Modeling Impurity Concentrations in Liquid Argon Detectors

Outline

1. Overview
2. Quantitative impurity distribution model
3. Test/Application of the model
4. Conclusions

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Overview: Large LAr TPC

- **Short-Baseline Neutrino (SBN) program and Deep Underground Neutrino Experiment (DUNE) with Liquid Argon Time Projection Chambers will address**
    - CP violation in the lepton sector
    - Neutrino mass hierarchy
    - Precision measurement of neutrinos
    - Search for sterile neutrino(s)
    - Proton decay
    - Supernova neutrinos detection
- **Characterizing the properties of LAr is very important for the design of the these detectors considering their high cost and long construction and operational period**
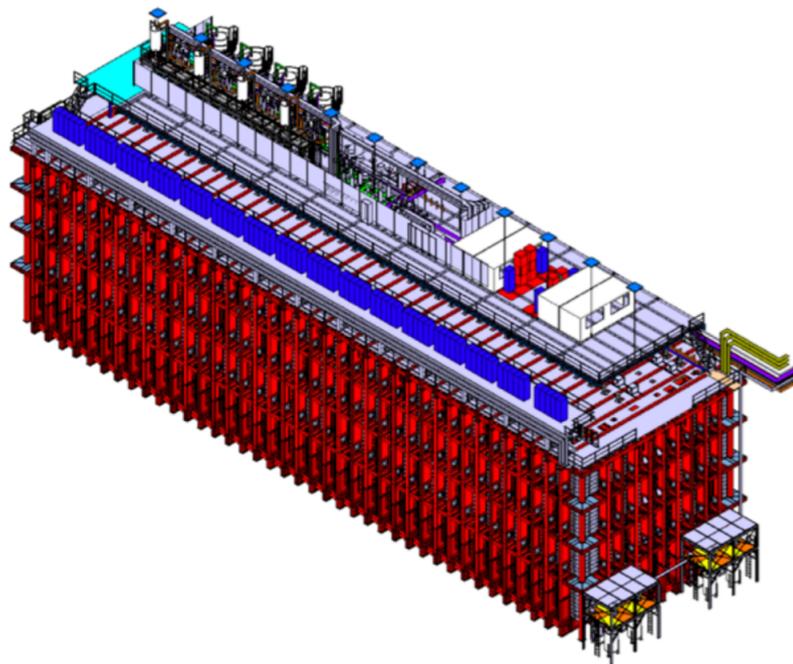
DUNE Single-Phase LAr TPC (4x10 kt)
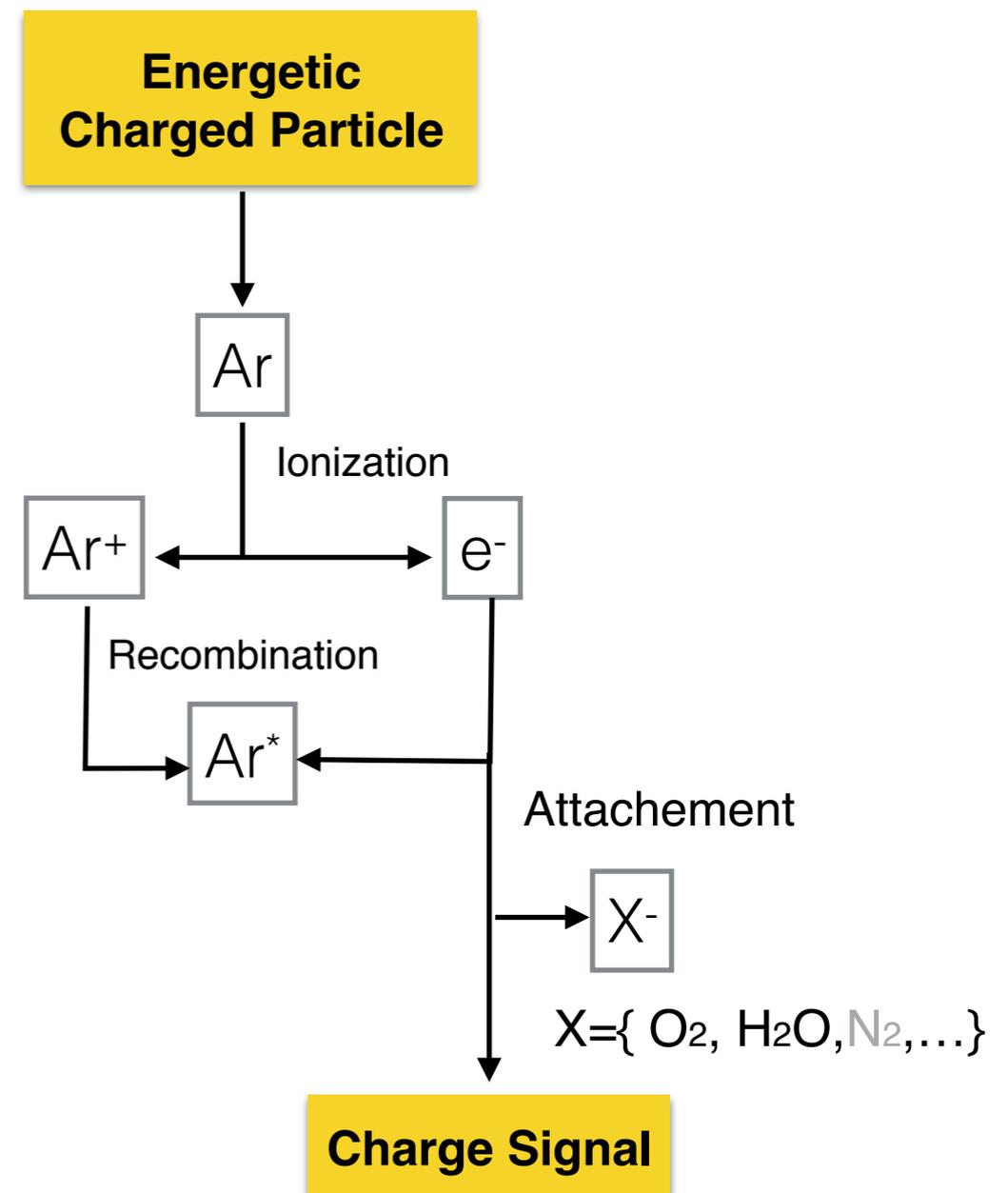*Drift Length from Cathode(C) to Anode(A) = 3.5m*
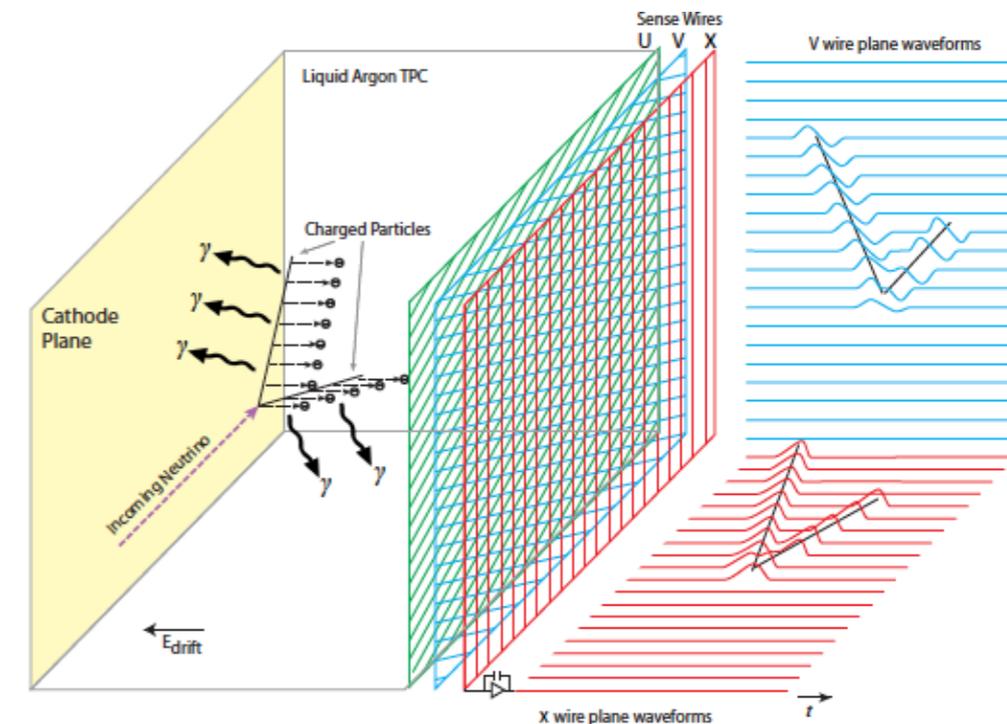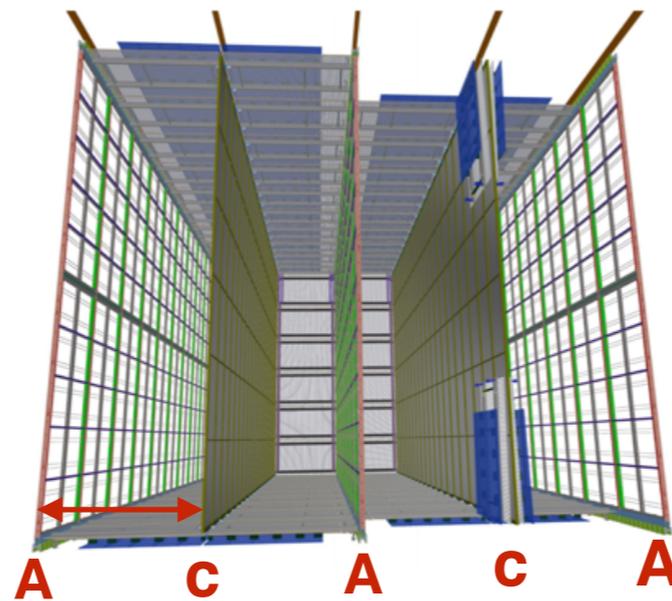
The Principle of single phase LArTPC
3D reconstruction

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Overview: Impact of Impurities

