

Introduction to LArTPC for Neutrino Detection and Cryogenic System

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Outline

▸ **Neutrino Detection**

- Requirements for Neutrino Detection—> Noble Elements
- LAr Properties

▸ **LArTPC**

- LArTPC operation principle
- Technical challenges

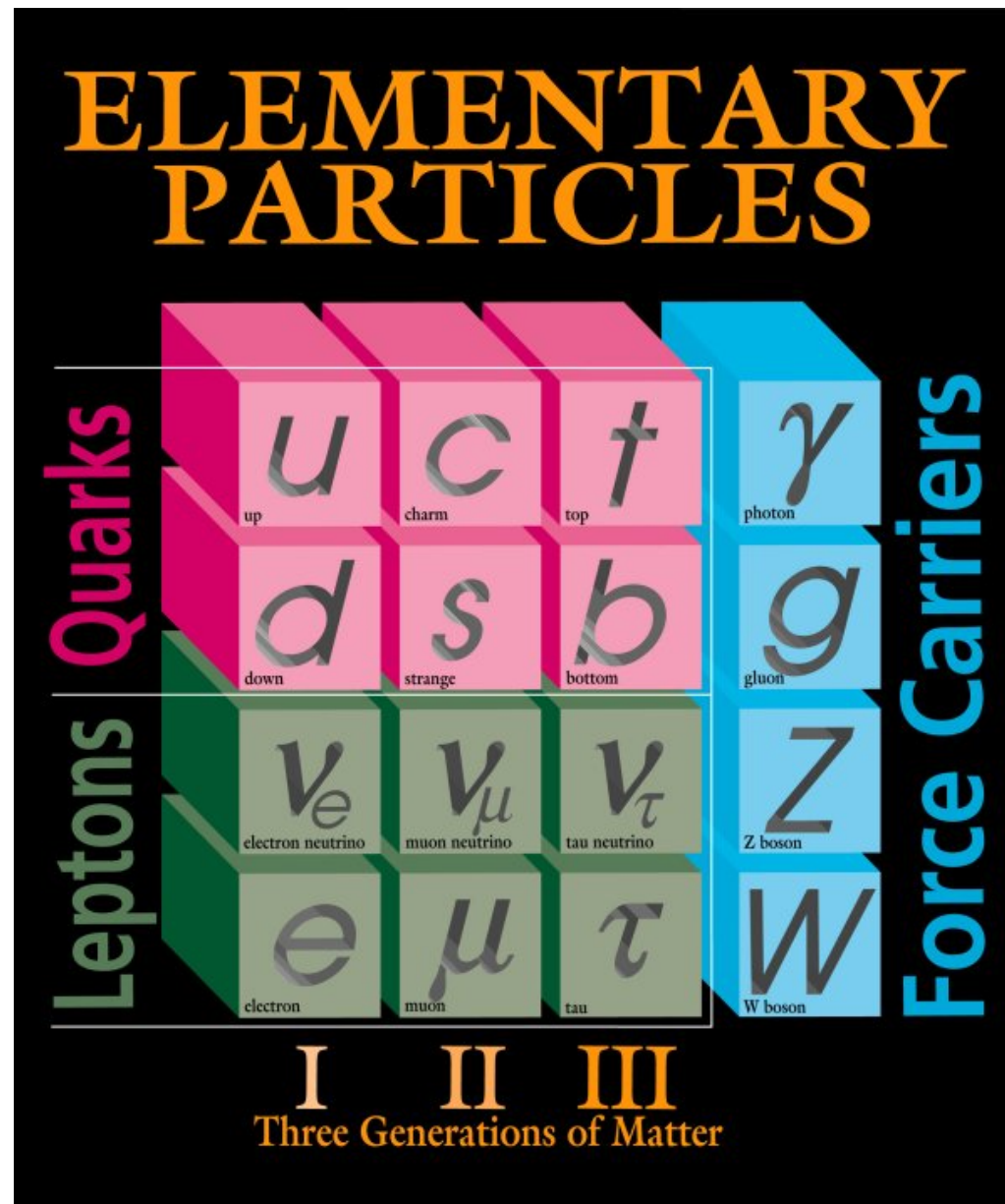
▸ **Cryostat Introduction**

- Overview of Cryogenic system
- Heat Transfers for cryostat
- Cryostat Insulations

▸ **Large LArTPC of MicroBooNE, ICARUS, DUNE/ProtoDUNE Cryostat**

- MicroBooNE cryostat
- ICARUS cryostats: Gran Sasso—>SBN
- ProtoDUNE Cryostat
- ND-LAR
- Summary

What is neutrino?



Fermilab 95-759

Interaction	Mediators	Relative Strength	Range (m)
Strong	g	10^{38}	10^{-15}
E&M	γ	10^{36}	[?]
Weak	W, Z	10^{25}	10^{-18}
Gravitation	gravitons	1	[?]

Neutrinos are fundamental particles in the standard model!

They interact through weak interaction

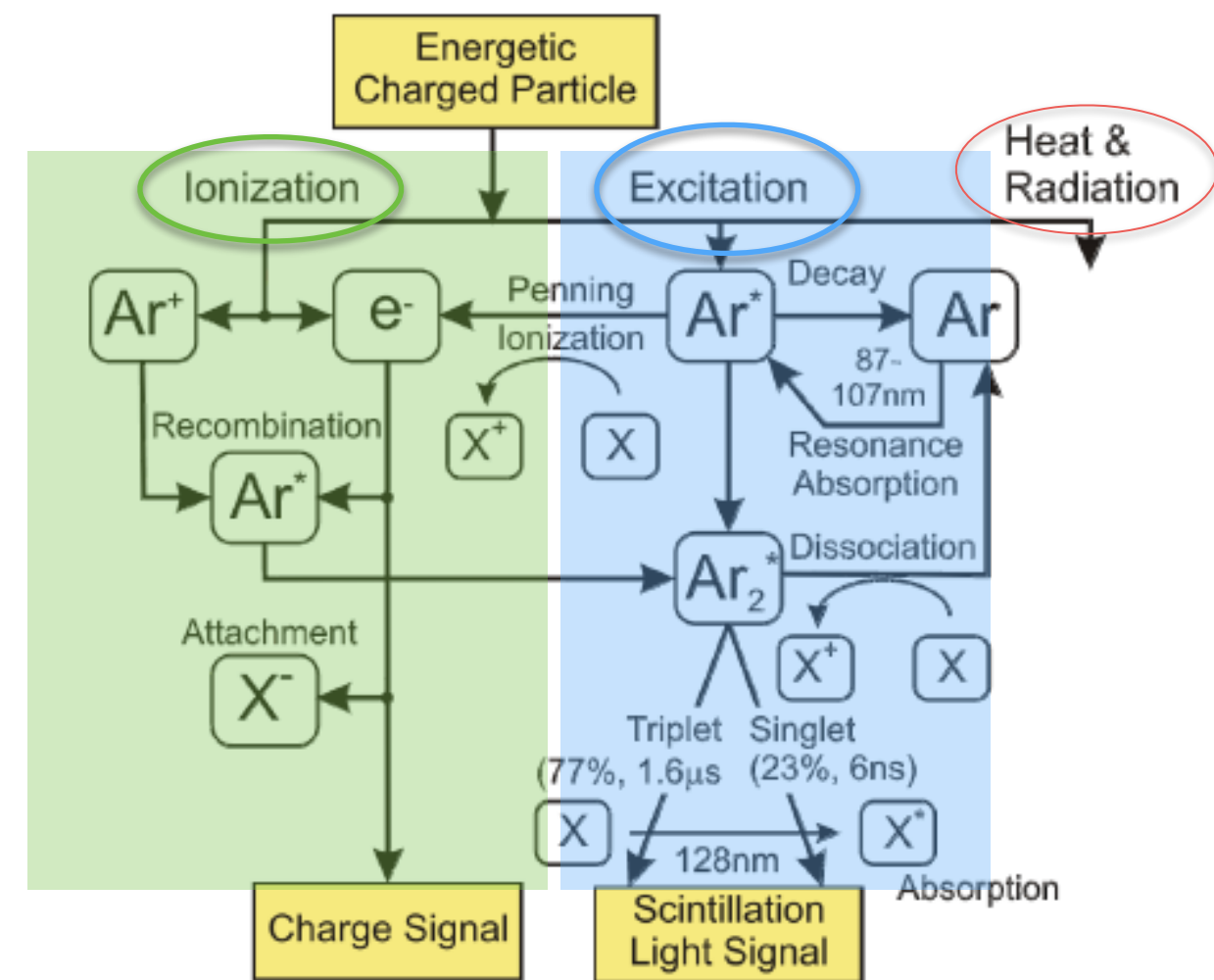
(More details in Chao's lecture this Tuesday)

Experimental Detection of Neutrino Interactions

- In general, the requirements for neutrino detection is to get data with sufficient statistics to study physics
- HEP experiments are indirect measurement
 - The particle of interest is too small to be visible
 - The particles are detected via the interactions with the detector medium
 - Charge and Light signals

$$N_{\text{det.}} = \epsilon \otimes \sigma \otimes \mathcal{L}$$

Signal observed \uparrow $N_{\text{det.}}$
 Detection Efficiency (Detector) \uparrow ϵ
 Cross-Section (Physics) \downarrow σ
 Luminosity (Flux+Medium Mass) \uparrow \mathcal{L}



Requirements for Neutrino Detector

- **Big/Massive**

- Guarantee sufficient number of events with small cross-section of neutrino interactions

- **Resolution**

- Sufficiently precise to extract physics information

- **Fast**

- Precisely determine event time and reject background

- **Affordable**

- Economically feasible to built a large scale detector

- **Versatile**

- Capable of detecting multiple types of interactions/particles

Why Liquid Argon?

- Large number of ionization electrons production and scintillation light yield
- If the purity is high (<0.1 ppb) Ionized charges can drift through long distance
- Dense to provide a large mass for neutrino interactions
- High dielectric strength to hold high voltage to drift electrons
- Argon is abundant in the air($\sim 1\%$ of atmosphere), byproduct of liquid oxygen and liquid nitrogen production, low production cost

Prices in ~2015

	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost (\$/kg)	52	330	5	330	1200

Why Liquid Argon?

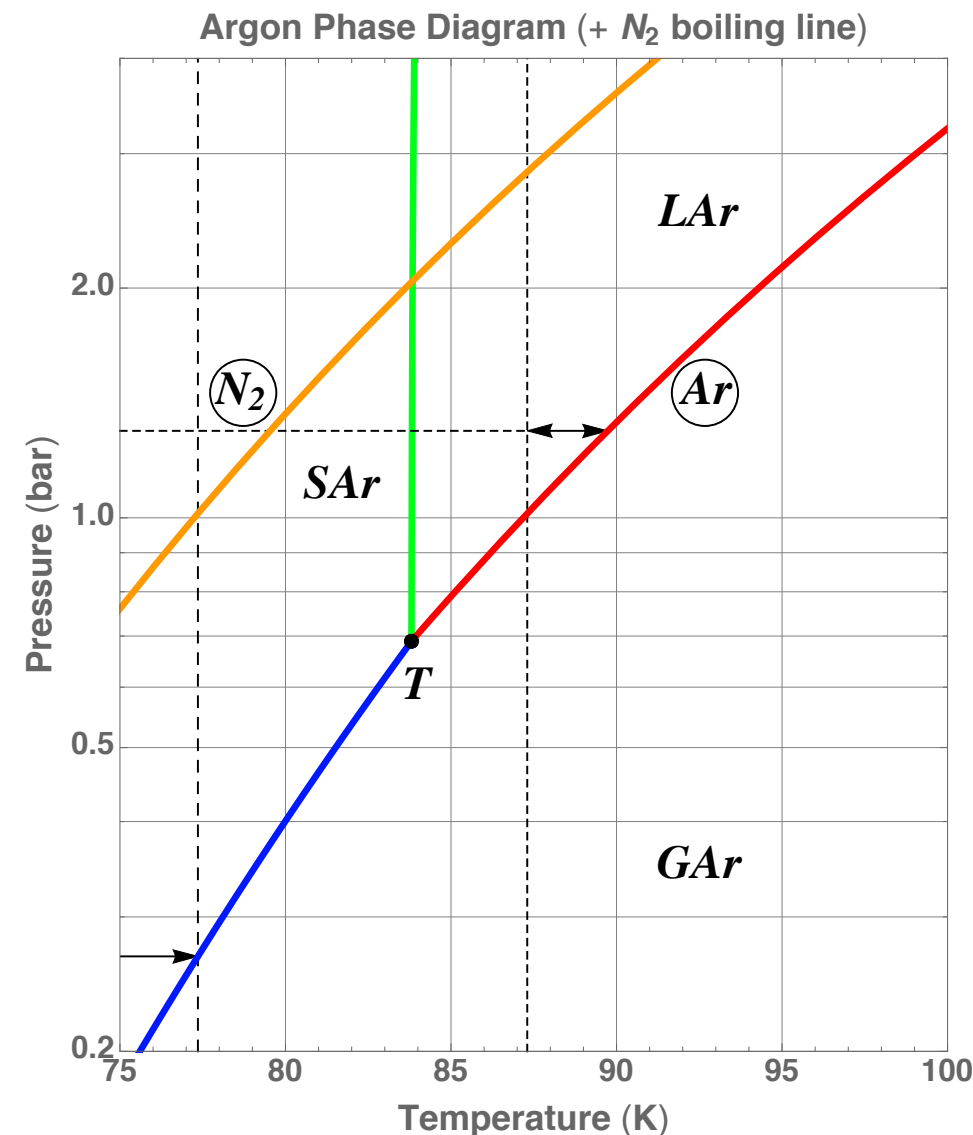
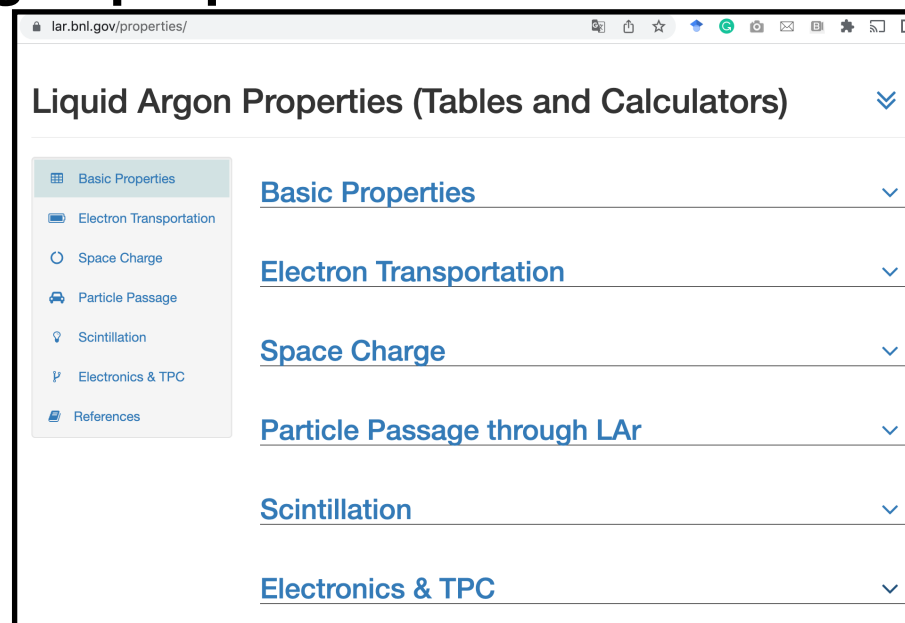
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Cost (\$/kg)	~110	~6000	10	~6000	~13000

