Overview of the DUNE Phase-II Program

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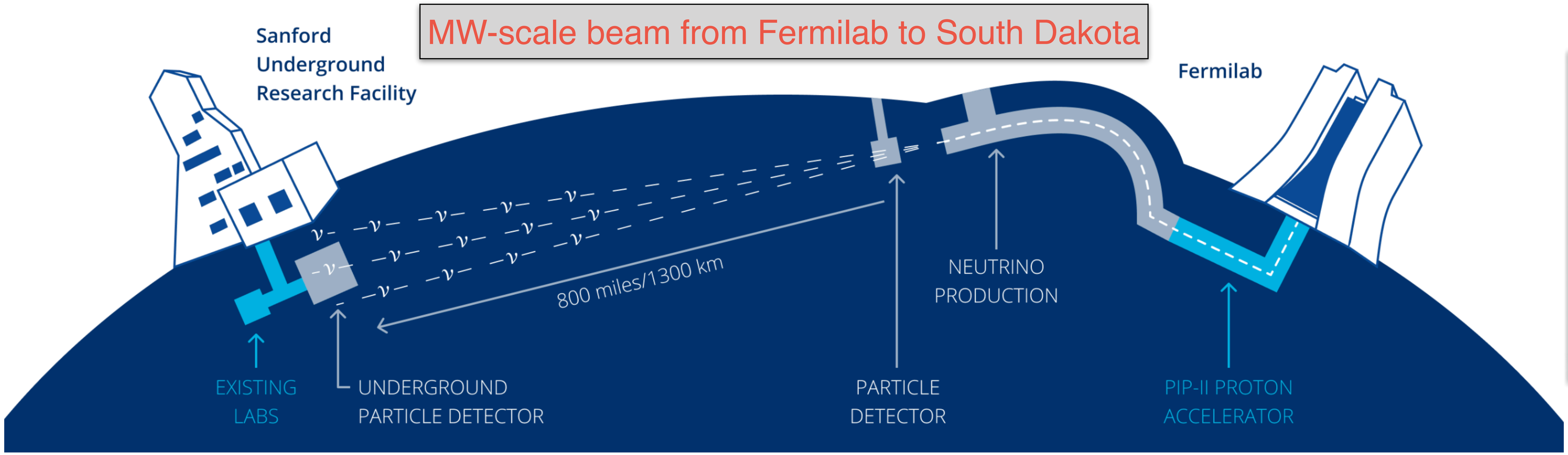
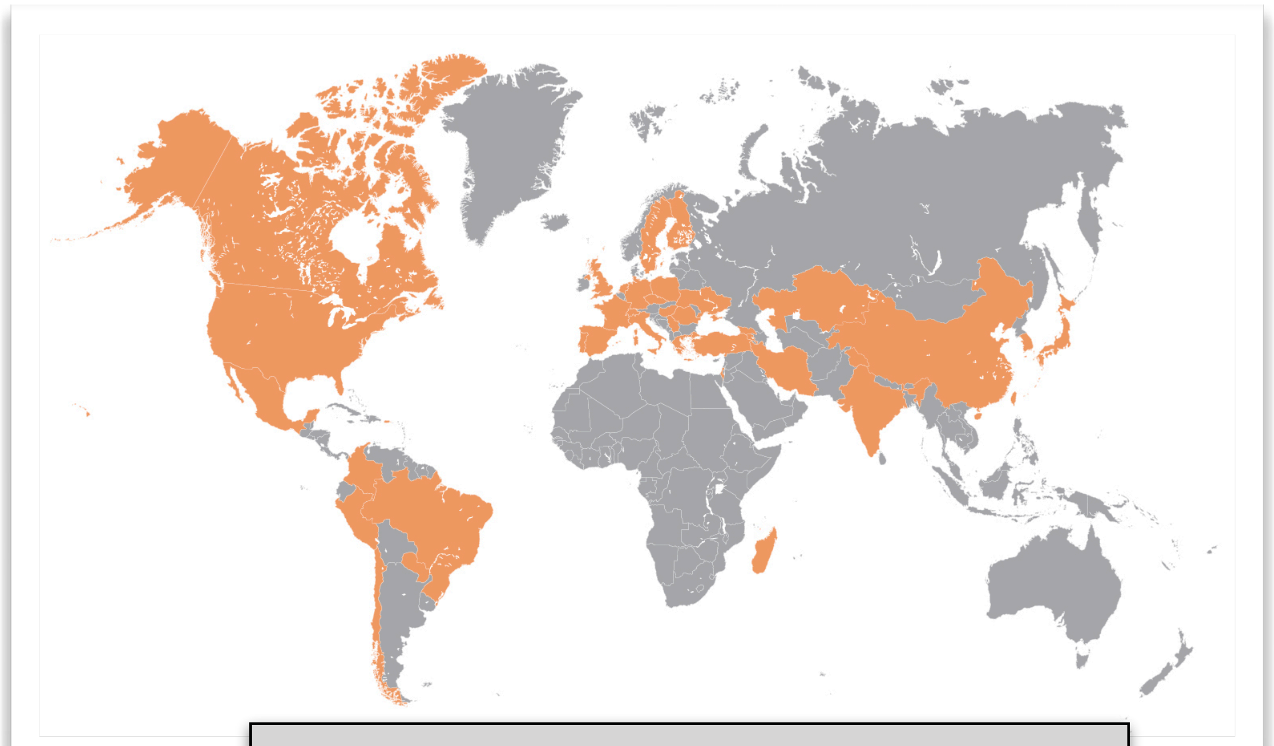
(On behalf of the DUNE Collaboration)

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

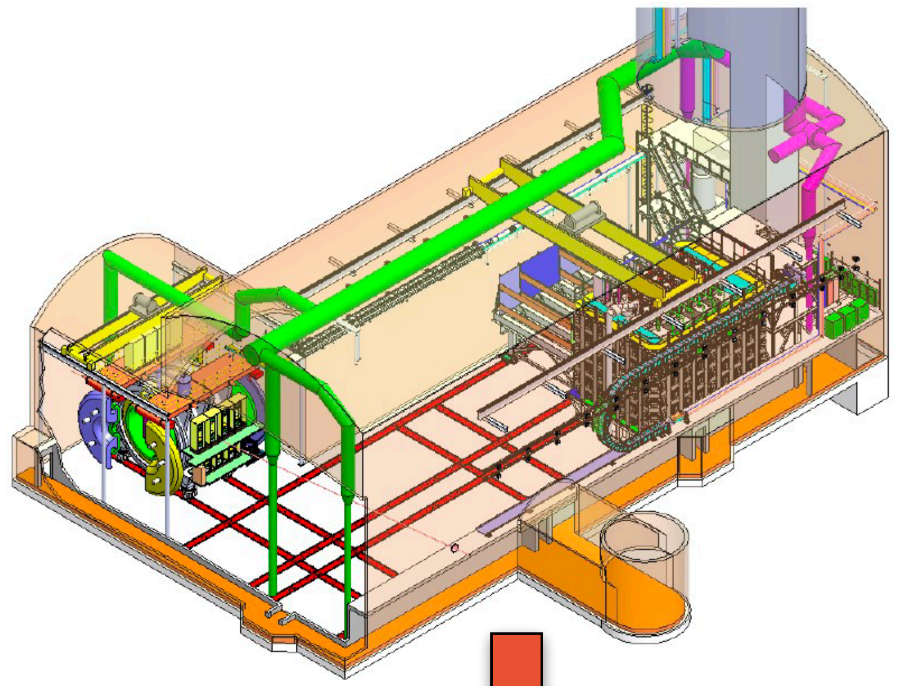
- A massive (70-kt total mass liquid argon equivalent) far detector a mile underground at Sanford Underground Research Facility (SURF)
- A capable near detector at Fermilab comprising of multiple technologies
- Far and Near site facilities and beam provided by the Long Baseline Neutrino Facility (LBNF)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

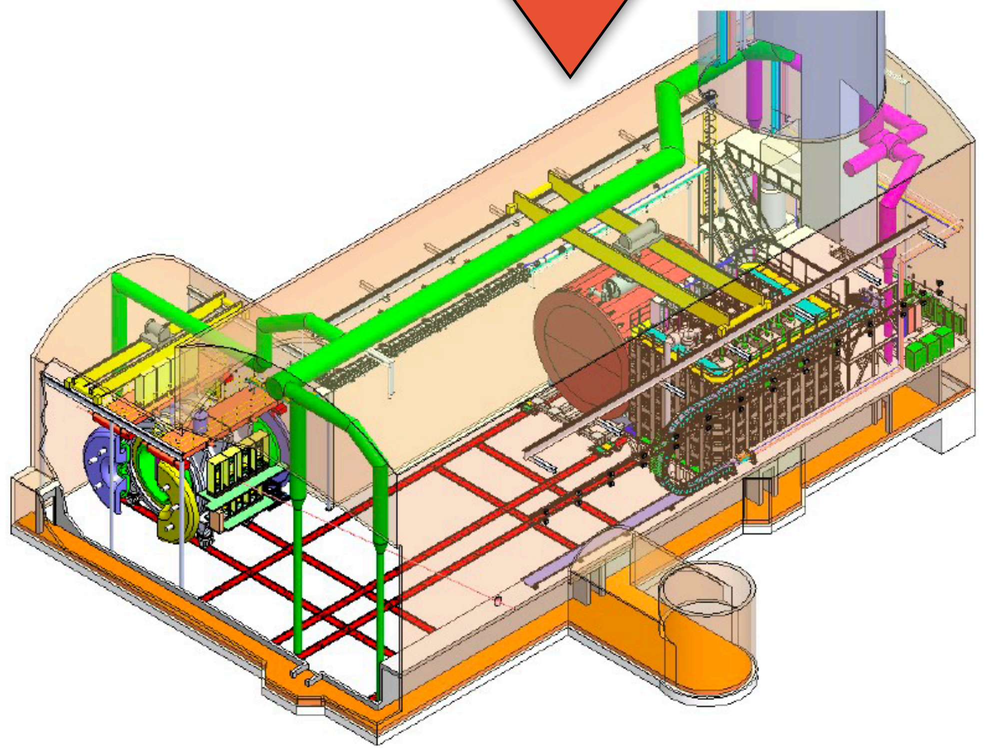
Underground Facility at SURF

- *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)





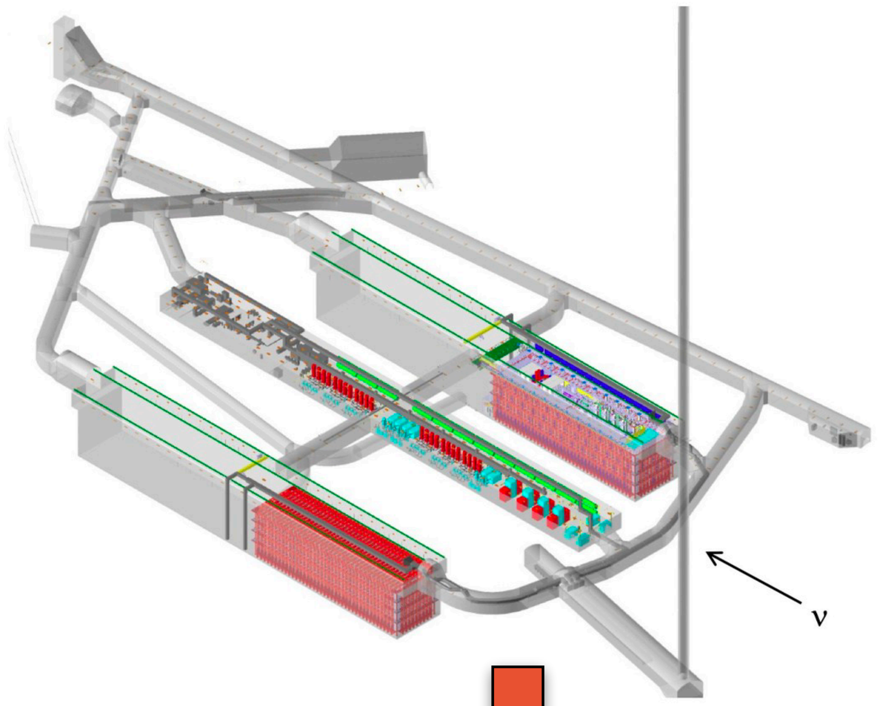
Phase I

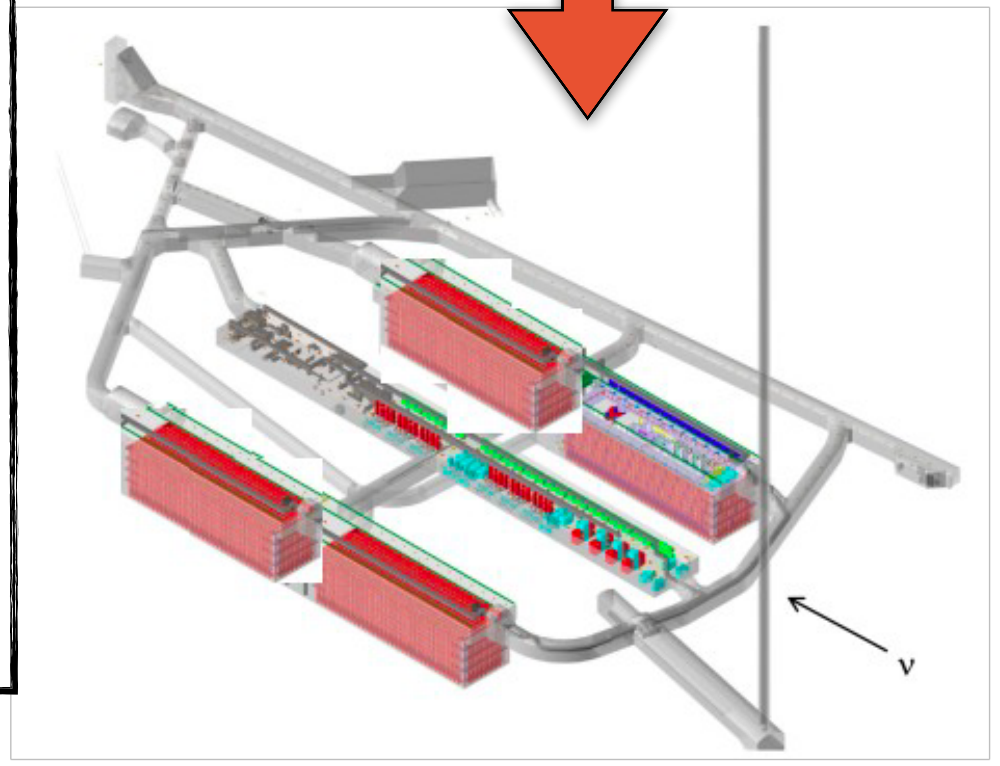
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

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*

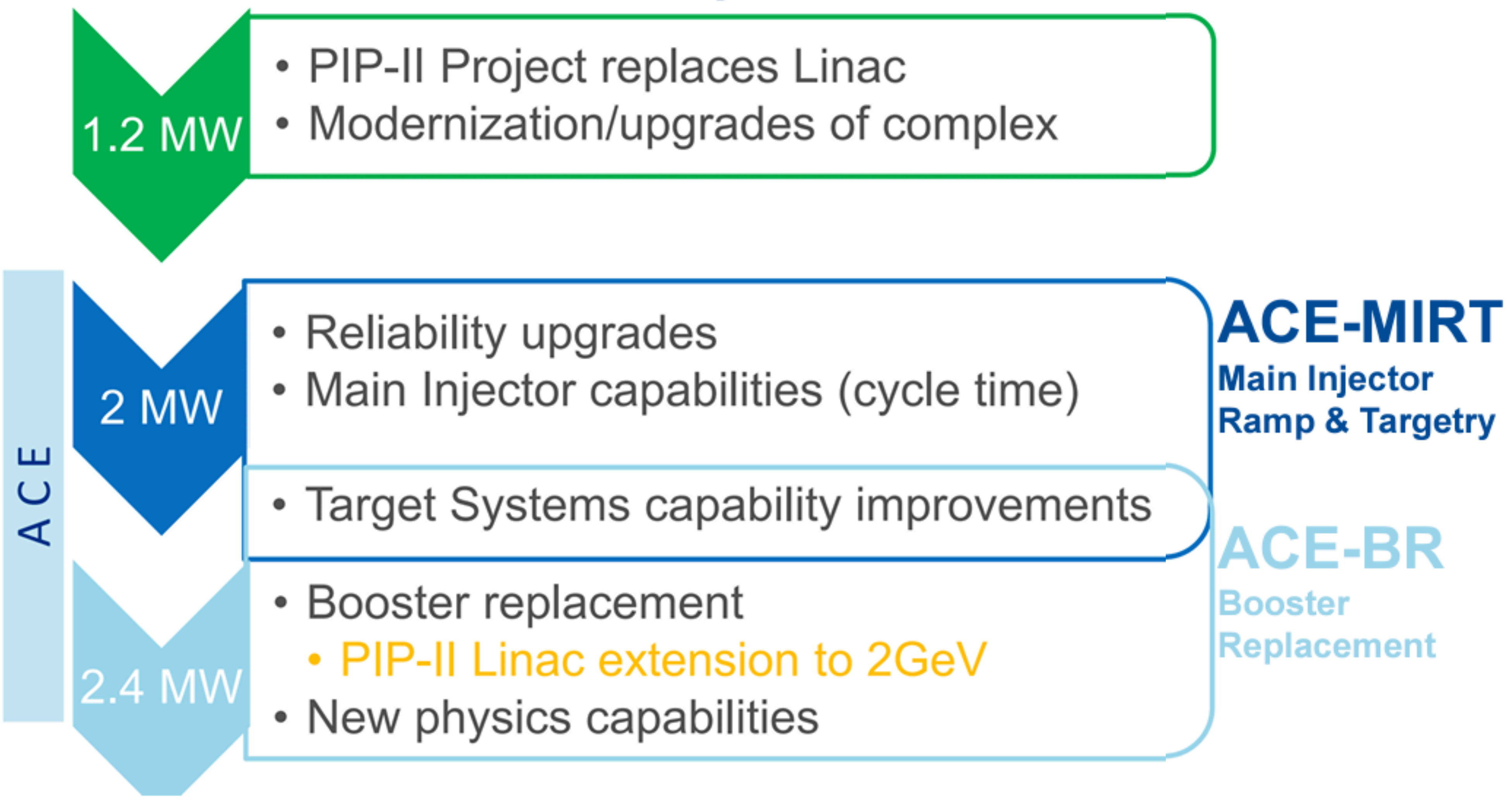
Accelerator Upgrades: PIP-II and ACE

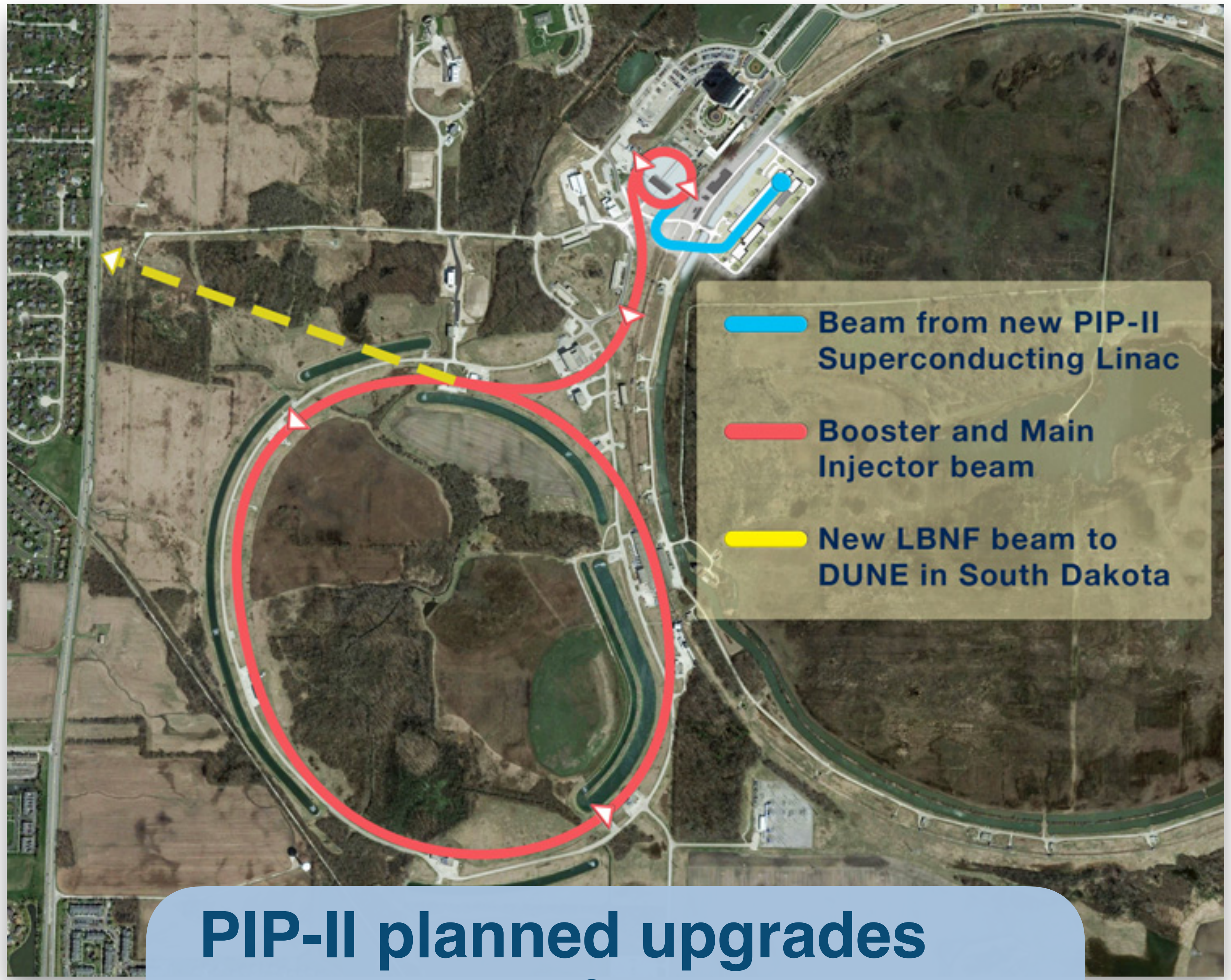
PIP-II

- 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)

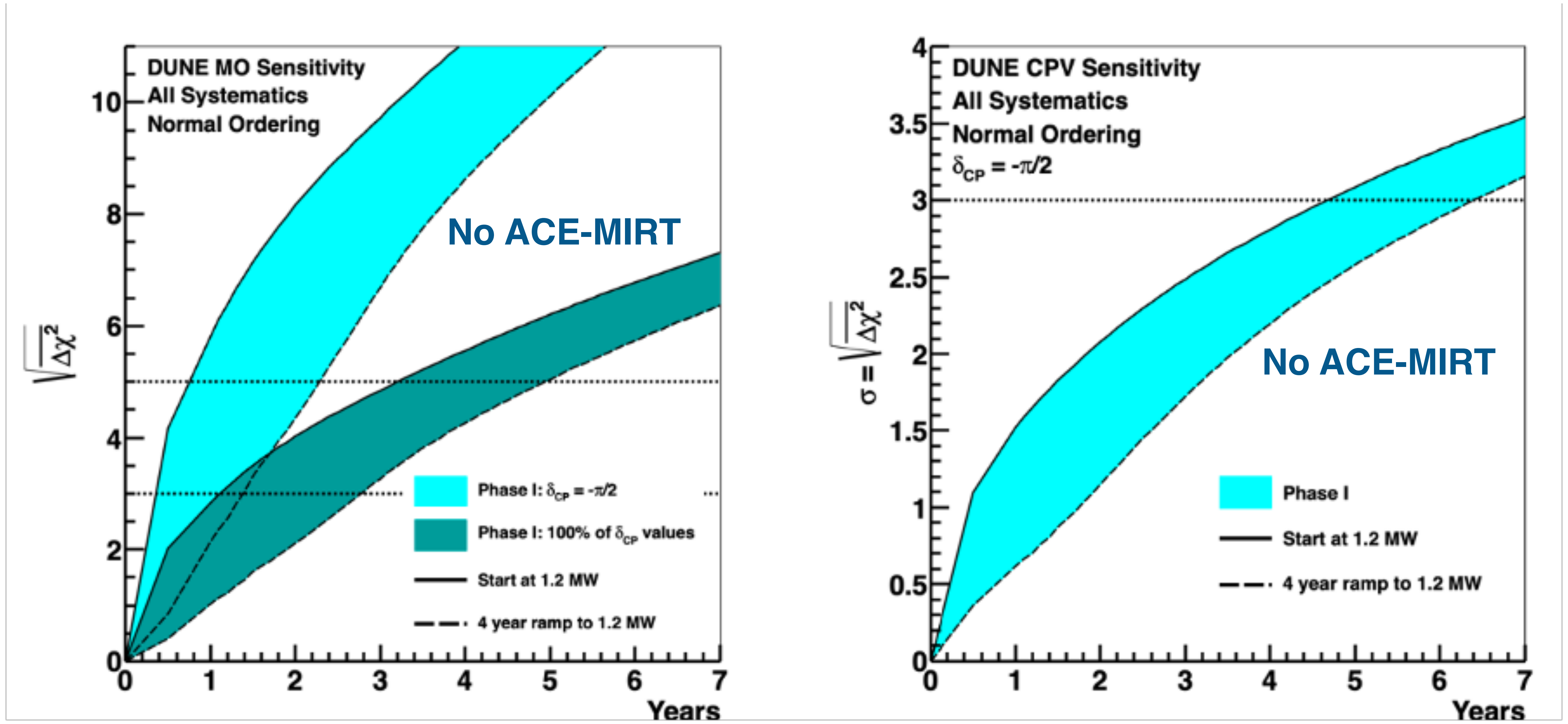
Science Drivers

- **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

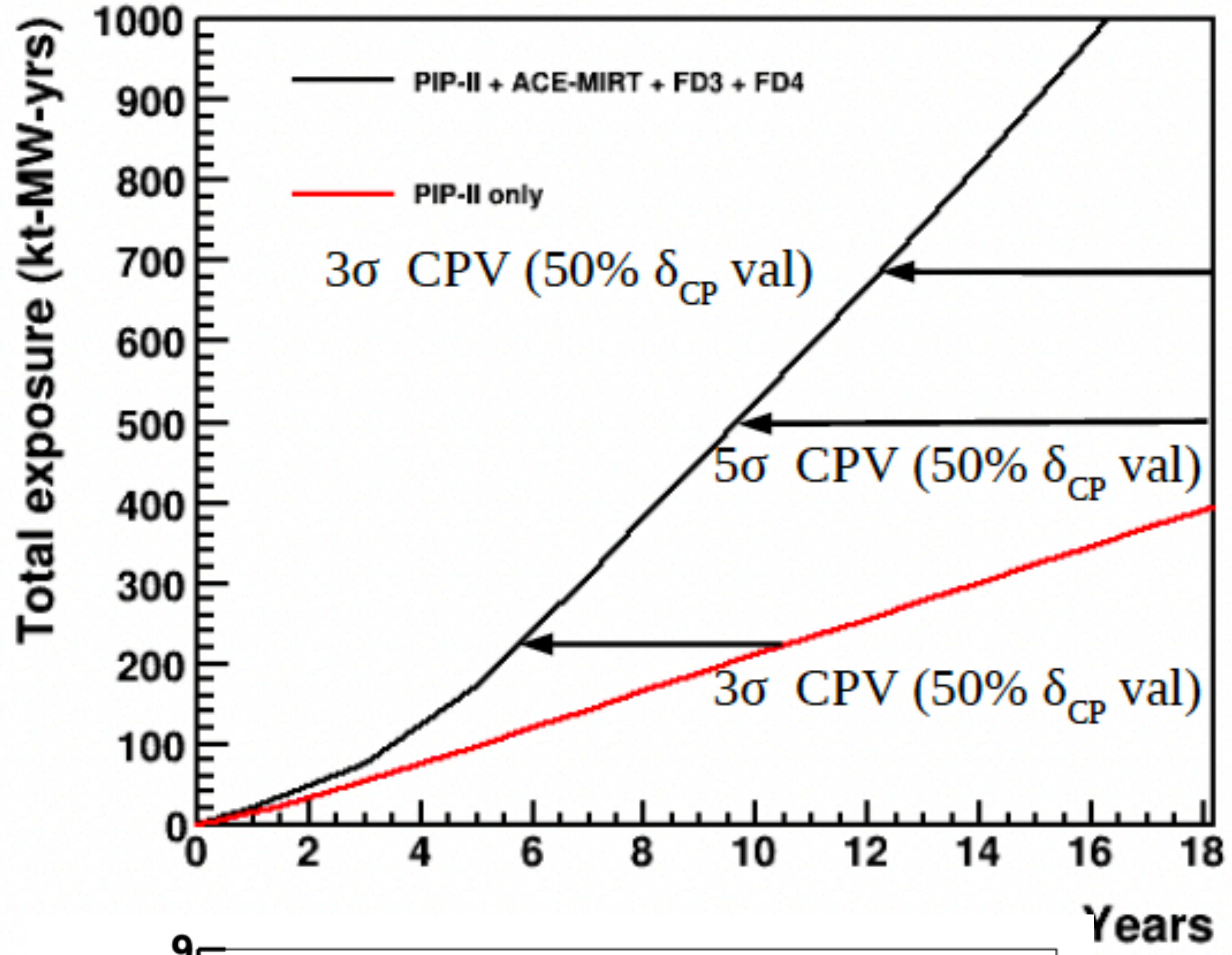
The statistics of Phase-I are not sufficient to determine the octant of θ_{23} or to establish CP violation except in the most favorable scenario

