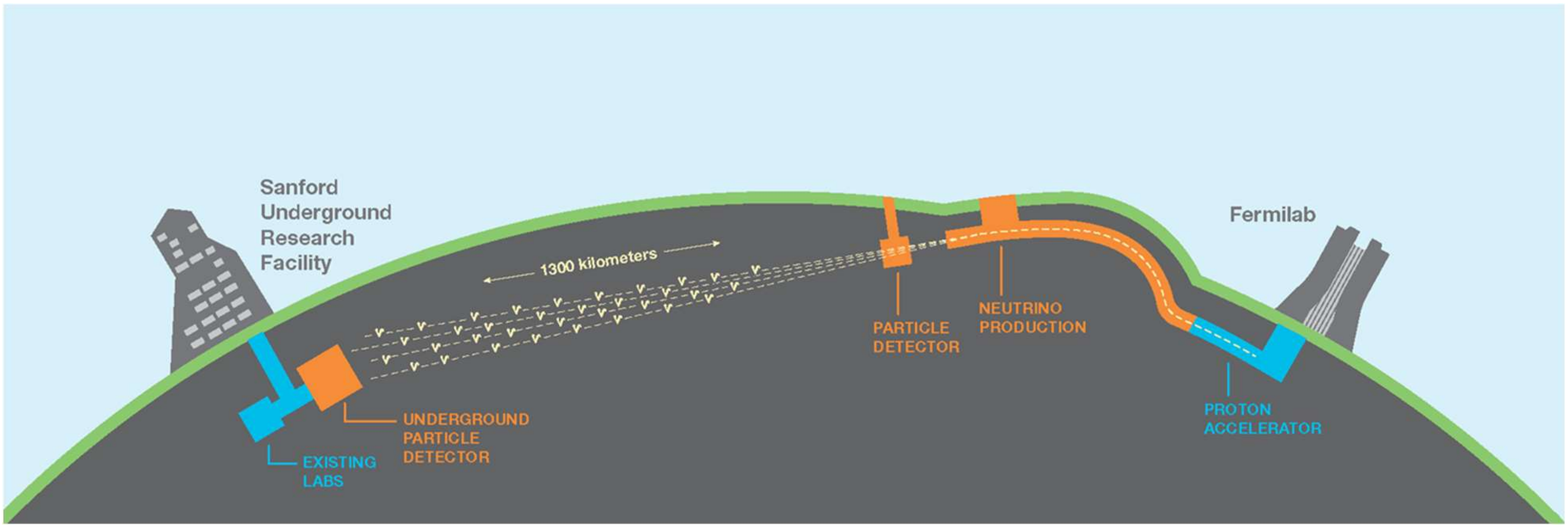
Deep Underground Neutrino Experiment



Kim Siyeon
Chung-A ng University

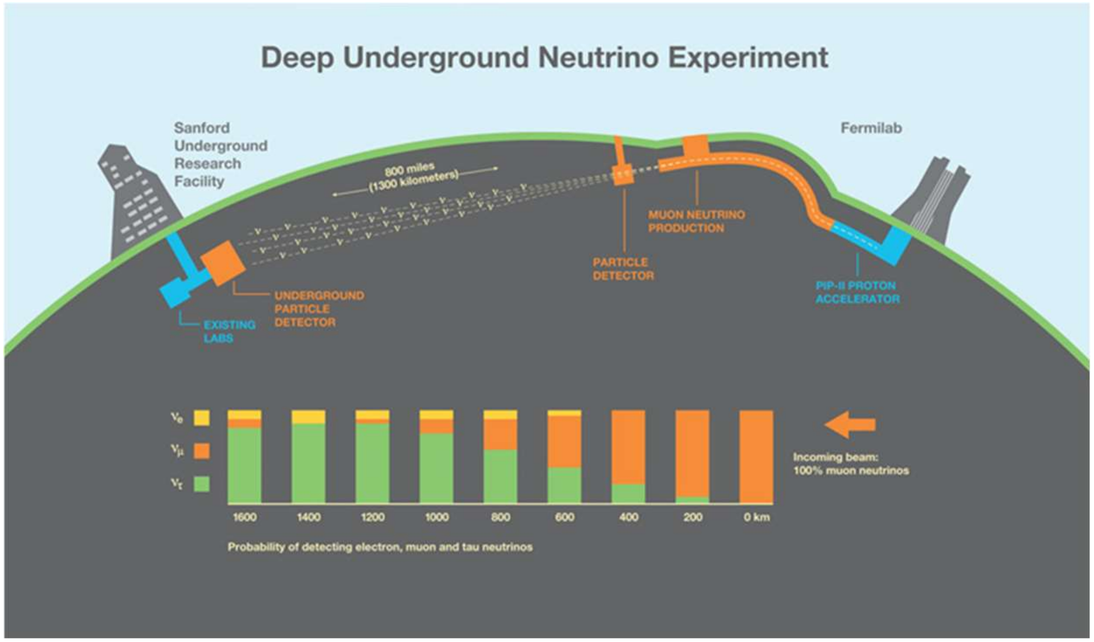
K-Neutrino Symposium
July 25~26, 2024

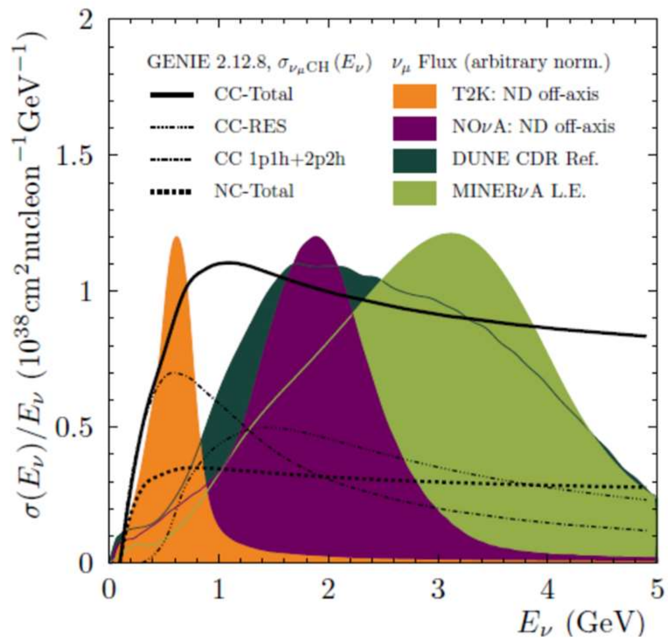
Outline

DUNE

- Physics Goals
- Progress
- Activities of Korean Group

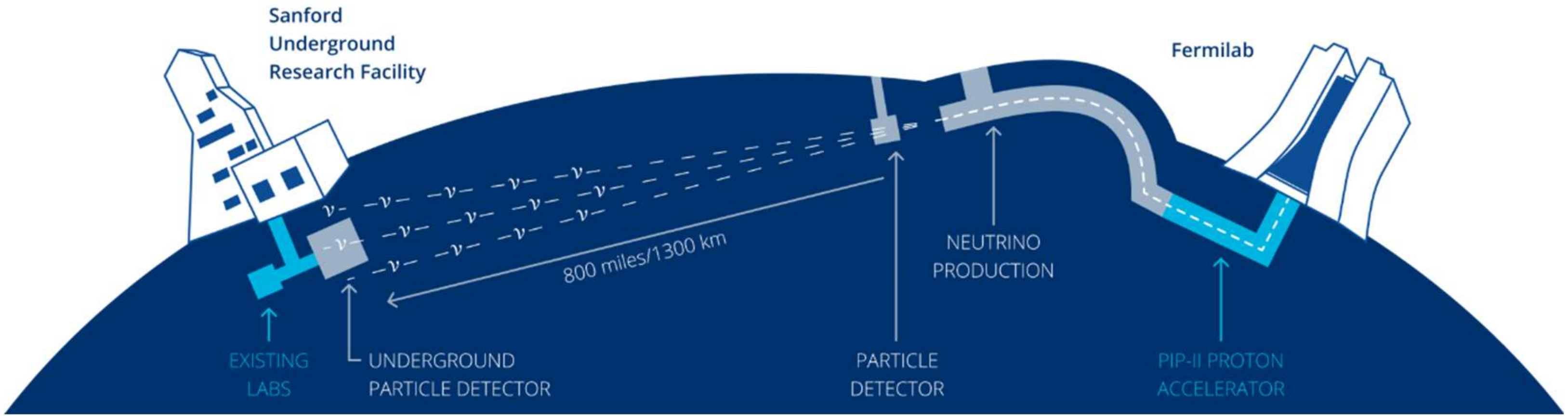
• Long-baseline oscillation





Experiment	Beam Source	Detector (threshold)	Interaction	Flavors	Physics	Status
DUNE	PIP-II NuMI (0.5~10 GeV)	L-Ar Time Projection Chamber, (a few MeV)	NC, CC, ES	all	Oscillation Interaction	Construction

Collaboration Structure



DUNE Collaboration

DUNE Cospokesperson
Mary Bishai (BNL)
Sergio Bertolucci (U. of Bologna)

Authorship and Publication Board
Speakers Committee

DUNE Institutional Board
LBNF/DUNE-US

DUNE Management Group

Technical Coordination
FD1: Eric James
FD2: S. Kettell
ND: H. Tanaka

Computing
M. Kirby

Phase II Group
S. Solder-Rembold

Physics Coordination
C. Marshall

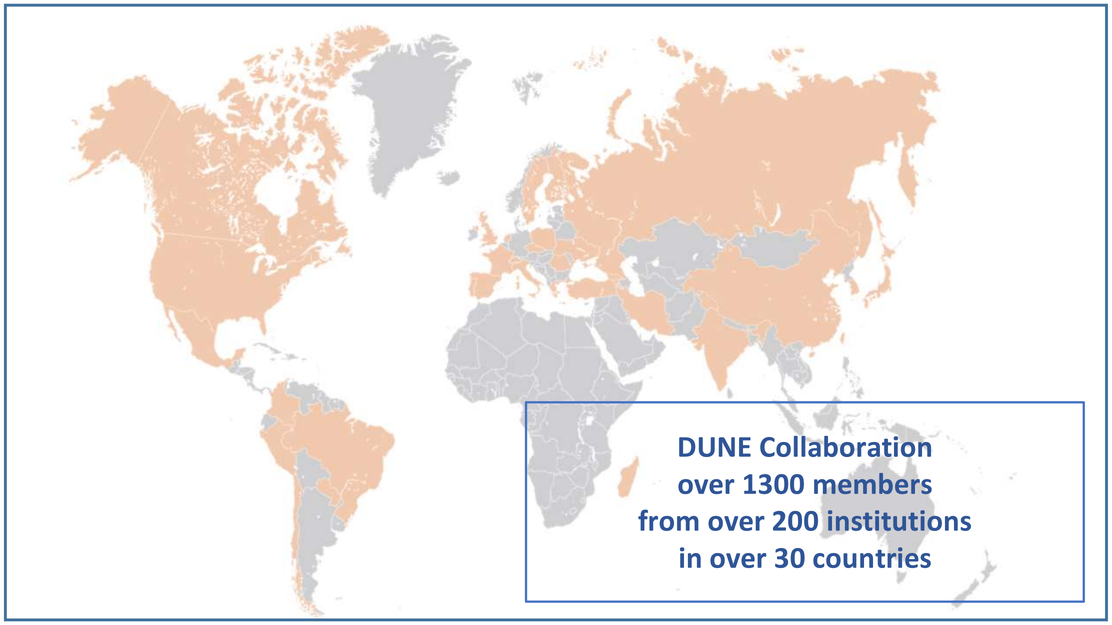
Resource Coordinator
G. Barker

FD Consortia

DAQ | APA | Photon Detector
HV | TPC Electronics | CRP
Top Drift Electronics | Calibration

ND Consortia

ND L_Ar | TMS | SAND



Korean members of DUNE Collaboration
(2024년 3월 1일 현재)

Chung-Ang University
: Gwon, Sunwoo (Research Fellow)
: Masud, Mehedi (Research Fellow)
: Park, Juseong (Graduate Student)
: Kim, Suhyeon (Graduate Student)
: Kim, Siyeon (Professor, IR)

Jeon-Buk National University
: Shin, Seodong (Professor, IR)

KISTI
: Cho, Kihyeon (Professor, IR)

POSTECH
: Chung, Moses (Professor, IR)

K – DUNE Physics WG Activities

Chung-Ang University (김시연)
Neutrino interaction (Gwon)
protoDUNE analysis (Gwon, Masud)
Beam BSM (Masud)
Long-Baseline osc (Masud)

Jeon-Buk Nat'l University (신서동)
Beam BSM
Atmospherics & Exotics

Beam/Detector Consortia

Chung-Ang University (김시연)
TPC Readout (w/BNL Cold Electronics Group)
Phase II Group (w/BNL WbLS, 권순우)
Software & Computing (w/ BNL Wire-Cell, Masud)

KISTI (조기현)
Data & Network

Postech (정모세)
Beam interphase

Physics Organization Chart

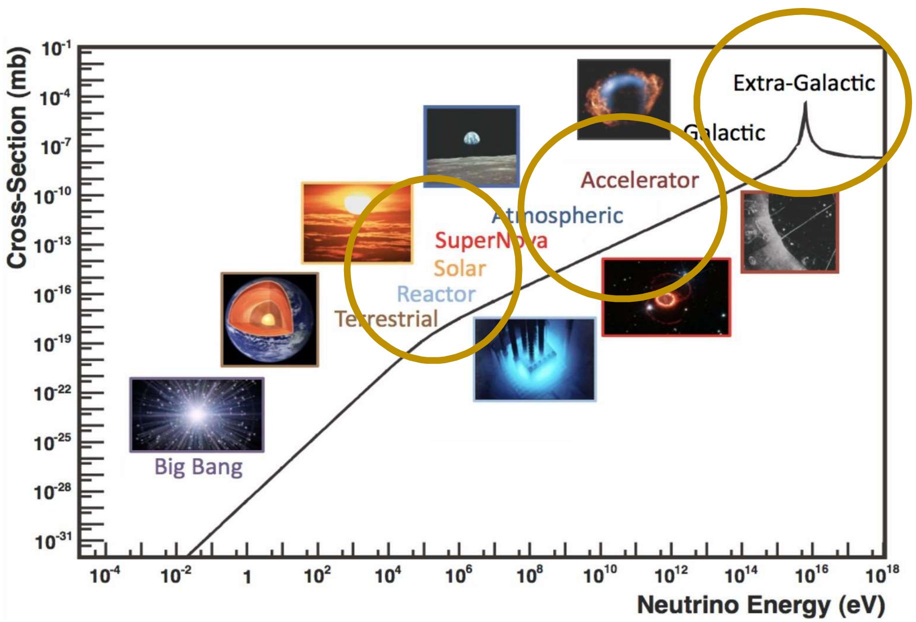
Physics Coordination Inés Gil-Botella Chris Marshall	**Long-baseline** Callum Wilkinson Luke Pickering	**Atmospherics & Exotics** Josh Barrow Yun-Tse Tsai	**FD sim/reco** Laura Paulucci Dom Brailsford
ND Prototype analysis Pedro Ochoa Zoya Vallari	**Neutrino Interactions Uncertainties** Rik Gran Laura Munteanu	**Beam BSM** Justo Martin-Albo Alex Sousa	**ND sim/reco** Linda Cremonesi Mat Muether
Liaisons Dan Cherdack (ND) Tom Junk (computing)	**Low Energy** Clara Cuesta Dan Pershey	**Calibration** Rhiannon Jones Mike Mooney	**protoDUNE analysis** Leigh Whitehead Laura Zambelli Wenqiang Gu

Physics Issues of DUNE

Accelerator-Neutrino Physics

- Long-baseline oscillation
- Neutrino interactions
- ProtoDUNE analysis

- Beyond Standard Model
- And more…



Non-Accelerator Physics

- High-Energy Neutrinos

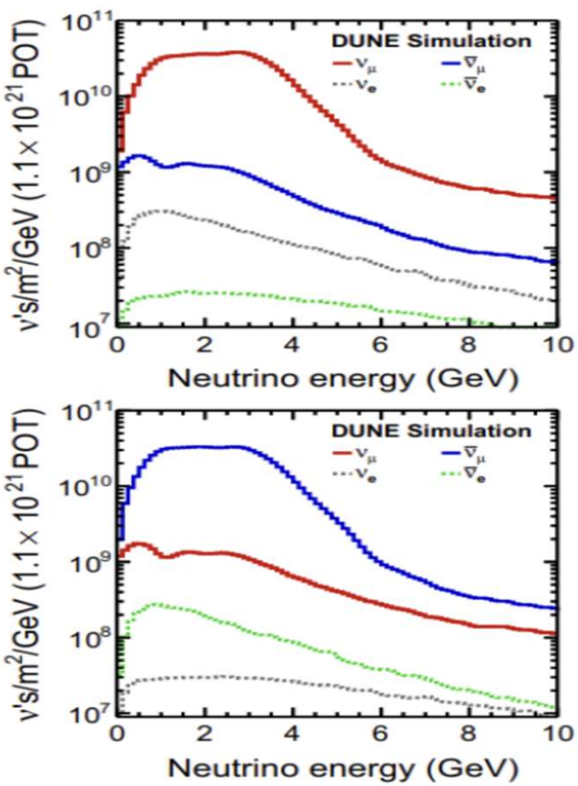
  GeV-scale: atmospheric neutrinos, nucleon decays and other signals where atm neutrinos are a background.

