A study of liquid helium scintillation in the presence of an electric field for the nEDM@SNS experiment

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Outline

- Motivation
- Introduction to LHe scintillation
- Measurement with an alpha source
- Ionization current measurement with a beta source
- Measurement with a conversion electron source
- Implications for nEDM@SNS
- Summary

LHe scintillation in nEDM@SNS

^{3}He as spin analyzer/ LHe as detector

- ^{3}He-n reaction cross section

$$\overrightarrow{^3\mathrm{He}} + \vec{n} \rightarrow t + p + 760\ \mathrm{keV}$$

$$\sigma(\mathrm{parallel}) < 10^2\ \mathrm{b}$$
$$\sigma(\mathrm{antiparallel}) \sim 10^4\ \mathrm{b}$$

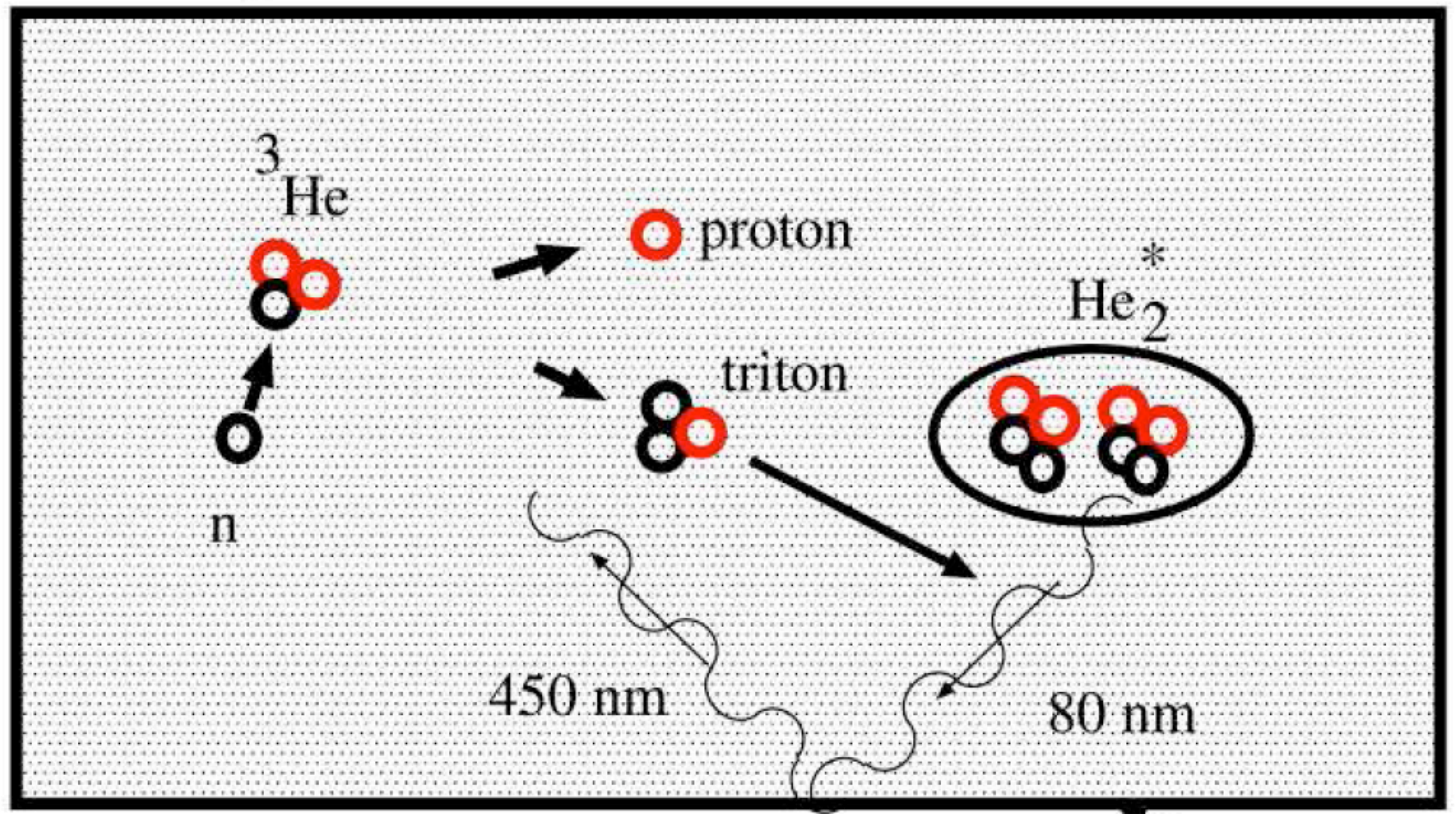
@thermal energy

- ^{3}He-UCN reaction rate

$$1 - \vec{p_3} \cdot \vec{p_n} = 1 - p_3 p_n \cos\left[(\gamma_n - \gamma_3)Bt\right]$$

$$|\gamma_n - \gamma_3| \approx |\gamma_n|/10$$

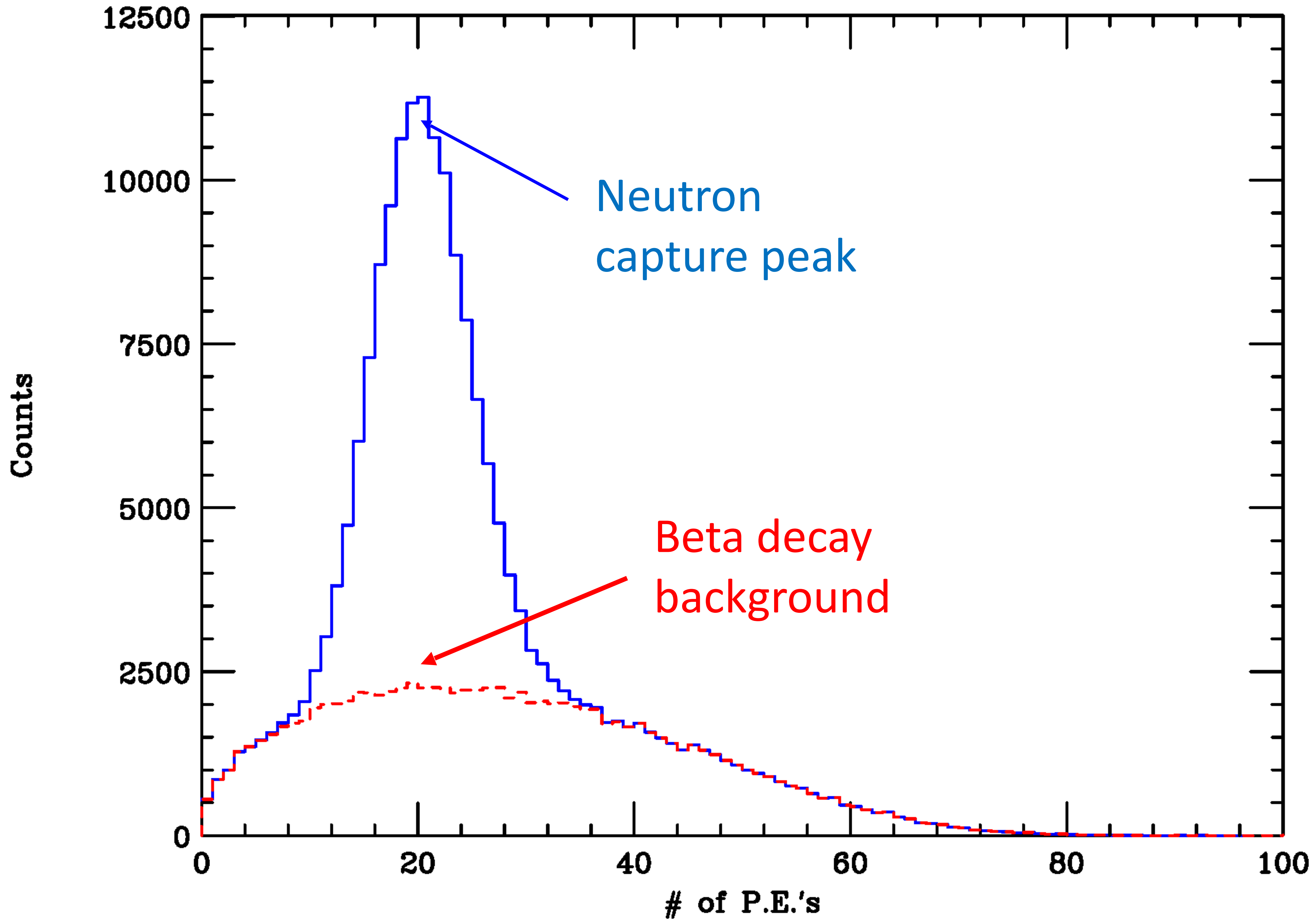
- Detect Scintillation light from the reaction products traveling in LHe



- Signature of EDM would appear as a shift in $\omega_3 - \omega_n$ corresponding to the reversal of E with respect to B with no change in ω_3

Why do we worry about the electric field?