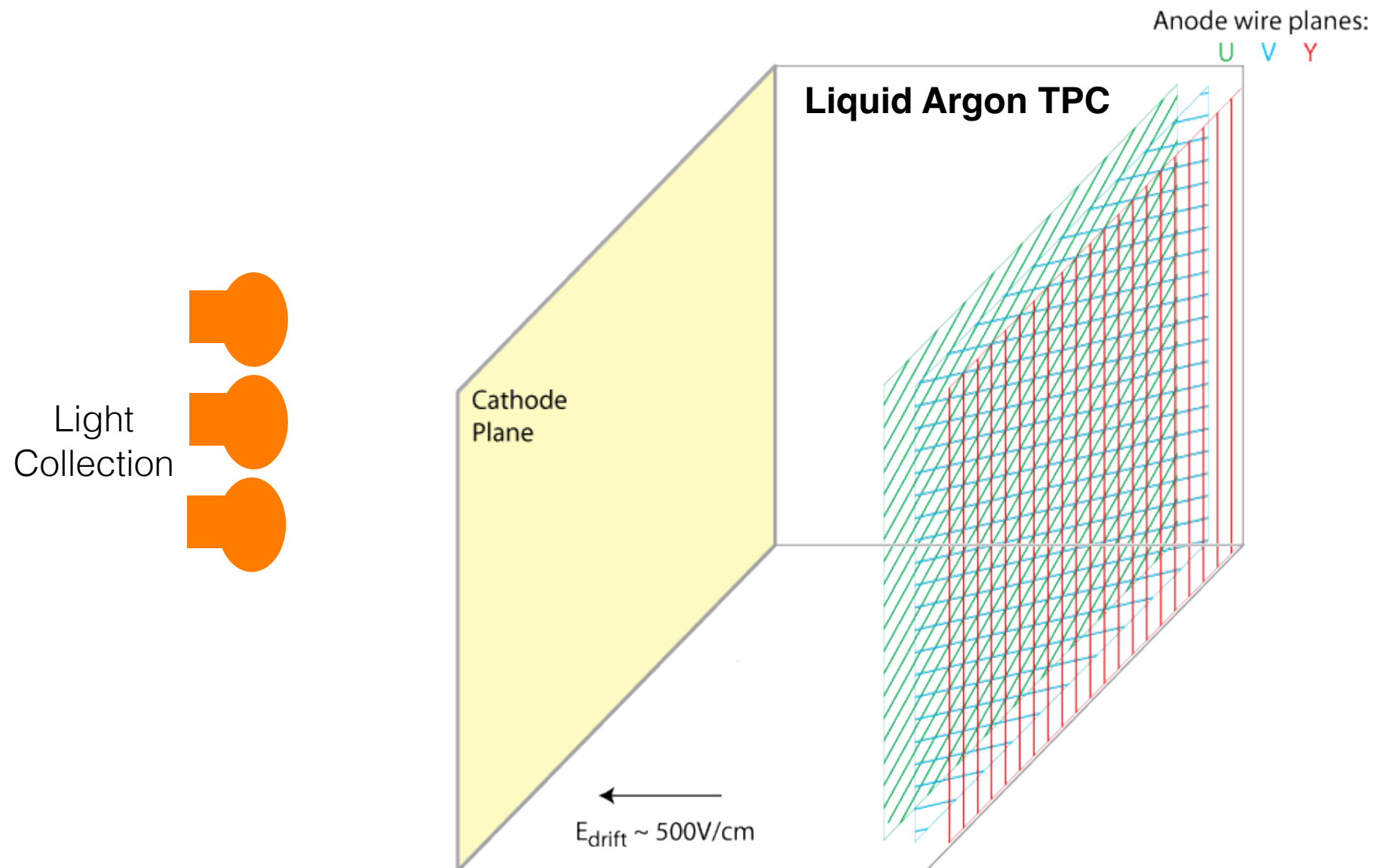
LAr Properties

- Thermal properties
 - Normal boiling point at 1 atm: 87.3K—>matches pressurized LN2 temperature for condensing
 - Triple point temperature: 83.8K
- Signal generations
 - W-value for ionization: 23.6 eV/pair
 - W-value for scintillation: 19.5 eV/photon
- Electron transportation properties:
 - Electron drift velocity $\sim 1.6\text{mm}/\mu\text{s}$ at 0.5kV/cm (3580 mph)
 - Electron drift velocity depends on LAr temperature
- Most information and homework:
<https://lar.bnl.gov/properties/>



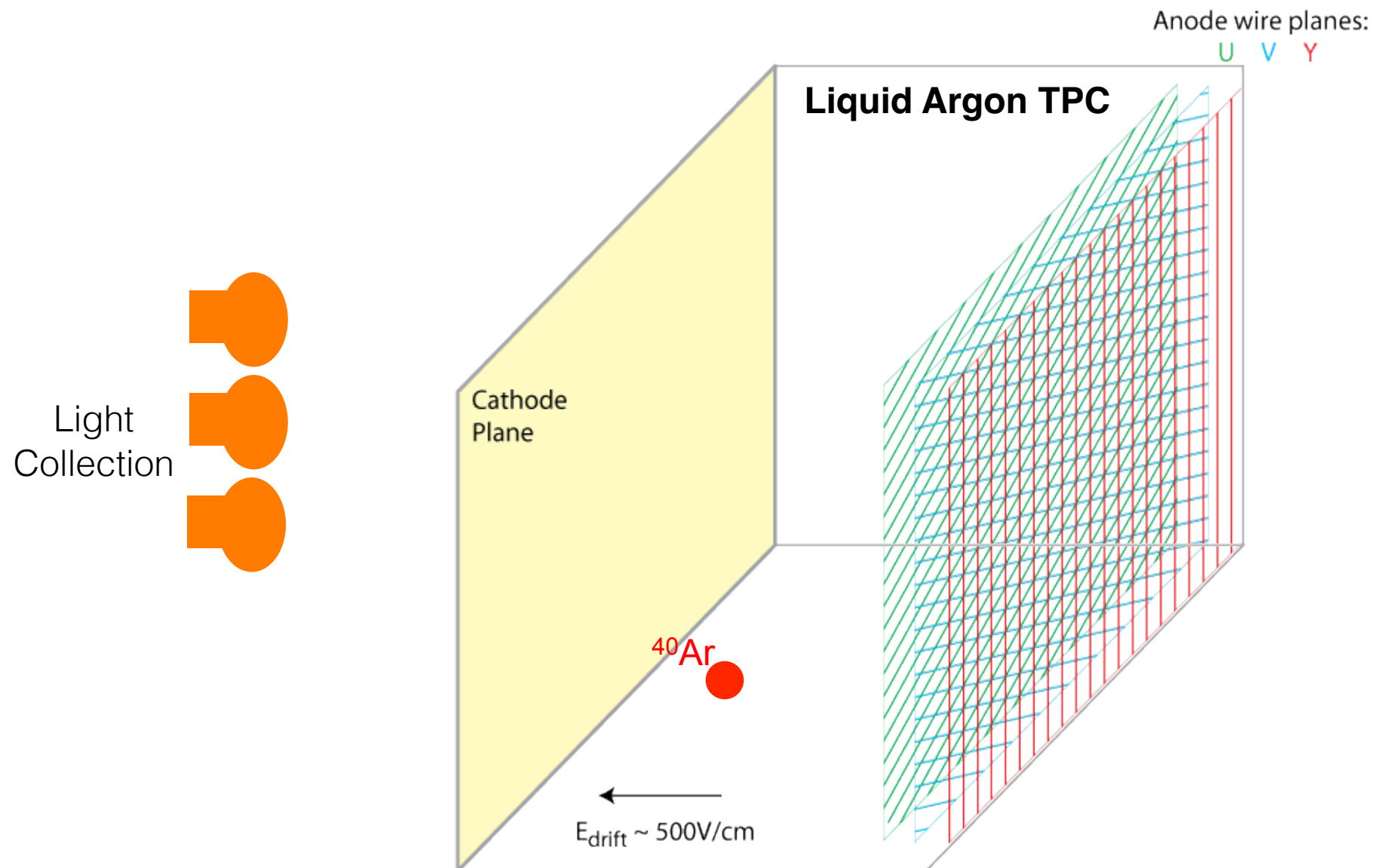
The Principle of LArTPC Detector

- Neutrino interaction with Ar
- Charged particle tracks ionized Ar atom.
- Scintillation Light (\sim ns) is detected by photo detector at the same time.
- Then ionized electrons are drifted to the anode plane(\sim ms in time, \sim meters in space).
- Electrons near the wires are collected first and electrons far from the wires are collected last, so drift coordinate information is converted into electron drift time(time is projected)
- Calorimetry information is extracted from wire pulse characteristics.