- Low-Energy Neutrinos

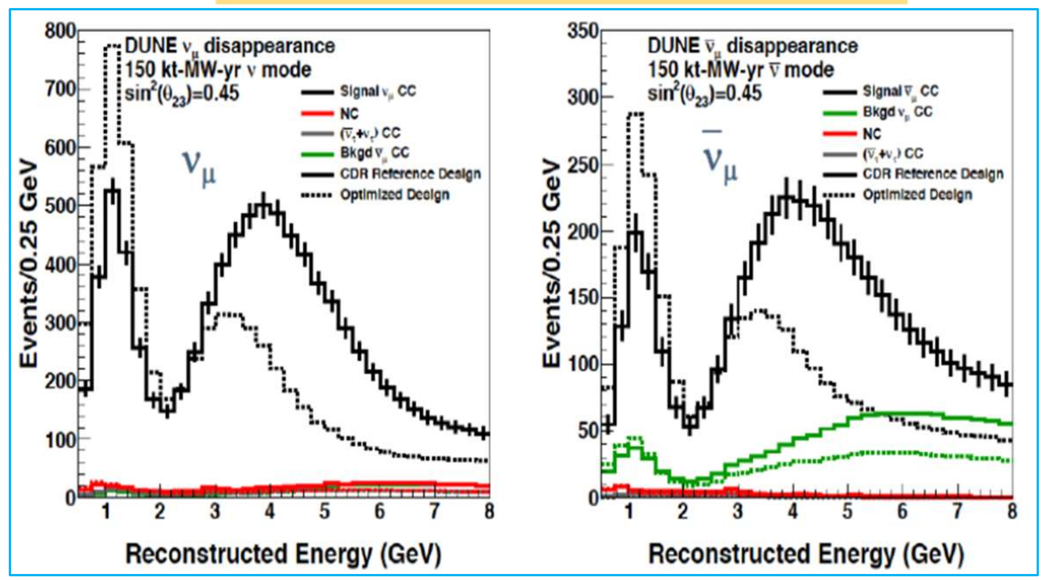
  1-10 MeV-scale physics: SN, Solar nu, Natural radioactivity background

Long-baseline oscillation

- 1285-km baseline
- Neutrino energy range Sub GeV ~ 10 GeV
- Neutrino mode(FHC) and antineutrino mode(RHC)
- Appearance of $\nu_e(\overline{\nu_e})$ and disappearance of $\nu_\mu(\overline{\nu_\mu})$ at FD

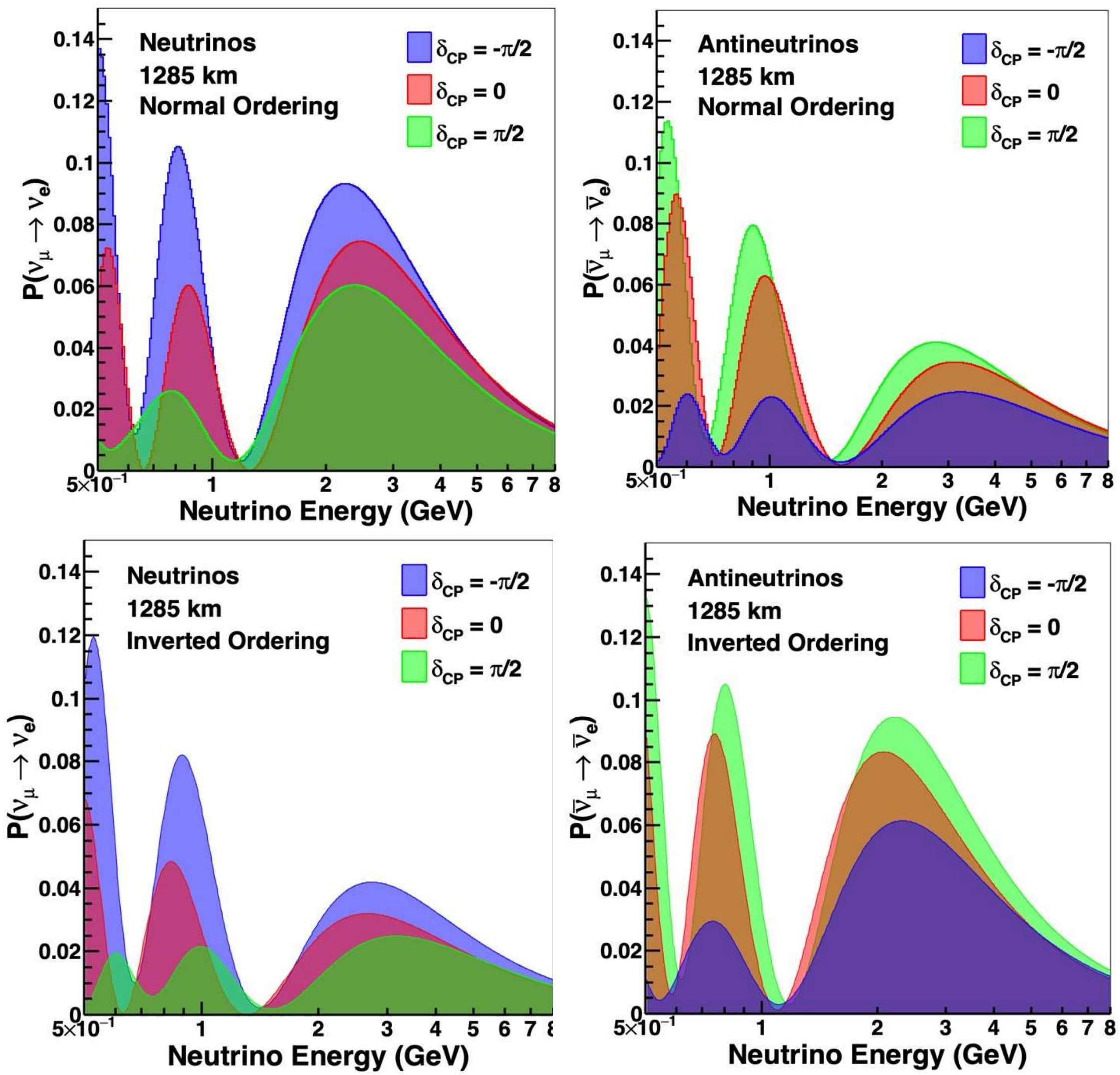


Beam Optimization



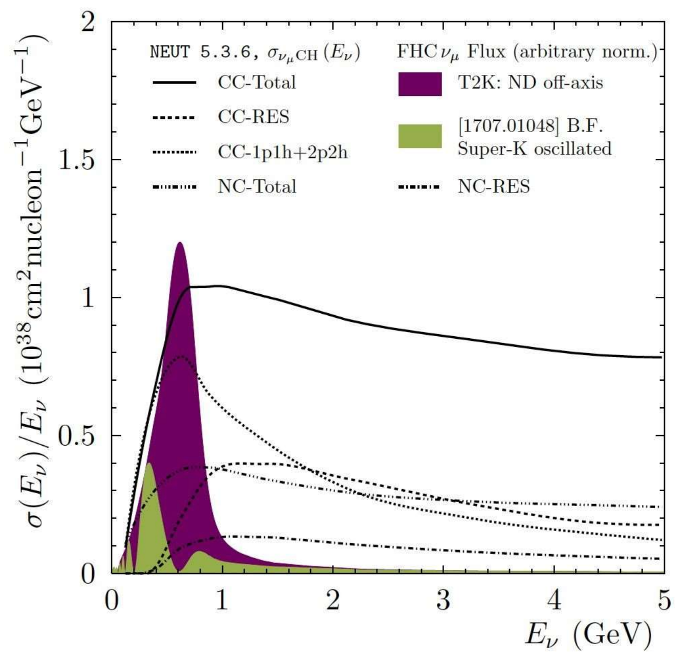
Neutrino-antineutrino asymmetry: P($\nu_\mu \rightarrow \nu_e$) vs. P($\nu_\mu \rightarrow \nu_e$)

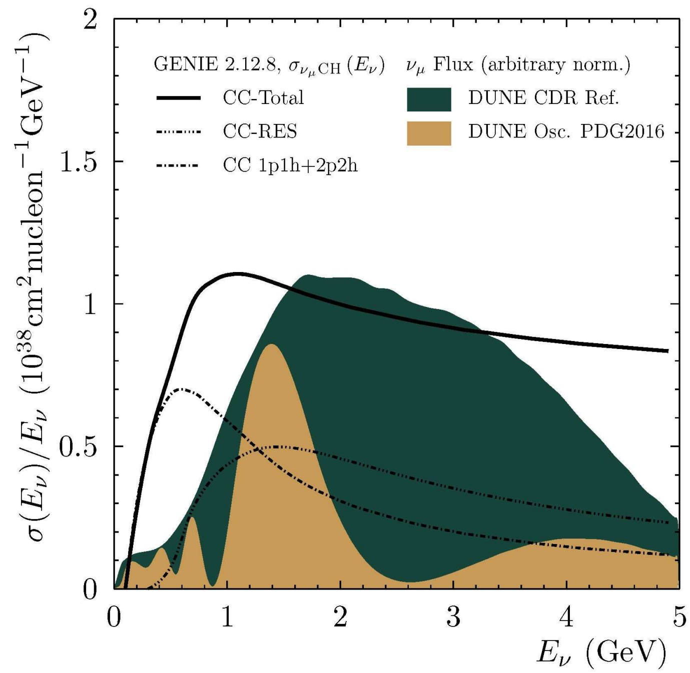
$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}}{\sin\theta_{23}\sin\theta_{13}} \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

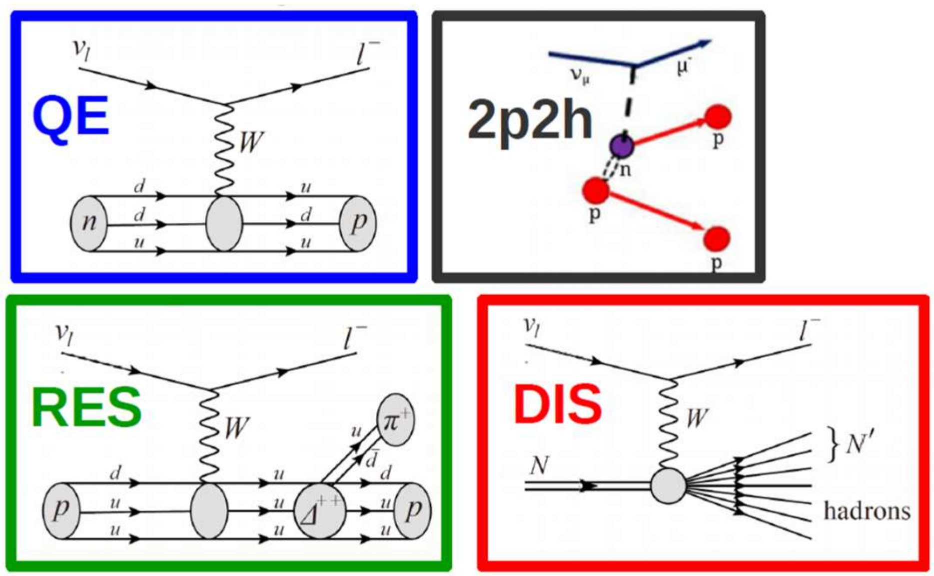


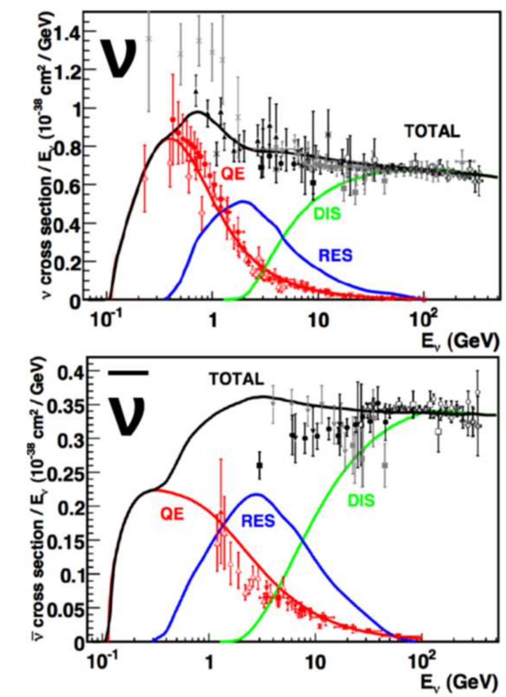
Neutrino Interactions

Kendall Mahn

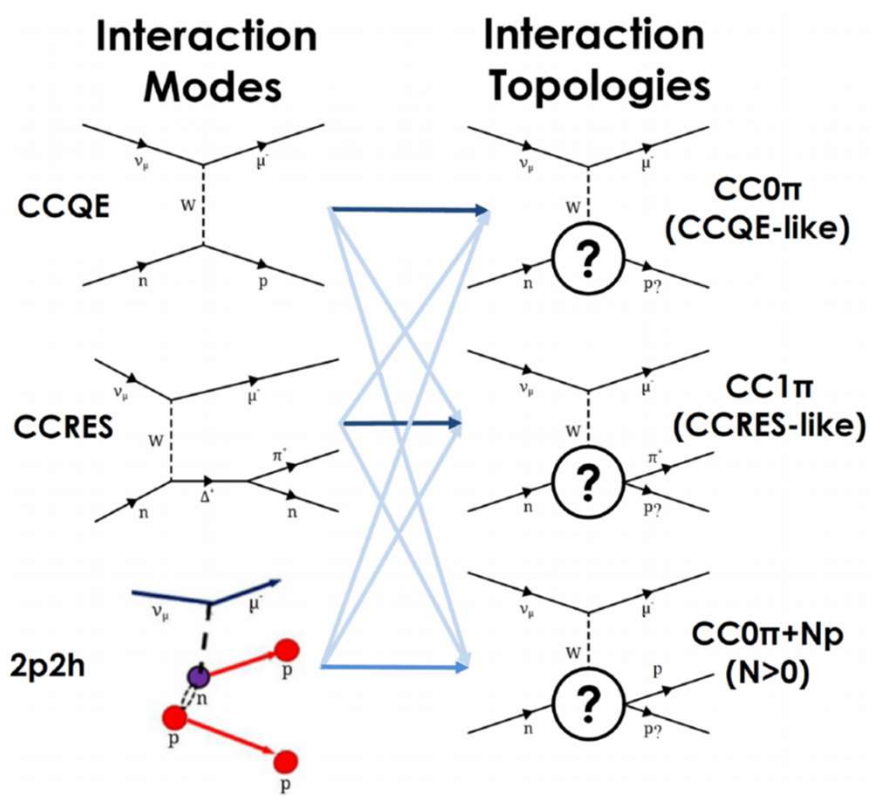








What do we actually measure?



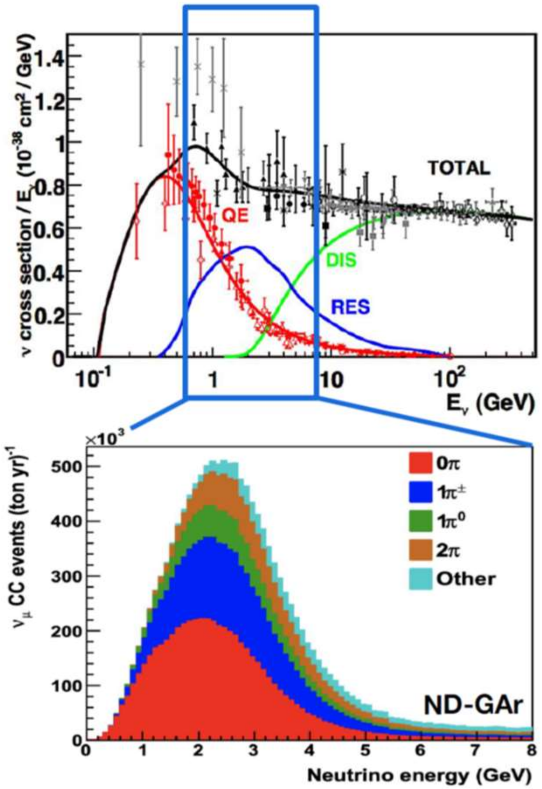
Many modes contribute to any measurement

Integrated over broad ω region

Difficult to tune theory models!

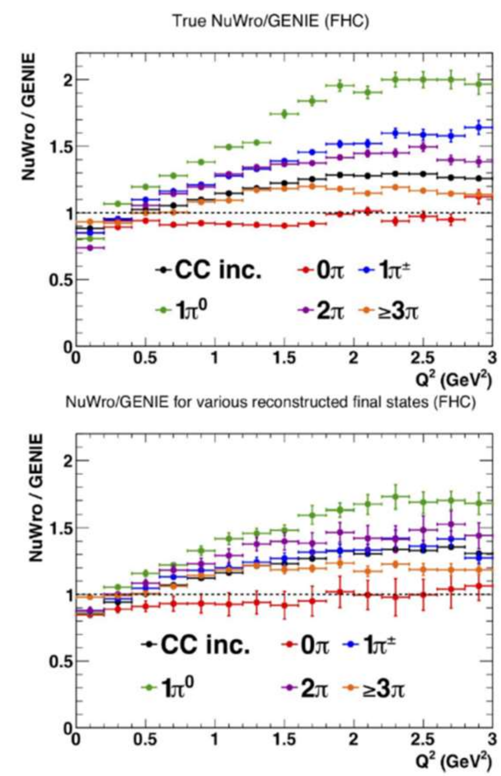
Graphic from S. Dolan

- Multi-scale problem
  - We have neutrino energy range .5 ~5 GeV and energy transfers from nearly zero to about 1 GeV
  - Nuclear response
    - Elastic
    - Metastable excitations
    - Quasi-elastic
    - Inelastic
  - The separation of processes failed.



	Interaction Channel			Event Rate	
				ND-LAr	ND-GAr
CC	ν_μ			8.2×10^7	1.64×10^6
		0π		2.9×10^7	5.8×10^5
		$1\pi^\pm$		2.0×10^7	4.1×10^5
		$1\pi^0$		8.1×10^6	1.6×10^5
		2π		1.1×10^7	2.1×10^5
		3π		4.6×10^6	9.3×10^4
		other		9.2×10^6	1.8×10^5
	$\bar{\nu}_\mu$			3.6×10^6	7.1×10^4
	ν_e			1.45×10^6	2.8×10^4
NC				5.3×10^5	5.5×10^5
$\nu + e$				8.3×10^3	1.7×10^2

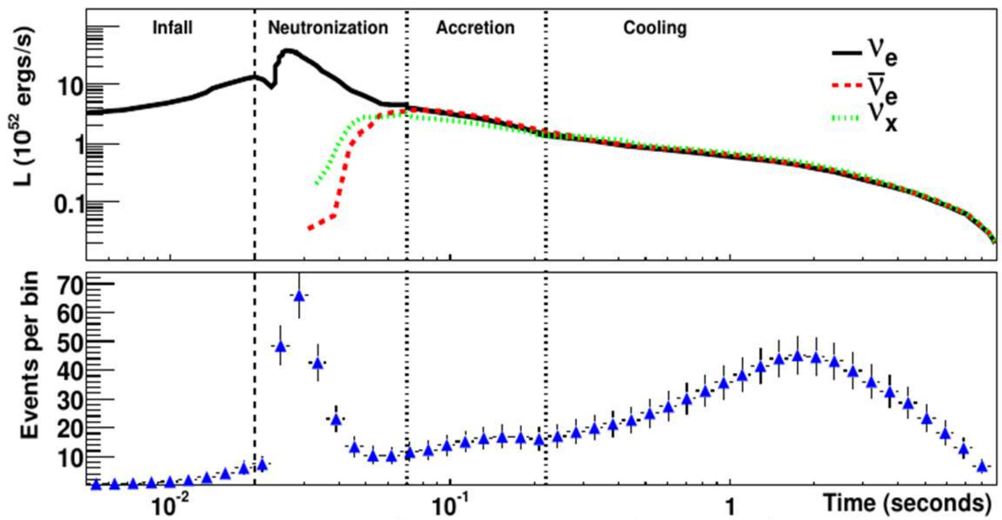
Events per year (1.1×1021 POT)



Non-beam physics with Phase I

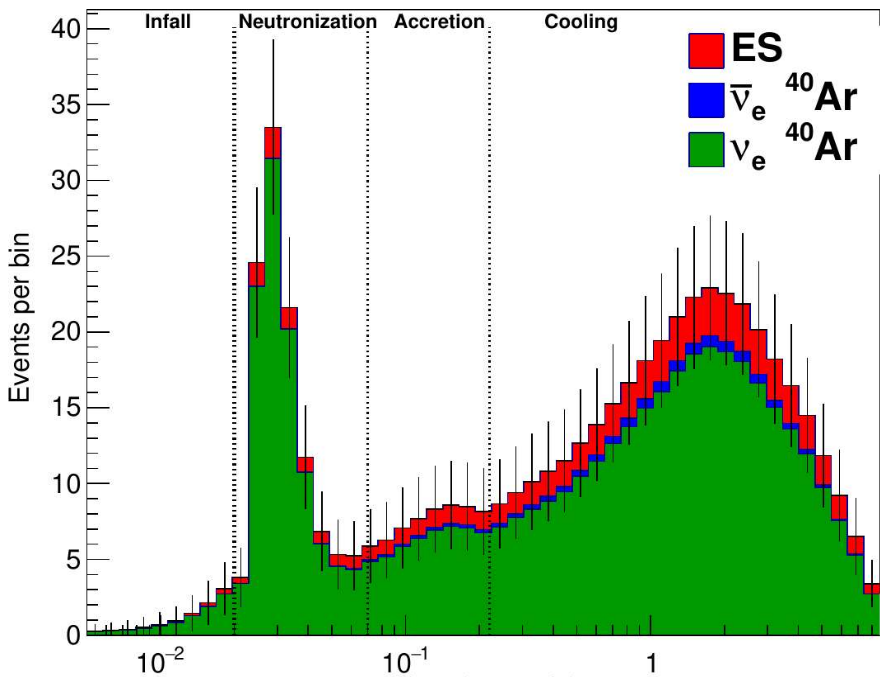
DUNE is already very sensitive to a galactic supernova burst with P hase I

