Ion transfer model in large LArTPC

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Motivation – Puzzle of High SPE rate

High rate of single photoelectrons have been observed in **large surface** LArTPC.

- MicroBooNE sees ~x10 higher SPE rate than expected dark rate.
- ProtoDUNE detector also sees high photon rate from the first Arapuca analysis (see next talk by Dante Totani)

Some explanations:

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

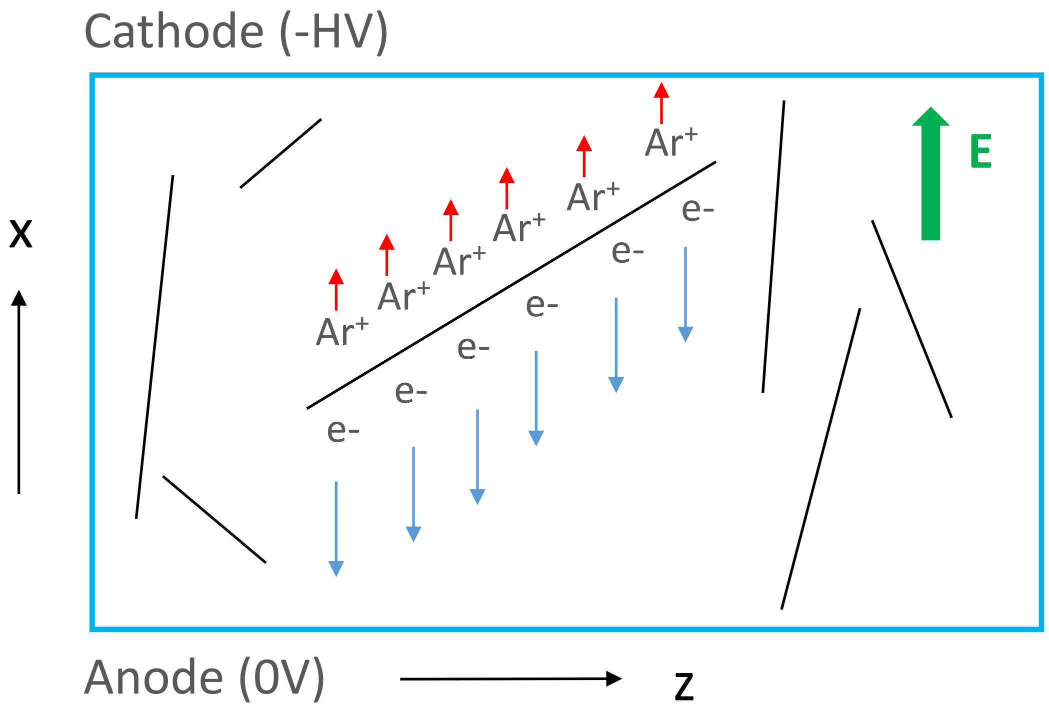
(Radon radioactivity in filters, Argon 39 decay, TPB dissolve in argon:) Small contributions to the total SPE rate

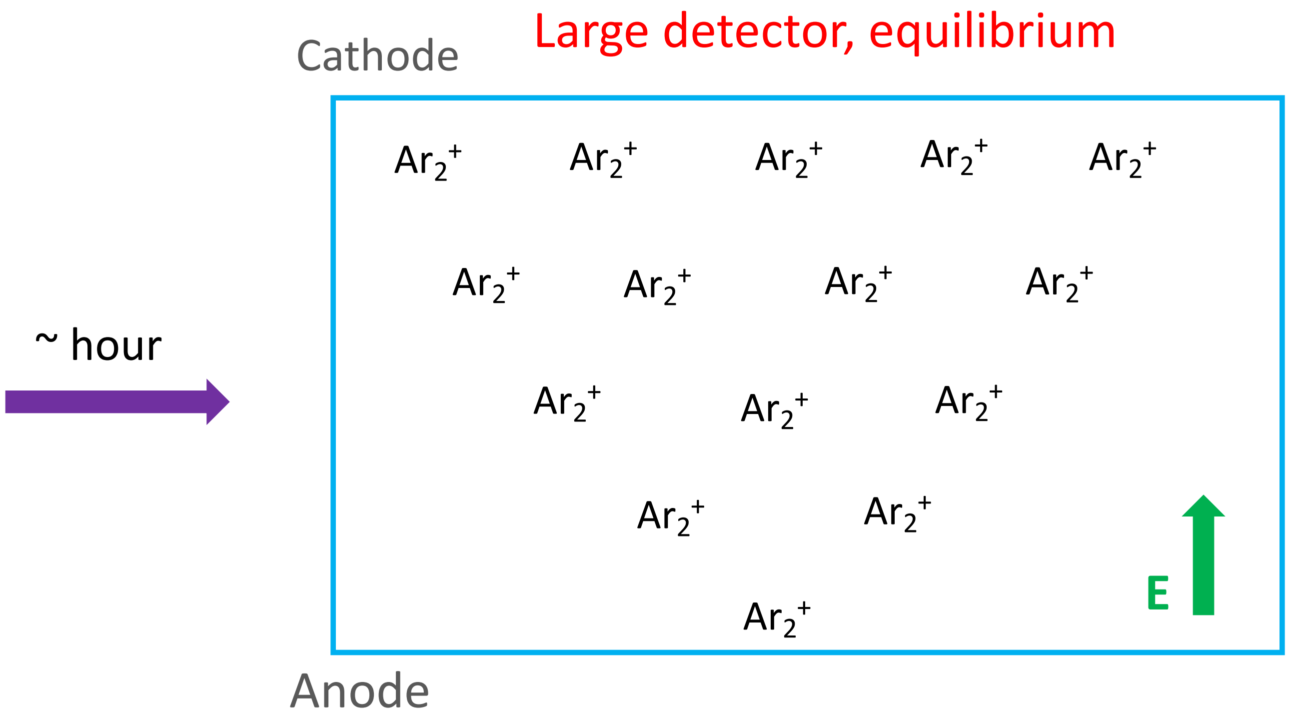
Some hints from the experiments:

- SPE rate is inversely correlated with E field: Higher E field, lower SPE rate
- SPE rate is positively correlated with the argon purity: Higher purity, higher SPE rate.

Need other explanations, we built a model centered around the microphysics of argon properties to address the SPE puzzle.

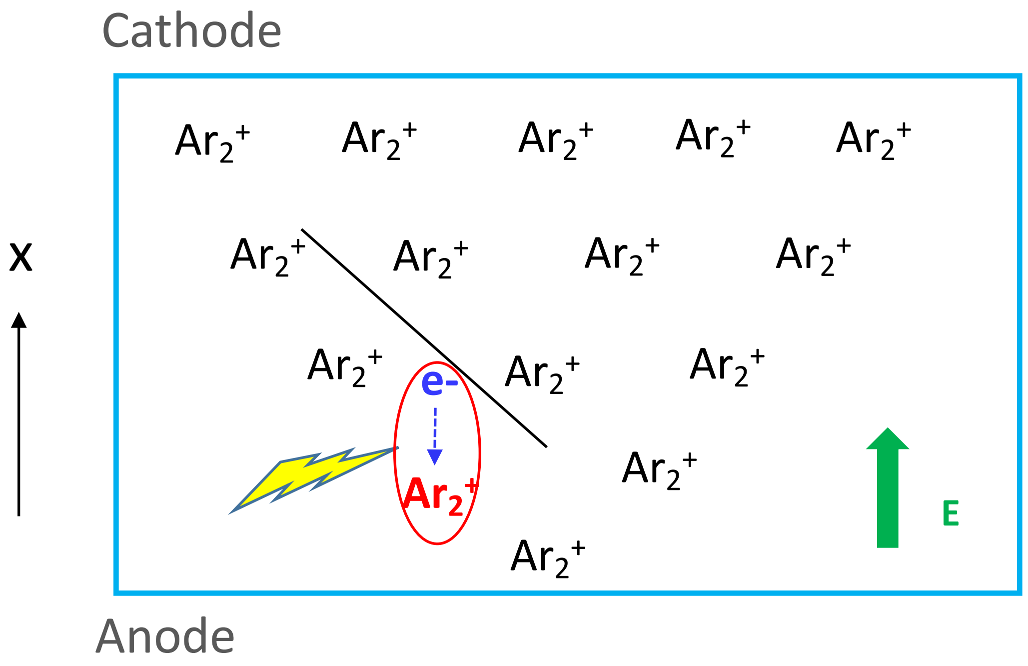
Ion transport Model





- 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.