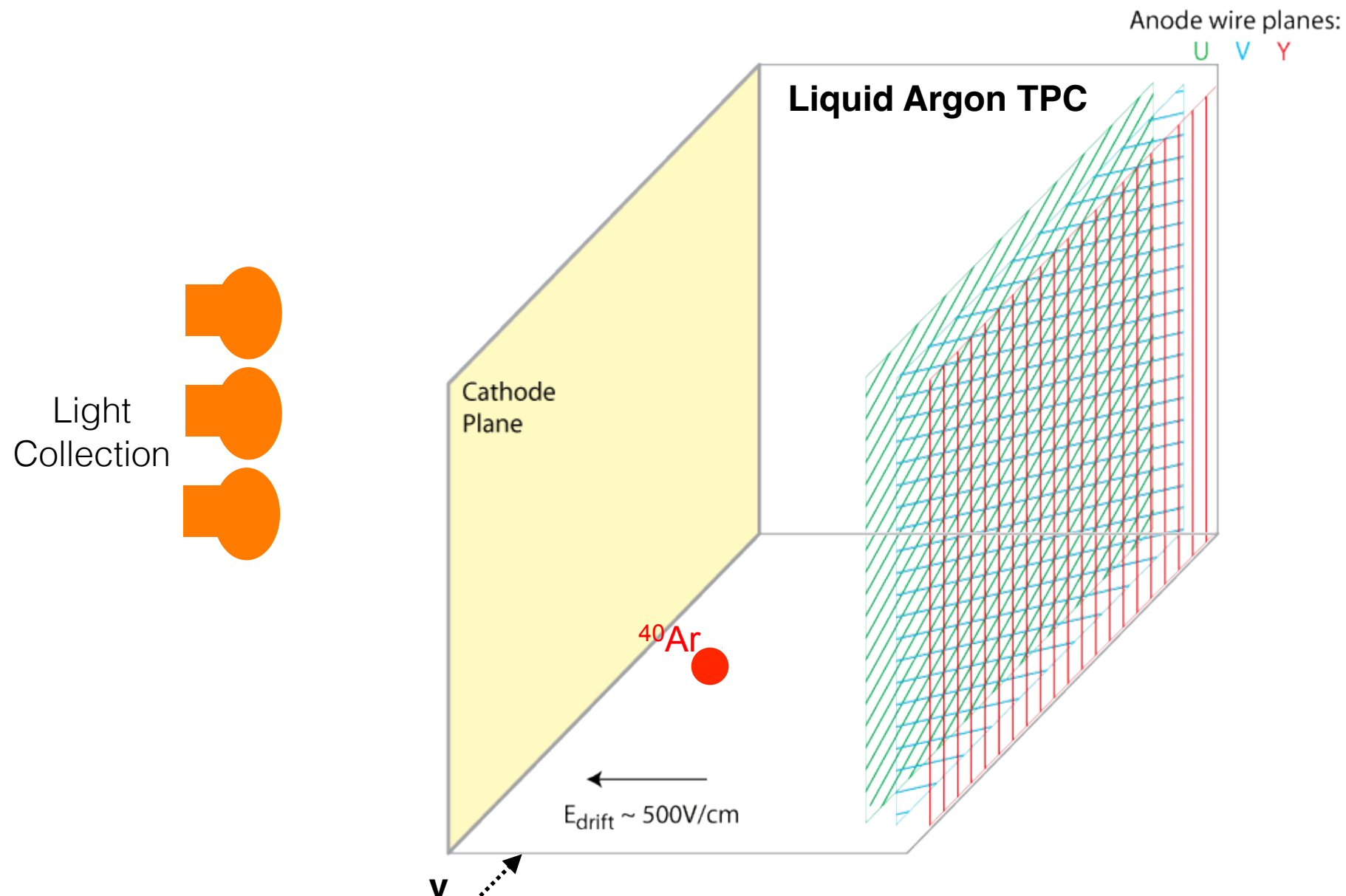
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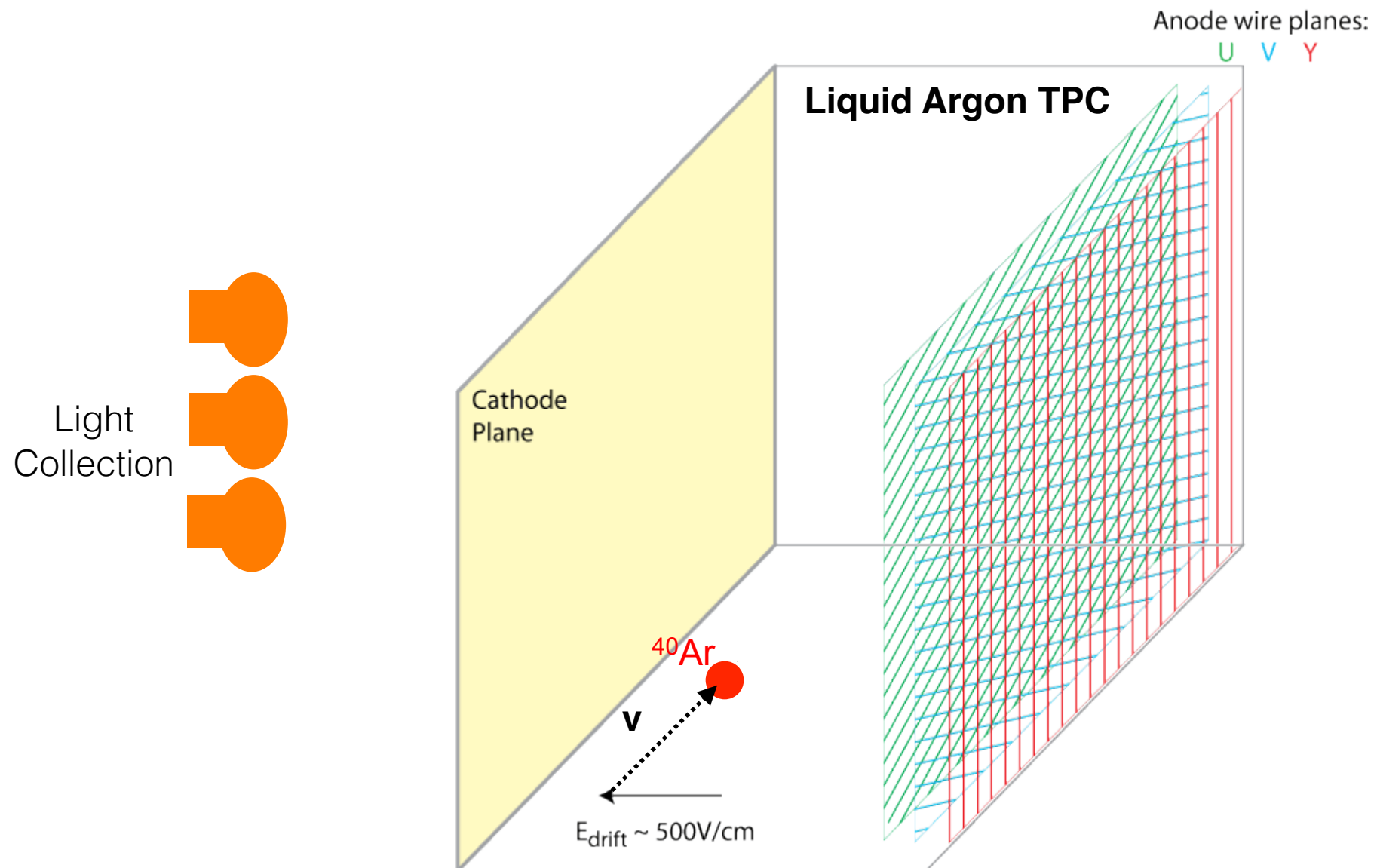
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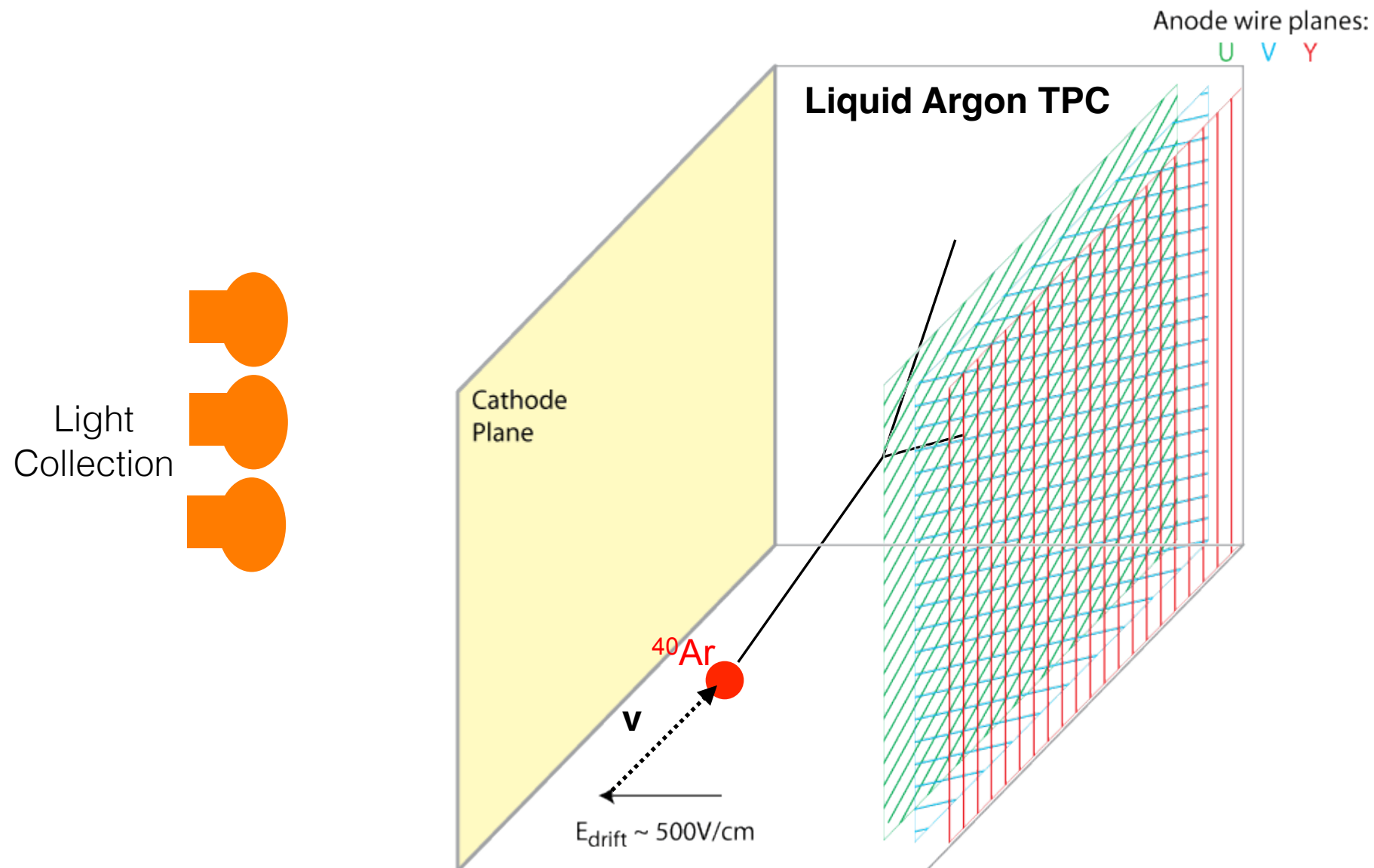
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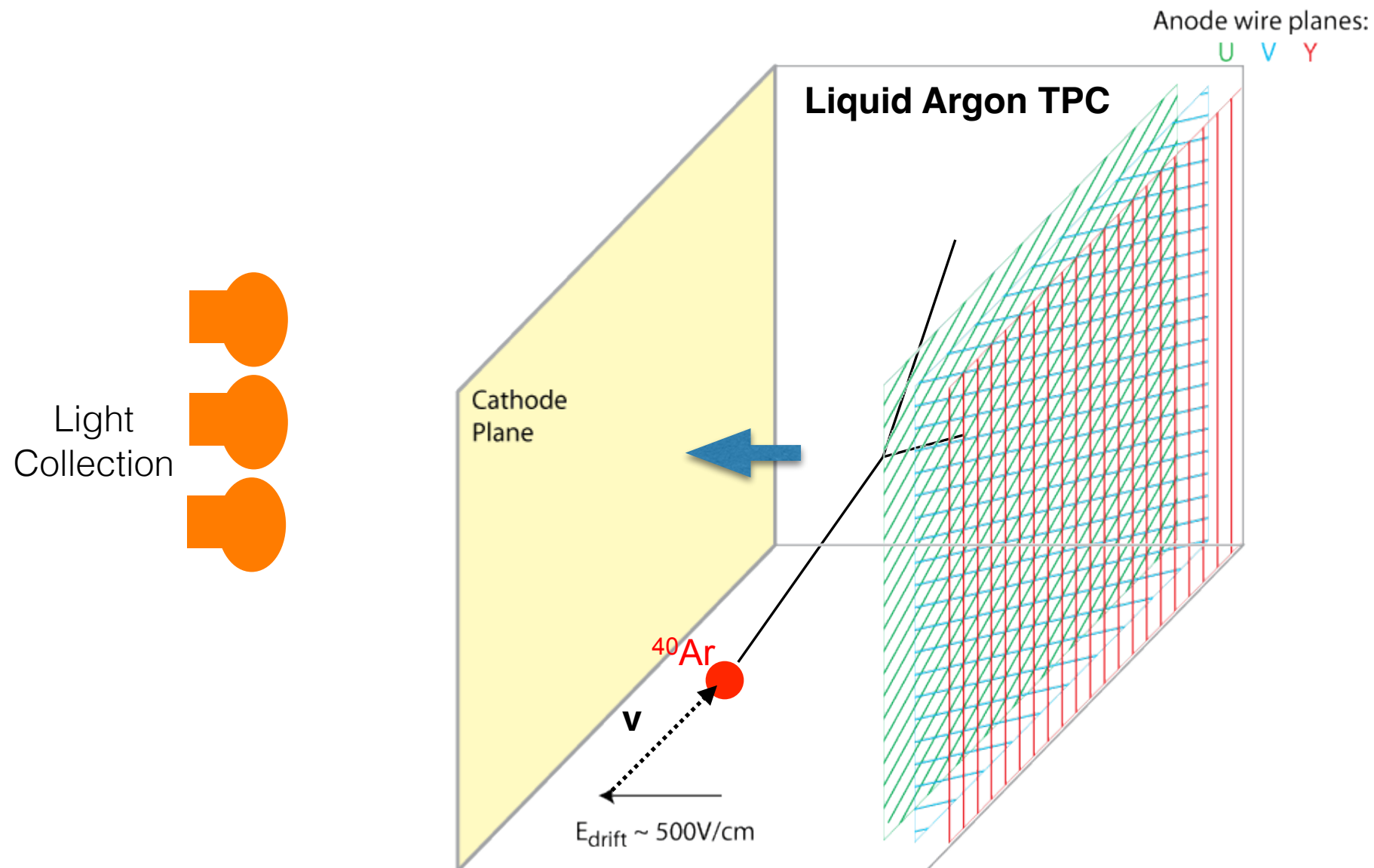
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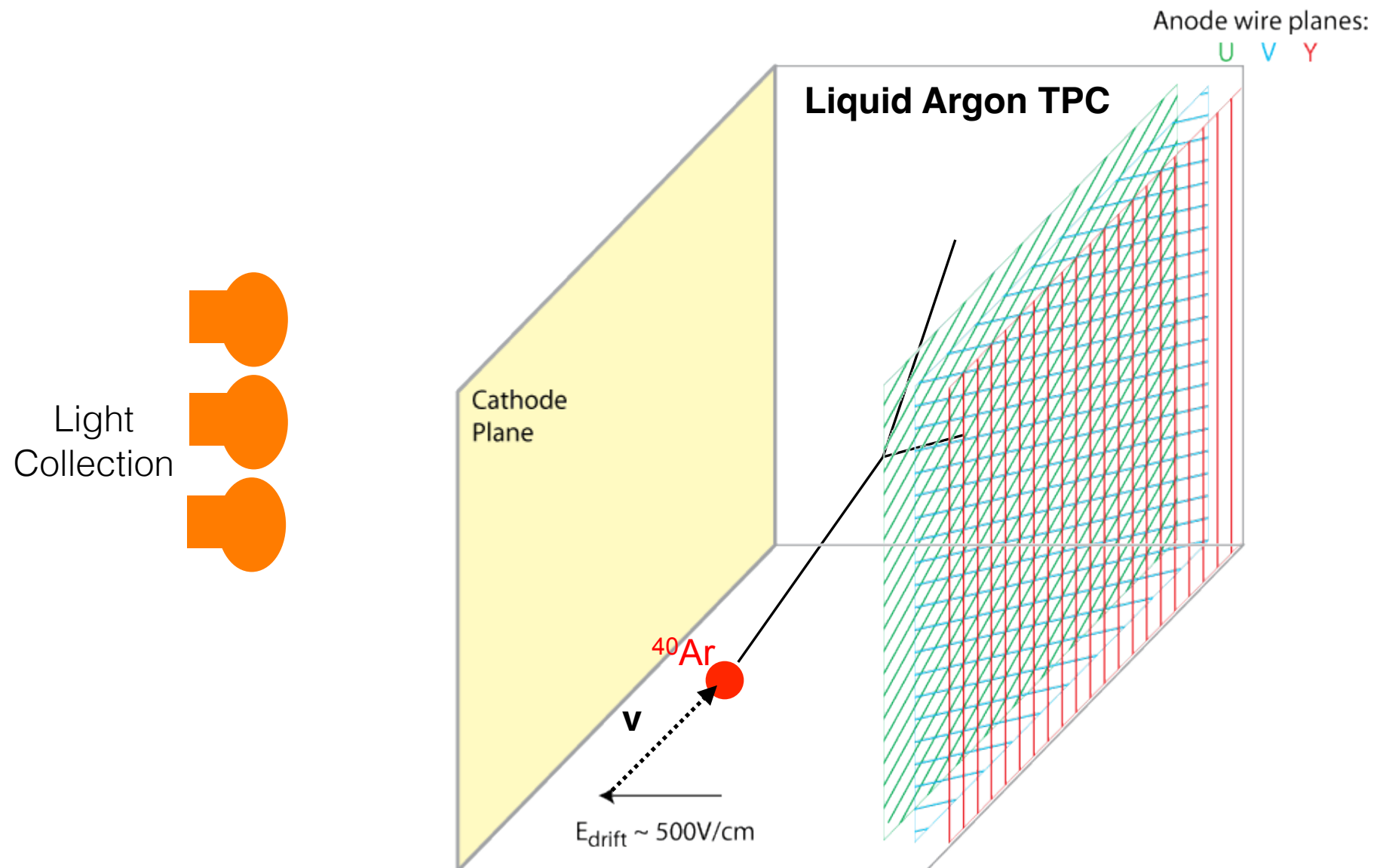
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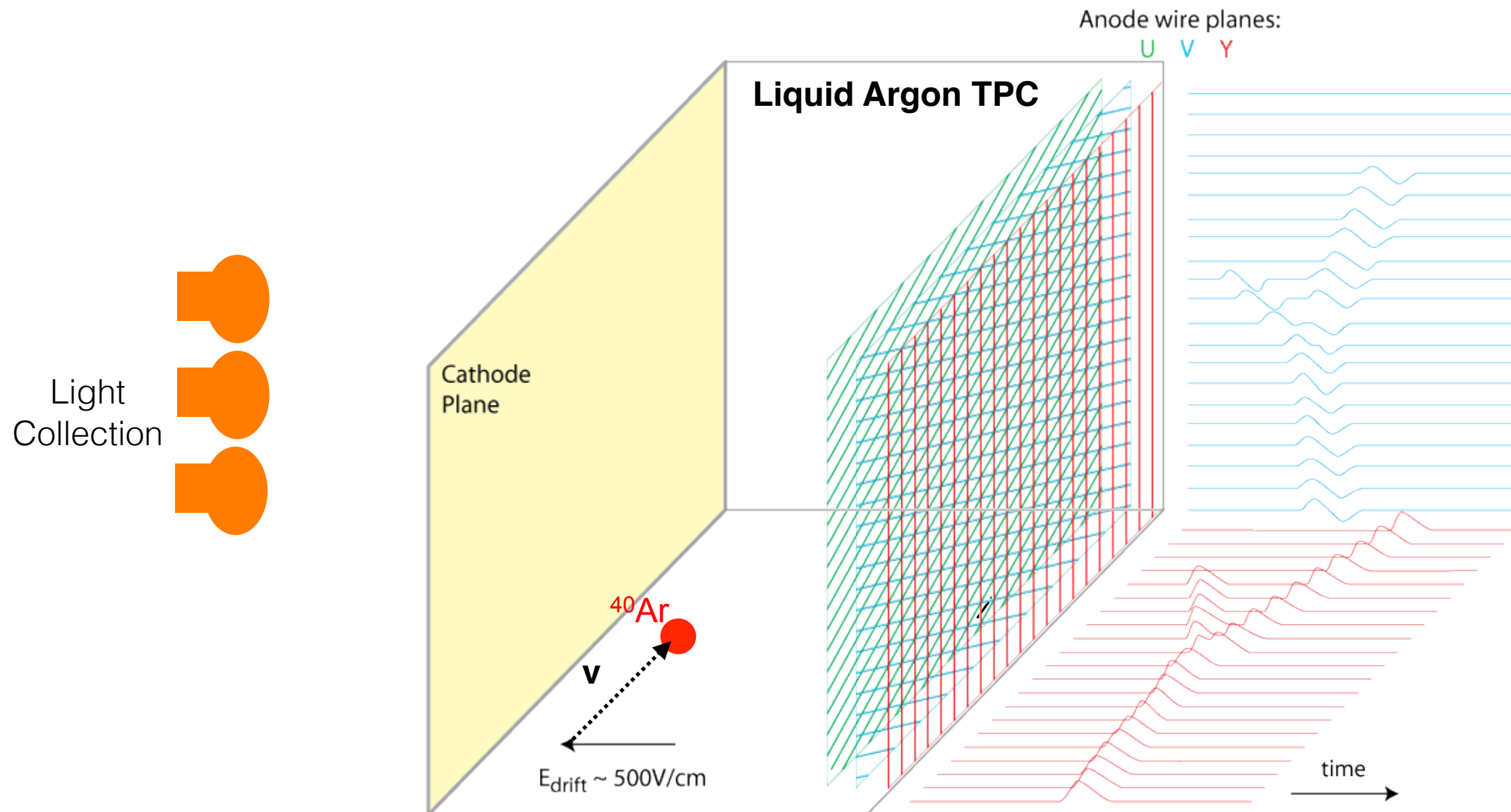
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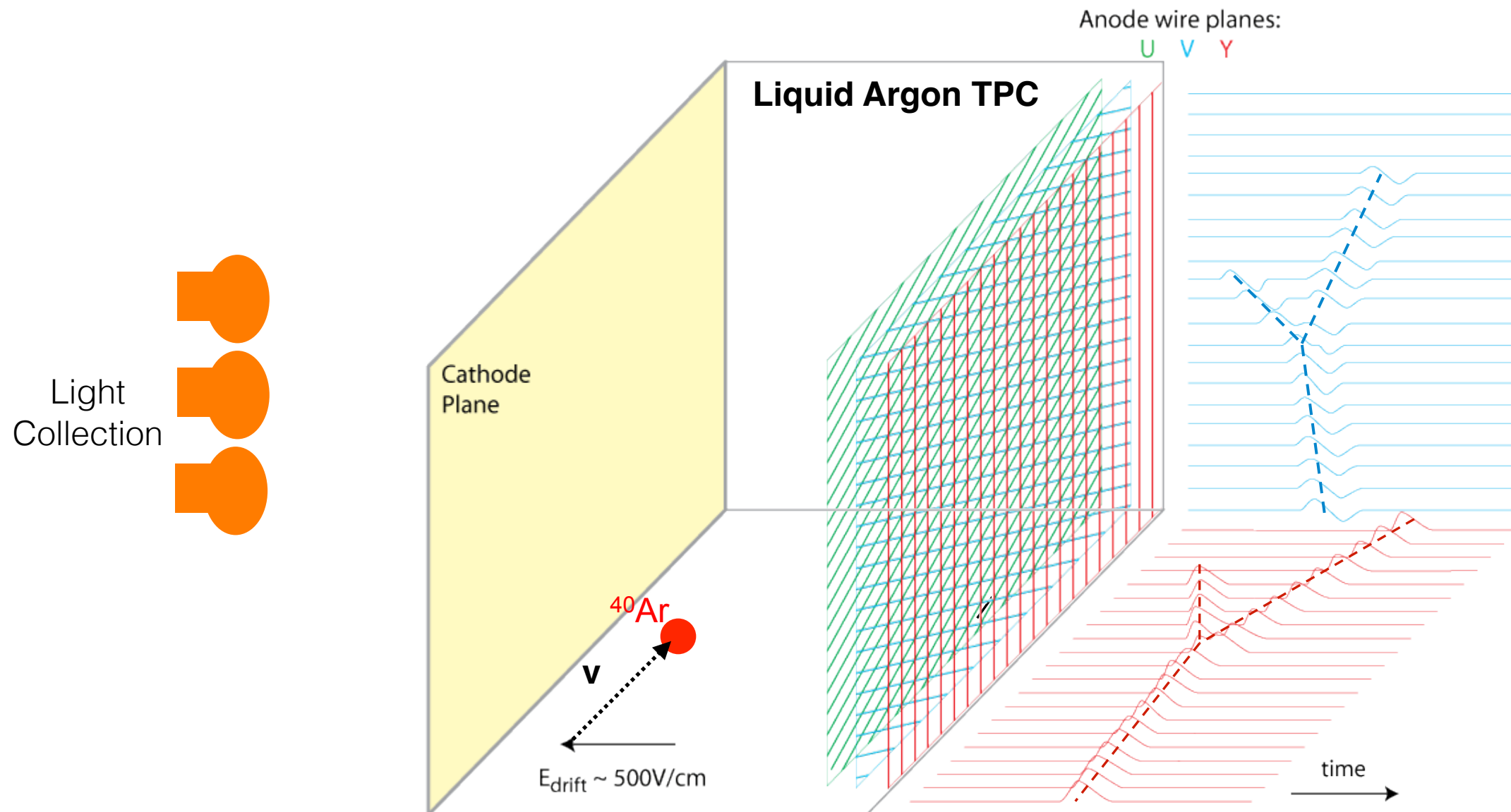
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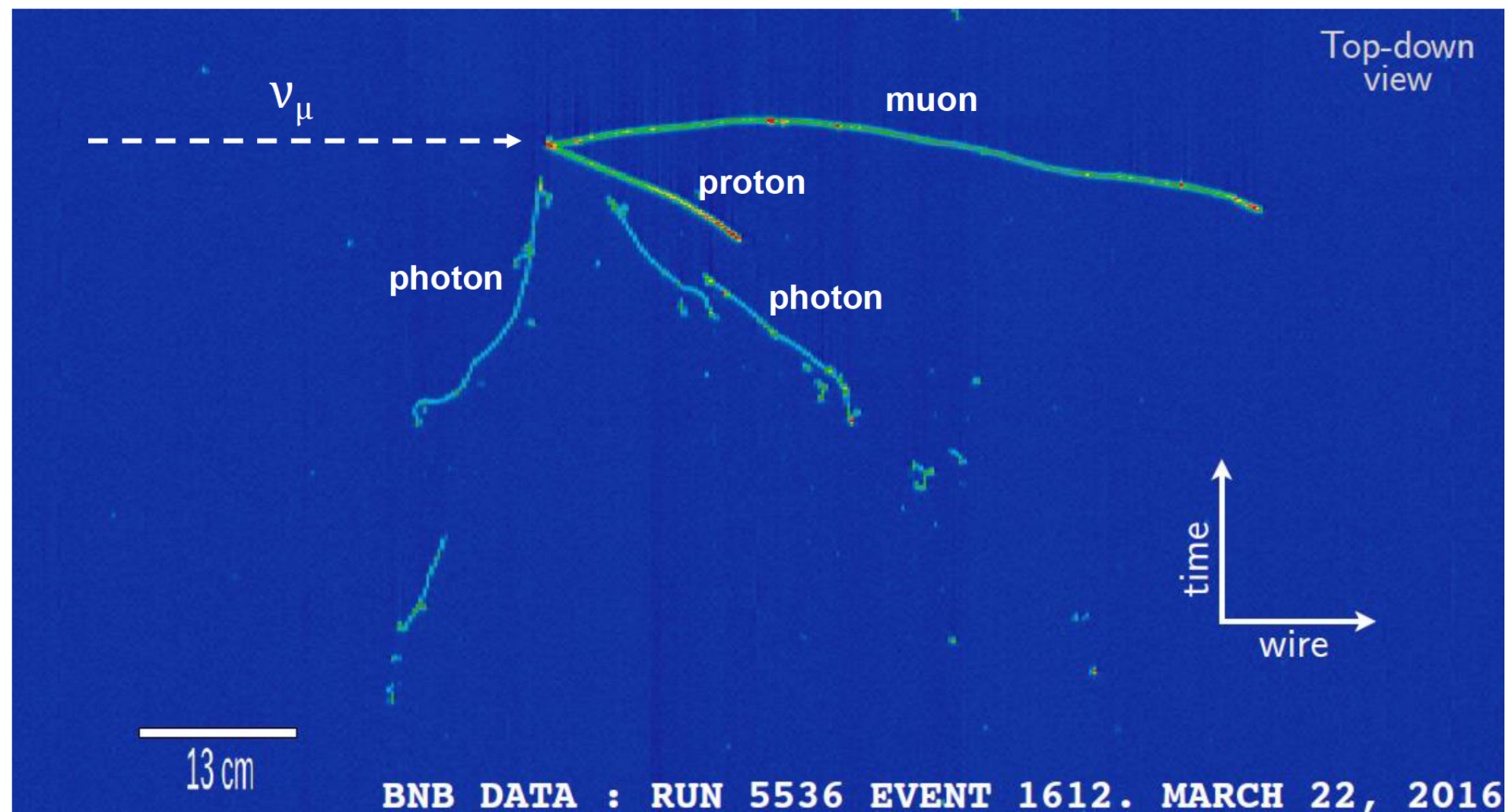
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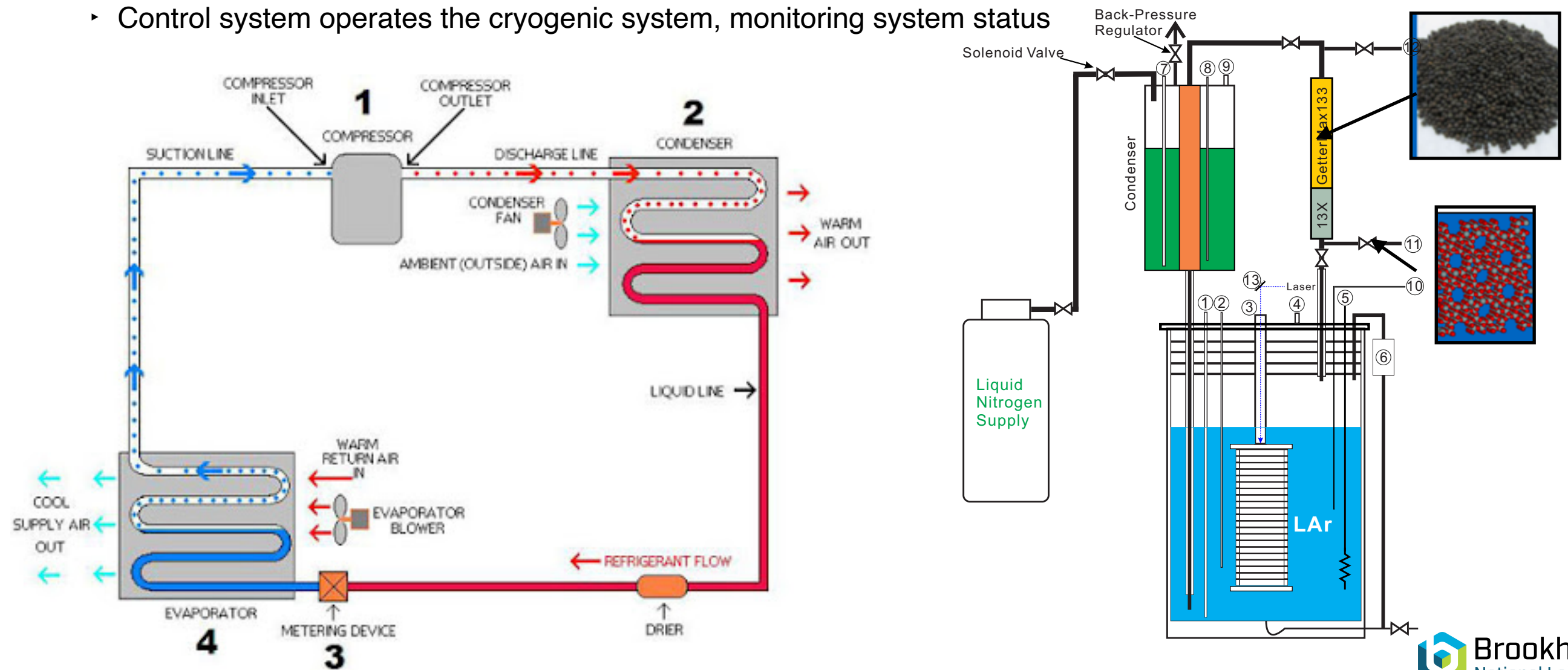
Technical Challenges of LArTPC

