SNeND: "Near Detector" for Supernova Neutrino Measurements in DUNE

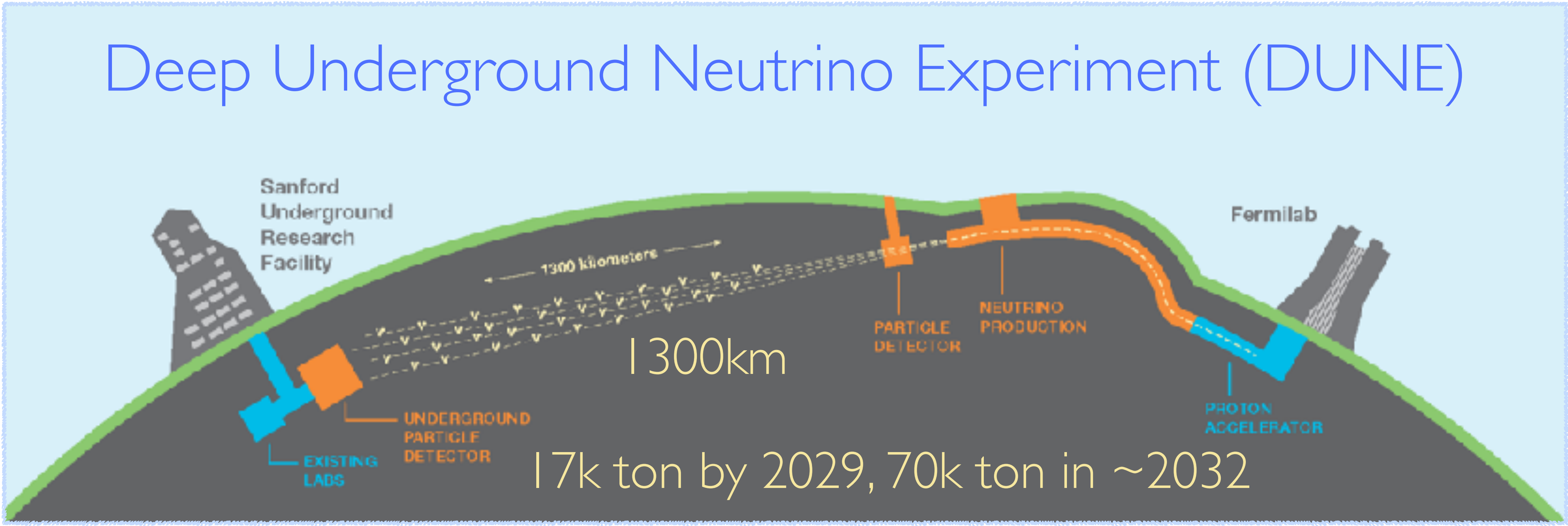
SLAC NATIONAL ACCELERATOR LABORATORY

Yun-Tse Tsai (SLAC)

INT Astrophysical Neutrino Workshop

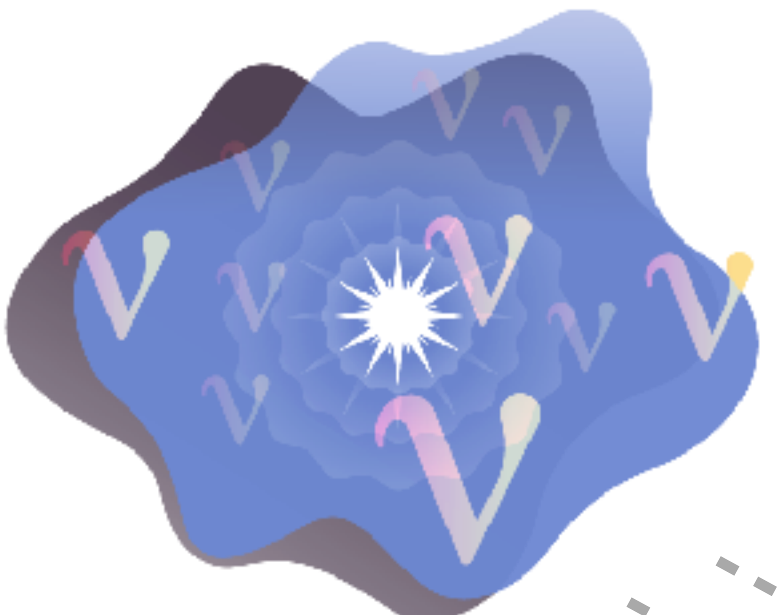
August 8th 2023

Long Baseline Experiment

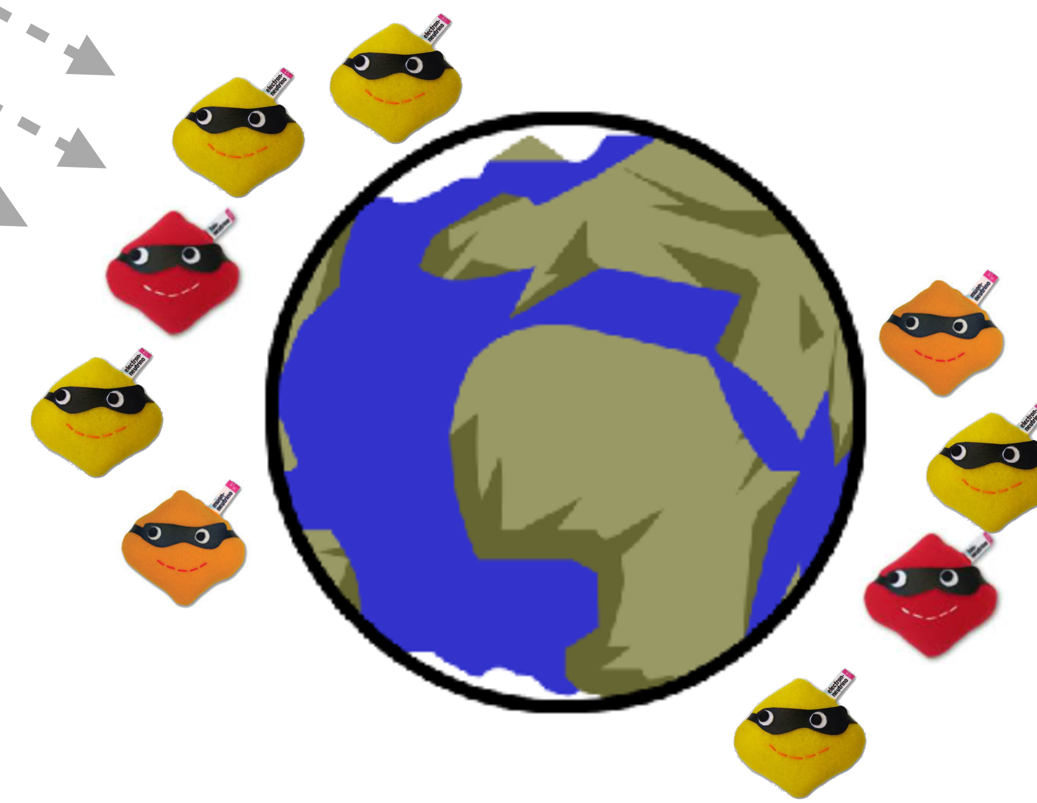


- Aim to measure:
  - CP violation in lepton sector
  - neutrino mass ordering
  - neutrinos from supernovae, proton decays, etc.
- ν_μ from Fermilab accelerator, detected by LArTPC

Supernova Neutrino

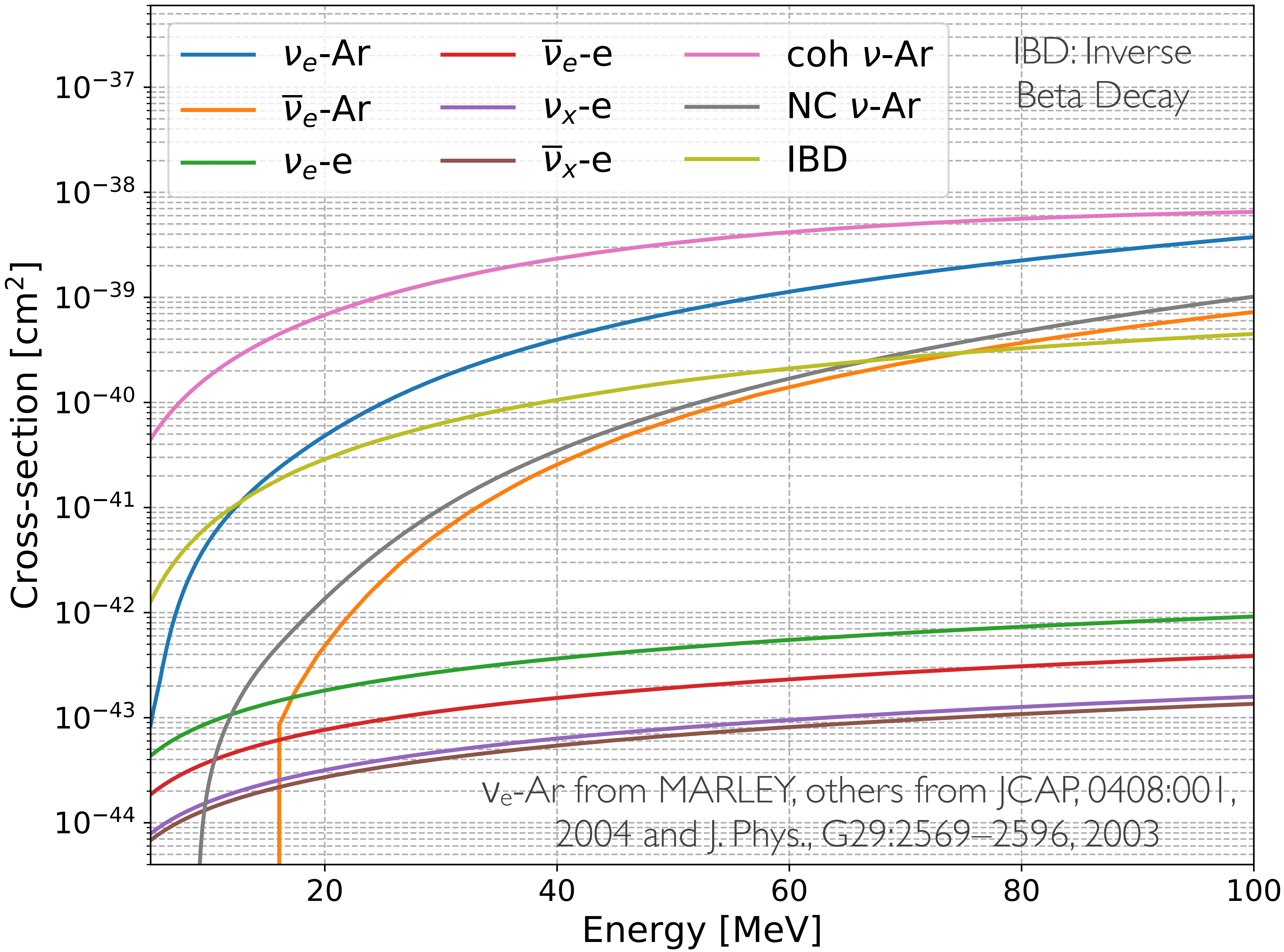


Core-collapse supernova neutrino energy: O(1-10) MeV

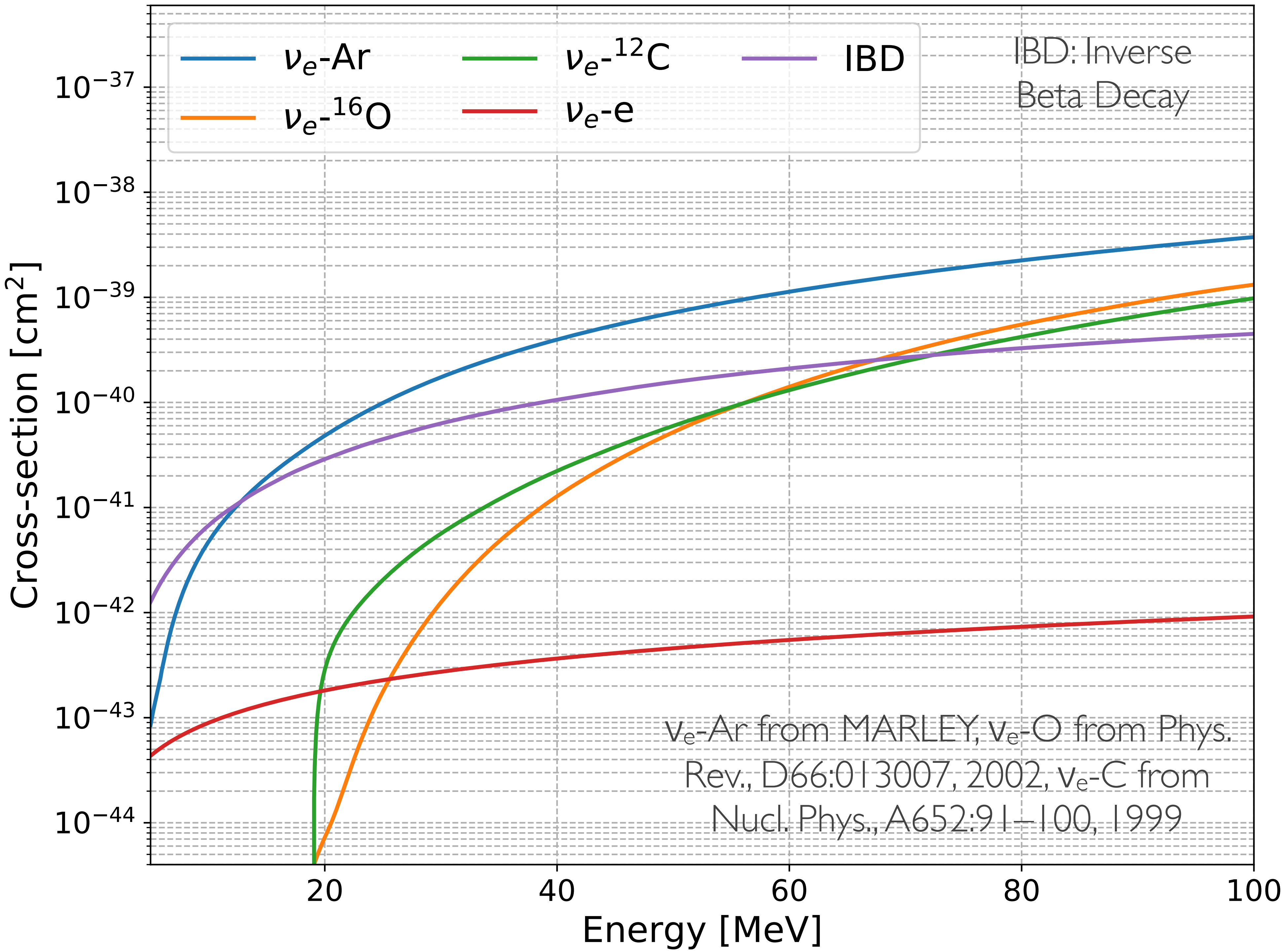


DUNE has unique sensitivity to ν_e via charged-current (CC) ν_e-Ar interactions

ν_e-Ar Cross Sections



ν_e Cross Sections



Supernova Neutrino Flux

Pinched-thermal form: to fit simulated flux

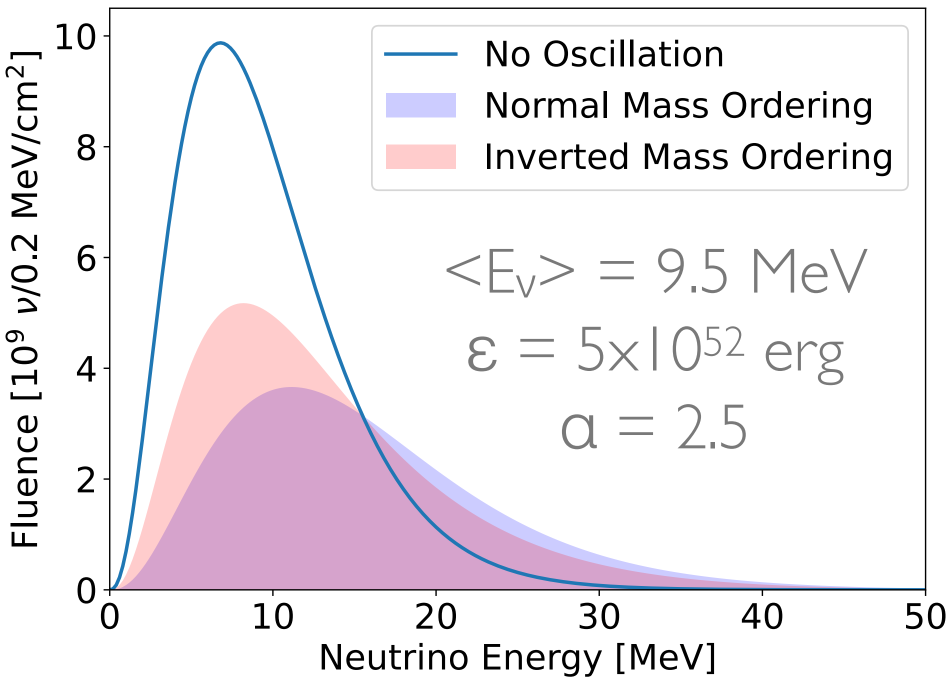
$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{< E_\nu >}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{< E_\nu >}\right]$$

E_ν: neutrino energy

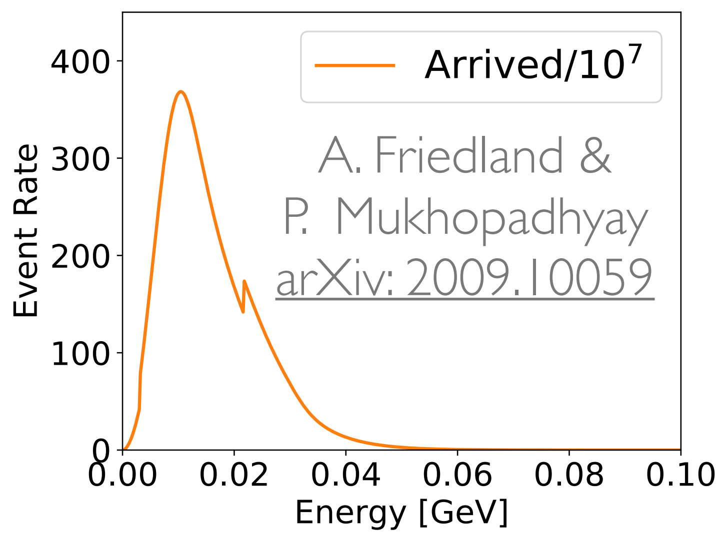
$<E_\nu>$: average E_ν

$N \propto \nu$ luminosity, ε

α: pinching parameter



SN Neutrino Detection



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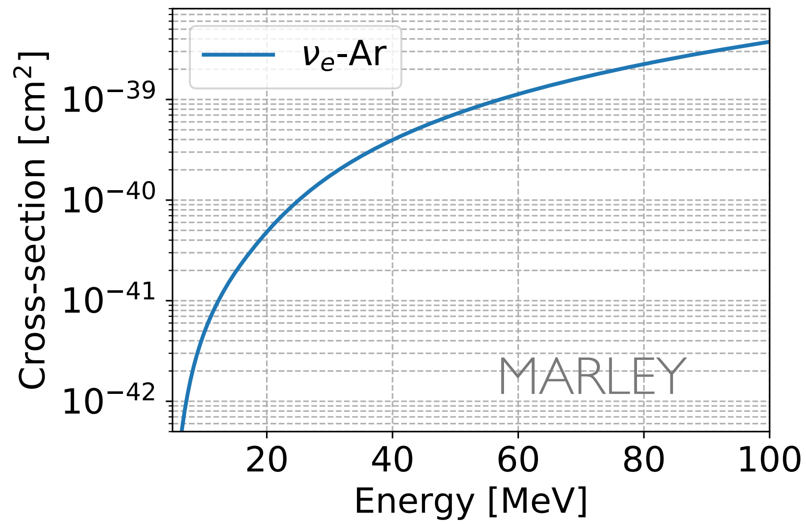

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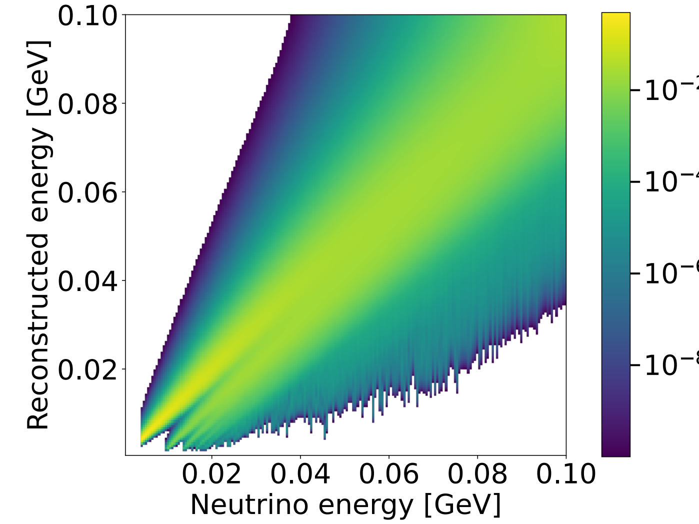
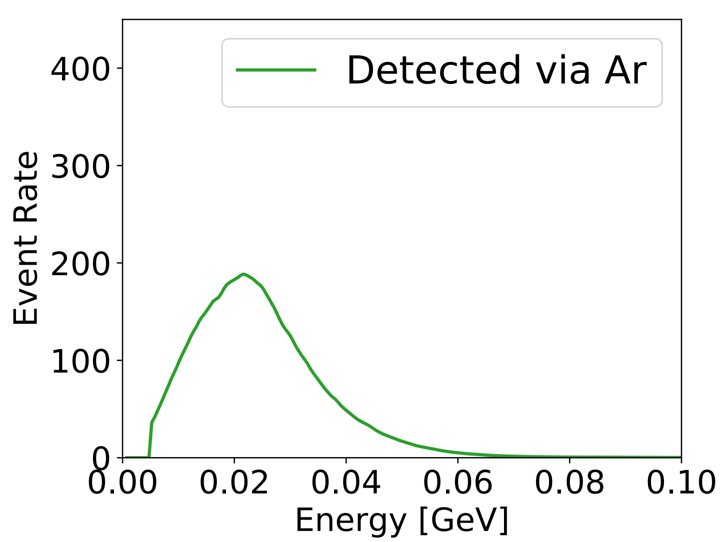
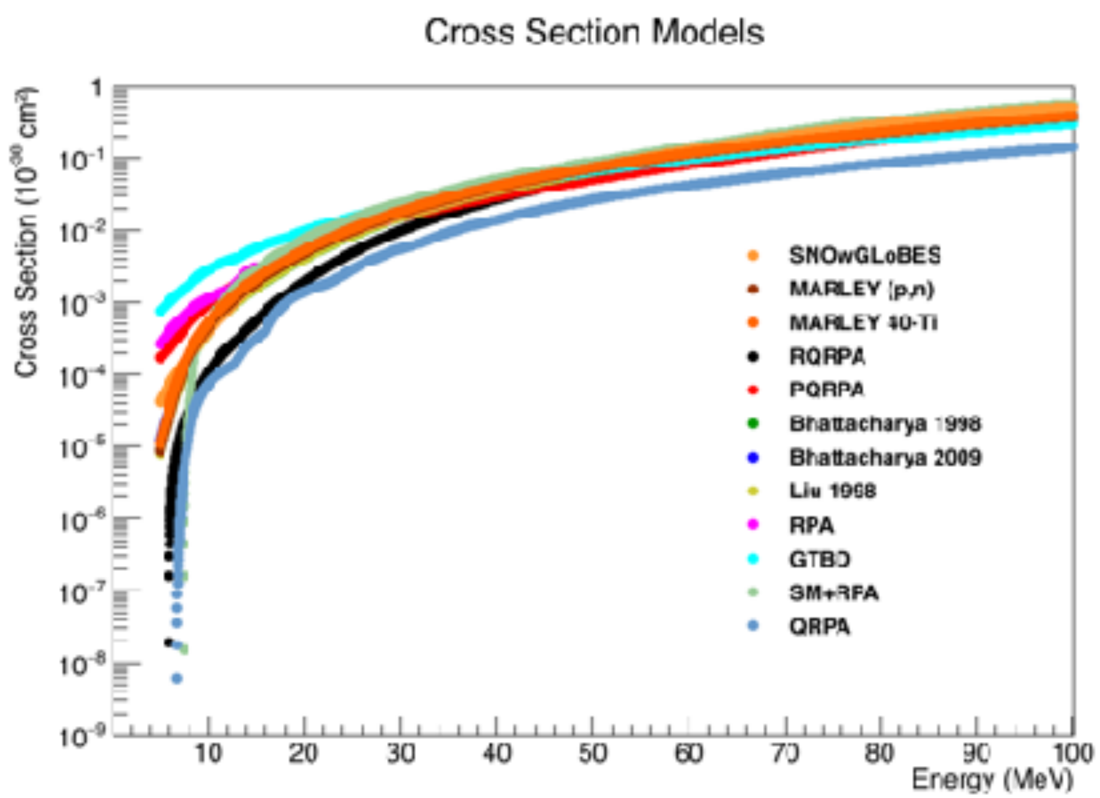


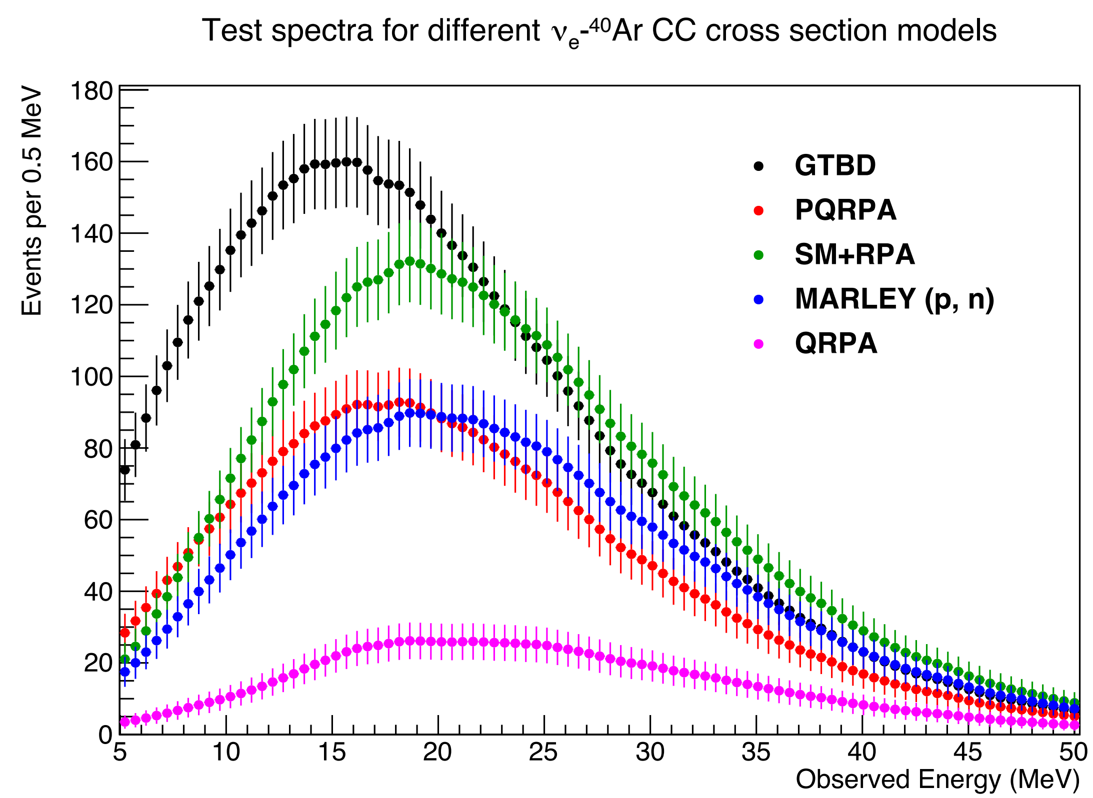


- Detect convolved ν flux and interaction cross sections
- Disentangled ν fluxes are desired
- These ν_e-Ar CC cross sections have never been measured
    - Uncertainties from cross section models are relevant

Impact from ν_e-Ar σ

- ν_e-Ar charged-current (CC) interaction cross section with E_ν<100 MeV has never been measured
  - Theoretical models vary > O(10%)
- Highly significant impacts on DUNE SN ν measurements, particularly on ε, biased from -94% to +1400% in extreme scenarios (PRD 107, 112012 (2023))



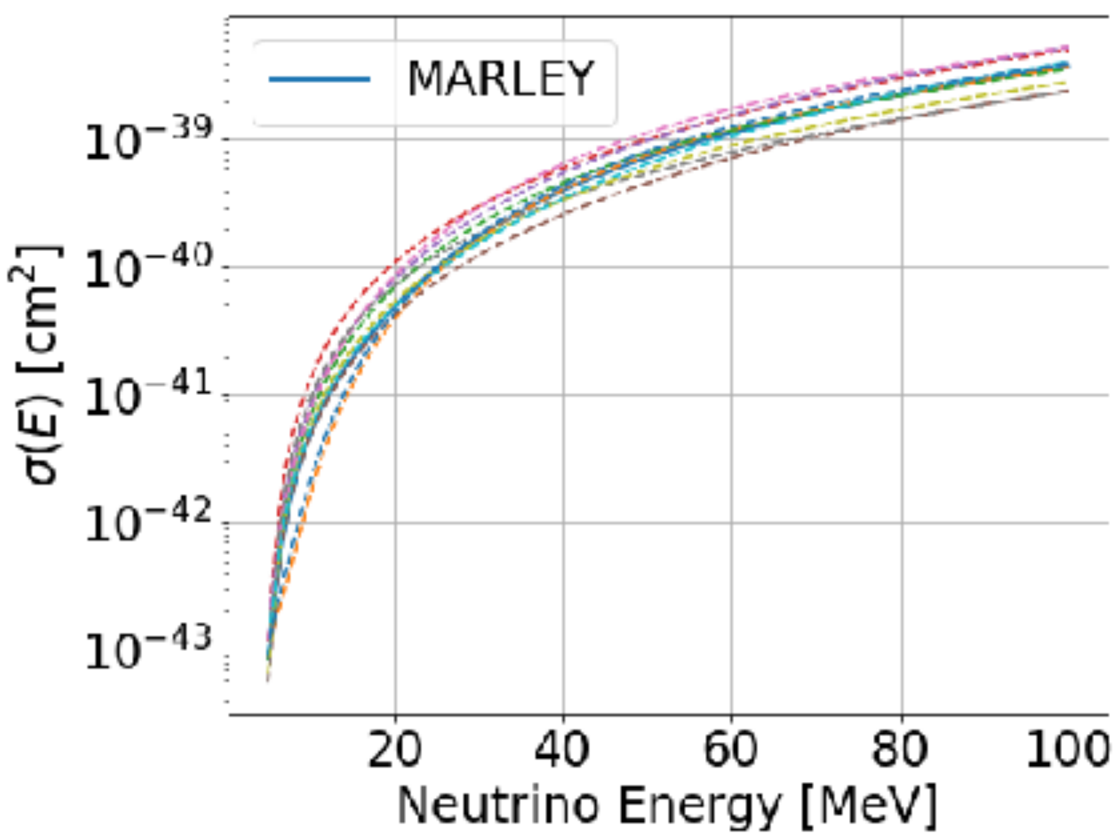


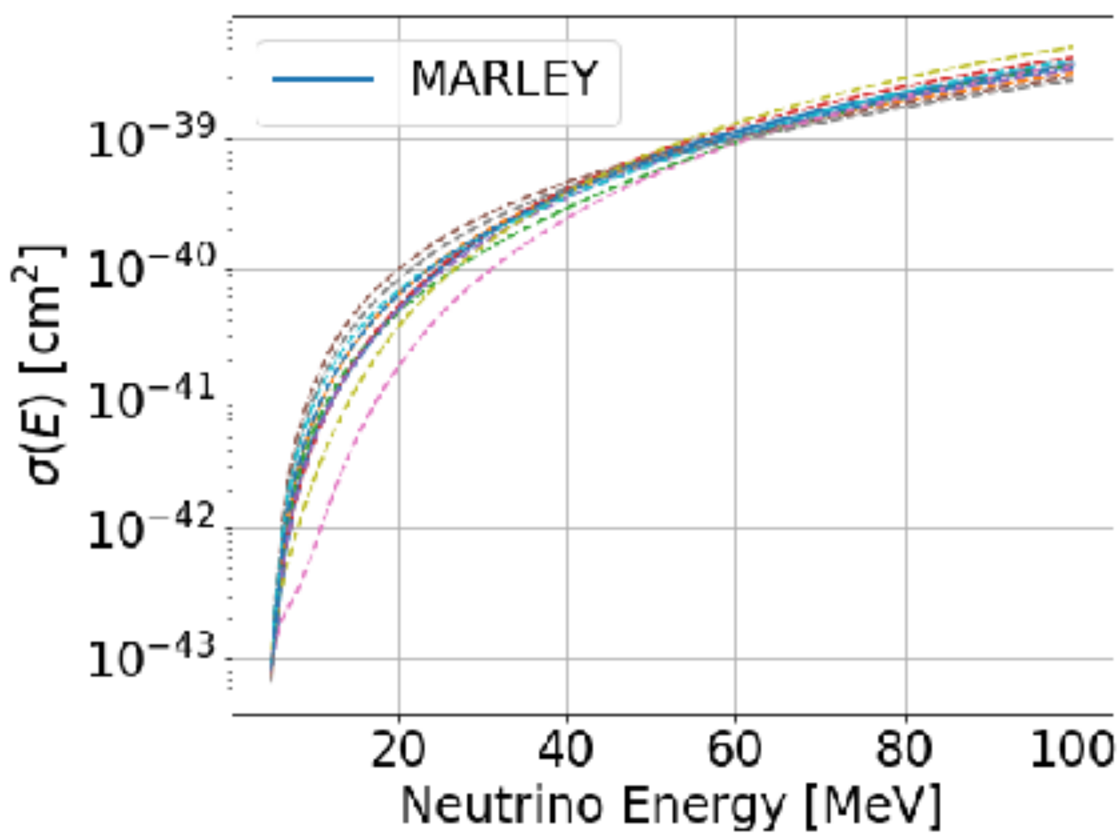
SNeND: Supernova Neutrino Near Detector

In collaboration with Gianluca Petrillo (SLAC), Yen-Hsun Lin (NCTS)

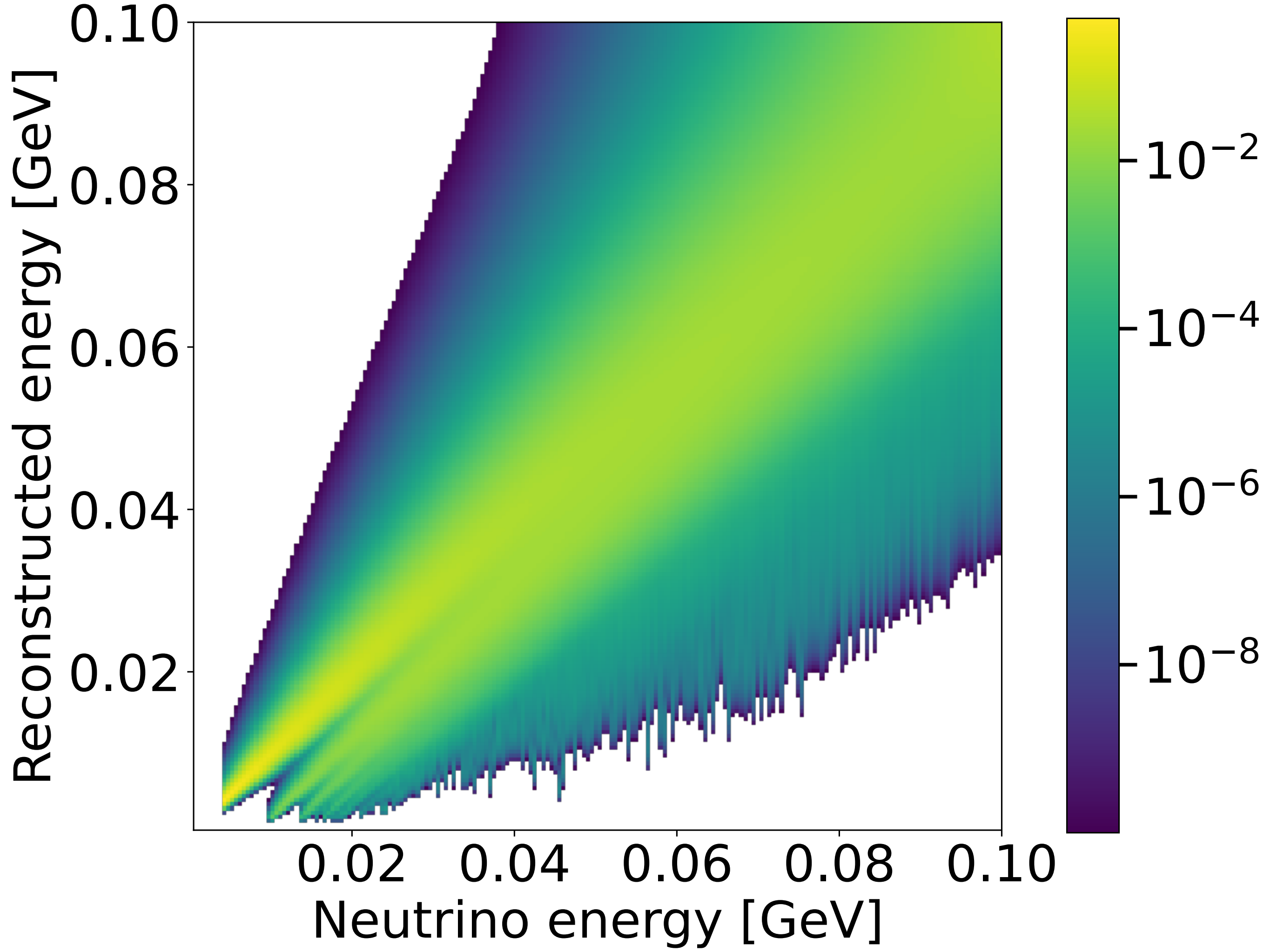
Uncertainty on ν_e-Ar CC σ

If we measure the total σ and σ(45 MeV) at the precision of 20%, as suggested by PRD 107, 112012 (2023)





Detector Resolution



Visible energy with the 10% resolution

Detection threshold: E_ν > 5 MeV

Identical to PRD 107, 112012 (2023)

Not relevant to SN ν measurements as long as the resolution is well characterized

Parameter Space

ν_e parameters only. Same as PRD 107, 112012 (2023), JCAP11(2017)036, JCAP04(2018)040.