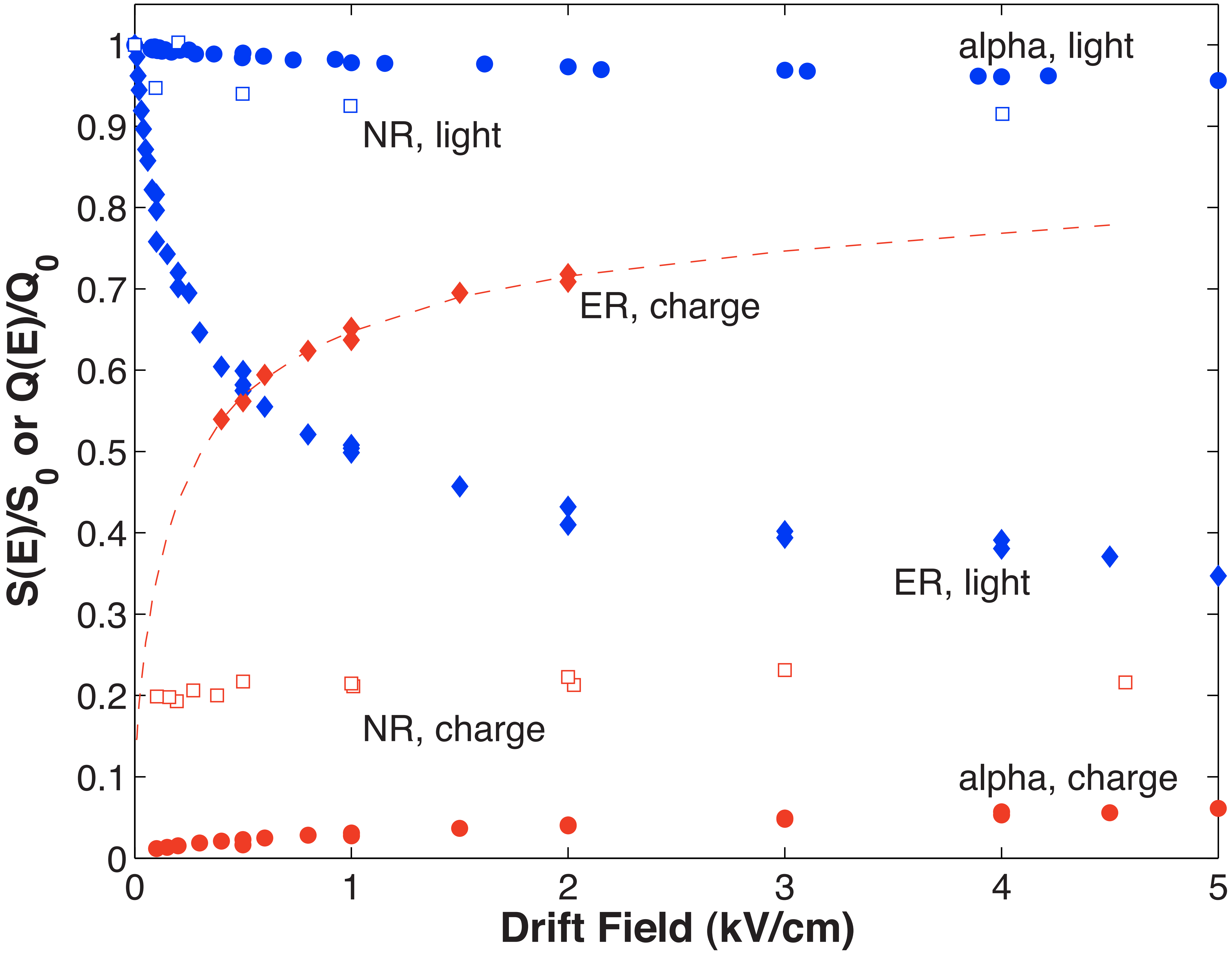
Simulated spectrum for E=0 kV/cm



Scintillation yield per energy deposition for electrons is assumed to be 3.5 times larger than that for n-^{3}He capture events

- How much does the light yield from the n-^{3}He capture events get suppressed at E = 75 kV/cm?
- Similarly, how much does the light yield from neutron beta decay events get suppressed at E = 75 kV/cm?

How does the scintillation yield change if an electric field is applied?



Example from liquid xenon

Two types of particles

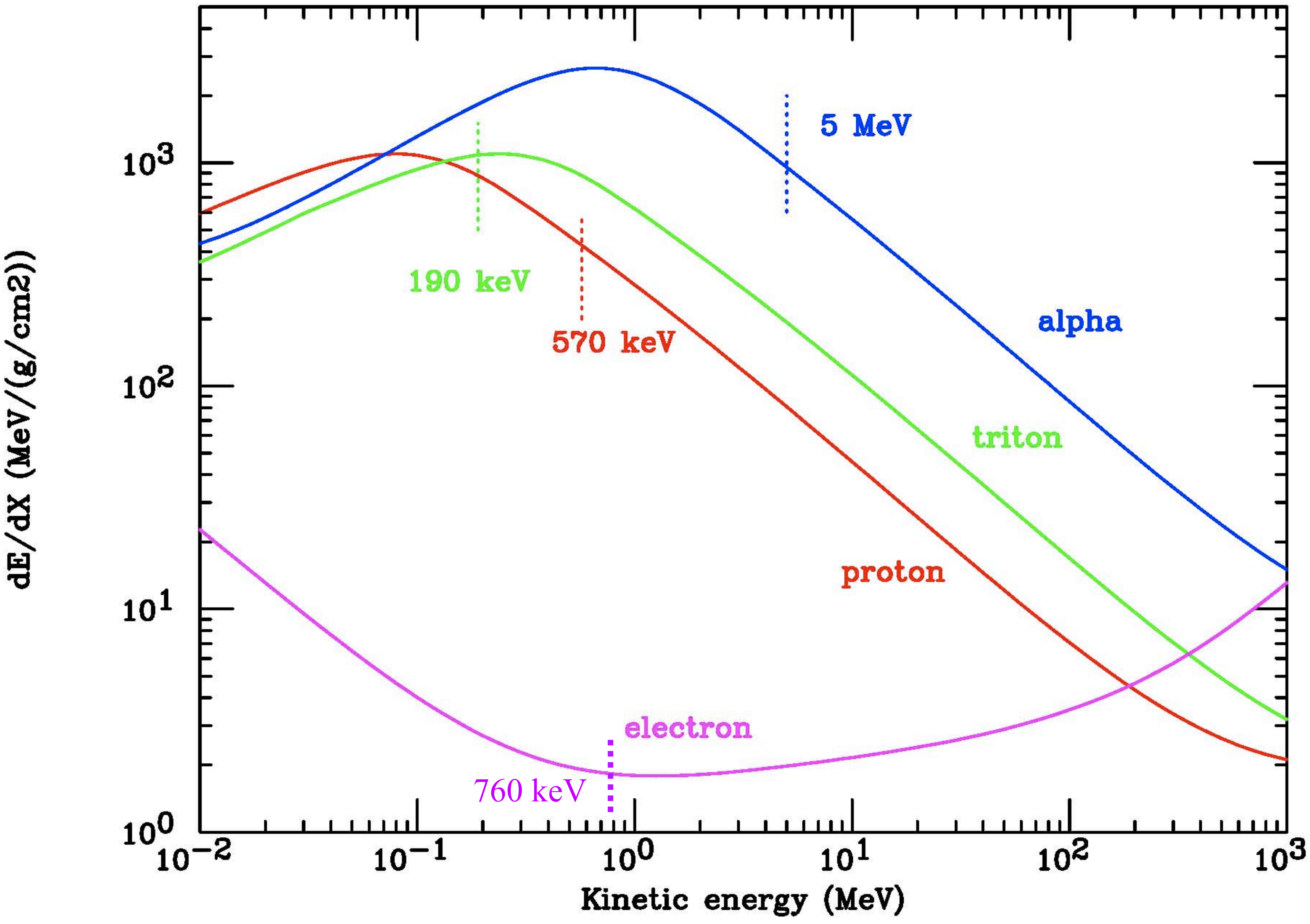
Fast/light particles

- Low ionization density
- Particles of this type include:
  - Electrons
  - cosmic ray muons

Heavy/slow particles

- High ionization density
- Particles of this type include:
  - alphas
  - reaction products from neutron capture on 3He (proton and triton)

