“Ion Transport Model” to solve **Single-PE puzzle** in large surface LArTPC

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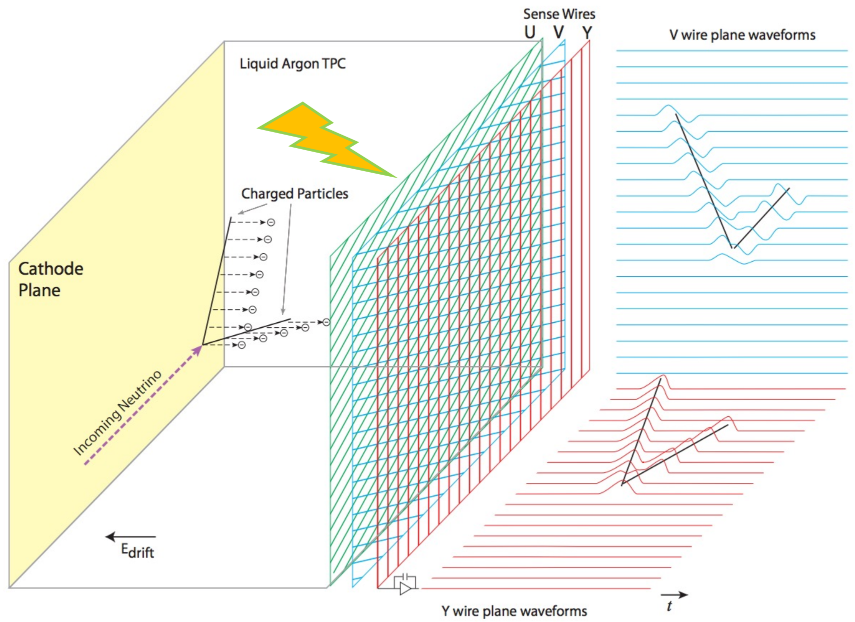
8th CYGNUS workshop on Directional Recoil Detection

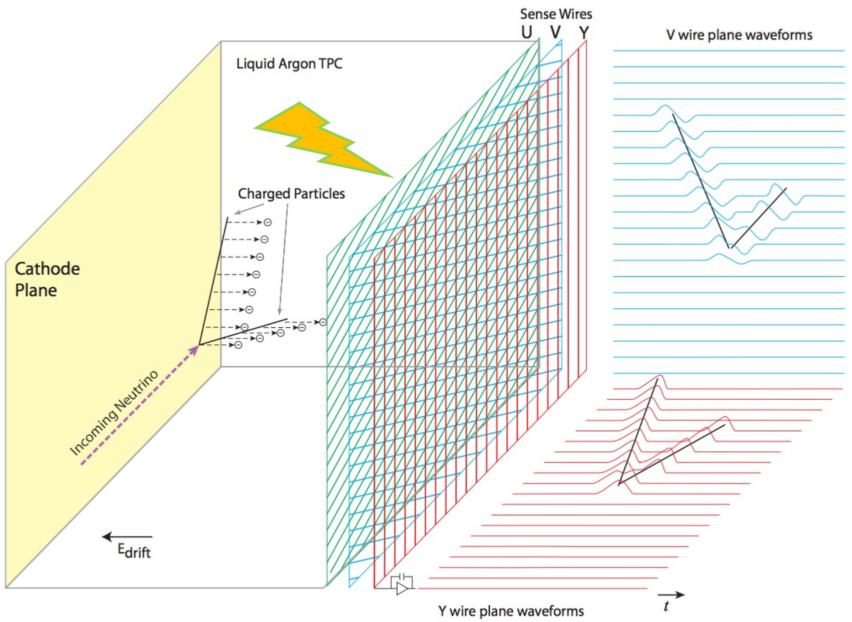
LArTPC working principle

Two type of signals

- **e- Charge** from ionization collected at the anode. Used for PID and calorimetry, but slow (~ms)
- Ar **Scintillation light** collected by light detectors. Used for T0 and triggering, and fast (ns-us)



LArTPC working principle



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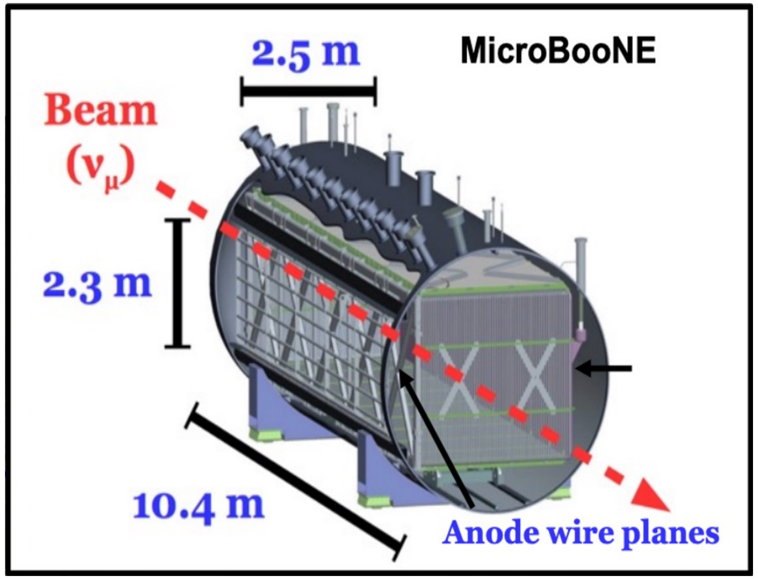
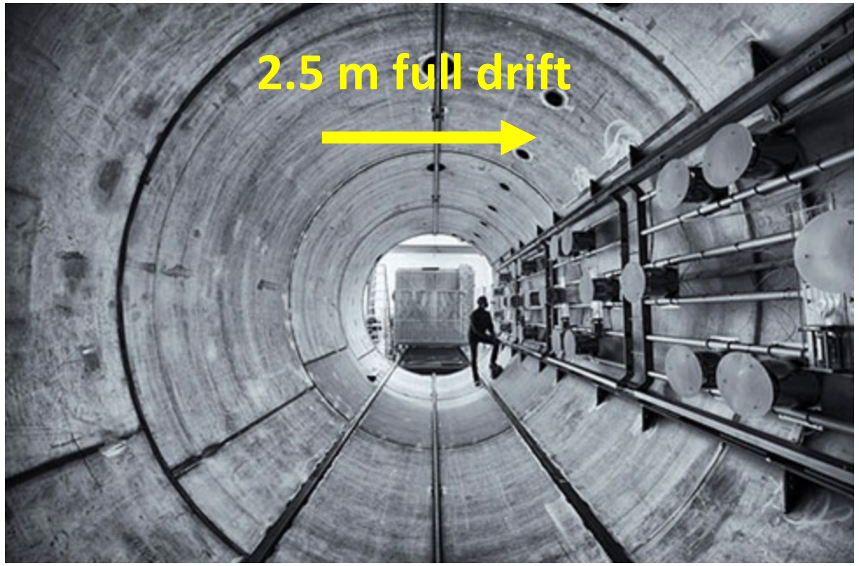
MicroBooNE LArTPC @Fermilab

~70 tons active volume





PMTs behind the anode

LArTPC working principle

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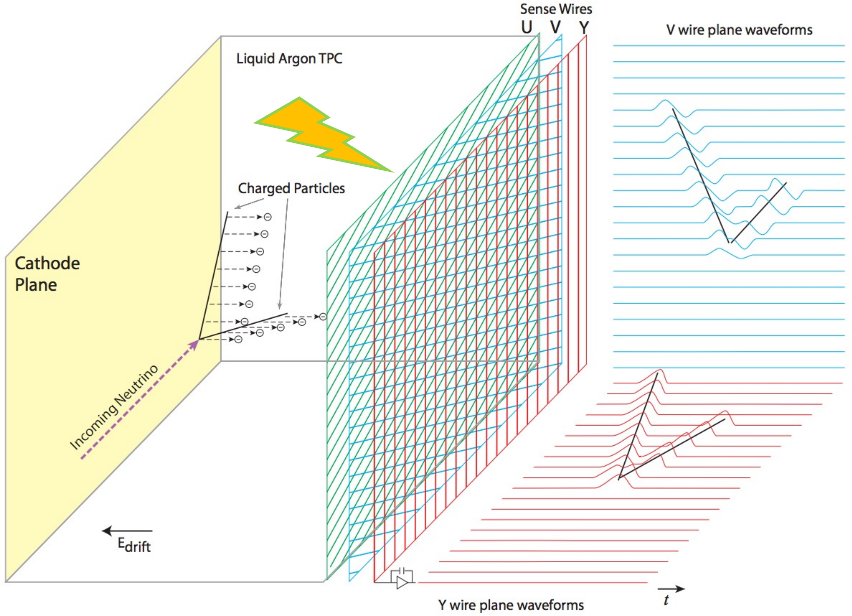
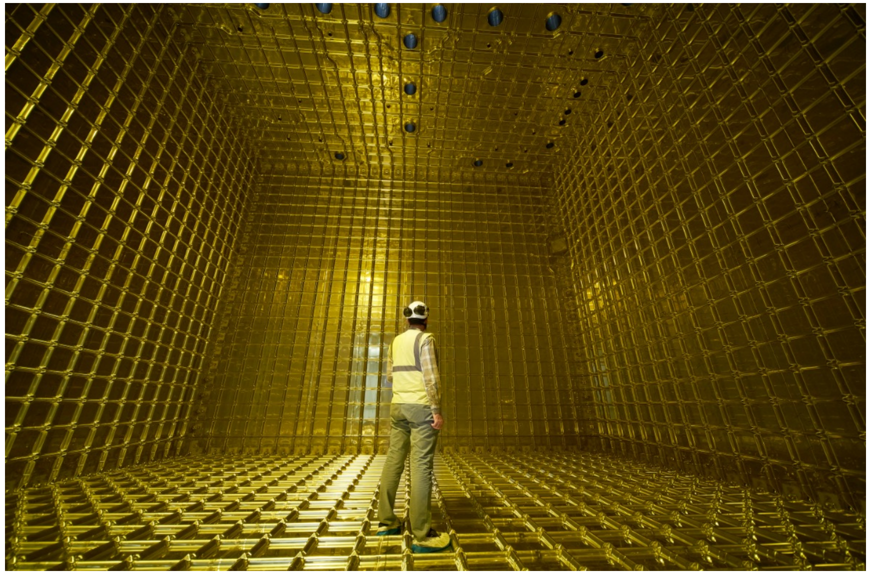
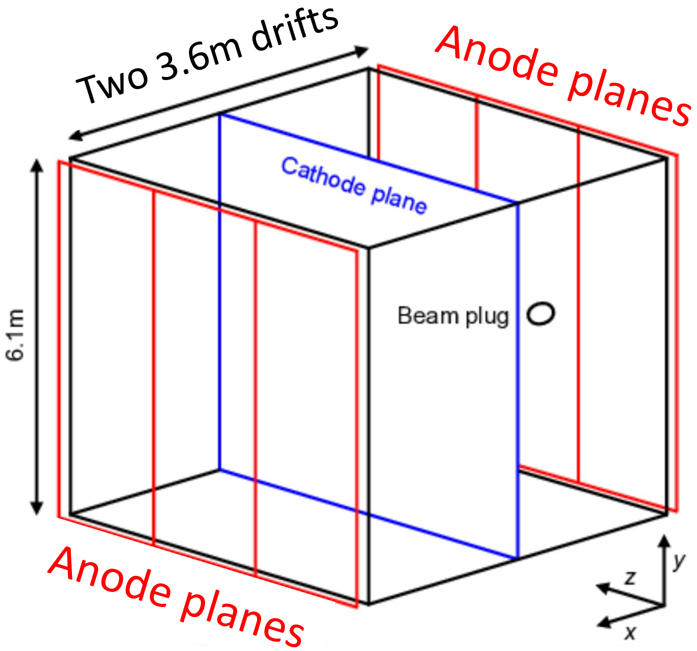


ProtoDUNE LArTPC @CERN

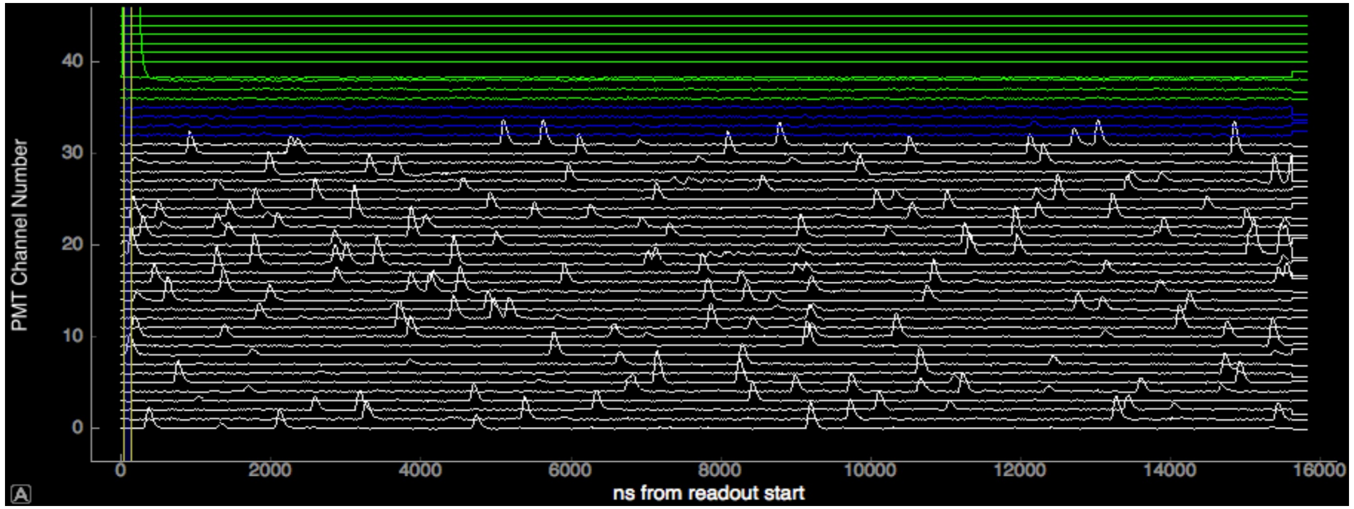
~700 tons liquid argon





Photon sensors integrated in the anode planes

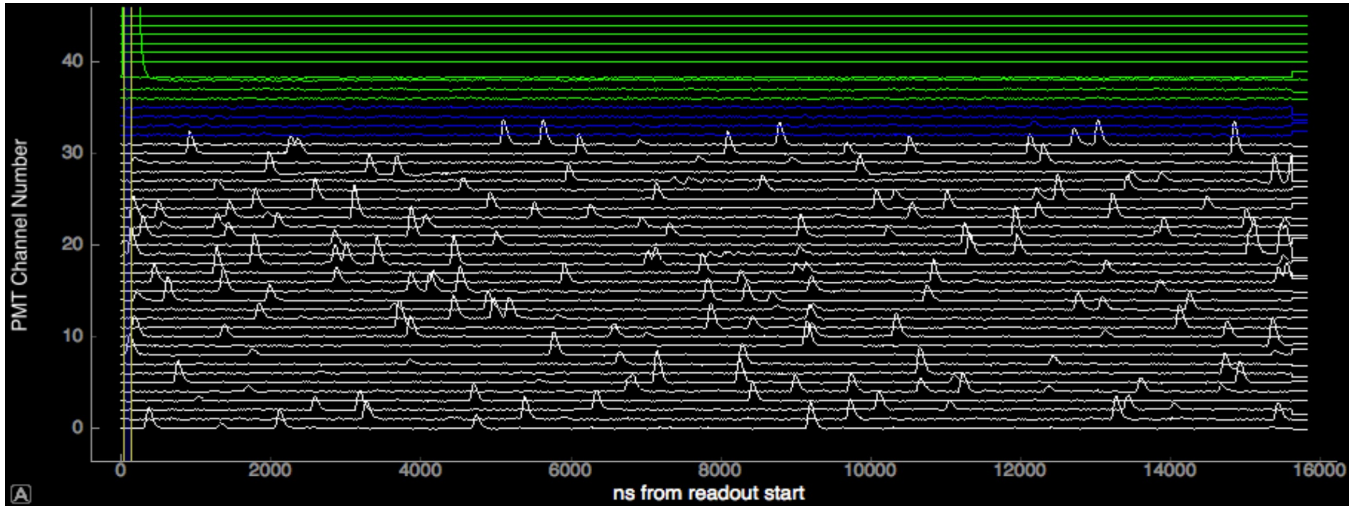
What is the “Single-PE puzzle”?



Unexpected high Single Photoelectrons (SPE) rate observed in large surface LArTPCs.

- MicroBooNE sees ~x10 higher SPE rate than expected dark rate.
- ProtoDUNE detector also sees similar order of SPE rate from its first light analysis

Problematic SPE background



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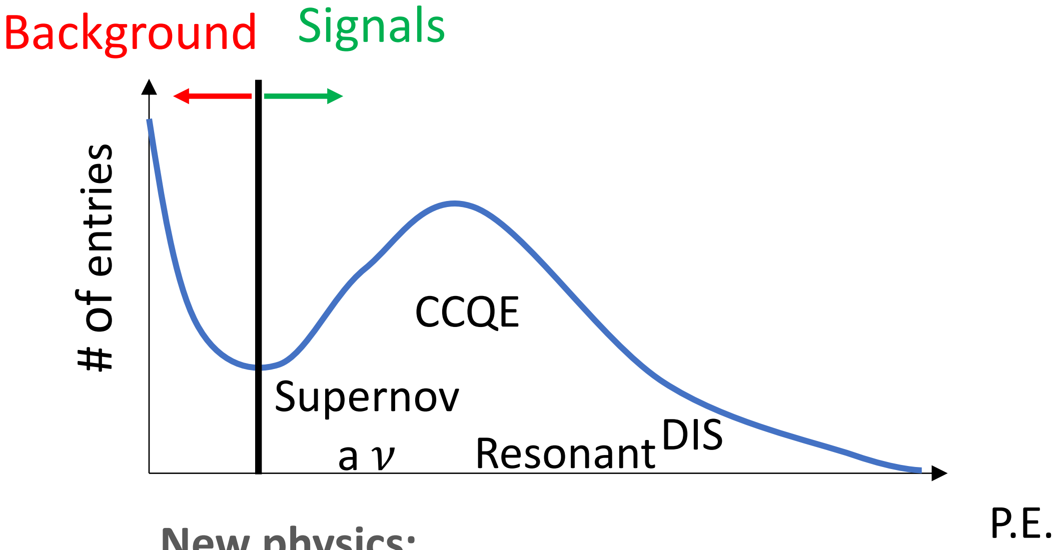
SPE is a unwanted background!