Parameter	ε [10^{53} erg]	$\langle E_\nu \rangle$ [MeV]	α
True Value	0.5	9.5	2.5
Tested Range	[0.2, 1]	[5, 30]	[0.1, 7]
Step	0.025	0.1	0.1

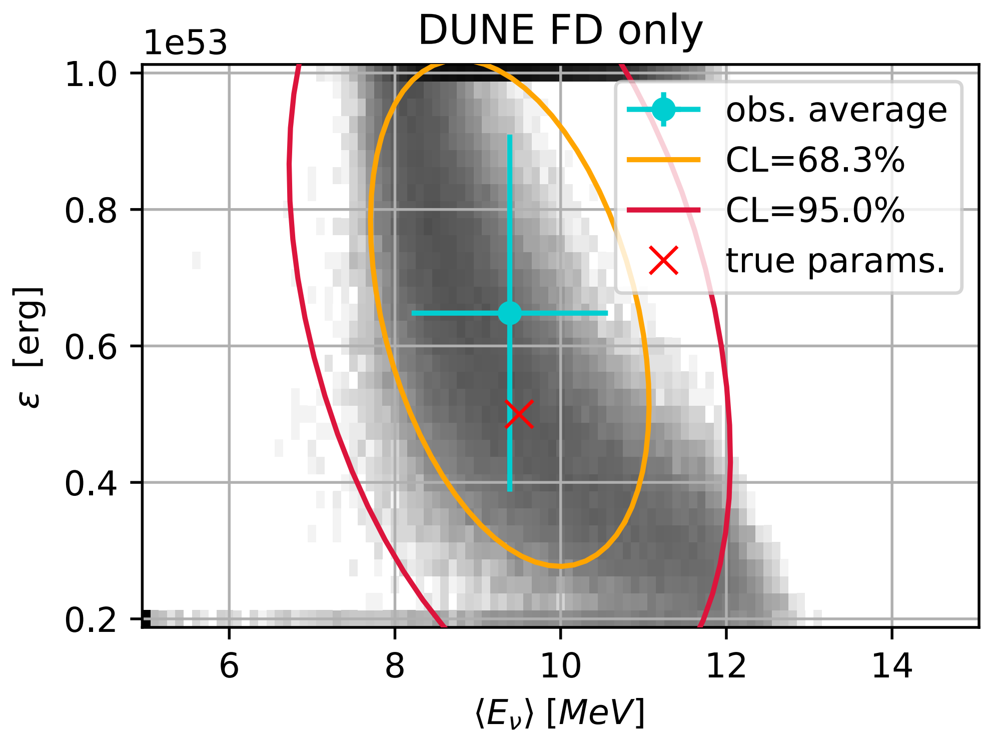
Observed Events

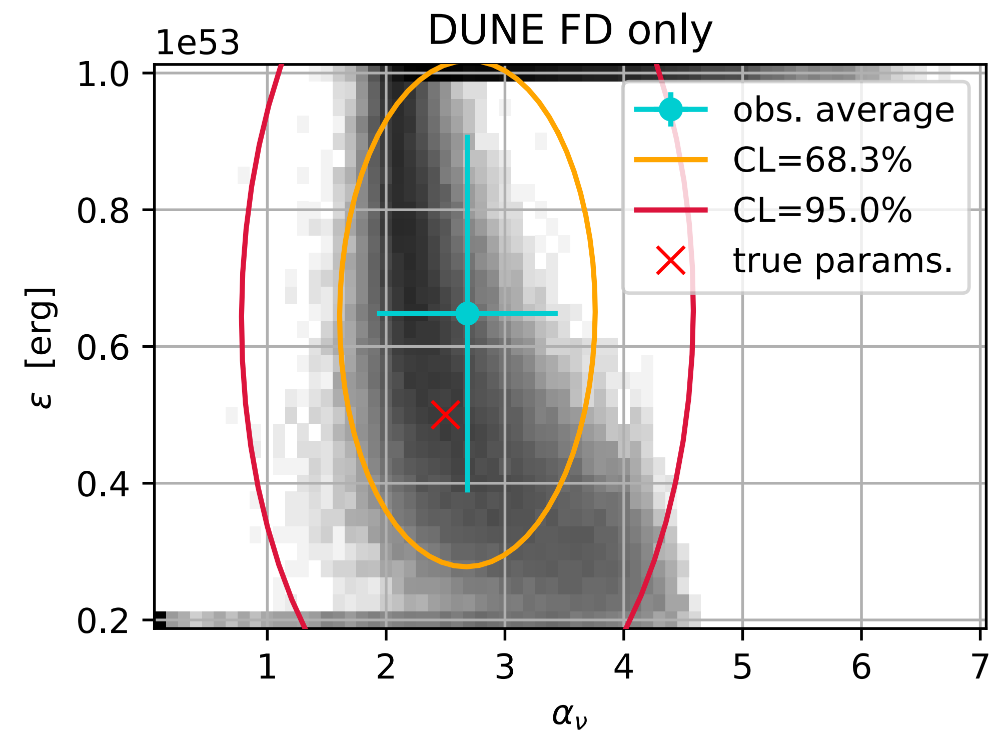
Observed events, N, in each E_ν bin, $E_{\nu,j}$,

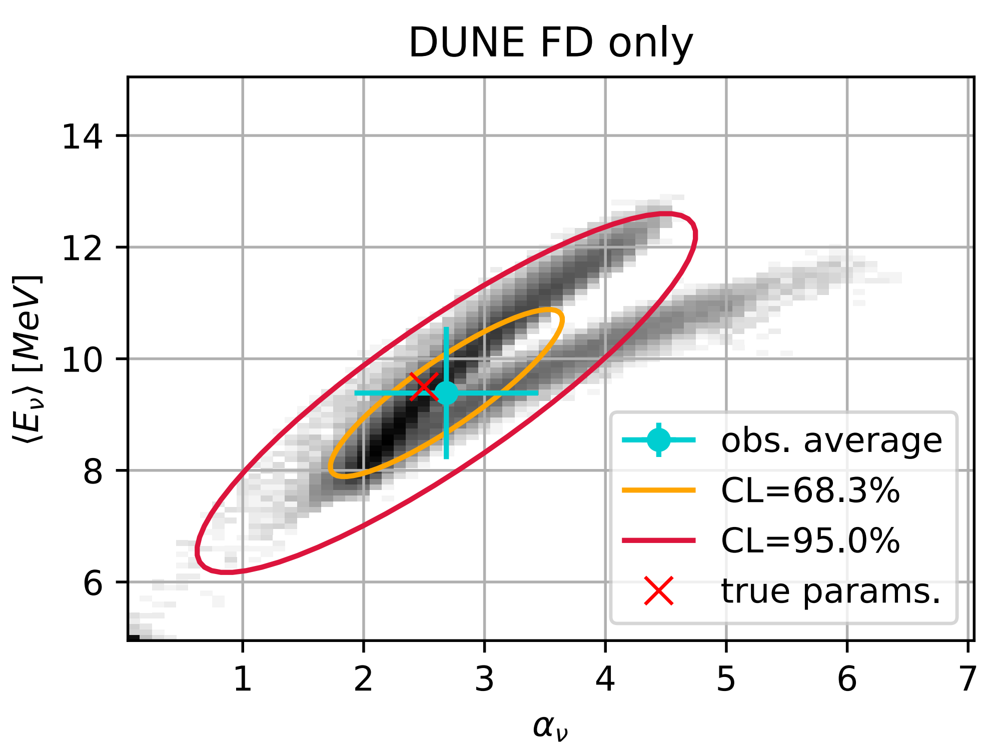
$$N(E_{\nu,j}) = \sum_k \phi_{\mathrm{SN}}(E_{\nu,k}) \times \sigma(E_{\nu,k}) \times R_{j,\mathrm{DUNE}}(E_{\nu,k})$$

- ϕ_{SN} = Supernova Neutrino flux, assuming normal mass ordering
- R_{DUNE} = DUNE detector resolution
- Fit the supernova neutrino flux parameters, $\langle E_\nu \rangle$, ε, α, by maximizing Poisson binned likelihood

SN ν_e Flux Parameters







100k pseudo-experiments, each with a pseudo-σ model

Normal mass ordering

Log scale in the grey scale

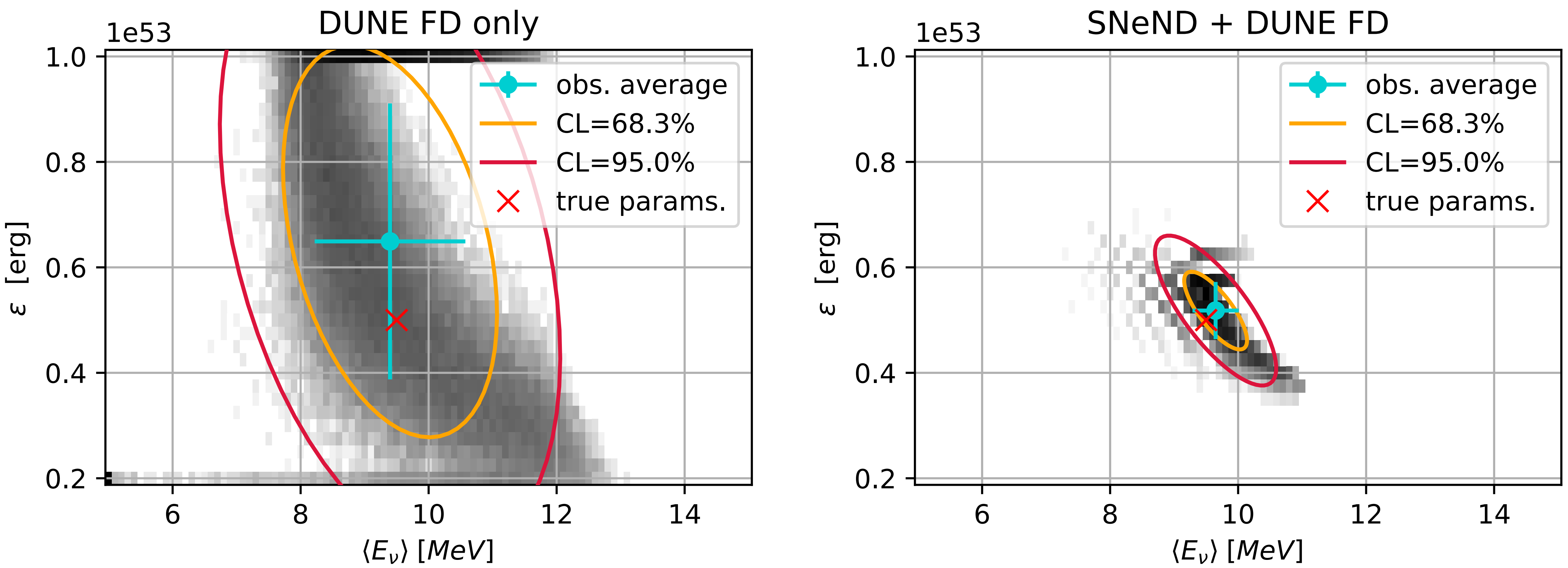
SNeND Constraint

Measure the ratio, ρ, of the numbers of the observed events in DUNE and SNeND in each E_ν bin

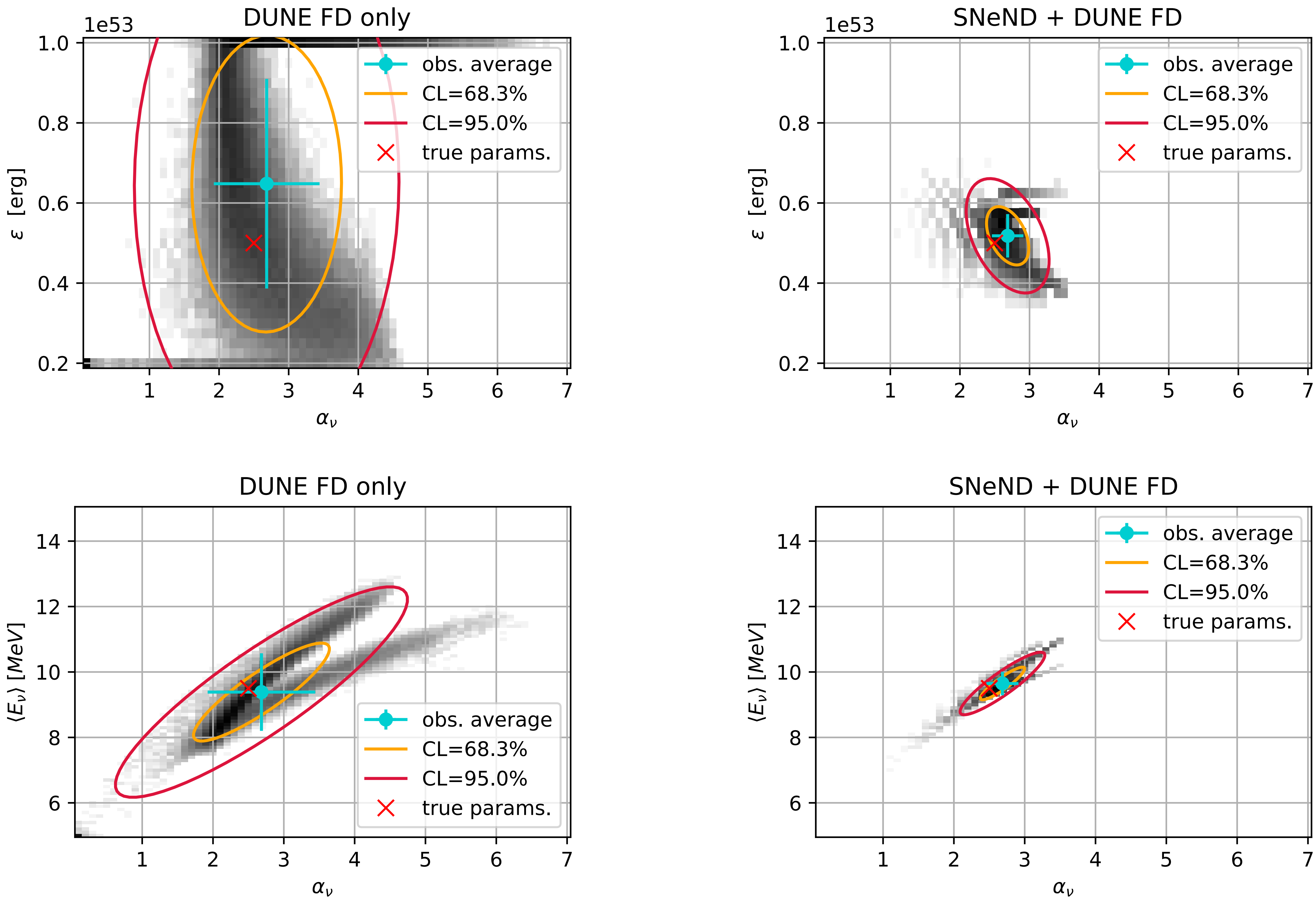
$$\rho(E_{\nu,j}) = \frac{\sum_k \phi_{\mathrm{SN}}(E_{\nu,k}) \times \sigma(E_{\nu,k}) \times R_{j,\mathrm{DUNE}}(E_{\nu,k})}{\sum_k \phi_{\mathrm{SNeND}}(E_{\nu,k}) \times \sigma(E_{\nu,k}) \times R_{j,\mathrm{SNeND}}(E_{\nu,k})}$$

- ϕ_{SNeND} = A well-controlled neutrino flux
- R_{SNeND} = The LArTPC "near detector," with the resolution identical to DUNE in this scenario
- Fit the supernova neutrino flux parameters, <E_ν>, ε, α, by maximizing Poisson binned likelihood

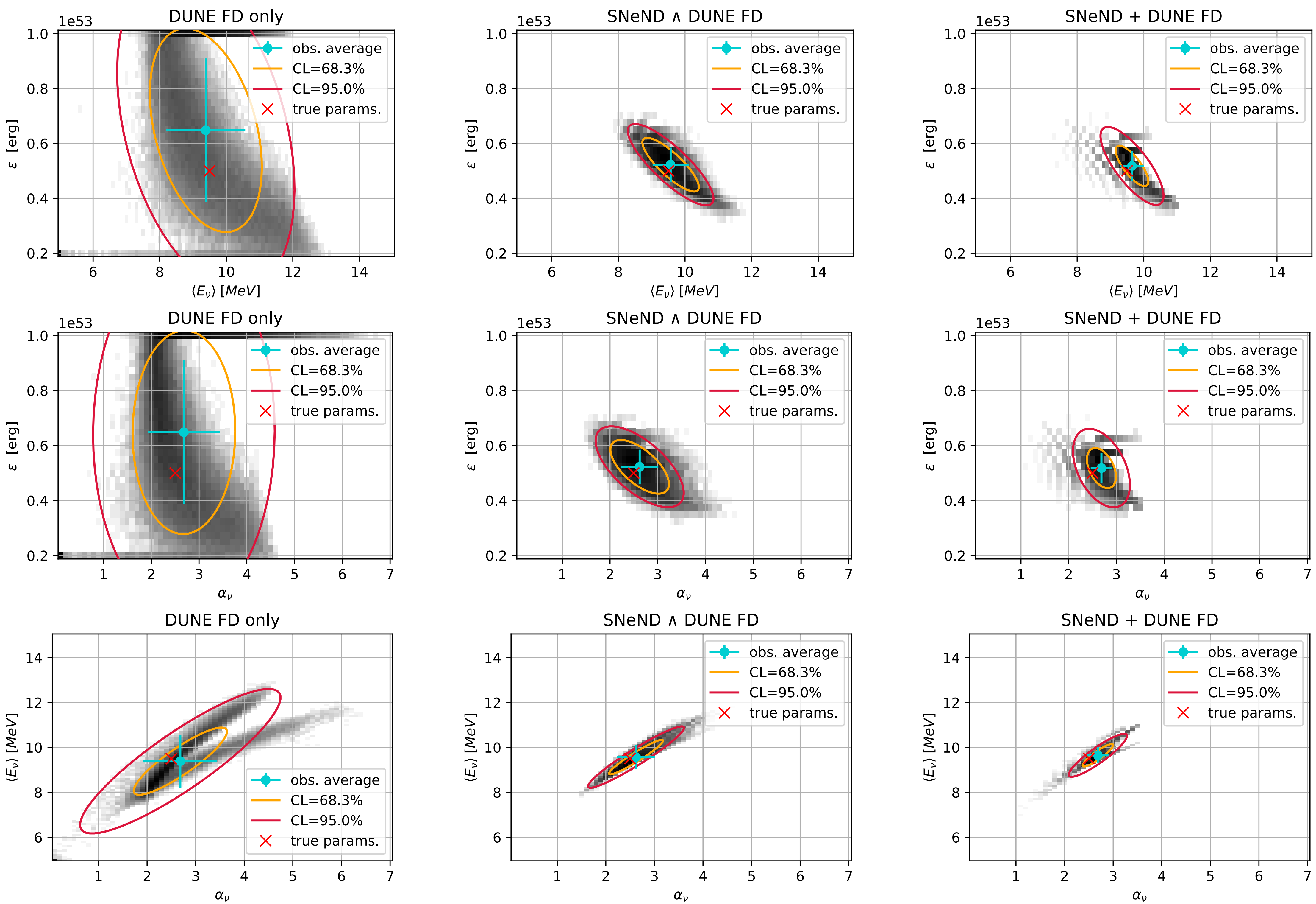
With SNeND Constraints



Improvement by SNeND



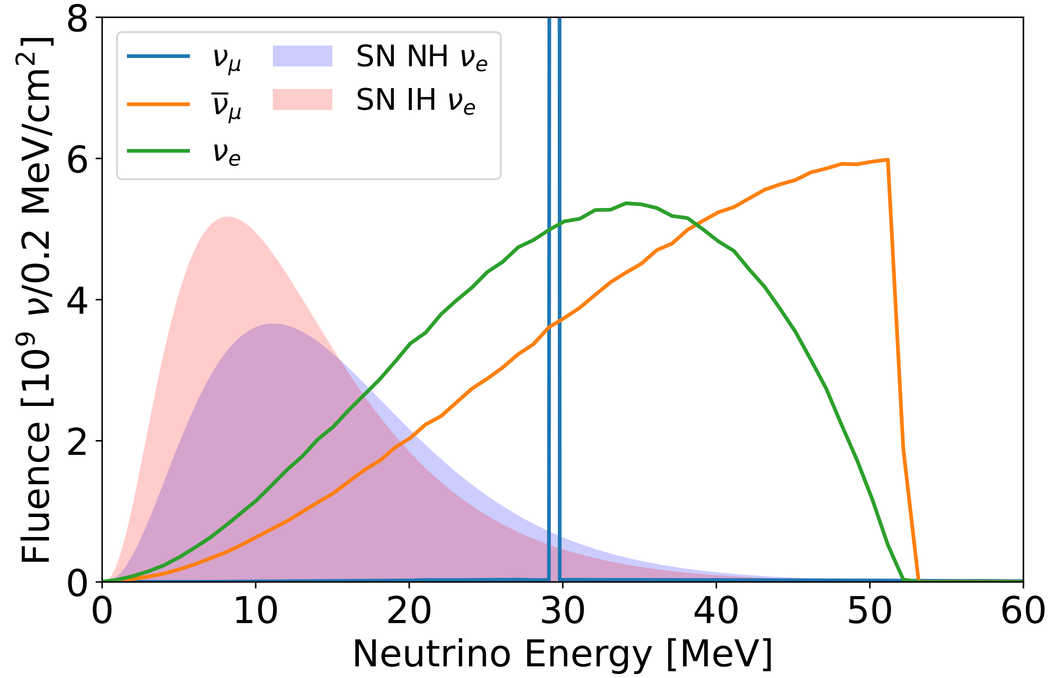
20% Uncertainty on σ

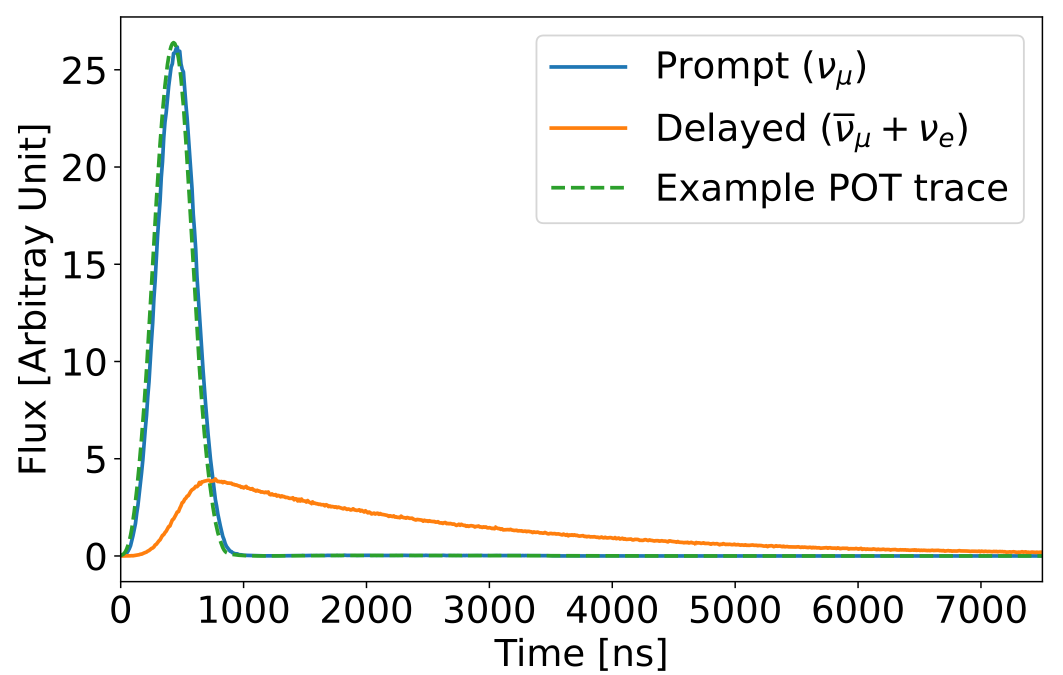


Spallation Neutron Source & COHERENT

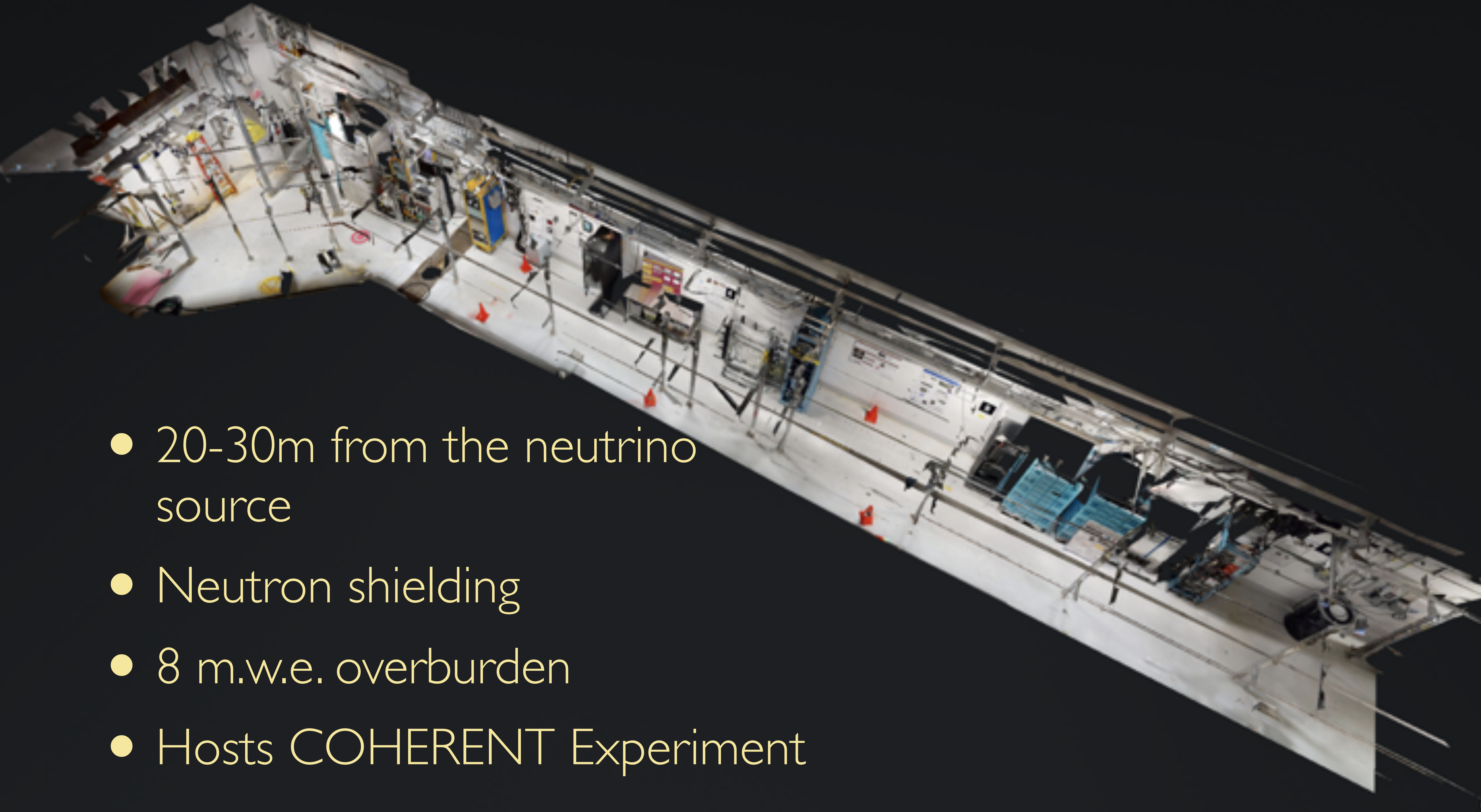
Measure ν_e-Ar CC σ@SNS

- Neutrinos produced from π^+ decay at rest, $E_\nu \sim O(10\text{MeV})$
  $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow (e^+\nu_e\overline{\nu}_\mu)\nu_\mu$
- H^- LINAC: 1GeV @1.4MW, 60 Hz; mostly pions
  - Will be upgraded 2024!
- Liquid mercury target
  - Minimize pions decay-in-flight
- Operate ~5000 hours/year
- $2.81\times10^{14}\nu/\text{cm}^2$/flavor/year @ 20m





First Target Station

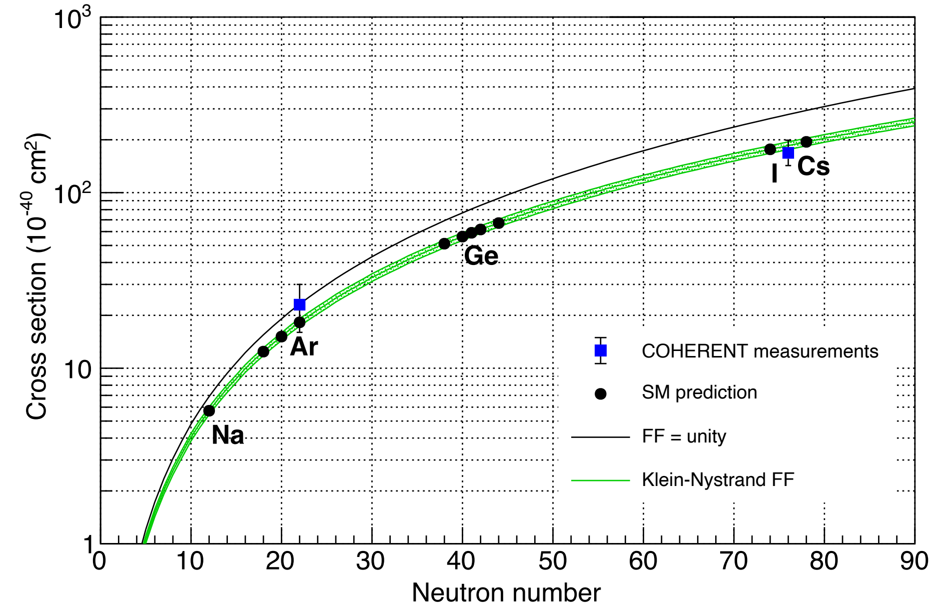


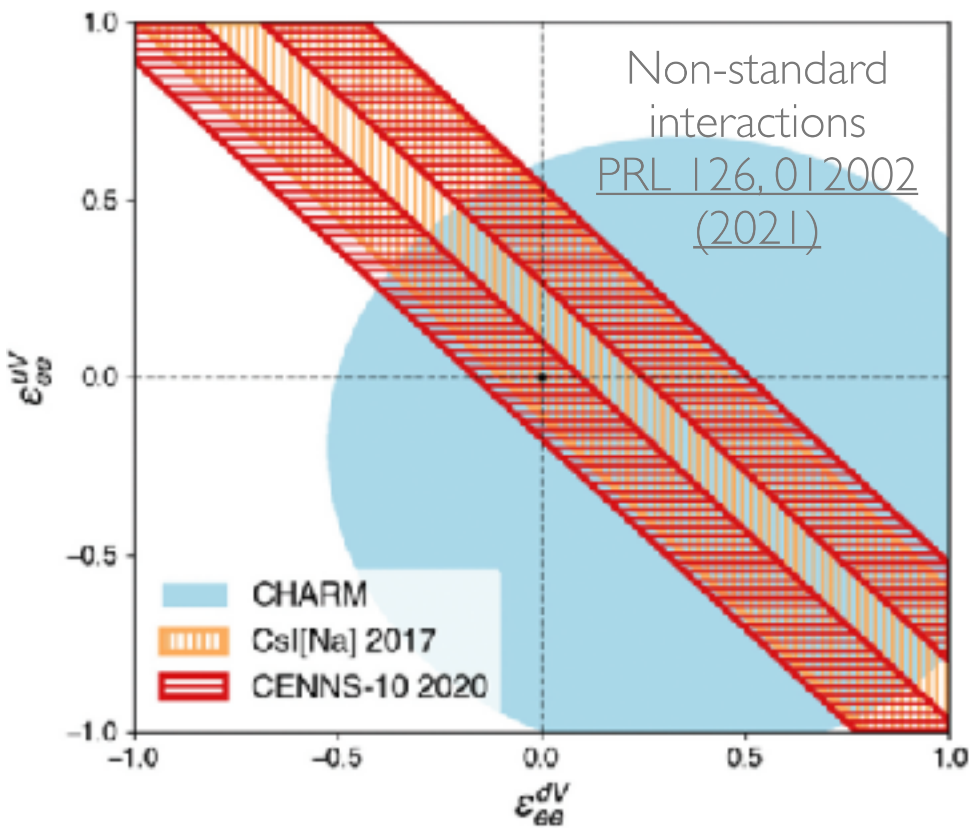
- 20-30m from the neutrino source
- Neutron shielding
- 8 m.w.e. overburden
- Hosts COHERENT Experiment

COHERENT

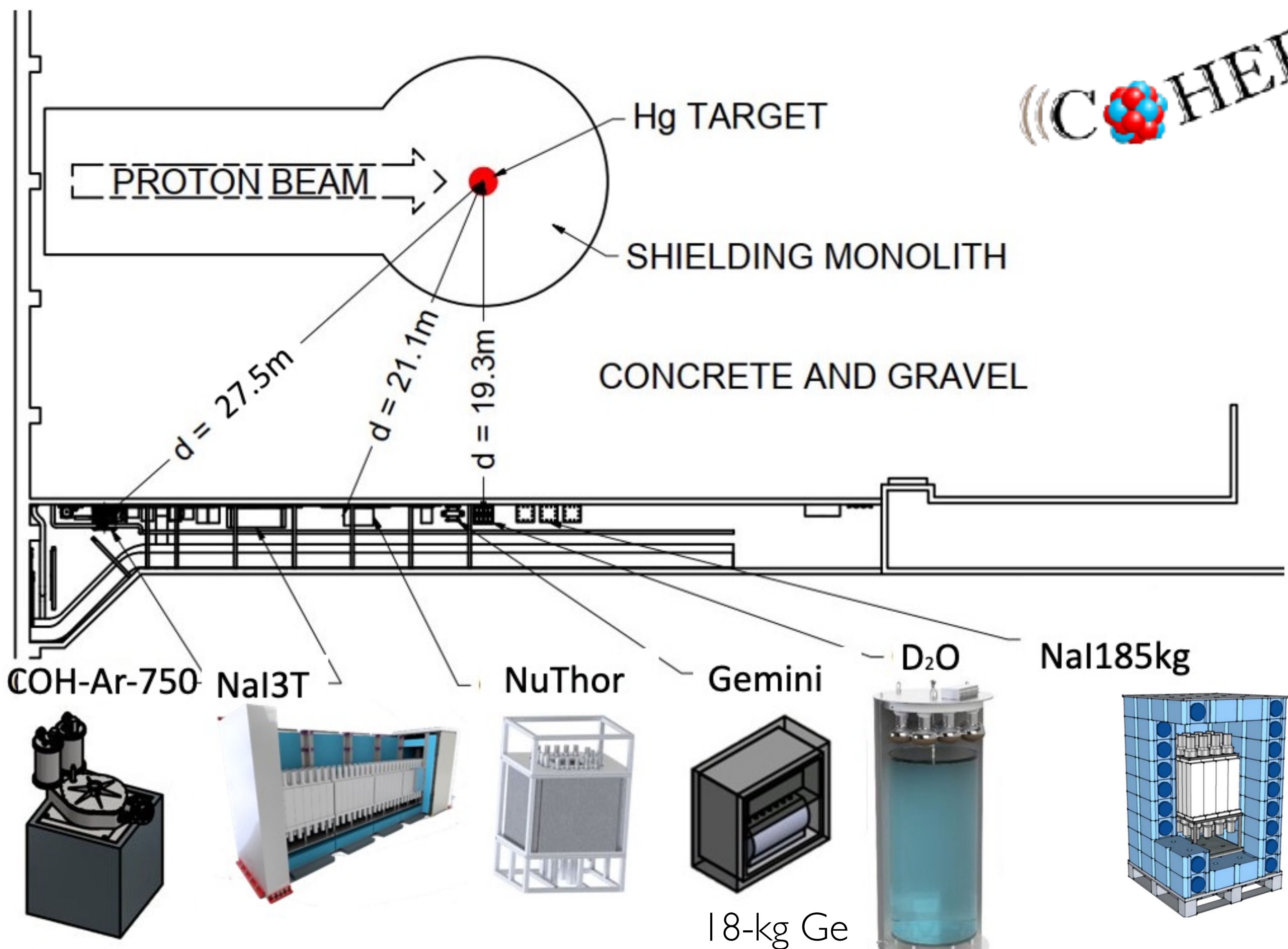
- Discovered the Coherent Elastic ν-Nucleus Scattering (CEvNS) in 2017
- Measure CEvNS (keV) and inelastic (MeV) scatterings
- Probe SM and BSM physics with the CEvNS cross sections
- Short baseline neutrino oscillation (L/E~1m/MeV)
- Search for exotic particles, e.g. dark matter & axion-like particles
- Inelastic scatterings: relevant to supernova ν measurements