New photon production process I - VR

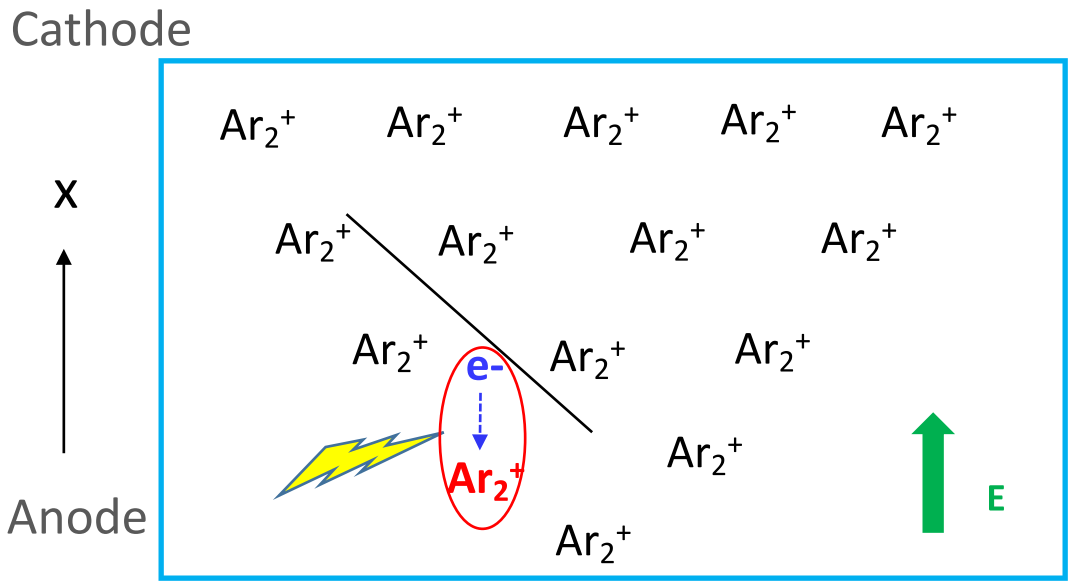


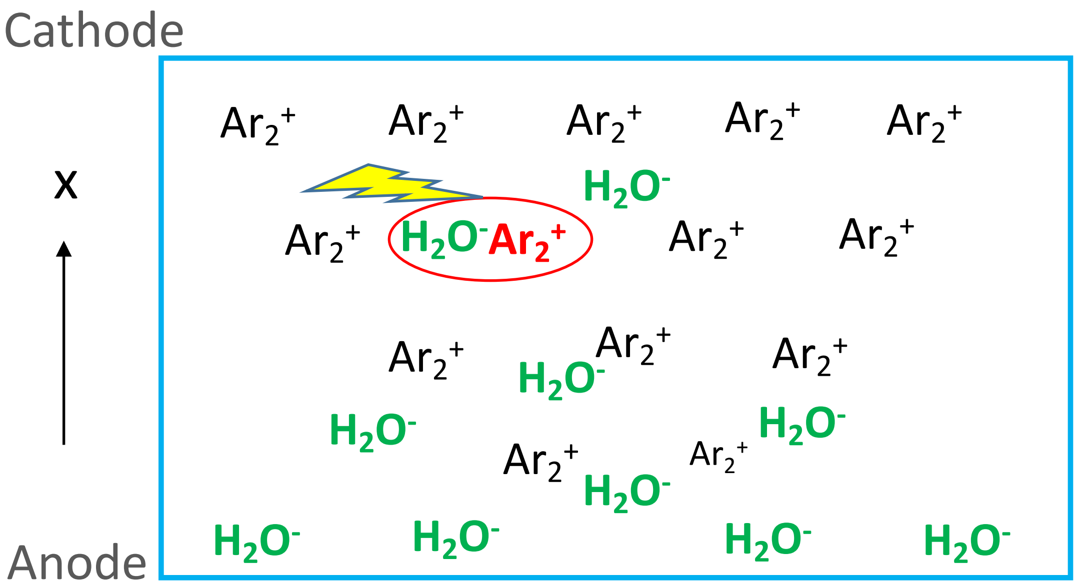
Drift electron recombines with other Ar_2^+ ion in the bulk, different from initial recombination

(1) Volume Recombination (VR)

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

New photon production process II - MN





(1) Volume Recombination (VR)

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

photons from slow ions

Impurity (O_2, H_2O...) attachment:

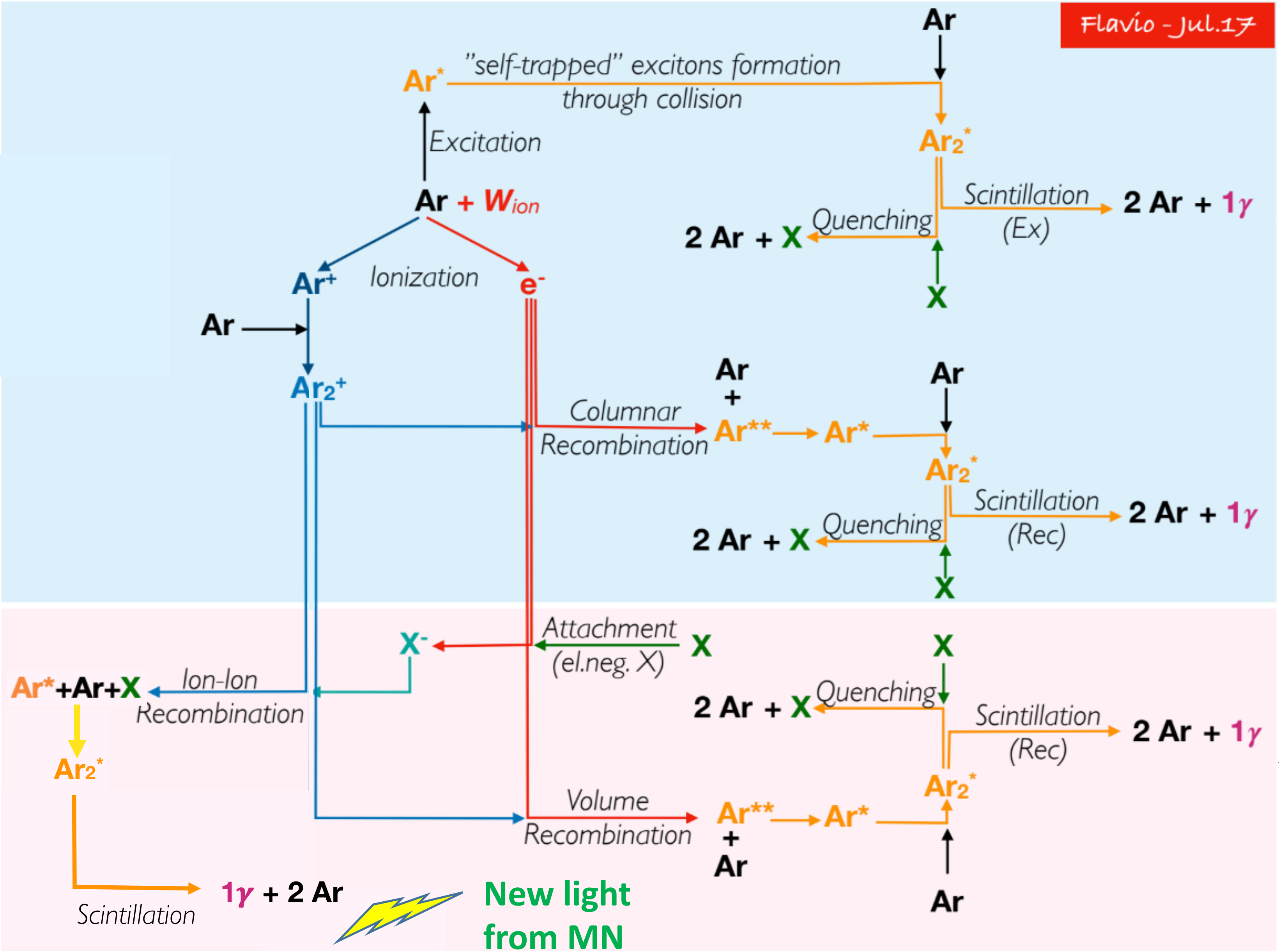
$$e^- + H_2O \rightarrow H_2O^-$$

(2) Mutual Neutralization (MN)