‣ Understanding the fundamental properties of LArTPC purity is important for detector operation and optimization

‣ At 500 V/cm, the drift time for 3.5 meter is 2.2 ms

‣ Ultra-high purity required for long electron lifetime in LArTPC

‣ Attachment to electron negative impurities (O2 and H2O) reduces charge signal

‣ O2 and N2 attachment constants are known[1,2], but H2O is not

Energetic Charged Particle

Ar

Ionization

Ar+   e⁻

Recombination

Ar*

Attachement

X⁻

X={ O2, H2O, N2,...}

Charge Signal

[1]. Proceedings of the Royal Societyof London A: Mathematical, Physical and EngineeringSciences, 221(1147):517-534, 1954.
[2].Trans. Faraday Soc., 58:1692-1704, 1962.

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Quantitative Impurity Distribution Model in LArTPC

‣ **Ultra-high purity (< 1.0 ppb for O2, H2O) is essential to operate LArTPC with long drift distances**

‣ **A quantitative kinetic model of impurity distribution is constructed**

LArTPC cryostat/cryogenic system model
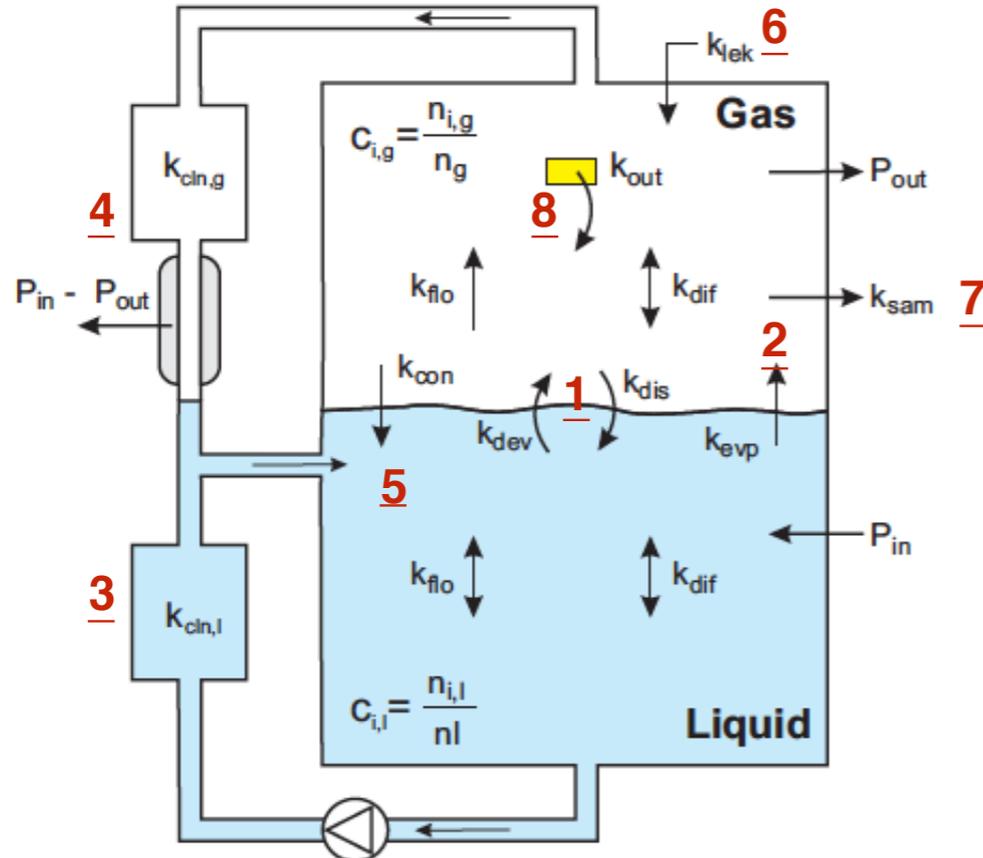
Processes included in the model

1. *Impurity exchange at the gas-to-liquid interface:*
2. *Evaporation of the liquid*
3. *Purification of the liquid*
4. *Purification of the gas followed by condensation*
5. *Condensation of the gas directly into the liquid*
6. *Leak from Atmosphere*
7. *Loss of LAr due to sampling*
8. *Outgassing of surfaces in contact with warm gas*