CEvNS Measurements





Current Detectors



750-kg LAr scintillation detector Under construction

2425-kg NaI Being deployed

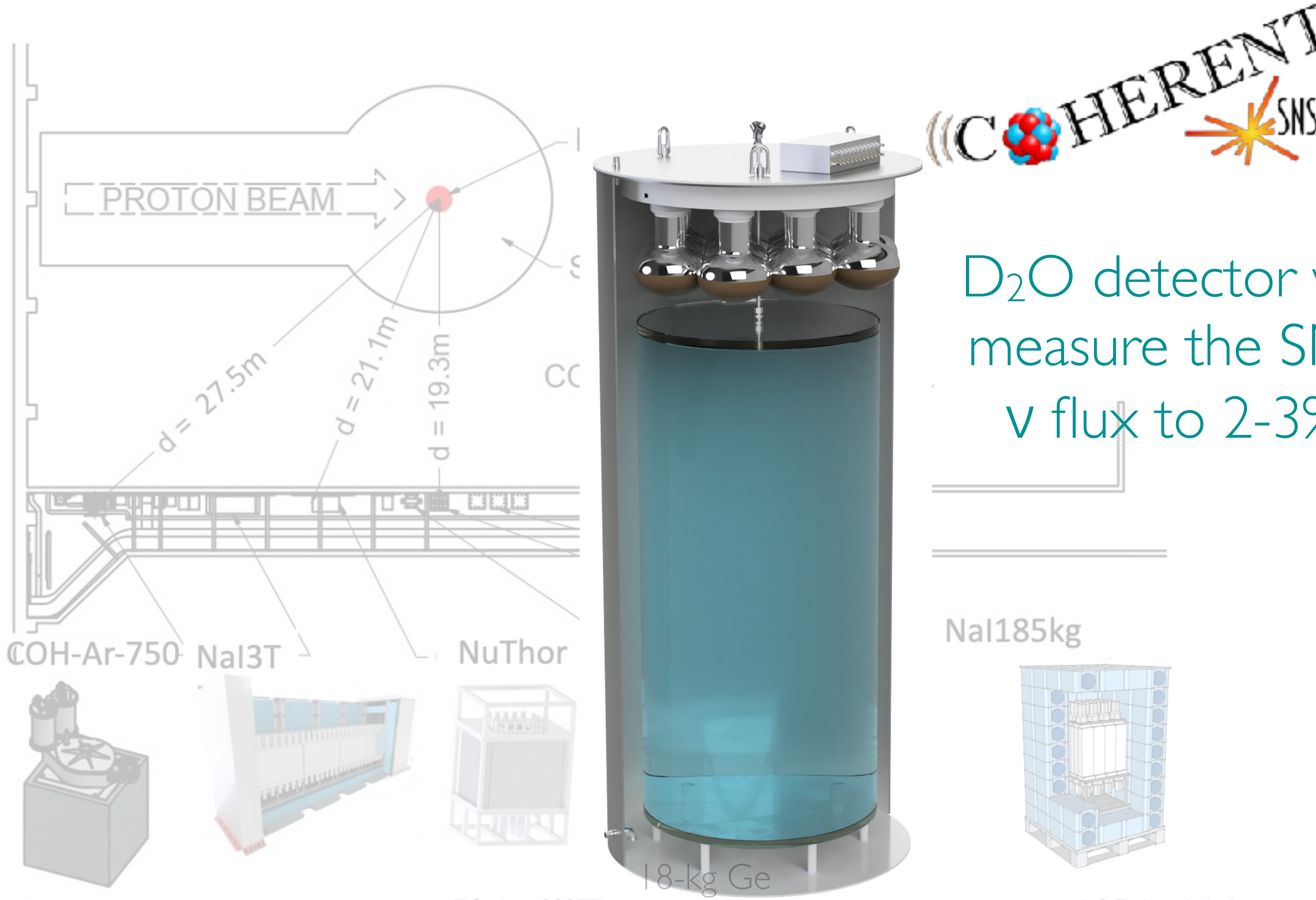
52-kg ^{232}Th ν_e-Th CC Since 2022

18-kg Ge Since 2022

2x592-kg D_2O Module 1 in commissioning

185-kg NaI ν_e-I CC Since 2016

Current Detectors



D$_2$O detector will measure the SNS ν flux to 2-3%

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2425-kg NaI Being deployed

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18-kg Ge Since 2022

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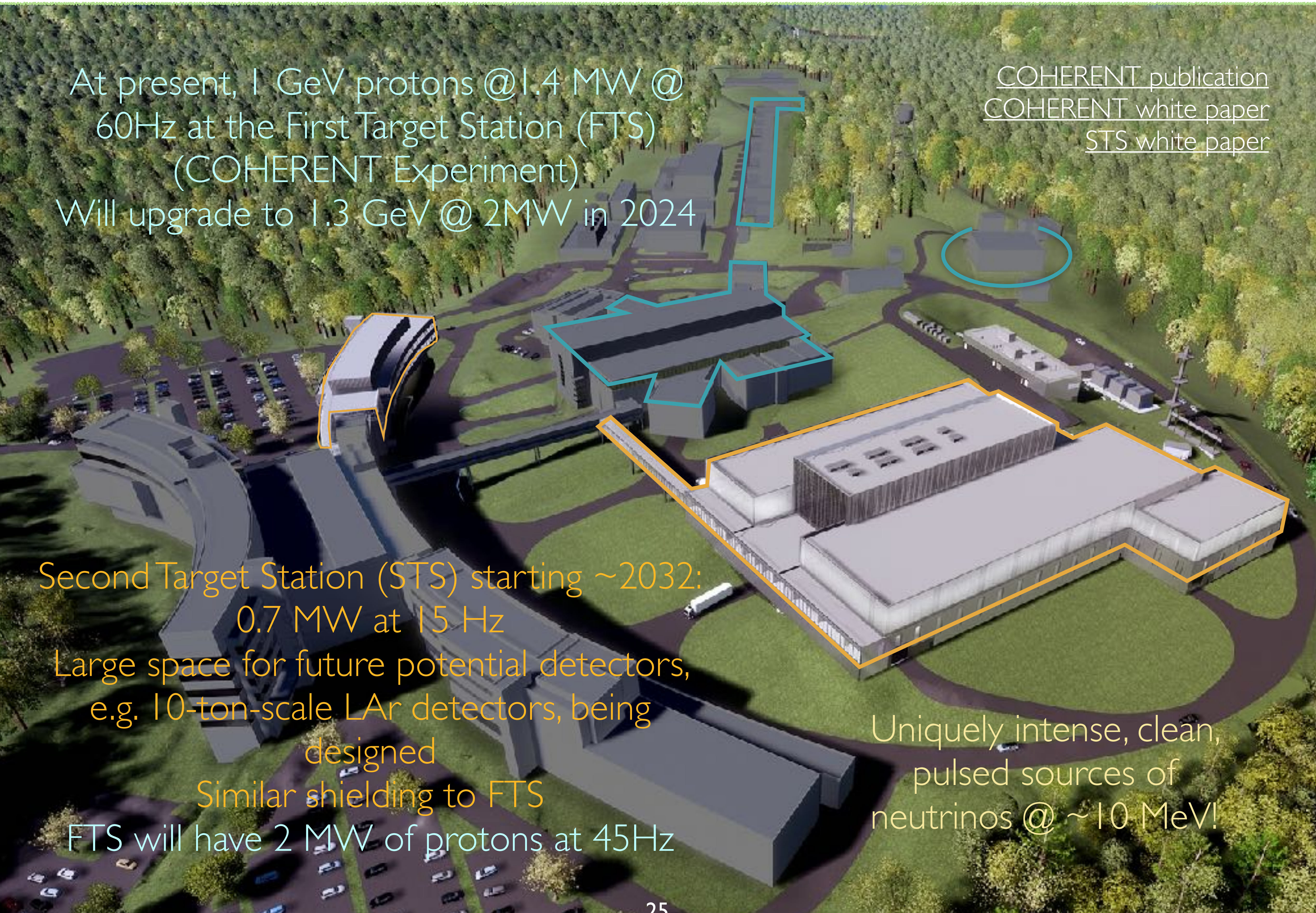

At present, 1 GeV protons @1.4 MW @
60Hz at the First Target Station (FTS)
(COHERENT Experiment)
Will upgrade to 1.3 GeV @ 2MW in 2024
COHERENT publication
COHERENT white paper
STS white paper
Second Target Station (STS) starting ~2032:
0.7 MW at 15 Hz
Large space for future potential detectors,
e.g. 10-ton-scale LAr detectors, being
designed
Similar shielding to FTS
FTS will have 2 MW of protons at 45Hz
Uniquely intense, clean,
pulsed sources of
neutrinos @ ~10 MeV!

Proposing a LArTPC detector in the COHERENT experiment to conduct SNeND measurements

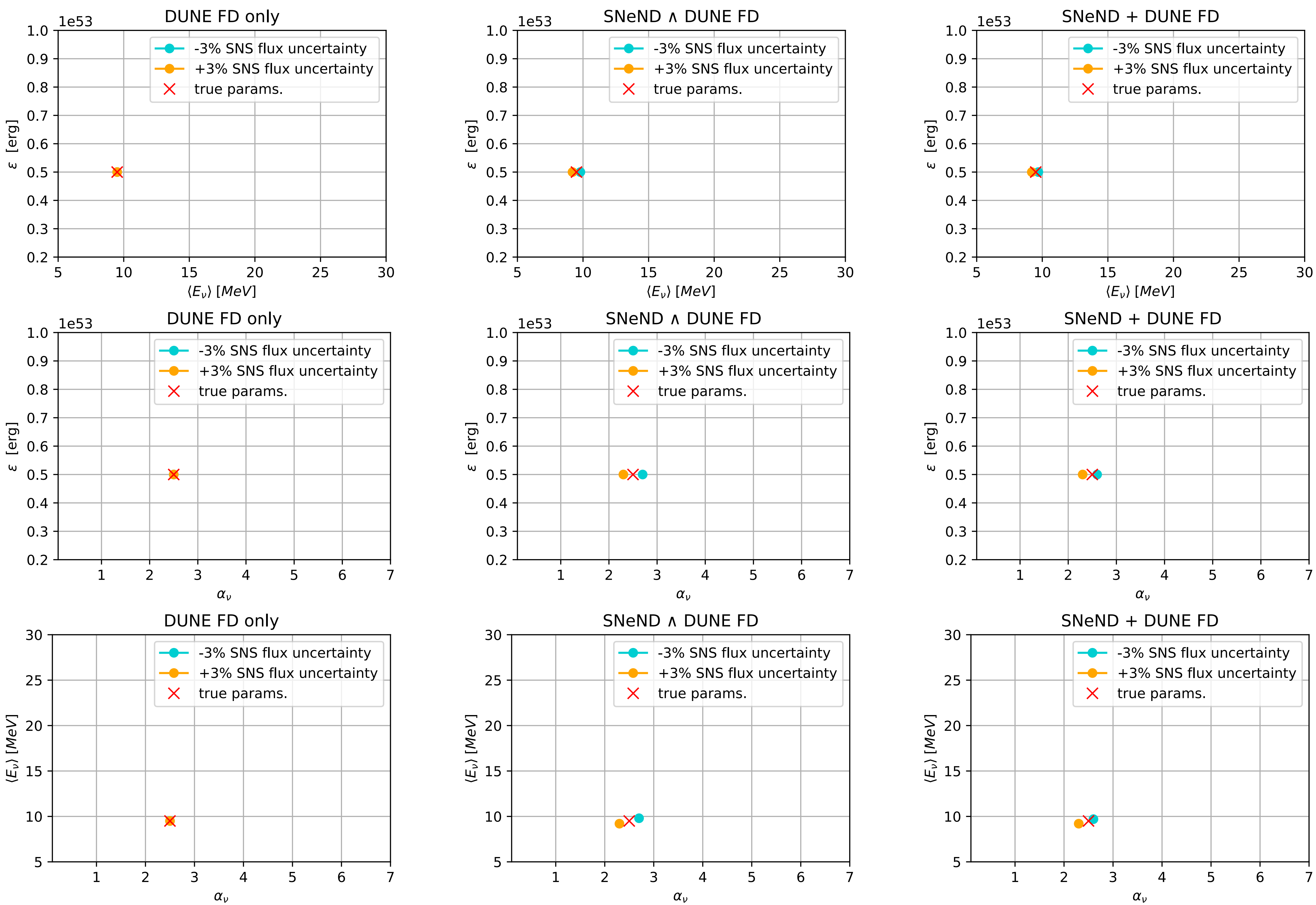
Proposing a LArTPC detector in the COHERENT experiment to conduct SNeND measurements

$$\rho(E_{\nu,j}) = \frac{\sum_k \phi_{\rm SN}(E_{\nu,k}) \times \sigma(E_{\nu,k}) \times R_{j,\rm DUNE}(E_{\nu,k})}{\sum_k \cancel{\phi_{\rm SNeND}}(E_{\nu,k}) \times \sigma(E_{\nu,k}) \times R_{j,\cancel{\rm SNeND}}(E_{\nu,k})}$$

ϕ_{SNS} at 2-3% precision

COHERENT-LArTPC

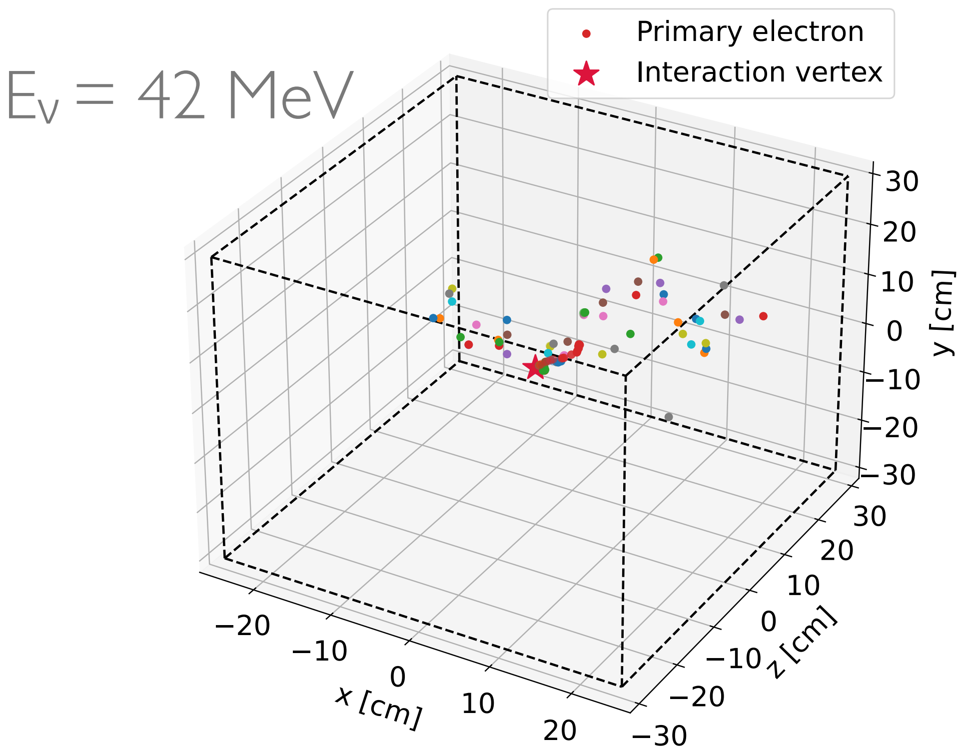
3% Uncertainty on SNS Flux

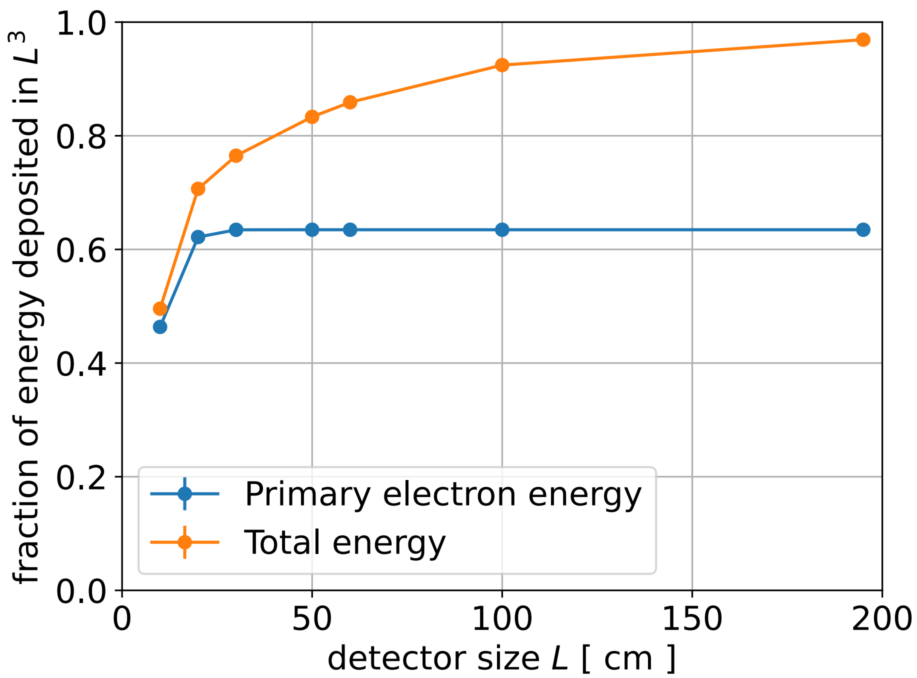


3% Uncertainty on SNS Flux

- 9017 events observed with the nominal SNS flux
- Uncertainty on the overall scale, not on shape
- The grid in ε is too coarse (5%) to accurately fit the bias from the 3% SNS flux shift
  - Fit with finer grid in progress
- The impact from the 3% SNS flux uncertainty is not relevant compared to that from the cross section uncertainty

Proposed LArTPC





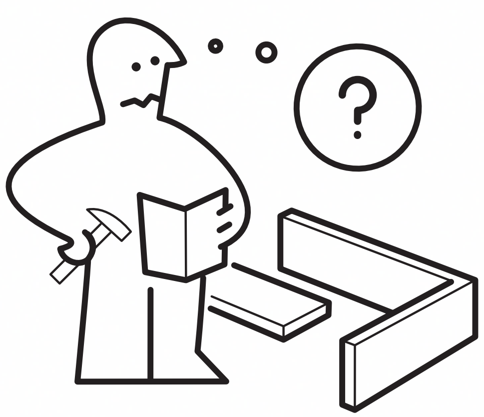
- 50x60x60cm^3, 250 kg Ar in the active volume
- Pixelated charge readout (LArPix): direct 3D information and much less signal processing
- 30cm drift distance: 2 TPCs
- Expected main background: Cosmic rays
- Upgrade opportunities
  - Muon veto & shielding
  - Pixelated charge readout
  - Light detector, etc.

LArTPC Dimension

- Assume proton beams 1.3 GeV at 2 MW, operating 5000 hours per year (SNS upgrade configuration)
- 50x60x60cm^3, 250 kg LAr in the active volume, 27.5m from the Hg target
- Cross section calculation from MARLEY

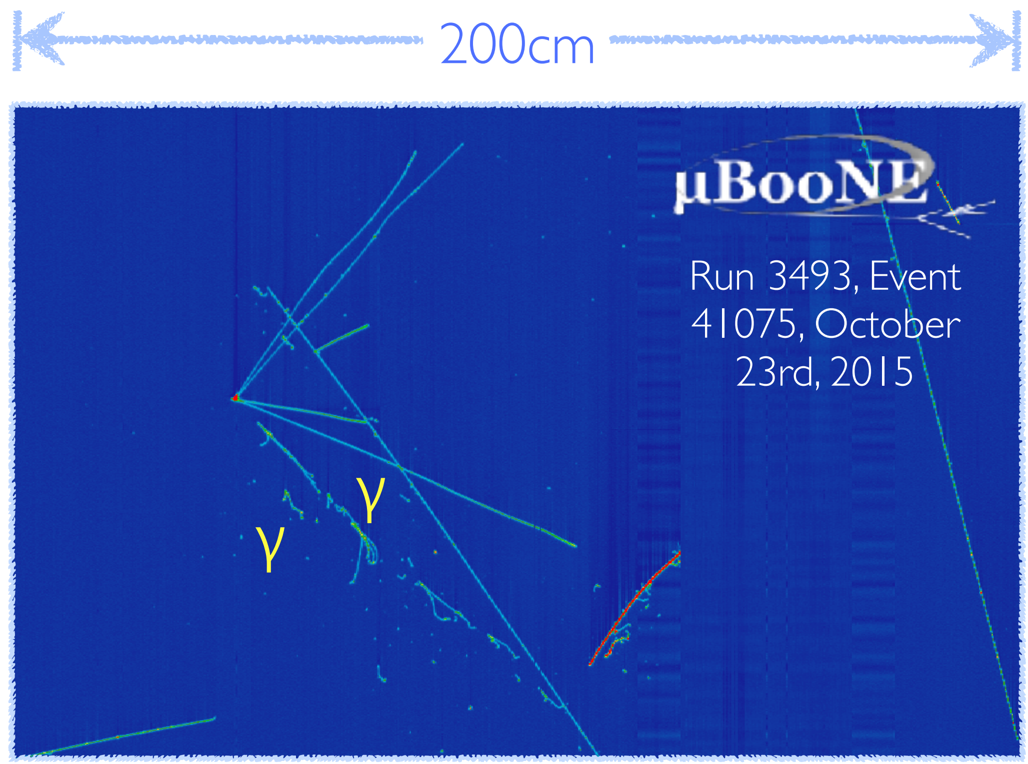
	Dimension (cm)	Ar Mass (kg)	Est. ν_e-Ar CC per year
Fiducial	30x40x40	66.72	55.9
Partly Contained	40x50x50 -30x40x40	72.28	60.6

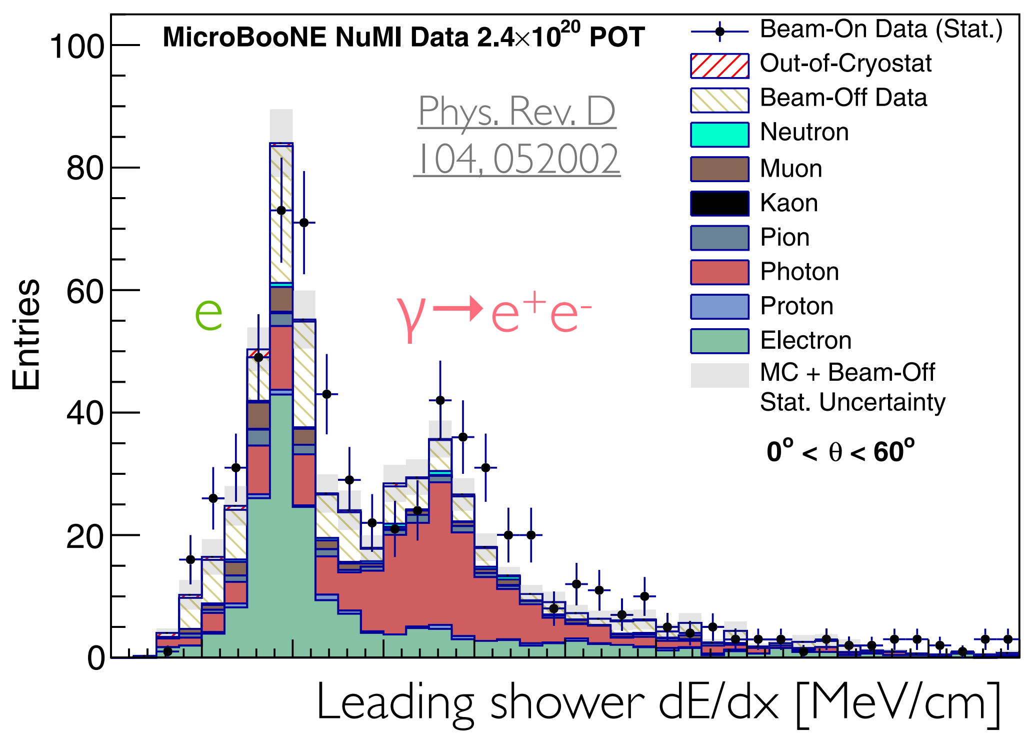
LArTPC DIY at SLAC



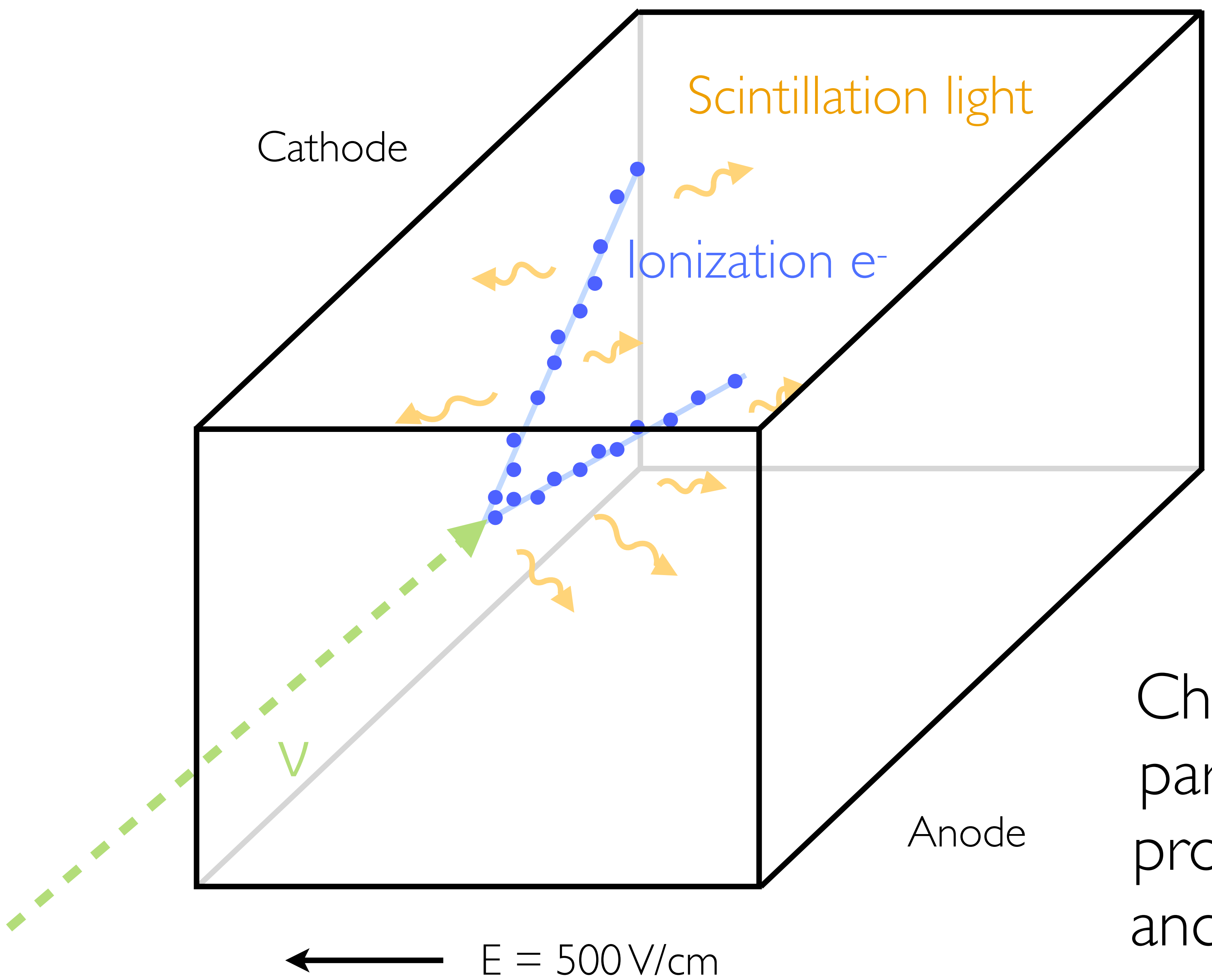
Why LArTPC?

- LAr: large interaction rate
- Modular and scalable
- Nearly fully instrumented
- Millimeter resolution
- Calorimetric measurement
  - e/γ separation
- Low detection threshold for protons
- Supernova ν_e (E~10 MeV)
- Potential for new physics





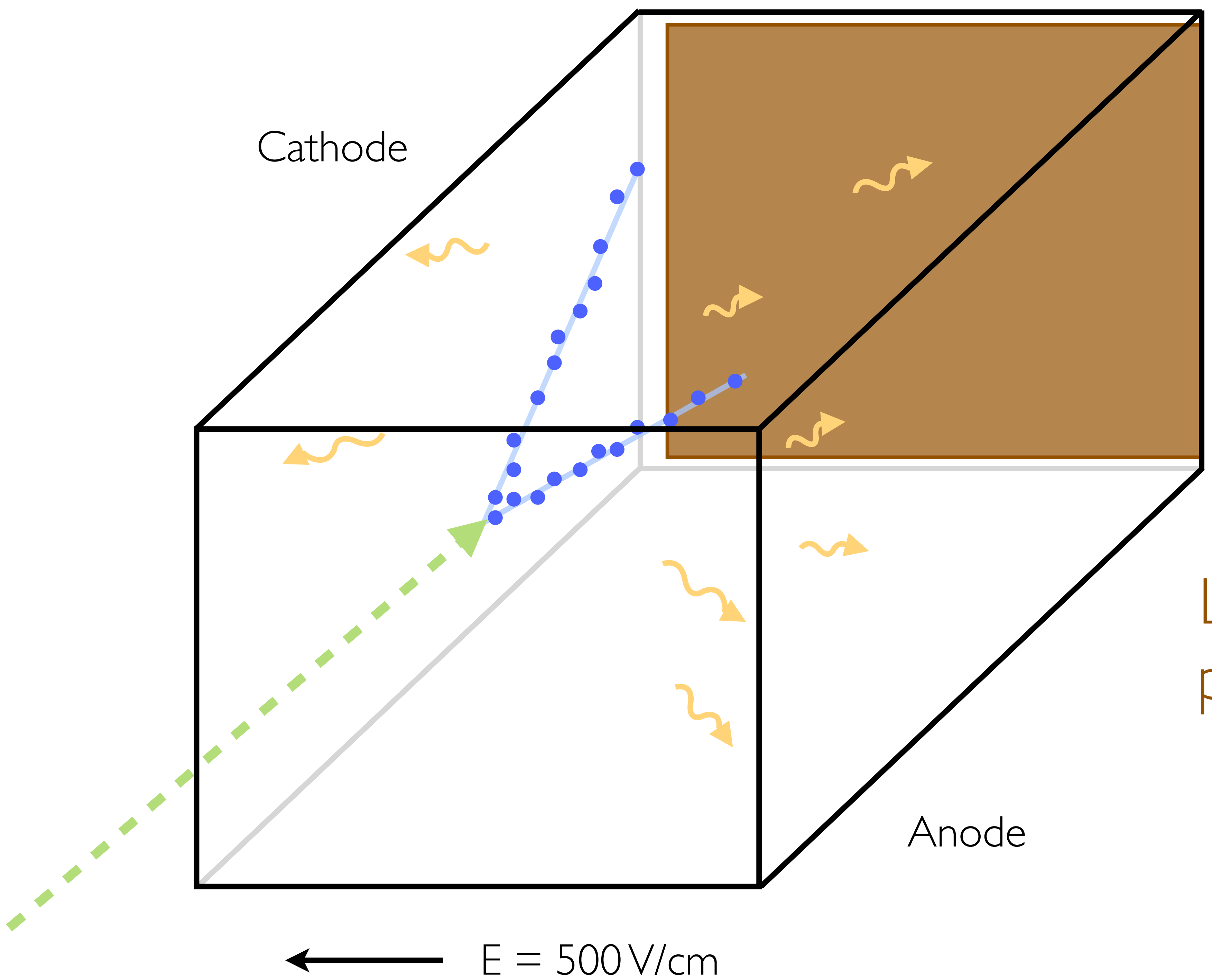
LArTPC



Incoming neutrino interacting with LAr

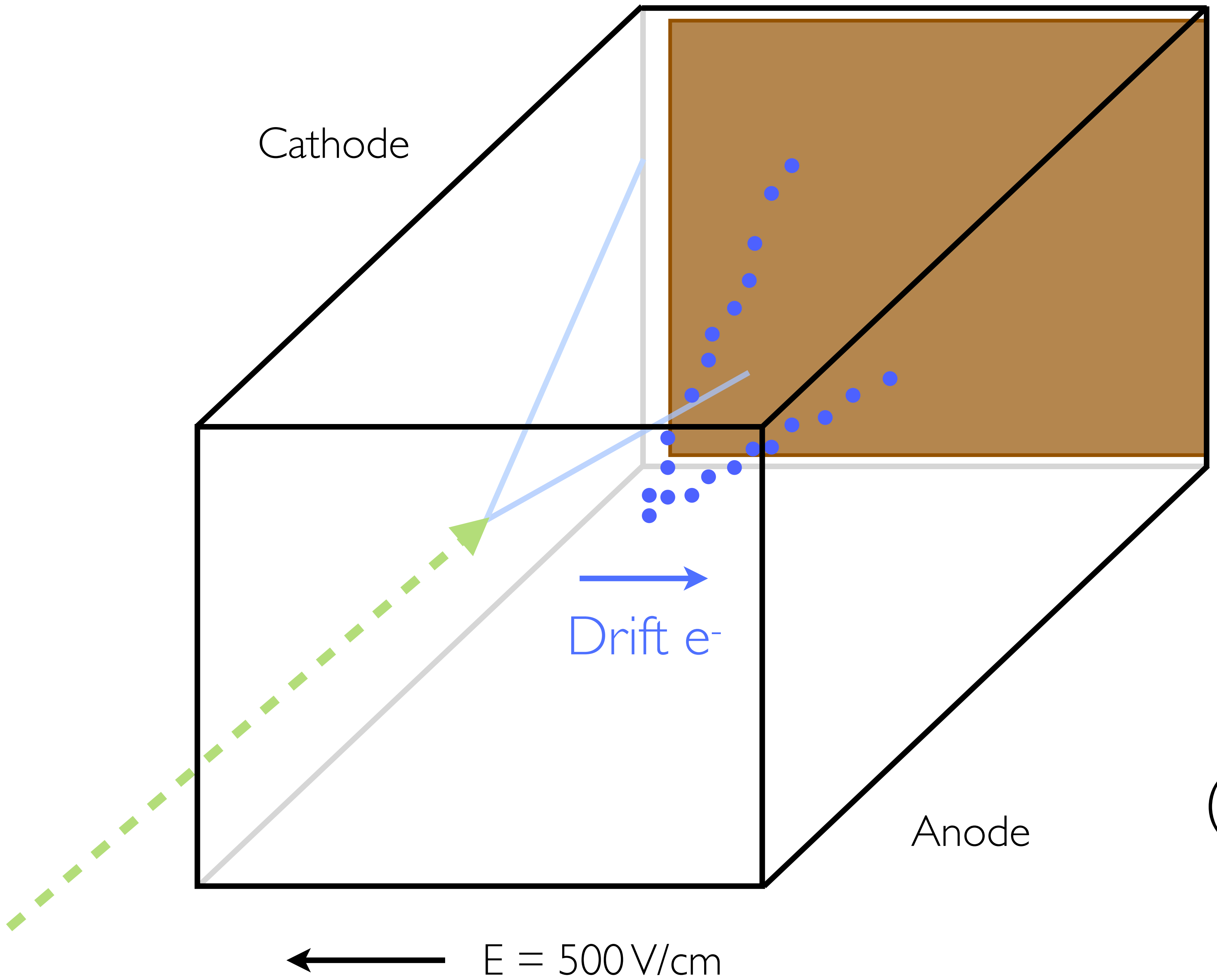
Charged secondary particles ionize LAr, producing electrons and scintillation light