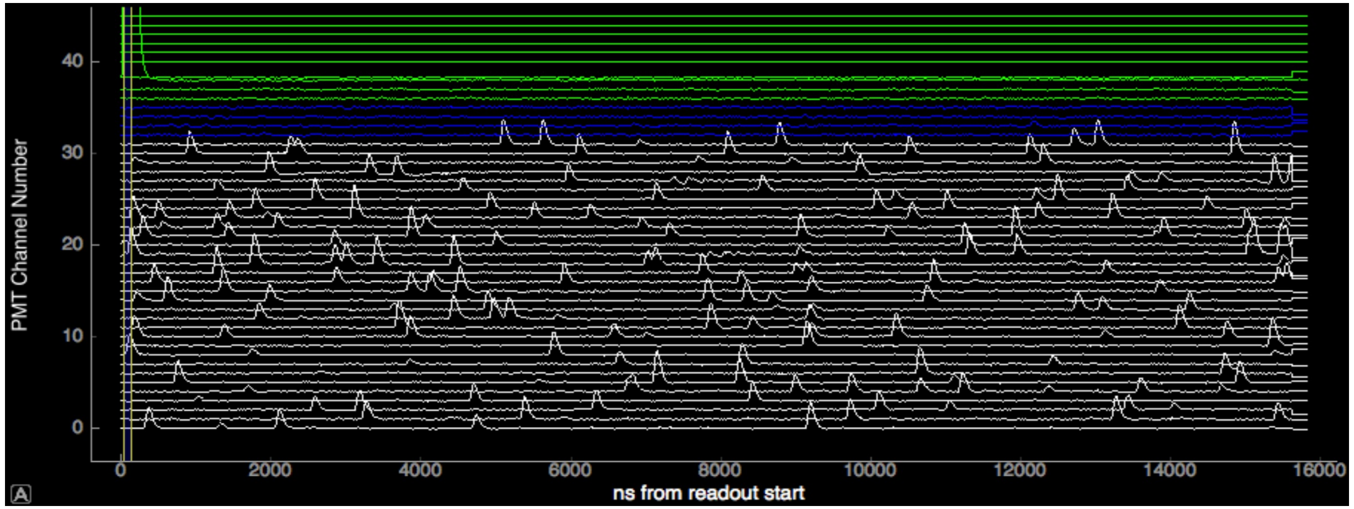
LArTPC uses light signal for triggering, so high SPE rate causes:

- high trigger threshold
- Bad S/B ratio for physics signals



New physics:
Dark Matter, Milicharge ...

Where are the SPEs from?



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Small contributions to SPE rate:

- Radon radioactivity in filters
- Argon 39 decay
- TPB dissolve in argon

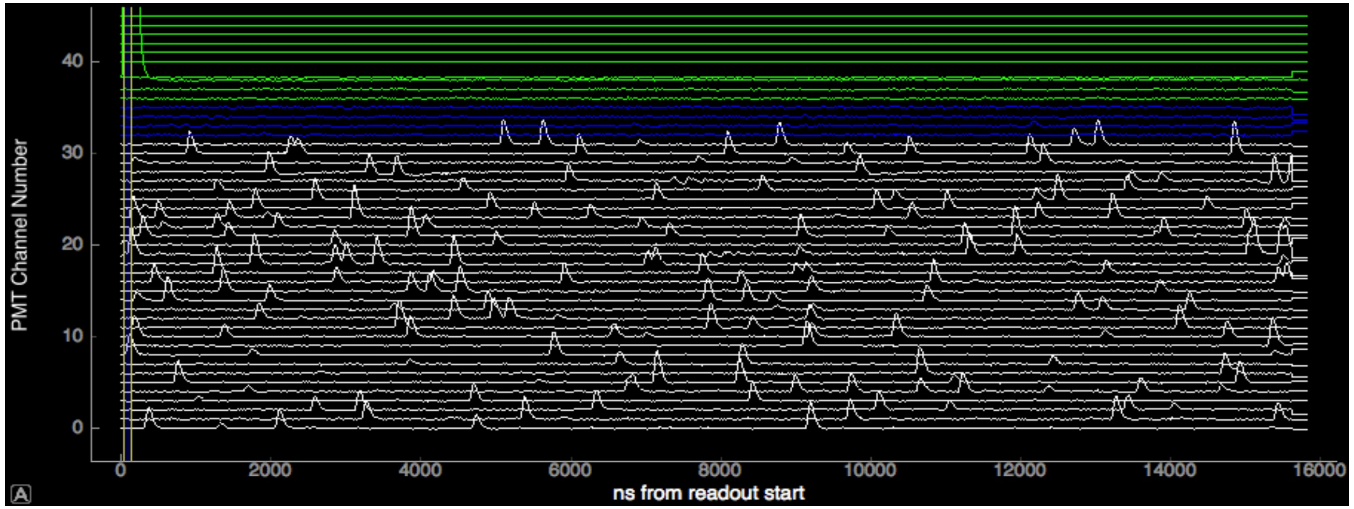
Not sufficient to explain the observed rate

A clue from experiments

SPE rate is inversely correlated with E field:

Higher E field, lower SPE rate

Where are the SPEs from?



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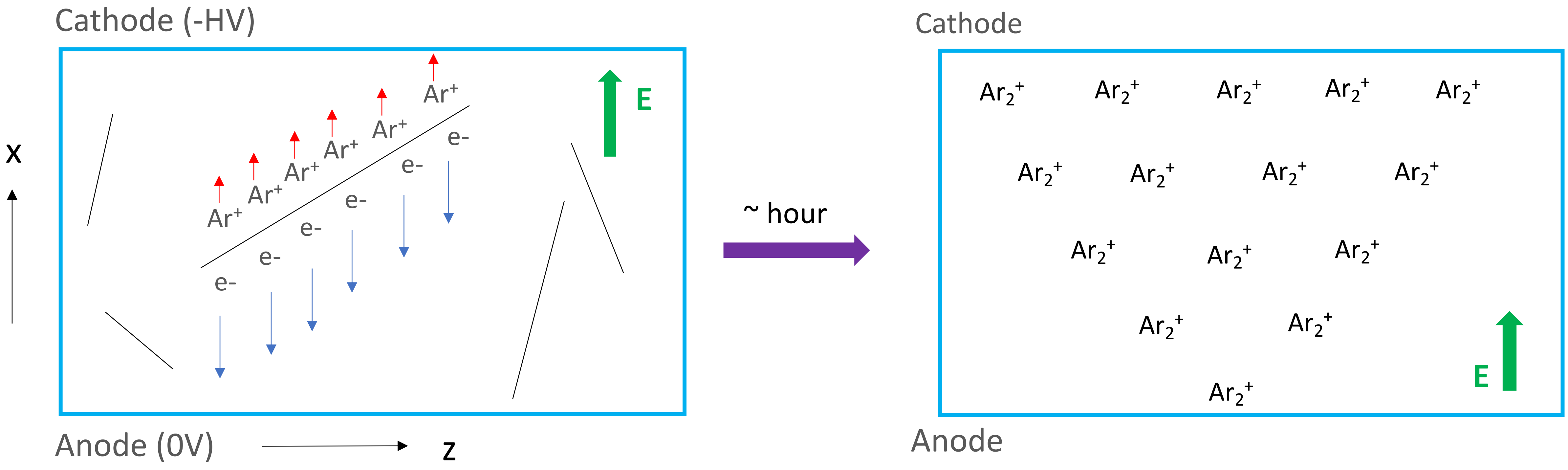
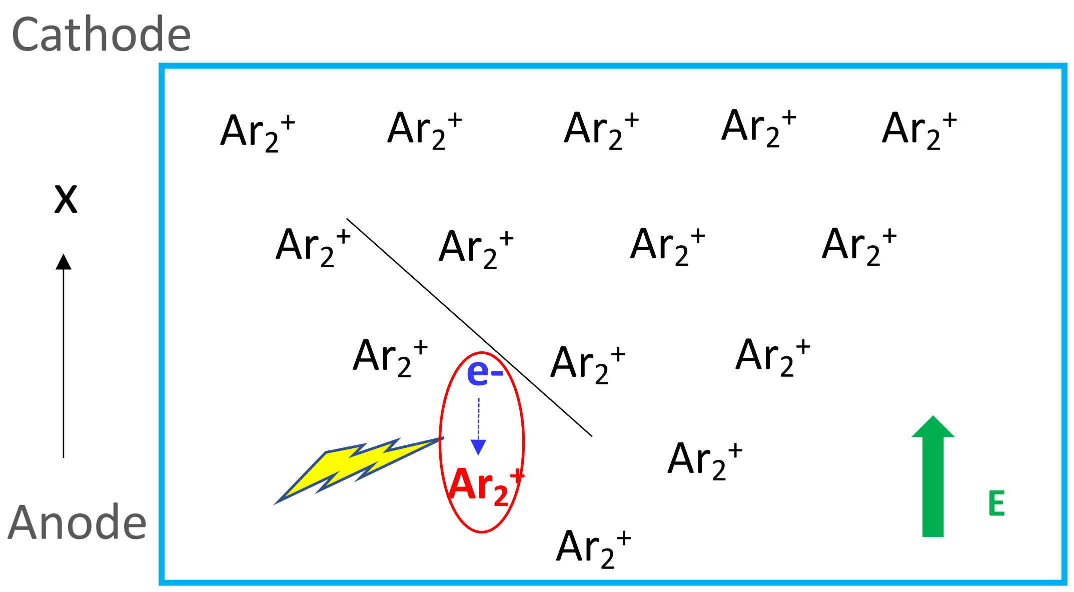
We built a model, related to microphysics processes in LArTPC, to explain the SPE puzzle.

Ion Transport Model – dynamic at equilibrium



- Ionization source (surface LArTPC): Cosmic rays ionize the argon and create e^-/ Ar^+ pairs along their trajectories.
- e^- drifts 100,000 faster than Ar_2^+. (e.g. It takes **20 mins** for Ar_2^+ drift from anode to cathode in MicroBooNE!)
- At equilibrium Ar_2^+ is roughly linearly distributed in X with maximum density at cathode.

Ion Transport Model – new VR process

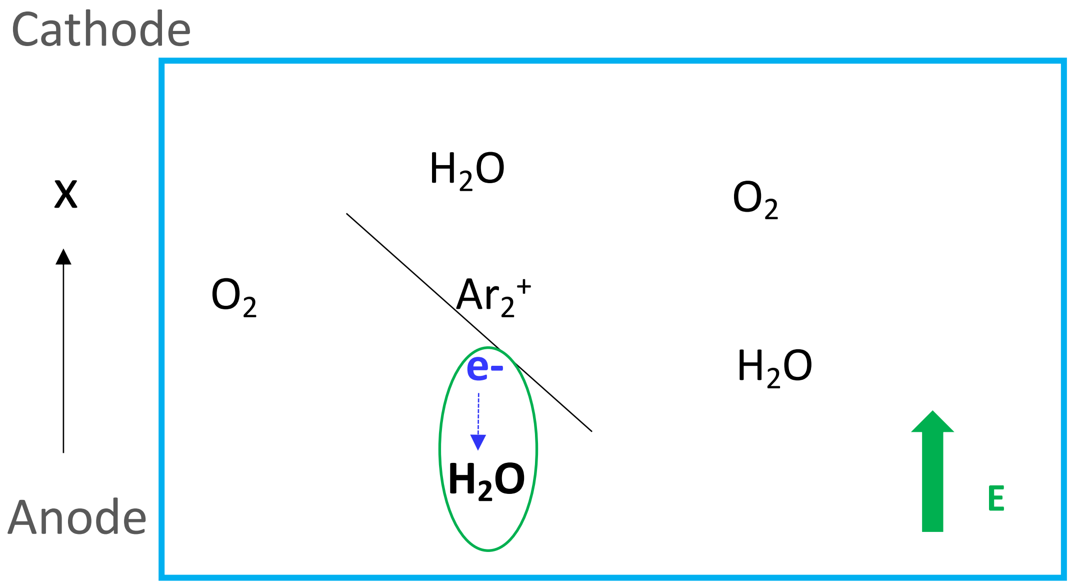


Drift electron recombines with other Ar_2^+ ion in the bulk, different from initial recombination ion

(1) Volume Recombination (VR)

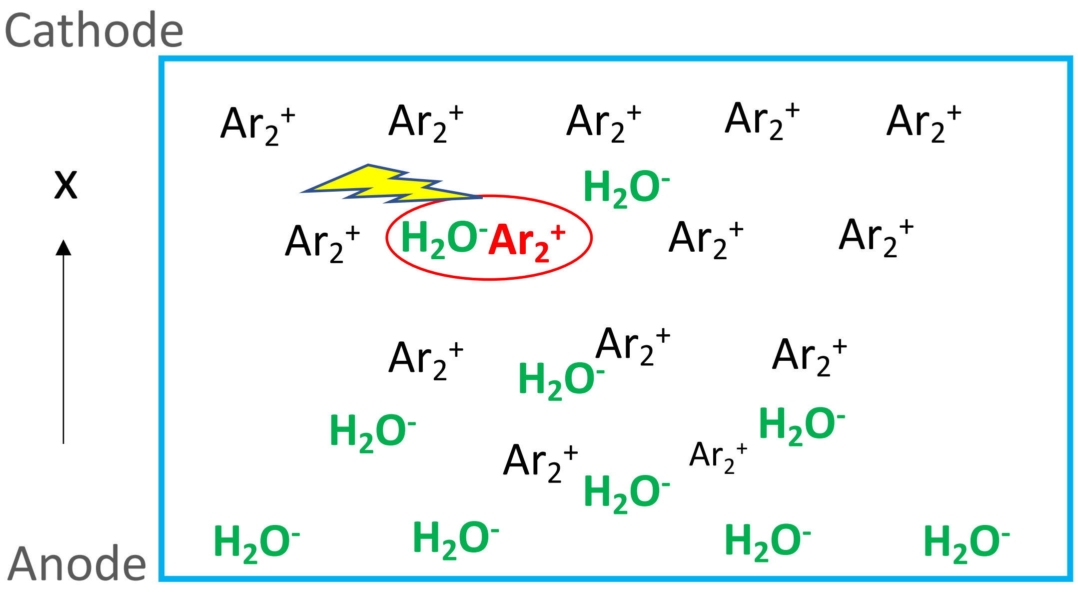
$$Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

Ion Transport Model – new MN process



Impurity (O_2, H_2O...) attachment to form negative ions:

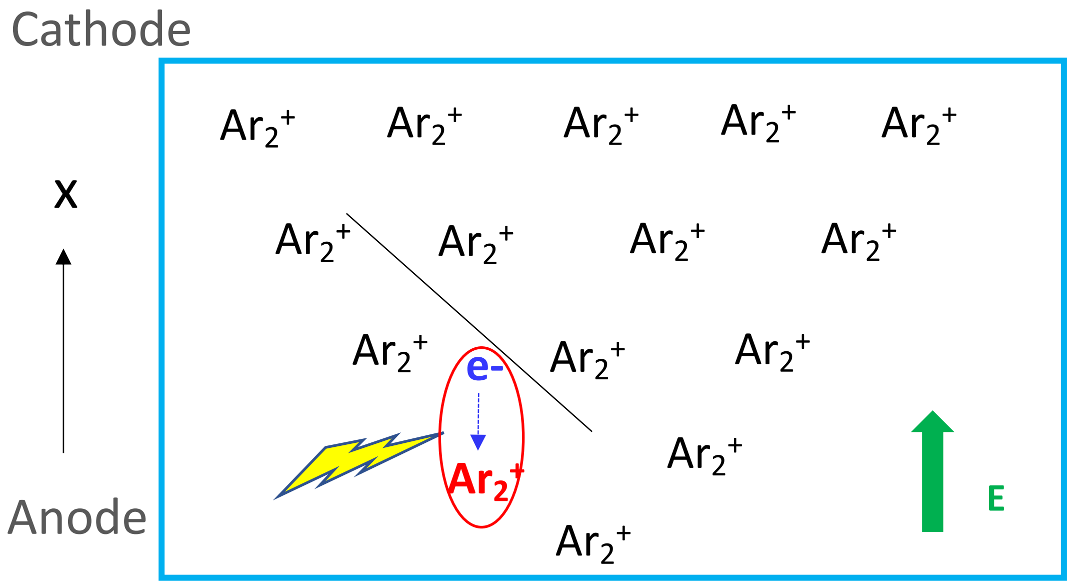
$$e^- + H_2O \rightarrow H_2O^-$$

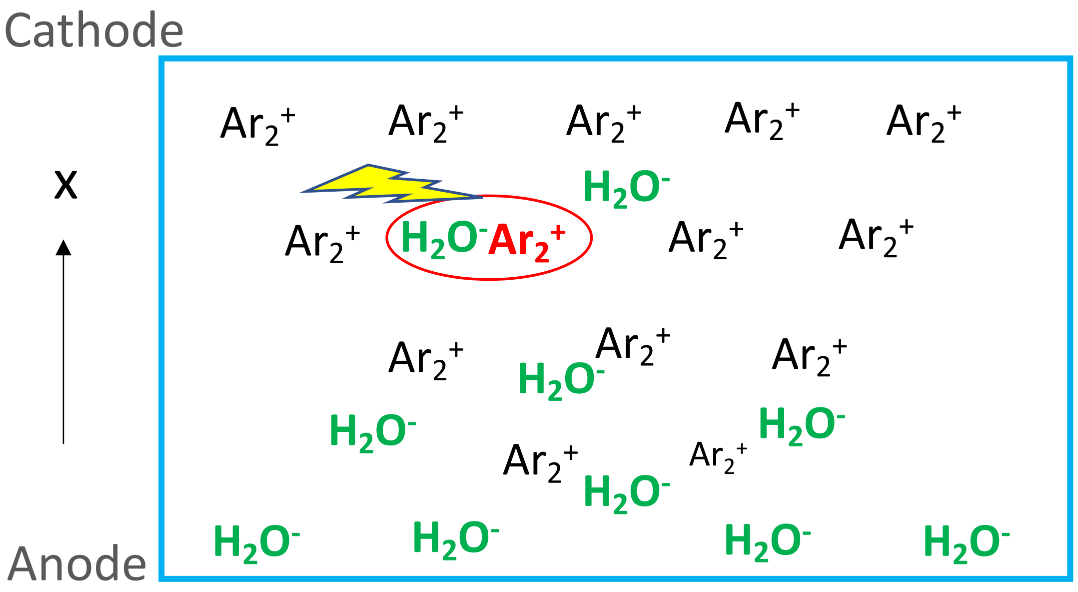


(2) Mutual Neutralization (MN)

