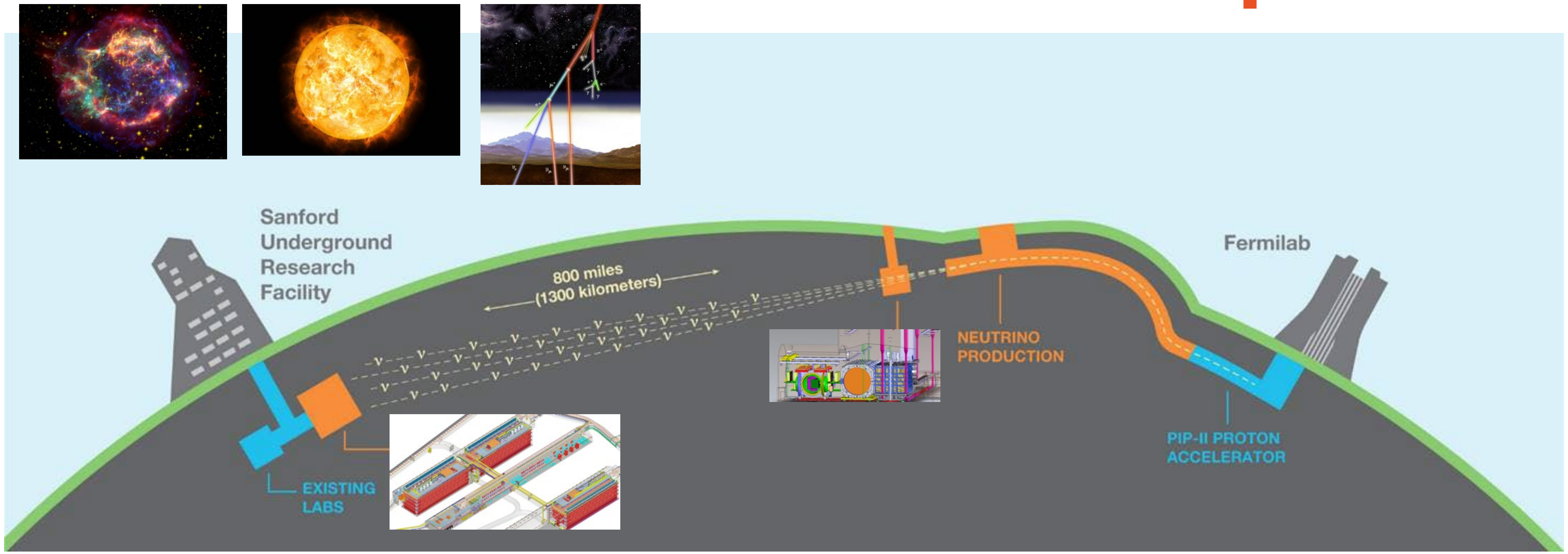
DUNE Phase II and P5

Particle Physics Prioritization Project Panel (P5)

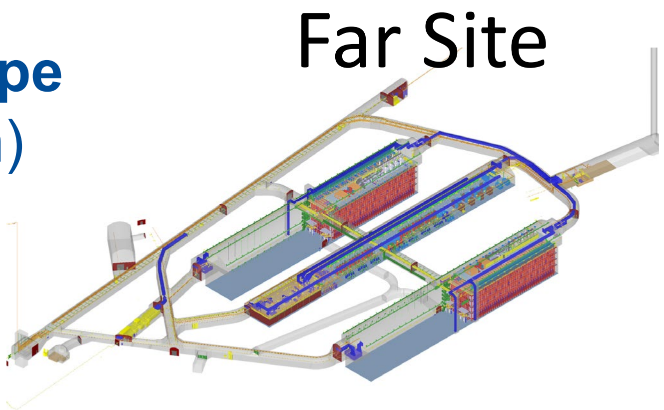
- P5 is a special committee that reports to the High-Energy Advisory Panel (HEPAP) that advises the High-Energy Physics office of the US DOE Office of Science (funds LBNF/DUNE US) and the Division of Physics of the US National Science Foundation (NSF). The P5 is convened every 7-10 years as needed and the committee is charged to build on the “Snowmass” US HEP community study to hash out funding priorities for the next 10 years with a 20-year context
- The 2023 P5 is chaired by Hitoshi Murayama (UC Berkeley and Univ. Tokyo) and deputy Karsten Heeger (Yale)
- P5 held 5 Town Hall style meetings at different US national labs:
  - P5 Town Hall at Lawrence Berkeley National Laboratory, February 22-24, 2023 with a focus on Cosmic Frontier (except for High-Energy Astrophysics)
  - P5 Town Hall at Fermilab/Argonne, March 21-24, 2023 with a focus on Neutrino, Rare Processes and Precision Frontier, High-Energy Astrophysics
  - P5 Town Hall at Brookhaven, April 11-14, 2023 with a focus on Energy, Instrumentation, Computational Frontiers
  - P5 Town Hall at SLAC, May 2-5, 2023 with a focus on Underground, Accelerator, Theory Frontiers, Community Engagement

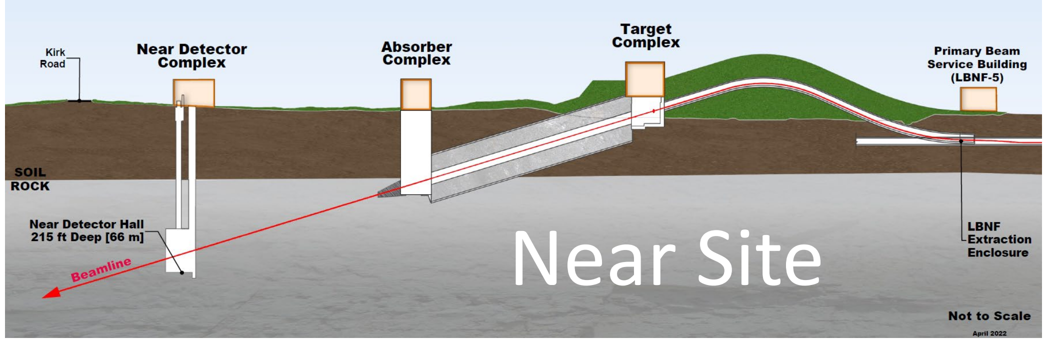
Reminder: Full DUNE scope



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

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





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

LBNF Status - Schedule

	Subproject	CD	Q1 2022	//	Q3 2022	Q4 2022	Q1 2023	Q2 2023	Q3 2023	Q4 2023	Q1 2024	Q2 2024	Q3 2024	//	Q2 2025	//	Q4 2025
	All	CD-1RR			✓ IPR 11-15 Jul		✓ ESAAB 19 Jan										
Far Site	Excavation	CD-2/3	✓ IPR 10 - 12 Jan		✓ ESAAB 19 Aug												
Far Site	Building & Site Infra	CD-2/3				✓ IPR 15-17 Nov	✓ ESAAB 23 Mar										
Far Site	Far Detectors and Cryo	CD-3a				✓ IPR 8 Nov	✓ ESAAB 21 Feb										
Far Site	Far Detectors and Cryo	CD-2/3						DR 20 -23 Jun	IPR 12-15 Sep		ESAAB TBD						
Near Site	Conven. Facilties and Beamline	CD-3a				✓ IPR 6 Dec	✓ ESAAB 23 Mar										
Near Site	Conven. Facilties and Beamline	CD-2/3								IPR TBD		ESAAB TBD					
Near Site	Near Detector	CD-2									IPR TBD		ESAAB TBD				
Near Site	Near Detector	CD-3													IPR TBD		ESAAB TBD

Project focused on next critical milestone for FDC

- Director's review is planned for next month
- DOE IPR is planned for mid-September

DOE critical milestone review | DOE critical decision (ESAAB) timeframe

Notes:

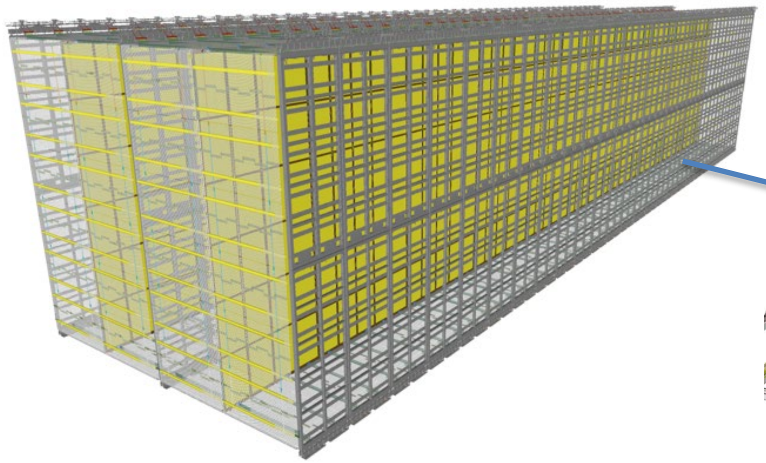
Quarters shown are calendar year

Bolded dates are set with DOE

Each subproject will also have a CD-4 milestone review (not shown).

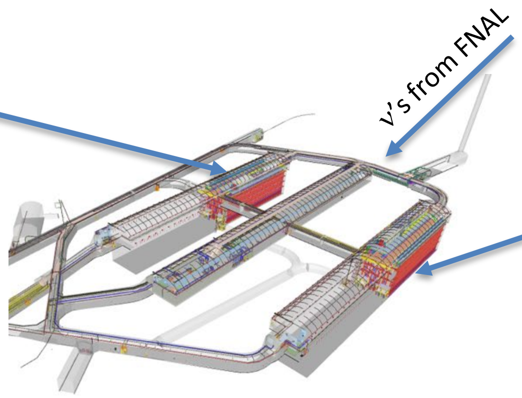
DUNE – Phase I Far Detectors (presentation by S. Zeller)

- ***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)

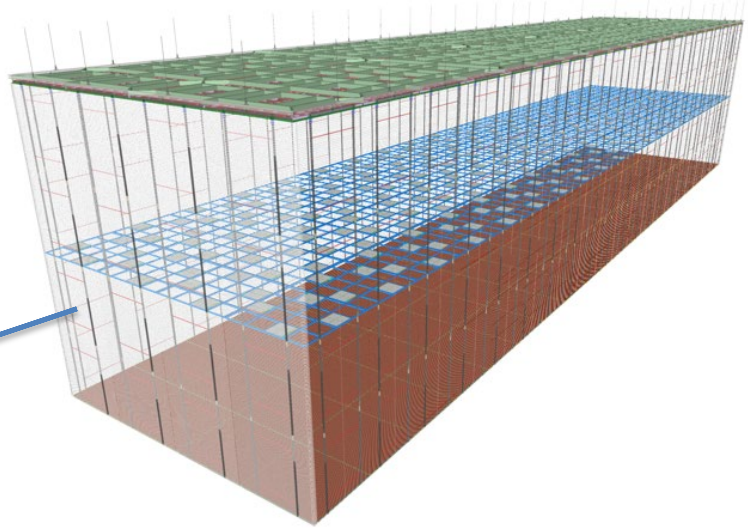


APA* Horizontal Drift

*Anode Plane Assemblies



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



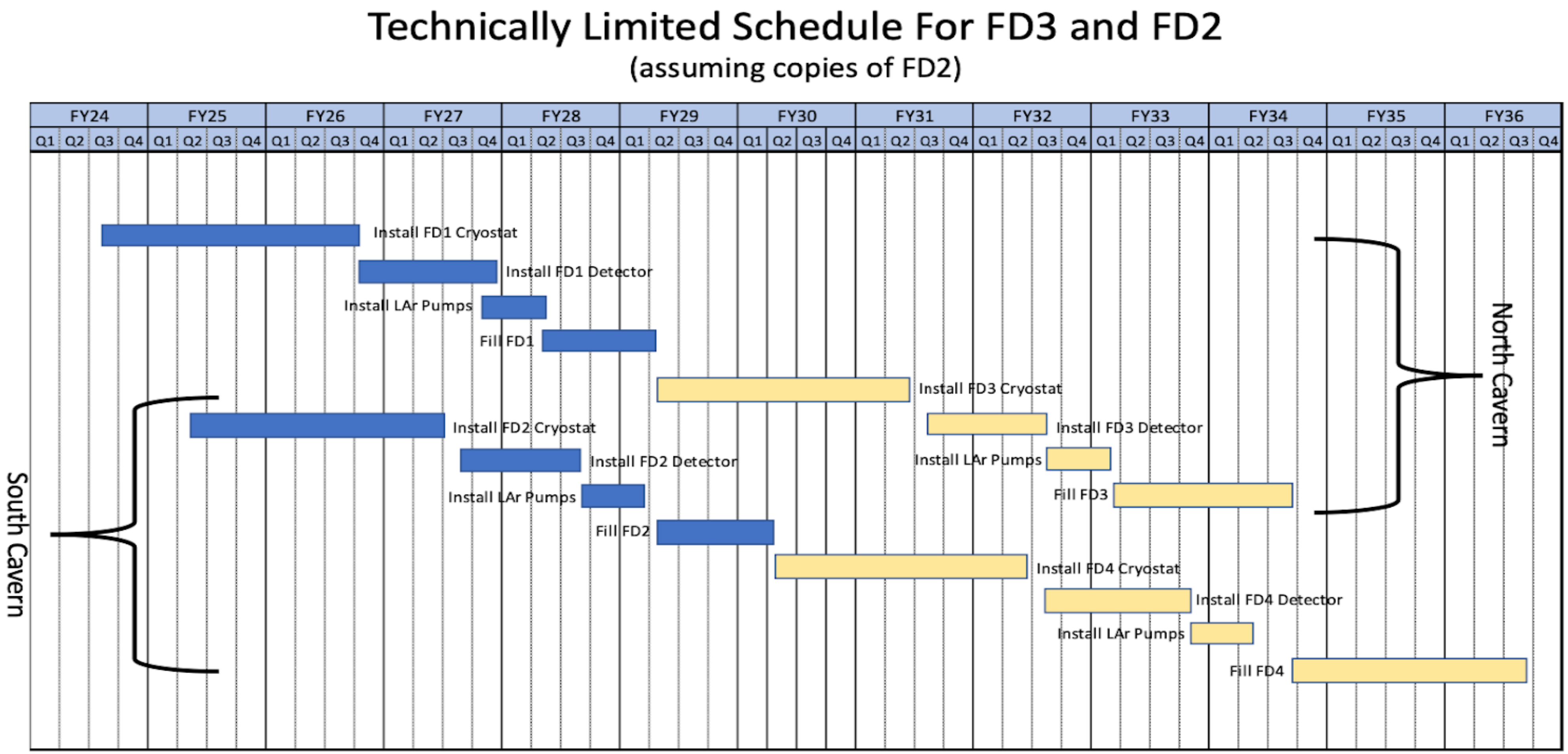
CRP** Vertical Drift

**Charge Readout Planes

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

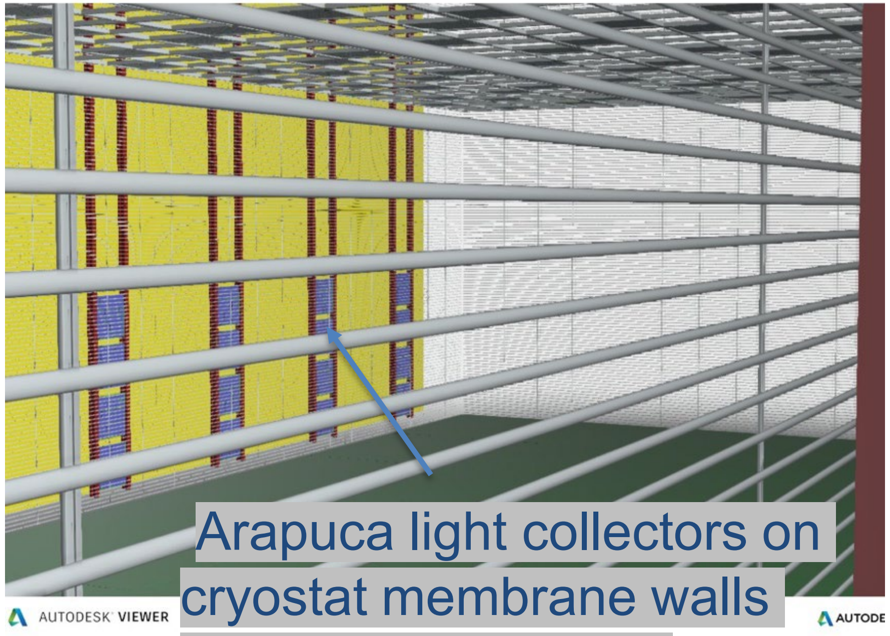
Outcome of MoD workshop in Valencia (Nov. 2022)

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

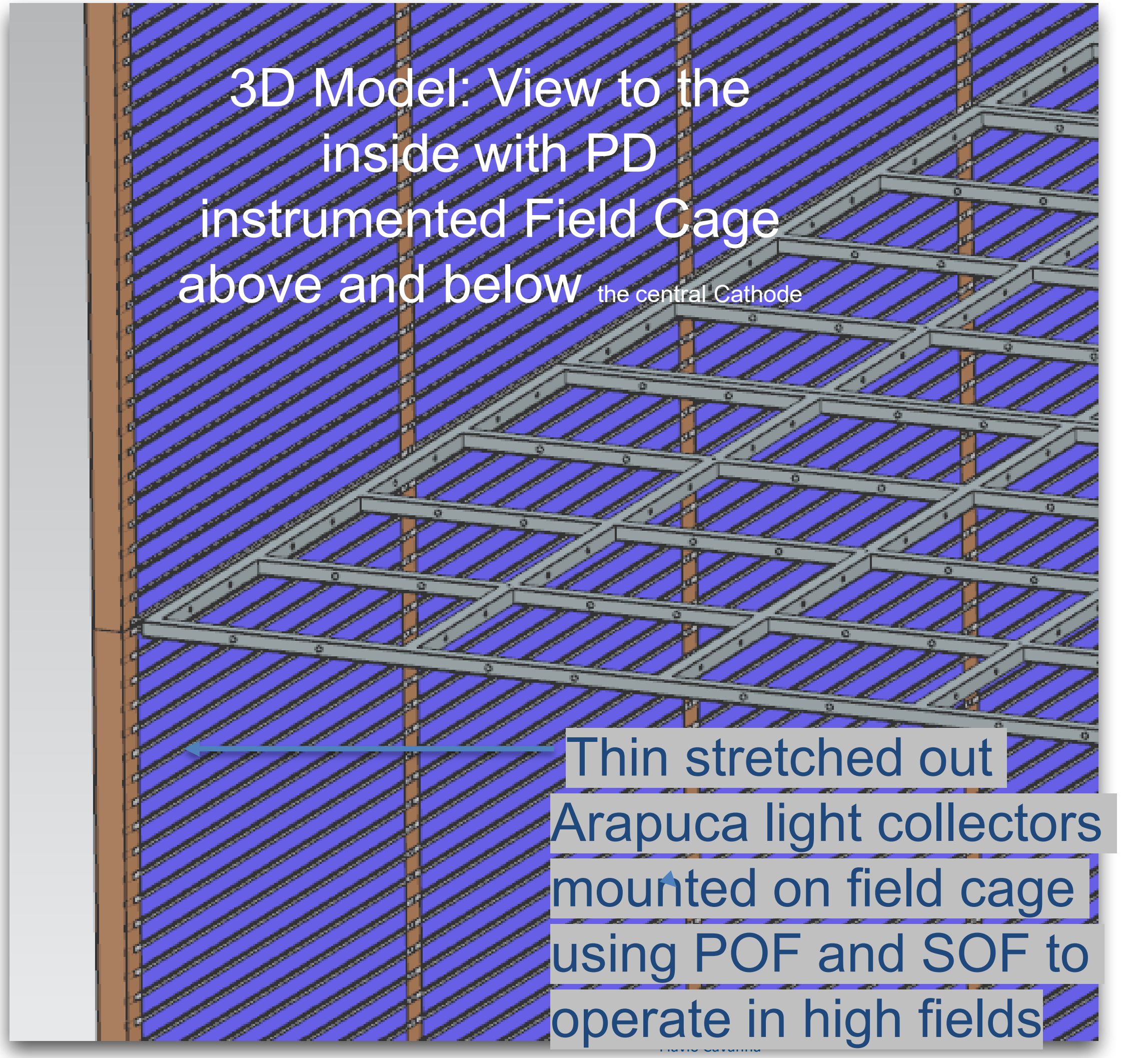
- **Incremental LArTPC R&D on mature options**
  - FD2 like (Vertical Drift) modules with “adiabatic” improvements, mainly in the light detection (baseline option)
  - Scalable options using pixel readout adapted from the near detector LArTPC
- **R&D for vertical drift LArTPC charge, light and combined 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