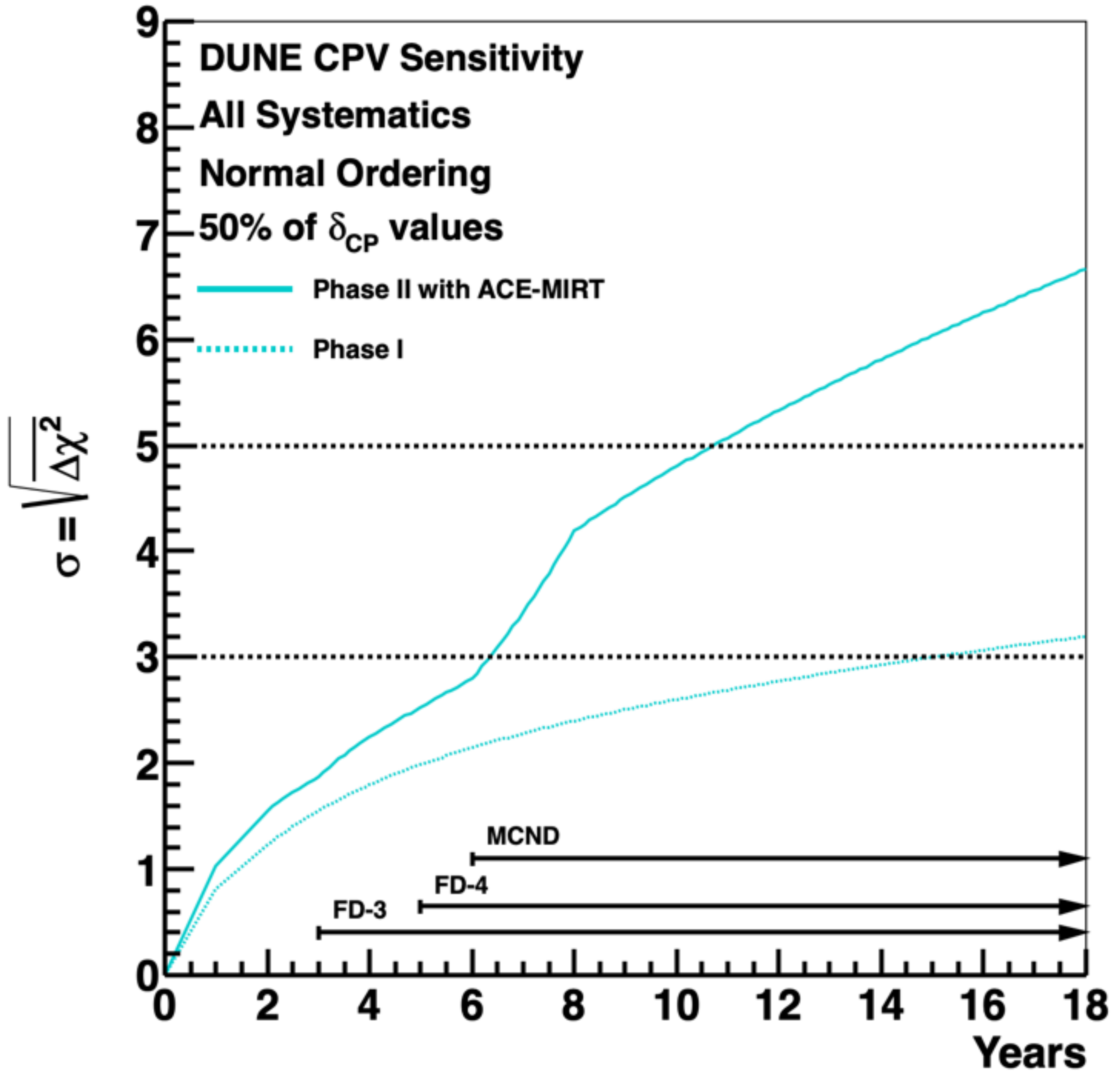


Los Alamos NATIONAL LABORATORY EST. 1943 DUNE

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.

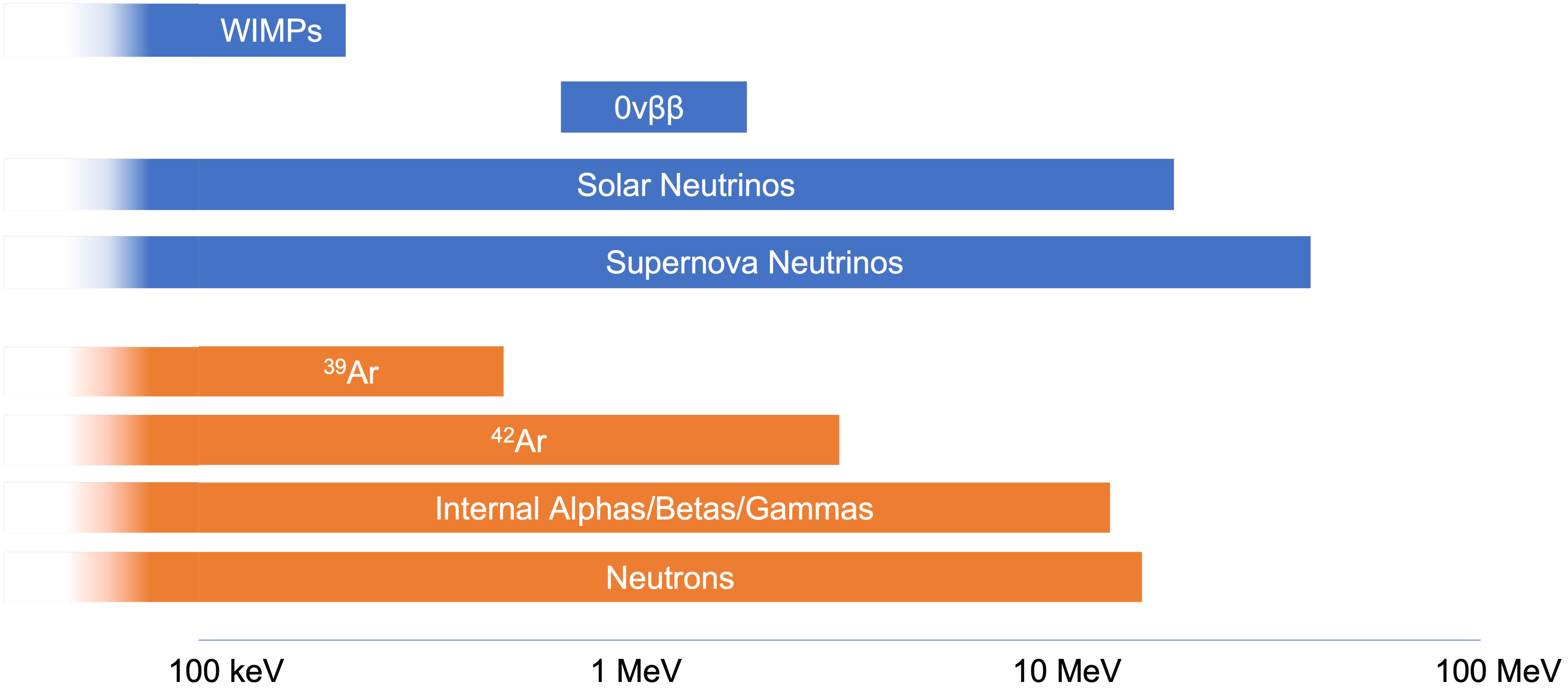


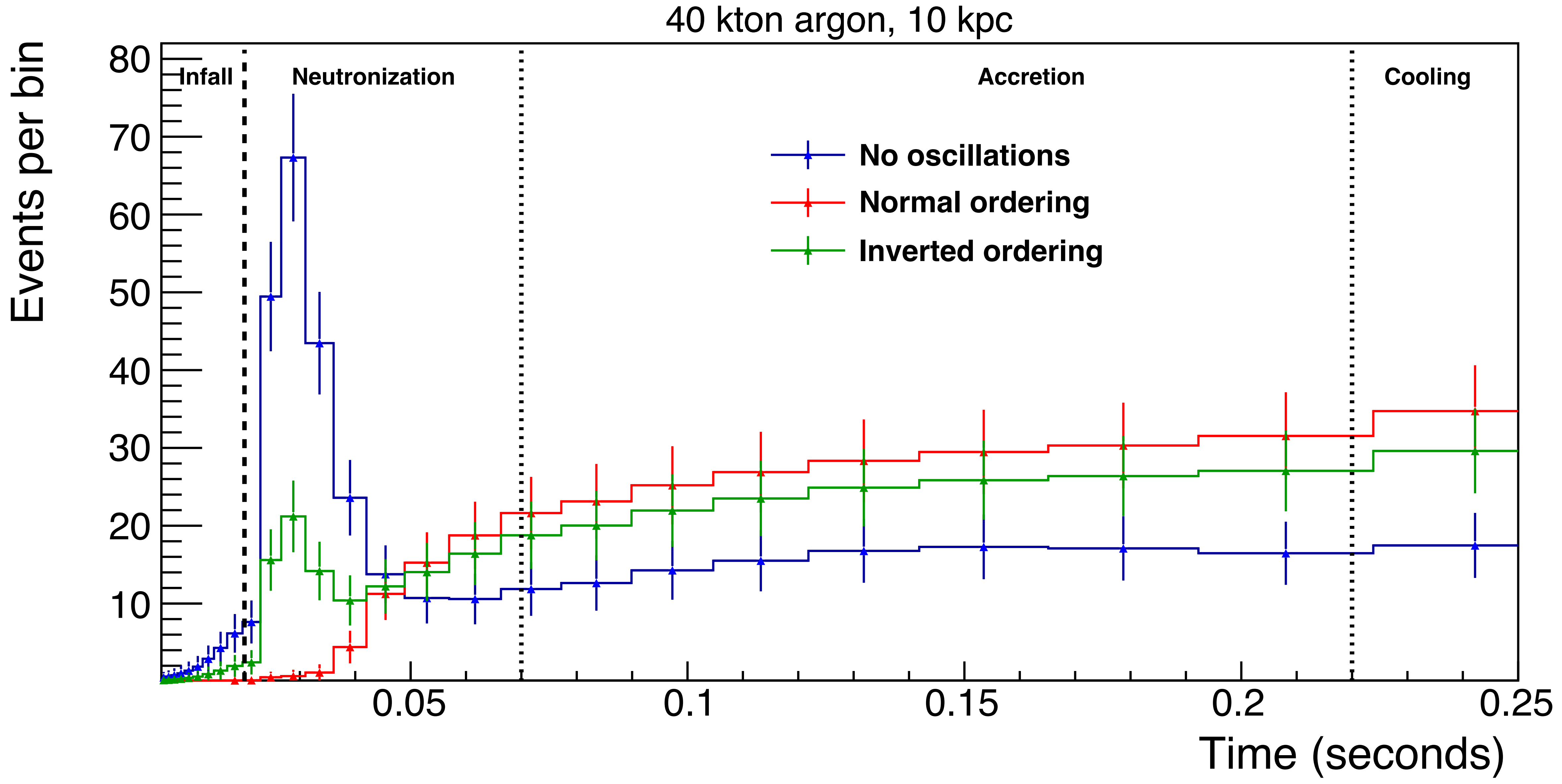


Neutrino Astrophysics with Phase-II

See DUNE talks in the Supernova and Solar Neutrino parallel

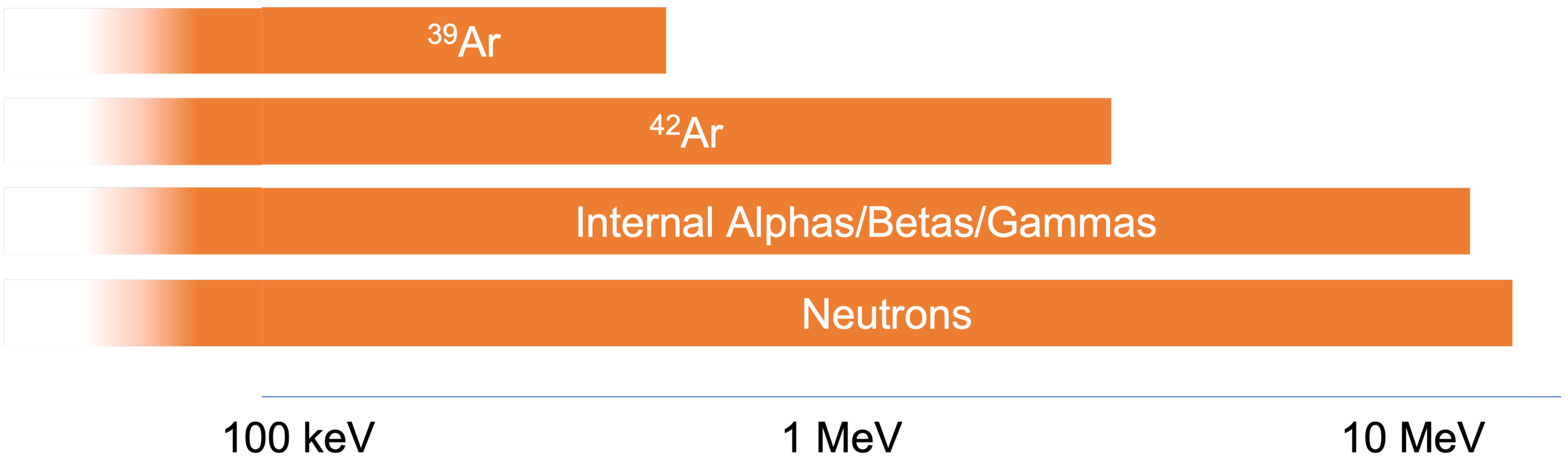
- Phase-II FD increased target mass, as well as potential improvements in energy resolution and background levels, key to improve detection of neutrinos from astrophysical sources in the MeV energy range
  - Supernova neutrino bursts, solar neutrinos, diffuse supernova neutrino background
  - Initial 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.

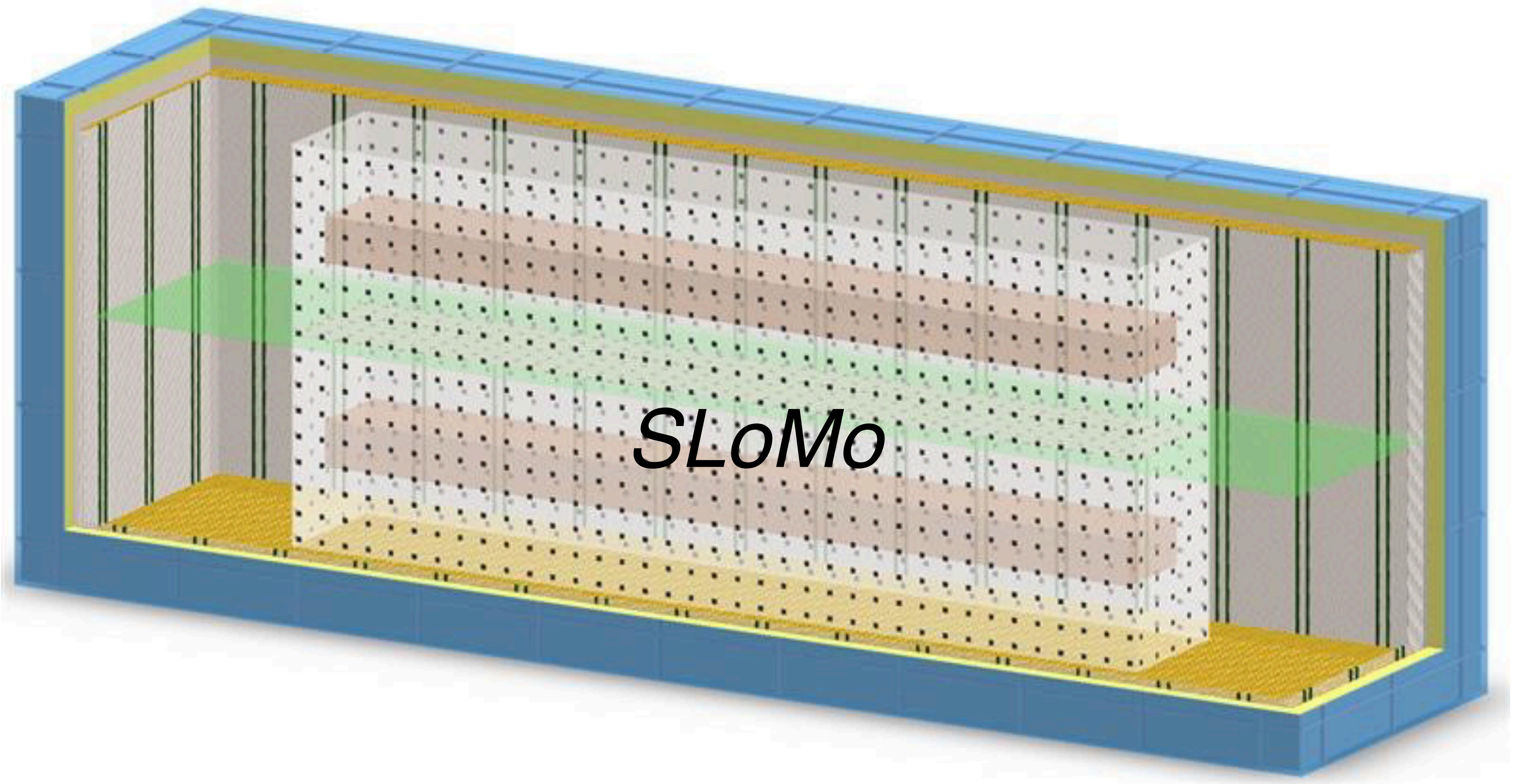




FD Background Control

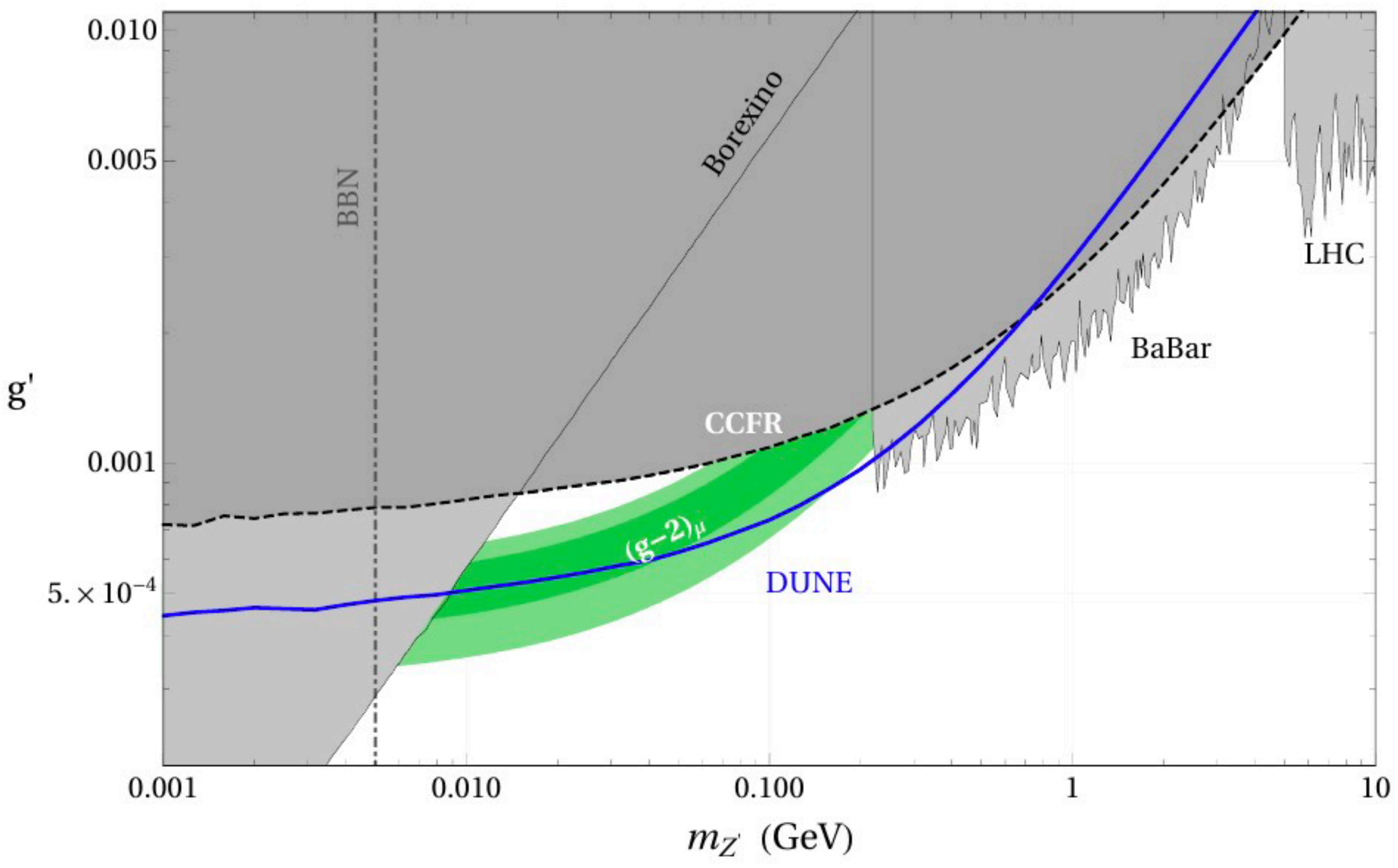
- Enhancement of DUNE physics to lower energies relies on lower radioactive backgrounds
- Realistic background target extends threshold down to 5 MeV, just above the ^{42}K beta endpoint from ^{42}Ar
- Most significant radioactive backgrounds and mitigation strategies
  - *External neutrons and gammas → 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*

