Model of space charge(s) and its connection to the photon rate in LArTPC

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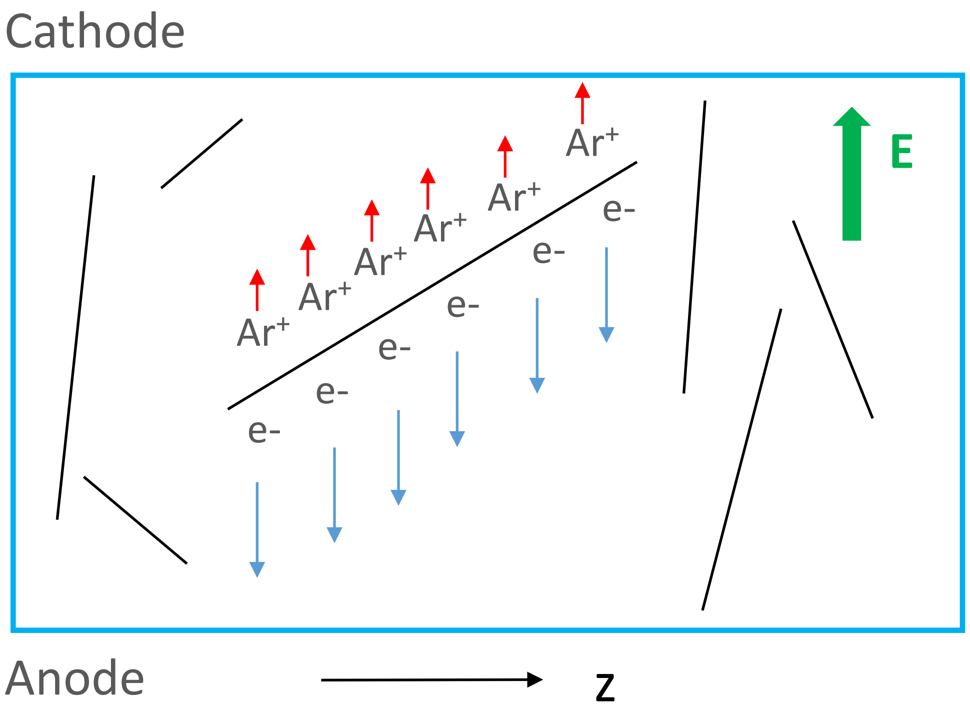
ProtoDUNE DRA meeting

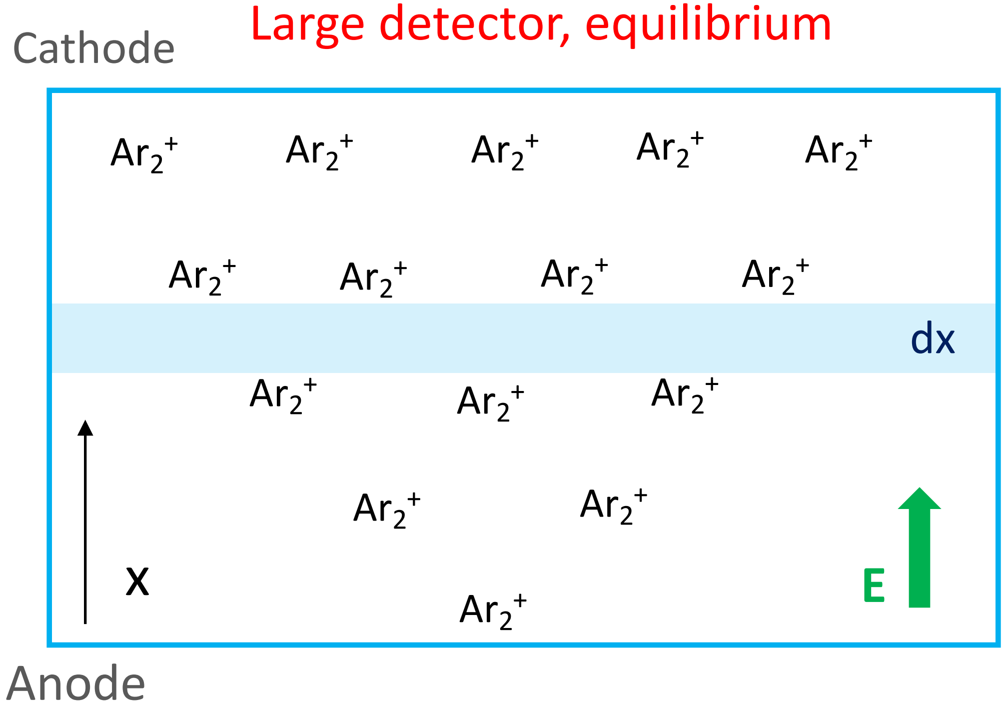
April 17th 2019

The origin - ionization charges

Electrons are the LArTPC signal, but our model focus the invisible ions (e.g. Ar_2^+)

The story starts with ions (space charges)...





Ion transport eq. at equilibrium:

$$\begin{cases} \frac{\partial J_e}{\partial x} = S_{Gen}(e^-) - S_{Loss}(e^-) \\ \frac{\partial J_+}{\partial x} = S_{Gen}(I^+) - S_{Loss}(I^+) \end{cases}$$

Considering the flux only in 1-D

Simplest case – ionization only

$$\begin{cases} \dfrac{\partial J_e}{\partial x} = S_{Gen}(e^-) - S_{Loss}(e^-) \\ \dfrac{\partial J_+}{\partial x} = S_{Gen}(I^+) - S_{Loss}(I^+) \end{cases} \Rightarrow \begin{cases} \dfrac{\partial(-\mu_e\ E\ n_e)}{\partial x} = n^i_{Pairs} \\ \dfrac{\partial(\mu_+\ E\ n_+)}{\partial x} = n^i_{Pairs} \\ \dfrac{\partial E}{\partial x} = \dfrac{1}{\epsilon}(n_+ - n_e) \end{cases}$$

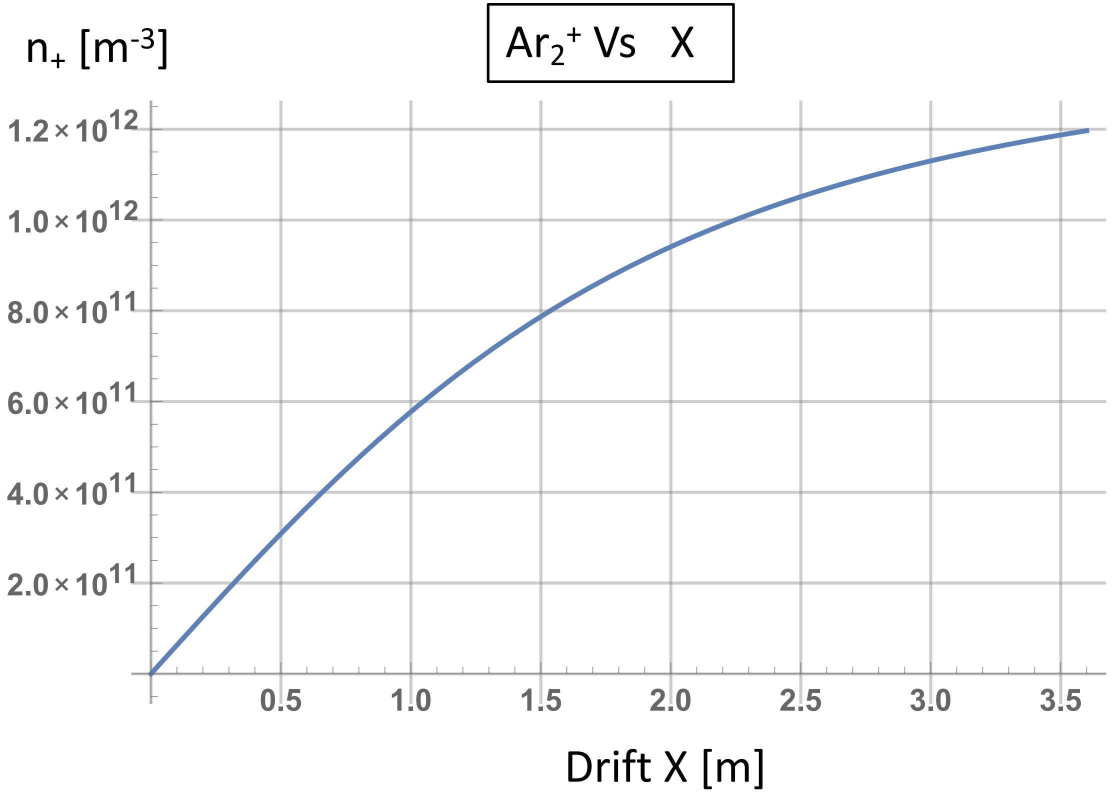
Parameters:

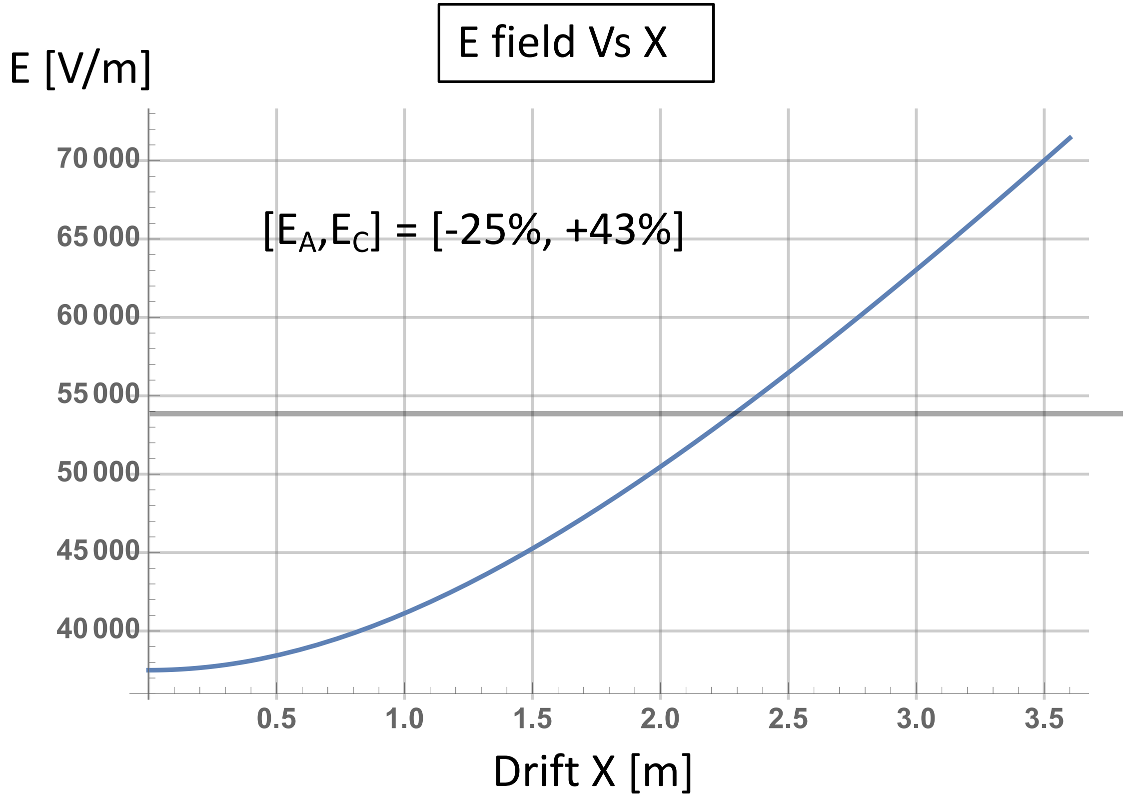
Cosmic muon rate: 13kHz

$\mathbf{n_{pair}}$ - rate of (e^-, I^+) pairs after initial recombination: 1.9e9 [$m^{-3}s^{-1}$]