Specific energy loss in LHe



LHe scintillation

Ionization track

$$\mathrm{He}^+ + e \rightarrow \left(\mathrm{He}_3{}^+\right)_{snawball} + \left(e^-\right)_{bubble} \rightarrow \mathrm{He}_2{}^* + \mathrm{He}$$

- W value ~ 43 eV
- Thermalized electrons form electron bubbles
- Thermalized He+ ions form snow balls
- An electron bubble and a snow ball recombine to form an exited helium molecule
- Exited helium molecules are formed in singlet and triplet electronic states

- Singlet state: decays within ~ 1 ns emitting a ~ 80 nm photon (prompt scintillation)

$$\mathrm{He}_2\left(A^1\Sigma_u^+\right) \rightarrow \mathrm{rad.\ decay}$$

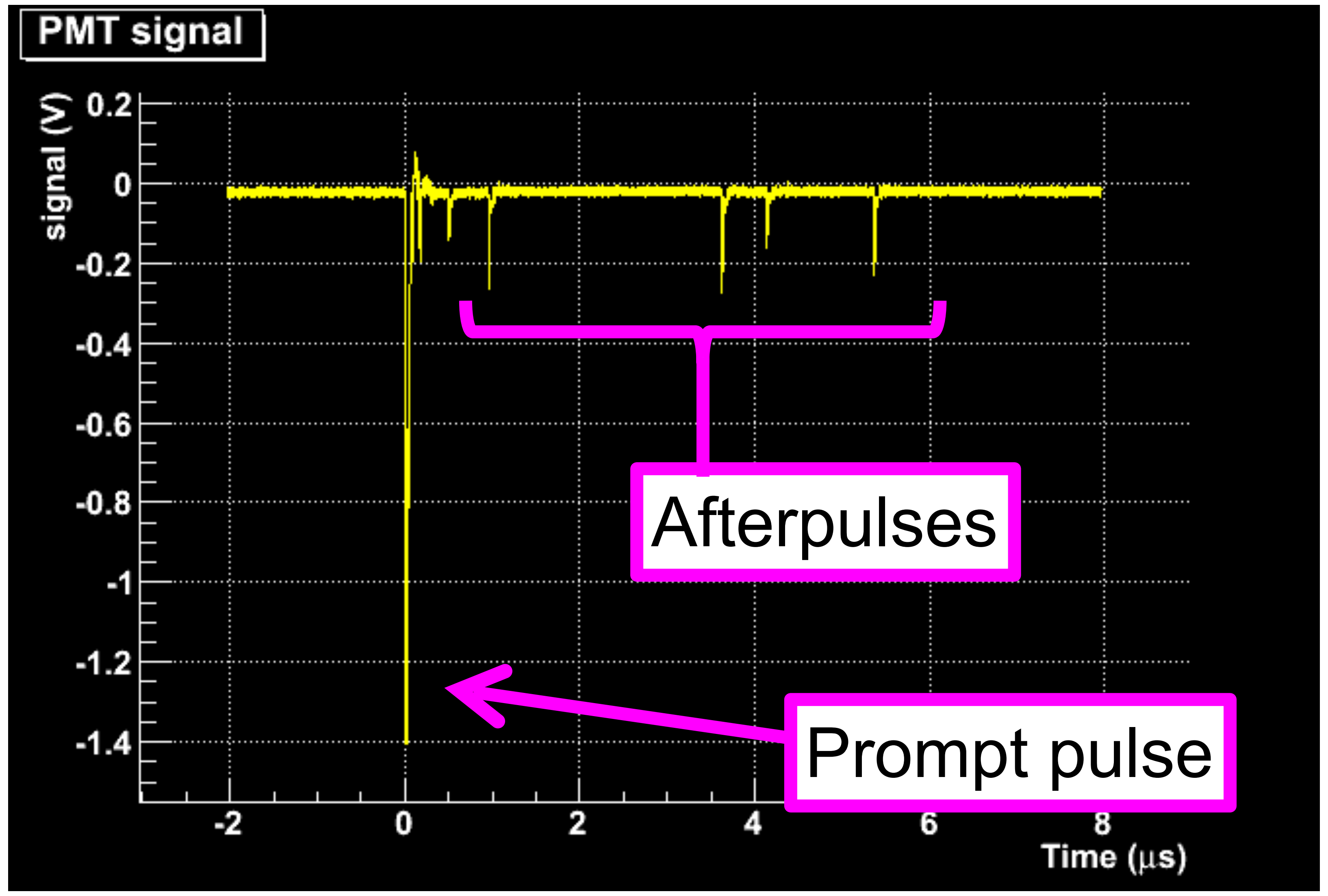
- Triplet state: has a lifetime of ~ 10 s in vacuum. In high ionization density environment, gives delayed photon emission through Penning ionization (destructive interaction with each other)

$$\mathrm{He}_2\left(a^3\Sigma_u^+\right) + \mathrm{He}_2\left(a^3\Sigma_u^+\right) \rightarrow 3\mathrm{He} + \mathrm{He}^+ + e^-$$

or

$$\mathrm{He}_2\left(a^3\Sigma_u^+\right) + \mathrm{He}_2\left(a^3\Sigma_u^+\right) \rightarrow 2\mathrm{He} + \mathrm{He}_2{}^+ + e^-$$

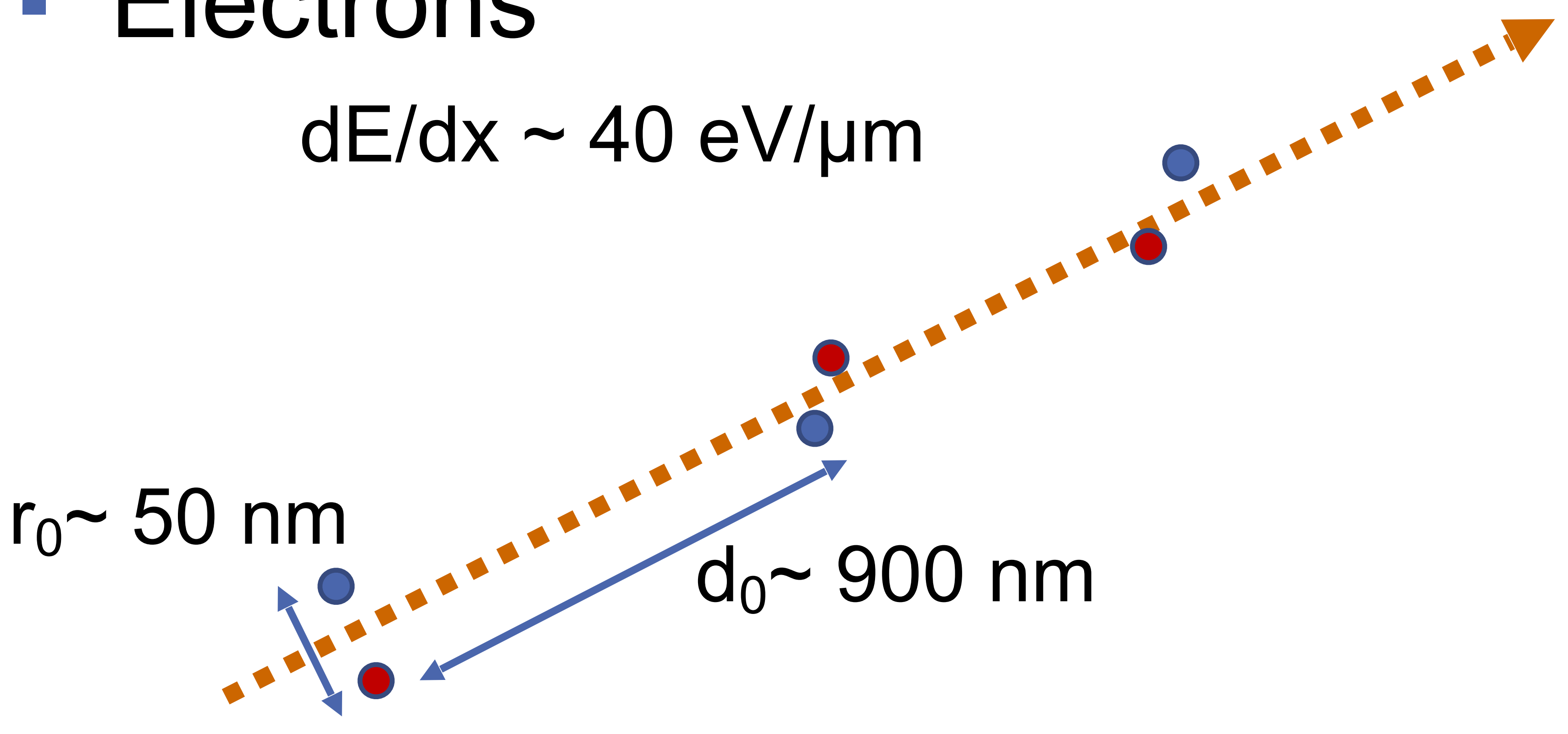
$$\mathrm{He}^+ + e \rightarrow \left(\mathrm{He}_3{}^+\right)_{snawball} + \left(e^-\right)_{bubble} \rightarrow \mathrm{He}_2{}^* + \mathrm{He}$$



Fast/light particles vs slow/heavy particles

$r_{0:}$ separation btw. ions in a pair
$d_{0:}$ separation btw pairs.