‣ Each process can be described by the an ordinary differential equation
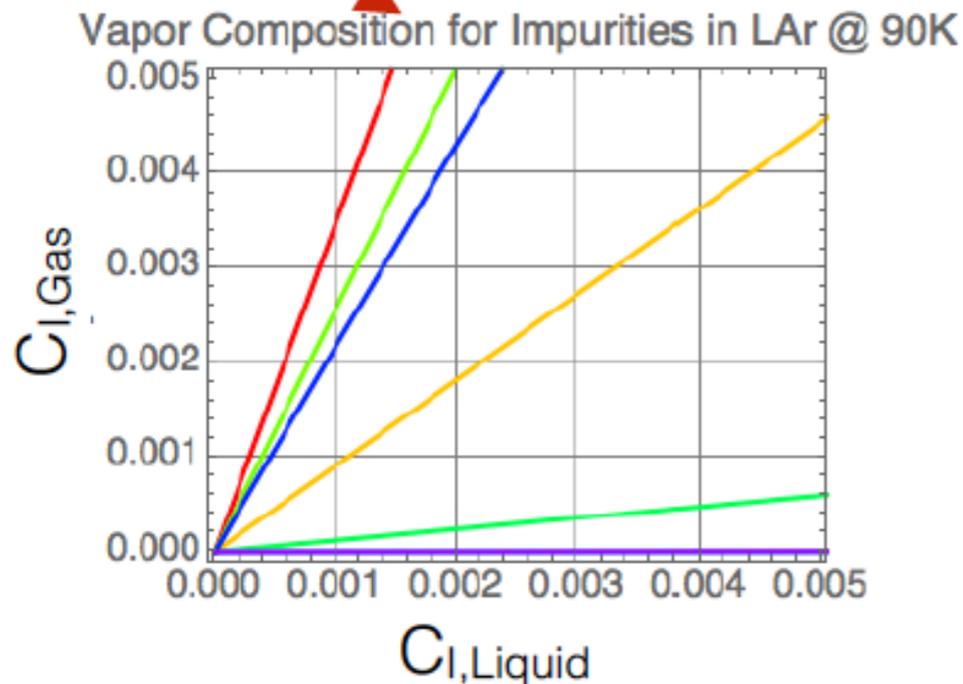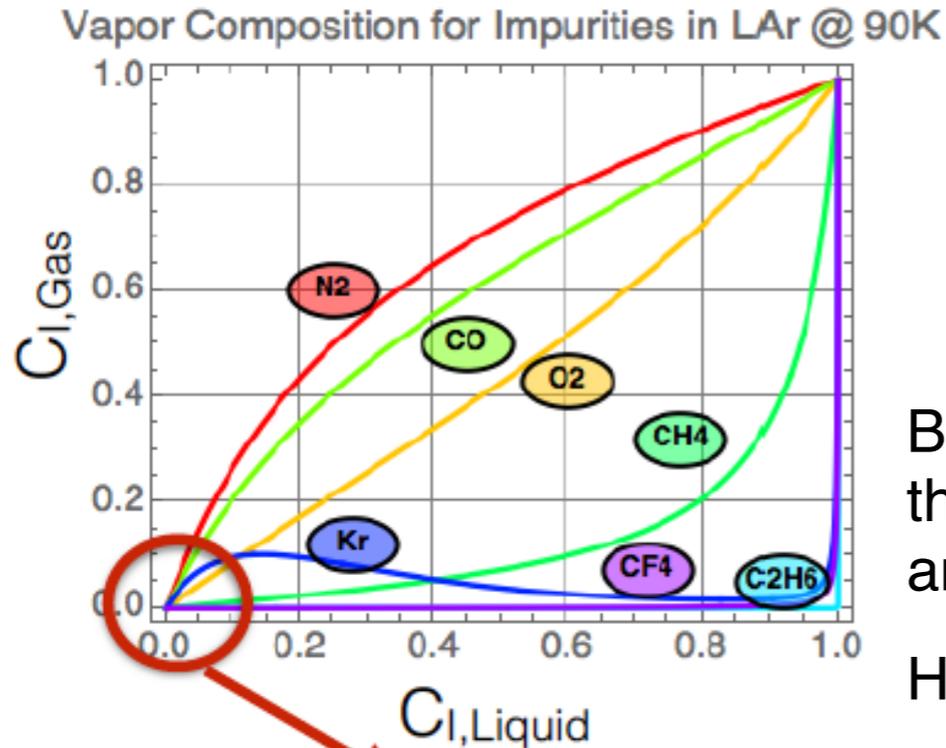
‣ The entire system is the sum of all 8 processes
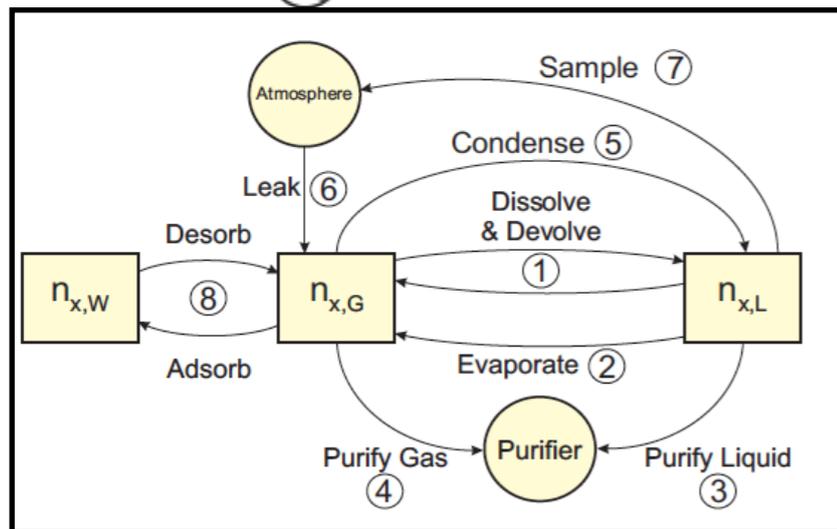
$$\left(\frac{dn_{i,\text{Liquid}}}{dt}\right) = \sum_{i=1}^{8}\left(\frac{dn_{i,\text{Liquid}}}{dt}\right)_i$$

$$\left(\frac{dn_{i,\text{Gas}}}{dt}\right) = \sum_{i=1}^{8}\left(\frac{dn_{i,\text{Gas}}}{dt}\right)_i$$