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

Fast and slow processes to produce photons

Fast process (ns - us)



Standard Ar scintillation light

Standard Ar scintillation light

slow process

New light from VR

New light from MN

Model to predict single photon rate

4 Ion transport equations (as function of X) + 4 Boundary conditions + 10 Input parameters

$$
\begin{cases}
-\mu_e \, n_e \frac{\partial E}{\partial x} - v_d^e \frac{\partial n_e}{\partial x} = + n_{pair}^i - k_A \, n_X^0 \, n_e - k_R \, n_+ \, n_e \\
-\mu_+ \, n_+ \frac{\partial E}{\partial x} + v_d^+ \frac{\partial n_+}{\partial x} = + n_{pair}^i - k_{MN} \, n_- \, n_+ - k_R \, n_+ \, n_e \\
-\mu_- \, n_- \frac{\partial E}{\partial x} - v_d^- \frac{\partial n_-}{\partial x} = + k_A \, n_X^0 \, n_e - k_{MN} \, n_- \, n_+ \\
\frac{\partial E}{\partial x} = \frac{1}{\epsilon_0 \epsilon_r}(n_+ - n_- - n_e)
\end{cases}
$$

$$
\begin{cases}
n_e(x = Cathode) = 0 \\
n_+(x = Anode) = 0 \\
n_-(x = Cathode) = 0 \\
\int_{Anode}^{Cathode} E(x)\,dx = HV_{Cathode}
\end{cases}
$$

- Cosmic flux
- Rate constant of VR
- Rate constant of MN
- Impurity concentration
- e- attach. rate to impurity
- Drift distance
- E field
- Mobility of ions

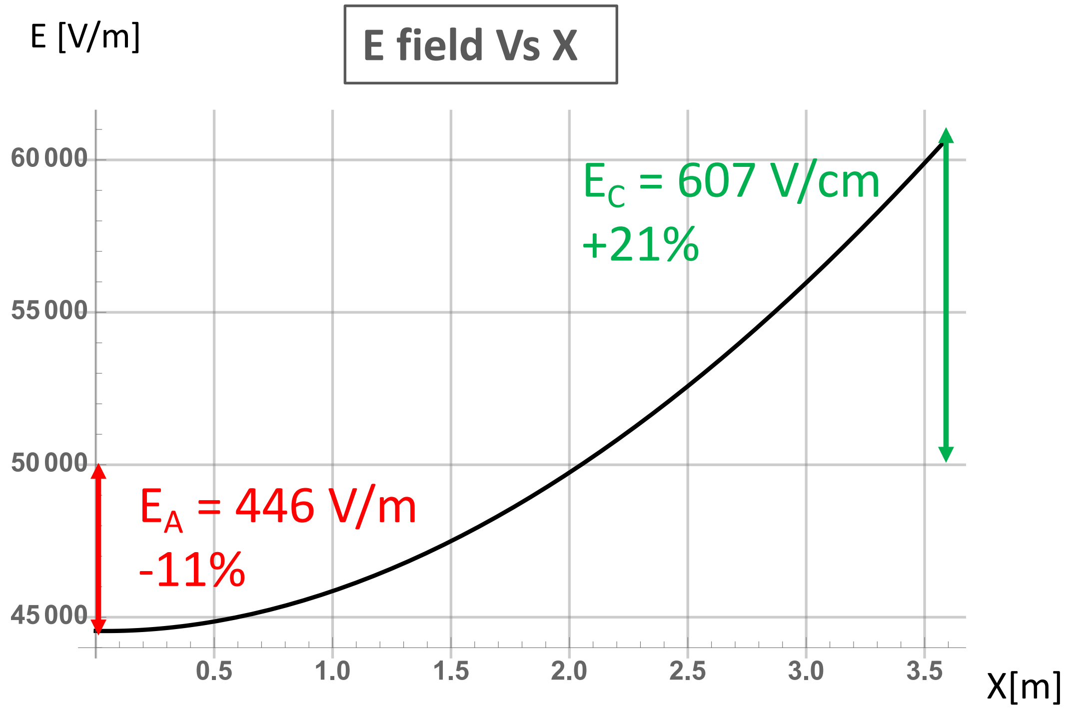
Red: Not well measured parameters

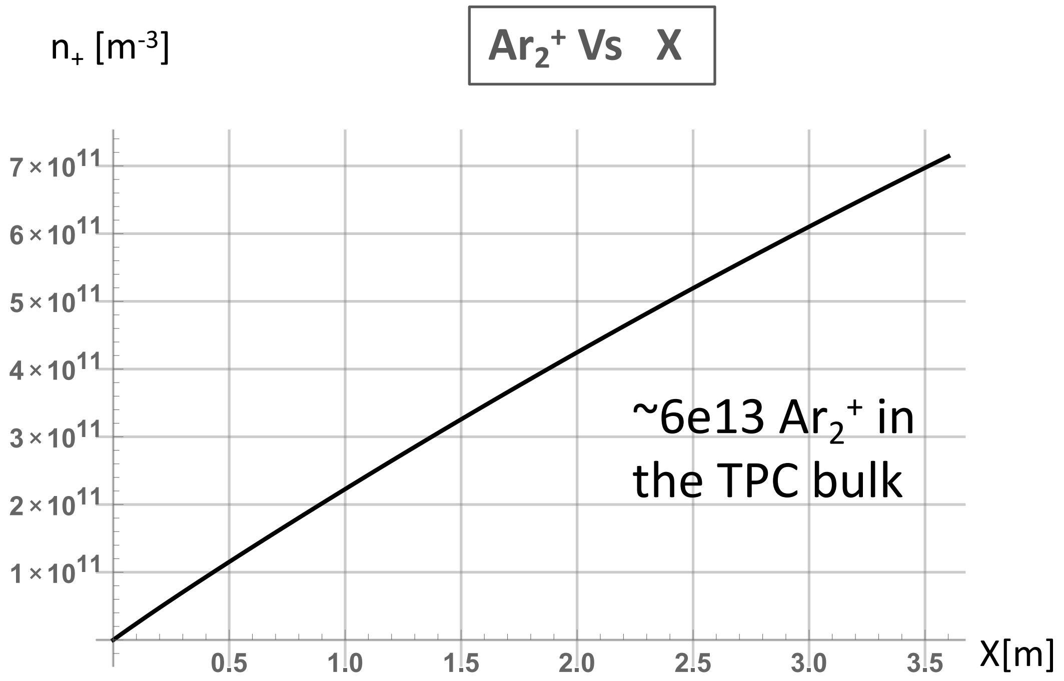
Solution: E field and ion density distributions $\{E(x), n_+(x), n_-(x), n_e(x)\}$

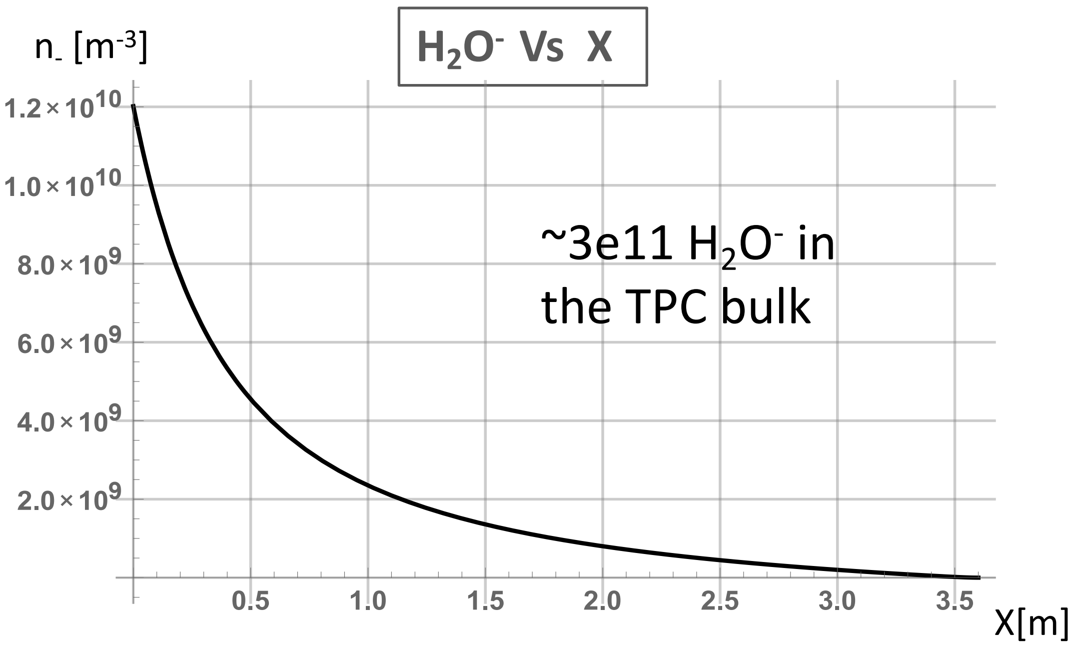
Mutual Neutralization: $Ar_2^+ + H_2O^- \rightarrow Ar_2^* + H_2O \rightarrow 2Ar + \gamma + H_2O$