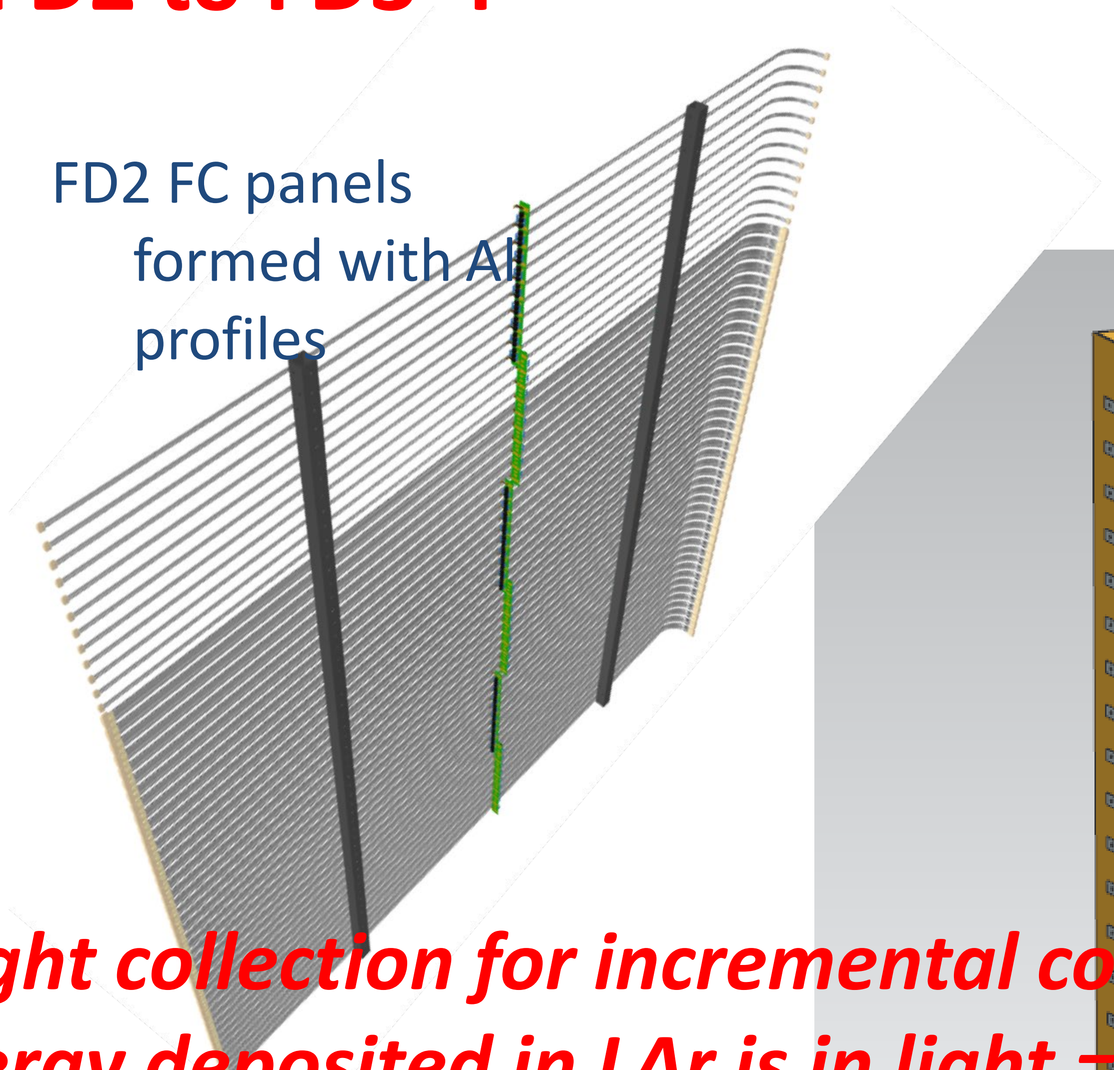


Using FD2 technological breakthroughs like power-over-fiber and signal-over fiber to increase light collection by instrumenting the field cage.

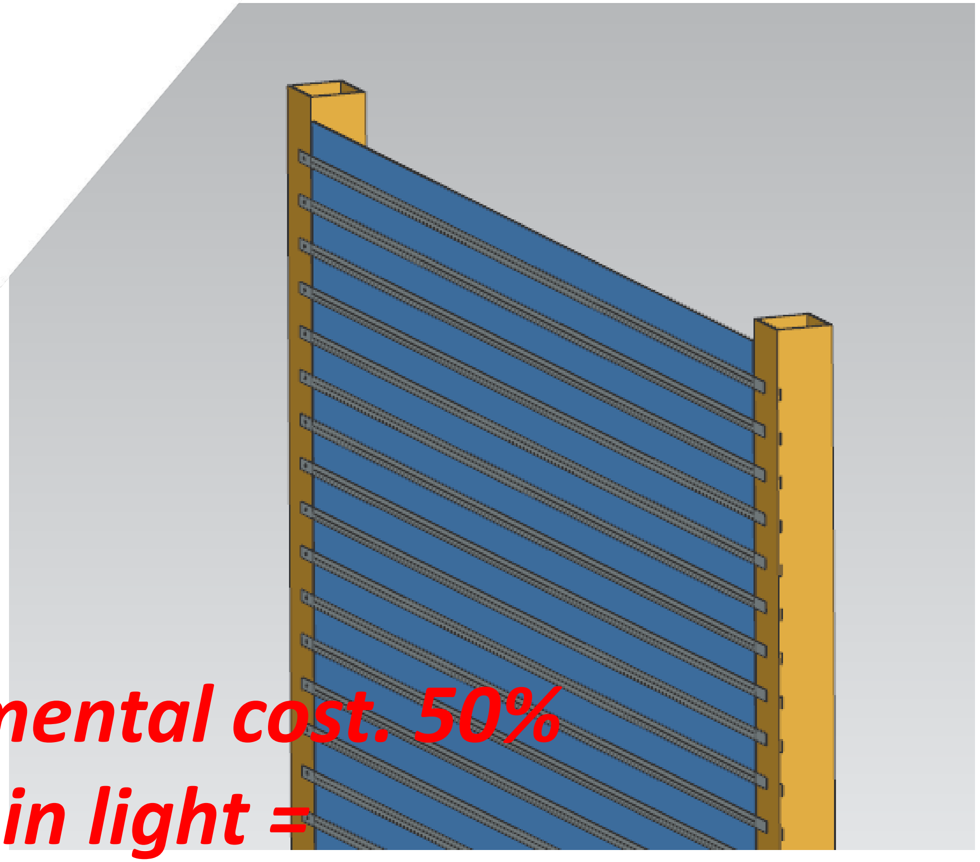


From FD2 to FD3-4

FD2 FC panels formed with Al profiles



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



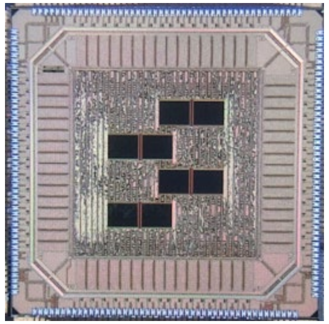
10x light collection for incremental cost. 50% of energy deposited in LAr is in light = improved calorimetery and energy resolution

Scalable Pixel Readout: LArPix & LightPix

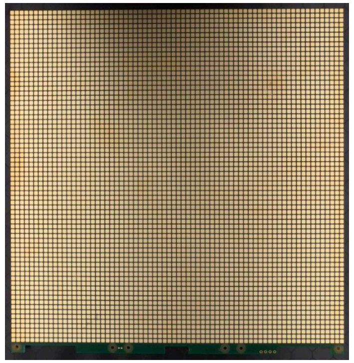
LArPix:

- **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

LArPix-v2 ASIC

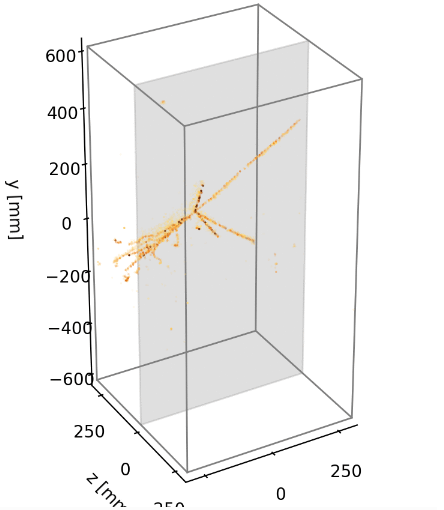


LArPix-v2 Tile

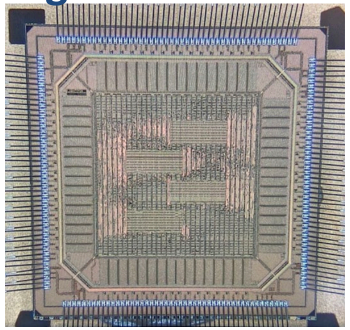


DUNE Near Detector Prototype LArTPC

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



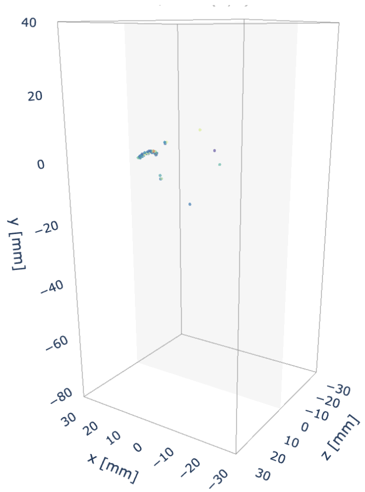
LIghtPix-v1 ASIC

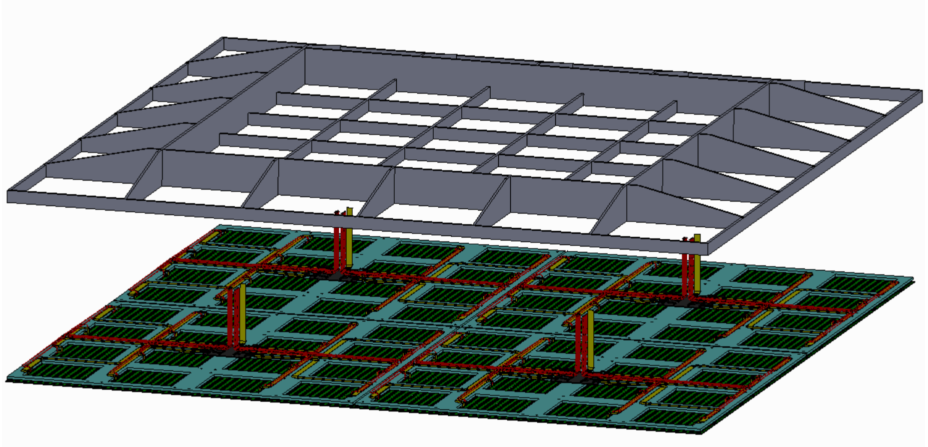


A LArPix Far Detector?

- 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

LArPix Supernova Simulation





Concept: LArPix in a Vertical Drift FD

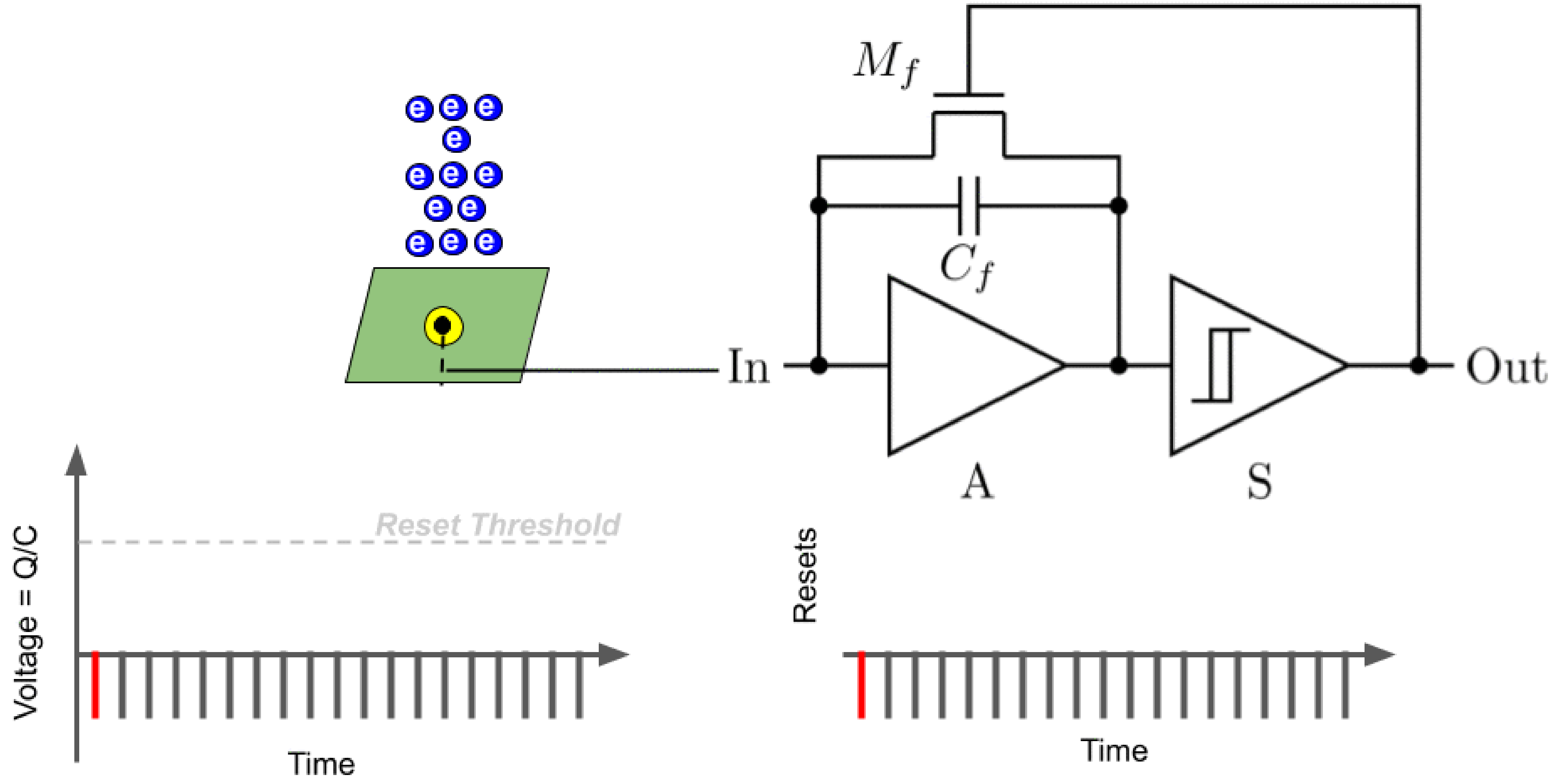
LightPix:

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

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

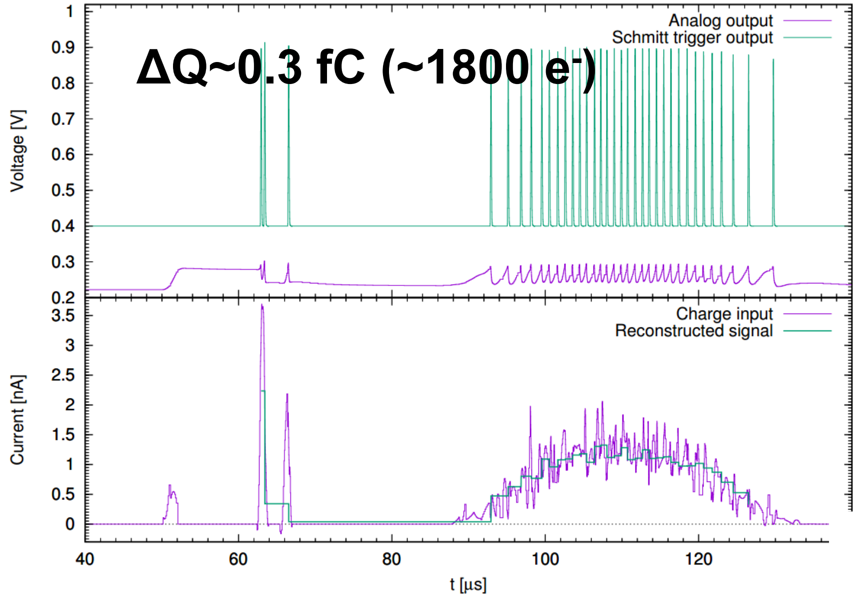
R&D on New LArTPC Charge,Light and Charge+Light Readout Options

Q-Pix: Pixelating kiloton scale detectors



LArTPC pixelated readout using Q-Pix

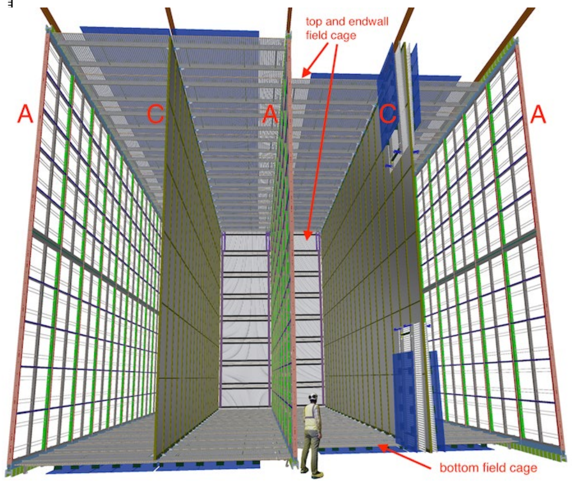
Q-Pix signal simulation

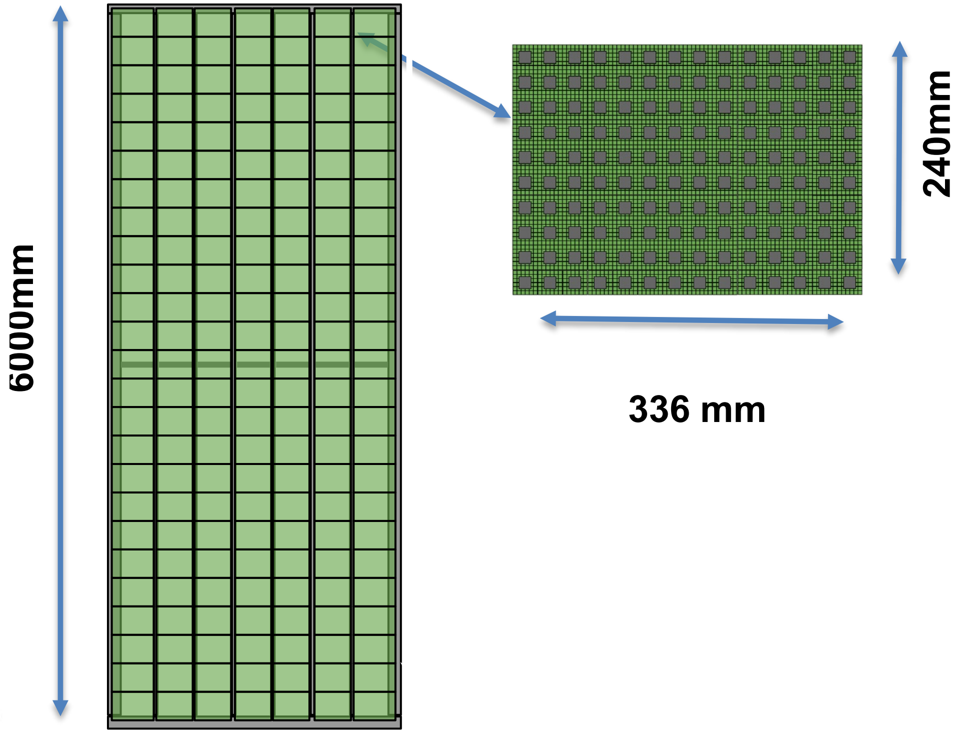


Q-Pix frame replacing anode plane in FD1 would be 2.4m across and 6m tall = 588x1500 pixels = 882K pixels per plane (24.5K ASICS). There are 150 anode planes in FD1

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

Phys. Rev. D 106, 032011 (2022)



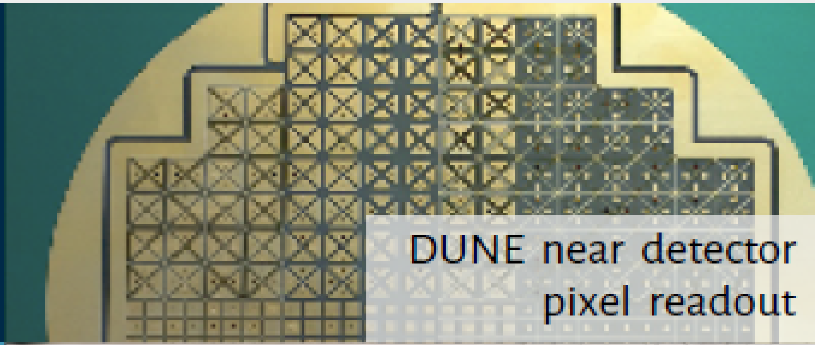


SoLAr: Integrated Q+L pixel readout

SoLAr: key concepts for the MeV-scale challenge

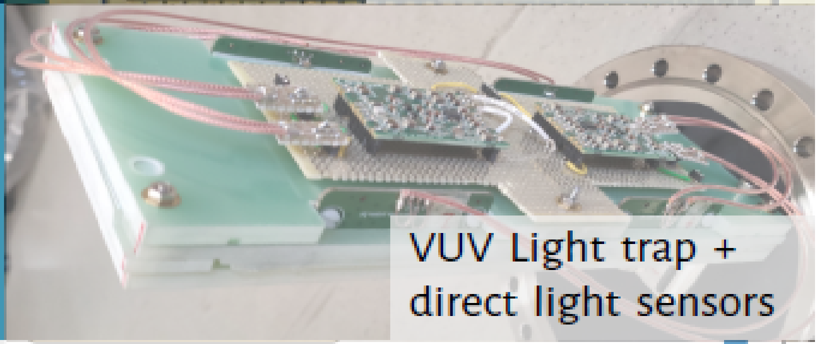
Improved reconstruction:

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 $\Delta E/E \approx 7\%$



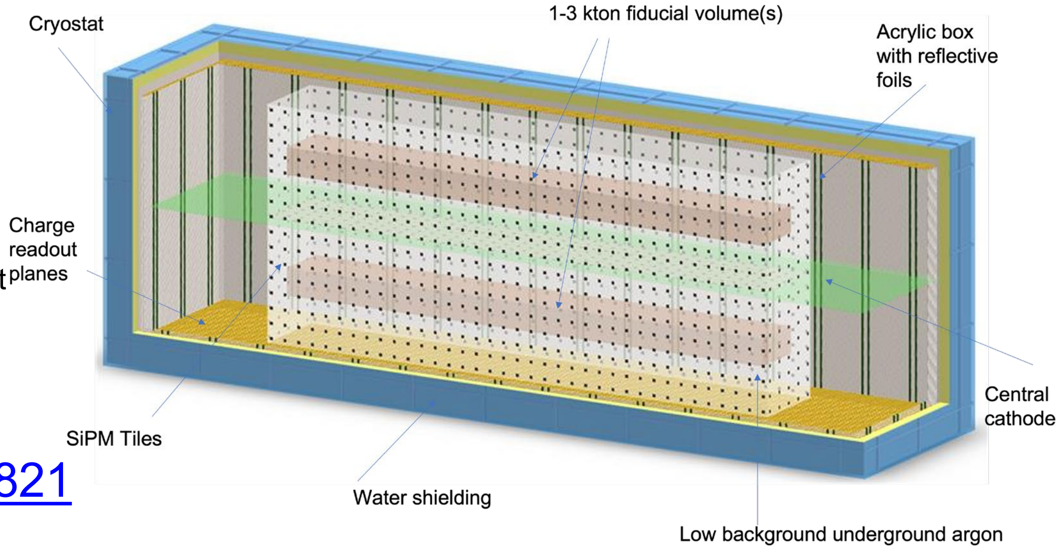
Improved background suppression

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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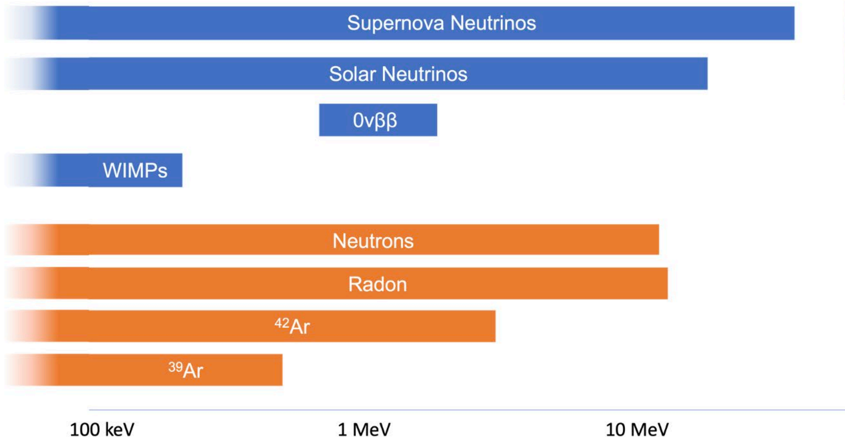
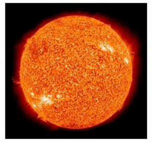
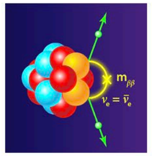
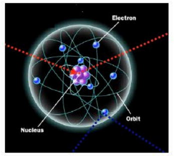


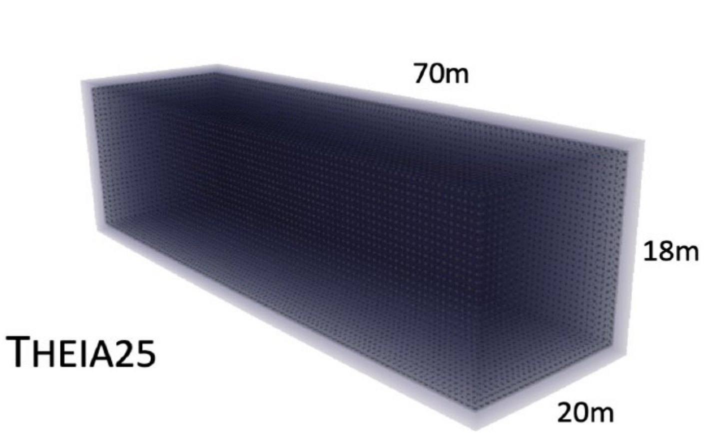


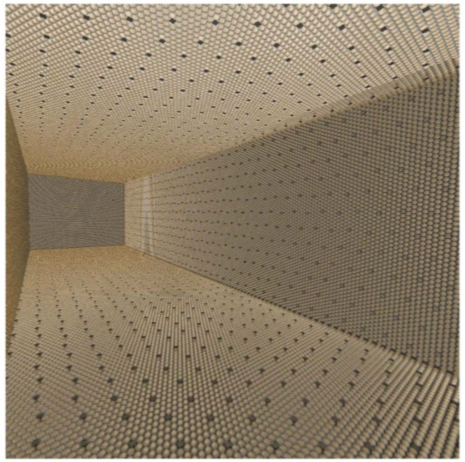




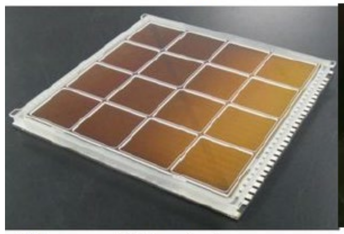
- **Solar neutrinos**: Precision Δm^2_{21}, NSI constraints, precision CNO, test solar metallicity
- **Supernova neutrinos**: Lower threshold, elastic scatters, early- and late-time information, detection beyond Magellanic Cloud, CEvNS glow
- **WIMP dark matter**: Competitive high mass search on fast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

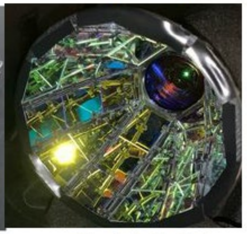
Hybrid Cherenkov/Scintillator Module ("Theia")





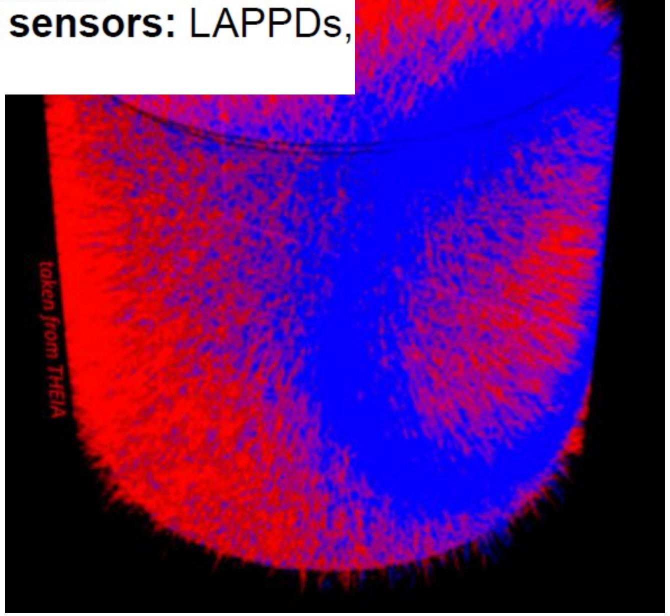
Novel target medium: (Wb)LS





Novel light sensors: LAPPDs, dichroicons

New technologies make this possible



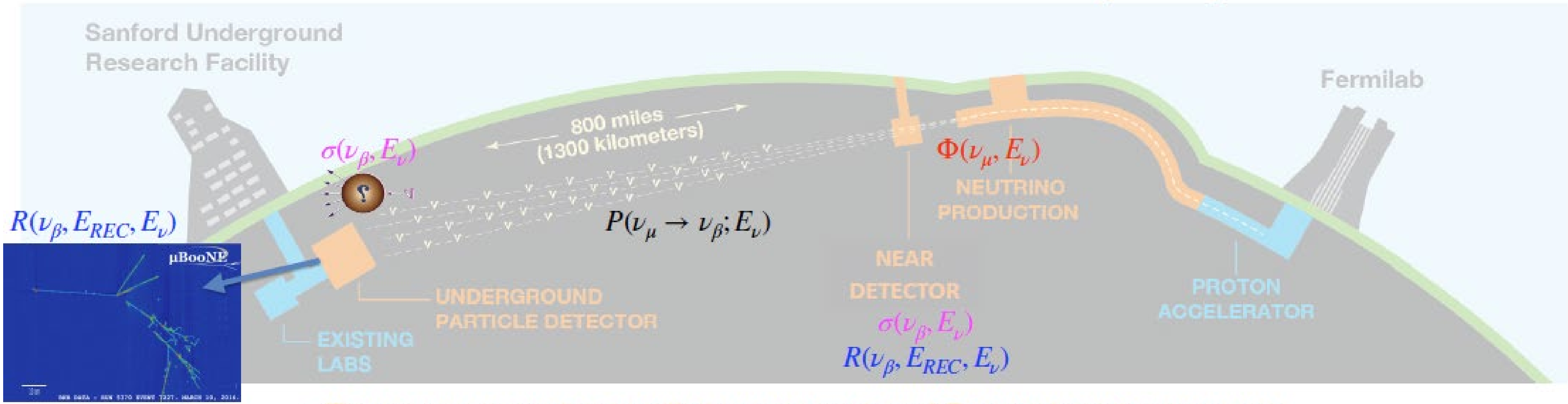
Hybrid signals allow broad extension of DUNE physics

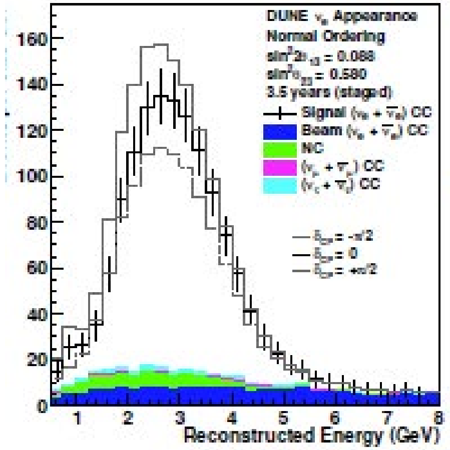
- CP violation with comparable sensitivity to 1 DUNE module
  - Low-Z target allows cross check with Hyper-K
  - Requires changes to ND suite
- Precision low-energy solar neutrinos (CNO, pep, ^{8}B MSW transition)
- Diffuse supernova background neutrinos
- Literally complementary supernova burst signal: 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

PURPOSE OF NEAR DETECTOR (ND)

From H. Tanaka



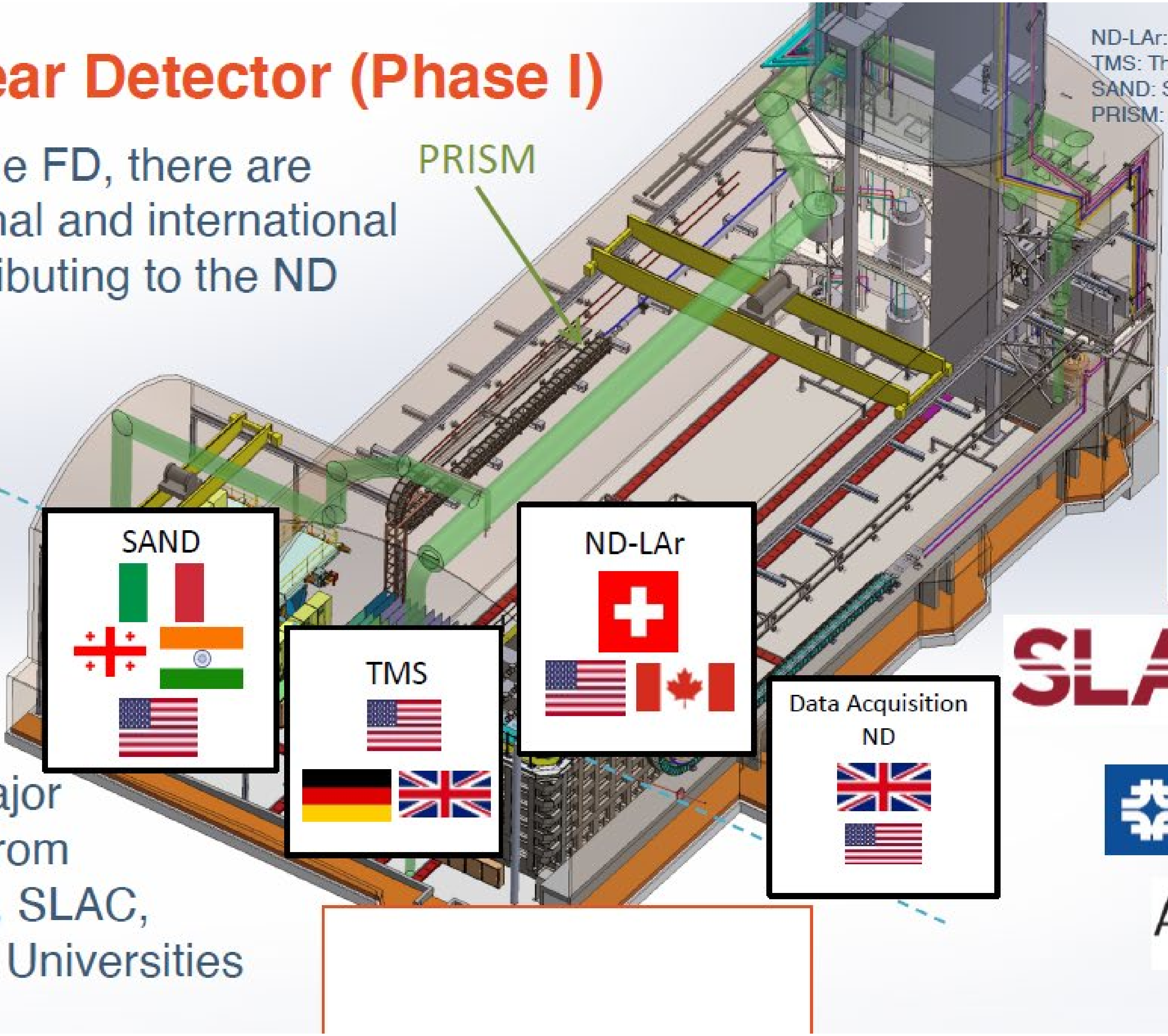


- To measure neutrino oscillation parameters, LB experiments compare:
  - Observed energy spectrum of flavor-tagged neutrinos at the far detector
  - Prediction as a function of neutrino oscillation parameters (both "signal" and background).
- This requires :
  - "following" neutrinos: production (Φ), oscillation (P), interaction (σ), detection (R) in far detector (FD)
  - The measurement is only as good as the prediction:
    - Systematic errors in the prediction result in degradation in precision/sensitivity
- Each element is critical in producing the prediction

DUNE Near Detector (Phase I)

ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

- Just as with the FD, there are multiple national and international partners contributing to the ND
- Our partners have been building prototypes & sending detector components
- In the U.S., major contributions from LBNL (pixels!), SLAC, ANL, FNAL, & Universities



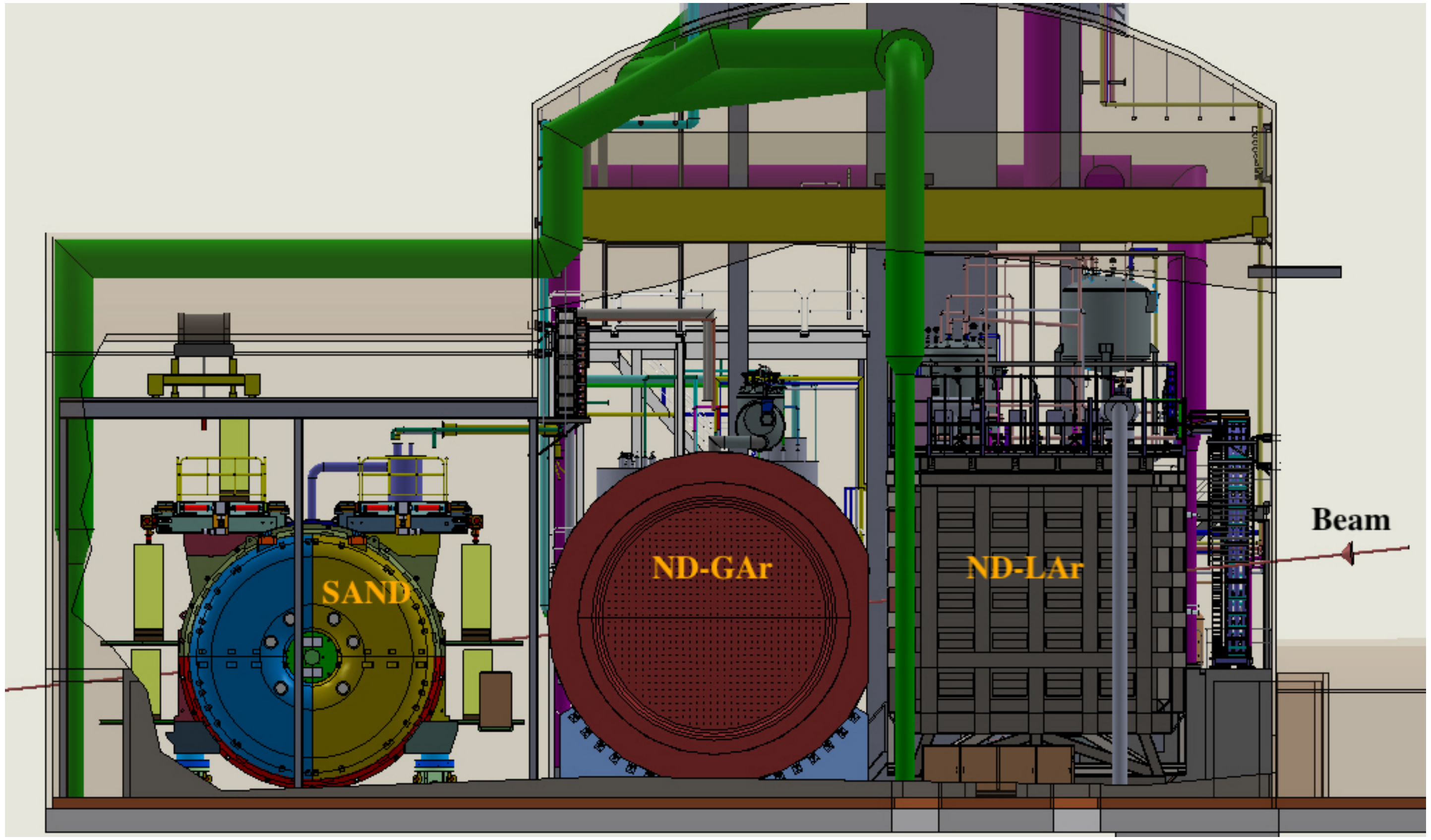
BERKELEY LAB

SLAC NATIONAL ACCELERATOR LABORATORY

Fermilab

Argonne NATIONAL LABORATORY

Developing the Phase II ND Concept

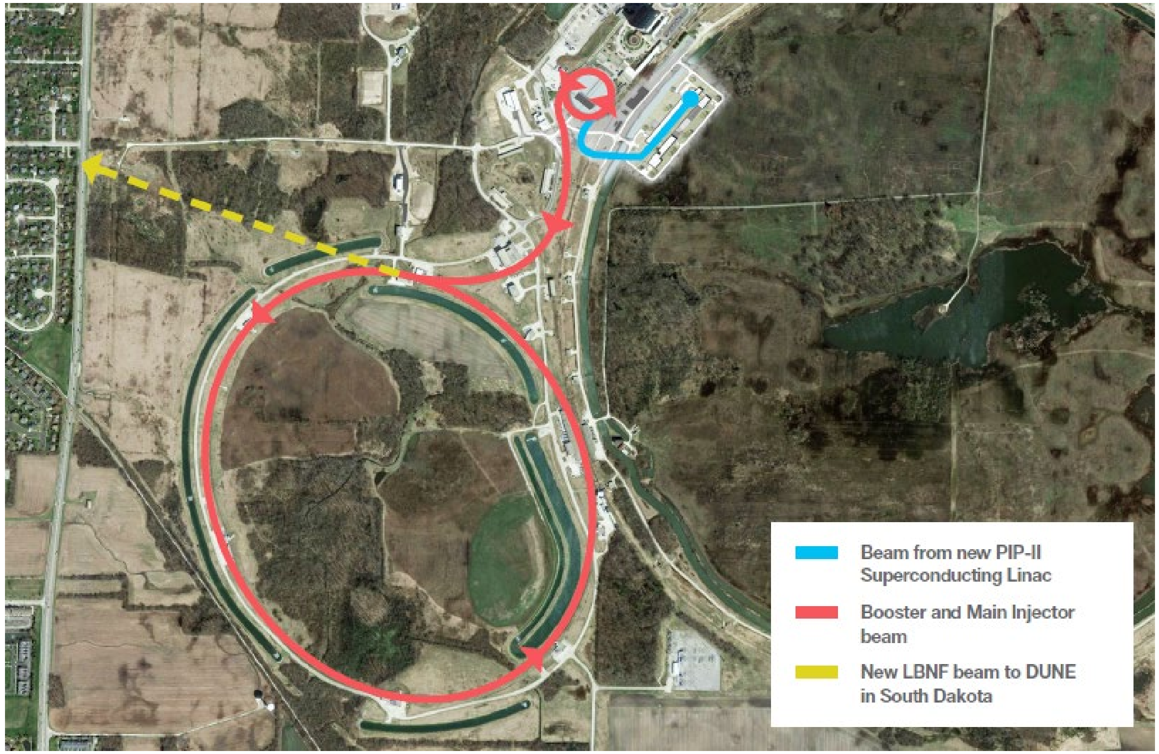


[Phase II ND Workshop, Imperial College, London June 20-22, 2023].