Shown is the time distribution for a hypothetical 10 kpc SNB with 20 kton fiducial mass



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

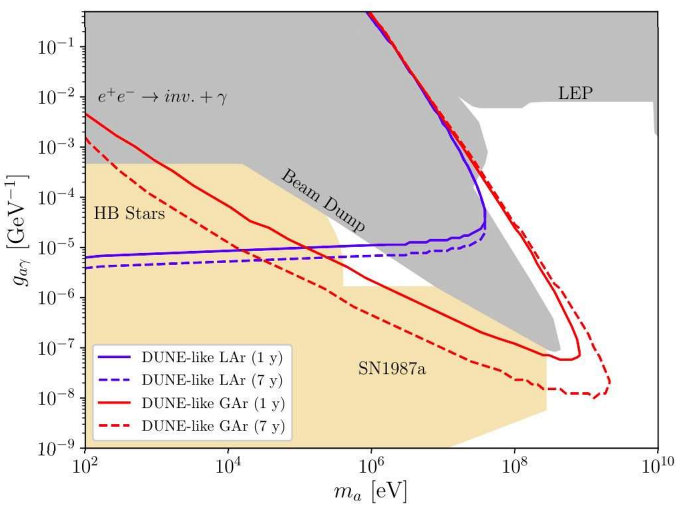
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

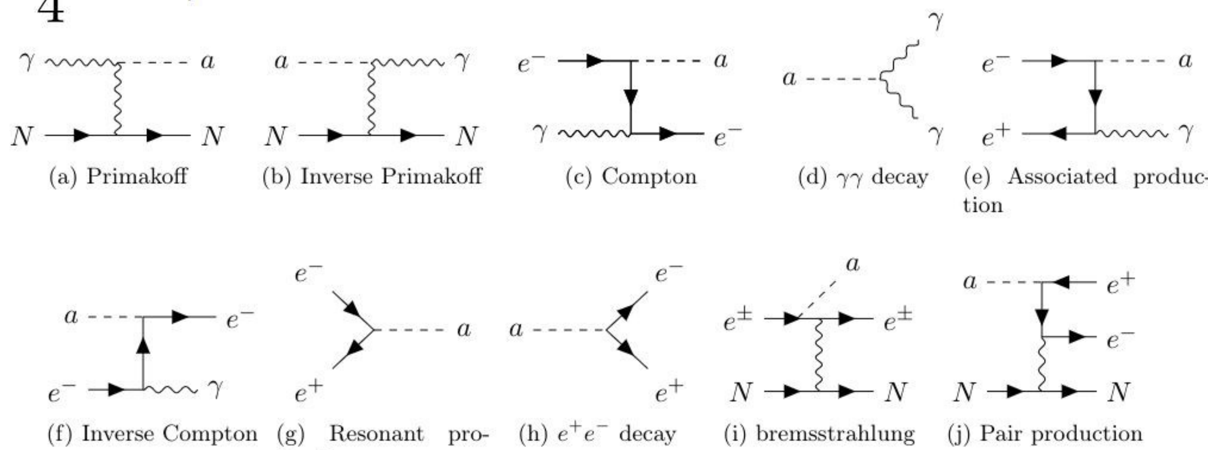


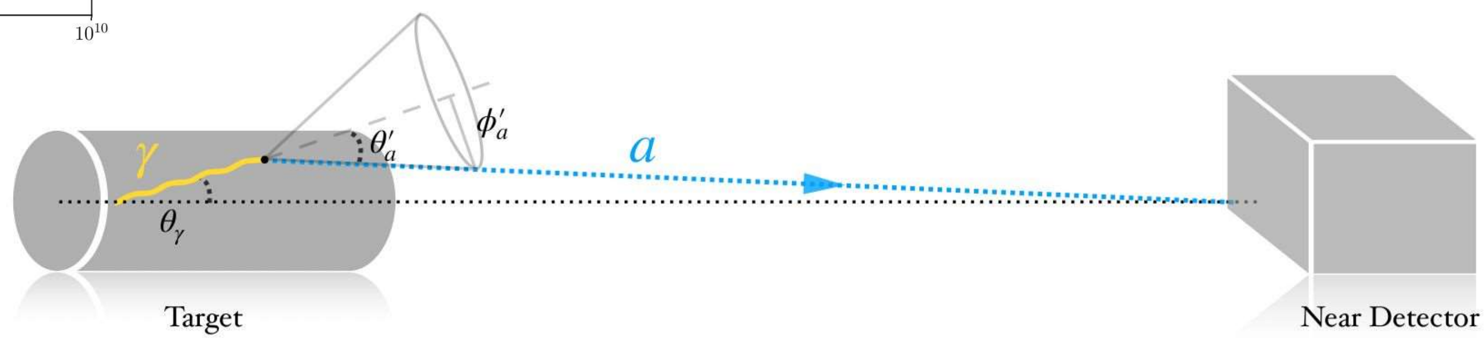
Axion-like Particles at the DUNE Near Detector:

- ALP with small effective couplings to photons or electrons;

$$\mathcal{L}_{\text{ALP}} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$







Simulated ALP flux from parent: γ, e+, e–

ALP propagates to detector without absorption

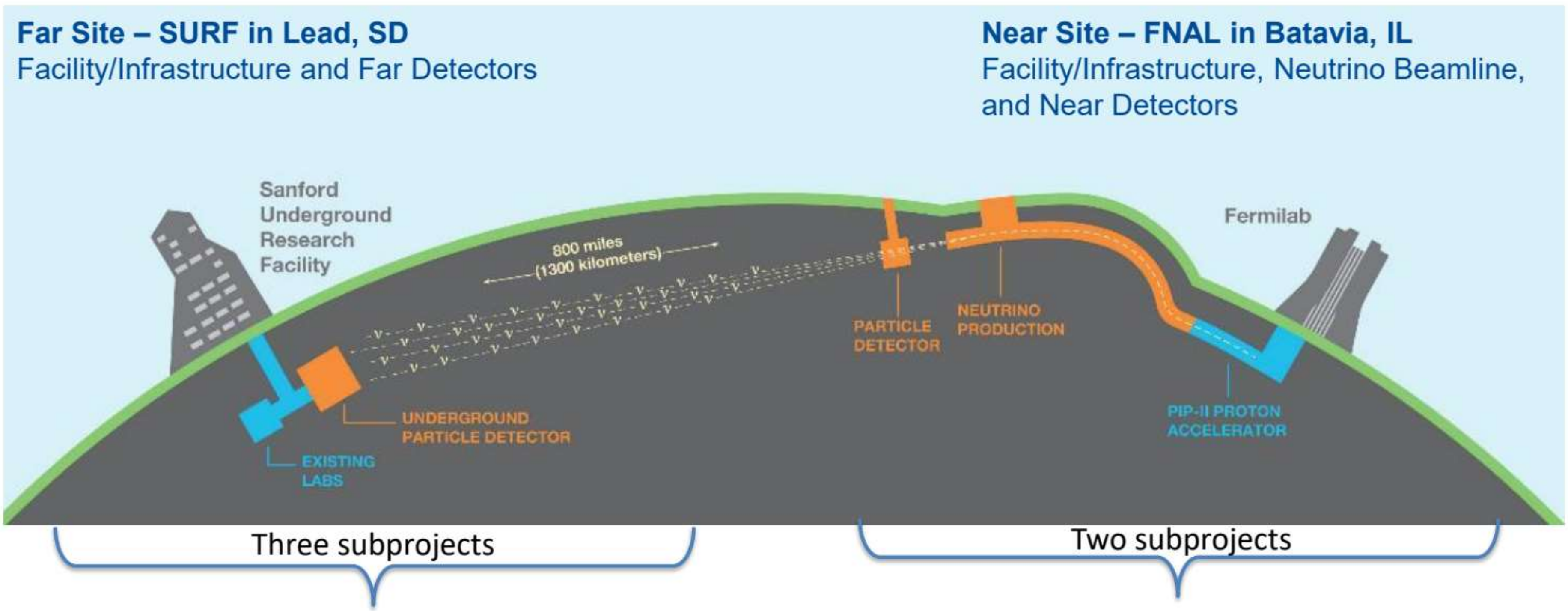
Detect either
- Scatterings
- Decays

Axion-like Particles at Future Neutrino Experiments: Closing the "Cosmological Triangle"

Vedran Brdar,[1,2,*] Bhaskar Dutta,[3,†] Wooyoung Jang,[4,‡] Doojin Kim,[3,§] Ian M. Shoemaker,[5,¶] Zahra Tabrizi,[5,**] Adrian Thompson,[3,††] and Jaehoon Yu[4,‡‡]

PRD 107, 055043 (2023)

LBNF/DUNE Project - Delivered at Two Sites through Five Subprojects



- **FSCF-EXC** – Far Site Excavation
- **FSCF-BSI** – Far Site Building & Site Infrastructure
- **FDC** – Far Detectors and Cryogenic Infrastructure

- **NSCF+B** – Near Site Conventional Facilities + Beamline
- **ND** – Near Detectors

Excavation of Underground Facility in South Dakota is complete!

- **Excavation completed in Feb 2024!**
- > 800,000 tons of rock removed
  - equivalent of 8 aircraft carriers
- ~6500 cubic yards of concrete
- Work was done safely
  - Excavation subcontractor exceeded 1 million hours without a lost time incident. Significantly exceeded industry safety metrics.
- Cryostat installation begins in 2025

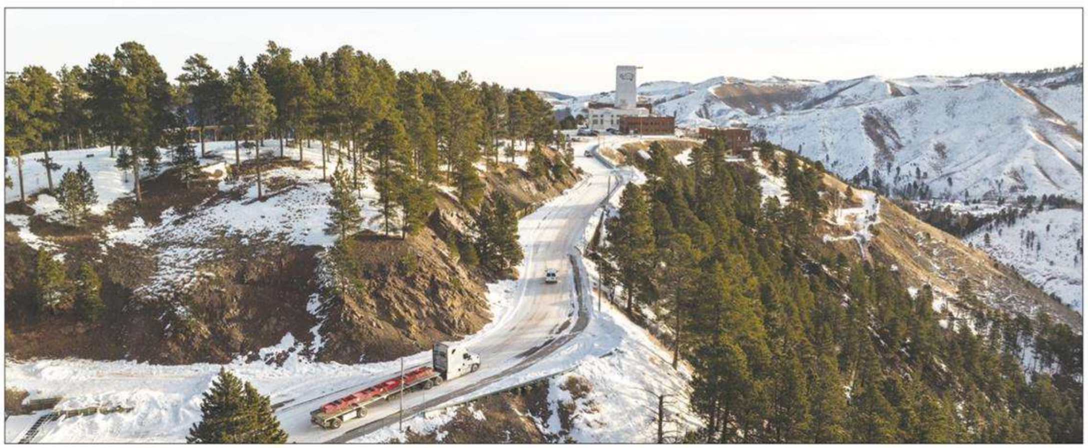
Far Detector Cryostat

- Departed Spain in May
  Arrive in Houston in June
- Warm structure 2,500 ton (3rd barrier, fastens and fittings)

Black Hills Pioneer

Friday, January 19, 2024 Vol. 148 No. 161 Since 1876 $1.50

First components for DUNE experiment in Lead



The first of what will eventually be 2,000 pieces of the cryostats for the deep underground neutrino experiment arrived in Lead last week. This spring members of the LBNF/DUNE team will work with Sanford Lab employees to begin tests to ensure the massive pieces can be safely and efficiently lowered down the Ross Shaft.
Photo by Stephen Kenny

By Wendy Pitlick
Black Hills Pioneer

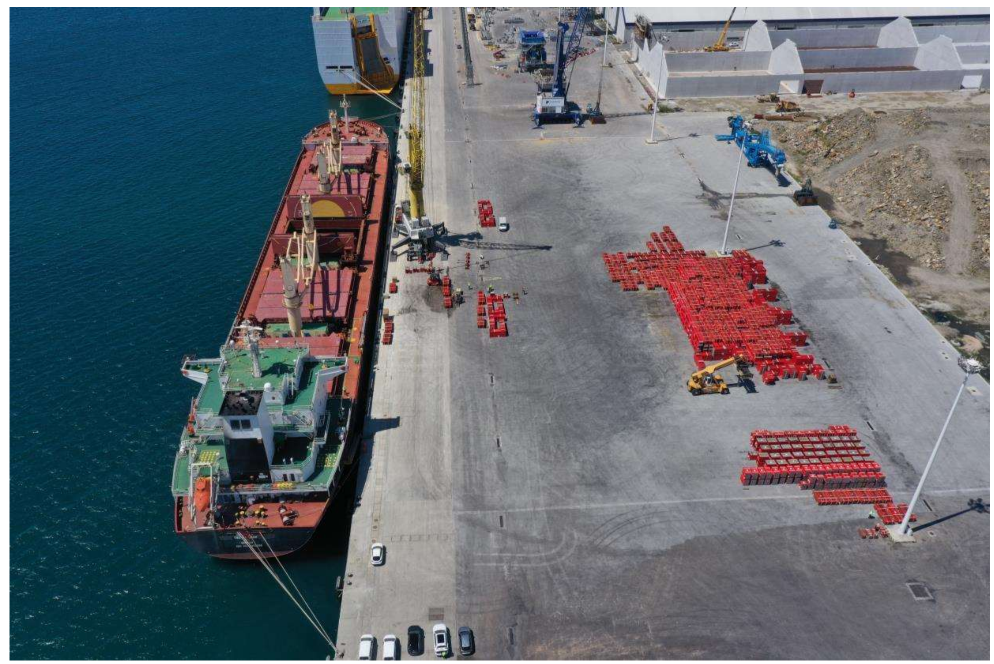
LEAD — The first components for the deep underground neutrino experiment have arrived in Lead, and starting this spring the LBNF/DUNE project team and officials with the Sanford Lab will begin tests to ensure cryostats for the experiment can be safely lowerd down the Ross Shaft.

That's because the components are massive. The first piece is more than 8 tons and 40 feet by 3 feet by 1.5 feet. The second piece is nearly 6 tons and 18 feet by 11 feet. Both pieces form just a corner of the massive cryostat for the deep underground neutrino experiment. When they're lowered down the Ross Shaft, they will have a clearance of about 3 inches on each side.

Jolie Macier, DUNE far detector and cryogenics project manager from Fermilab, said the size of the pieces present challenges that members of the collaboration wanted to work out before it is time to actually assemble the cryostats underground. Besides the massive size of the first piece, the smaller piece, referred to as the "L beam," has its own set of complications, Macier said.

"It has a center of gravity that is a challenge," she said. "That's why we wanted some extra time to be able

DUNE COMPONENTS Pg 6



DUNE Day 1 : When FD1 is filled and turned on, Science begins.

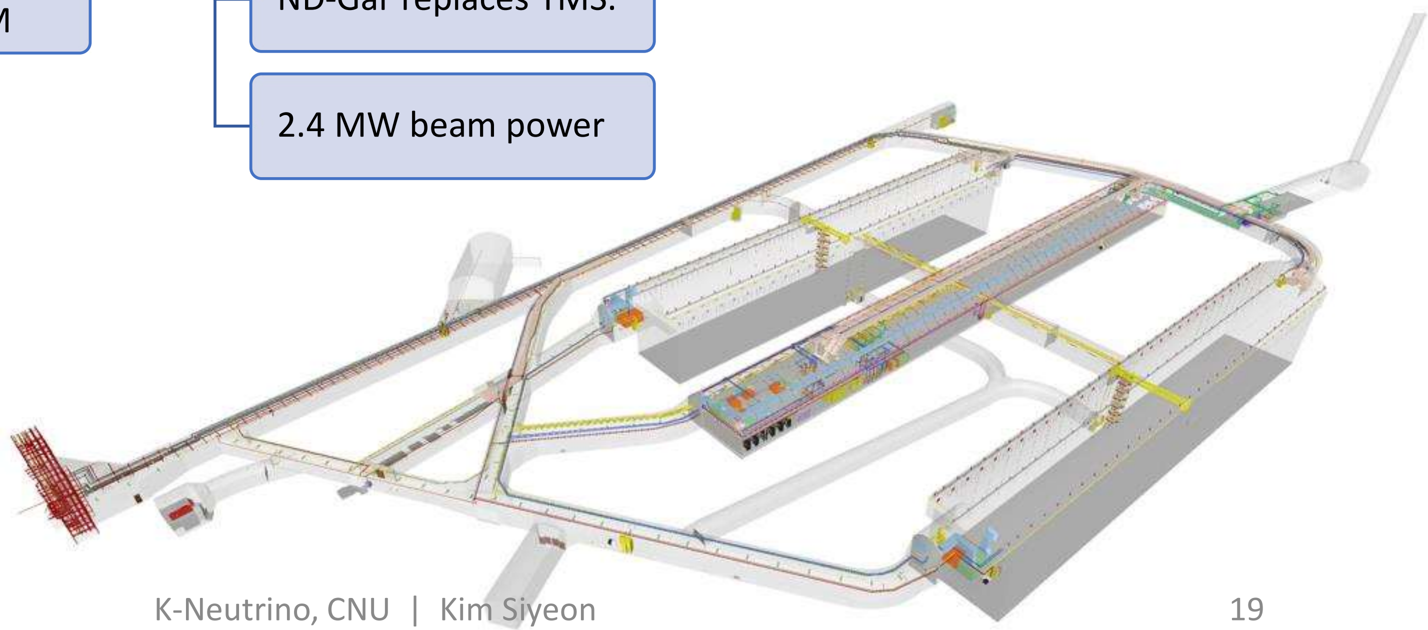
2018: ProtoDUNEs at CERN → 2019: FD TDR → 2020: Excavation starts → 2024: Installation of first module → 2026: First physics data: Atm, SN, & solar Proton decay. Calibration → 2028: ND & PIP II available

DUNE Phase I

- 2 Far Detectors : Horizontal Drift (HD) + Vertical Drift (VD) LAr
- Near Detectors : ND LAr + TMS + SAND + PRISM
- 1.2 MW beam power