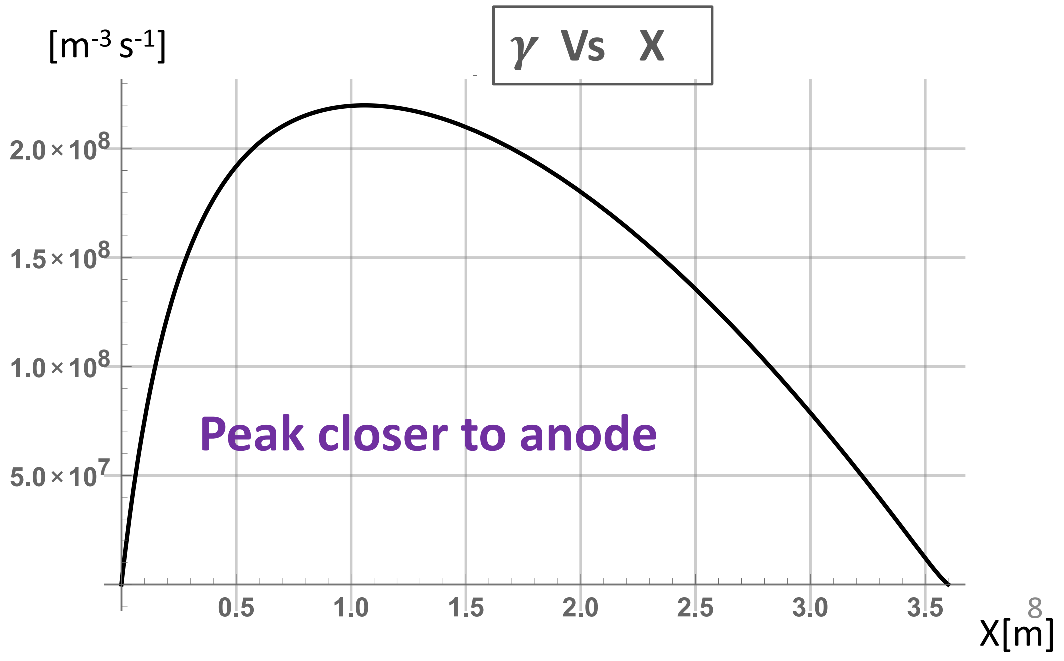
Volume Recombination: $Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$

→ **Single photon production rate**

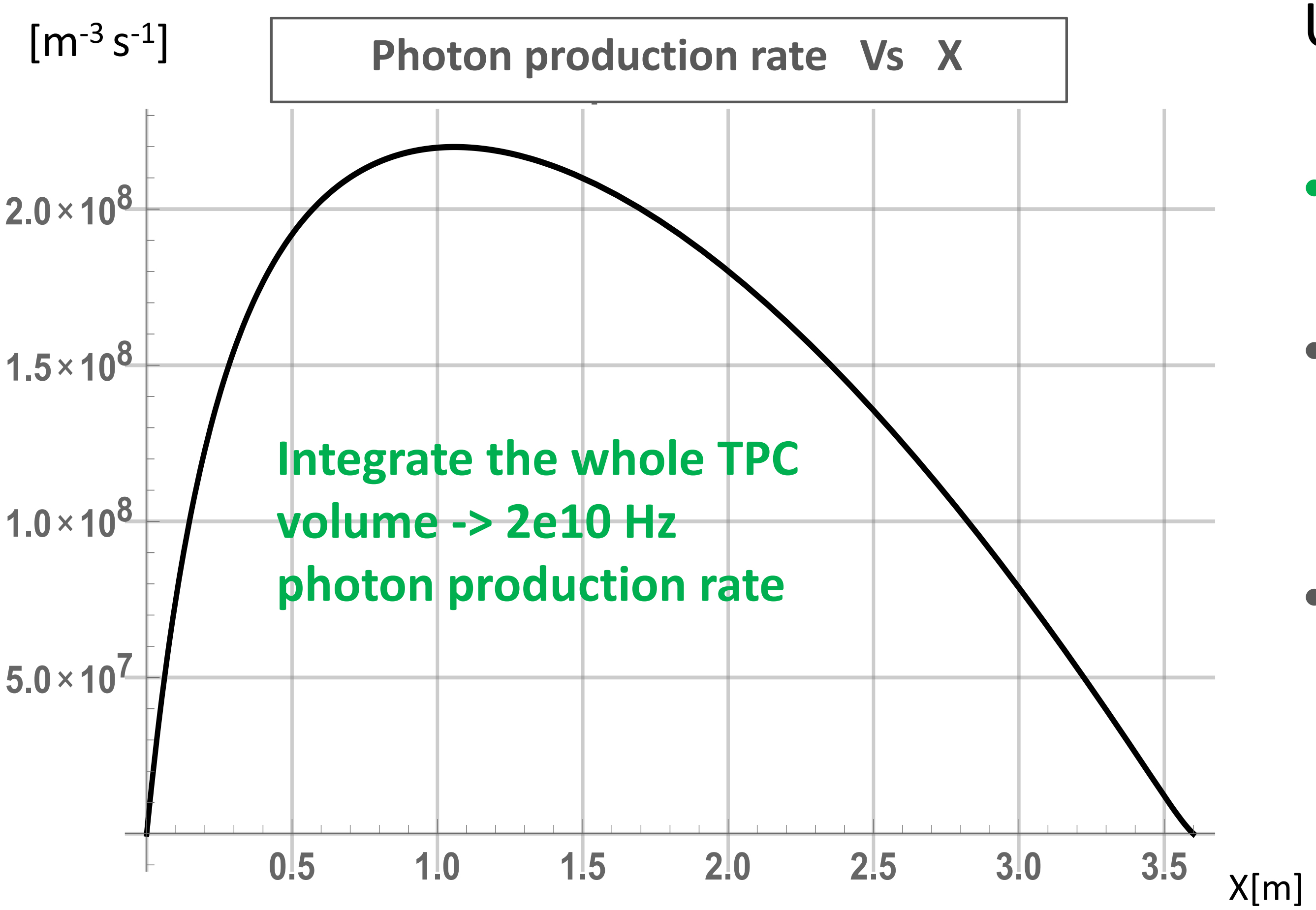

E field Vs X
E [V/m]
60 000
55 000
50 000
45 000
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X[m]
E_C = 607 V/cm
+21%
E_A = 446 V/m
-11%


Ar_2^+ Vs X
n_+ [m^{-3}]
7×10^{11}
6×10^{11}
5×10^{11}
4×10^{11}
3×10^{11}
2×10^{11}
1×10^{11}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X[m]
~6e13 Ar_2^+ in
the TPC bulk


H_2O^- Vs X
n_- [m^{-3}]
1.2×10^{10}
1.0×10^{10}
8.0×10^{9}
6.0×10^{9}
4.0×10^{9}
2.0×10^{9}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X[m]
~3e11 H_2O^- in
the TPC bulk


γ Vs X
[m^{-3} s^{-1}]
2.0×10^{8}
1.5×10^{8}
1.0×10^{8}
5.0×10^{7}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X[m]
Peak closer to anode

