Introduction to LArTPC for Neutrino Detection and Cryogenic System

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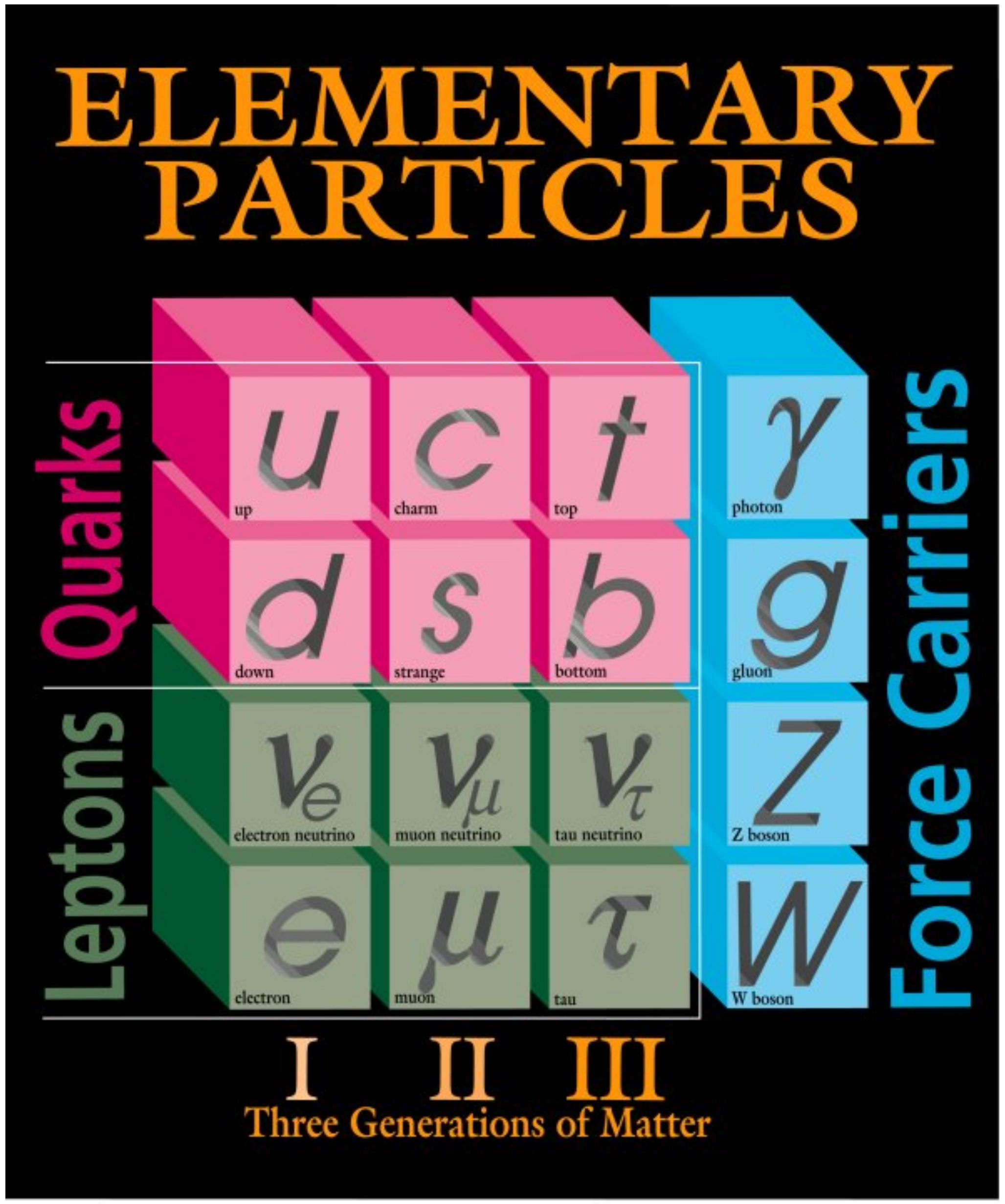
Outline

- **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 Monday)

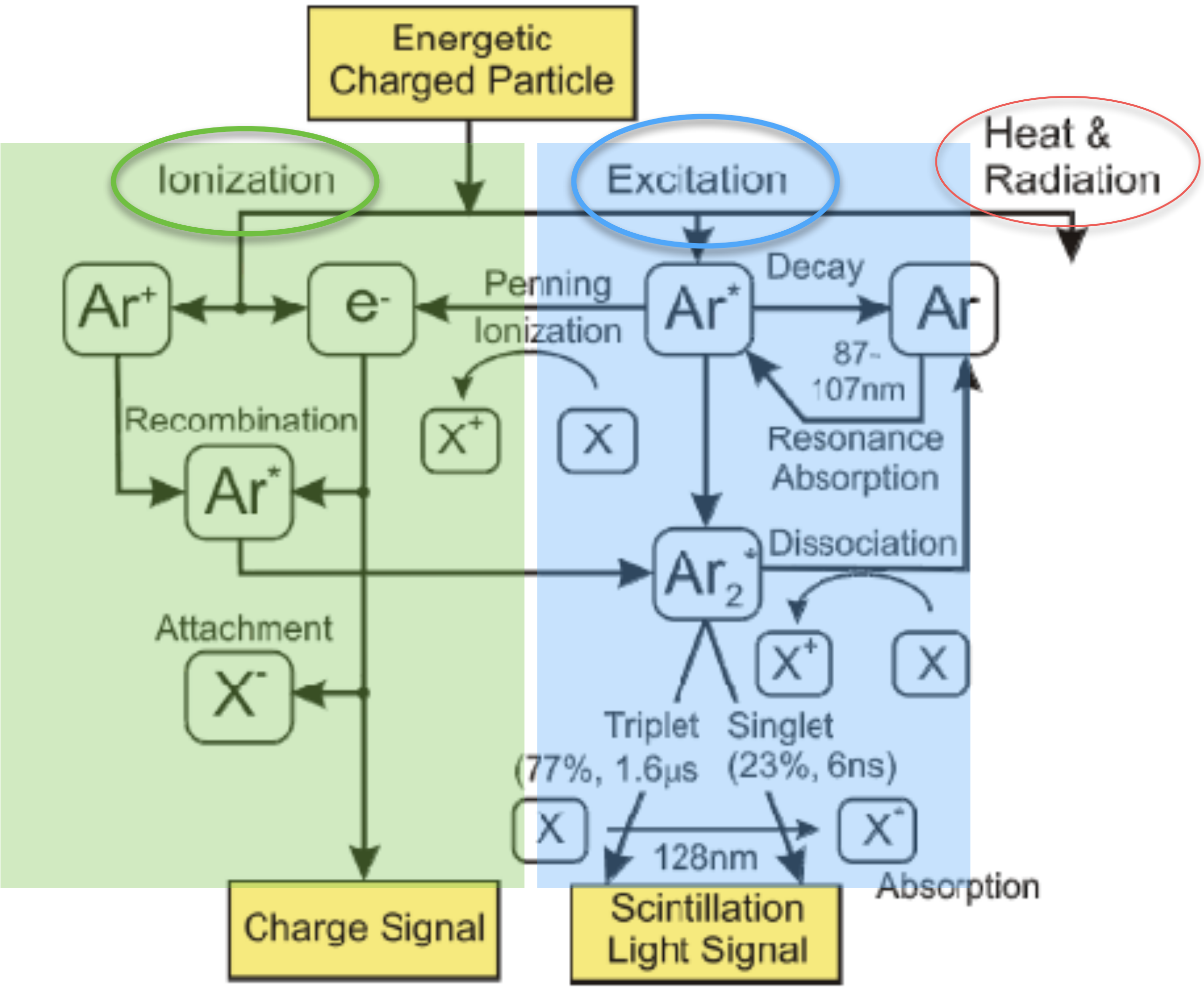
Experimental Detection of Neutrino Interactions

- 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

Cross-Section (Physics)

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

Signal observed — Detection Efficiency (Detector) — Luminosity (Flux+Medium Mass)



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(~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

From: Mitch Soderberg

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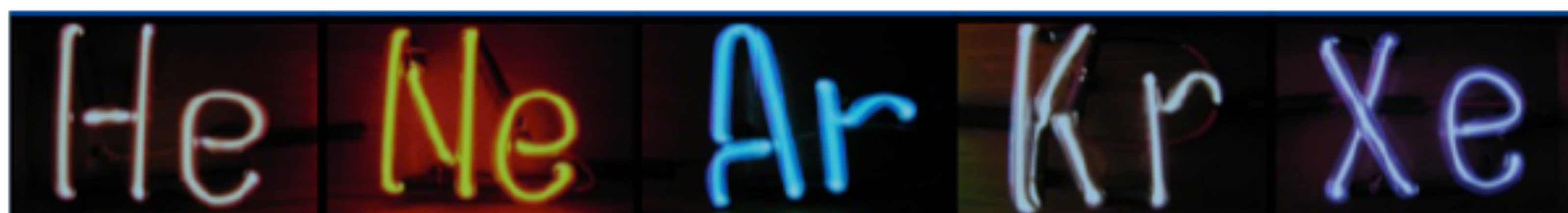
Prices in ~2024



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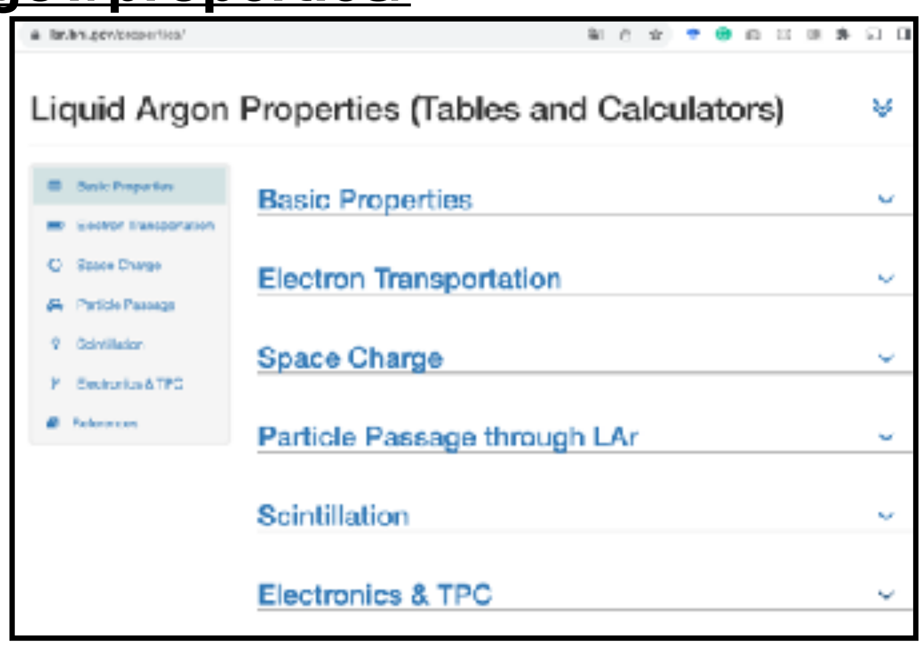
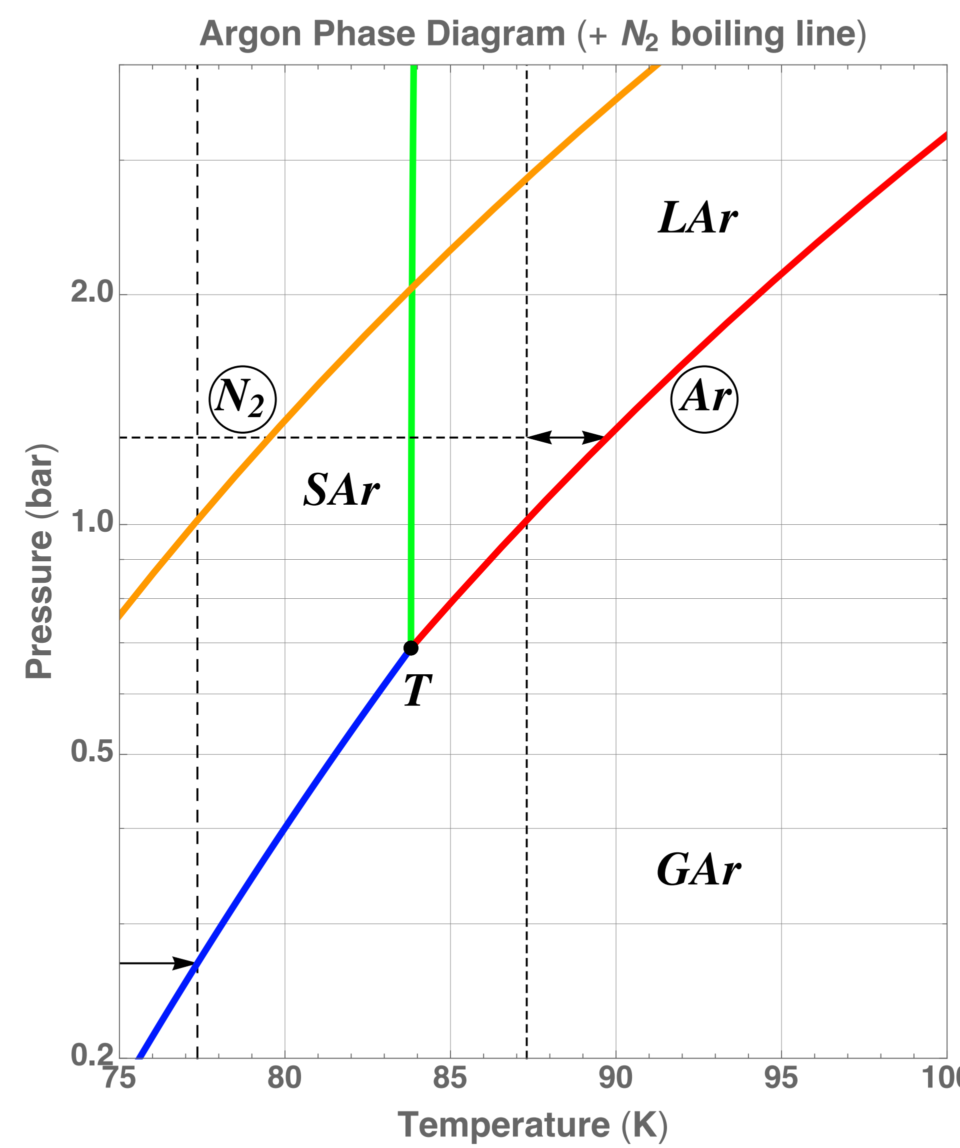
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	~100	~5000	9	~5000	~16000

