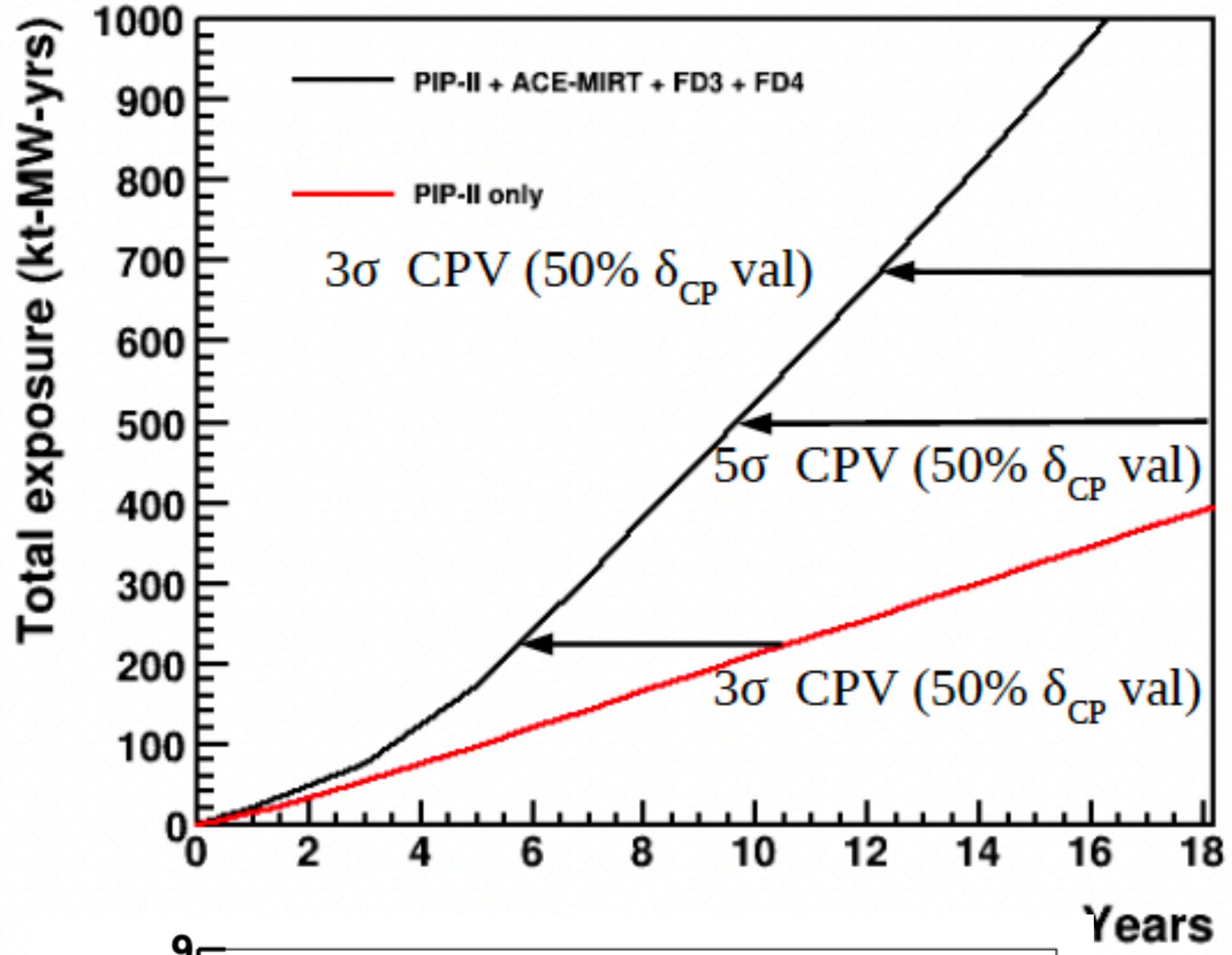
The statistics of Phase-I are not sufficient to determine the octant of θ_{23} or to establish CP violation except in the most favorable scenario

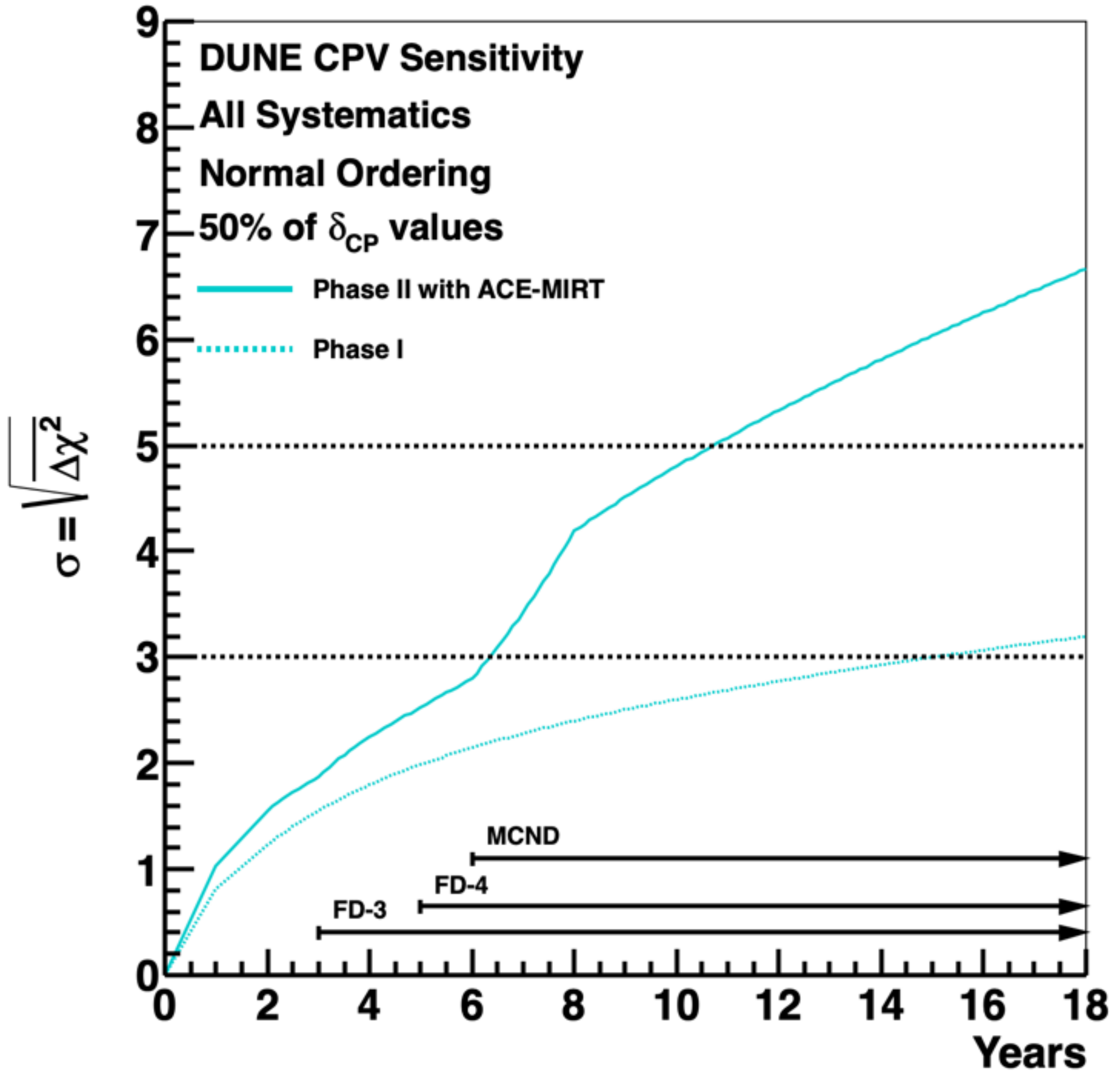


Los Alamos NATIONAL LABORATORY EST. 1943 DUNE

Long Baseline Physics with Phase-II

- All elements of Phase-II ***(ACE-MIRT, FD3, FD4, MCND)*** essential for DUNE to achieve its full physics potential
  - *ACE-MIRT would enable more rapid acquisition of beam neutrino statistics*
  - *MCND provides important systematic constraints as precision increases*
- Phase-II will enable high precision measurements of all four parameters governing long-baseline oscillations (Δm^2_{32}, θ_{13}, θ_{23}, and δ_{CP})
- Establish CP violation at high significance over a broad range of possible values of δ_{CP}, and test the 3-flavor paradigm as a way to search for new physics in neutrino oscillations.

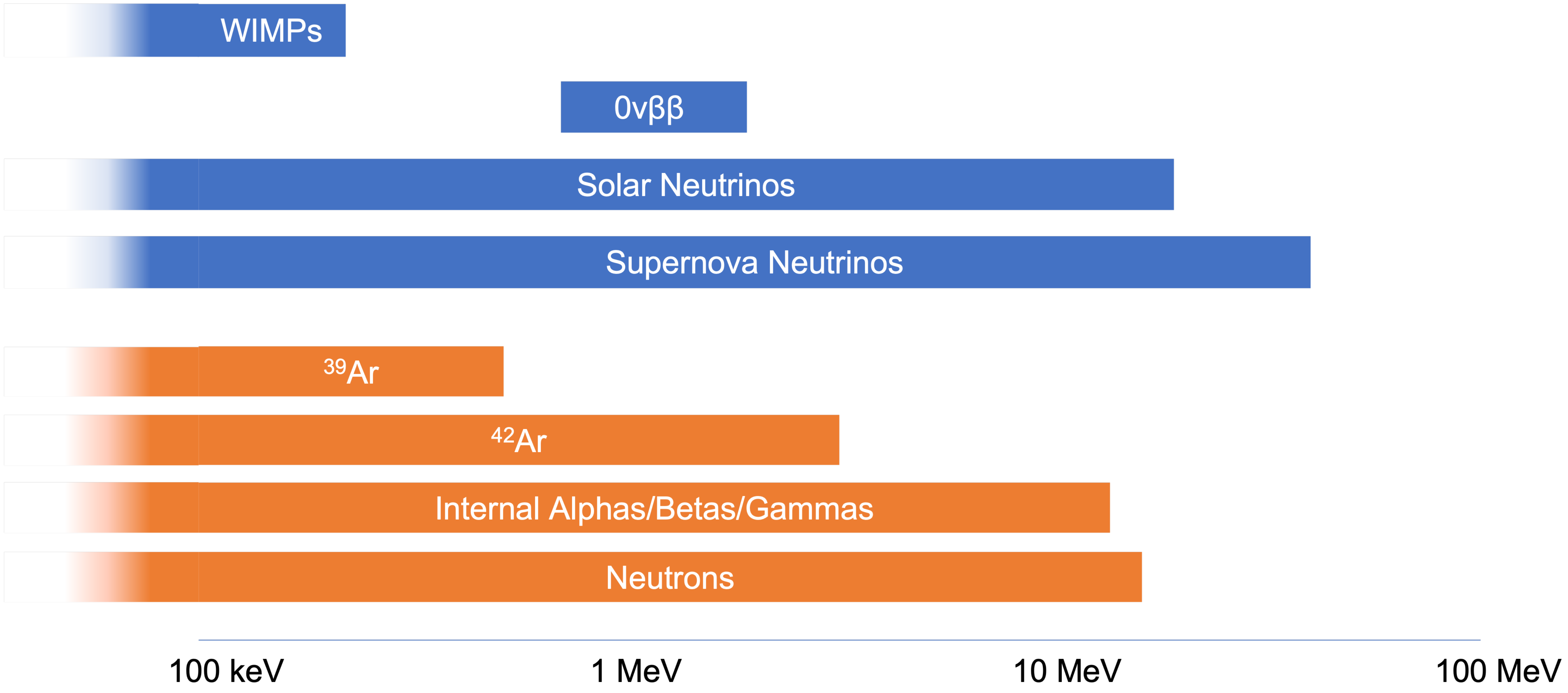


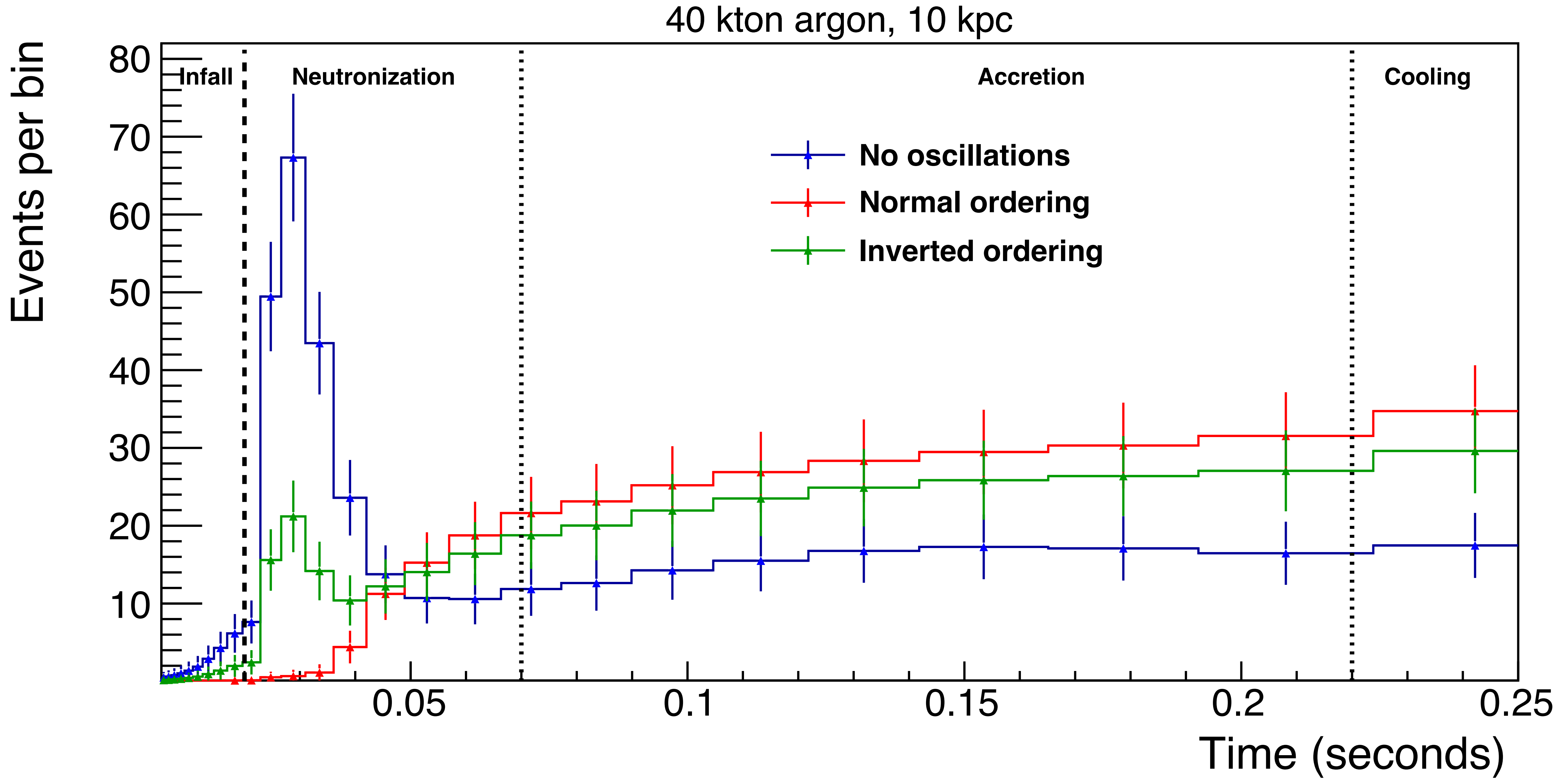


Neutrino Astrophysics with Phase-II

See DUNE talks in the Supernova and Solar Neutrino parallel

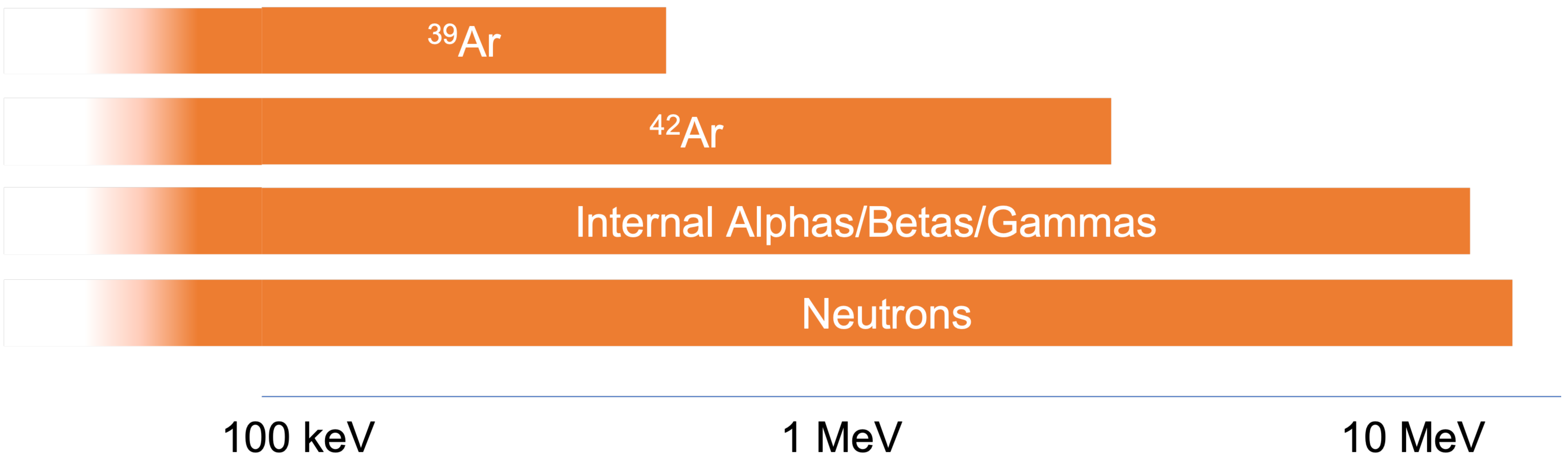
- Phase-II FD increased target mass, as well as potential improvements in energy resolution and background levels, key to improve detection of neutrinos from astrophysical sources in the MeV energy range
  - Supernova neutrino bursts, solar neutrinos, diffuse supernova neutrino background
  - Initial studies suggest that a significant improvement in the measurement of Δm^2_{21} is possible in DUNE Phase-II, as well as a first observation at > 5σ of the hep solar neutrino flux, produced via the nuclear fusion reaction ($^3He + p \rightarrow {}^4He + e^+ + \nu_e$) in the Sun's interior.

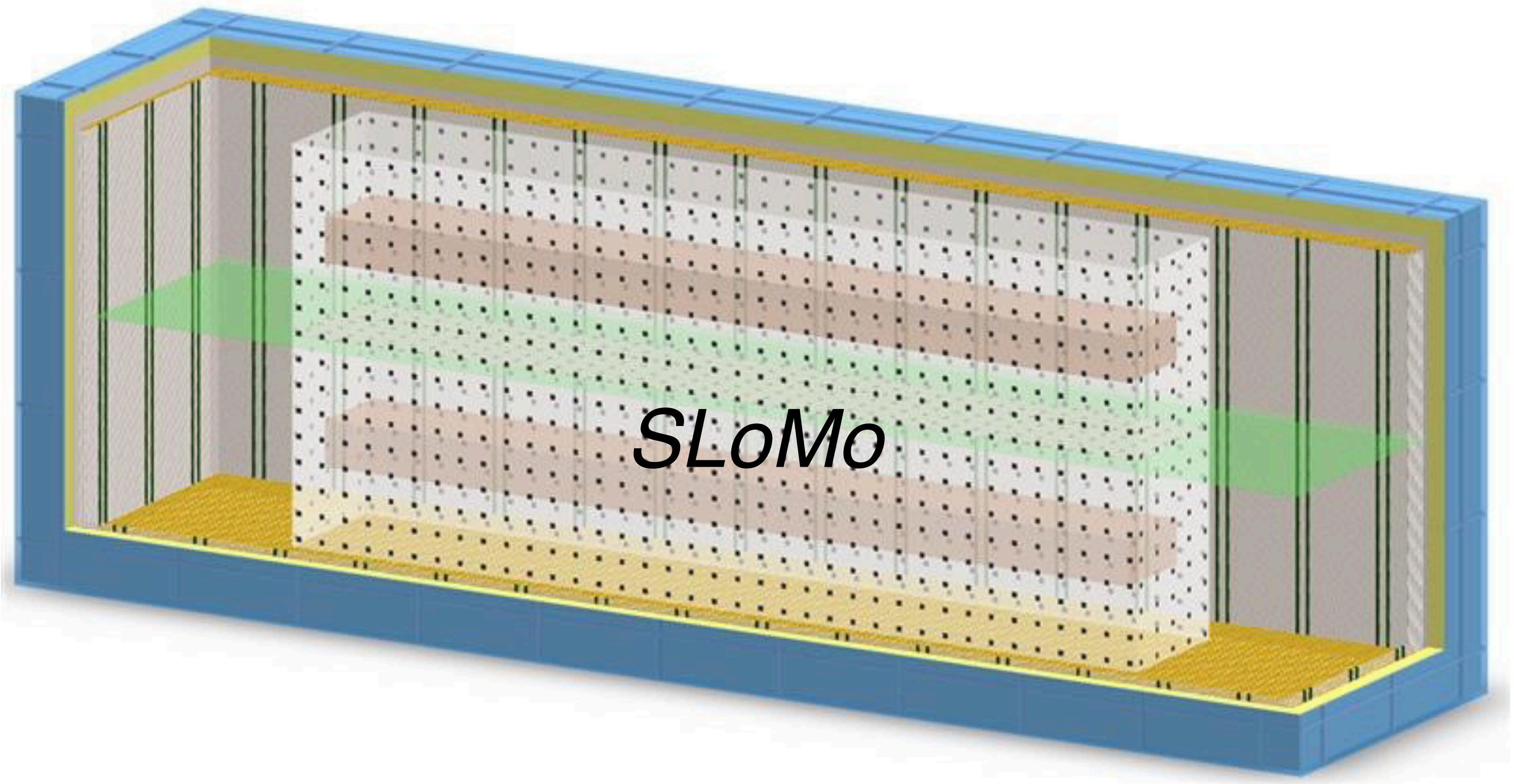




FD Background Control

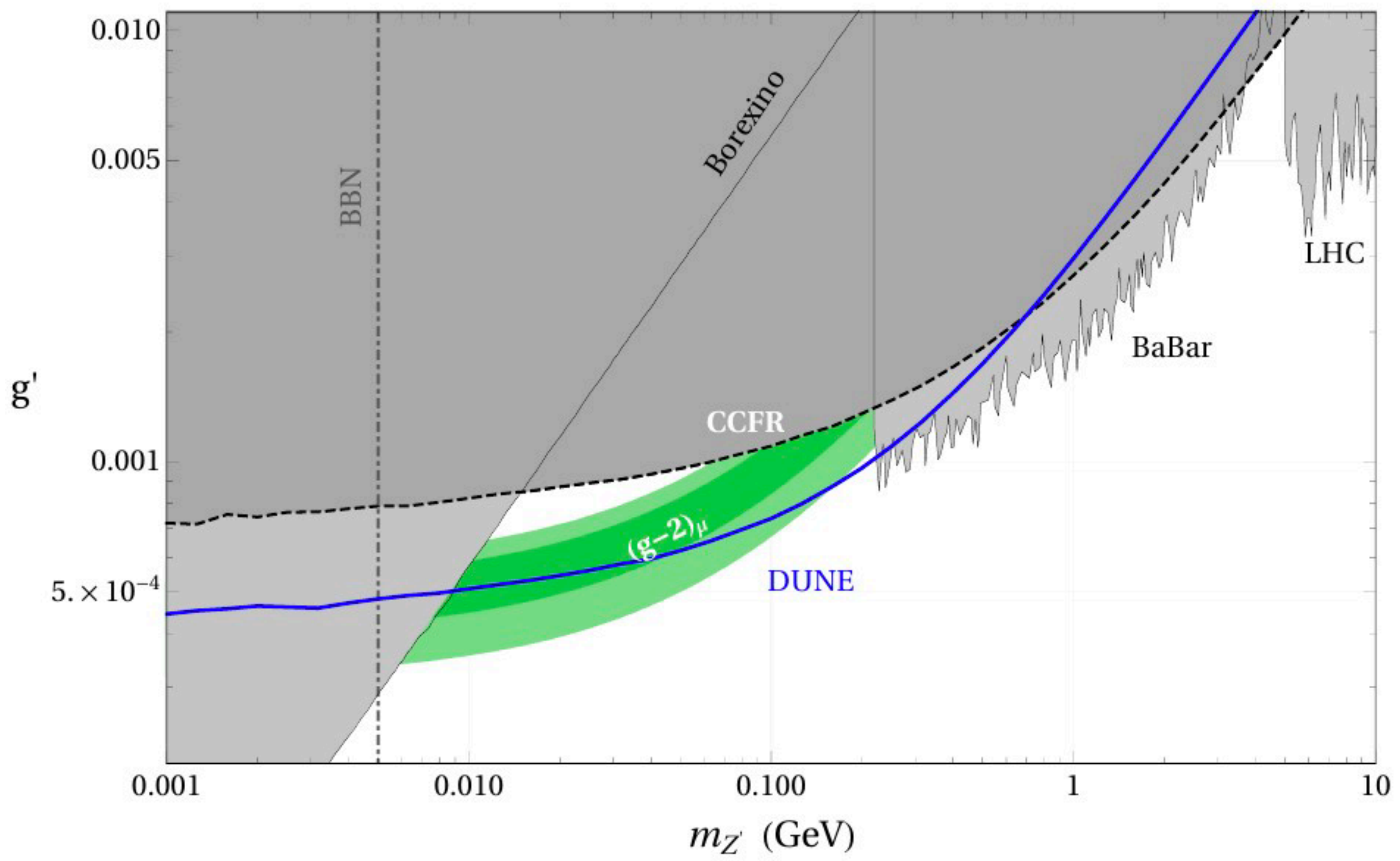
- Enhancement of DUNE physics to lower energies relies on lower radioactive backgrounds
- Realistic background target extends threshold down to 5 MeV, just above the ^{42}K beta endpoint from ^{42}Ar
- Most significant radioactive backgrounds and mitigation strategies
  - *External neutrons and gammas → passive shielding (eg, water)*
  - *Internal backgrounds from detector materials → careful material selection programs*
  - *Radon gas → inline radon trap, detector materials with low radon emanation*
  - *Intrinsic argon backgrounds (^{39}Ar, ^{42}Ar) → argon from underground sources*
  - *use underground argon in an acrylic vessel, reduce background (eg, SLoMo) See talk by C. Jackson*