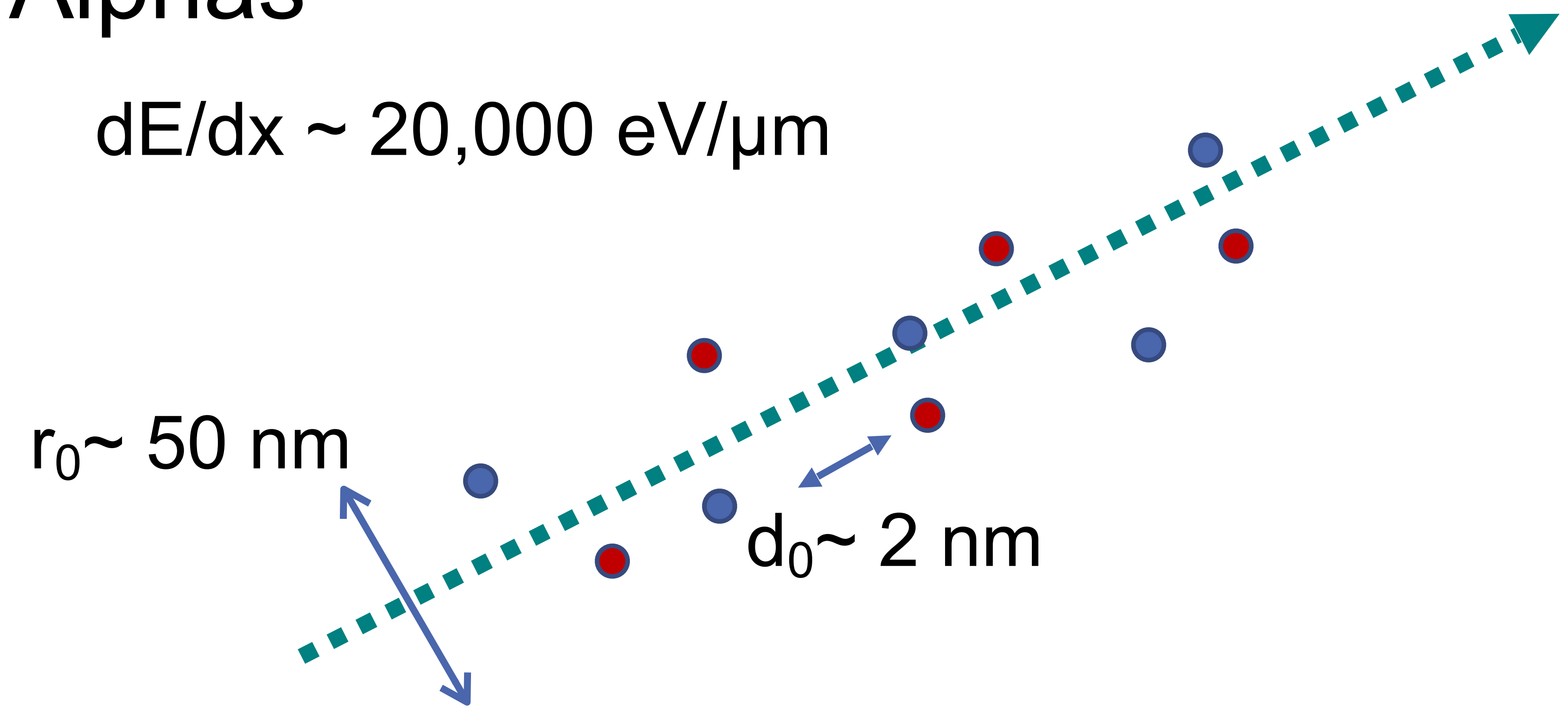
- Electrons



The relative number of excitations to ionizations is 0.31 to 0.69, respectively.

The charges are most likely to recombine with their partners → geminate recombination (Onsager).

- Alphas



Electron-ion pairs overlap → columnar recombination (Jaffe, Kramer).

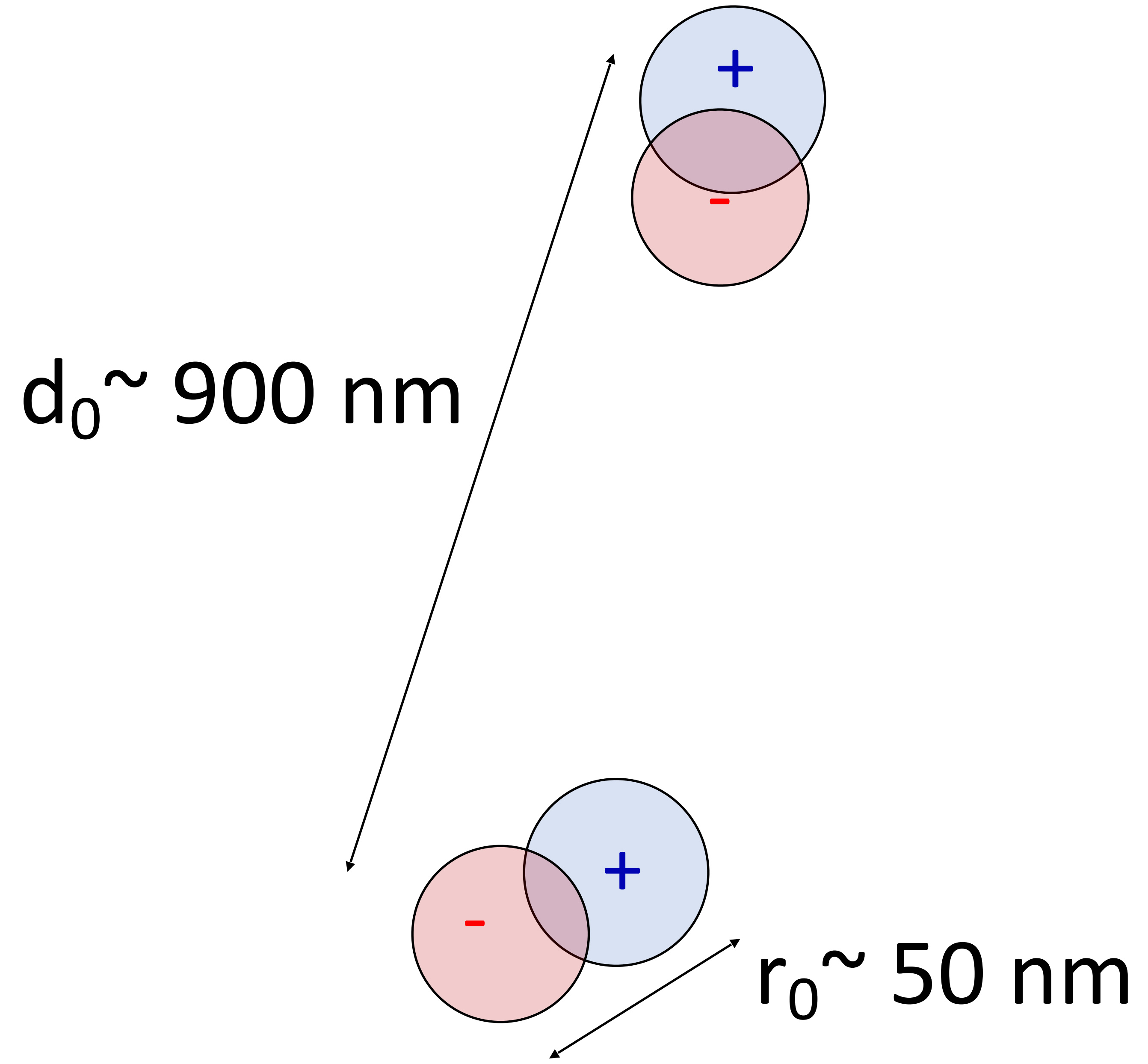
Cylindrical Gaussian charge distribution with width ~ 60 nm.