LArTPC



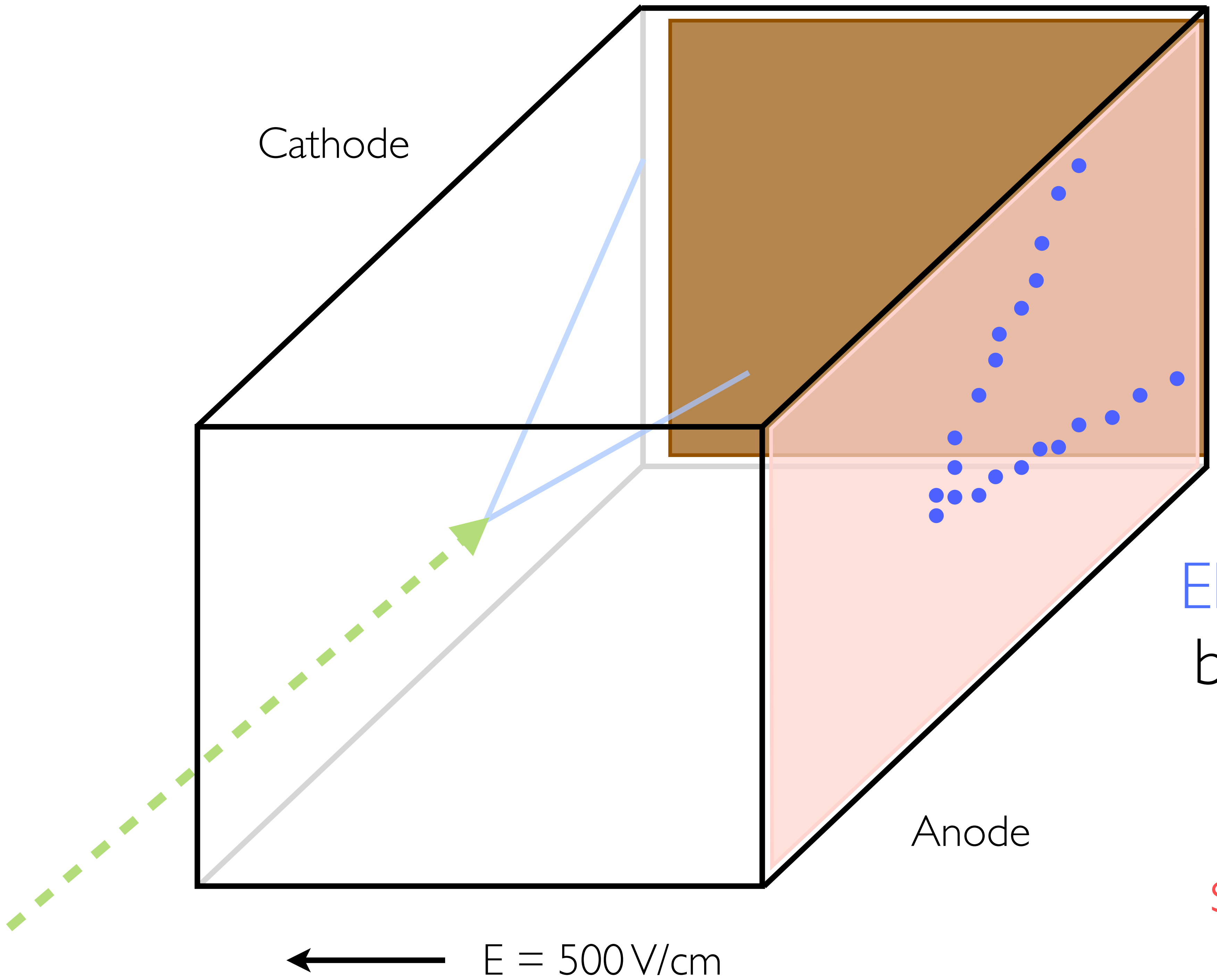
Light collected by photon detectors (10-100ns), determining event time t_0

LArTPC



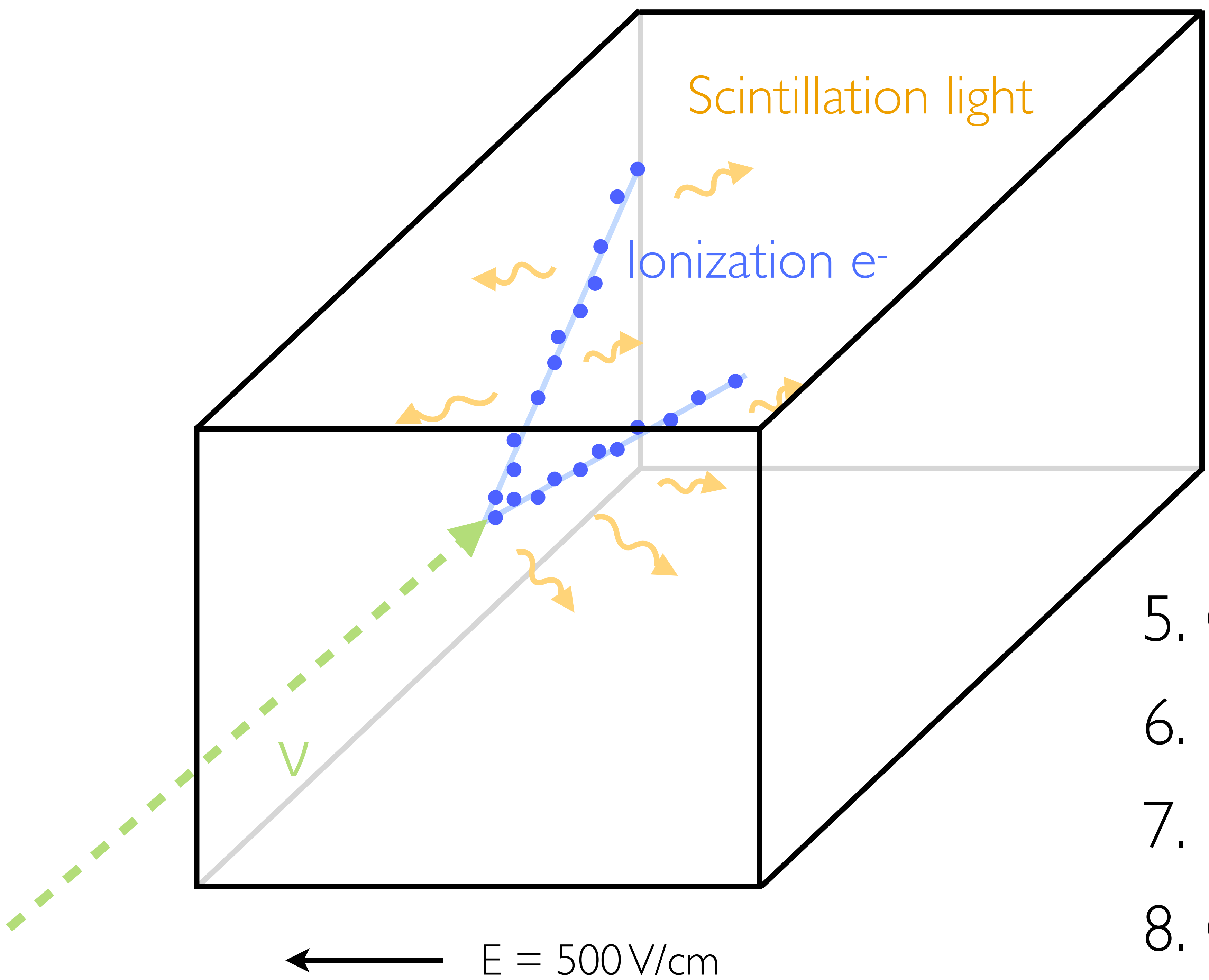
Electrons drift towards anode (drift time at ms scale)

LArTPC



Electrons detected by the pixel plane at anode, providing the spatial, kinematic information.

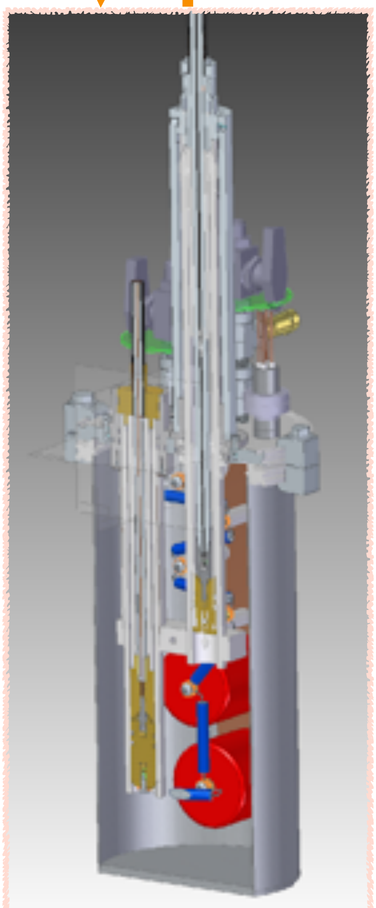
LArTPC



1. Cryogenic system
2. Detector control
3. High voltage
4. Field shell
5. Charge detector
6. Light detector
7. Pure LAr
8. Calibration

DUNE
ND-LAr
Concept

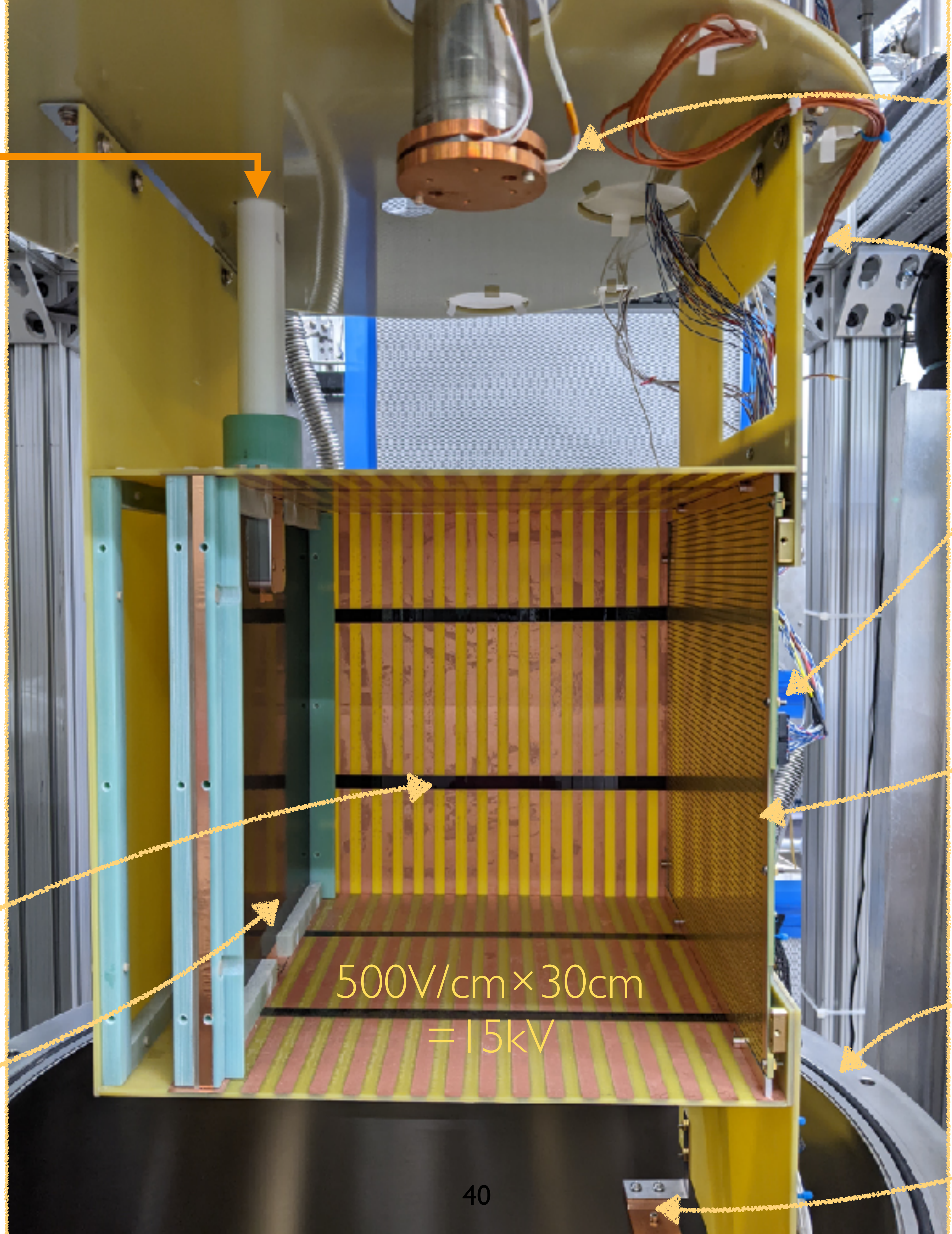
High Voltage



High Voltage Filter (low pass)

Field Cage/Shell

Cathode



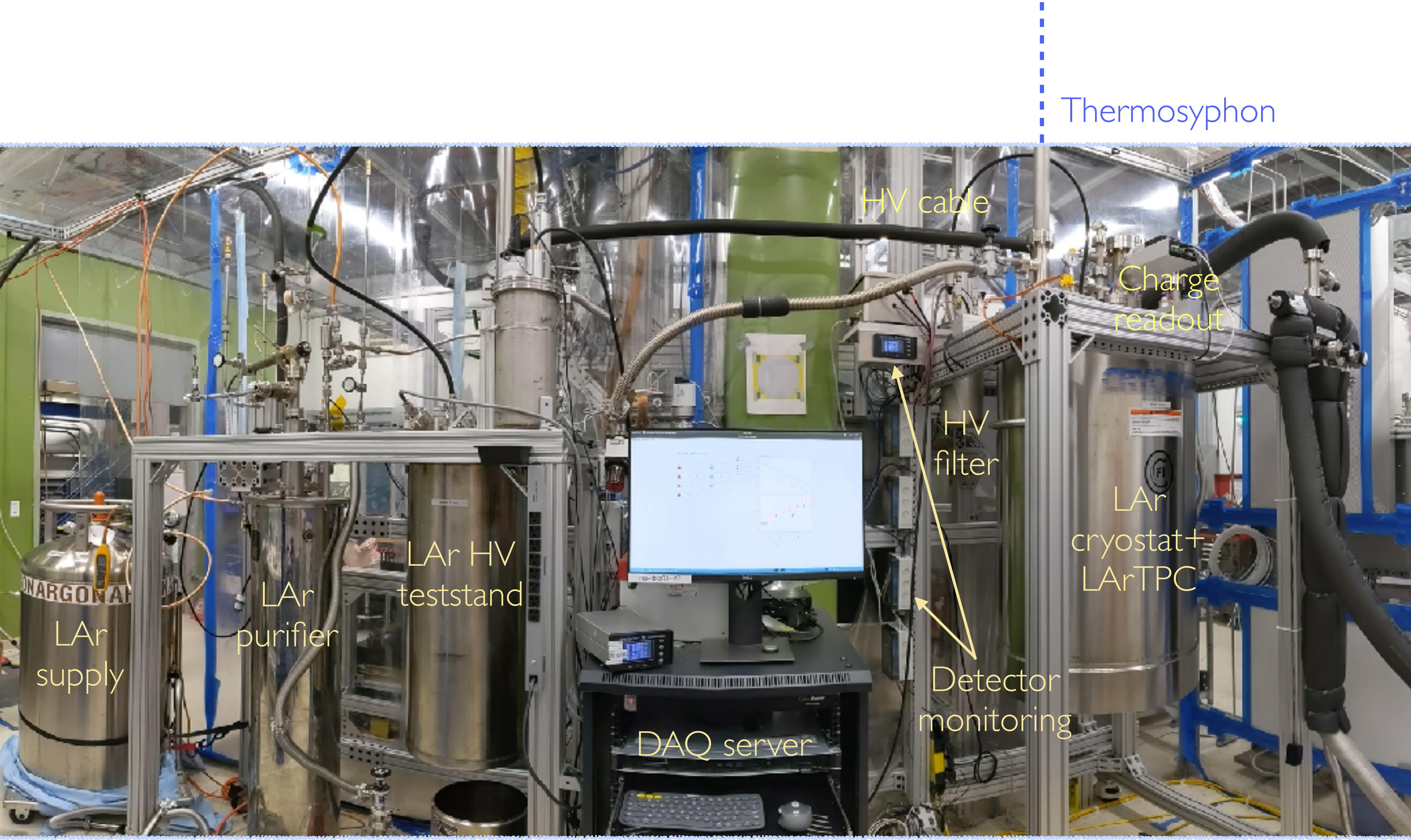
Cooling power; Thermosyphon

Temperature Sensors

Charge Readout (LArPix)

Cryostat

Heaters


Thermosyphon
HV cable
Charge readout
HV filter
LAr cryostat+ LArTPC
LAr HV teststand
LAr purifier
LAr supply
Detector monitoring
DAQ server

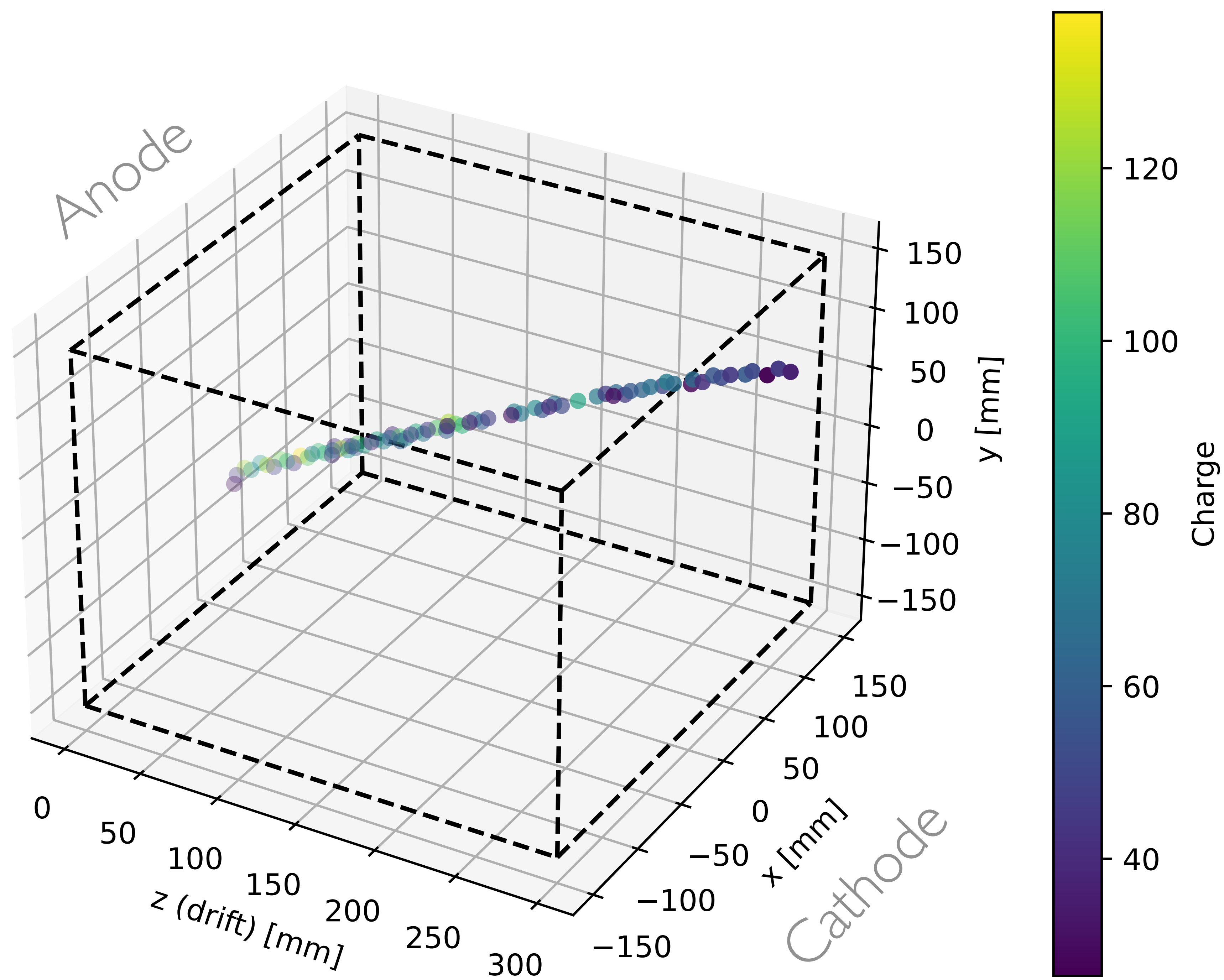
Cosmic Muon Track

E = 500 V/cm

Electron lifetime (LAr purity) ~ 225 μs

Data taken on July 31st (P. Tsang)

~1 cosmic ray track every 2 minutes



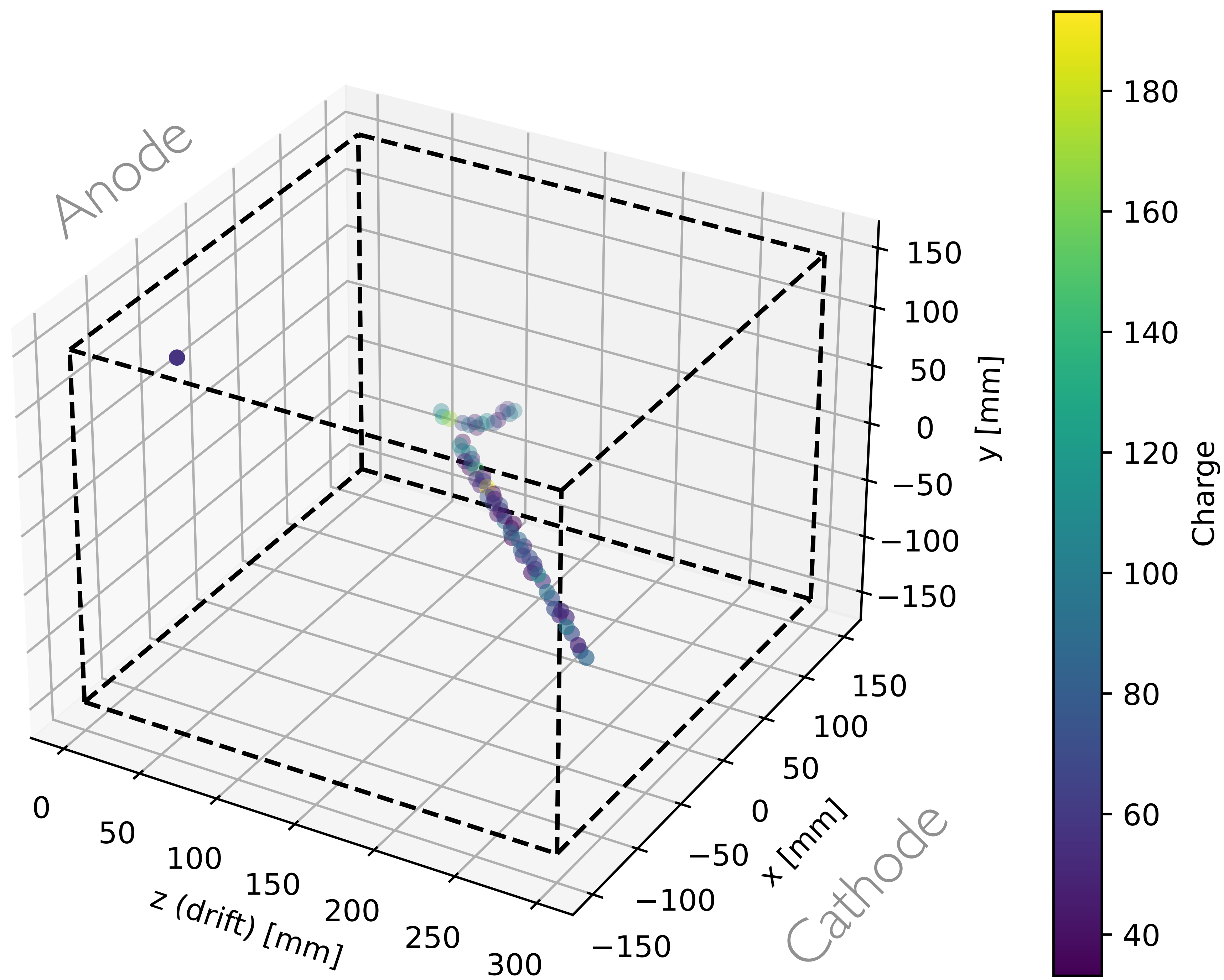
Michel Electron

E = 500 V/cm

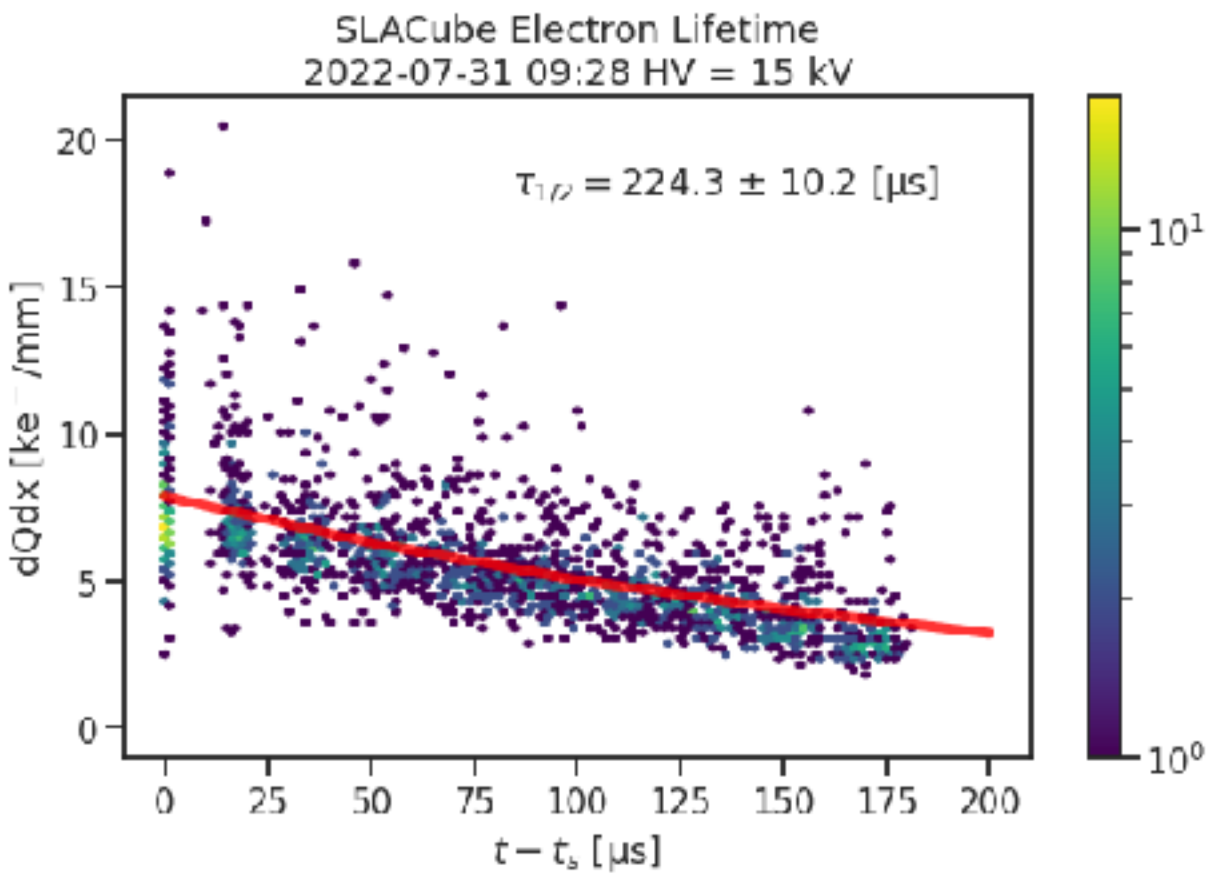
Electron lifetime (LAr purity) ~ 225 μs

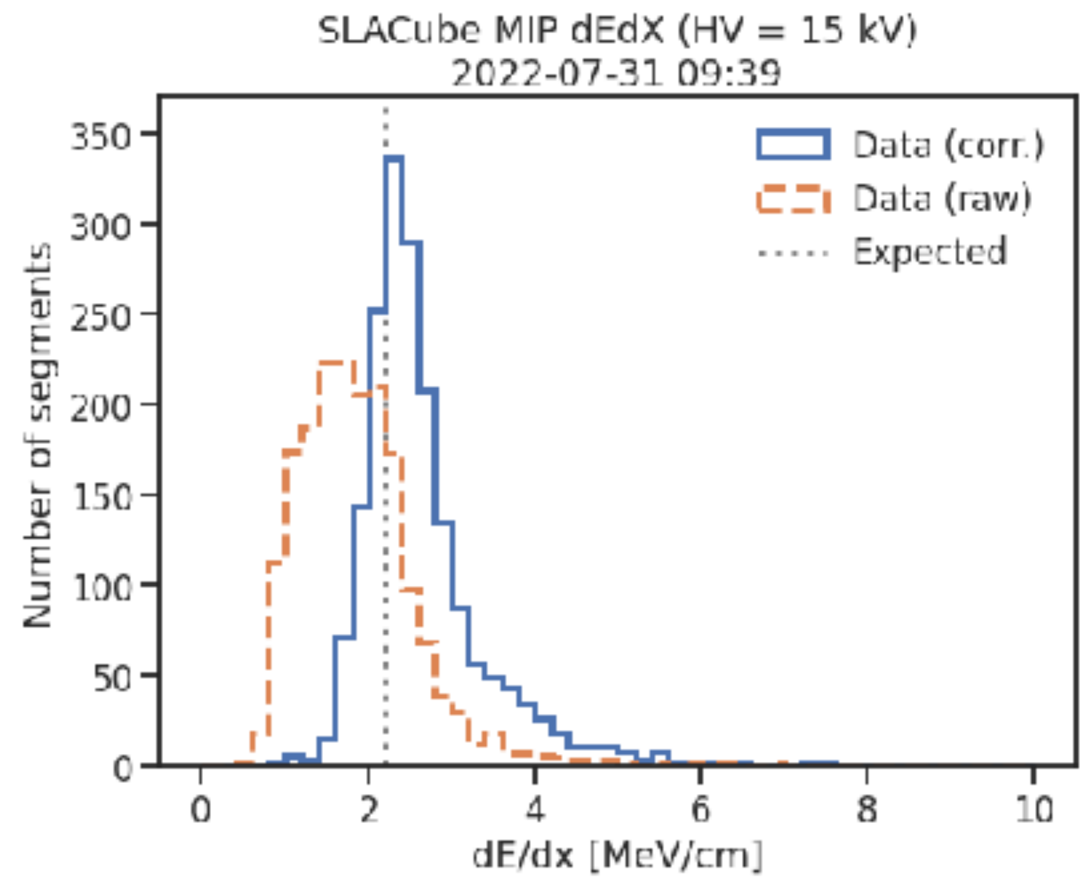
Data taken on July 31st (P. Tsang)

~1 cosmic ray track every 2 minutes



Detector Characterization

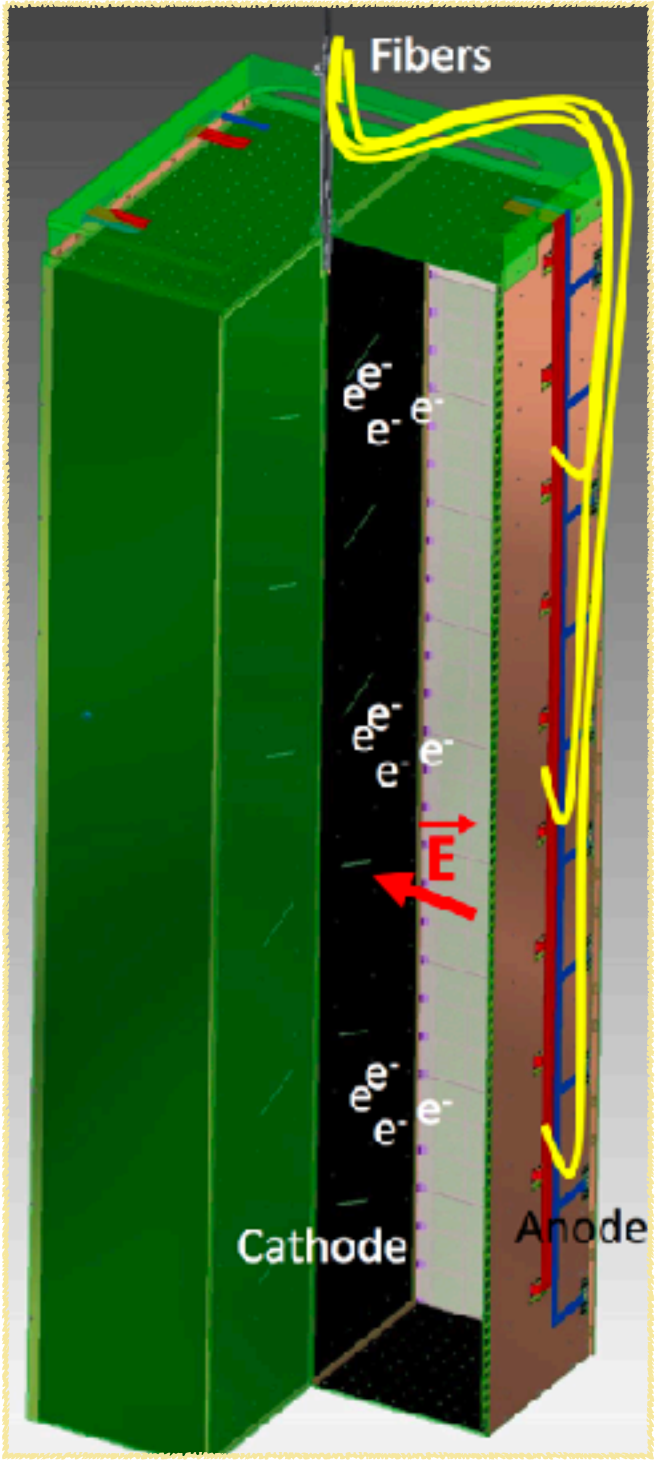




Plots and analyses by P. Tsang

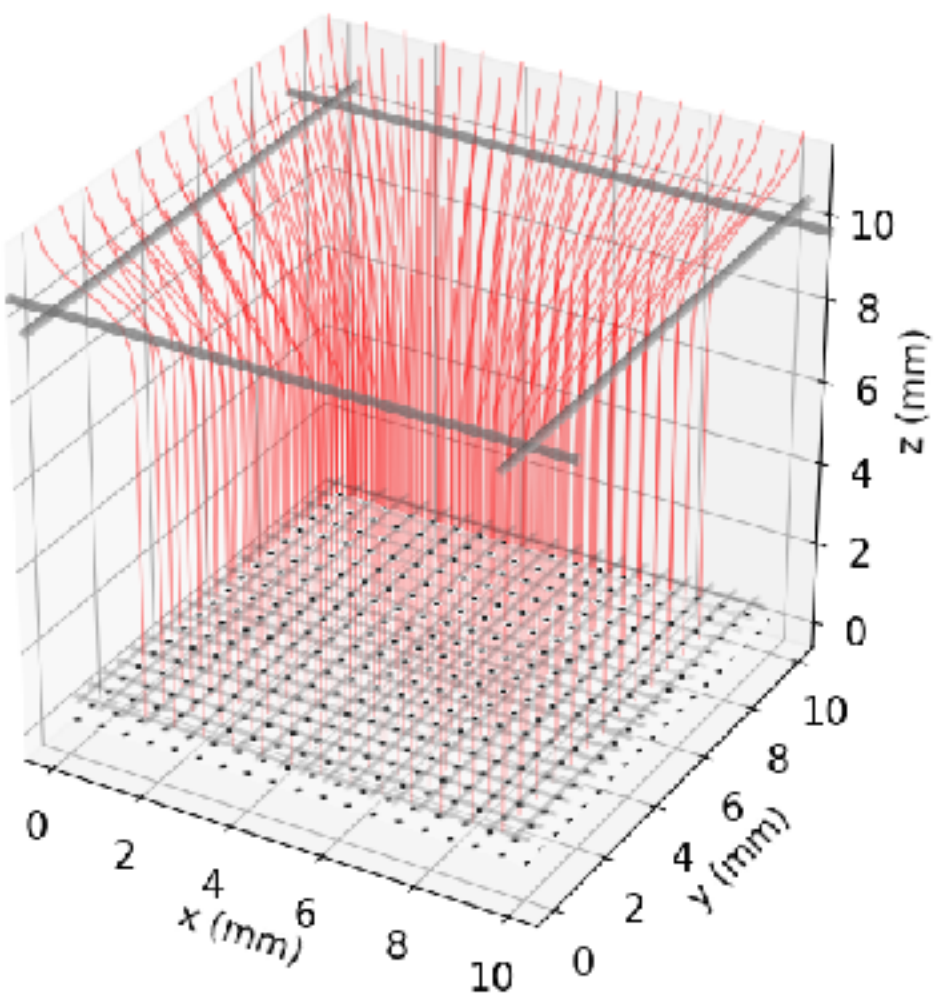
Laser Calibration

- Developed by the U of Hawaii (J. Maricic) and Michigan State U (K. Mahn) for DUNE ND-LAr
- 266nm laser shooting the metal target on the cathode
- Photoelectric effects creating a known number of electrons
- Measure the number of electrons at anode to calibrate the charge readout
- First operation expected in Fall