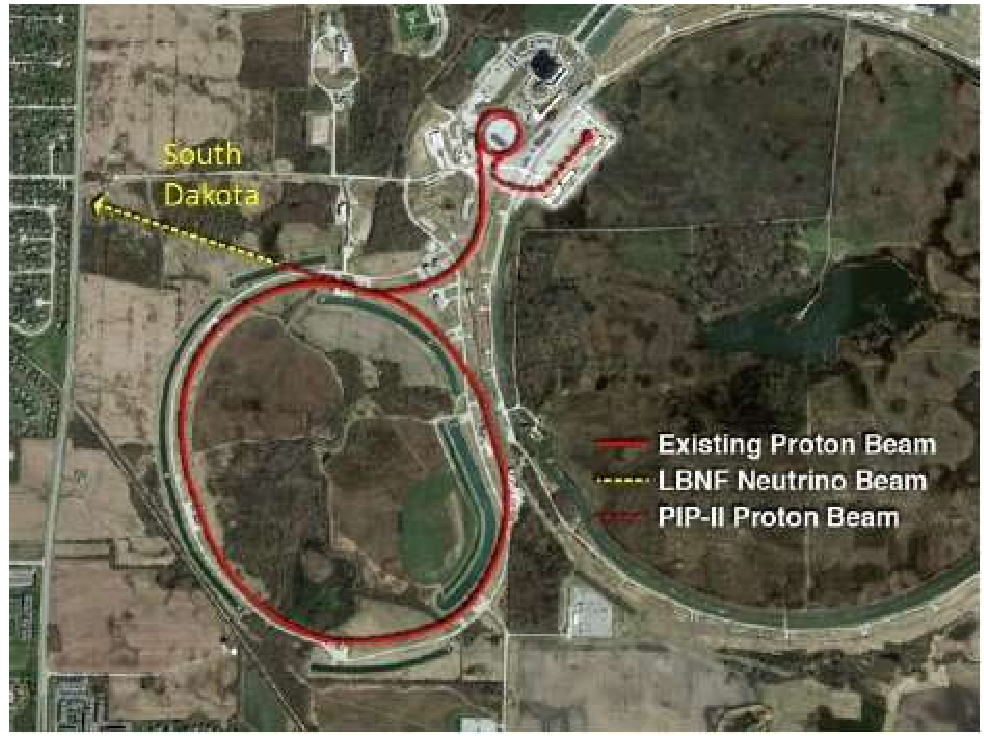
DUNE Phase II

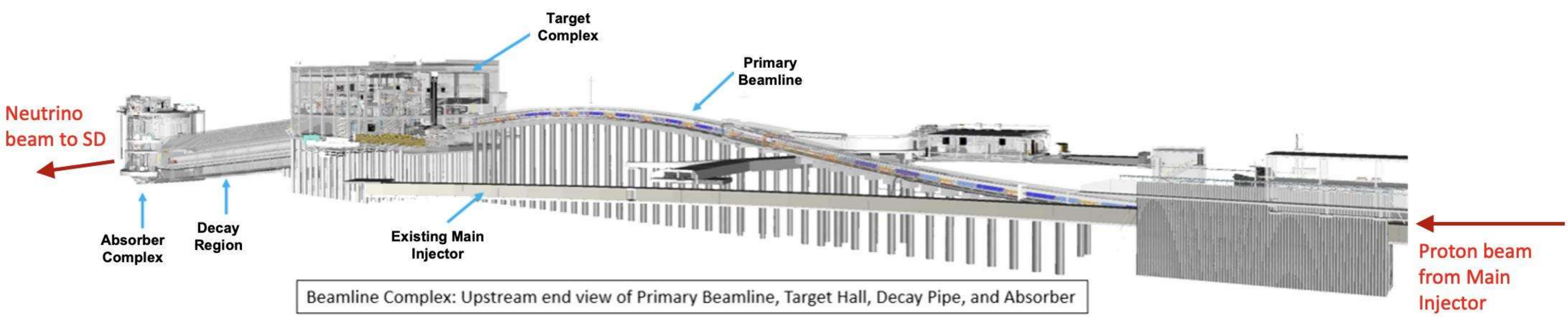
- FD3 + FD4
- ND-Gar replaces TMS.
- 2.4 MW beam power



LBNF: intense beam, underground facilities and infrastructure

- Construction of the beamline enclosure and the ND enclosure begins in 2025.
- Conventional facilities design is completed.
- Initial site work is completed.
- Full construction begins in 2025.
- 1.2 MW neutrino beam from PIP-II proton beam, upgradeable to 2.4 MW

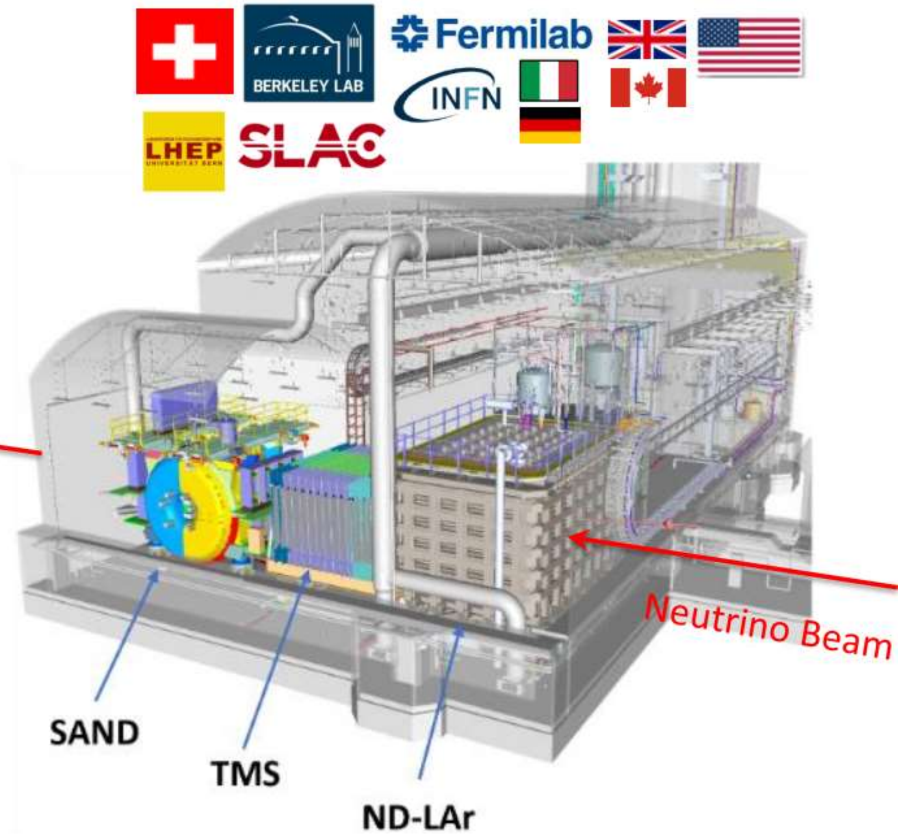


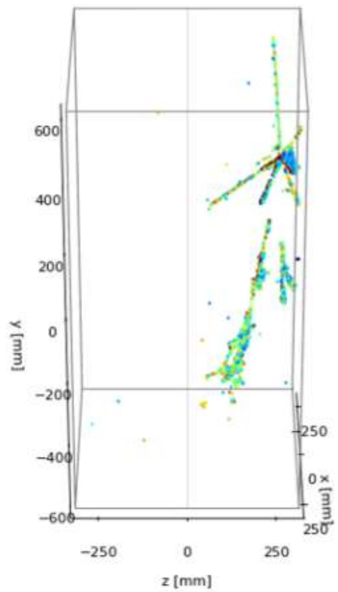


Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

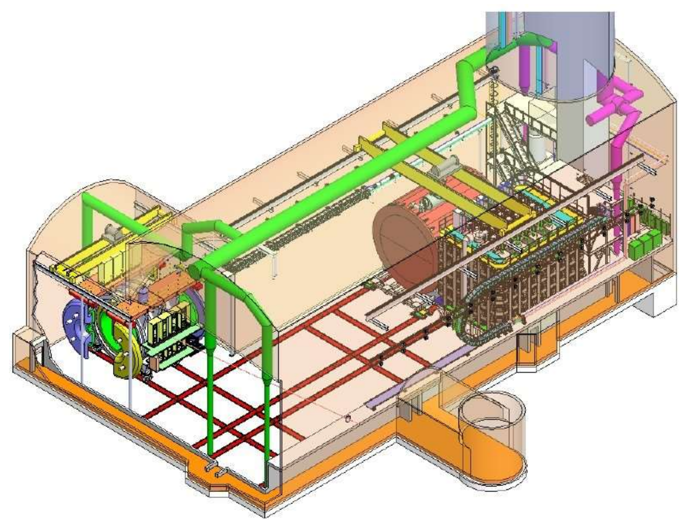
Near Detector

- Innovative design enables the first-ever operation of a liquid argon near detector in the world's most intense neutrino beam.
- Near detector critical to precision neutrino science.
- Near detector prototype installed in neutrino beam at Fermilab. Taking data this spring.



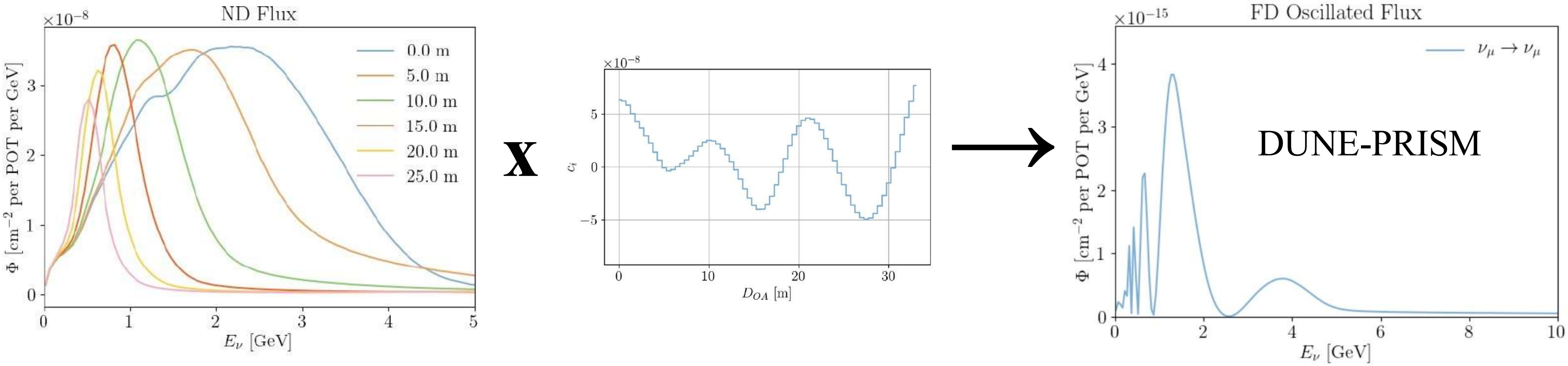


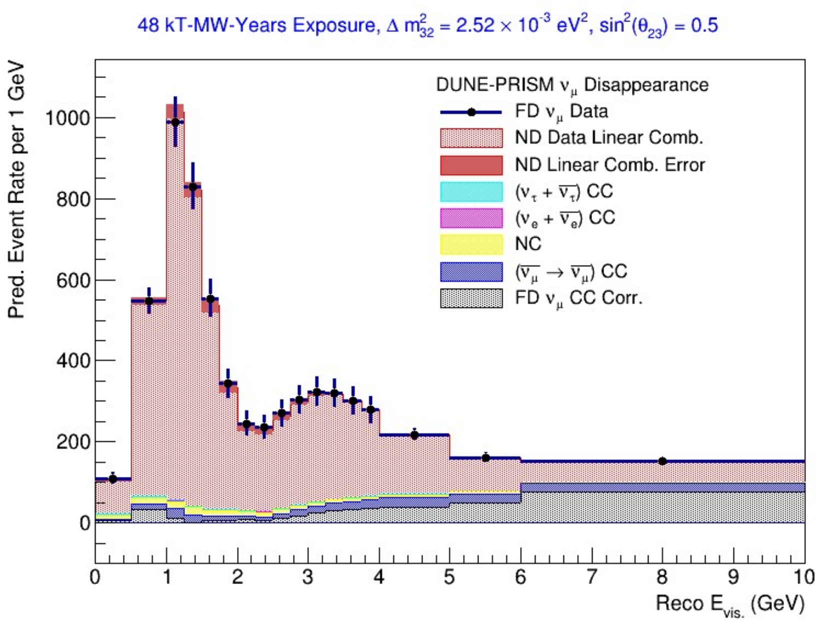
Cosmic data in ND-LAr prototype in Switzerland



Phase II ND

PRISM plays a critical role in DUNE's precision

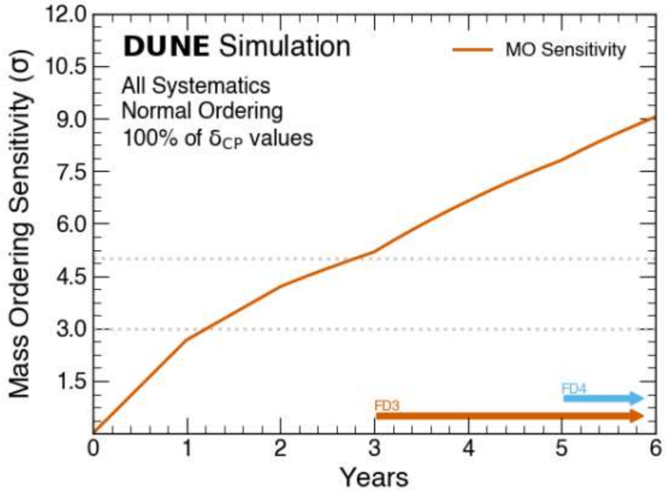


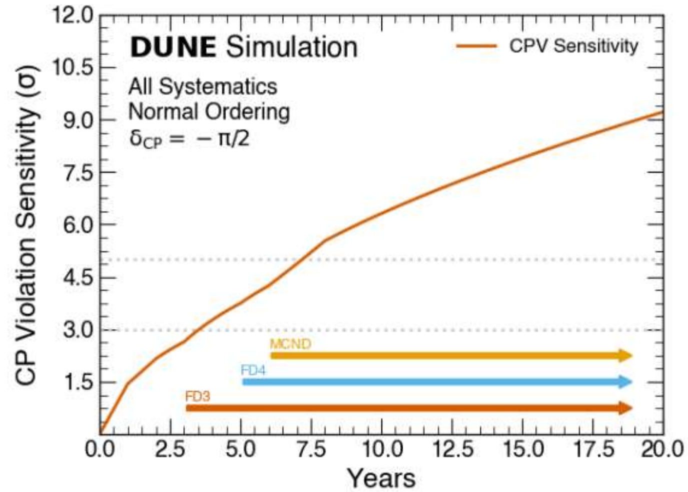


- FD flux ≠ ND flux → uncertainties in energy dependence of flux, cross sections
- ND flux changes with angle → take ND data in different fluxes→build linear combination to match FD *oscillated* spectra
- For LBL: robust analysis approach with very minimal dependence on interaction modeling
- Also extends dark matter sensitivity

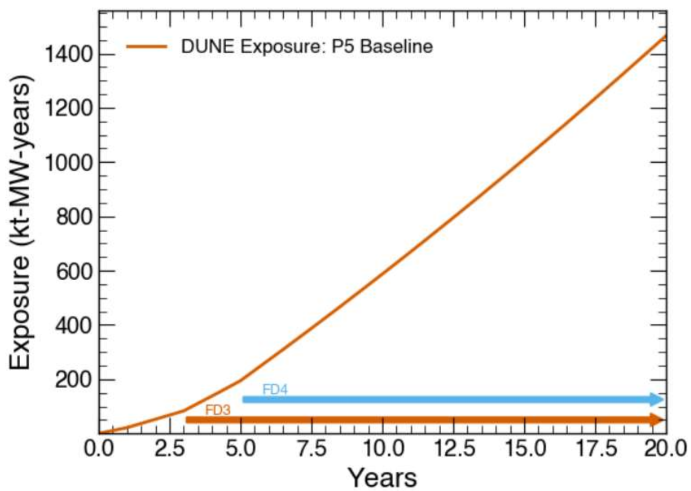
New Staging assumption based on P5 recommendation

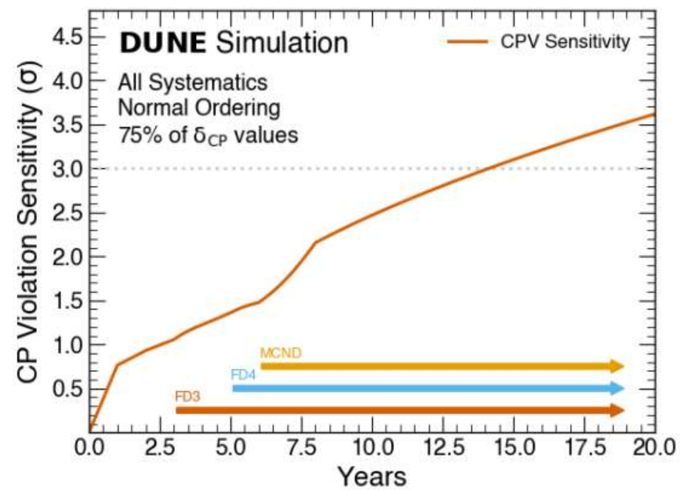
Phase-1 physics milestones





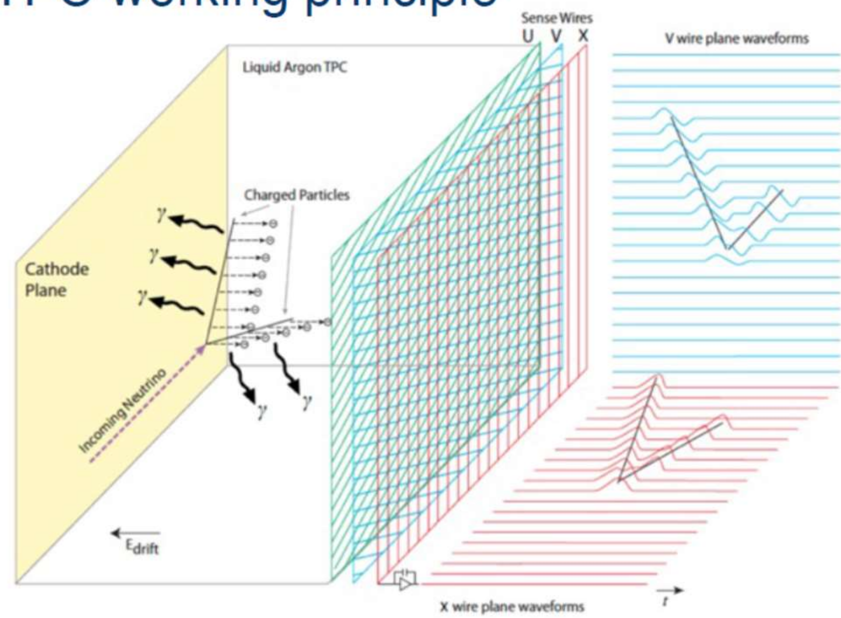
Long-term CPV





The Single-Phase LAr-TPC

TPC working principle



- Ionization electrons [~5 fC/cm] drift to the anode in pure LAr & uniform E-field (~500 V/cm)
  - Few mm pitch and ~MHz sampling frequency
  - 3D via multiple 2D view (wire# vs drift time)
  - high imaging capabilities → kinematic reconstruction with mm-scale spatial resolution
  - Intrinsically excellent Calorimetry and Particle Identification (dE/dx) capability
- Prompt scintillation light (@128 nm)
  - T = 0, trigger, calorimetry