From: Mitch Soderberg

LAr Properties

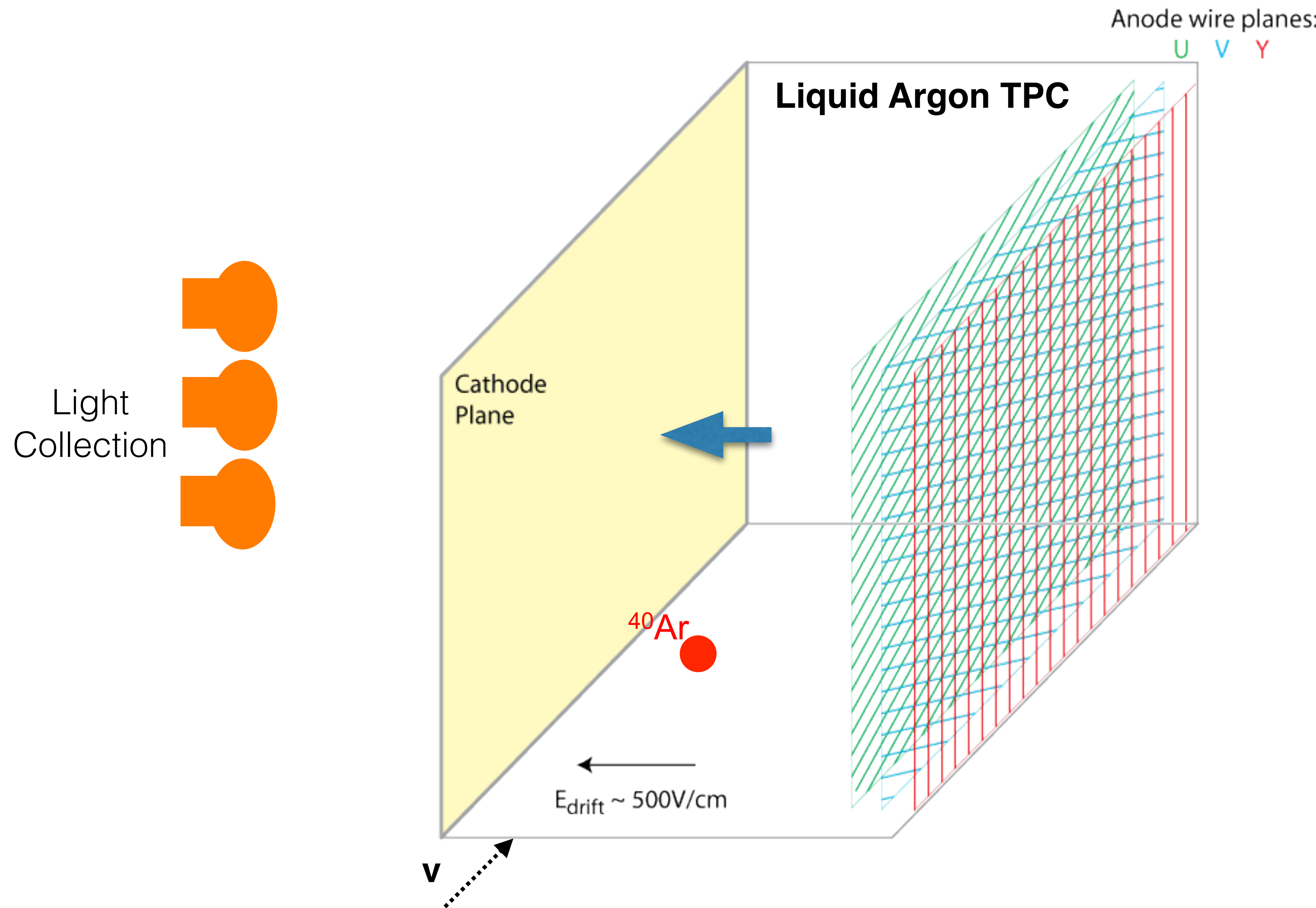
- Thermal properties
  - Normal boiling point at 1 atm: 87.3K—>matches pressurized LN2 temperature for condensing
  - Triple point temperature: 83.8K
- Signal generations
  - W-value for ionization: 23.6 eV/pair
  - W-value for scintillation: 19.5 eV/photon
- Electron transportation properties:
  - Electron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





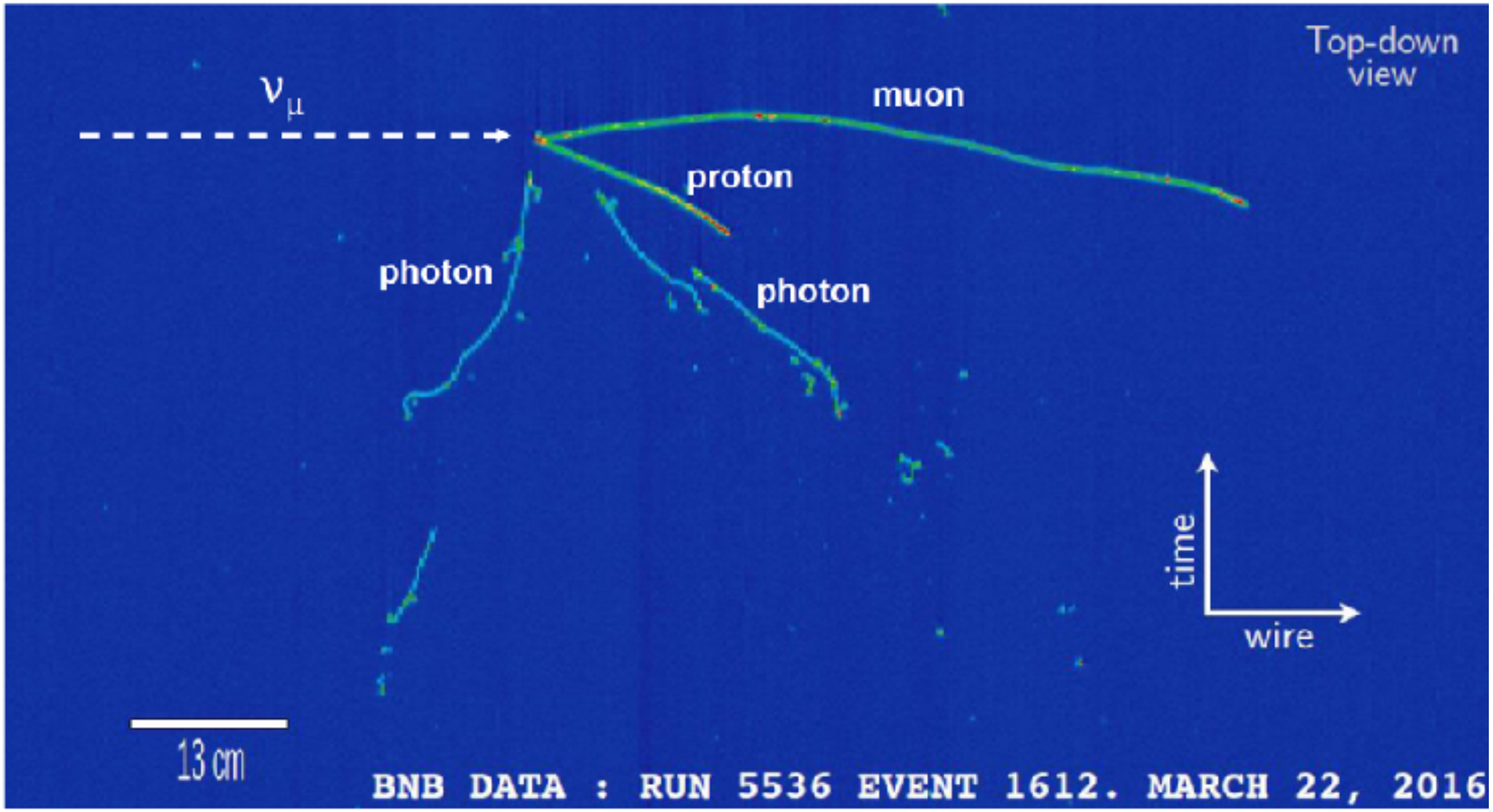
The Principle of LArTPC Detector

- Neutrino interaction with Ar
- Charged particle tracks ionized Ar atom.
- Scintillation Light (~ns) is detected by photo detector at the same time.
- Then ionized electrons are drifted to the anode plane(~ms in time, ~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.



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 < 10s of part-per-trillion level is required for LArTPC.
- Cold electronics to minimize noise. Cryogenic condition is challenging for the electronics
- Breakdown with HV: ~10^2 kV HV required for electron drift. Breakdown mechanism not fully understood for LAr
- Space charge effect for surface detector.