Does model predict the observed SPE rate? Yes

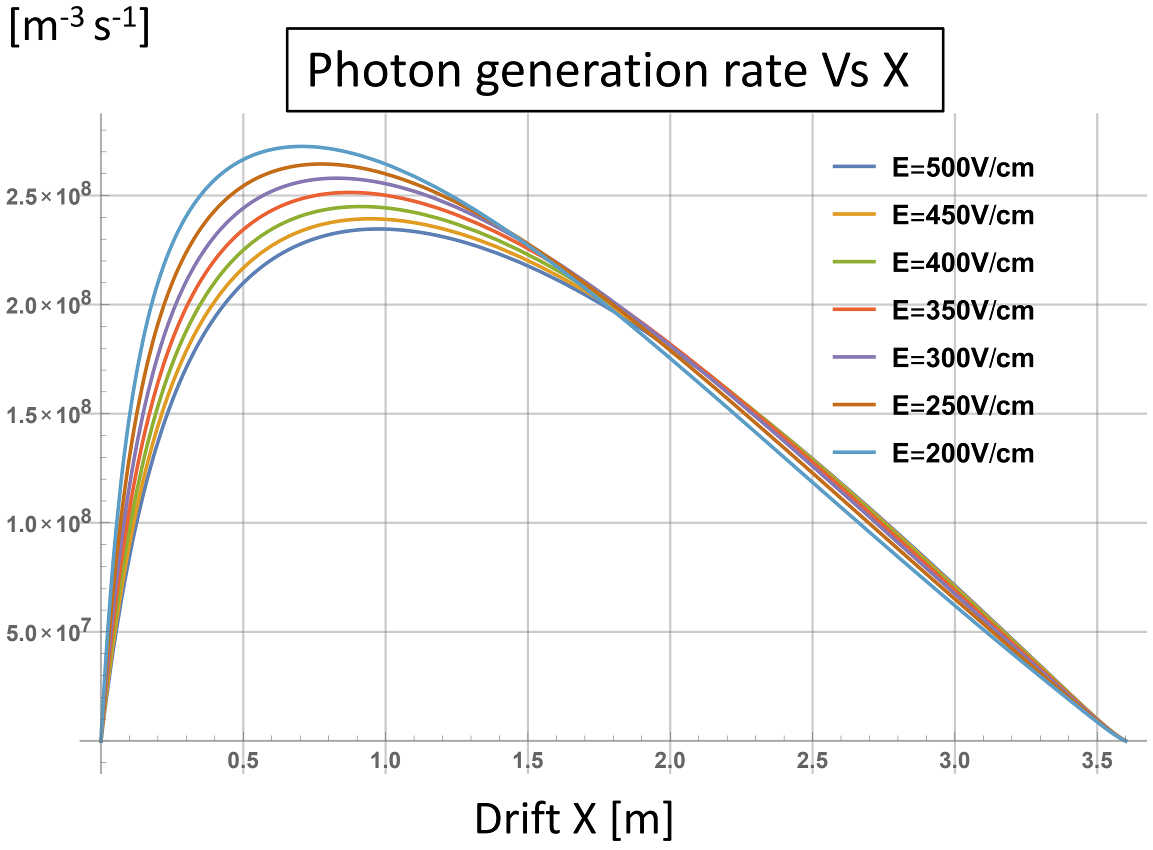


Use ProtoDUNE detector geometry:

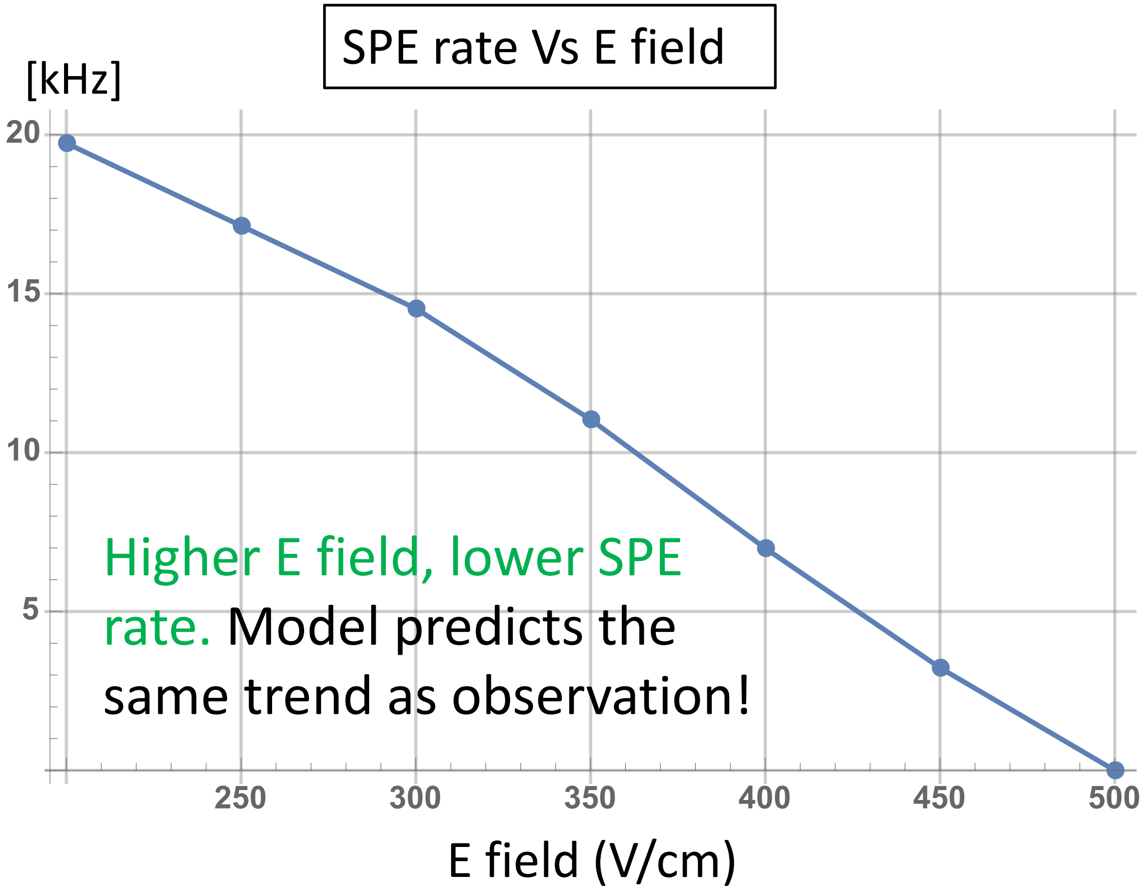
- ~2e10 Hz photon production rate in the TPC bulk.
- With geometric acceptance and detection efficiency of one Arapuca PD module...
- Model predict ~180 kHz SPE rate. Well matched with preliminary ProtoDUNE SPE rate measurement!

See Dante's ProtoDUNE talk next

Photon rate with different E field



Lower E field shift the photon generation closer to anode.