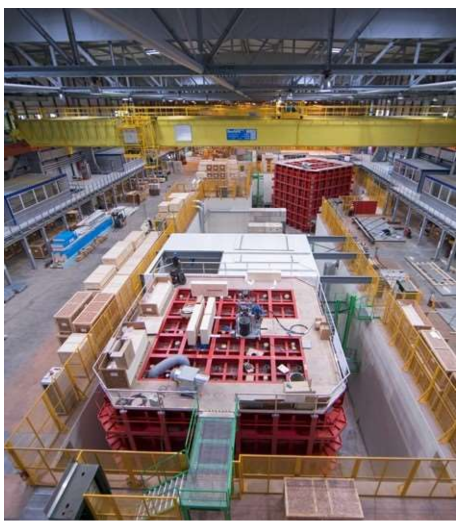
LAr as radiation detection medium

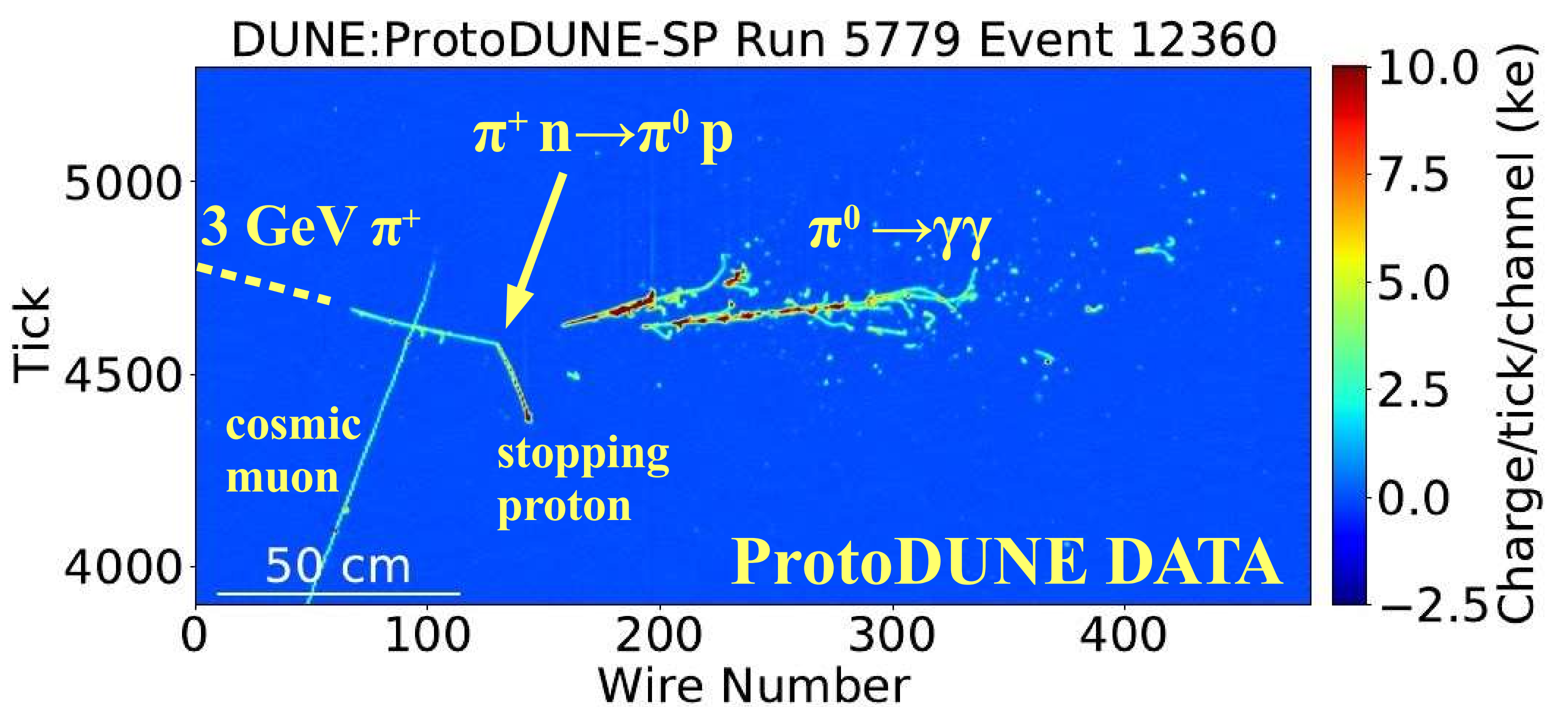
- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^-/MeV
- High electron lifetime if purified → long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: $2/L ($3000/L for Xe, $500/L for Ne)

- Technological challenges
  - LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
  - Imaging & anode planes
  - Very low noise front end amplifiers to detect ~ fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wave length
  - HV system to provide uniform/stable E-field in large drift volume
- Pioneered by ICARUS and adopted in present and next generation neutrino ezperiment (μBoone, SBND, DUNE)
  - DUNE: scaling to multi-kt size

LArTPC technology provides exquisite resolution

- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- High Resolution & Low thresholds:
  - sensitivity to few-MeV neutrinos, hadrons
  - excellent for LE neutrino and BSM Search





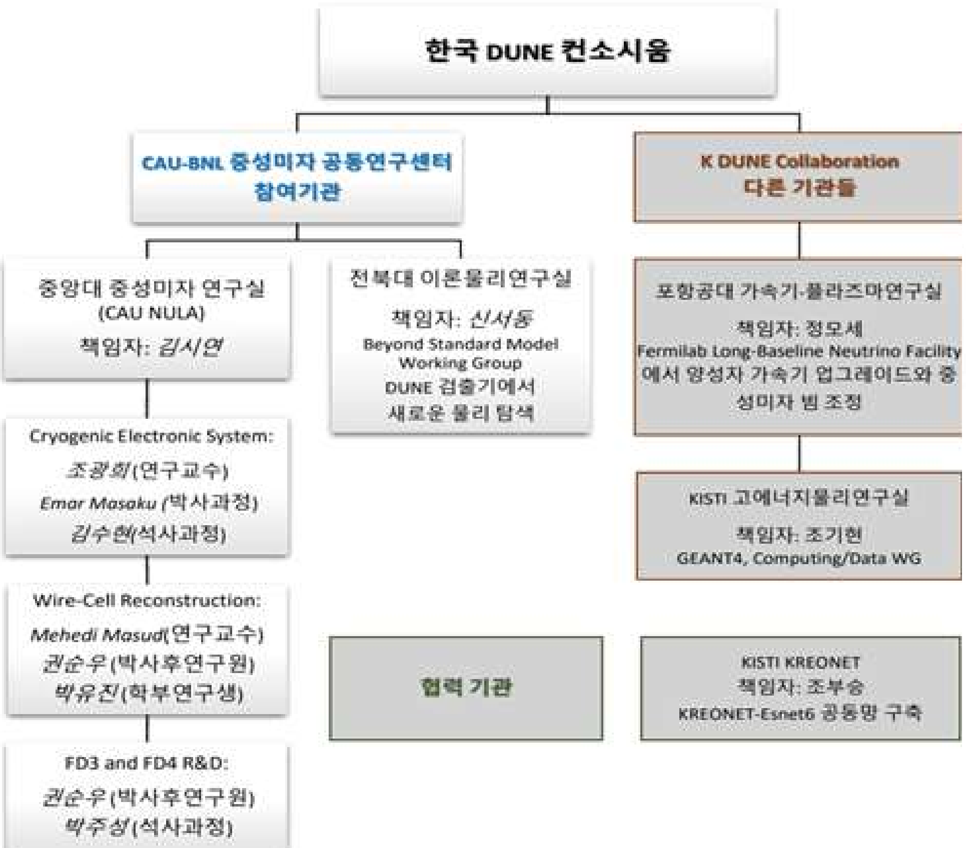
DUNE site activities

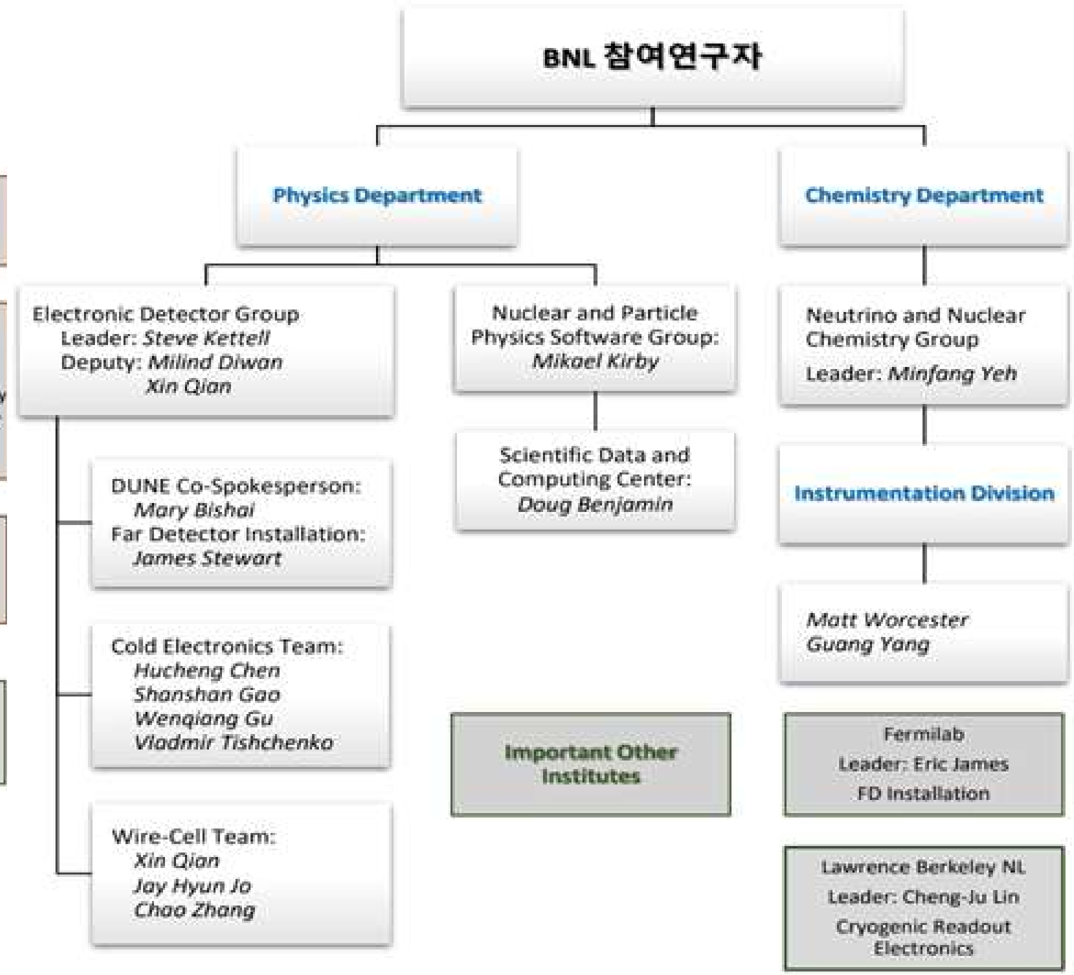
- 2016.05 CAU joined DUNE Collaboration
- 2017 ~ 2018 — ProtoDUNE L-Ar TPC Single Phase
Cold Electronics Module test
- 2018 ~ 2021 — 3DST Working Group,
3DST (3-dim Scintillator Tracker) for SAND/ND
- Joint consortium with T2K SuperFGD Group
- Prototype LANL Neutron beam test 2019 & 2020
- 2022 — ???
- 2023.01 ~ — ProtoDUNE HD Data Analysis
ProtoDUNE VD Cold Electronics
Cold Electronics QC and update
Wire-Cell Reconstruction

BNL Electronic Detector Group**과**

공동연구를 위한 방문 및 파견 기록

YYYY.MM	교수	대학원생	학부생	총인원	
2017.07-08	김시연	장창환		2	
2018.01-02		장창환	권순우, 정연우, 설대원	4	
2019.01-02		권순우, 정연우		2	6~8주 방문
2021.01-02		권순우	정기영	2*	연인원 19명
2021.07-08		권순우, 정기영		2*	코비드 기간*
2023.02	김시연			1	스토니브룩대학
2023.02-03		권순우, 정기영	박유진	3	으로 방문하여
2024.01-02		권순우, 김수현, Emar Masaku	박주성, 고경의	5	활동


한국 DUNE 컨소시움
CAU-BNL 중성미자 공동연구센터 참여기관
K DUNE Collaboration 다른 기관들
중앙대 중성미자 연구실 (CAU NULA) 책임자: 김시연
전북대 이론물리연구실 책임자: 신서동 Beyond Standard Model Working Group DUNE 검출기에서 새로운 물리 탐색
포항공대 가속기-플라즈마연구실 책임자: 정모세 Fermilab Long-Baseline Neutrino Facility 에서 양성자 가속기 업그레이드와 중성미자 빔 조정
Cryogenic Electronic System: 조광희(연구교수) Emar Masaku (박사과정) 김수현(석사과정)
KISTI 고에너지물리연구실 책임자: 조기현 GEANT4, Computing/Data WG
Wire-Cell Reconstruction: Mehedi Masud(연구교수) 권순우(박사후연구원) 박유진(학부연구생)
협력 기관
KISTI KREONET 책임자: 조부승 KREONET-Esnet6 공동망 구축
FD3 and FD4 R&D: 권순우(박사후연구원) 박주성(석사과정)

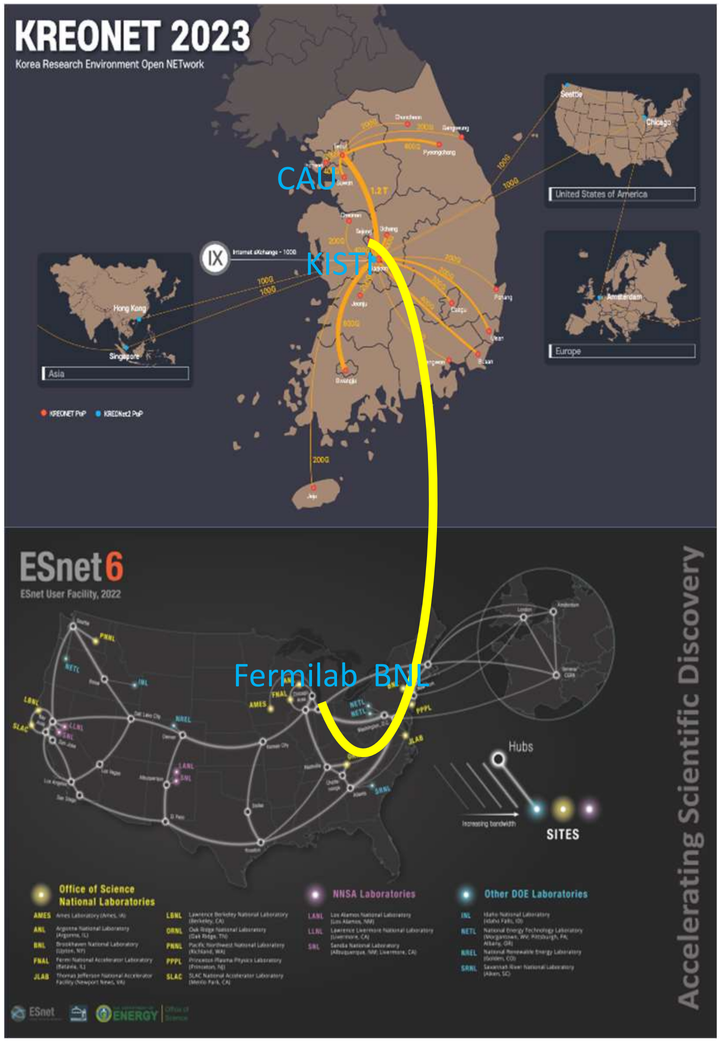

BNL 참여연구자
Physics Department
Chemistry Department
Electronic Detector Group Leader: Steve Kettell Deputy: Milind Diwan Xin Qian
Nuclear and Particle Physics Software Group: Mikael Kirby
Neutrino and Nuclear Chemistry Group Leader: Minfang Yeh
Scientific Data and Computing Center: Doug Benjamin
Instrumentation Division
DUNE Co-Spokesperson: Mary Bishai Far Detector Installation: James Stewart
Matt Worcester Guang Yang
Cold Electronics Team: Hucheng Chen Shanshan Gao Wenqiang Gu Vladmir Tishchenko
Important Other Institutes
Fermilab Leader: Eric James FD Installation
Wire-Cell Team: Xin Qian Jay Hyun Jo Chao Zhang
Lawrence Berkeley NL Leader: Cheng-Ju Lin Cryogenic Readout Electronics

DUNE Computing is "internationalizing"

- This means DUNE will organize computing ~similar way to LHC experiments
- Expect international contributions according to some sensible split
- Expect a significant fraction of computing from outside of the USA (50% ?)

Main DUNE Computing sites are currently:

- USA
  - FNAL
  - BNL
  - Universities
- Europe
  - UK -all GridPP
  - Czech Republic: FZU
  - NL: Sara
  - FR: IN2P3 Lyon
  - CH: CERN
  - ES: PIC
  - IT: INFN



Thus from network point of view

- Strong overlap with WLCG sites
- We are well served by ESNET, Geant, and European NRENs

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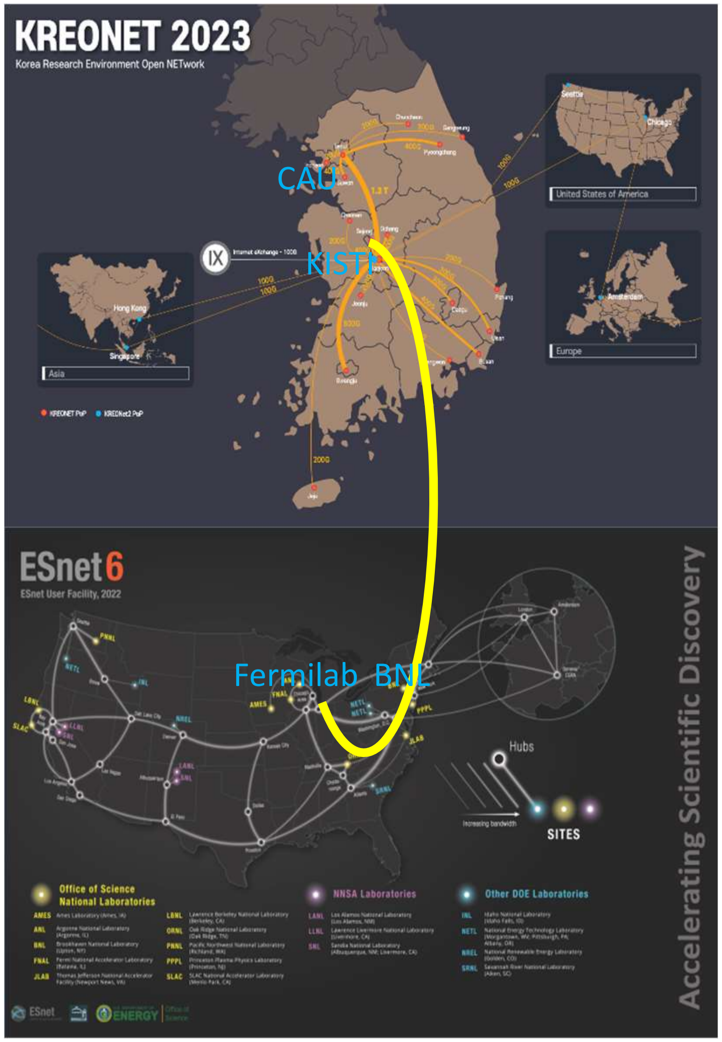
    - ES: PIC
    - IT: INFN