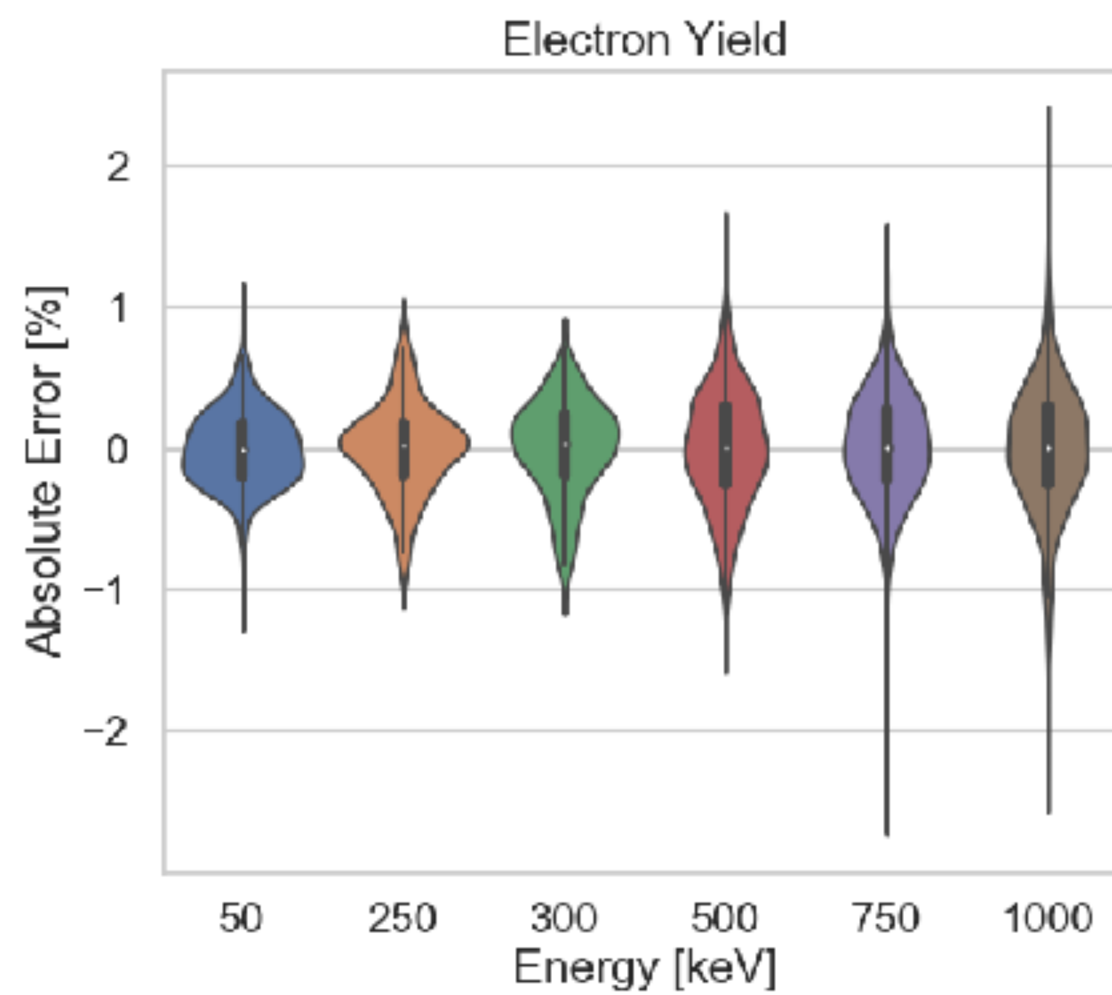
GAMPix

500μm-pixels triggered by mm scale wire readout. Low noise level (50e-) for MeV γ detection



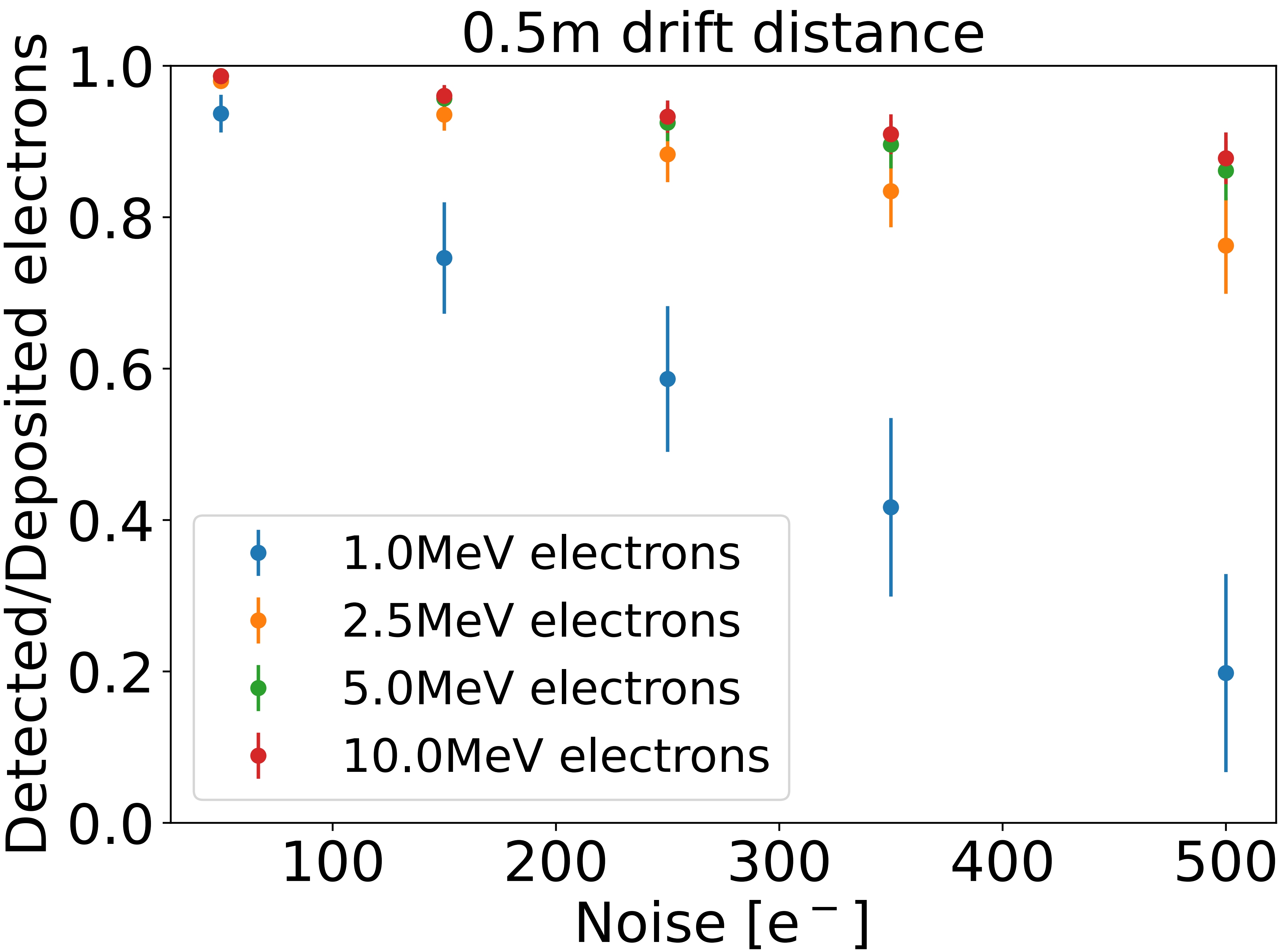
R&D underway at SLAC

Combine the signals on wires and pixels to obtain fine tracking, calorimetry, drift distance, etc.

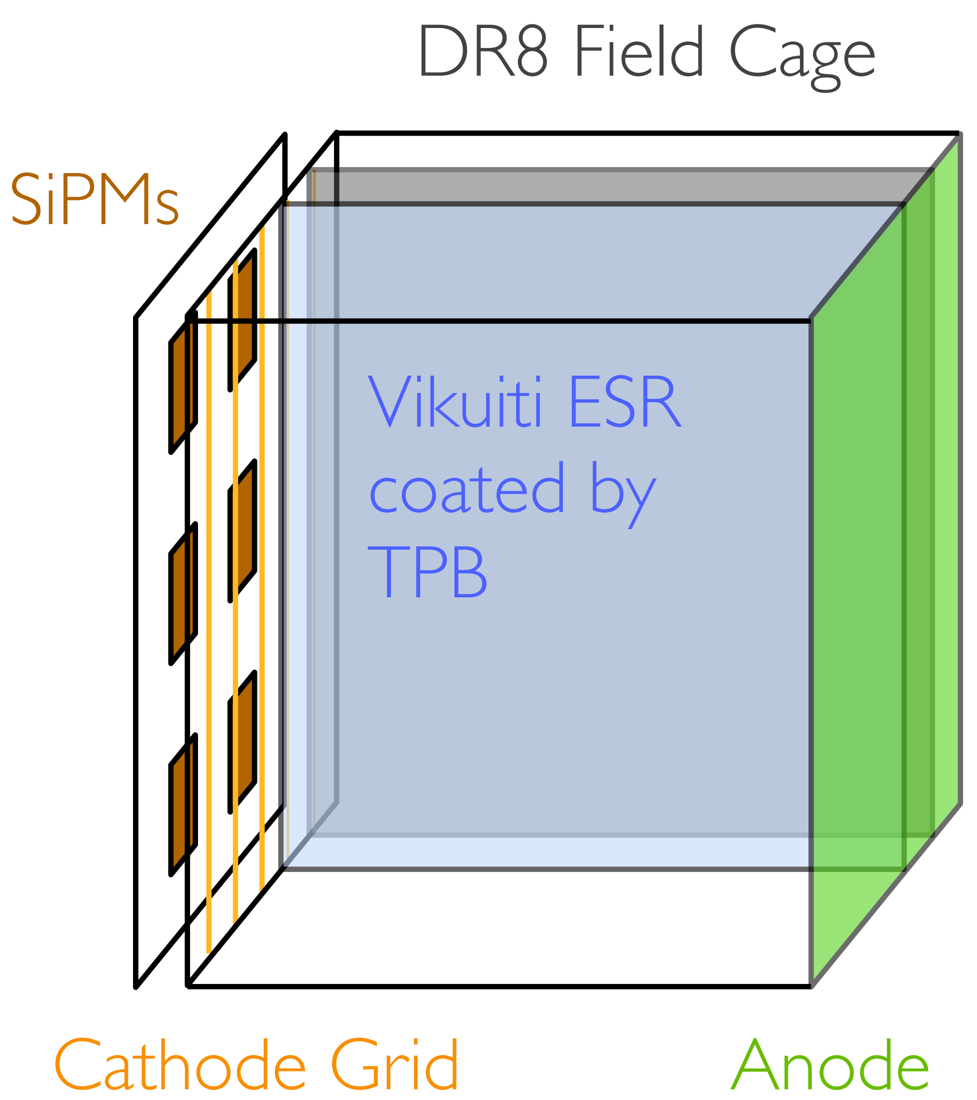


Plots by B. Trbalic (SLAC/Stanford)

MeV Particle Detection



Light Detector R&D



- Locate light sensors, Hamamatsu SiPMs, on the cathode side
  - Enlarge sensitive areas
- Laminate reflective foils, 3M Vikuiti enhanced specular reflector (ESR), on the slim field shell
  - Enhance the amount of light reaching the sensitive areas
- Coat wavelength shifters, TPB, on the reflective foils
- Aim for the light detection efficiency of O(5%)
- A sweet spot design!

Summary & Remark

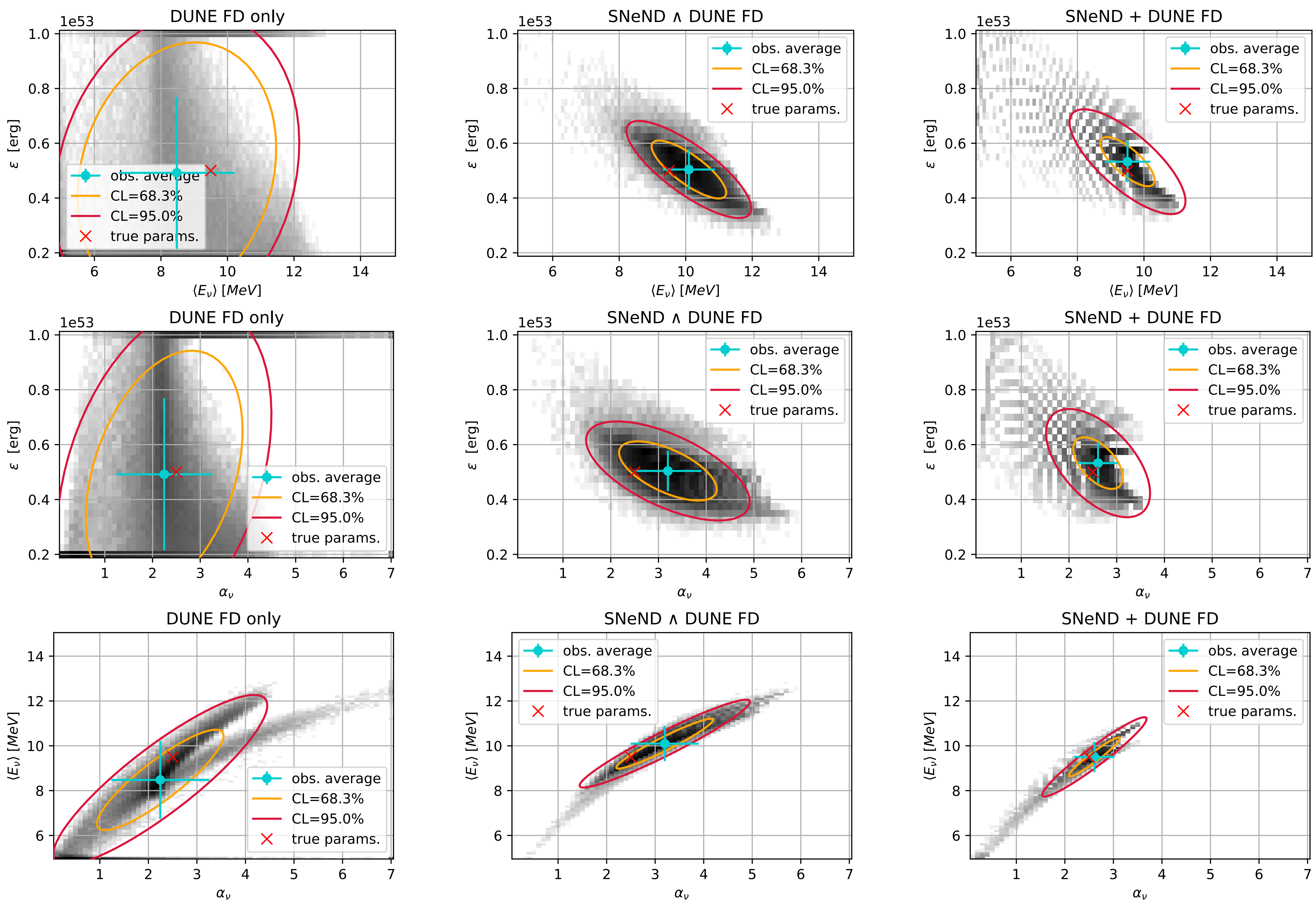
- Supernova neutrino measurements: one of the primary physics goals in DUNE
- SNeND constraints, including ν_e-Ar CC cross section measurements in LArTPCs with SNS, will reduce the bias
  - Proposing to deploy a LArTPC at COHERENT
- Tracking capabilities of LArTPCs enable ν-Ar σ studies and BSM searches
- MeV-scale detection in LArTPCs not largely explored; a number of R&Ds underway
- First LArTPC operating at SLAC, demonstrating the functionality

Backup

Big Questions in ν Physics

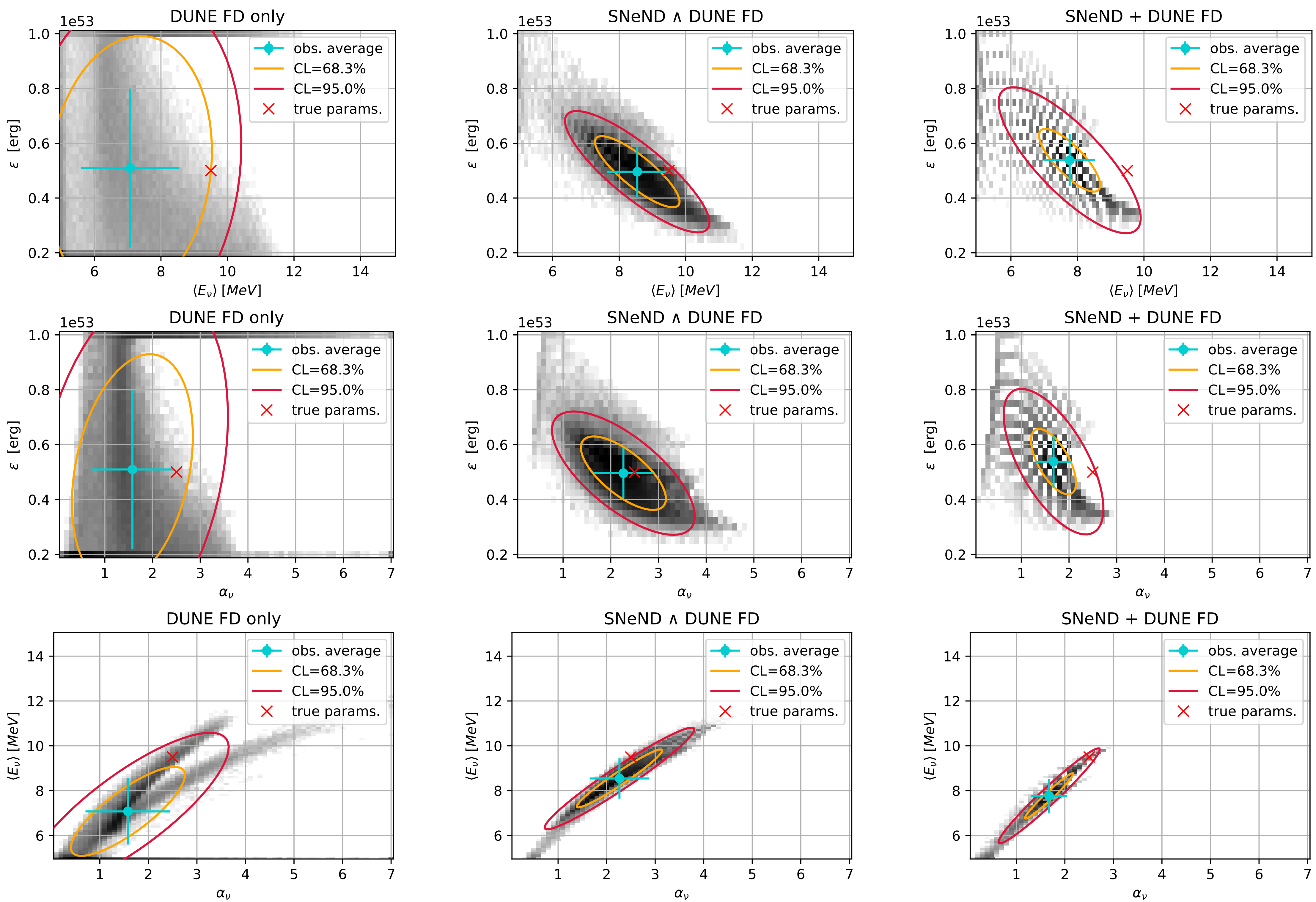
- Is there charge-parity (CP) violation in the lepton sector? What is δ_{CP}?
- Which is the mass ordering (hierarchy) and the origin of neutrino masses?
- Are there unknown neutrino states (sterile neutrino)?
- Neutrino properties
  - What are the absolute neutrino masses?
  - Is a neutrino a Dirac or Majorana particle?
- What can we learn from the neutrino burst when a supernova explodes?
- Can we detect dark matter in neutrino detectors?

33% on σ NH-NH



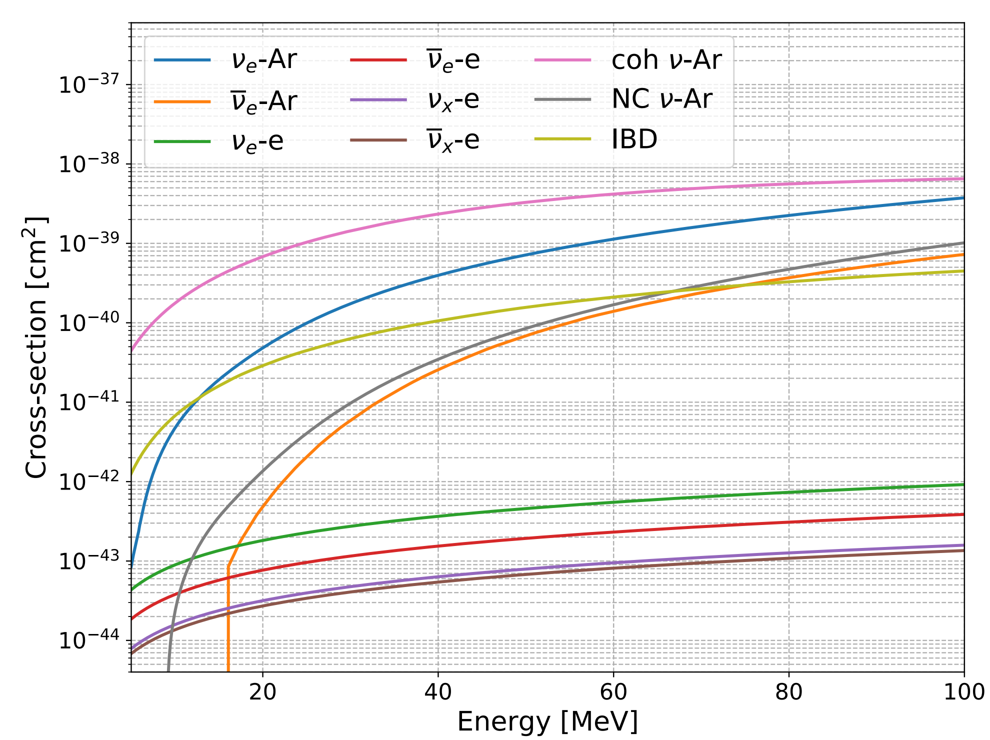
DUNE FD only
SNeND ∧ DUNE FD
SNeND + DUNE FD
1e53
ε [erg]
⟨Eν⟩ [MeV]
αν
obs. average
CL=68.3%
CL=95.0%
true params.

33% on σ NH-IH

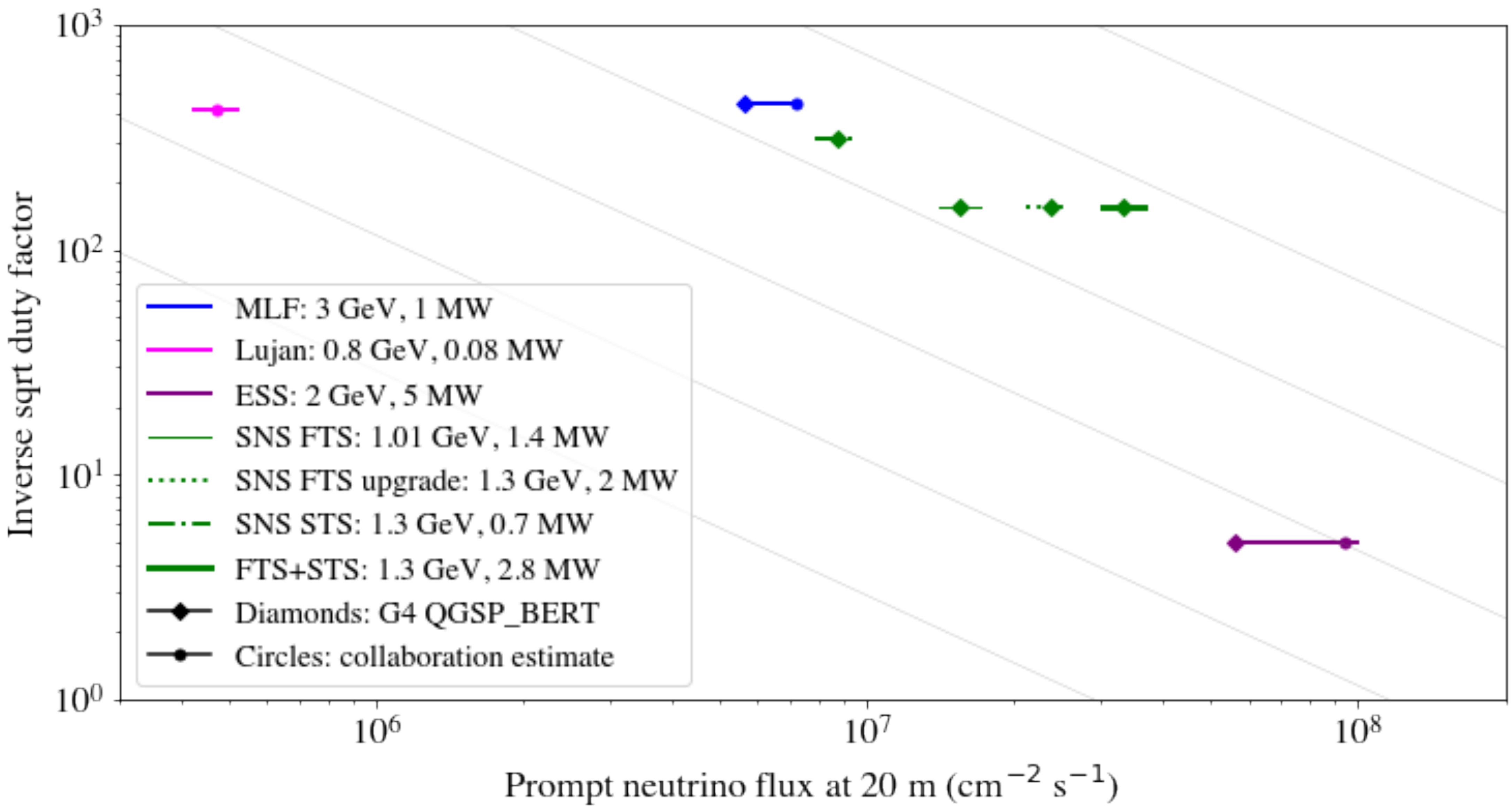

DUNE FD only
SNeND ∧ DUNE FD
SNeND + DUNE FD
1e53
ε [erg]
⟨Eν⟩ [MeV]
αν
obs. average
CL=68.3%
CL=95.0%
true params.

CEvNS

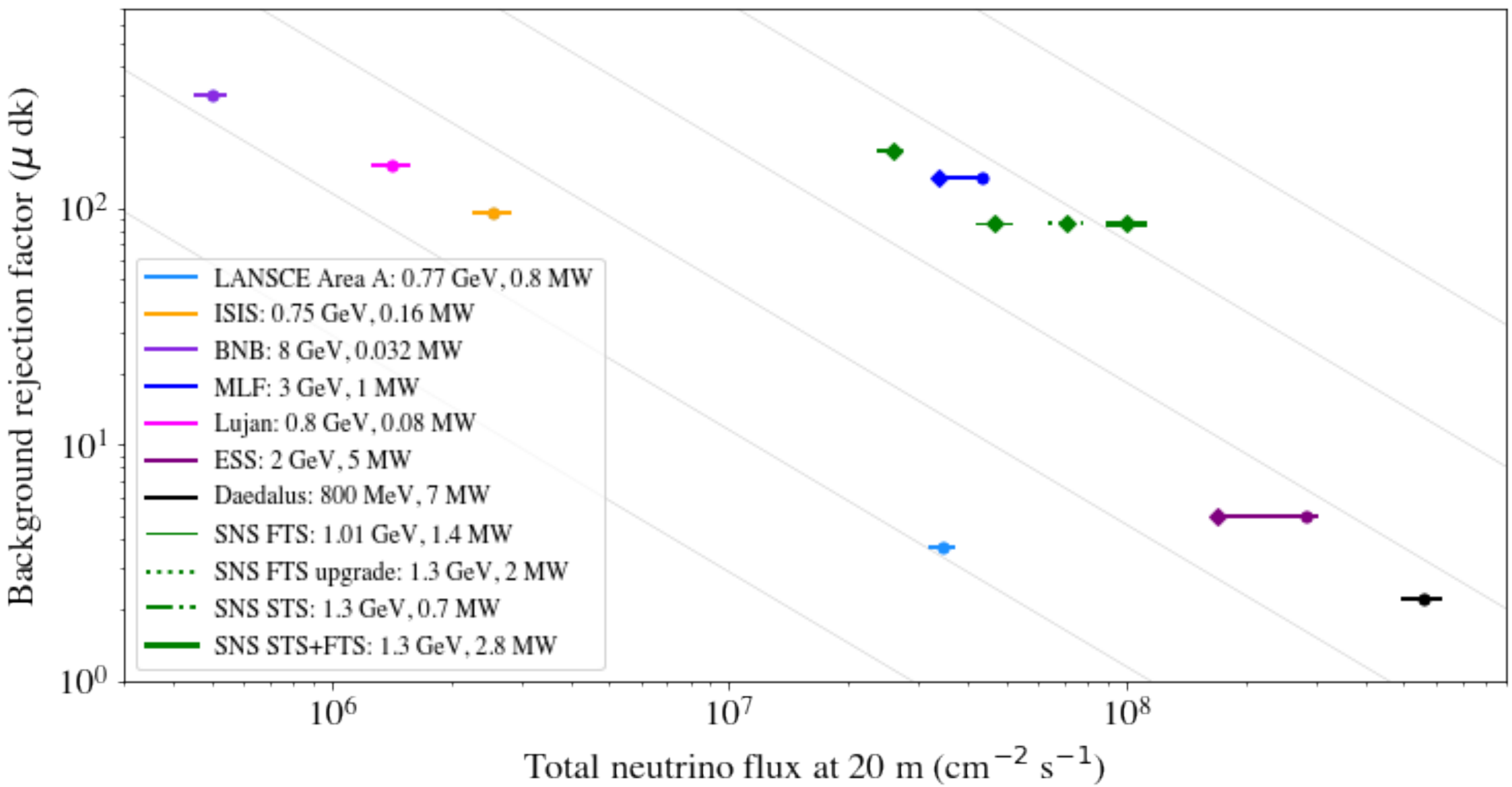
- Neutral-current scattering, predicted in 1974
- Small momentum transfer (qR<1) to the nucleon so that the nucleus recoils as a whole
  - q: momentum transfer; R: nuclear radius
- Dominant cross section when E_ν < 50 MeV; $\propto N^2$
- Observable: nucleus recoils with O(10 keV) energy
- Background events for WIMP search
- First observed in 2017 by COHERENT using SNS



π Decay-at-Rest Source

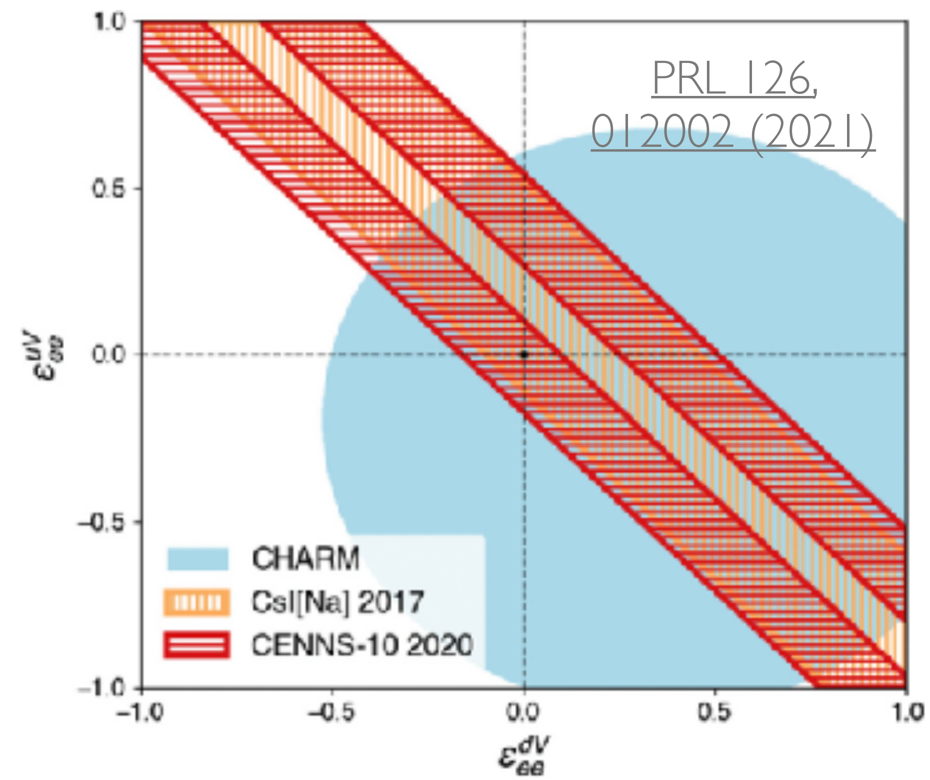


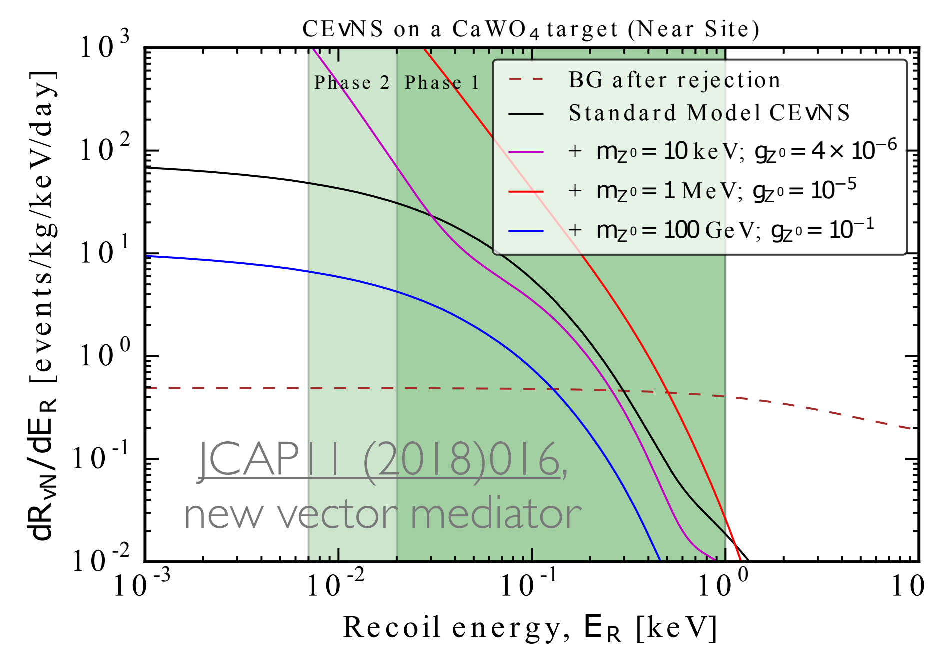
π Decay-at-Rest Source



SM & BSM Physics Probe

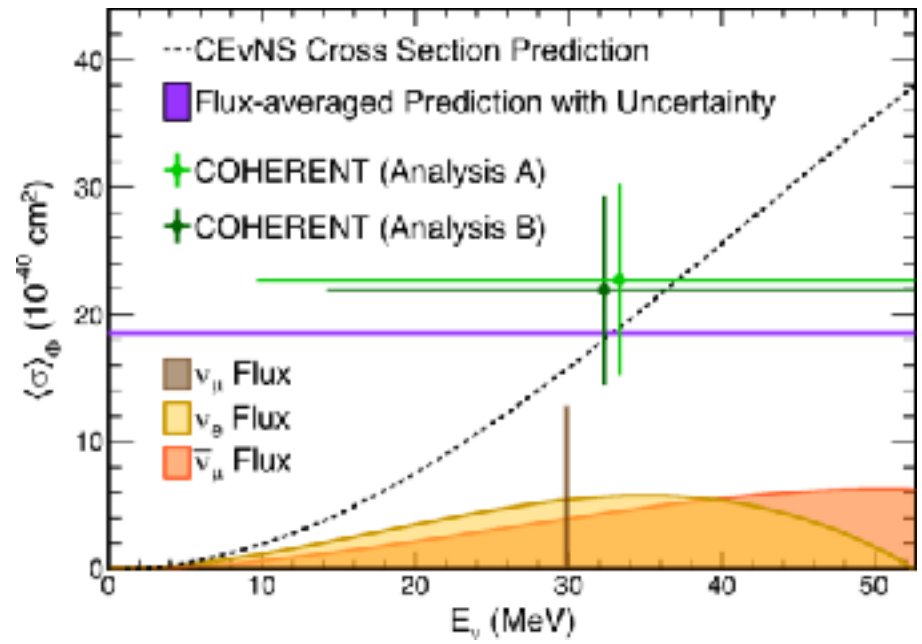
- Physics probed by CEvNS
  - Non-standard interaction
  - Dark scalar and vector mediators
  - Weak mixing angle
  - Neutrino magnetic moment
  - Effective neutrino charge radius
- BSM physics changes the cross sections
- Low threshold detector

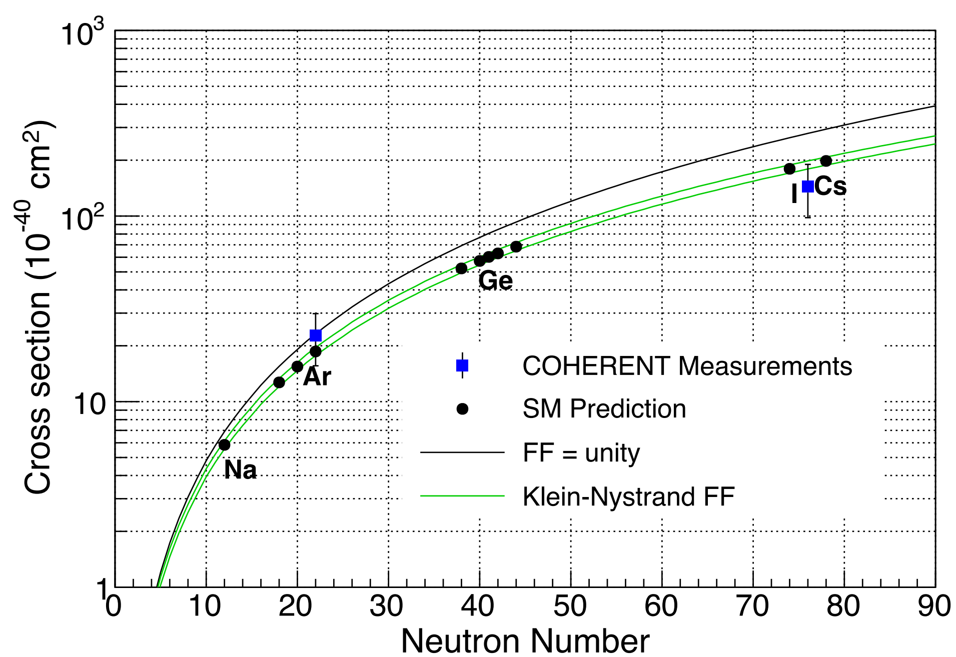




COHERENT Status & Plan

- First observation of CEvNS (CsI)
- First evidence of CEvNS on Ar
- First confirmation on SM N^2 dependence
- More statistics to come
- Inelastic neutrino scattering measurements on Pb and I
- BSM probes
- Plans on 1.3t D_2O ν flux monitor and 750kg LAr scintillator