$$Ar_2^+ + H_2O^- \rightarrow Ar_2^* + H_2O \rightarrow 2Ar + \gamma + H_2O$$

Ion Transport Model – new MN process





(1) Volume Recombination (VR)

$$Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

photons from slow ions

(2) Mutual Neutralization (MN)

$$Ar_2^+ + H_2O^- \rightarrow Ar_2^* + H_2O \rightarrow 2Ar + \gamma + H_2O$$

Ion Transport Model – solving differential equations

X. Luo and F. Cavanna
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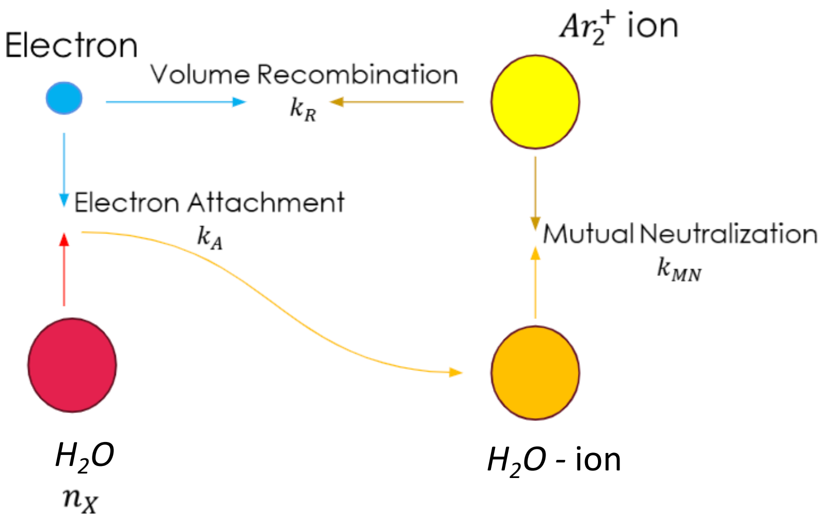
4 Differential Equations

e-, + ion, - ion, E field:

$$\begin{cases} -v_e(x) \cdot \dfrac{\partial n_e(x)}{\partial x} - n_e(x) \cdot \dfrac{\partial v_e(x)}{\partial x} = n_{\text{pair}} - k_A n_X n_e(x) - k_R n_+(x) n_e(x) \\ v_+(x) \cdot \dfrac{\partial n_+(x)}{\partial x} + n_+(x) \cdot \dfrac{\partial v_+(x)}{\partial x} = n_{\text{pair}} - k_{MN} n_-(x) n_+(x) - k_R n_+(x) n_e(x) \\ -v_-(x) \cdot \dfrac{\partial n_-(x)}{\partial x} - n_-(x) \cdot \dfrac{\partial v_-(x)}{\partial x} = k_A n_X n_e(x) - k_{MN} n_-(x) n_+(X) \\ \dfrac{\partial E(x)}{\partial x} = (n_+(x) - n_-(x) - n_e(x)) \cdot \dfrac{\rho_e}{\epsilon} \end{cases}$$



O(10) parameters
Cosmic flux (n_{pair})
Drift distance
E field
Impurity concentration (n_X)
Rate constant of VR (k_R)
Rate constant of MN ((k_{MN})
e- attachment rate to impurity
((k_A)
Mobility of ions

Ion Transport Model – solving differential equations

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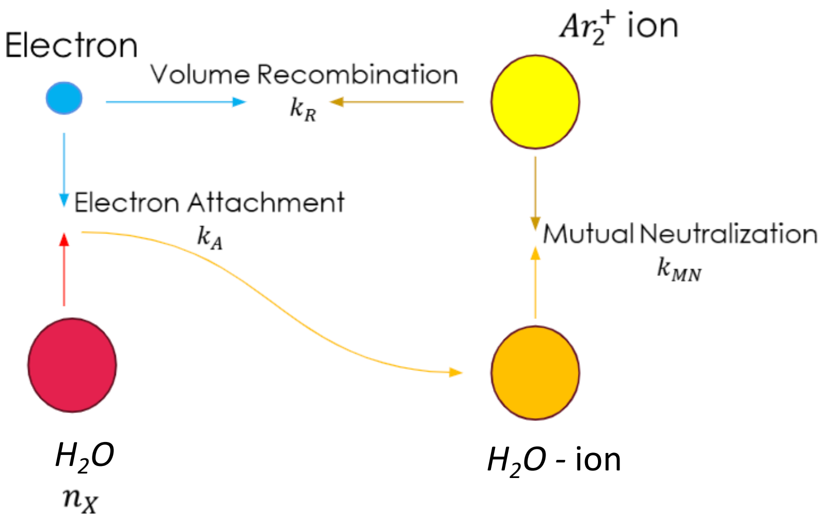
4 Boundary Conditions

$$\left.\begin{aligned} n_e(@\text{Cathode}) &= 0 \\ n_+(@\text{Anode}) &= 0 \\ n_-(@\text{Cathode}) &= 0 \\ \int_{\text{Anode}}^{\text{Cathode}} E(x)\,dx &= \text{HV}_{\text{Cathode}} \end{aligned}\right\}$$



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Cosmic flux (n_{pair})
Drift distance
E field
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Rate constant of VR (k_R)
Rate constant of MN ((k_{MN})
e- attachment rate to impurity ((k_A)
Mobility of ions

D.E. Solution: {E(x), n_+(x), n_-(x), n_e(x)}
MN: $Ar_2^+ + H_2O^- \rightarrow 2Ar + \boldsymbol{\gamma} + H_2O$
VR: $Ar_2^+ + e^- \rightarrow 2Ar + \boldsymbol{\gamma}$

→ **Single photon production rate**

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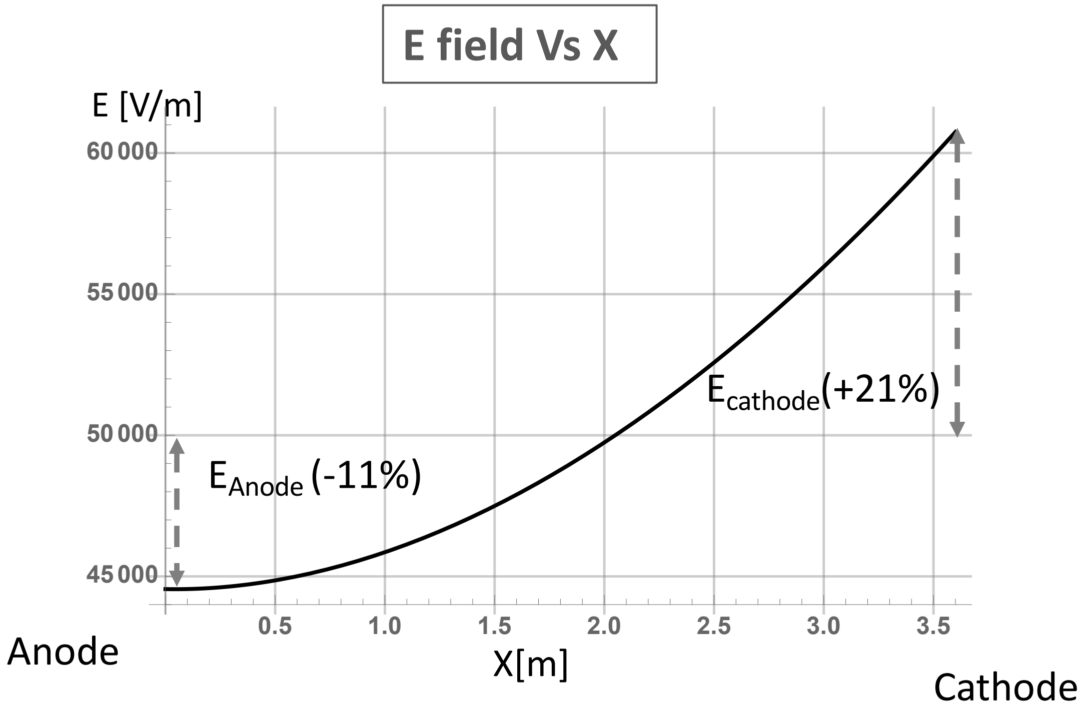