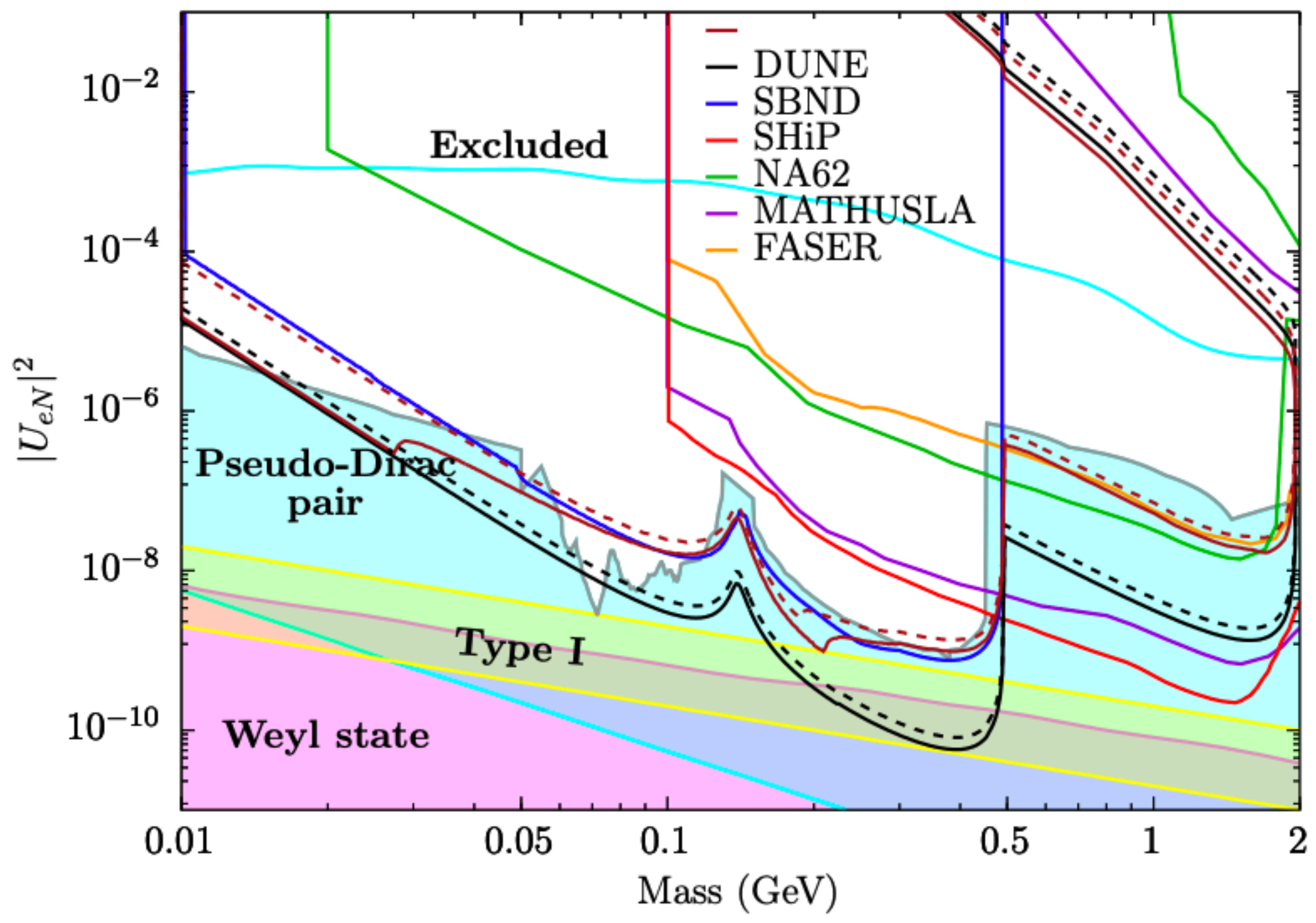




BSM Physics with Phase-II

- 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

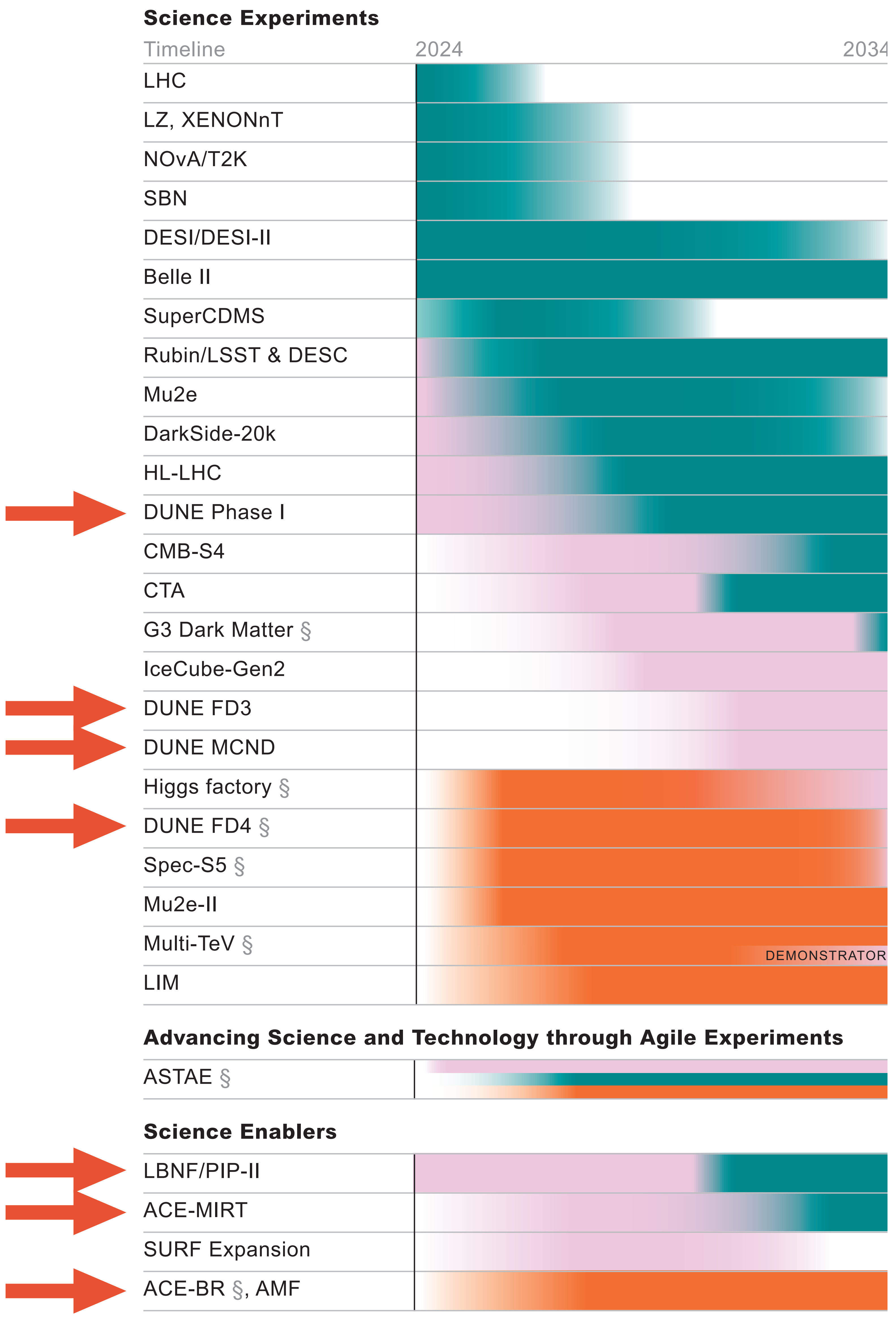


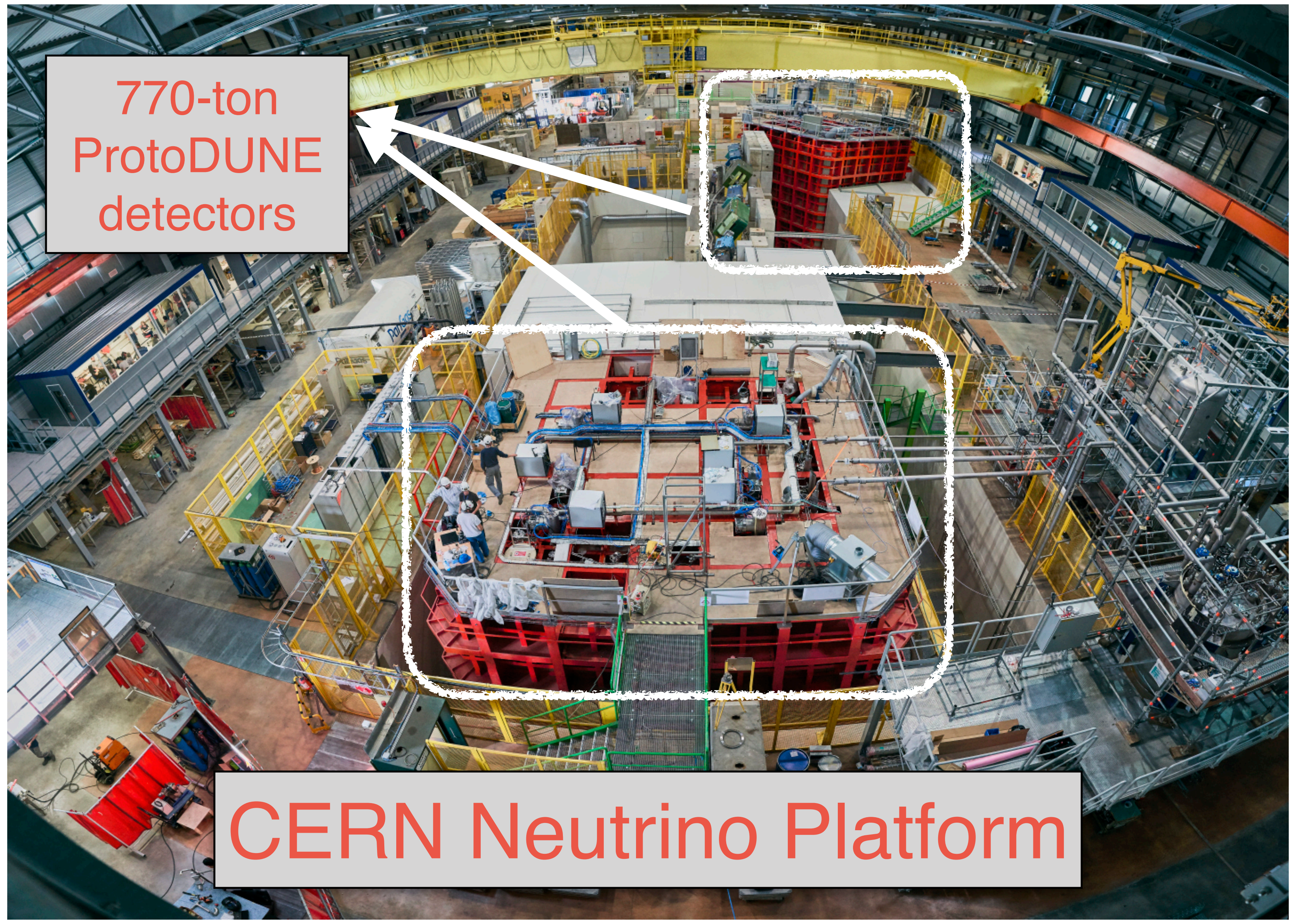
Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

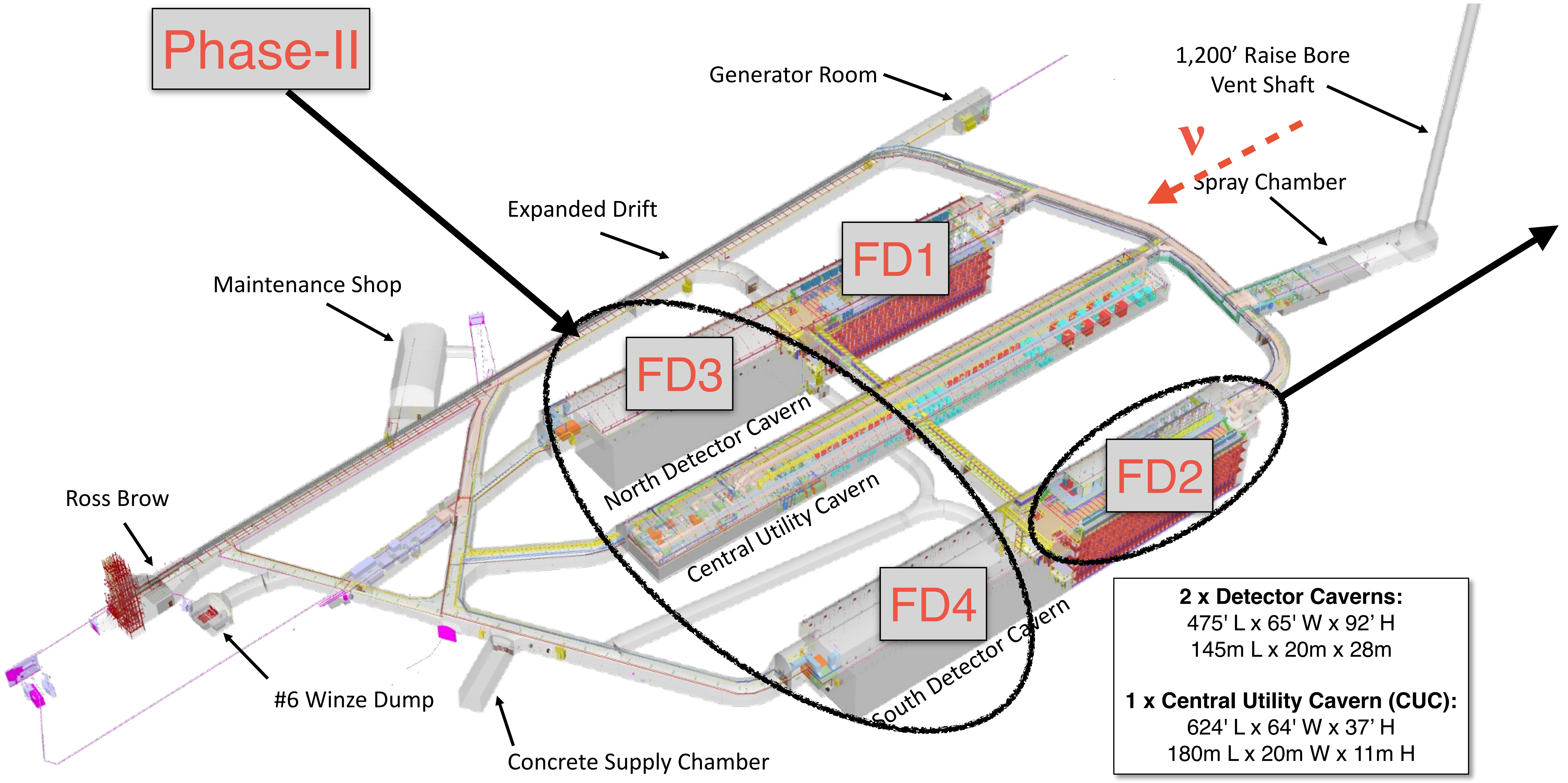
A Global R&D is Forming

- 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)*



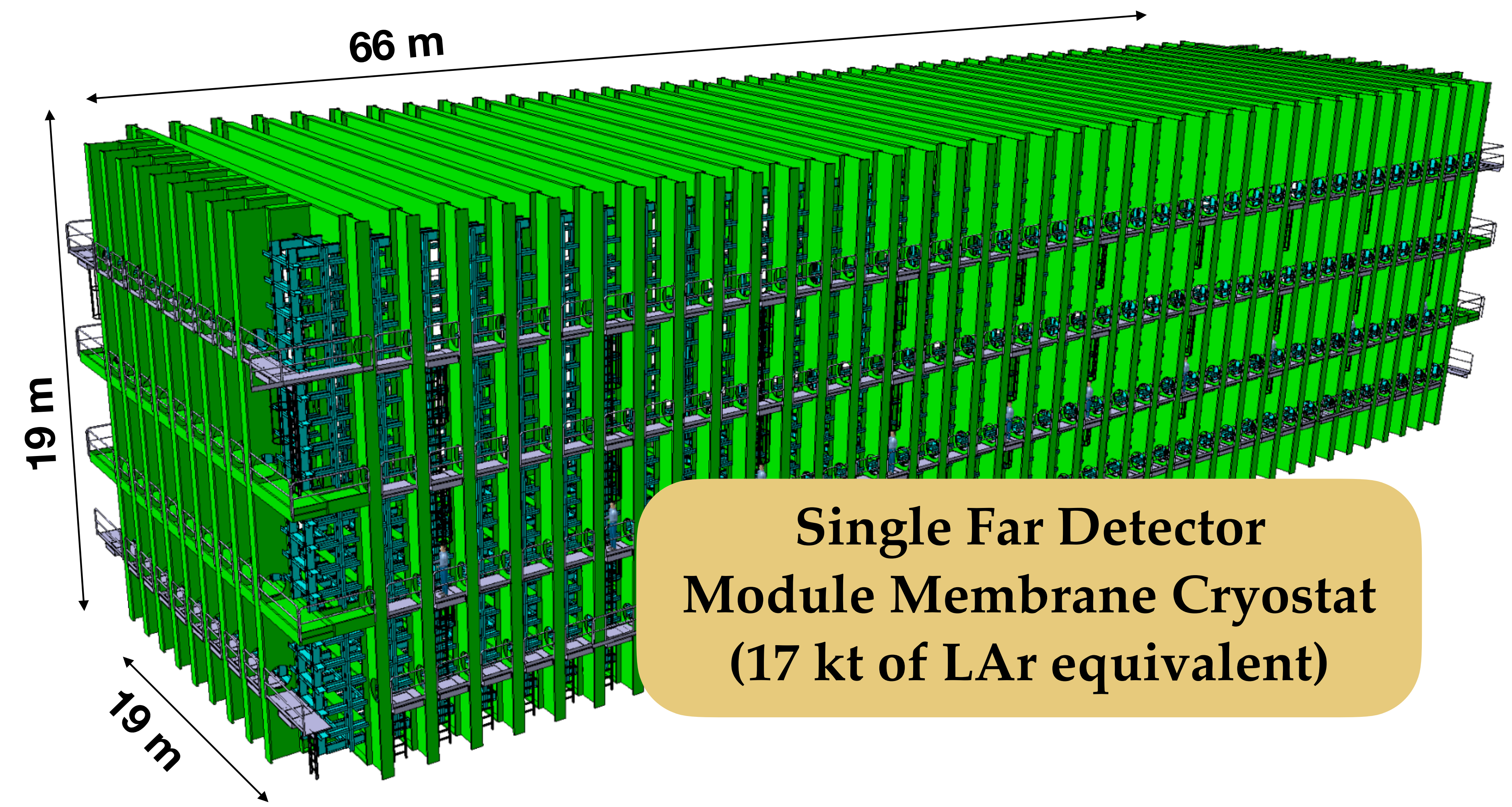
Phase-II Far Detector

The DUNE Far Detector



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

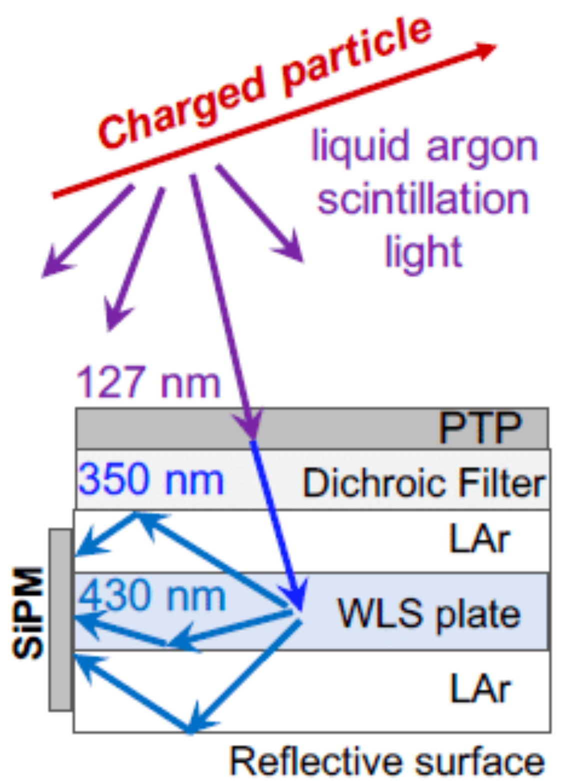


The first three DUNE FD modules will be Liquid Argon Time Projection Chambers (LArTPCs) with 17 kt total mass each

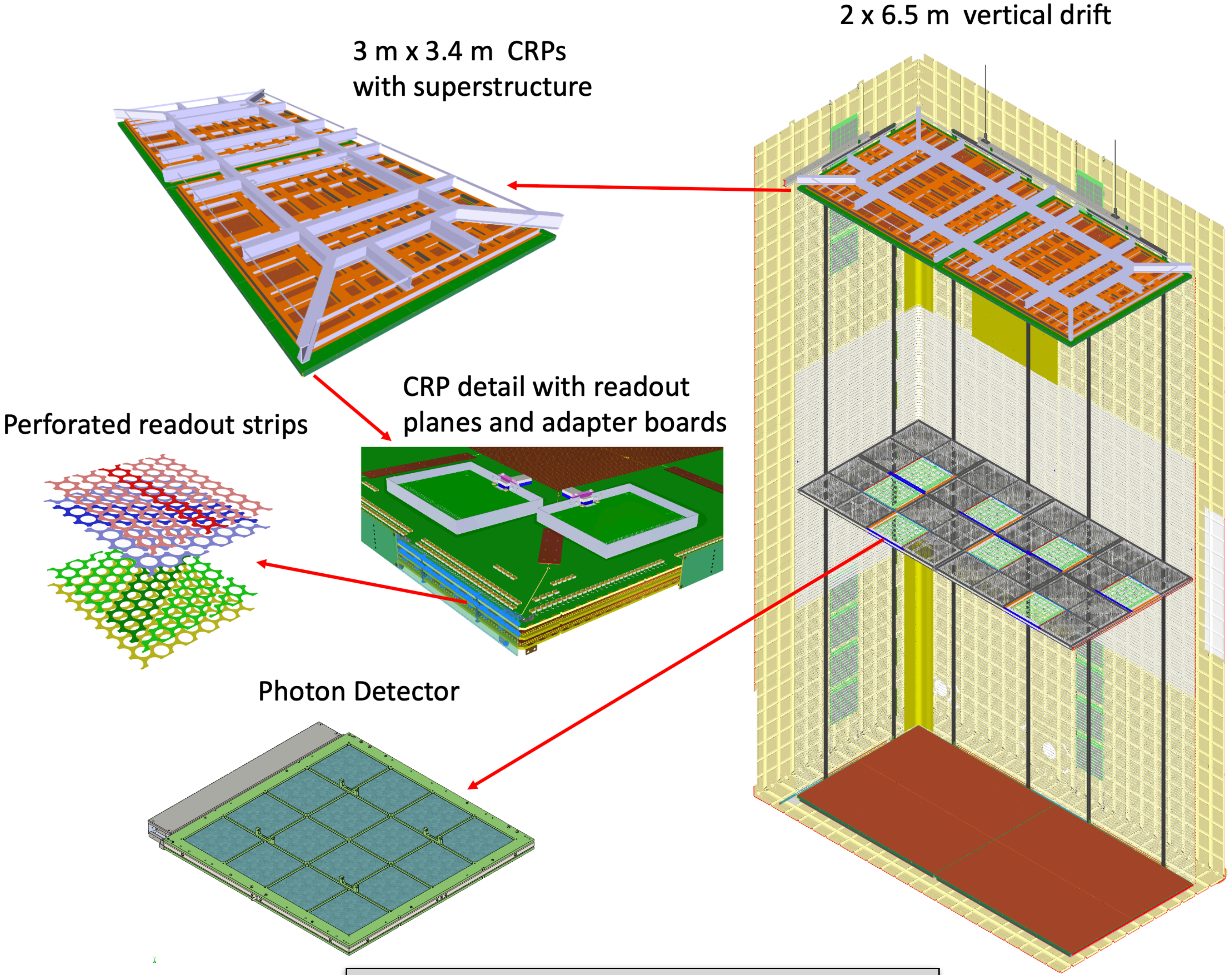
- **FD1**: Horizontal Drift (HD)
- **FD2**: Vertical Drift (VD)
- **FD3**: Improved LArTPC
- **FD4:** Module of opportunity *(both LAr and non-Argon options being explored)*

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



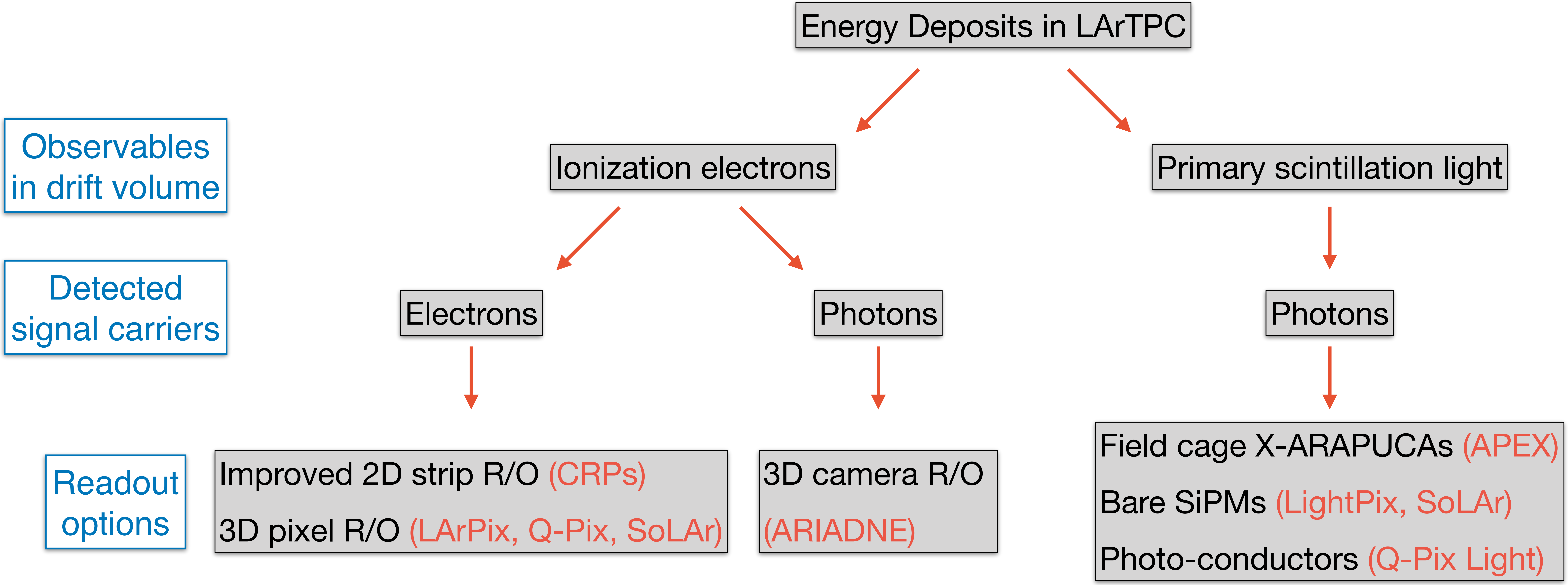
X-ARAPUCA working principle



FD2 Vertical Drift Concept

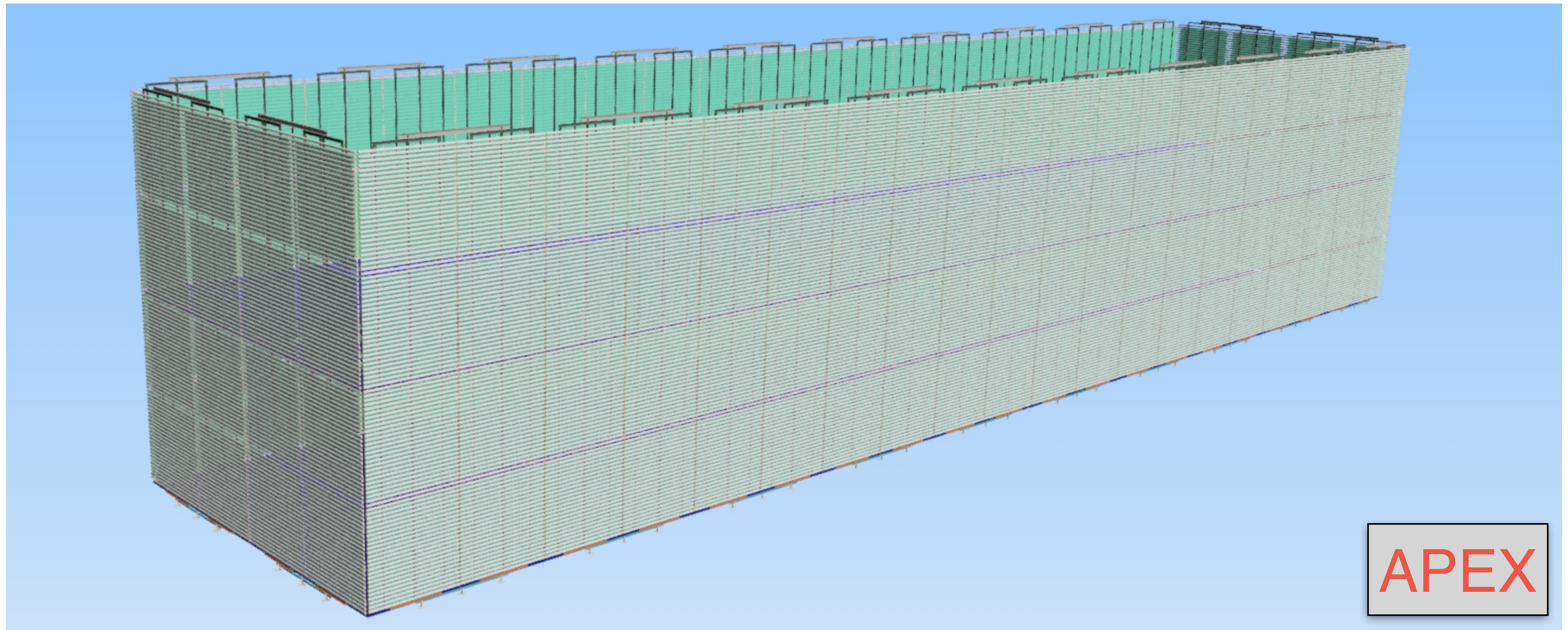
Potential Improvements to FD2 Charge/Light Readouts