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Application of the Model

▸ Henry's constant is the partition of an impurity between liquid and gas phases

Vapor Composition for Impurities in LAr @ 90K

Vapor Composition for Impurities in LAr @ 90K

$$H_{xx}(T) = \frac{c_{i,\mathrm{Gas}}}{c_{i,\mathrm{Liquid}}}$$

By solving the equations with some approximations by assuming the dissolution rate is large compared to the evaporation rate and the amount of gas is small comparing to amount of liquid

Henry's constant of impurities in LAr derived by the model as

$$H_{xx}(T) = \frac{k_{\mathrm{Clean}} \cdot n_{\mathrm{Ar,Liquid}}}{k_{\mathrm{Evap}}}$$

Amount of the Liquid in the system

Evaporation rat of the system determined by the heat input

$$k_{\mathrm{Clean}} = \frac{1}{\tau_{\mathrm{Clean}}}$$

Time constant of the impurity concentration

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Experimental Setup: BNL 20-L LAr Test Stand

- **The 20L test stand used for the purity model measurement**

- **Details of the system in JINST_16_06_t06001**

  - High purity < 0.2 ppb achieved with gas purification only

  - H2O, O2, N2 concentrations monitored by commercial analyzers

  - The evaporation determined by the heater power in LAr
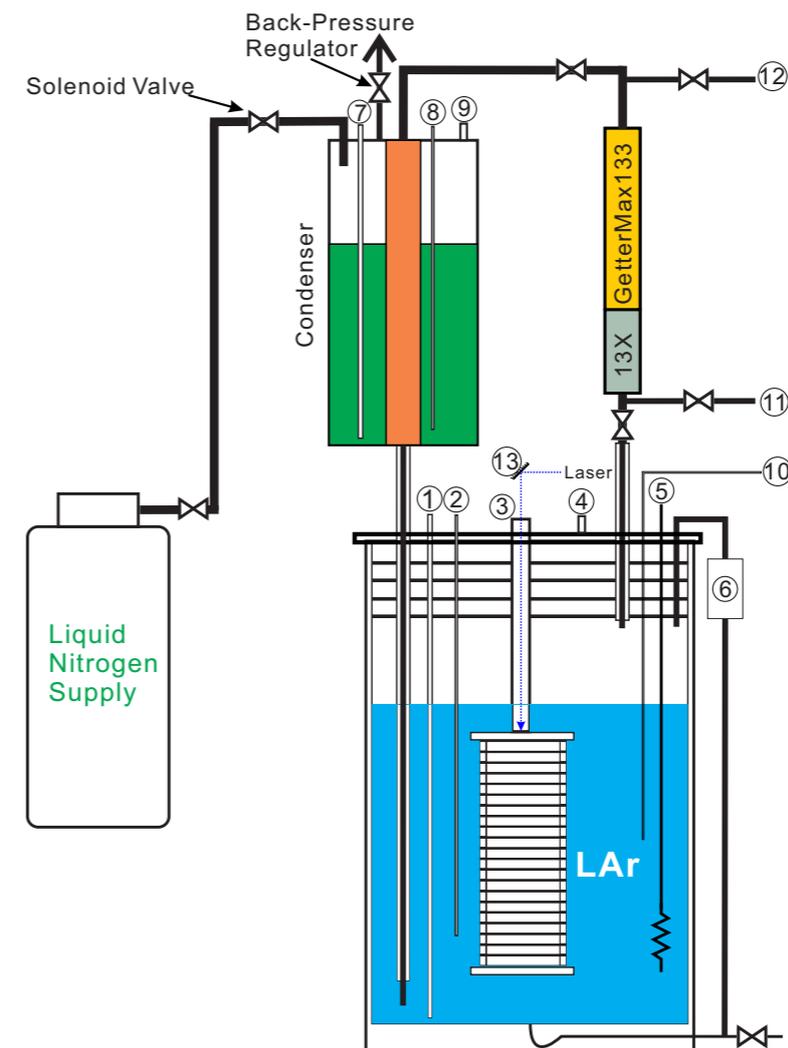
# Purification Process Measurement