Experiments for CEvNS

- Neutrinos produced from pions decaying at rest
    - COHERENT: CsI, LAr, NaI, Germanium, etc.
    - Accelerator-based neutrino experiments: DUNE GAr TPC (LBNF), etc.
- Reactor neutrinos
    - MINER: Si and Ge bolometer
    - NuCLEUS: $CaWO_4$ and Al_2O_3 bolometer
    - RICOCHET: Zn and Ge detectors

SNS Status & Plan

2021 — 2024 — ~2032

Current SNS

- 1.4MW, 1GeV, 20mA, 60Hz
- Available for a couple of ton-scale LAr detectors
- A 750kg LAr scintillator is under construction

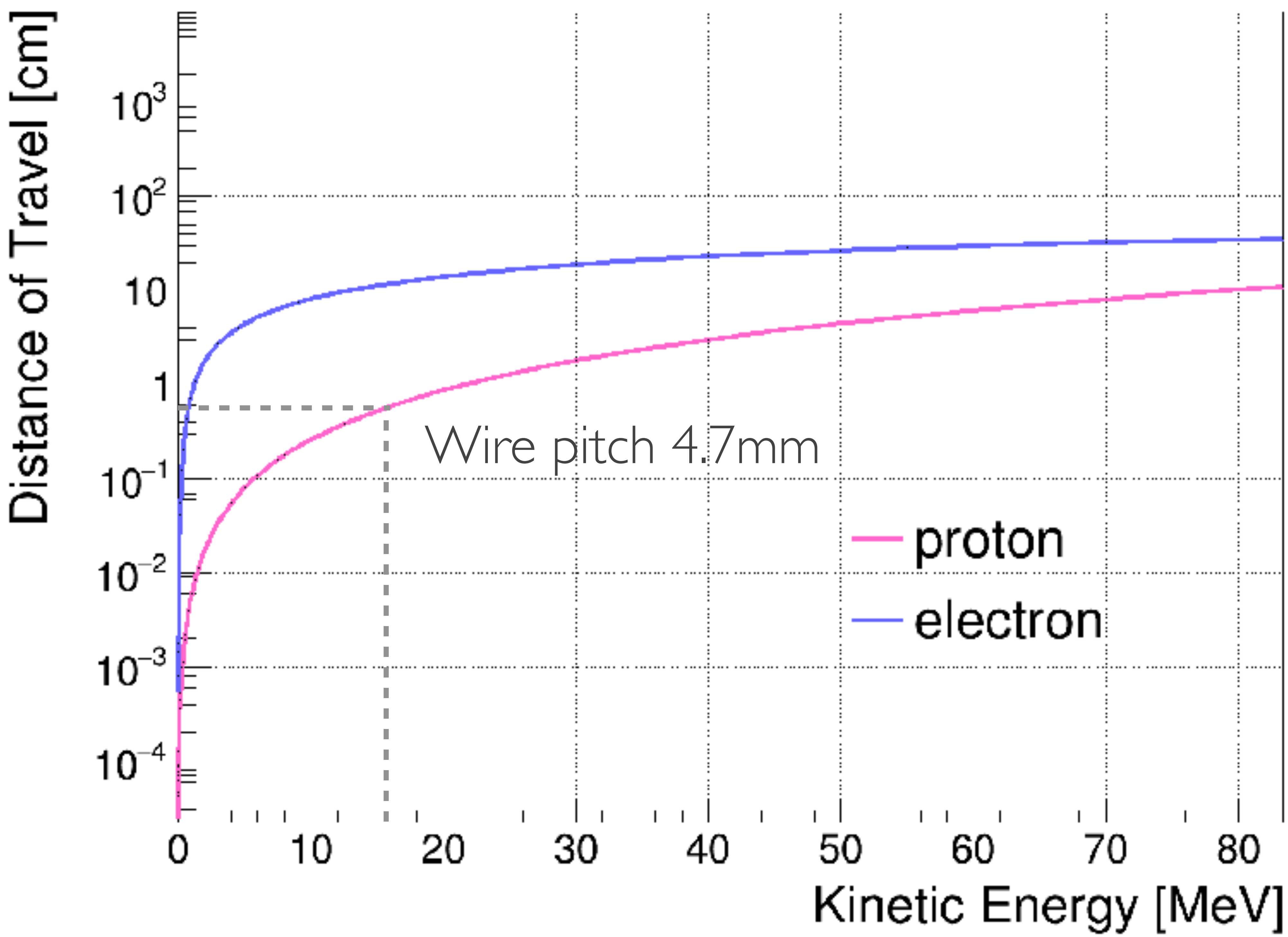
Proton Power Upgrade (PPU)

- 2MW, 1.3GeV, 27mA, 60Hz
- D_2O flux monitor

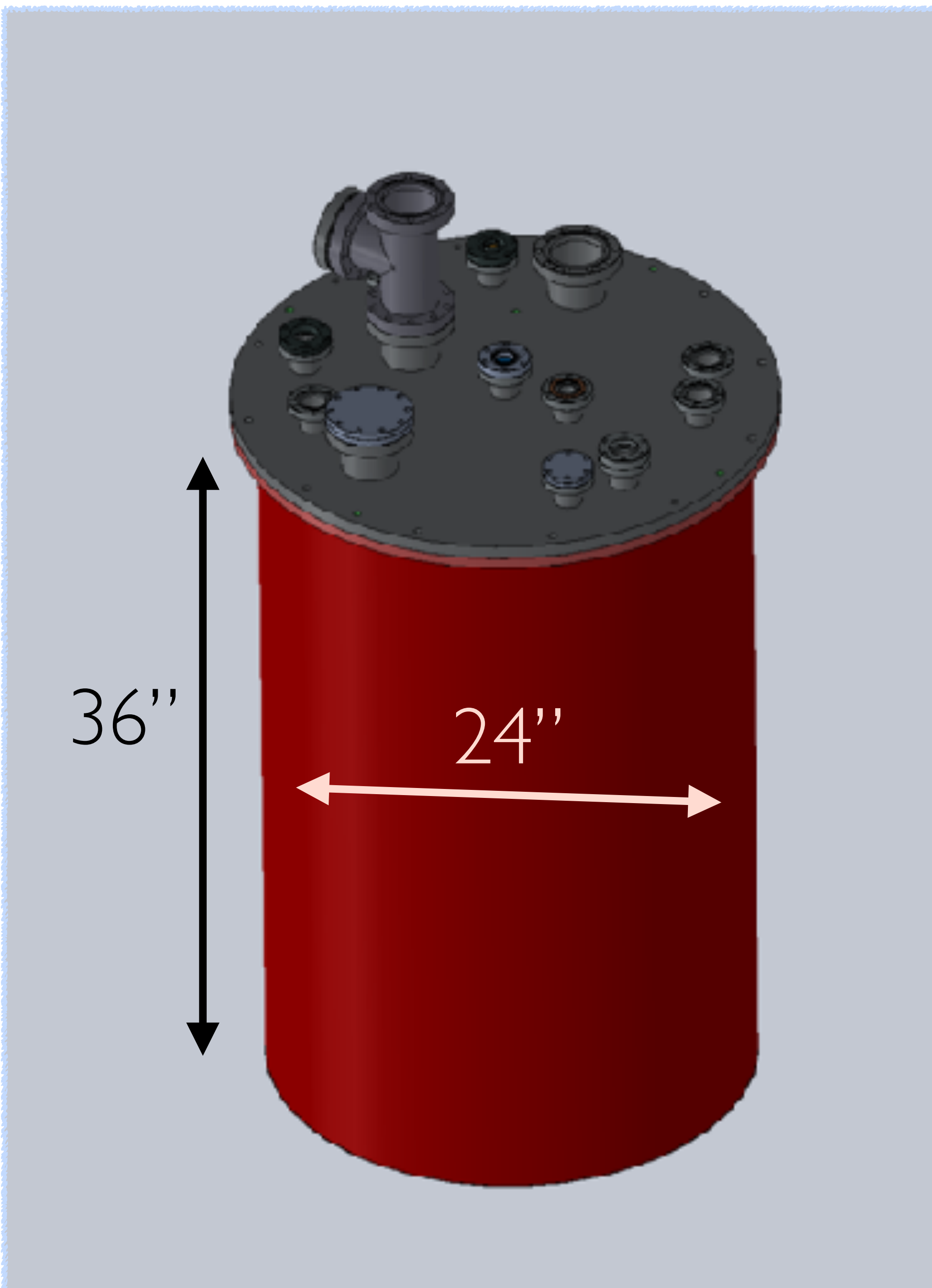
Second Target Station (STS) Project

- 2.8MW, 1.3GeV, 38mA, 60Hz
- First Target Station (FTS) 2MW, 45Hz
- STS 0.7MW, 15Hz, tungsten target
- Available for 10-ton scale LAr detectors

Low Energy Threshold



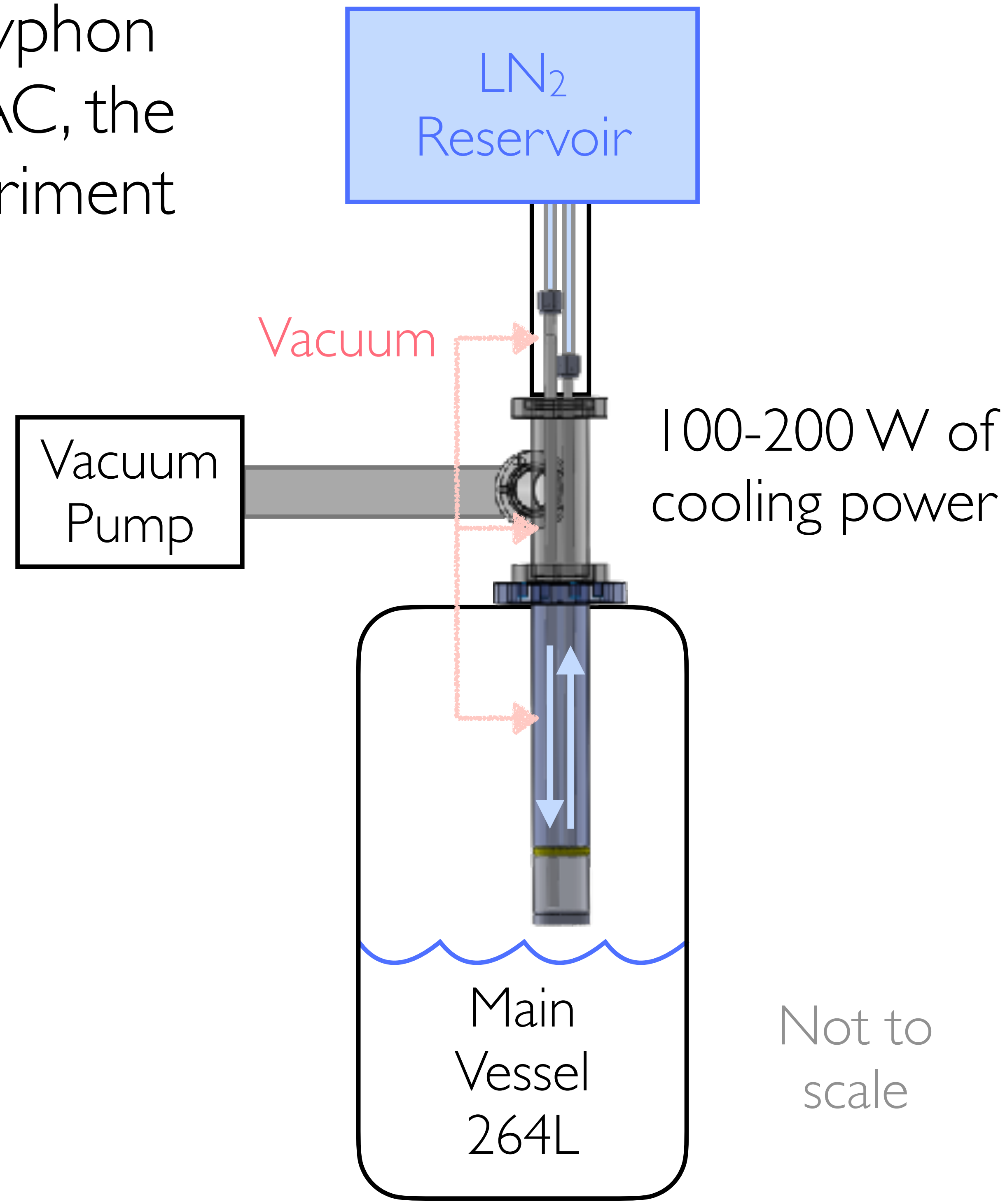
Cryogenic System



- Standard Cryofab dewar for LAr
  - Inner diameter: 24'', height: 36''
  - Gross capacity: 264 L
  - Maximal allowable working pressure: 10 psig
- Customized top lid
  - Feedthroughs for power, data and detector sensors
  - LAr filling and venting
  - Cooling power
  - Pressure relief devices

Cooling Power

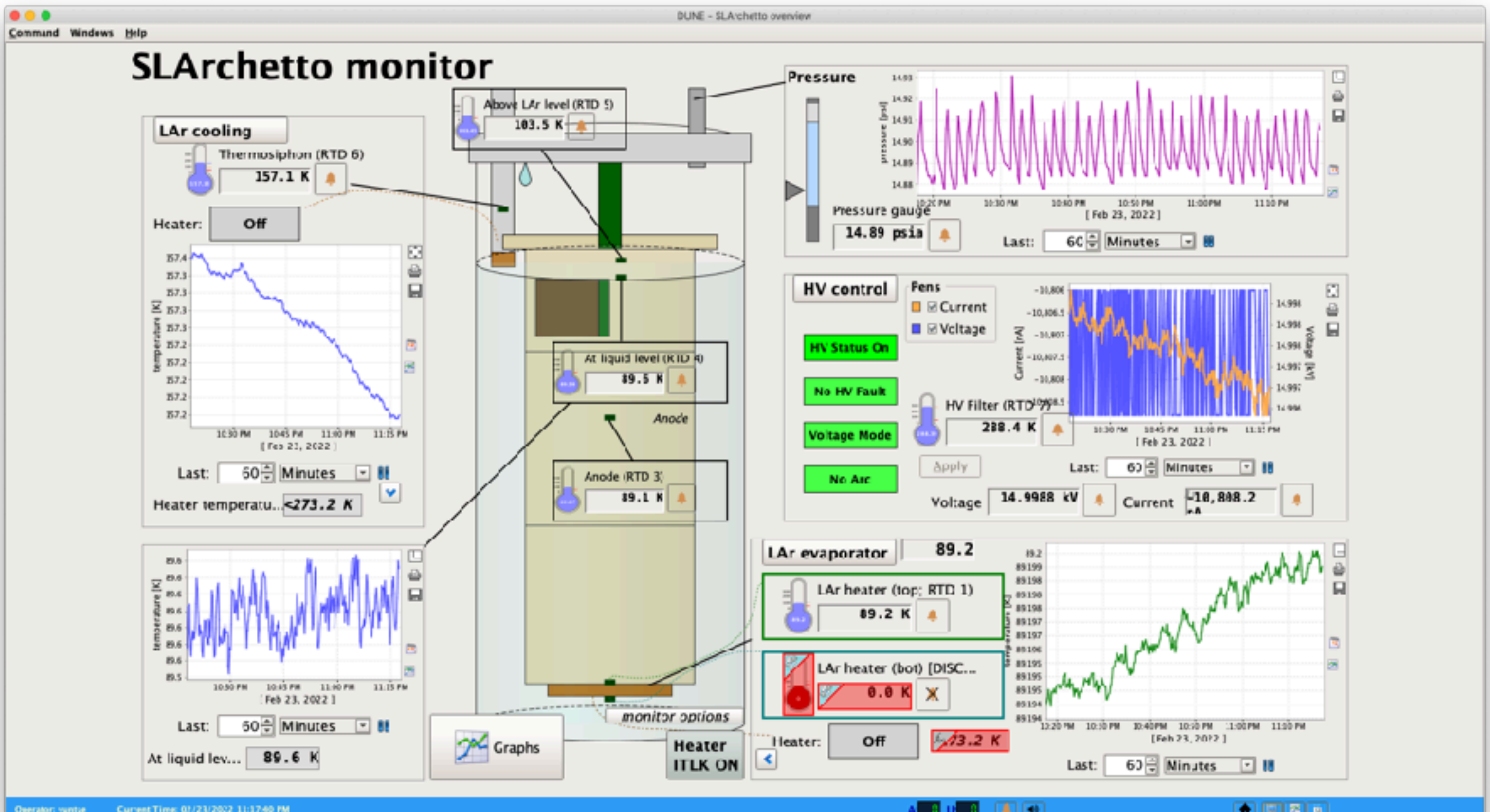
Cooling power from the thermosyphon at Liquid Noble Test Facility at SLAC, the same technology used in LZ experiment



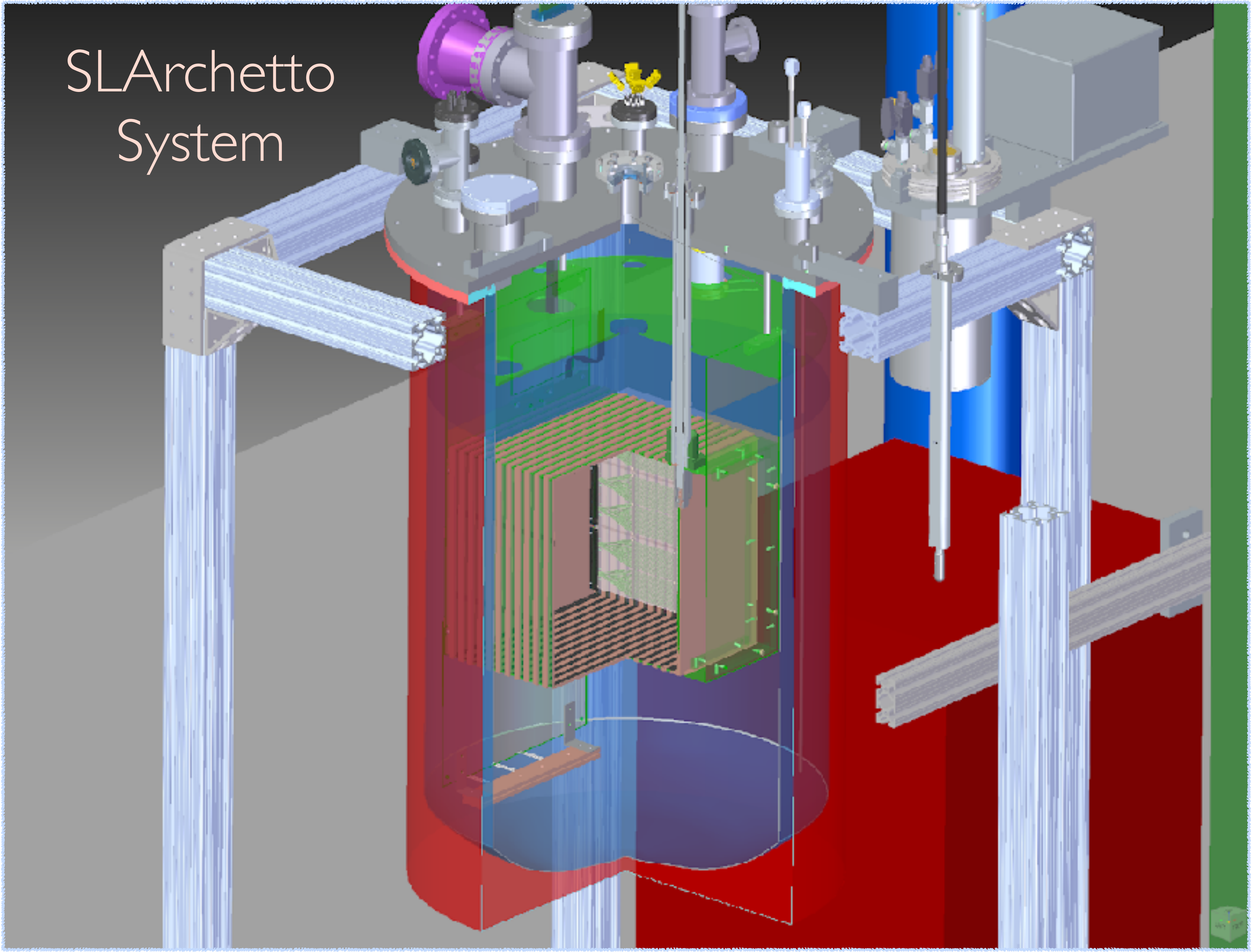
Not to scale

Detector Control

Based on Ignition: industrial detector control & monitoring, programmable in python



SLArchetto System

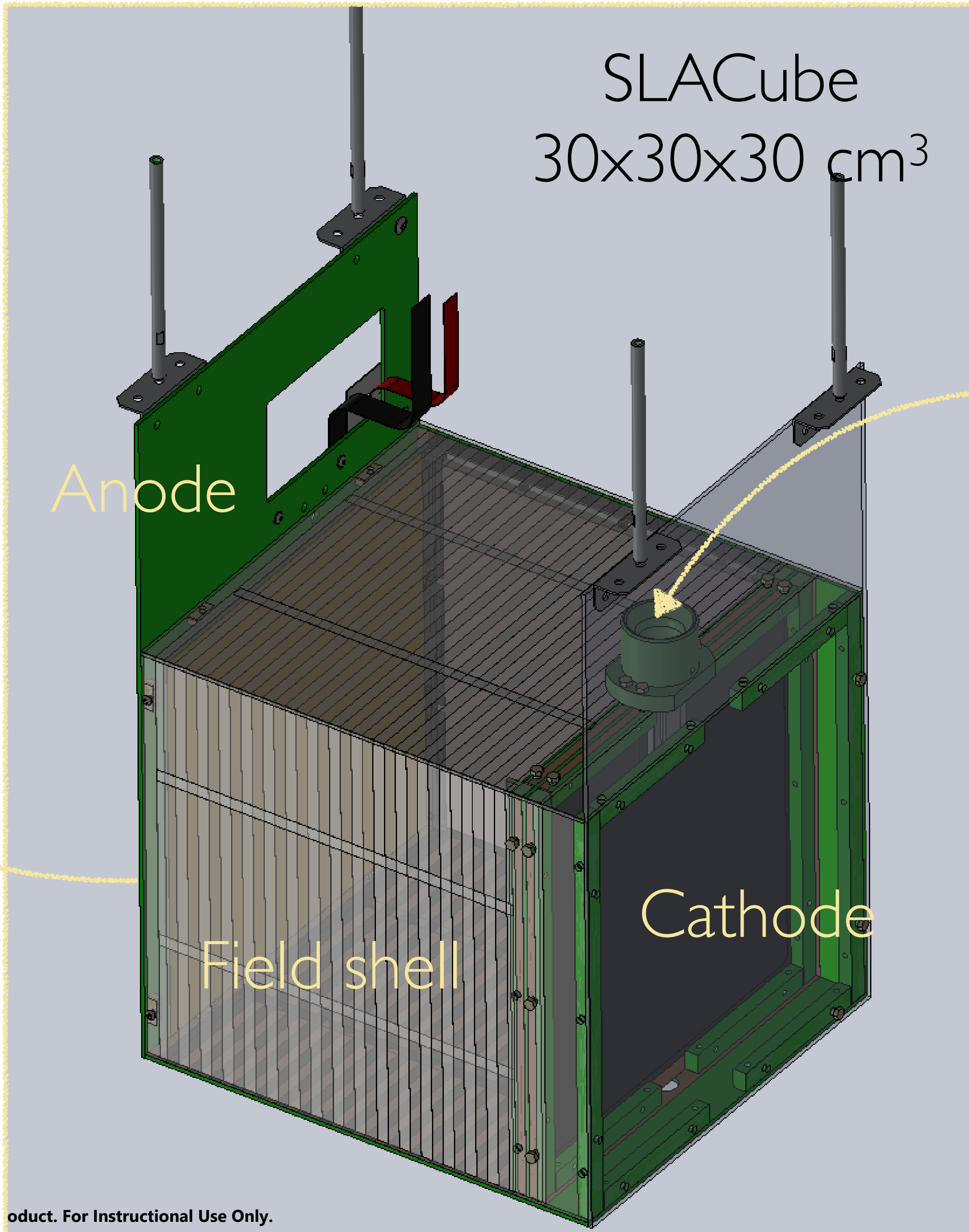


Time-Projection Chamber

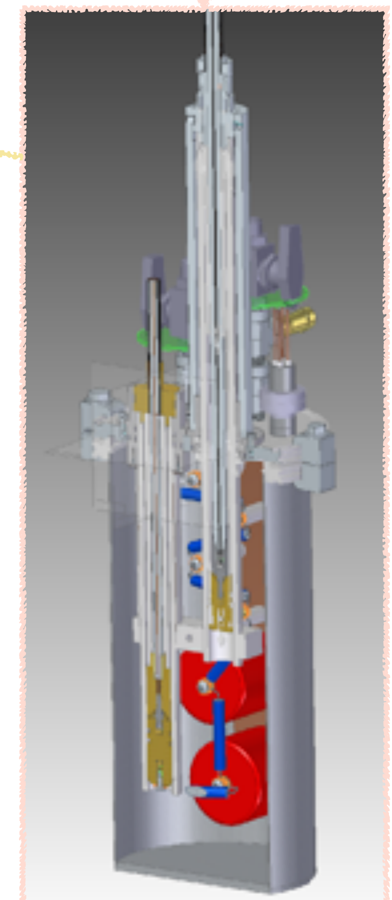
High voltage (HV) power supply ground = building ground

PicoAmmeter (Current measurement)

Nominal field:
500 V/cm
(15 kV total)



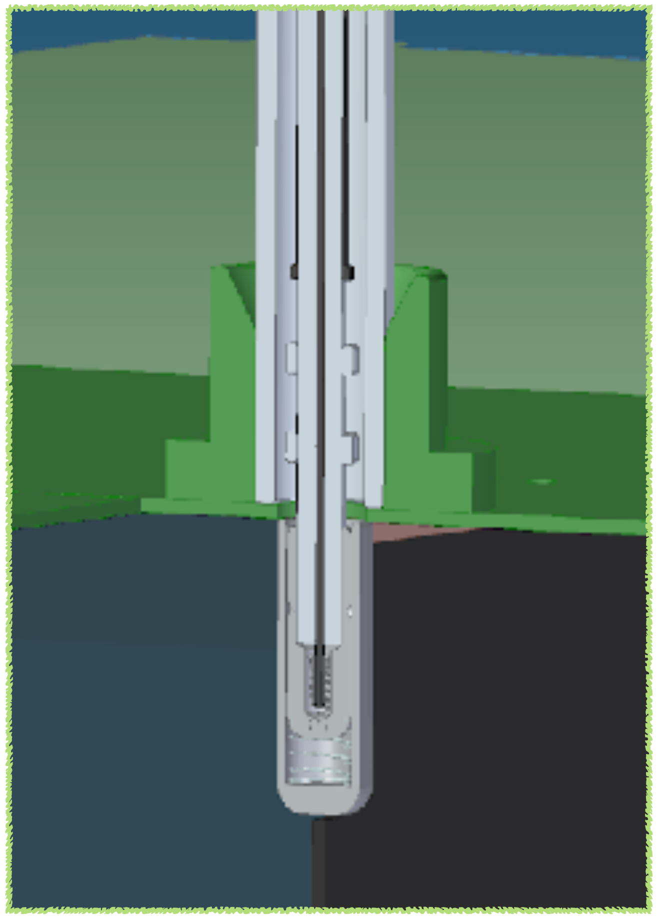
HV power supply



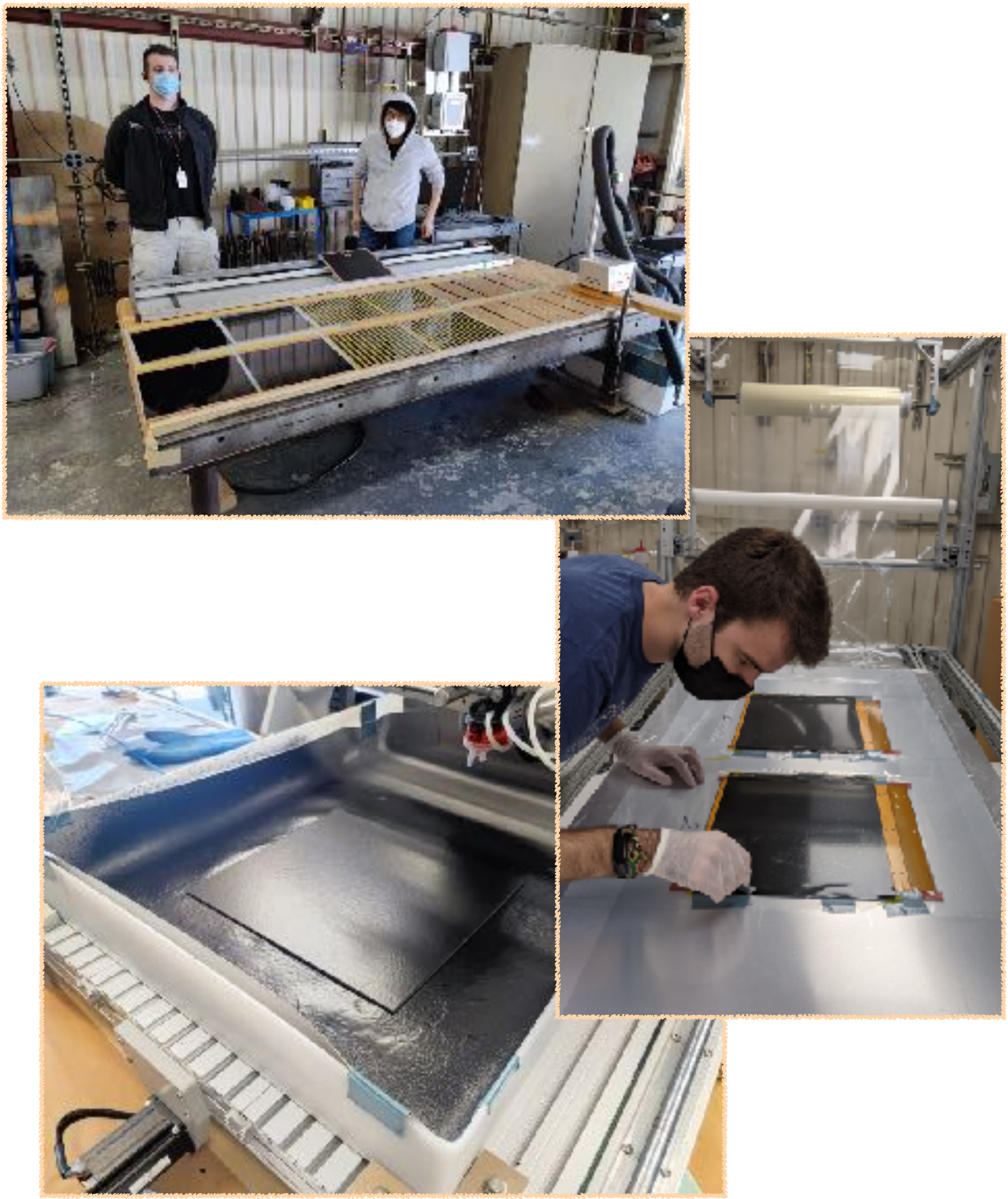
HV filter (low pass)

High Voltage

- Designed by Knut Skarpaas (SLAC engineer)
- HV cable originally designed for nEXO, and similar to the final DUNE ND-LAr design
  - Consideration for sealing, grounding, thermal contraction, buckling, etc.
- RC-circuits to filter high-frequency noise
  - Placed in a pot with electrical insulation oil



Field Shell



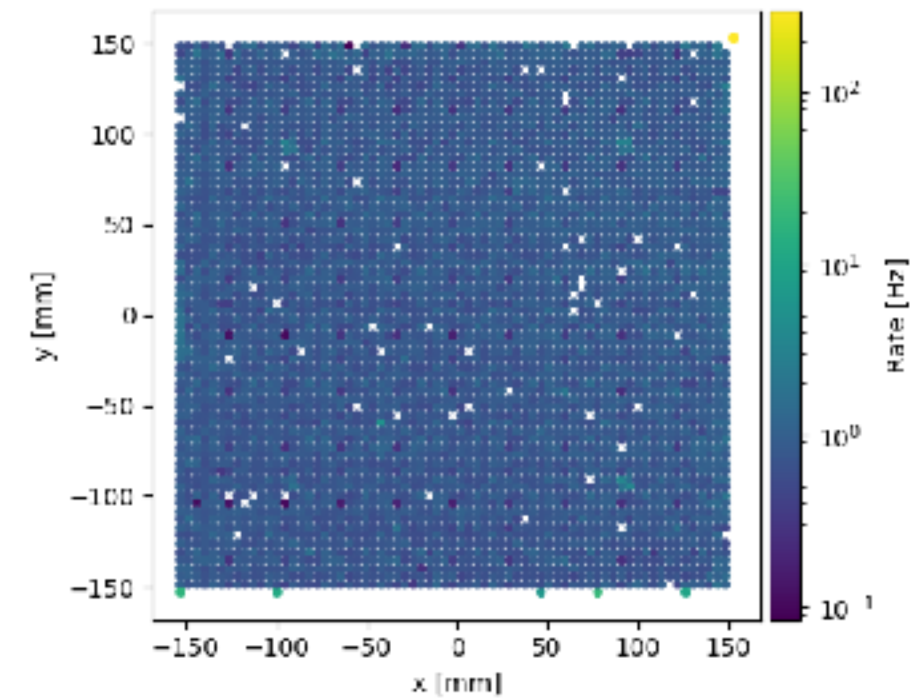
- Time projection requires uniform electric field
- Maximize the active volume in a modular TPC → thin panels
- Keep the electric potential linear and smooth → resistive materials
- Operate at 500V/cm
- Heat local density < 100 mW/cm^2

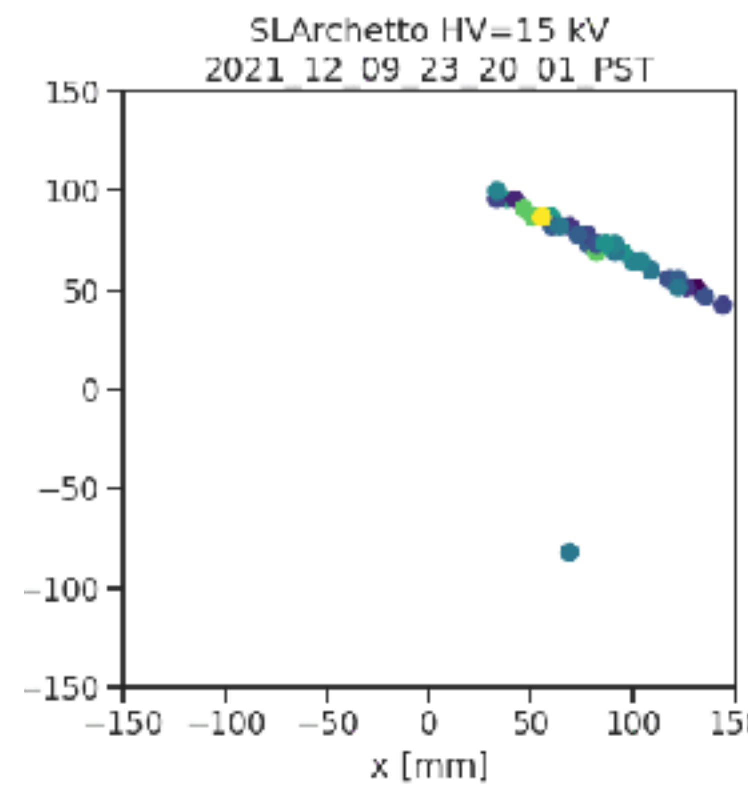
➡ Dupont Kapton sheets or carbon coated panels

Charge Collection System

- LArPix: Pixelated charge collection system developed by LBNL for DUNE ND-LAr
- 4 mm pixel, 4900 channels in a 30x30 cm^2 tile
- 2.5 μs time-binning
- ~62 μW/channel
- Self-triggering channel by channel
- First tracks observed in December 2021
- DAQ implemented and maintained by P.Tsang