- 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*

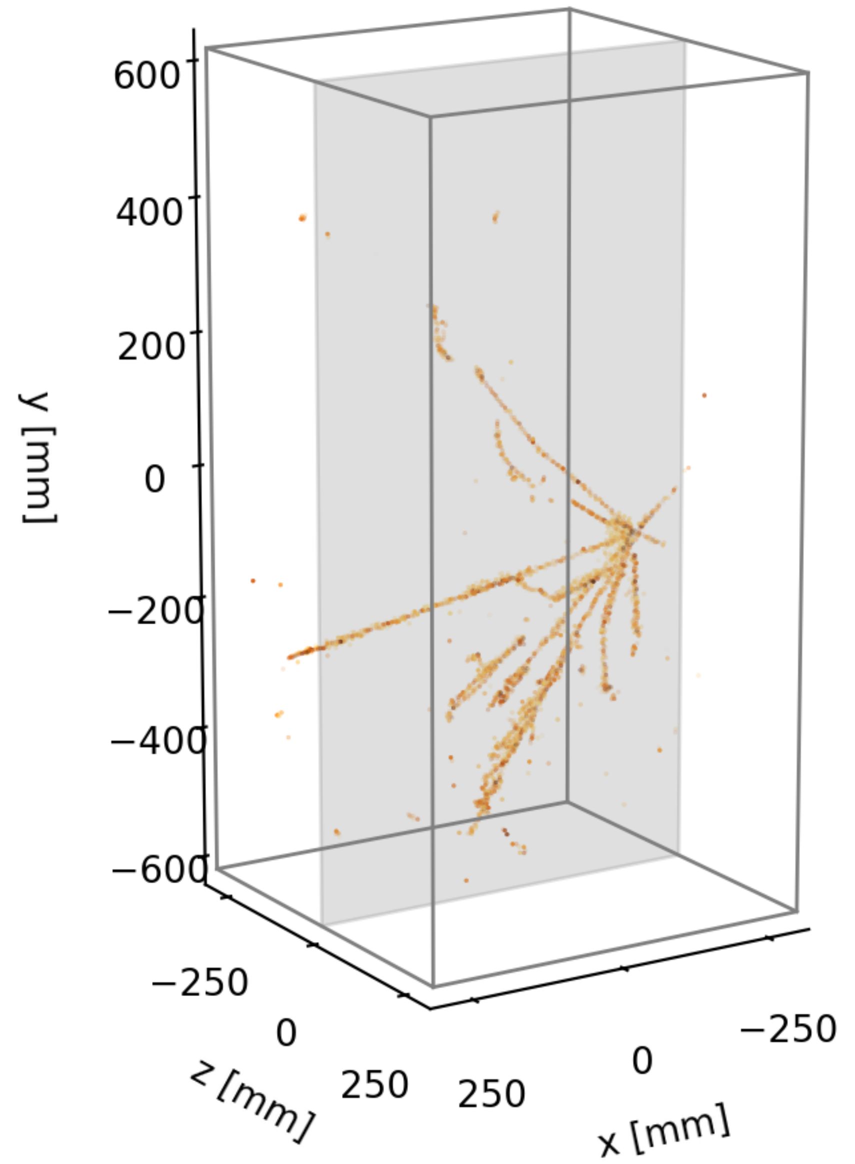


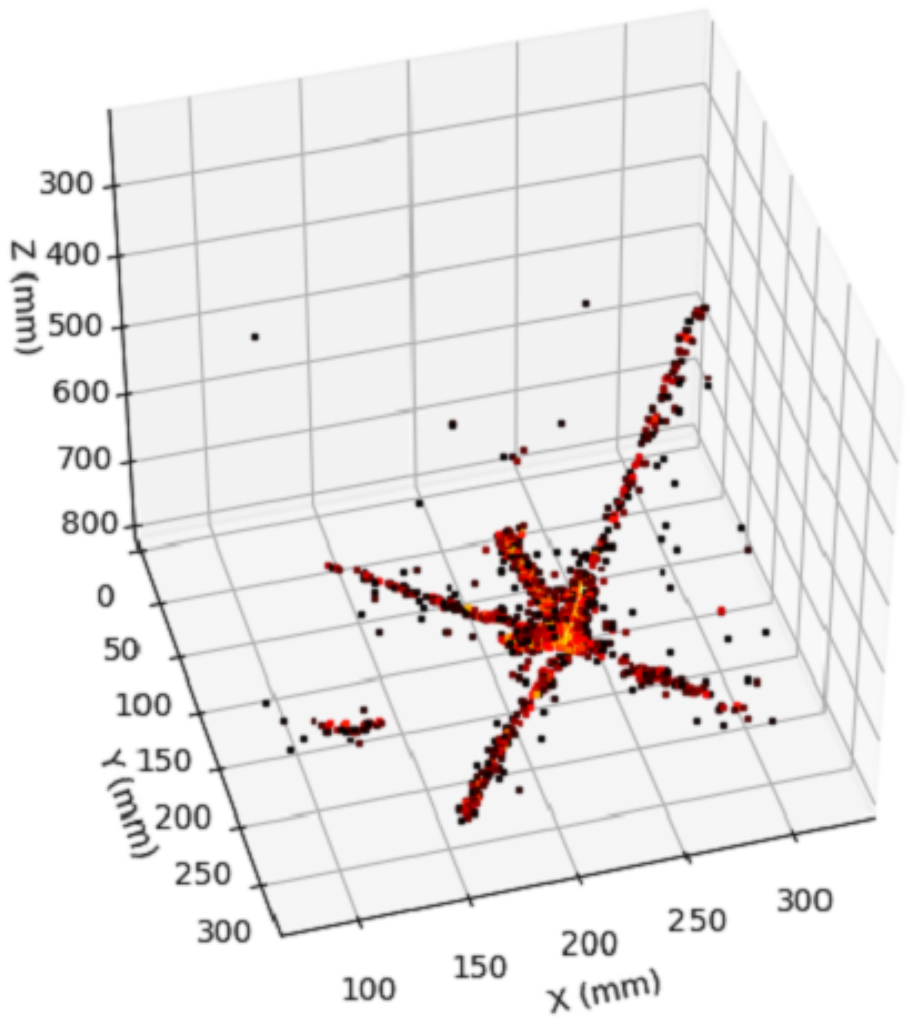
See talk by W. Shi on APEX (DUNE Phase-II parallel)

Detector Concepts: FD4 Baseline

- **FD4 baseline**: VD-LArTPC with central cathode, and native 3D 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*

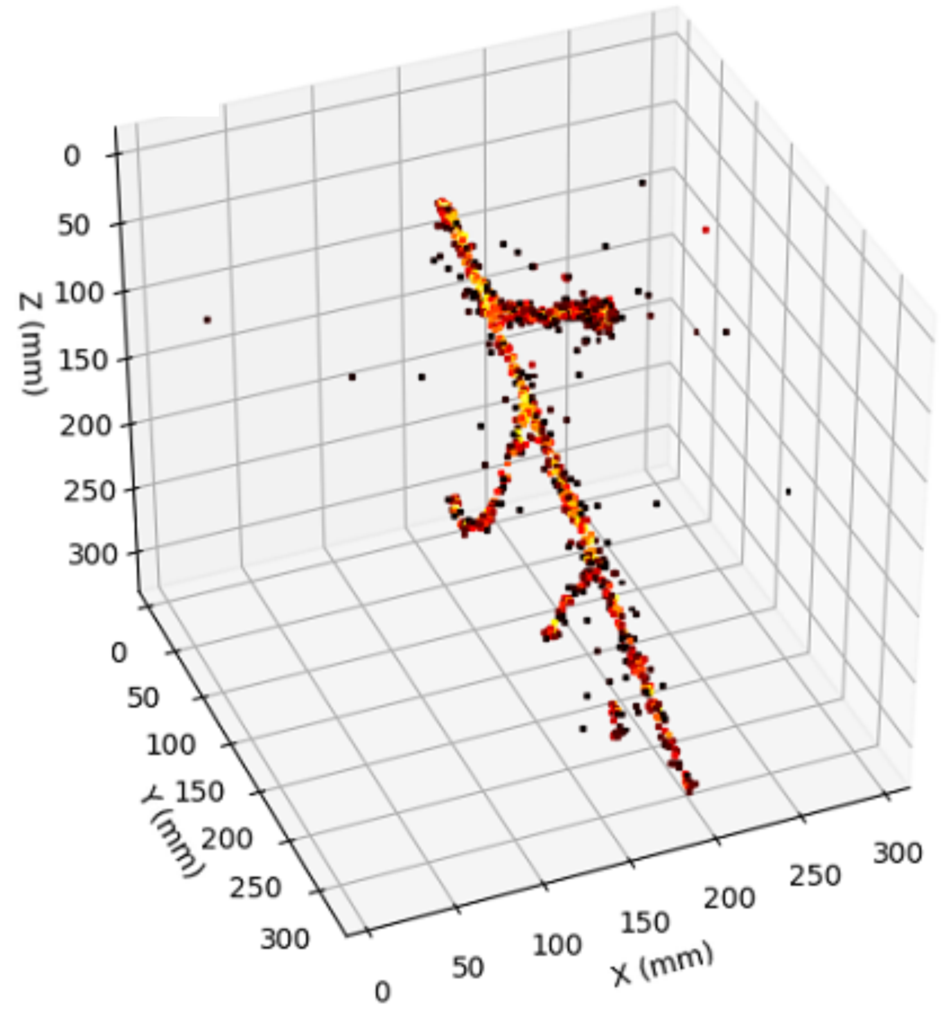
LArPix





ARIADNE

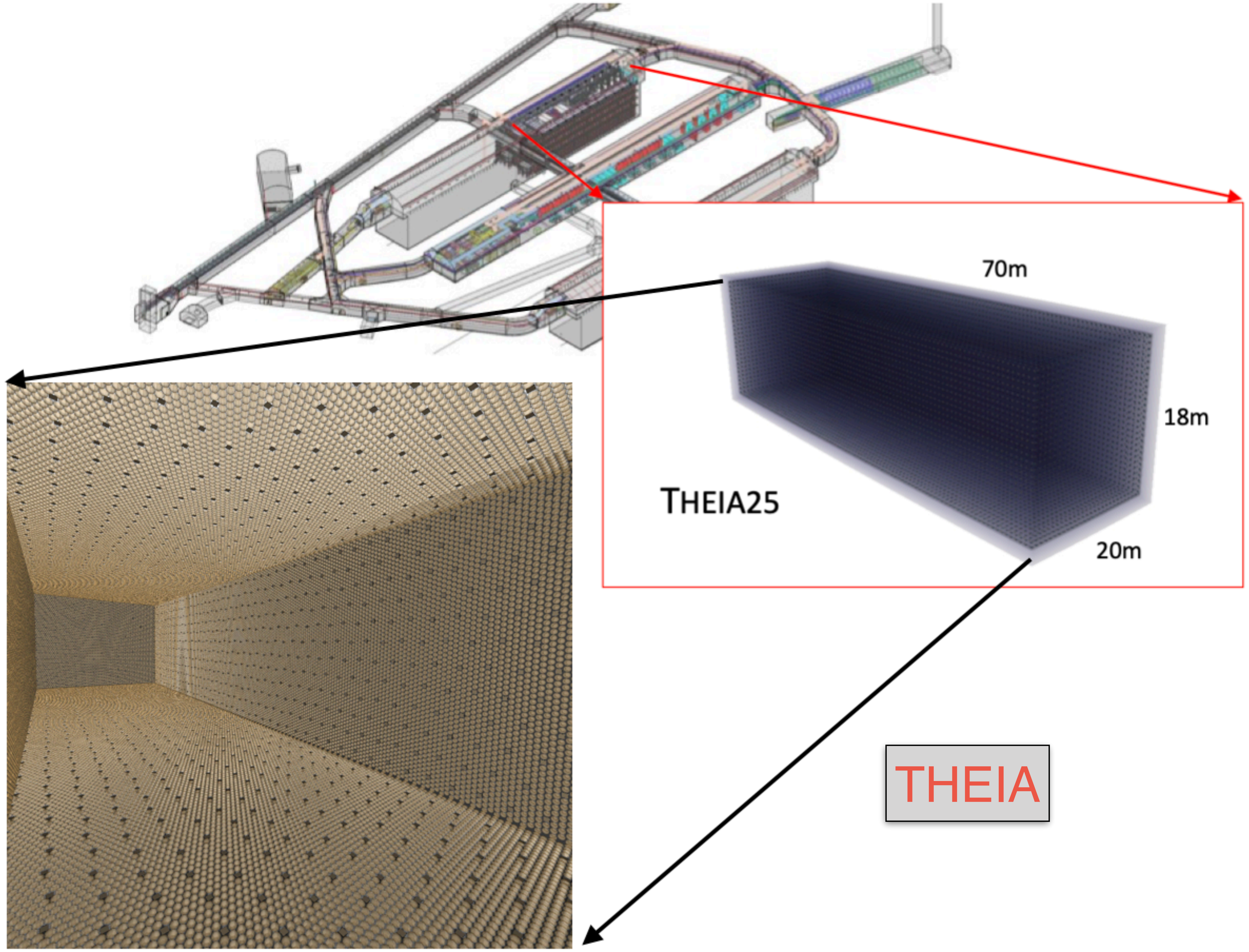
See talk by K. Mavrokaridis (DUNE Phase-II parallel)



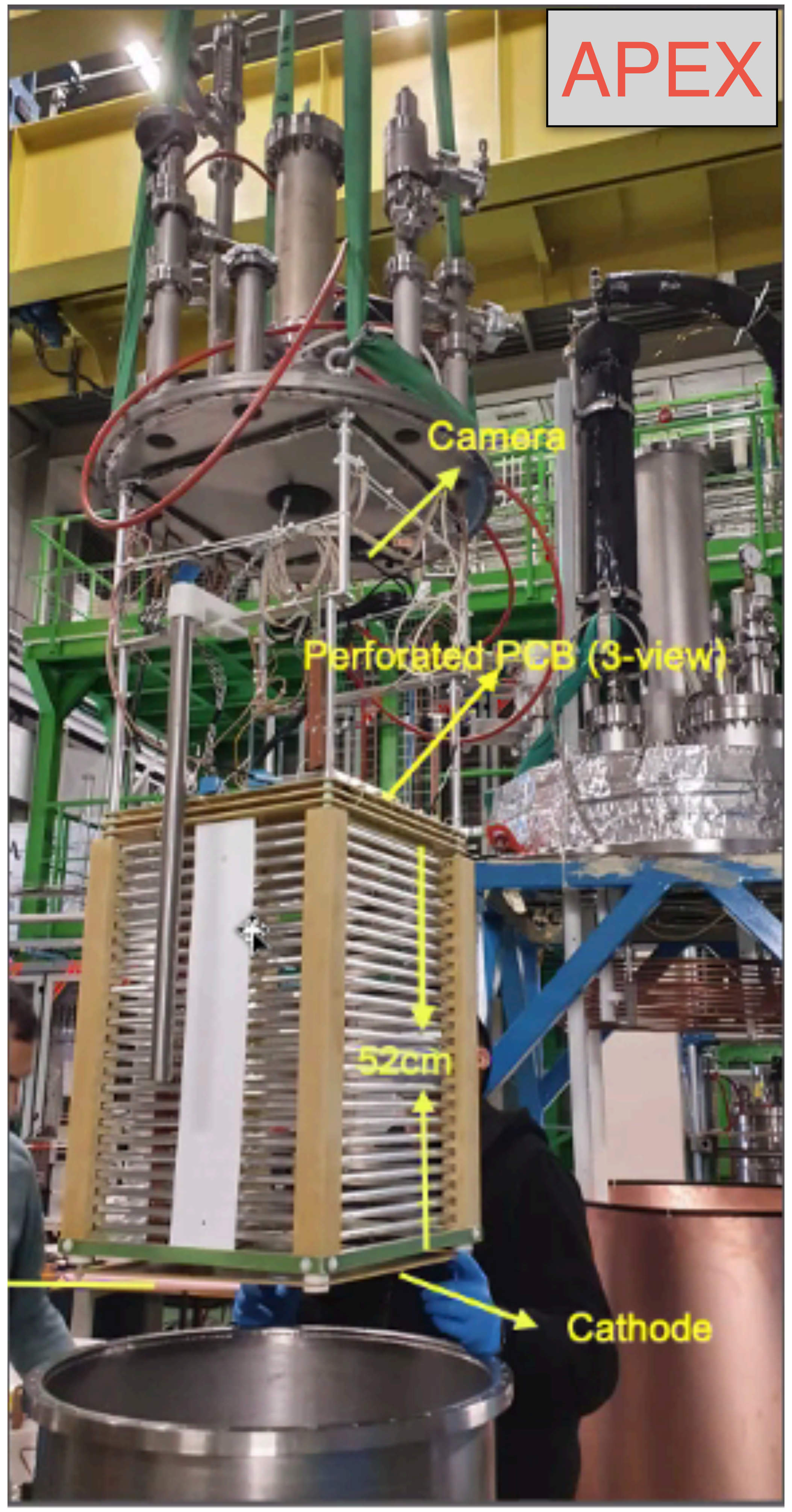
Detector Concepts: FD4 Alternative

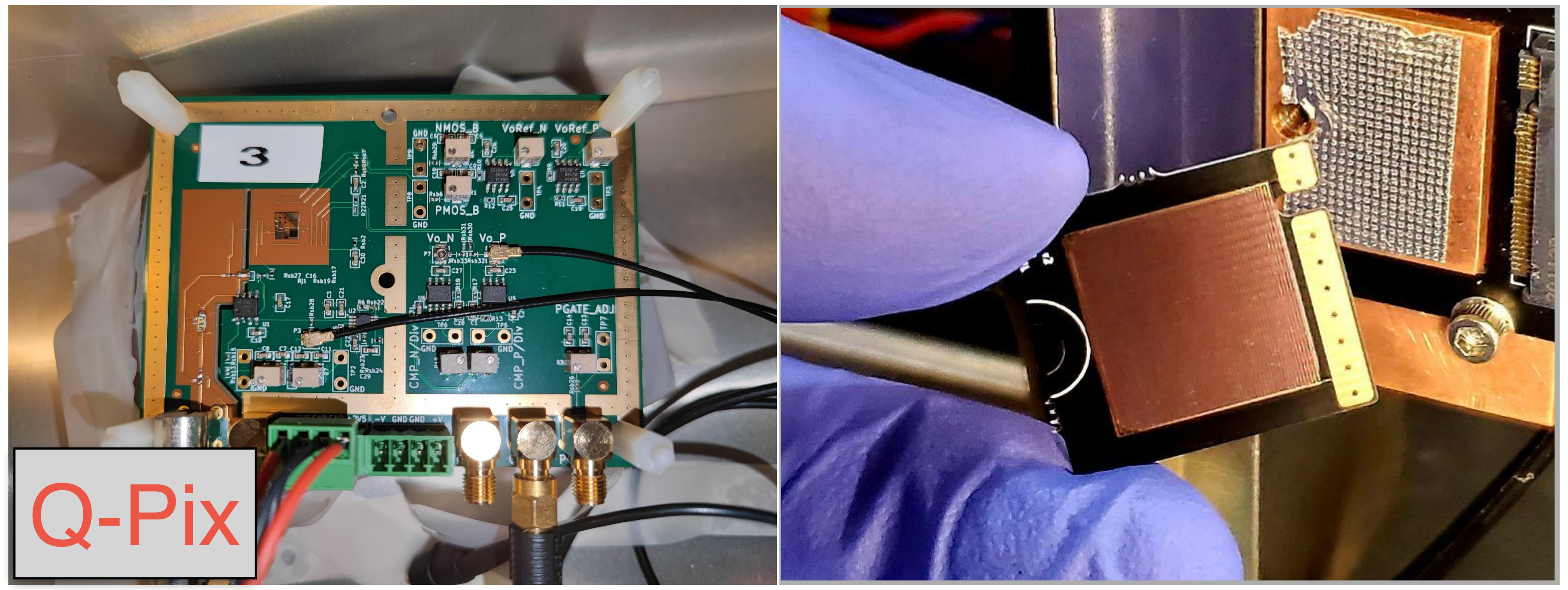
- Water-based liquid scintillator module measuring scintillation and Cherenkov light separately (**THEIA**)
- Cherenkov light offers e/μ discrimination via ring imaging, and sensitivity to particle direction
- Scintillation light offers improved energy and vertex resolution, Particle-ID capability via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

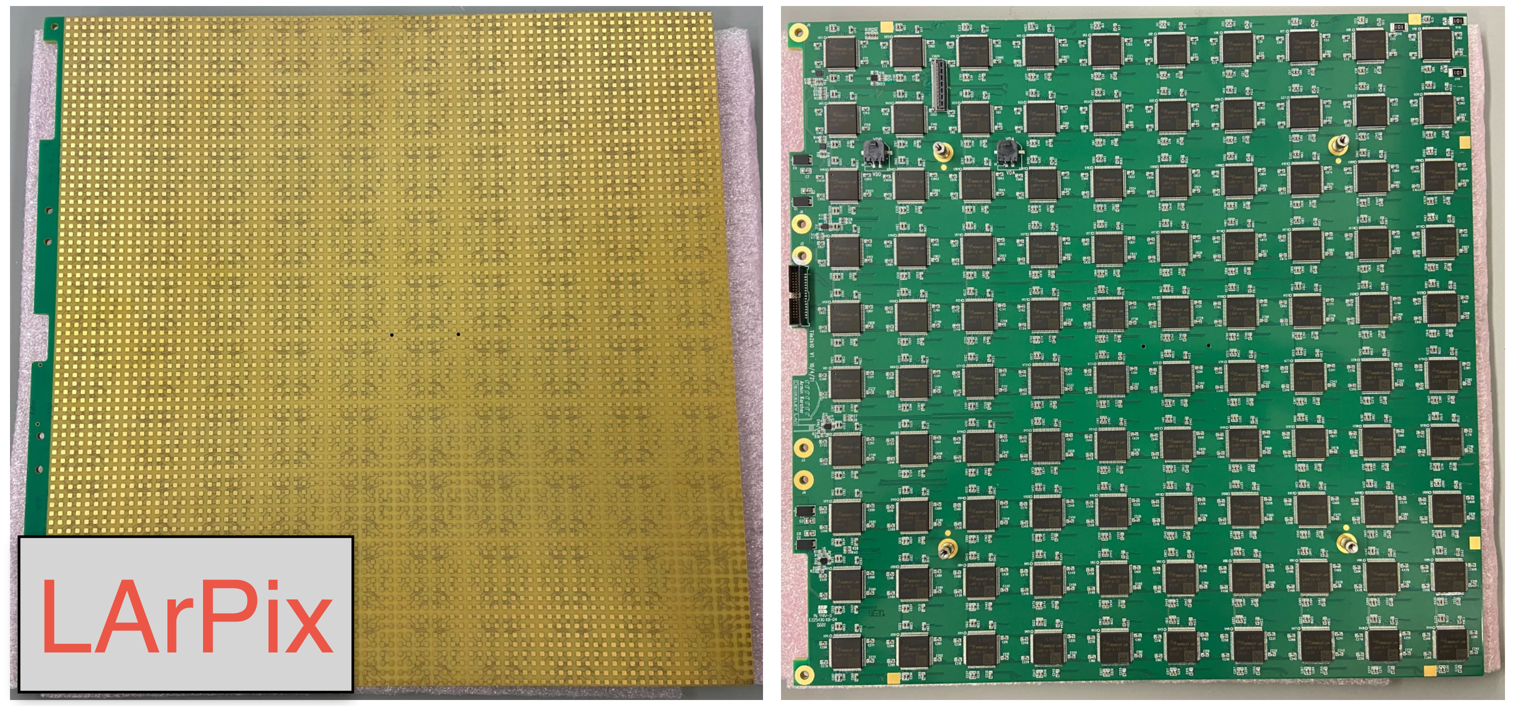
See talk by L. Pickard on THEIA (DUNE Phase-II parallel)