Fermilab Accelerator Complex Evolution (ACE) Plan and Phase II LBNF Beamline plans

Accelerator Complex in PIP-II / LBNF era (pre ACE plan)

- PIP-II Project provides
  - New SRF linac for injection into Booster at 800 MeV (present 400 MeV)
  - Booster cycle rate upgraded to 20 Hz from 15 Hz
  - Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI
- LBNF/DUNE-US Project provides
  - New proton beamline for up to 2.4 MW
  - Target systems for 1.2 MW
  - Shielding and absorber for up to 2.4 MW

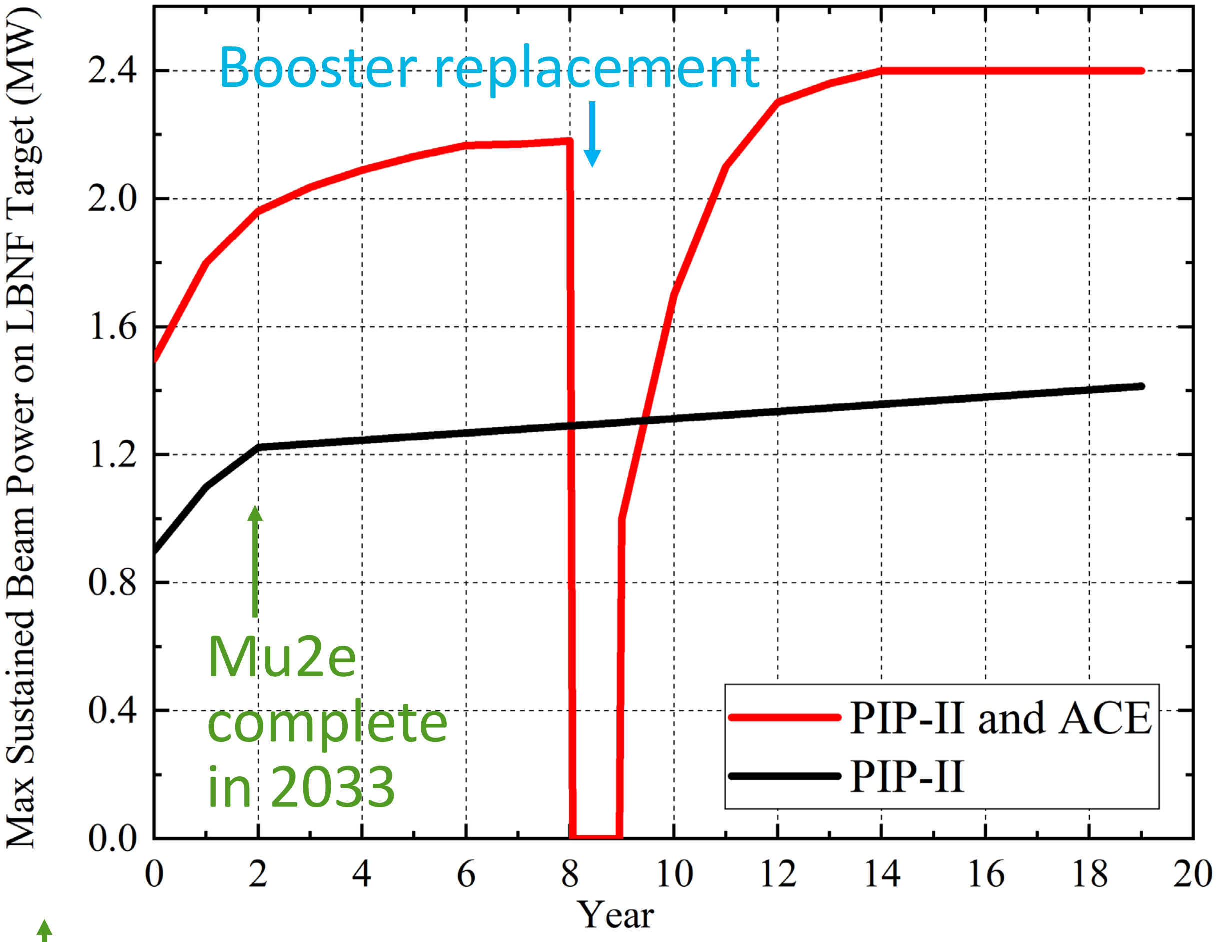


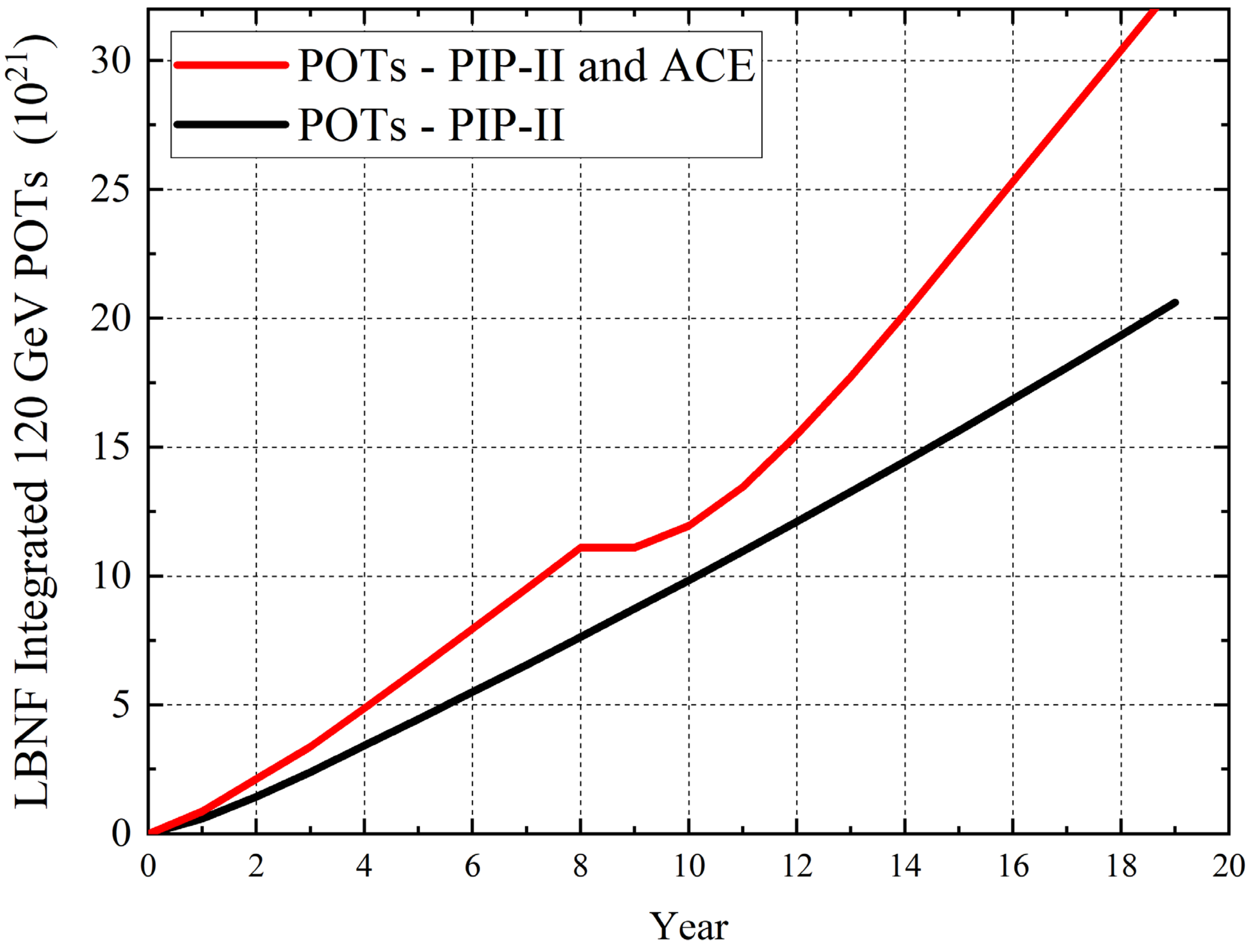
Accelerator Complex Evolution (ACE) plan

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex
- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

Previously referred to as PIP-III

DUNE power and POT implications

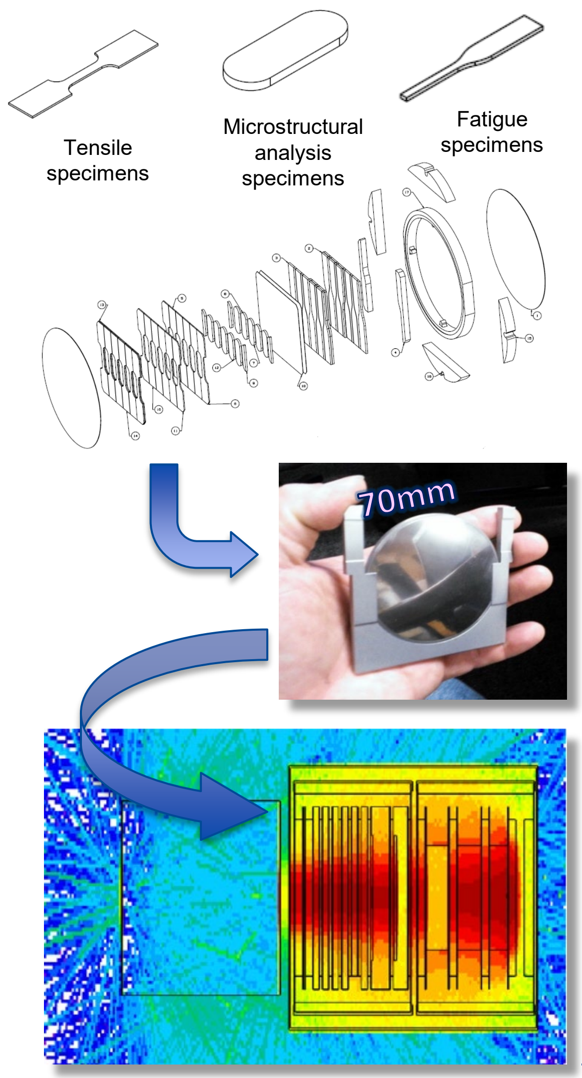




(Mu2e restarts 2029)

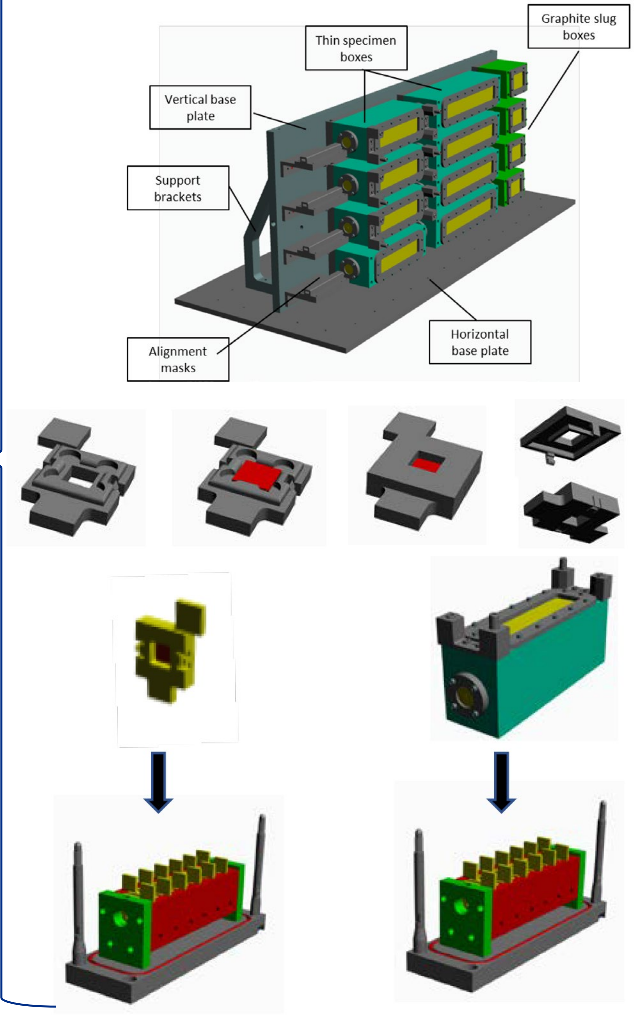
Fermilab

Target materials R&D on critical path to 2+ MW target



1. Identify candidate materials
2. High-energy proton irradiation of material specimens to reach expected radiation damage
3. Pulsed-beam experiments of irradiated specimens to duplicate loading conditions of beam interactions
4. Non-beam PIE (Post-Irradiation Examination) of specimens
   – Material properties
   – Microscopic structural changes
   – High-cycle fatigue testing

Five-year cycle needs to start ASAP



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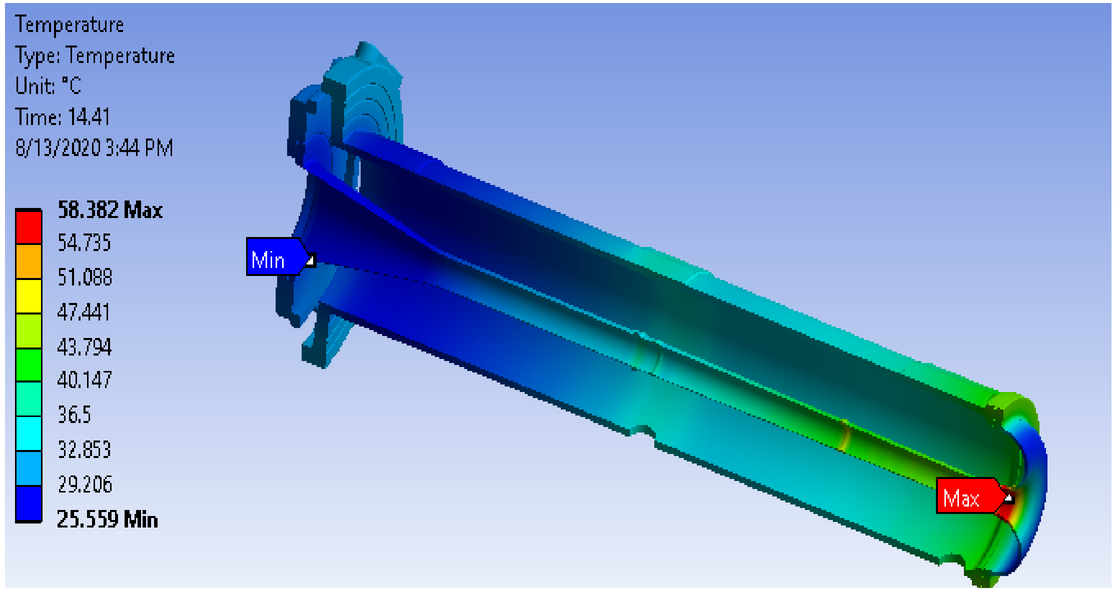
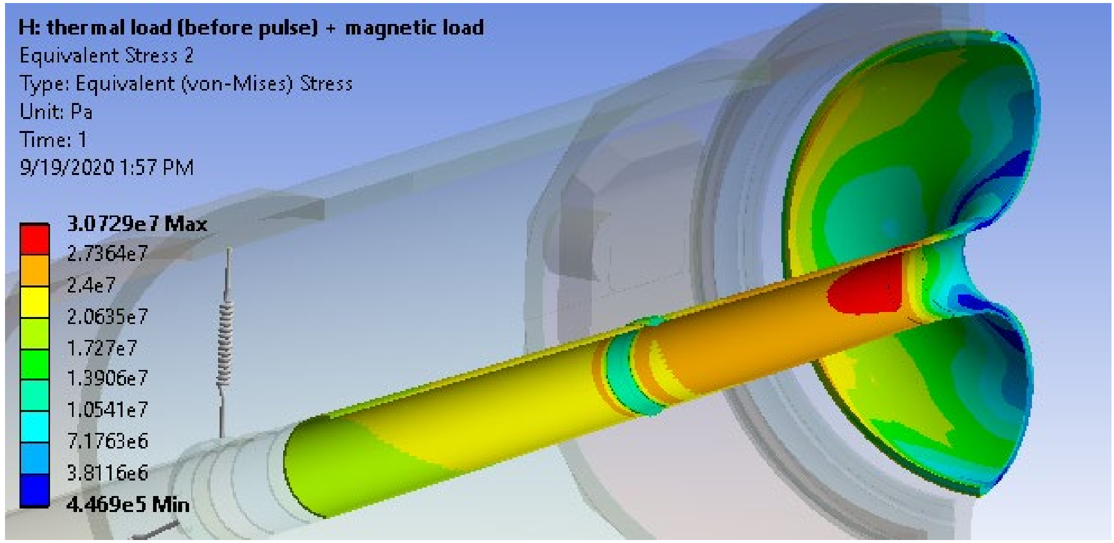
Horns for 2.4 MW performance

- Horn A requires reanalysis and likely redesign
  - 1.2 MW analysis indicates 2.7 safety factor on fatigue endurance limit
  - Likely redesign to:
    - Avoid beam heating in critical locations
    - Strengthen structure in critical locations
- Horns B&C see less beam heating
  - Safety factor: 7.3 for 1.2 MW operation
  - Require reanalysis, but less likely redesign





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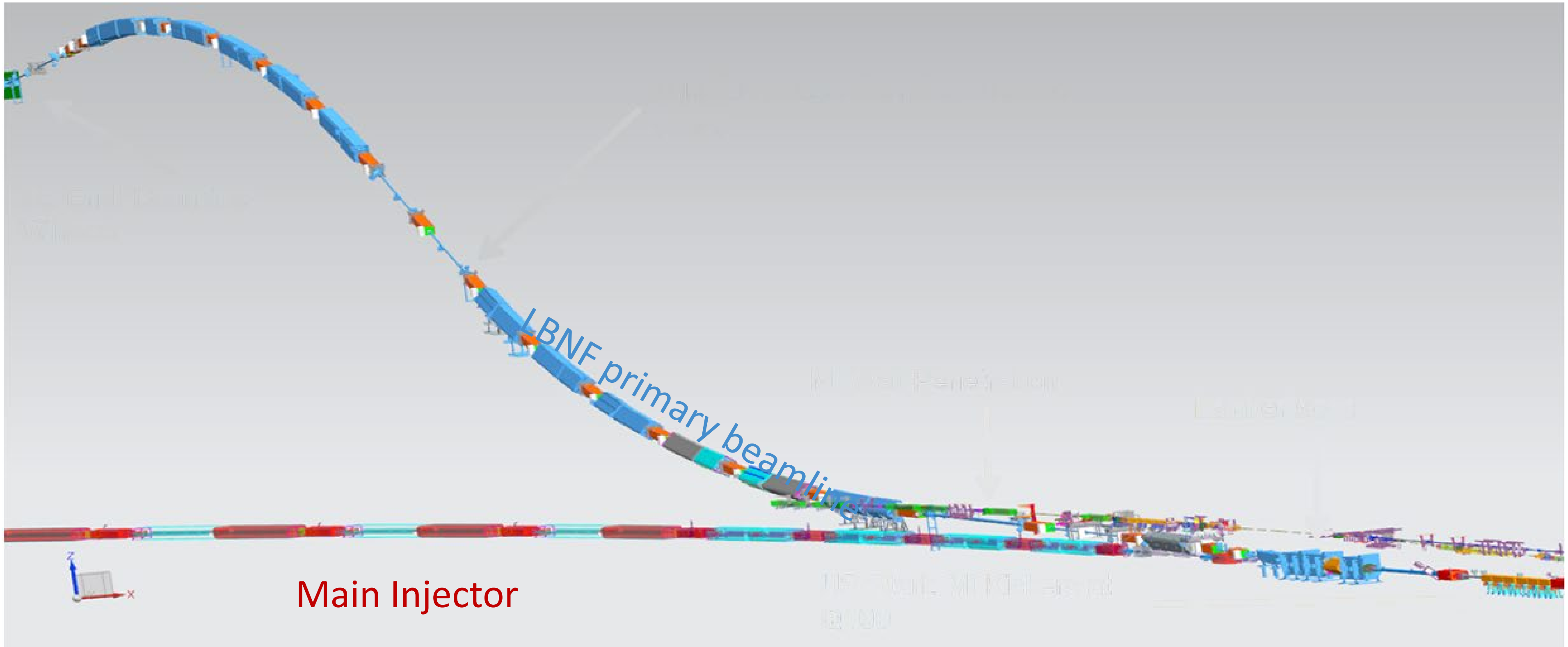
LBNF beamline