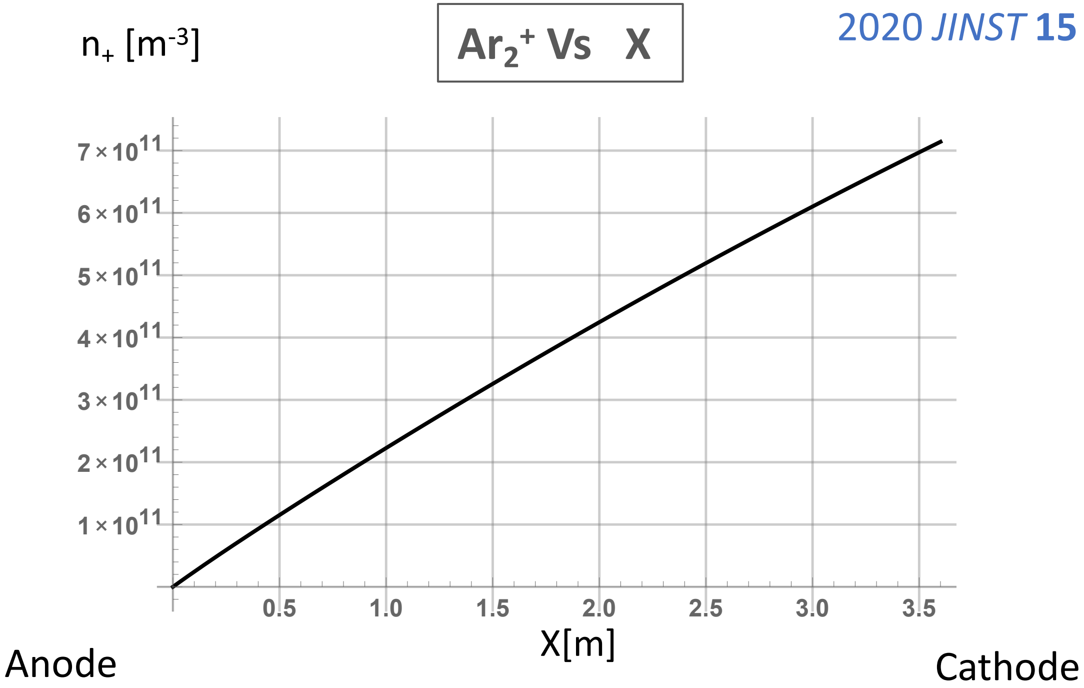

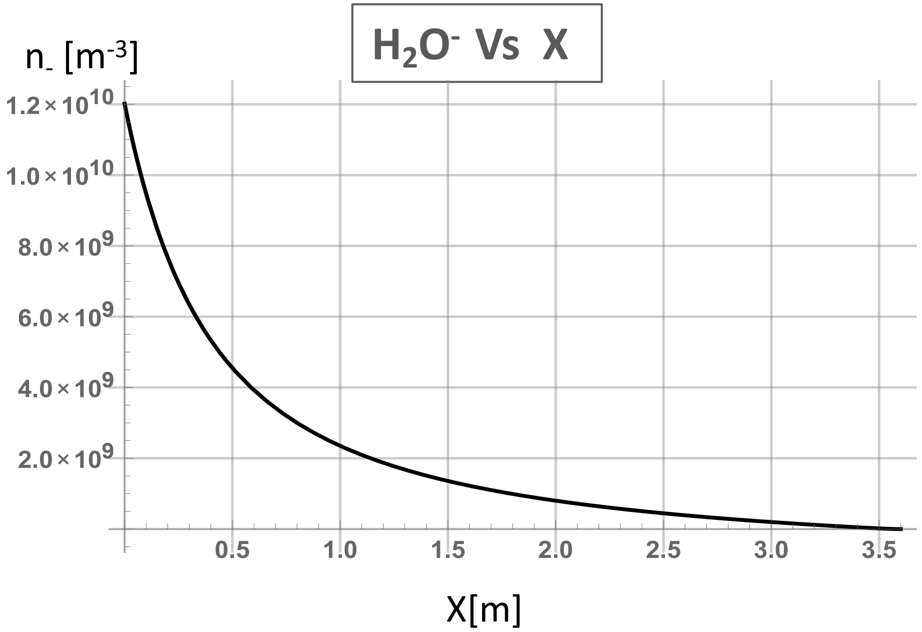

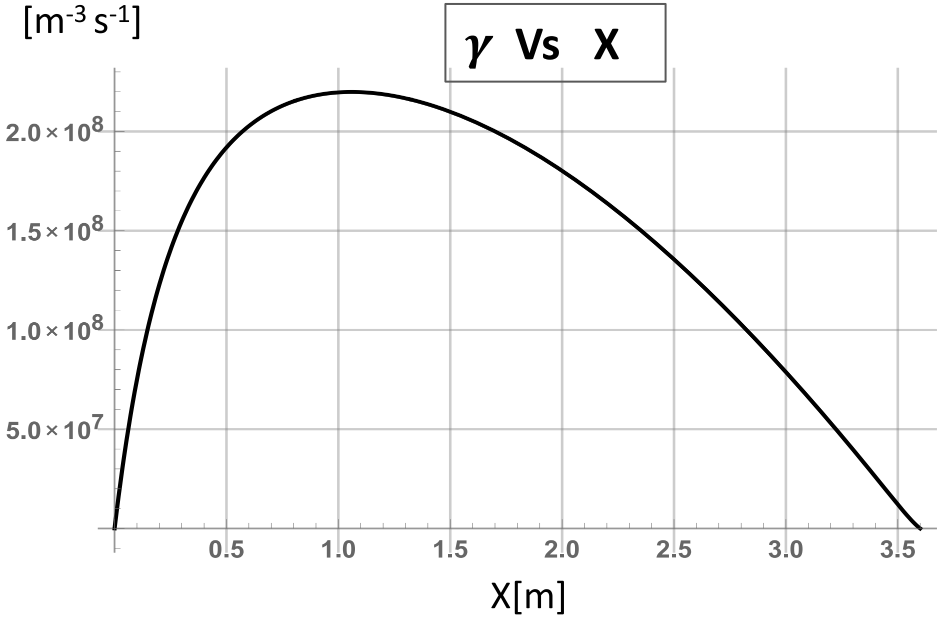

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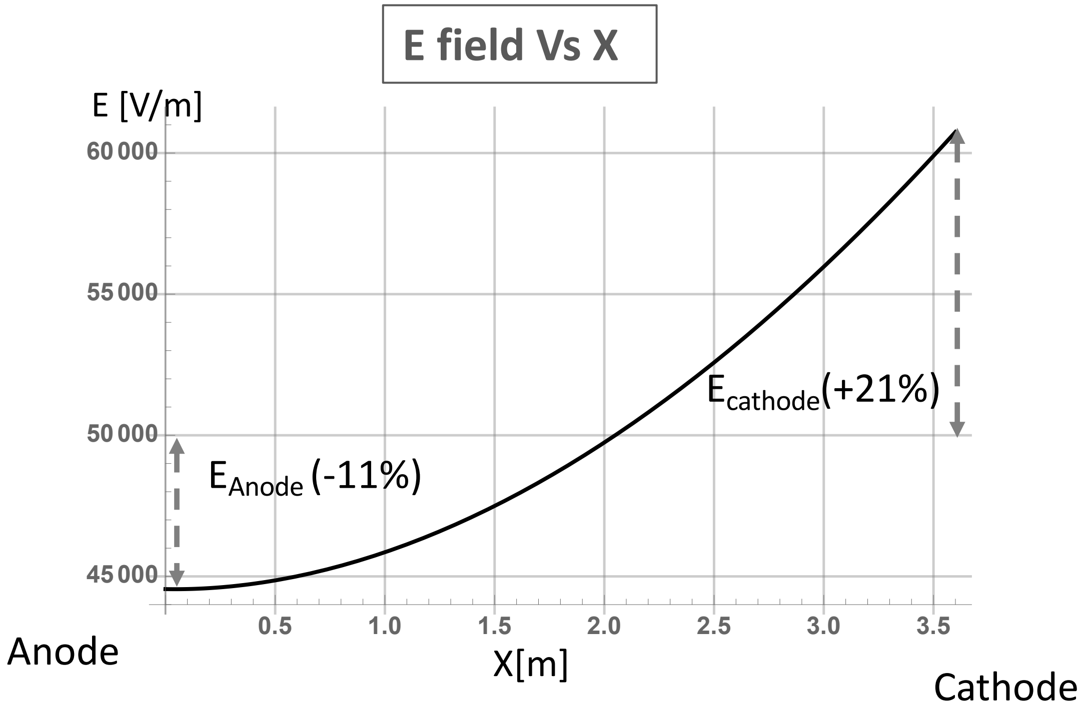
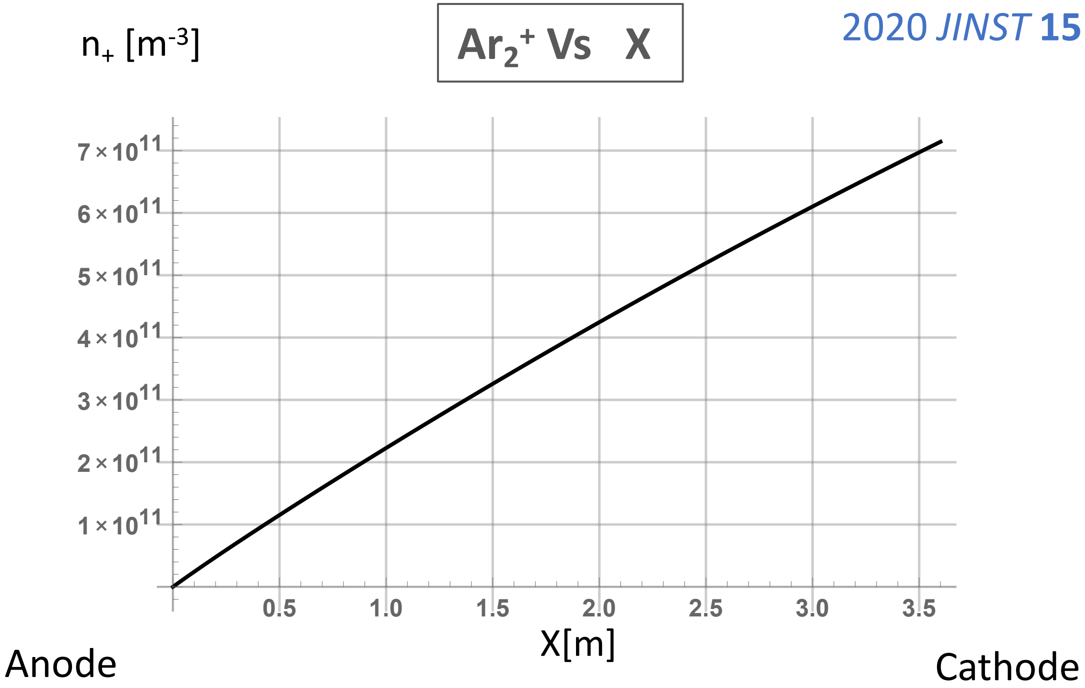
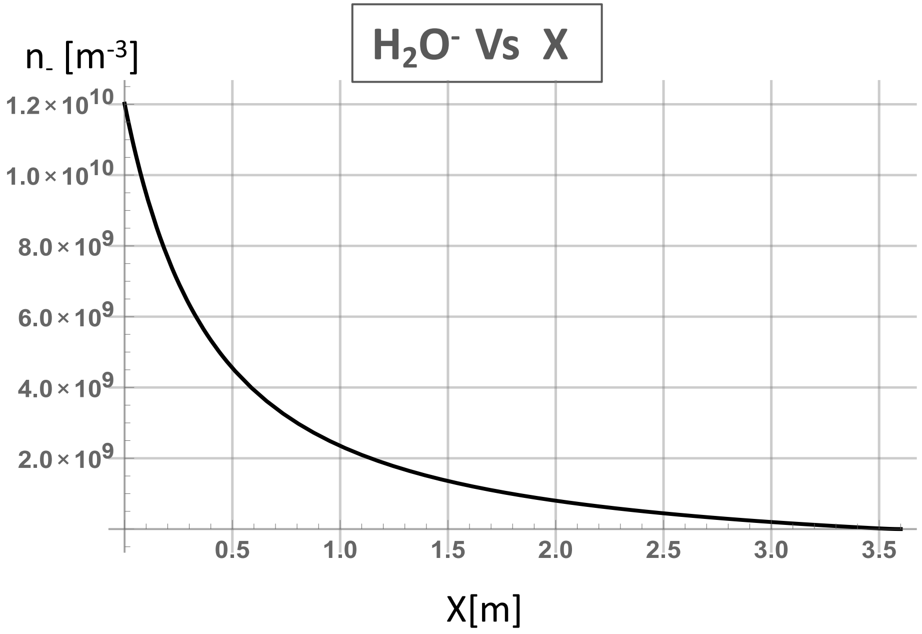
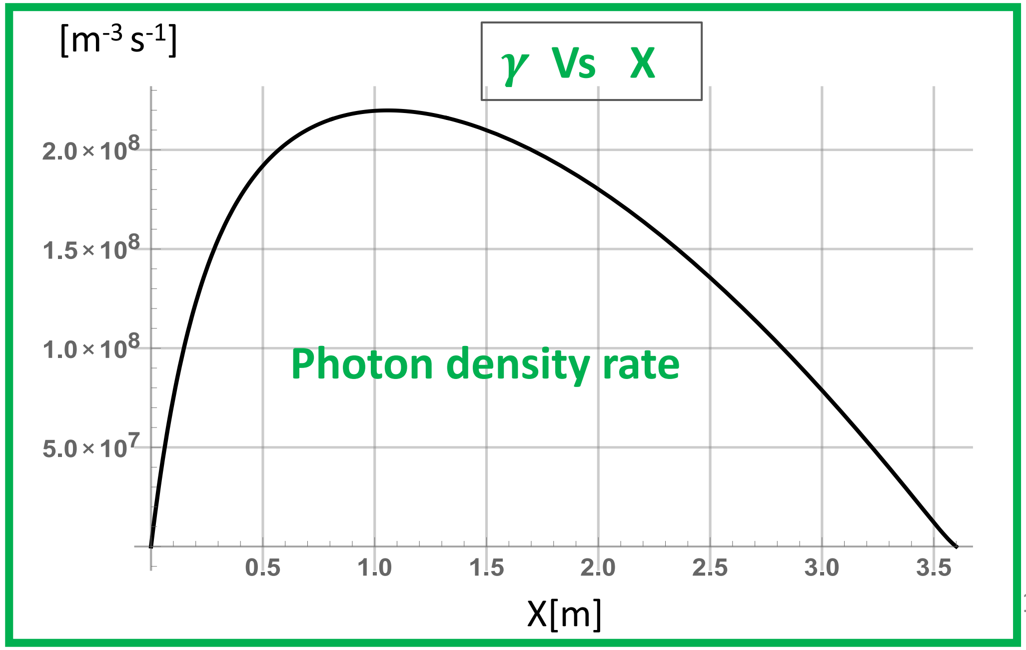
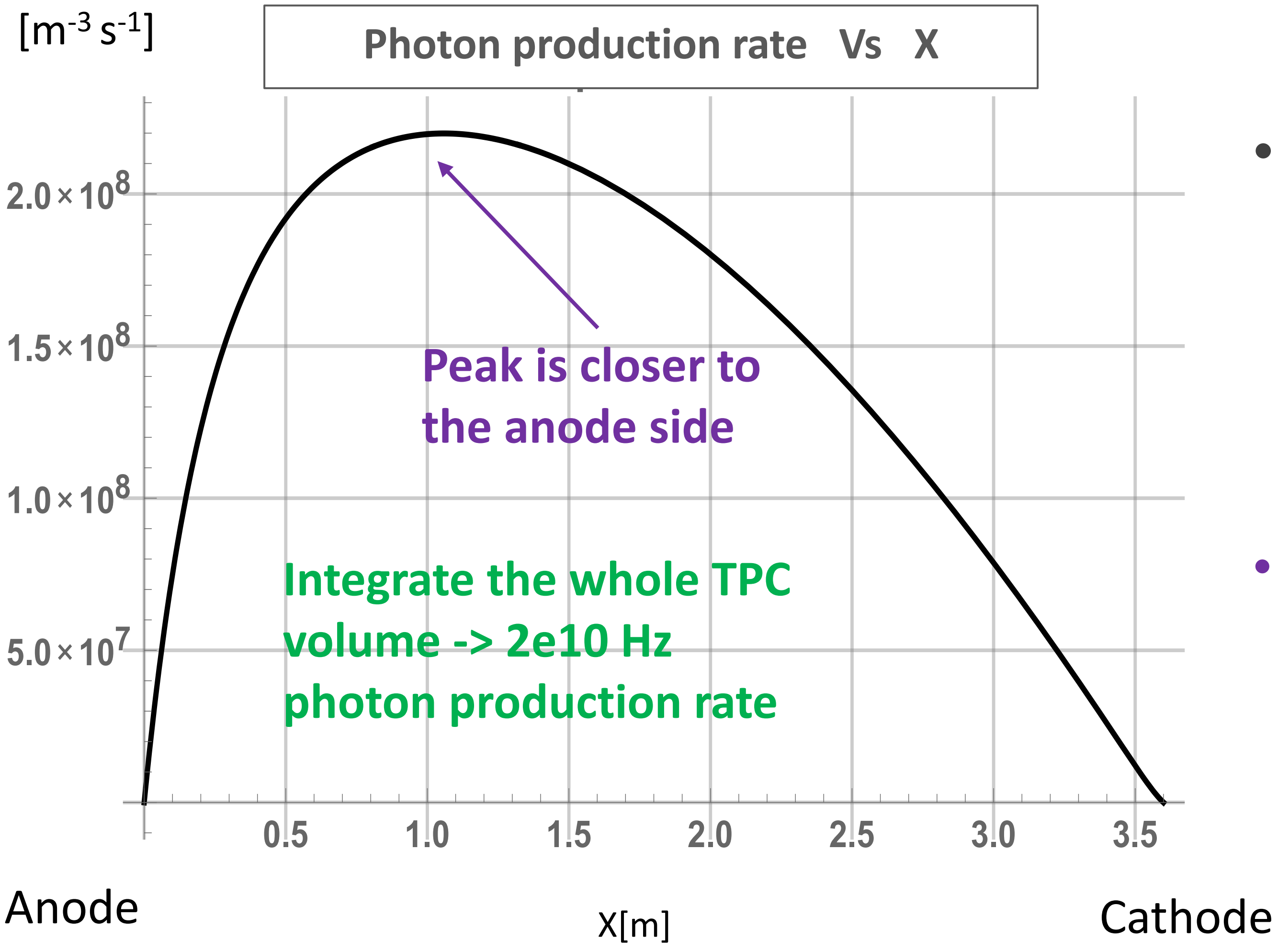






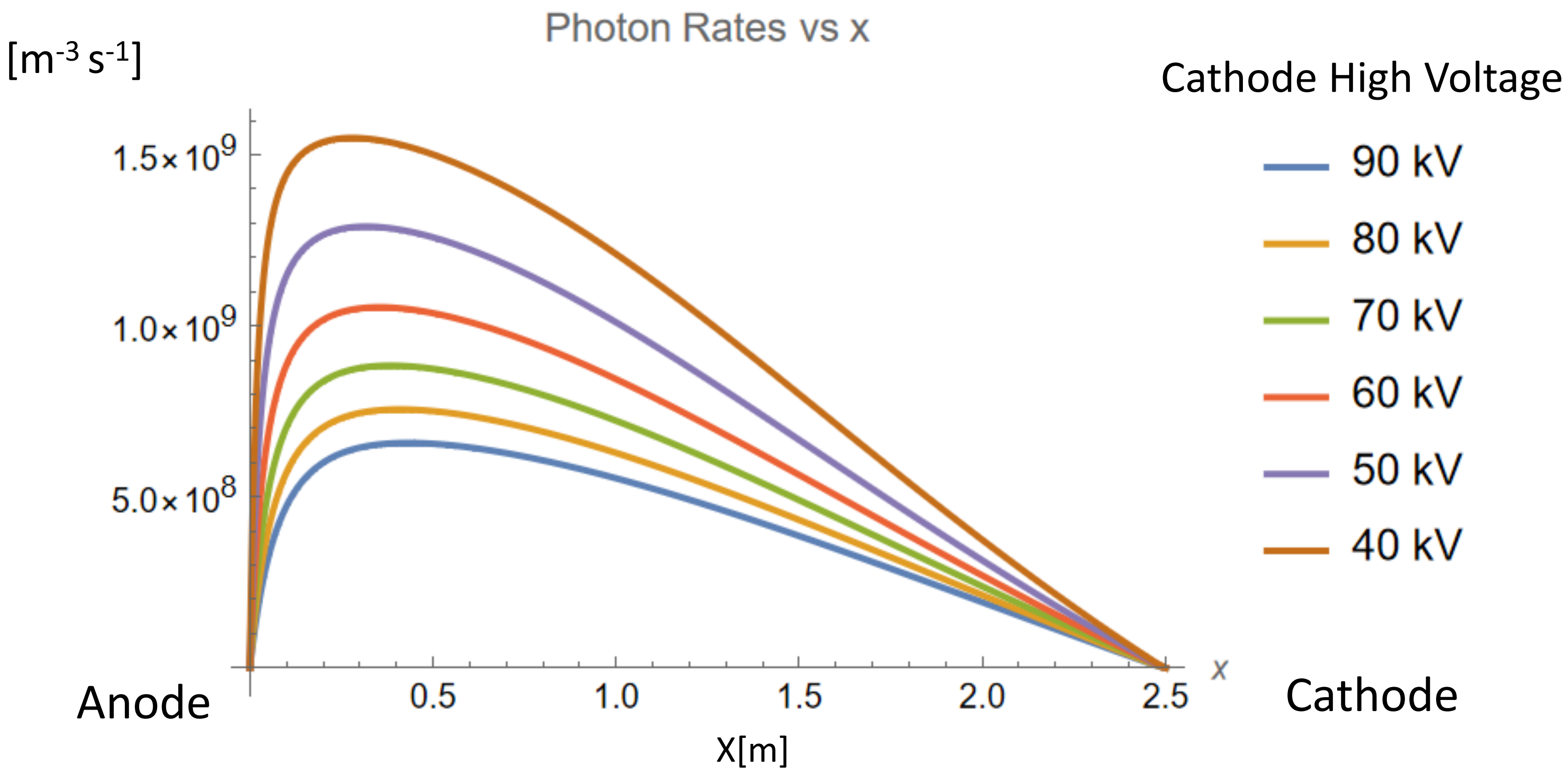


Ion Transport Model: SPE rate prediction



- Use ProtoDUNE detector geometry, model predicts ~2e10 Hz photon production rate in the TPC bulk. Folding in detection efficiency, this is O(100) kHz SPE rate, same order as measured SPE rate
- **Asymmetric distribution** of photons: more at anode than cathode. Photon sensors are located at the anode side.

Ion Transport Model: predicted SPE rate Vs E field



Model predicts **higher SPE** rate with **lower E field**

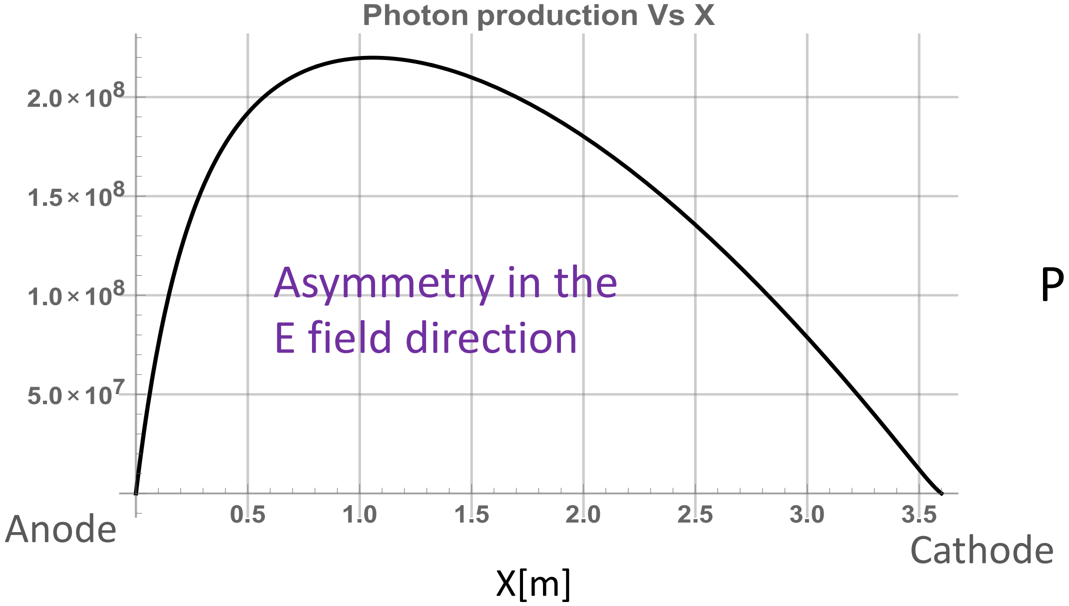
Agree with experimental observation: SPE rate **inversely correlated** with E field