- Ultra high purity is required to minimize electron loss:
 - No charge gain in LAr. Common electronegative impurities are Oxygen and Water
 - Impurity concentration < 10 s of part-per-trillion level is required for LArTPC.
- Cold electronics to minimize noise. Cryogenic condition is challenging for the electronics
- Breakdown with HV: $\sim 10^2$ kV HV required for electron drift. Breakdown mechanism not fully understood for LAr
- Space charge effect for surface detector.



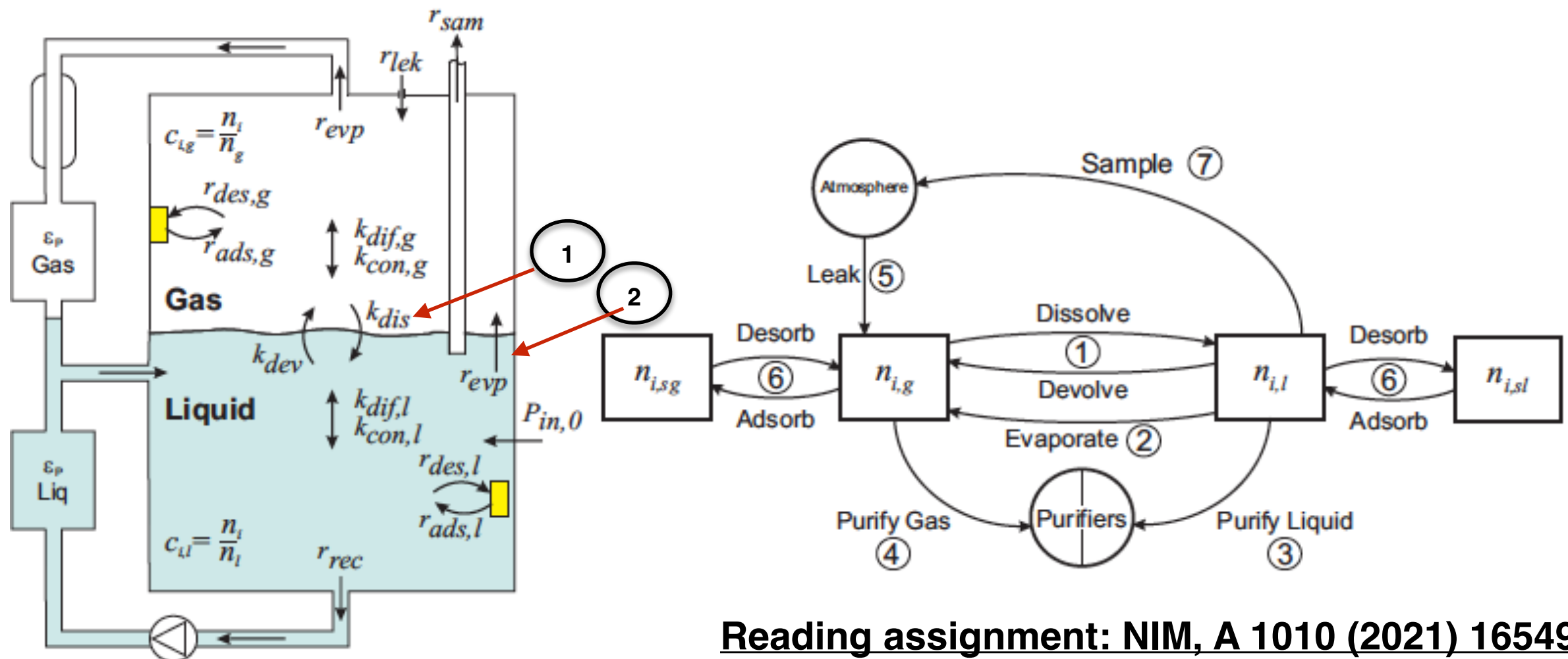
LArTPC Cryogenic System

- LArTPC cryogenic system is actually a large refrigerator at very **low** temperature!
 - LAr evaporates needs to be condensed to maintain the stable operation
 - Sufficient condensing power
 - Good insulation quality
- Achieve desired purity level by passing argon through filters containing molecular sieve (to remove water) and copper based catalyst(to remove oxygen)
- Detector components must also be properly chosen to minimize contaminations
- Continuous recirculation necessary to reach/maintain high purity
- Control system operates the cryogenic system, monitoring system status