- Larger power supplies to ramp twice as fast, may need more building space
- Kicker power supply modifications to charge up faster
- Cooling water: additional pumps to remove and exhaust additional heat



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DUNE: Overview & Science

Chris Marshall, University of Rochester
P5 Town Hall, Fermilab
21 March, 2023

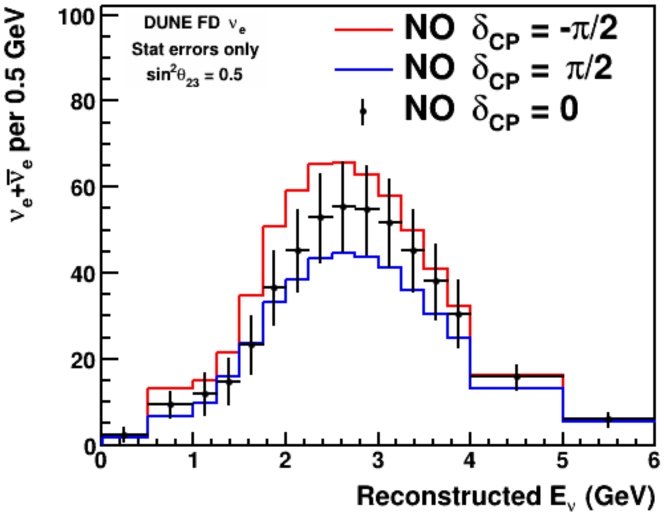
DUNE ν_e and $\bar{\nu}_e$ spectra can distinguish MO in Phase I

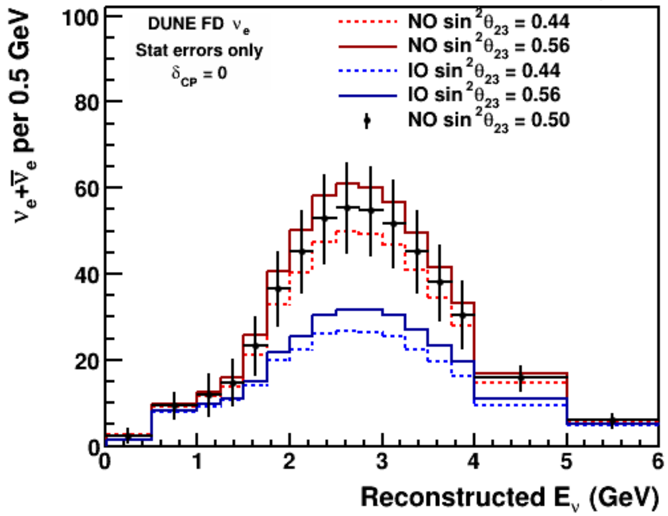
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

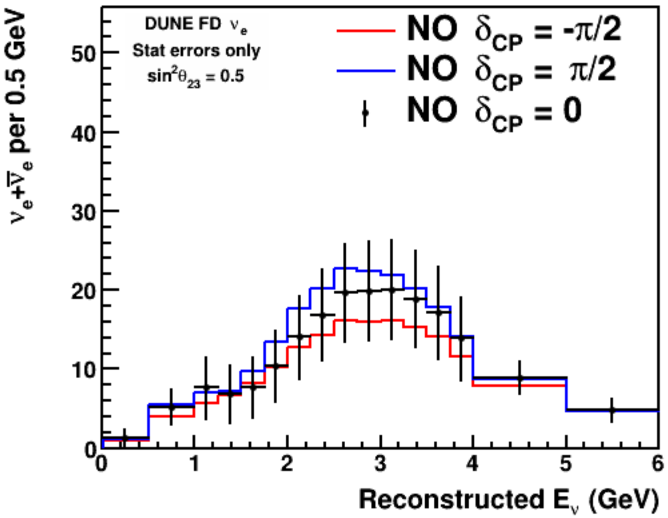
Neutrino mode

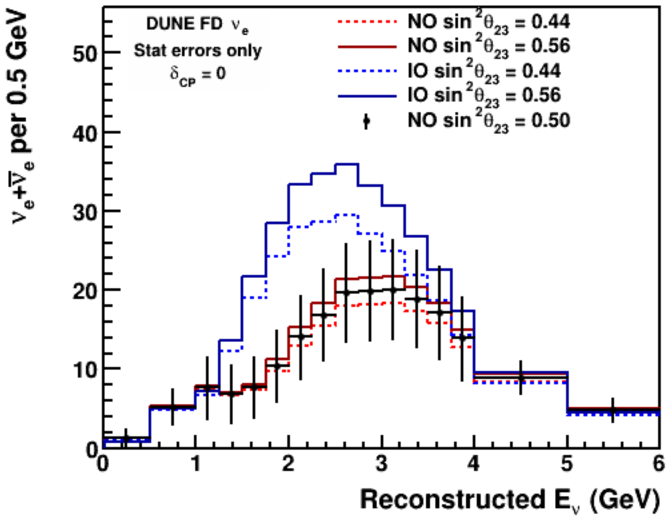




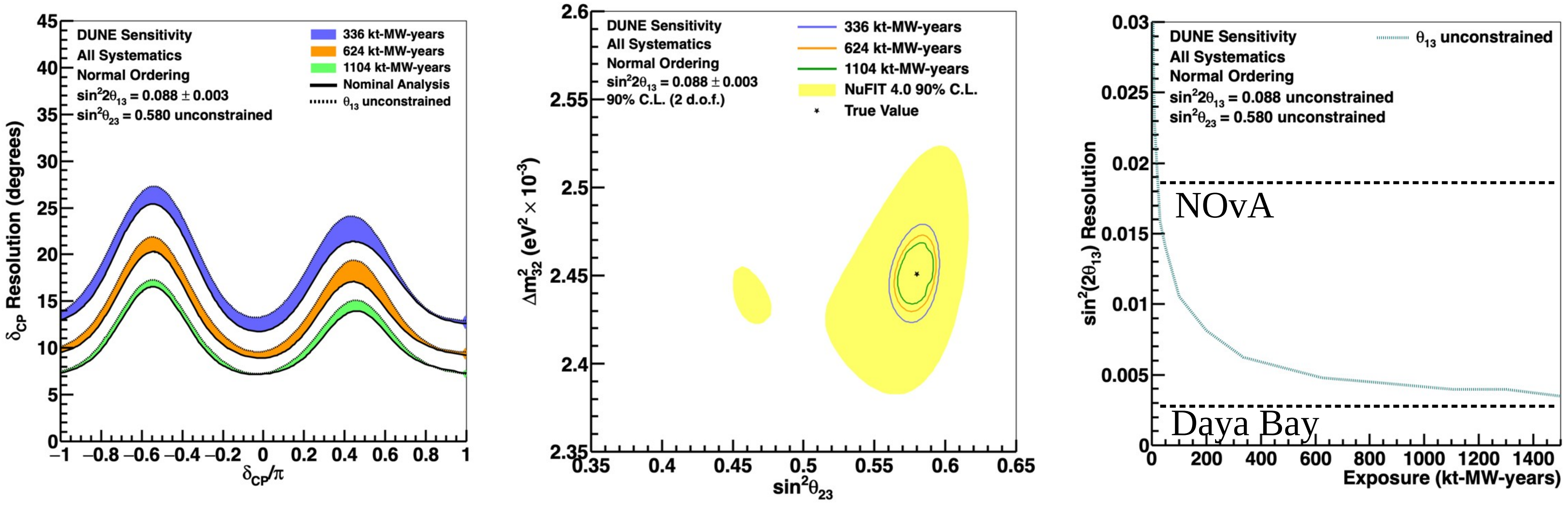
Phase I

Antineutrino mode



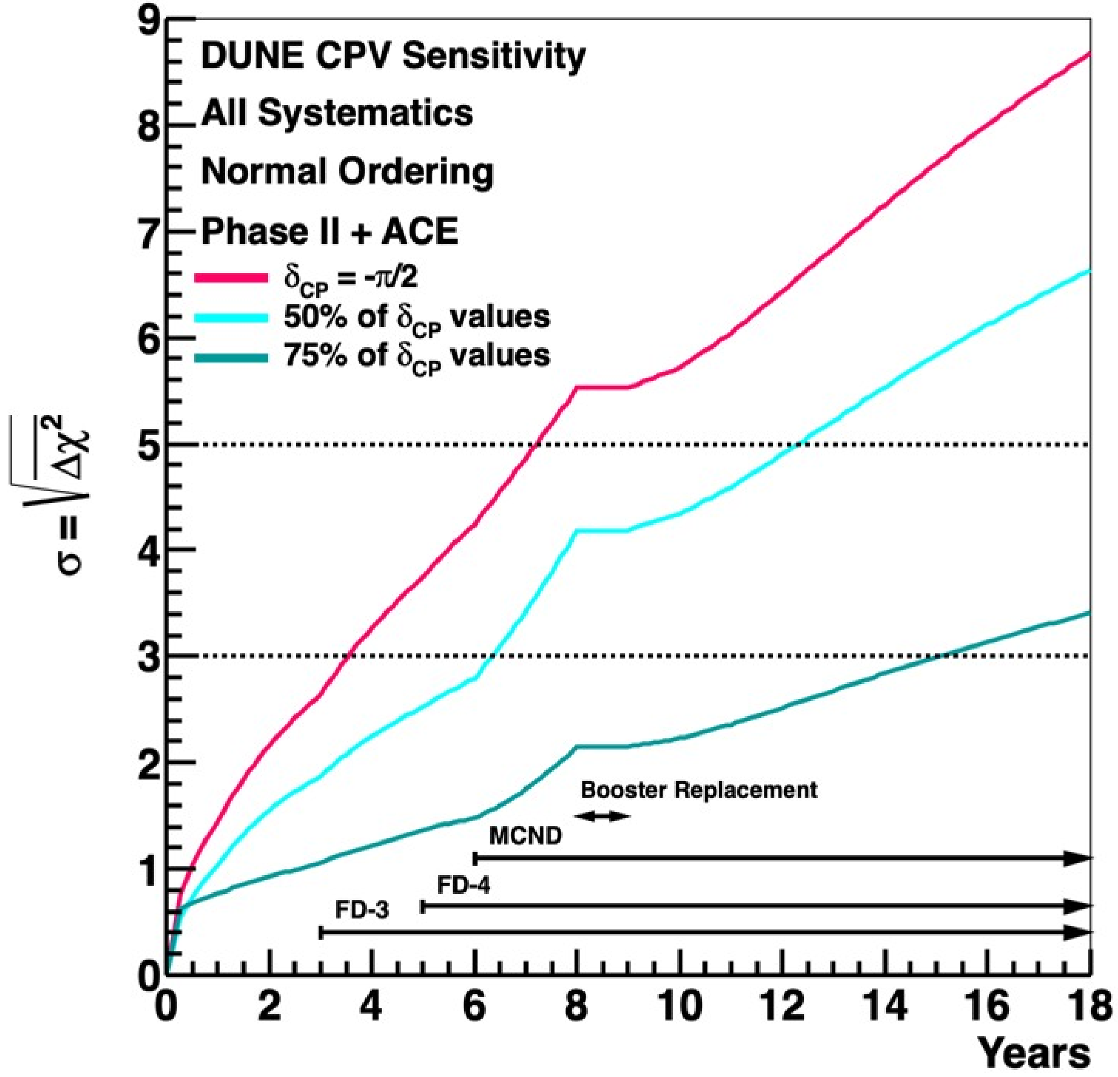


DUNE Phase II: precision long-baseline physics



- Resolution to δ_{CP} is ~6-16° depending on true value, and sensitivity to CPV even if Nature is relatively unkind
- Excellent resolution to θ_{23}, including octant discovery potential
- Resolution to θ_{13} approaches Daya Bay, DUNE-reactor comparison is sensitive to new physics

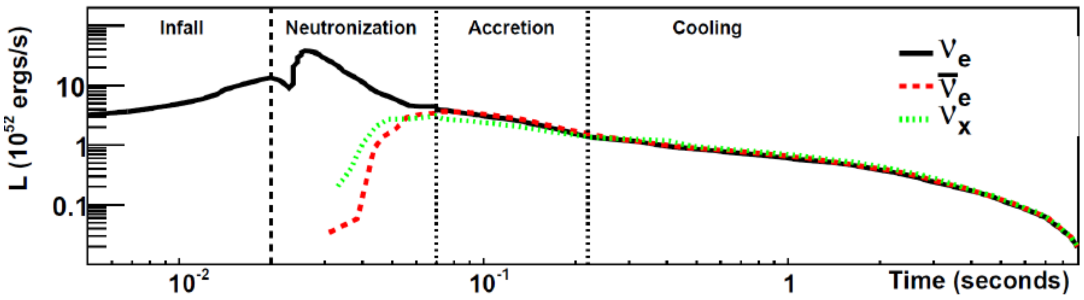
Timeline for CP violation: it depends on the value of δ

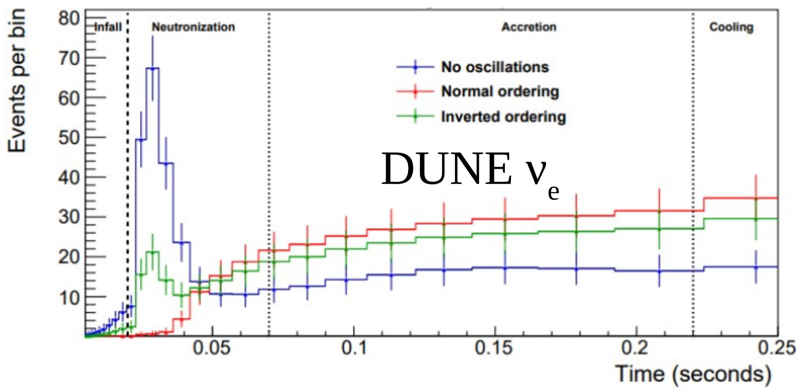


- If $\delta_{CP} = \pm 90°$, DUNE reaches 3σ CPV in 3.5 years, 5σ in 7 years
  - Hyper-K will likely get there first, if/when the mass ordering is known
- If $\delta_{CP} = \pm 23°$, it is extremely challenging to establish CP violation at 3σ → DUNE and Hyper-K are competitive and complementary

Supernova physics: unique sensitivity to electron neutrinos

10 kpc supernova burst





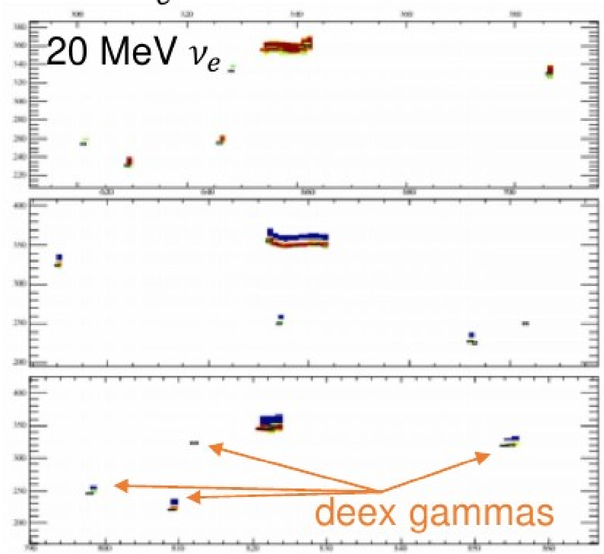
	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

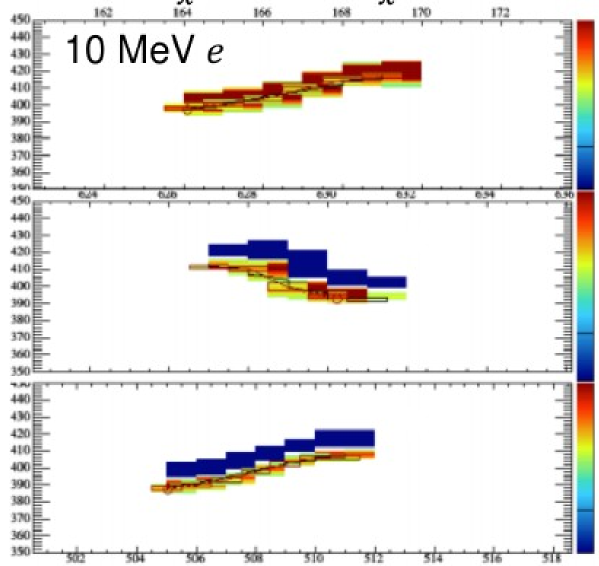
- Time (and energy) profile of the flux is rich in supernova astrophysics
- Flux contains ν_e and $\bar{\nu}_e$ as well as a component of the other flavors (ν_x) – DUNE has **unique sensitivity to ν_e** component
- Phase I: O(100s) events per FD module for galactic SNB
- Phase II: Reach extends reach beyond the Milky Way
- Enhancements to LArTPC design in Phase II could greatly extend low energy science (see talk by Mary Bishai)

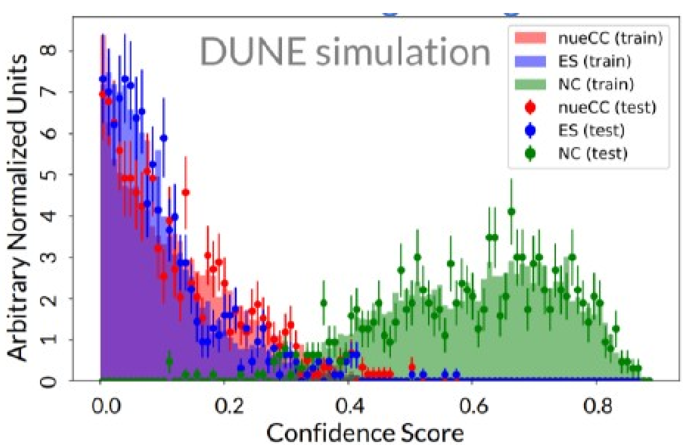
Supernova pointing in DUNE

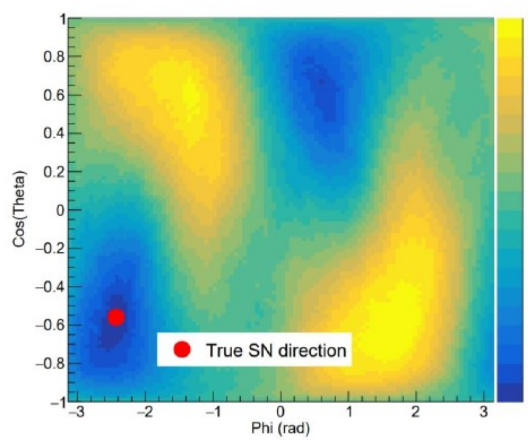
CC: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

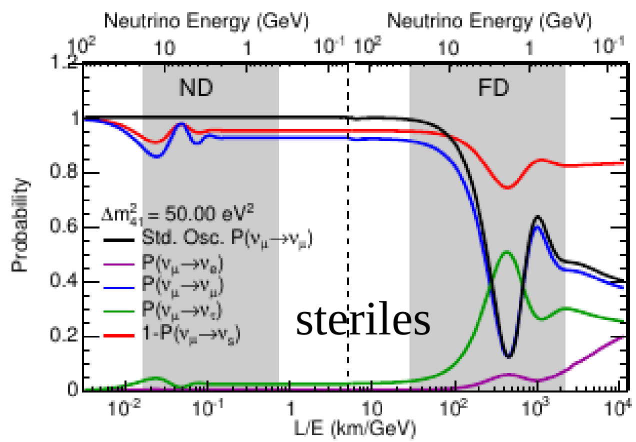


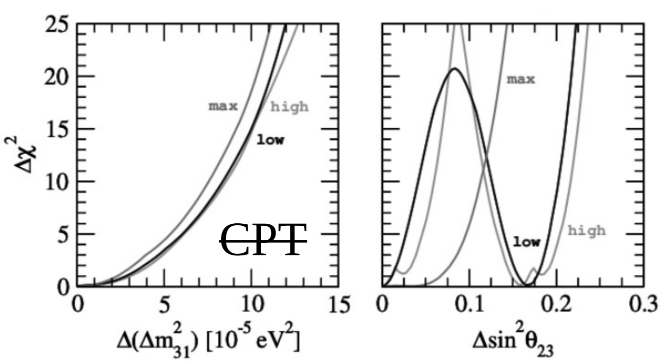


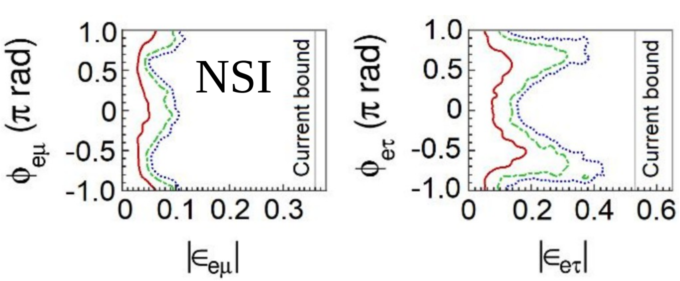


- DUNE can see low-energy de-excitation photons, which gives separation between charged-current (isotropic) and elastic scattering (very forward)
- Provides ~5° resolution
- The neutrino signal will arrive ~hours before light, DUNE can predict the location of supernovae

