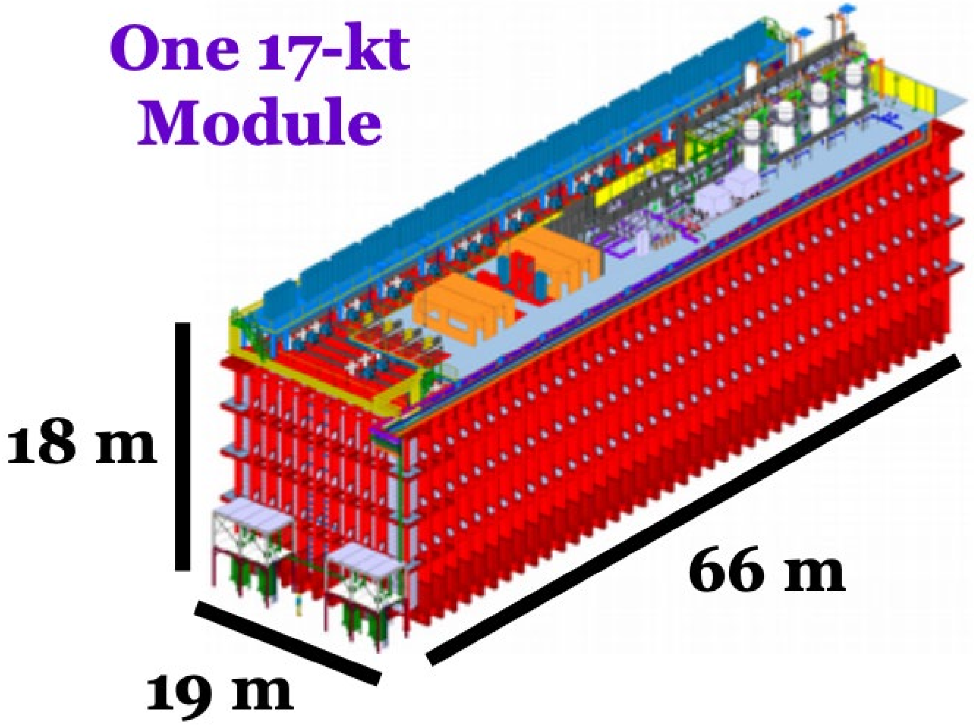
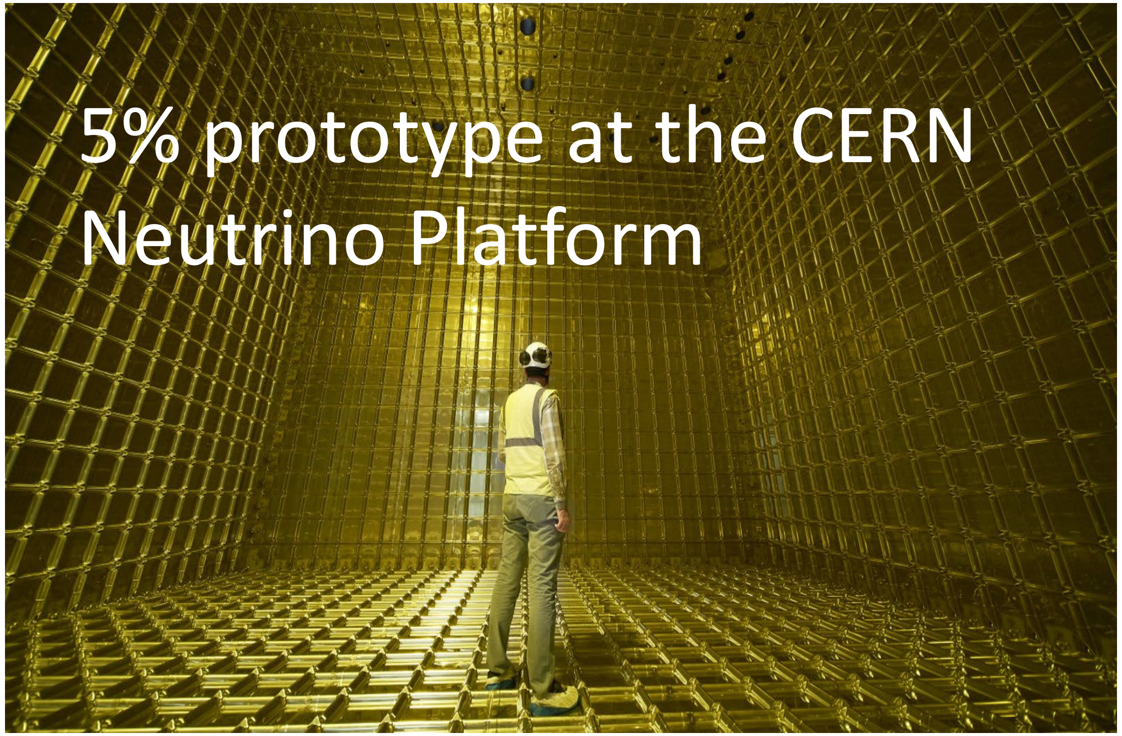
DUNE Far Detectors – Phase II

Mary Bishai, Brookhaven Lab (for the DUNE Collaboration)