Self-triggering rate





Plots made by P.Tsang

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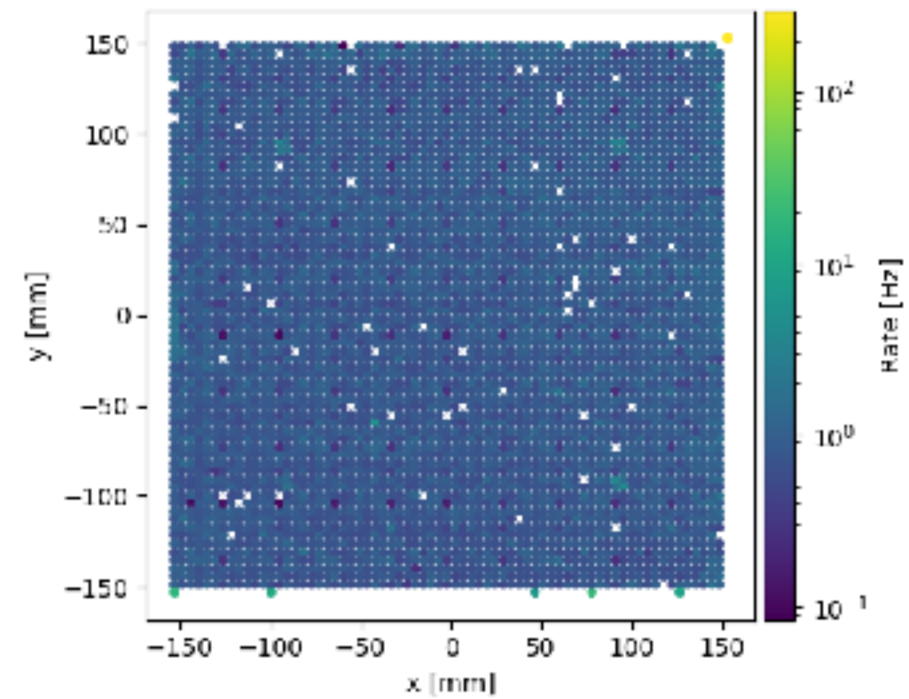
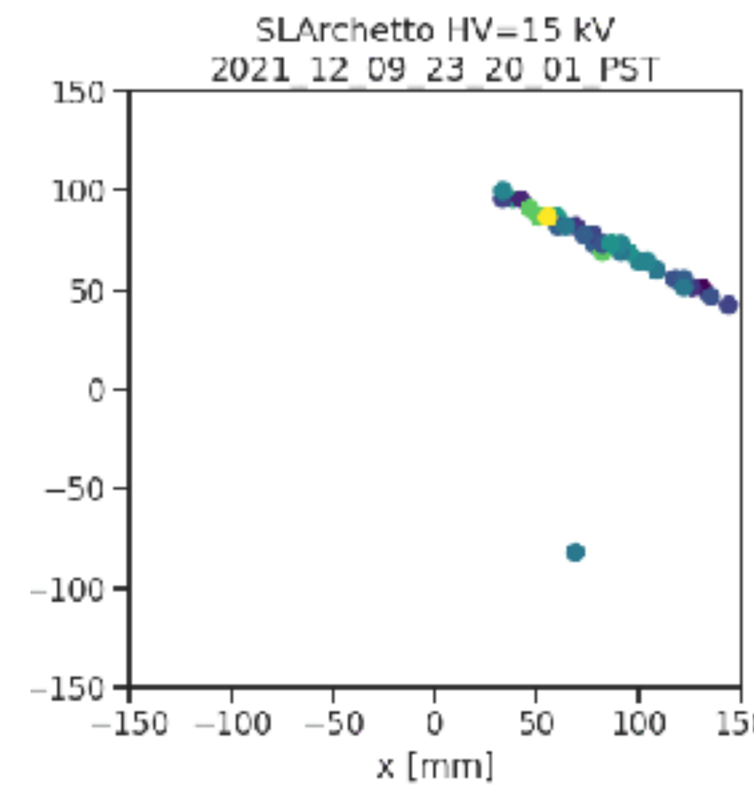
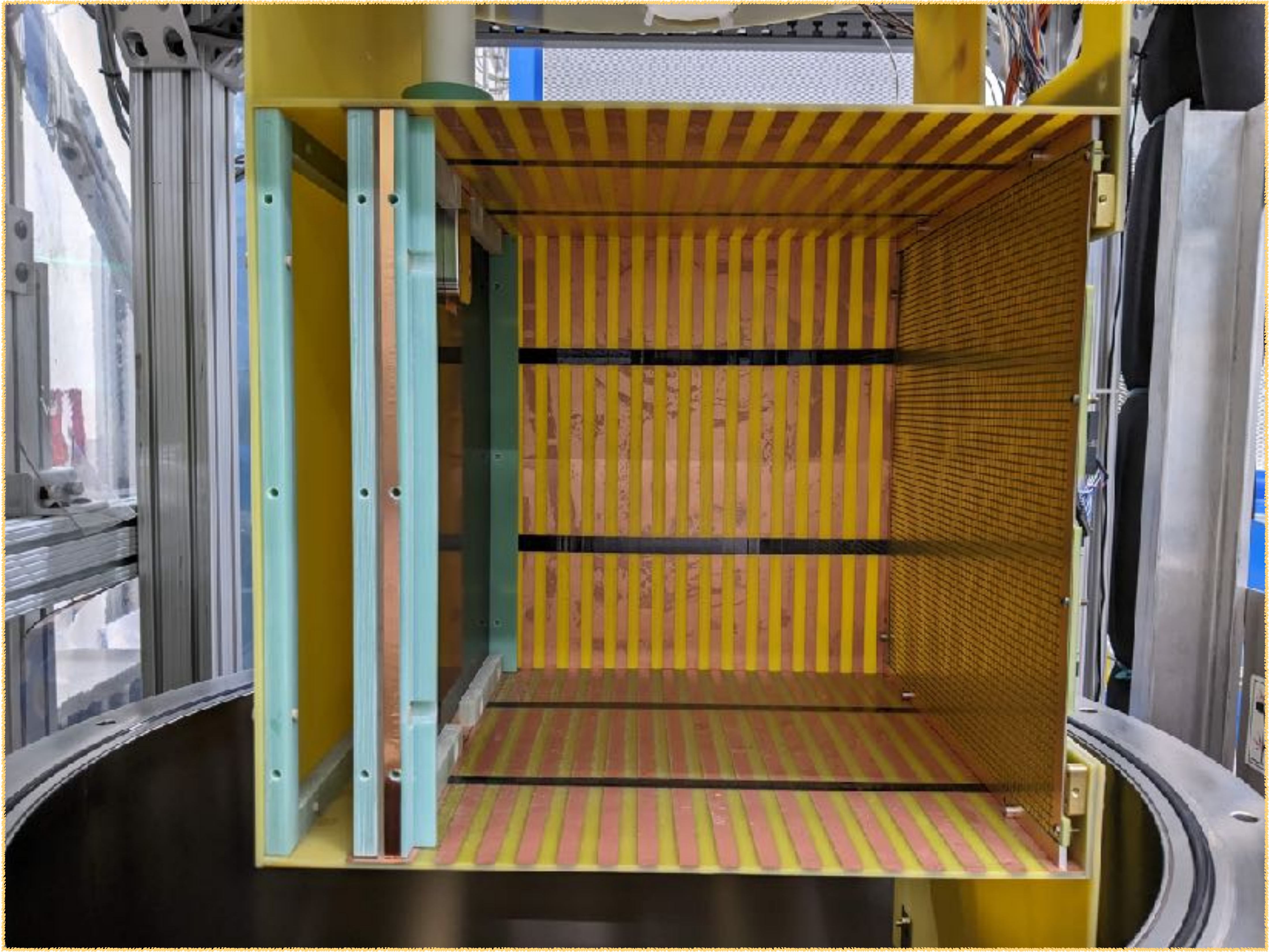


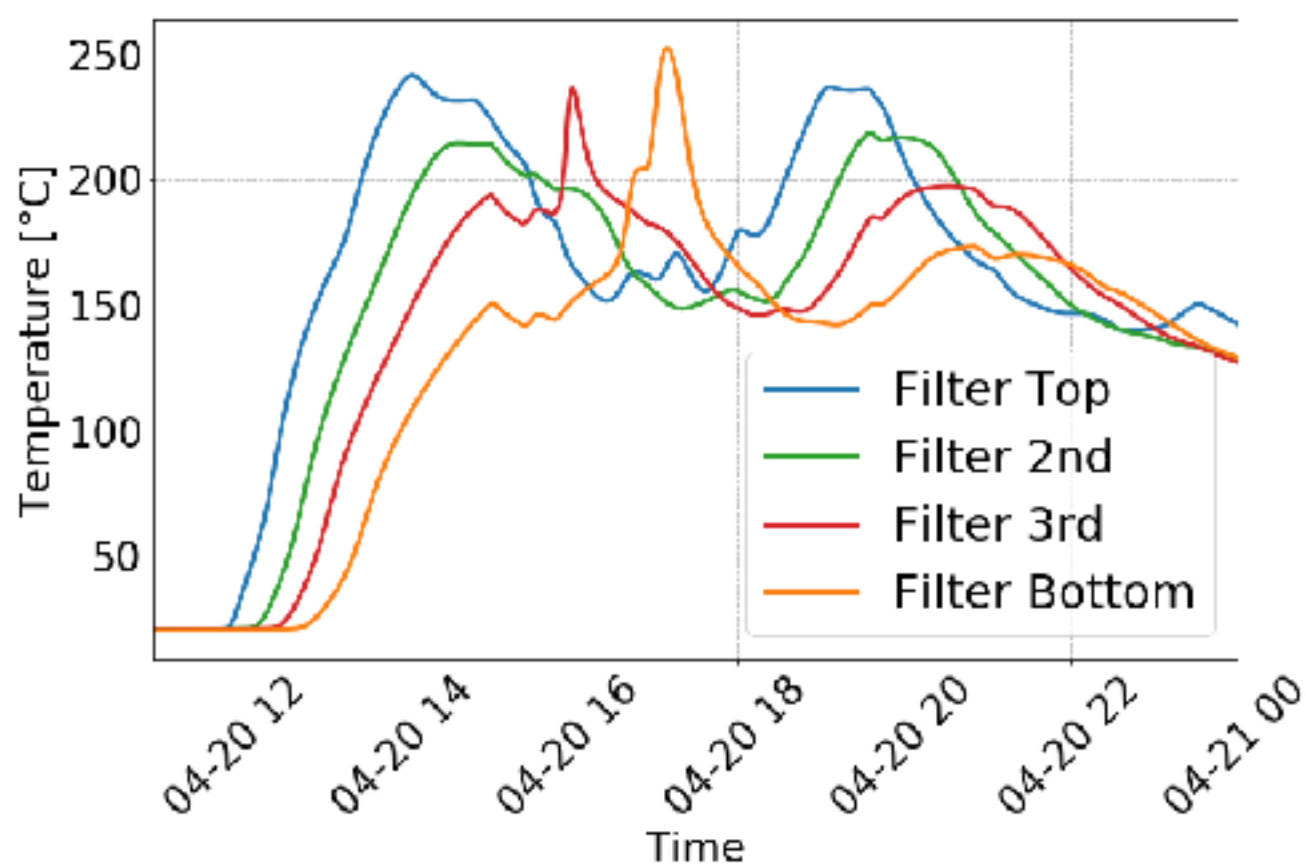


Plots made by P. Tsang



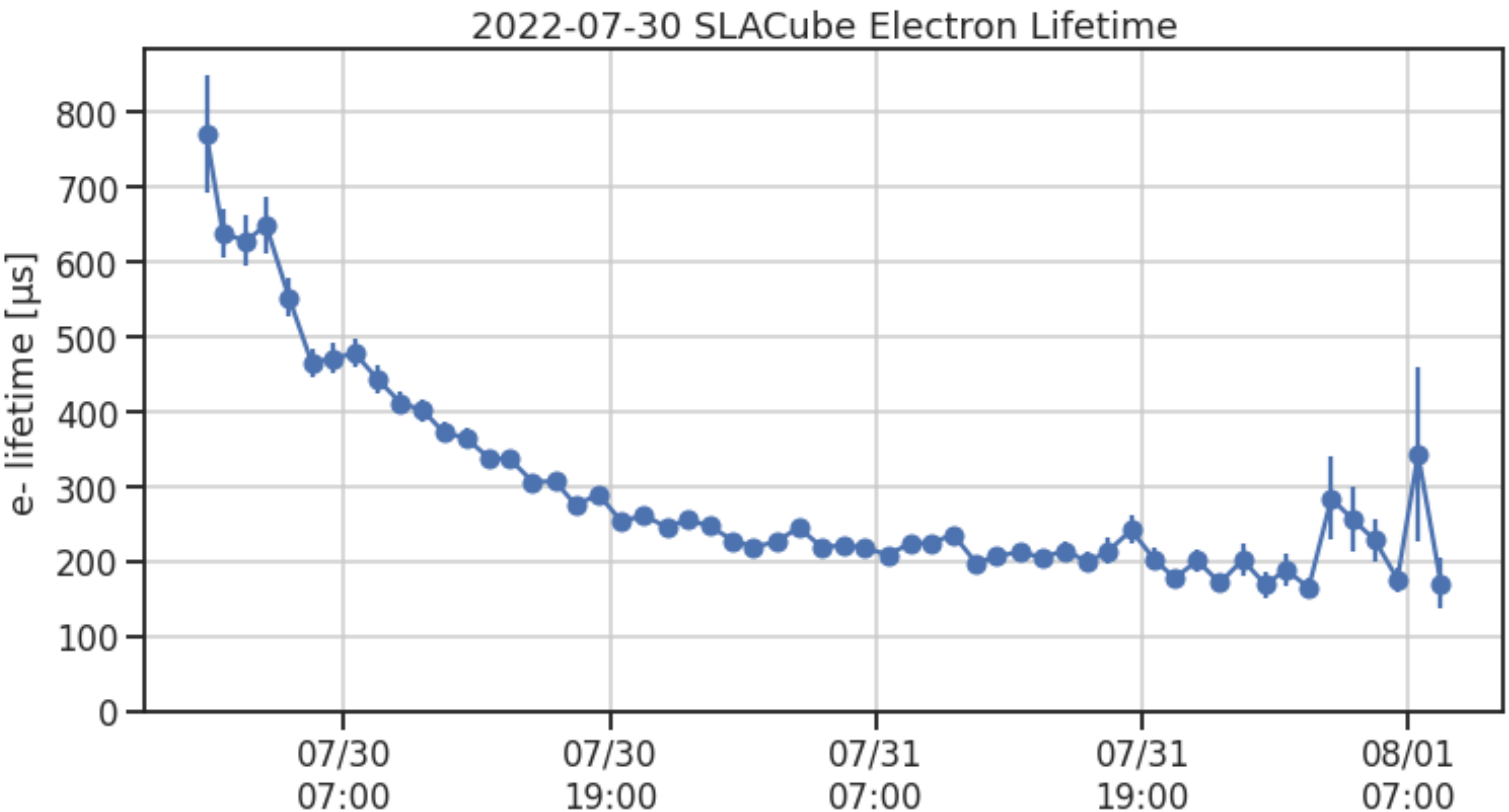
LAr Purifier

- Single pass purifier
- Top: 4.6 kg molecular sieves (water)
- Bottom: 5.2 kg copper sieves (oxygen)
- Ar and 2% H_2+Ar gas to regenerate the molecular and copper sieves



- 15 L/min gas flow/kg
- ~200°C
- H+O→H_2O exothermal reaction

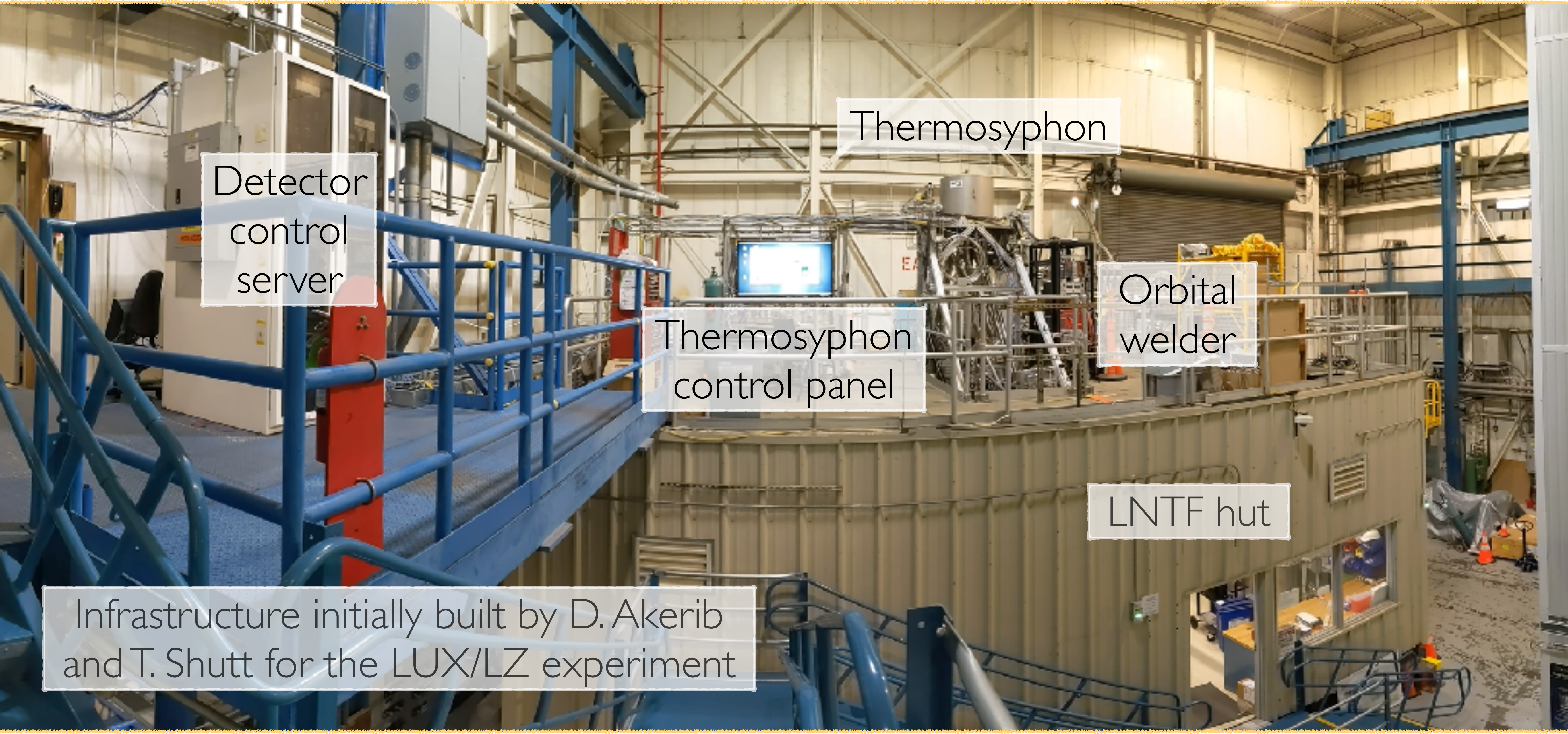
Evolution of LAr Purity



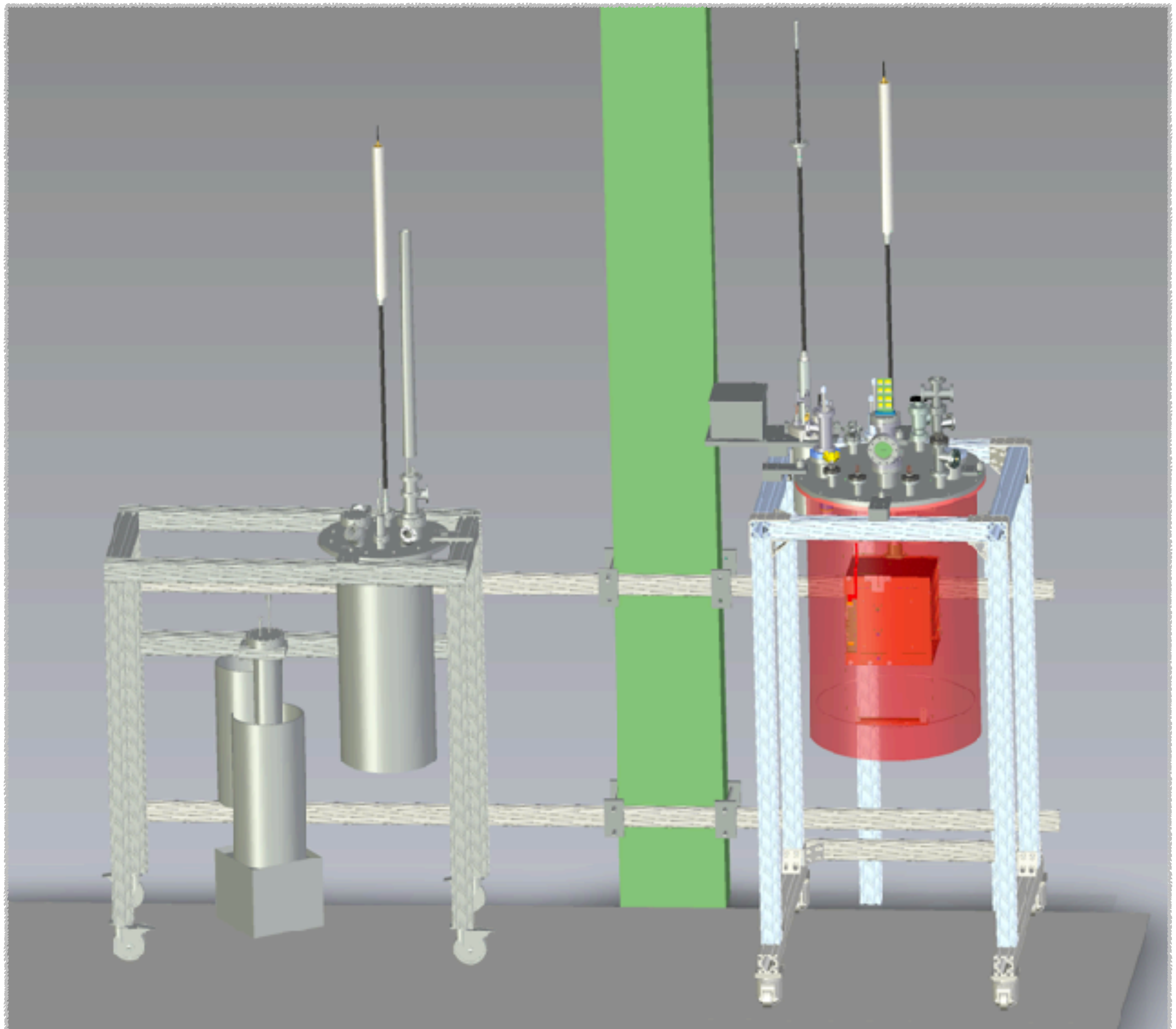
Plots and analyses by P.Tsang

Liquid Noble Test Facility

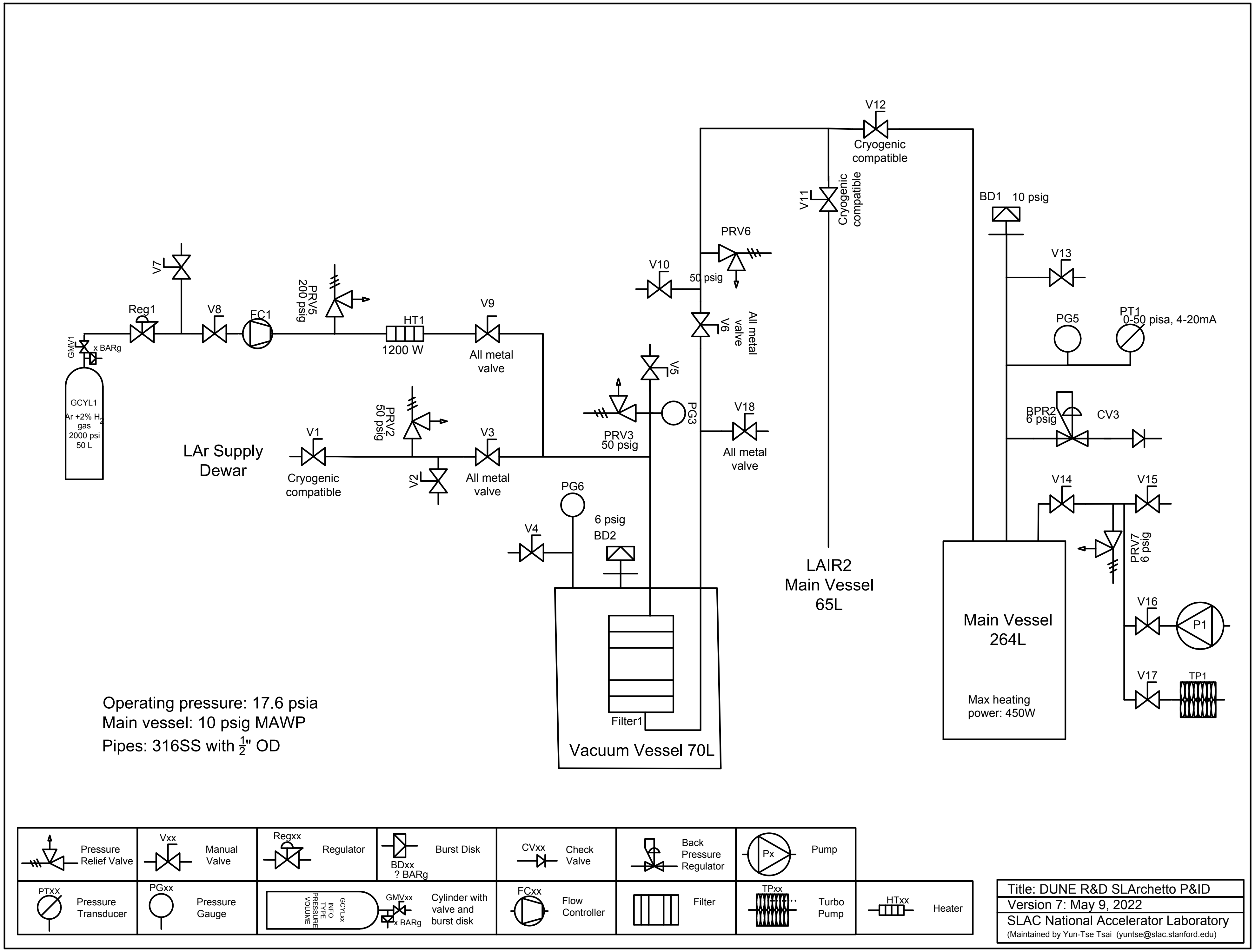
Liquid Noble Test Facility



LAr Setup at LNTF

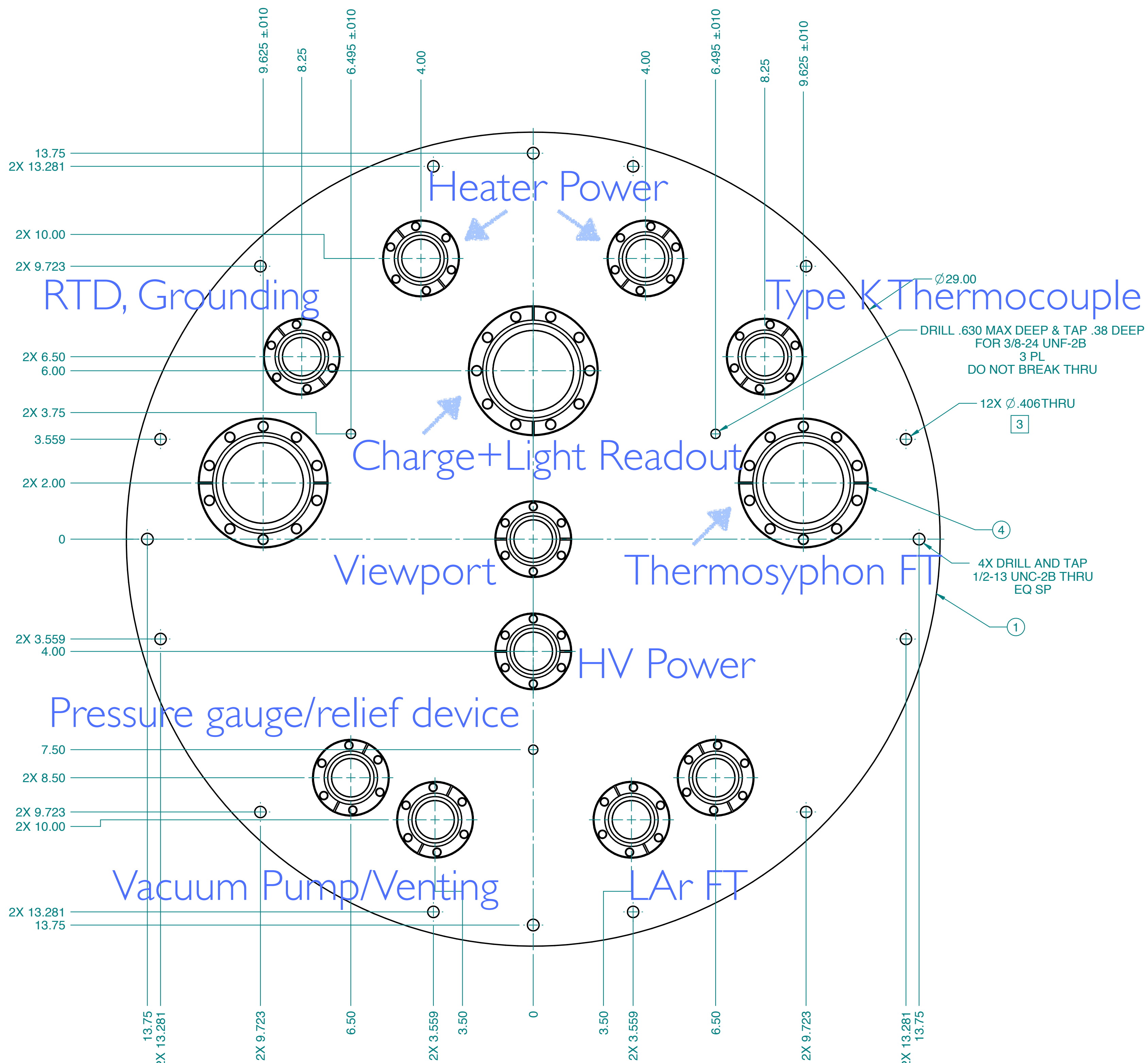


P&ID

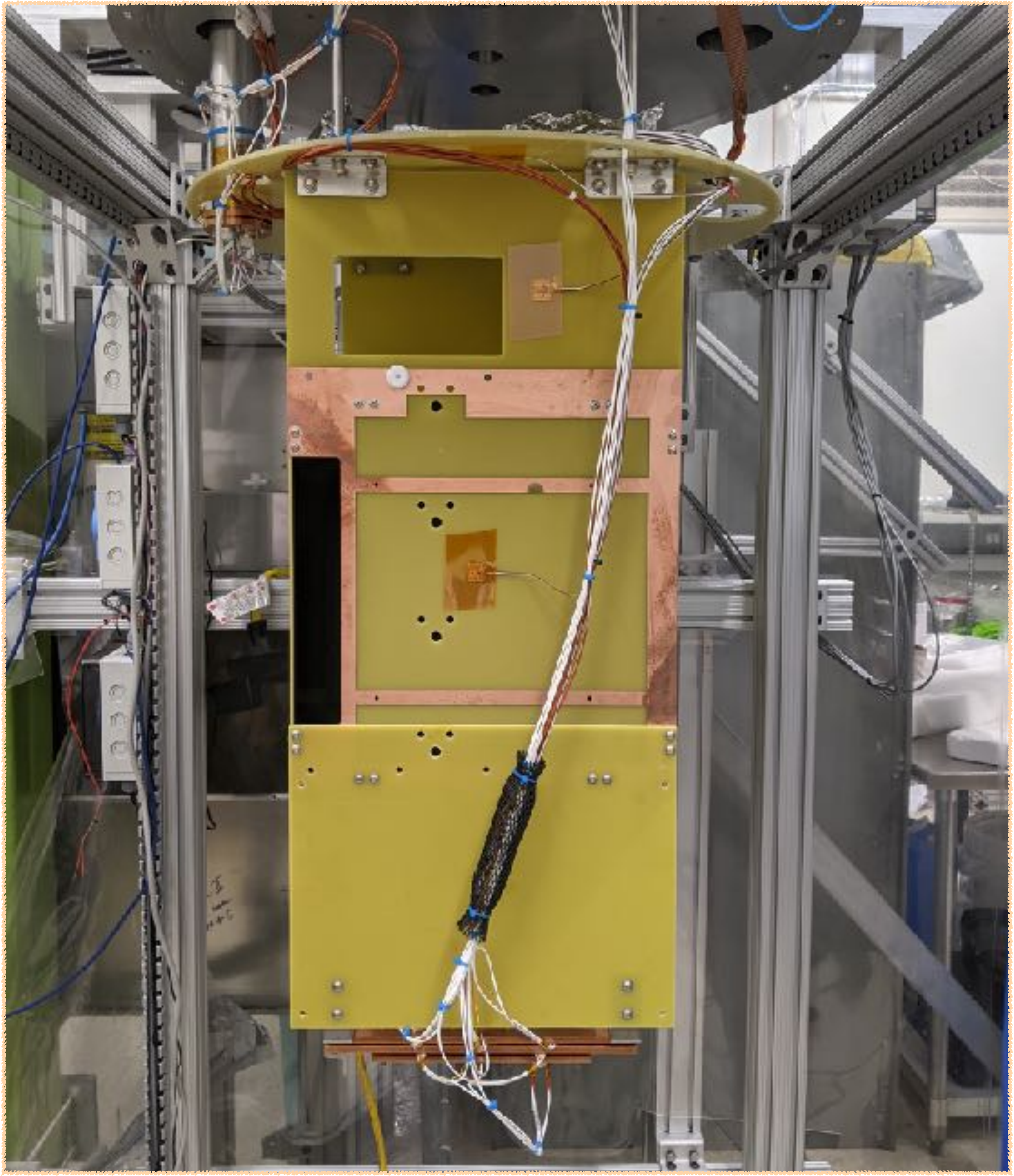


V12
Cryogenic compatible
V11
Cryogenic compatible
BD1 10 psig
V13
PG5
PT1 0-50 pisa, 4-20mA
BPR2 6 psig
CV3
V14
V15
PRV7 6 psig
V16
P1
V17
TP1
Main Vessel 264L
Max heating power: 450W
LAIR2 Main Vessel 65L
PRV6
V10
50 psig
V6
All metal valve
V5
PG3
PRV3 50 psig
V18
All metal valve
PG6
6 psig
BD2
V4
Filter1
Vacuum Vessel 70L
V7
Reg1
V8
FC1
PRV5 200 psig
HT1
1200 W
V9
All metal valve
GMV1
x BARg
GCYL1
Ar +2% H2 gas
2000 psi
50 L
LAr Supply Dewar
V1
Cryogenic compatible
PRV2 50 psig
V2
V3
All metal valve
Operating pressure: 17.6 psia
Main vessel: 10 psig MAWP
Pipes: 316SS with ½" OD
Pressure Relief Valve
Vxx
Manual Valve
Regxx
Regulator
BDxx
? BARg
Burst Disk
CVxx
Check Valve
Back Pressure Regulator
Px
Pump
PTXX
Pressure Transducer
PGxx
Pressure Gauge
GCYLxx
INFO
TYPE
PRESSURE
VOLUME
GMVxx
x BARg
Cylinder with valve and burst disk
FCxx
Flow Controller
Filter
TPxx
Turbo Pump
HTxx
Heater
Title: DUNE R&D SLArchetto P&ID
Version 7: May 9, 2022
SLAC National Accelerator Laboratory
(Maintained by Yun-Tse Tsai (yuntse@slac.stanford.edu)

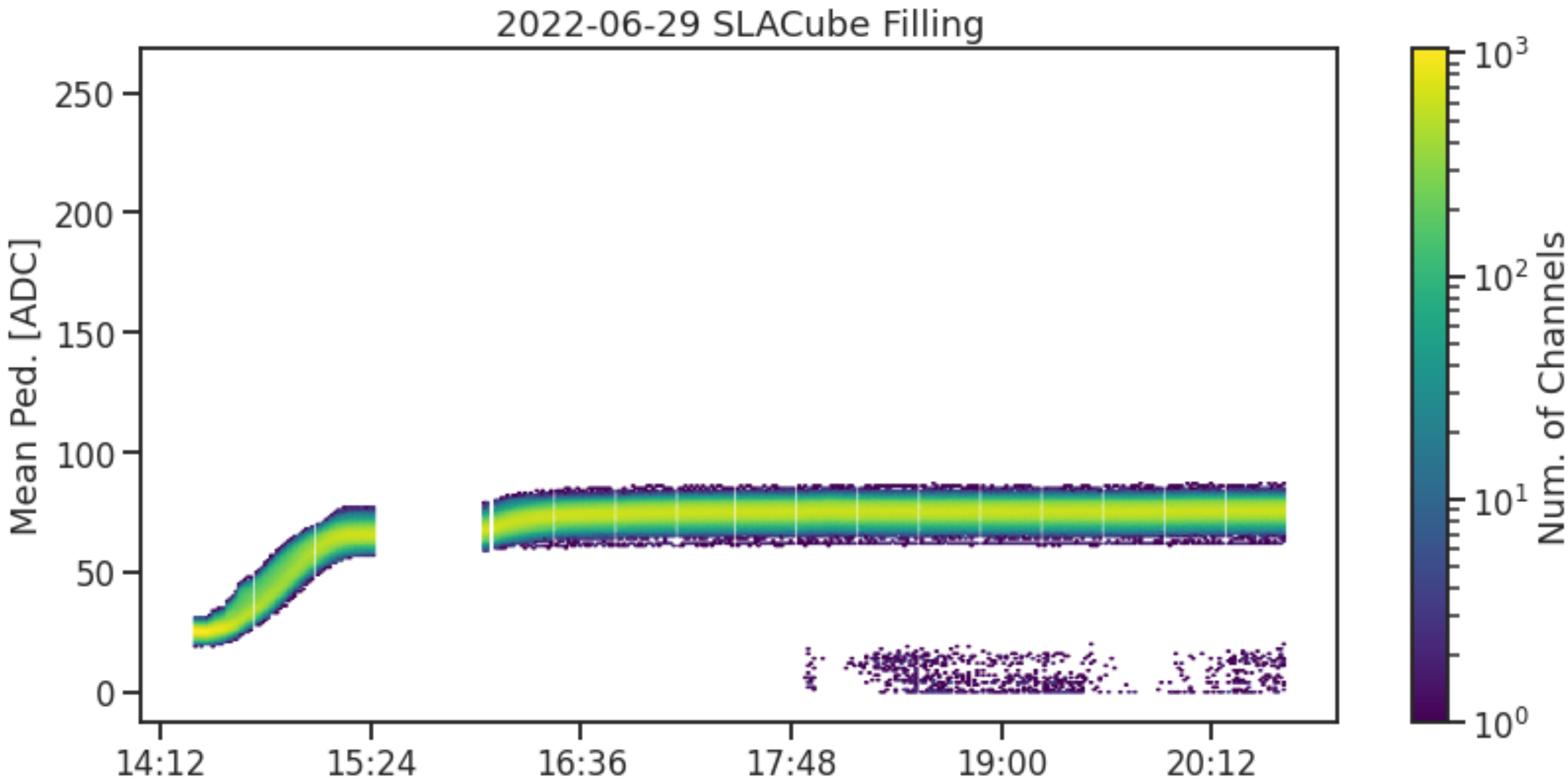
Top Lid



Heater Power
RTD, Grounding
Type K Thermocouple
Charge+Light Readout
Viewport
Thermosyphon FT
HV Power
Pressure gauge/relief device
Vacuum Pump/Venting
LAr FT
∅29.00
DRILL .630 MAX DEEP & TAP .38 DEEP
FOR 3/8-24 UNF-2B
3 PL
DO NOT BREAK THRU
12X ∅.406THRU
3
4
4X DRILL AND TAP
1/2-13 UNC-2B THRU
EQ SP
1
13.75
2X 13.281
2X 10.00
2X 9.723
2X 6.50
6.00
2X 3.75
3.559
2X 2.00
0
2X 3.559
4.00
7.50
2X 8.50
2X 9.723
2X 10.00
2X 13.281
13.75
9.625 ±.010
8.25
6.495 ±.010
4.00
4.00
6.495 ±.010
8.25
9.625 ±.010
13.75
2X 13.281
2X 9.723
6.50
2X 3.559
3.50
0
3.50
2X 3.559
6.50
2X 9.723
2X 13.281
13.75