DUNE is sensitive to new physics in neutrino oscillations

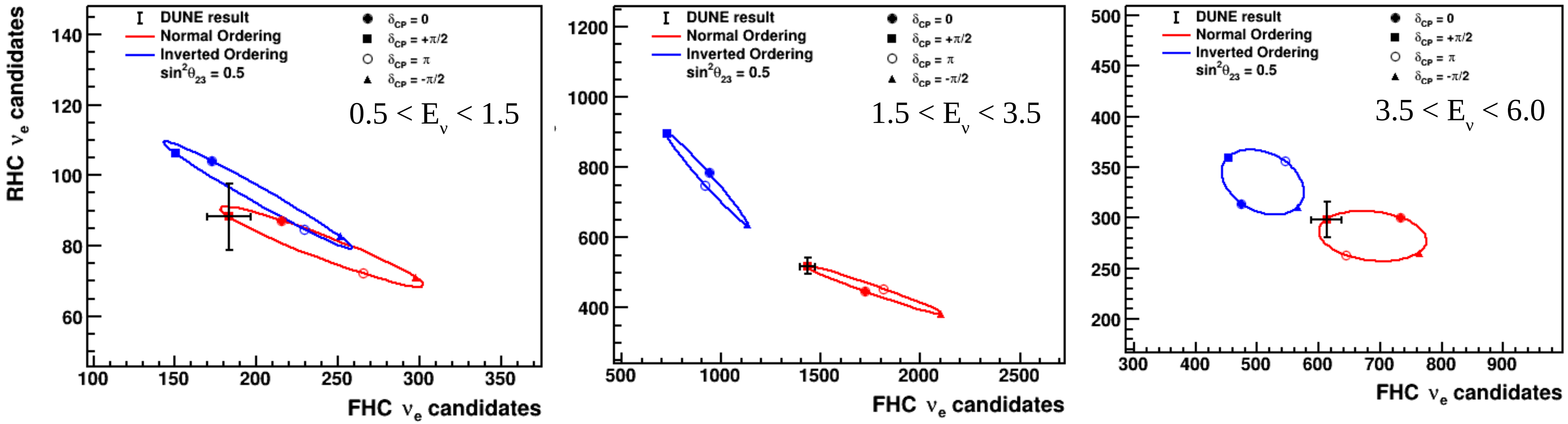






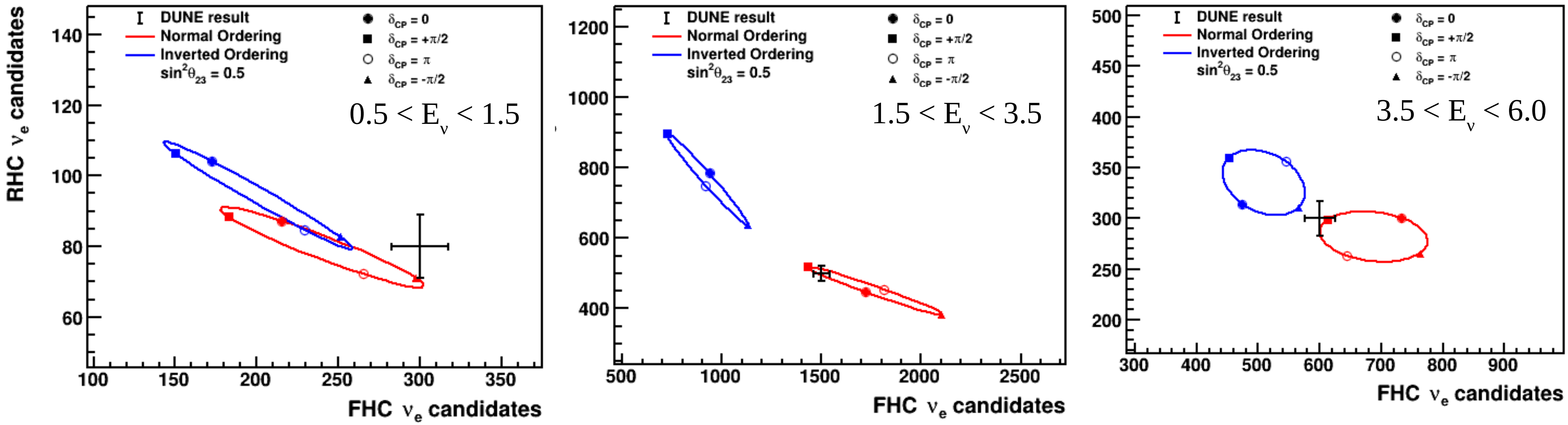
- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos (top), CPT violation (middle), or NSI (bottom)
  - DUNE covers a very broad range of L/E at both the ND and FD
  - DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
  - DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: precise measurements with small matter effect in Hyper-K **and** large matter effect in DUNE Phase II likely required

DUNE is extremely sensitive to new physics



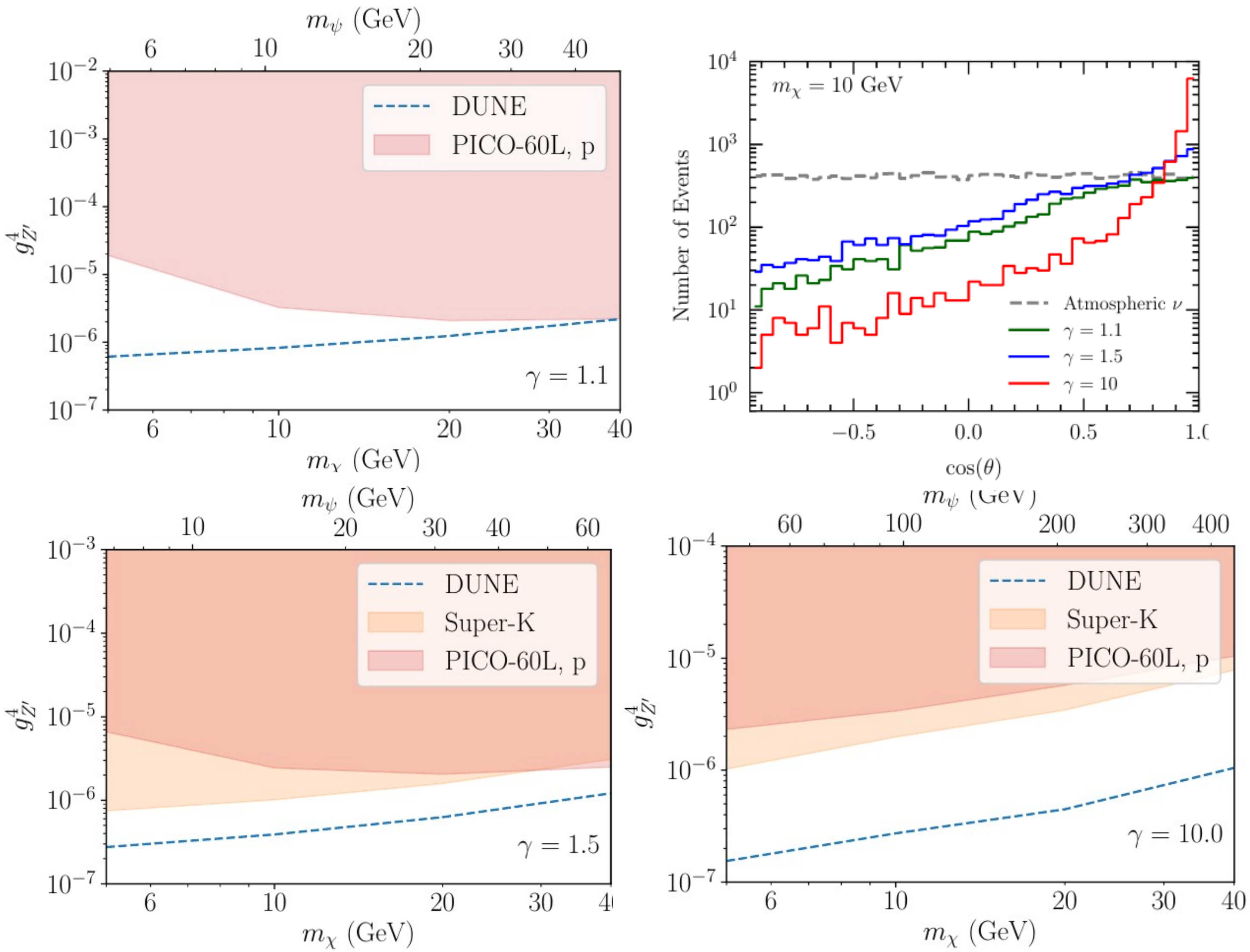
- If the three-flavor model is correct, oscillations depend only on L/E, and the data point will be at the same point on the same ellipse in every single energy bin
- We can search for deviations across a broad range of L/E

Example of definitive evidence of new physics



- We might see an anomaly only in a particular energy range
- Having broad L/E coverage with large matter effect is synergistic with Hyper-K
- Does this new physics depend on E rather than L/E? Is it matter dependent? Is it only present in the rapid oscillation region? Difficult to *characterize* the new physics with only one experiment, but DUNE + Hyper-K could probably answer all of these questions

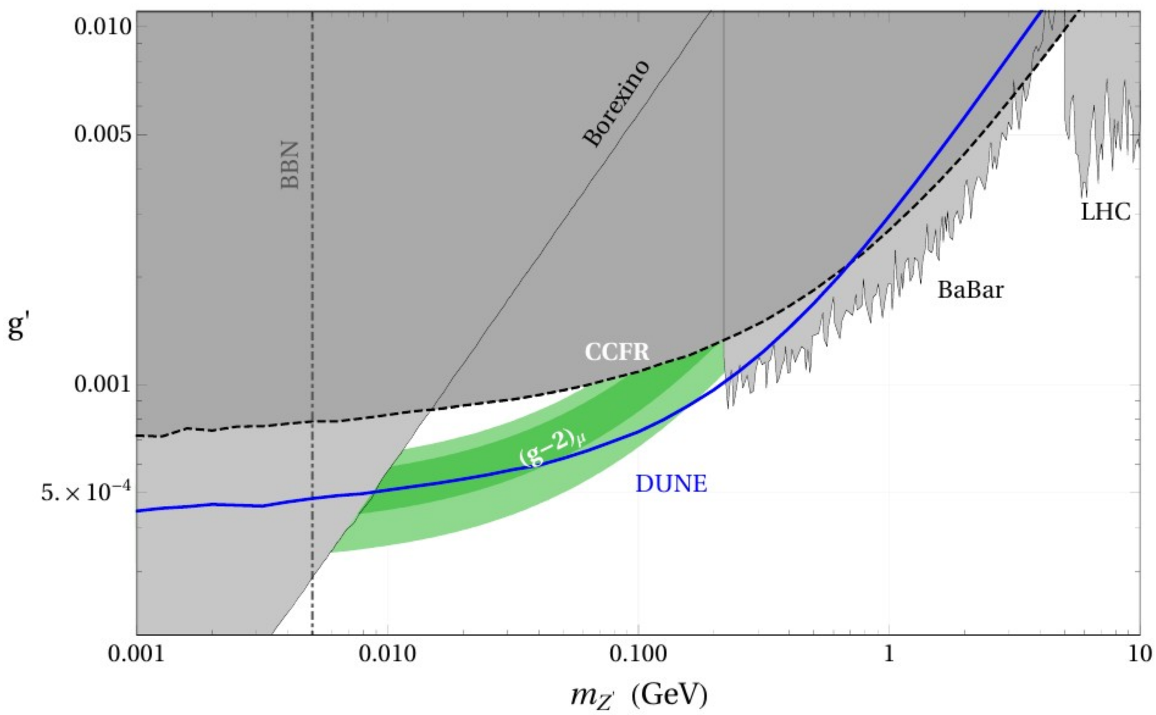
BDM from sun via hadronic channels

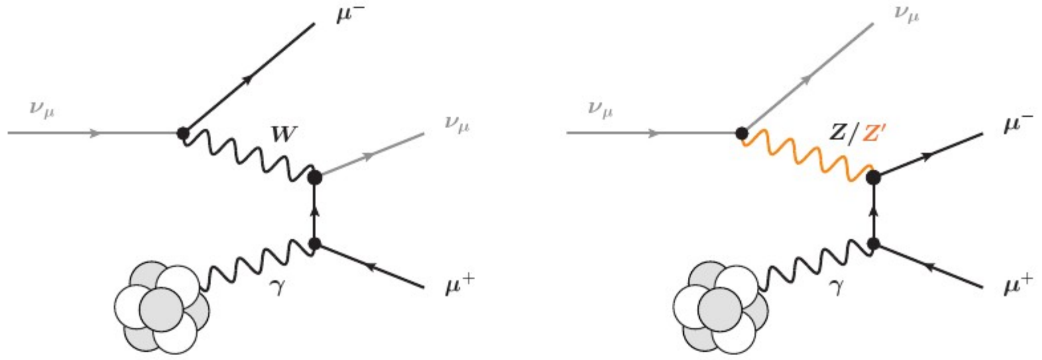


Phys. Rev. D 103, 095012 (2021)

- $\chi N \rightarrow \chi X$ hadronic processes
- Reconstruct direction in DUNE FD LArTPC, point back to Sun
- Low hadron thresholds are critical → at lower boost factors, SK/HK does not have sensitivity because protons are invisible
- DUNE can surpass current limits from PICO

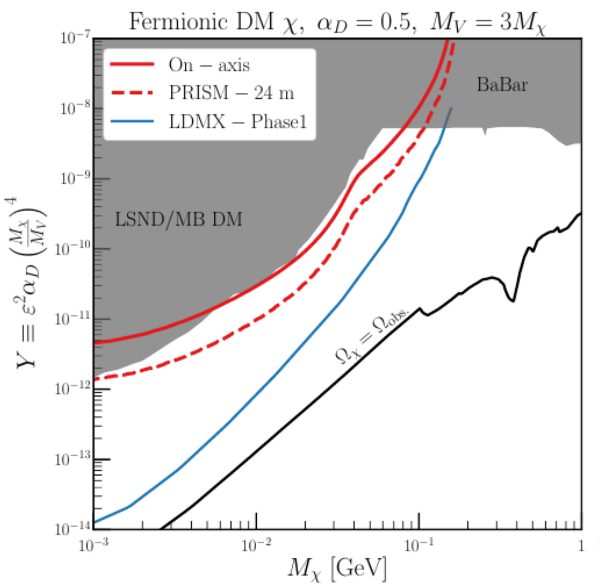
BSM physics with the LBNF beam: Neutrino tridents at the ND

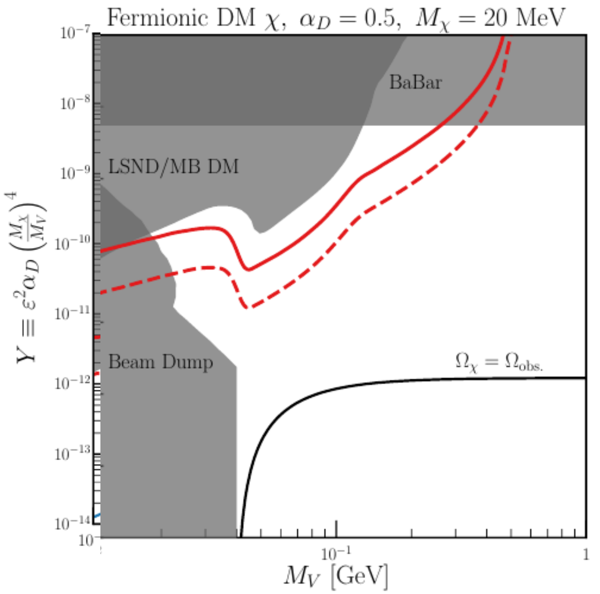




- DUNE ND-LAr will see ~100 μμ tridents per year (at 1.2 MW; XS scales with energy and Z^2)
- Backgrounds (mainly CC1π) can be mitigated by requiring clean vertex, two long, non-scattering tracks
- Tiny SM cross section, DUNE can search for enhancement due to Z'
- World-leading reach at low Z' mass is complementary to collider searches, and covers much of the remaining region that is consistent with a possible $(g-2)_\mu$ anomaly
- Also at ND (in backups): Heavy neutral leptons, boosted dark matter

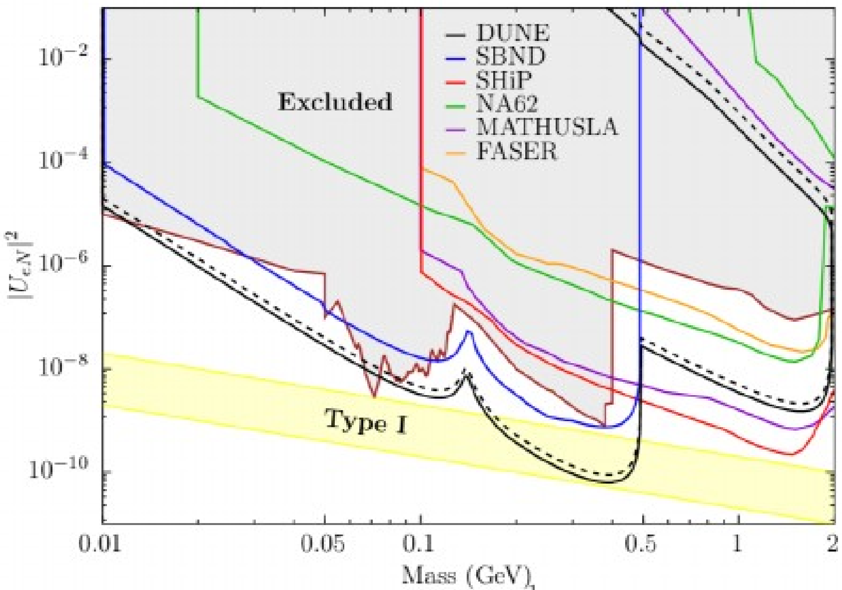
BDM from the beam

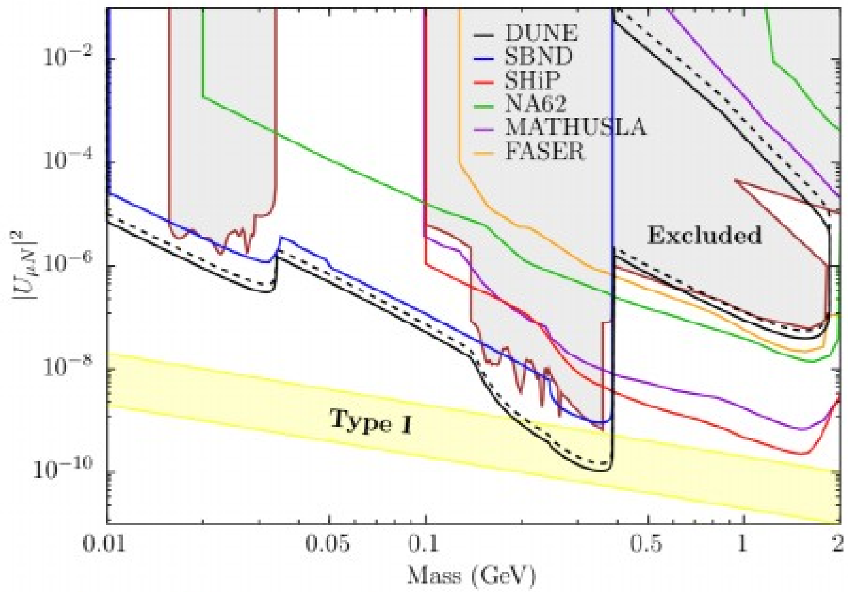


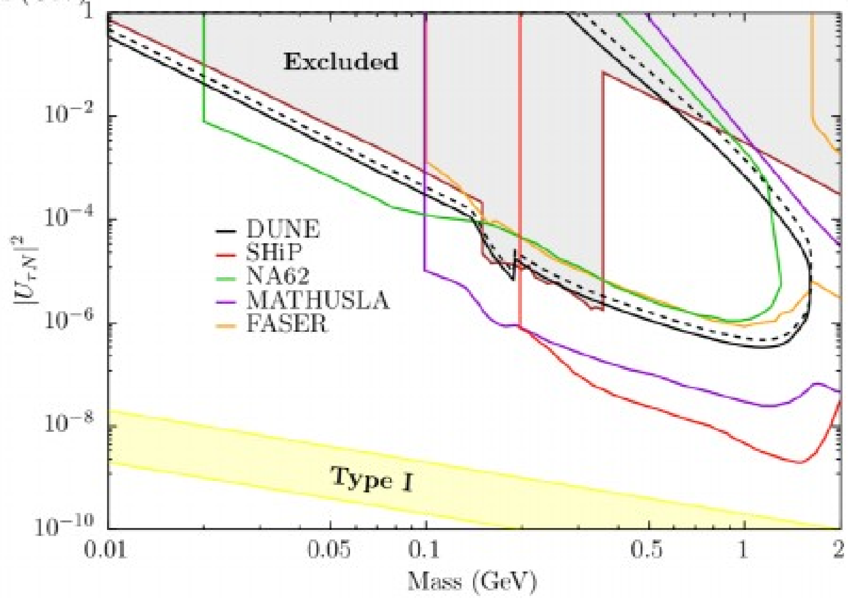


- χe → χe scattering in ND-LAr, from boosted DM produced in the beamline
- Backgrounds from νe → νe have different spectrum
- DM and ν have different dispersion, and looking at off-axis ND-LAr data improves the statistical separation
- Sensitivity at low mass is potentially world-leading