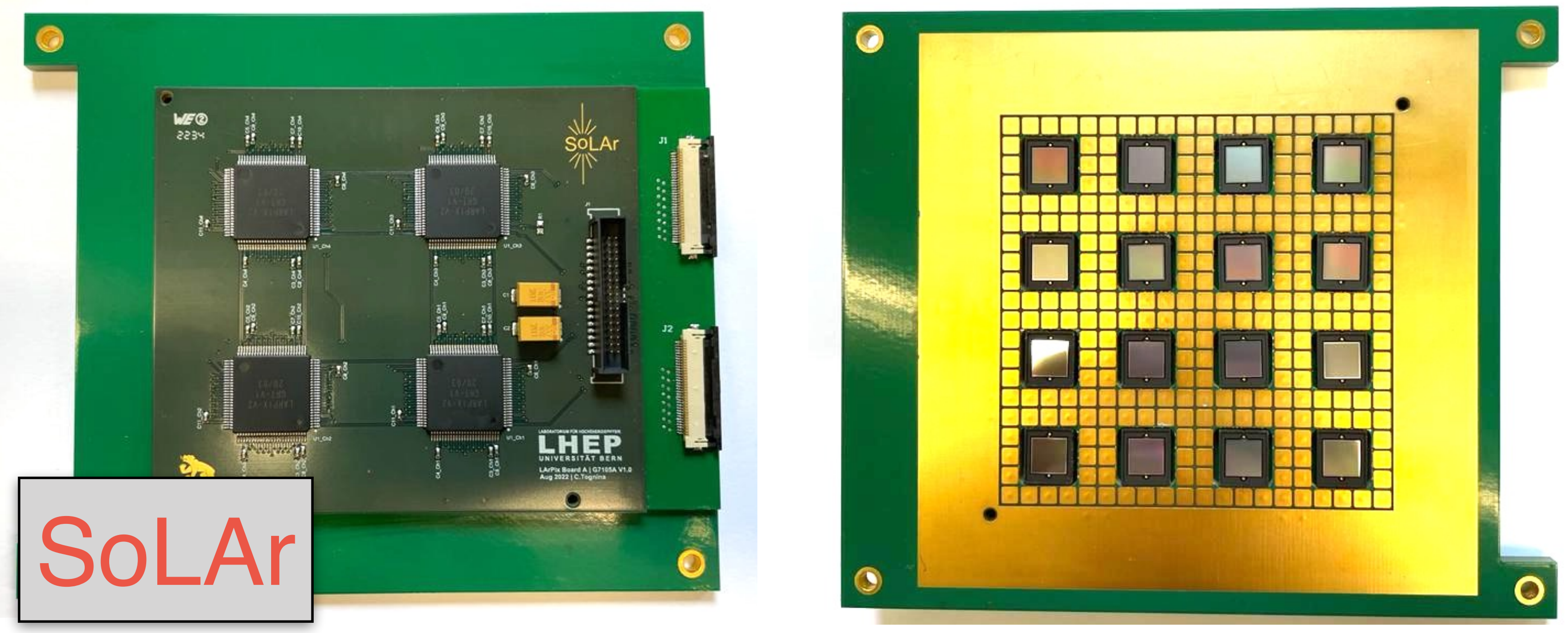


Active Prototyping Underway for FD3/4 Technologies

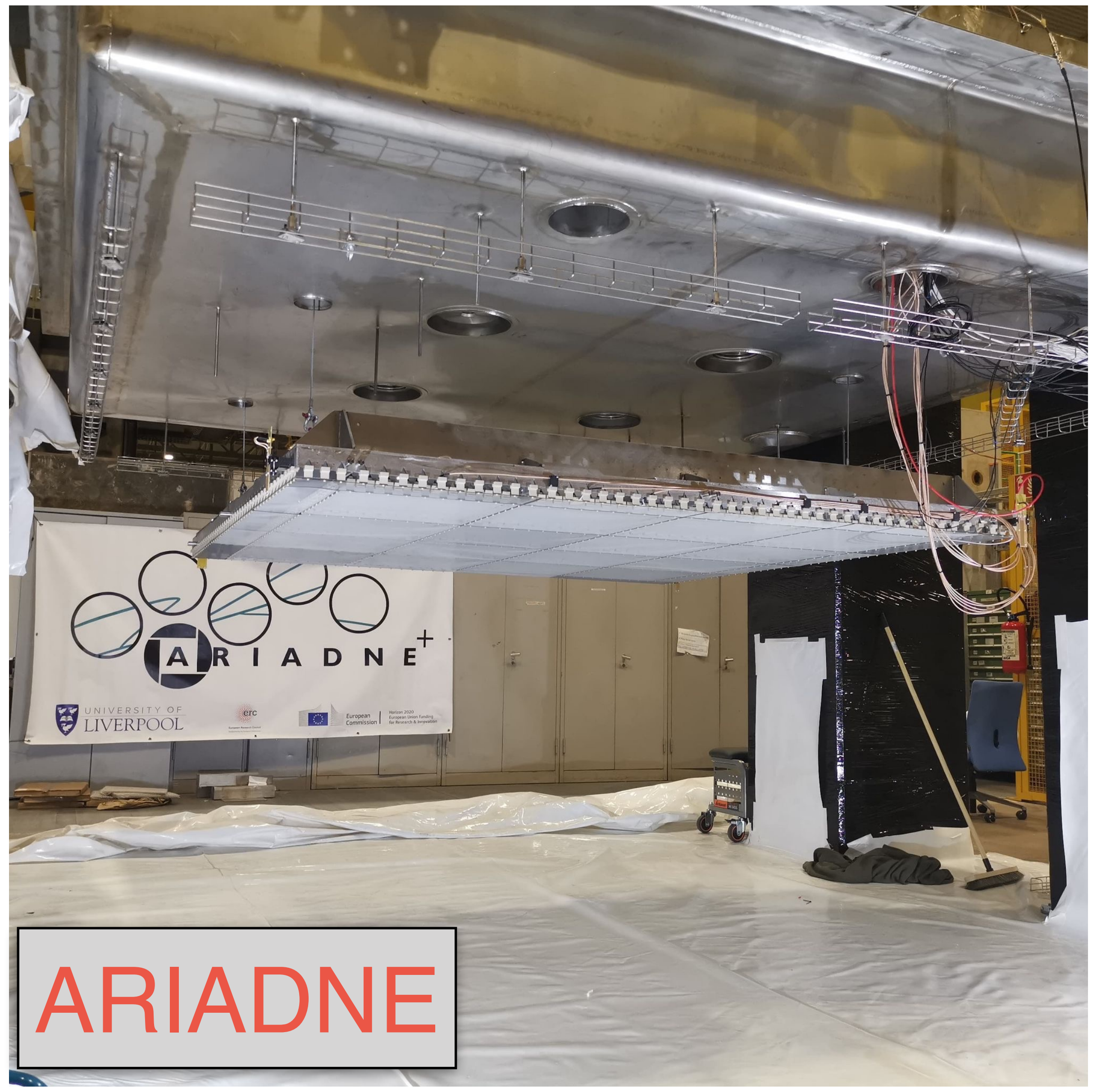


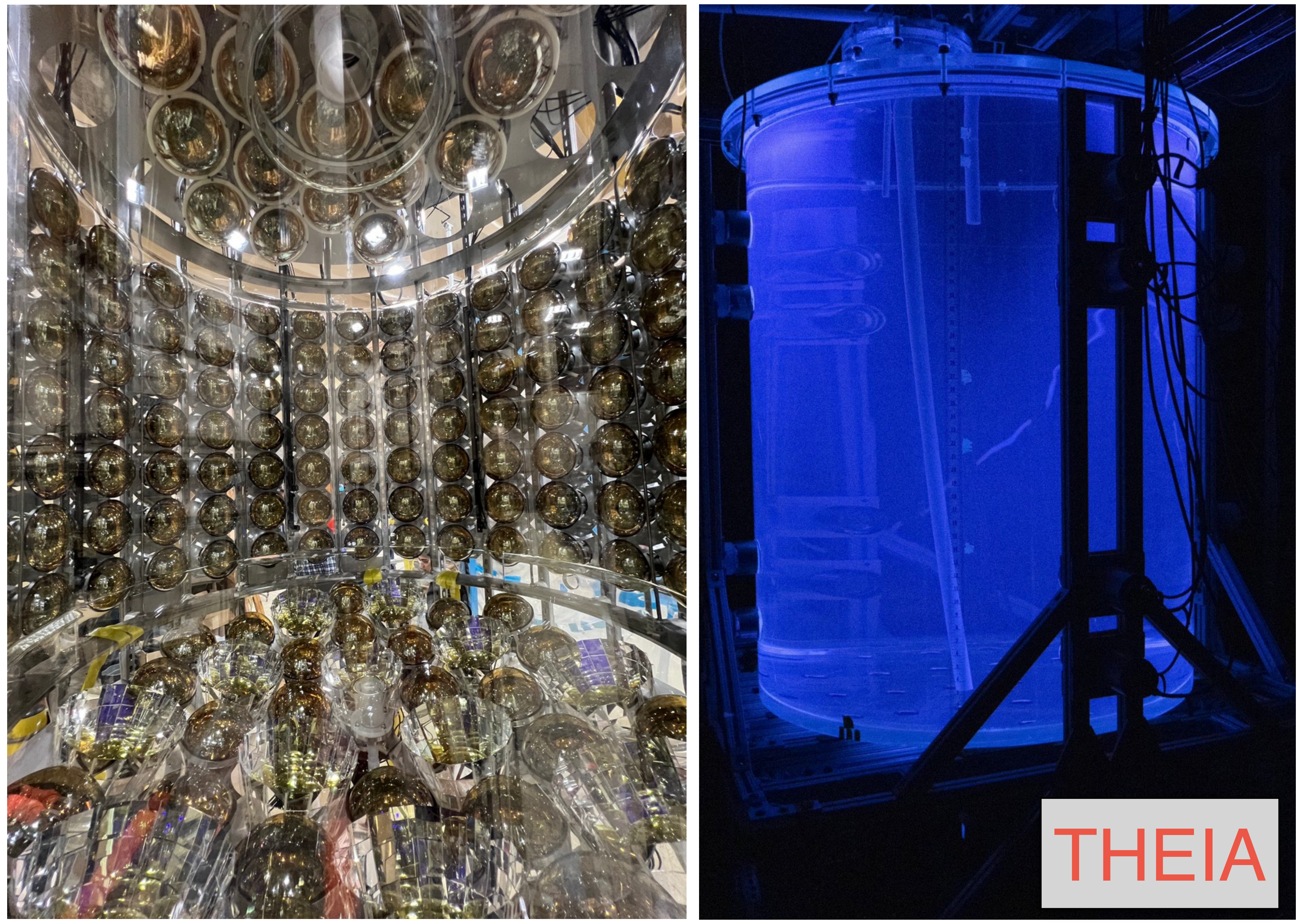






See talks in the DUNE Phase-II parallel session





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

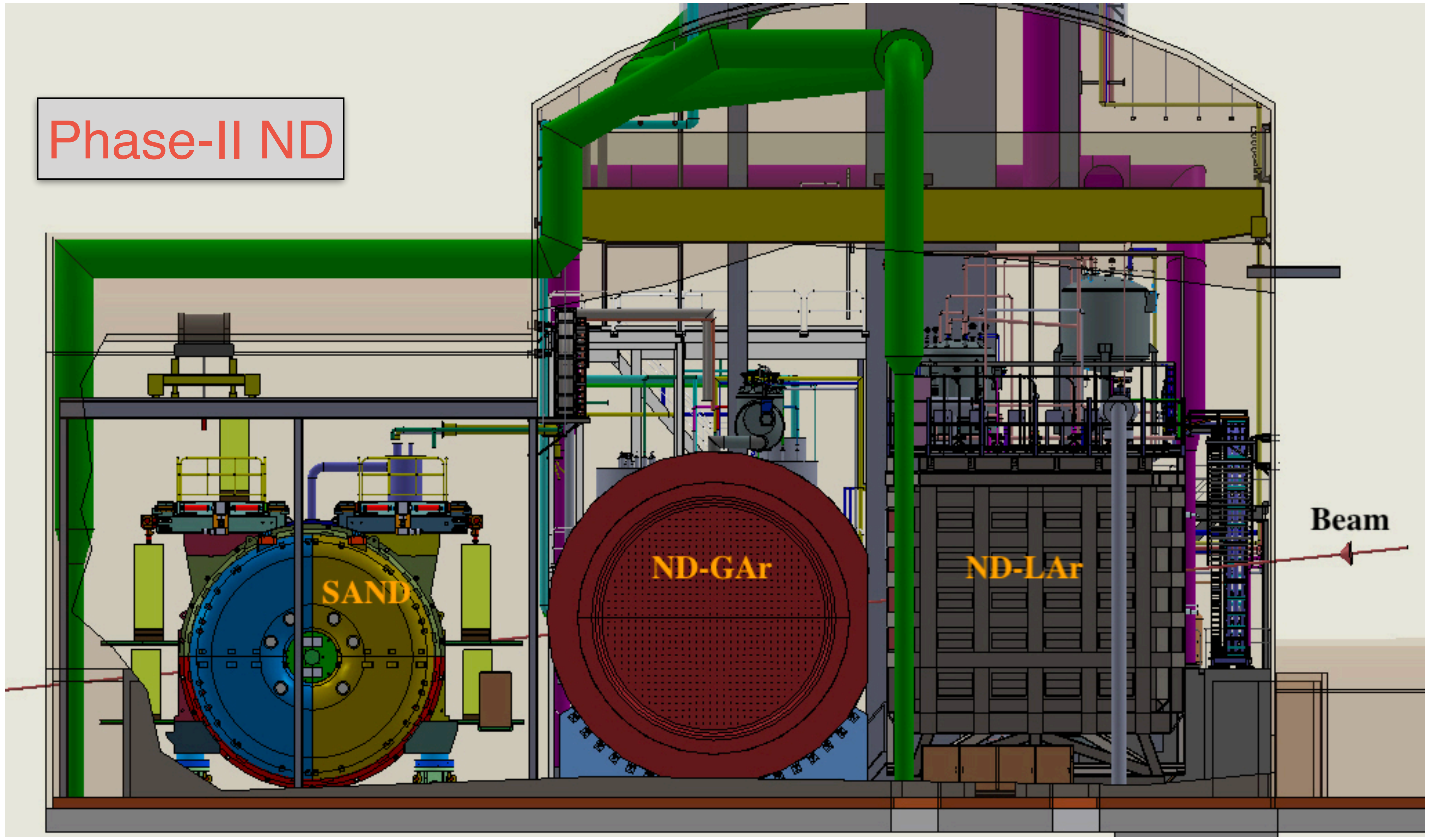
- All leading technologies have identified the main R&D challenges
  - *Technology Readiness Levels (TRL) currently achieved: TRL ≥ 3 on all items*
- They all have small- and medium-scale prototypes in operation or planned
- The ProtoDUNEs at CERN will continue to serve as an important platform to demonstrate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



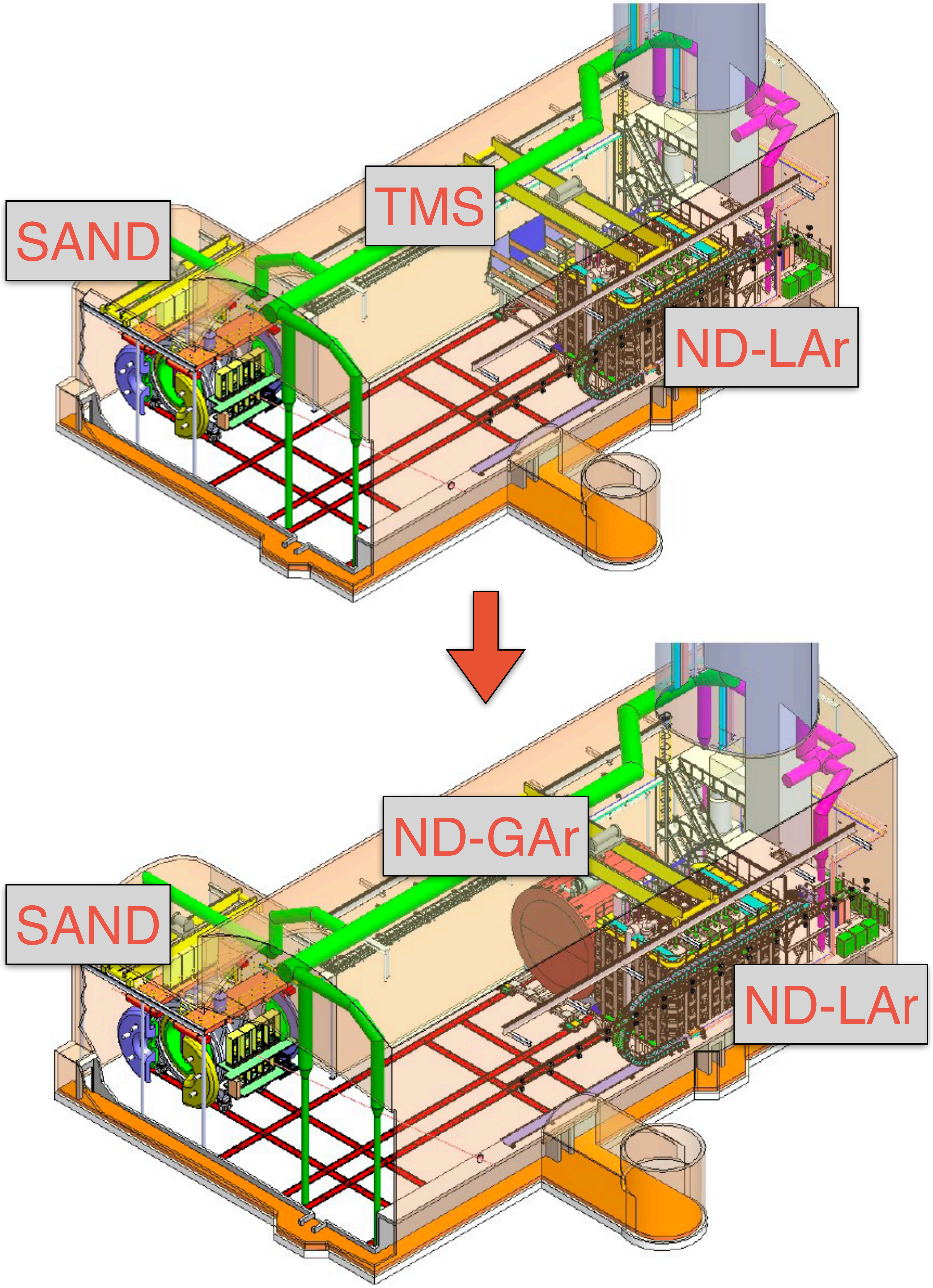
SAND
Tracker, ECAL, Magnet, On axis beam monitor

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

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

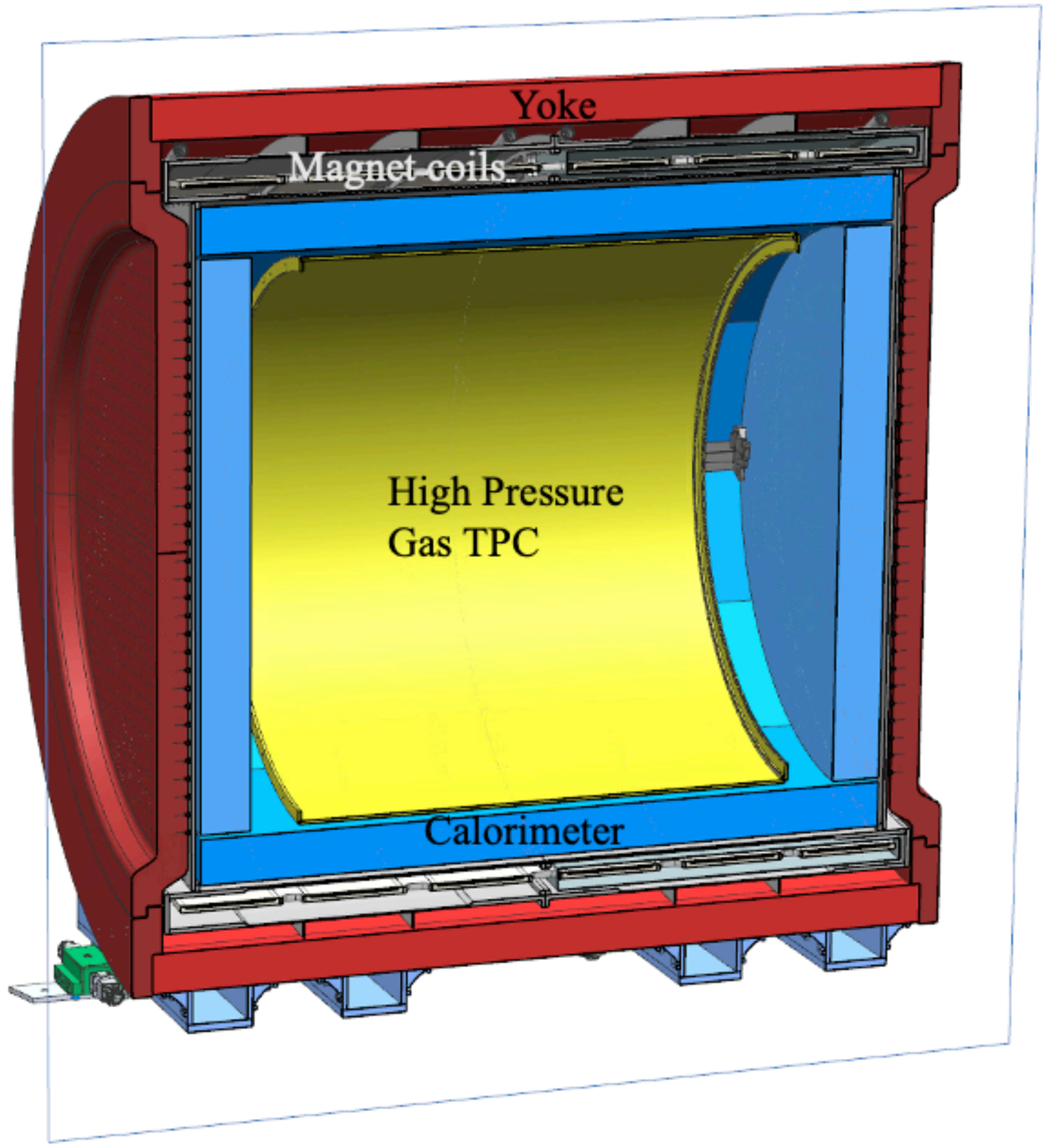
Phase-I → Phase-II ND

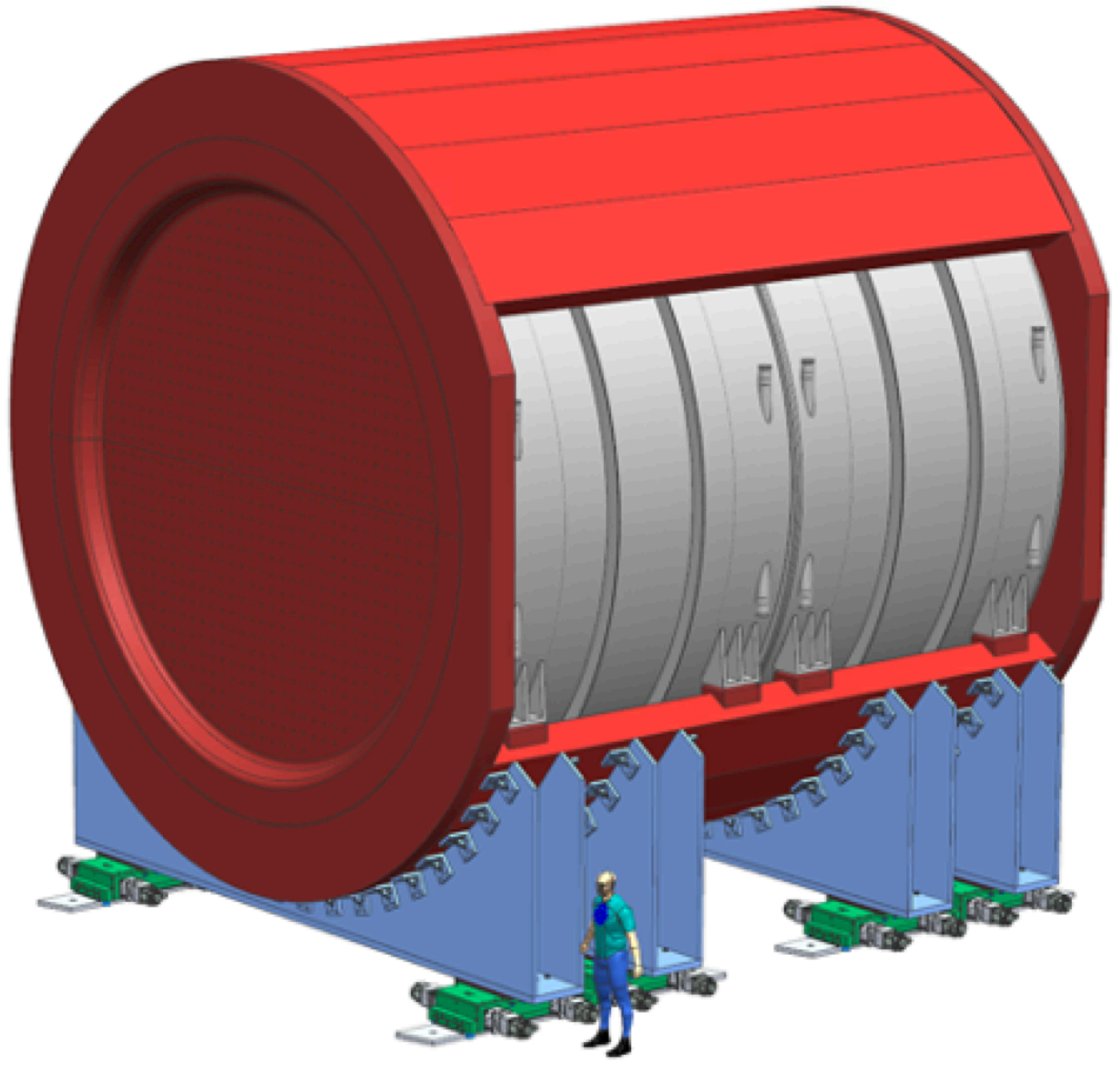
- Gaseous argon detector (ND-GAr) will replace the Temporary Muon Spectrometer (TMS) in DUNE ND Phase-II upgrade
- Upgrades to ND-LAr and SAND are also possible
- If FD4 neutrino target is not Ar (e.g., THEIA), Phase-II ND would need to measure neutrino interactions on those target nuclei
  - *Several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



ND-GAr Baseline Concept

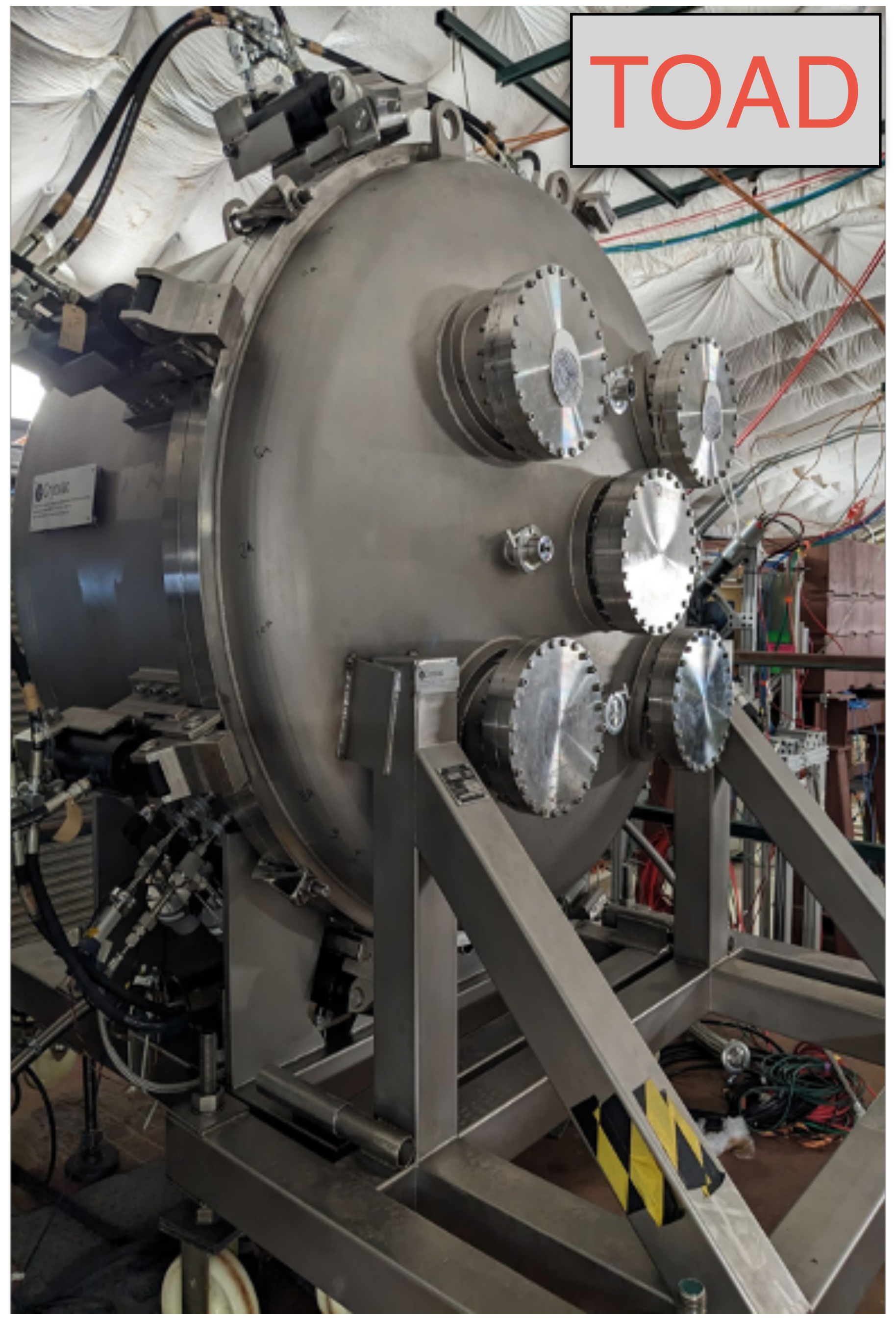
- Cylindrical volume of 5 m linear dimensions filled with gas at 10 bar (~1 ton of Ar)
- Baseline concept includes:
  - *Pressurized gaseous argon TPC*
  - *Surrounding calorimeter*
  - *Magnet: solenoid with partial return yoke*
  - *Muon-tagging system*
- Light detection system maybe necessary to reduce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