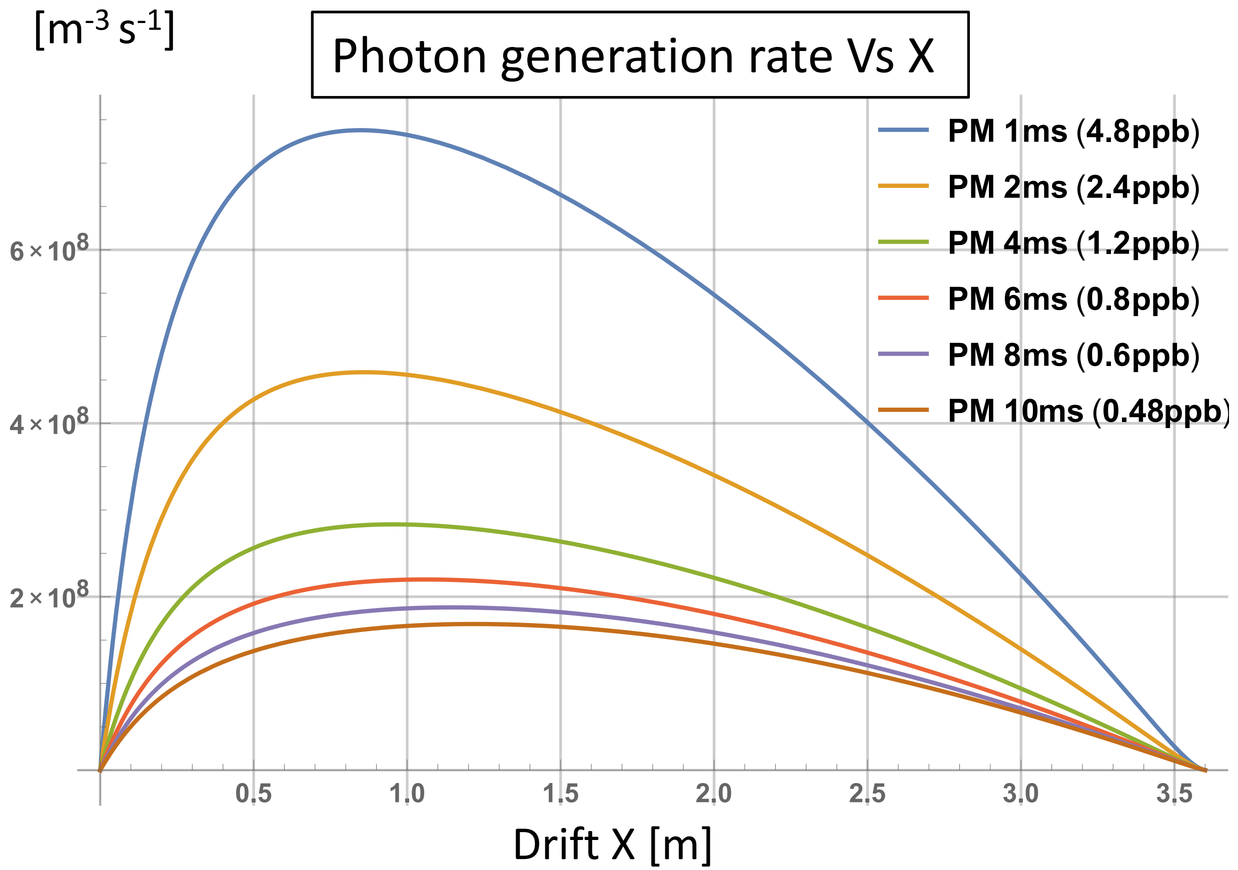


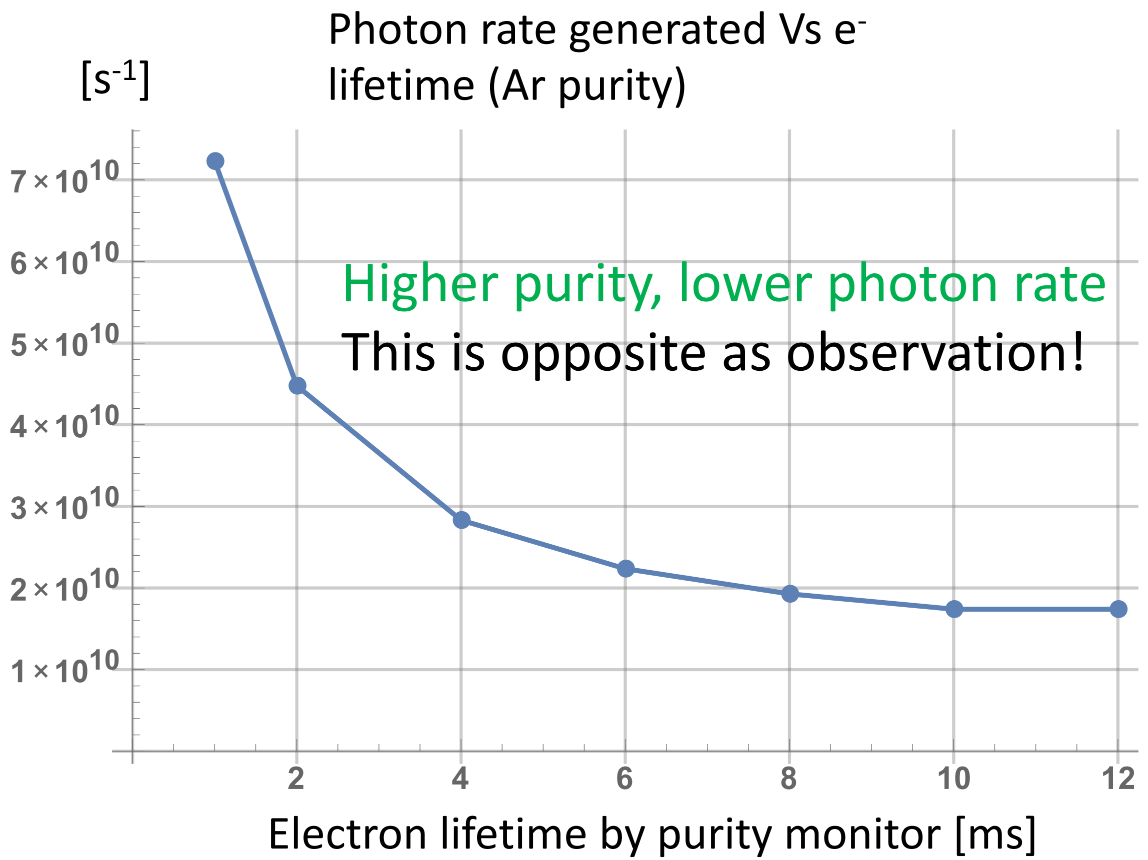
Higher E field, lower SPE rate. Model predicts the same trend as observation!

First look is well matched with ProtoDUNE data (See Dante's talk next).

Caveat: Below 150V/cm, model failed to converge to a solution. TPC stop working at very low E field.

Photon rate with different purity

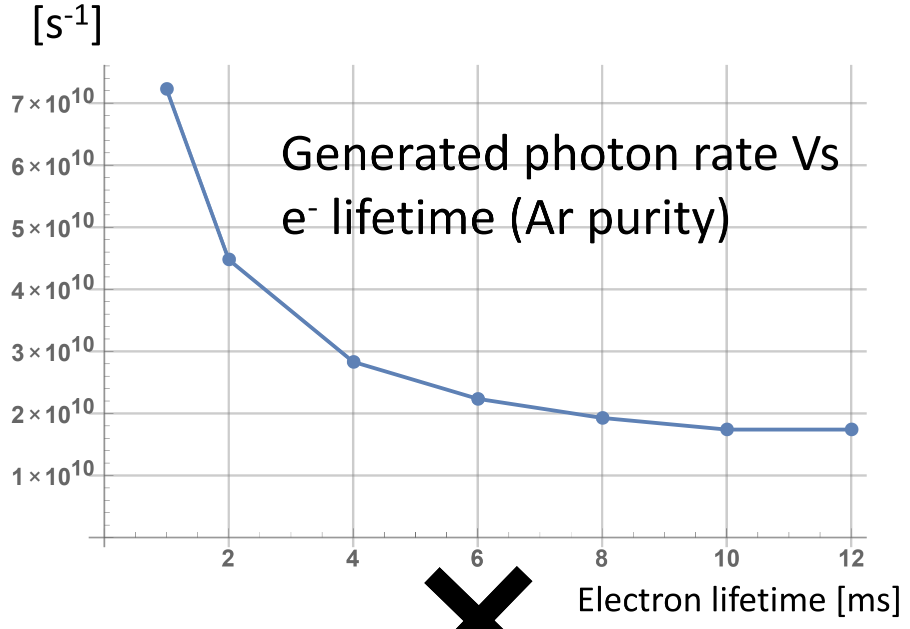




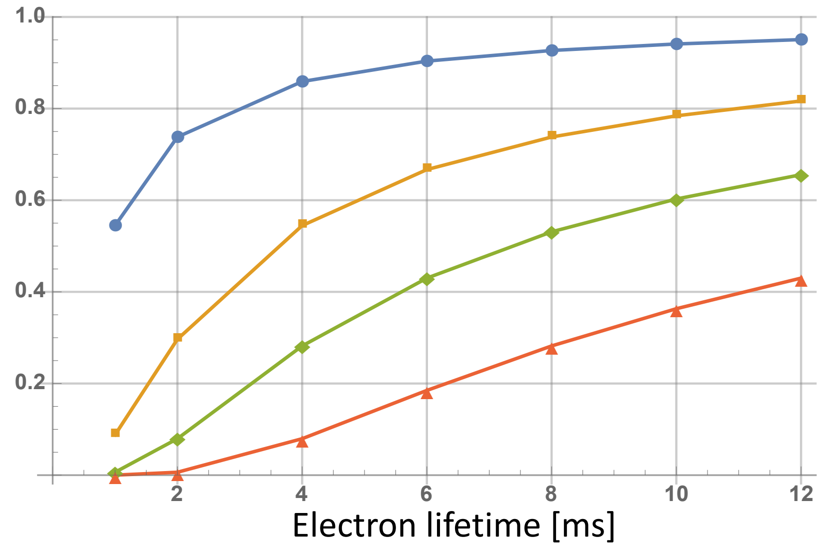
- Impurities produce photons: more impurity more photons.
- Because impurities are electric negative, more photons are produced closer to the anode.