Effect of an electric field on LHe scintillation

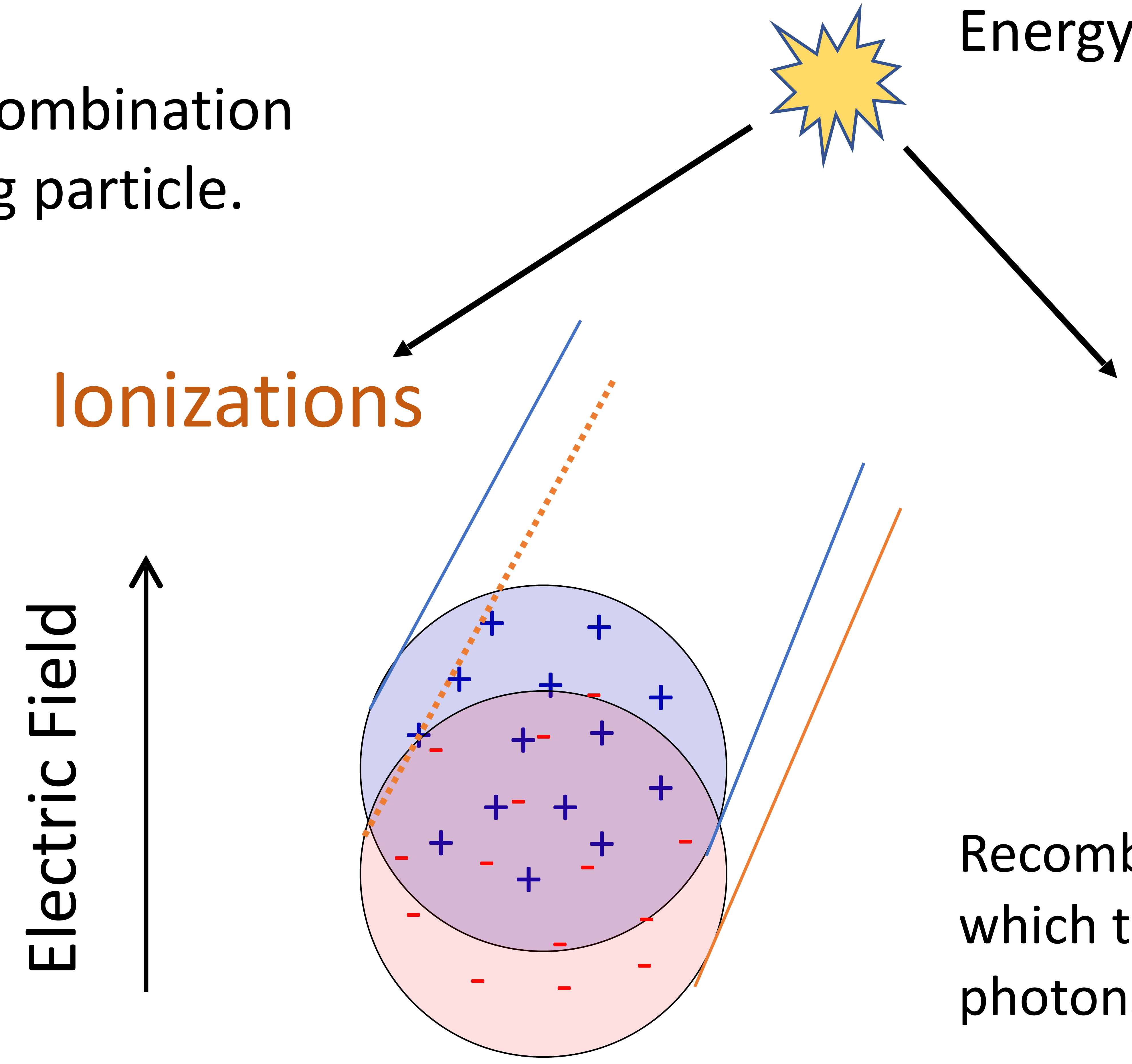
Distribution of charges and recombination depends on the type of ionizing particle.

Energy deposition

Excitations
(Field independent)



Geminate recombination (electrons)



Columnar recombination (alphas, protons, tritons, etc.)

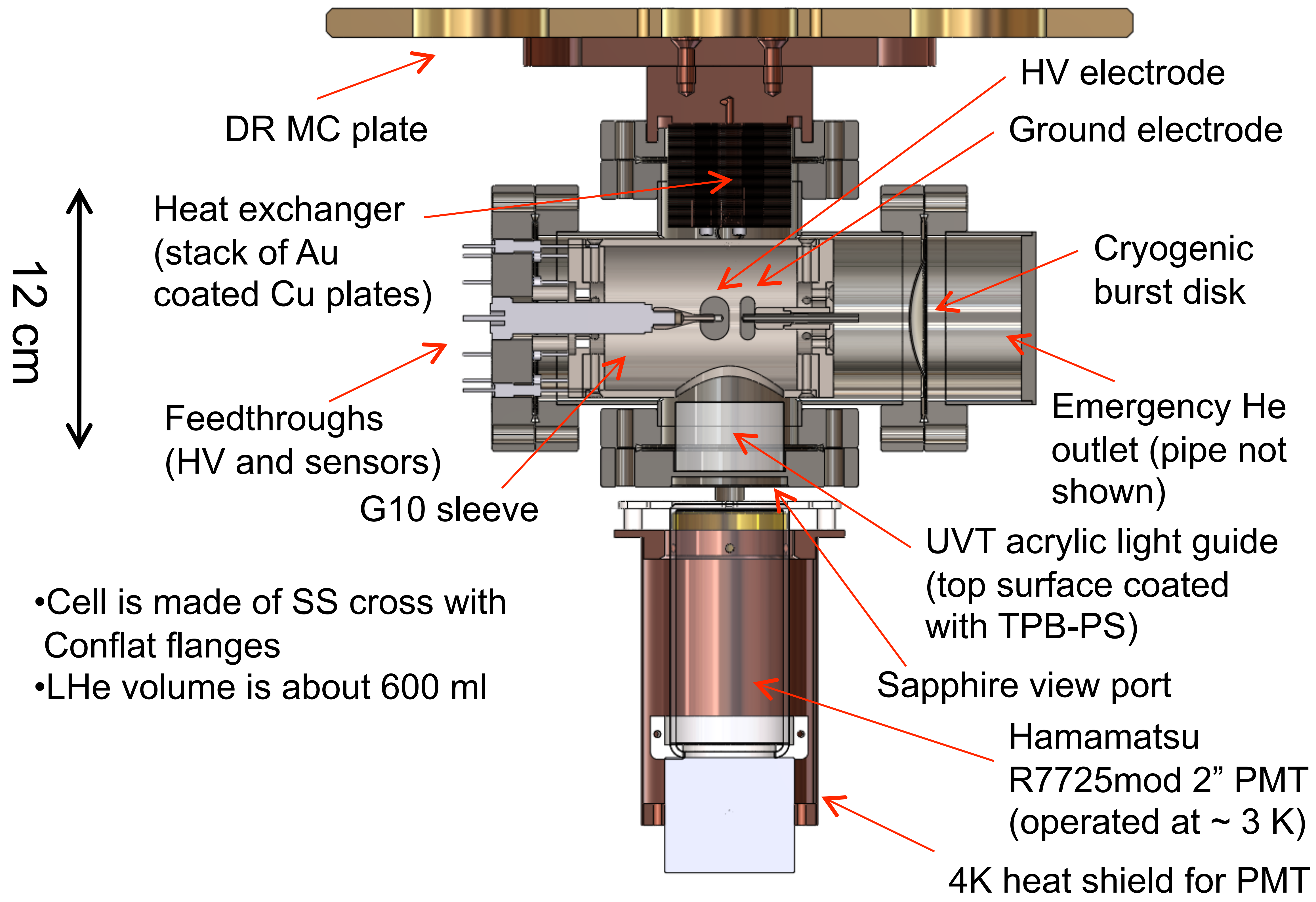
Recombination leads to excited molecules which then decay by emitting 80 nm EUV photons.