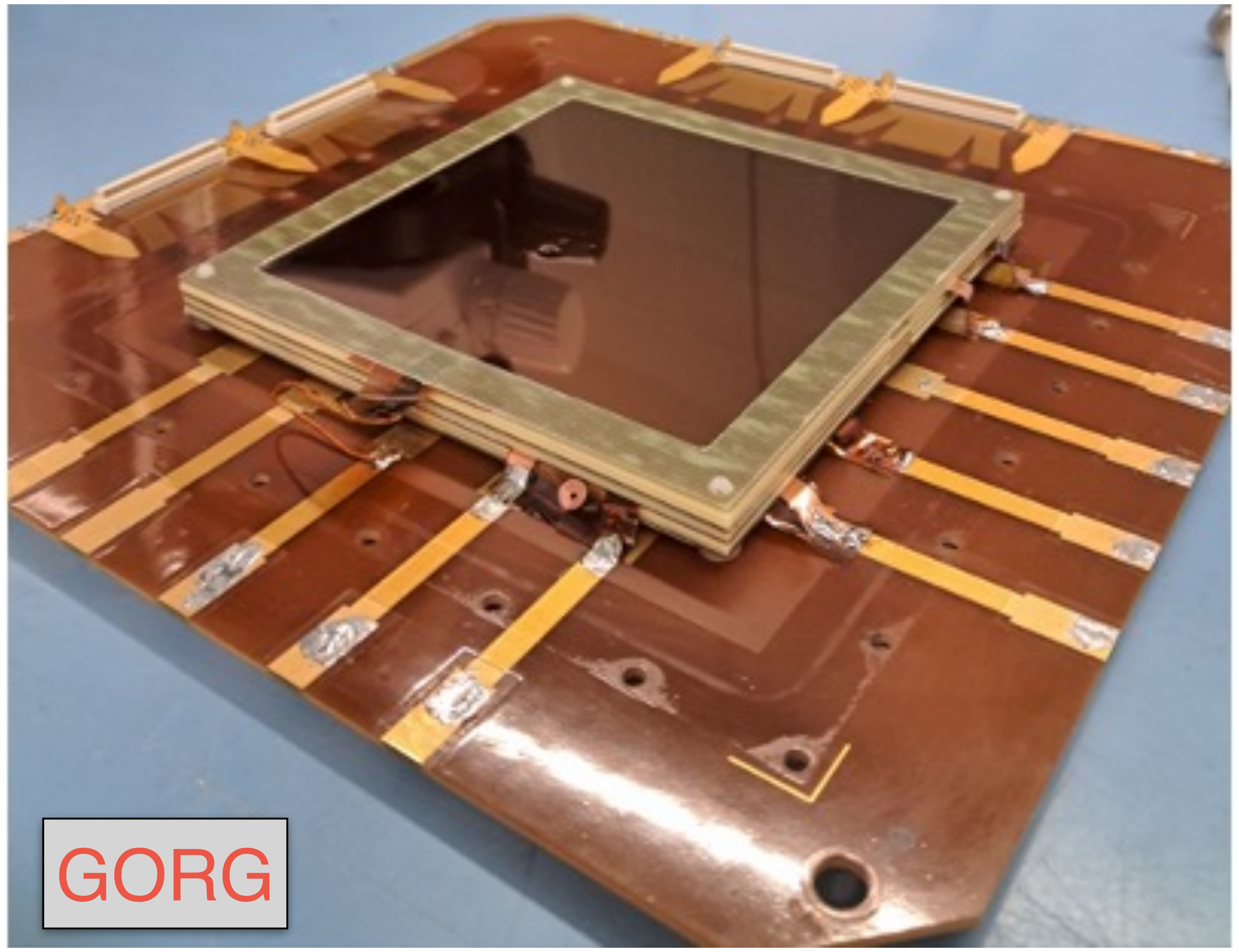




ND-GAr R&D Roadmap

- 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

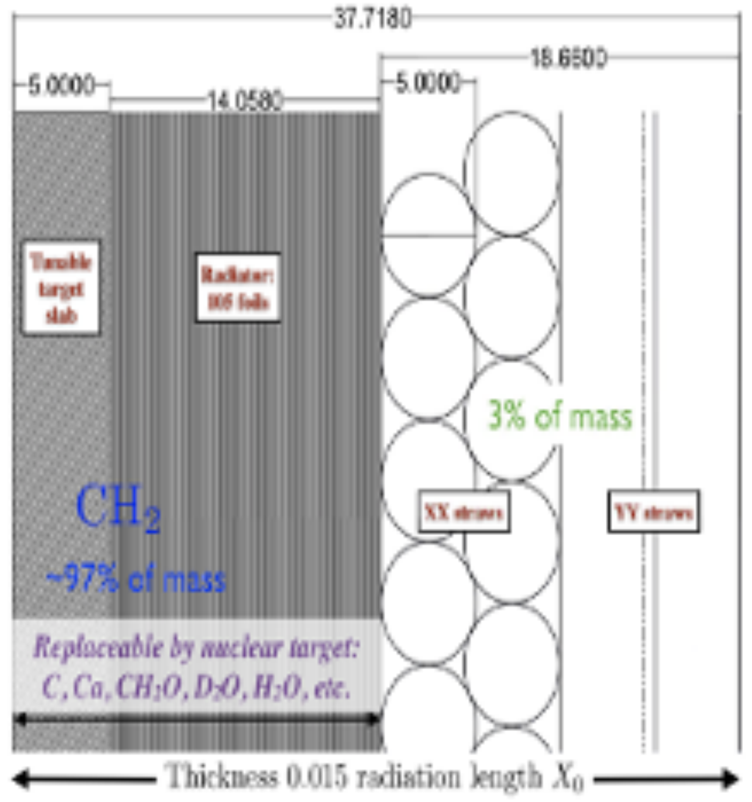




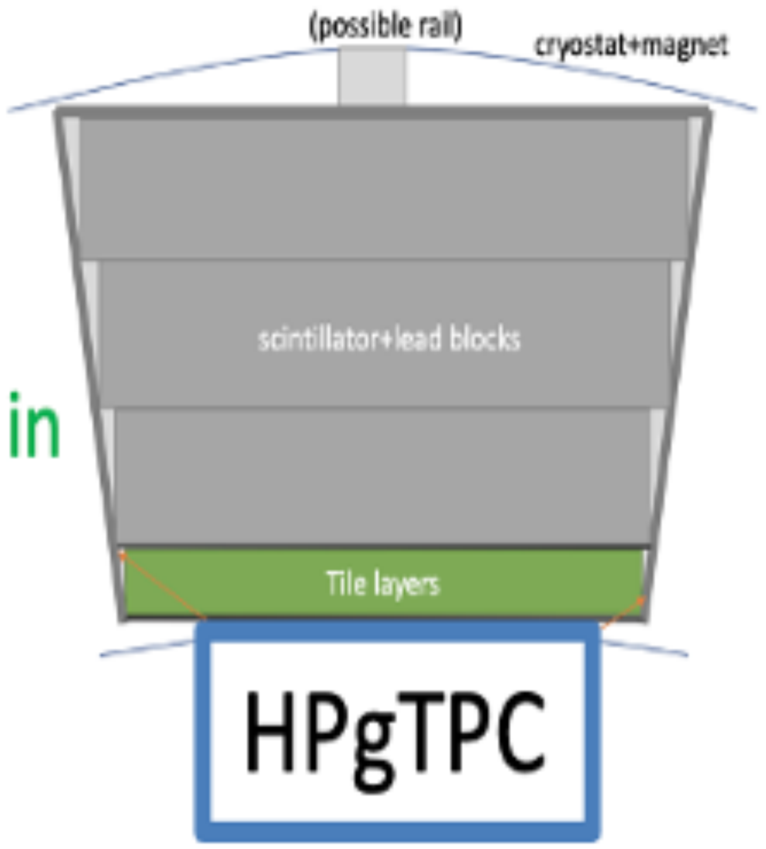
ND Options for Non-Argon Far Detectors

- Several options under consideration

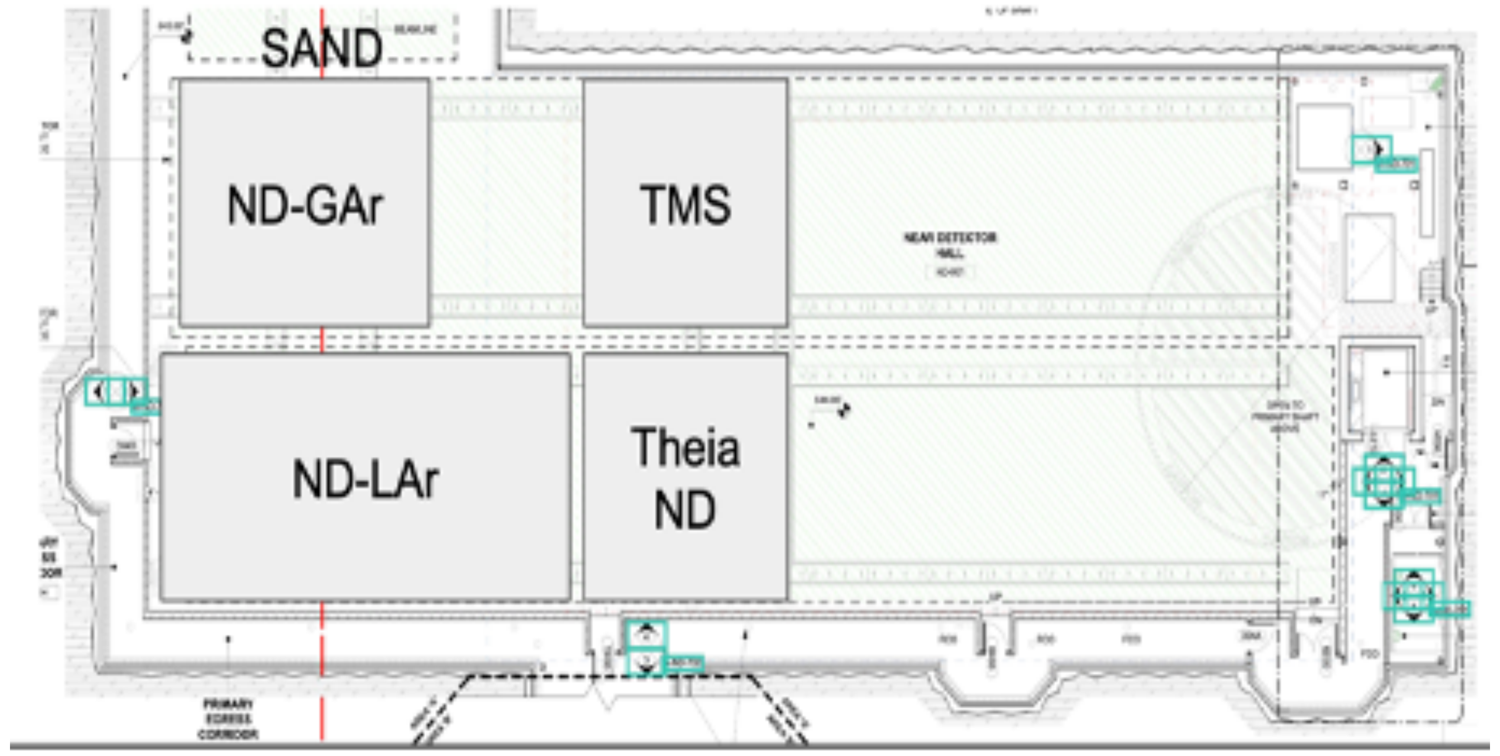
Additional nuclear targets in SAND



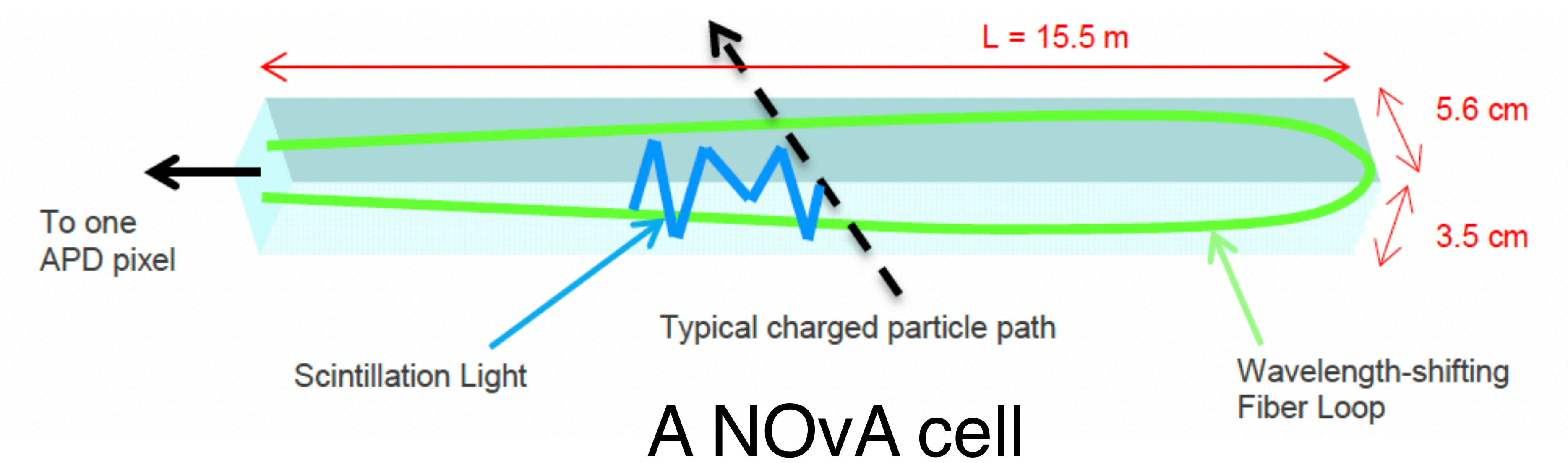
WbLS targets in ND-GAr ECAL



Dedicated Theia ND

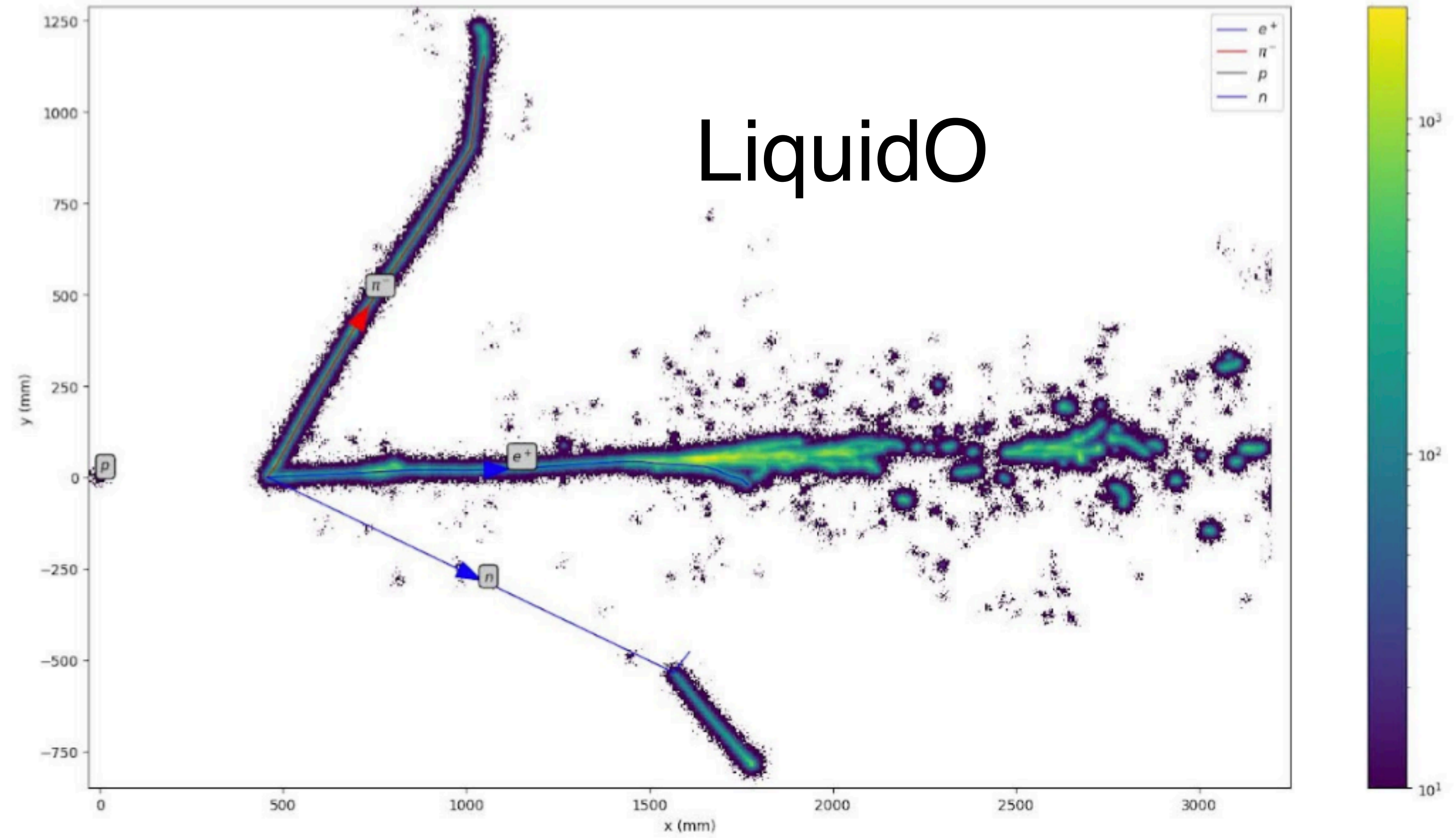


Complexity



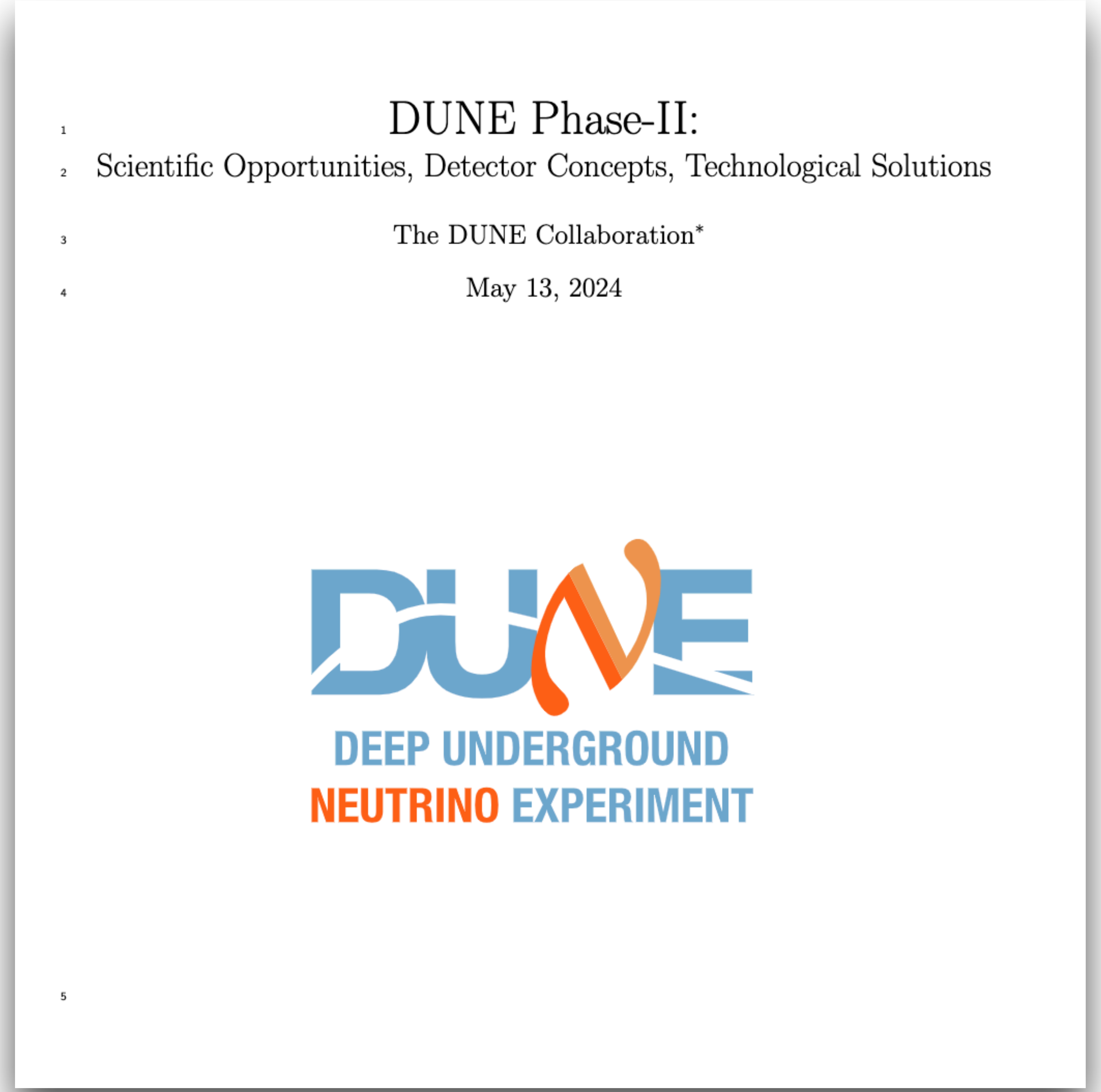
A NOvA cell

- 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



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

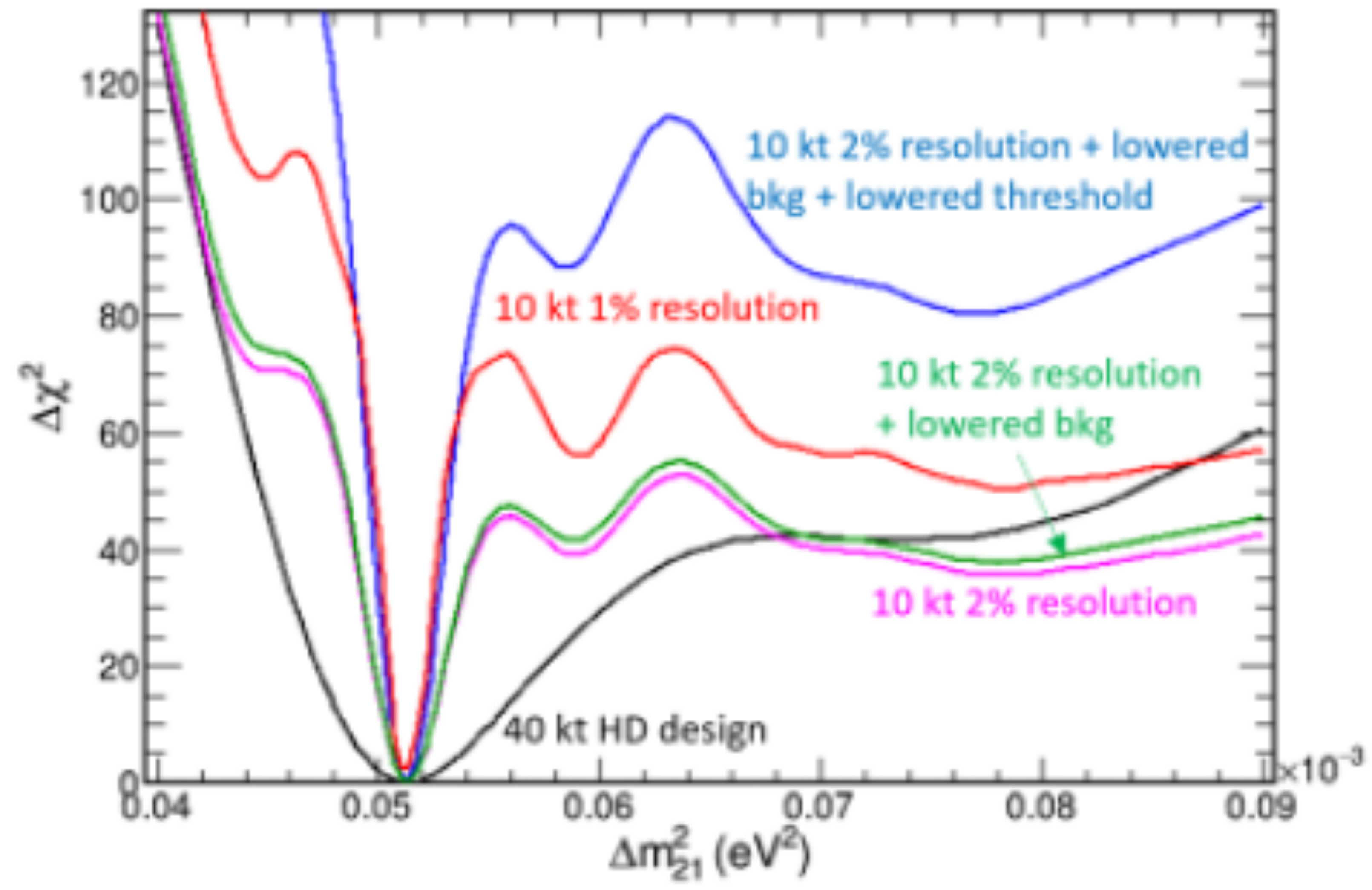
Summary

- **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.

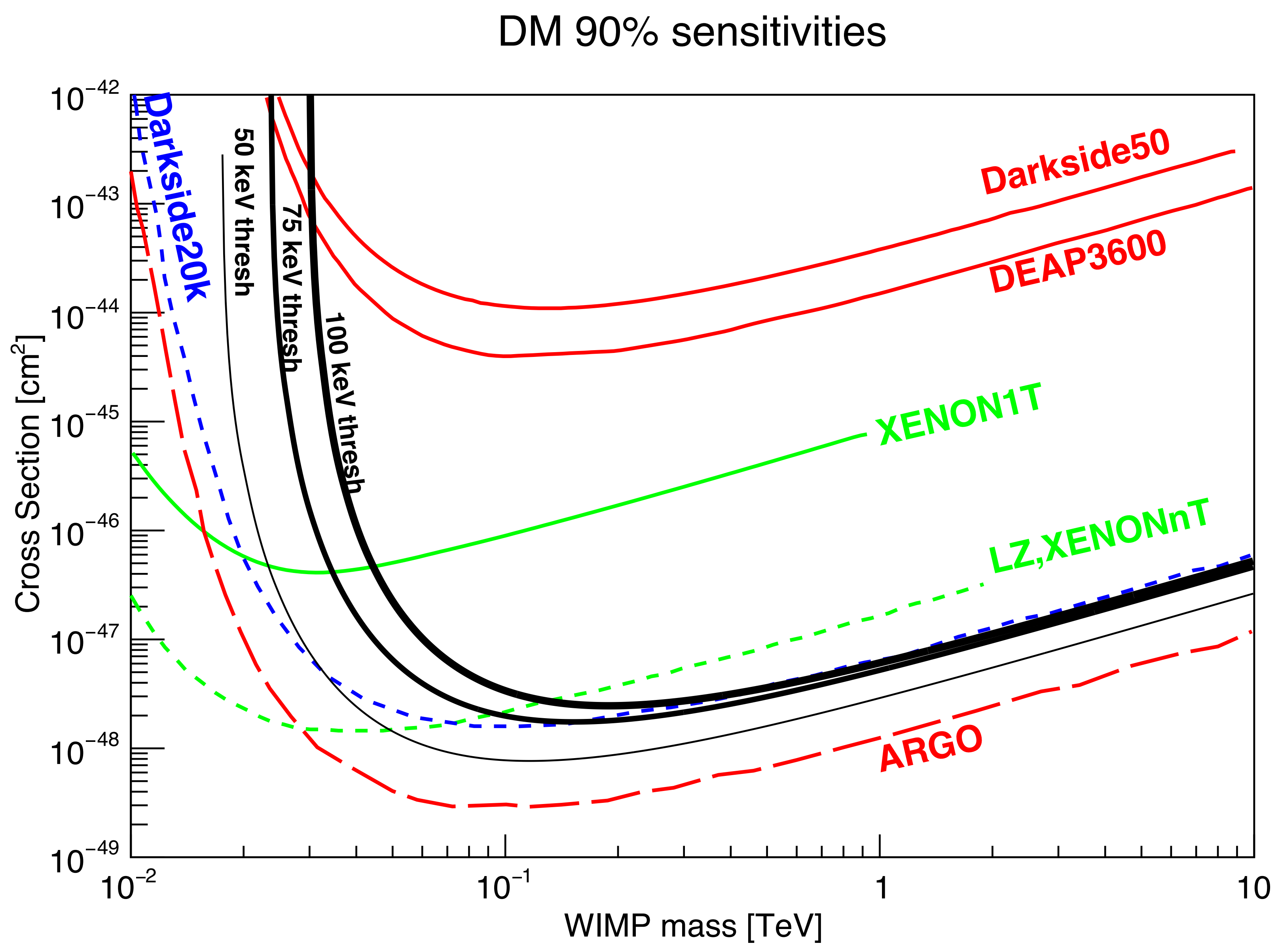
EXTRAS

Physics Enabled by Low Backgrounds

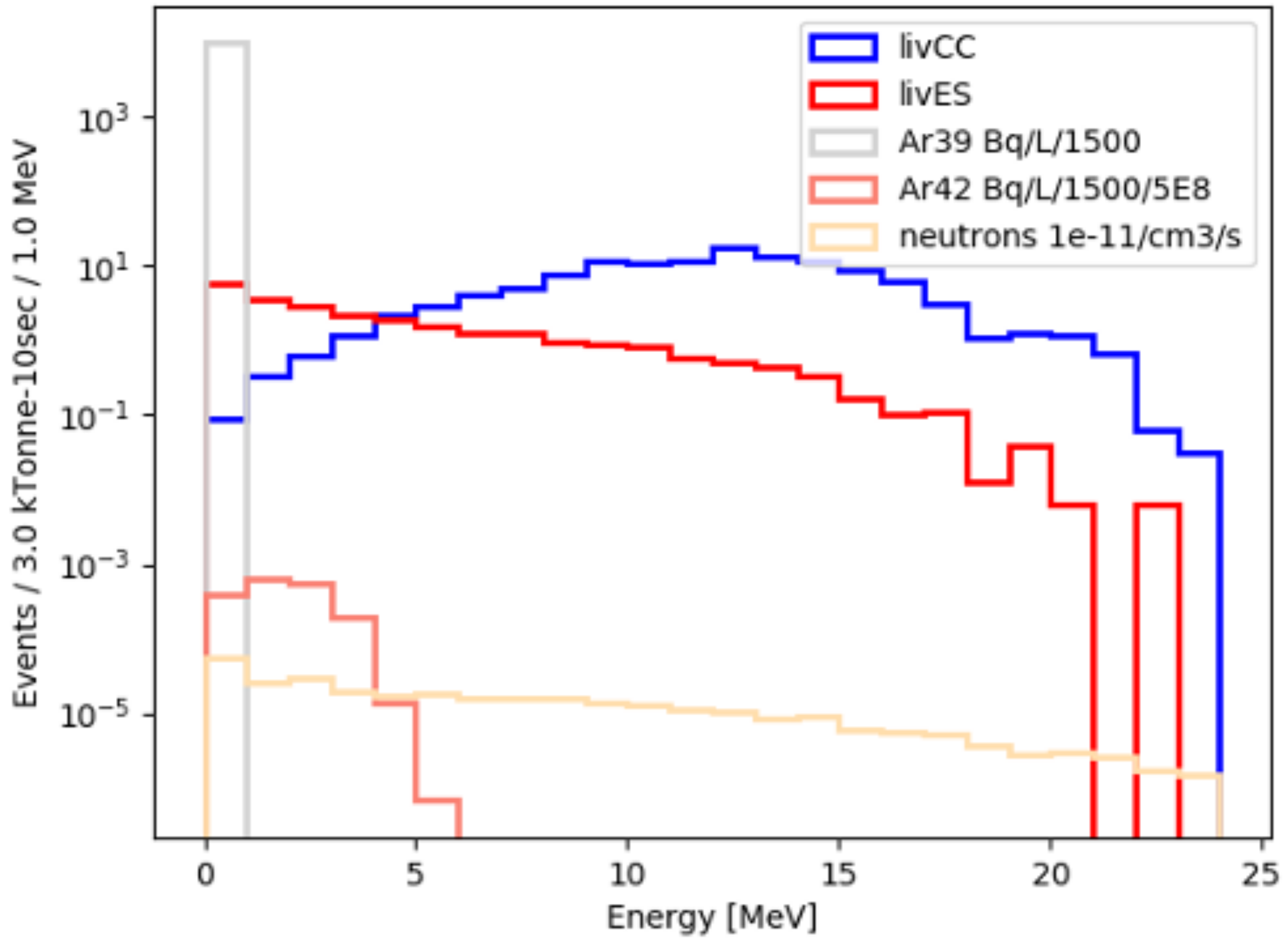
- Example physics enabled by low backgrounds and radio purity control