1. The system filled with commercial LAr

2. The purification ON/OFF controlled by proper valving

3. k_{Evap} varied by different heater powers

4. The k_{Clean} measured by an exponential fit to the O_2 concentration as a function of time with purifier is ON

5. Outgassing/leakage observed when the purification turned OFF

$$H_{xx}(T) = \frac{k_{Clean} \cdot n_{Ar,Liquid}}{k_{Evap}}$$
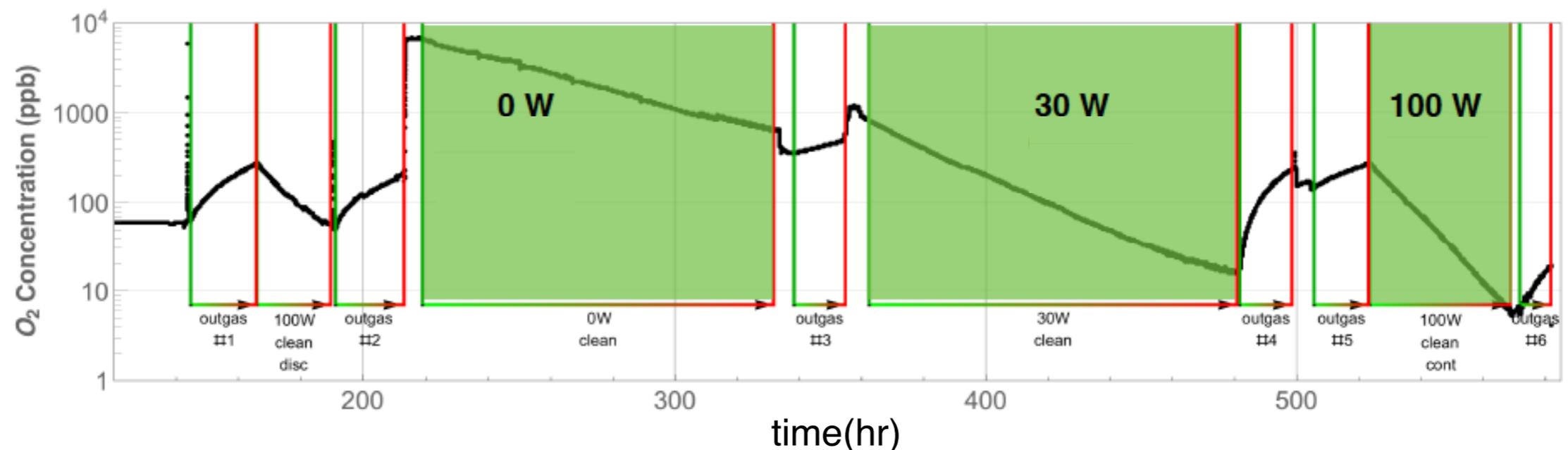
Henry's Constant Results for O_2 in LAr