- ASIA
  - KR: CAU Data Center



- Thus from network point of view
  - Strong overlap with WLCG sites
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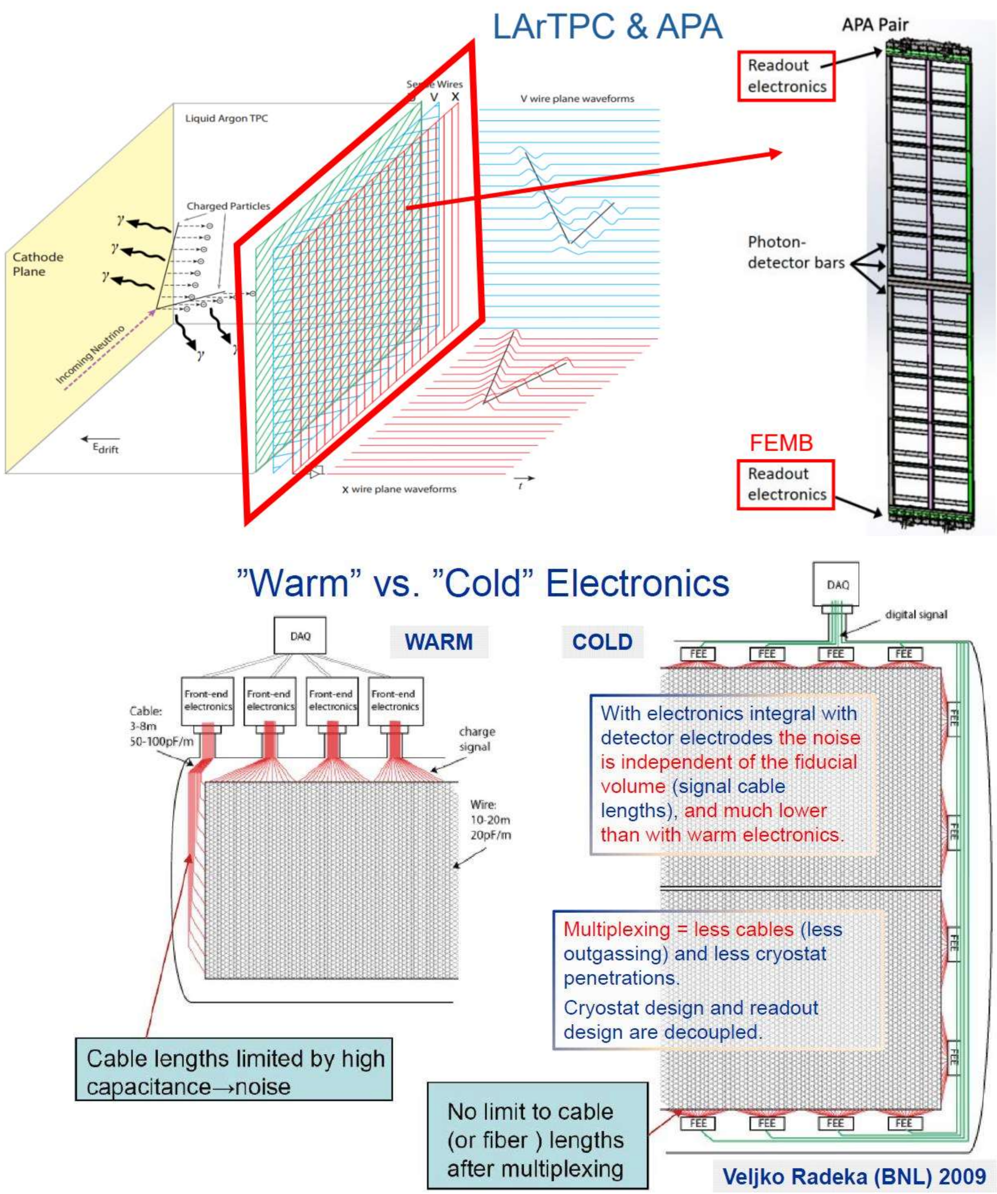
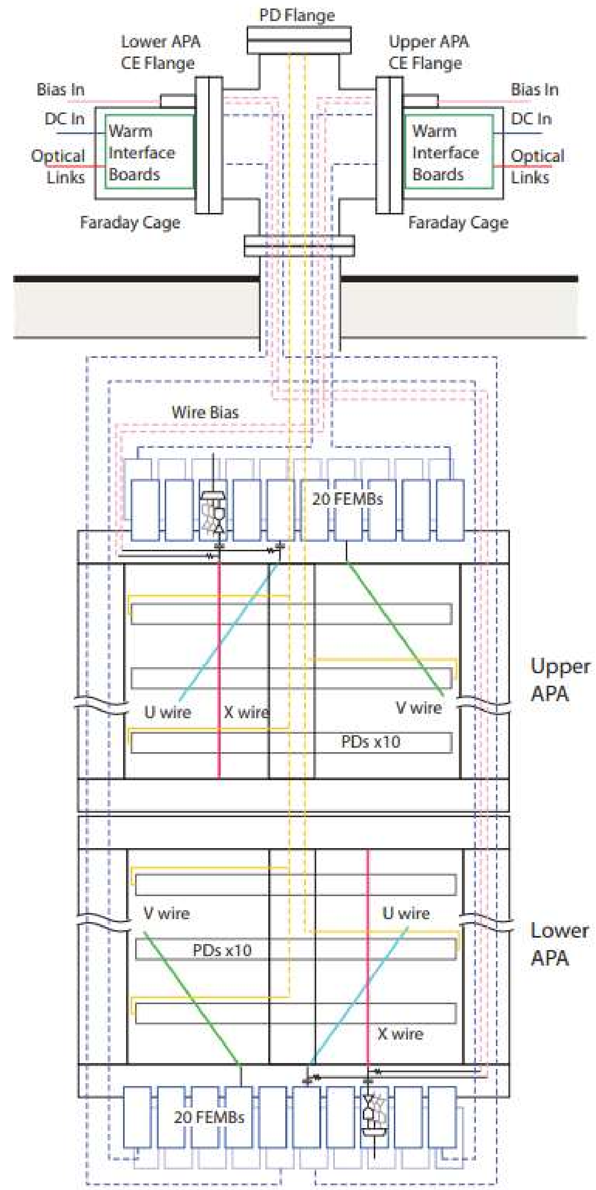
CAU-BNL Collaboration for DUNE (since 2017)

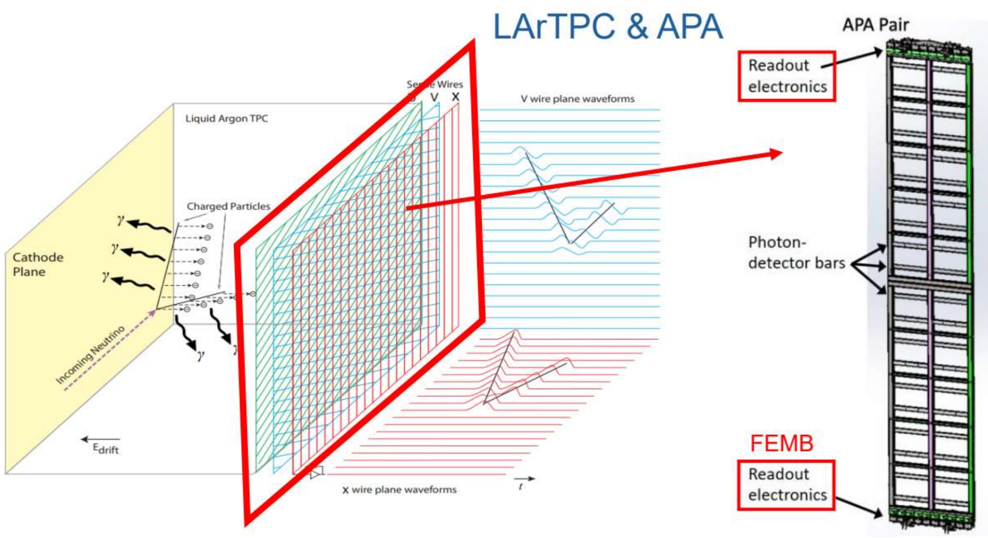
연구목표	중앙대학교	Brookhaven National Lab
원거리 검출기 FD2 설치	Integration of Cold Electronic Readout and TPC (권순우, 김수현, 남호경)	Technical Coordinator으로서 FD 제작 총괄 James Stewart(L), Hucheng Chen, Shanshan Gao, Cheng-Ju Lin (LBNL)
Wire-Cell A	ProtoDUNE 결과 획득, 데이터 분석을 통한 SW 패키지 검증 (Mehedi Masud(L), 남호경, 박유진, 김선홍)	패키지 개발과 DUNE Collaboration에서의 보급 (Xin-Qian(L), Jay Hyun Jo)
Wire-Cell B	DUNE Phase I에서 Liquid Argon TPC 맞춤 Reconstruction Tool Package 보급과 분석에 활용 (Mehedi Masud(L), 박유진, 김선홍)	DUNE Phase I에서 Liquid Argon TPC 맞춤 Reconstruction Tool Package 보급과 분석에 활용 (Xin-Qian(L), Jay Hyun Jo)
Cold Electronics	LArASIC, FEMB 테스트와 업그레이드 (김수현, 남호경, 박유진)	LArASIC, ColdADC, COLDATA 칩 관리와 Quality Control. (V. Tishchenko(L), Shanshan Gao, Wenchiang Gu)
Data Center	물리적 환경 확보, DUNE Data Storage와 HPC 수요 조사와 사업 여건에 맞는 시설 확보 (KREONET, 조부승 센터장 협조)	DUNE Data Storage와 HPC 수요 공급 관리, (Mike Kirby(L), Doug Benjamin)
FD4 R&D	Water-based Liquid Scintillator 1T Prototype data analysis, 30T Geometric Design and Construction (권순우(L), 박주성)	WbLS의 DUNE FD4 추진 (Minfang Yeh(L), Milind Diwan, Guang Yang)

Cryogenic Readout Electronic System

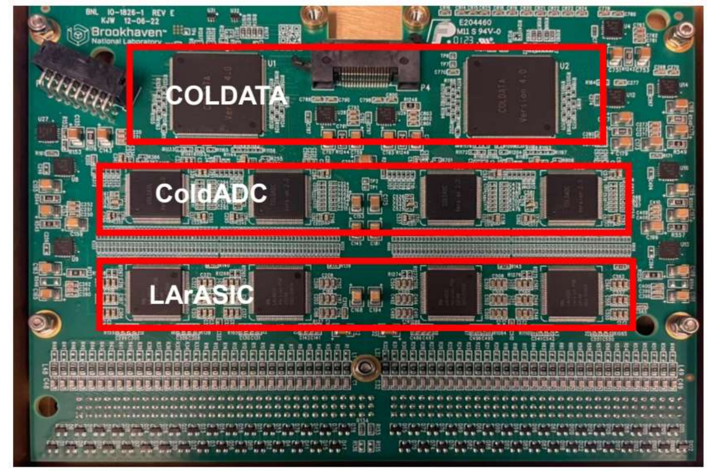




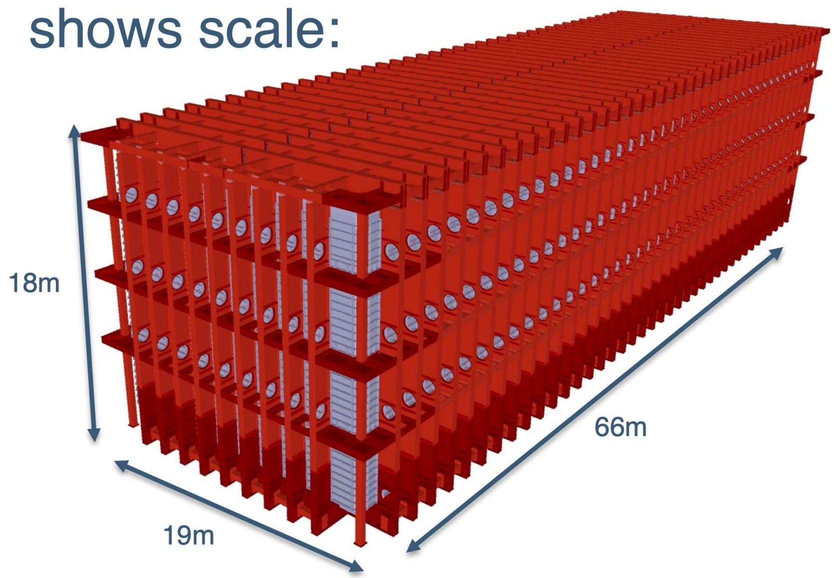
Cryogenic Readout Electronic System



FEMB(Front-End Mother Board) with 3-ASICs



shows scale:



Element	Quantity
Anode Plane Assembly(APA)	150 per TPC
Front-end mother board(FEMB)	20 per APA
FE ASIC(LArASIC) chip	8 per FEMB
ADC ASIC(ColdADC) chip	8 per FEMB
COLDATA ASIC chip	2 per FEMB
Warm interface board(WIB)	5 per APA
Sense wires	2560 per APA
Cold cable and etc.	1 per APA

Table 1 : TPC electronics components and quantities

Wire-Cell Packeage and ProtoDUNE Analysis

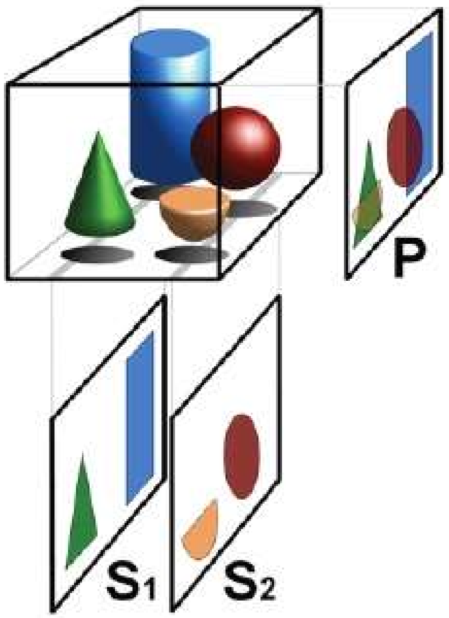
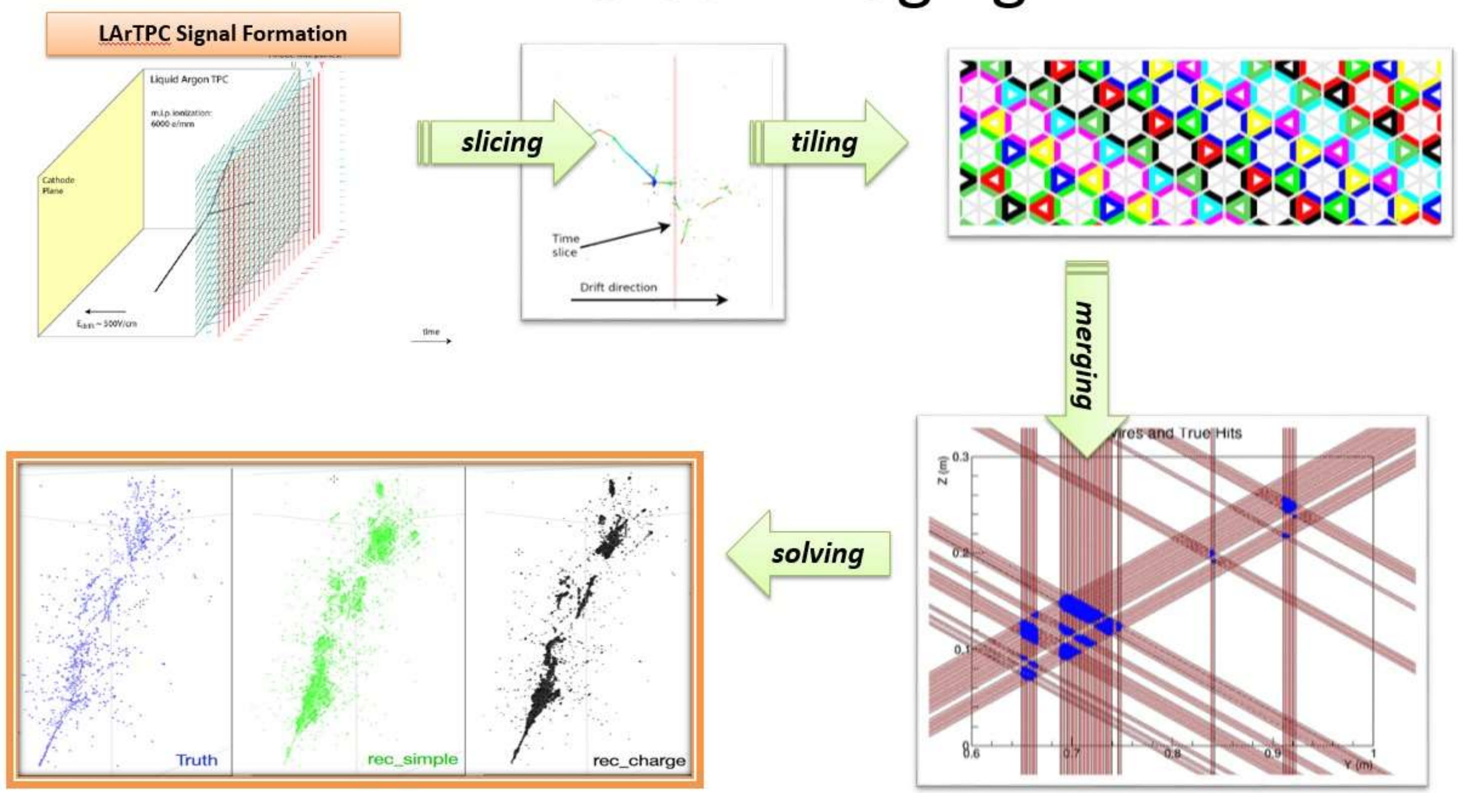


Fig.1:Basic principle of tomography: superposition free tomographic cross sections S1 and S2 compared with the projected image P

https://en.wikipedia.org/wiki/Tomography

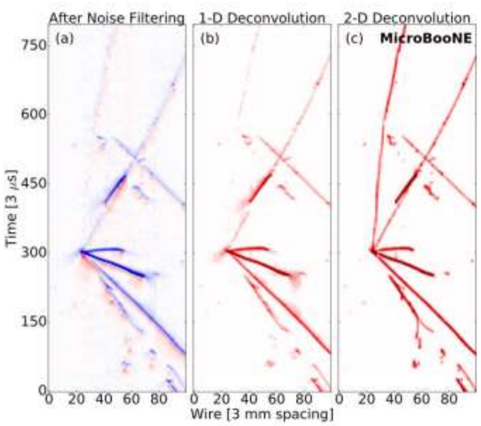
Wire-Cell Imaging



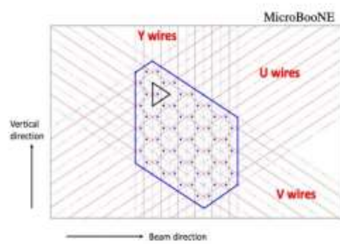
"Three-dimensional Imaging for Large LArTPCs", JINST 13, P05032 (2018)

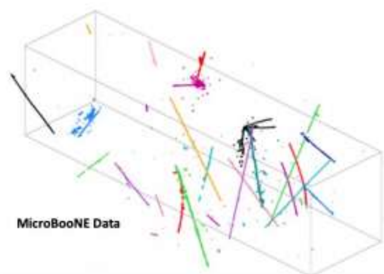
Wire-Cell Packeage and ProtoDUNE Analysis

TPC simulation noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting DL-3D vertexing particle identification

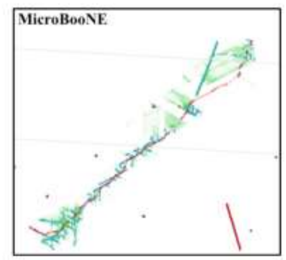


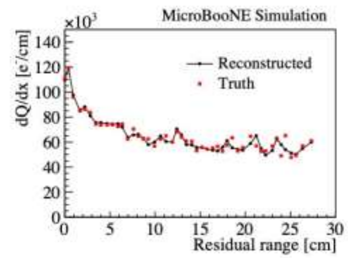
JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)



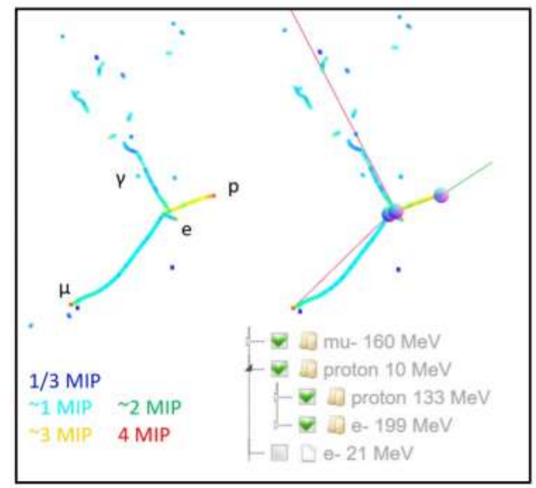


JINST 13 P05032 (2018)
JINST 16 P06043 (2021)





Phys. Rev. Applied 15, 064071 (2021)