Ion mobility: 8e-8 [$m^2V^{-1}s^{-1}$]

Ion velocity (E=500V/cm): 4e-3 [m/s]





Add e- attachment: $e^- + X \rightarrow X^-$

$$
\begin{cases}
-\mu_e \; n_e \dfrac{\partial E}{\partial x} - v_d^e \dfrac{\partial n_e}{\partial x} = + \; n^i_{pair} - k_A \; n^0_X \; n_e \\
-\mu_+ \; n_+ \dfrac{\partial E}{\partial x} + v_d^+ \dfrac{\partial n_+}{\partial x} = + \; n^i_{pair} \\
-\mu_- \; n_- \dfrac{\partial E}{\partial x} - v_d^- \dfrac{\partial n_-}{\partial x} = + \; k_A \; n^0_X \; n_e \\
\dfrac{\partial E}{\partial x} = \dfrac{1}{\epsilon_0 \epsilon_r}(n_+ - n_- - n_e)
\end{cases}
$$

e- attachment to impurity (e.g. H_2O):

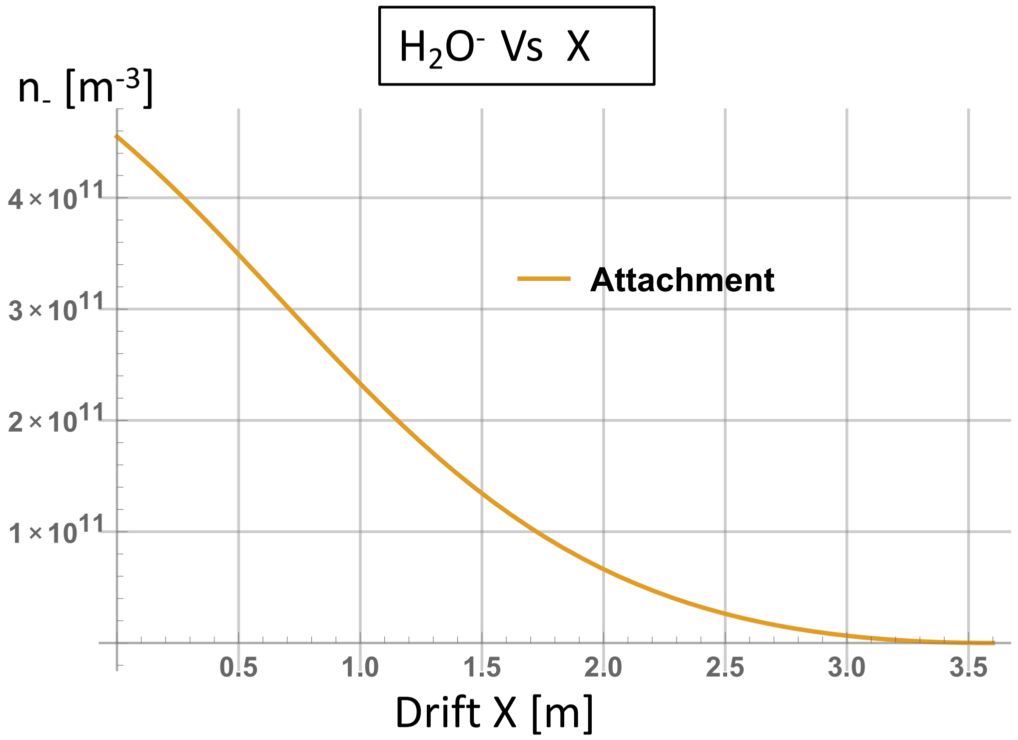
$$e^- + H_2O \rightarrow H_2O^-$$

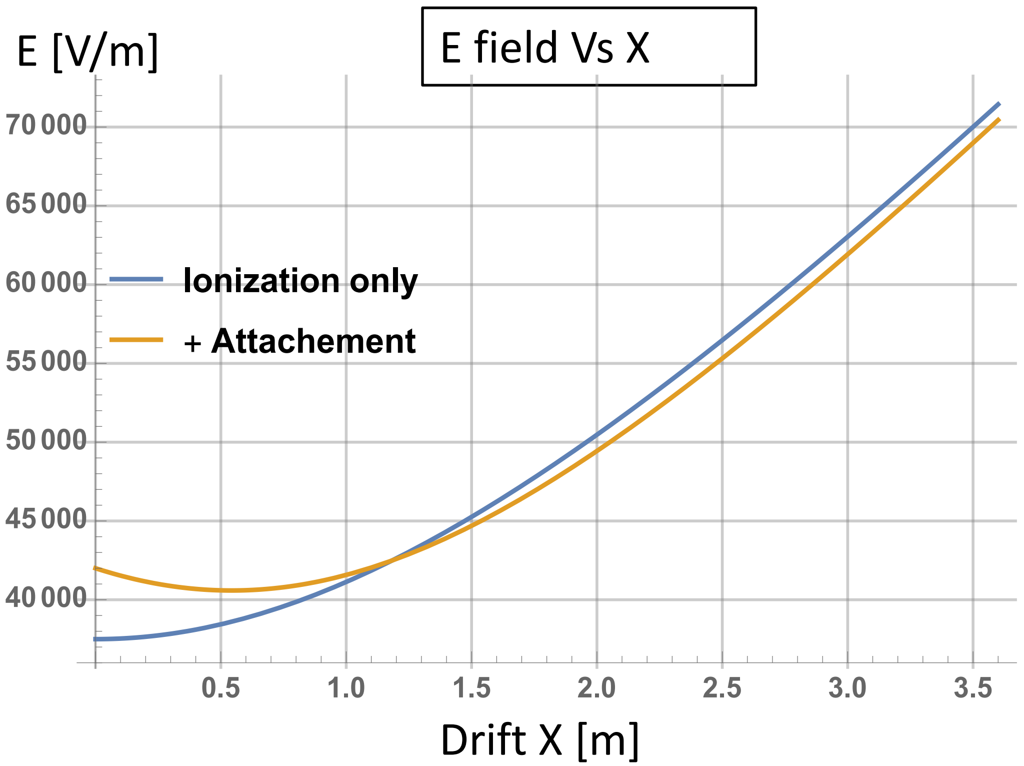
Parameters:

Atta. (to H_2O) Rate: $\mathbf{k_A}$ [H2O]= 1.4 x 10^{-15} [m^3s^{-1}]

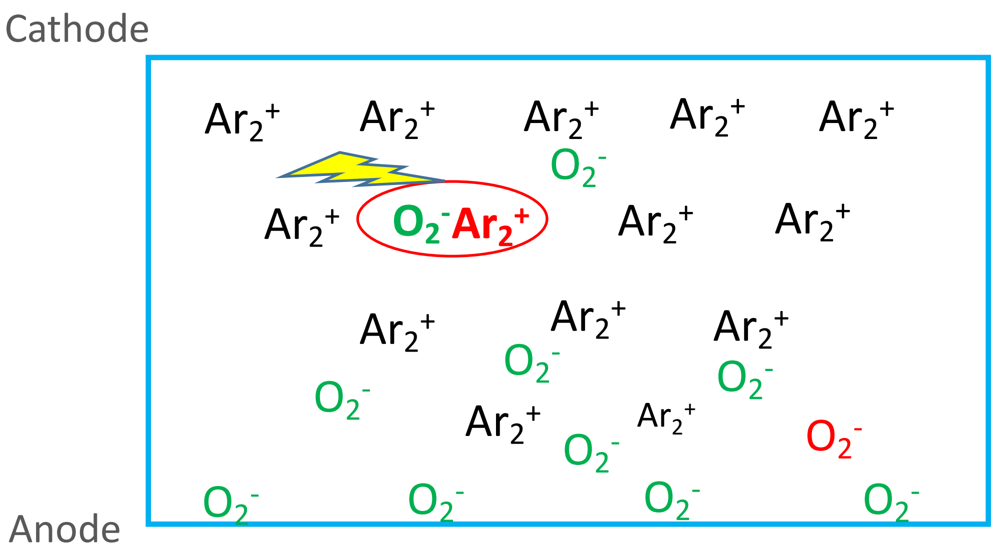
H_2O Concentration: c[H_2O] = 3ppt

Lifetime: 6ms.





Add Mutual Neutralization



New process we incorporate in our model:

Mutual Neutralization (MN)

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

Assume each time MN happens, generating 1 VUV photon

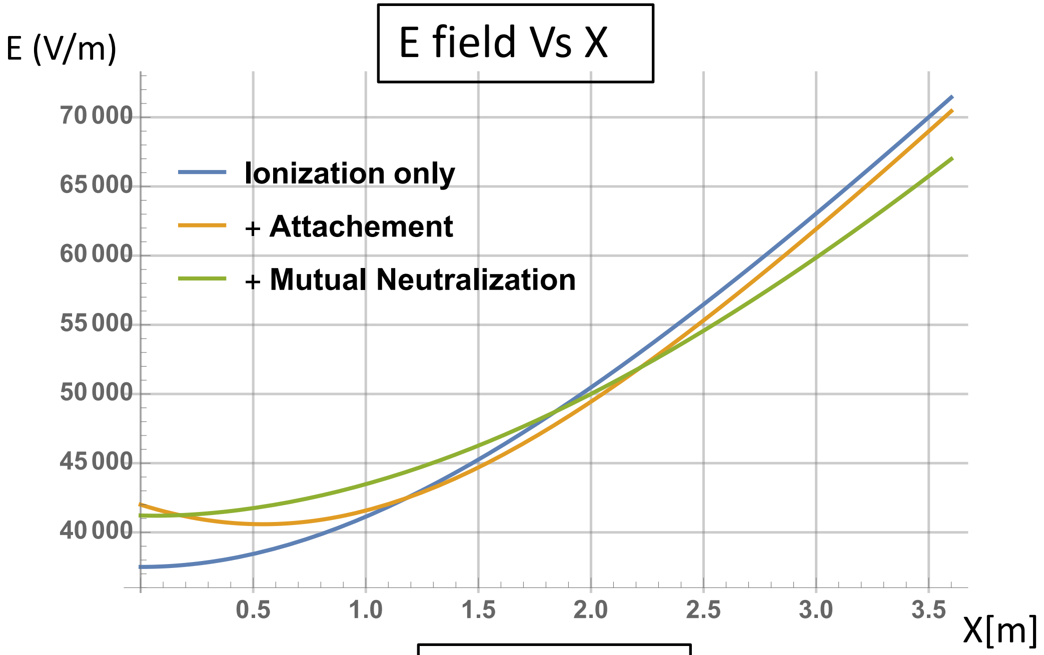
Parameters asso. with this process:

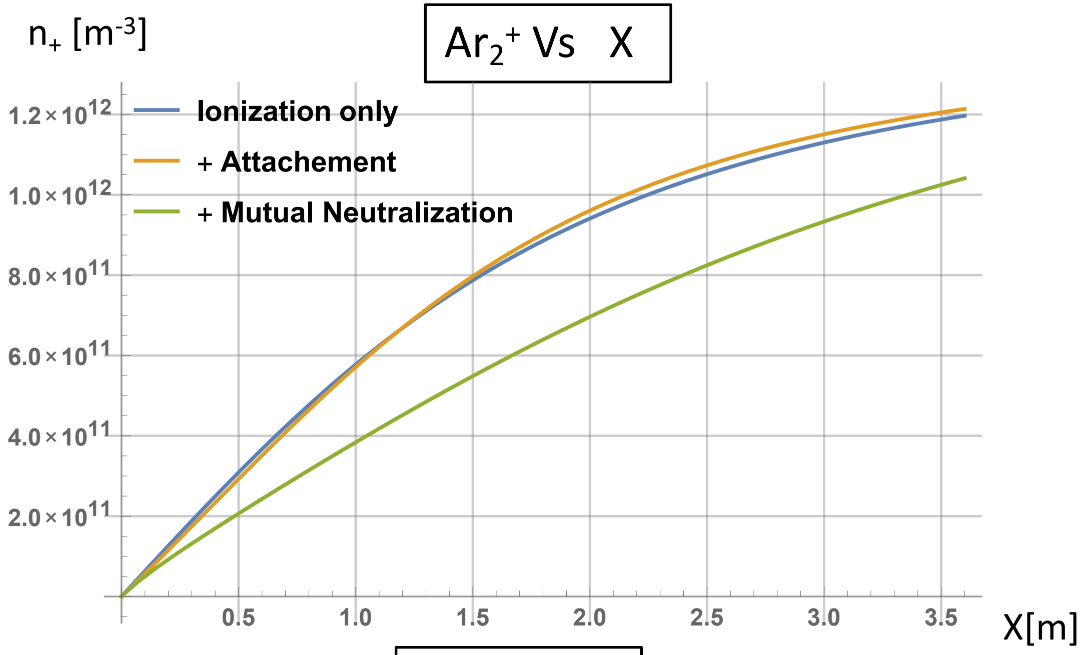
MN rate constant: k_{MN} = 2.8e-13 [m^3/s]

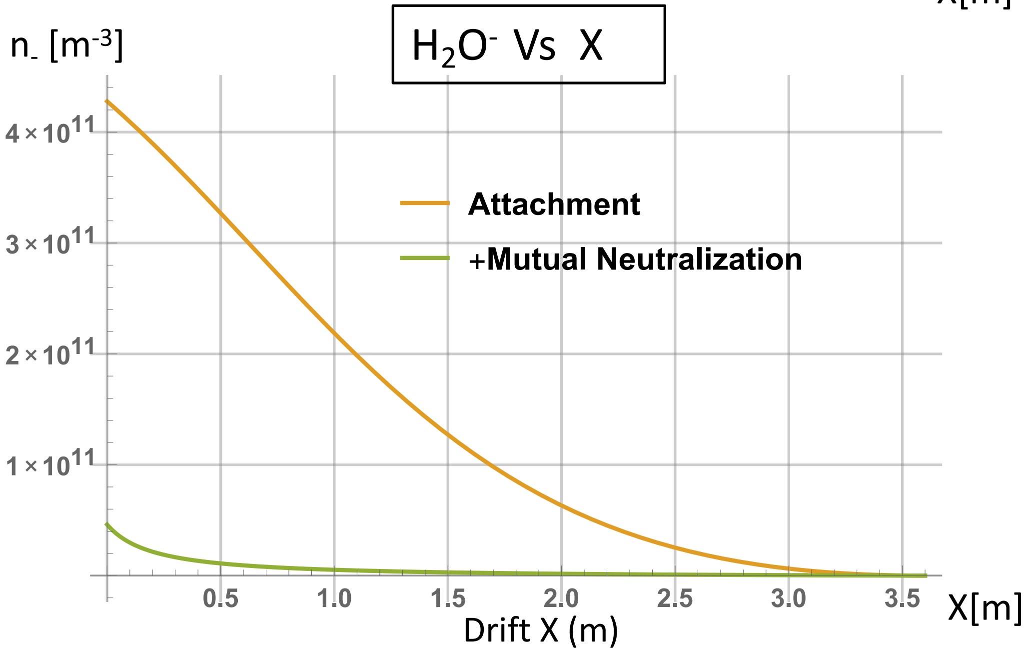
Photon generation rate is $k_{MN} n_- n_+$

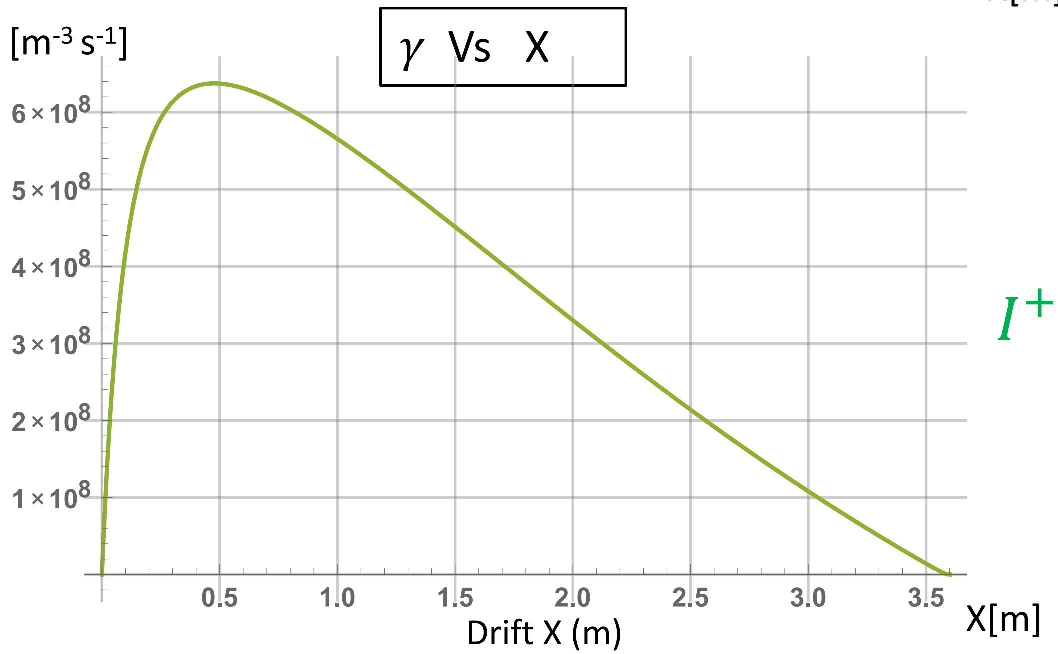
$$\begin{cases} -\mu_e\, n_e \dfrac{\partial E}{\partial x} - v_d^e \dfrac{\partial n_e}{\partial x} = +\, n_{pair}^i - k_A\, n_X^0\, n_e \\ -\mu_+\, n_+ \dfrac{\partial E}{\partial x} + v_d^+ \dfrac{\partial n_+}{\partial x} = +\, n_{pair}^i - k_{MN}\, n_-\, n_+ \\ -\mu_-\, n_- \dfrac{\partial E}{\partial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

Mutual Neutralization cont.



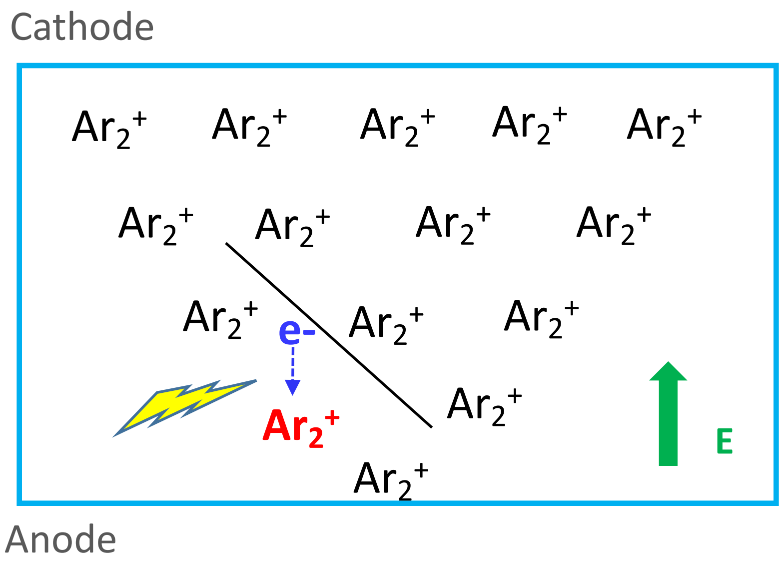






$$I^+ + I^- \rightarrow \gamma$$

Add the Volume Recombination



New process that we incorporate in our model. Note the difference from the well-known initial recombination process

Volume Recombination (VR)

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

Assume each time VR happens, generating 1 UVU photon

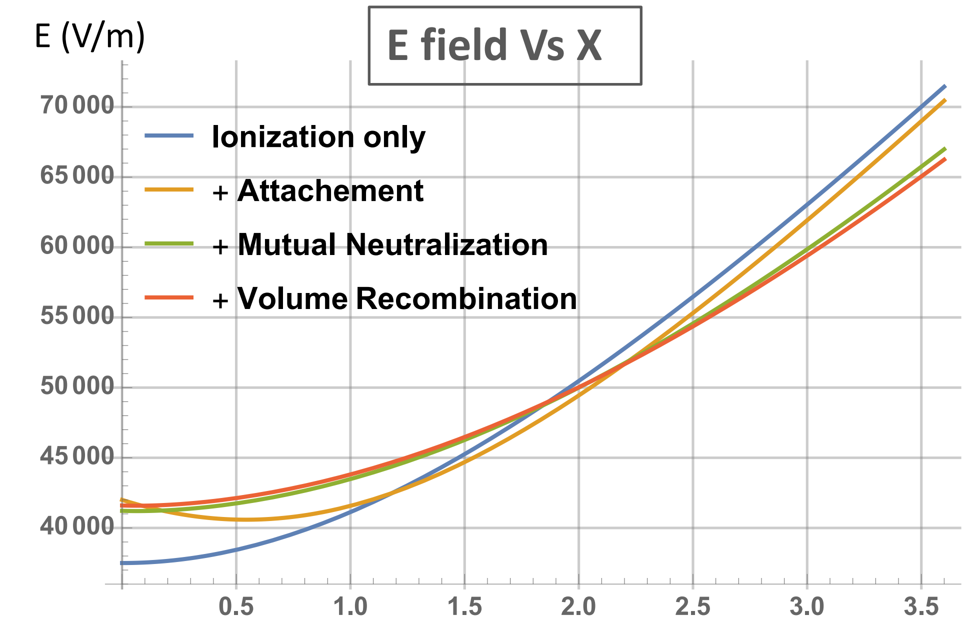
Parameters asso. with this process:

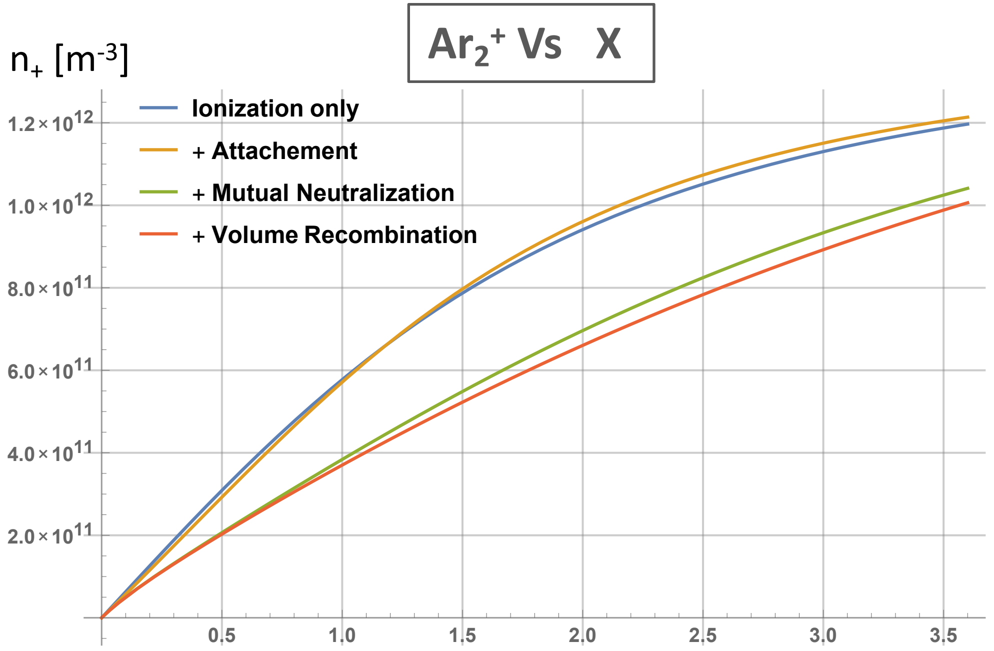
VR rate constant: k_R = 1.1e-10 m^3/s

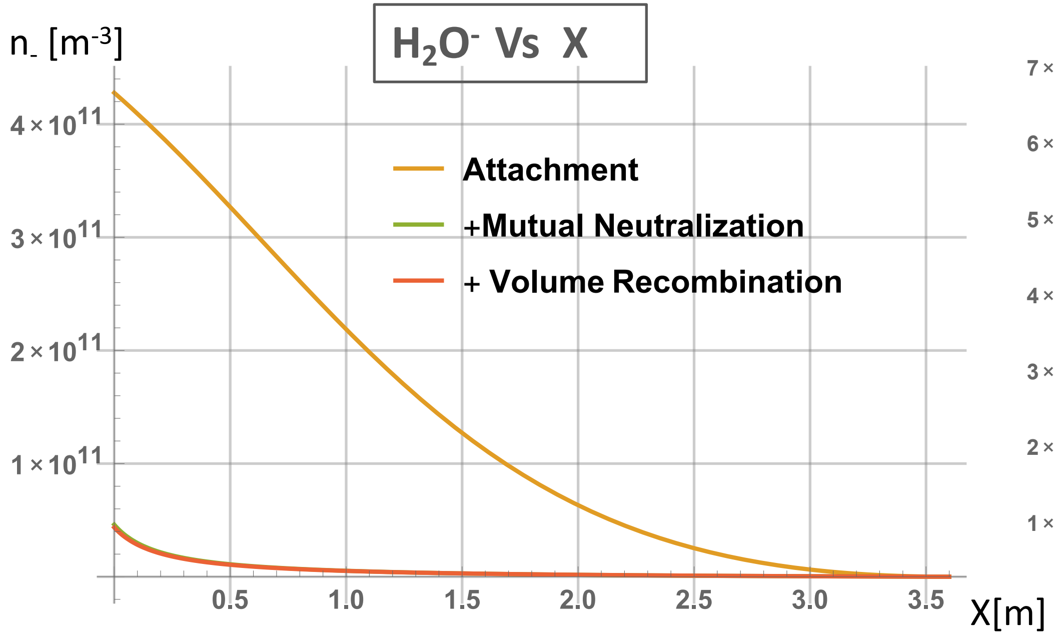
Photon generation rate is $k_R n_+ n_e$

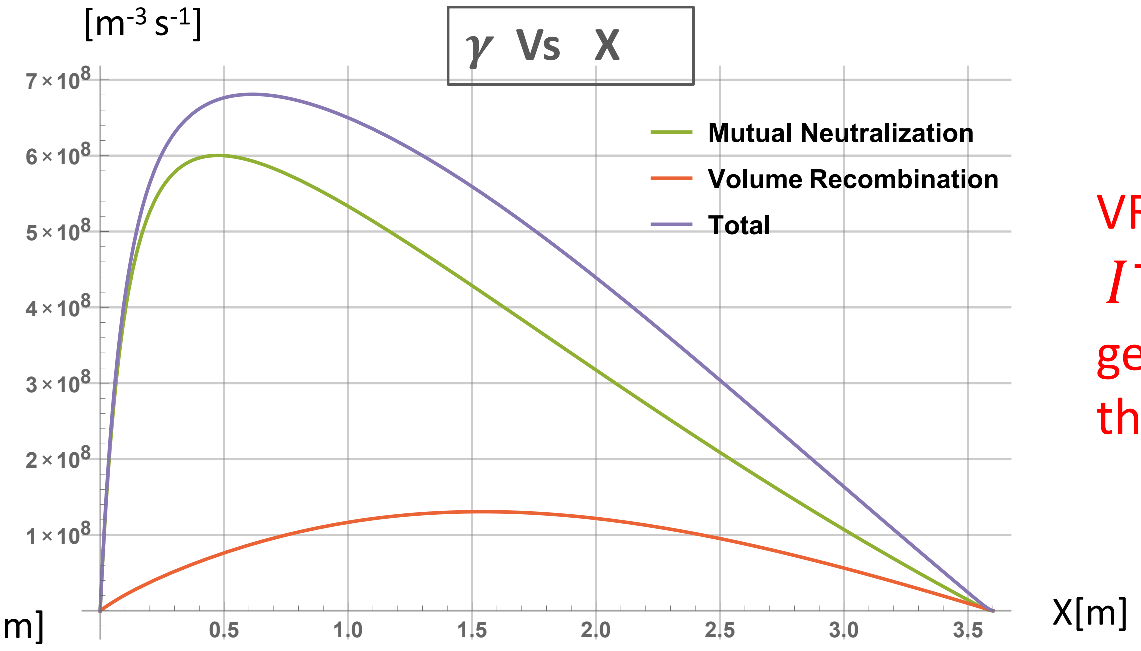
$$\begin{cases} -\mu_e\, n_e\, \frac{\partial E}{\partial x} - v_d^e\, \frac{\partial n_e}{\partial x} = +\, n_{pair}^i - k_A\, n_X^0\, n_e - k_R\, n_+\, n_e \\ -\mu_+\, n_+\, \frac{\partial E}{\partial x} + v_d^+\, \frac{\partial n_+}{\partial x} = +\, n_{pair}^i - k_{MN}\, n_-\, n_+ - k_R\, n_+\, n_e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

Volume Recombination cont.







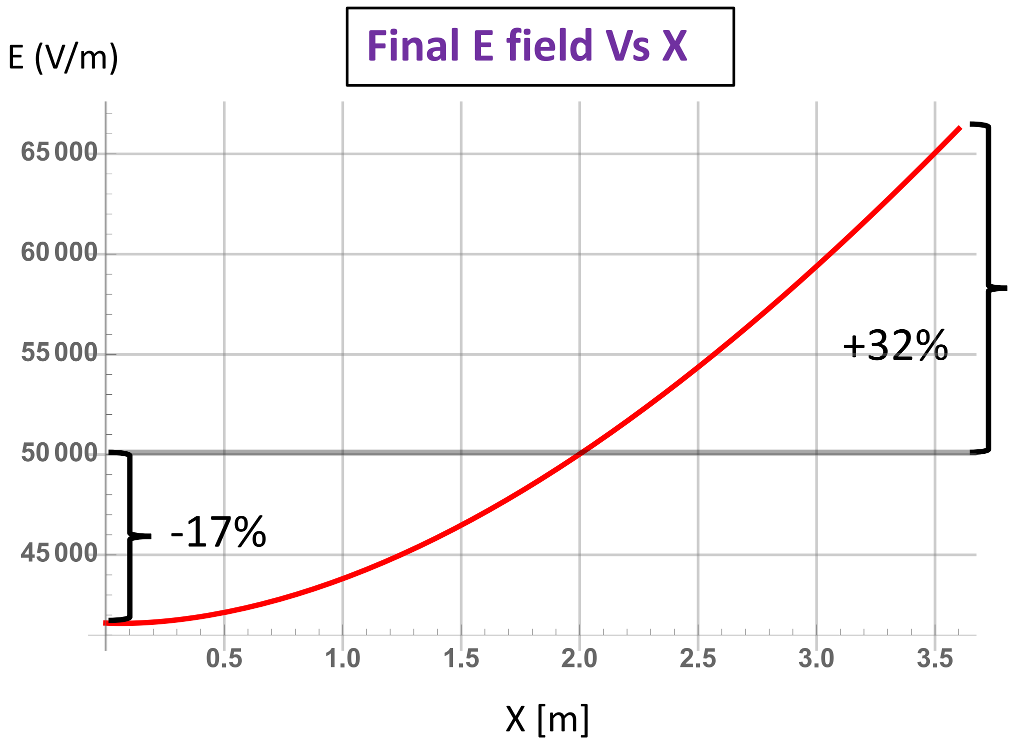


VR:

$I^+ + e^- \rightarrow \gamma$

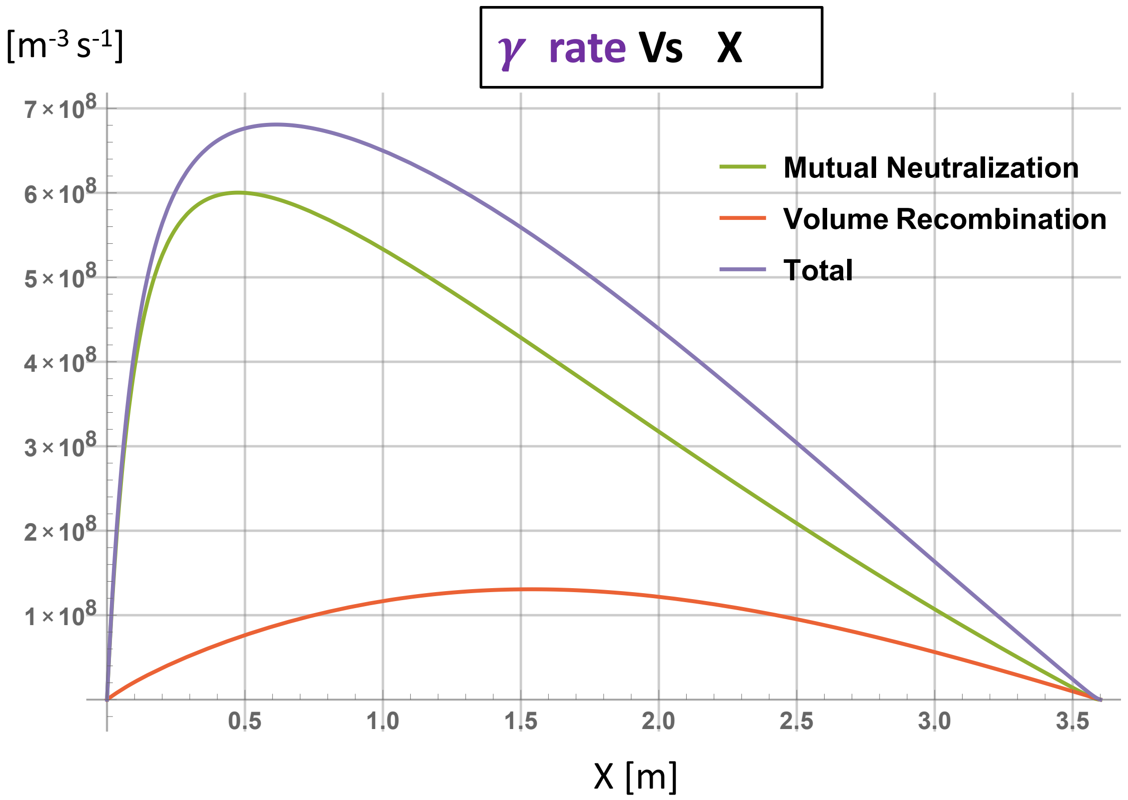
generates less γ than MN.

Use experimental observable to constrain the model parameters.



Final solution (the red line) of E field has E_{anode} = 416 V/cm and $E_{cathode}$ = 662 V/cm. This is a larger distortion comparing to the ProtoDUNE experimental measurements.

Final solution (from our model) of photon production rate (the purple line) in the entire ProtoDUNE volume is: **6.3 X 10^{10} Hz**



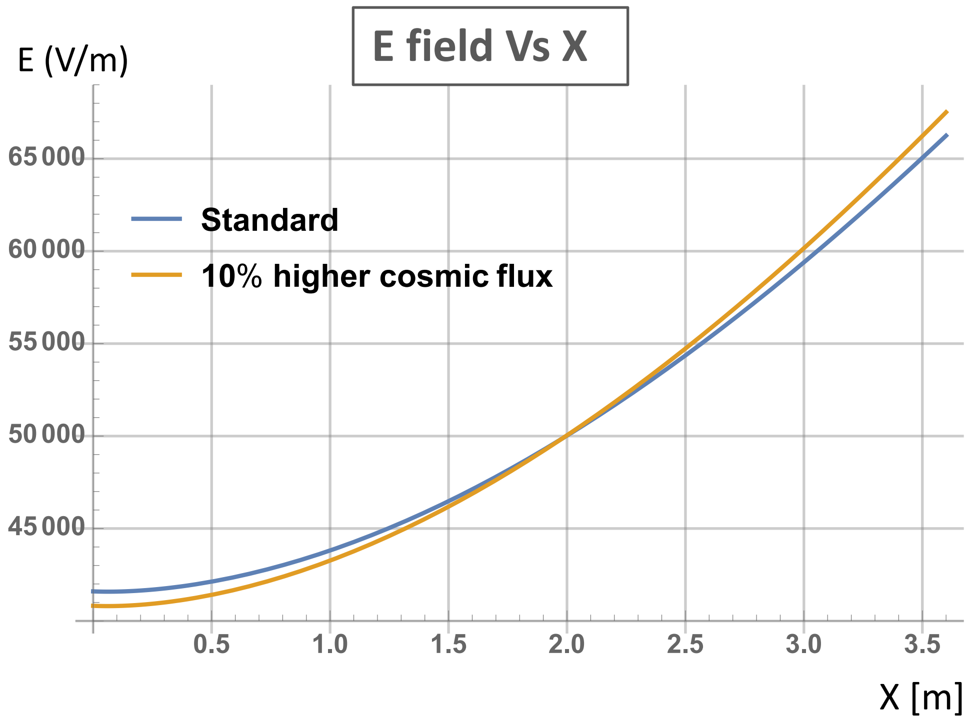
Many parameters in our model are uncertain, next I will describe the impact of the size of the effect (mainly on the E field distortion and photon rate) by varying:

- Cosmic flux or other ionization source (Ar_{39})
- Lifetime: attachment rate to impurity and impurity concentration
- Ion mobility
- E field central value

Cosmic flux/Ar39

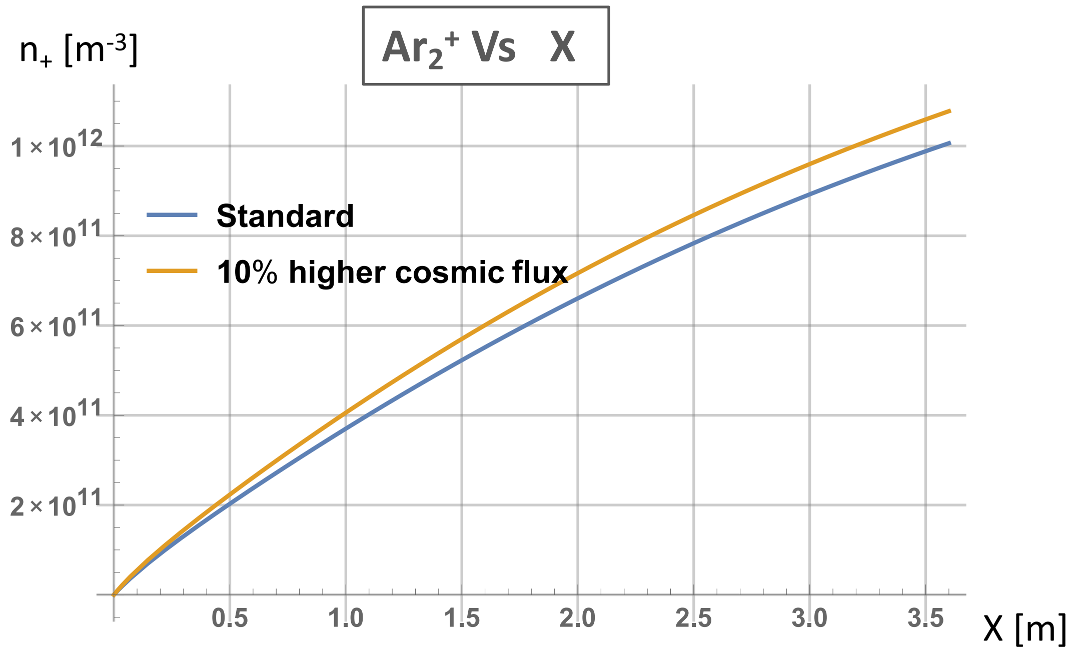
~ 10% seasonal variation of the cosmic flux.
Ar39 beta decay is another source of the ionization charges (~1Bq/kg in natural Argon) – this add 0.5% of npair comparing to the cosmic at surface.

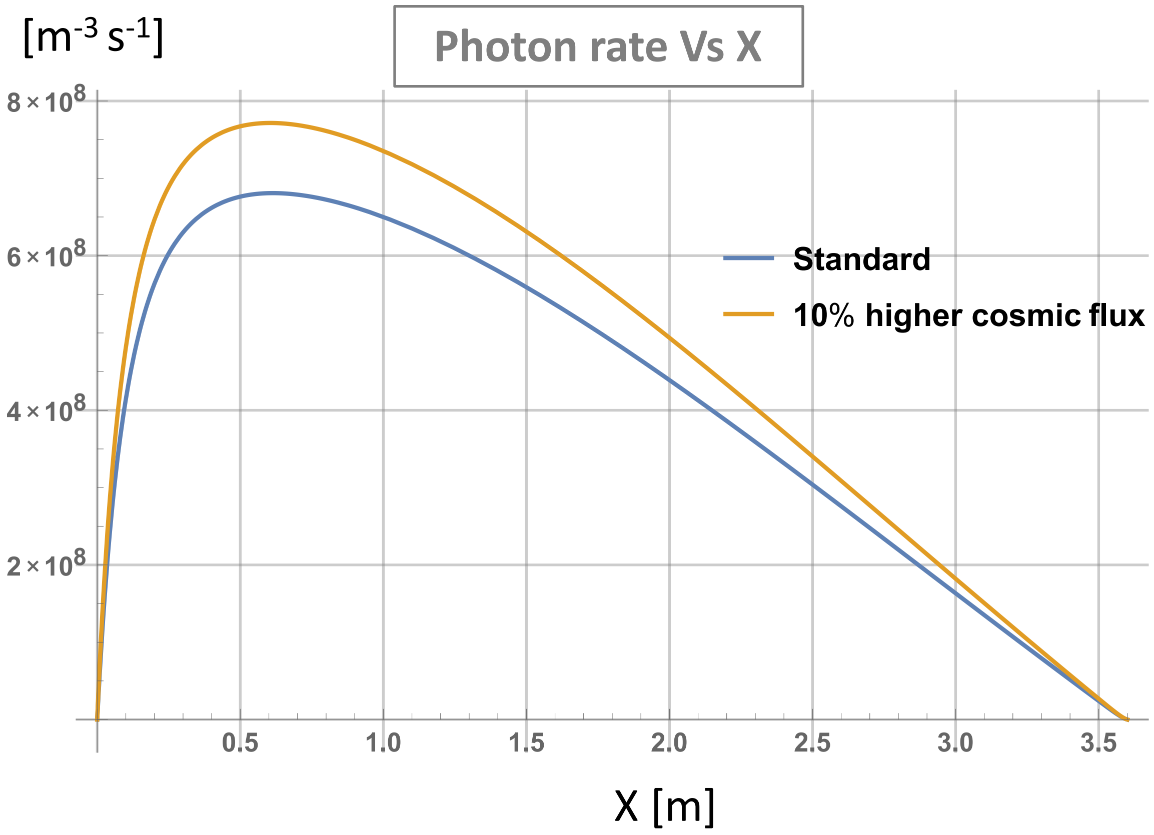
Next I compare effect with standard cosmic flux to 10% higher cosmic flux.



Hard to observe the E field change induced by the cosmic flux seasonal change.

10% higher cosmic flux -> 13% more photon rate.