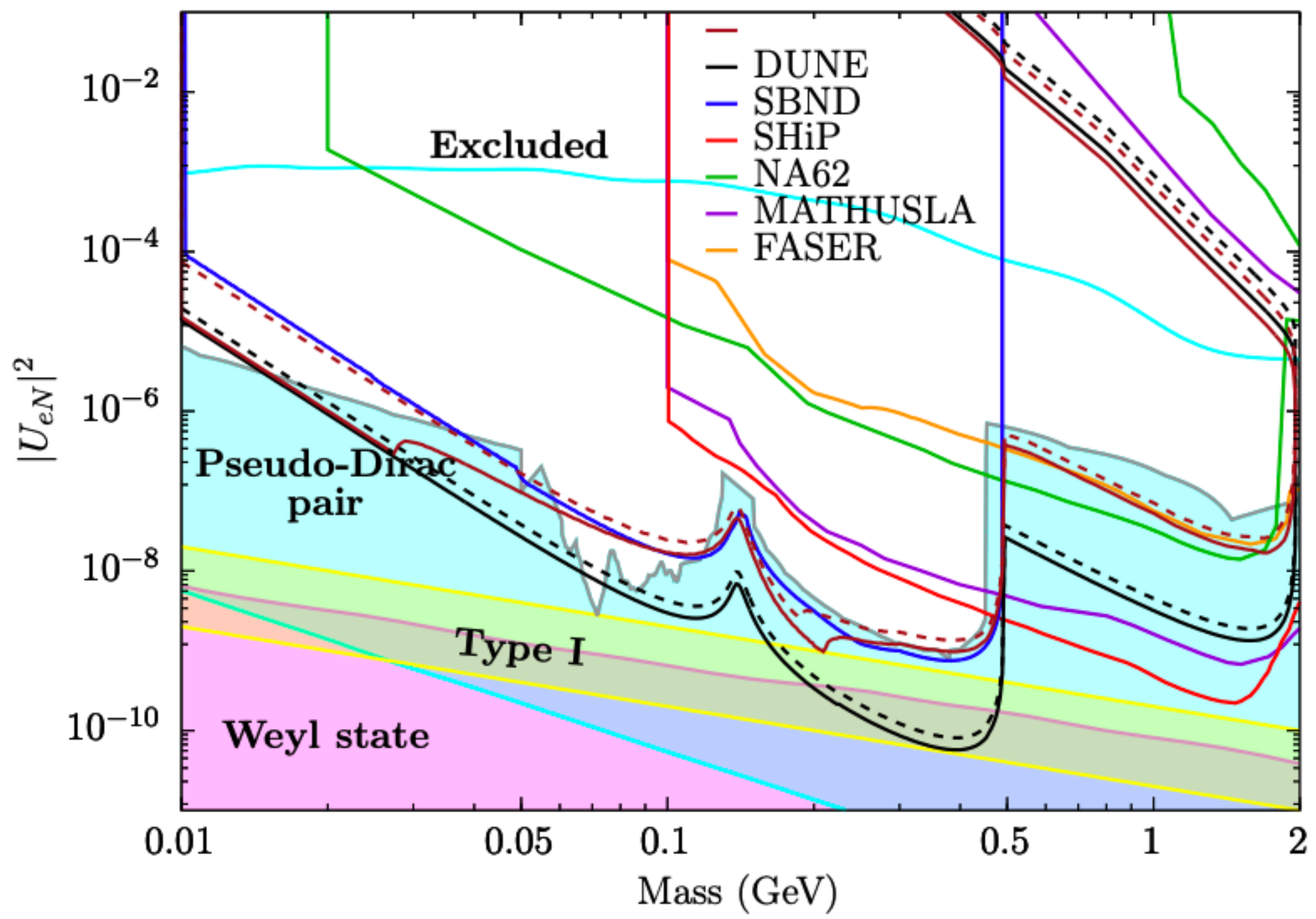




BSM Physics with Phase-II

- Low-density ND-GAr adds additional unique sensitivity to any BSM search involving neutral particles produced in the beam and decaying in the ND (e.g., Heavy Neutral Leptons, Axion-Like Particles)
- Phase-II FD particularly beneficial for searches that are expected to be virtually background-free at the scale of the experiment's full exposure (e.g., some Baryon Number Violation searches)
- Phase-II improves ν_τ detection capabilities at both ND and FD
  - a promising tool to search for non-standard oscillations, for example created by light or heavy sterile neutrino mixing, or by Non-Standard Interactions (NSIs)





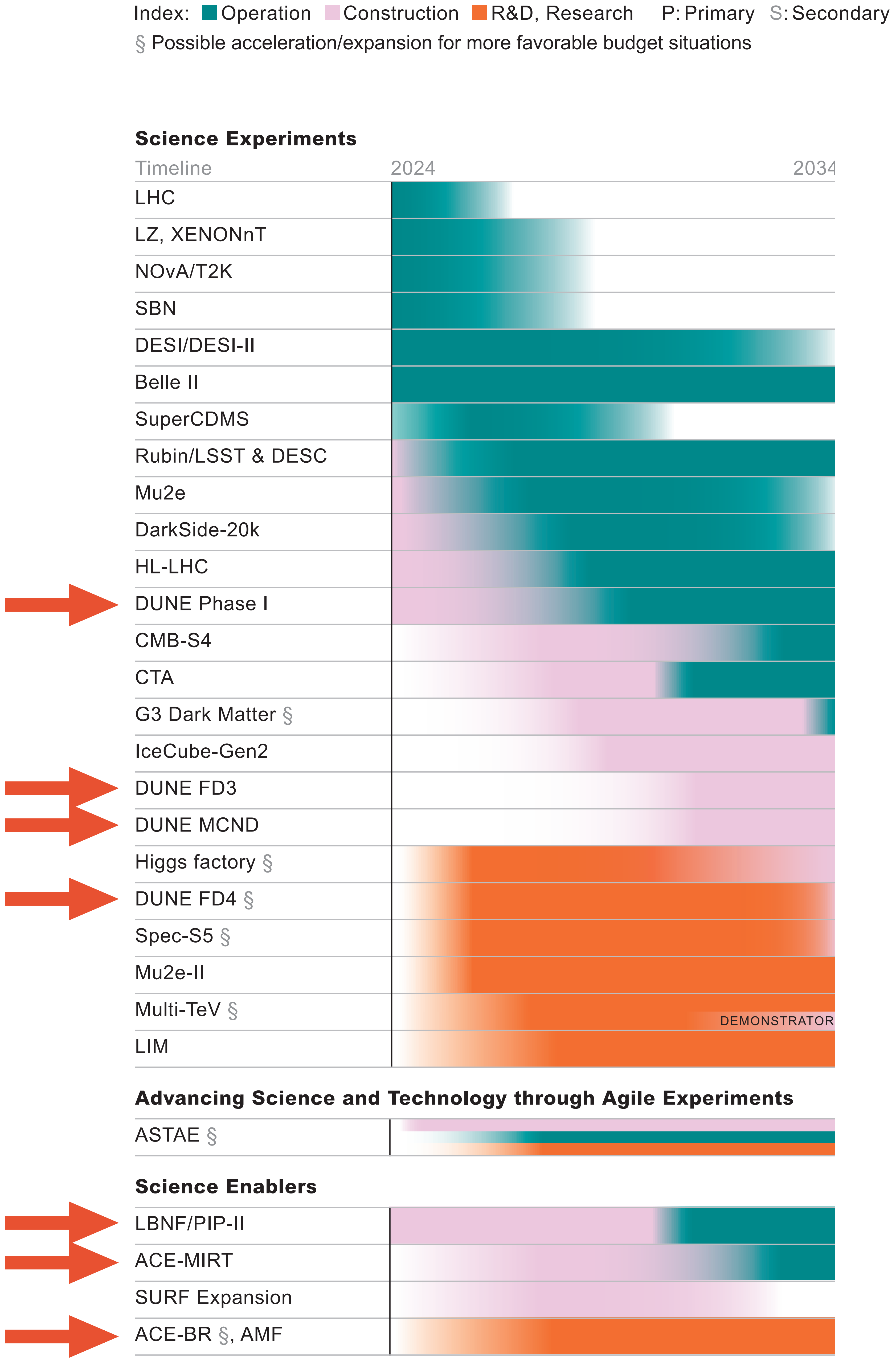
2023 P5 Strongly Endorses Phase-II

- DUNE Phase-II (> 2 MW beam ACE-MIRT, FD3, and MCND) endorsed as second highest priority (**Recommendation 2**), *"as the definitive long-baseline neutrino oscillation experiment of its kind"*

- The Panel also endorsed the DUNE FD4 concept as a "Module of Opportunity" and recommended an accelerated/expanded R&D program in the next decade including initiating construction of FD4 if budget scenarios are favorable

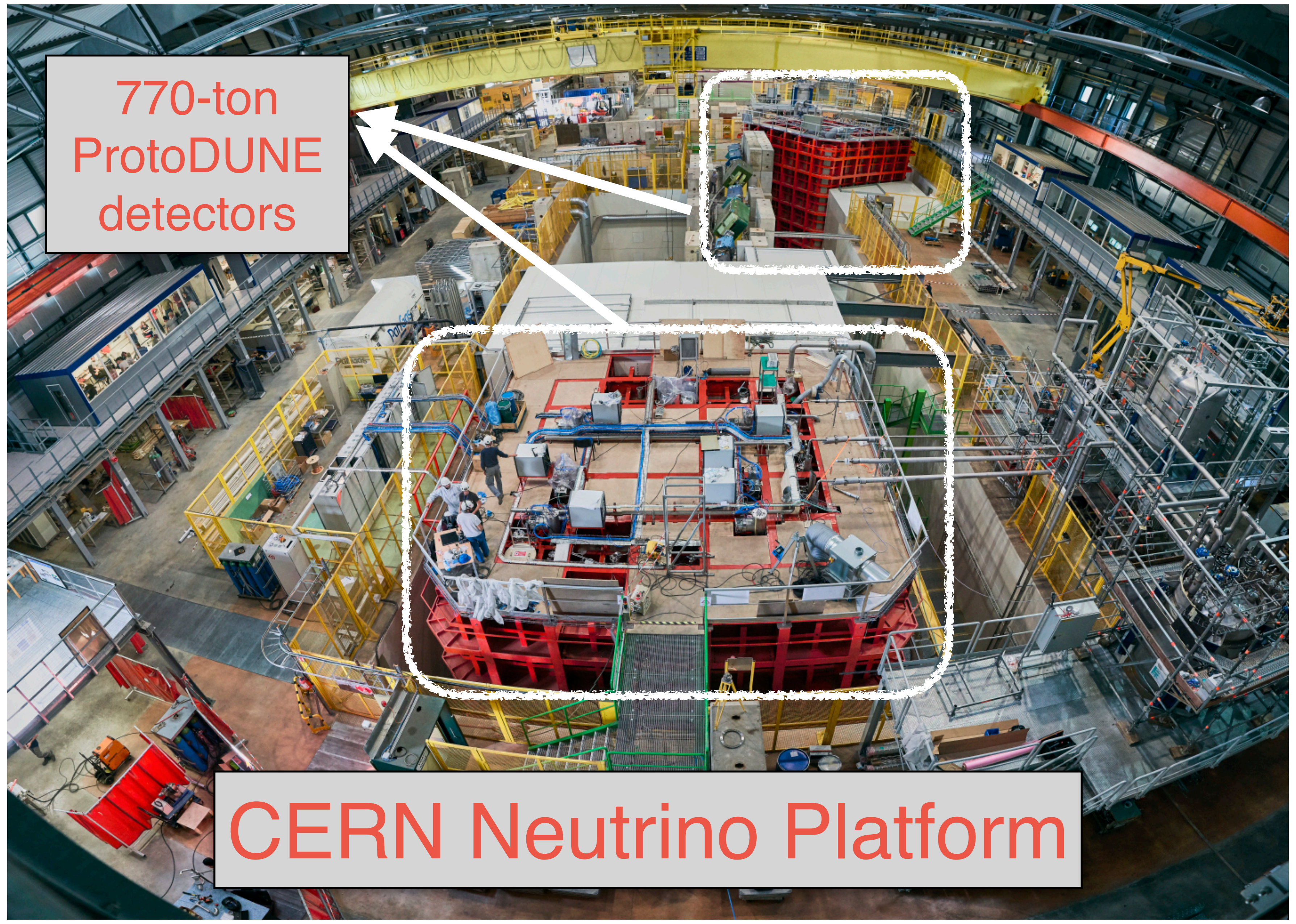
P5 = Particle Physics Project Prioritization Panel

Figure 1 – Program and Timeline in Baseline Scenario (B)



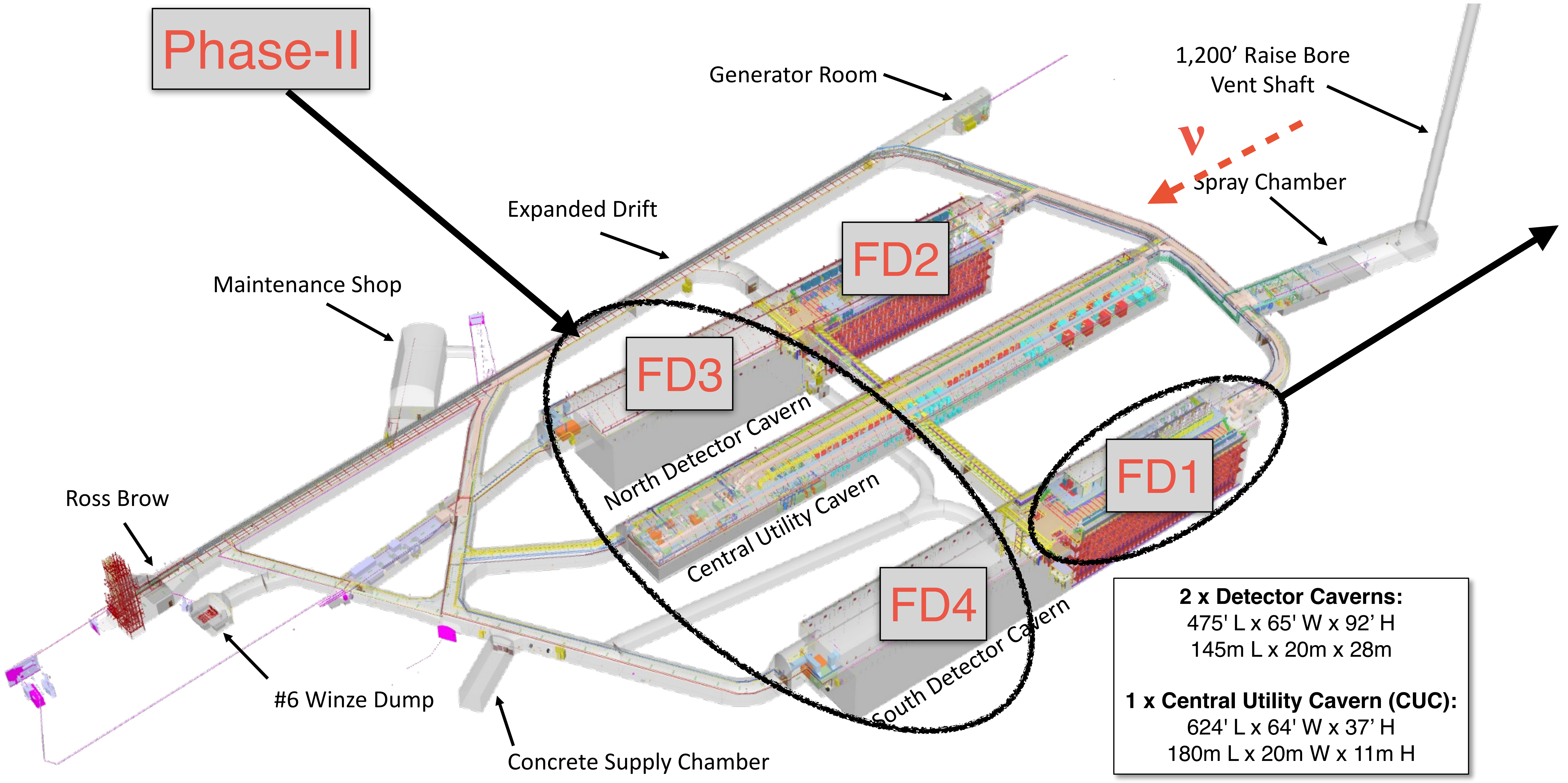
A Global R&D is Forming

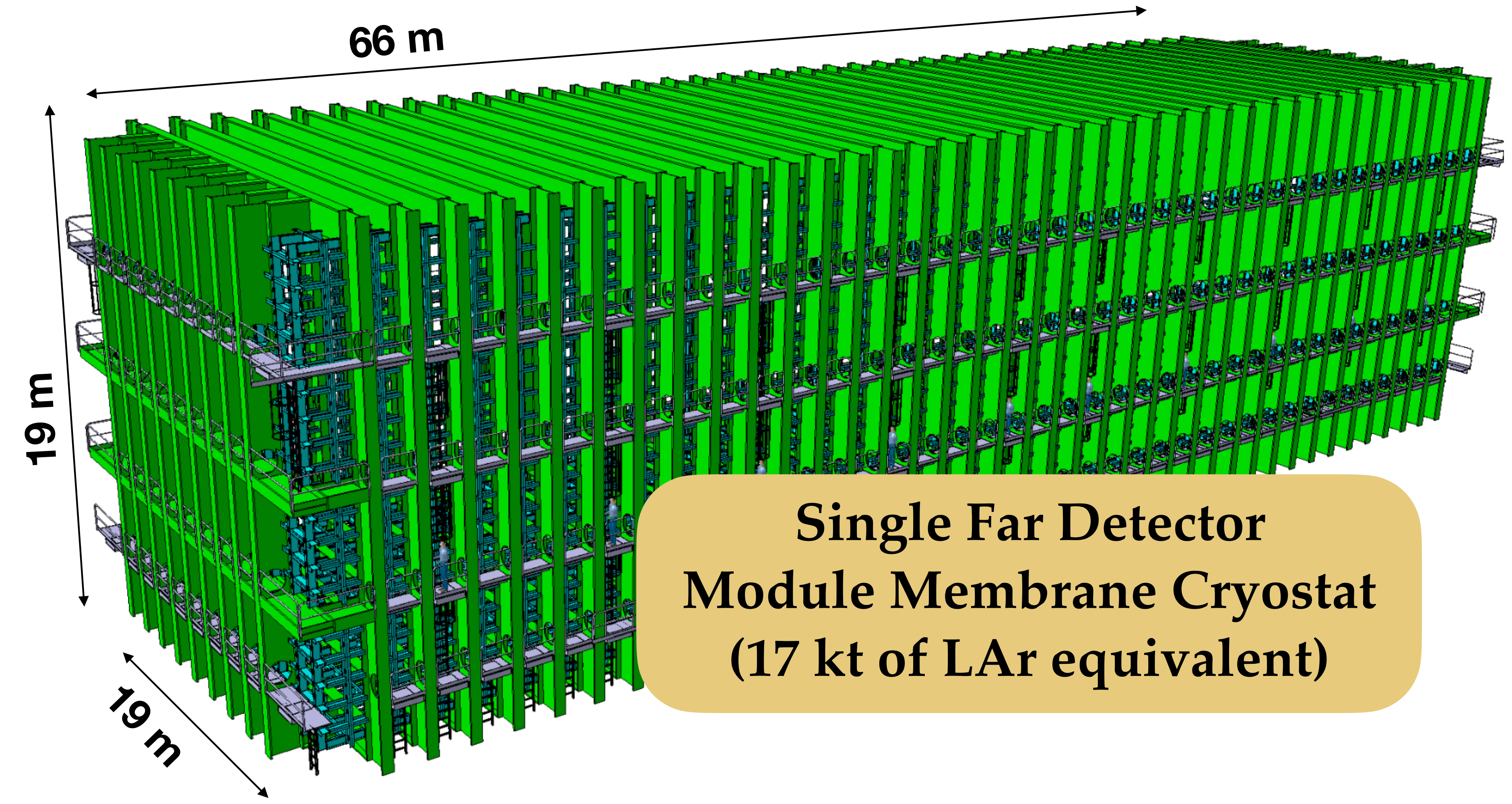
- The 2013 Update of the **European Strategy for Particle Physics** and its 2020 update recommended that *"Europe and CERN continue to collaborate towards the successful implementation of full scope of LBNF and DUNE"*
- The R&D underpinning the Phase-II concepts is performed as part of a global program which includes the ***European Committee for Future Accelerators (ECFA)*** and the ***Coordinating Panel for Advanced Detectors (CPAD)*** in the United States
- Ongoing coordination between U.S. R&D Collaborations (RDCs) and non-U.S. Detector R&D (DRD) groups on synergistic areas of R&D and towards achieving common DUNE Phase-II goals
  - ***DRDs:*** *Liquid Detectors (DRD2); Gaseous Detectors (DRD1)*
  - ***RDCs:*** *Noble Element Detectors (RDC1); Photodetectors (RDC2); Gaseous Detectors (RDC6)*



Phase-II Far Detector

The DUNE Far Detector



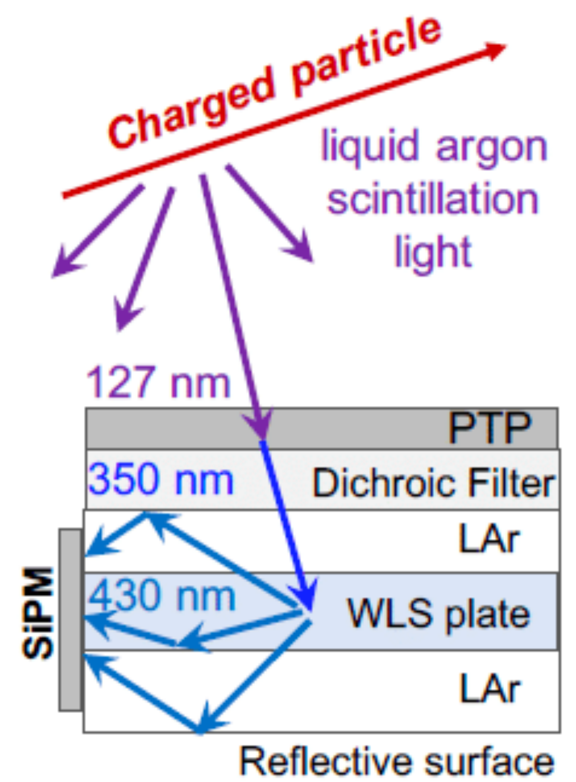


The first three DUNE FD modules will be Liquid Argon Time Projection Chambers (LArTPCs) with 17 kt total mass each

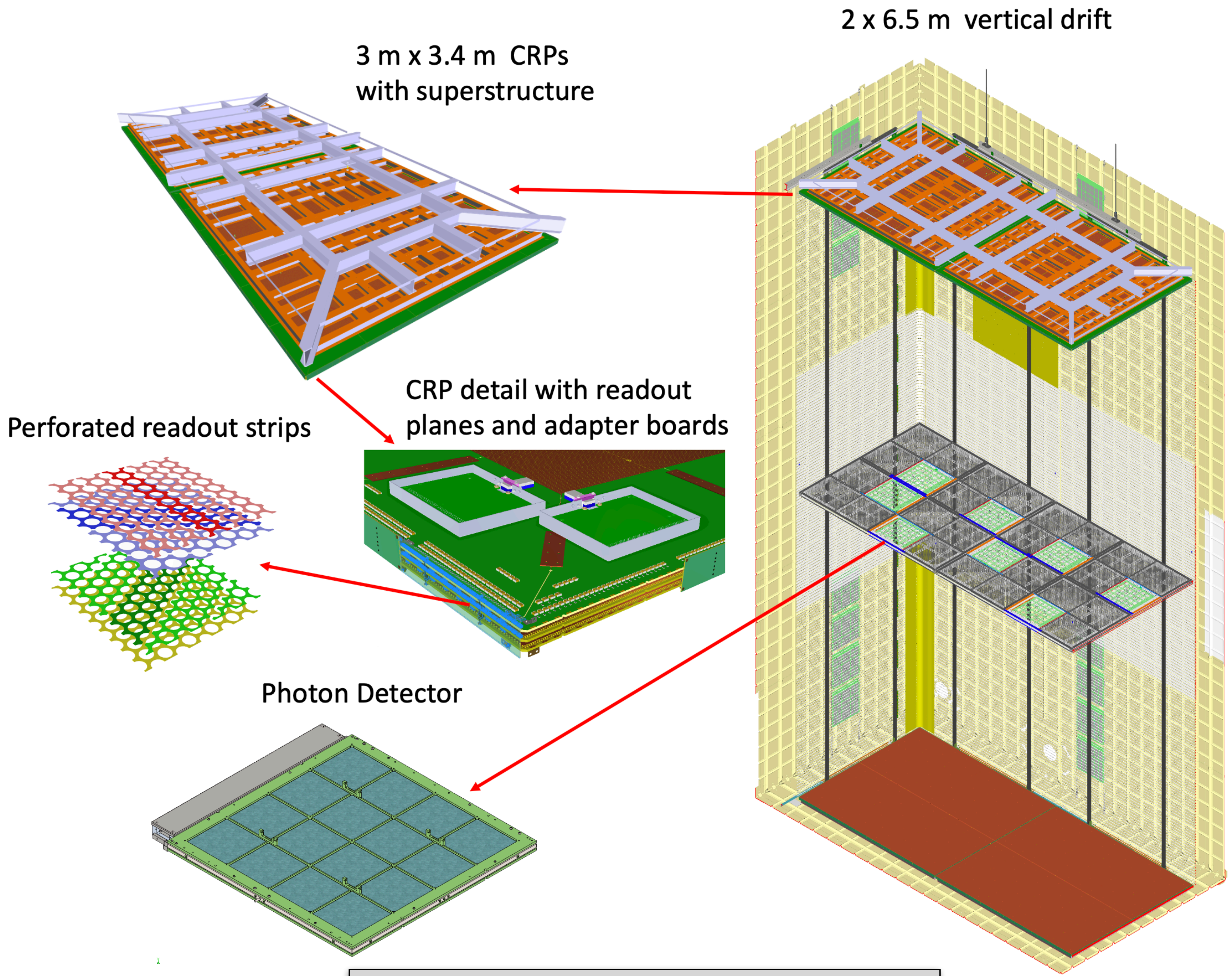
- **FD1**: Horizontal Drift (HD)
- **FD2**: Vertical Drift (VD)
- **FD3**: Improved LArTPC
- **FD4:** Module of opportunity *(both LAr and non-Argon options being explored)*