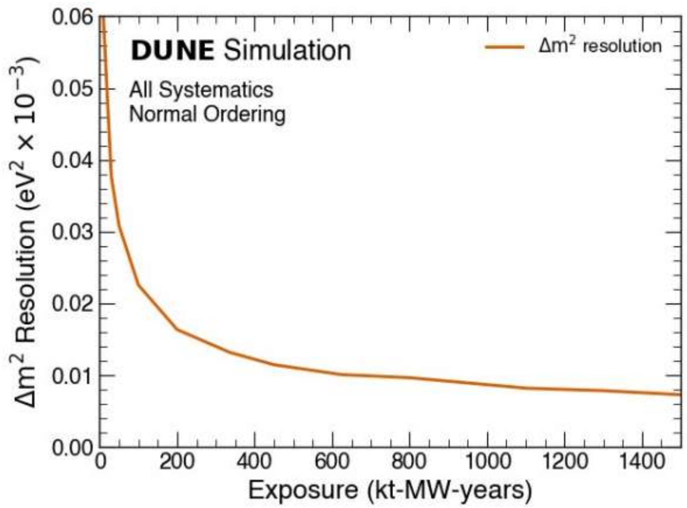
JINST 17 P01037 (2022)

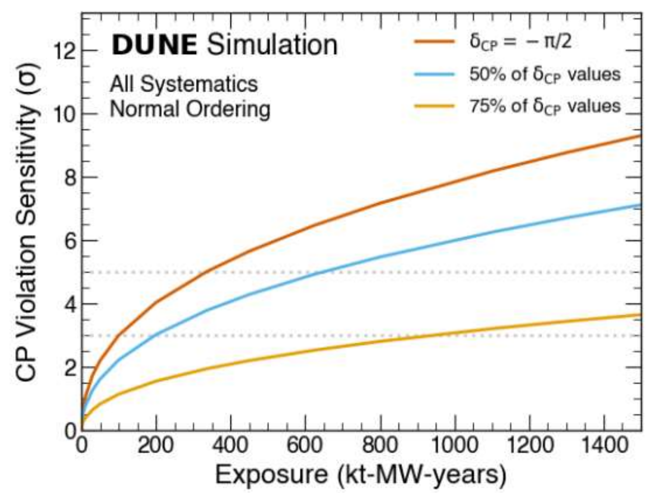
연도	CAU-BNL 협력연구와 DUNE 실험의 주요 예상 결과물	DUNE 원거리 주검출기의 기술적 진행 단계			DUNE 검출기 데이터 기반 물리학
		데이터 I 분석	원거리 검출기 제작 및 설치	FD3&4 R&D 제작 및 설치	
2024 2025 2026	- FD 2 조립완성과 설치후 성공적인 가동 - Wire-Cell 재구성 Package의 완성과 보급, - 관련 보고서와 논문 다수	* ProtoDUNE DAQ Wire-Cell Reconstruction	* FD2-VD Integration of Readout and TPC. FD1-HD Installation	* FD4 R&D WbLS 타입 검출기 디자인과 시뮬레이션	비가속기 중성미자 물리 분석 시작 (계속)
2027 2028 2029 2030	- 데이터센터 구축 완료 - 중앙대-KISTI-Fermilab-BNL 고속연구망 가동 - 중요 물리적 목표 Mass Hierachy 와 CP Violation 결과	실험 가동 데이터 수집 DUNE Data Acquisition	FD2-VD Assembly & Installation	FD3&4 Assembly & Installation	가속기 중성미자 물리 (진동, 질량순서 CP대칭성 붕괴 중성미자 상호작용) 분석 (CPV 5시그마)
2031 2032 2033	-중성미자 질량과 PMNS 변환행렬에 대한 높은 정확도(5시그마 이상) 도달 - 암흑물질이나 비표준모형 현상 탐색 결과 예상				(계속) 새로운 물리학과 암흑물질 탐색 가속기/비가속기 중성미자 물리 분석 (양성자붕괴 태양 및 초신성중성미자 우주선과 대기중성미자)
2035 2040 2050 2060	예측할 수 없는 새로운 미래 기술과 우주 시대에, 우주와 물질의 기원에 대한 난제들이 중성미자에 대한 규명으로 비롯해서 풀리는 연구 결과 가능		DUNE Upgrade		

백업

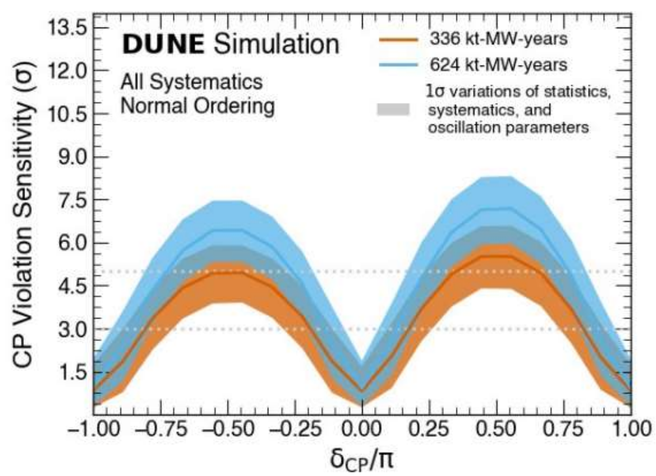
Nothing has changed from the TDR resolutions and sensitivities.

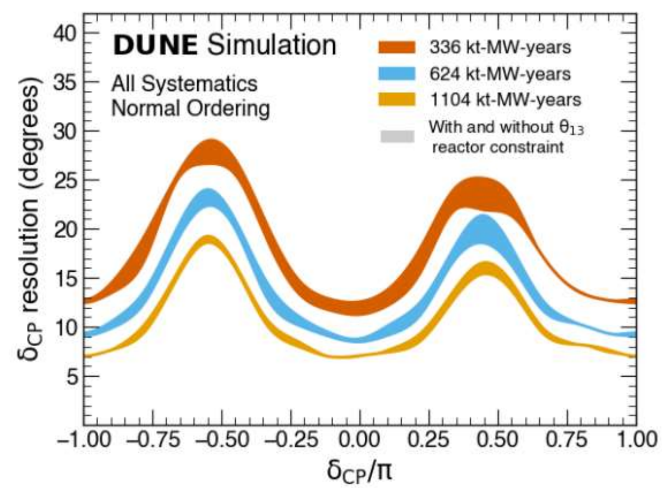
Plots vs. exposure



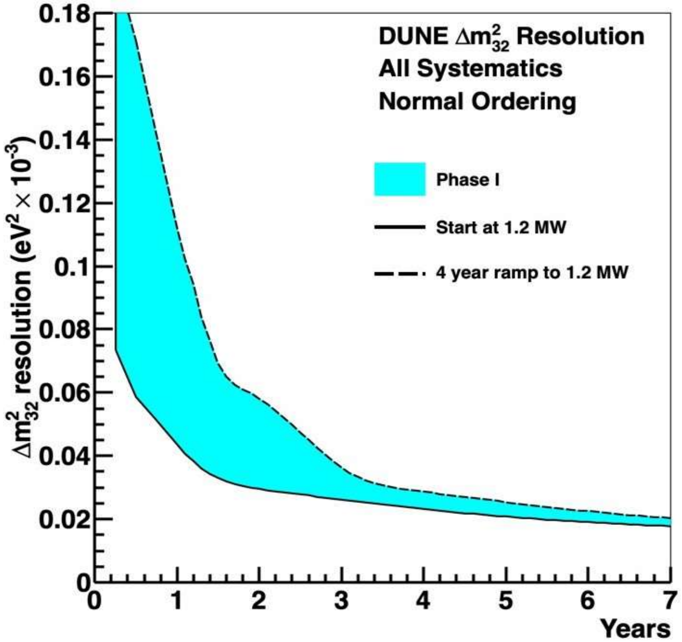


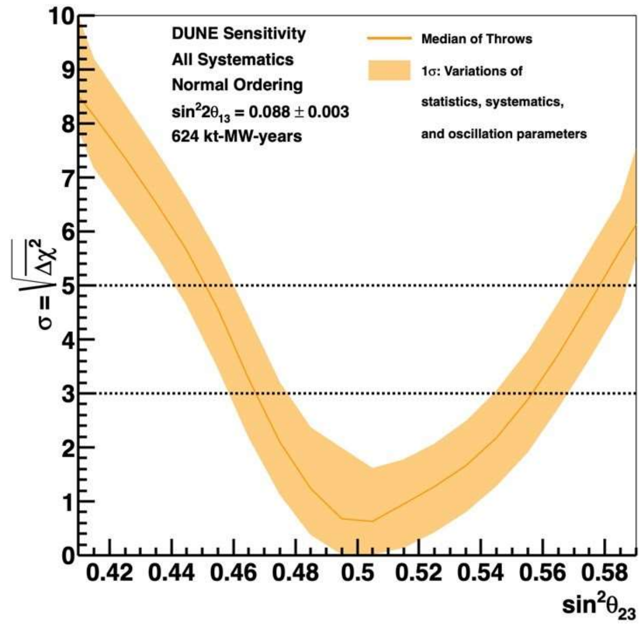
Plots vs. true value of delta

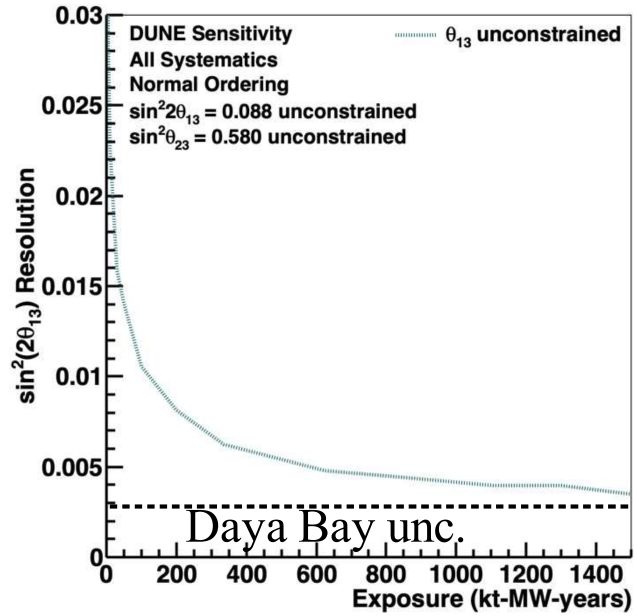




Physics potential:
Precision measurements,non-unitarity tests





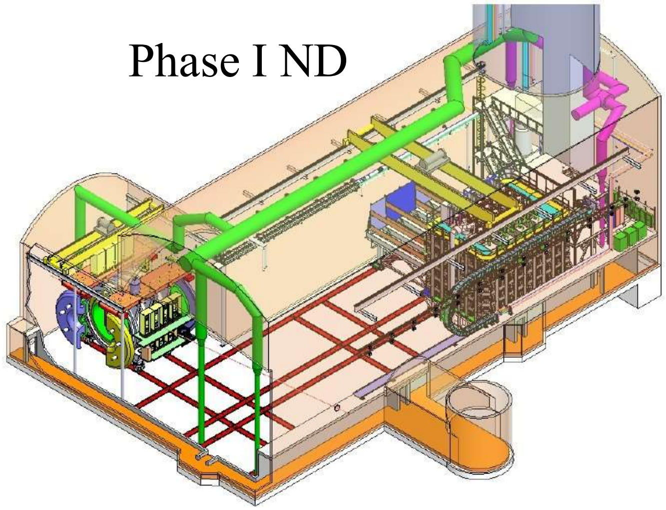


- Excellent on Δm^2_{32} and θ_{23} , including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

Getting there: phased construction

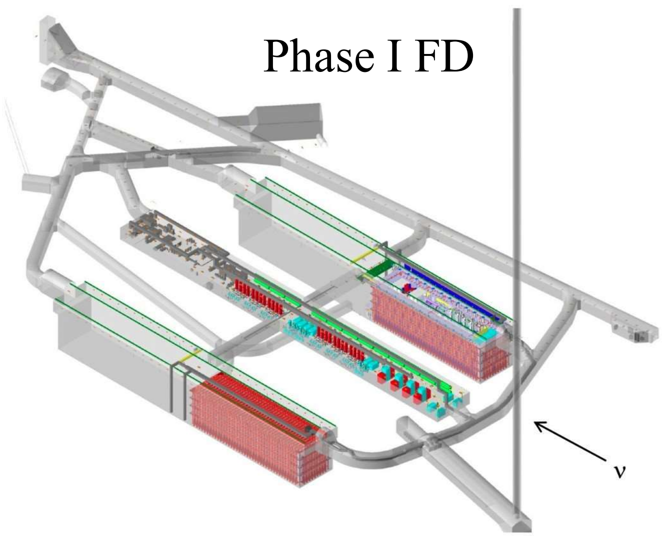
DUNE Phase I:

- Neutrino beam with 1.2 MW intensity
- Two 17kt LAr TPC FD modules, but underground fac ilities and cryogenic infrastructure to support four mo dules
- Near detector: ND-LAr + TMS (movable), SAND
- FD 1&2 taking physics data in 2029, beamline and ND by 2031



DUNE Phase II:

- Fermilab proton beam upgrade to 2.4 MW
- Two additional 17kt FD modules
- Near detector: ND-LAr + MCND (movable), SAND



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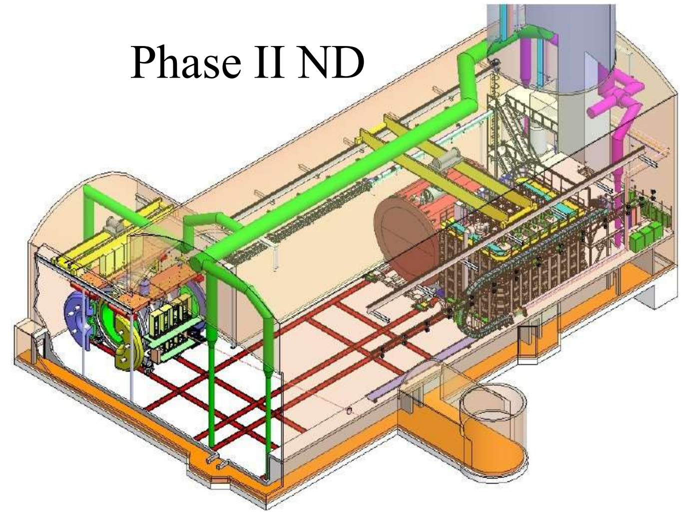
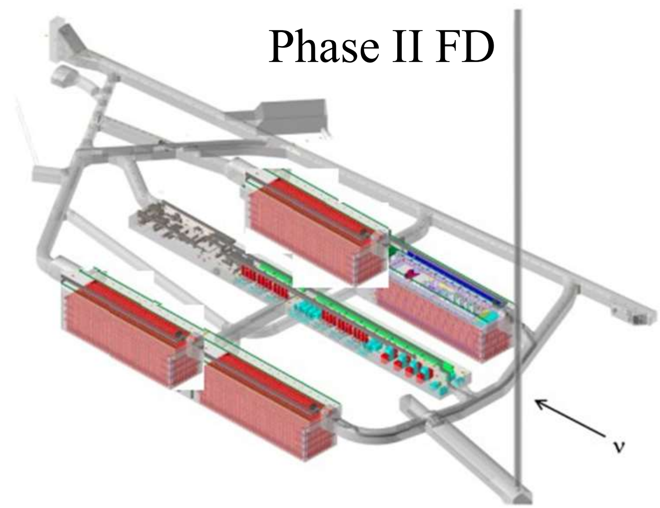
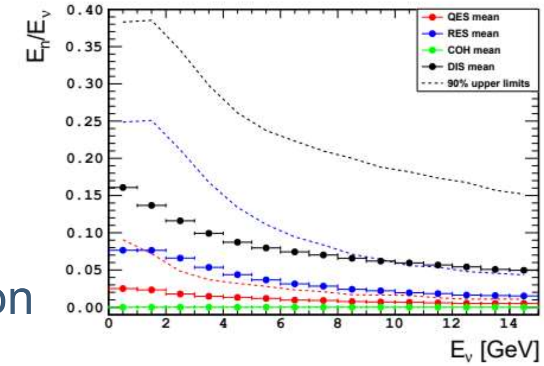
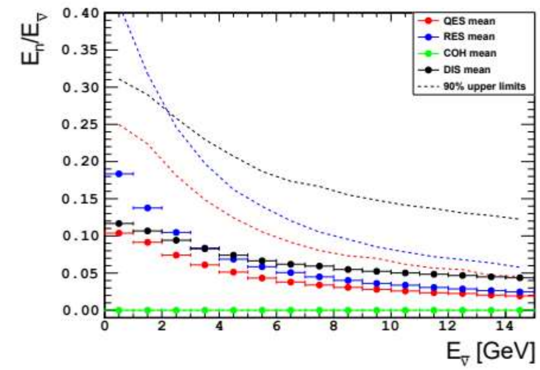




중성미자 상호작용과 중성자 검출

- Neutrino-nucleus interaction: nu-Ar, nu-C,H
  COH, QE, RES, DIS
- Neutrons in final states: Missing energy in neutrino detection
- Neutron identification: - Event-by-event Energy Reconstruction
- 3-dim Scintillator Tracker:
  - DUNE neutrino beam and CH target
  - CCQE-like (cc0pi) event analysis
  - Low-nu fitting for flux constraint
- LANL neutron beam test (3DST & SuperFGD/T2K):
  - Study of secondary neutrons





ıge energy fraction delivered to the primary ve to the neutrino energy(top) and the an- ·gy(bottom). The average ratios E_n/E_ν are according to the CC Quasi-elastic (QES), CC), CC coherent (COH) and CC deep-inelastic ·) interaction modes.