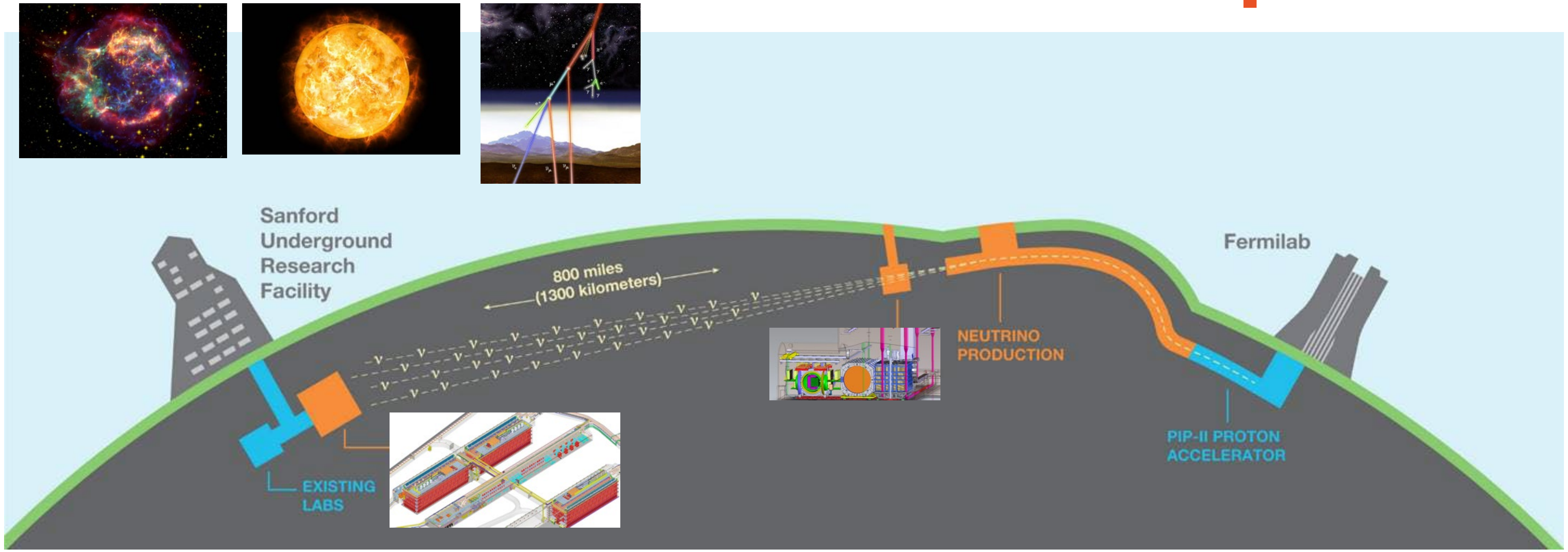
P5 Townhall Meeting, Fermilab

March 21, 2023





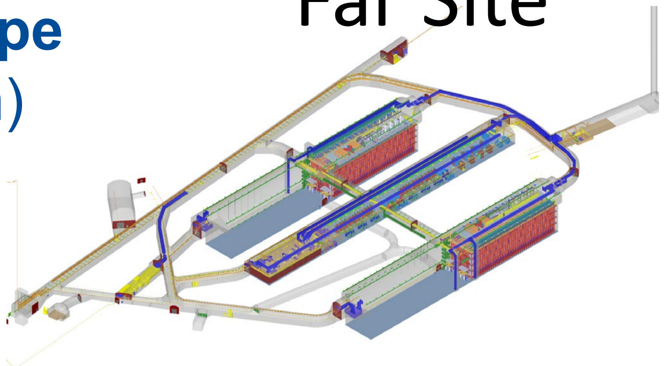
Reminder: Full DUNE scope

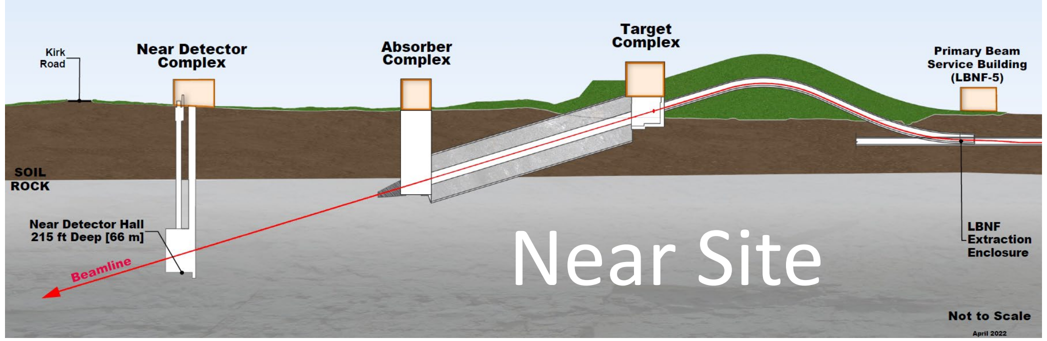


- The <u>complete</u> DUNE detector
  - <u>***Four Far Detector 17 kton LAr TPC modules***</u> with ≥ 40 kt fiducial volume.
  - A Near Detector which includes a liquid-argon TPC.
  - A 1.2 MW beam <u>upgradeable to 2.4 MW</u>.

LBNF/DUNE-US Project Scope
(see C. Mossey's presentation)

Far Site



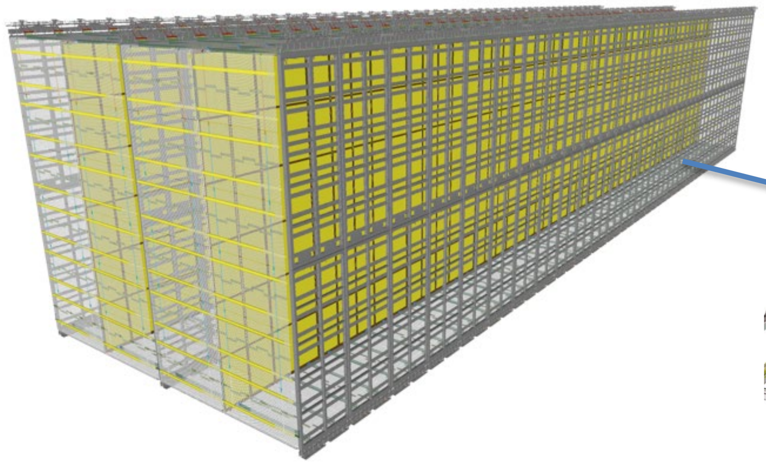


LBNF/DUNE-US Project Scope

	Component	DOE Project Scope (meets 2014 P5 minimum to proceed – Phase I)	Phase II Requirements (meets 2014 P5 goal)
Near Site	Conventional Facilities	• Constructed to support 2.4MW primary and neutrino beamline • Constructed to support underground Ph I & II Near Detector	• NONE
	Neutrino Beamline	• Wide-band output neutrino beam, 1.2MW initially, designed to be upgradeable to 2.4MW	• 2.4MW capable target and new horns • New decay pipe window • Some additional cooling and instrumentation
	Near Detector	• US contribution to the DUNE Near Detector (Ph I)	• US contribution to more capable Near Detector (Ph II)
Far Site	Conventional Facilities	• Surface and underground facilities & infrastructure for 4 detector modules	• NONE
	Cryostats	• For 2 detector modules (CERN)	• For 2 detector modules
	Cryogenics	• 3 x nitrogen units; 35 kton liquid argon for detector modules	• 1 x nitrogen unit; 35 kton liquid argon for detector modules
	Far Detector	• US contributions to 2 x DUNE LAr TPC modules	• US contributions to 2 x DUNE LAr TPC modules

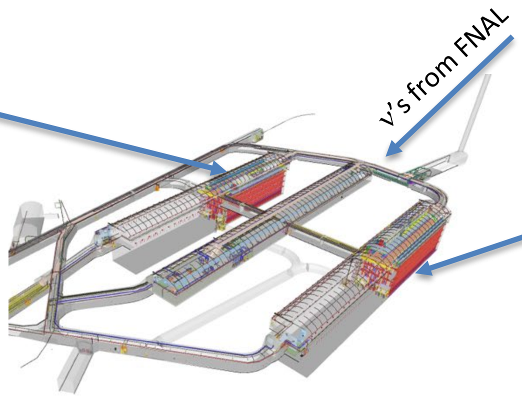
DUNE – Phase I Far Detectors (presentation by S. Zeller)

- ***LBNF has provided caverns at SURF + most of the cryogenic infrastructures for 4 detector modulesl (each with a FV ≥ 10Kt) in Phase I***
  - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and MicroBooNE)
  - 2nd detector will go into SE cavern and has vertical drift (capitalizing on elements of the dual phase development)

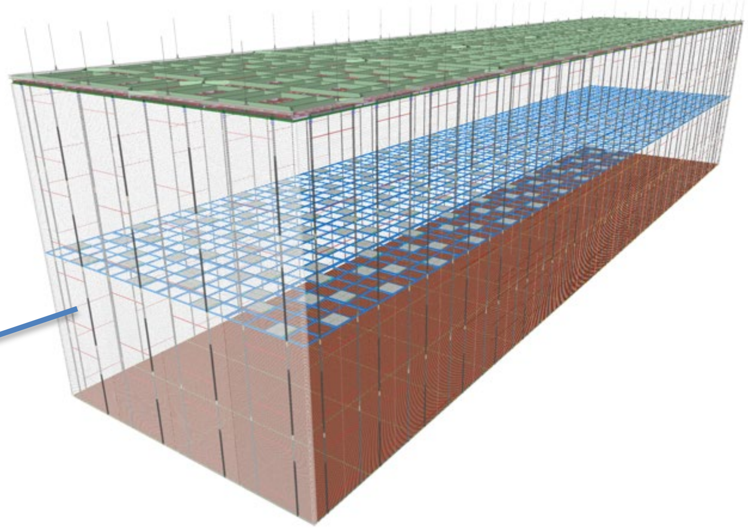


APA* Horizontal Drift

*Anode Plane Assemblies



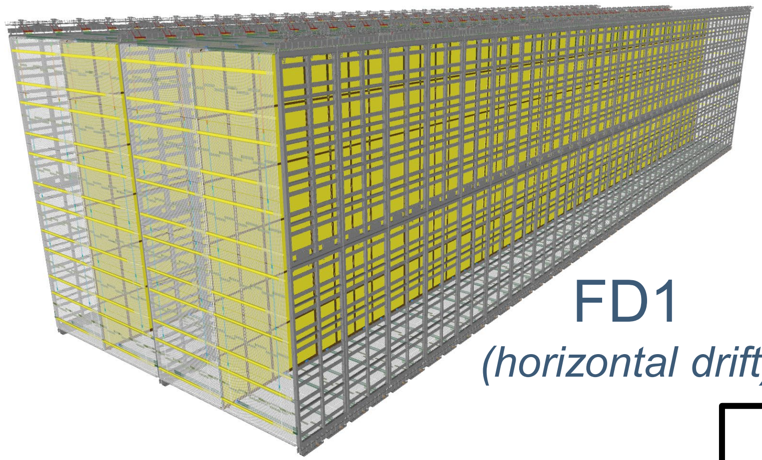
Note : DUNE Science begins when FD1 is filled and turned on and recording tracks



CRP** Vertical Drift

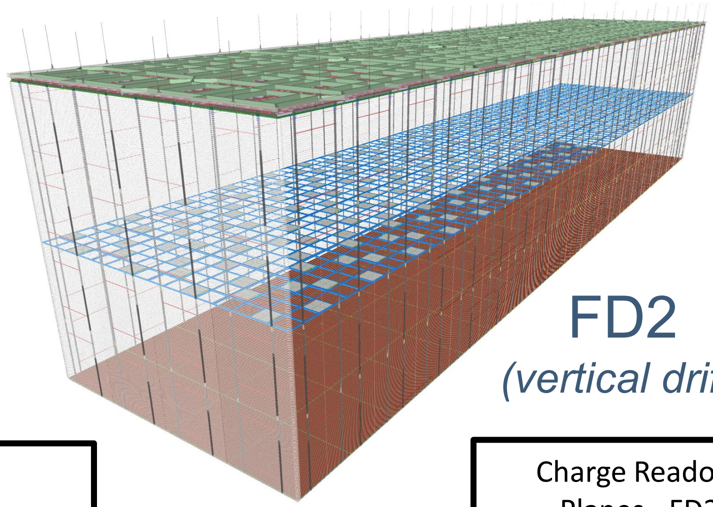
**Charge Readout Planes

DUNE – Phase I FD Partners



FD1
(horizontal drift)