Impurity in LArTPC

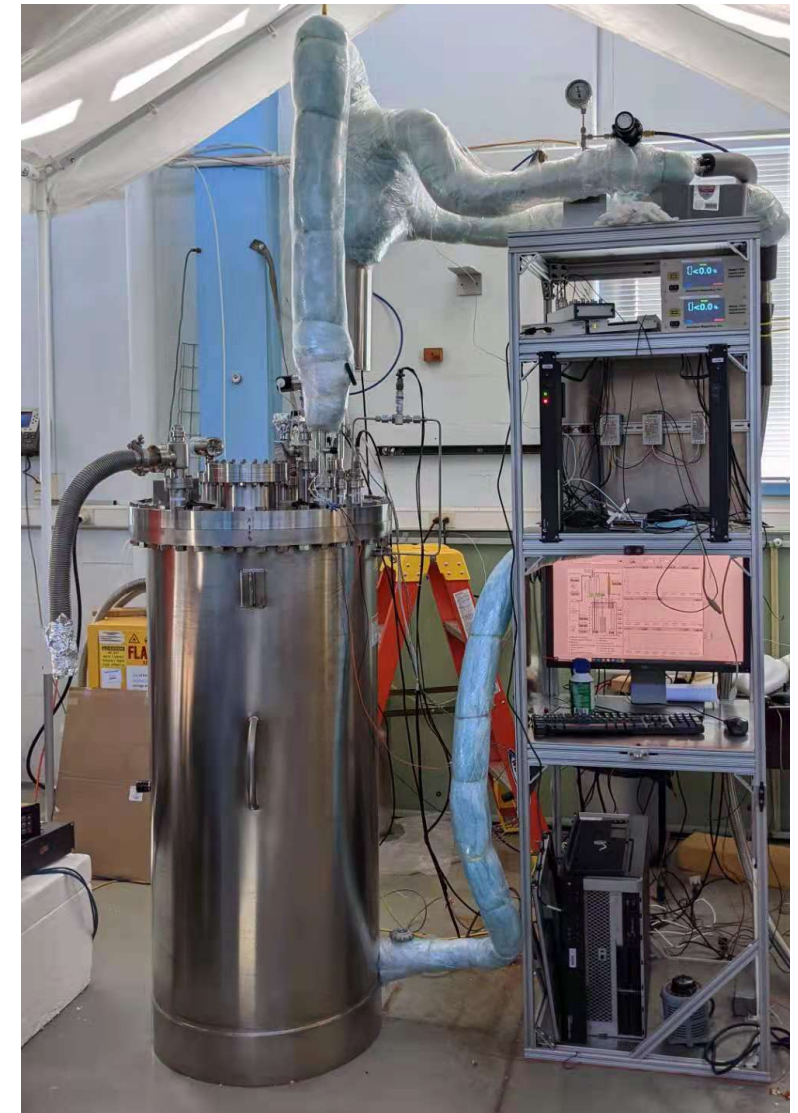
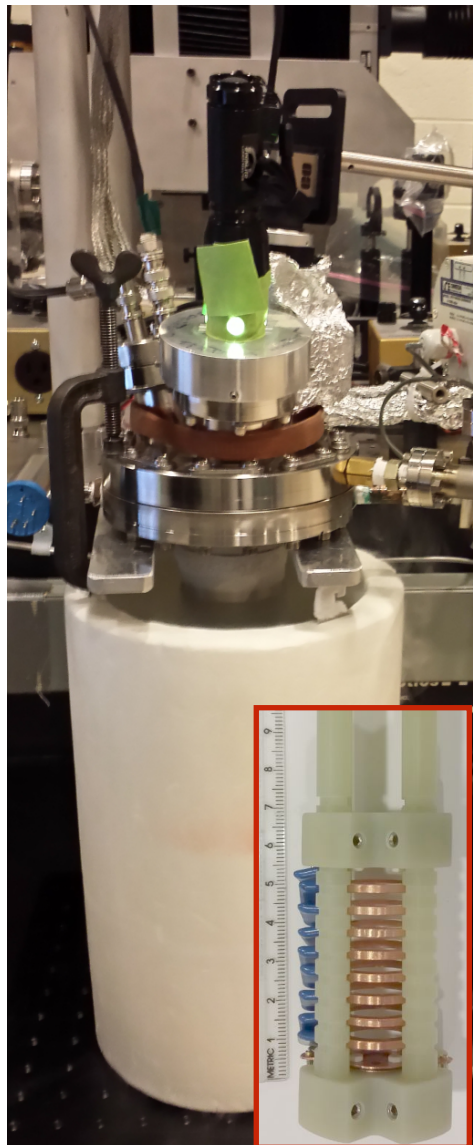
- Impurities in LAr attenuate the signals
- They come from the leak, outgassing and residual impurities in the supply LAr
- Commercial LAr typically contains ~ppm impurity, LArTPC requires <1ppb
- Purification required to achieve the required purity level
- A quantitative kinetic model of impurity distribution is constructed



Reading assignment: NIM, A 1010 (2021) 165491

LAr R&D Experimental Setup at BNL

- ▶ 2L test stand is cooled by LN₂+Dry ice bath and LAr is formed by liquefying purified commercial GAr
- ▶ 20L test stand is an upgraded and improved apparatus with LAr circulation and GAr purification
- ▶ The 260L LAr test platform is commissioned with high purity achieved
- ▶ Only gas purification is implemented in our local setup
 - ▶ Also added liquid purification in the LAr filling line



2 L Test Stand
NuSTEAM 2025

20 L Test Stand
7/17/25

260L LAr Platform
Brookhaven
National Laboratory

Cryogenic System Overview

► Cryogenic system required for Noble Liquid detectors

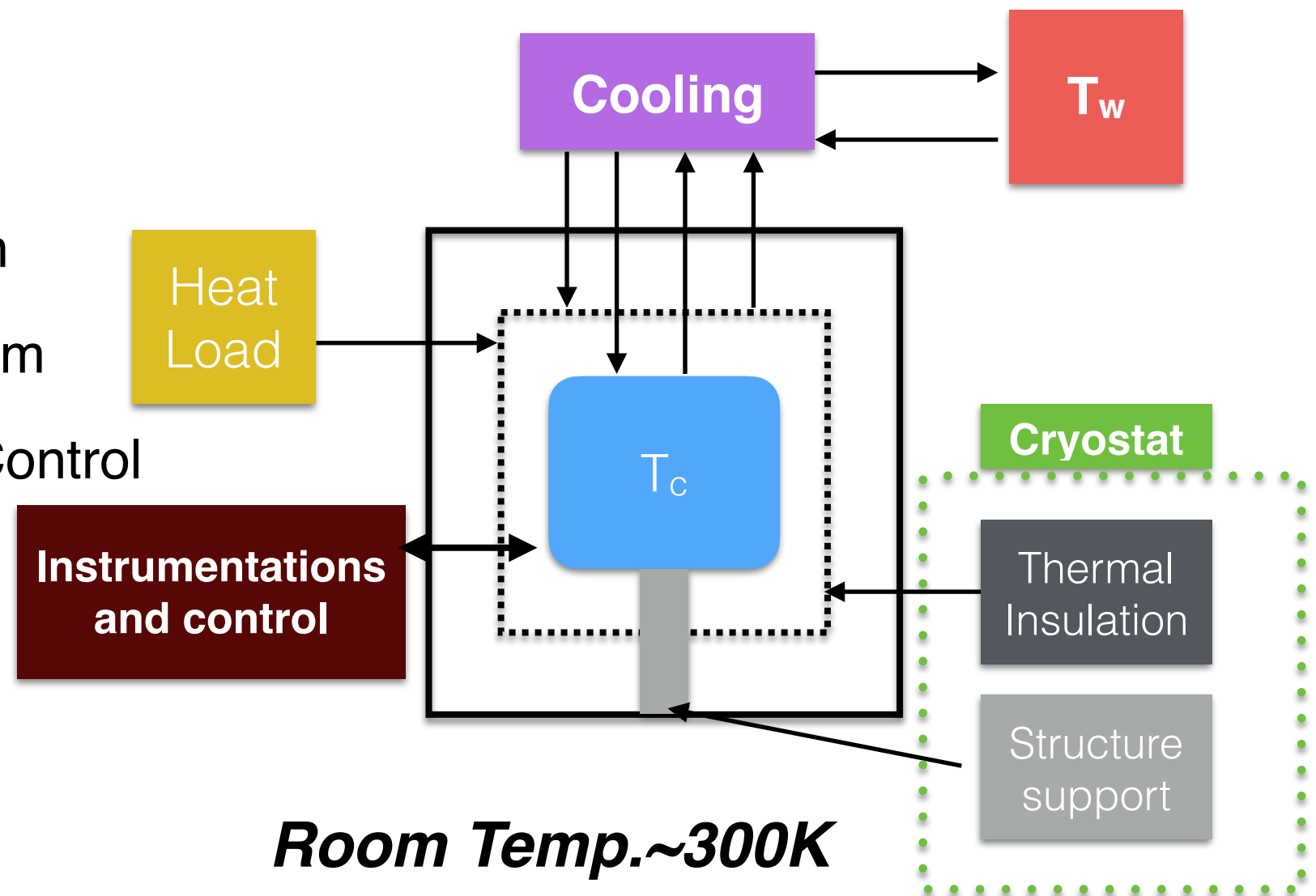
- Low temperature environment—>LN2 temperature range

► Cryostat

- Thermal Insulation
- Structure Support

► Cooling System

- Source of refrigeration
- Heat exchange medium
- Instrumentation and Control

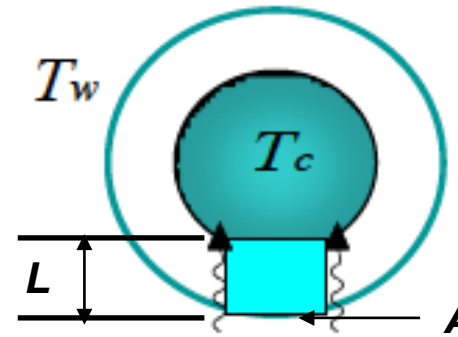


Heat transfers for Cryostat

► Solid conduction

$$Q_c = \frac{A \cdot k}{L} (T_w - T_c)$$

- Reduce heat load → Low thermal conductivity, small contact area thicker insulation

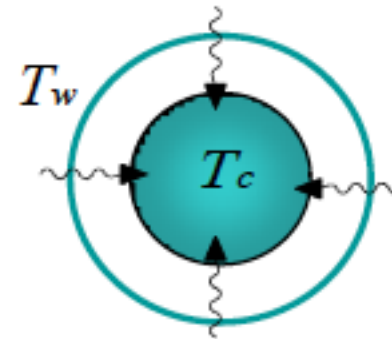


► Thermal radiation

- For the case of enclosed cylinder

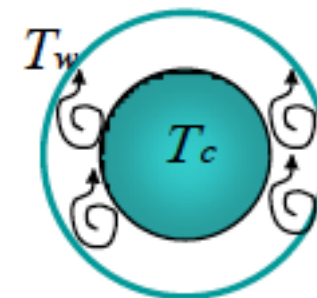
$$Q_r = \frac{\sigma A_c (T_w^4 - T_c^4)}{\frac{1}{\epsilon_c} + \frac{A_c}{A_w} \left(\frac{1}{\epsilon_w} - 1 \right)}$$

- Reduce heat load → Reduce A_w and Emissivities



► Natural convection

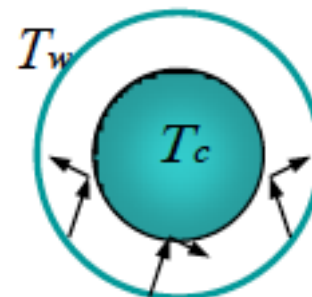
- Negligible with good insulation vacuum $< 10^{-4}$ Pa



► Residual Gas conduction

- Molecular regime

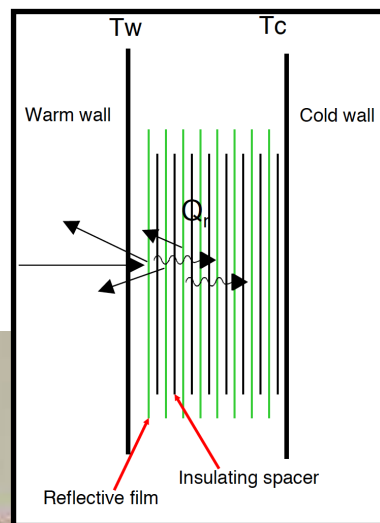
$$Q_{res} = A_c \cdot \alpha(T) \cdot \Omega \cdot P (T_w - T_c)$$



Cryostat Insulations (Passive)

- ▶ **All Cryogenic Insulation material applications can be divided Into 3 Types , based on their apparent thermal conductivities (k values)**
 - Multi-layer insulation (MLI) with vacuum below 10^{-4} Torr, $k \sim 0.05 \text{ mW}/(\text{m}\cdot\text{K})$
 - Bulk Fill materials (Perlite Powder) work in a soft vacuum ($>10^{-3}$ Torr), $k \sim 1.5 \text{ mW}/(\text{m}\cdot\text{K})$
 - Mechanical insulation at ambient pressure, k values are $\sim 30 \text{ mW}/(\text{m}\cdot\text{K})$

MLI



Bulk Fill



Mechanical



Cryostat Insulations (Active Cooling)

► Another insulation approach is active cooling

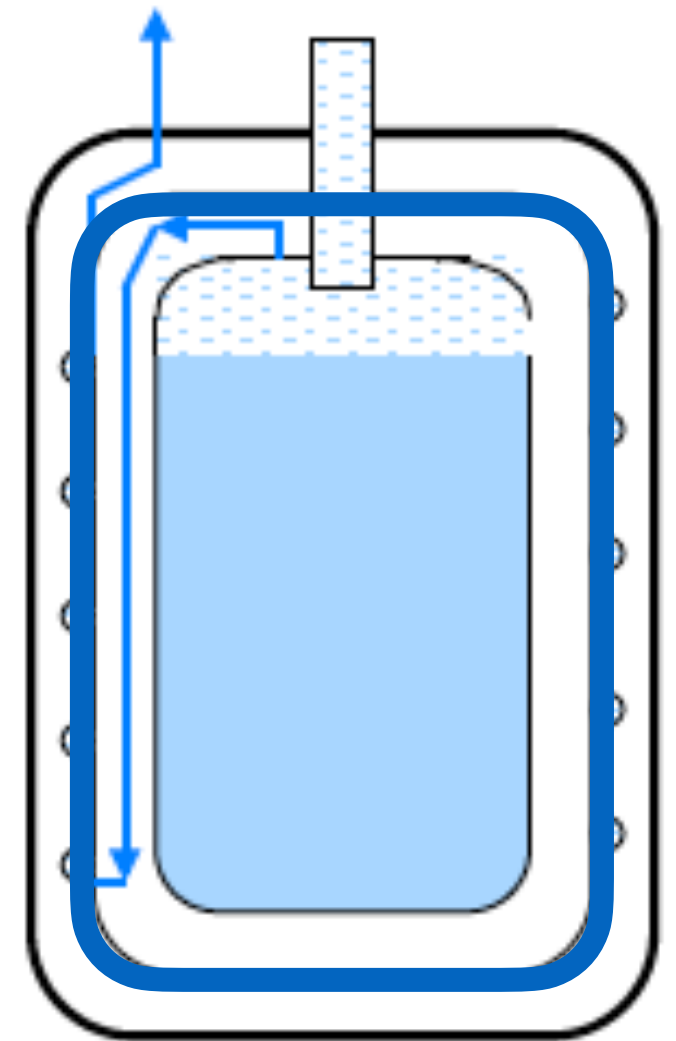
- Create an actively cooling radiation shields
 - Lower emissivity at low temperature
 - Heat extraction at higher temperature
- Adapted in ICARUS

► Pros

- Higher heat extraction efficiency by removing heat at higher temperature
- Reduce boil-off of expensive fluid (LHe)
- Can be done in conjunction with active cooling of other components (structural supports, current leads)