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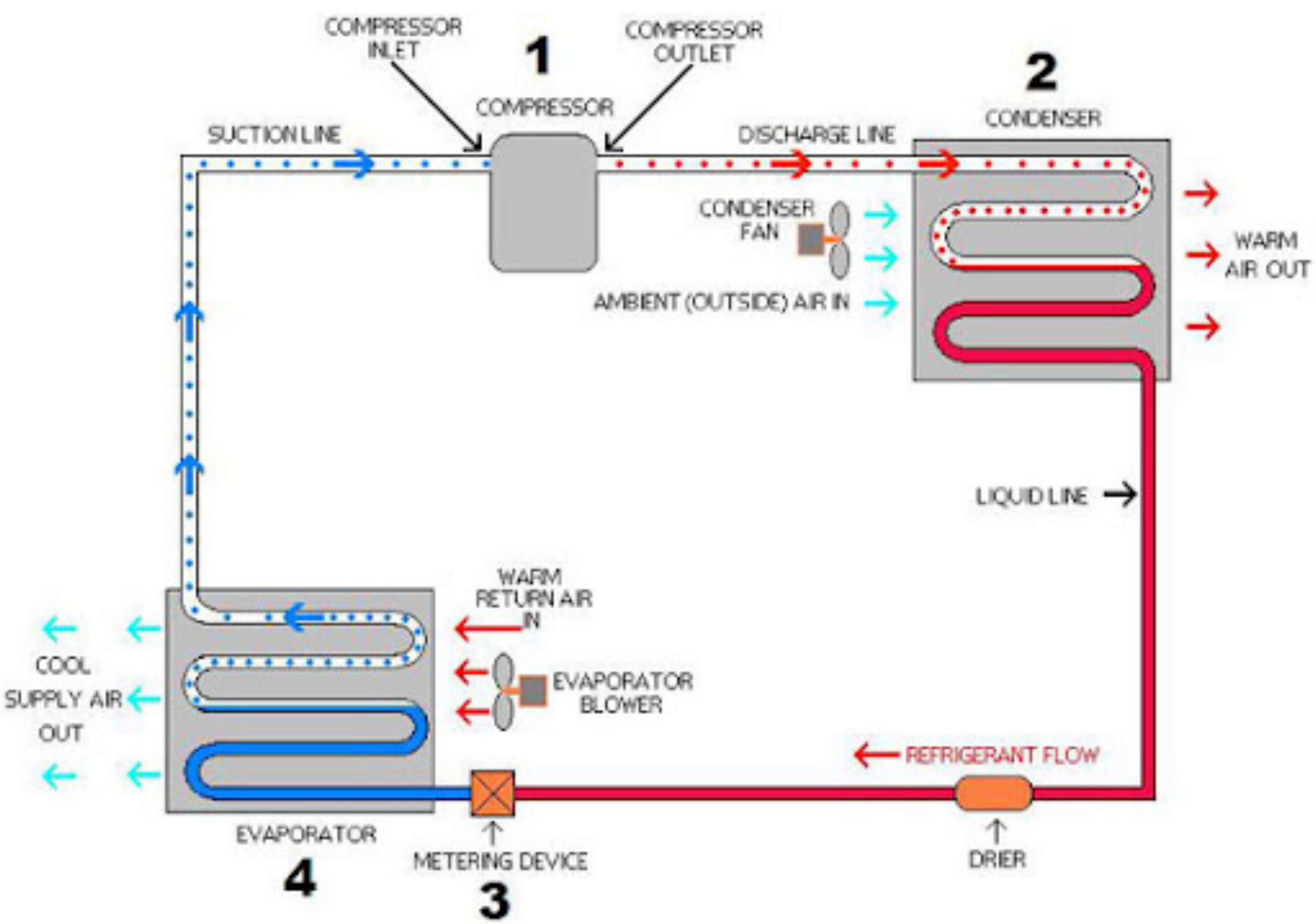
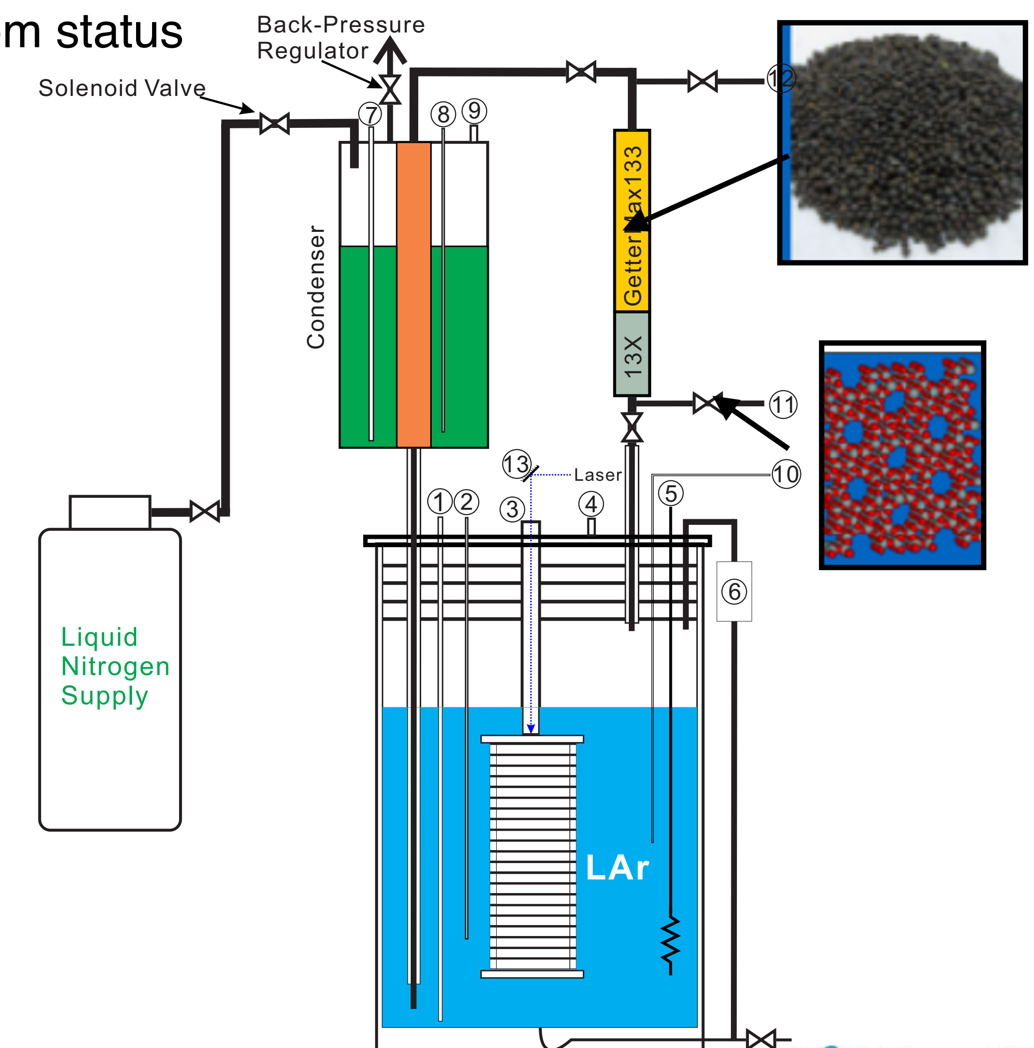
LArTPC Cryogenic System

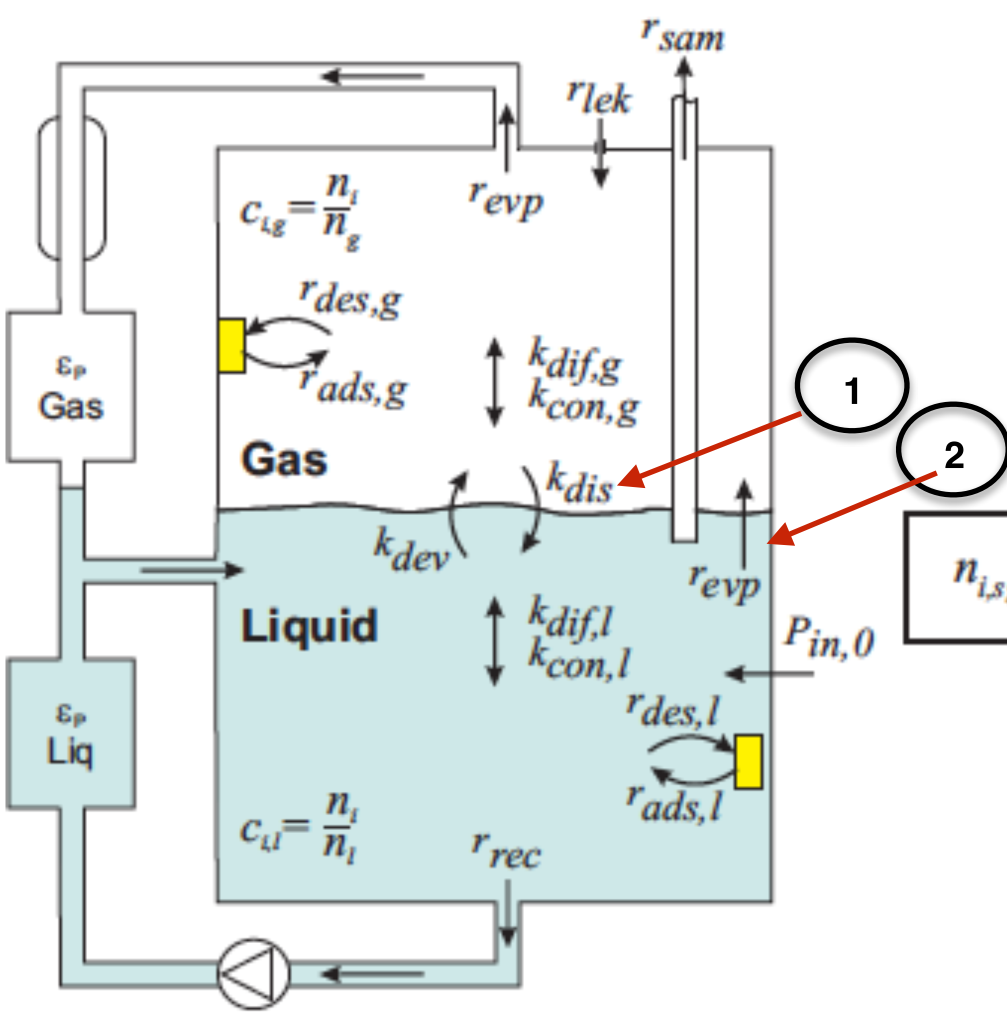
- LArTPC cryogenic system is actually a large refrigerator at very **low** temperature!
  - LAr evaporates needs to be condensed to maintain the stable operation
  - Sufficient condensing power
  - Good insulation quality
- Achieve desired purity level by passing argon through filters containing molecular 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