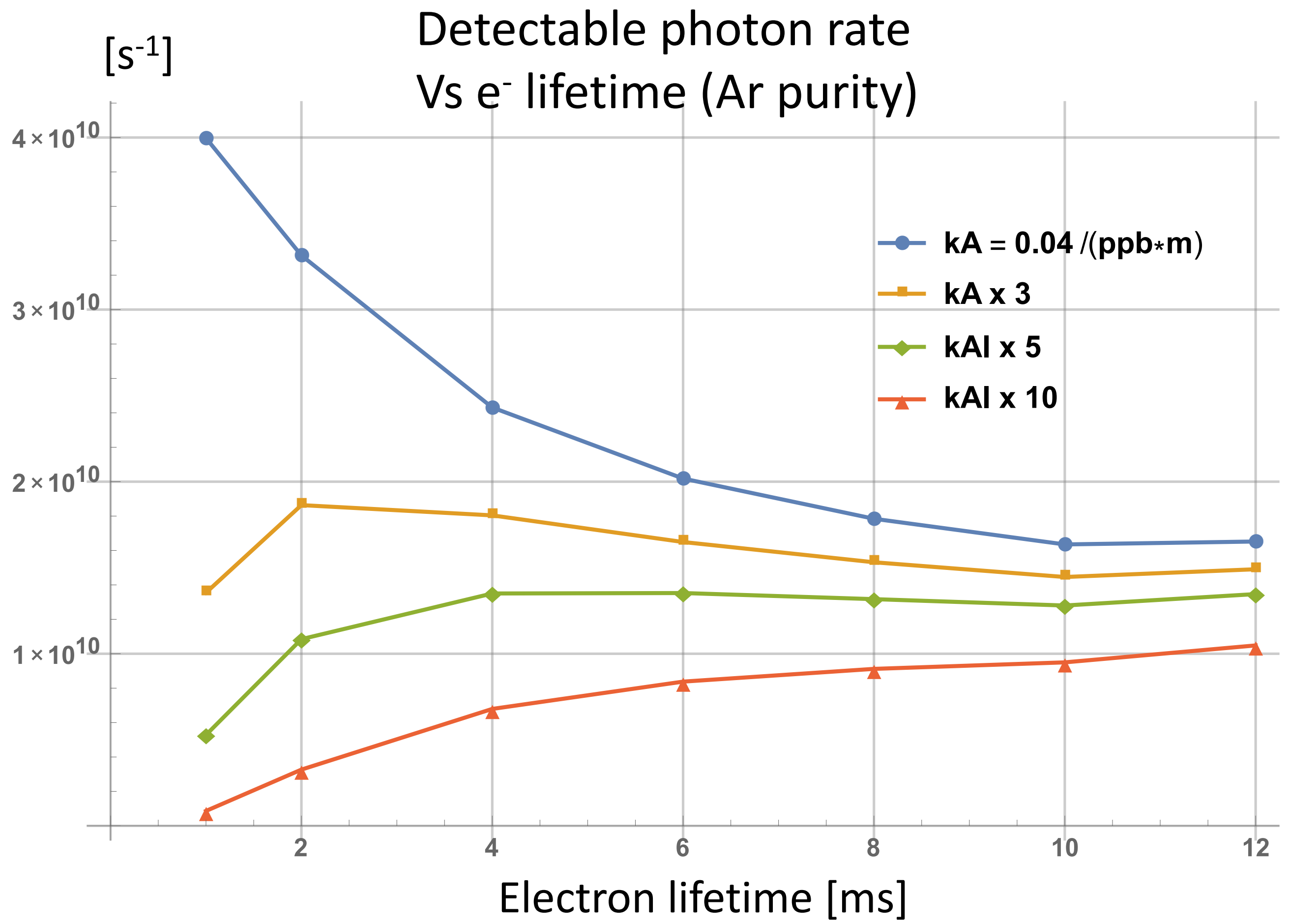
One way to explain the opposite trend in experiment is Impurity also absorb light: More impurities, less photons reached to the detectors.

Photon rate with different purity



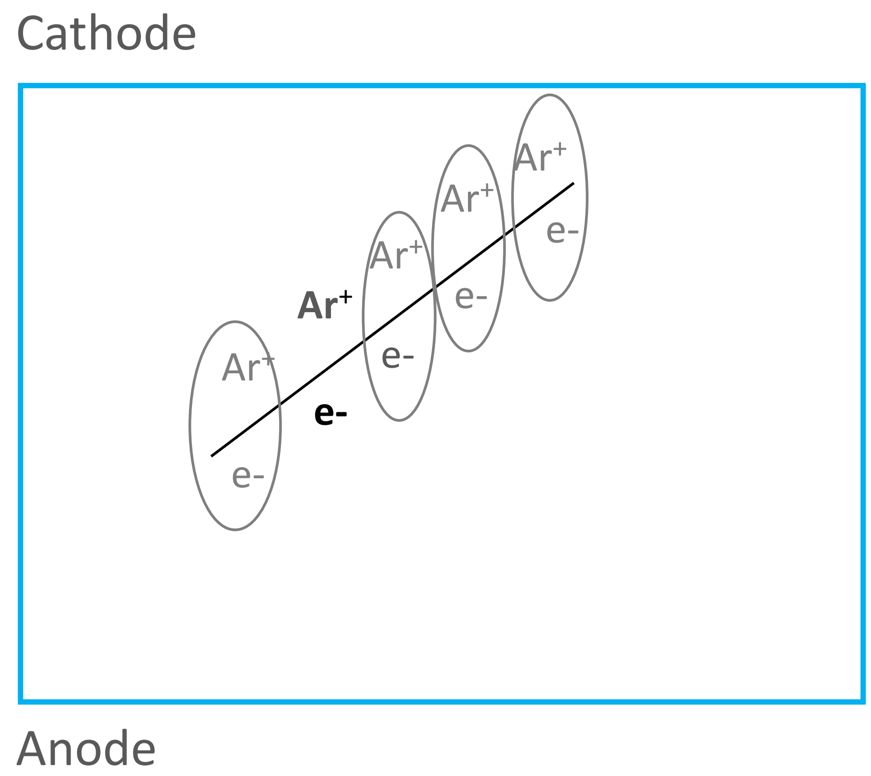
Photon survival fraction after H_2O absorption





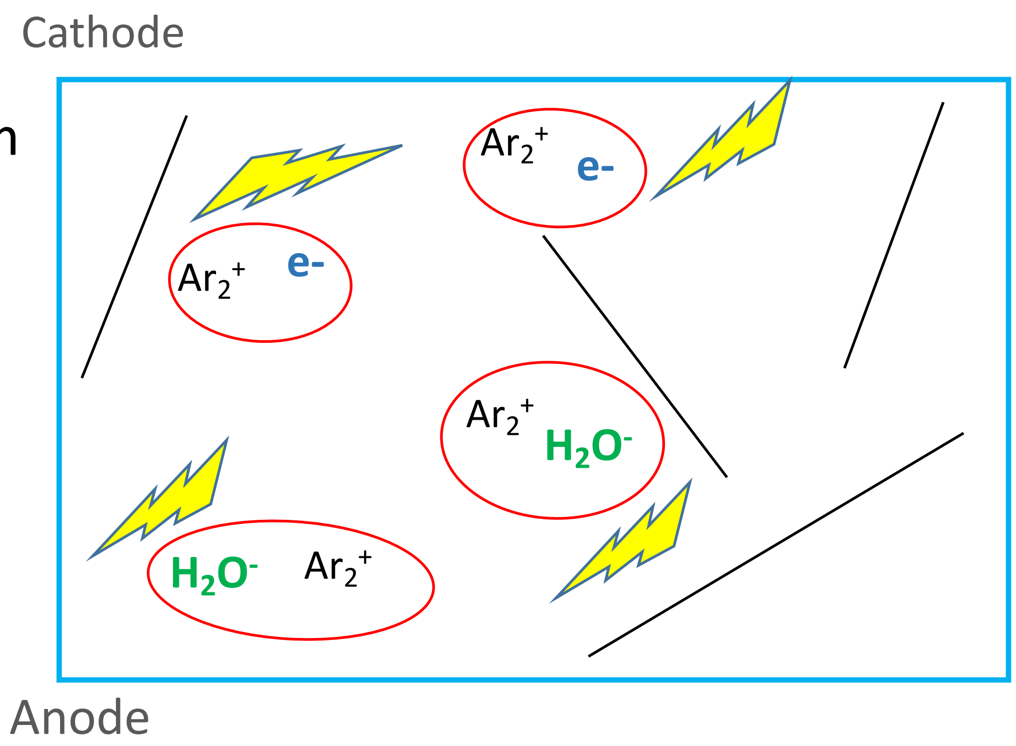
- H_2O absorption rate constant kA is not a well measured constant, free parameter in the model.
- Can compare the trend with data and constrain kA. On-going with ProtoDUNE.