Pedestal During LAr Filling



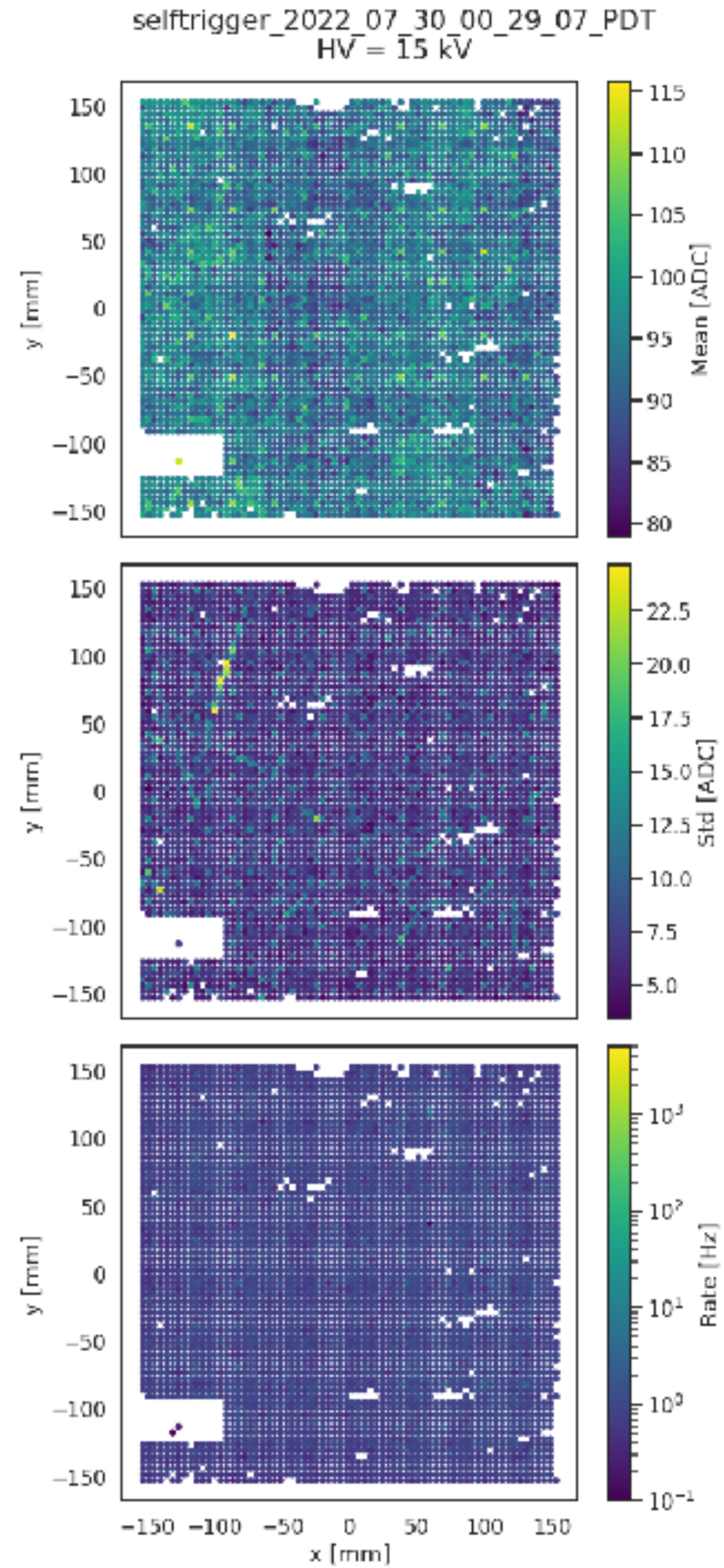
Plots and analyses by P.Tsang

Operation at Nominal E-field

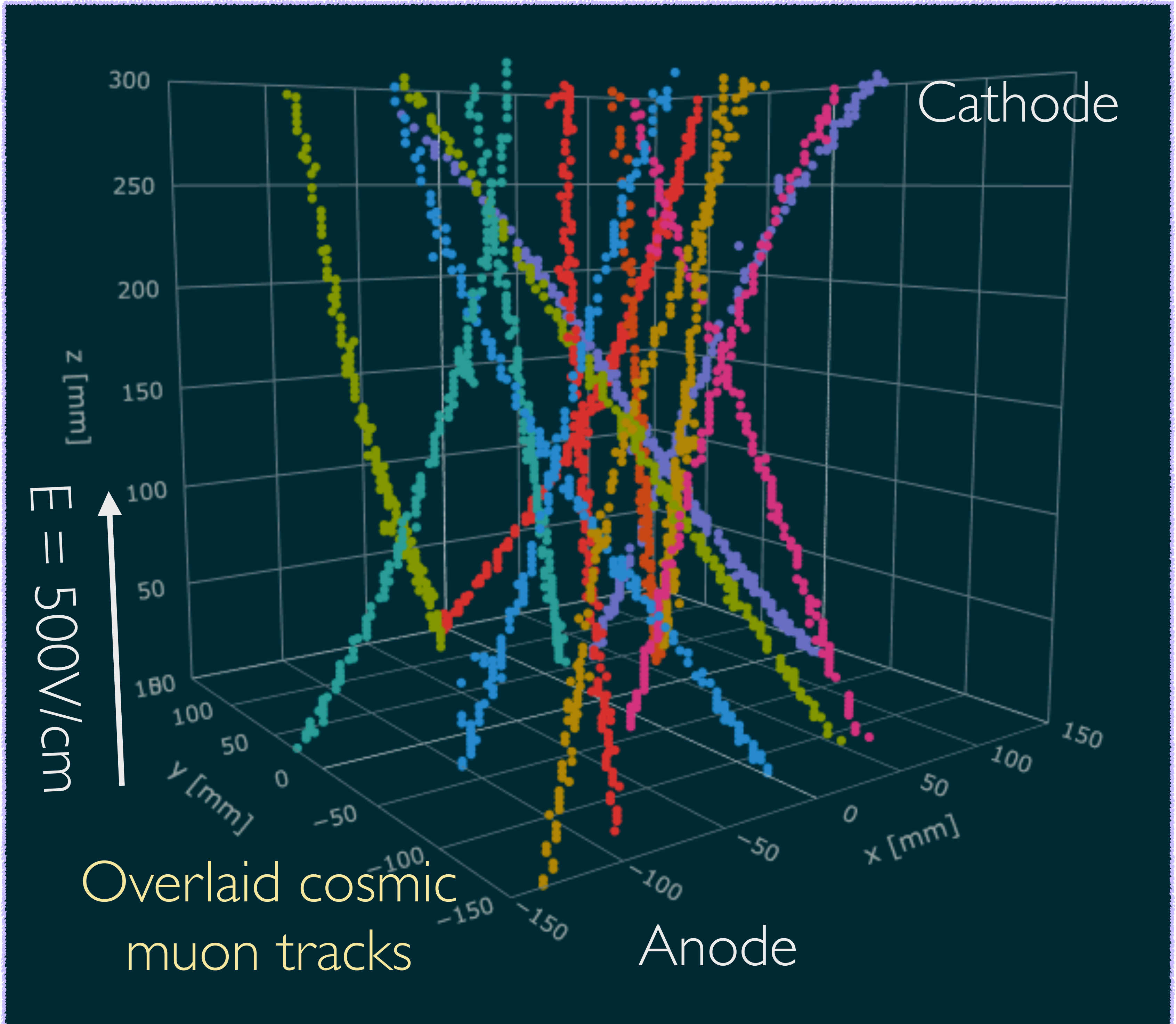
500V/cm, totally 15 kV

First time operating LArPix at the nominal E-field with reasonable noise level (manageable trigger rate)

Plots and analyses by P.Tsang



Cosmic Muon Track



E = 500 V/cm

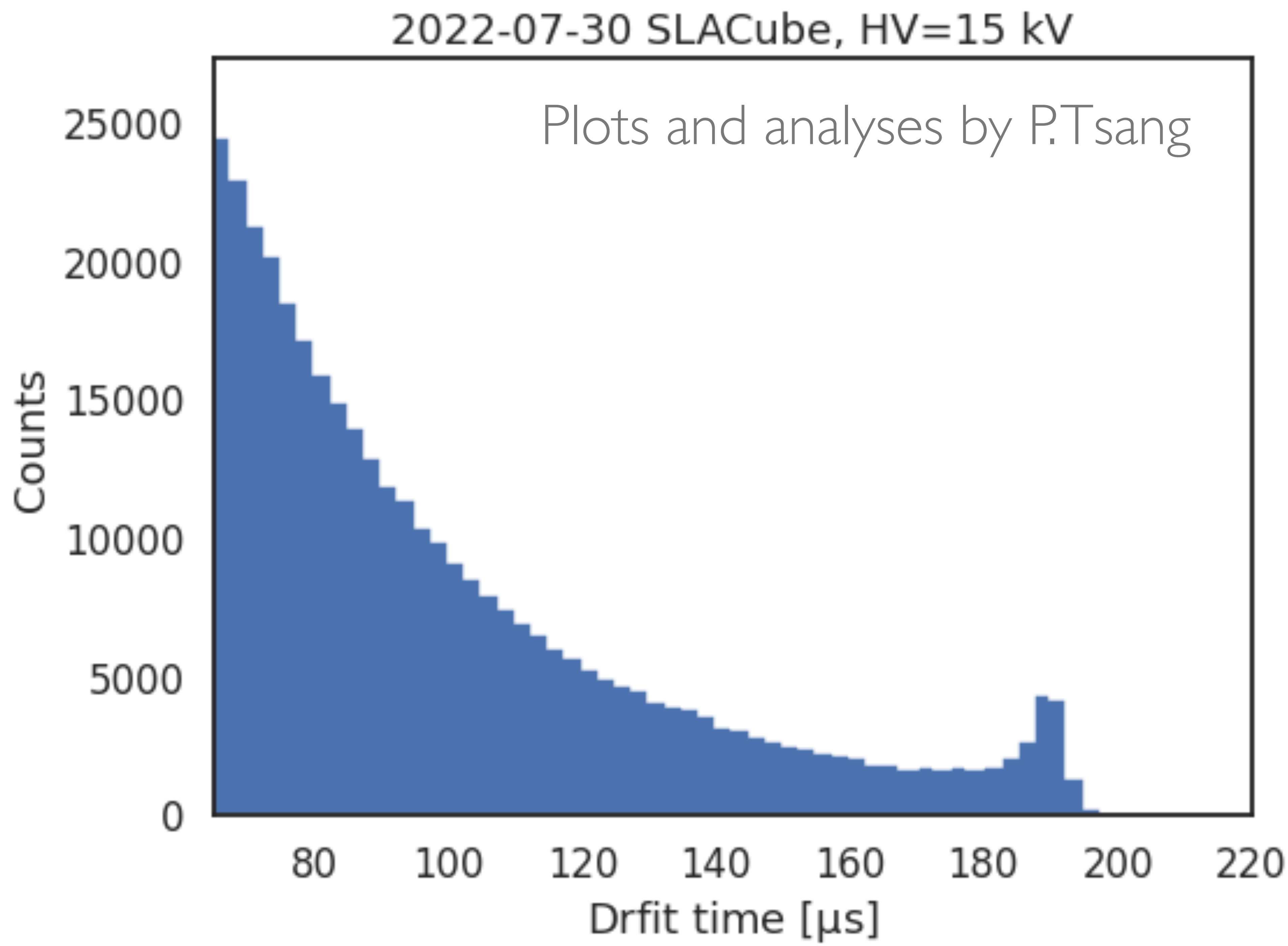
Electron lifetime (LAr purity) ~ 225 μs

Data taken on July 30th

~1 cosmic ray track every 2 minutes

Plots, analyses by P. Tsang

Electron Drift Time



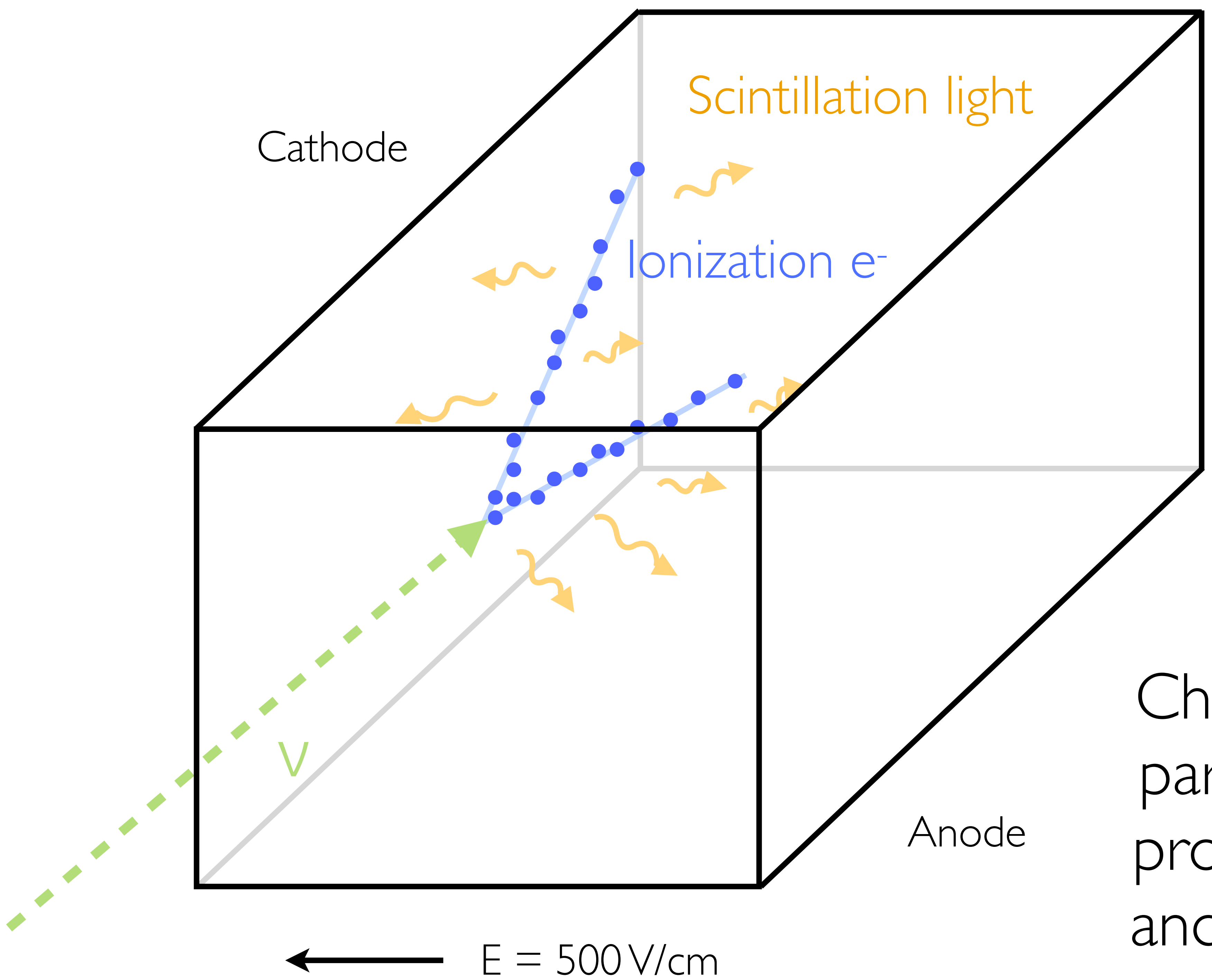
SLAC (former members included):
Haufai Auyeung, Dan Carber, Yifan Chen, Bob Conley, Laura Domine, Francois Drielsma, Zach Hulcher, Patin Inkaew, Ran Itay, Dae Heun Koh, Nadine Kurita, Gianluca Petrillo, Norm Picker, Brian Qiu, Gabe Shutt, James Sinclair, Knut Skarpaas, Hiro Tanaka, Yun-Tse Tsai, Patrick Tsang

Michigan State University (MSU):
Dan Douglas, Kendall Mahn, DeMario Ross, Liz Triller

University of Hawaii:
Ranjan Dharmapalan, Alex Dvornikov, Jelena Maricic

Special thanks to SLAC LZ and nEXO groups

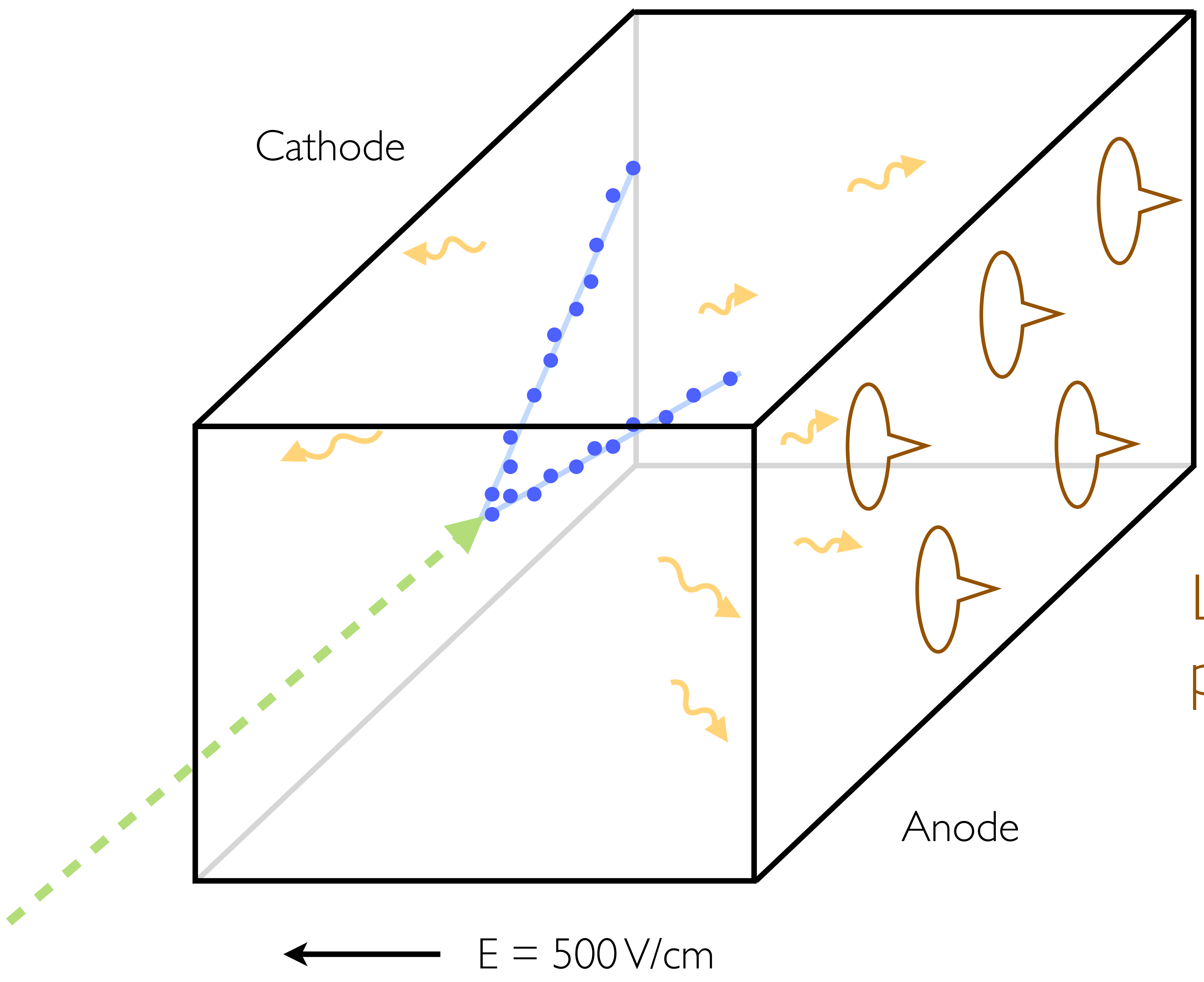
LArTPC



Incoming neutrino interacting with LAr

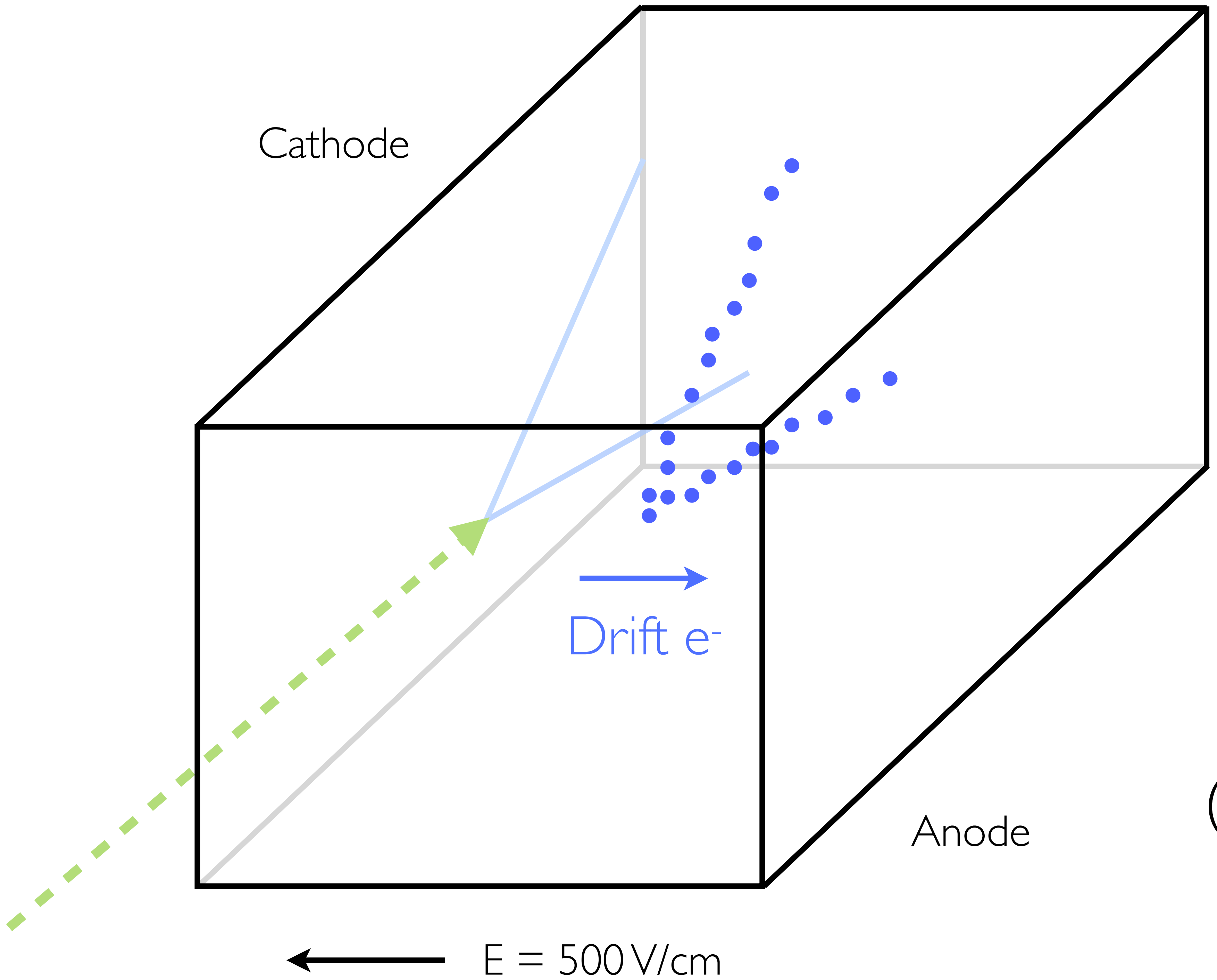
Charged secondary particles ionize LAr, producing electrons and scintillation light

LArTPC



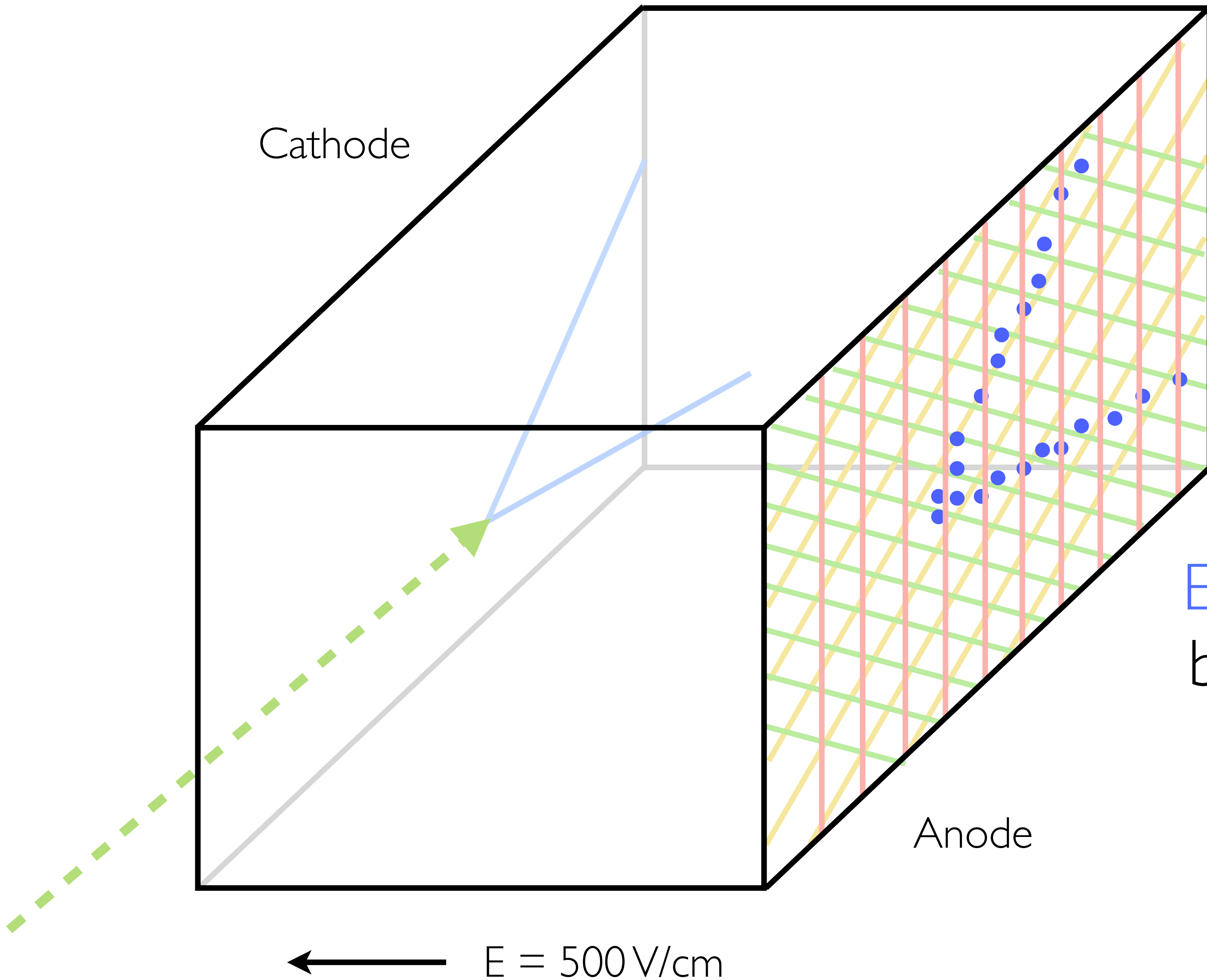
Light collected by photon detectors (10-100ns), determining event time t_0

LArTPC



Electrons drift towards anode (drift time at ms scale)

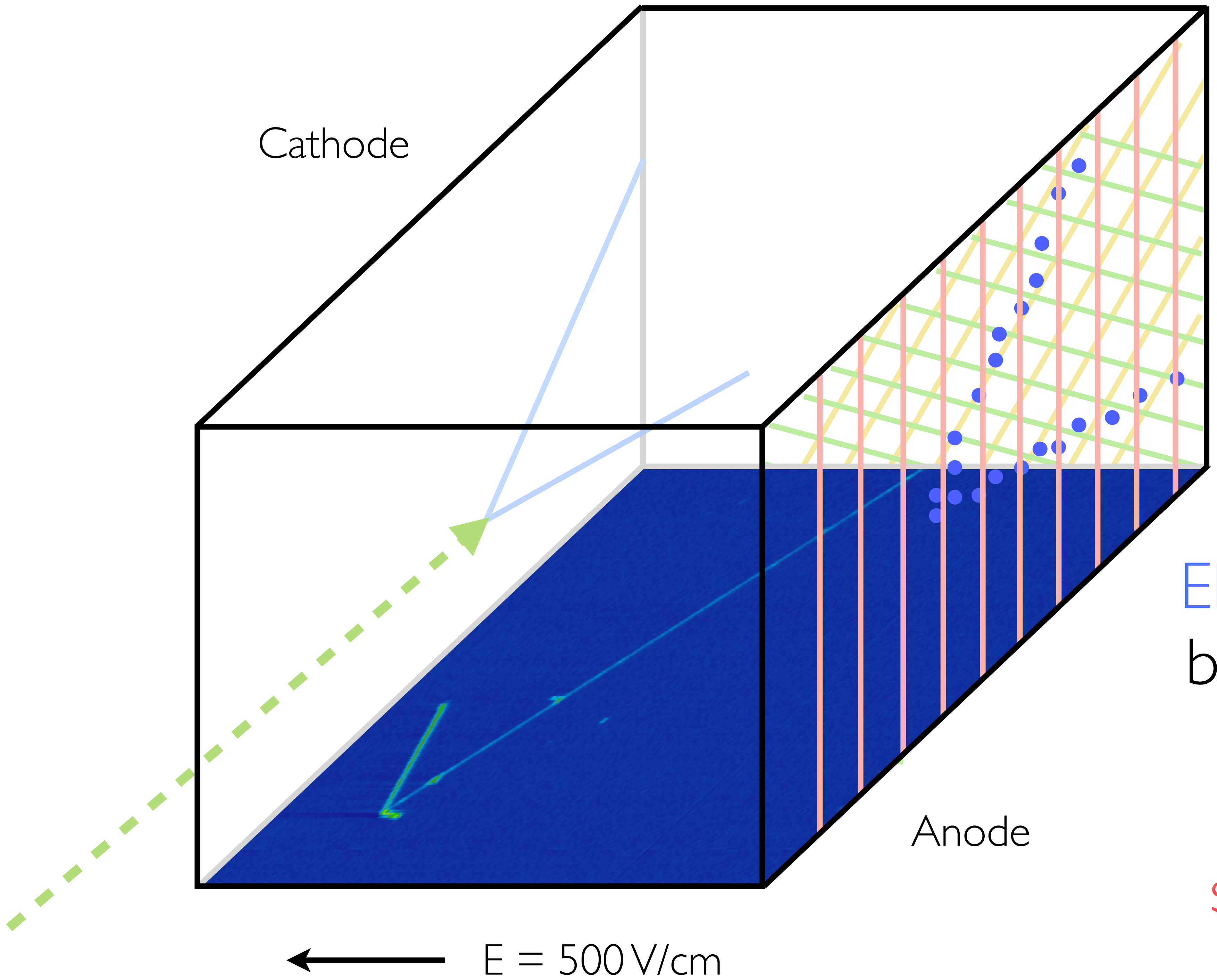
LArTPC



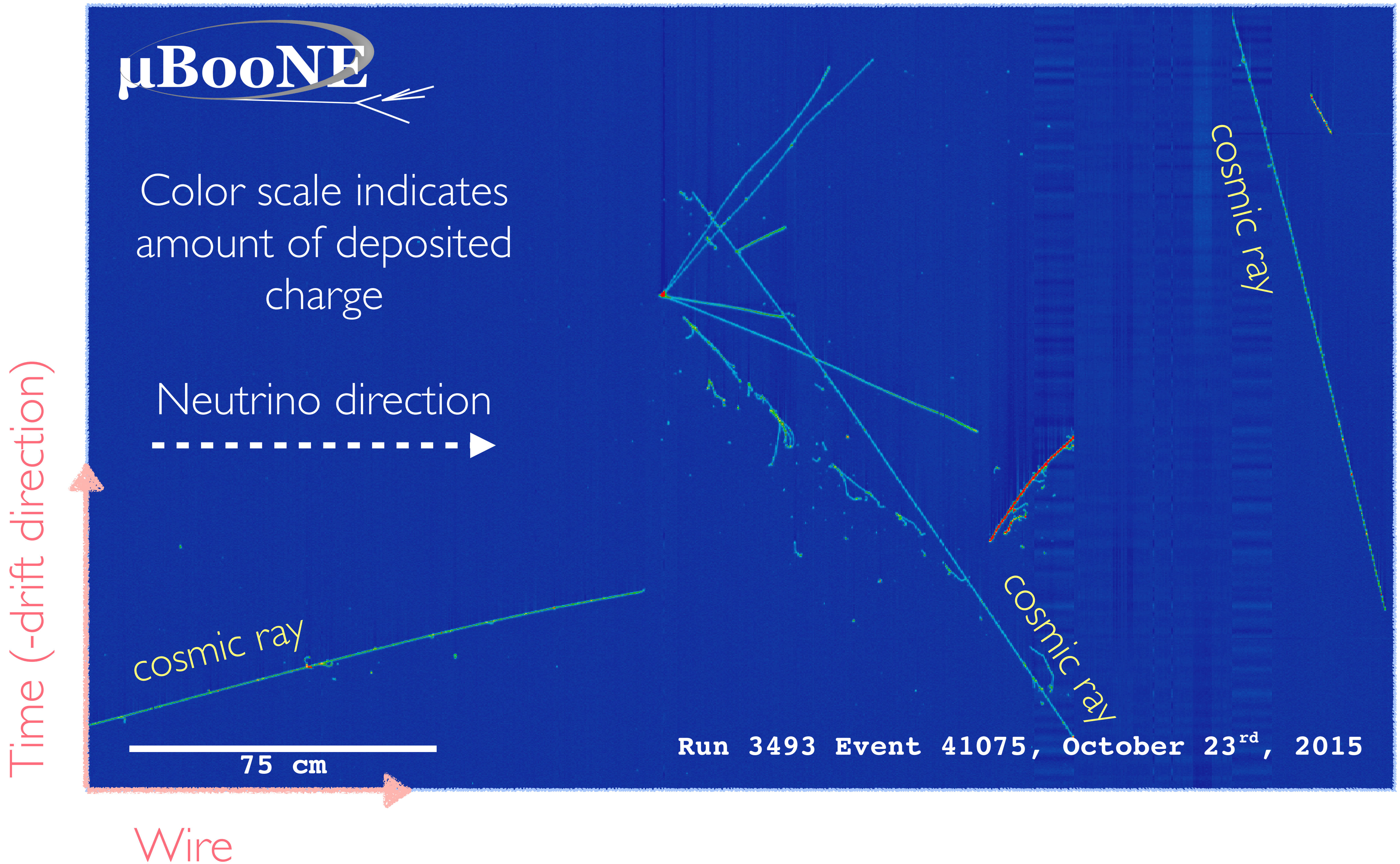
2 induction planes
1 collection plane

Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

LArTPC



Electrons detected by the wire planes at anode, providing the spatial, kinematic information.


μBooNE
Color scale indicates amount of deposited charge
Neutrino direction
cosmic ray
cosmic ray
cosmic ray
75 cm
Run 3493 Event 41075, October 23rd, 2015
Time (-drift direction)
Wire