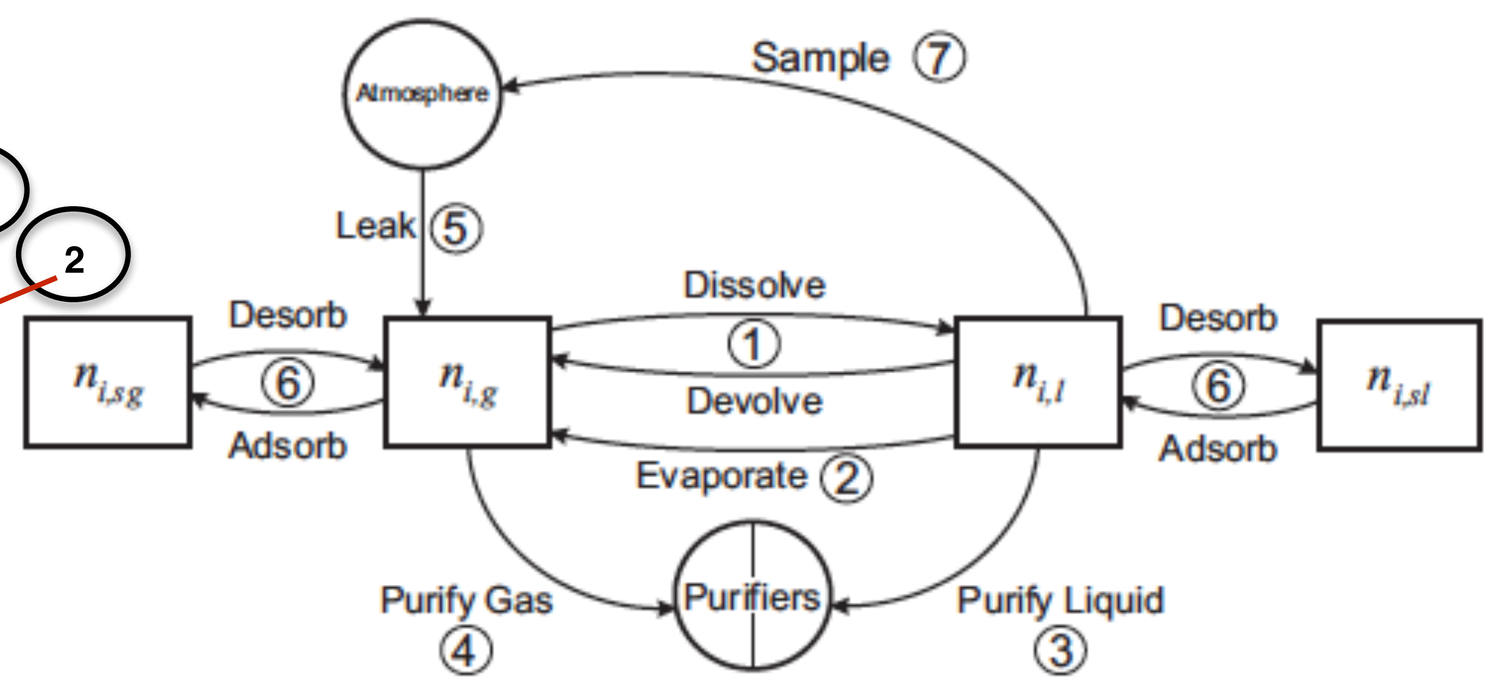




Impurity in LArTPC

- 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

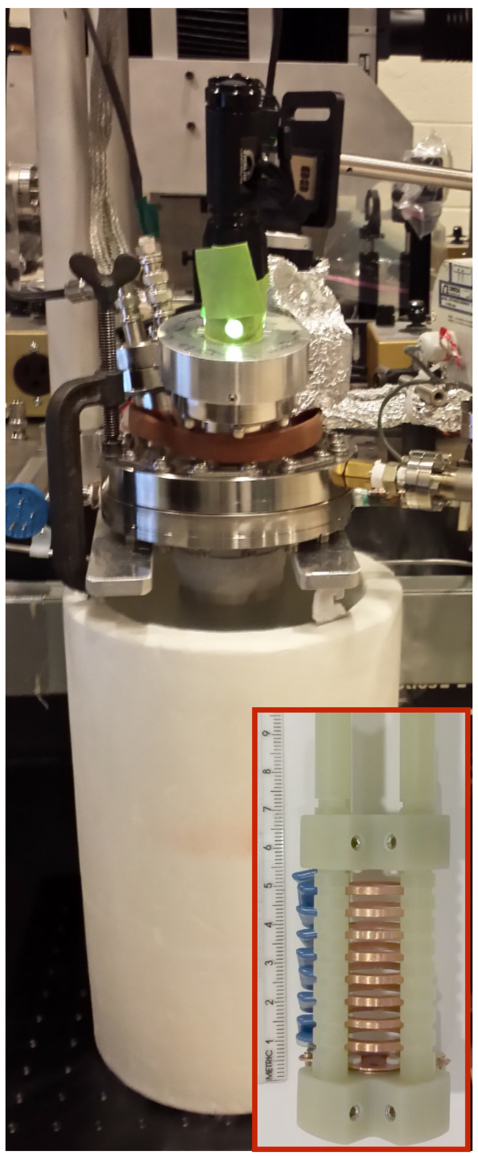




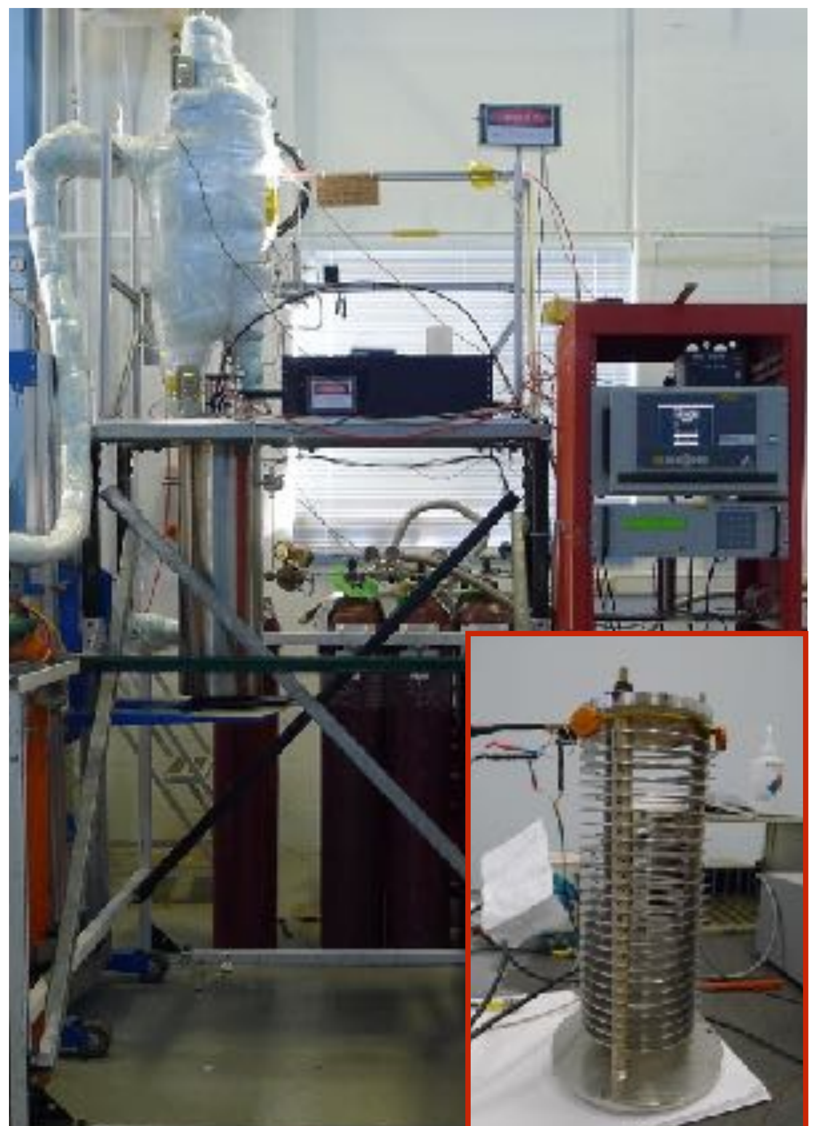
Reading assignment: NIM, A 1010 (2021) 165491

LAr R&D Experimental Setup at BNL

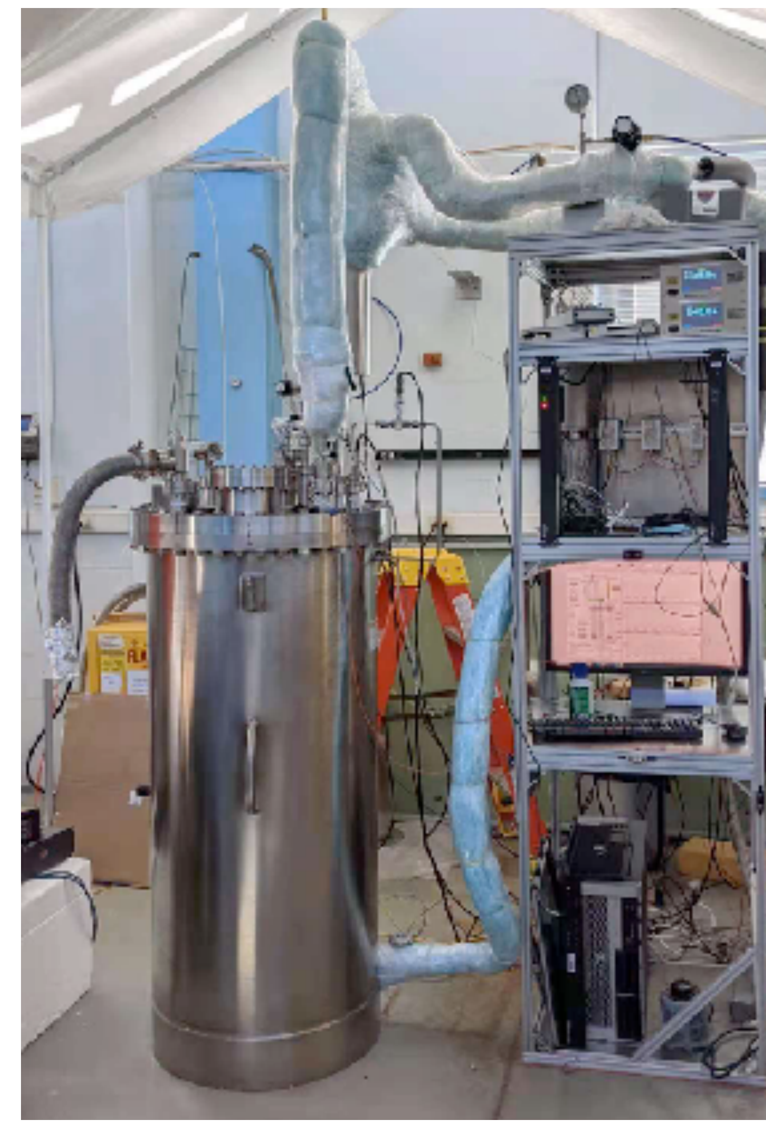
- 2L test stand is cooled by LN_2+Dry ice bath and LAr is formed by liquefying purified commercial GAr
- 20L test stand is an upgraded and improved apparatus with LAr circulation and GAr purification
- The 260L LAr test platform is commissioned with high purity achieved
- Only gas purification is implemented in our local setup
  - Also added liquid purification in the LAr filling line