► Cons

- Cost and more complicated cryogenic system



MicroBooNE Cryostat Conceptual Design

► Switch to Mechanical Insulation Option

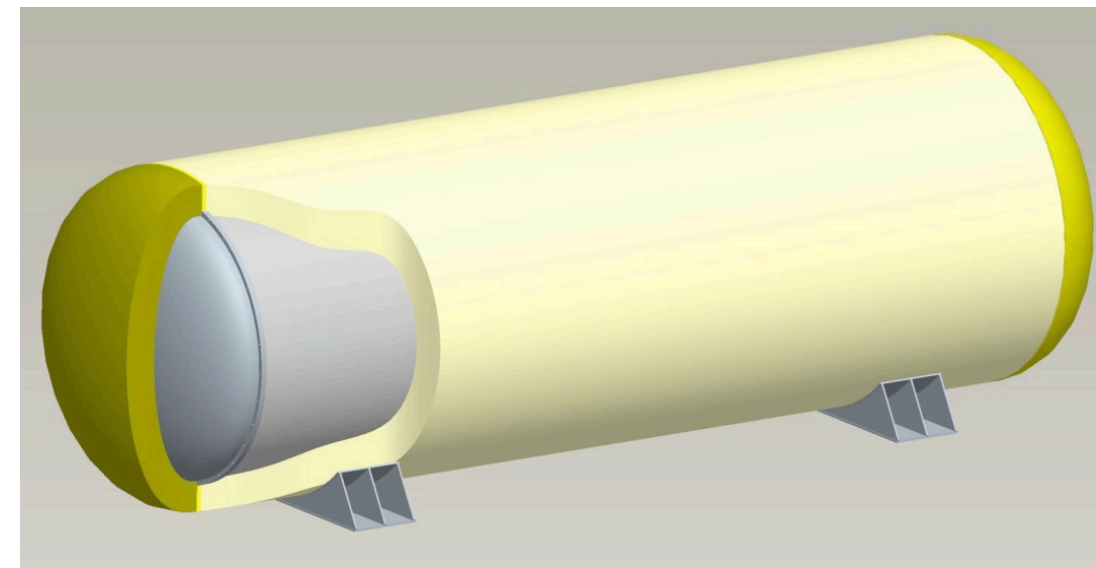
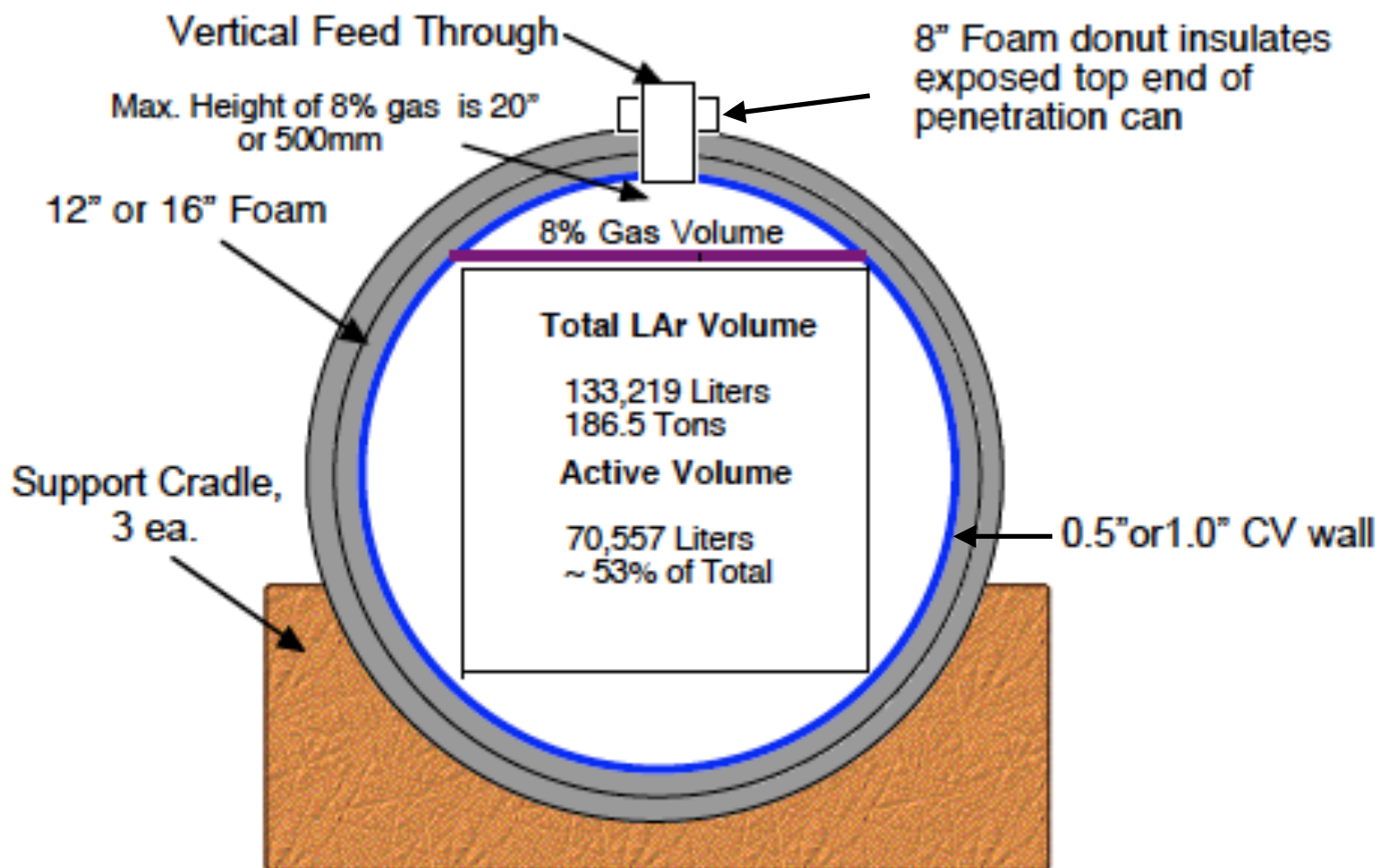
- Fiber glass panel—> Polyurethane Spray-on insulation

► Pros

- Cost reduction of ~\$600k by eliminating outer vessel
- Simpler supporting and penetrations

► Cons

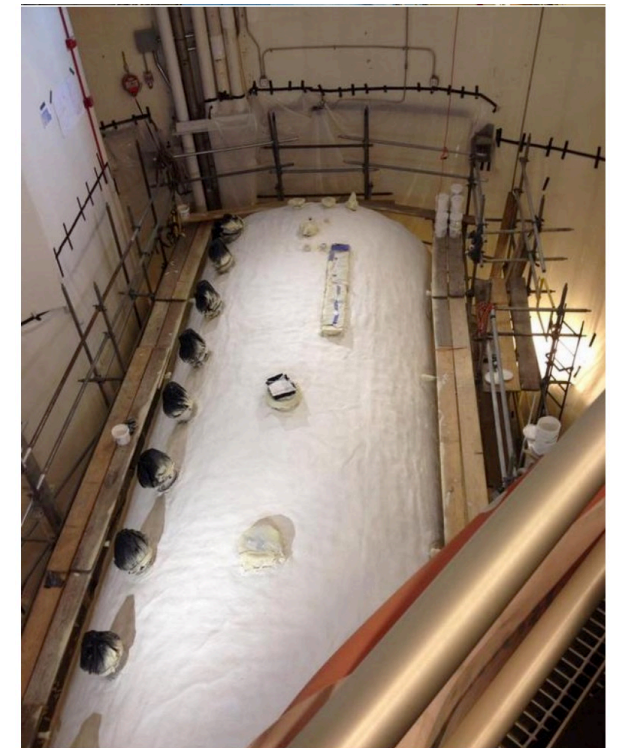
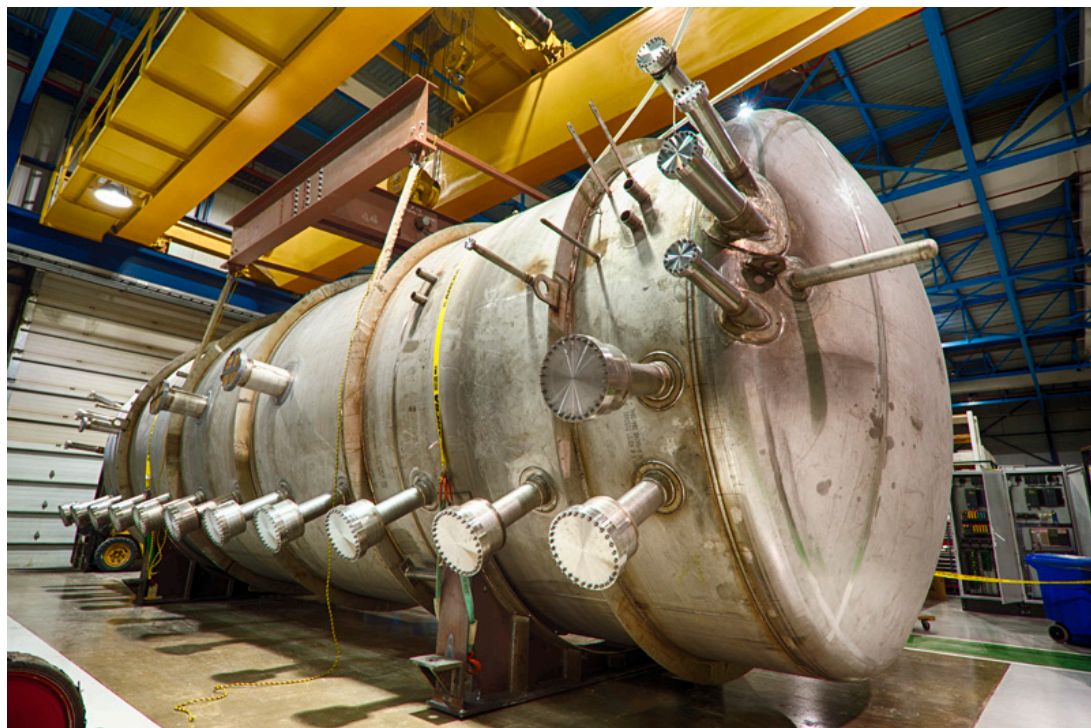
- Heat leak rate is estimated to be $\sim 12 \text{ W/m}^2$ about twice of MLI insulation
- Trade-off with higher LN2 consumption than MLI insulation
 - Break-even time is ~ 8 years estimated with BNL LN2 price back in 2008



MicroBooNE Cryostat Final Production Version

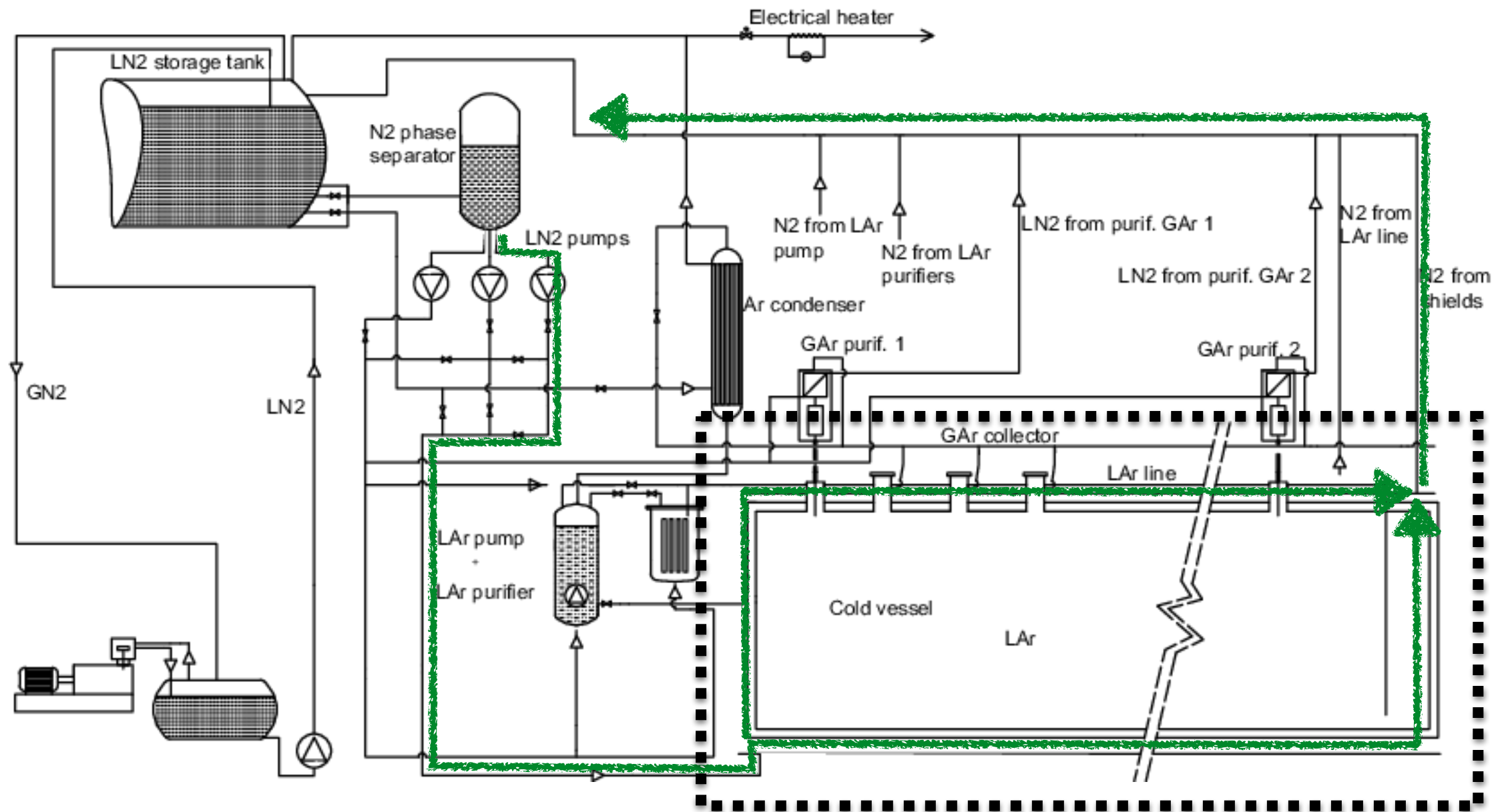
► **MicroBooNE cryostat only used PU foam insulation with 16" Polyurethane**

- ASME U-Stamped Pressure Vessel
- Pressure tested to from full vacuum to 110% of 30 psig
- 159681 Liters total volume
- Operate with ~12700L gal(~170 ton) LAr or ~4.1% ullage
- 7/16" thick shell, 150" ID, ~40' long, reinforcing outer ribs
- Mounted on high density Polyurethane Saddle base with one end movable
- Insulation with 16" (400 mm) Polyurethane sprayed on, Heat leak ~ 13 W/m²
- Insulation weight ~32 kg/m³