High Voltage
FD1, FD2



FD2
(vertical drift)

Anode Plane
Assemblies - FD1

TPC
Electronics
FD1, FD2-B

Photon Detection
FD1, FD2

Data Acquisition
FD1, FD2

Charge Readout
Planes - FD2

CALCI
FD1, FD2

Brookhaven National Laboratory

Argonne NATIONAL LABORATORY

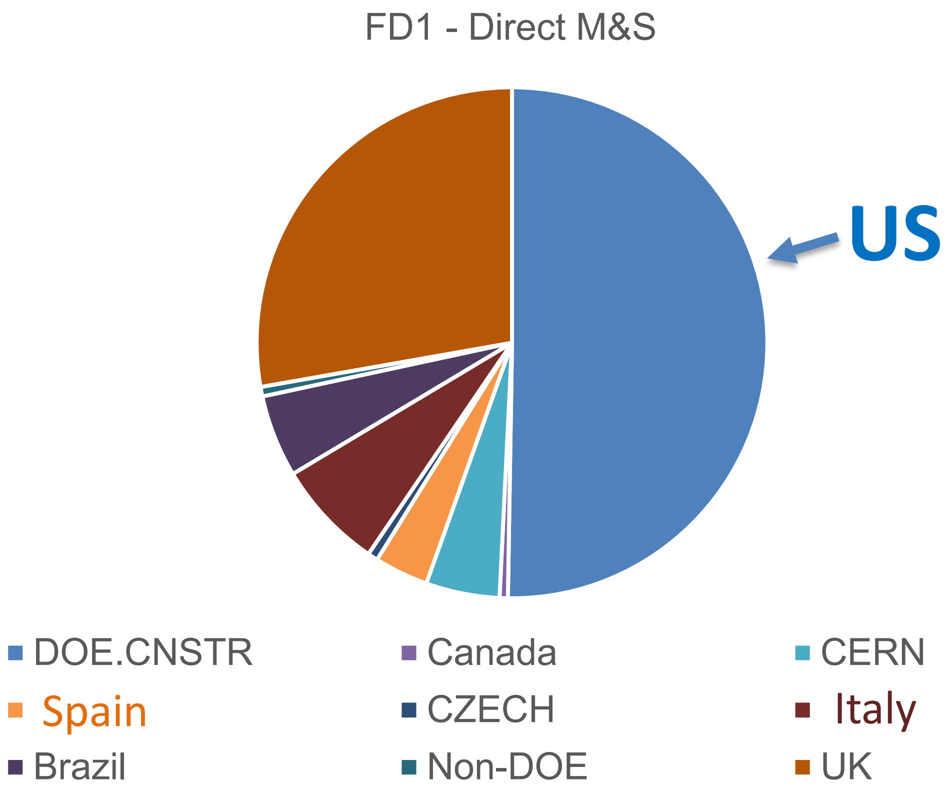
Electronics
FD2-T

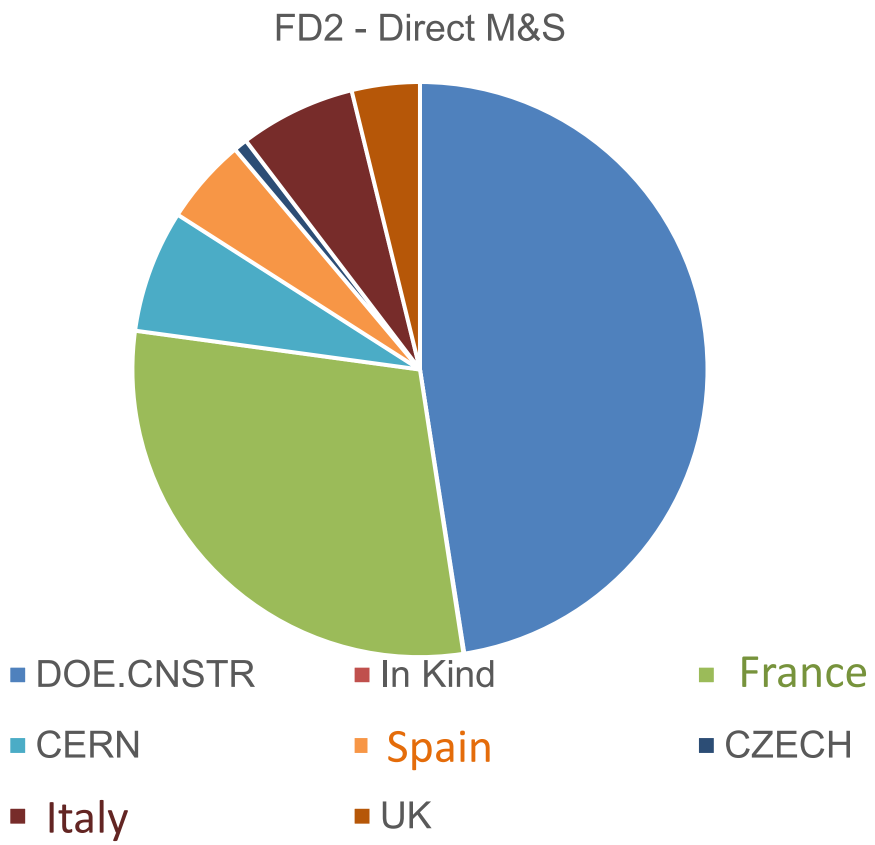
Los Alamos NATIONAL LABORATORY

Fermilab

BERKELEY LAB

Contributions to DUNE Far Detectors (Phase I)



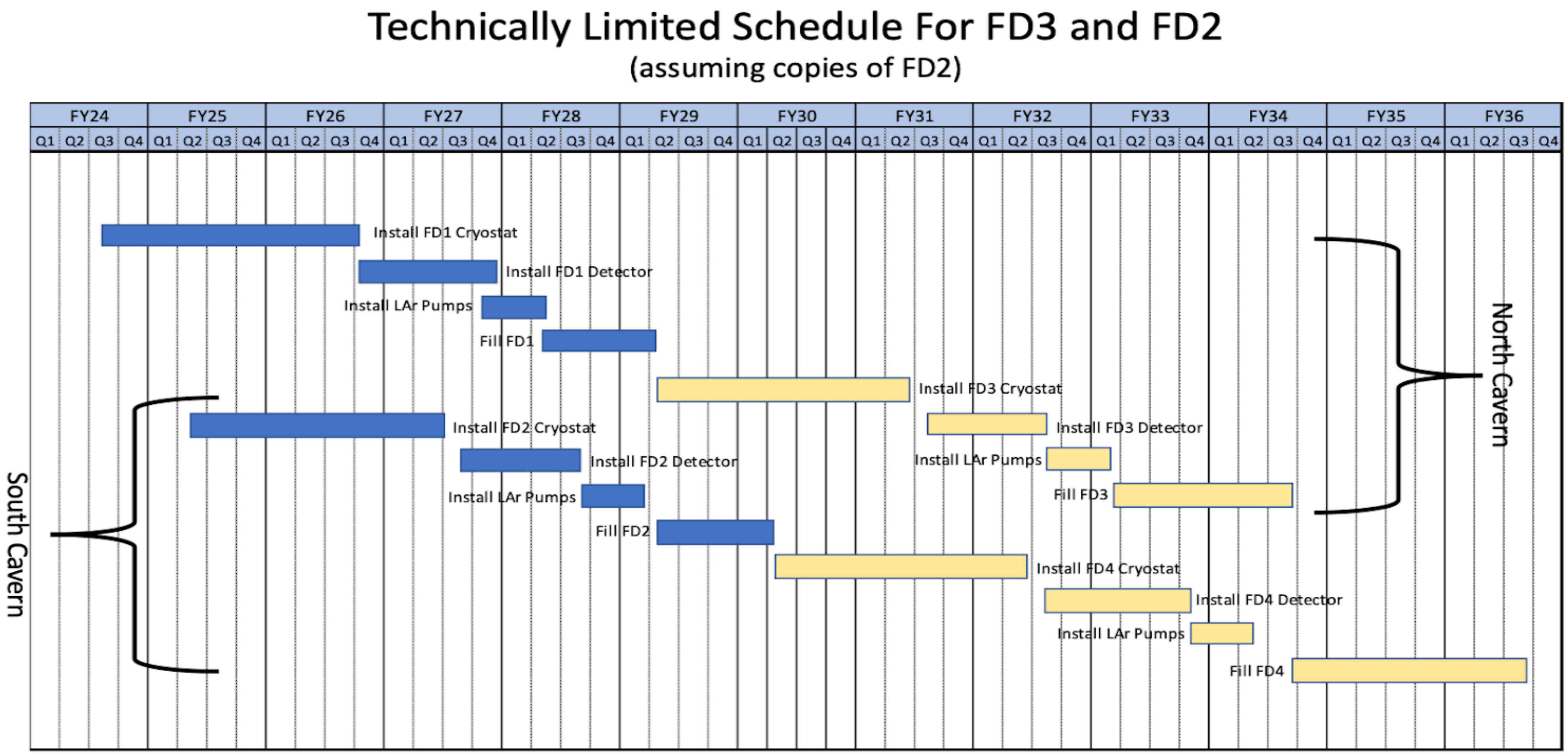


The international community is strongly committed to DUNE with 50%/50% share US/partners in material and labor for the far detectors. *These contributions are in addition to CERN's 2 cryostats (not included in chart)*