2 L Test Stand



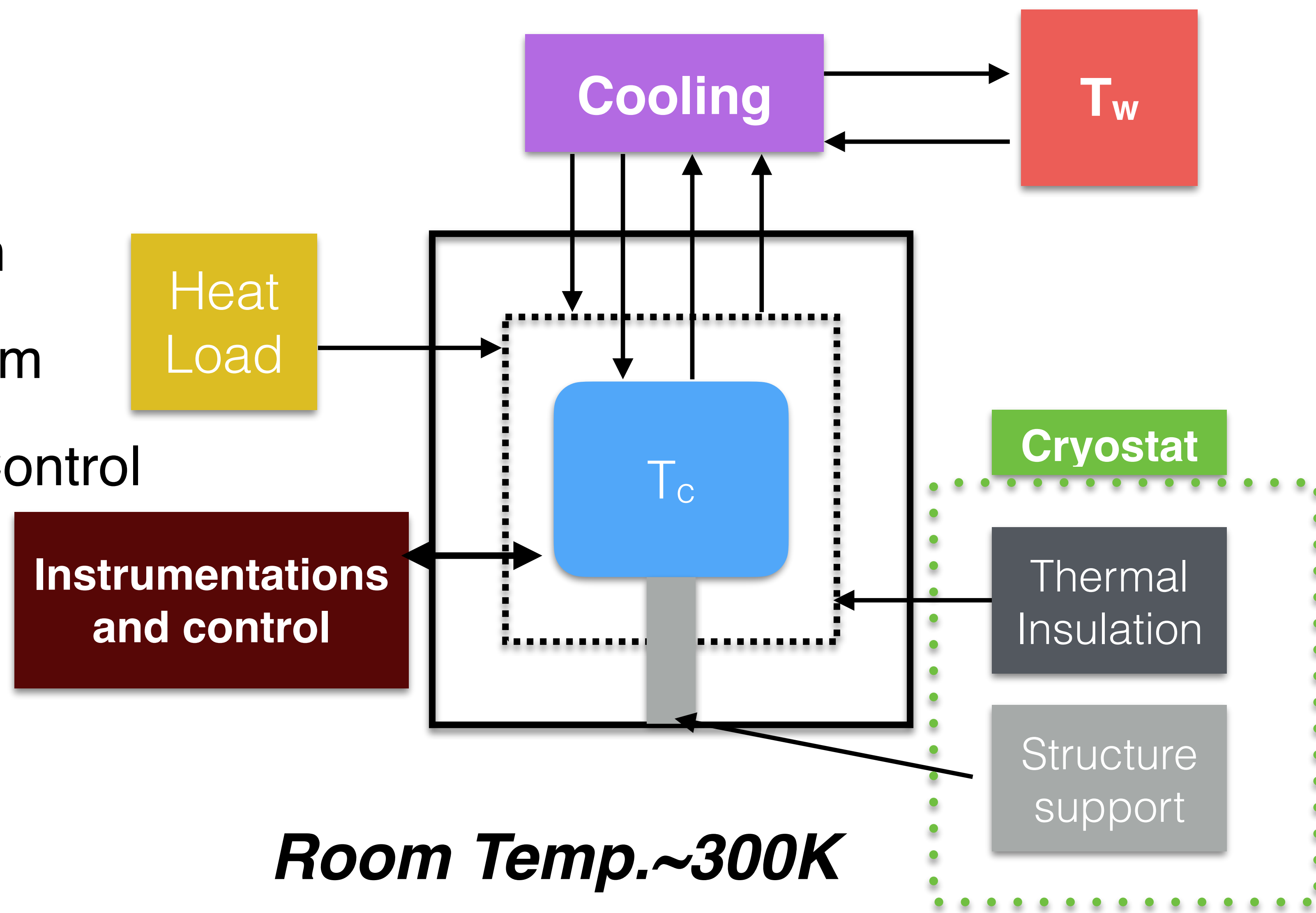
20 L Test Stand



260L LAr Platform

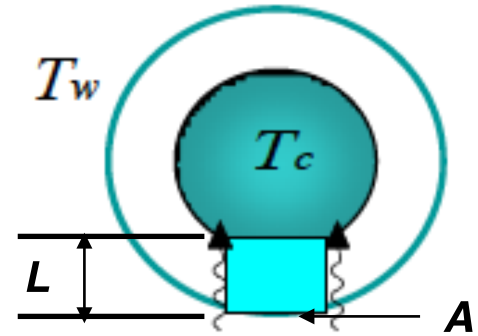
Cryogenic System Overview

- **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



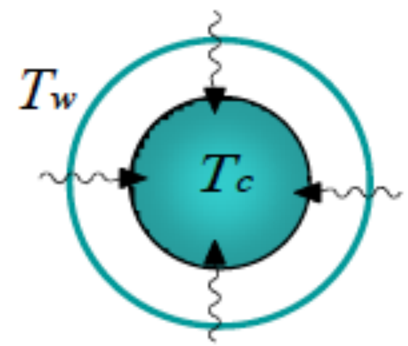
Heat transfers for Cryostat

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



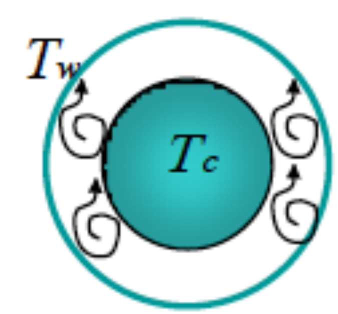
  - Reduce heat load—>Low thermal conductivity, small contact area thicker insulation

- **Thermal radiation**
  - For the case of enclosed cylinder



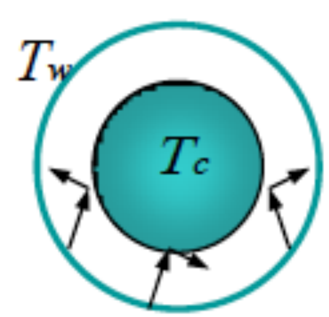
  - $$Q_r = \frac{\sigma A_c({T_w}^4 - {T_c}^4)}{\frac{1}{\epsilon_c} + \frac{A_c}{A_w}(\frac{1}{\epsilon_w} - 1)}$$
  - Reduce heat load—>Reduce A_w and Emissivities

- **Natural convection**



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

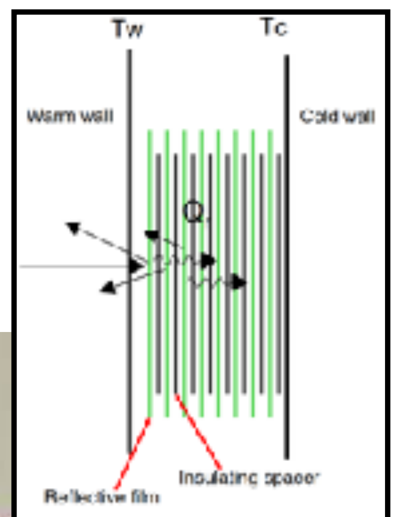
- **Residual Gas conduction**
  - Molecular regime
  - $$Q_{res} = A_c \cdot \alpha(T) \cdot \Omega \cdot P(T_w - T_c)$$

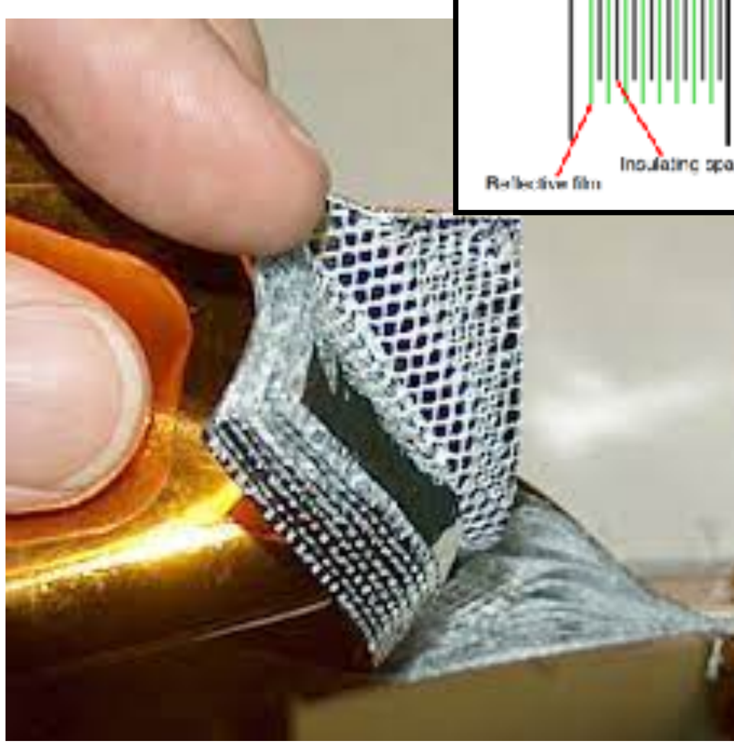


Cryostat Insulations (Passive)

- **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, $k \sim 0.05\ mW/(m \cdot K)$
  - Bulk Fill materials (Perlite Powder) work in a soft vacuum ($>10^{-3}$ Torr), $k \sim 1.5\ mW/(m \cdot K)$
  - Mechanical insulation at ambient pressure, k values are $\sim 30\ mW/(m \cdot K)$

MLI



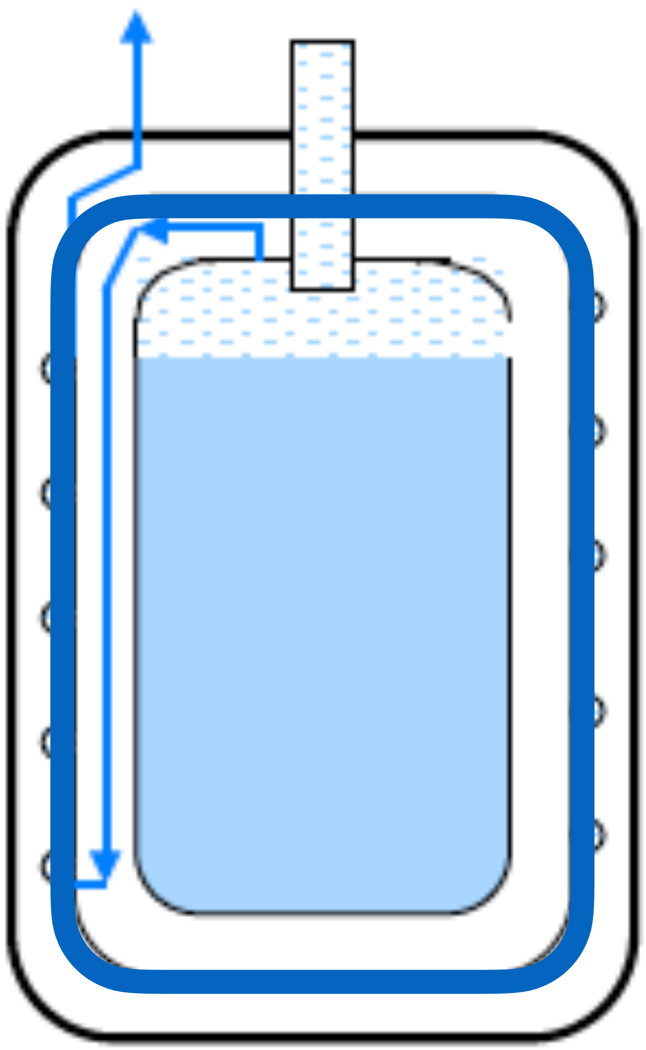


Bulk Fill

Mechanical

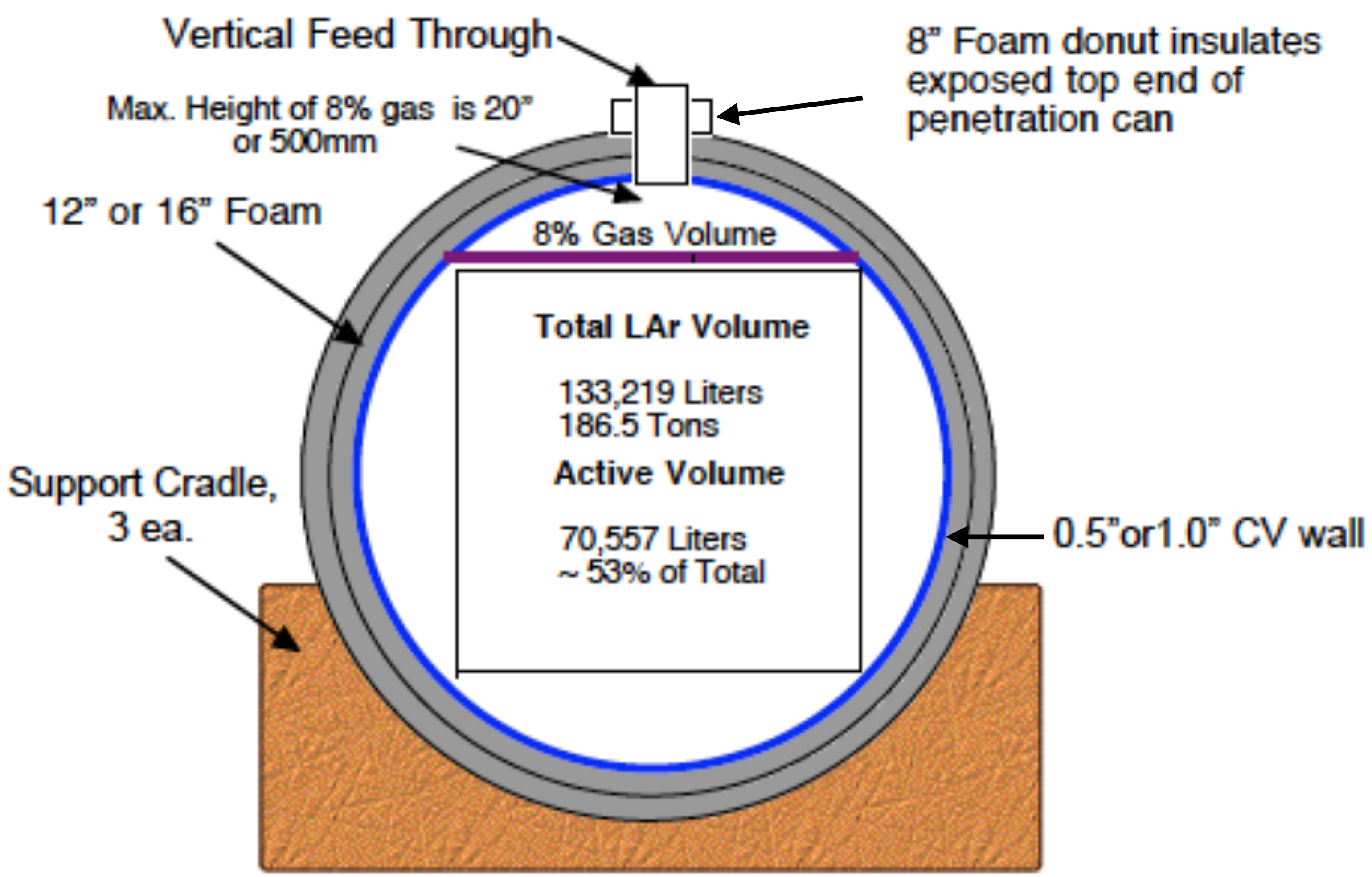
Cryostat Insulations (Active Cooling)