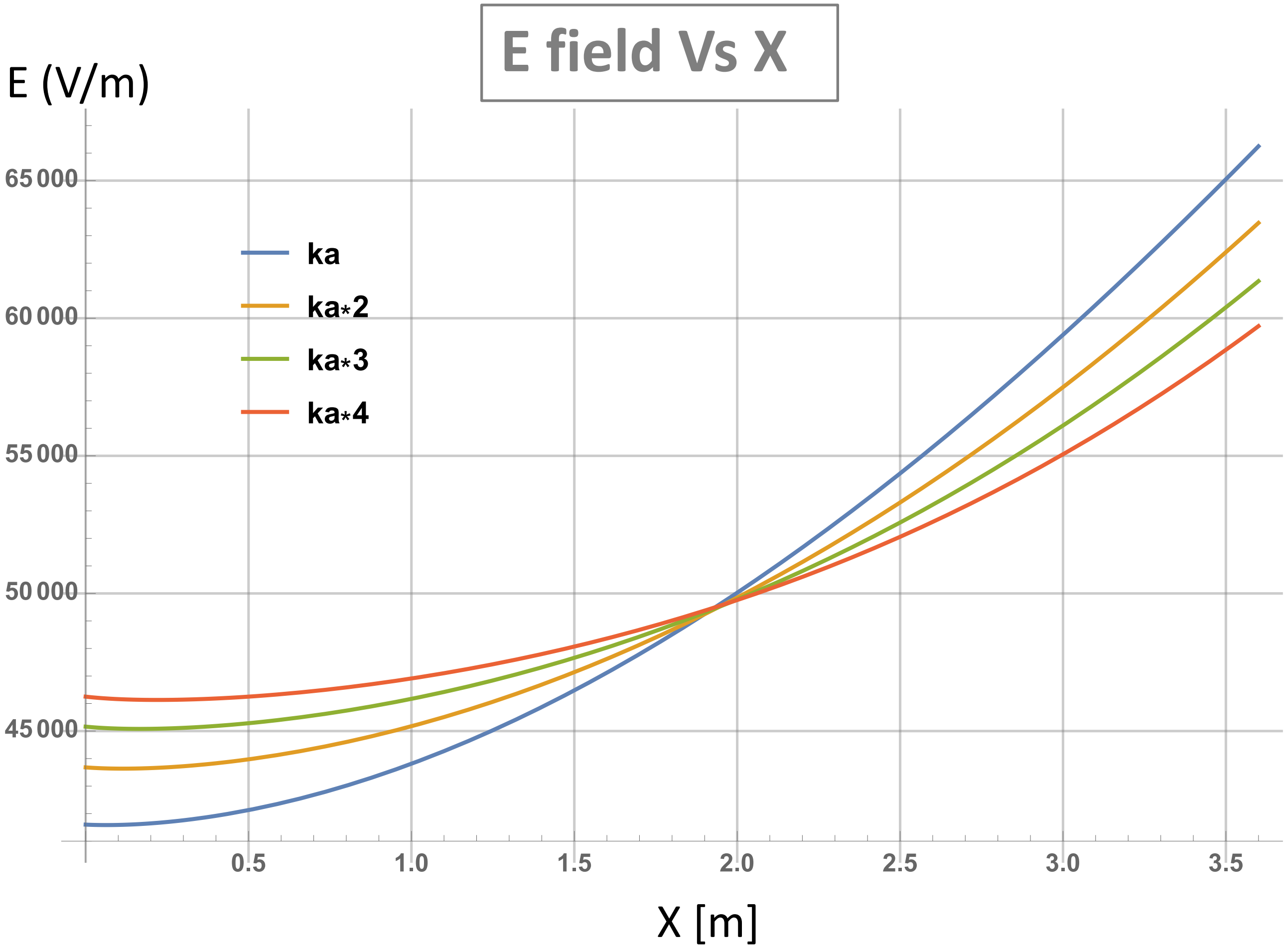


Purity / k_A dependence:

Impurity concentration c[H2O] and e- attachment rate to impurity (k_A) always couple together in our differential equation - $k_A \, n_X^0 \, n_e$, this term also proportional to $1/\tau$, where τ is the electron lifetime (a measureable quantity in the experiment)

Intuitively, more impurities, more photons generated from the Mutual Neutralization.
Prediction: effect negatively correlated with lifetime
In this study, vary the product (c[H2O] * ka) from standard 6ms to 3ms, 2ms, 1.5ms

”purity” modifies the E field!



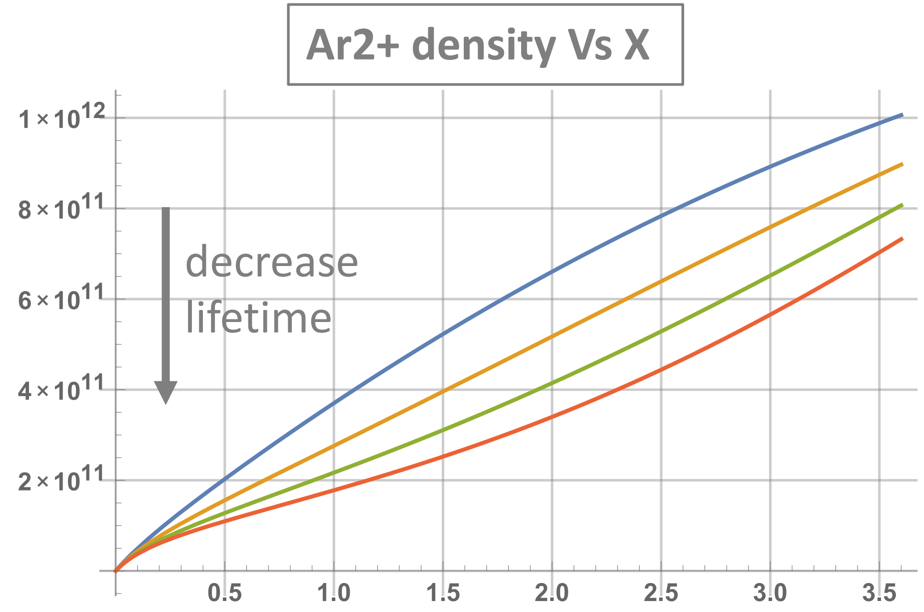
lifetime	E_A	E_C	E_C/E_0 %
6ms	416 V/cm	662 V/cm	[-17%,+32%]
3ms	437 V/cm	635 V/cm	[-13%, +27%]
2ms	452 V/cm	613 V/cm	[-10%,+23%]
1.5ms	463 V/cm	597 V/cm	[-7%,+19%]

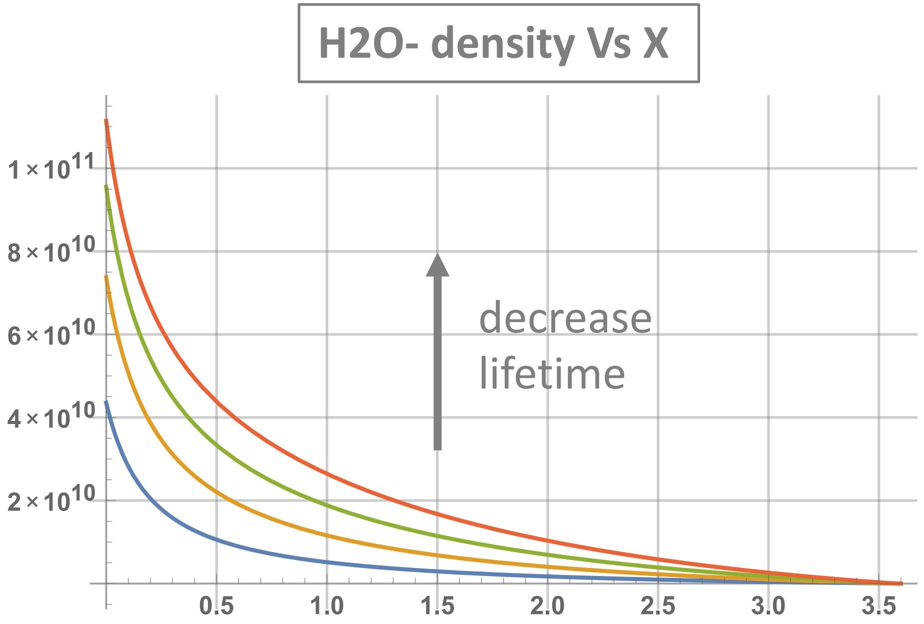
The data measurements of E field constrain the model to prefer shorter lifetime than 6ms.

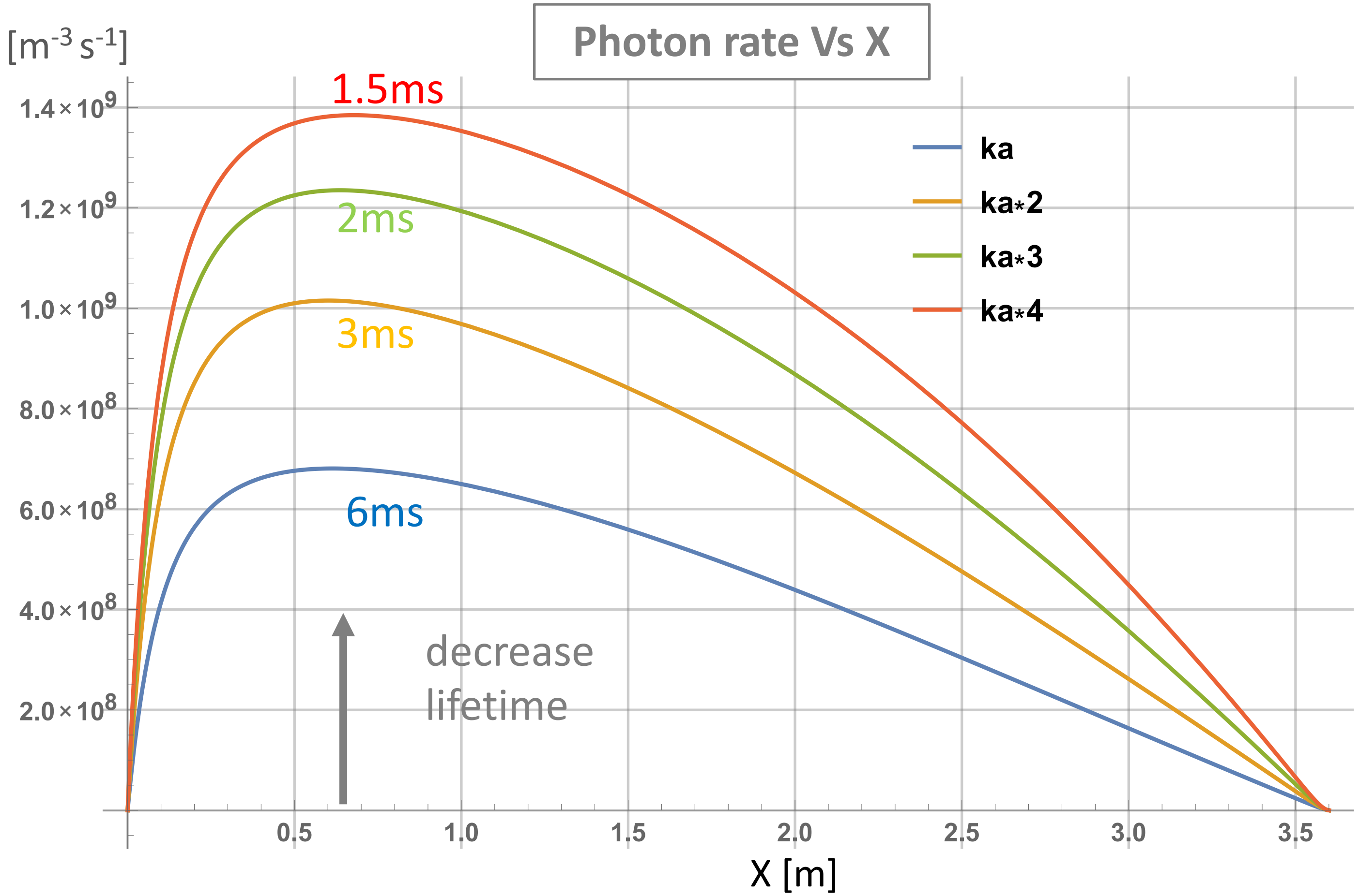
"purity" modifies photon rate!