Solar neutrino parameters tighten up considerably



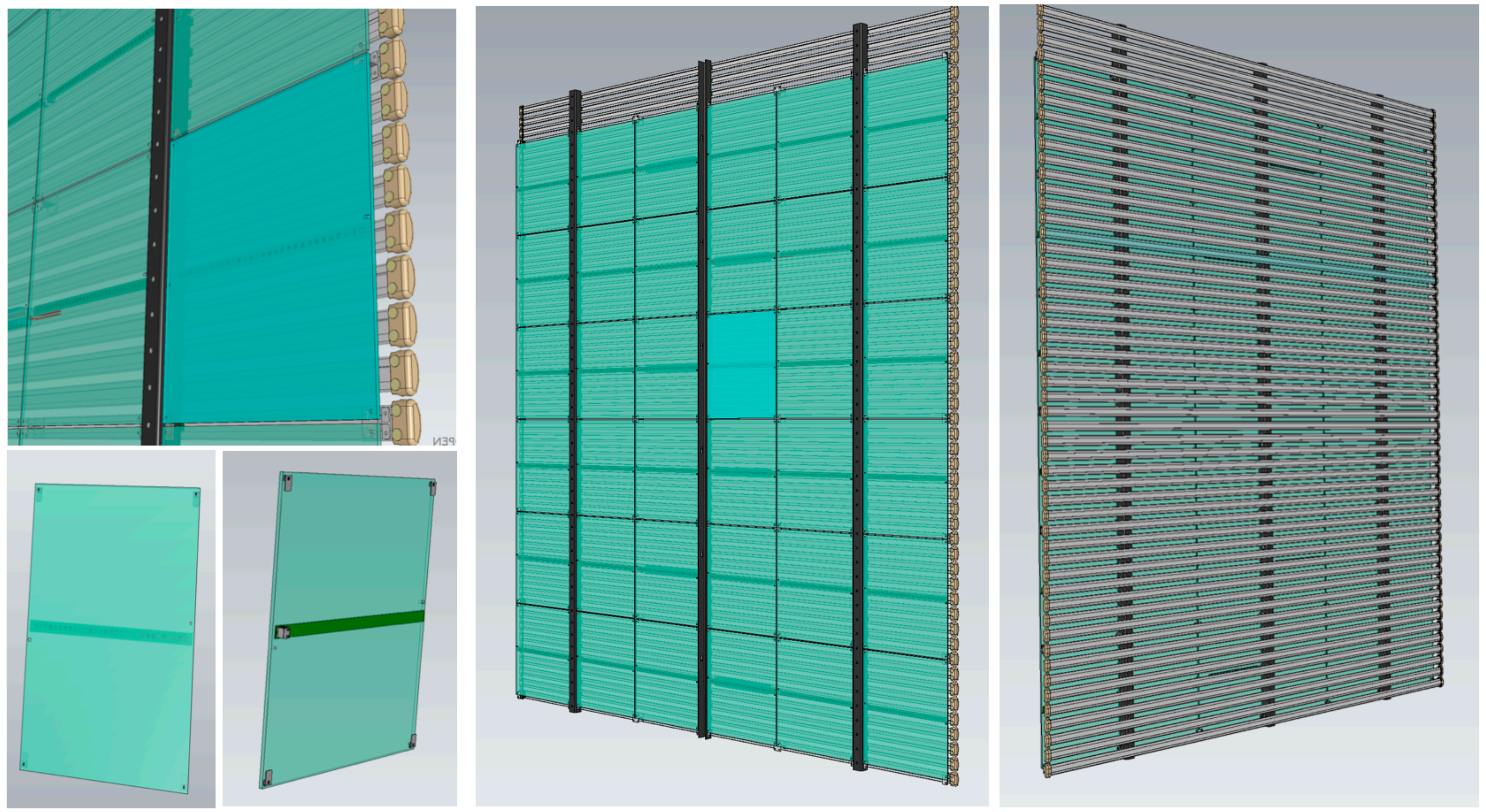
A WIMP search becomes possible with FD module's enormous volume, the interior of which can be fiduciaries and densely instrumented

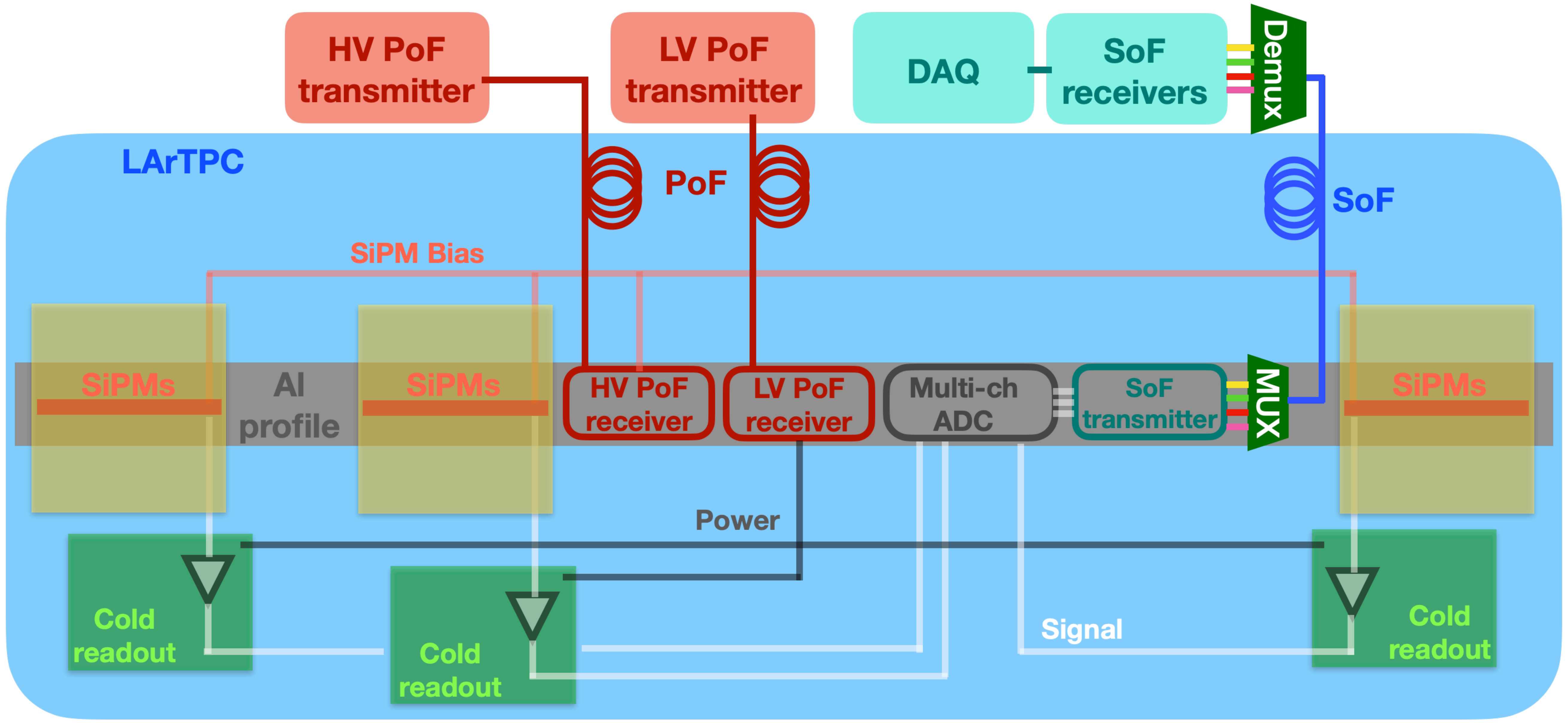


Supernova distance sensitivity and pointing accuracy (due to access to elastics) increases

APEX (Aluminum Profiles with Embedded X-Arapucas)

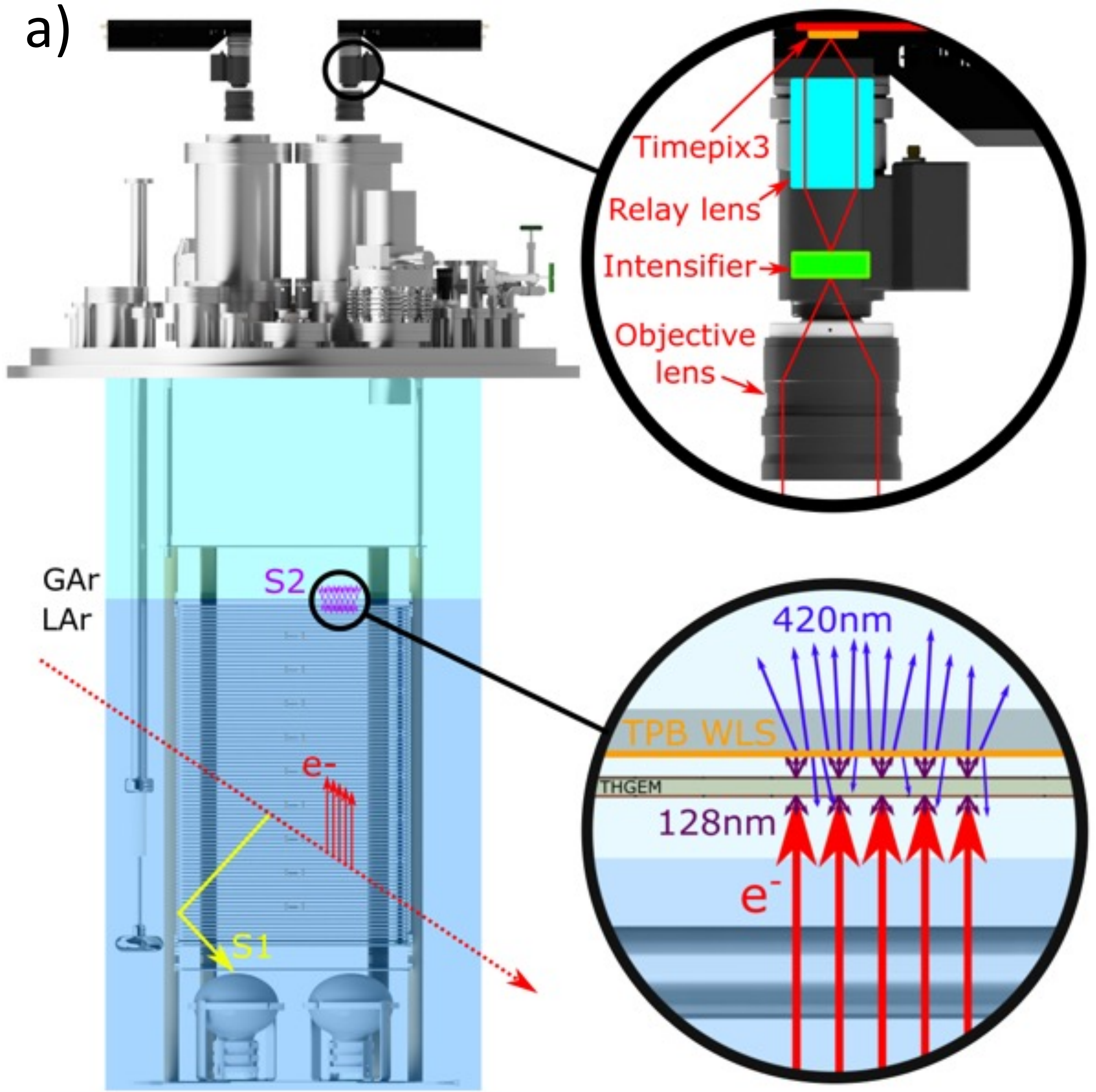
- A fully integrated VD TPC field cage + Photon Detector System
- Keep the same FC structure as designed for the DUNE FD2 VD Module
- Simplify the ARAPUCA concept, and significantly increase photon system coverage
- Expand Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) technologies developed for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

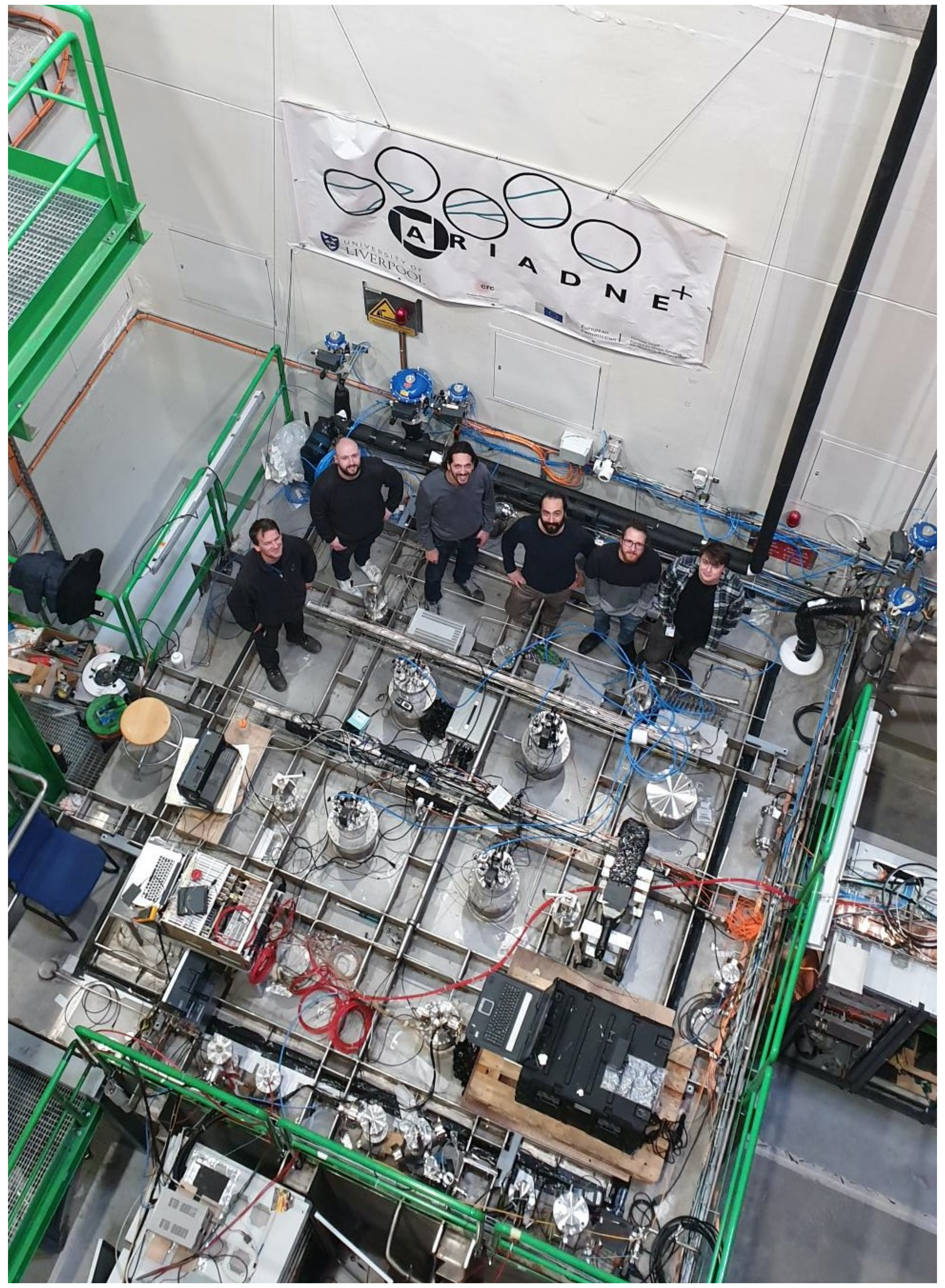




ARIADNE

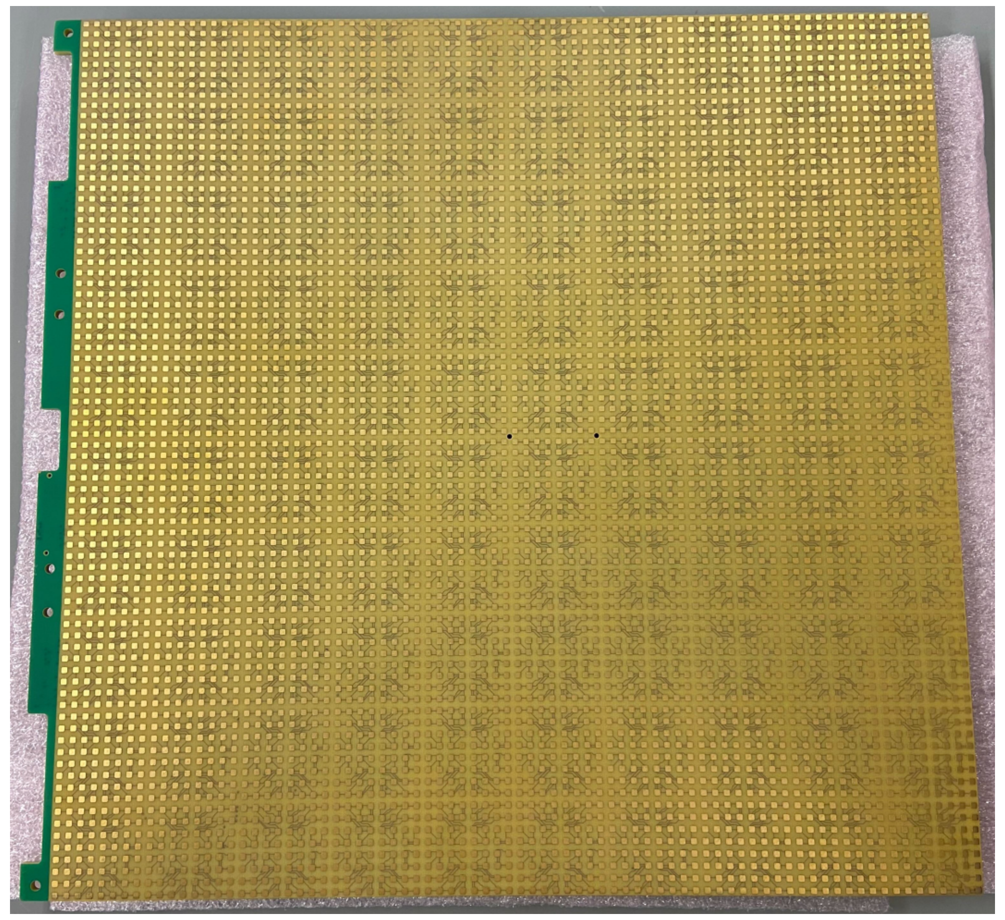
- Optical-based charge readout: S2 light produced in THGEM holes can be captured by fast cameras (eg, TimePIX3) to reconstruct in 3D the primary ionization track
- Successfully prototyped with 1-ton ARIADNE and ARIADNE+

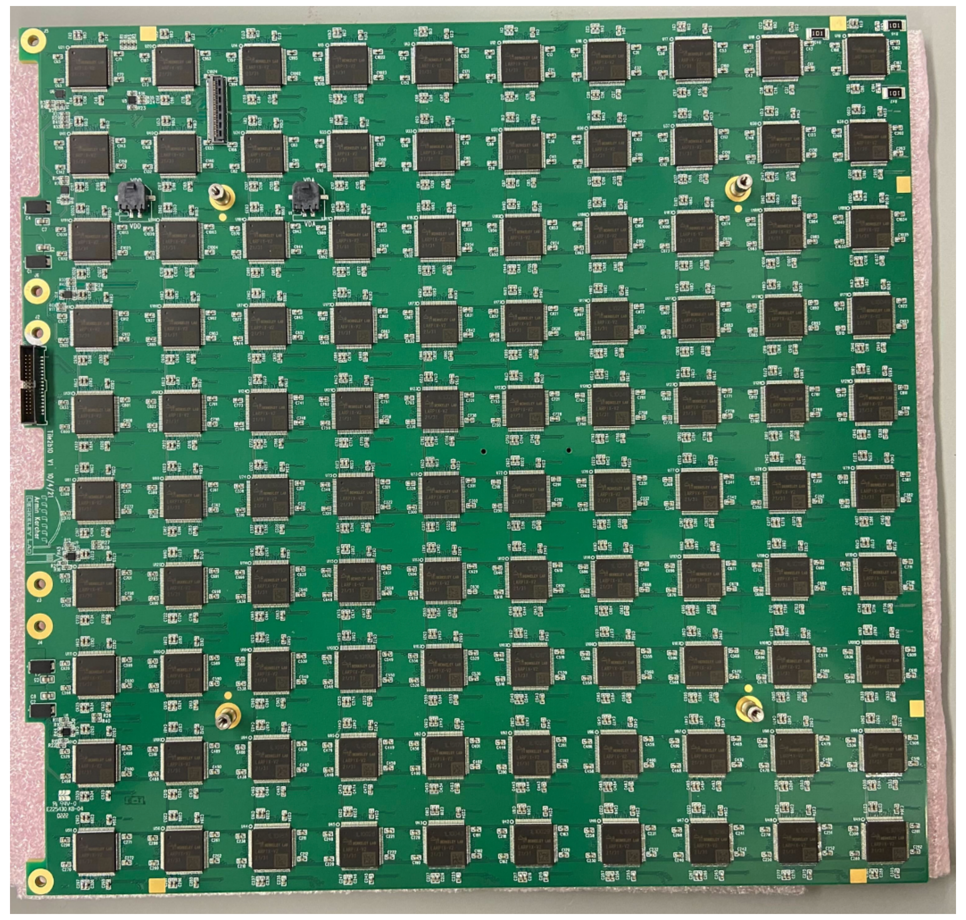




LArPix

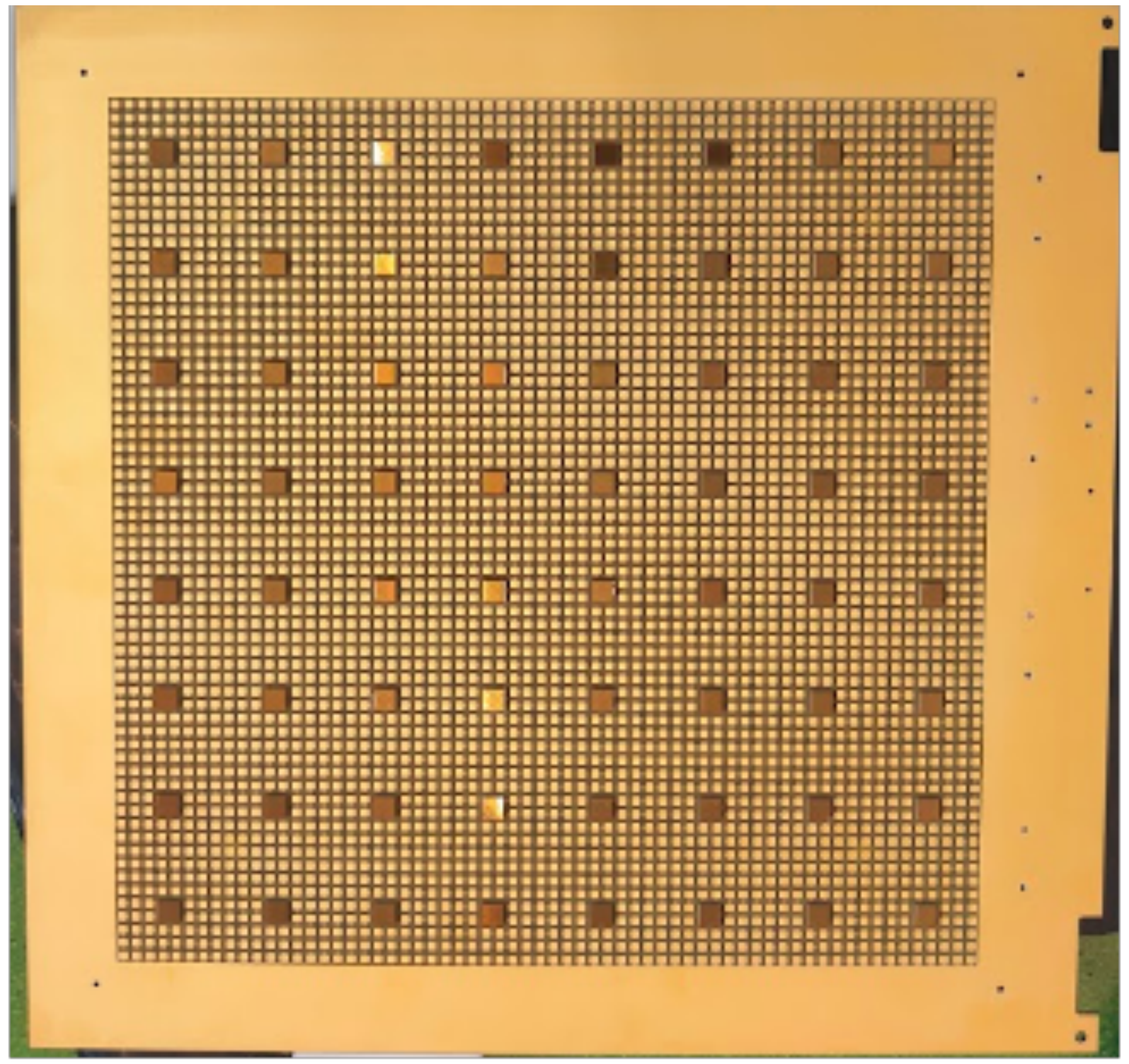
- Complete pixel readout system for LArTPCs, developed for ND-LAr
- Relies on LArPix ASIC, a 64-ch detector system-on-a-chip including analog amplification, self-triggering, digitization, multiplexing, and a configuration controller
- Current LArPix-v2 pixel tile has 32x32 cm^2 size, 6400 pixels at 3.8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