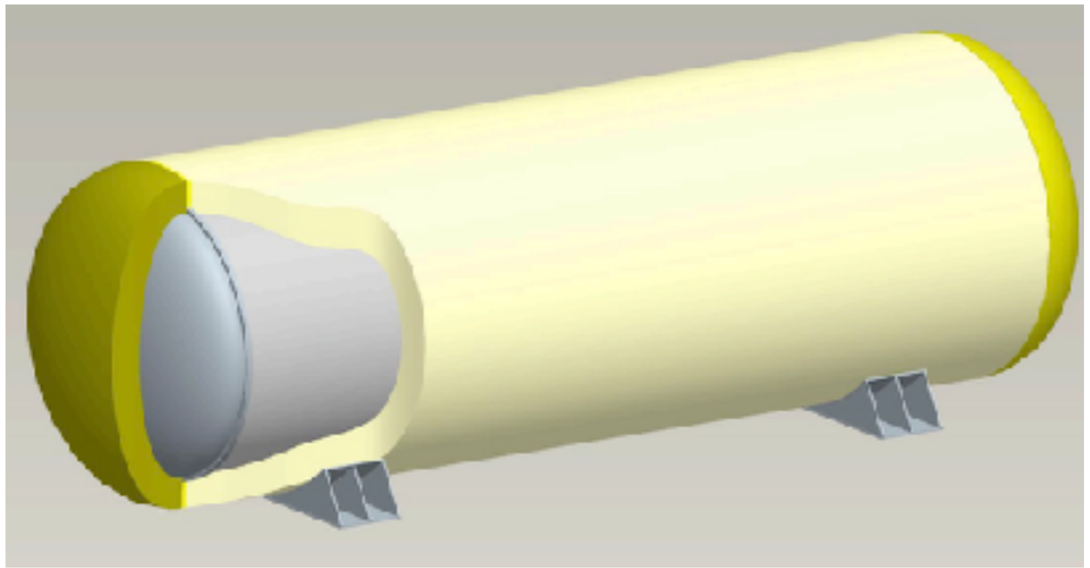
- **Another insulation approach is active cooling**
  - Create an actively cooling radiation shields
    - Lower emissivity at low temperature
    - Heat extraction at higher temperature
  - Adapted in ICARUS
- **Pros**
  - Higher heat extraction efficiency by removing heat at higher temperature
  - 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 ~12 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





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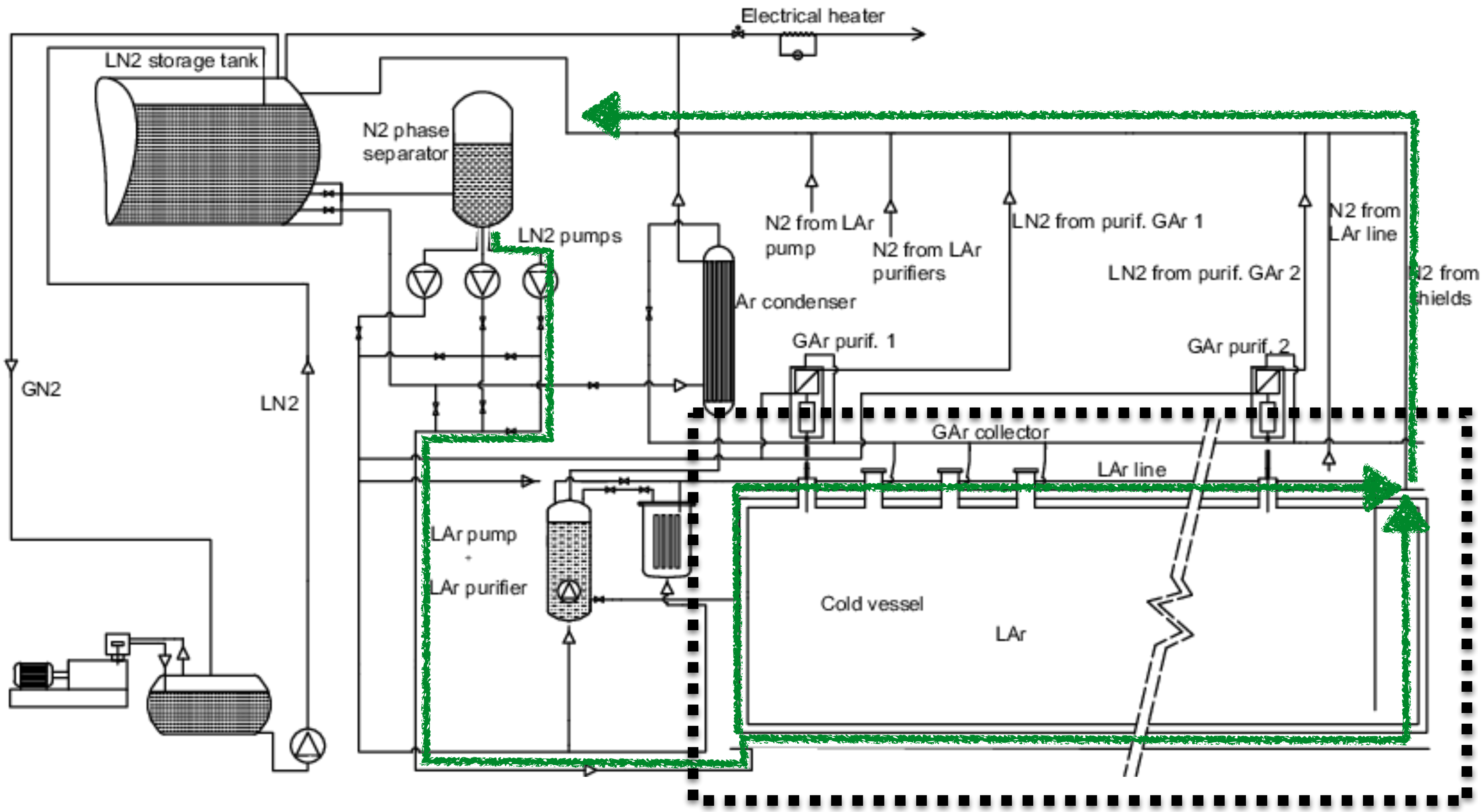
MicroBooNE Cryostat Final Production Version

- **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 spayed on, Heat leak ~ 13 W/m^2
  - Insulation weight ~32 kg/m^3

ICARUS T-600 Cryogenic

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



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

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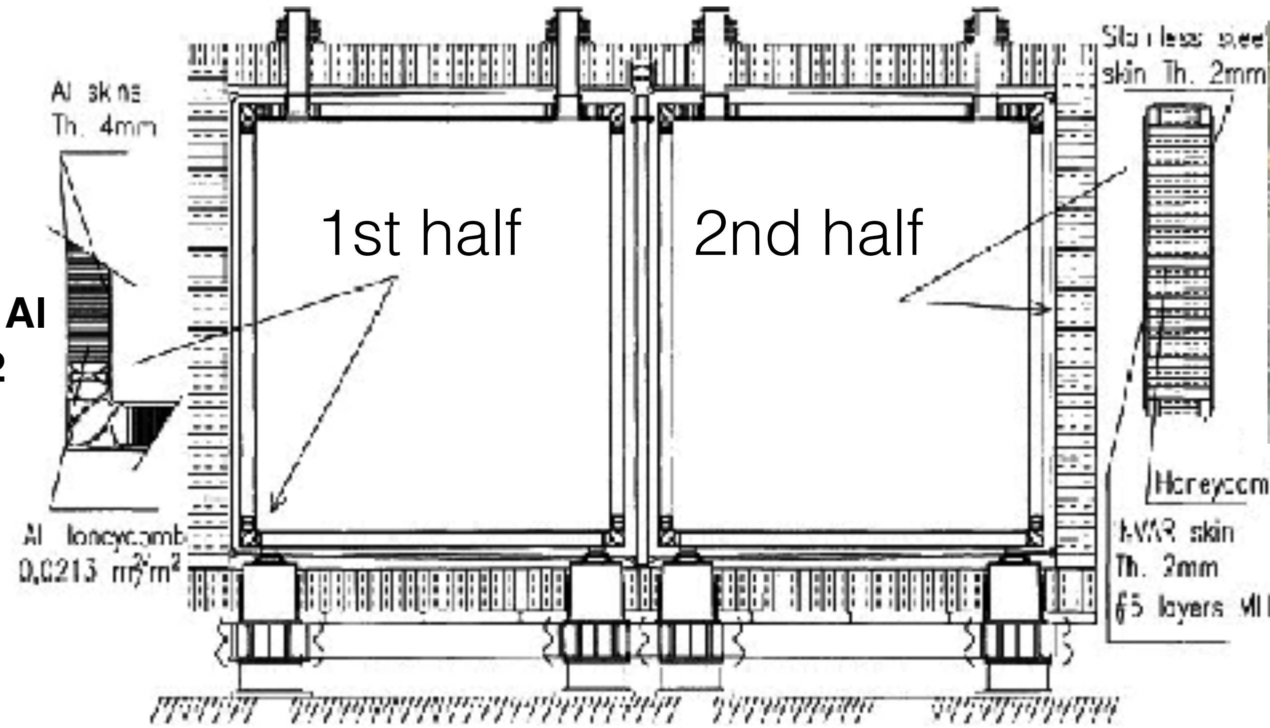
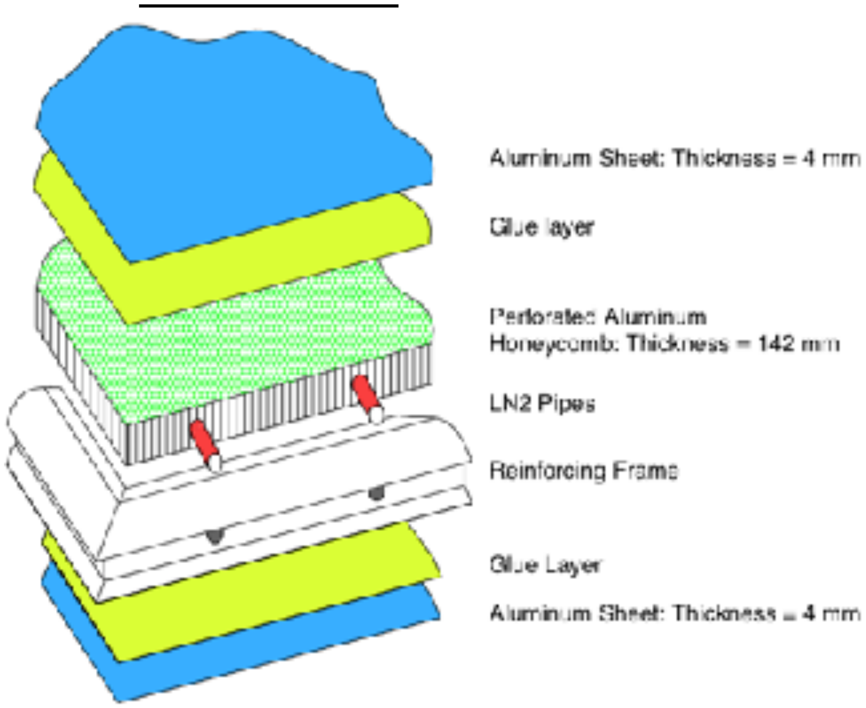
ICARUS T600 Cryostat at Gran Sasso