Electric field suppresses recombination → suppression in scintillation light production & ionization current

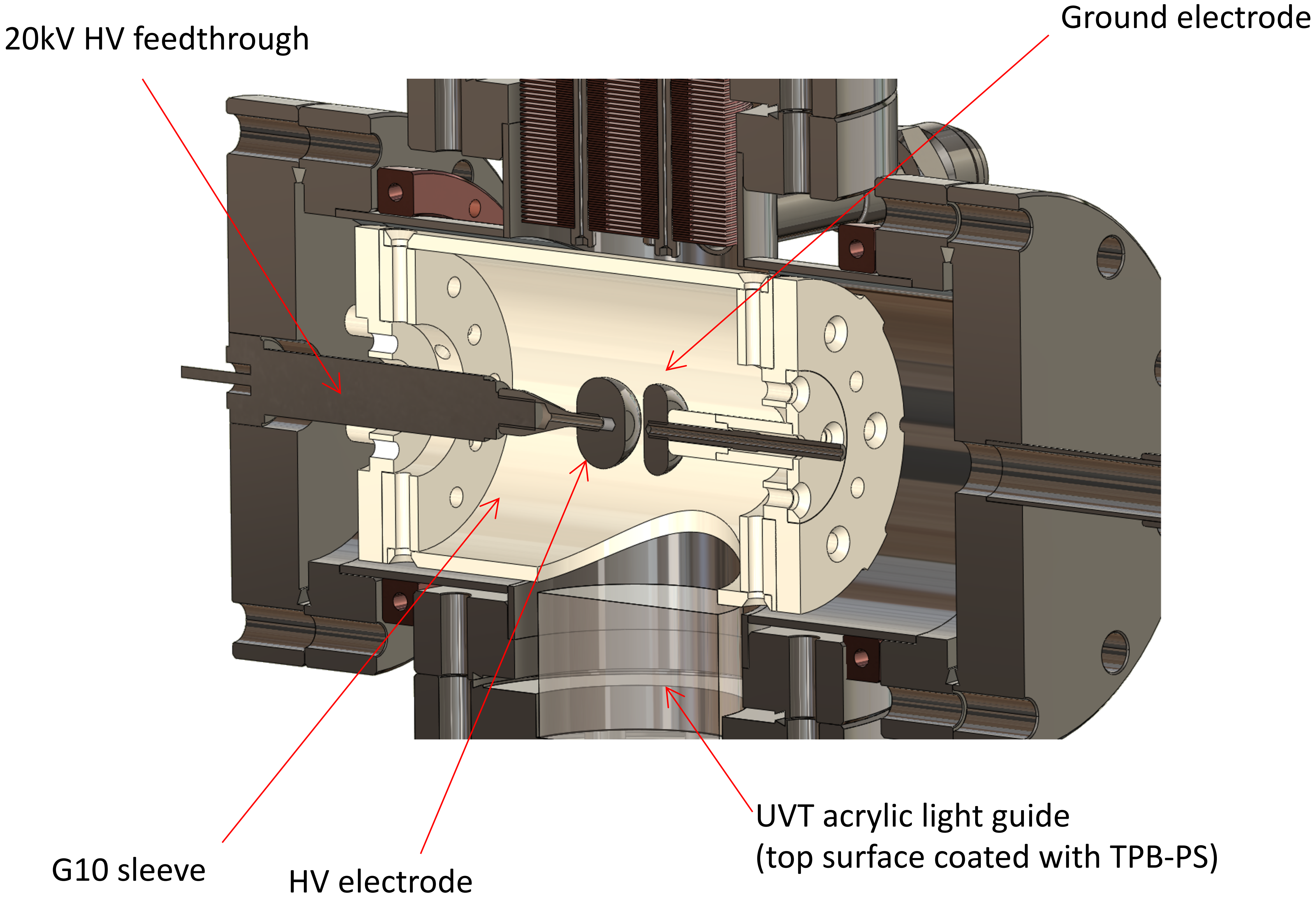
Three experiments

- Scintillation measurement with alpha particles
  - $E \leq 45$ kV/cm
  - $0.2 \text{ K} \leq T \leq 1.1 \text{ K}$
  - Source: ^{241}Am (α energy: 5.5 MeV)
- Ionization current measurement with electrons
  - $E \leq 10$ kV/cm
  - Source: ^{63}Ni (β endpoint energy: 66 keV)
- Scintillation measurement with electrons and alpha particles
  - $E \leq 40$ kV/cm
  - $0.44 \text{ K} \leq T \leq 3.12 \text{ K}$
  - Sources: ^{241}Am (α energy: 5.5 MeV) and ^{113}Sn (conversion electron energy: 364 keV)