DUNE HNL sensitivity at ND

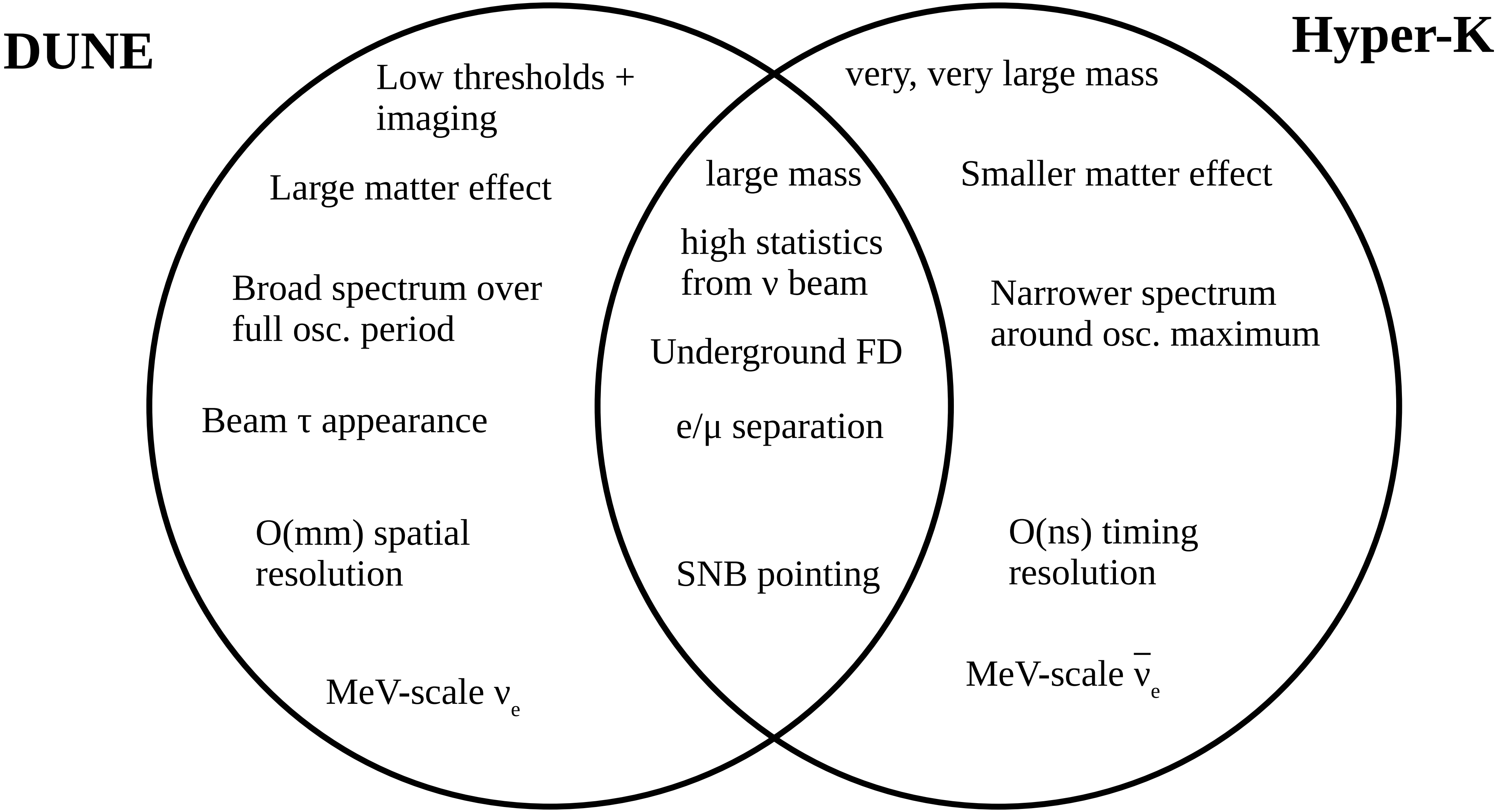




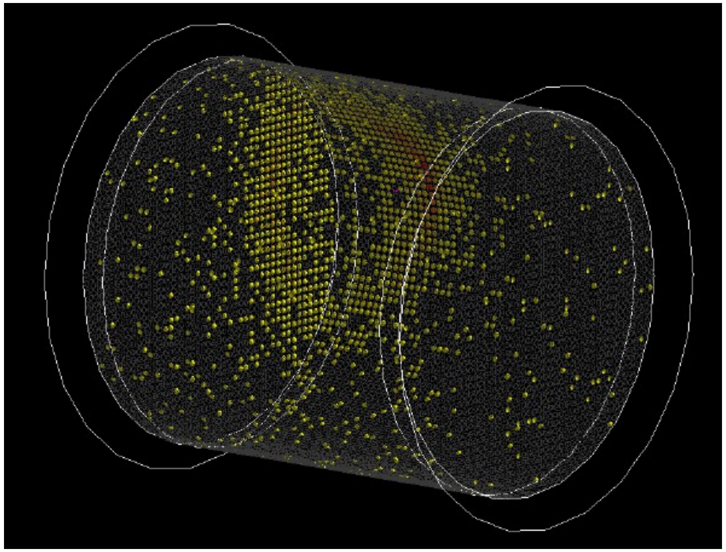


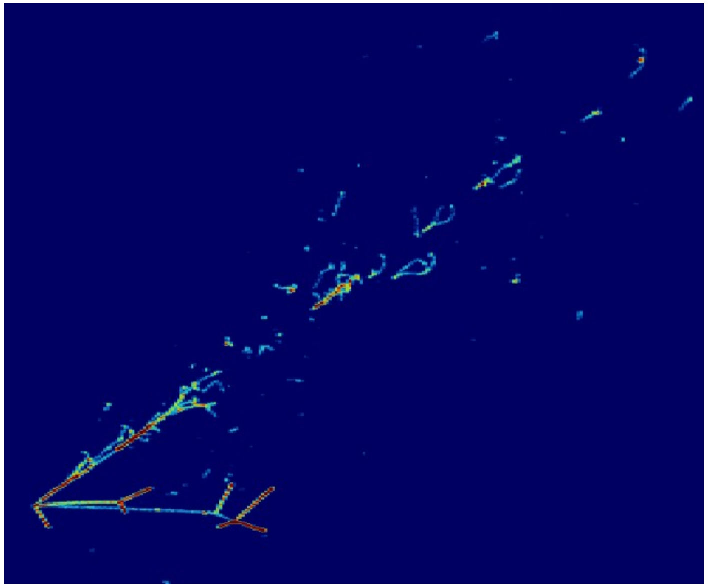
N → νee, νeμ, νμμ, $\nu\pi^0$, eπ, μπ
Phase II (22 MW-yrs)
no backgrounds → may require ND-GAr to reach zero background

Complementarity



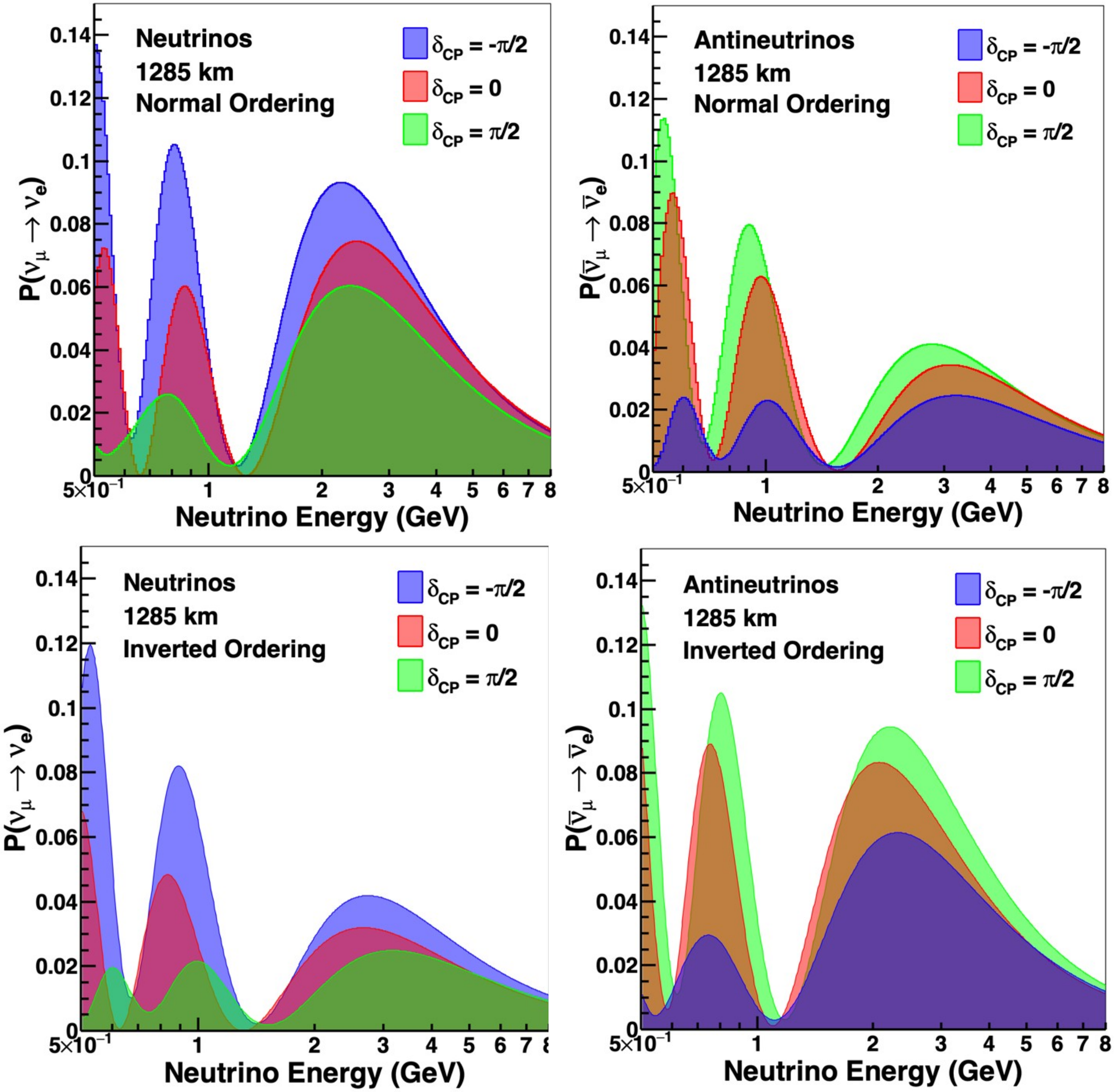
Different optimizations → different strengths for non-beam physics





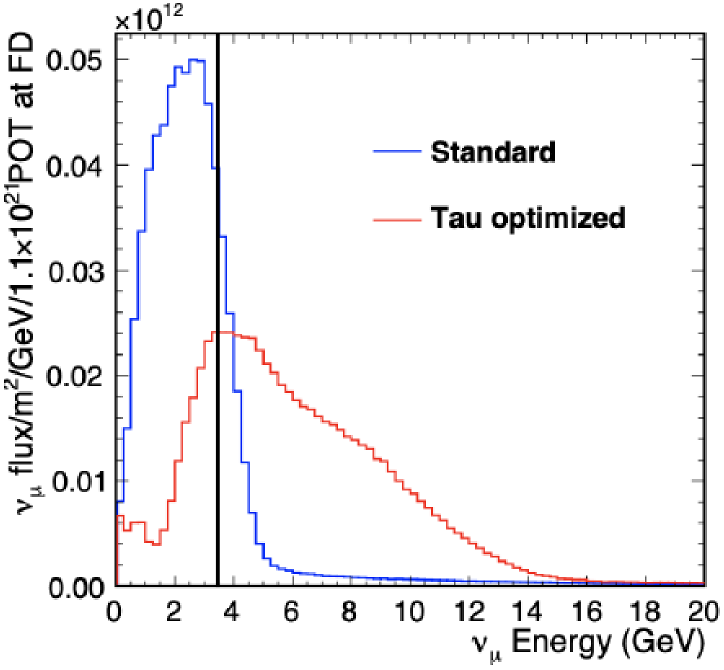
- Pictured: ν_e CC interaction in Hyper-K and DUNE
- For long-baseline oscillation physics, Hyper-K and DUNE are both well suited for their respective neutrino beams
- For non-beam physics, Hyper-K and DUNE are very complementary:
  - Hyper-K has higher mass, better timing
  - DUNE has lower thresholds for charged particles, better imaging and event identification

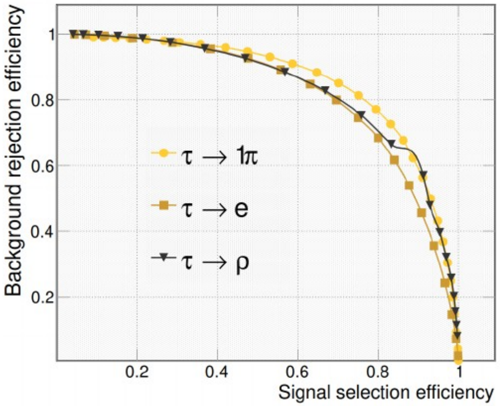
DUNE: large matter effect, broad neutrino beam



- Large matter effect → CPV and mass ordering are totally non-degenerate
- Spectral information resolves degeneracies between θ_{23}, θ_{13}, and δ_{CP}, and enables searches for non-standard oscillations

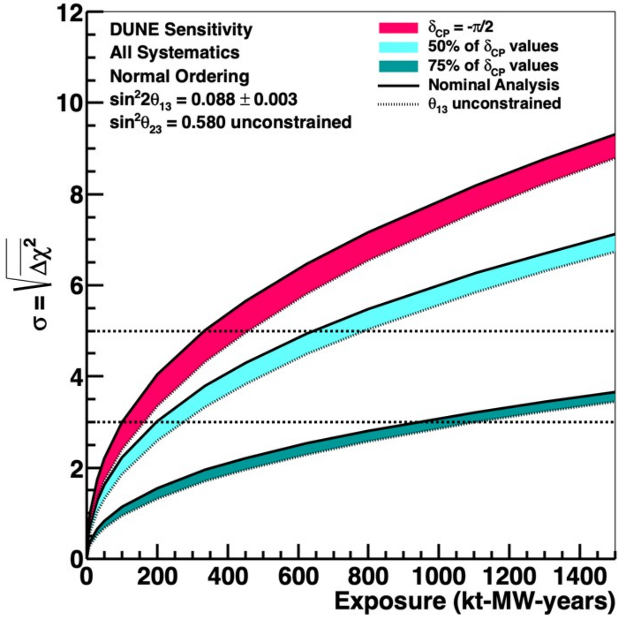
Unique to DUNE: three-flavor measurements, including taus

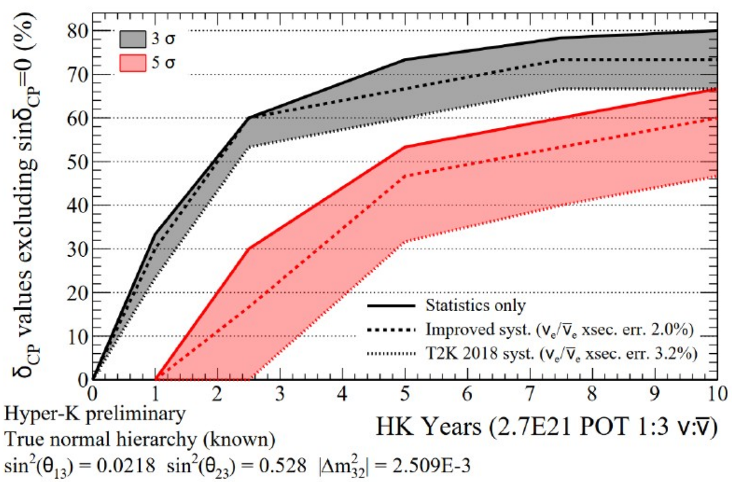




- Three-flavor unitarity tests are limited by the dearth of ν_τ data
- LArTPC presents a unique opportunity to image hadrons and improve the reconstruction of ν_τ CC interactions
- LBNF has significant flux above the τ production threshold, and the beam could be re-optimized (by moving the focusing components) to enhance ν_τ CC
- This is unique for accelerator beams, and complementary to atmospheric τ physics that is accessible in IceCube

When will CP violation be established?





- DUNE can establish CP violation at 3σ in 4 years (if δ_{CP} = 90°), or 6 years (δ_{CP} = 45°), or 14 years (if δ_{CP} = 22°), or establish that CP is **not** violated (if δ_{CP} = 0°)
- DUNE can establish CP violation at 5σ in 7 years (if δ_{CP} = 90°), or 10 years (δ_{CP} = 45°), or ~16 years (if δ_{CP} = 30°)
- With current T2K systematics, and assuming that J-PARC turns on at full power, Hyper-K can establish CP violation at 3σ in 1 year (if δ_{CP} = 90°), or 2 years (δ_{CP} = 45°), becoming systematically limited around δ_{CP} = 30°
- With "improved" systematics, 3σ reach goes out to ~24°
- For 5σ, depending on systematics Hyper-K can establish CP violation for δ_{CP} = 45° between 6-13 years, and becomes limited between 35-45°
- Hyper-K reach assumes that the mass ordering is determined externally

When will CP violation be established?

- Assuming that JUNO determines the mass ordering at 3σ by 2030, Hyper-K data begi … Phase II is …
- If δ_{CP} … at 5σ in 20 …
- If δ_{CP} … at 5σ in be … matics, with DUNE mass ordering)
- If δ_{CP} … r DUN … signi … per-K comb …
- If δ_{CP} … Hype …
- If $\delta_{CP} = 0°$, then DUNE and Hyper-K will measure δ_{CP} with a precision of ~6°

Nature is very kind:
Hyper-K establishes CPV
with mass ordering from JUNO (3σ)
or DUNE (5σ)

Nature is less kind:
DUNE and Hyper-K are competitive,
and both may be required

DUNE Phase II and beyond can also provide valuable tests of unitarity

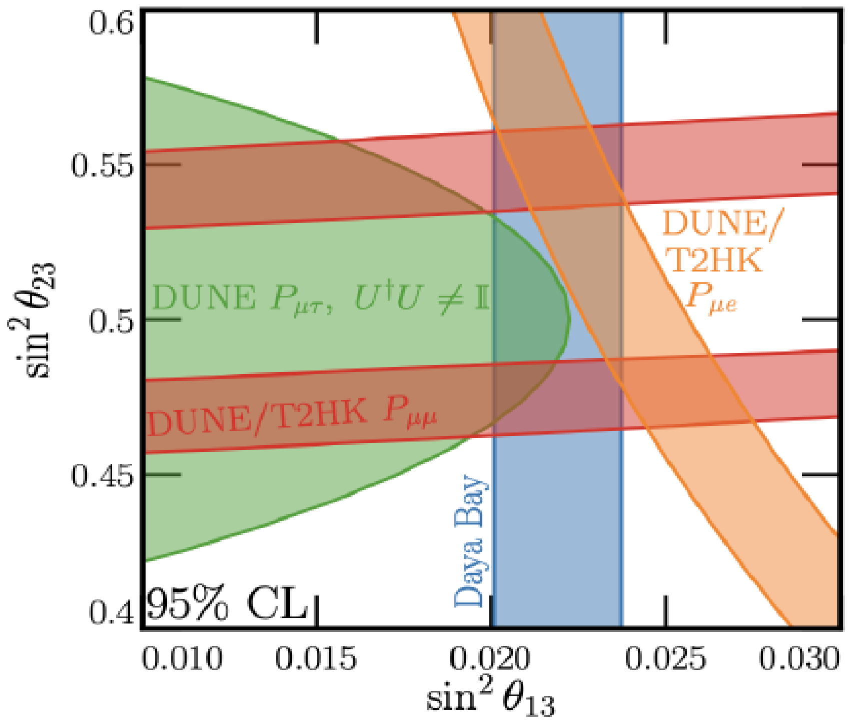
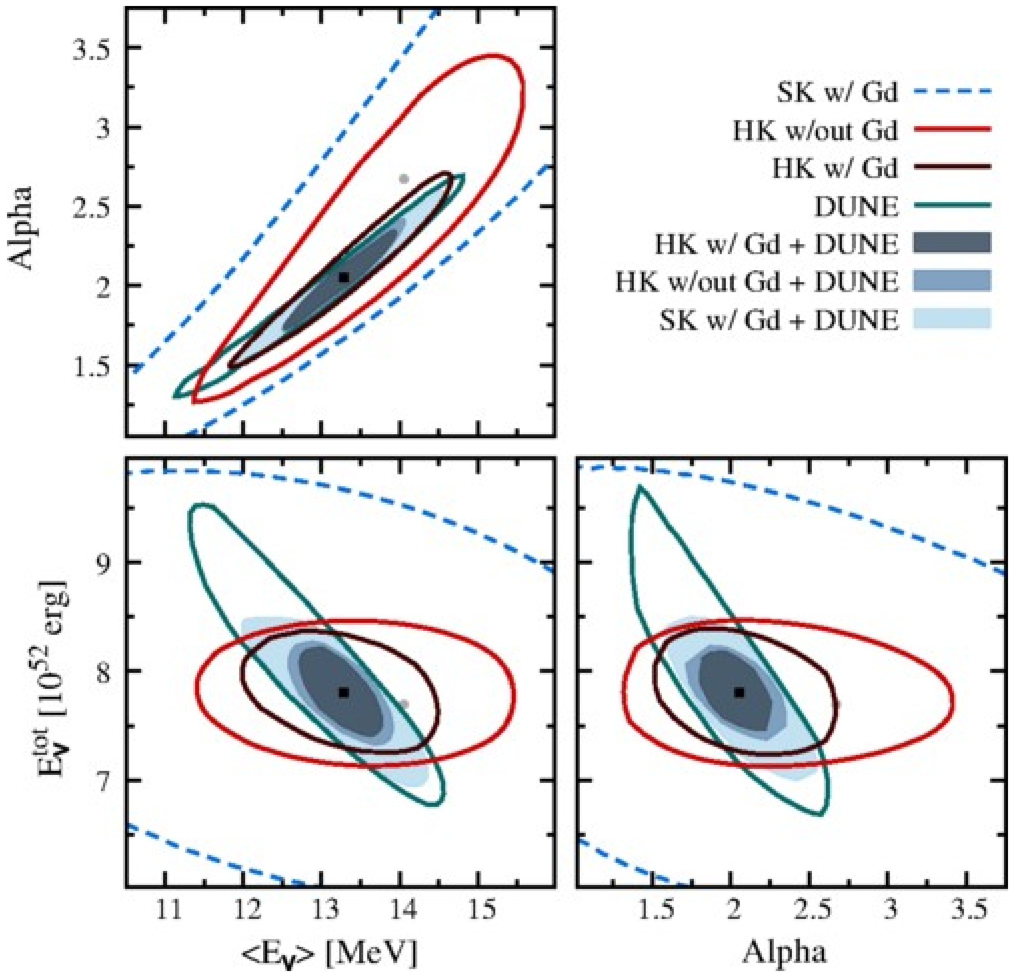


Figure 6. Projected measurements of $\sin^2\theta_{13}$ vs. $\sin^2\theta_{23}$ when unitarity is violated ($N_3 \approx 2$). For DUNE's long-baseline measurement of $P_{\mu\tau}$ (green), we simulate data assuming the underlying mixing matrix is non-unitary, and extract the measurement of these parameters assuming the matrix is unitary.