FD2 as a Starting Point for FD3/4

- FD2 Vertical Drift (VD) LArTPC forms the starting point for FD3/4
- Charge Readout Planes (CRPs) provide three-view charge readout: two induction planes and one collection plane
- Cathode plane at mid-height, two drift volumes of 6.5 m each
- X-ARAPUCA-based Photon Detector System (PDS) on cathode and membrane walls



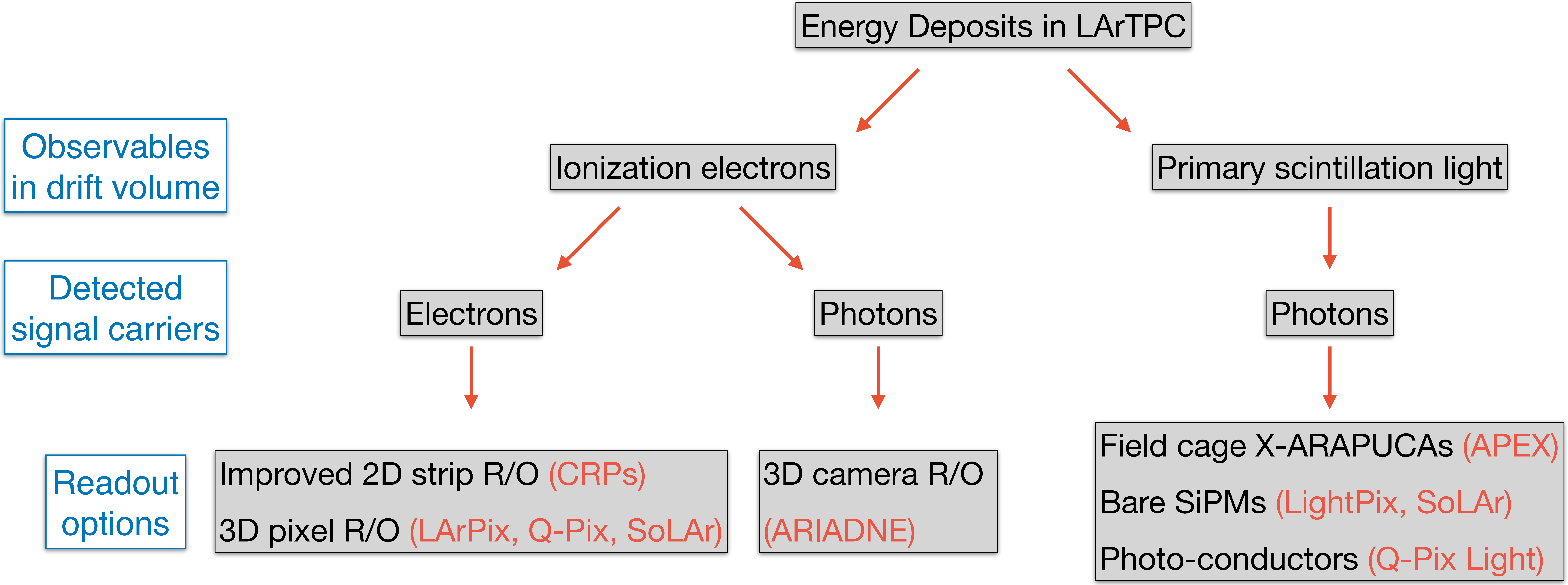
X-ARAPUCA working principle



FD2 Vertical Drift Concept

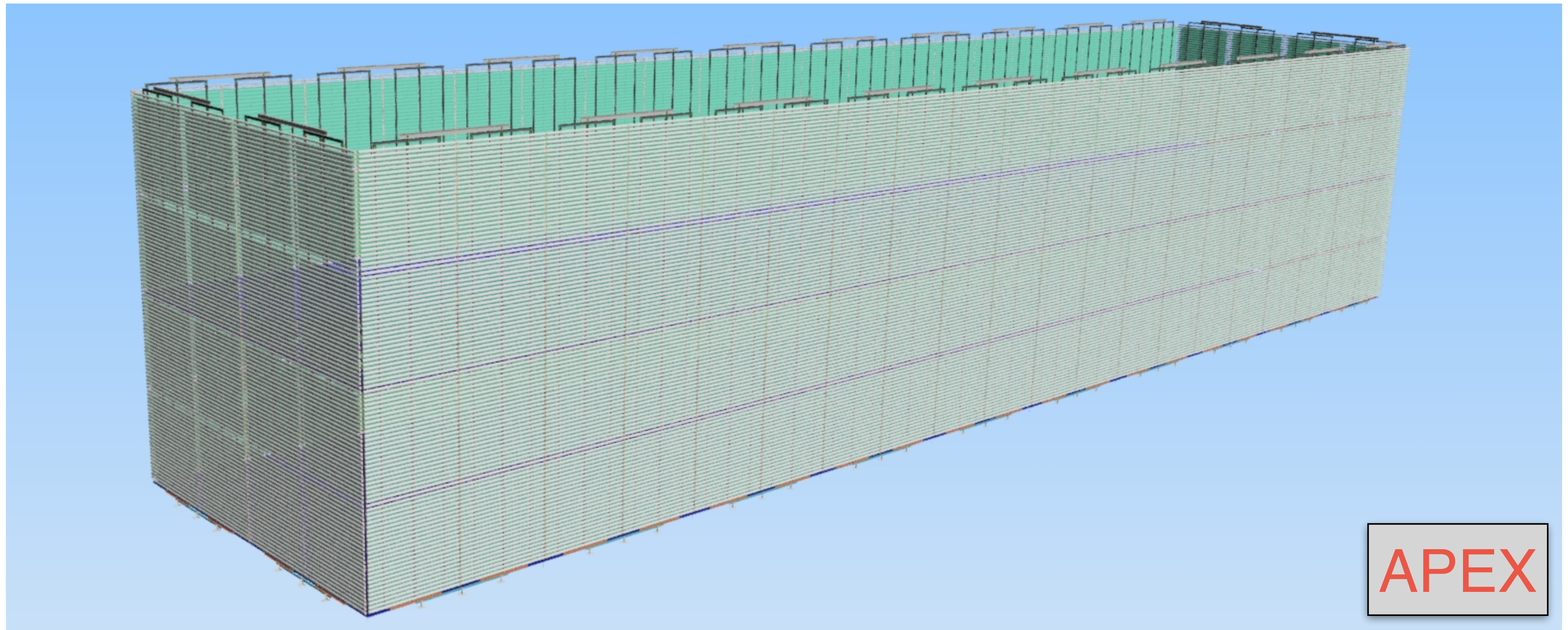
Potential Improvements to FD2 Charge/Light Readouts

- FD3/4 R&D aimed at optimizing or upgrading VD designs for charge and light readout in an effort to broaden the physics program towards expanded sensitivity for MeV-scale physics



Detector Concepts: FD3

- **FD3**: FD2-like, with improvements to CRP-based TPC readout and X-ARAPUCA-based PDS
  - *Single-phase and two vertical drift volumes, 6.5 m each*
  - *Possible CRP optimizations: strip pitch, simpler construction techniques, ASIC upgrade*
  - *Possible PDS optimizations (via APEX R&D): Photon detector system on field cage, larger (up to x10) coverage compared to FD2 (~60% optical coverage of LAr active volume), digital optical transmission*

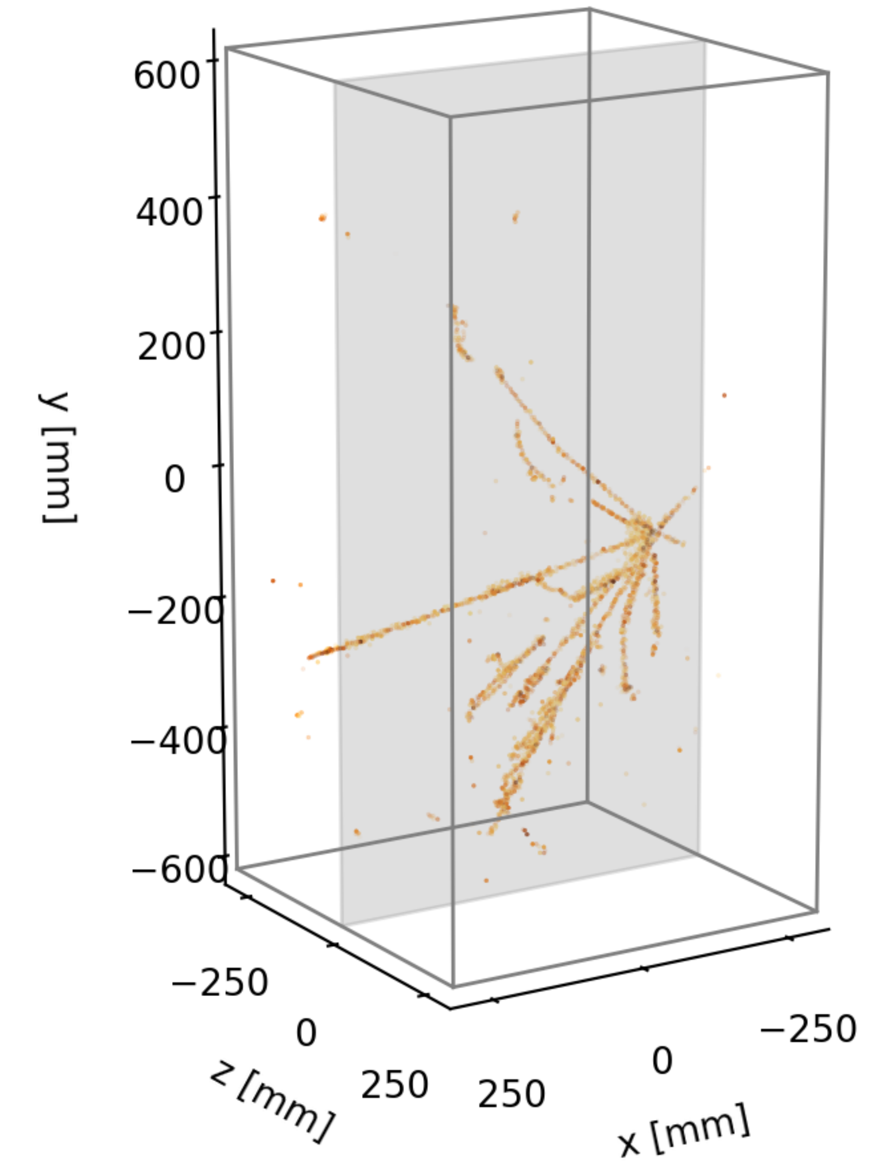


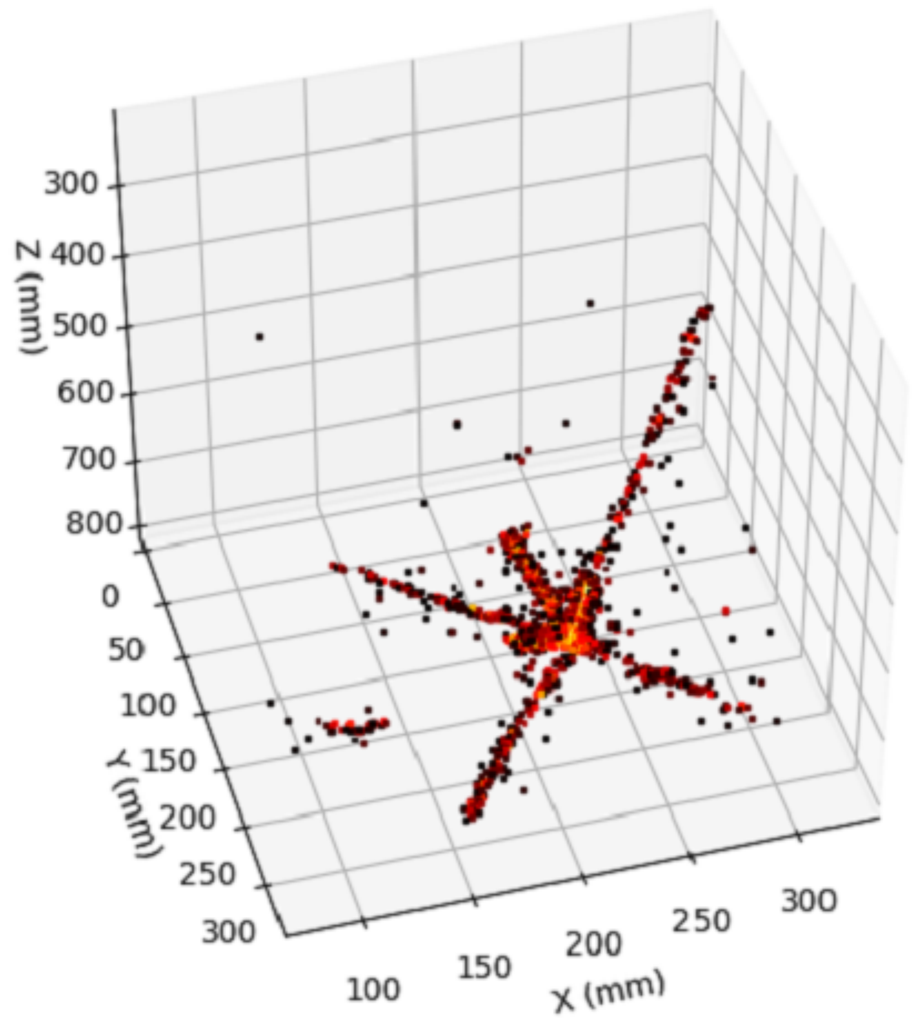
See talk by W. Shi on APEX (DUNE Phase-II parallel)

Detector Concepts: FD4 Baseline

- **FD4 baseline**: VD-LArTPC with central cathode, and <u>native 3D</u> anode readouts
  - *Either charge pixels (LArPix or Q-Pix) or optical-based readout (ARIADNE)*
  - *Pixels may also serve for integrated charge/light readout (SoLAr, LightPix or Q-Pix Light)*
  - *Different solutions for top/bottom anodes in principle possible. Compact shield design*

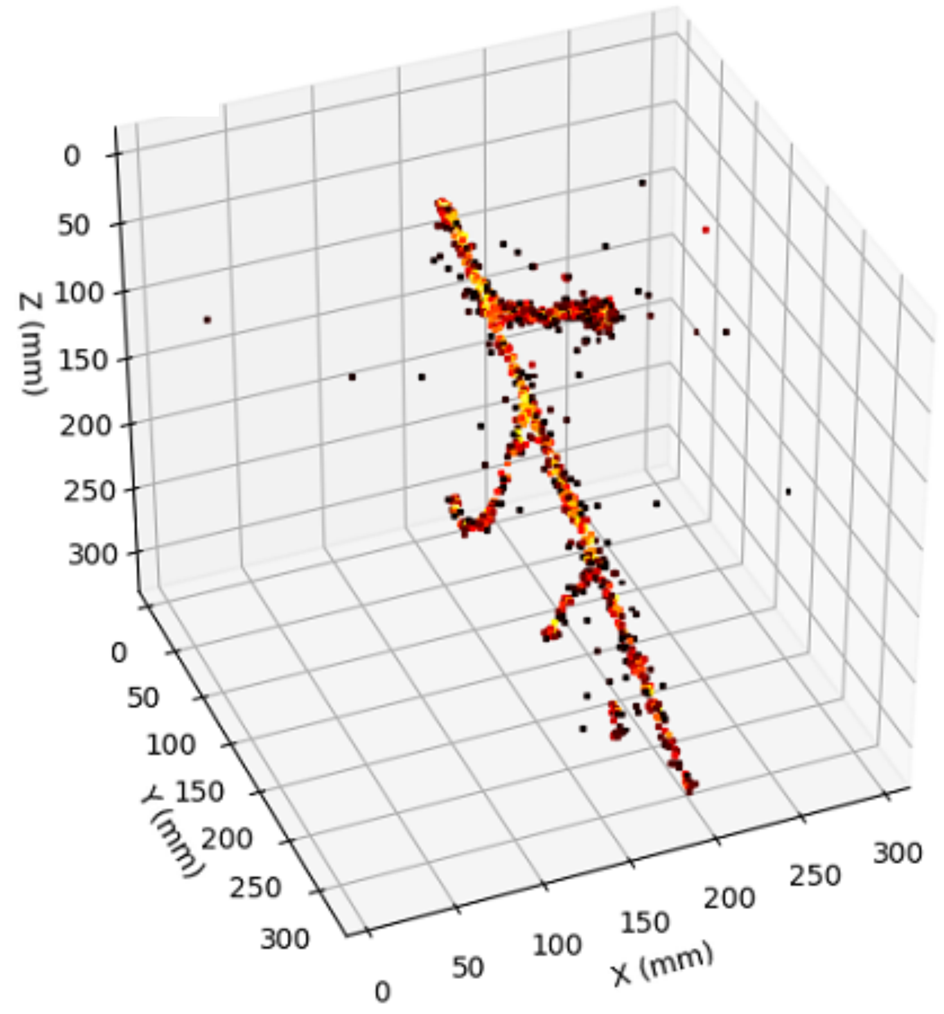
LArPix





ARIADNE

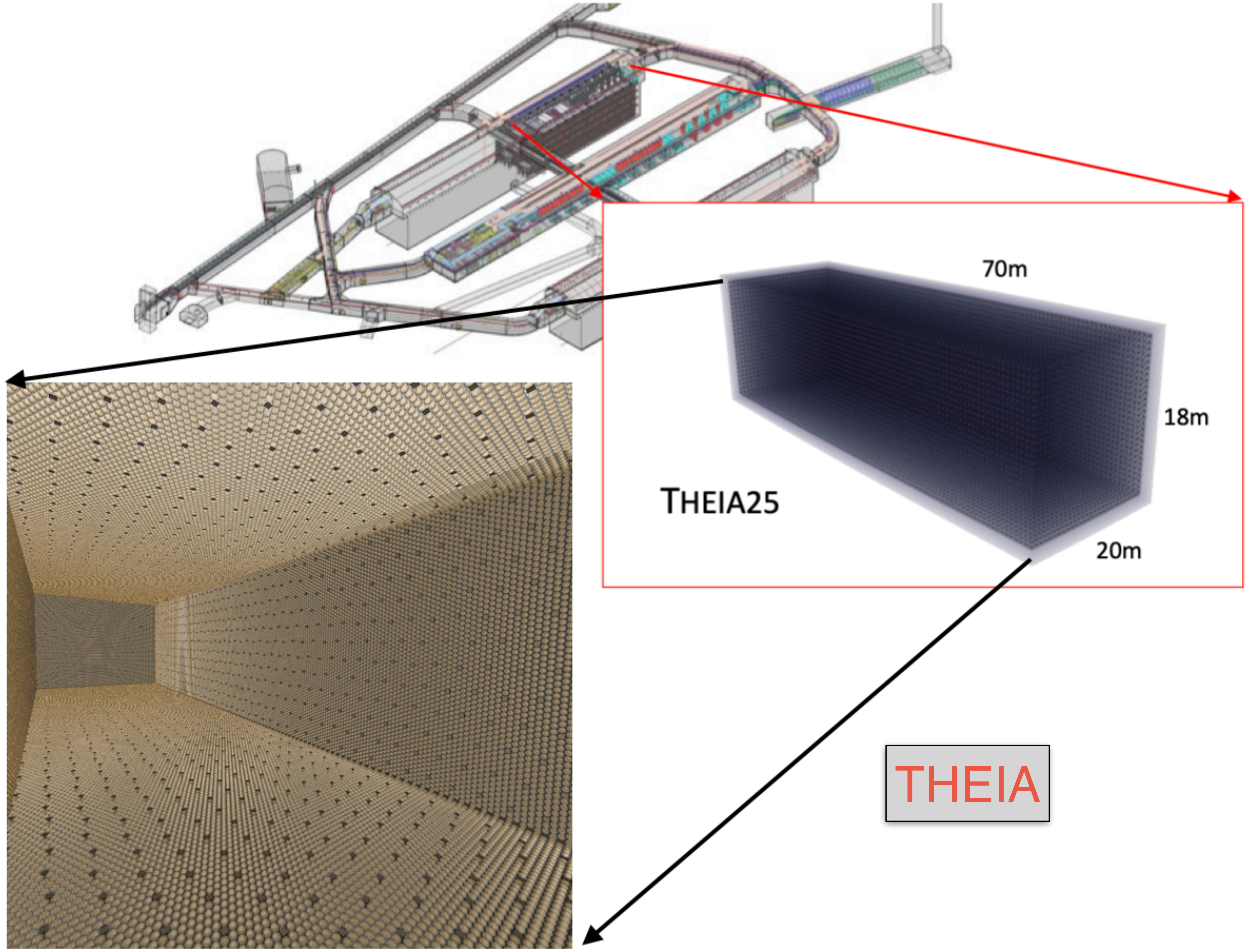
See talk by K. Mavrokaridis (DUNE Phase-II parallel)



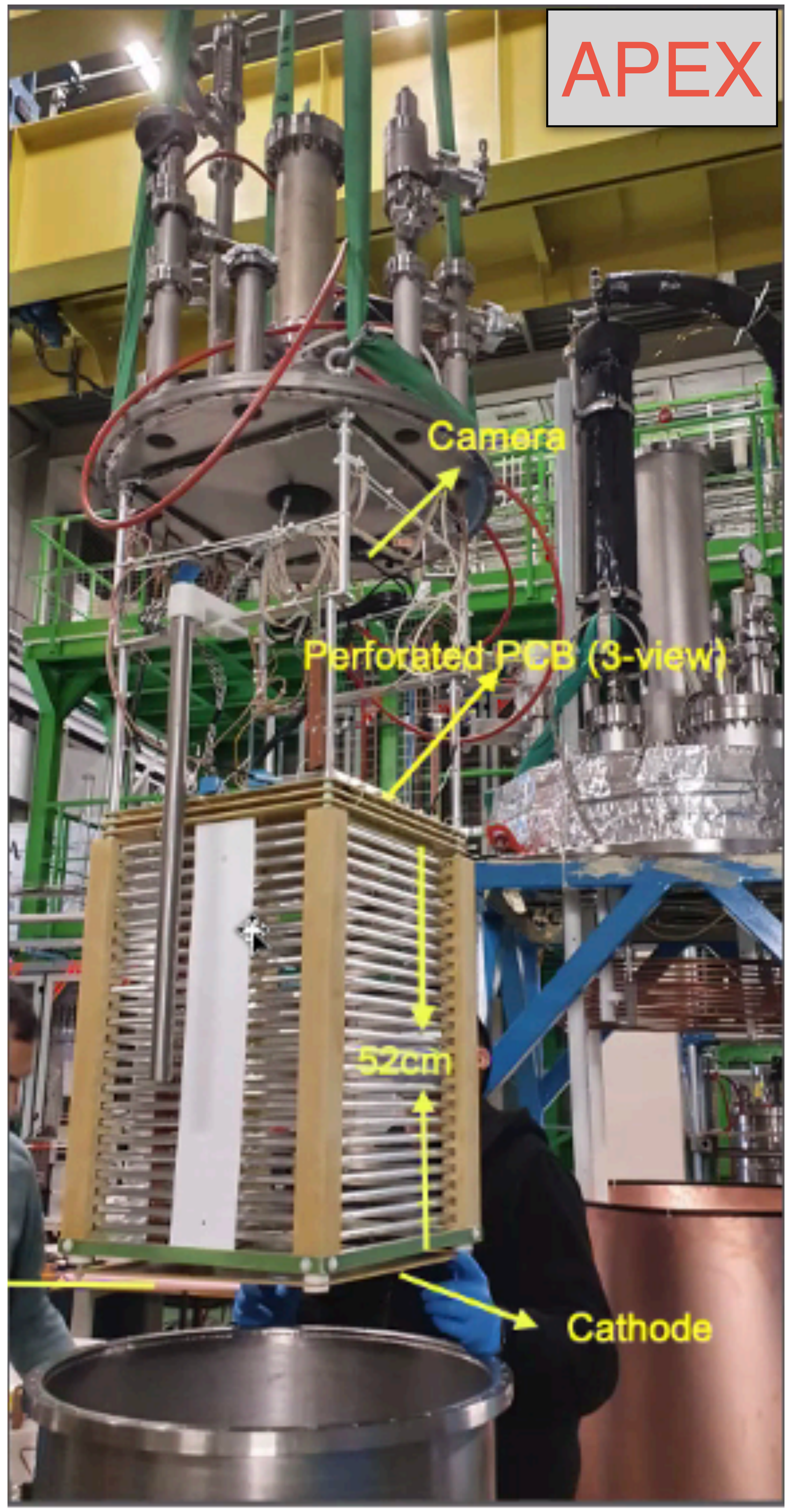
Detector Concepts: FD4 Alternative

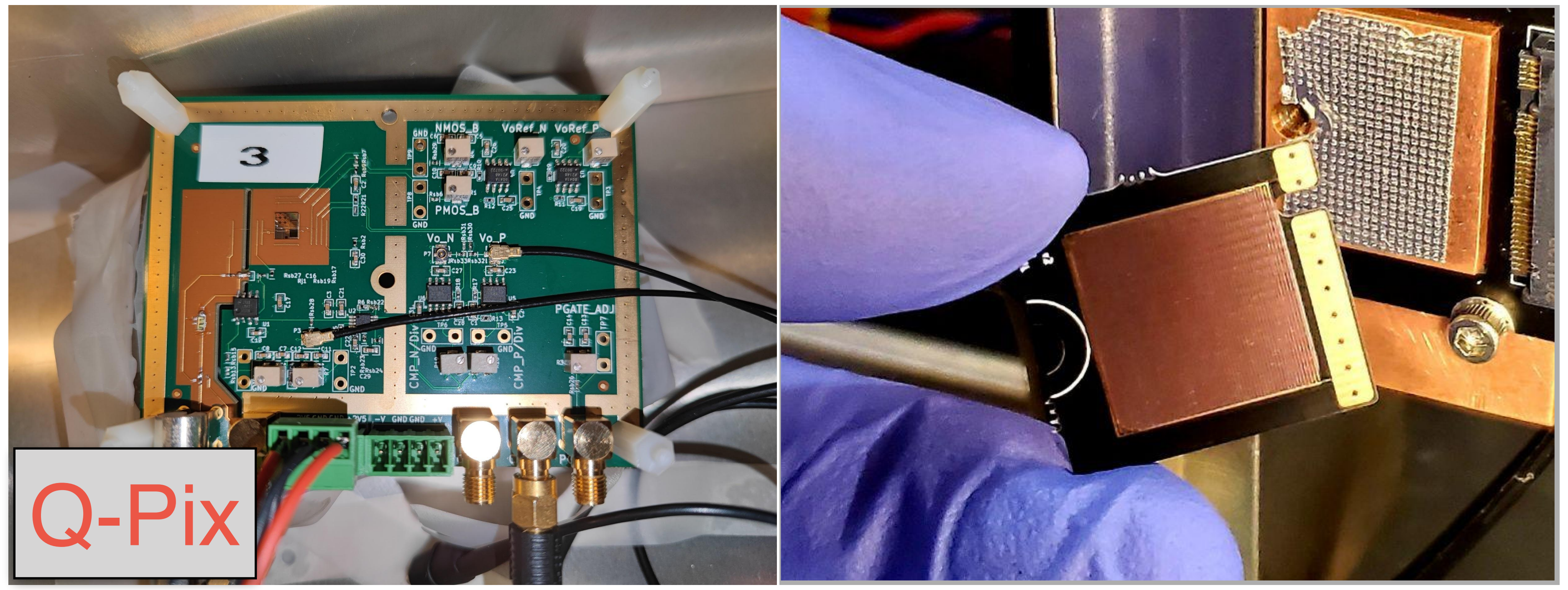
- Water-based liquid scintillator module measuring scintillation and Cherenkov light separately (**THEIA**)
- Cherenkov light offers e/μ discrimination via ring imaging, and sensitivity to particle direction
- Scintillation light offers improved energy and vertex resolution, Particle-ID capability via quenching effects, and sub-Cherenkov-threshold particle detection
- Requires corresponding modifications to ND to carry out long-baseline oscillation program