PHYSICAL REVIEW D **107**, 032012 (2023)

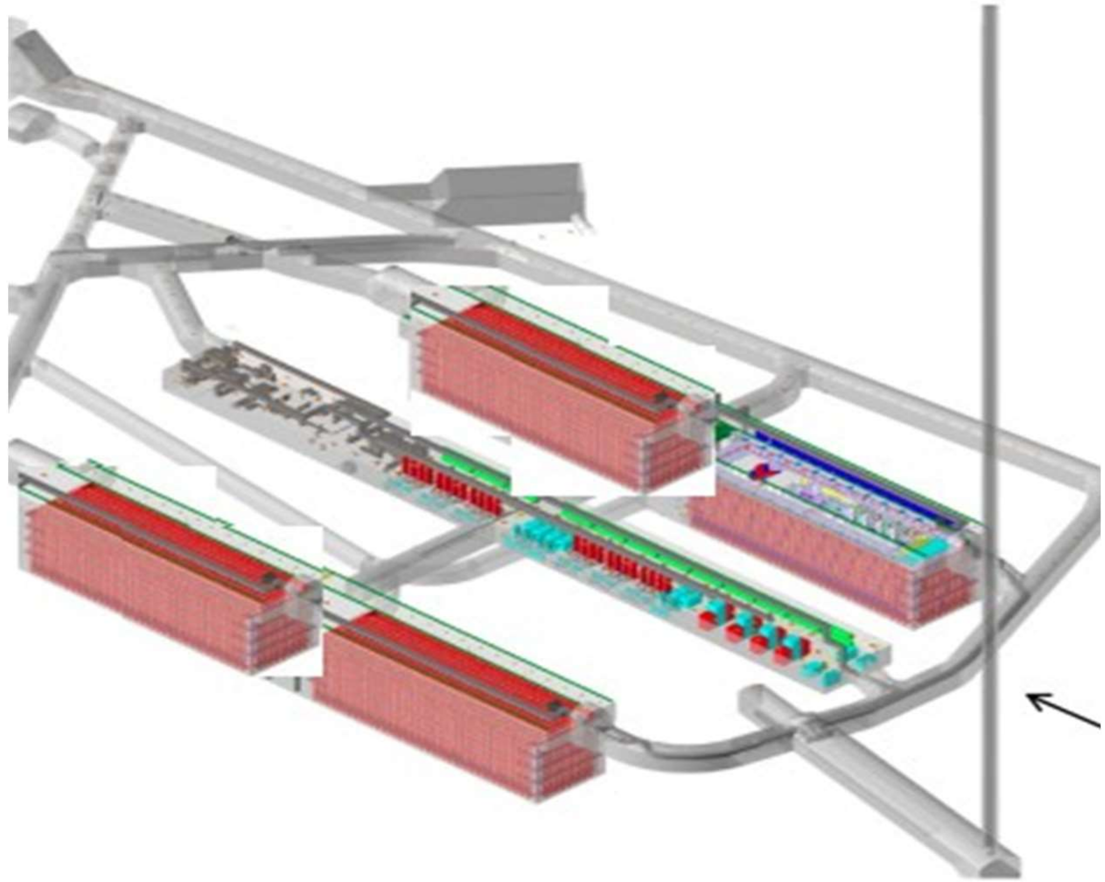
Neutron detection and application with a novel 3D-projection scintillator tracker in the future long-baseline neutrino oscillation experiments

S. Gwon,[1] P. Granger,[2] G. Yang,[3,4,*] S. Bolognesi,[2] T. Cai,[5] M. Danilov,[6] A. Delbart,[2] A. De Roeck,[7] S. Dolan,[7] G. Eurin,[2] R. F. Razakamiandra,[8] S. Fedotov,[9] G. Fiorentini Aguirre,[10] R. Flight,[5] R. Gran,[11] C. Ha,[1] C. K. Jung,[12] K. Y. Jung,[1] S. Kettell,[13] M. Khabibullin,[9] A. Khotjantsev,[9] M. Kordosky,[14] Y. Kudenko,[9,15,16] T. Kutter,[17] J. Maneira,[18] S. Manly,[5] D. A. Martinez Caicedo,[10] C. Mauger,[19] K. McFarland,[5] C. McGrew,[12] A. Mefodev,[9] O. Mineev,[9] D. Naples,[20] A. Olivier,[5] V. Paolone,[20] S. Prasad,[17] C. Riccio,[12] J. Rodriguez Rondon,[10] D. Sgalaberna,[21] A. Sitraka,[10] K. Siyeon,[1] N. Skrobova,[6] H. Su,[20] S. Suvorov,[9] A. Teklu,[12] M. Tzanov,[17] E. Valencia,[14] K. Wood,[12] E. Worcester,[13] and N. Yershov[9]

[1]*Chung-Ang University, 06974 Seoul, South Korea*

최근 중요 실적 및 기여

- 신서동(전북대):
  Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment, *Eur.Phys.J.C* 81 (2021) 4, 322,
  Boosted dark matter search 집필 기여
- 권순우(중앙대):
  Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report, *Instruments* 5 (2021) 4, 31,
  Neutron detection from antineutrino events in the 3DST, 분석결과 수록, 집필 기여
- 정기영(중앙대):
  Muon antineutrino CC 1 neutral pion interaction selection using the invariant mass, DUNE-doc-23681-v1,
  Technical note 작성
- 권순우(중앙대):
  Neutron detection and application with a novel 3D projection scintillator tracker in the future long-baseline neutrino oscillation experiments e-Print: 2211.17037 [hep-ex] -> Published in PRD.



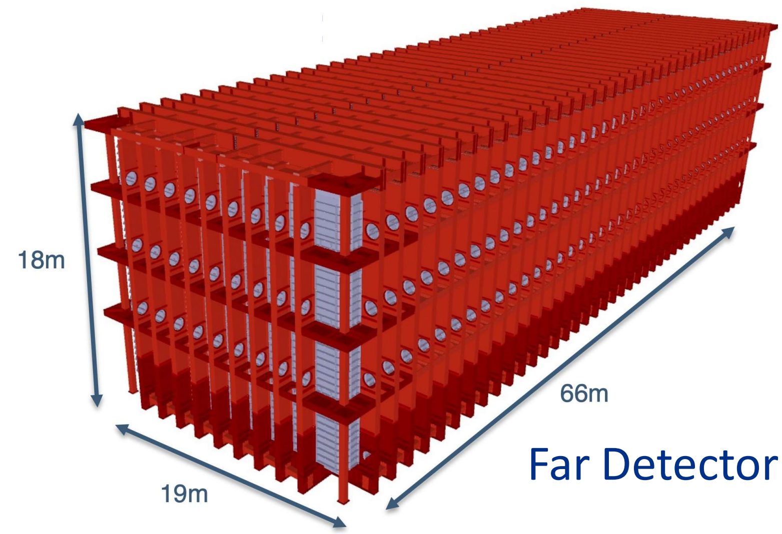
ProtoDUNE at CERN Neutrino Platform

- ProtoDUNE II 의 목적:

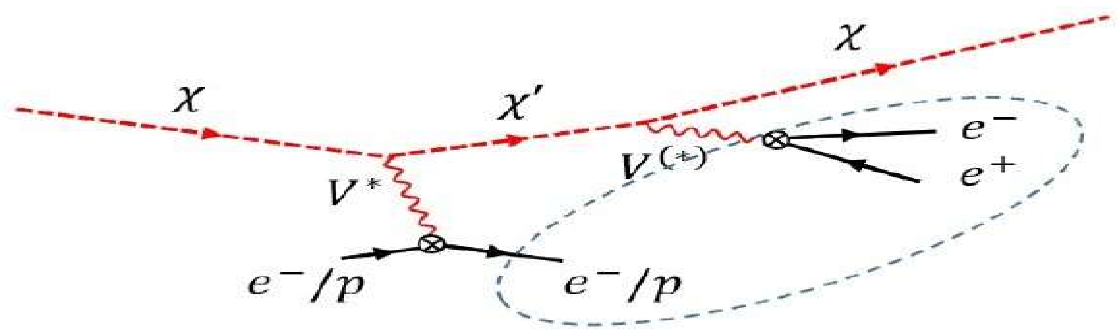
- 원거리검출기의 각 성분의 수행능력과 검출기의 안정성 테스트
- 아르곤에 대한 강입자 크로스섹션을 측정
- 캘리브레이션 방법의 개발과 테스트: 레이저, 중성자 외 여러가지 저에너지 소스 활용
- 스케줄: 6~7월 중성미자 빔가동, 12월 빔데이터 수집, 데이터 분석

Far Detector Dataflow and Trigger Records

- beam coincidence events are extremely important, but of limited total volume
  - ~1 Hz beam rate
  - active online trigger in development
  - Region-of-Interest within module
  - online compression and zero-suppression being considered
- solar neutrino triggered events
- cosmic ray events and calibrations
- supernova readout events
  - ~140 TB in 100 seconds - one FD module
  - work w/ trigger primitives for immediate optical follow up
  - transfer out 4 hours and process in 4 hours for precision optical observations
- DUNE requirement - less than 30 PB/year tot al to permanent storage from all active FDs



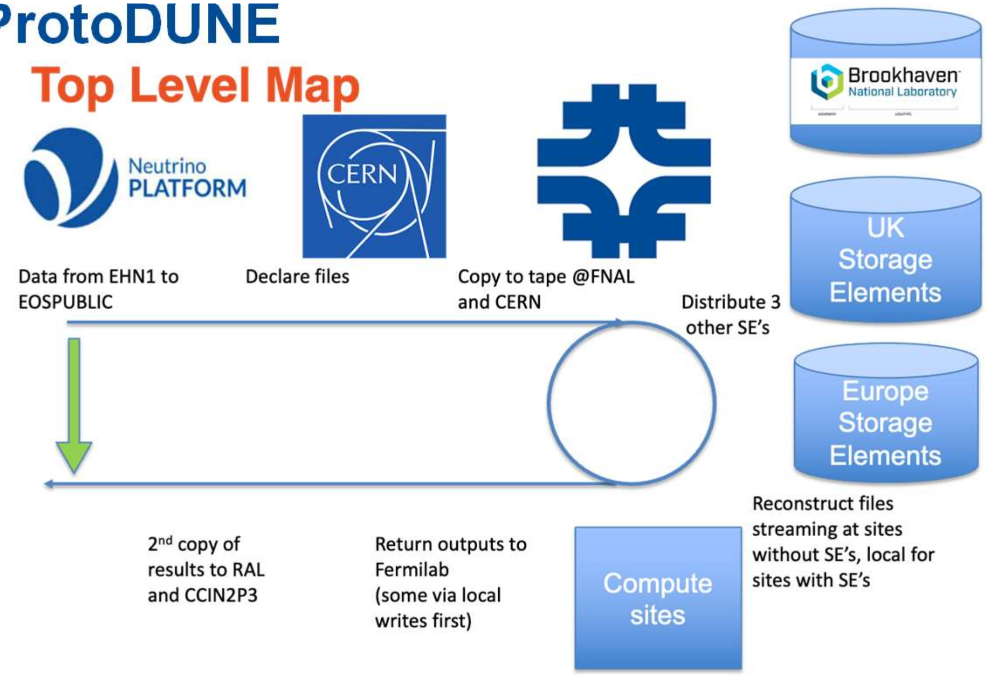
Far Detector Cryostat

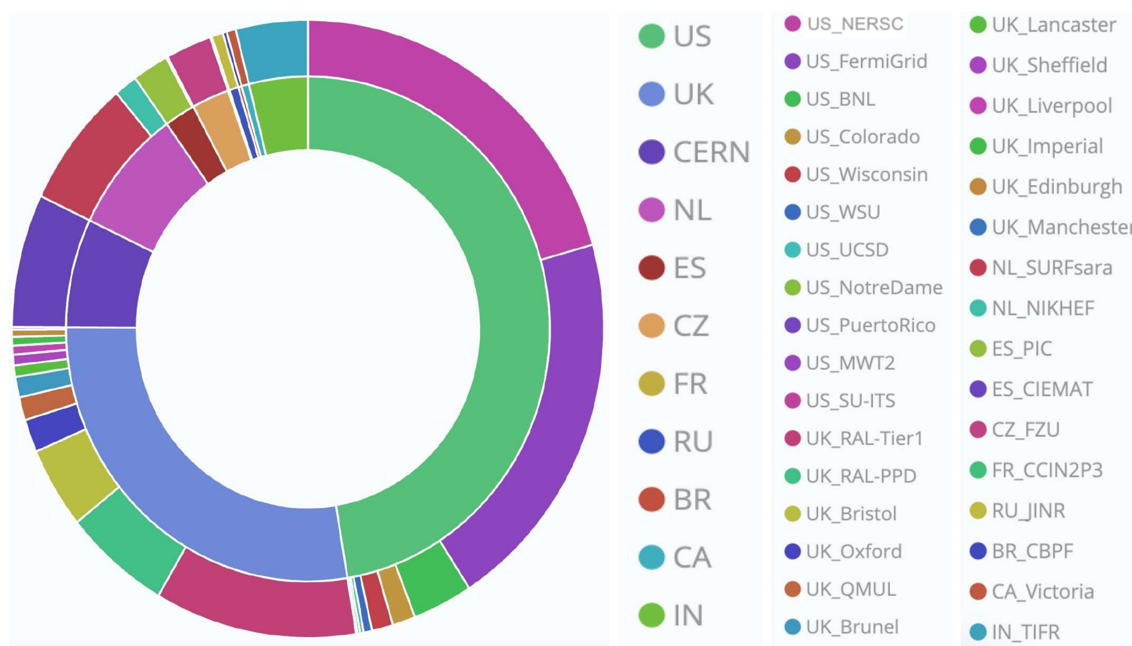


Recently published DUNE Computing CDR - https://arxiv.org/abs/2210.15665

Summer 2022 Data Challenge 4 - ProtoDUNE

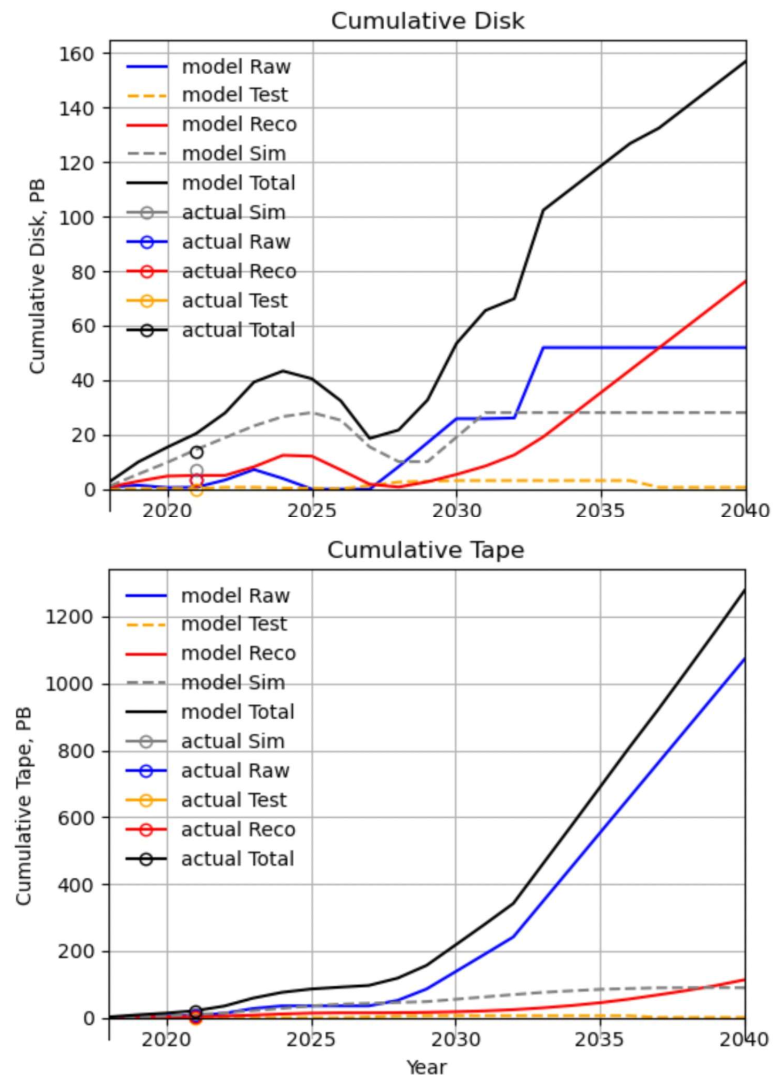
- Goals of the Data Challenge 4 - test all t he services and procedures that will be used in the forthcoming beam runs of P D-HD and PD-VD
- Phase 1 - Data Pipeline
  - Goal - test data path EHN1->CERN->FNAL
  - transfer, declare, and replicate "raw data" at needed scale
  - 3.6 GBytes/s achieved across atlantic
- Phase 2 - Data Processing
  - Goal - sustain 5000 concurrent jobs for keep up processing
  - significant drop in CPU efficiency for jobs where large input data files not located "near" job
  - The Workflow System (now "justIN")
  - The Data Dispatcher





Data Placement Strategy

- accomplished with Rucio and FTS3 - Scale tests of new DUNE data pipeline - S. Timm
- 2 copies of raw data on tape
  - one copy on each side of an ocean
  - 6 months on disk
- 1 replica of reco/sim on tape
  - distribute across global Rucio SEs
  - annual reco pass over all data
  - annual sim campaign to match
  - production resident on disk for 2 years
- Assume 2 disk copies of reco and sim
  - impose shorter lifetimes on tests & sim stages
  - R&D exploring data tiers and formats
- DUNE HDF5 Experience - B. Chowdhury

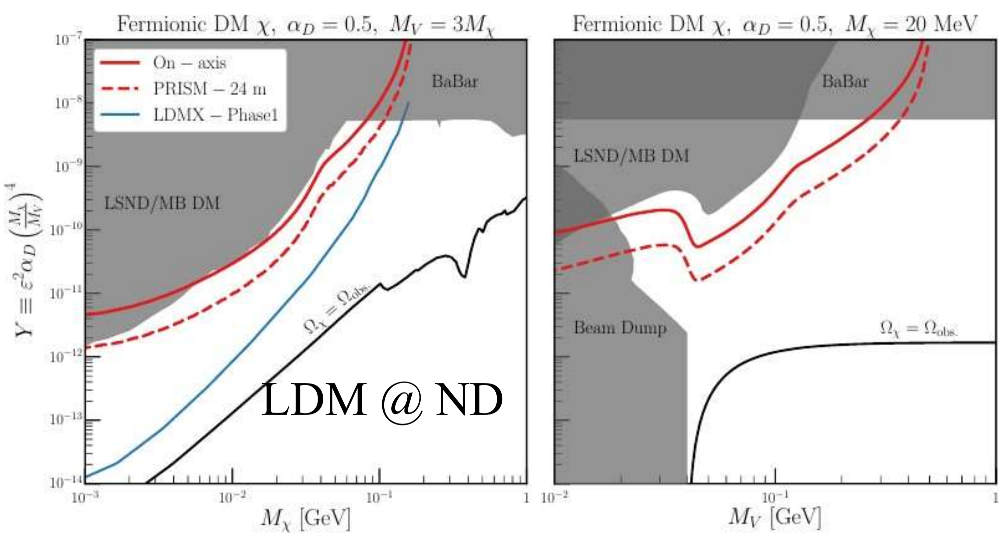


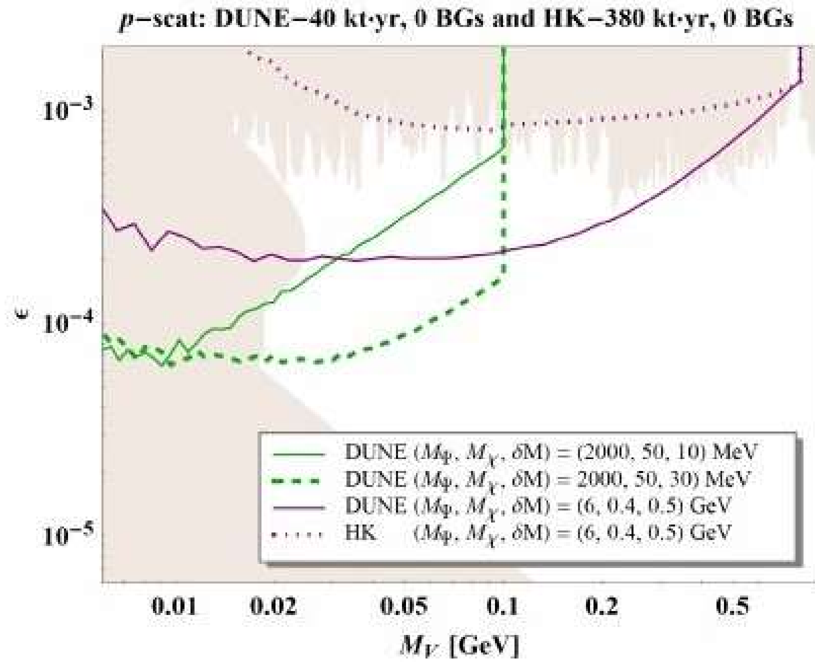
DUNE Computing CDR

DUNE is an excellent BSM physics experiment

- For exotics of cosmic origin:
  - Large target mass
  - Deep underground → low background
  - Exquisite imaging, sensitivity to hadro ns
- For exotics produced in hadron- nucleus collisions:
  - Very intense proton beam
  - Excellent detectors at ~500m, including a 1 50-ton detector (scattering), and a large, low density detector (decays)

Dark matter at DUNE ND & FD





- ND-LAr is sensitive to DM produced in beamline, off- axis data helps to contro l SM backgrounds

  FD is sensitive to inelastic dark matter of
- cosmic origin