Experimental setup for alpha scintillation measurements

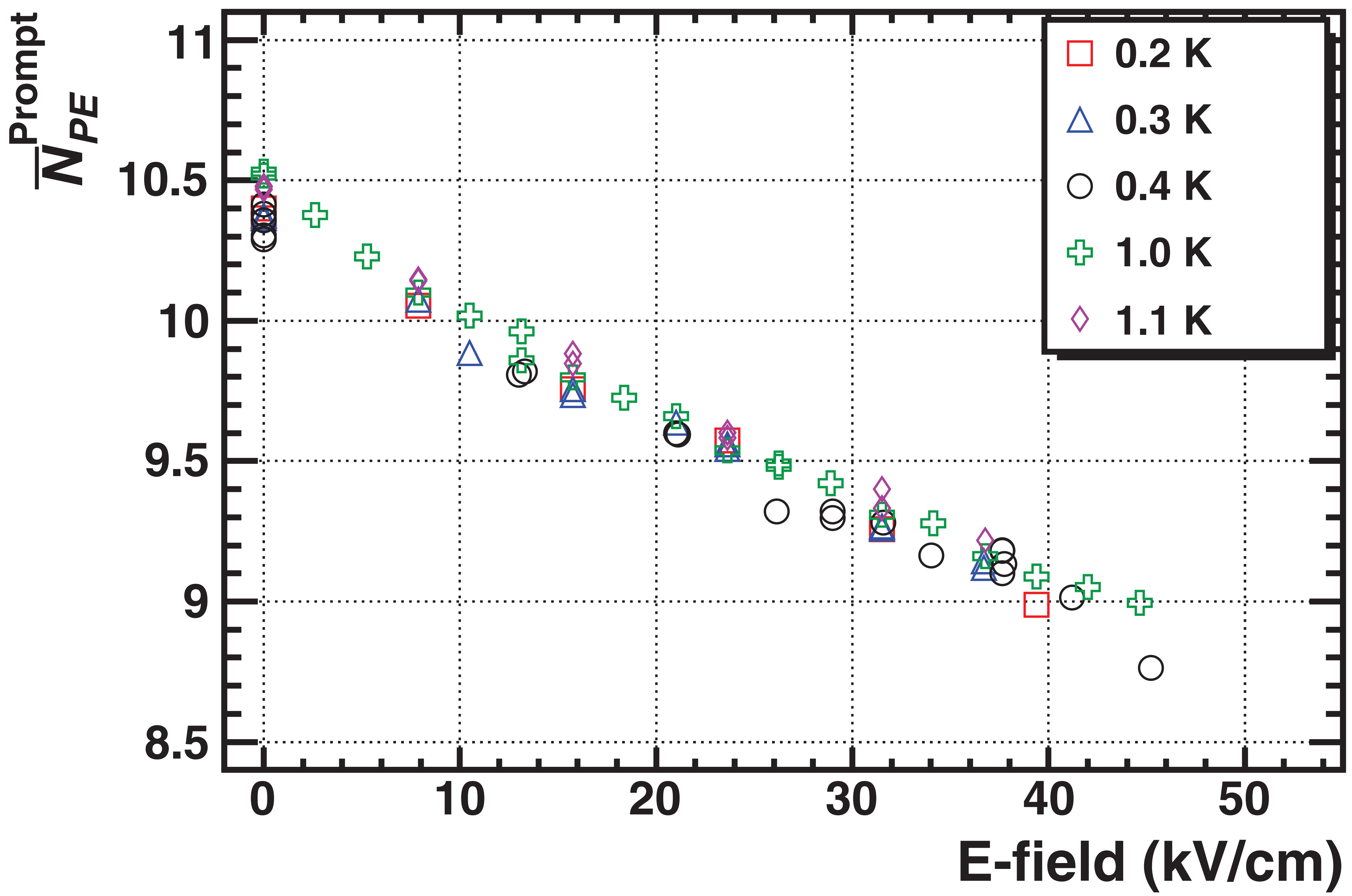


- Cell is made of SS cross with Conflat flanges
- LHe volume is about 600 ml

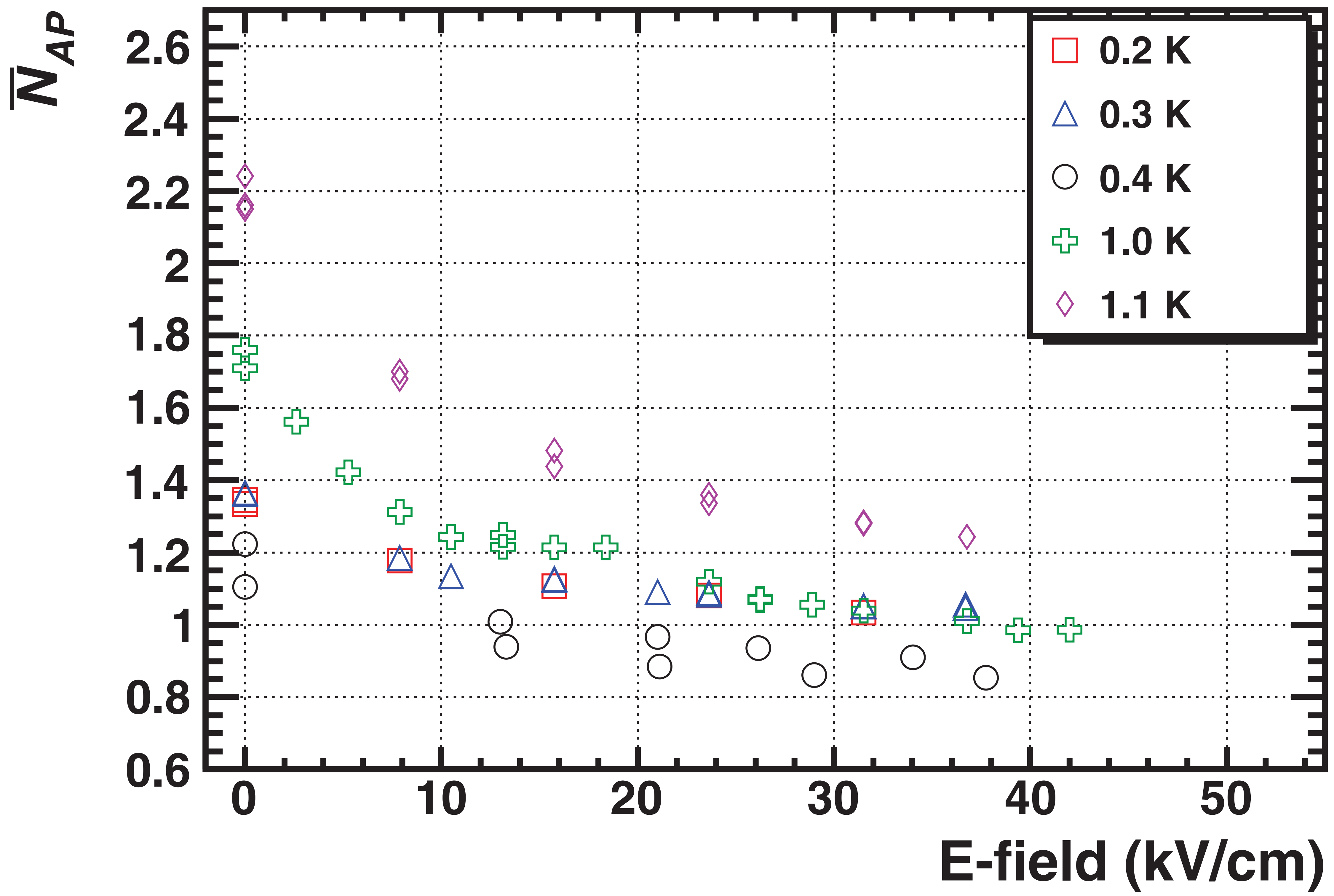


Results for alpha scintillation

Prompt (first 80 ns)



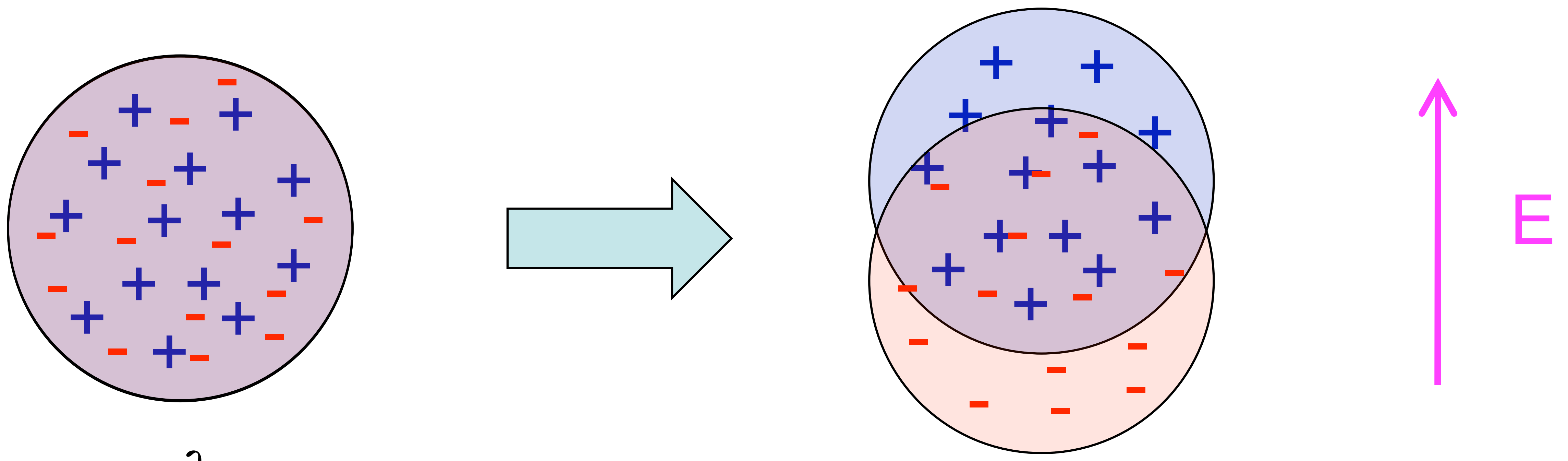
Afterpulse
(during the 14 μs following the promopt)



- The prompt yield reduction is about 15% at 45 kV/cm.
- Very little temperature dependence in both the scintillation yield at 0 field and the effect of E field.

- The after pulse counts reduce with both decreasing temperature and increasing E field.

Columnar theory of recombination



$$\frac{\partial n_+}{\partial t} = -\mu_+ \mathbf{E} \cdot \nabla n_+ + D_+ \nabla^2 n_+ - \alpha n_+ n_-$$

$$\frac{\partial n_-}{\partial t} = \mu_- \mathbf{E} \cdot \nabla n_- + D_- \nabla^2 n_- - \alpha n_+ n_-$$

$n_\pm$: ion density

$\mu_\pm$: ion mobility

$\mathbf{E}$: electric field

$D_\pm$: diffusion coefficient

α : recombination coefficient

Langevin relation : $\alpha = e(\mu_+ + \mu_-)/\varepsilon_0$

- Ignore the diffusion term (Kramers): valid in dense fluid
- Furthermore, when $\mu_+=\mu_-$, the theory is independent of mobility.
- If a cylindrical Gaussian charge distribution is assumed, the theory only depends on the radius of the column *b*:

$$n_\pm(t=0) = \frac{n_0}{\pi b^2} e^{-r^2/b^2}$$

- The fraction of ions that do not recombine and are observed as ionization current is given by

$$f_{ion} = \frac{2f}{\sqrt{\pi}} \int_0^\infty \frac{\sqrt{\zeta}\, d\zeta}{f e^{\zeta} + 1} \approx \frac{2}{3} f(-\log f)^{2/3} \text{ for small } f, \quad \text{where } f = \frac{\sqrt{\pi} b E \varepsilon_0}{N_0 e}$$