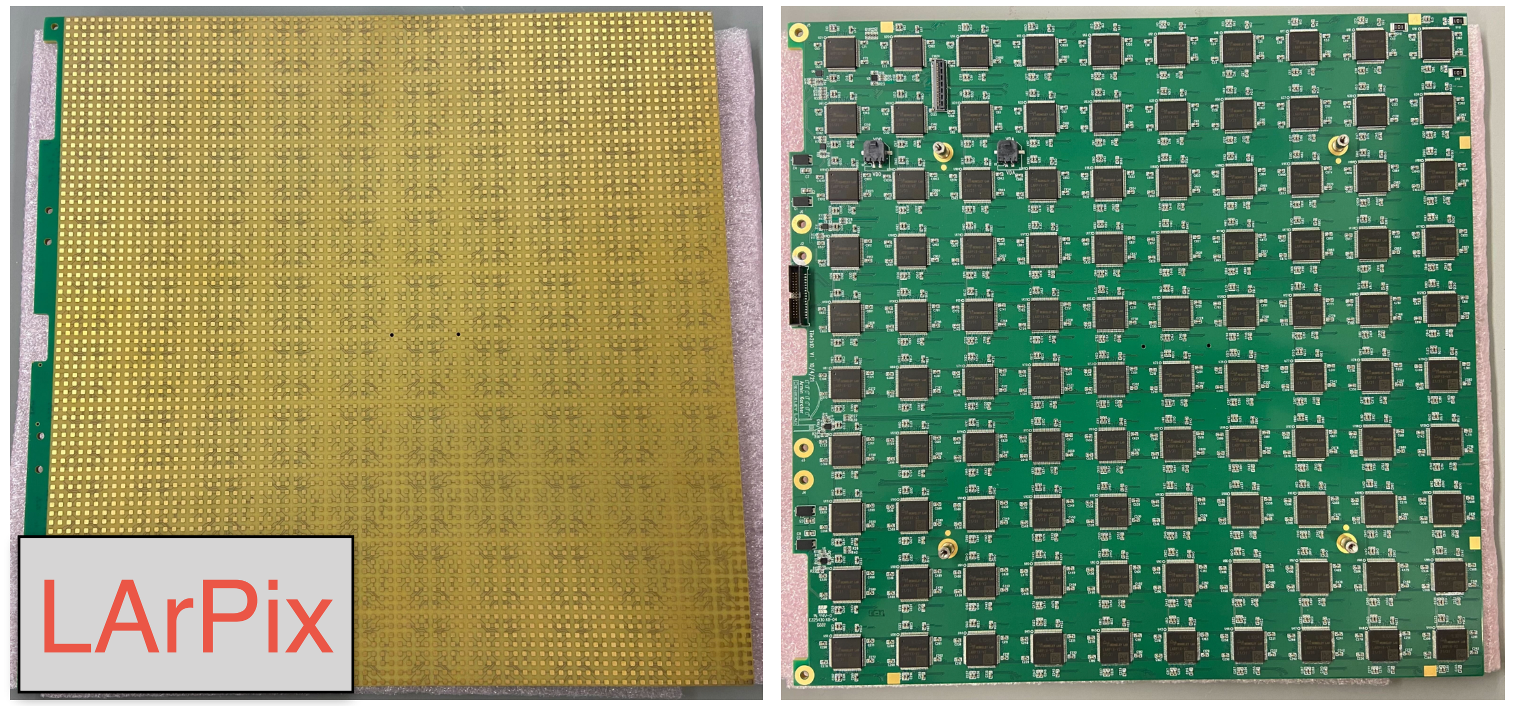
See talk by L. Pickard on THEIA (DUNE Phase-II parallel)

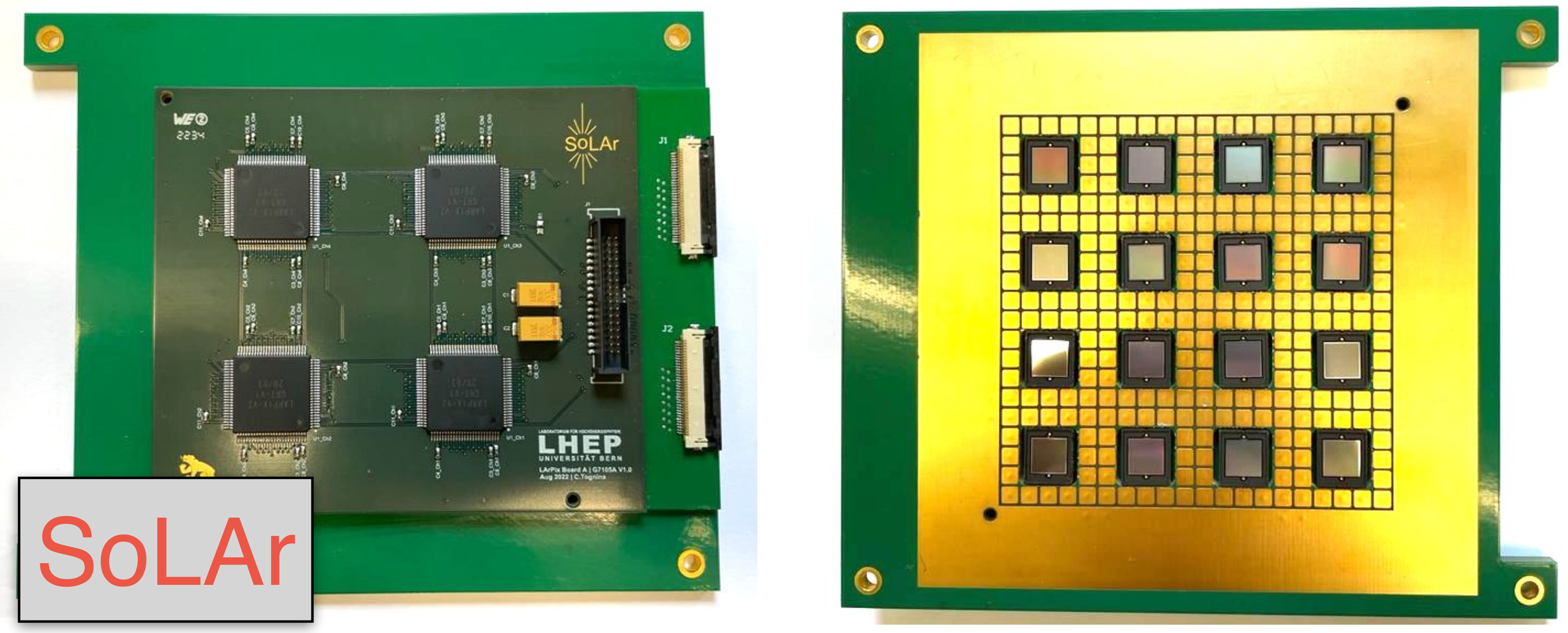


Active Prototyping Underway for FD3/4 Technologies

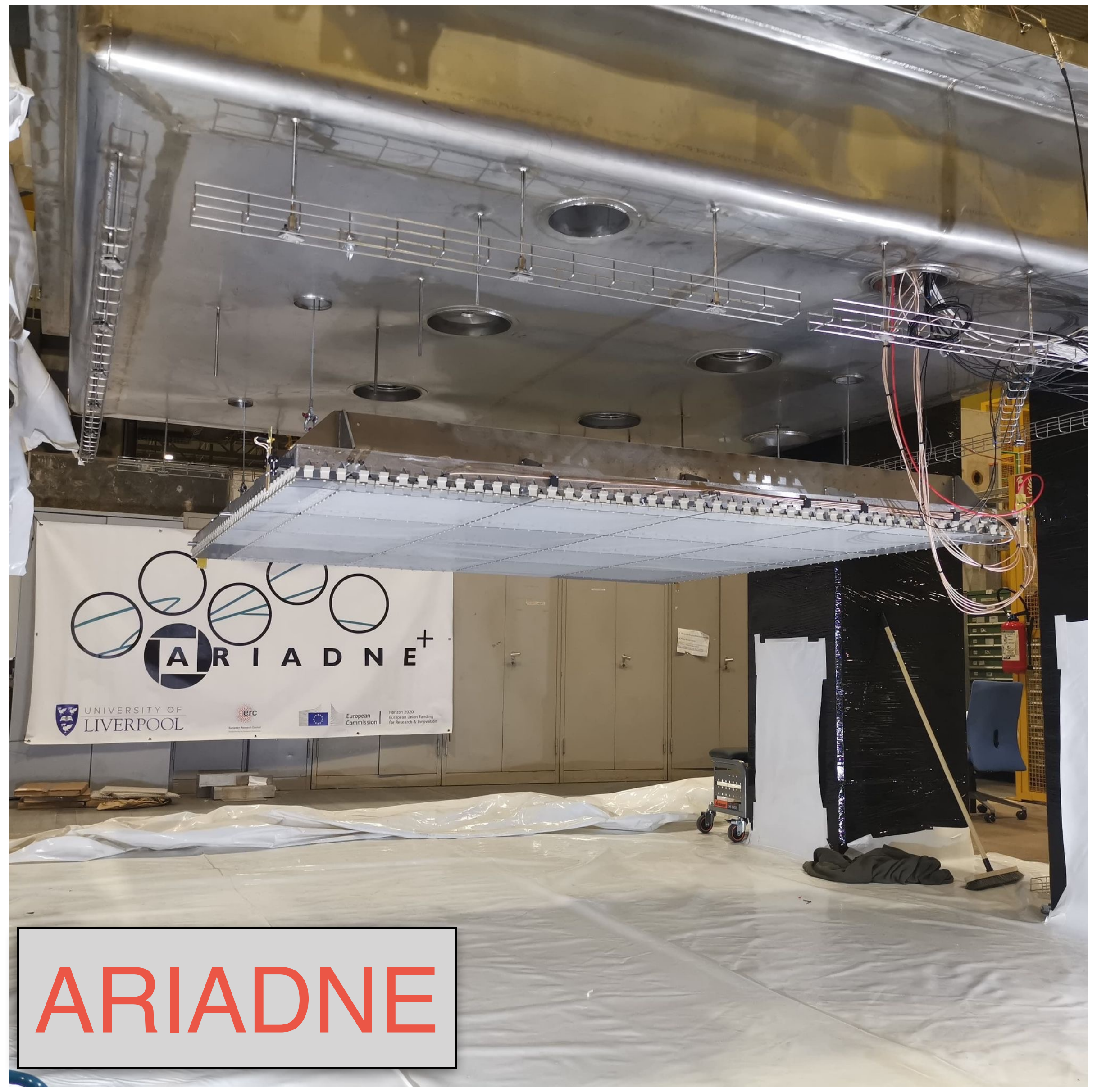


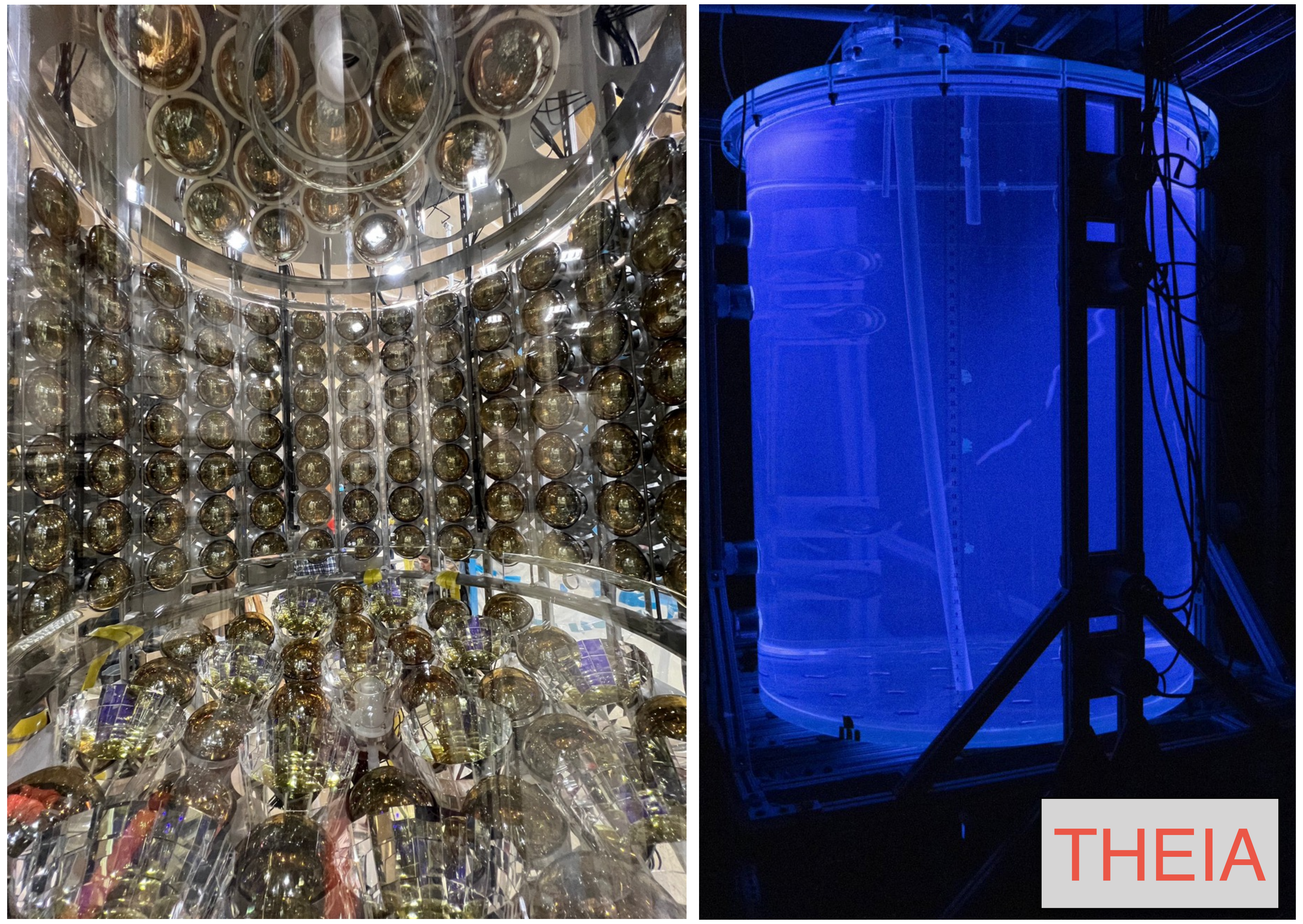






See talks in the DUNE Phase-II parallel session





Phase-II FD Technology Integration Options

- All LArTPC technologies can be combined or integrated with others
- The WbLS technology being considered for FD4 will be complementary to LAr

Technology	LArTPC Integration
CRP (Strip-based charge readout)	APEX
APEX (X-ARAPUCA-based light readout on field cage with SiPMs)	CRP, LArPix, Q-Pix, ARIADNE, SoLAr
LArPix, **LightPix** (Pixel-based charge and light readout)	APEX, SoLAr
Q-Pix, **Q-Pix-LILAr** (Pixel-based charge and light readout)	APEX, SoLAr
ARIADNE (Dual-phase with optical readout of ionization signal)	APEX
SoLAr (Integrated charge-light pixel readout)	APEX, LArPix, Q-Pix
WbLS (Water-based liquid scintillator)	None (complementary to LAr)

FD4 Prototyping Plans and Key R&D Goals

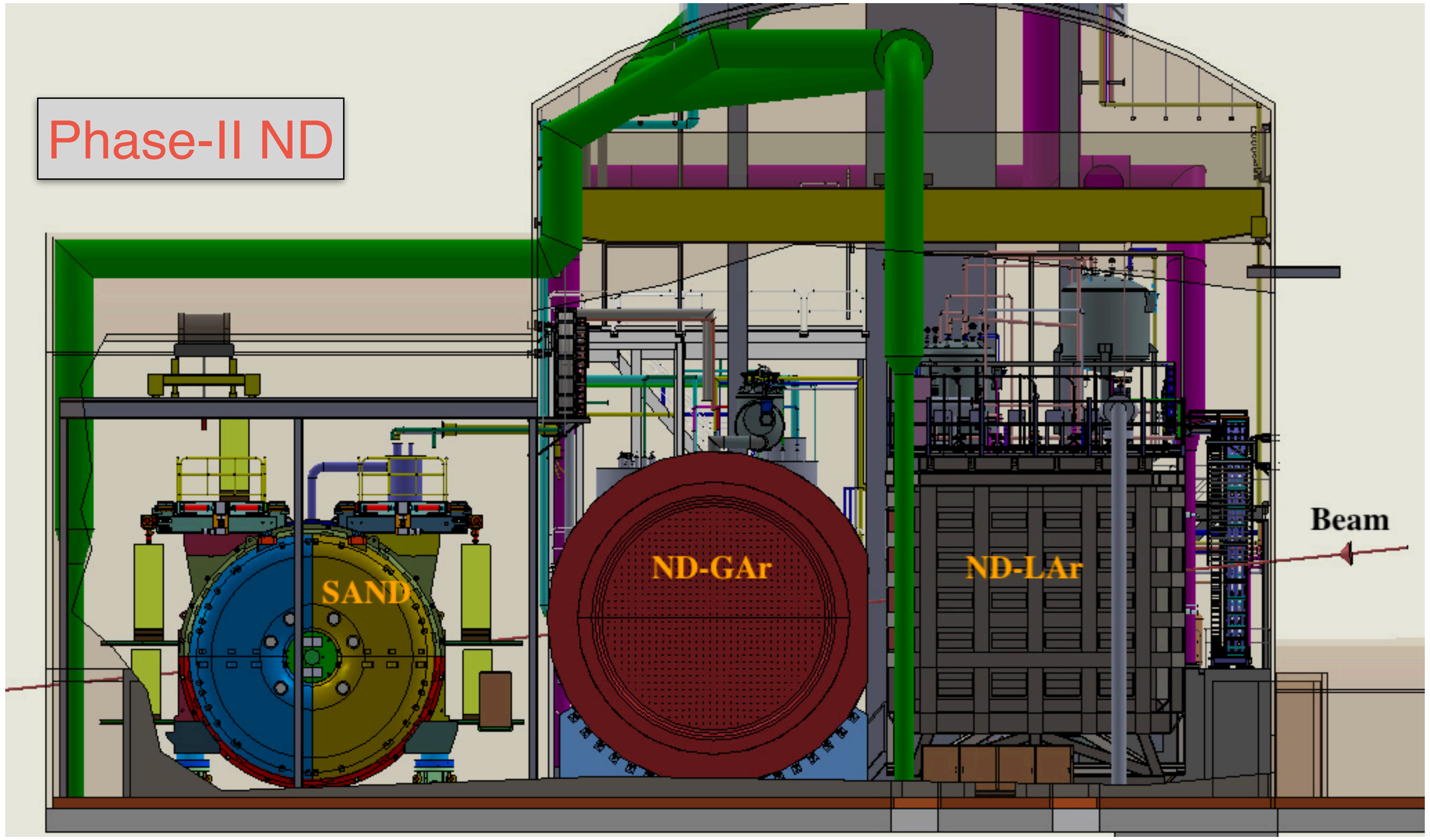
- All leading technologies have identified the main R&D challenges
  - *Technology Readiness Levels (TRL) currently achieved: TRL ≥ 3 on all items*
- They all have small- and medium-scale prototypes in operation or planned
- The ProtoDUNEs at CERN will continue to serve as an important platform to demonstrate several of these technologies and their potential for integration.