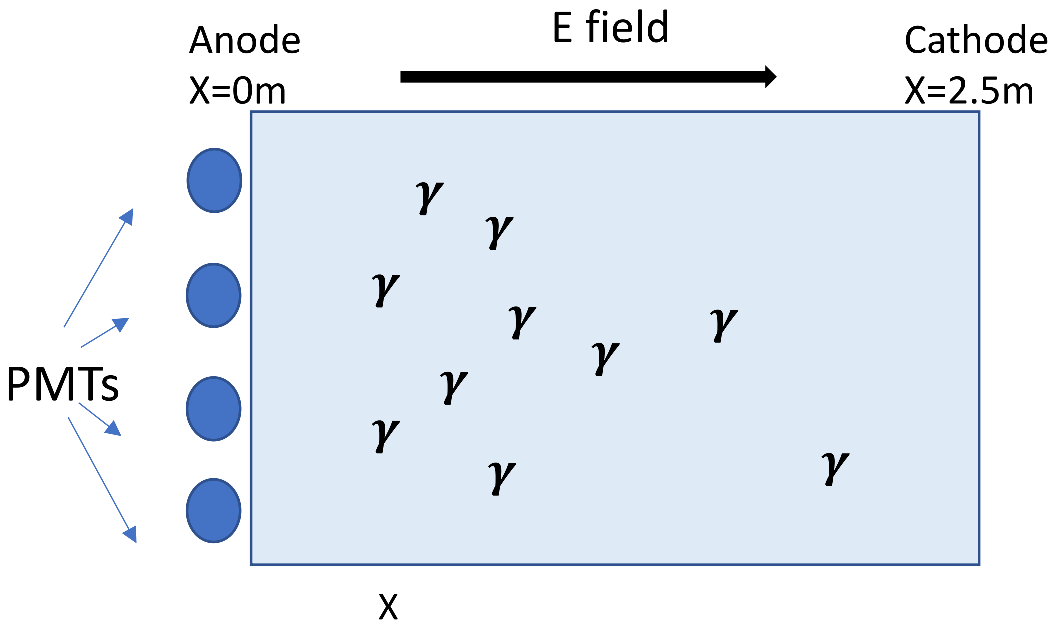
- Ion Transport Model can predict the SPE rate at the rough order as the experimental observation
- Ion Transport Model can predict correct trend of SPE rate correlation with electric field

... But before claiming that we solve the SPE rate puzzle, need more validation test of the model

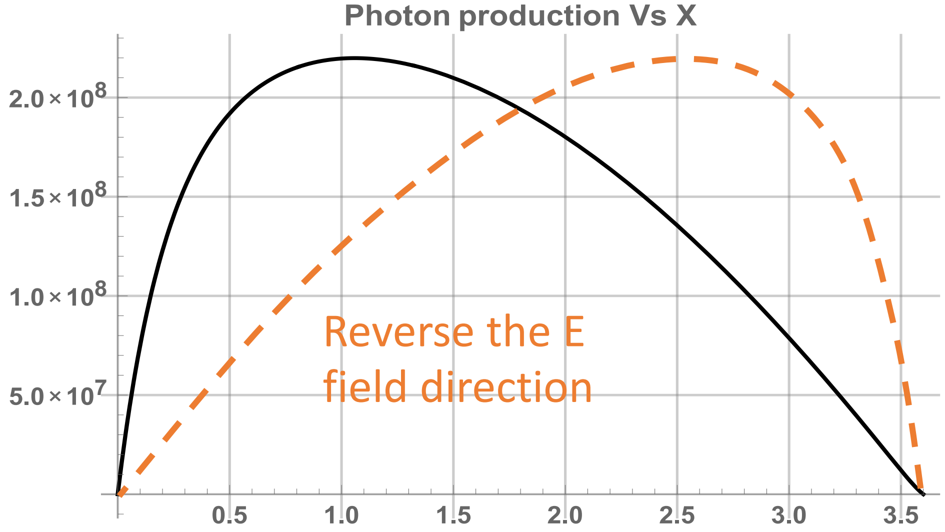
Next, special R&D run @ MicroBooNE detector!

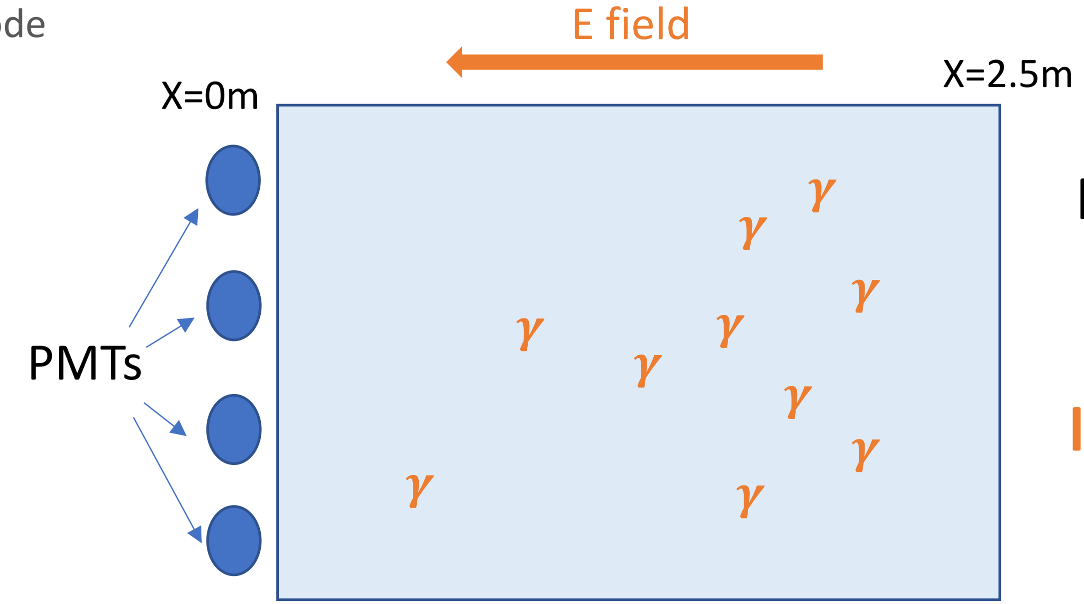
Experimental design – reverse E field





Standard Setup

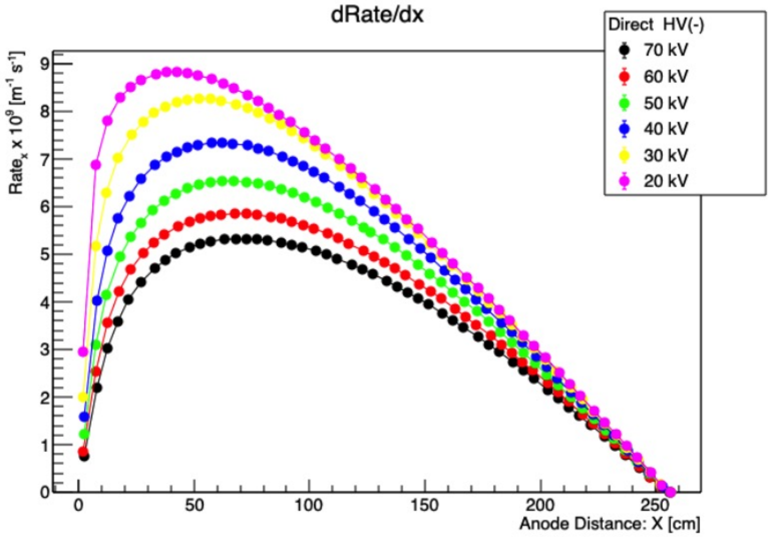


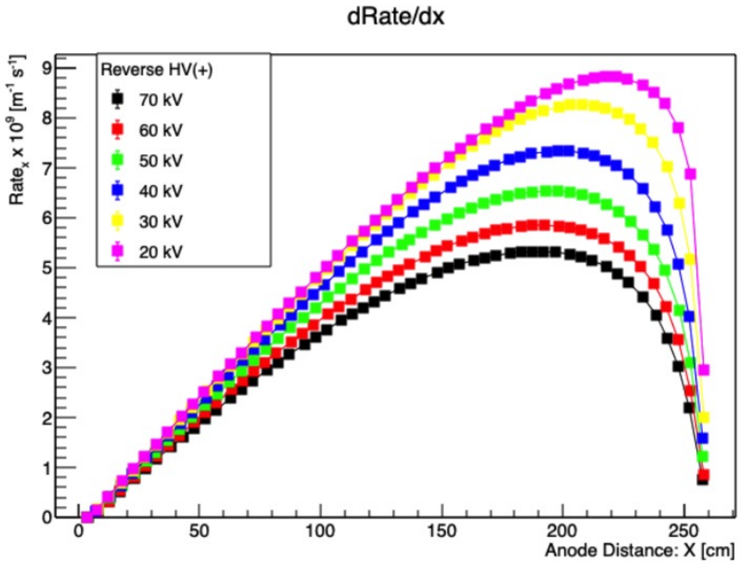


Reverse E field will result in **lower SPE rate**

Special data with reversed E field

Recall the Ion Transport Model contains ~10 parameters, and some of them are not well known.
To constrain these parameters, we designed the experiment to measure the SPE rate at different E fields.





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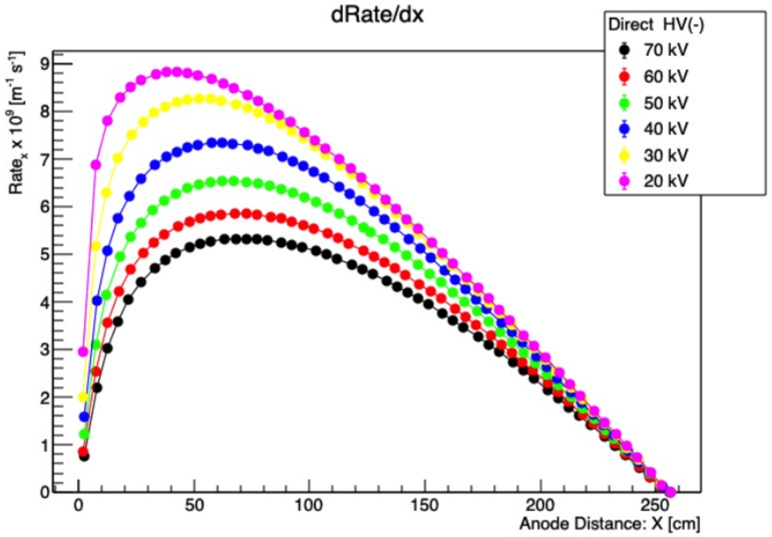
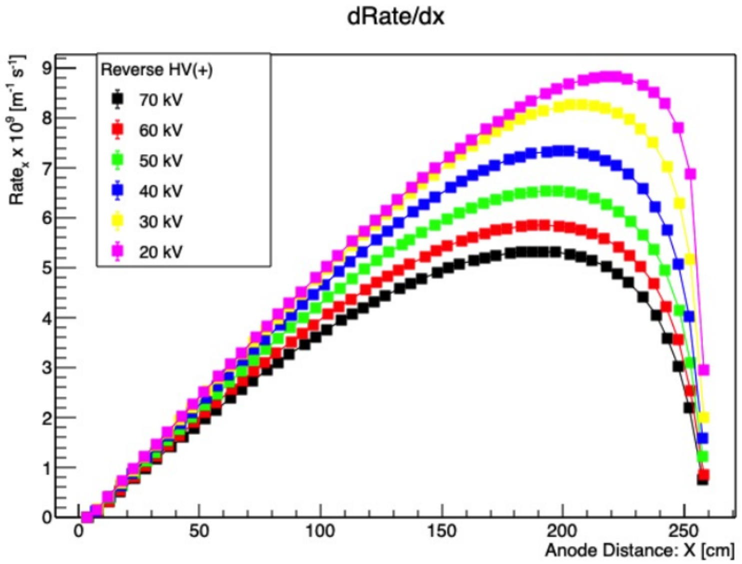
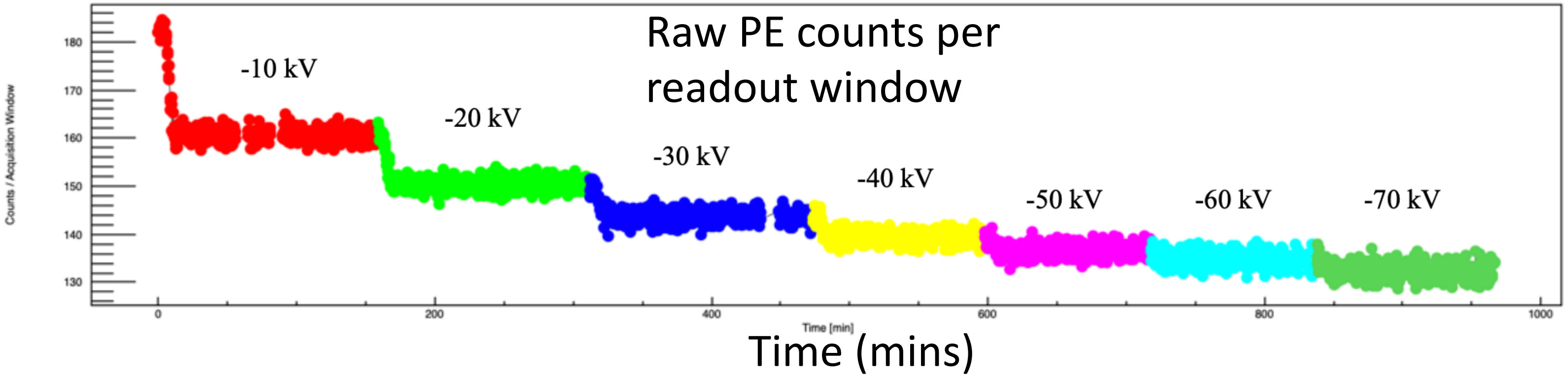




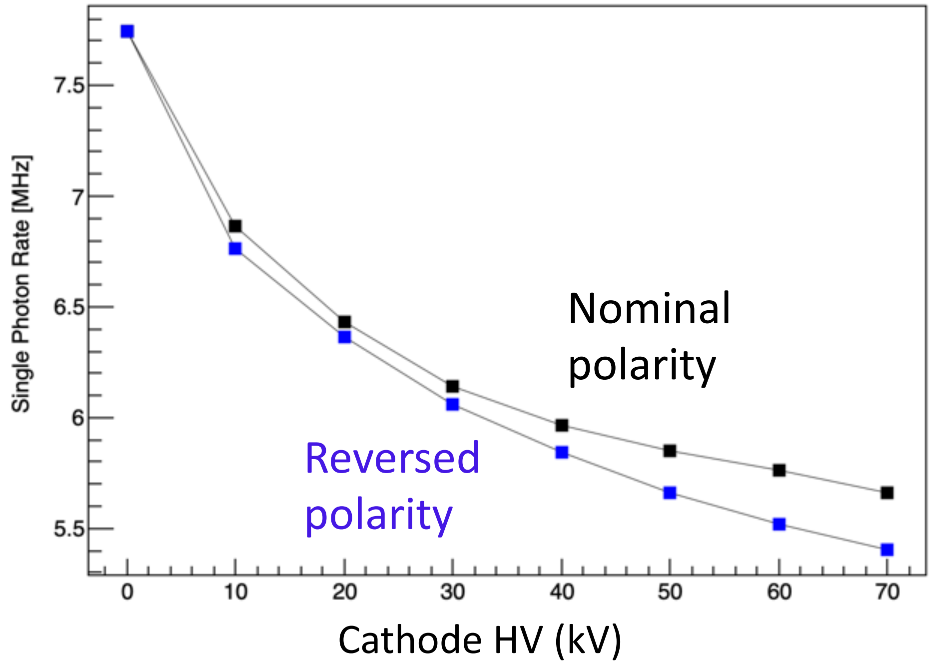
First time with a LArTPC detector!

- Special R&D run with MicroBooNE LArTPC in summer 2021
- Five scans of Cathode HV: between -70kV to +70 kV over ~2 weeks
- PMT data were collected for 2 hours at each E field

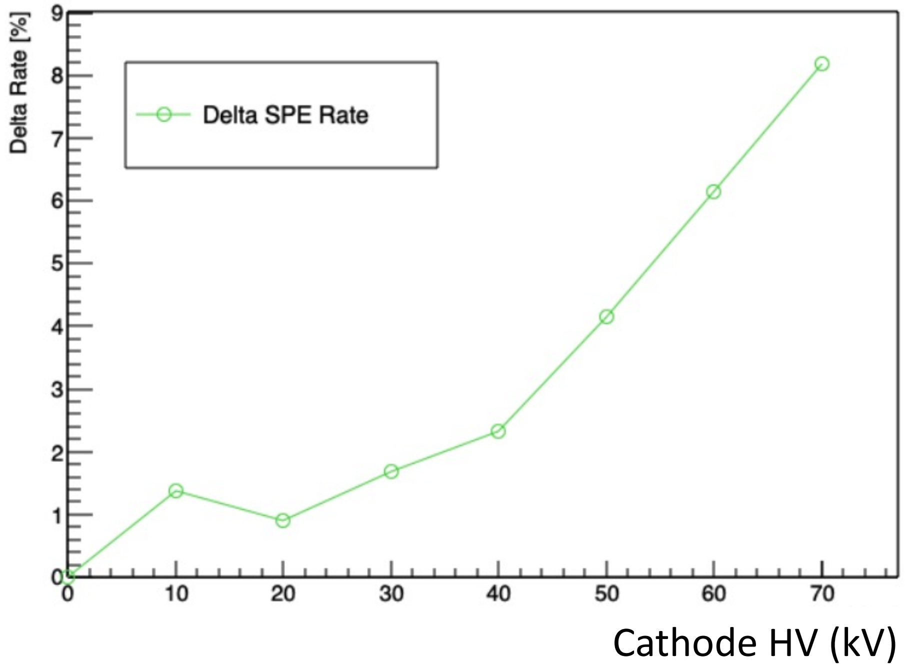


Example of Cathode HV ramp (nominal polarity)

What does the data say?