▸ Measurement of the Henry's constant with 3 dataset
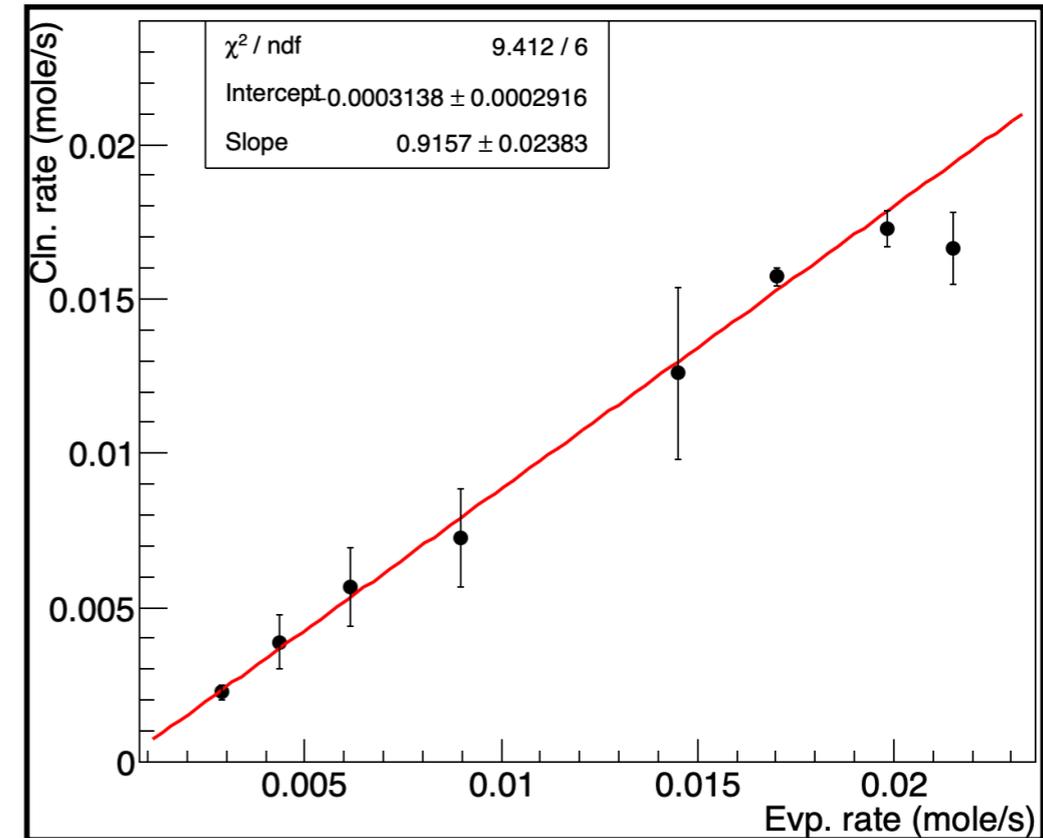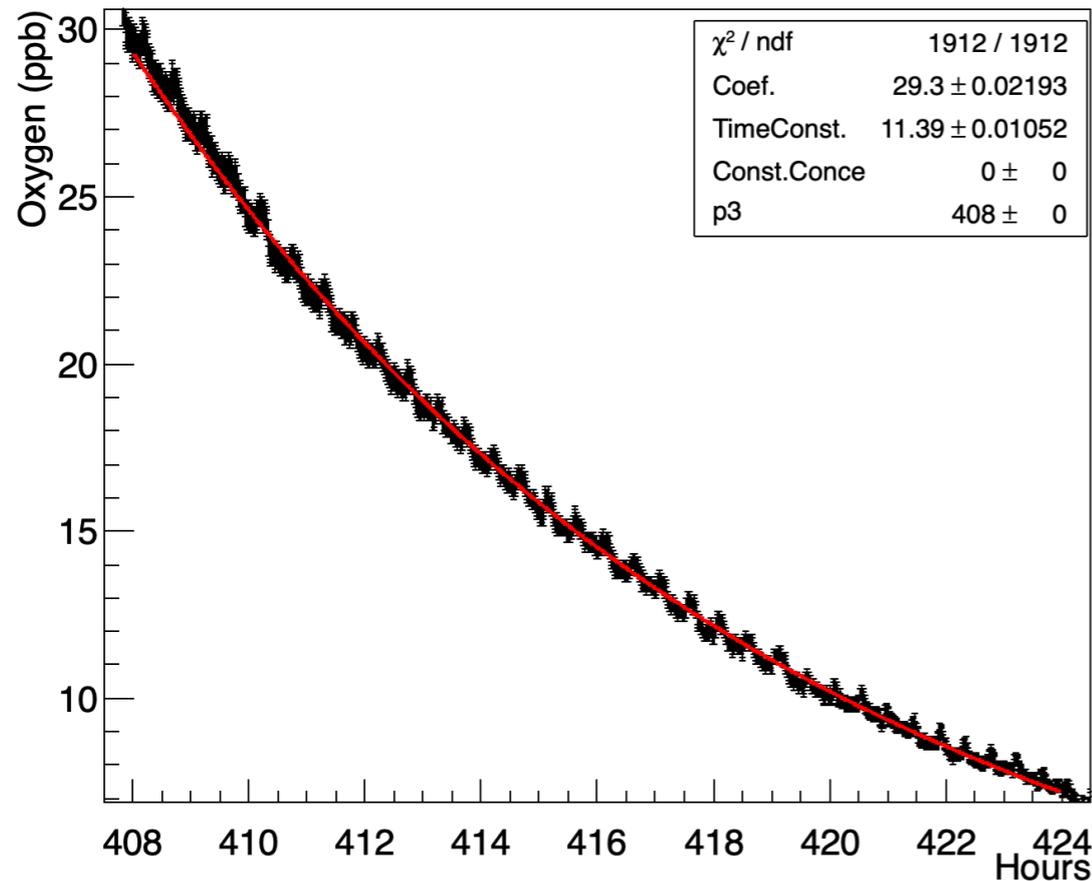
▸ Our best fit **Hxx= 0.92±0.02**[1], Literature value is H_{xx} =0.91±0.02

▸ Our results agree very well with the literature values for Oxygen in LAr

▸ Another check of the model

[1]. Proceedings of the Royal Societyof London A: Mathematical, Physical and Engineering Sciences, 221(1147):517-534, 1954.

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Henry's Constant Result for H2O in LAr