Technology	Prototyping Plans	Key R&D Goals
CRP	**2024:** Cold Box tests at CERN. **2025-2026:** ProtoDUNE-VD at CERN.	Port LArASIC to 65 nm process
APEX	**2024:** 50lt & 1-ton prototypes at CERN. **2024-25:** $\mathcal{O}(100)$-channel demonstrator at Fermilab. **2025-28:** ProtoDUNE-VD at CERN.	Mechanical integration of APEX PD in FC Signal conditioning, digitization and multiplexing in cold
LArPix, LightPix	**2024:** 2x2 ND demonstrator at Fermilab. **2024-25:** Cold Box tests at CERN. **2026-28:** ProtoDUNE at CERN.	Micropower, cryo-compatible, detector-on-a-chip ASIC Scalable integrated 3D pixel anode tile Digital aggregator ASIC and PCB
Q-Pix, Q-Pix-LILAr	**2024:** Prototype chips in small-scale demonstrator. **2025-26:** 16 channels/chip prototypes in ton-scale demonstrator at ORNL. **2026-27:** Full 32-64 channel "physics chip".	Charge replenishment and measurement of reset time Power consumption R&D on aSe-based devices and other photoconductors
ARIADNE	**2024:** Glass THGEM production at Liverpool. **2025-26:** ProtoDUNE-VD at CERN.	Custom optics for TPX3 camera Light Readout Plane design with glass-THGEMs Characterization of next-generation TPX4 camera
SoLAr	**2024:** Small-size prototypes at Bern. **2025-2028:** Mid-scale demonstrator at Boulby.	Development of VUV-sensitive SiPMs ASIC-based readout electronics
WbLS	**2024-25:** Prototypes at BNL (1- & 30-ton), LBNL (EOS), Fermilab (ANNIE). **2025-26:** BUTTON at Boulby.	WbLS organic component manufacturing WbLS *in situ* purification Spectral photon sorting (dichoicons)

Phase-II Near Detector

Phase-II ND Requirements

- To ensure that DUNE is not systematically limited, important to have a More Capable ND in Phase-II
- MCND should expand the physics capabilities of the liquid-argon ND (ND-LAr)
- Phase-II ND Requirements for an Ar target
  - *Argon as primary target nucleus*
  - *Very high particle ID efficiency*
  - *Low thresholds for protons and pions*
  - *4π acceptance over a wide range of momenta and angles*
  - *Magnetization for sign selection*



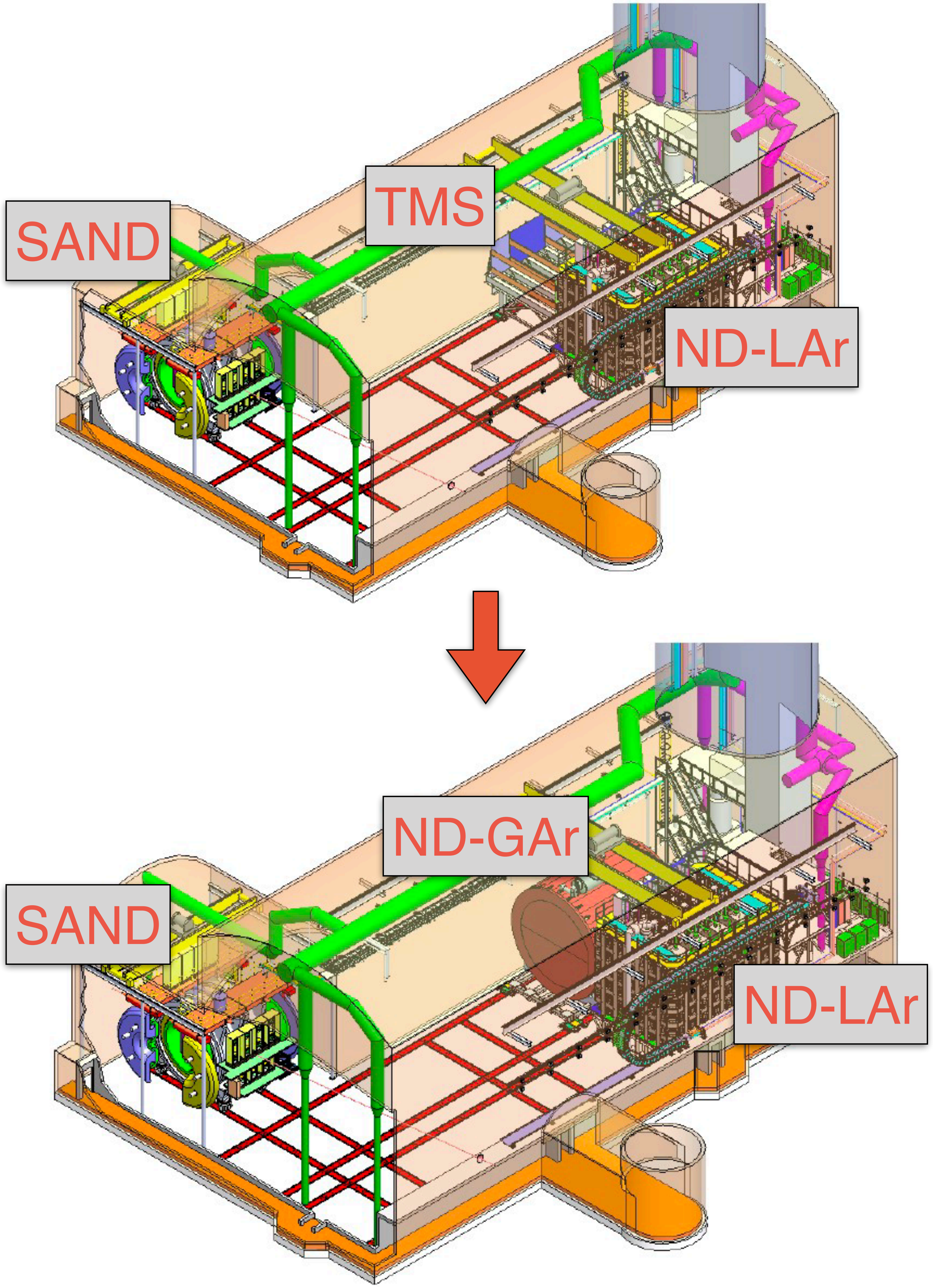
SAND
Tracker, ECAL, Magnet,
On axis beam monitor

ND-GAr
High pressure
GArTPC, ECAL, Magnet.
Muon spectrometer

ND-LAr
Modular, pixelated LArTPC
(most similar to FD)

Phase-I → Phase-II ND

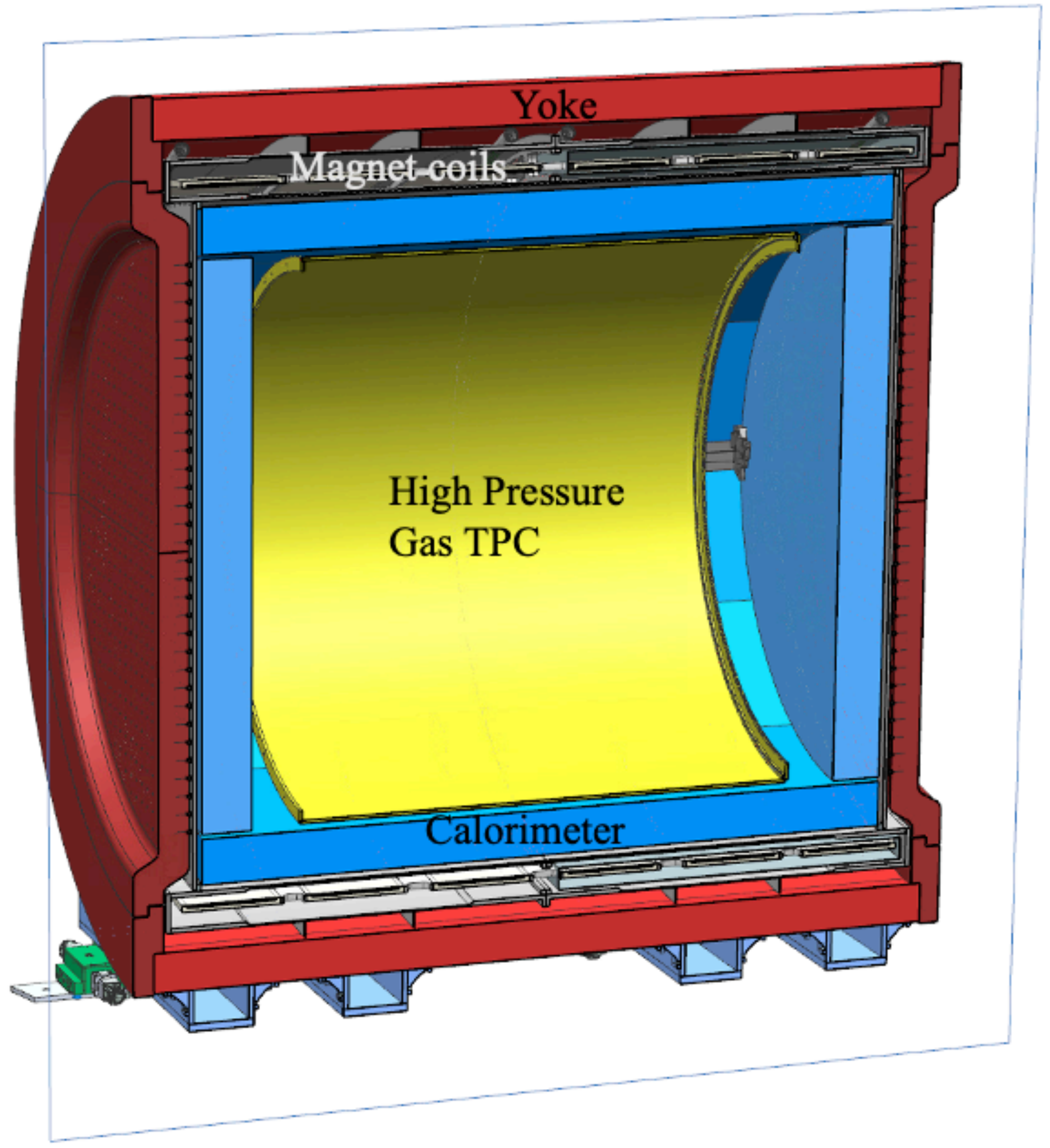
- Gaseous argon detector (ND-GAr) will replace the Temporary Muon Spectrometer (TMS) in DUNE ND Phase-II upgrade
- Upgrades to ND-LAr and SAND are also possible
- If FD4 neutrino target is not Ar (e.g., THEIA), Phase-II ND would need to measure neutrino interactions on those target nuclei
  - *Several options under consideration*

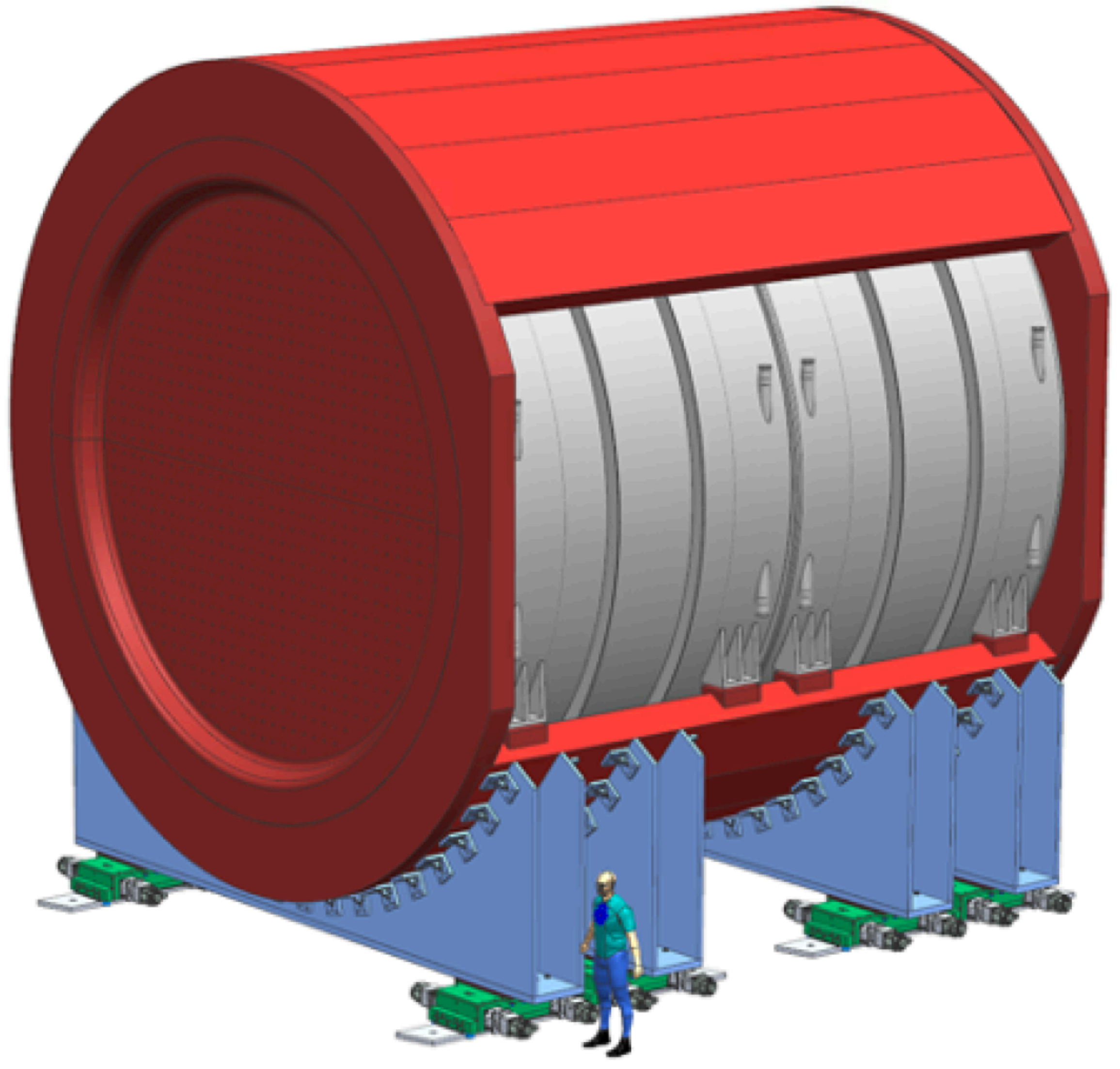


ND-GAr Baseline Concept

- Cylindrical volume of 5 m linear dimensions filled with gas at 10 bar (~1 ton of Ar)
- Baseline concept includes:
  - *Pressurized gaseous argon TPC*
  - *Surrounding calorimeter*
  - *Magnet: solenoid with partial return yoke*
  - *Muon-tagging system*

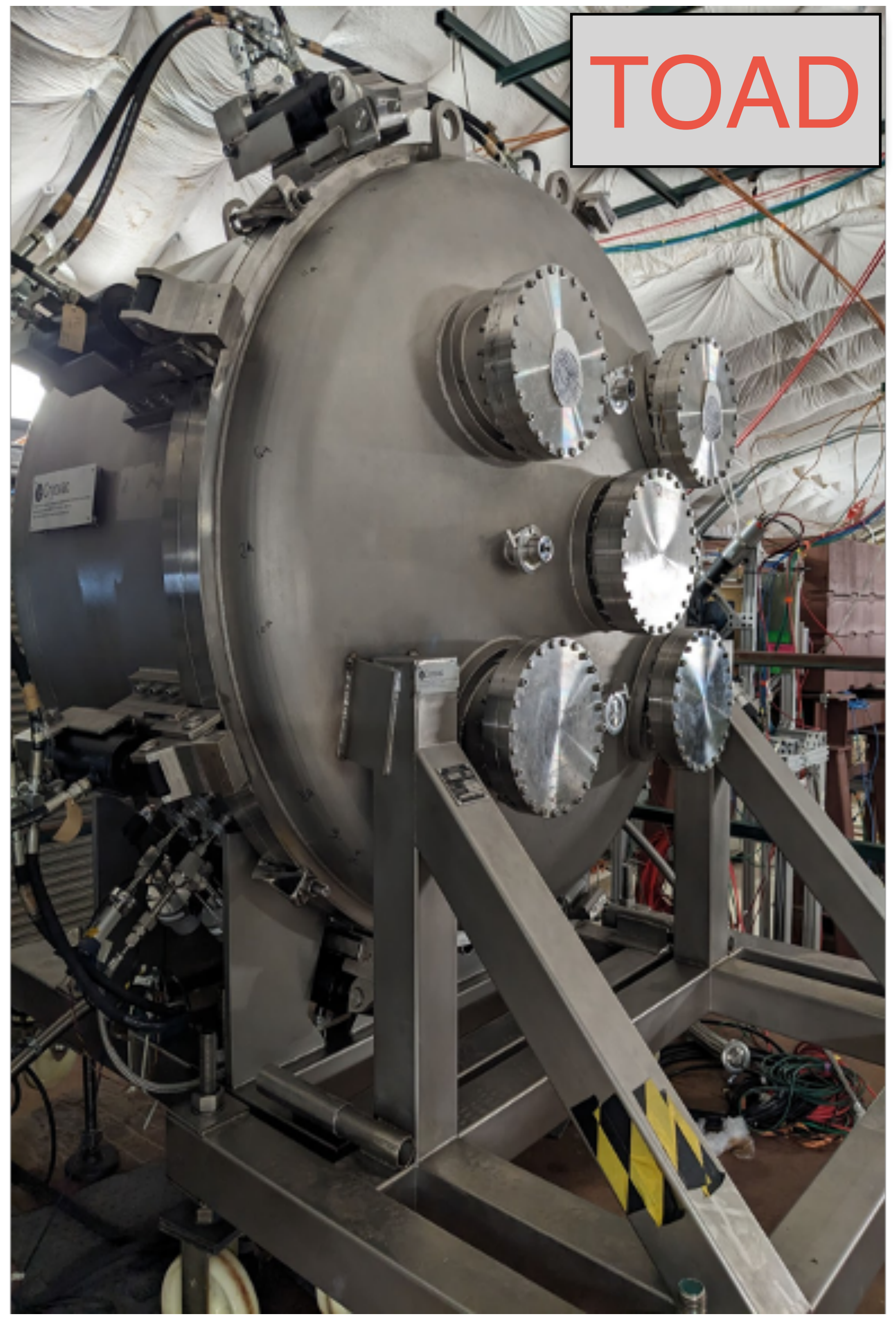
- Light detection system maybe necessary to reduce pileup, and to provide the event t0 in events that do not reach the calorimeter
- Will move perpendicularly to beam with ND-LAr (DUNE-PRISM concept)

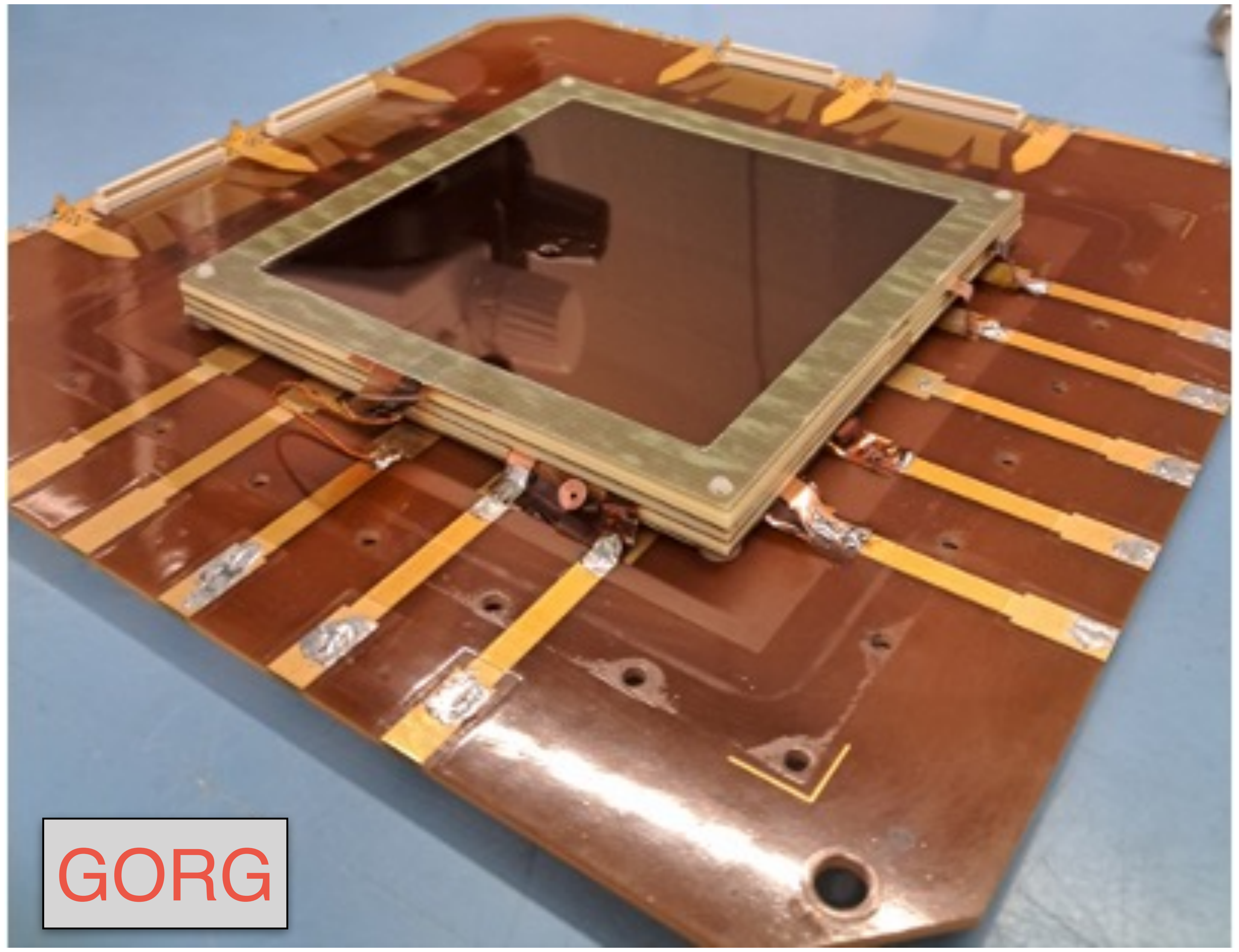




ND-GAr R&D Roadmap

- Current R&D priority: testing the full chain from amplification technology to readout electronics in a high-pressure test stand
  - *Ensure adequate stability and gain in a non-flammable gas with a high argon fraction*
- Amplification technology: both MWPCs and GEMs currently being tested