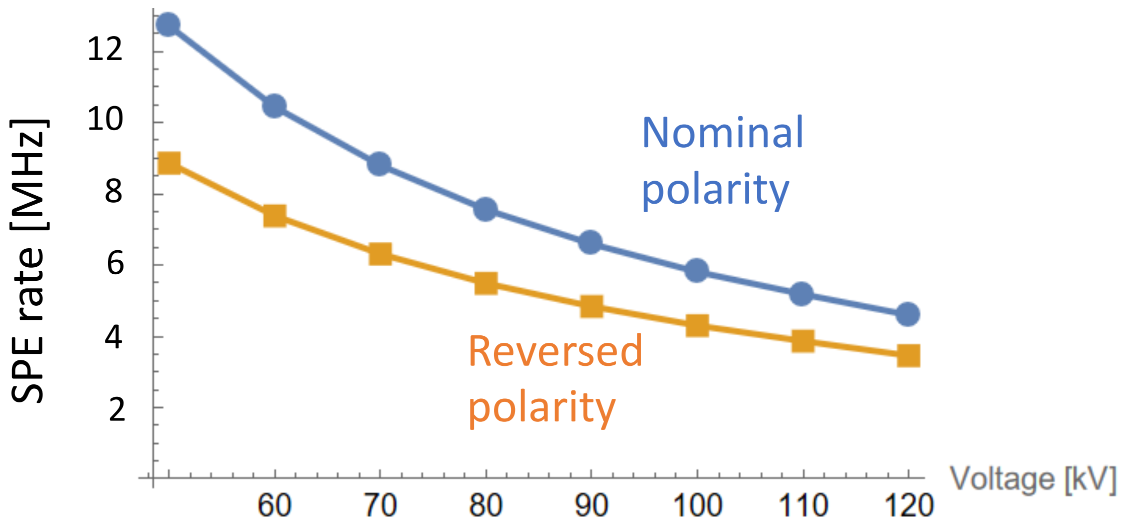
% difference between two polarities



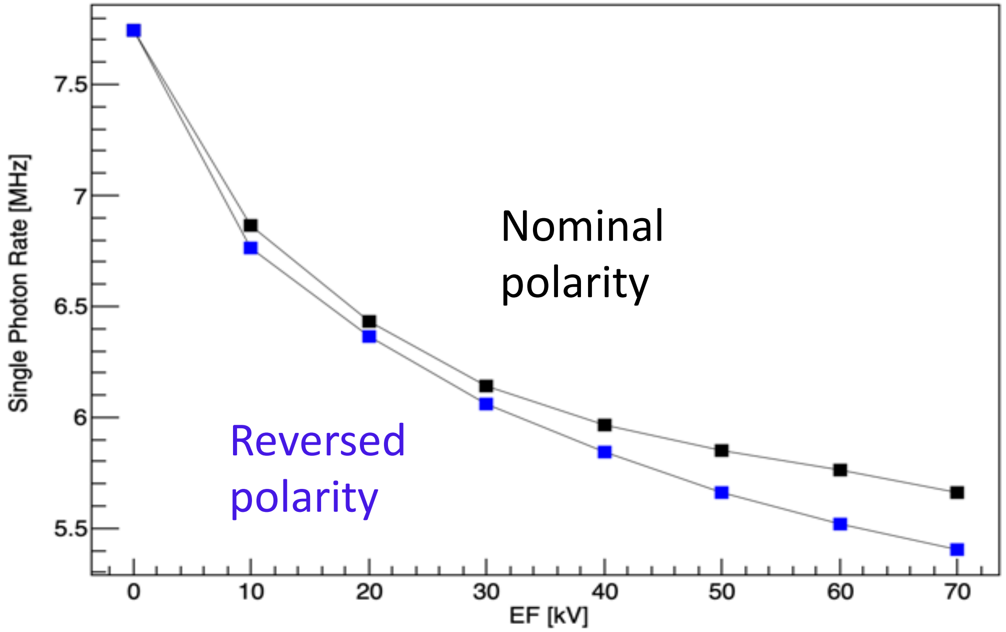
- SPE rate decrease with growing E field magnitude for both polarities
- Lower SPE rate with the reversed E field direction
- % diff. grows to ~10% at maximum E field (~300V/cm)

Model prediction Vs. Data

Model Prediction
SPE rate at different Cathode HV



Measured Data
SPE rate at different Cathode HV

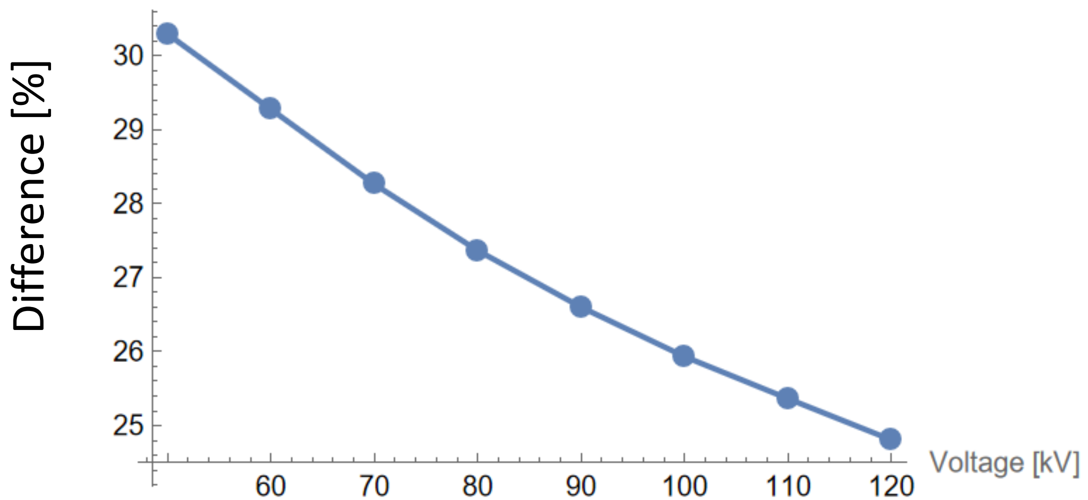


Conflict 1: X2 predicted SPE rate compared to data

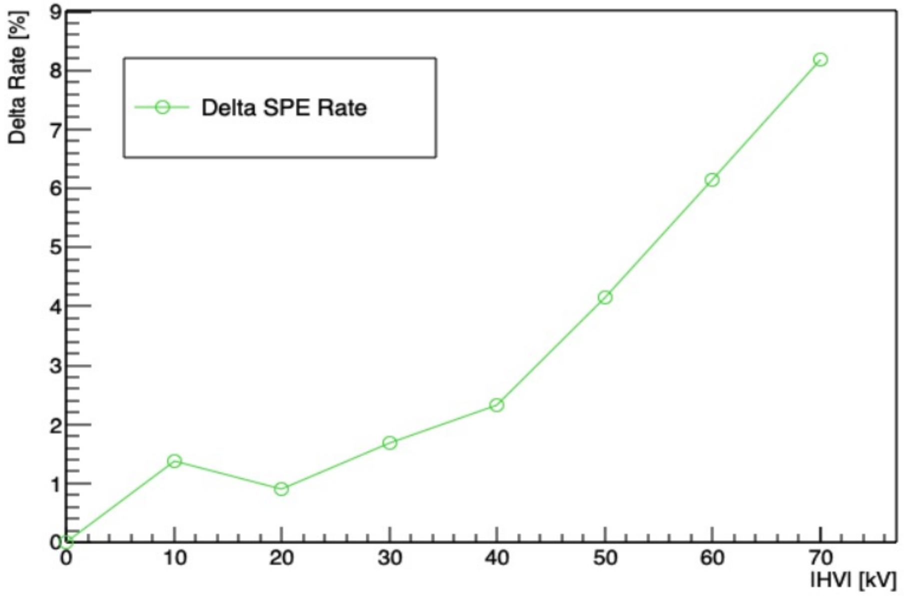
Conflict 2: Model predicts a decreased gap between two polarities with growing E field magnitude, conflicts with data ("shrinking gap")

Model prediction Vs. Data

Model Prediction
% diff. between polarities



Measured Data
% diff between polarities



Conflict 1: X2 predicted SPE rate compared to data

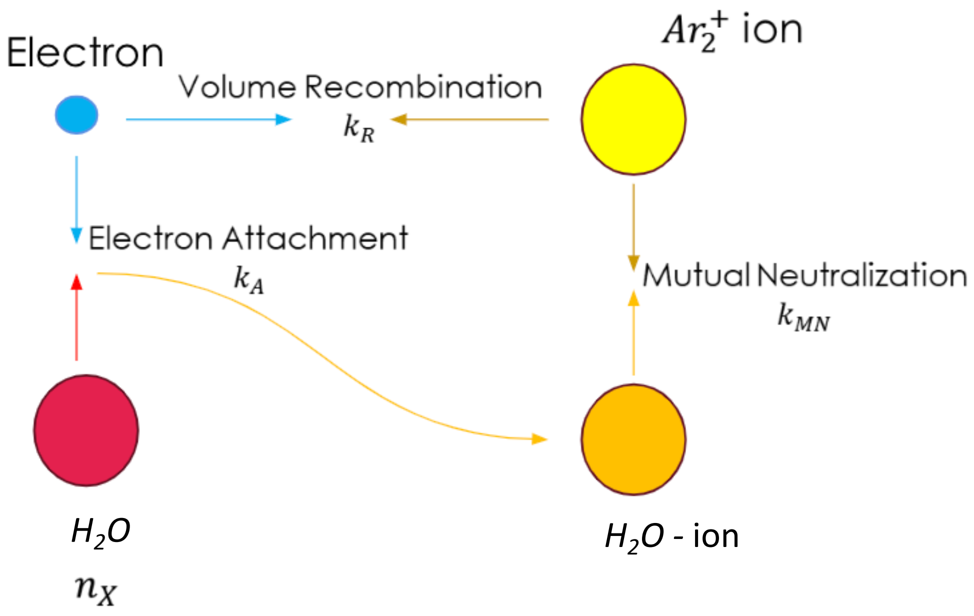
Conflict 2: Model predicts a decreased gap between two polarities with growing E field magnitude, conflicts with data (“shrinking gap”)

Conflict 3: Model predicts larger % difference than data

Need to tune the model to better match with data

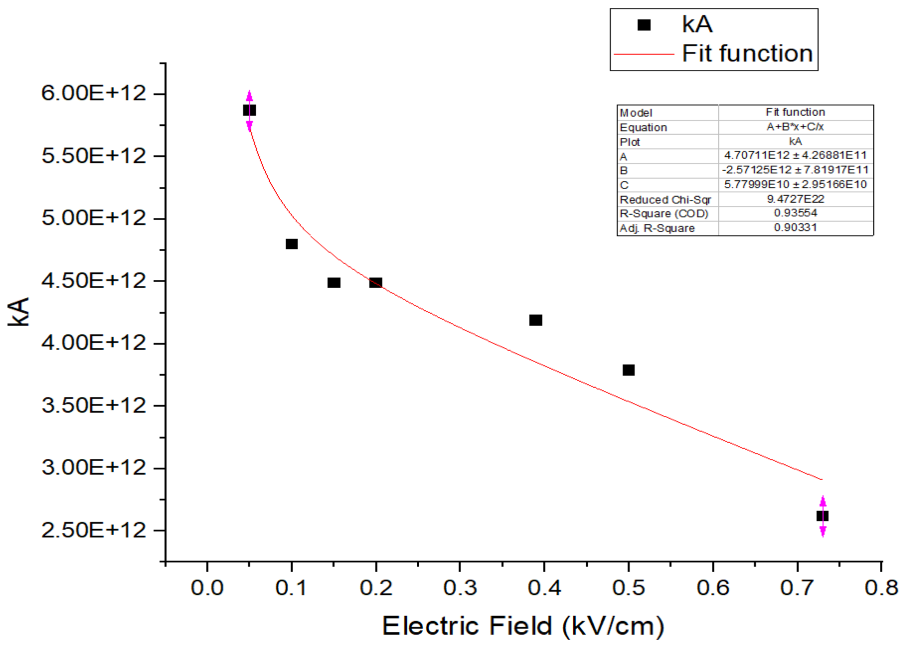
O(10) parameters in Ion Transport Model

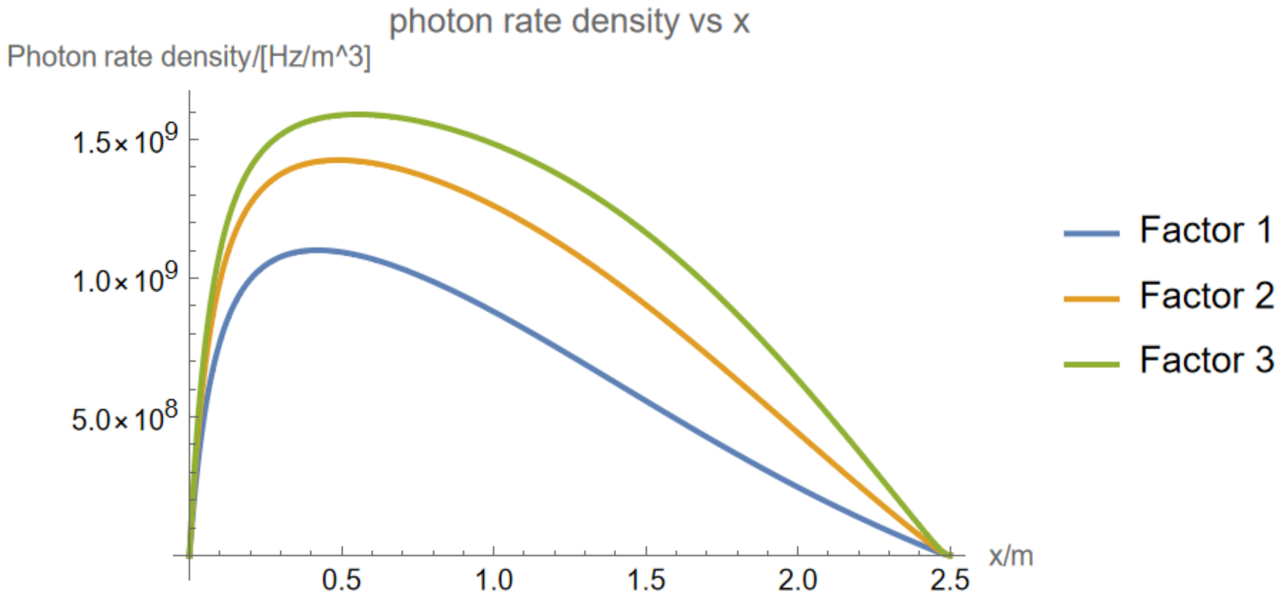
- Cosmic flux (n_{pair})
- Drift distance
- E field
- Impurity concentration (n_X)
- Mobility of ions
- e- attachment rate to impurity ((k_A)
- Rate constant of MN ((k_{MN})
- Rate constant of VR (k_R)



Next, focus on the not well-known parameters:
Electron attachment rate to impurity: k_A
Mutual Neutralization rate constant: K_{MN}

Tuning electron attachment rate K_A

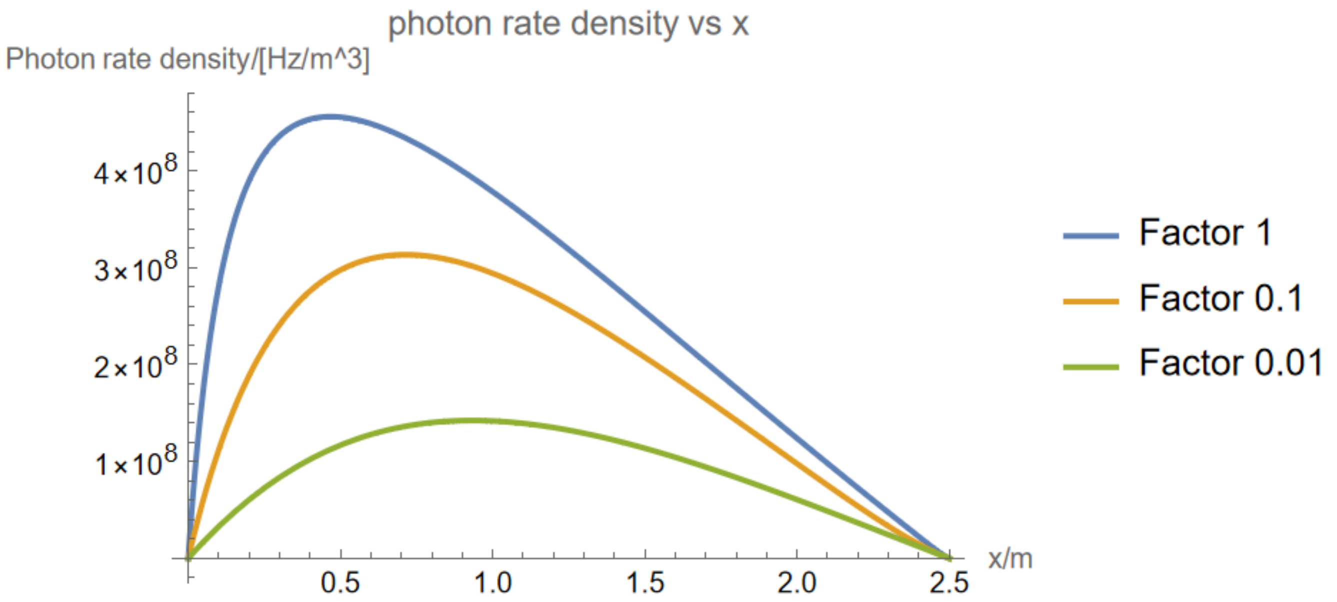




kA was constant in the original model. In practice, it's a function of E field.
We add this E field dependence to the model to make it more realistic

Increase kA reduces the asymmetry of photon density, This helps to alleviate conflict 2 ("shrinking gap")