Phase II FD Baseline and Boundary Conditions

- ***For the purpose of planning the DUNE collaboration will assume FD3 and FD4 are vertical-drift LArTPCs similar to FD2 as the baseline options***
- ***DUNE is actively exploring LArTPC detector options for Phase II with enhanced capabilities that could bring in significant contributions from existing partners and/or new partners.***
- ***DUNE is open to different detector proposals for FD4 that demonstrate that the following boundary conditions can be met:***
  - Sensitive to beam neutrinos of different flavor with good flavor separation on par with the Phase-I detector performance
  - Neutrino energy reconstruction with similar performance to LArTPC over the entire beam energy range (500 MeV to ~5 GeV
  - Demonstrate that the near detector complex can be updated to accommodate precision LBL physics if one of the Phase II FDs is not a LArTPC (for e.g. liquid scintillator)

FD 3 and 4 Timeline



Earliest installation start in 2029 with FD3 completed in Q4,2034 and FD4 in Q4,2036

DUNE Phase II FD R&D Goals

- *Pursue possible enhancements that make use of recent technological breakthroughs and are well motivated by unique additional physics capabilities.*
- Other considerations are increased funding/resources and/or reduced risk in an international context.
- Enhancements are mainly driven by 1) better energy resolution 2) lower energy thresholds, and 3) lower intrinsic backgrounds,
- Possible expanded physics scope
  - Solar (and supernova) neutrinos in new energy regime.
  - Low-mass dark matter
  - Physics enabled by increased Xe doping

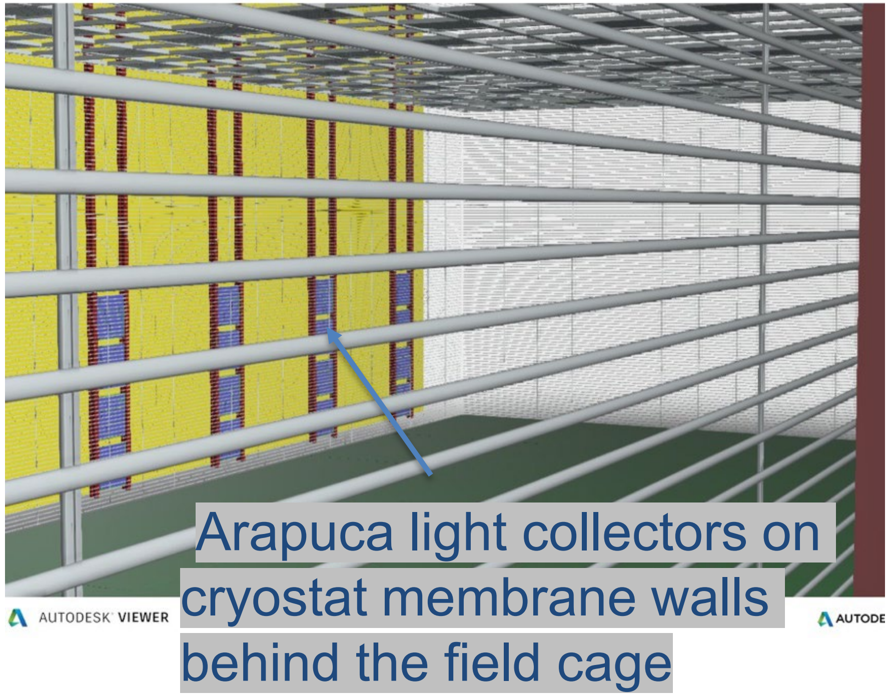
Outcome of MoD workshop in Valencia (Nov. 2022)

(92 participants and R&D from US, Brazil,France,Germany,Israel,Italy,Spain,Switzerland,UK)

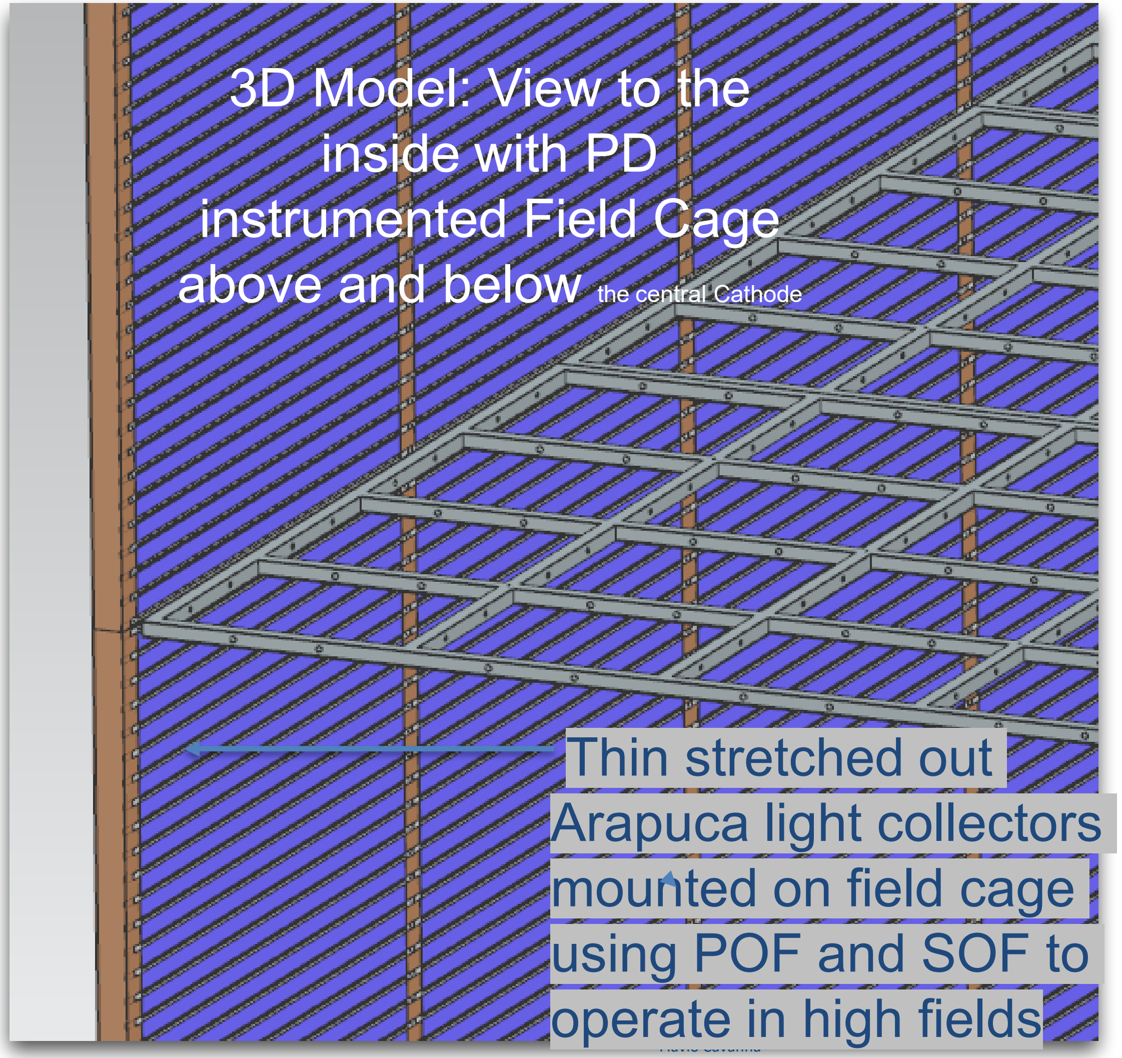
- **Incremental LArTPC R&D on mature options**
  - FD2 like (Vertical Drift) modules with “adiabatic” improvements, mainly in the light detection (baseline option)
  - Scalable options using pixel readout adapted from the near detector LArTPC
- **R&D for vertical drift LArTPC charge, light and combined charge+light readout options**
  - Ariadne: fast optical read-out using cameras, with Arapuca add-on
  - Q-Pix: pixel readout with reset time stamps to reduce data rates and lower thresholds
  - SoLAr/Q-Pix: pixel detector with integrated light pixels, Arapuca
- **R&D on new detector concepts**
  - Water-based liquid scintillator (Theia); separation of Cherenkov and scintillation light and improved timing.
  - SloMo: use underground argon in an acrylic vessel, reduce background.
  - “DUNE-β”: 2% xenon and photo-sensitive dopant.