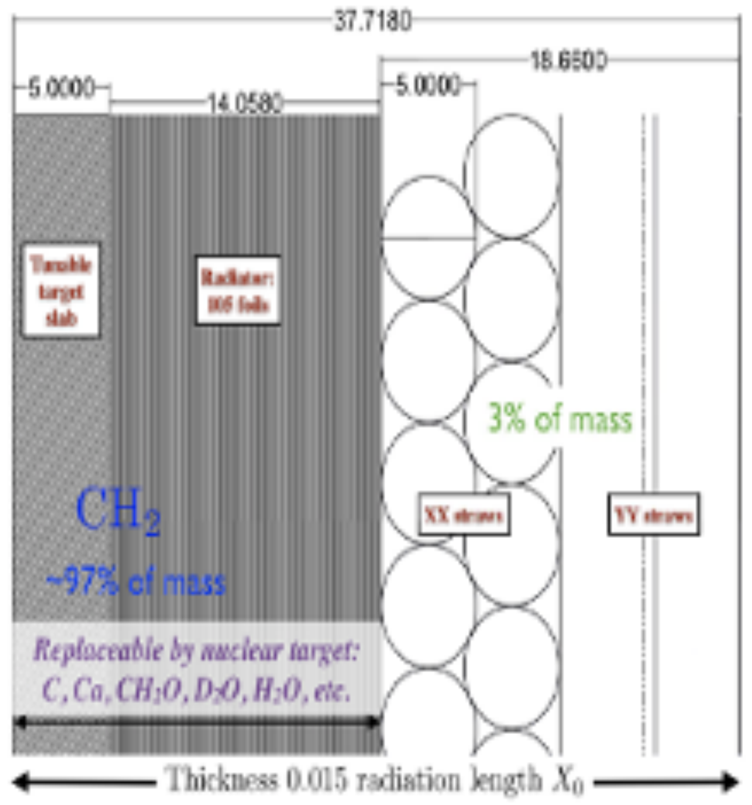




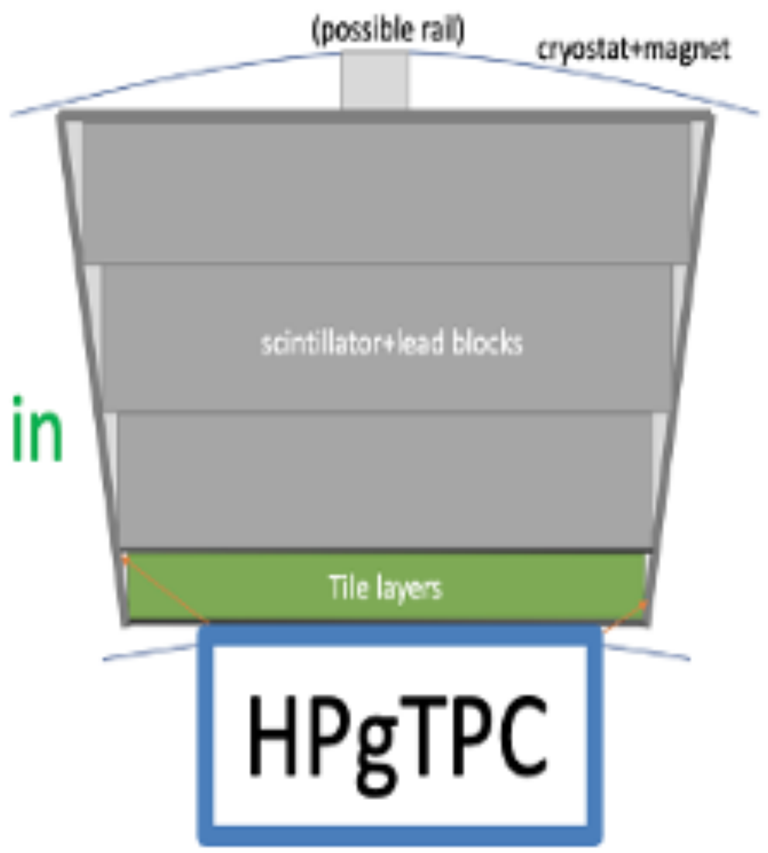
ND Options for Non-Argon Far Detectors

- Several options under consideration

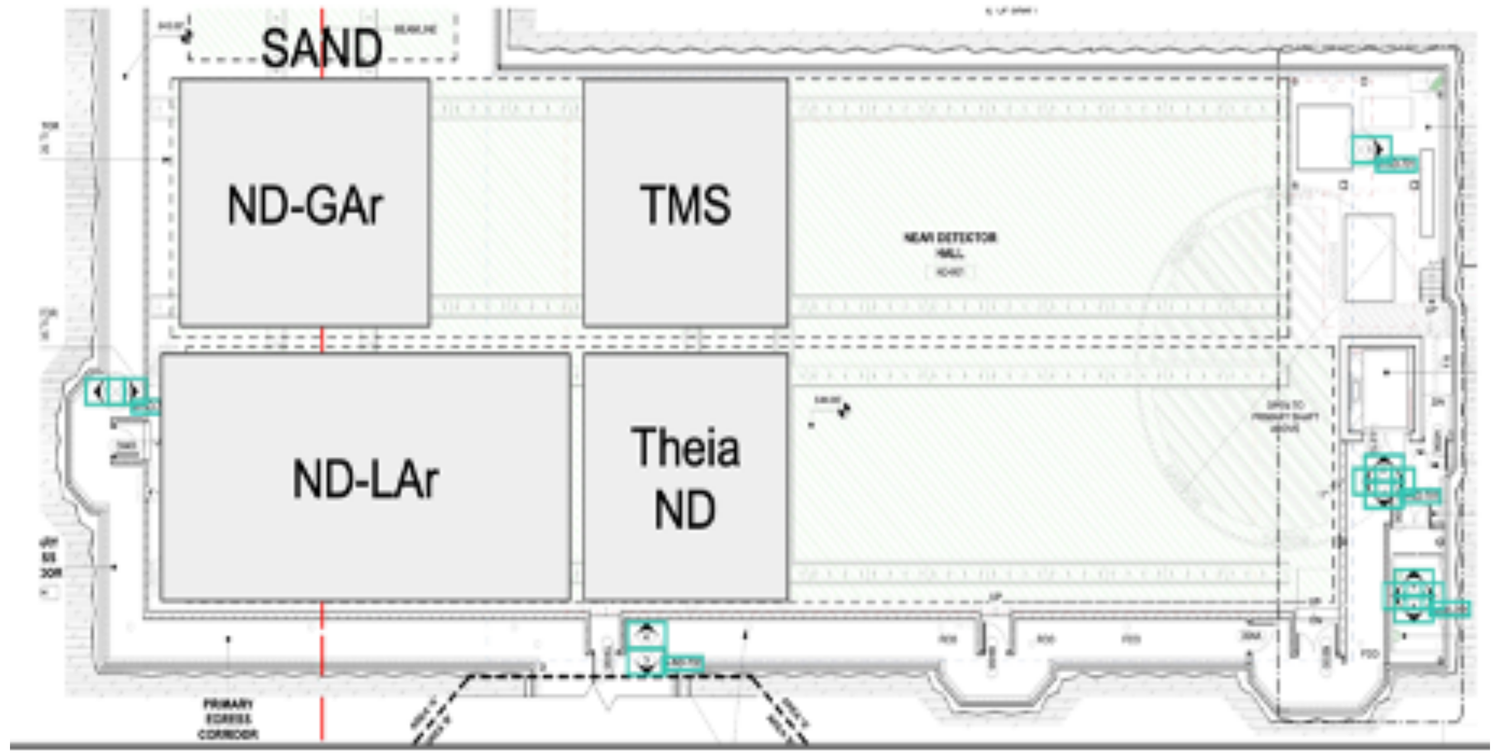
Additional nuclear targets in SAND



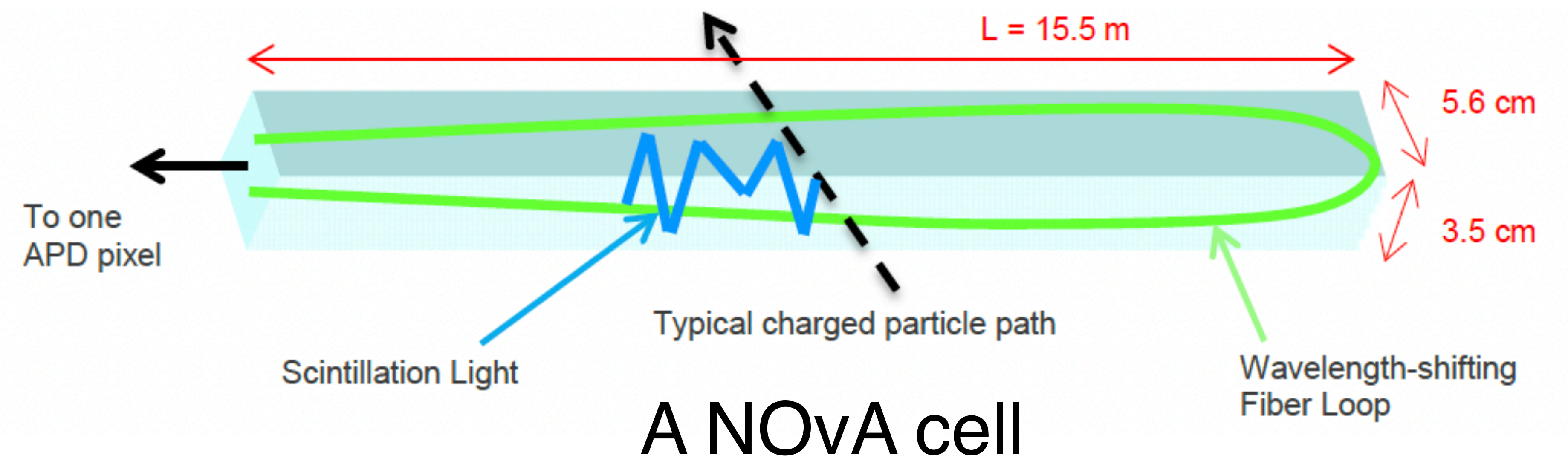
WbLS targets in ND-GAr ECAL



Dedicated Theia ND

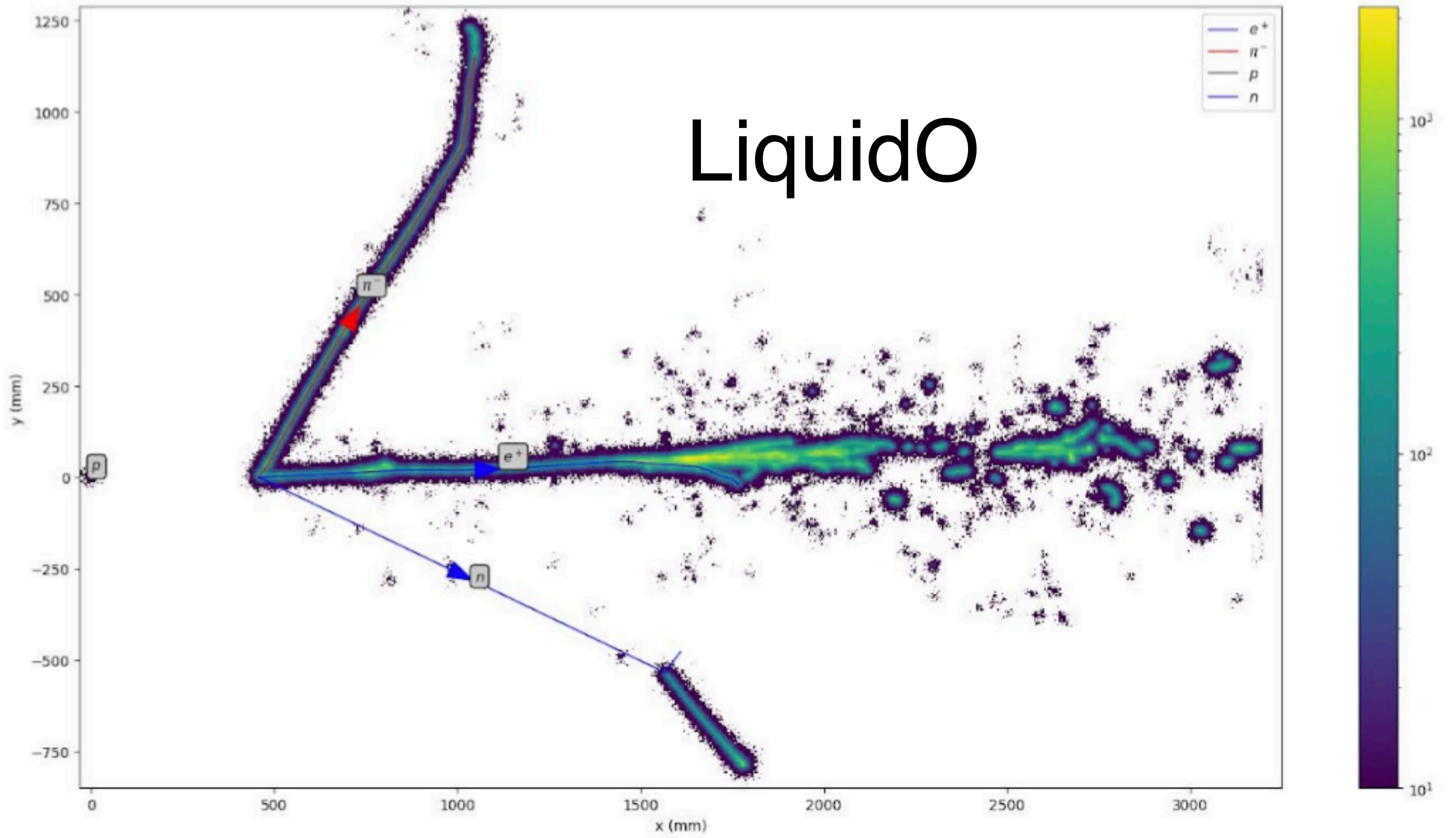


Complexity



A NOvA cell

- Options for a dedicated WbND
  - **NOvA-style ND** (replace NOvA scintillator with WbLS)
  - **LiquidO ND** (use opaque scintillators with mm-scale scattering length to produce high resolution images of ν interactions



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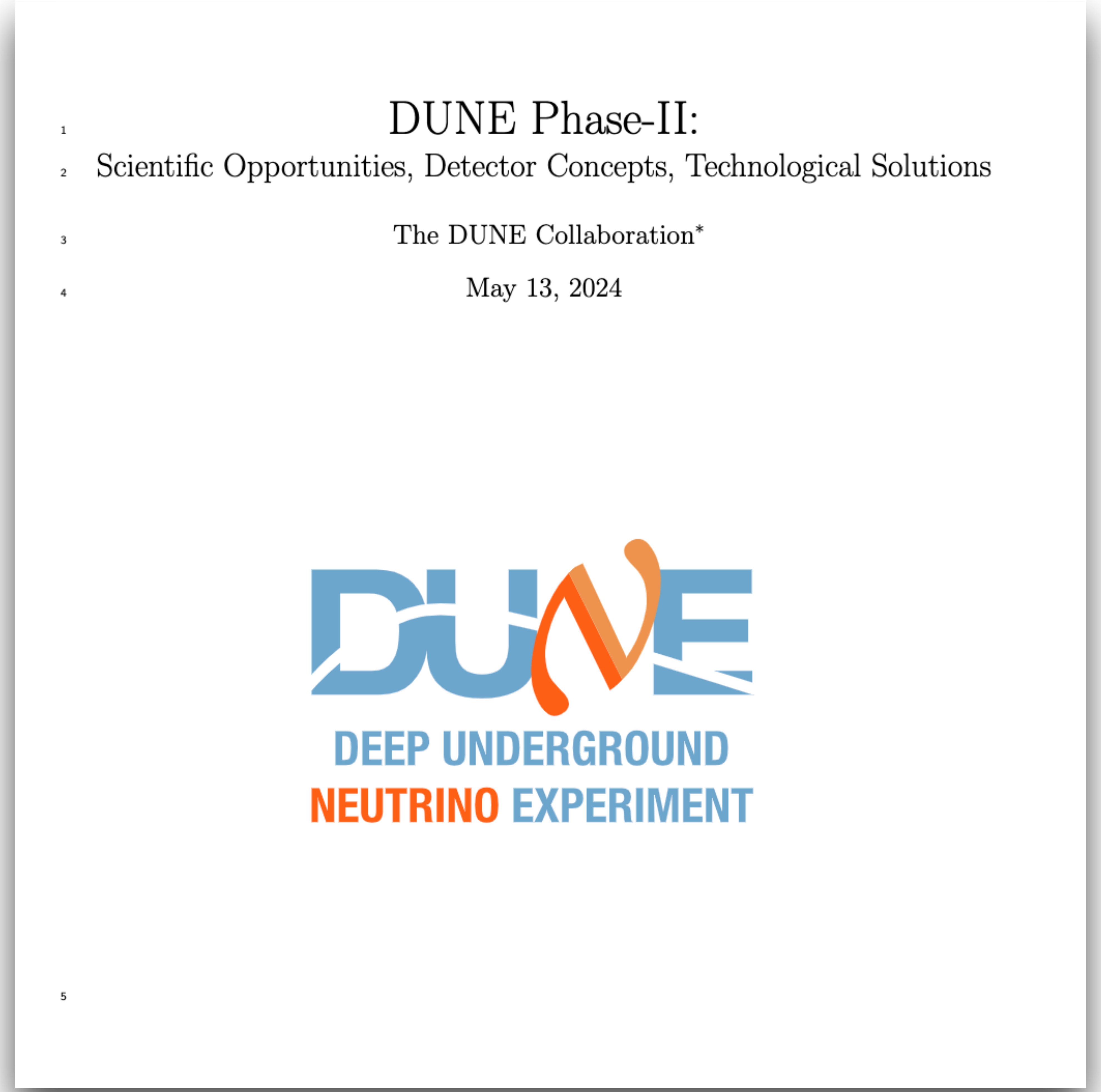
A Phase-II White Paper

- A White Paper (~70 pages) that discusses scientific opportunities and detector concepts along with a R&D roadmap for Phase-II near and far detector is underway
- Will be made public soon (arXiv and journal publication)
- Currently going through internal collaboration review
- Will serve as a reference for various stakeholders (e.g. funding agencies, new collaborators etc.)
- *All Phase-II efforts are also open to institutions that are currently not part of DUNE Phase-I*


DUNE Phase-II:
Scientific Opportunities, Detector Concepts, Technological Solutions

The DUNE Collaboration*

May 13, 2024

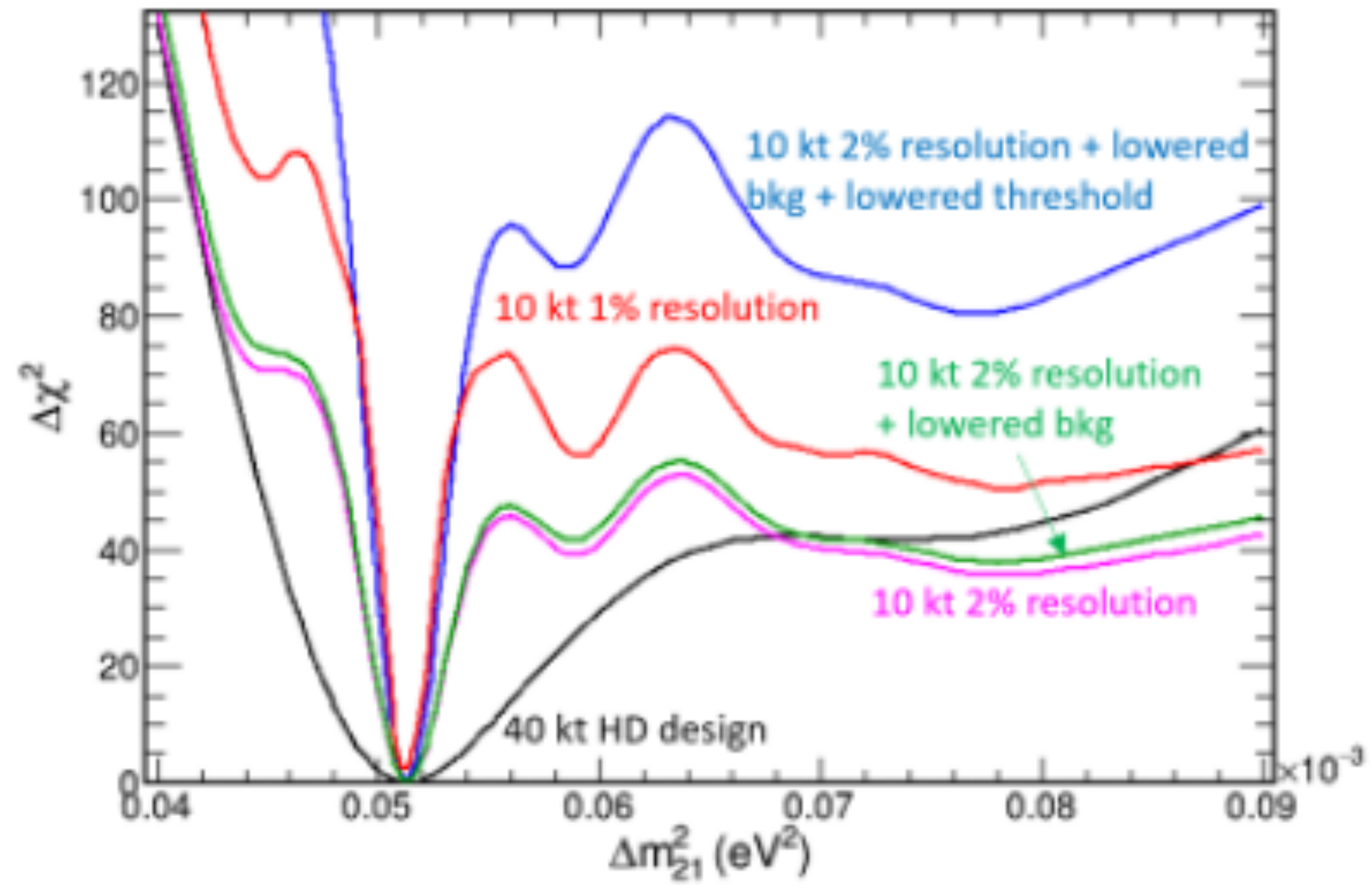
Summary

- **Science**: Phase-II is essential to realize DUNE’s full physics potential, as strongly endorsed also by 2023 P5 and European Strategy for Particle Physics
- **Design and R&D**: Significant progress in the past months towards defining a baseline scenario for Phase-II FD & ND
  - *Detector requirements and concepts are being developed*
  - *Key R&D goals have been identified, prototyping actively underway*
  - *Details in DUNE Phase-II White Paper, to be made public soon*
- **Infrastructures**: LBNF facilities at both the near and far sites support Phase-II beam and detectors from the beginning (part of Phase-I scope), simplifying Phase-II implementation
- **Resources**: Phase-II project highly international, with funding expected to be shared between US and non-US partners similarly to Phase-I
- **Timeline**: In a technically-limited schedule, FD3 cryostat installation could start in 2029, with FD3 filling in 2034. MCND and FD4 would follow after that.

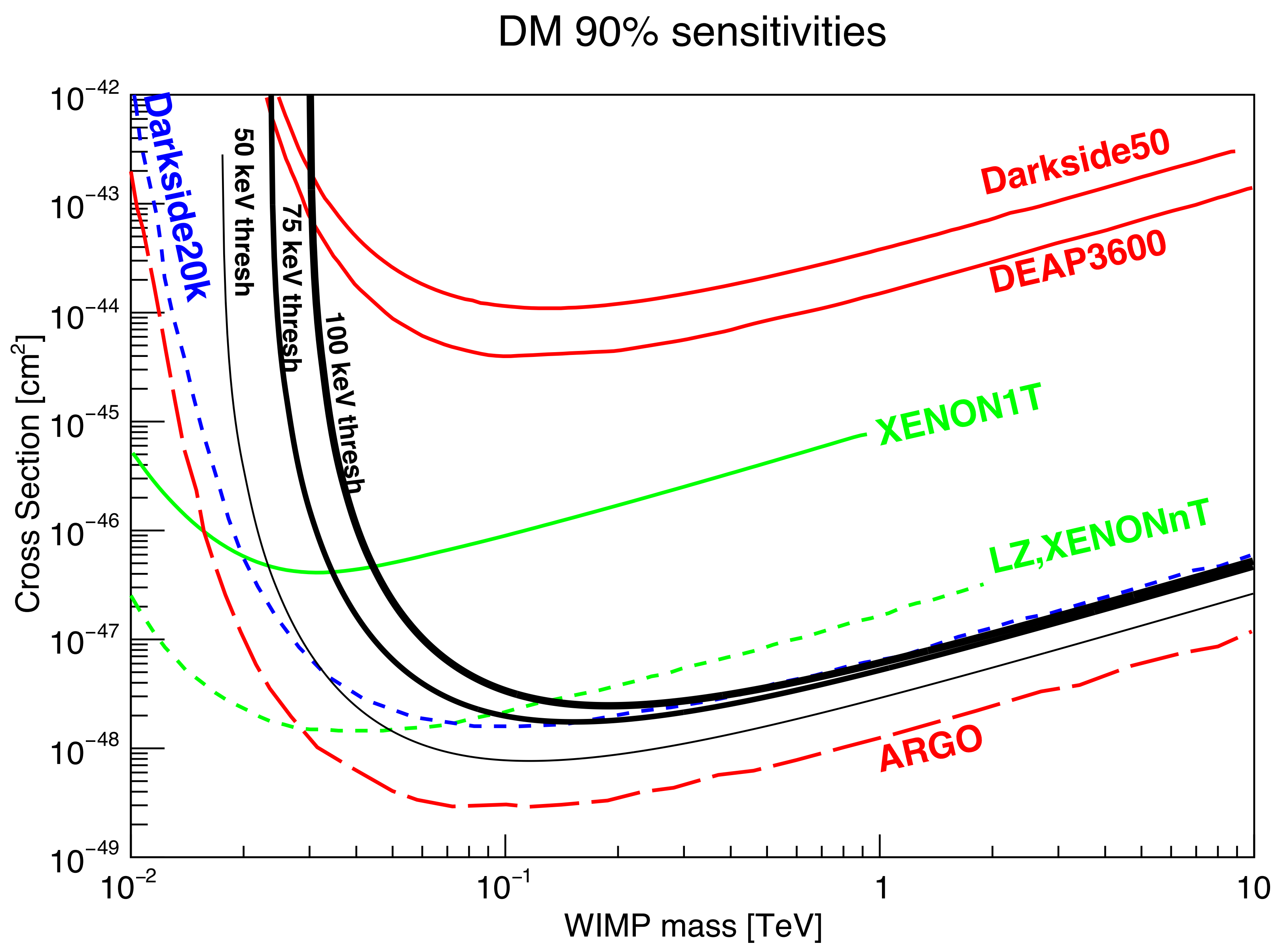
EXTRAS

Physics Enabled by Low Backgrounds

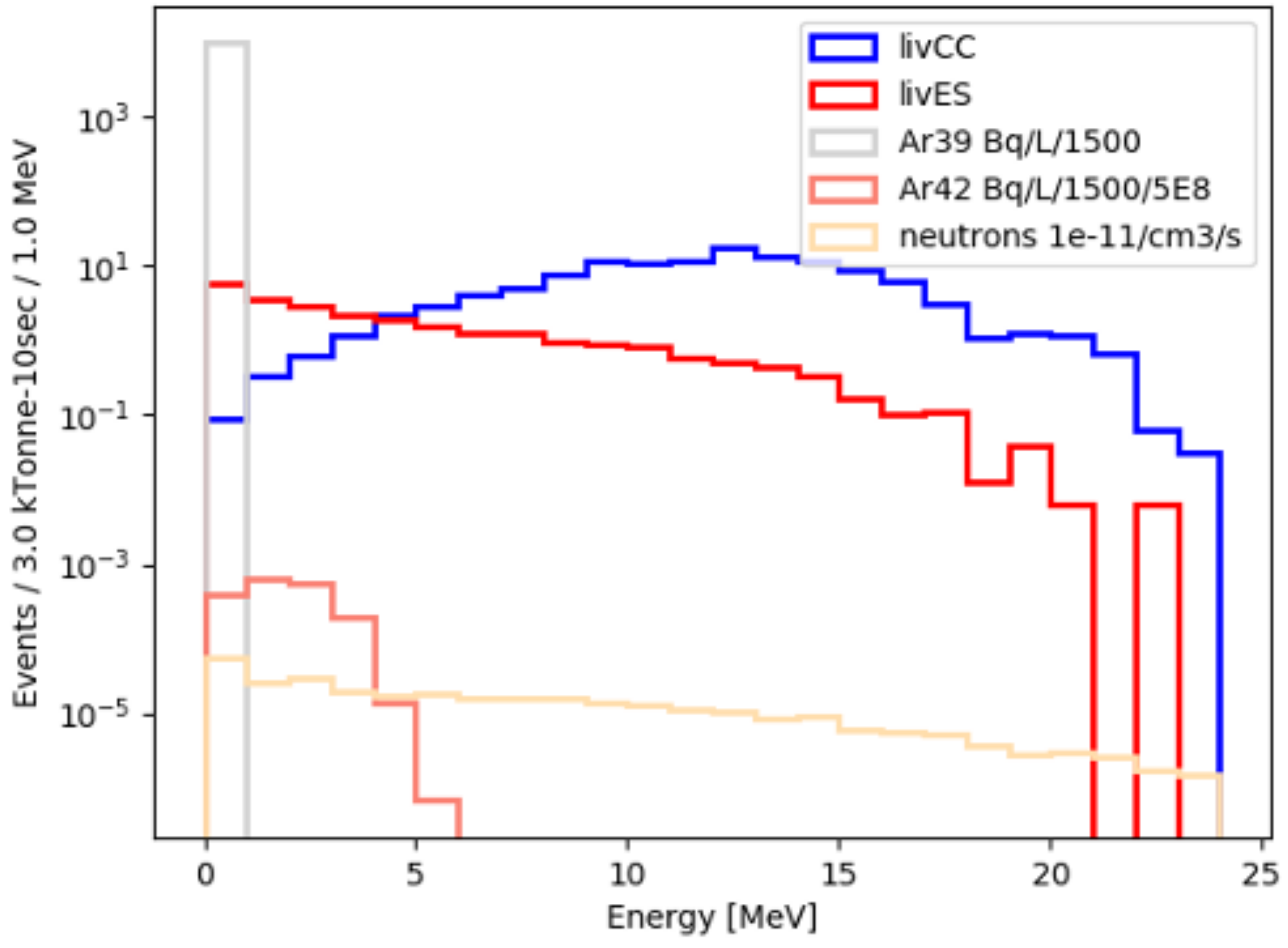
- Example physics enabled by low backgrounds and radio purity control