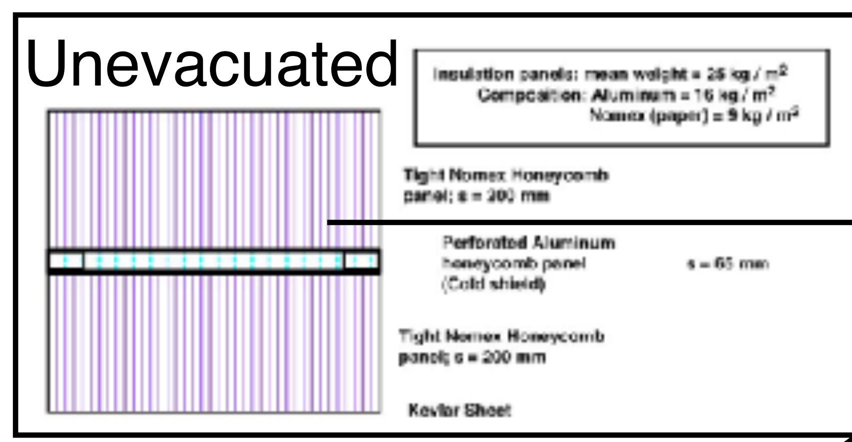
- **The cryostat composed of two parts**
  - Aluminum box for TPC(3.9m x 3.6m x 19.6m inner)
  - Outer Insulation panels
- **Active LN2 cool shield applied on the Al box and between outer insulations，2 versions of insulation**
  - Unevacuated: ~22 W/m²
  - Evacuated: ~ 7 W/m²
- **Parameters**
  - TPC box: ~20cm thickness, 35kg/m³
  - Insulation panel ~45cm thickness, 25kg/m³

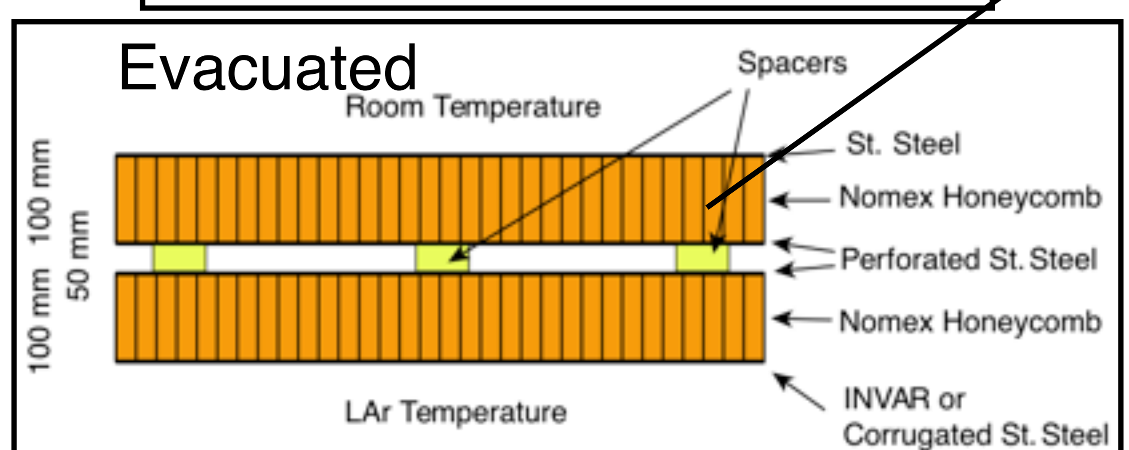


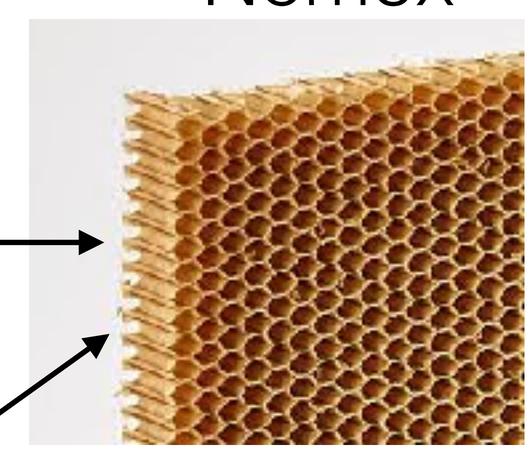
TPC box



Insulation panel



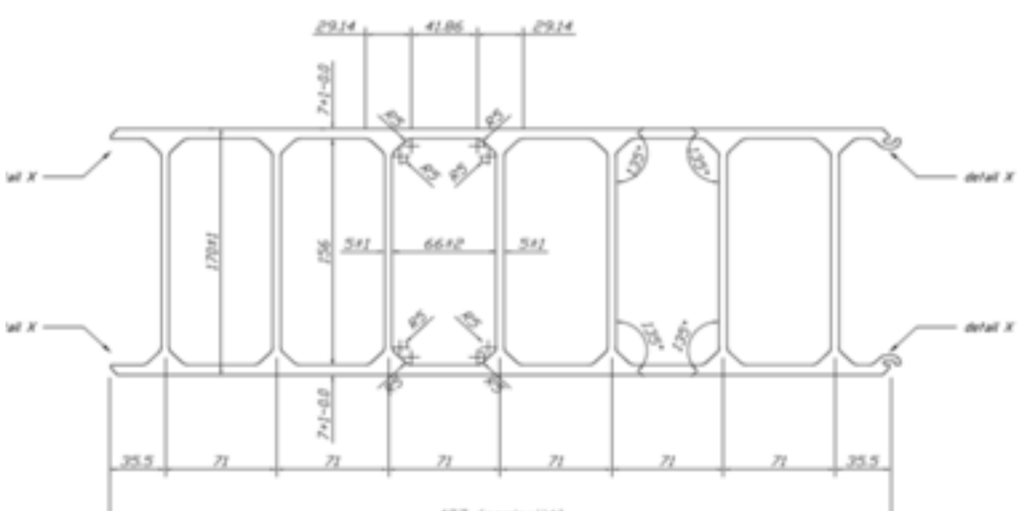




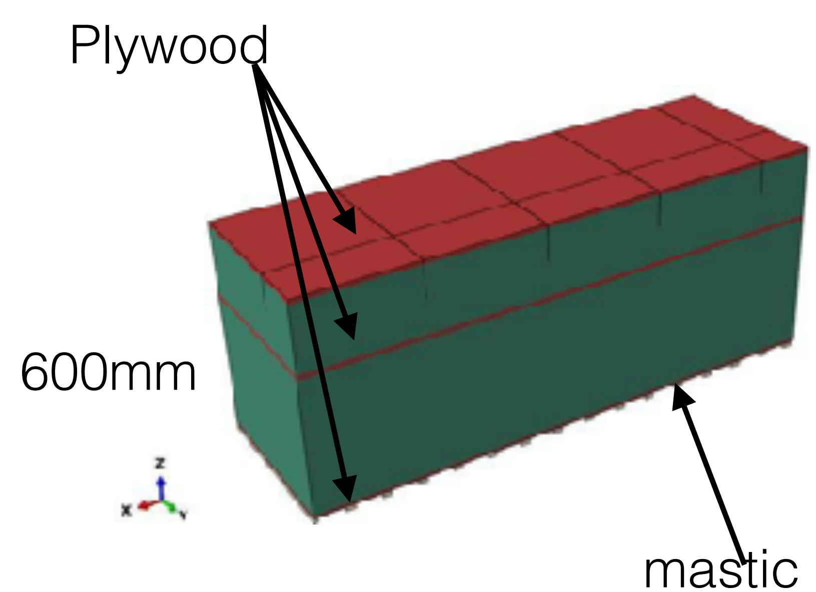
ICARUS T600 Cryostat at SBN

- **New Al box and Insulation made for T600 at SBN**
  - TPC box: Nomex honeycomb repalced 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

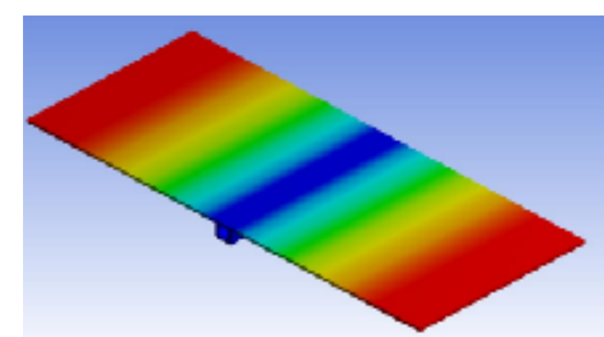
TPC box



Insulation panel

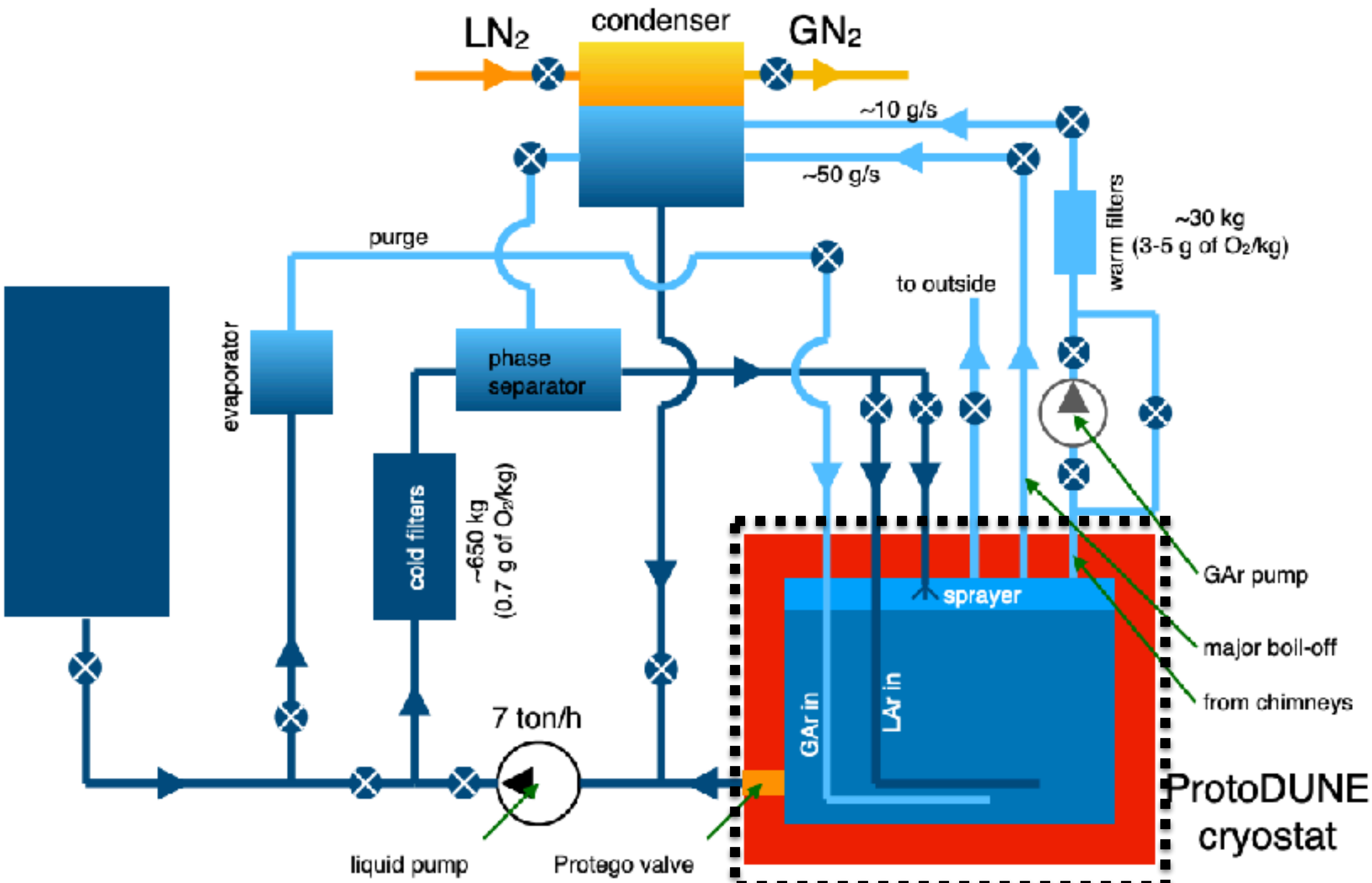


Cold shield



ProtoDUNE Cryogenic

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



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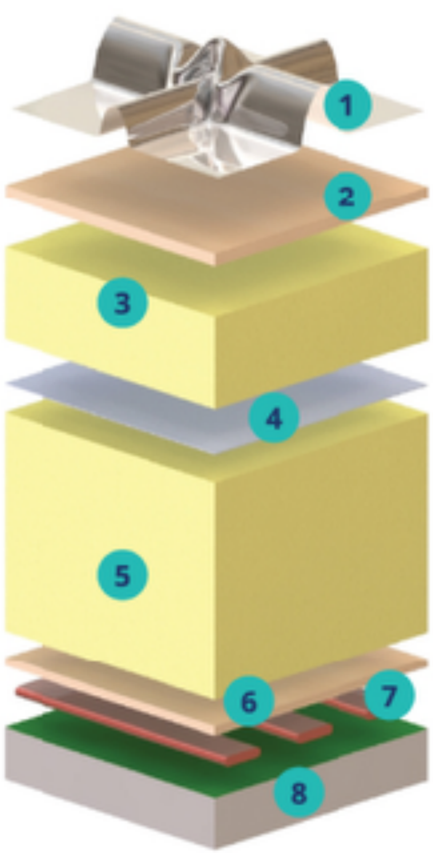
ProtoDUNE Cryostat