ICARUS T-600 Cryogenic

- Active cooling used in ICARUS
 - Cool shield circulated with LN2



LN2 for LAr volume cooling(cold shields)-87K

ICARUS T600 Cryostat at Gran Sasso

► The cryostat composed of two parts

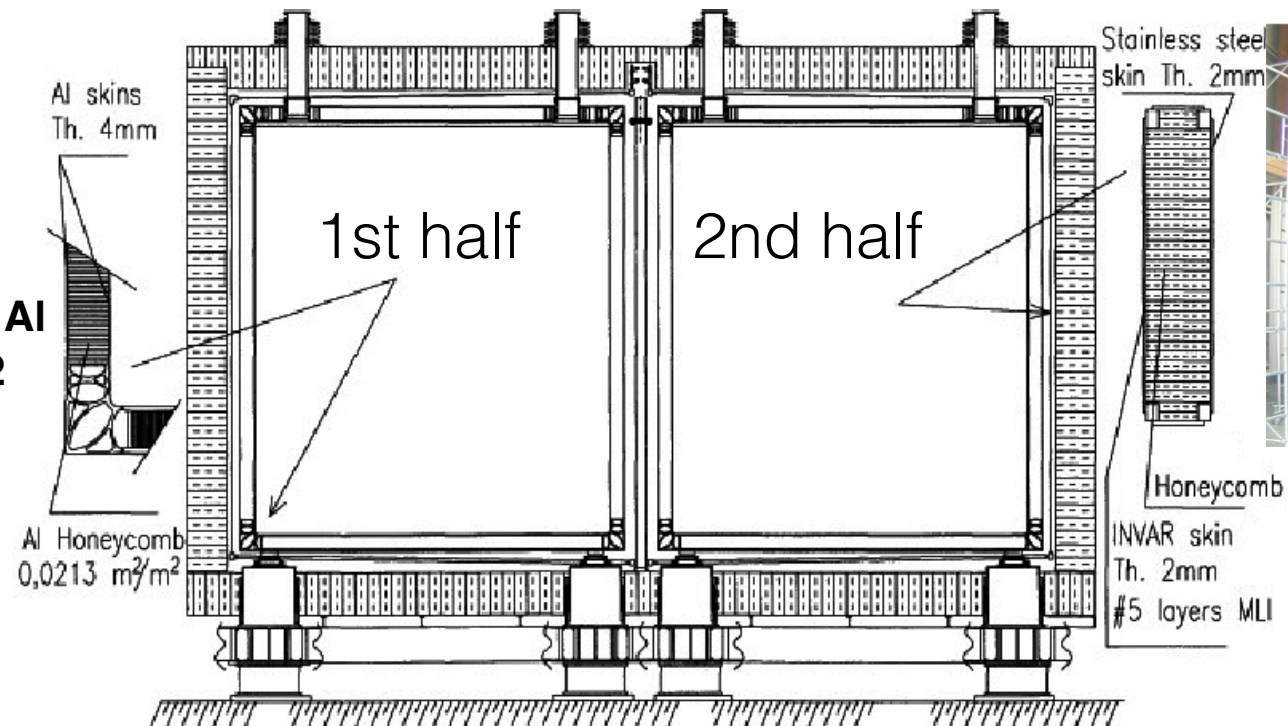
- Aluminum box for TPC(3.9m x 3.6m x 19.6m inner)
- Outer Insulation panels

► Active LN2 cool shield applied on the Al box and between outer insulations, 2 versions of insulation

- Unevacuated: $\sim 22 \text{ W/m}^2$
- Evacuated: $\sim 7 \text{ W/m}^2$

► Parameters

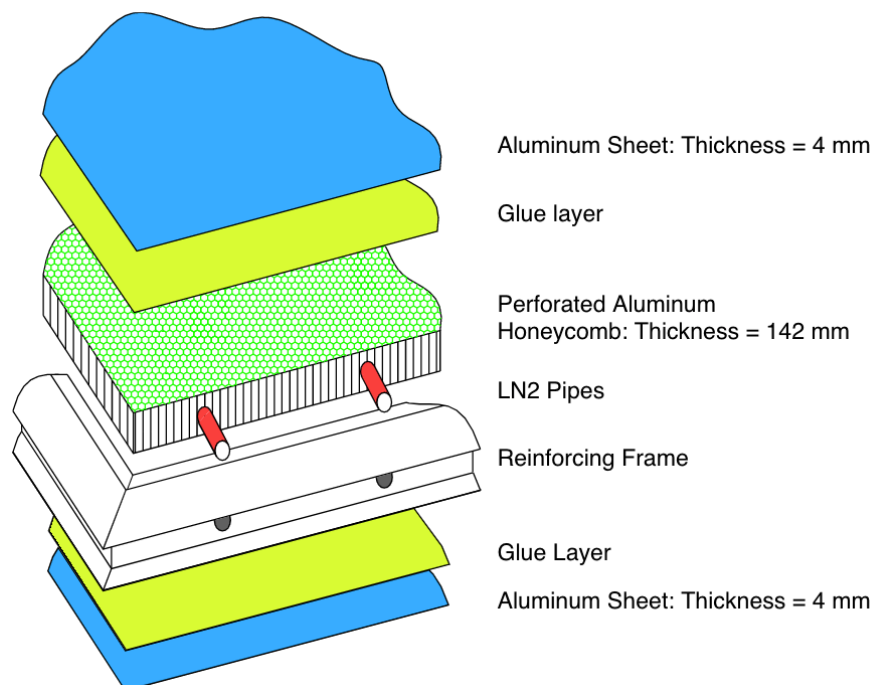
- TPC box: $\sim 20\text{cm}$ thickness, 35kg/m^3
- Insulation panel $\sim 45\text{cm}$ thickness, 25kg/m^3



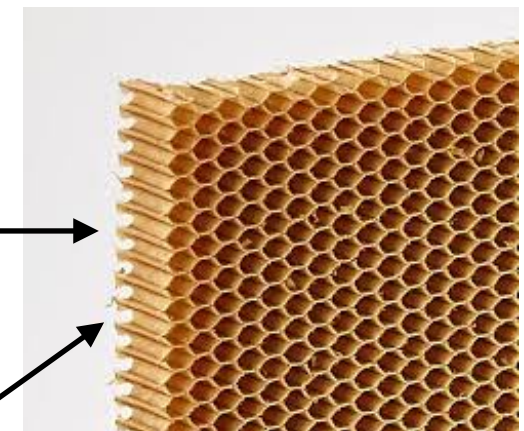
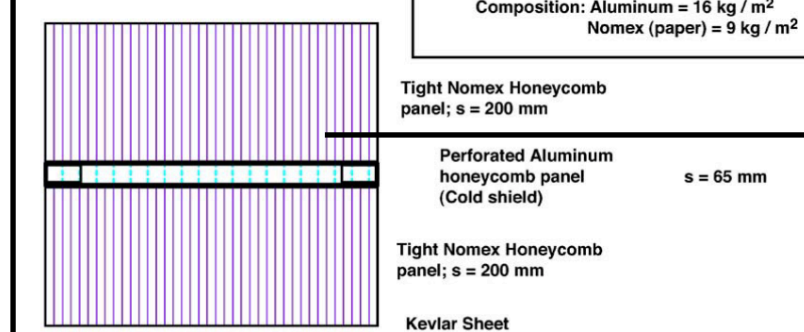
Insulation panel

Nomex

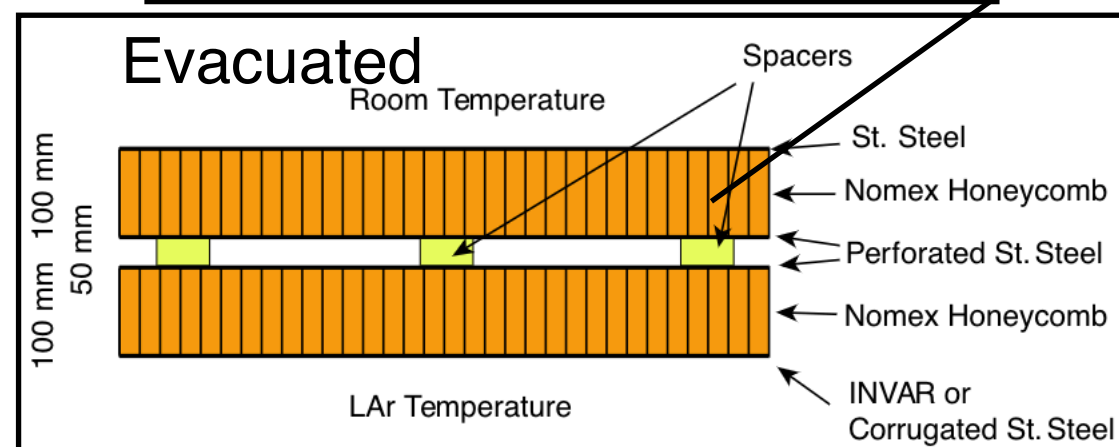
TPC box



Unevacuated



Evacuated



ICARUS T600 Cryostat at SBN

► New Al box and Insulation made for T600 at SBN

- TPC box: Nomex honeycomb replaced by Self-supporting boxes made of aluminum extruded profiles welded together, not evacuated
- Insulation panel: replaced with the same insulation structure used in ProtoDUNE, but no membranes
- New cold shield: Stainless steel pipes attached to aluminum flat panels circulated with LN2

TPC box



Insulation panel

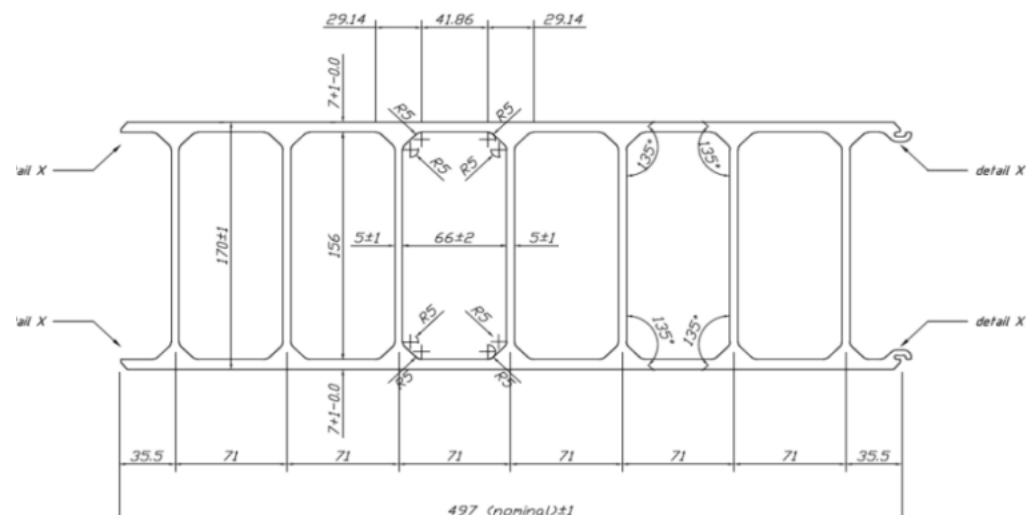
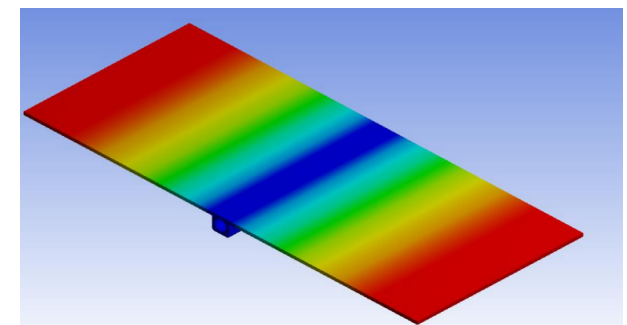
Plywood

600mm



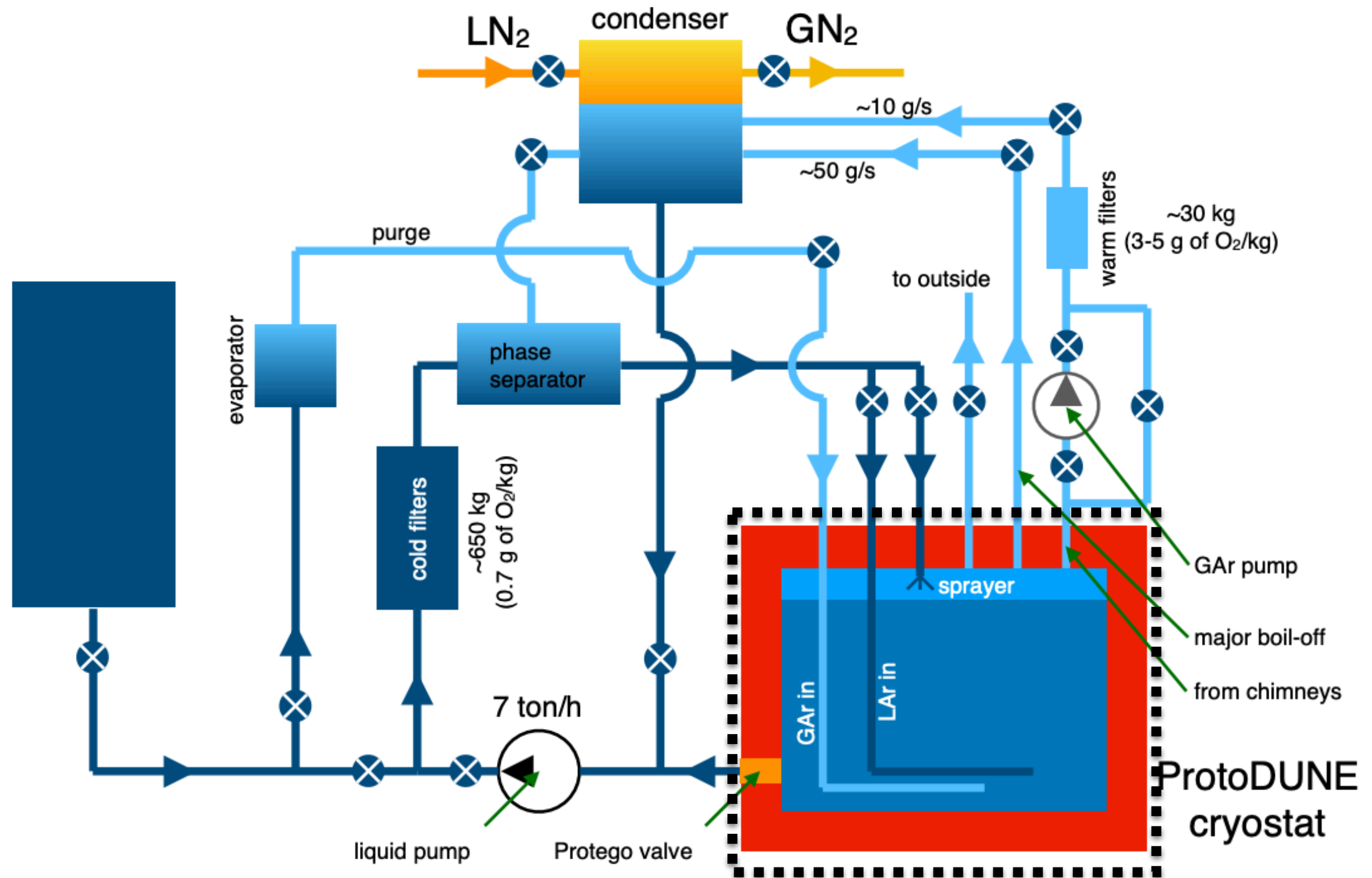
mastic

Cold shield



ProtoDUNE Cryogenic

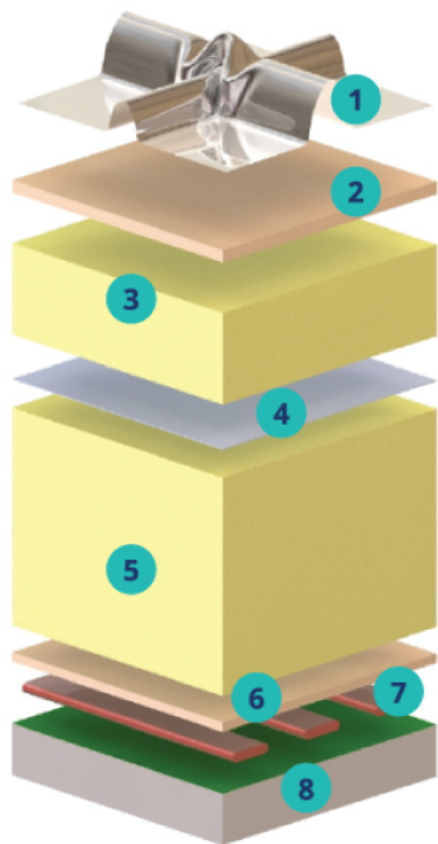
- **Standard Membrane Insulation used**
 - No cold shields