Tuning electron attachment rate K_{MN}

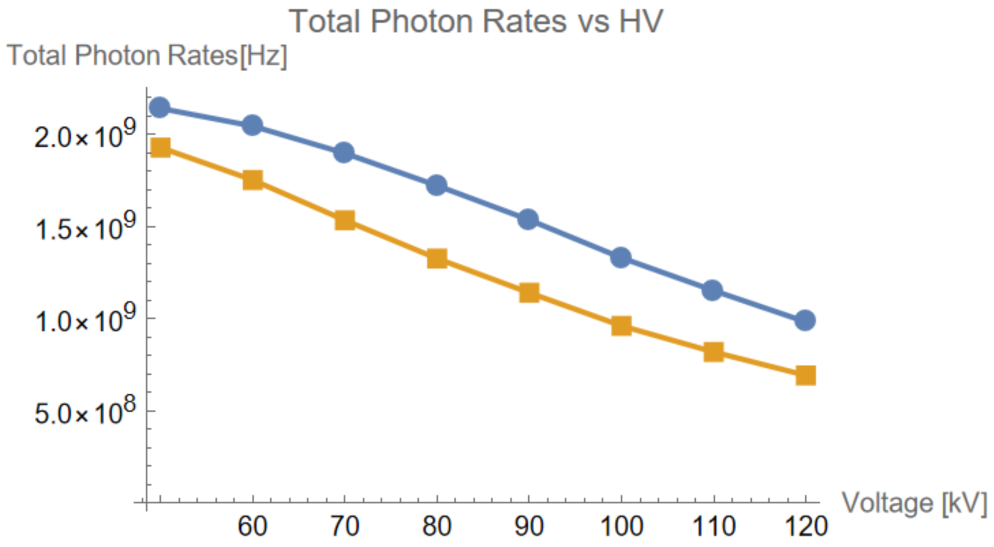


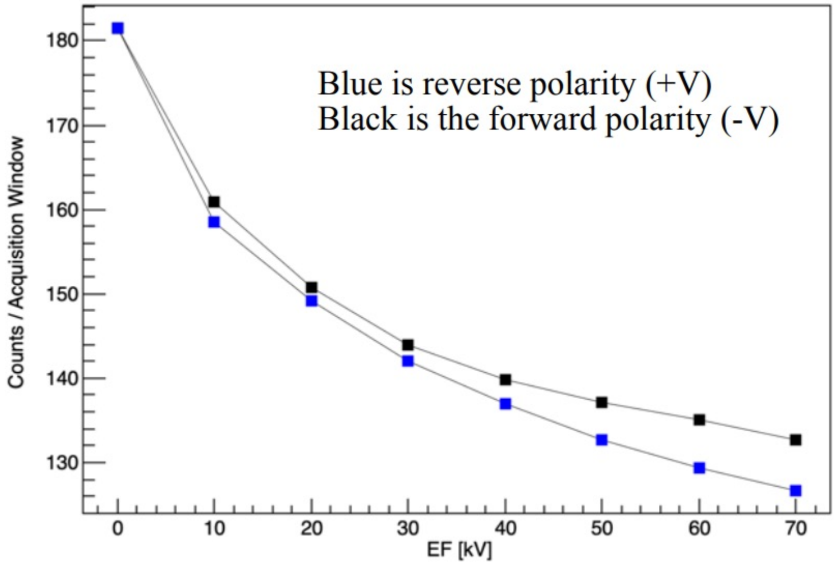
k_{MN} was constant in the original model. In practice, it might also depend E field.
We add a rough linear dependence

There is almost no previous experimental data for this parameter, so we explored a bigger range

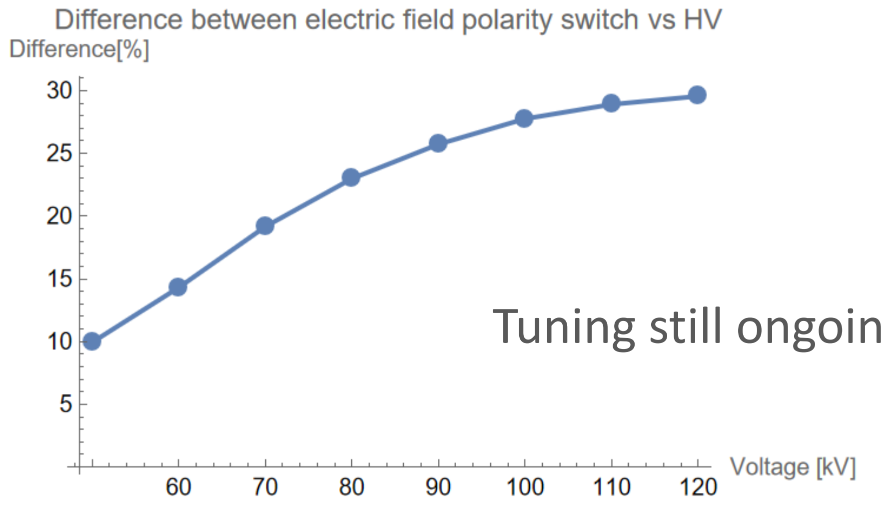
Decrease k_{MN} reduces the overall SPE rate, this helps to alleviate conflict 1
Decrease k_{MN} reduces the asymmetry of photon density, This helps to alleviate conflict 2

Model Vs Data (After tunning)

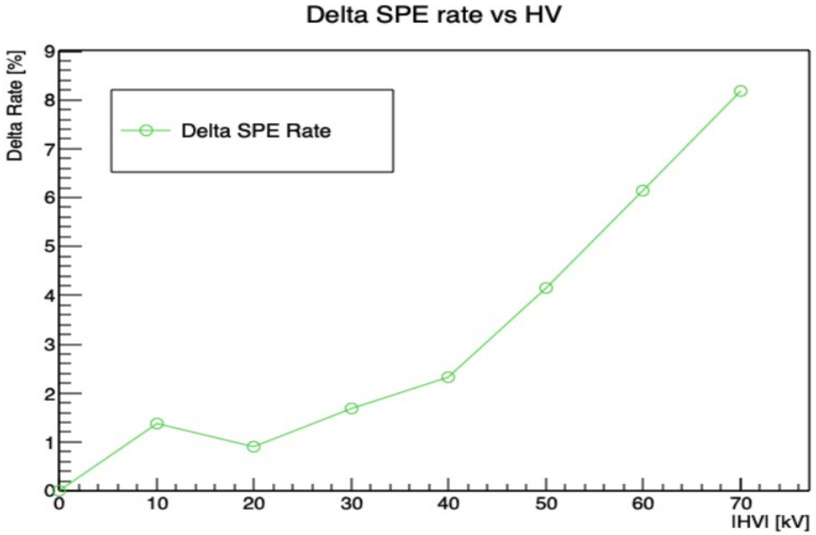




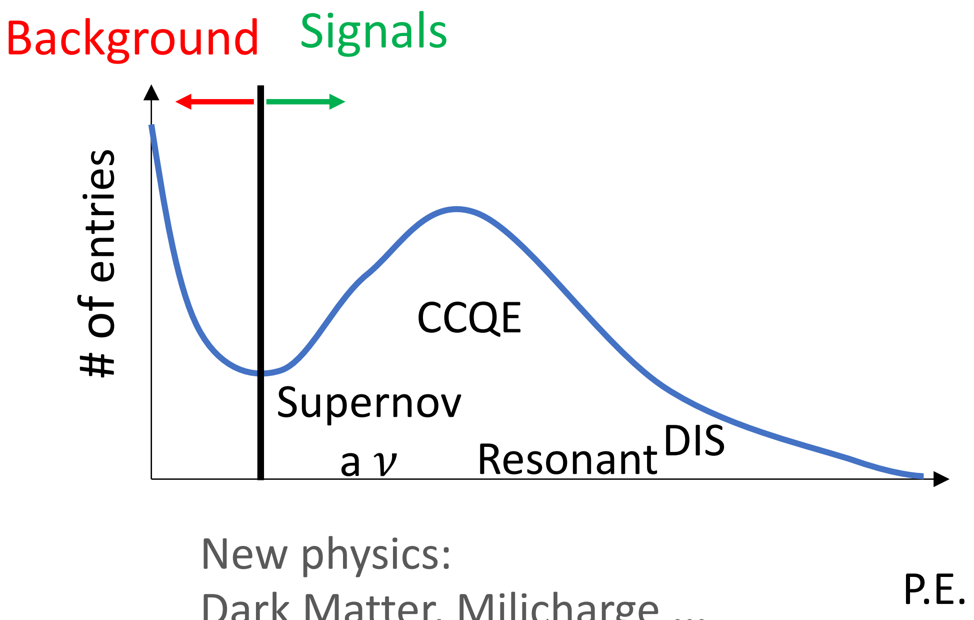
We are able to flip the trend and reduce the % difference



Tuning still ongoing...



Impact to new physics searches



New physics:
Dark Matter, Milicharge ...

LArTPC uses light signal for triggering,
We want to lower SPE rate to:

- Lower trigger energy threshold
- Increase Signal/Background ratio, enhance sensitivity to new physics

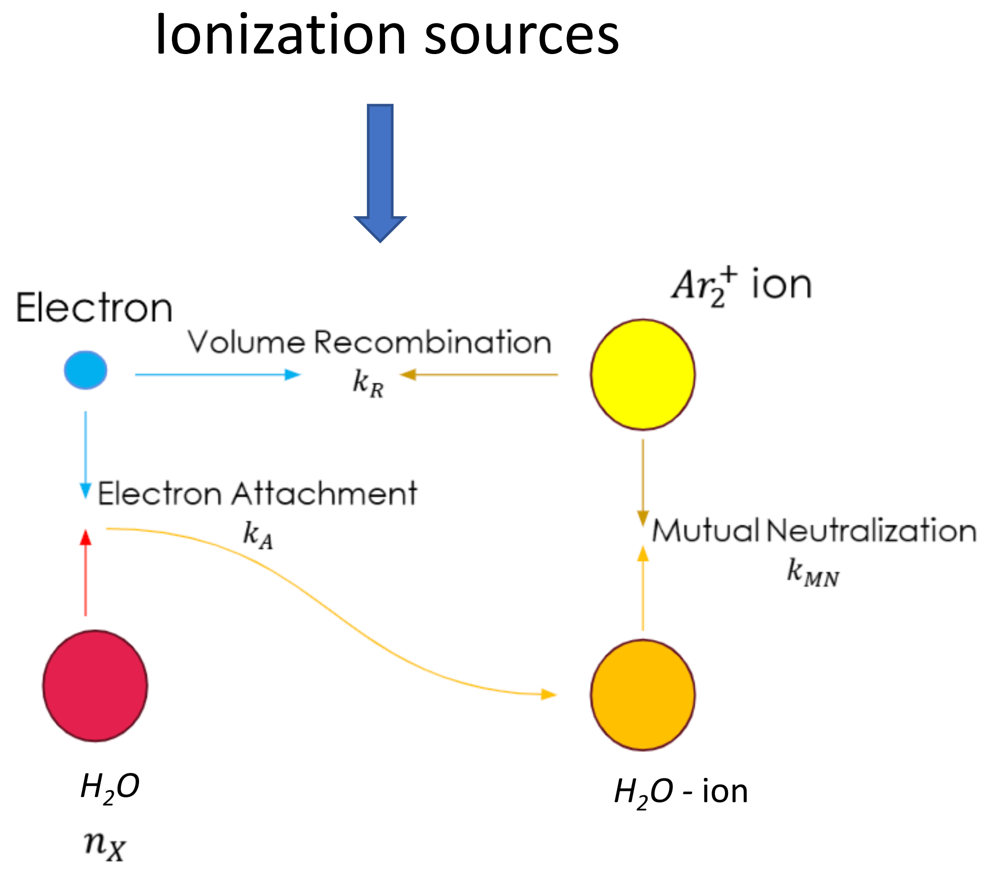
Once fully validated and tuned, Ion Transport Model offers a powerful tool to guide the experimental design with reduced SPE rate

Next, will show how to suppress the SPE rate in LArTPC detector

SPE rate suppression – reduce ionizations

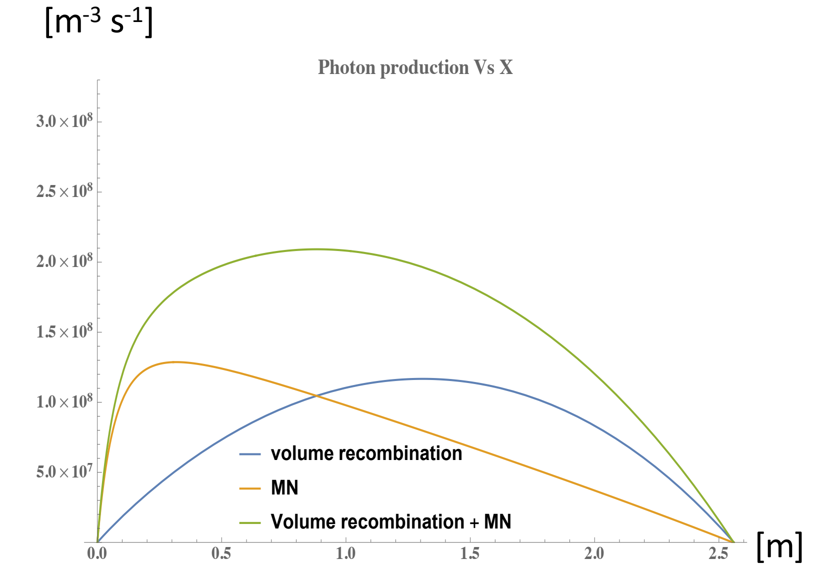
Cosmic Rays: large surface LArTPCs are exposed with high rate of cosmic rays. To 0^{th} order, the γ rate $\propto$ (cosmic flux)^{2}.
-> Move detector underground: 100m rock could suppress cosmic flux by O(100)

Ar39 is another ionization source (~1/100 of cosmic ray at surface), dominant ion producer underground.



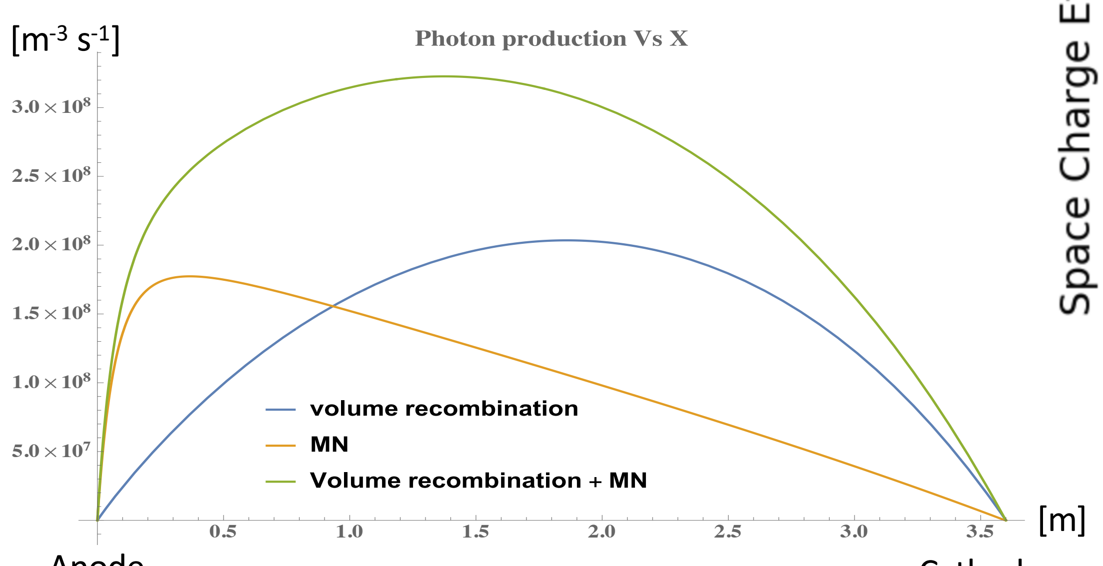
SPE rate suppression – shorten drift distance