‣ Henry's constant of H2O is unknown

‣ Water is not more difficult to remove than O2 through purifying the gas

‣ Our preliminary results suggest Hxx = 1.12 ± 0.19

‣ Additional measurements can help understand the systematic uncertainties

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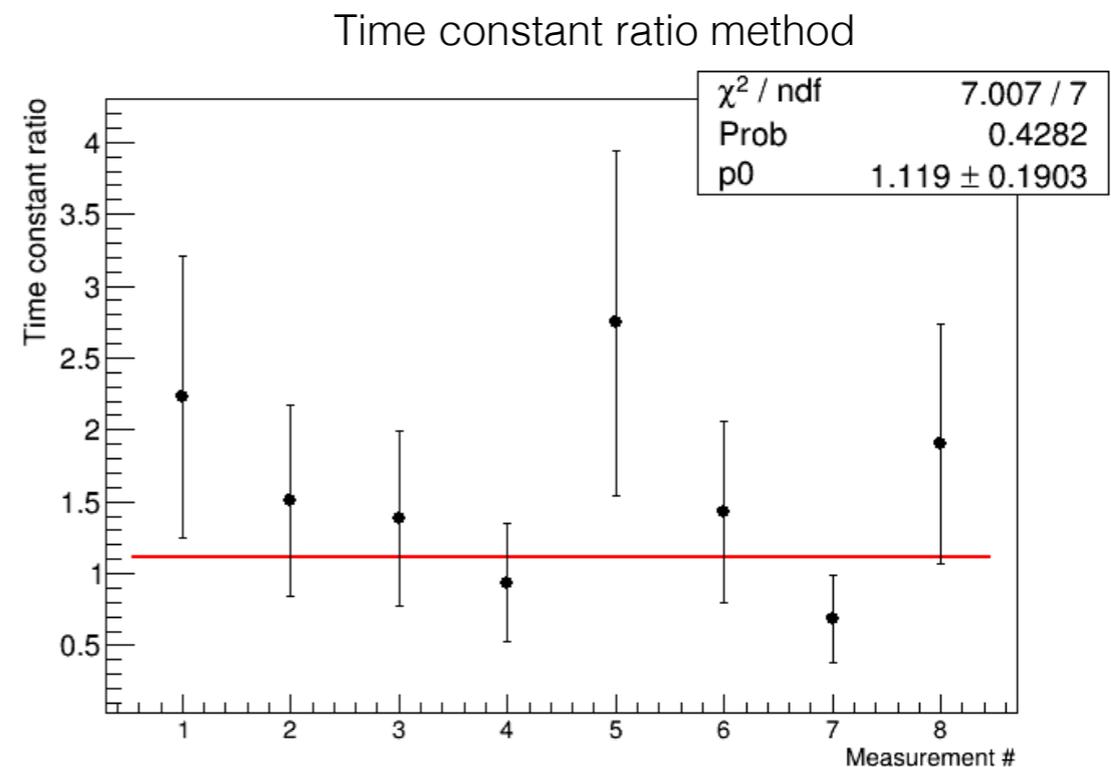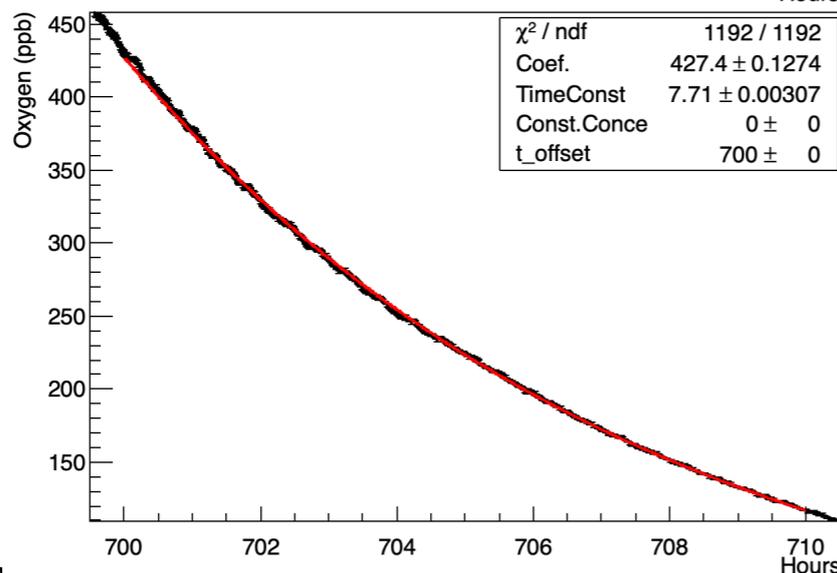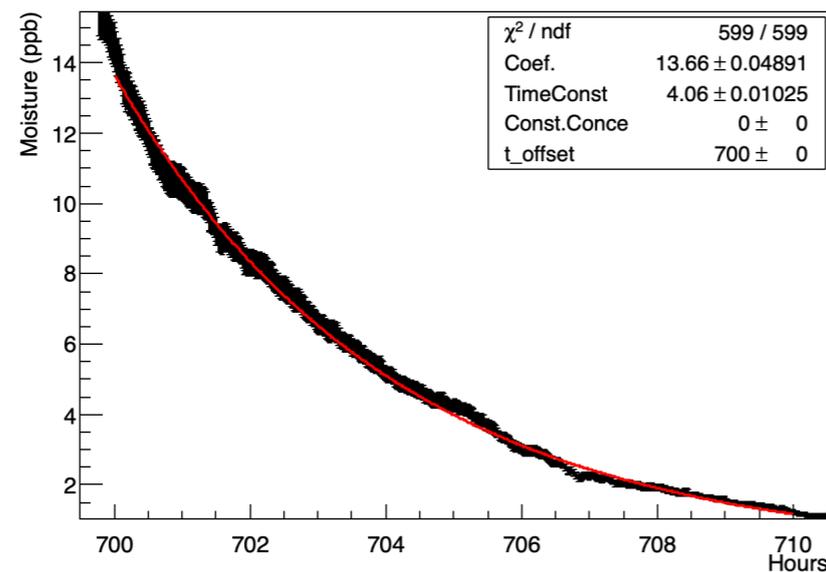
Conclusions

‣ We developed a quantitative impurity distribution model for LArTPC

‣ The model has been checked by comparing the Henry's constant for O2 derived to the literatures. The result agrees with the literatures

‣ The Henry's constant for H2O is measured for the first time

‣ High Henry's constant implies that GAr purification may be enough to maintain the purity

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