[Ellis, Kelly, Li, arXiv:2008.01088]

DUNE+HK complementarity: supernova neutrinos



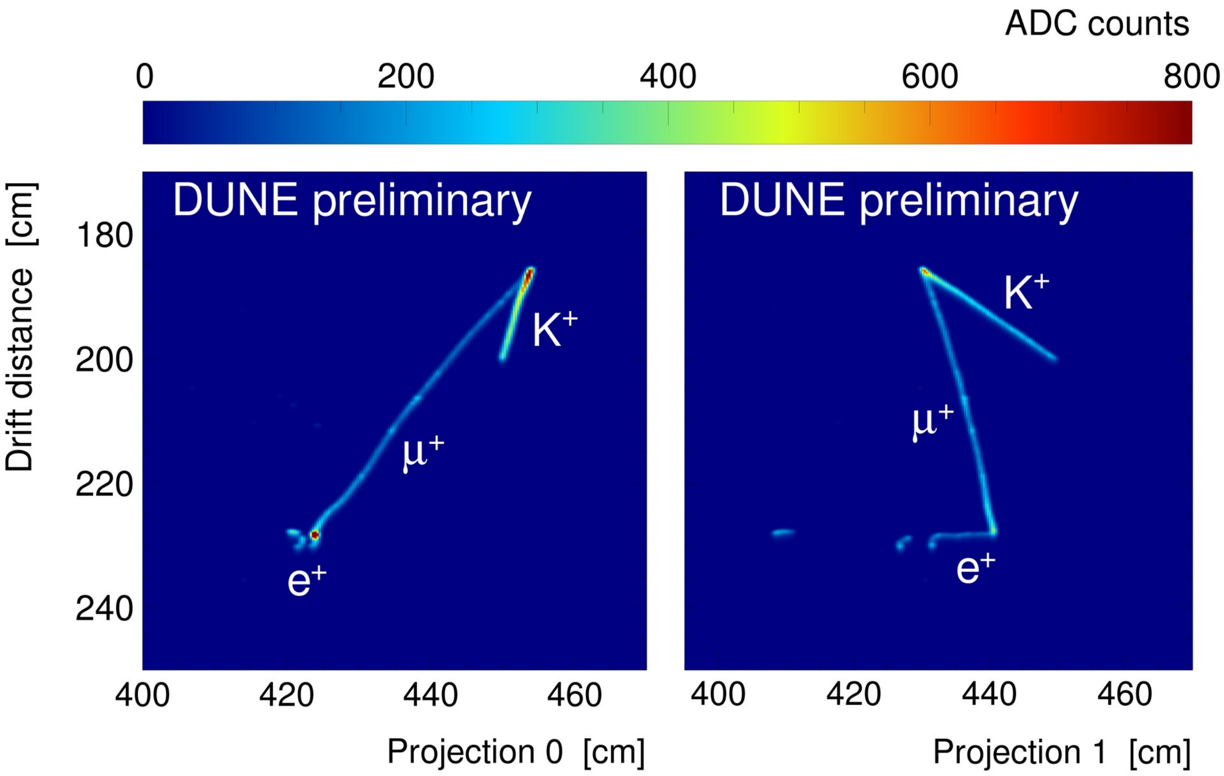
Nikrant, Laha, and Horiuchi
Phys. Rev. D 97, 023019

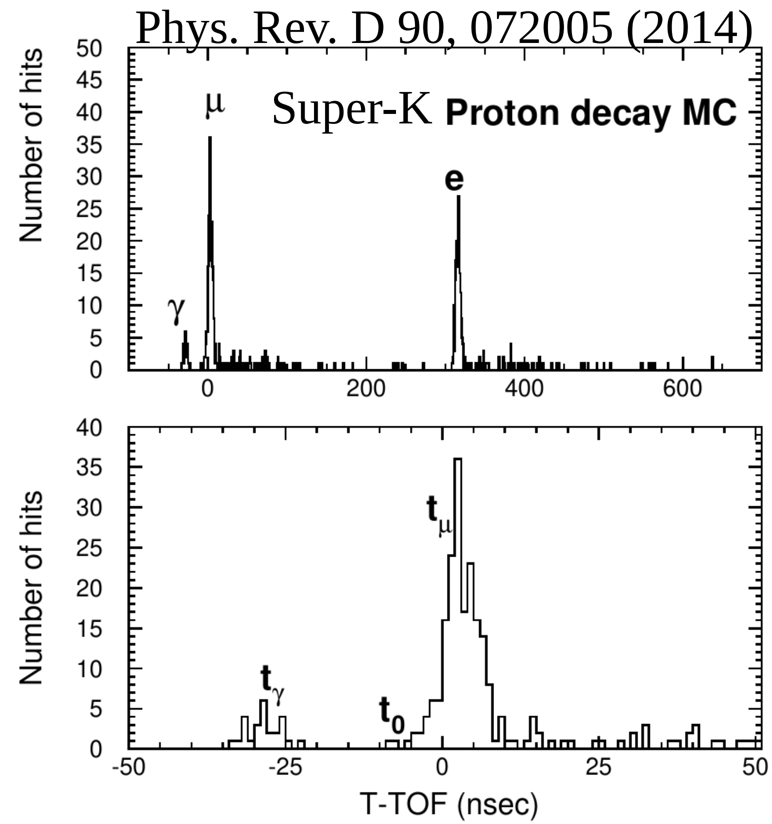
$$\frac{dN_\nu}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

$$A = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

- Supernova spectrum can be parameterized by average neutrino energy and α
- DUNE and HK measure different fluxes → complementary ability to constrain spectral parameters
- DUNE Phase II (40 kt) shown in figure

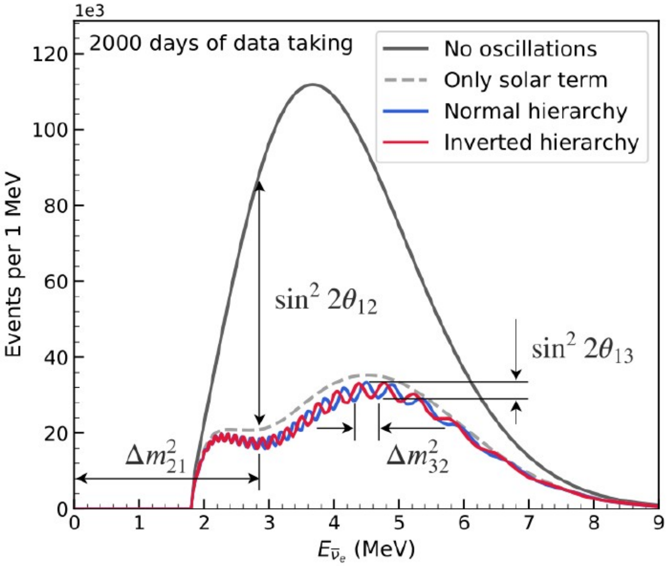
Nucleon decay $p \rightarrow K^+\nu$



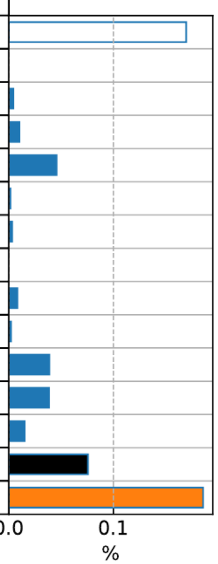


- Hyper-K can identify $p \rightarrow K^+\nu$ by timing, and identification of monoenergetic muon from kaon decay, with sensitivity to $\tau = 3\times10^{34}$ yrs
- DUNE can image all three particles, and has sensitivity beyond current Super-K limit (Phase II only)
- While DUNE is not competitive in exclusion reach, if a signal is observed in Hyper-K it will be extremely valuable to confirm the detection with a very different detector, different backgrounds, etc.

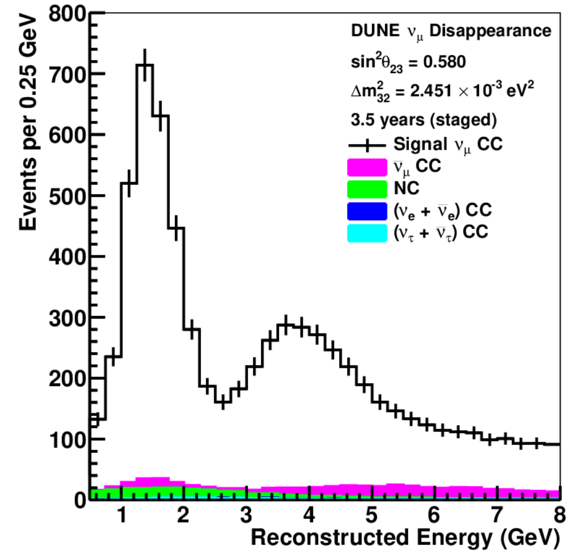
JUNO & DUNE Phase I: competition and complementarity

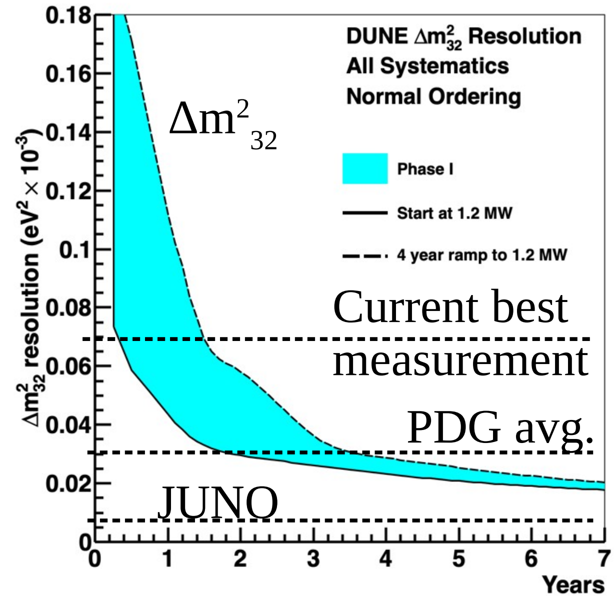


Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

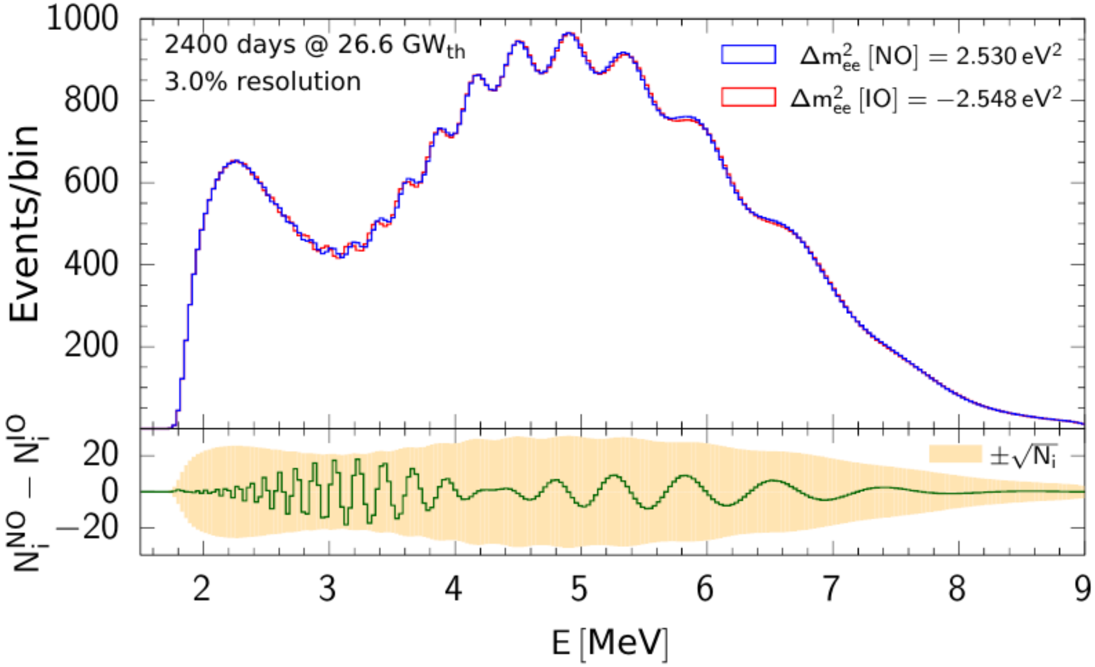


- JUNO sees a wiggle due to Δm^2_{32}
- Mass ordering is a phase
  - JUNO will probably have a ~3σ mass ordering observation when DUNE turns on
  - DUNE will catch up very quickly and reach 5σ far sooner
- Δm^2_{32} is a *frequency*, which JUNO can measure with incredible precision, ~4x better than current global fit
  - By the end of DUNE Phase I, we will have a ~0.2% measurement from $\bar{\nu}_e$, and a ~0.8% measurement from ν_μ
  - These are different transitions, but if our picture is complete we should get the same answer





Mass ordering in JUNO



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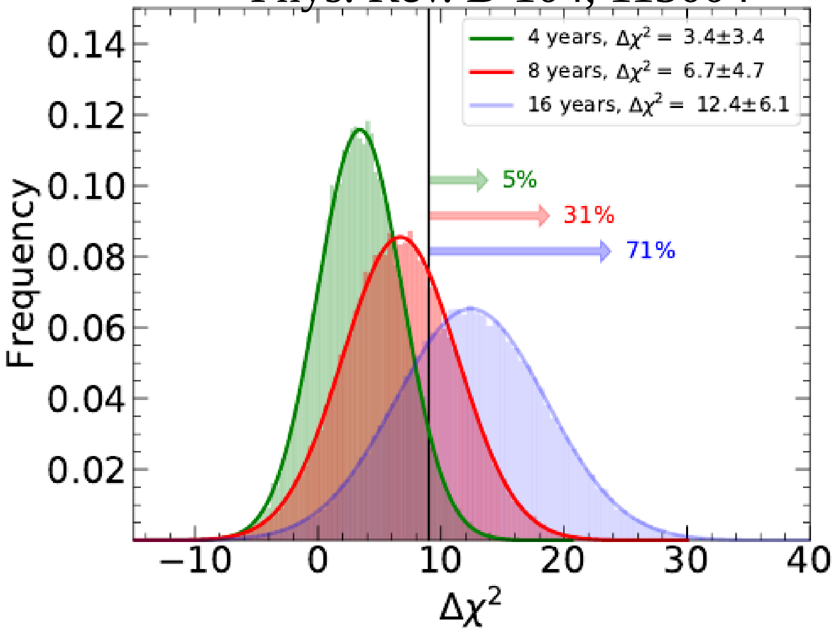
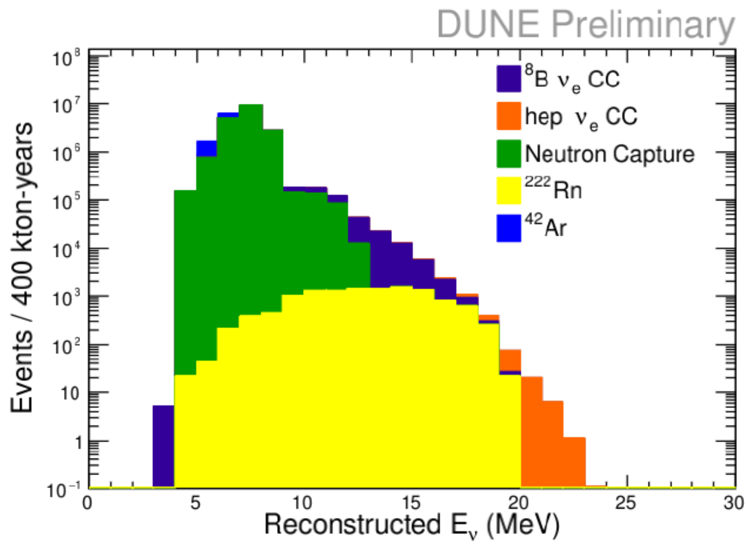
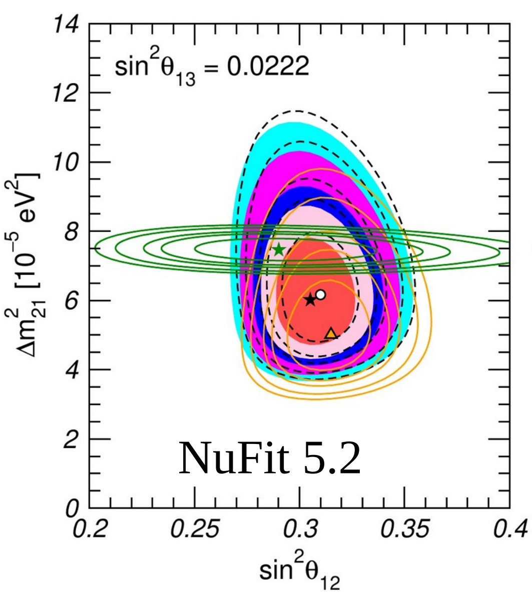
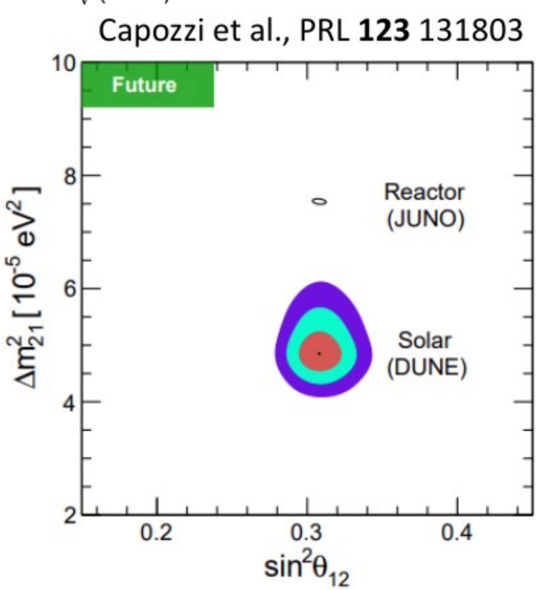


- Theory paper by Forero, Parke, Ternes, and Funchal studies the impact of various parameters (true values of oscillation parameters, energy resolution, nonlinearity, etc.) and shows how challenging MO measurement is in JUNO
- They conclude 31% chance of 3σ significance after 8 years (roughly when DUNE starts, assuming JUNO starts this year)
- This is somewhat (but not significantly) more pessimistic than JUNO’s published median sensitivity of 3σ in 6 years

Solar neutrinos: search for new physics with DUNE and JUNO







- Despite large neutron background below ~10 MeV, DUNE can measure ^{8}B solar flux and observe hep flux
- Phase I: >5σ sensitivity to hep flux
- Phase II: DUNE can improve existing θ_{12} and Δm^2_{21} measurements with solar neutrinos
- JUNO will have by far the best precision in θ_{12} and Δm^2_{21}; DUNE-JUNO comparison is sensitive to new physics

Thank You!