Special case – @ zero E field



Increasing ions # from cosmic ionization

Ions could disappear via Volume recombination and Mutual Neutralization

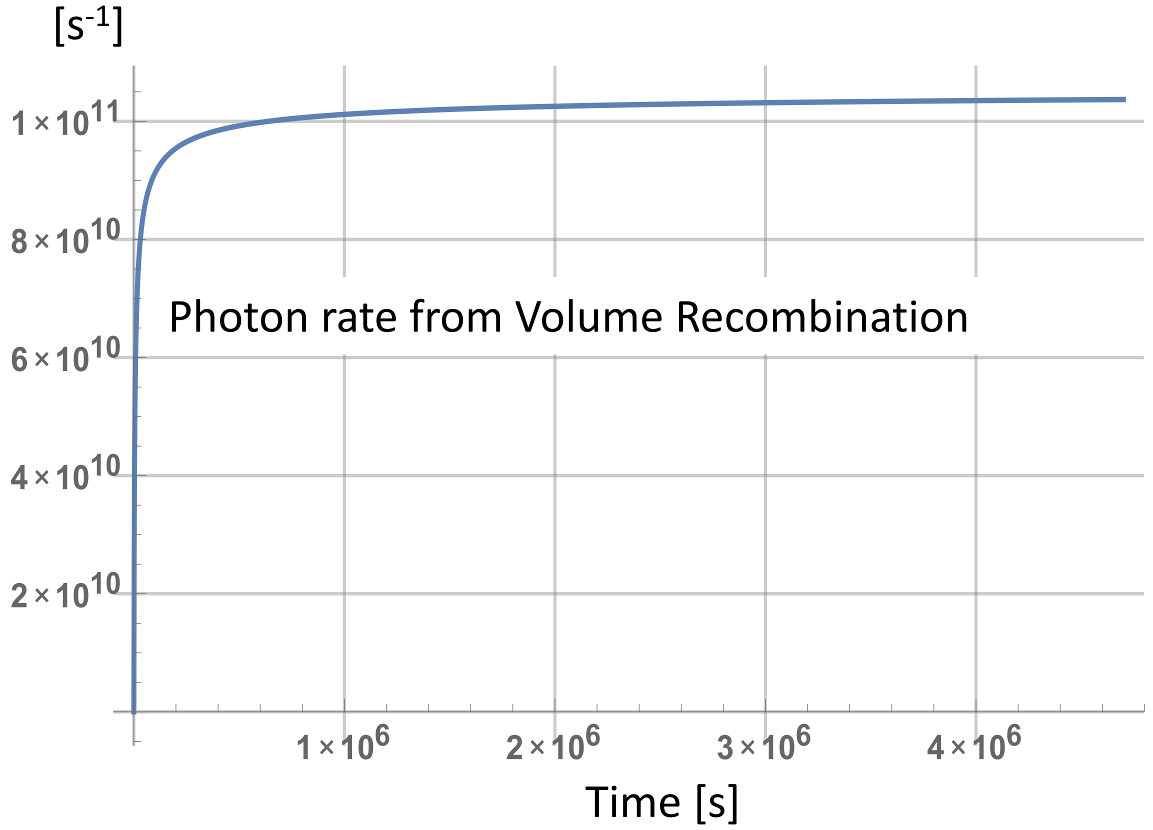


@ E = 0V/cm
~20% electrons escape the initial recombination.

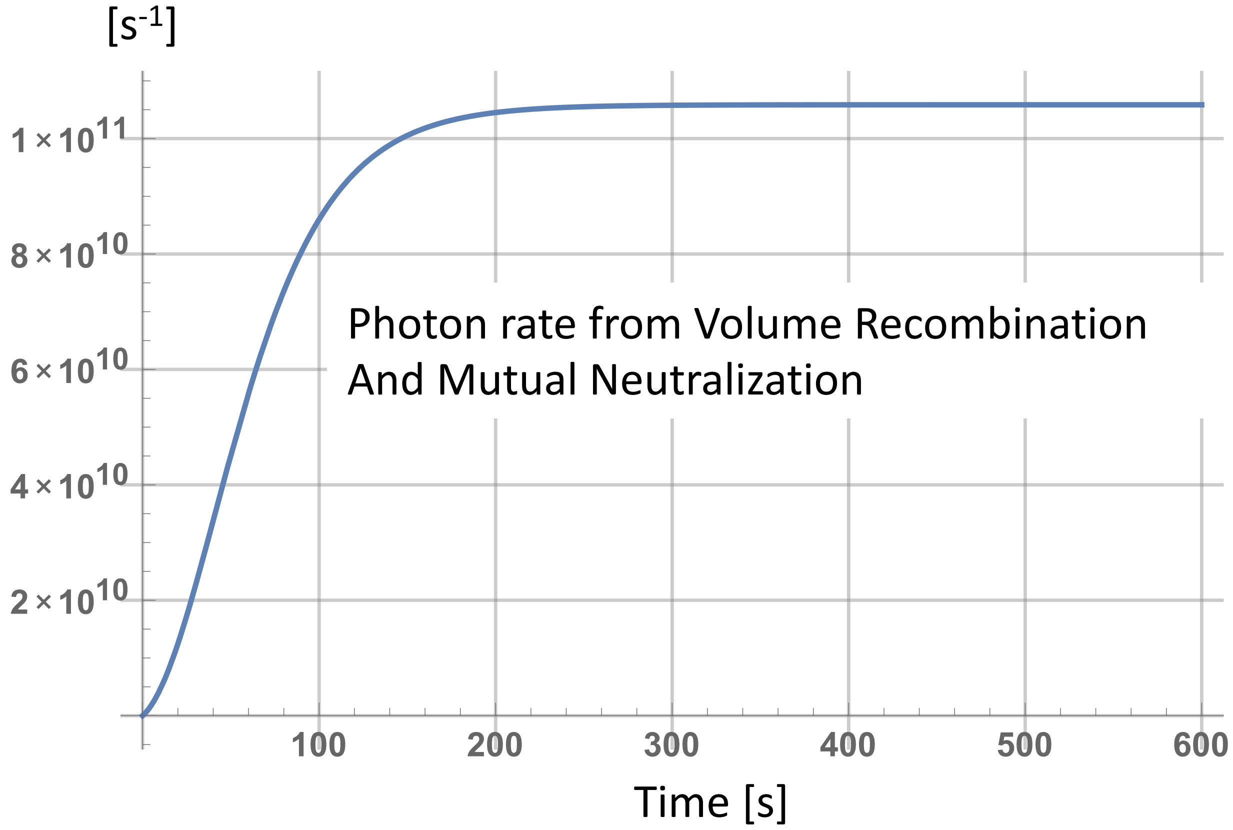
T. Doke et al., Chem.Phys.Lett. 115,165 n(1985)
T. Doke et al., Jpn. J. Apps. Phys. 41,

Method: Set up differential equations as function of time and solve photon rate.
Boundary condition: If reaching equilibrium, the photon rate will become stable, photon rate equals to cosmic ionization rate.
Caveat: the rate constants asso. with VR and MN are unknown at 0 field.

Special case – time evolution @ zero E field



If single photons only come from Volume Recombination, it takes about 12 days to stabilize the photon rate.



If single photons come from both Volume Recombination and Mutual Neutralization, it takes about 5 mins to stabilize the photon rate.

Measure the SPE rate time structure in the experiment will tell us the amount of Mutual Neutralization.

Conclusion

- Presented the **Ion transport model** to explain the high rate of SPE observed on large surface LArTPC.
- Model includes **two** non-standard photon generation processes.
- **SPE rate** predicted by model is well matched with preliminary ProtoDUNE measurement.
- Model predicts correct trend of **SPE rate Vs E field**.
- Model predicts wrong trend of **SEP rate Vs Ar purity**, maybe due to light loss by **H2O absorption**.
- Initial look of the time structure of photon rate at Zero E field.