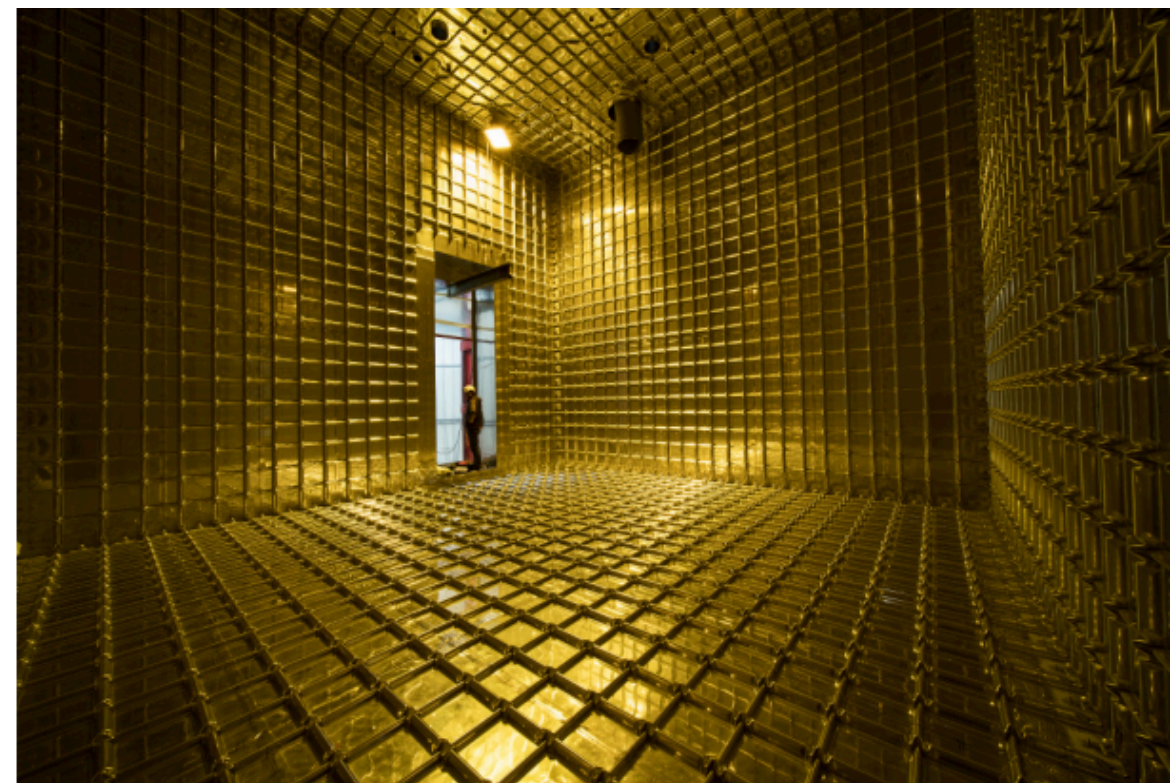
ProtoDUNE Cryostat

► Membrane cryostat

- Inner dimension 7.9 m x 8.55 m x 8.55 m, total volume of 580 m³
- ProtoDUNE/DUNE cryostat is based on the mature LNG transport membrane technology developed by the firm GTT (Gaztransport & Technigaz)
- Heat leak ~ 8 W/m²
- Insulation thickness ~ 800 mm
- Insulation weight 90 kg/m³



- 1 Stainless steel primary membrane
- 2 Plywood board
- 3 Reinforced polyurethane foam
- 4 Secondary barrier
- 5 Reinforced polyurethane foam
- 6 Plywood board
- 7 Bearing mastic
- 8 Steel structure with moisture barrier



ND-LAr detector cryostat

► DUNE-ND in a comparable setting like FPF

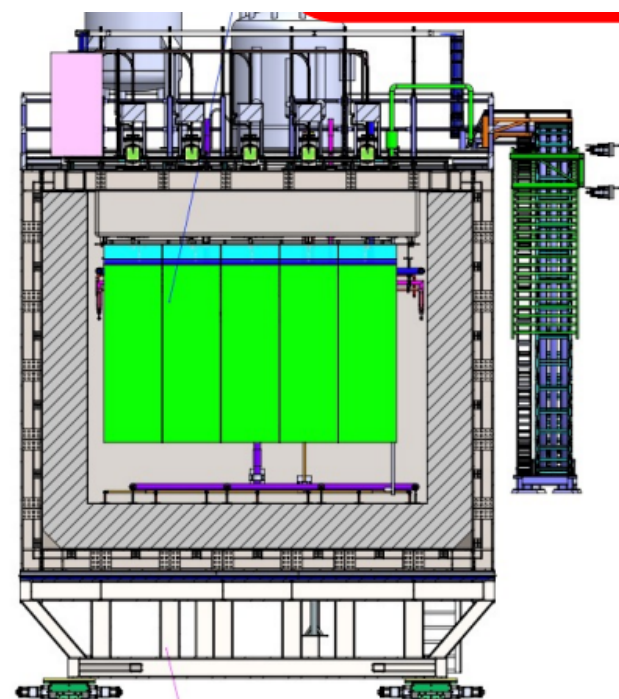
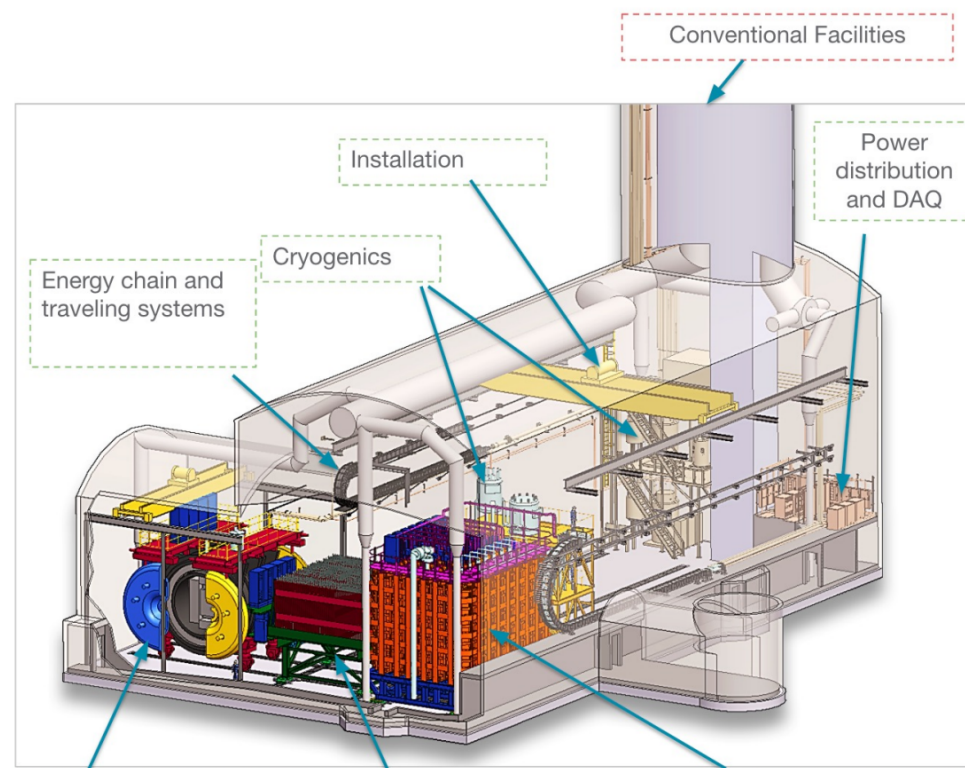
- Underground cave
- limited space shared with other detector

► ND-LAr detector

- Cryostat active volume: 3m x 7m x 5m
- Active mass ~ 150t
- Divided into 35 modules (5x7): 1 m x 1 m x 3.5 m
- Can move off axis

► ND-LAR cryostat

- Same “standard” GTT membrane cryostat as SBND



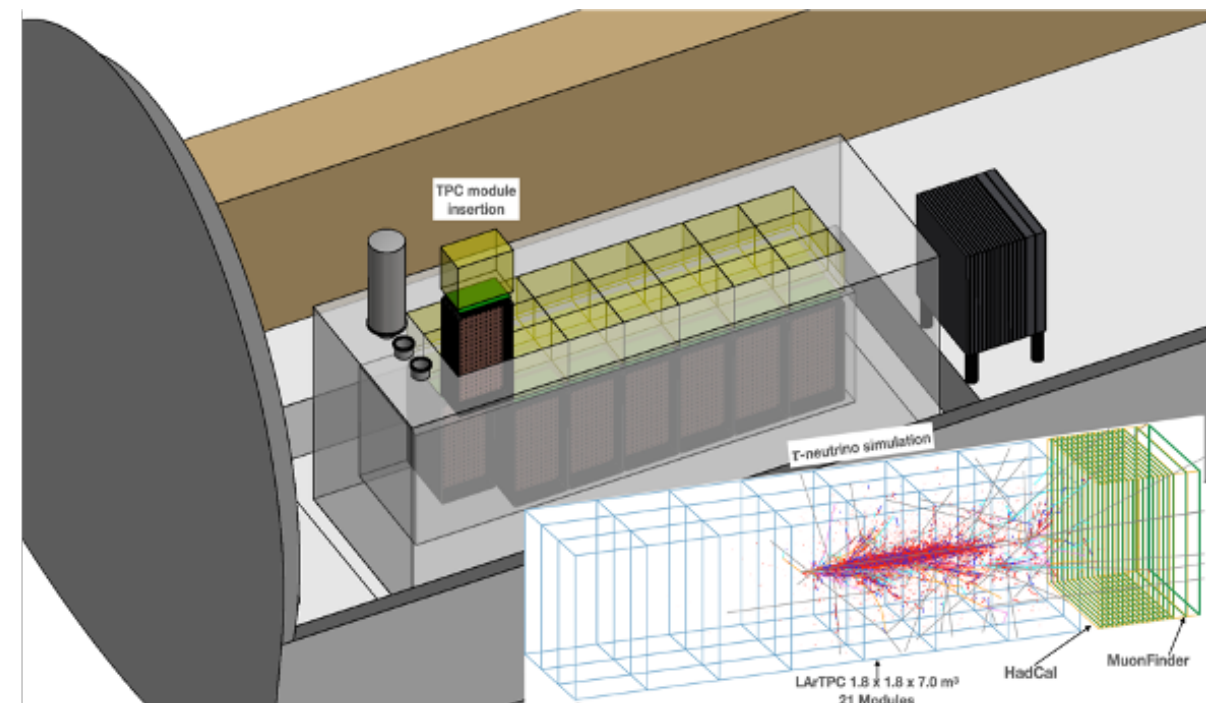
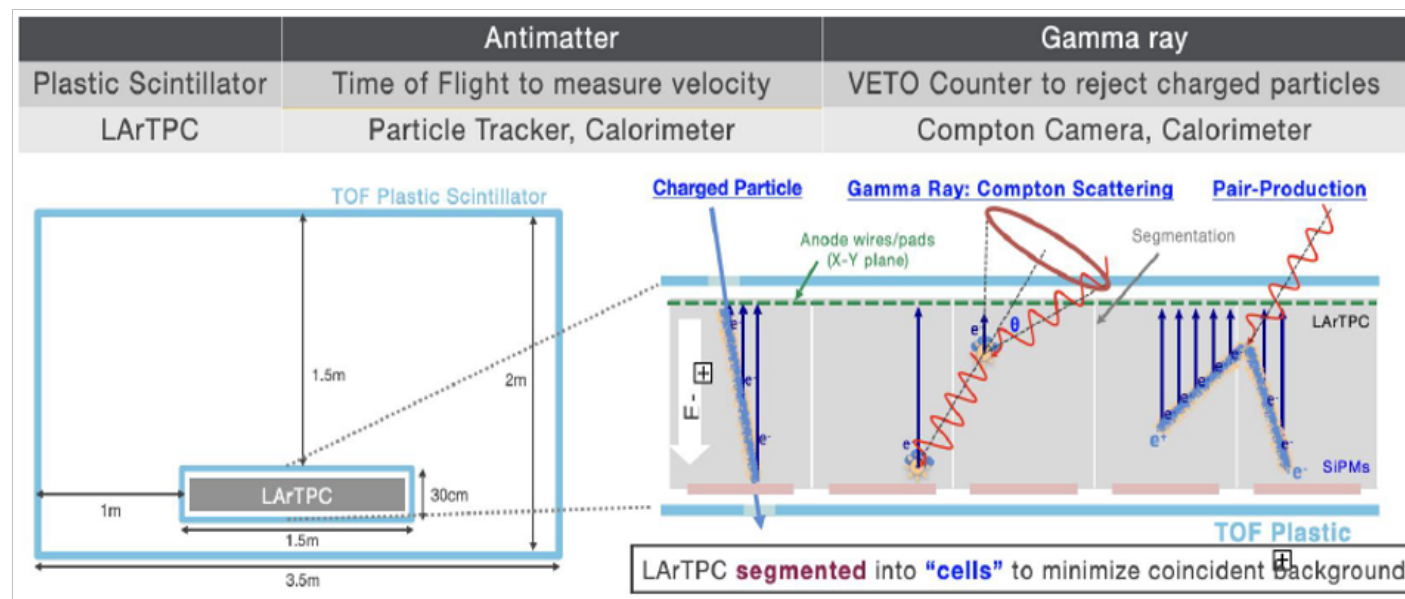
Summary of Cryostats

	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
CAPTAIN	2.58m dia x 2.9m	MLI	44mm(bottom) 71mm(side)	<1kg/m ³ (MLI only)	~1.5 W/m²	No
MicroBooNE	3.8m dia x 12m	Polyurethane Foam	400mm	32 kg/m ³	~13 W/m²	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Perforated Al honeycomb(In) Nomex honeycomb(Out)	665 mm+ (combined)	25-35 kg/m ³	7-22 W/m²	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion(In) GTT foam no membrane(Out)	665 mm+ (combined)	25-35 kg/m ³	10-15 W/ m²	Yes
ProtoDUNE	7.9m x 8.55m x 8.55m	GTT membrane	800mm	90 kg/m ³	~8 W/m²	No
ND-LAr	3m x 5m x 7m	GTT membrane	800mm	90 kg/m ³	~8 W/m²	No

Some Future LArTPC Experiments

- Gamma Ray and AntiMatter Survey (GRAMS) is a proposed experiment for the next-generation space missions targeting both gamma-ray observations in the poorly explored MeV energy band and indirect dark matter searches with antimatter
- GRAMS can have significantly improved sensitivity to MeV gamma rays and to antideuteron
- Novel segmented LArTPC design
- First LArTPC working at extreme conditions in the air/space

- The Forward Physics Facility is a natural new step for the high luminosity LHC era with very high energy neutrino beam
- A modularized liquid argon time projection detector (FLArE) is under development for the suite of detectors for the FPF
- The ultra-high granularity LArTPC with **sub mm** spatial resolution with pixel readout, and full photon coverage with SiPM readouts, both challenging for detector and electronics



Lab Tour

- **LAr R&D lab tour**
 - Please wear your safety glass
 - Follow the safety signs and boundaries in the lab