Decrease lifetime from 6ms to 2ms increase photon rate by 90%.

Comparing to SPE rate for different purity data samples are on-going.





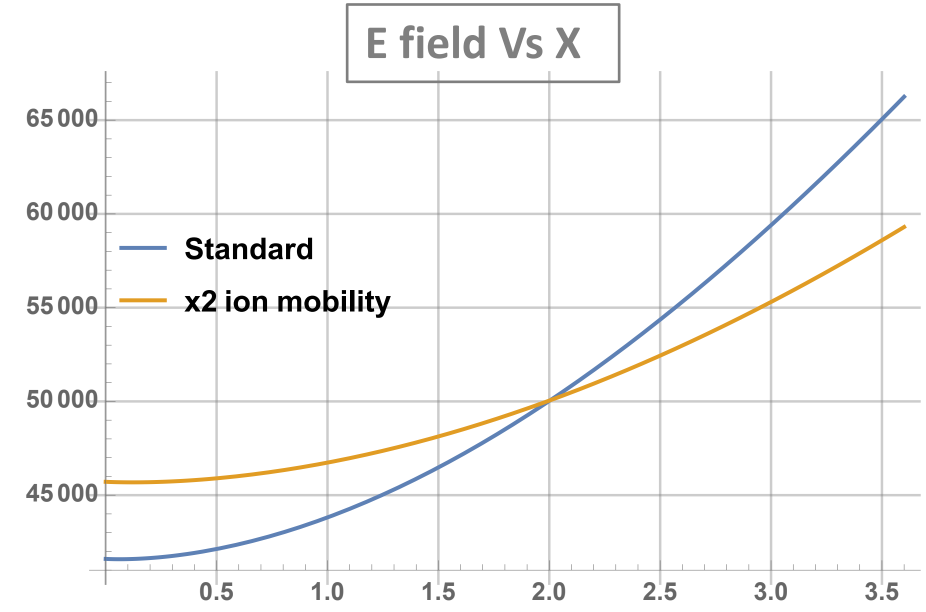


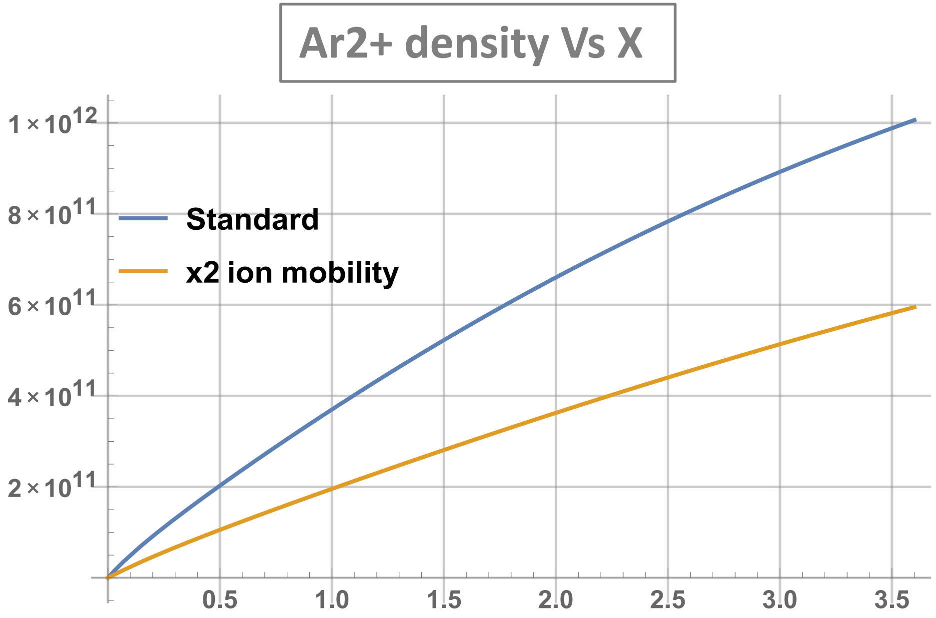
Ion mobility dependence:

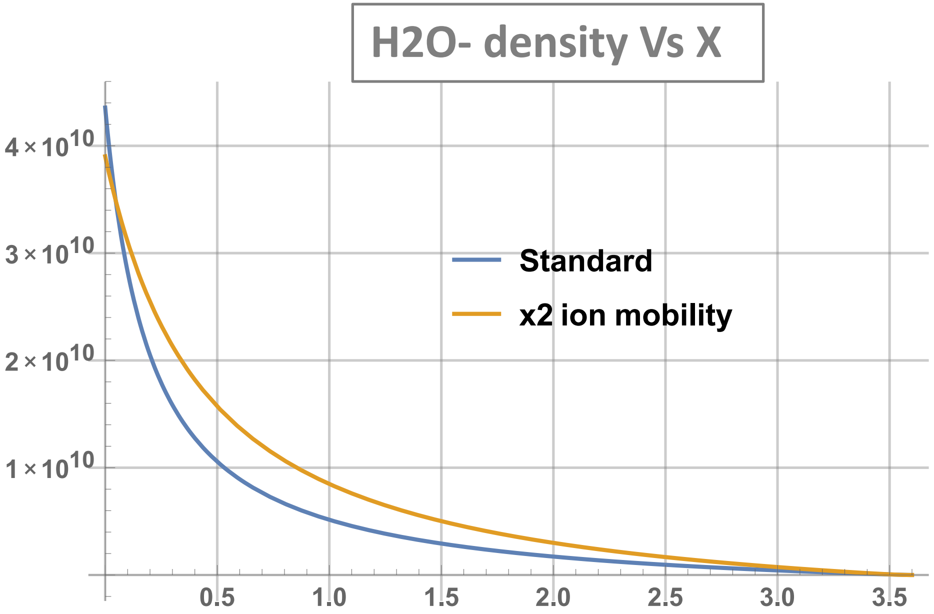
There could be a big uncertainty of the ion mobility. In the standard calculation we use **8×10^{-8} [$m^2 V^{-1} s^{-1}$]** as Ar2+ mobility (this corresponds to **4×10^{-3} m/s** drift velocity at 500V/cm Field).

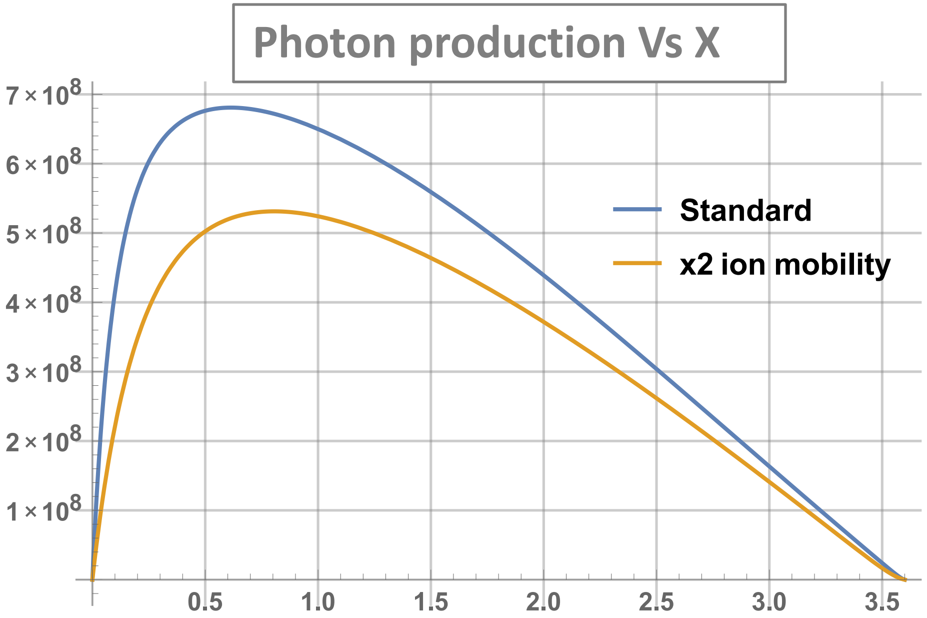
Intuitively, increase the mobility will decrease the density of the ions, which decrease the photon generation rate.
Prediction: effect negatively correlated with ion mobility
In this study, compare the effect with x2 of the standard mobility for both positive and negative ions.

Comparing to slower ion mobility









Twice of the ion mobility:

- Decrease E field distortion from [-17%, +32%] to **[-9%,+19%].**
- Decrease the photon rate by 21%.

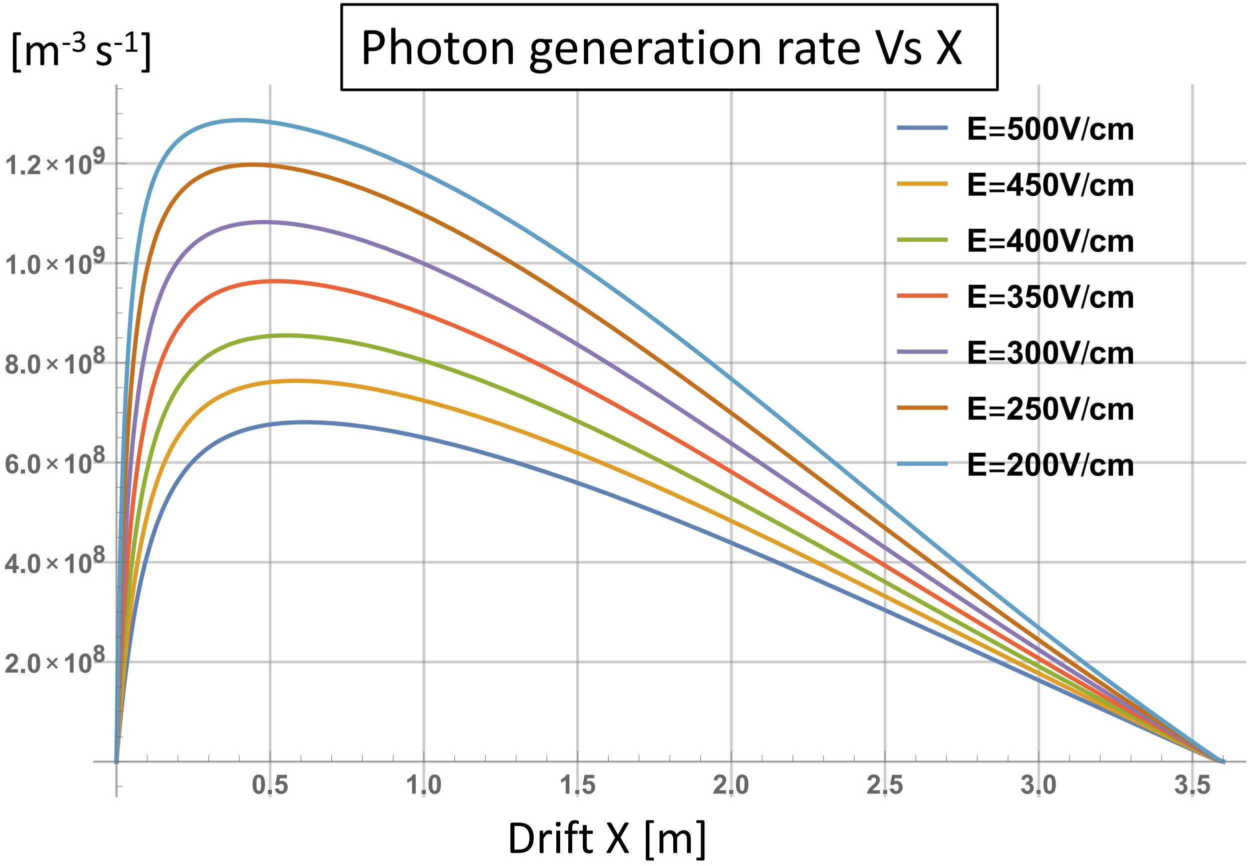
E field dependence:

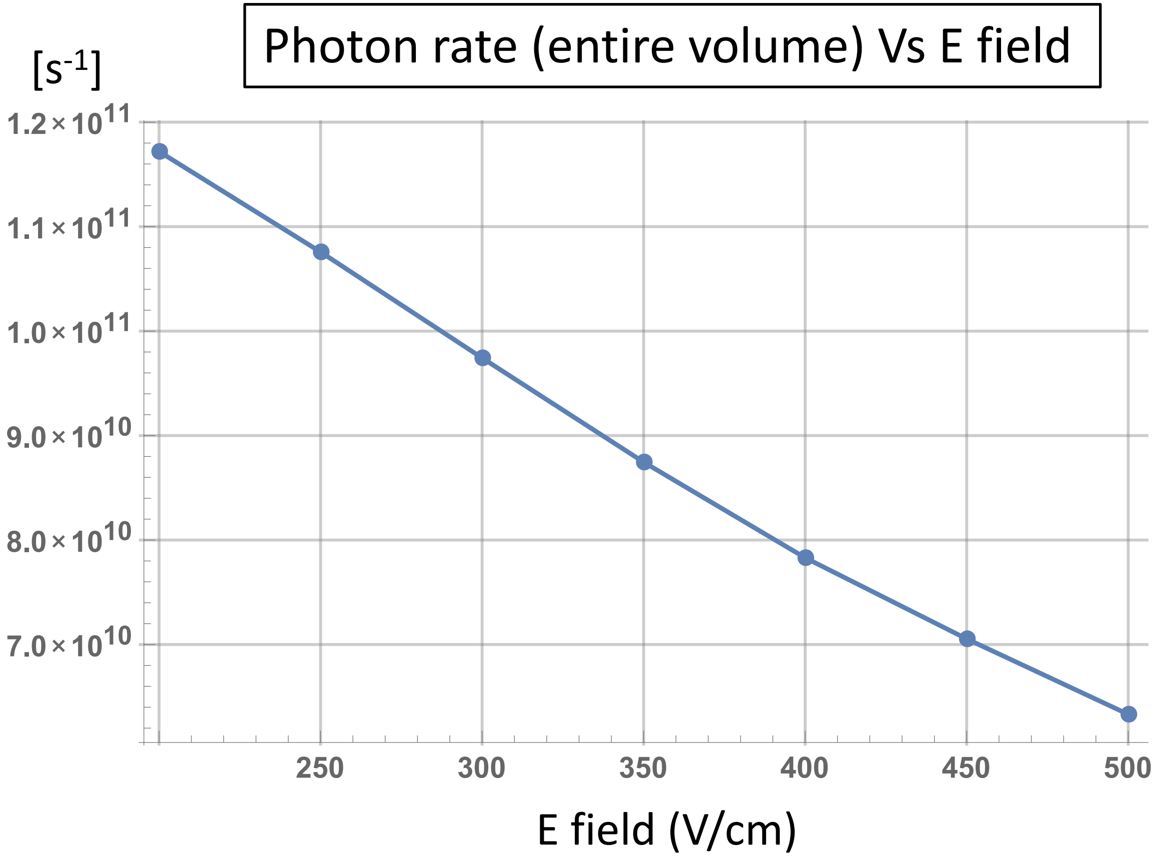
- higher E field, faster drift velocity, less ion densities, less photons.
- higher E field, less initial recombination, more Ar_2^+, more photons

Changing E field leads to two competing processes, that decides final photon generation rate.

For simplicity, ignore the gauss law for this study. Vary E field from 500 V/cm to 200 V/cm with 50V/cm step.

As a function of E field





Photon rate at E0 = 250 V/cm is 60% higher of the rate at E0=500V/cm

Comparing to the SPE measurements with different E field data samples are on-going.

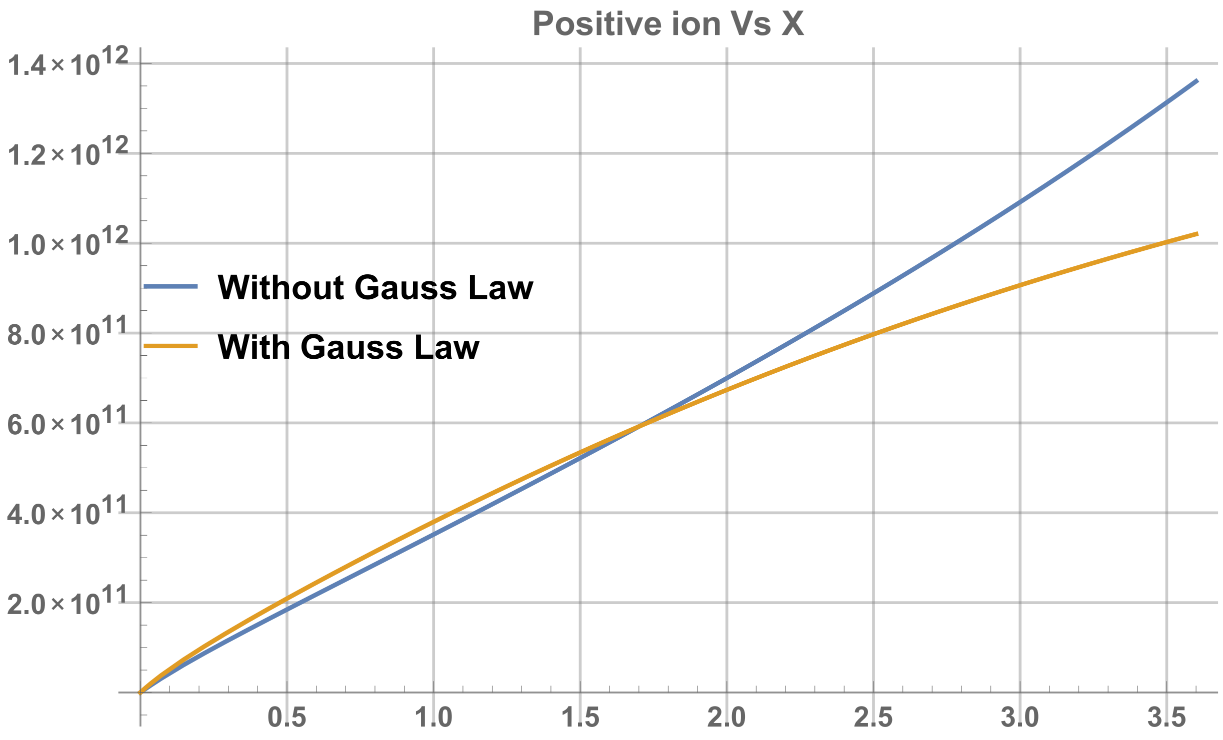
Summary & Outlook

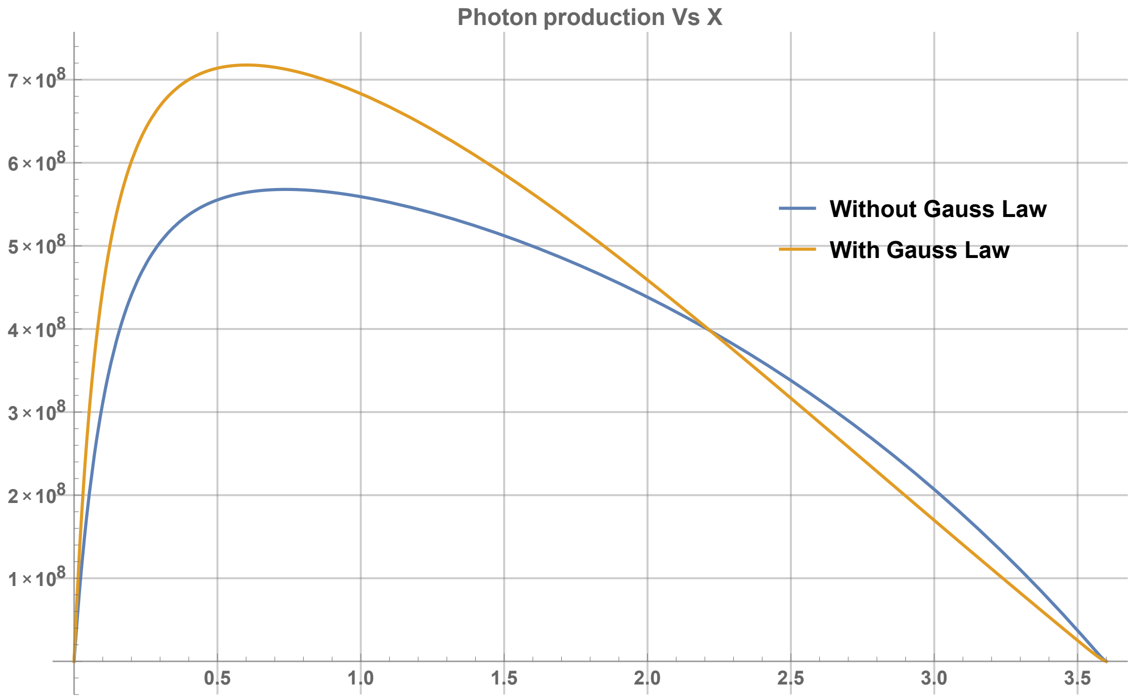
- We presented a model that describes the space charges (+ & -) distributions and their impact to E field and photon generation. - done
- The model is robust – predict the trends that correlate with experimental observables. - done
- The model contains many parameters that can be constrained by protoDUNE data. – on-going
- This model can then be used to optimize the detector design to reduce the single PE rate background and enable the LArTPC physics capability at low energy (link to my PONDD talk)

Backup

How big is the effect if we ignore the space charge distortion on the E field?
– remove the Gauss Law from the differential equation set

Comparison of wi and wo Gauss law





Mostly change the positive ion distribution

13% lower photon rate if not considering Gauss Law