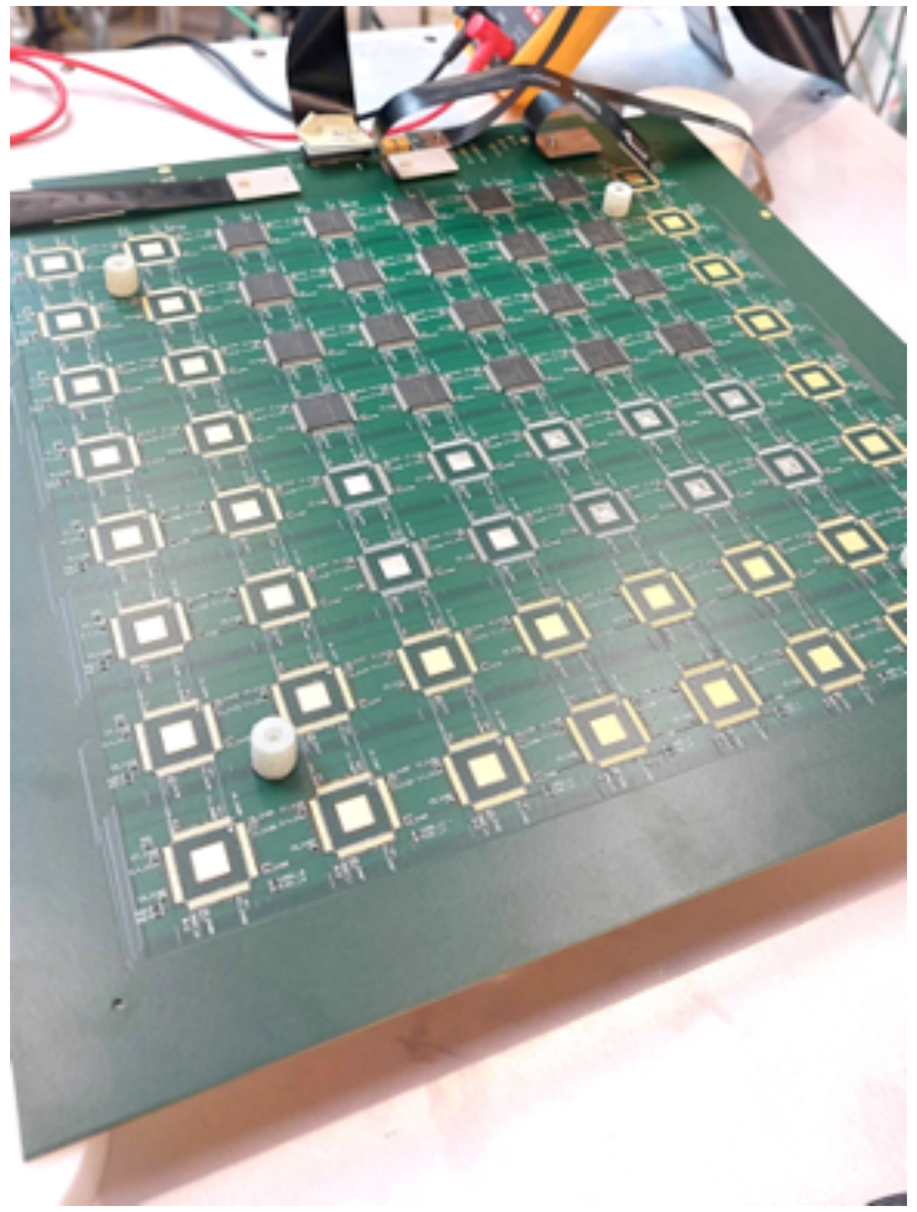




SoLAr

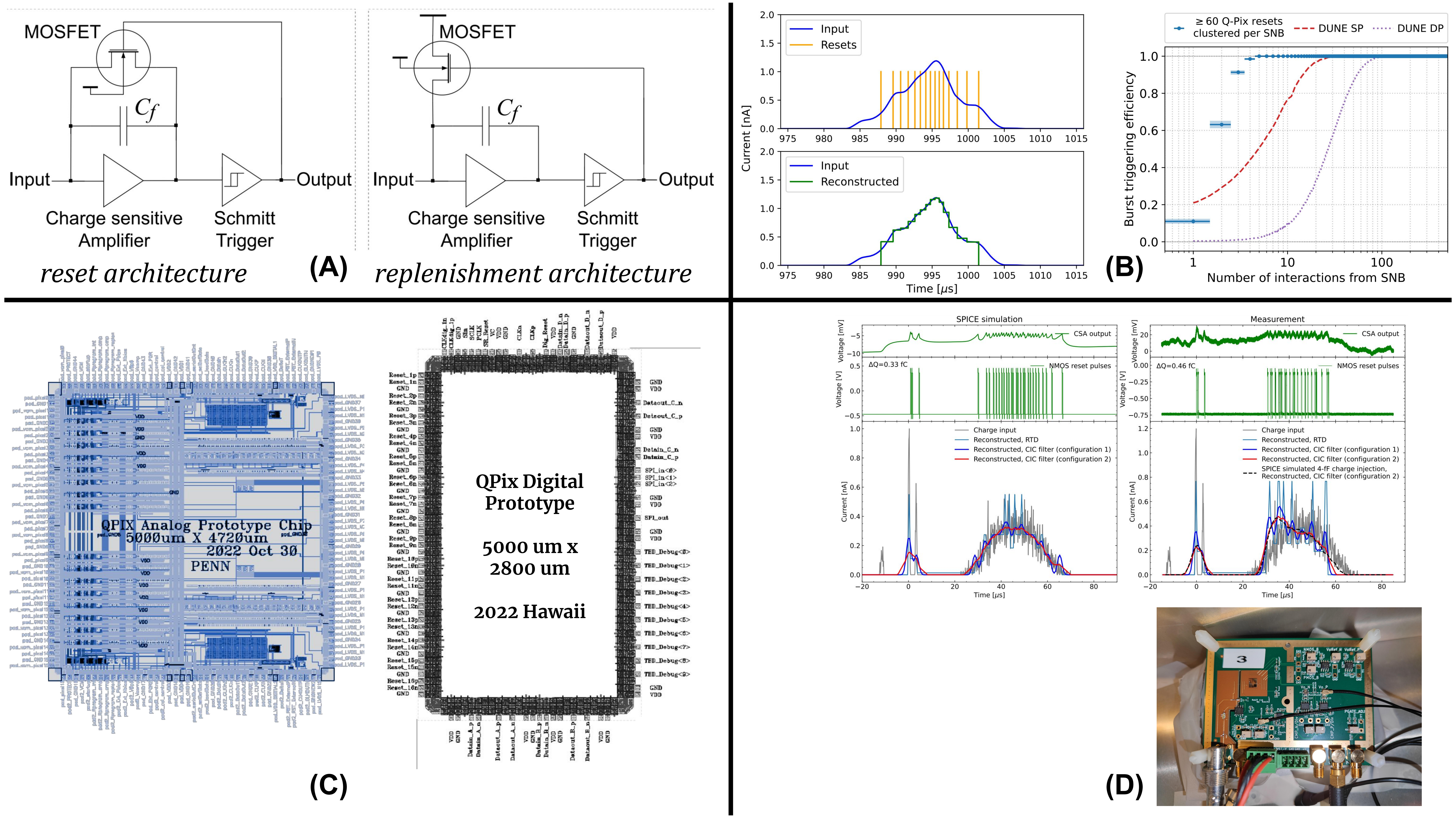
- Integrated array of VUV SiPMs on pixelated anode
- Online localized triggering for dealing with high data rates
- Existing prototypes:
  - *SoLAr v1: 7x7 cm² anode plane, 16 VUV SiPMs, 3.5 mm pitch, 4 LArPix v2a chips*
  - *SoLAr v2: 30x30 cm² anode plane, 64 VUV SiPMs, 4 mm pitch, 20 LArPix v2b chips*





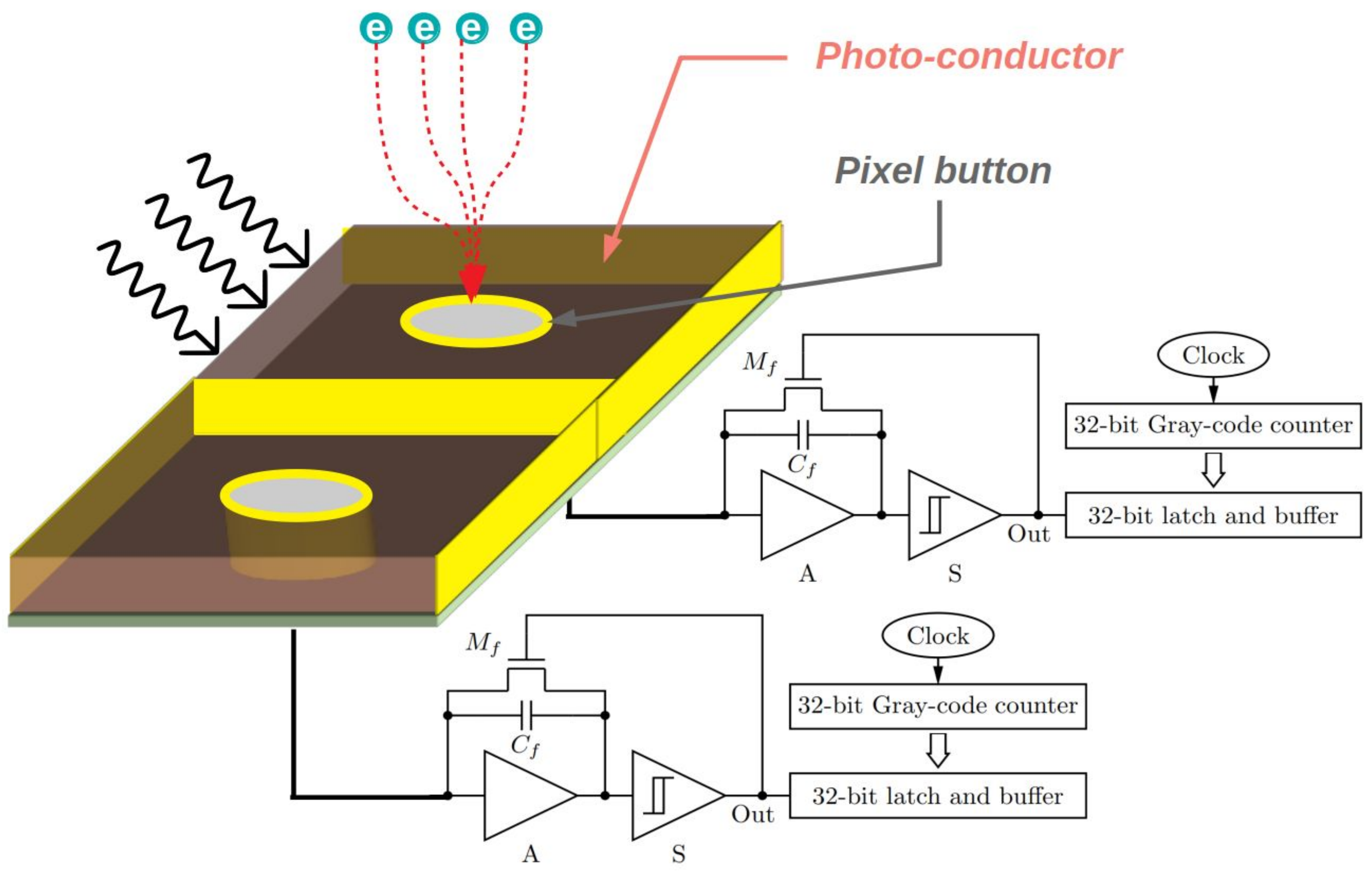
Q-Pix

- 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

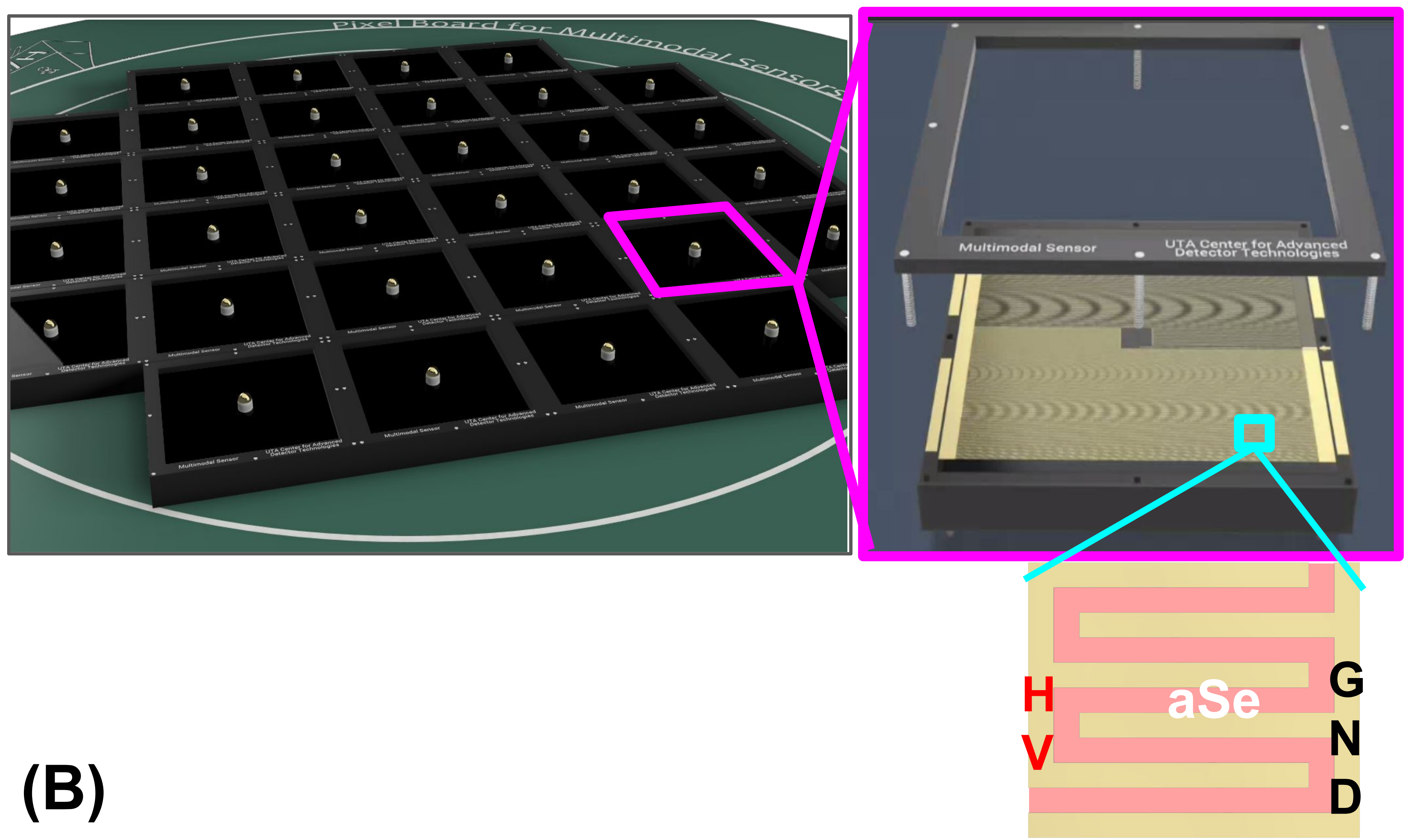


Q-Pix Light

- 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



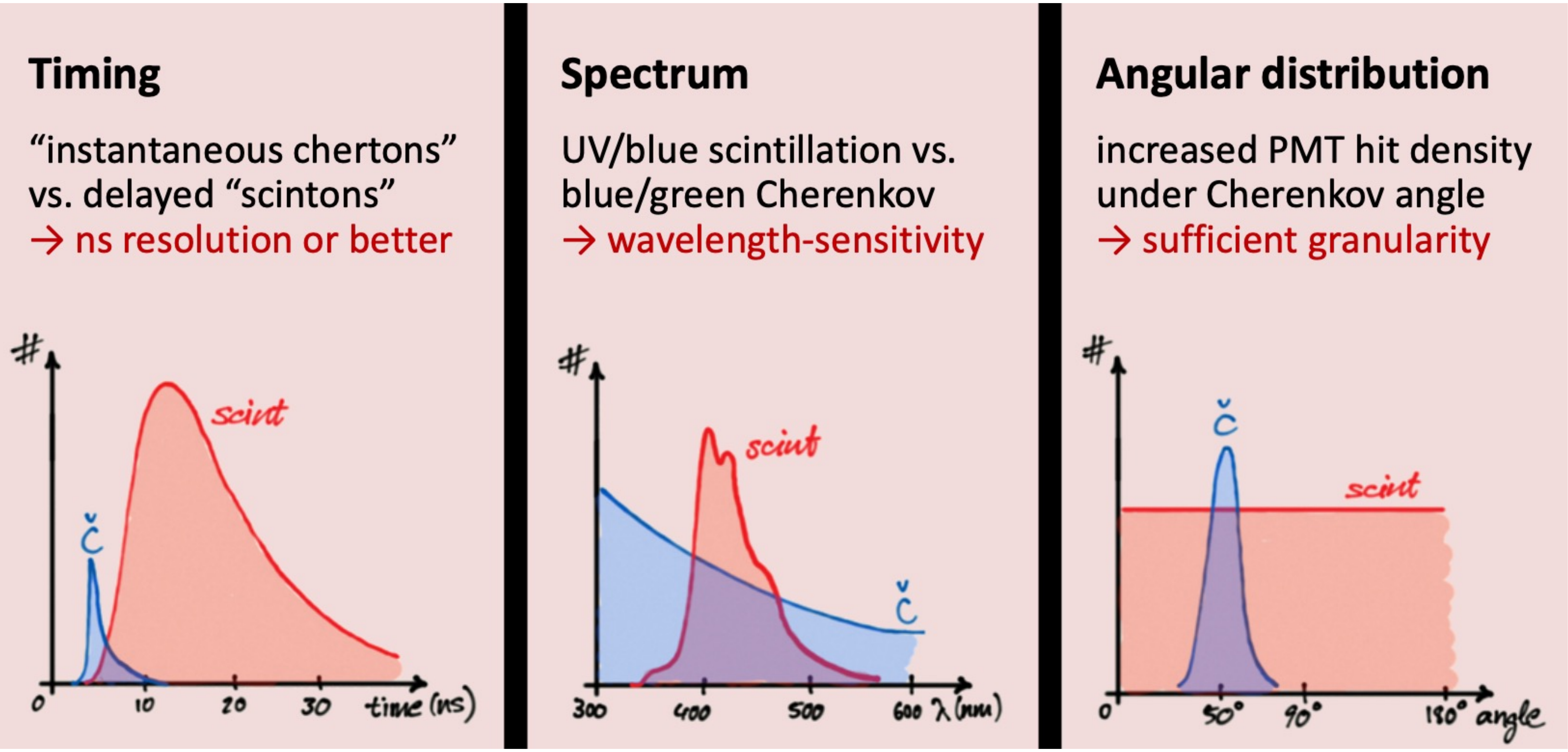
(A)

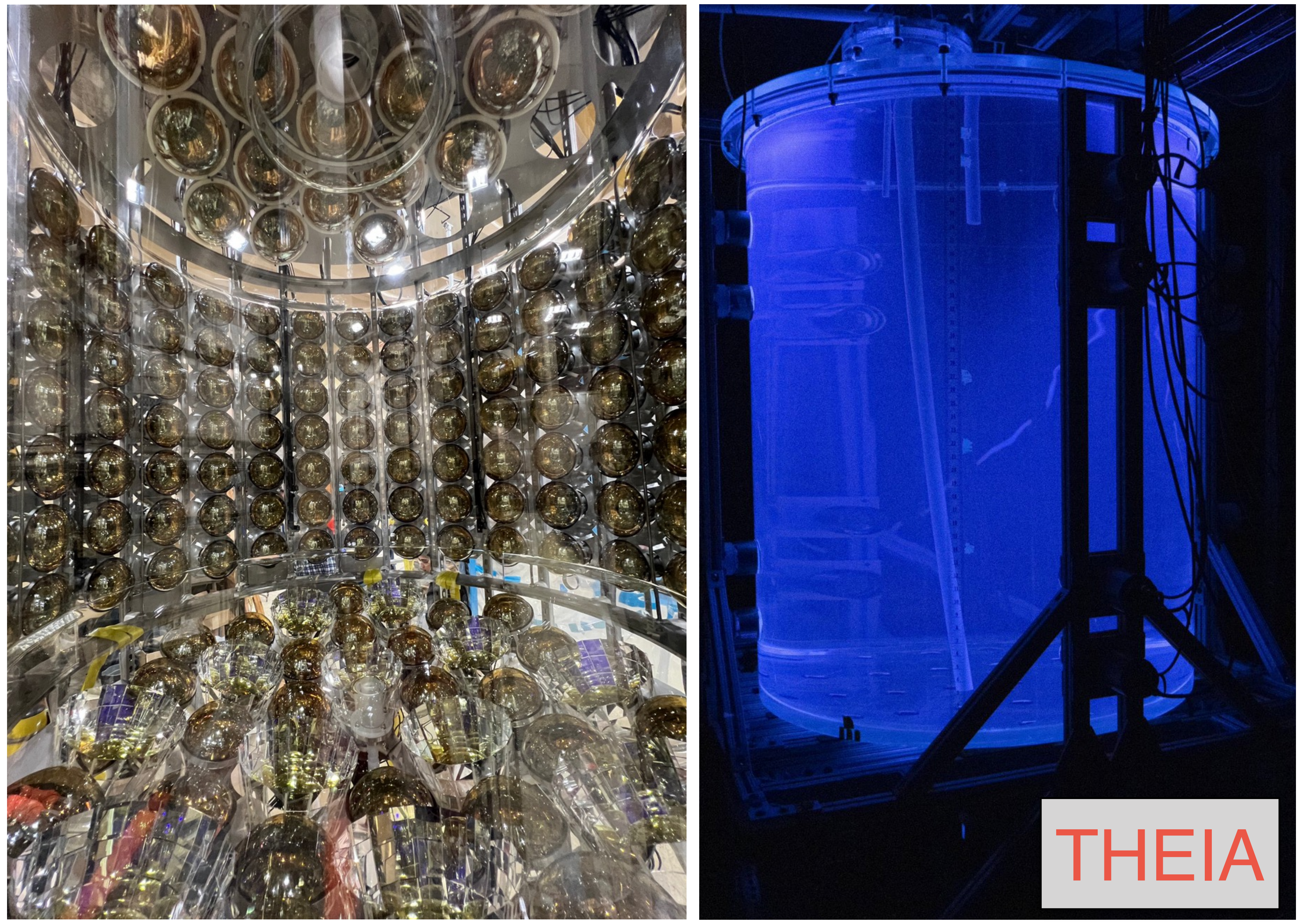


(B)

THEIA

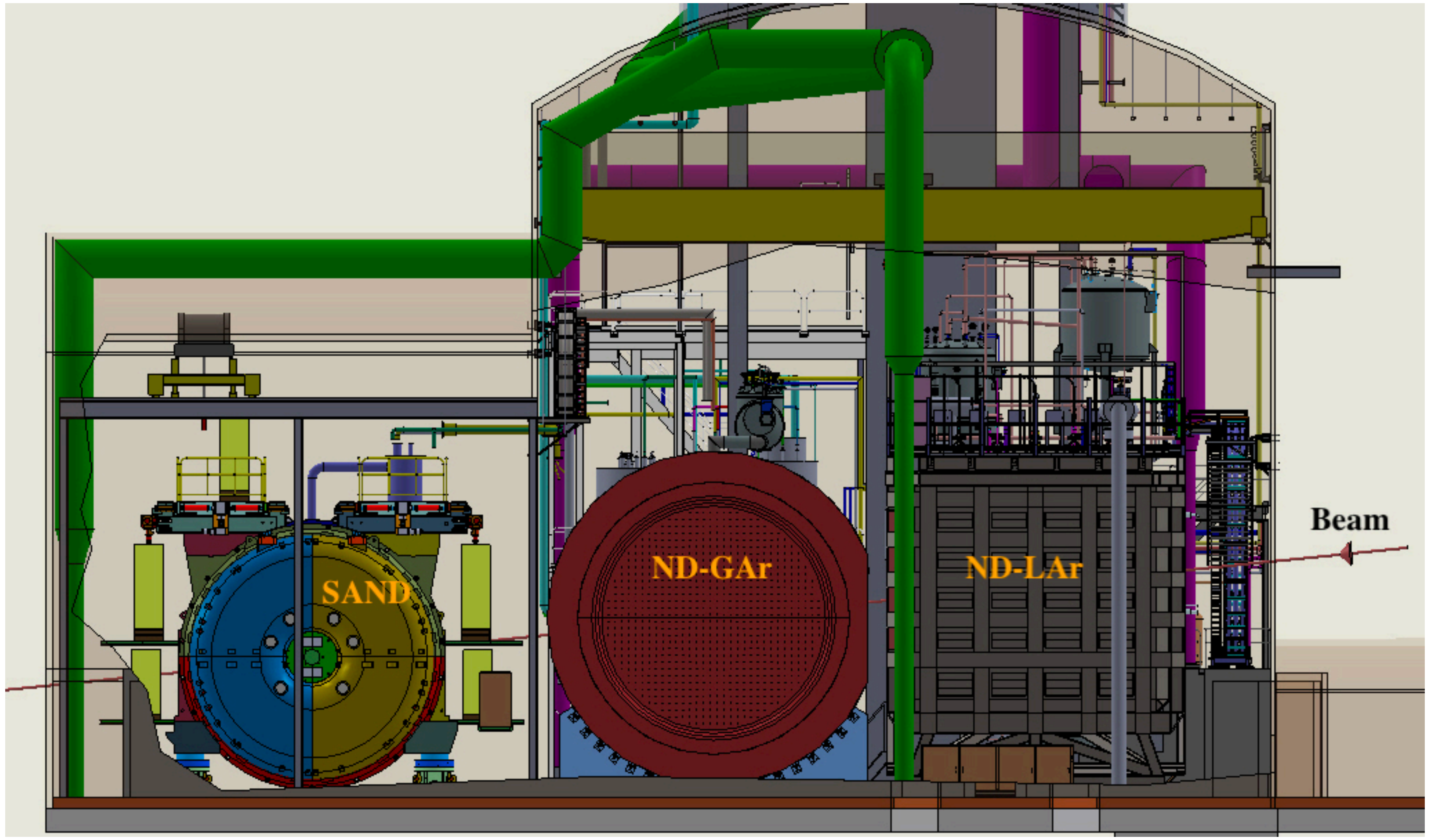
- THEIA technologies: WbLS, fast photon detectors (PMTs or LAPPDs) and dichroic filters
- THEIA prototypes: 1-/30-ton at BNL, EOS at LBNL, ANNIE at Fermilab, BUTTON at Boulby
- Hybrid optical technology: practical Cherenkov/Scintillation light separation





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*