Incremental R&D on current DUNE LArTPC designs

From FD2 to FD3-4: light collectors deployed on field cage

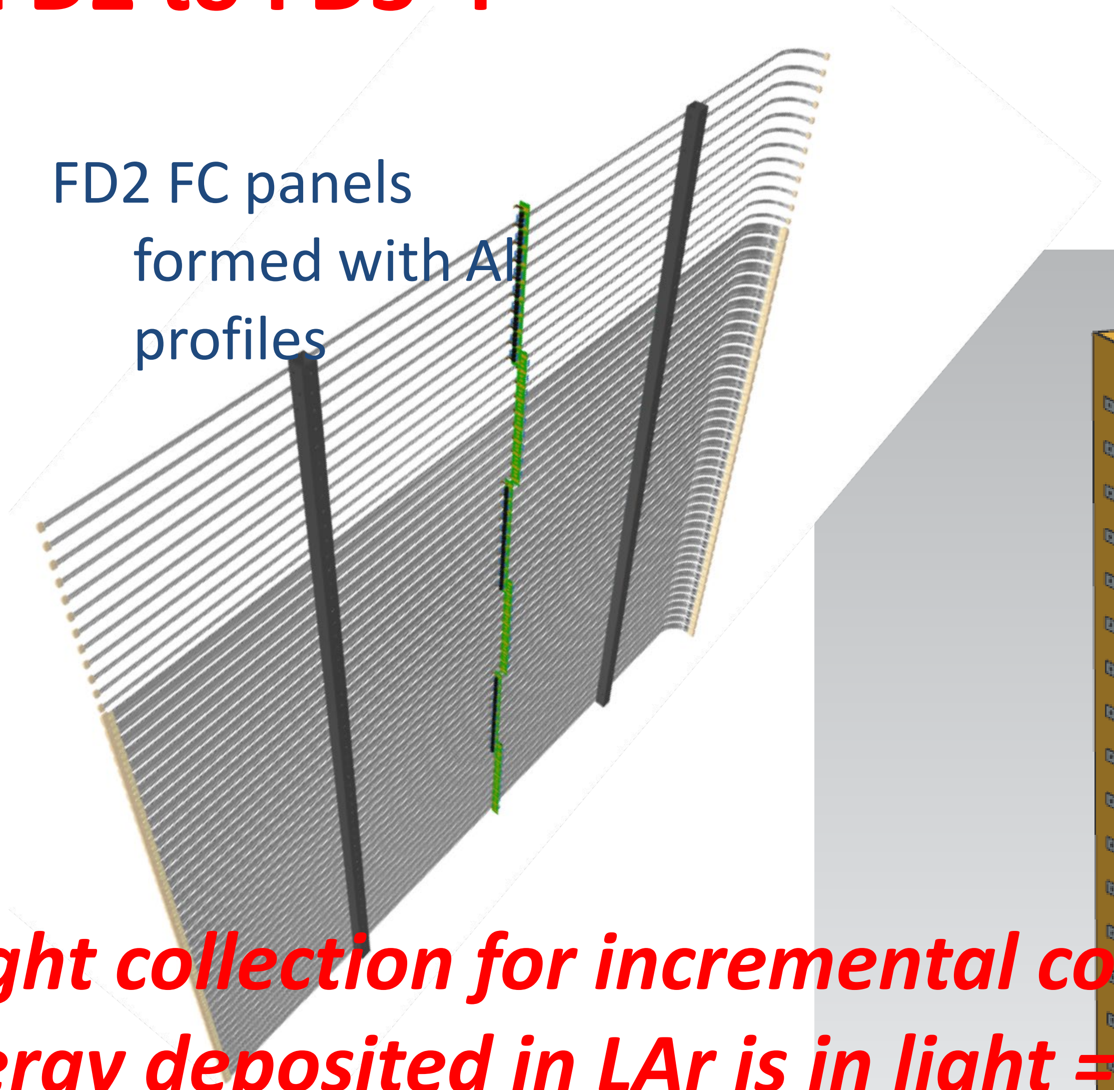


Using FD2 technological breakthroughs like power-over-fiber and signal-over fiber to increase light collection by instrumenting the field cage.

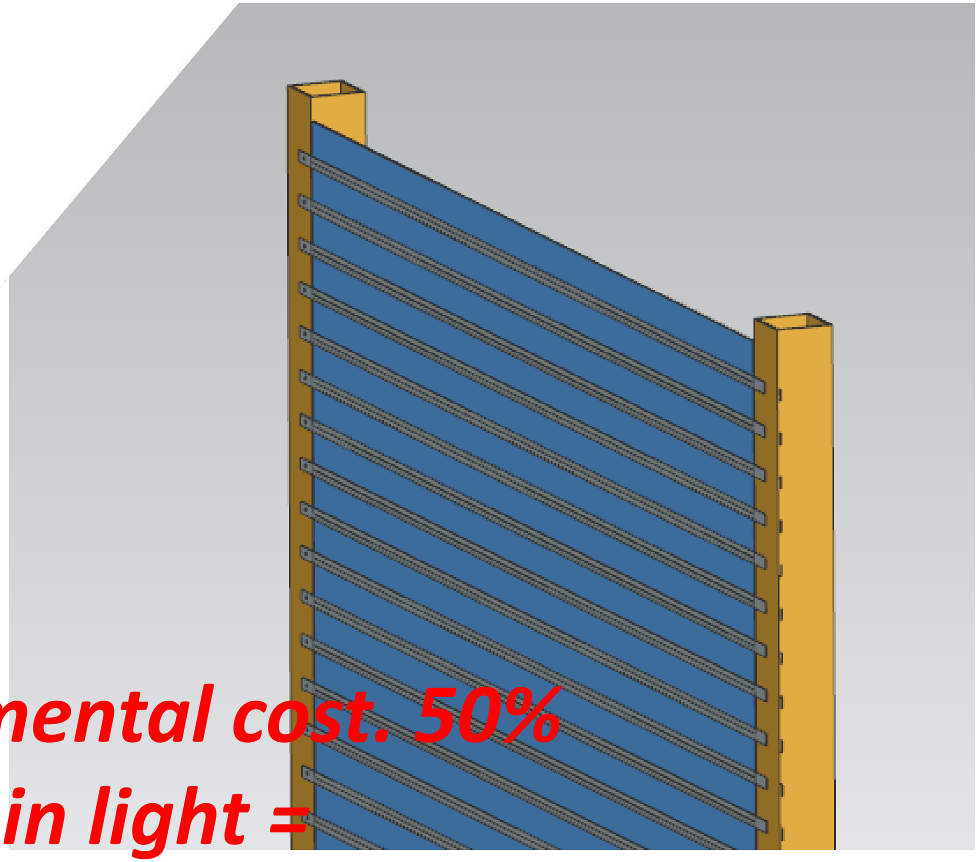


From FD2 to FD3-4

FD2 FC panels formed with Al profiles



FD3-4 FC panels with long, thin xARAPUCA detectors between Al profiles



10x light collection for incremental cost. 50% of energy deposited in LAr is in light = improved calorimetery and energy resolution

Scalable Pixel Readout: LArPix & LightPix

LArPix:

- **True 3D pixelated charge readout for LArTPCs**
- Low-noise, low-power, cryogenic-compatible
- Self-triggering, ~100% live
- Scalable anode design leverages commercial production
- Four recent 80k-pixel ton-scale prototypes exceeded expectations
- Production costs on-par with existing readout technologies
- Baseline technology for the DUNE Near Detector

A LArPix Far Detector?

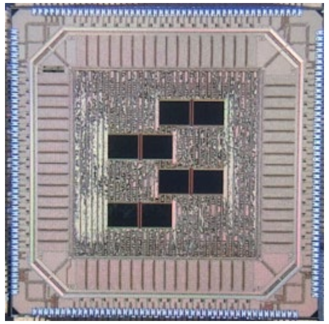
- Existing LArPix performance specs (for ND) seem viable for FD
- For FD-scale deployment, need:
  - Digital aggregator to reduce cabling and feedthroughs
  - Expanded QC testing program to provide sufficient throughput
  - ProtoDUNE-scale demonstration

LightPix:

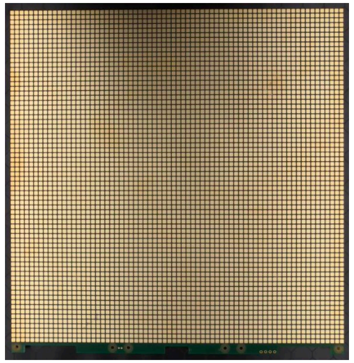
- Highly-scalable readout for cryogenic SiPMs
- Reuses much of LArPix system design