Solar neutrino parameters tighten up considerably



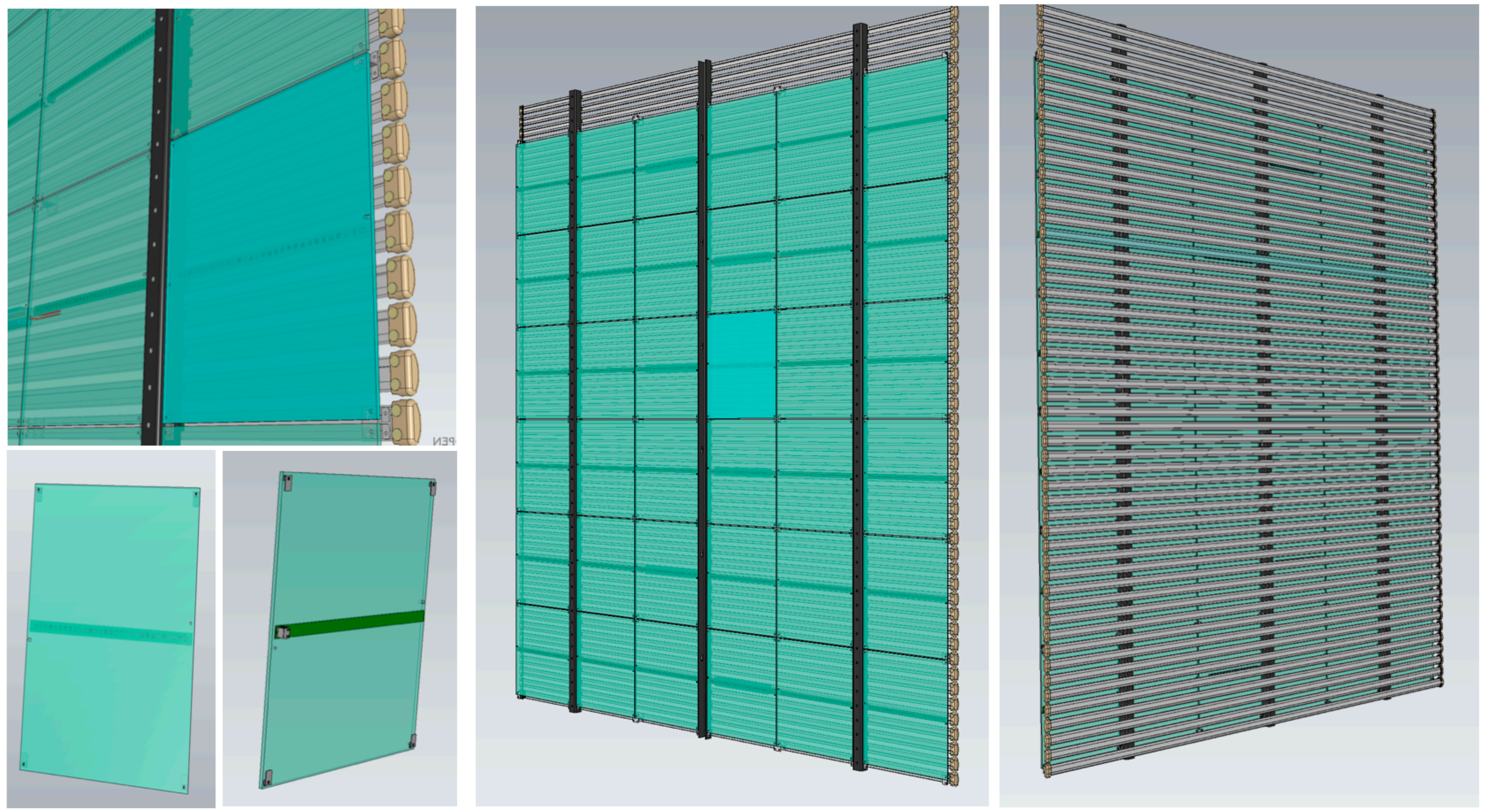
Supernova distance sensitivity and pointing accuracy (due to access to elastics) increases

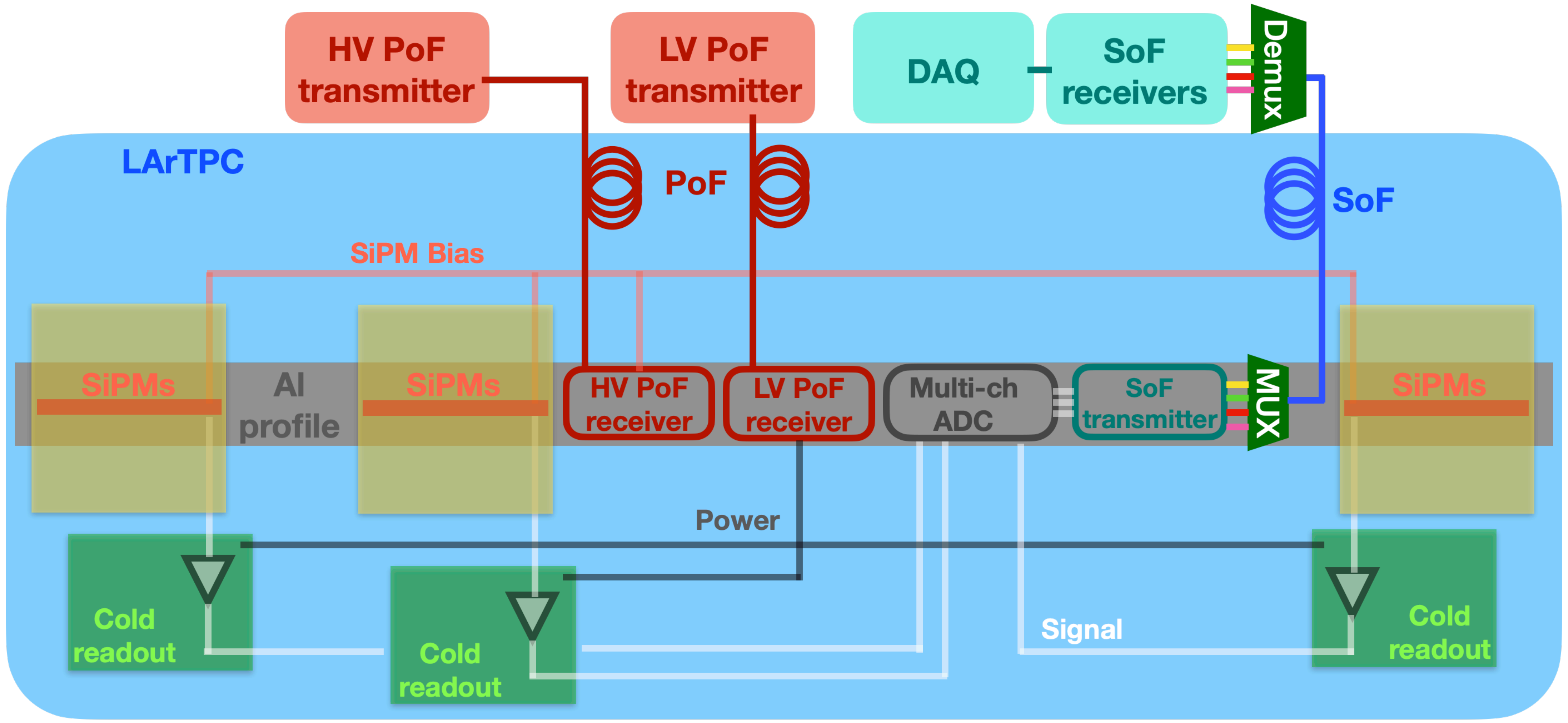


A WIMP search becomes possible with FD module's enormous volume, the interior of which can be fiduciaries and densely instrumented

APEX (Aluminum Profiles with Embedded X-Arapucas)

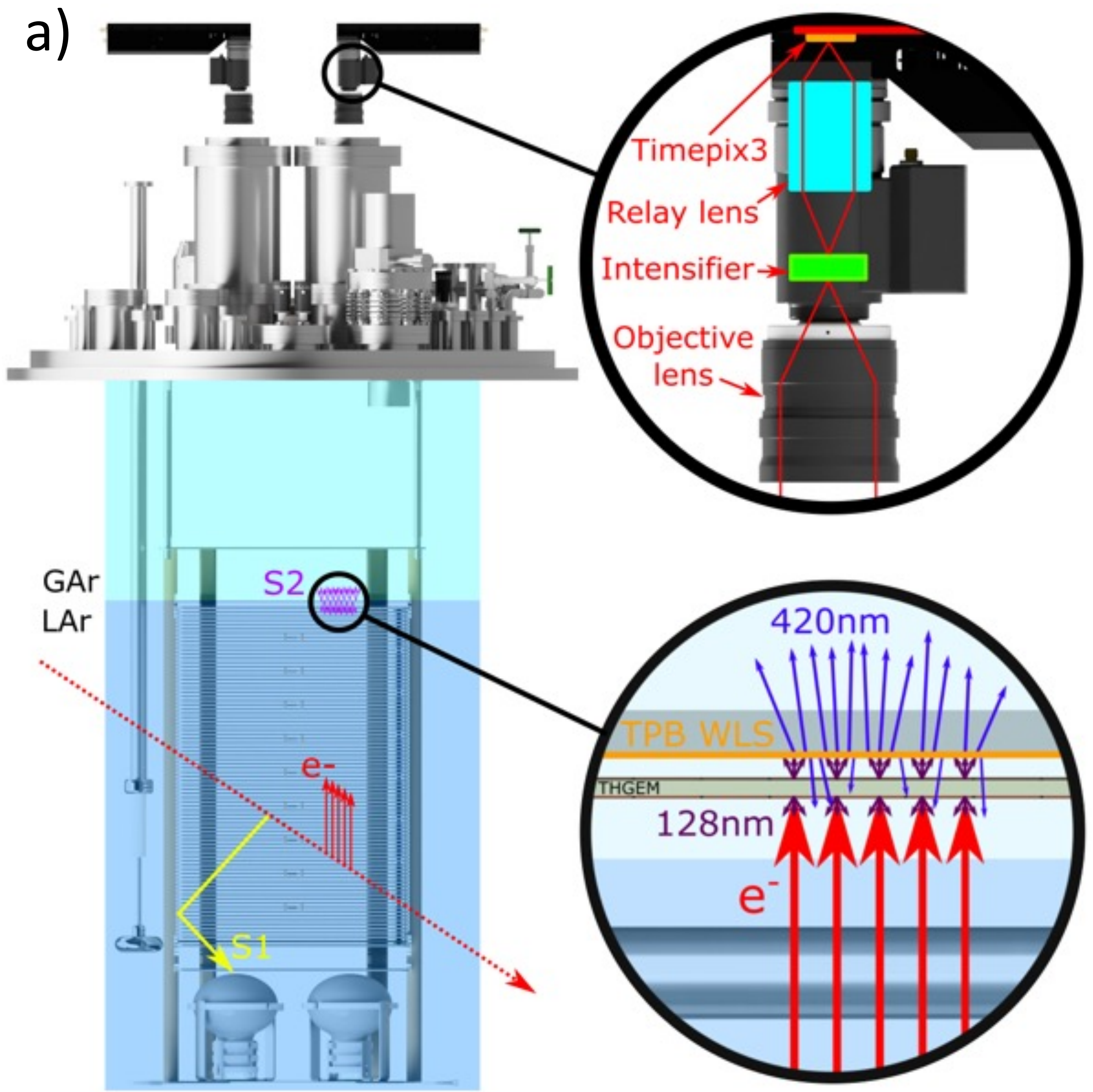
- A fully integrated VD TPC field cage + Photon Detector System
- Keep the same FC structure as designed for the DUNE FD2 VD Module
- Simplify the ARAPUCA concept, and significantly increase photon system coverage
- Expand Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) technologies developed for FD2, adopt digital optical readout

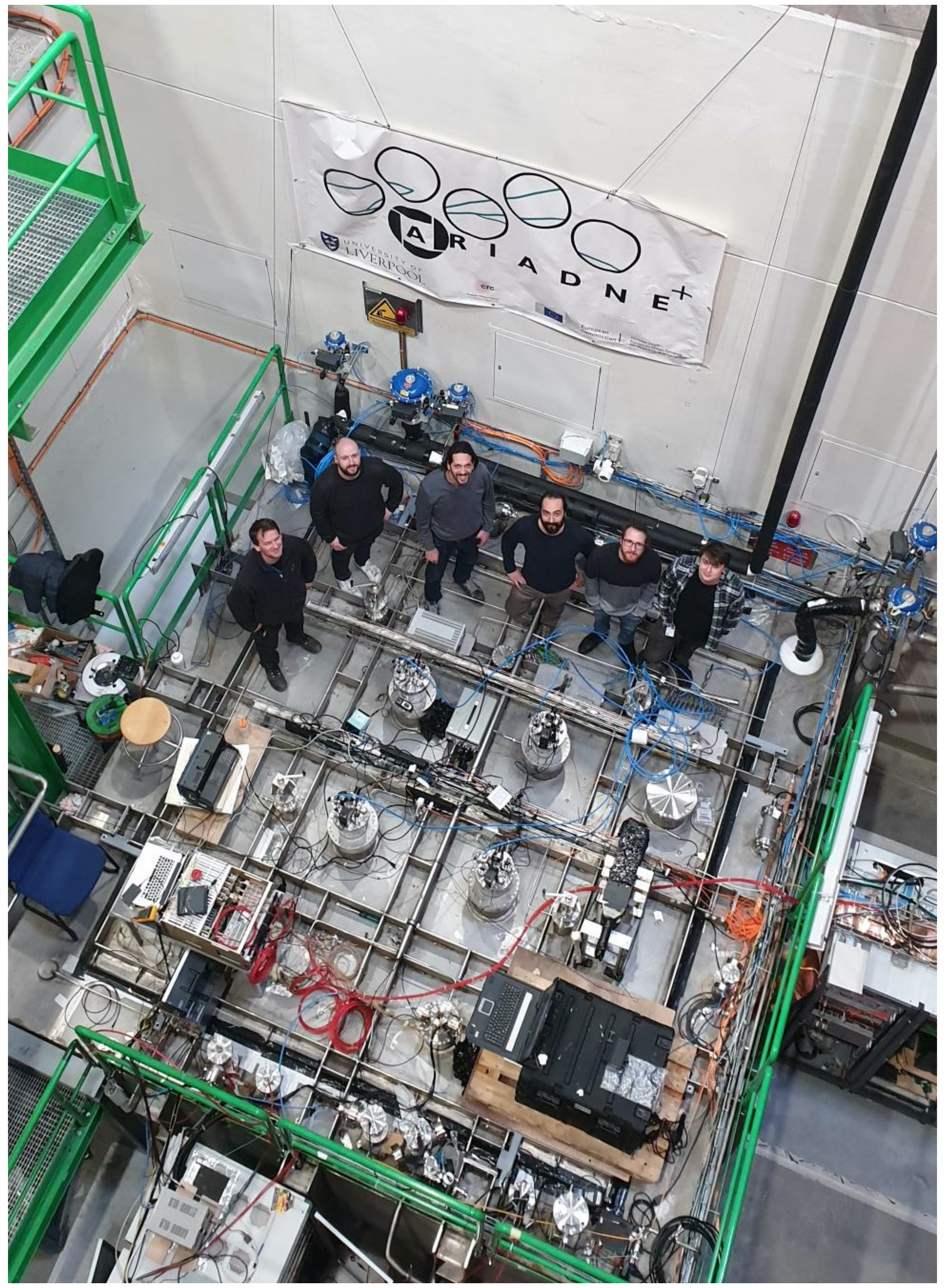




ARIADNE

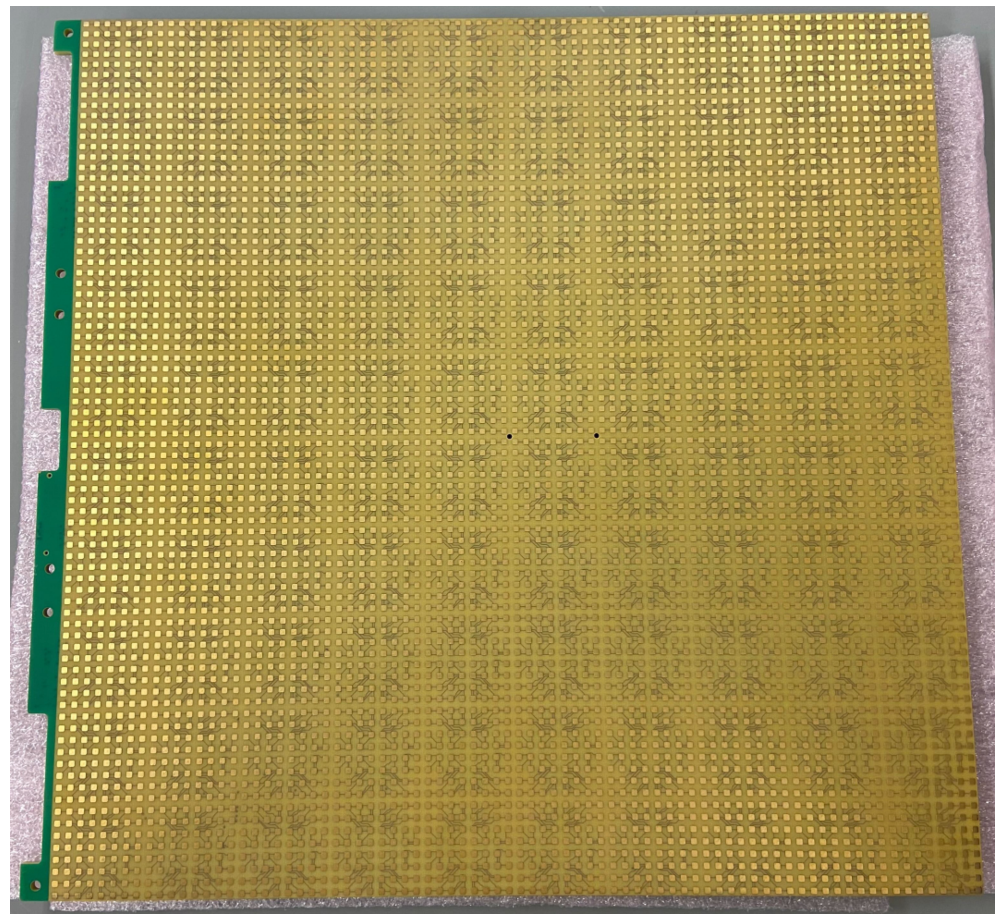
- Optical-based charge readout: S2 light produced in THGEM holes can be captured by fast cameras (eg, TimePIX3) to reconstruct in 3D the primary ionization track
- Successfully prototyped with 1-ton ARIADNE and ARIADNE+

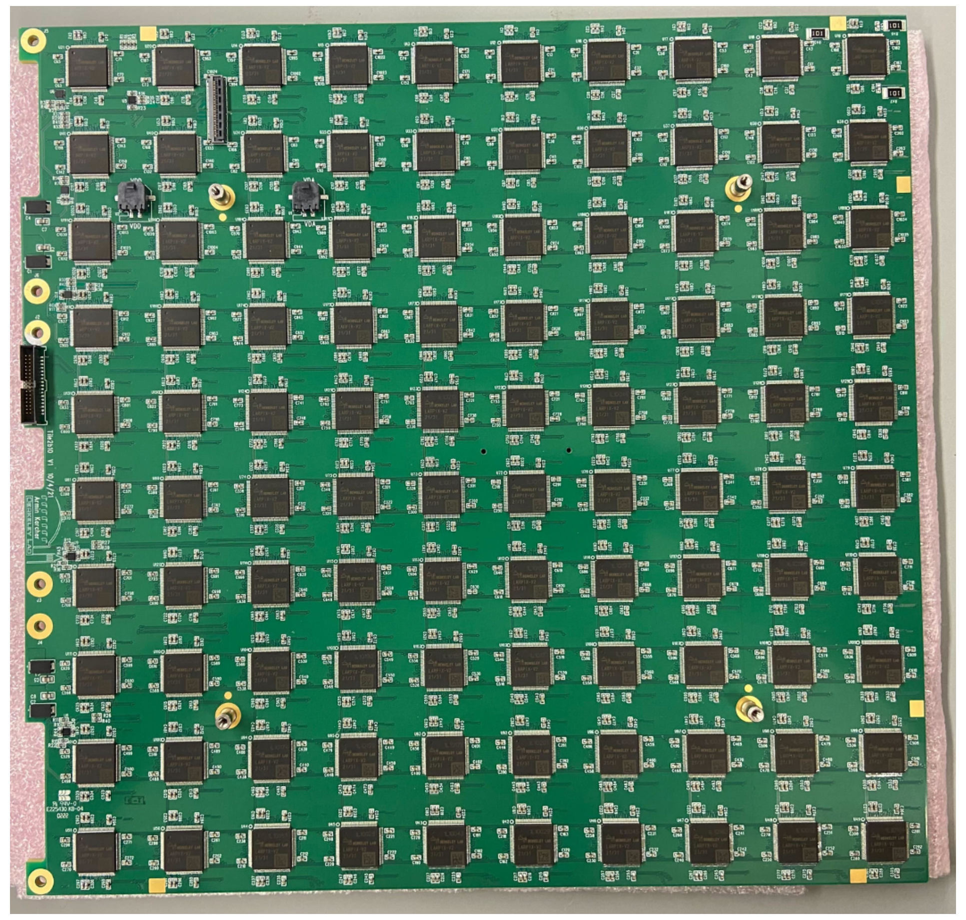




LArPix

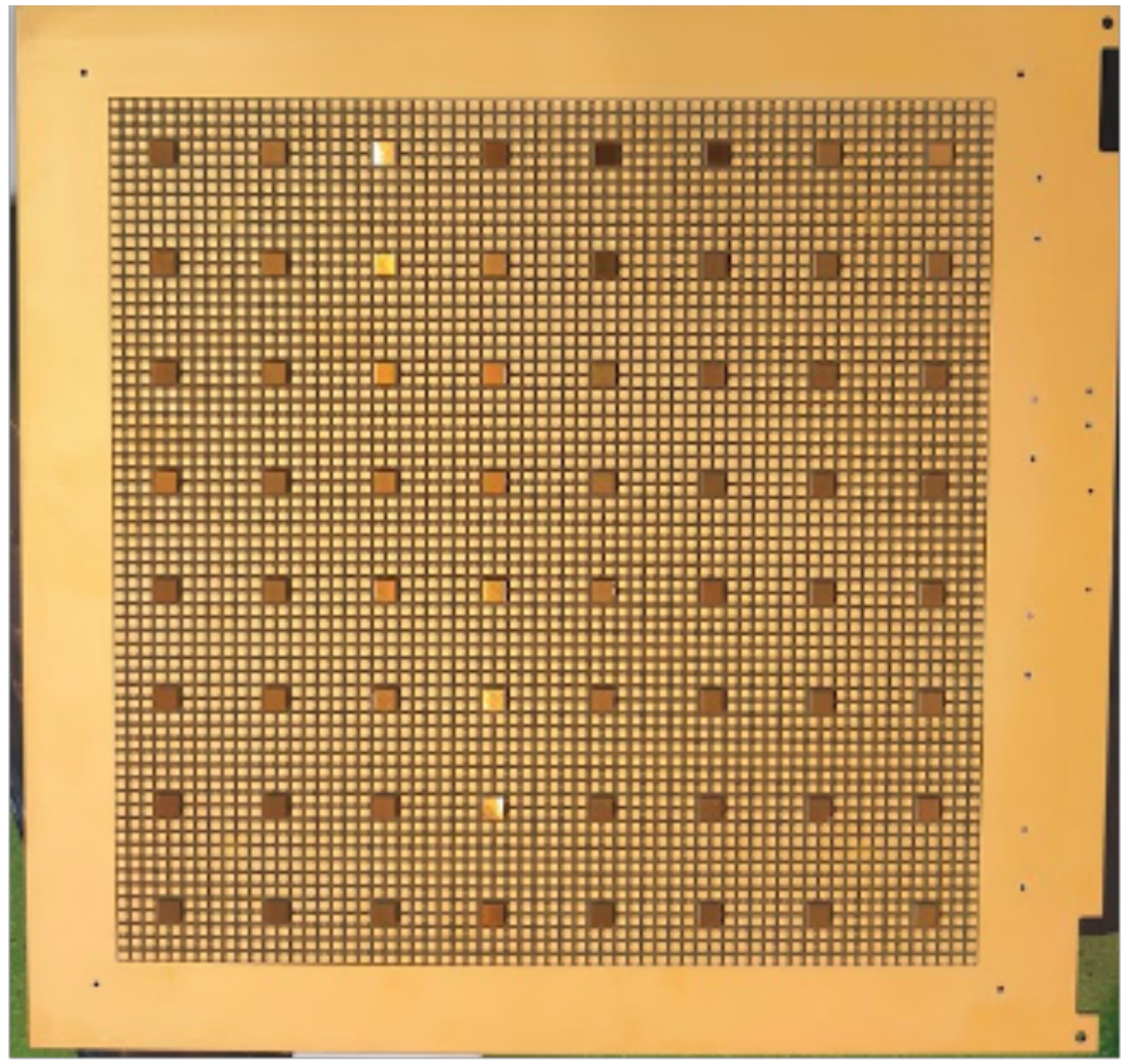
- Complete pixel readout system for LArTPCs, developed for ND-LAr
- Relies on LArPix ASIC, a 64-ch detector system-on-a-chip including analog amplification, self-triggering, digitization, multiplexing, and a configuration controller
- Current LArPix-v2 pixel tile has 32x32 cm^2 size, 6400 pixels at 3.8 mm pitch, and 100 ASICs
- LightPix: LArPix ASIC variant designed for scalable readout of very large arrays of SiPMs