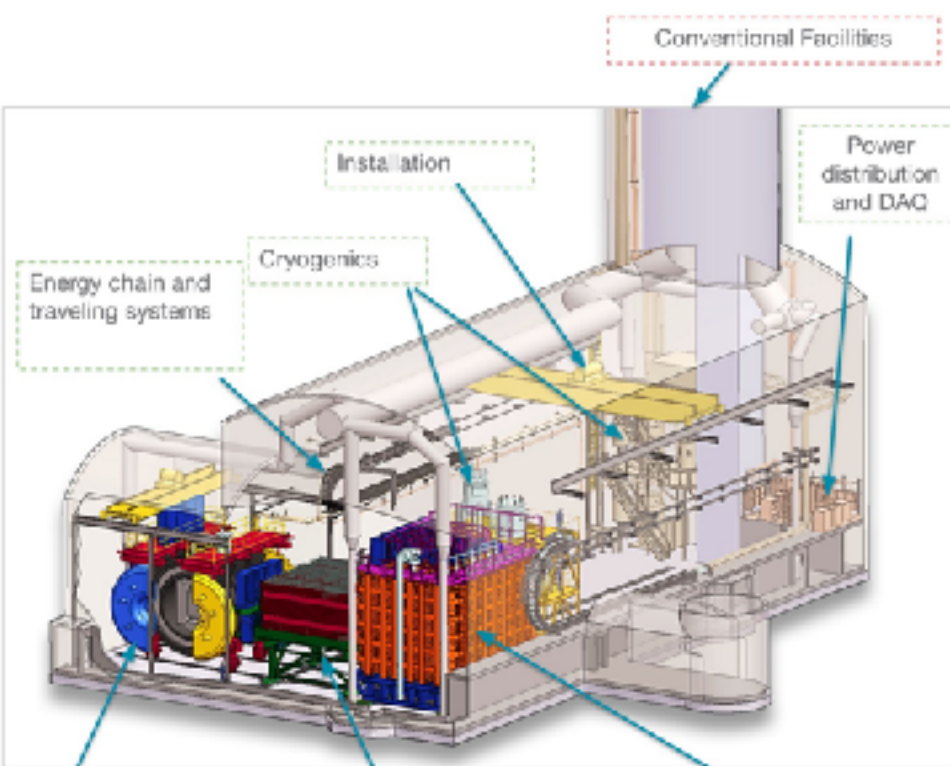
- **Membrane cryostat**
  - Inner dimension 7.9 m x 8.55 m x 8.55 m, total volume of 580 m^3
  - ProtoDUNE/DUNE cryostat is based on the mature LNG transport membrane technology developed by the firm GTT (Gaztransport & Technigaz)
  - Heat leak ~8 W/m^2
  - Insulation thickness ~ 800mm
  - Insulation weight 90 kg/m^3

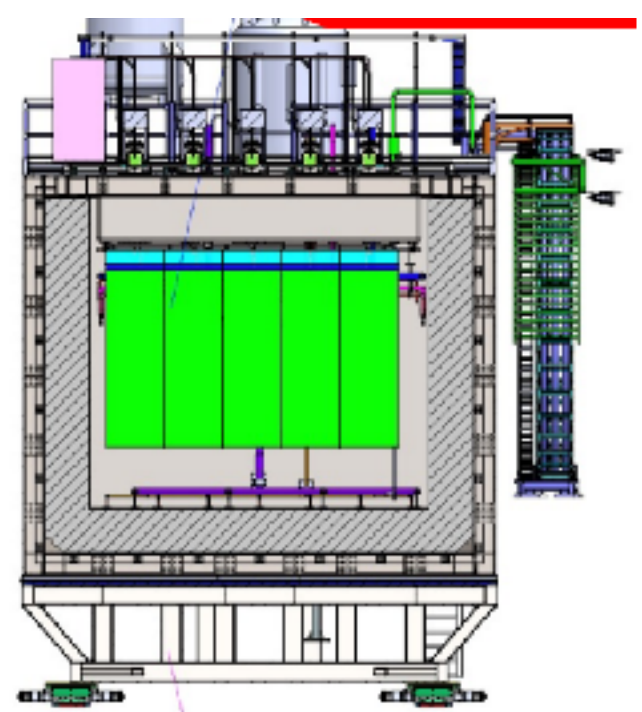


1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier

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



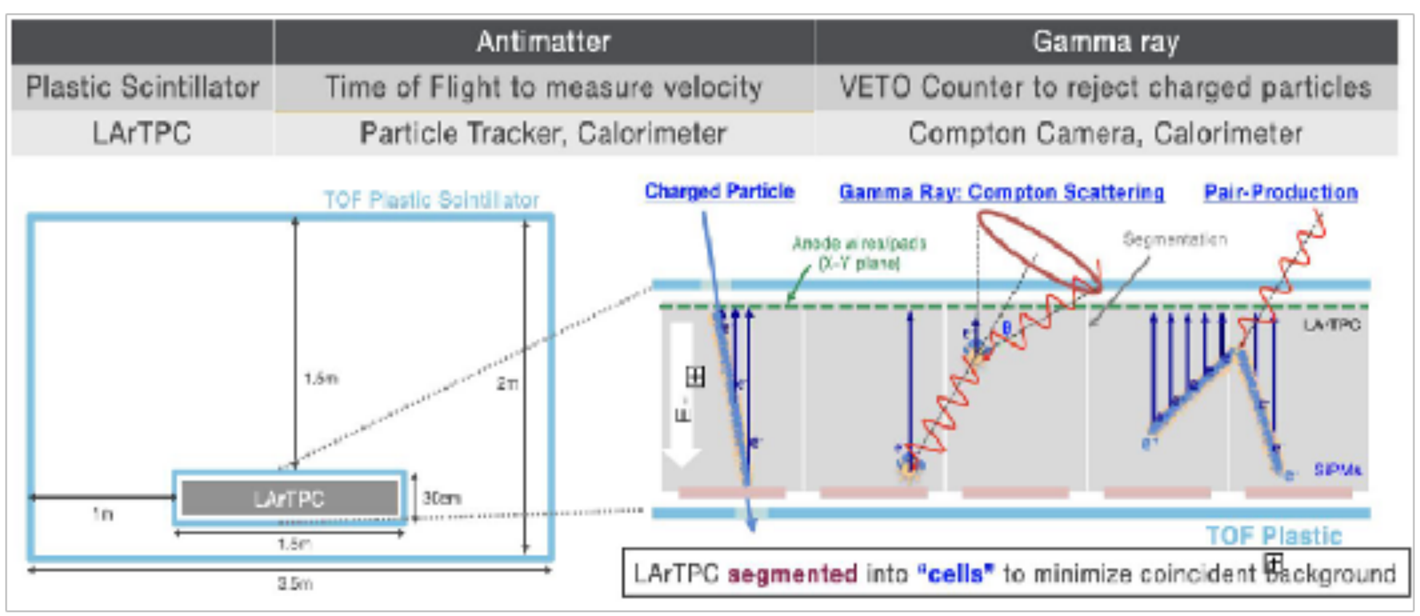


Summary of Cryostats

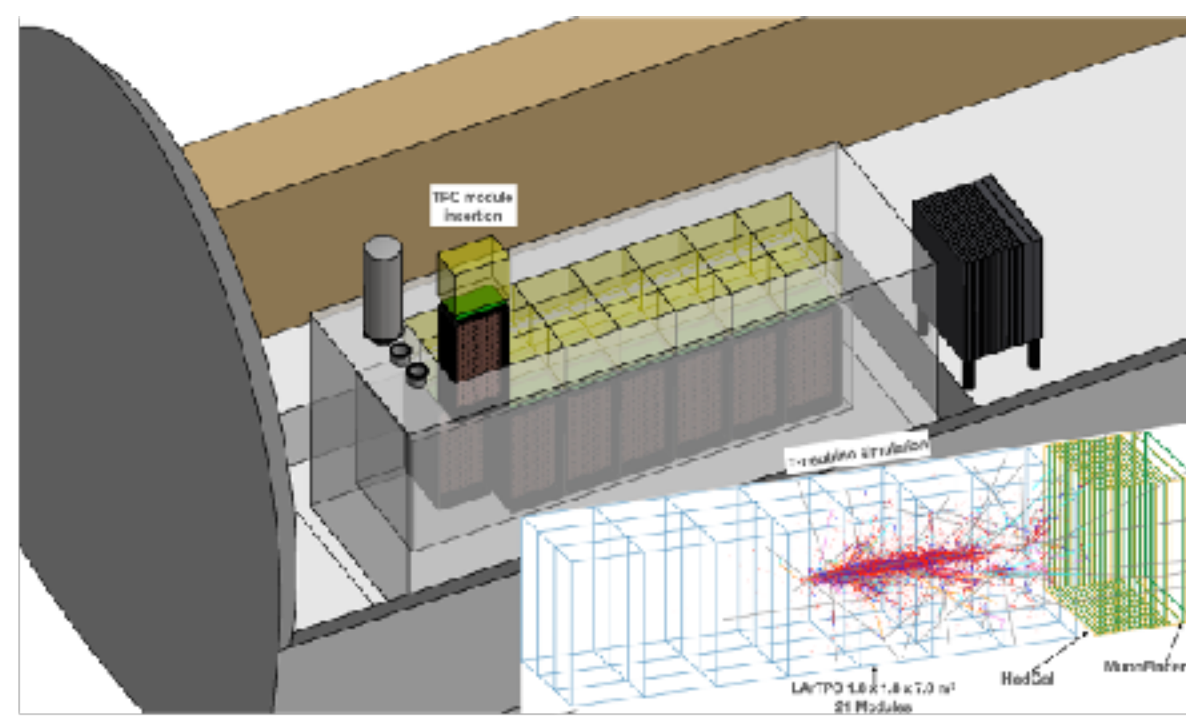
	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
CAPTAIN	2.58m dia x 2.9m	MLI	**44mm(bottom) 71mm(side)**	<1kg/m³ (MLI only)	**~1.5 W/m²**	No
MicroBooNE	3.8m dia x 12m	Polyurethane Foam	**400mm**	32 kg/m³	**~13 W/m²**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Perforated Al honeycomb(In) Nomex honeycomb(Out)	**665 mm+ (combined)**	25-35 kg/m³	**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/m³	**10-15 W/m²**	Yes
ProtoDUNE	7.9m x 8.55m x 8.55m	GTT membrane	**800mm**	90 kg/m³	**~8 W/m²**	No
ND-LAr	3m x 5m x 7m	GTT membrane	**800mm**	90 kg/m³	**~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 antideuterons
- 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