MicroBooNE
2.5m Drift



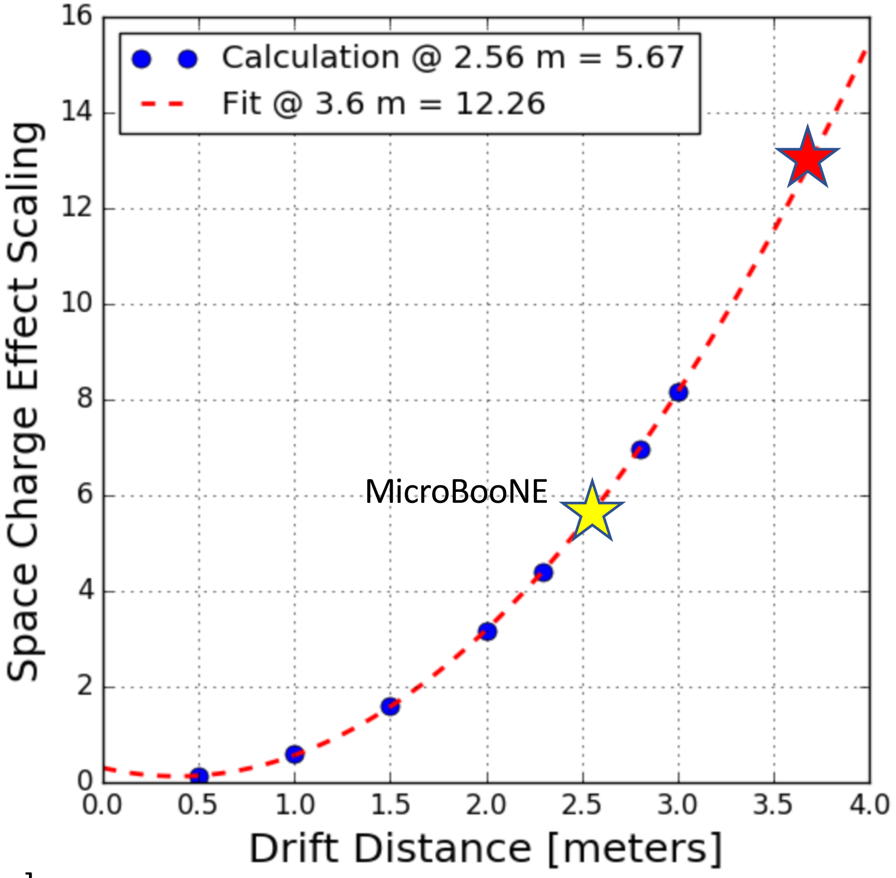
ProtoDUNE
3.6m Drift

X 2.2 γ rate

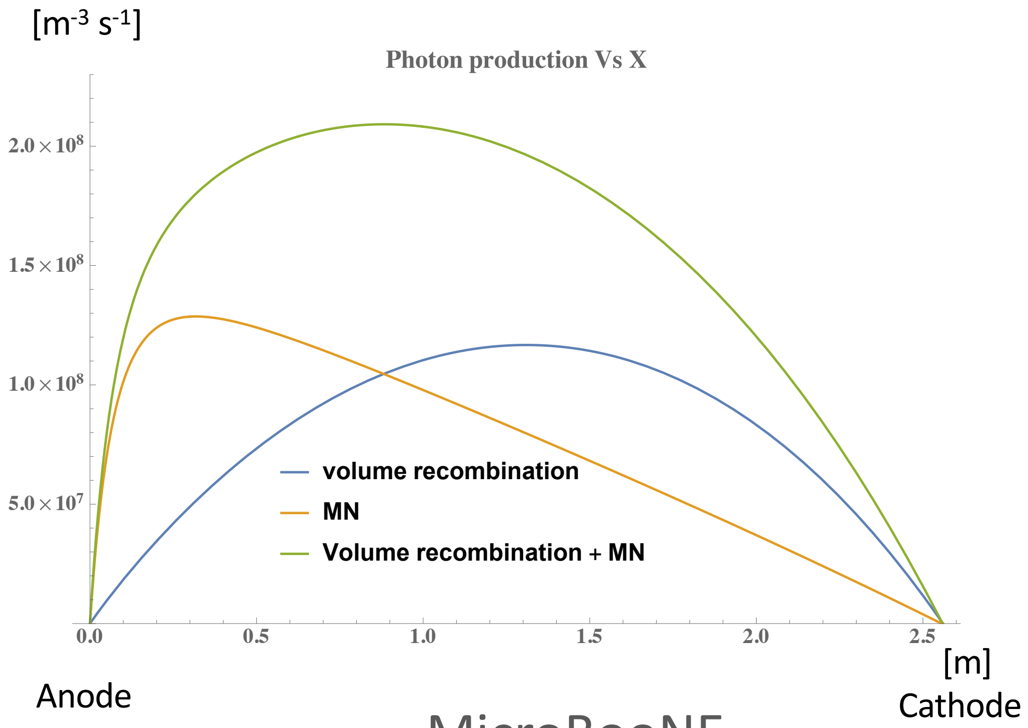


Drift distance ↑, γ rate ↑

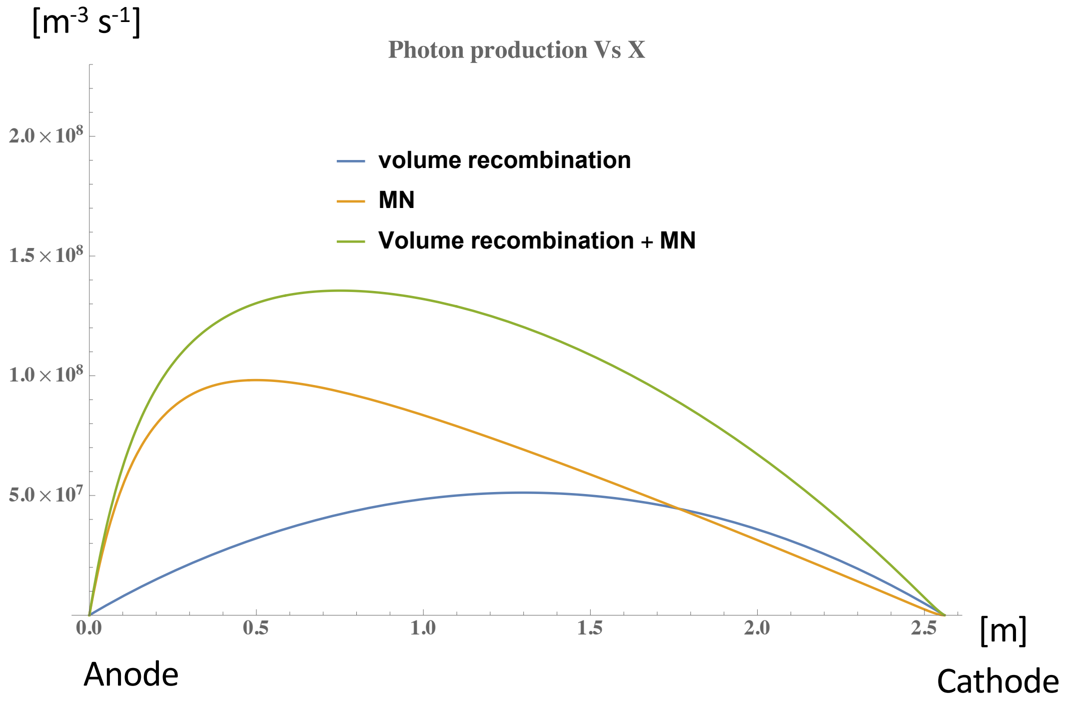
SPE rate scaling with TPC drift distance



SPE rate suppression – increase E field



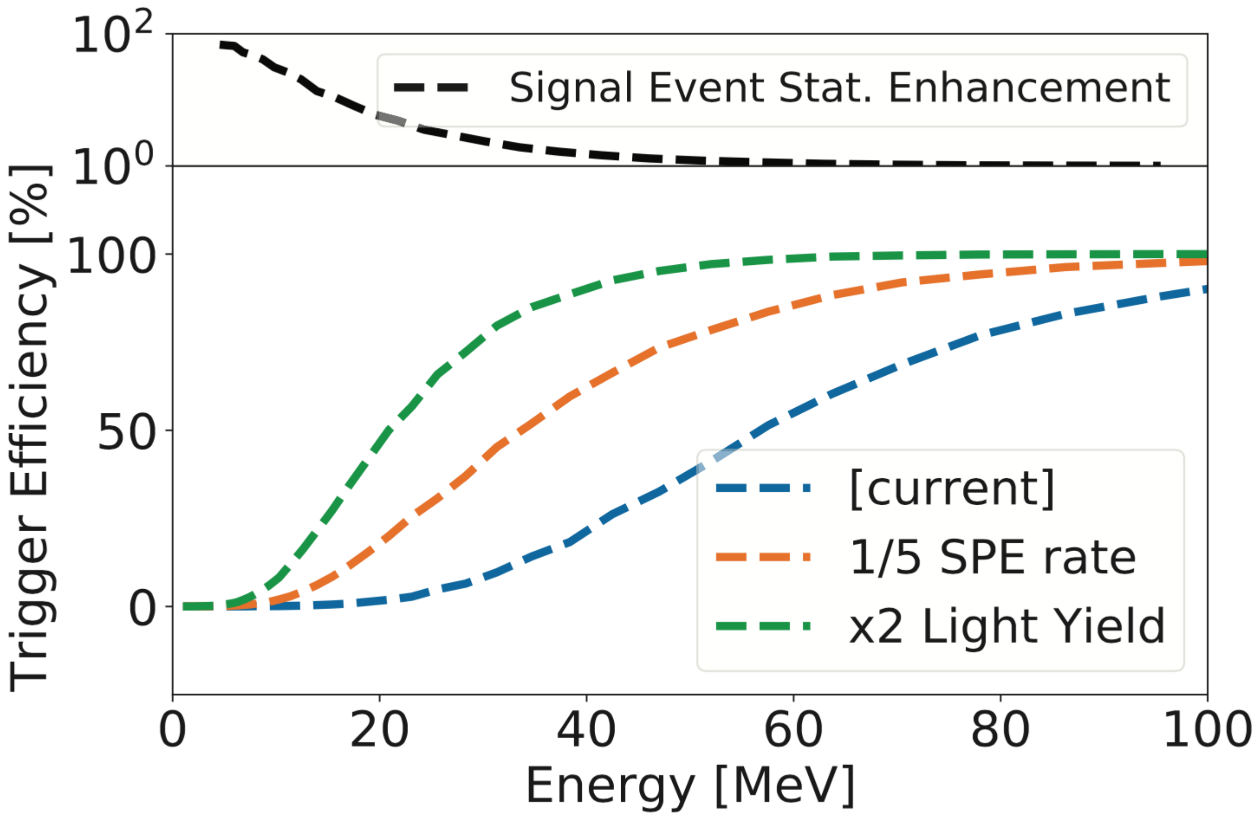
MicroBooNE
E field: 273 V/cm



ProtoDUNE
E field: 500 V/cm

- Higher E field in protoDUNE leads to lower (**X 0.67** MicroBooNE) γ rate. E field ↑ SPE rate ↓
- Model is consistent with the experimental observation.

Impact on trigger efficiency



A case study of BSM trigger efficiency
@ MicroBooNE LArTPC

Summary

- Proposed the **Ion Transport Model** that explain the high SPE rate observed in the large surface LArTPC detectors

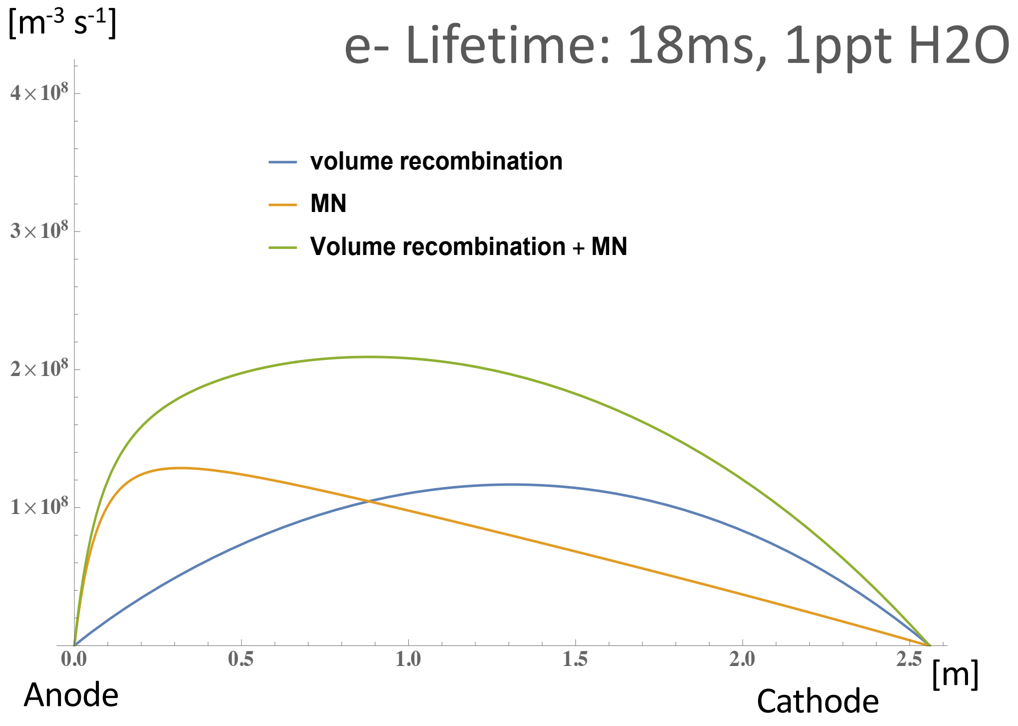
- Special **data with reversed E field** were collected with MicroBooNE detector to verify and over constrain the model

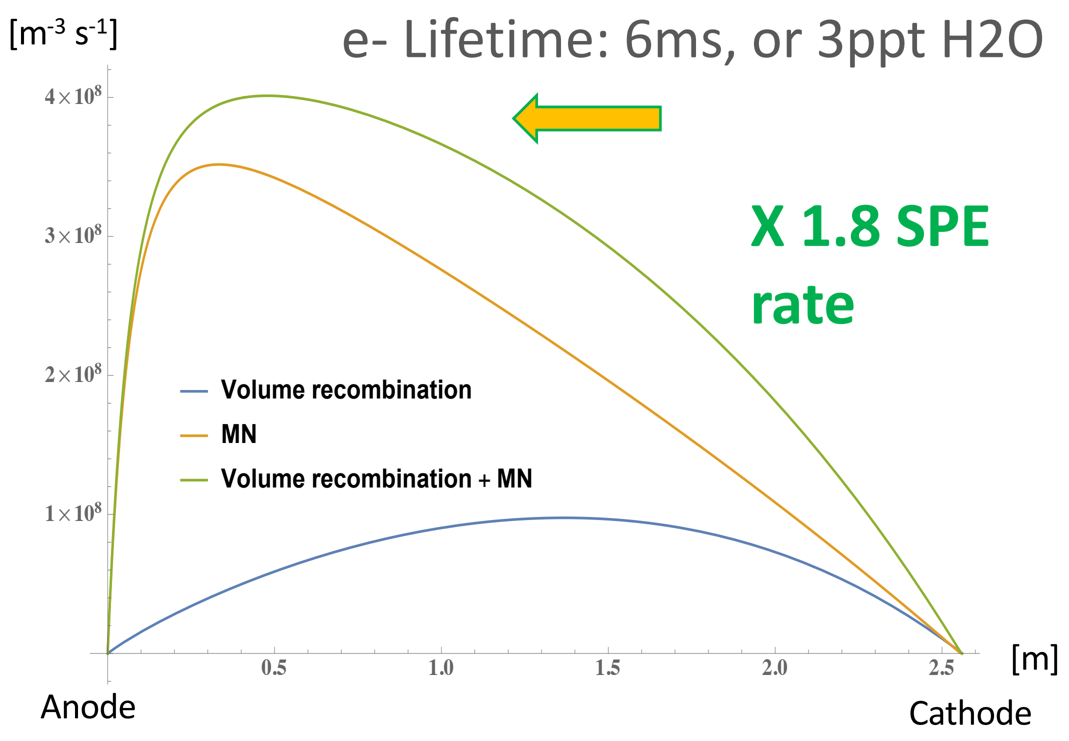
- Model is tuned to better agree with data (ongoing)

- Once fully validated, model is a powerful tool to guide future experimental design to reduce SPE rate-> **enhanced BSM discovery potential**

Backup

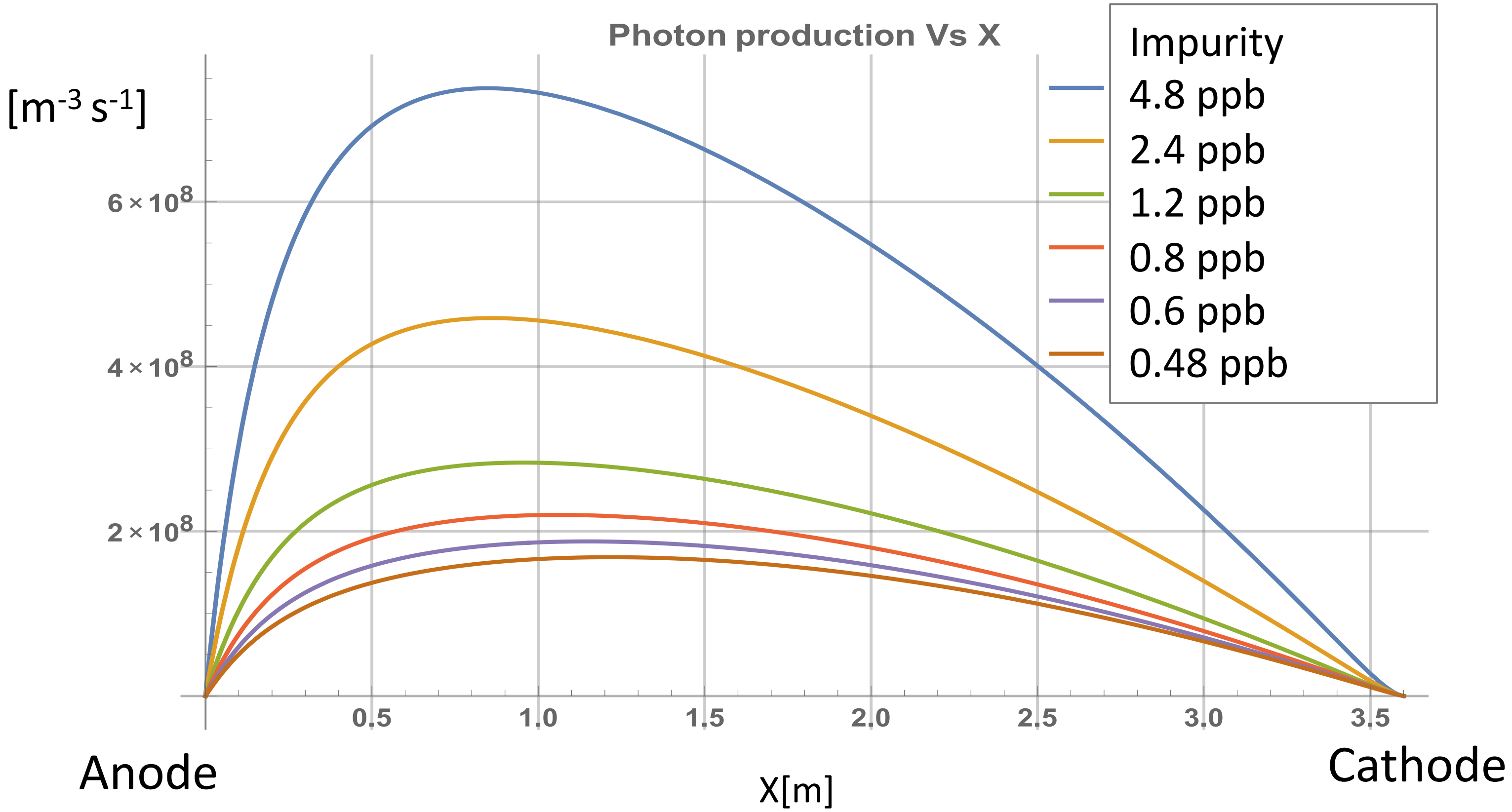
Experimental SPE rate suppression – clear out impurities





- Impurity negative ion could potentially generate photons through Mutual Neutralization with positive Ar ion. Impurity concentration ↑, γ rate ↑
- However, impurity also absorb the light and quench the light detection.

Ion Transport Model: predicted SPE rate Vs impurity



Model predicts **higher SPE** rate with **higher impurity concentration**

Agree with experimental observation: SPE **positively correlated** with impurity