Improved fidelity and enhanced low-energy program for future DUNE Far Detectors

LArPix-v2 ASIC

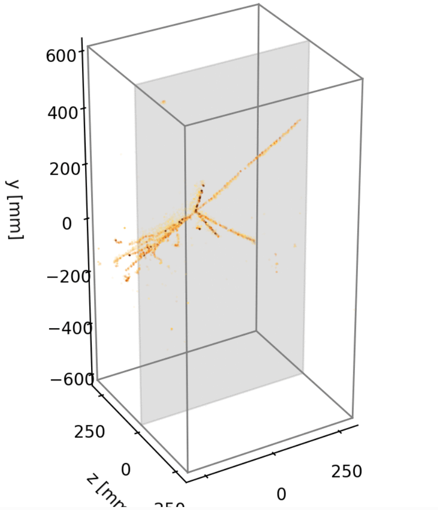


LArPix-v2 Tile

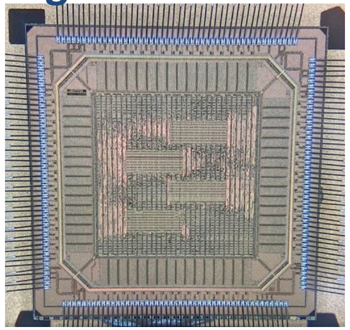


DUNE Near Detector Prototype LArTPC

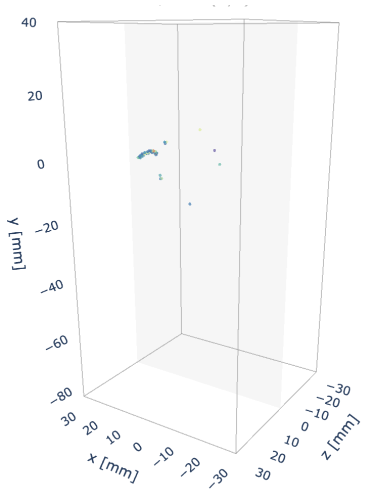
Raw 3D images of cosmic rays in ton-scale prototype

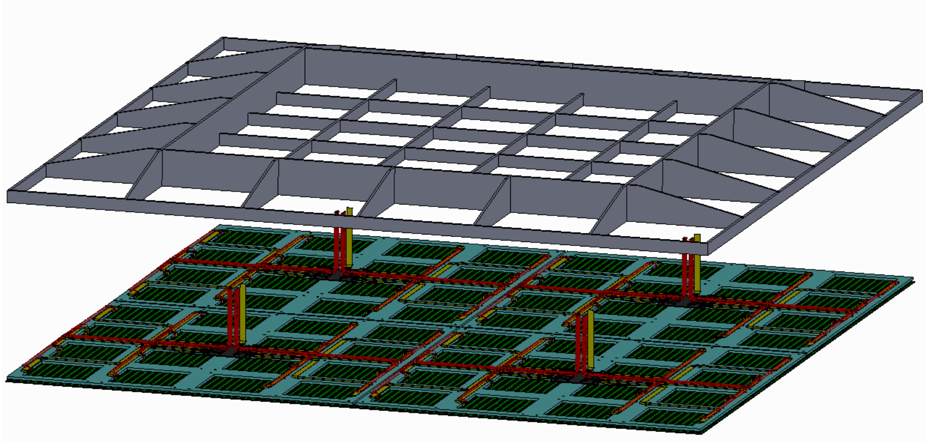


LIghtPix-v1 ASIC



LArPix Supernova Simulation

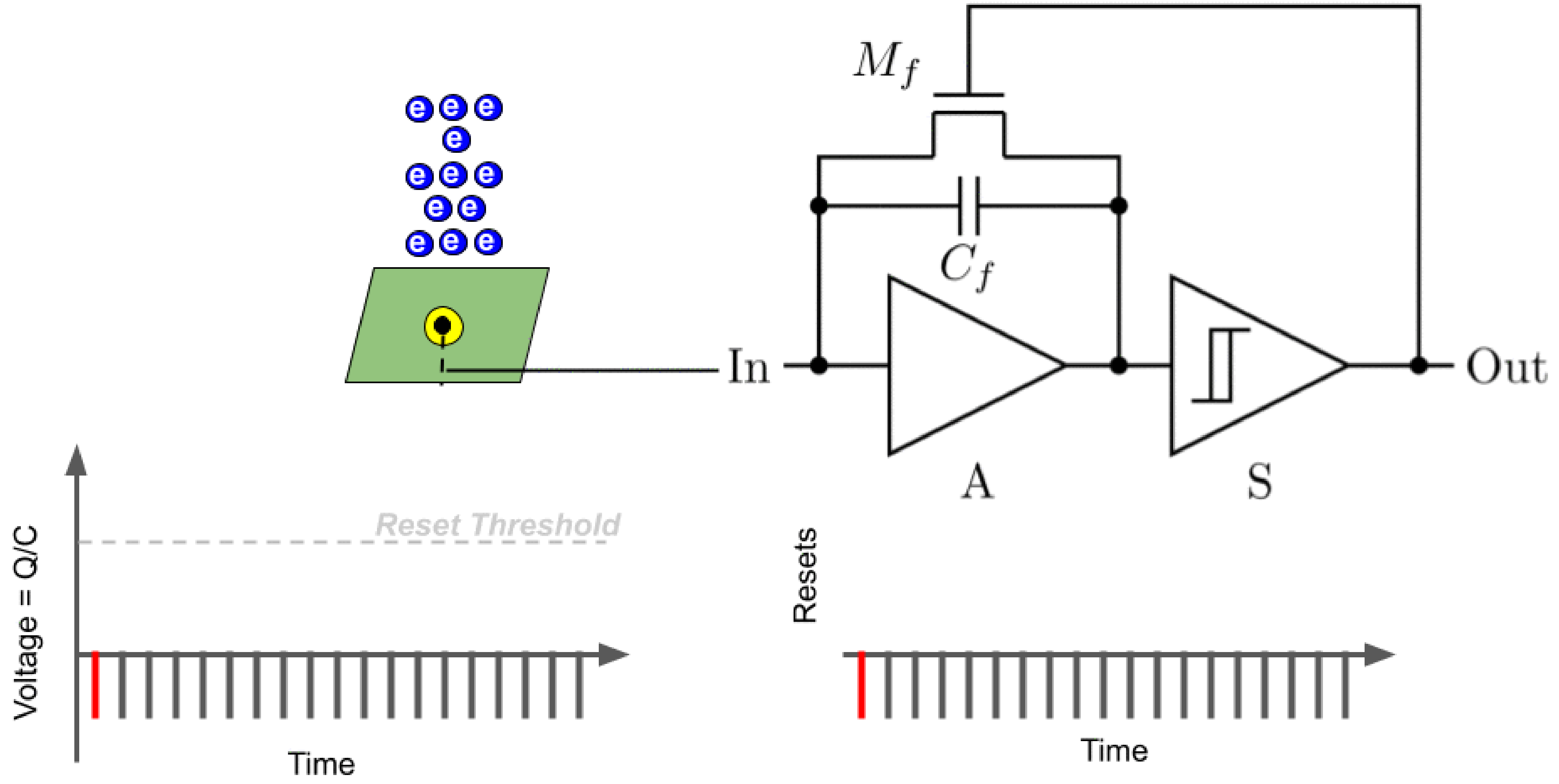




Concept: LArPix in a Vertical Drift FD

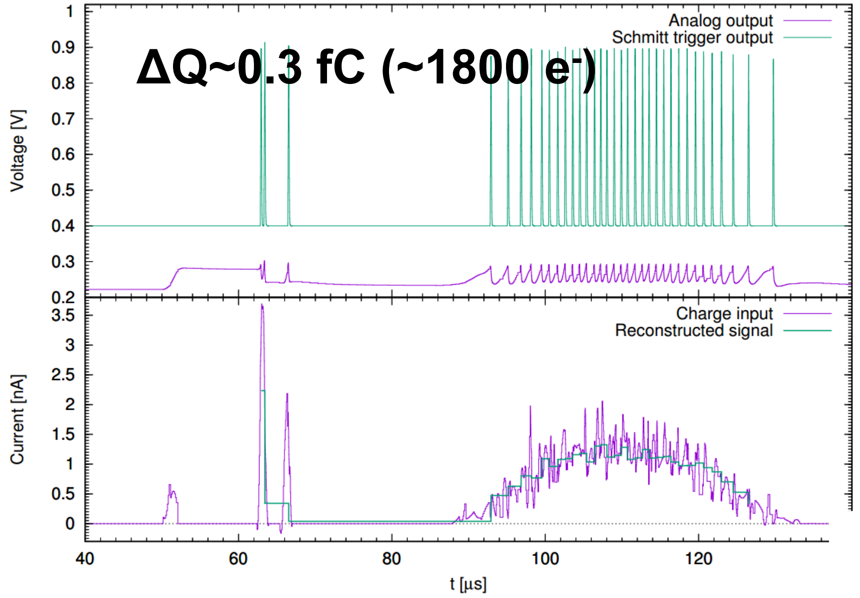
R&D on New LArTPC Charge,Light and Charge+Light Readout Options