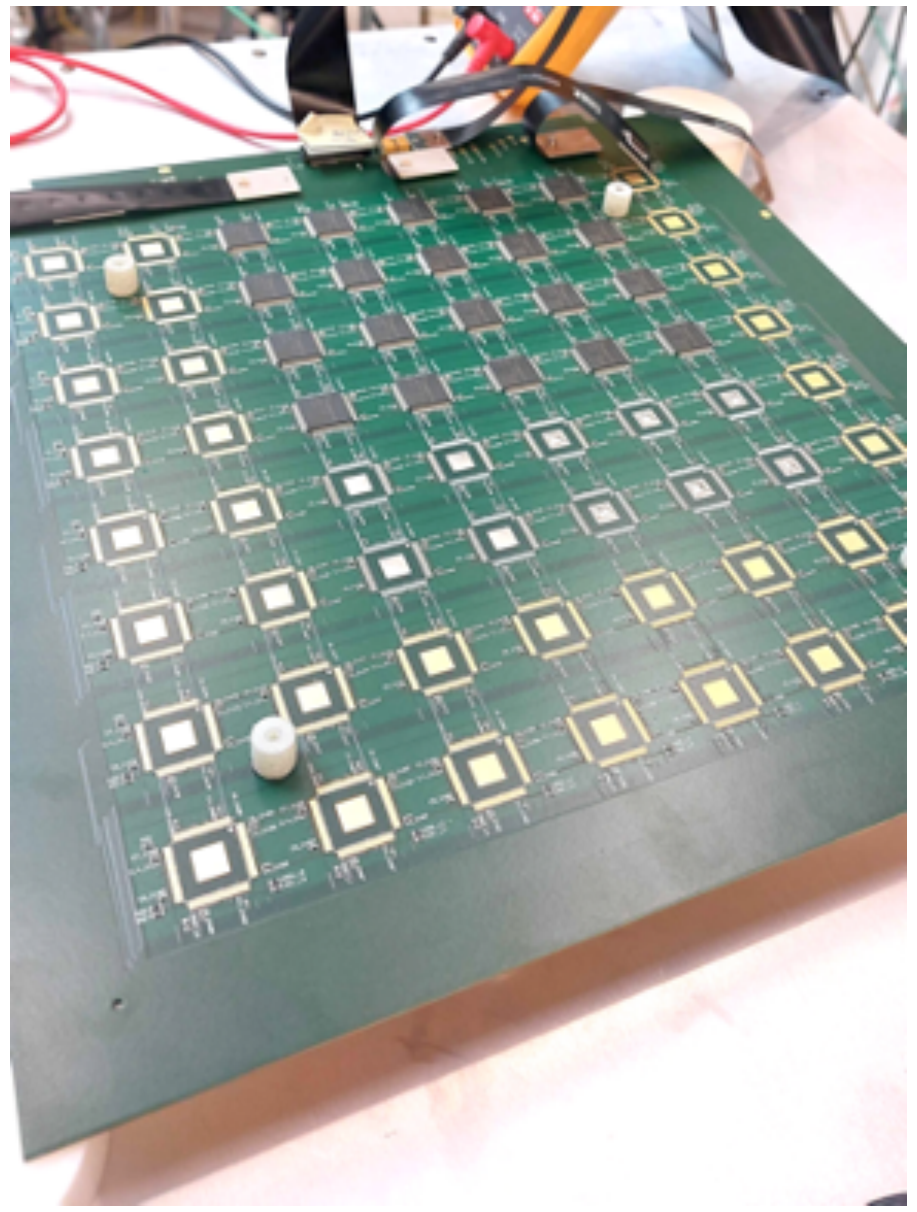




SoLAr

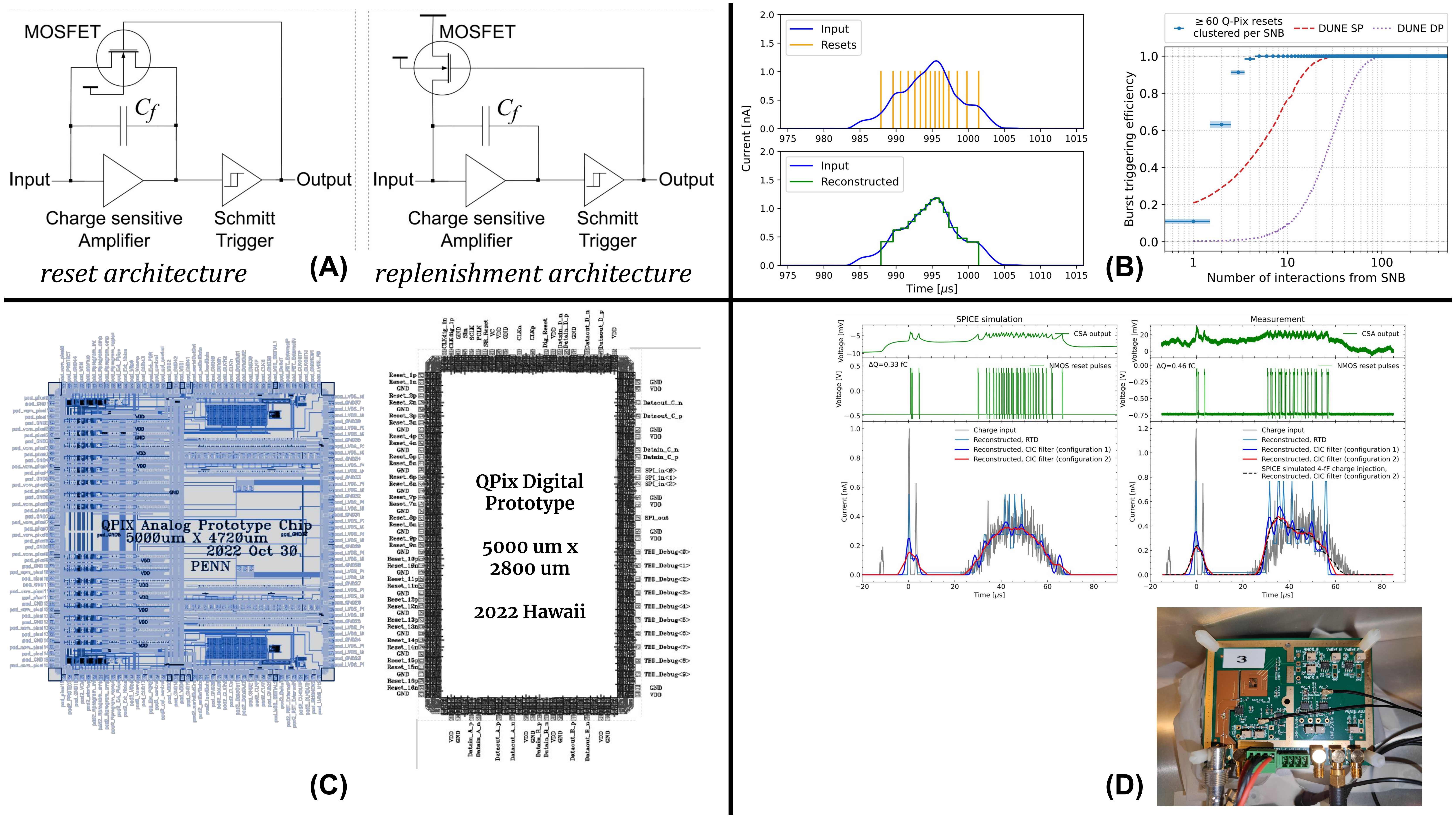
- Integrated array of VUV SiPMs on pixelated anode
- Online localized triggering for dealing with high data rates
- Existing prototypes:
  - *SoLAr v1: 7x7 cm^2 anode plane, 16 VUV SiPMs, 3.5 mm pitch, 4 LArPix v2a chips*
  - *SoLAr v2: 30x30 cm^2 anode plane, 64 VUV SiPMs, 4 mm pitch, 20 LArPix v2b chips*





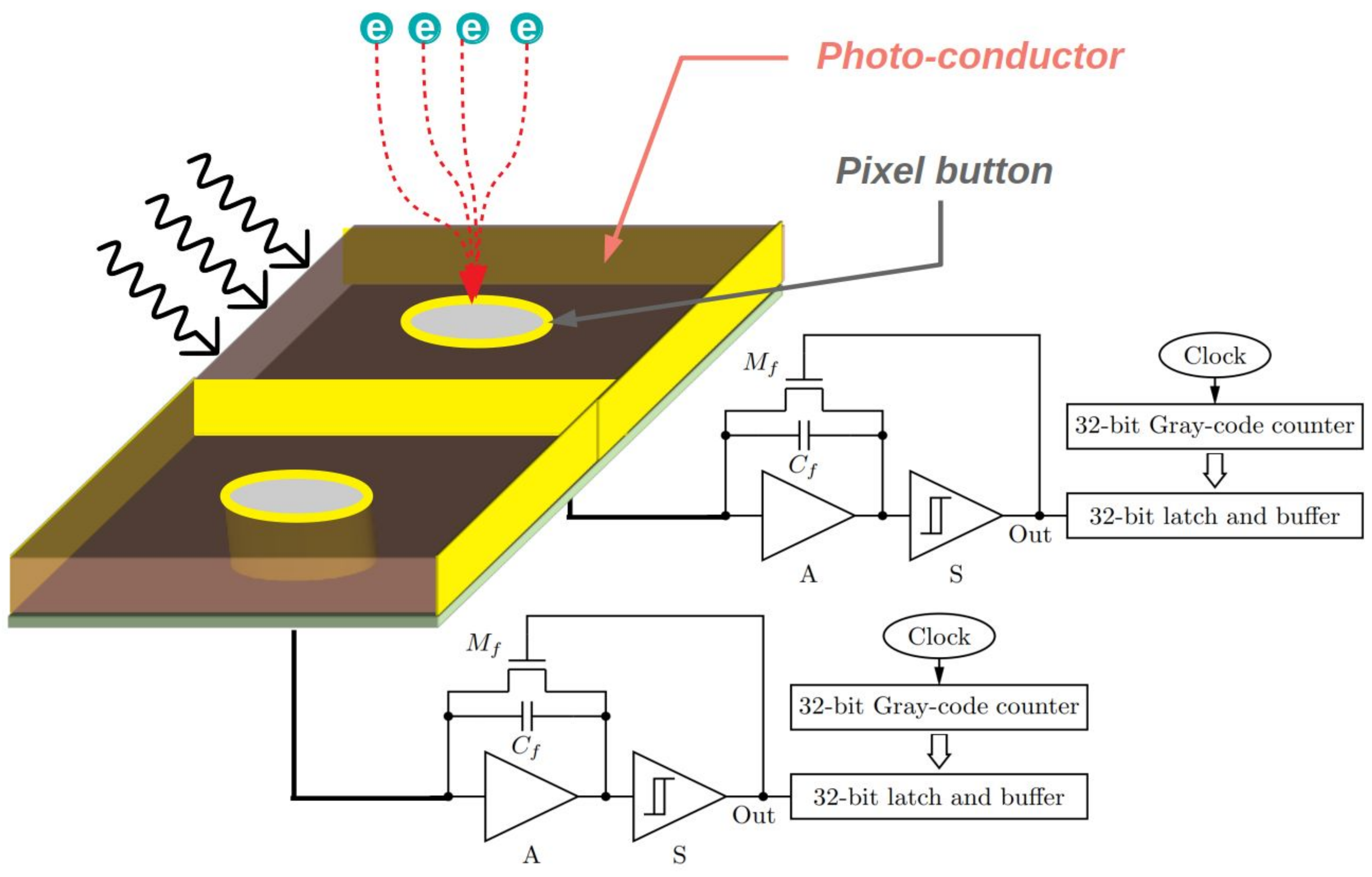
Q-Pix

- Self-triggering, low-threshold, high-granularity pixelated readout
- Changes basic quantum of information from traditional “charge per unit of time” data format to time difference between clock captures for a fixed ΔQ → low data throughput
- A number of prototypes are currently under construction and evaluation

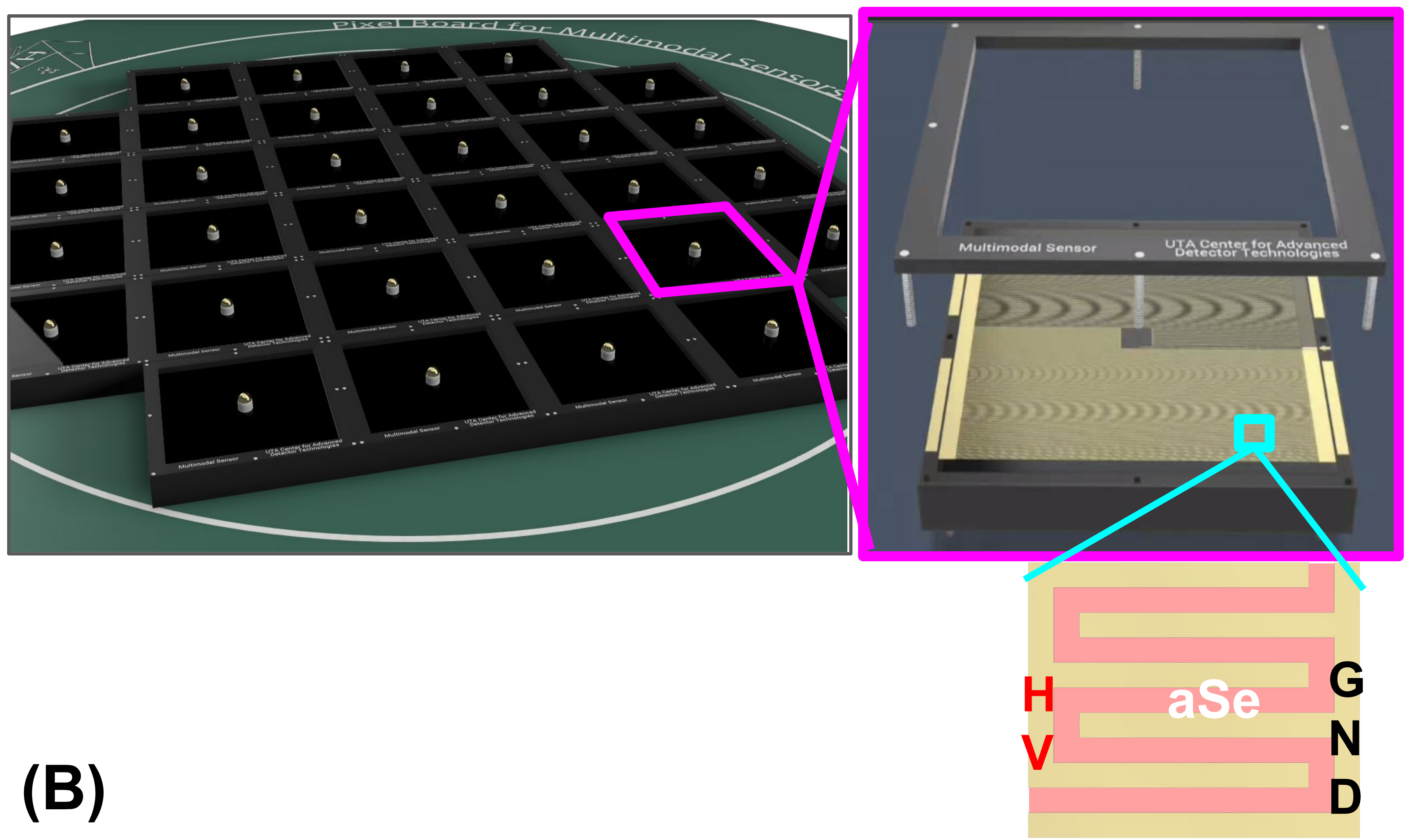


Q-Pix Light

- Integrated charge and light readout on anode: coating of Q-Pix charge readout with photoconductive material (eg, aSe) that, when struck by a VUV photon, would generate a signal detectable by the same readout scheme used for ionization charge
- Viability of an aSe-based device at cryogenic temperatures with response to VUV photons has been demonstrated



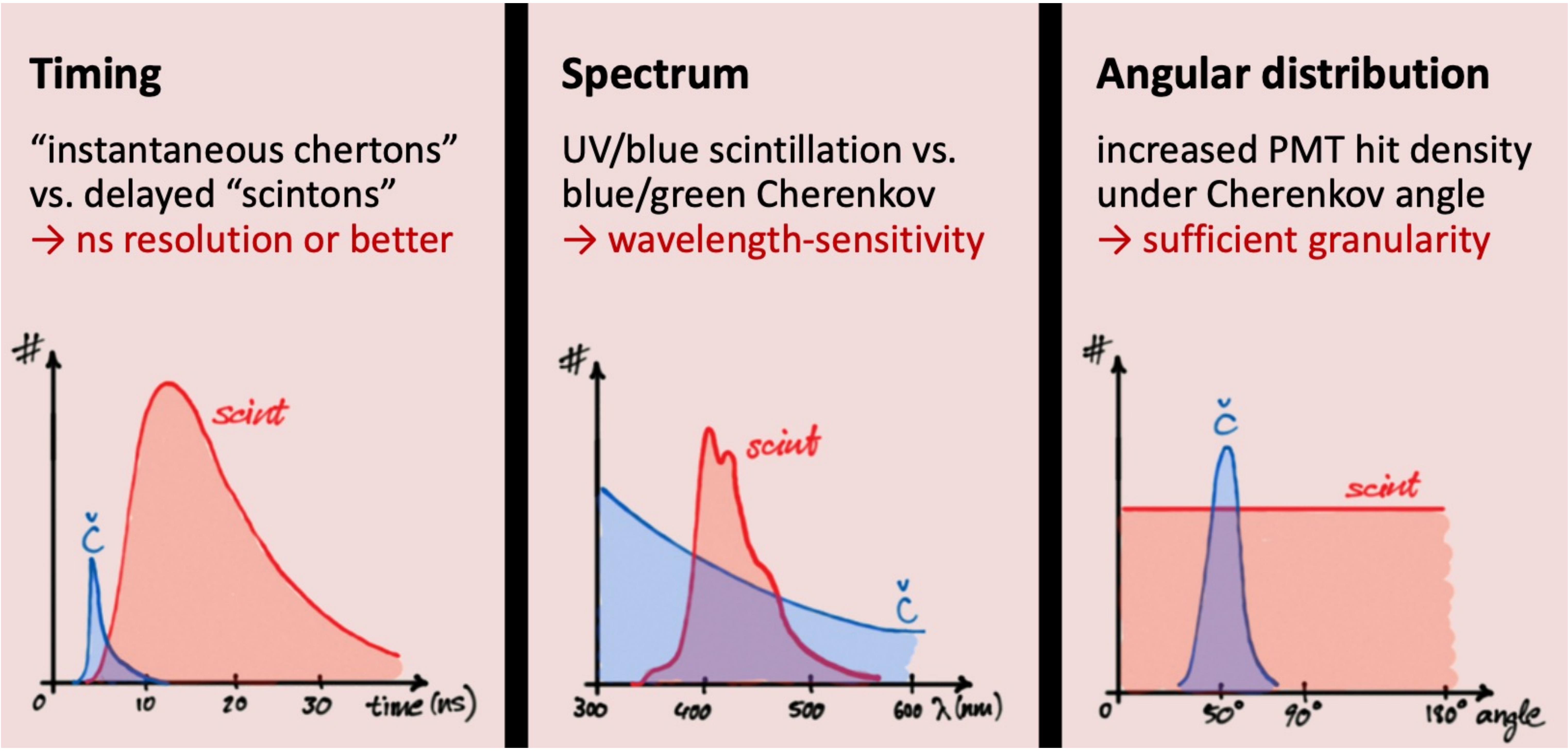
(A)

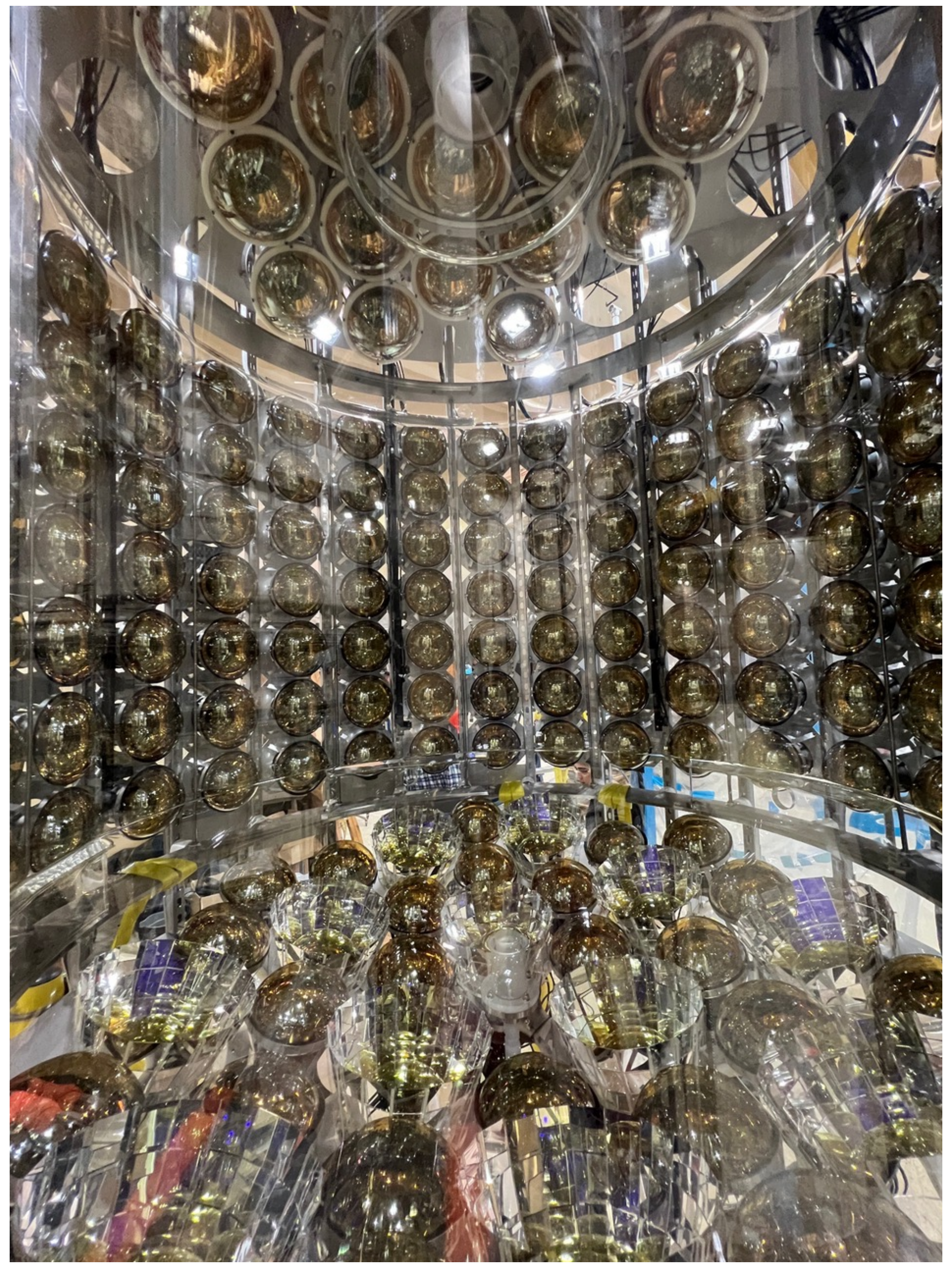


(B)

THEIA

- THEIA technologies: WbLS, fast photon detectors (PMTs or LAPPDs) and dichroic filters
- THEIA prototypes: 1-/30-ton at BNL, EOS at LBNL, ANNIE at Fermilab, BUTTON at Boulby
- Hybrid optical technology: practical Cherenkov/Scintillation light separation



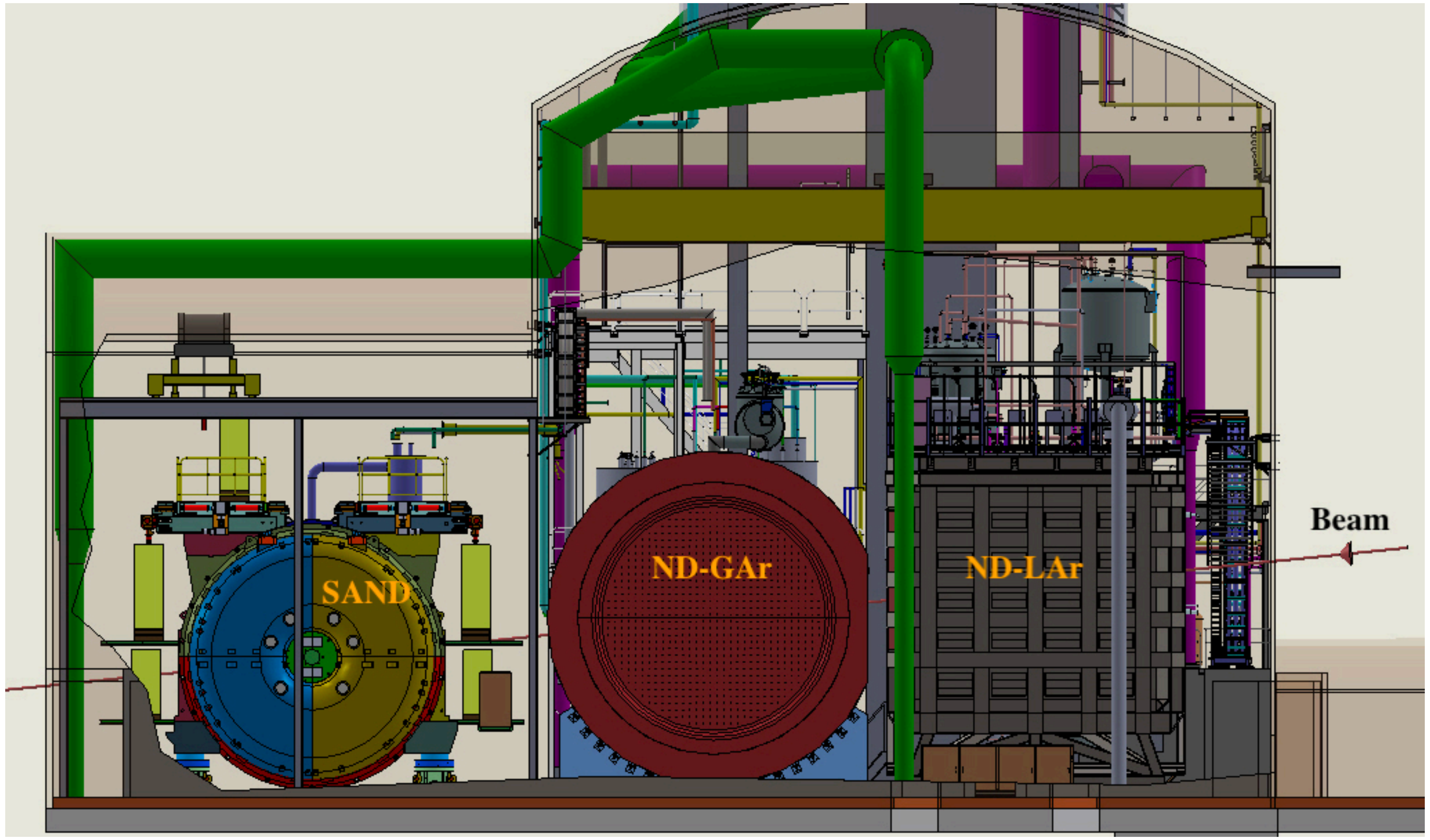


Potential Upgrades to ND-LAr and SAND

- ND-LAr upgrades that require emptying: improved neutron detection with ^{6}Li-glass scintillator, replacement of charge tiles with smaller pixels and lower threshold

- ND-LAr upgrades that do not require emptying: upgrade of the off-detector electronics, addition of an upstream rock muon tracker

- SAND upgrades: improving light collection with backside illuminated SiPMs



FD3 and FD4 Timeline

- Earliest installation start in 2029 with FD3 completed in 2034 and FD4 in 2036
- The final schedule for FD4 will be driven by the technology choice and extent of upgrades planned in the case of a LArTPC

Figure: *A notional, technically limited schedule for FD3/4 assuming it is a vertical drift LArTPC similar to FD2*