Q-Pix: Pixelating kiloton scale detectors



LArTPC pixelated readout using Q-Pix

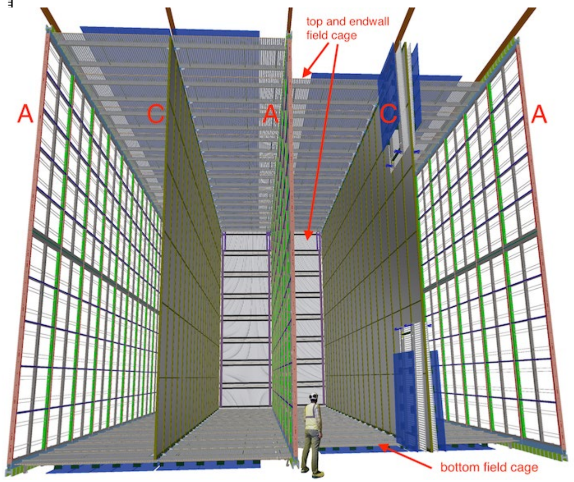
Q-Pix signal simulation

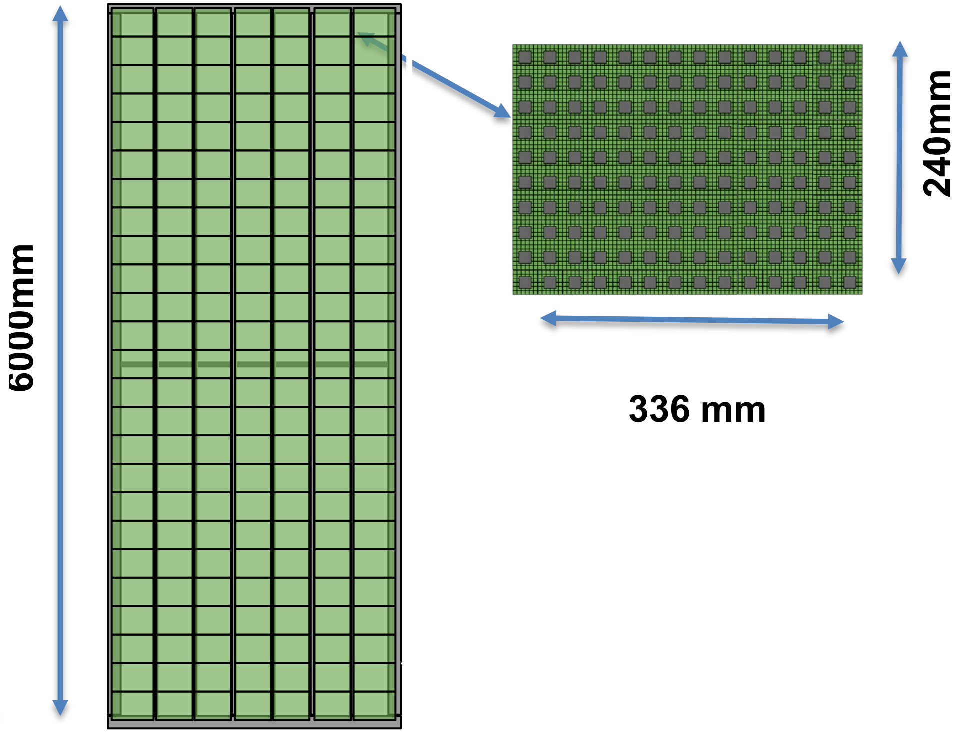


Q-Pix frame replacing anode plane in FD1 would be 2.4m across and 6m tall = 588x1500 pixels = 882K pixels per plane (24.5K ASICS). There are 150 anode planes in FD1

Study to show how Q-Pix enhances the low energy physics capabilities of a kTon scale LArTPC

Phys. Rev. D 106, 032011 (2022)



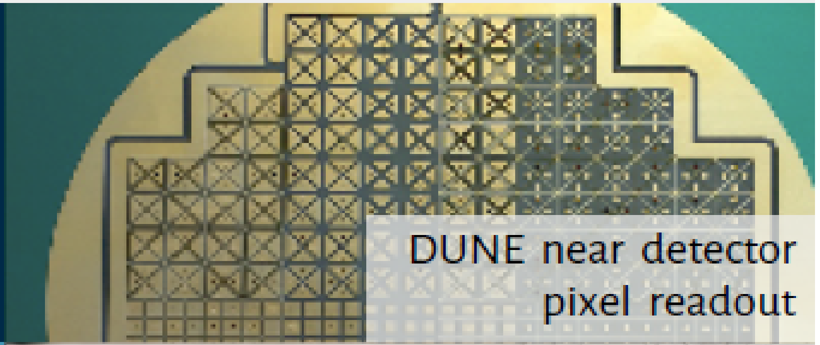


SoLAr: Integrated Q+L pixel readout

SoLAr: key concepts for the MeV-scale challenge

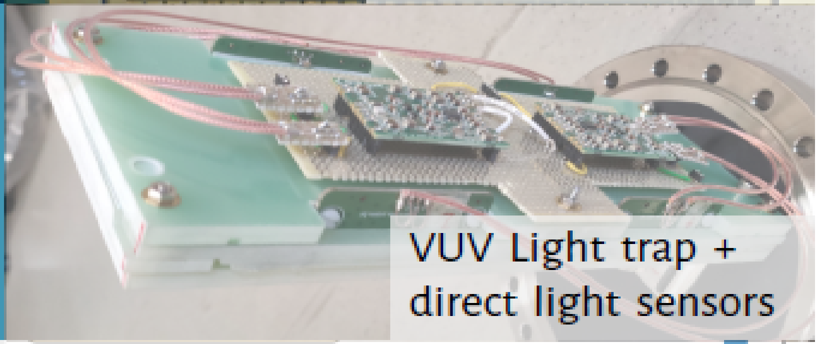
Improved reconstruction:

Pixelated readout plane will enhance event reconstruction, while replacing TPC wires is expected to simplify construction and installation



LAr TPC as tracking scintillator detector:

Arapuca-style modules + **VUV SiPMs** integrated on the anode
Exploit the light signal in LAr to perform
combined Q + L calorimetry: Target $\Delta E/E \approx 7\%$



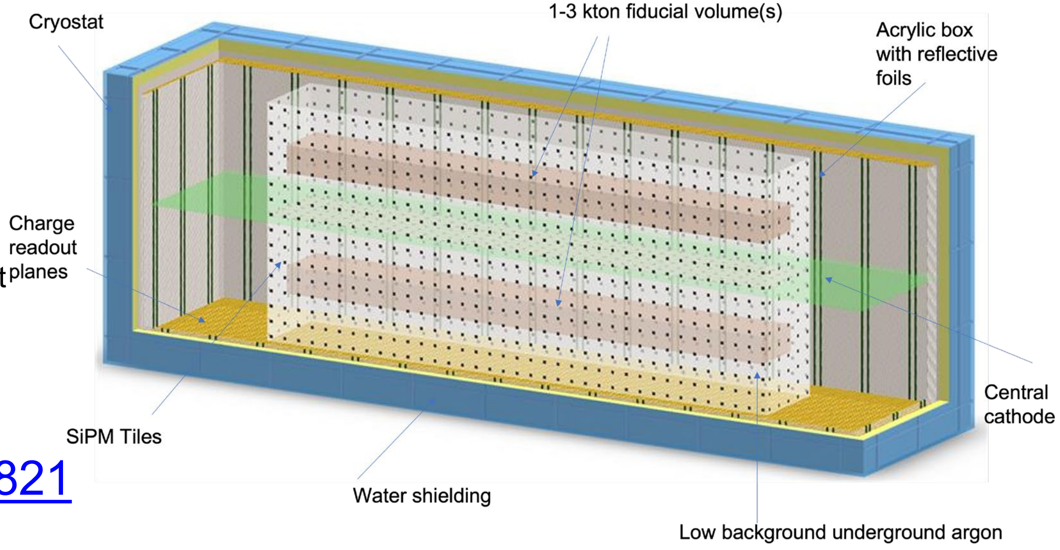
Improved background suppression

More accurate material selection, passive shielding,
pulse-shape discrimination, **direction** reconstruction

R&D on New Detector Options

SLoMo: SURF Low Background Module

- Development of **vertical drift** design
- **Background Reduction** Targets:
  - 10^3 reduction external neutrons
    - 40 cm water shield outside detector
  - 10^3 reduction internal backgrounds
    - Largescale materials and assay campaign, internal shielding in cryostat
  - 10^3 reduction radon
    - Inline purification system, emanation control
  - 10^8 reduction ^{42}Ar, 10^3 reduction ^{39}Ar,
    - Low radioactivity underground argon
- **Light Collection** Target:
  - Energy resolution of 2% at 1 MeV



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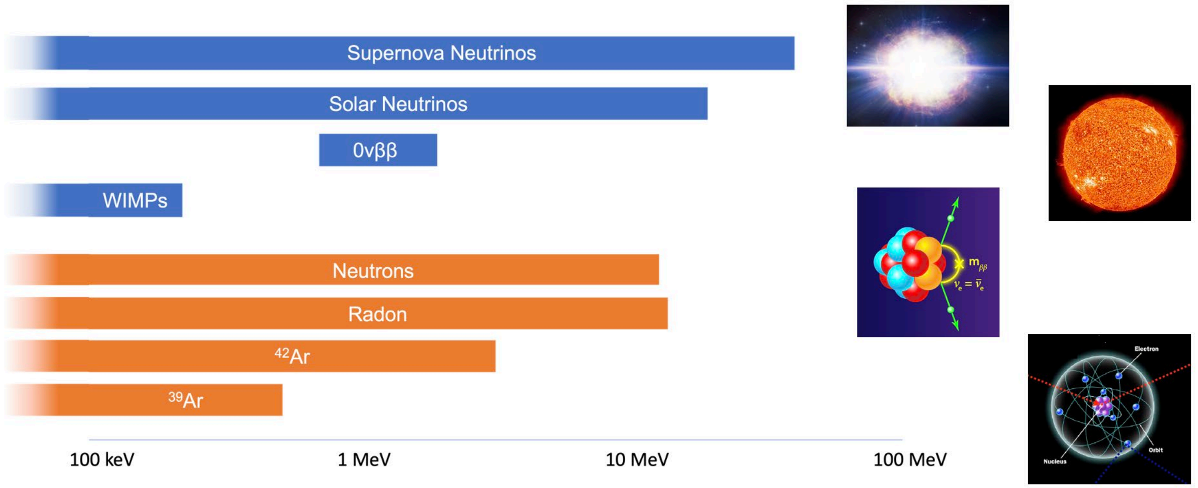
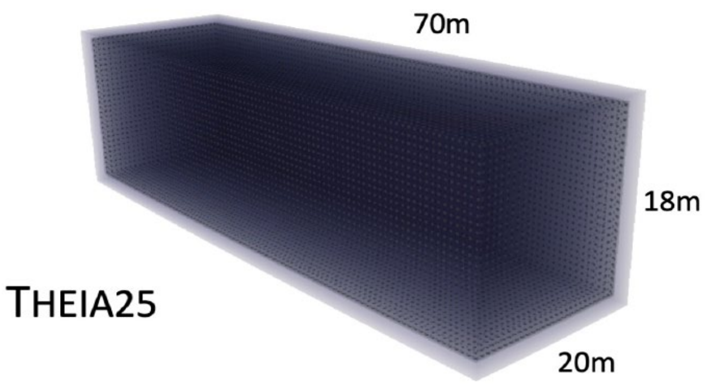
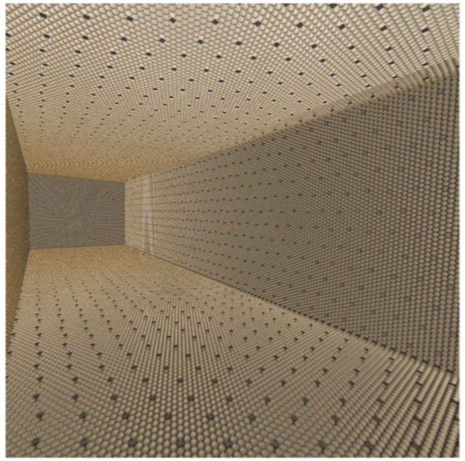


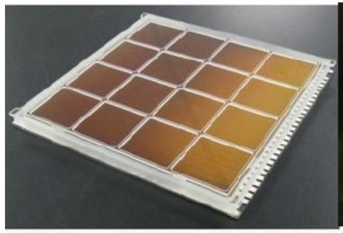
- **Solar neutrinos**: Precision Δm^2_{21}, NSI constraints, precision CNO, test solar metallicity
- **Supernova neutrinos**: Lower threshold, elastic scatters, early- and late-time information, detection beyond Magellanic Cloud, CEvNS glow
- **WIMP dark matter**: Competitive high mass search on fast timescale, confirm G2 signal with annual modulation

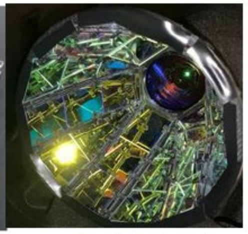
Hybrid Cherenkov/Scintillator Module ("Theia")





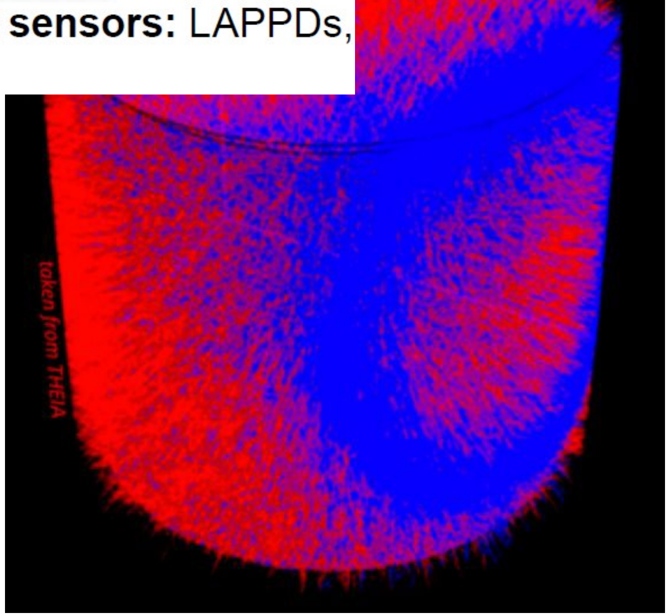
Novel target medium: (Wb)LS





Novel light sensors: LAPPDs, dichroicons

New technologies make this possible



Hybrid signals allow broad extension of DUNE physics

- CP violation with comparable sensitivity to 1 DUNE module
    - Low-Z target allows cross check with Hyper-K
    - Requires changes to ND suite
- Precision low-energy solar neutrinos (CNO, pep, ^{8}B MSW transition)
- Diffuse supernova background neutrinos
- Literally complementary supernova burst signal: anti-ν_e vs. ν_e
- Eventual $0\nu\beta\beta$ experiment with sensitivity beyond inverted ordering

Broad international community interest, with opportunity for new funding sources

DUNE Phase II Planning

DUNE Spokes and EB:

DUNE Phase II Group formed and charged:

DUNE will need to address in a timely fashion the strategy for the implementation of the Phase II, which is necessary for the achievement of its physics goals indicated by the 2014 P5 in the next decade.

Phase II consists of:

1. More usable mass at the Far Site (MoO 3 & 4)
2. A More Capable Near Detector System (e.g. ND-Gar)
3. More neutrinos (e.g. beam power upgrade to 2.4 MW)

*We propose to form a standing organization within DUNE, **yet open to a wider community**, with the following mandate:*

- ***Provide within a few months a realistic assessment of a baseline scenario for Phase II on points 1 and 2 to be communicated to P5***
- ***Explore the opportunities and the associated challenges of enlarging the physics reach of DUNE***
- ***Assess (and recommend) the needed R&D***
- ***Connect the effort on Phase II with the ongoing work on Phase I, by integrating it within the same software/simulation and physics organization.***

The group will have one coordinator and a deputy coordinator. → ***Stefan Söldner Rembold and Michel Sorel***
The coordinator will join the DUNE Management Group and the EB.

DUNE Phase II Organisational Structure

- Embedded in DUNE management structure and led by its own small management team.
- Essential not to divert efforts from Phase I construction – remains priority for DUNE.
- Separate FD and ND working groups (not consortia) – currently being formed.
- Phase II structure should be open to new groups and collaborators interested in expanded science scope and new technologies, but who do not necessarily want to (or can) contribute to Phase I. Allow membership of both existing and new collaborators (and funding agencies), but do not require contributions to Phase I. .
- Initial goal: create a Phase II“white paper/CDR-light” for summer 2023.

Summary

- **DUNE Phase II (beam+detectors) will be essential to complete the DUNE program as outlined by the 2014 P5: reach 3σ sensitivity for 75% of δ_{cp}**
- The DUNE Phase II Far Detector baseline design is based on two vertical-drift LArTPC modules which meets all the requirements needed to reach the full DUNE physics goals.The technically driven schedule for Phase II would have FD4 completed by end of2036
- Several LArTPC R&D lines have been identified that will enhance the physics performance of the DUNE FDs. Non LArTPC options for FD4 such as WbLS detectors could be considered if they meet the performance requirements of DUNE.
- *DUNE Phase II R&D is already engaging potential partners from the existing effort and attracting new communities.*
- *The enhanced physics potential of DUNE enabled by Phase II far detectors ranges from physics at 10 GeV ($\nu\tau$ appearance) to physics at ~ few MeV (solar ν) and below (DM?)*
- *Reaffirming the US commitment to full DUNE scope would ensure continued support of the international community and the realization a transformational scientific program*