Fitting the prompt data with the Columnar theory

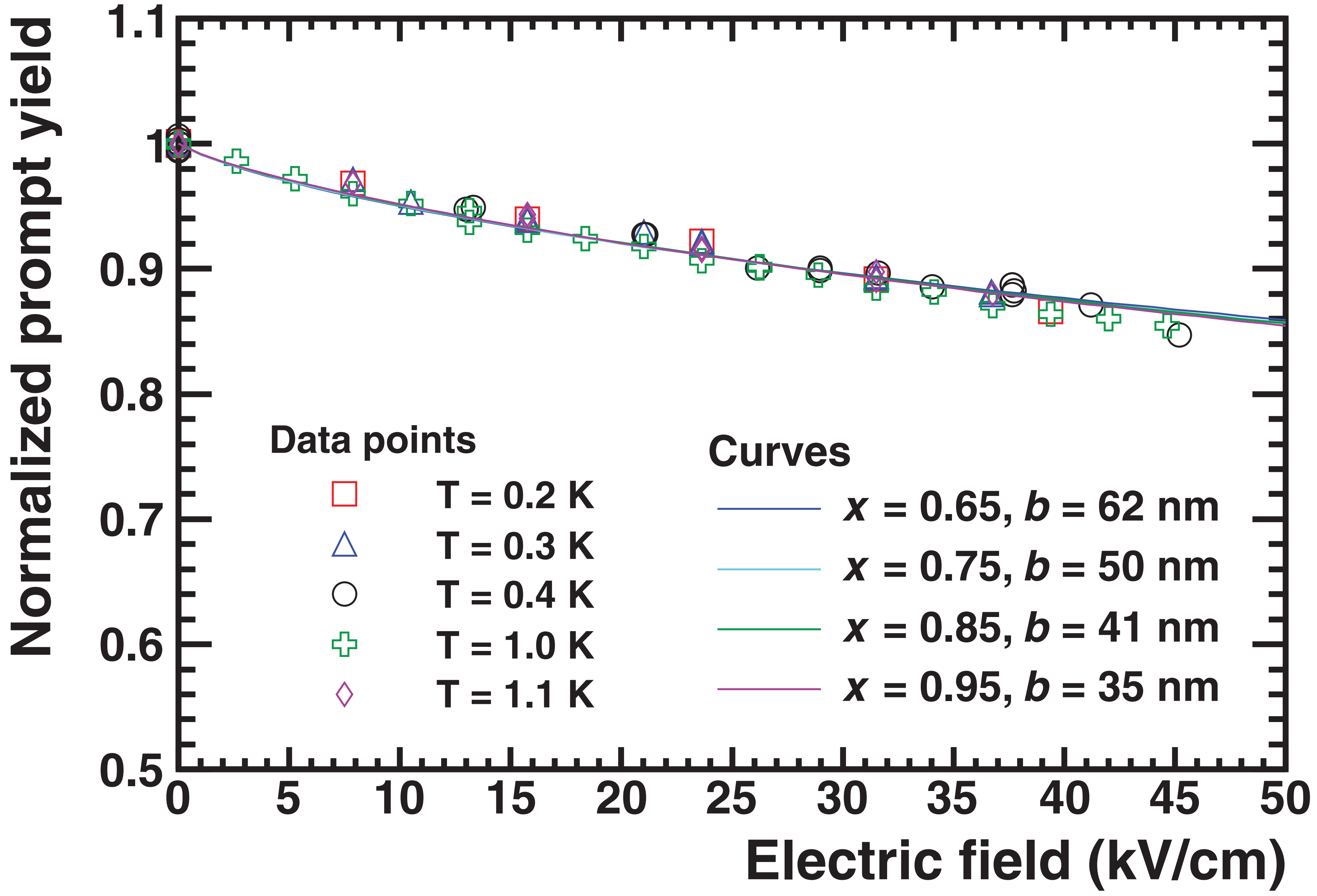
Need to consider the contribution from excited atoms to the prompt scintillation

- Define: $$x = \frac{P_R}{P_R + R_E}$$
- Estimate based on theoretical calculation of ionization process [1] gives x = 0.4
  - excitations : ionizations = 0.45 : 1 [1]
  - singlet atoms : triplet atoms = 5 : 1 [1]
  - singlet excimers : singlet excimers = 1:3
- This gets further modified by Hornbeck-Molnar process:

$$\mathrm{He}^*(n \geq 3) + \mathrm{He} \rightarrow \mathrm{He}_2^+ + e^-$$

- 1/3 of the atoms promoted to excited states will have n≥3, the other 2/3 having n = 2 [2], giving, x ~ 0.6.

[1] Sato, Okazaki, Ohno, Bull. Chem. Soc. Jpn. 47, 2174 (1974).
[2] Berkowitz, J. Phys. B, 30, 81 (1997).



x = 0.6 gives b = 60 nm

Predicting LHe scintillation yield and its E-field dependence for n-^{3}He capture events

- The difference in the ionization density between alphas and the n-3He capture products (proton and triton) causes the scintillation from n-3He capture to differ from that from alpha in the following ways:
  - The high ionization density for both alphas and the n-3He capture products causes quenching of scintillation yield, due to nonradiative destruction of singlet species. (We expect 23% of deposited energy to be emitted as prompt scintillation in the absence of quenching but only 10% of the deposited energy is emitted as prompt scintillation.) The lower ionization density for the n-3He capture products makes the quenching less.
  - The E field dependence also depends on the ionization density through the parameter

$$f = \frac{\sqrt{\pi}\epsilon_0 b E}{N_0 e}$$

Model for quenching and prediction for n-3He

- Penning ionization of singlet excimers and atoms

$$\frac{dn_s}{dt} = -\gamma_s\left(\kappa_{ss}n_s^2 + \kappa_{st}n_s n_t\right) + \underbrace{\kappa_{tt}\gamma_t n_t^2}_{\text{These terms can be neglected}} - D_s\nabla^2 n_s - \frac{n_s}{\tau_s}$$

$$\kappa_{ss} = \frac{7}{4},\ \kappa_{st} = \frac{3}{2},\ \kappa_{tt} = -\frac{1}{4}$$

For every two excimers destroyed, a new one is formed, ¼ of the time in the singlet state and ¾ of the time in the triplet state.

- The fraction of singlets that contribute to prompt scintillation

$$f_s = \frac{1}{n_{s0}}\int \frac{n_s}{\tau_s}dt = \frac{\log(1+\xi)}{\xi}$$

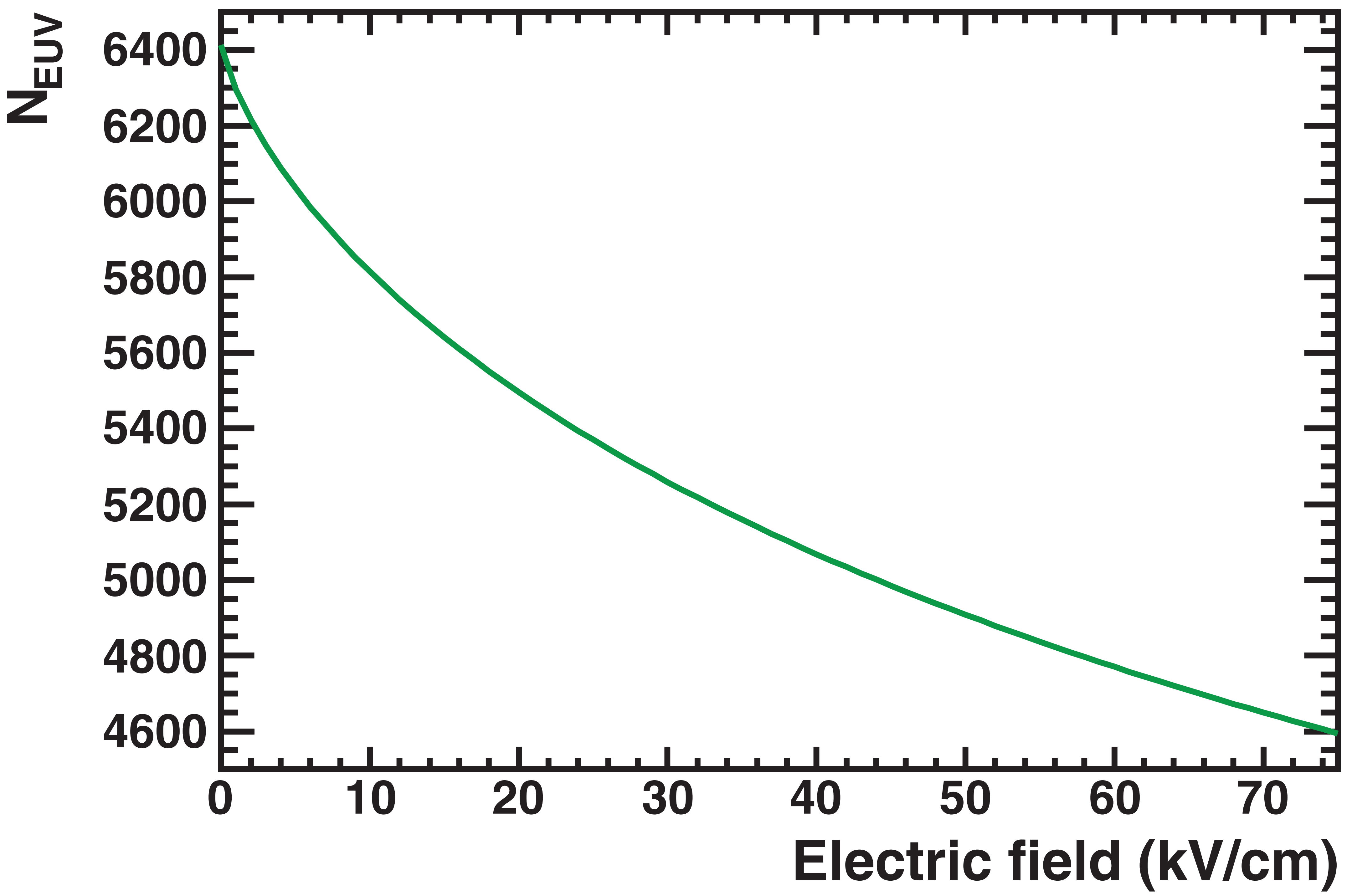
$$\xi = n_{s0}\gamma_s'\tau_s$$

$$\gamma_s' = \gamma_s(\kappa_{ss}+\kappa_{st}r_{ts}) \quad \text{where } n_t = r_{ts}n_s$$

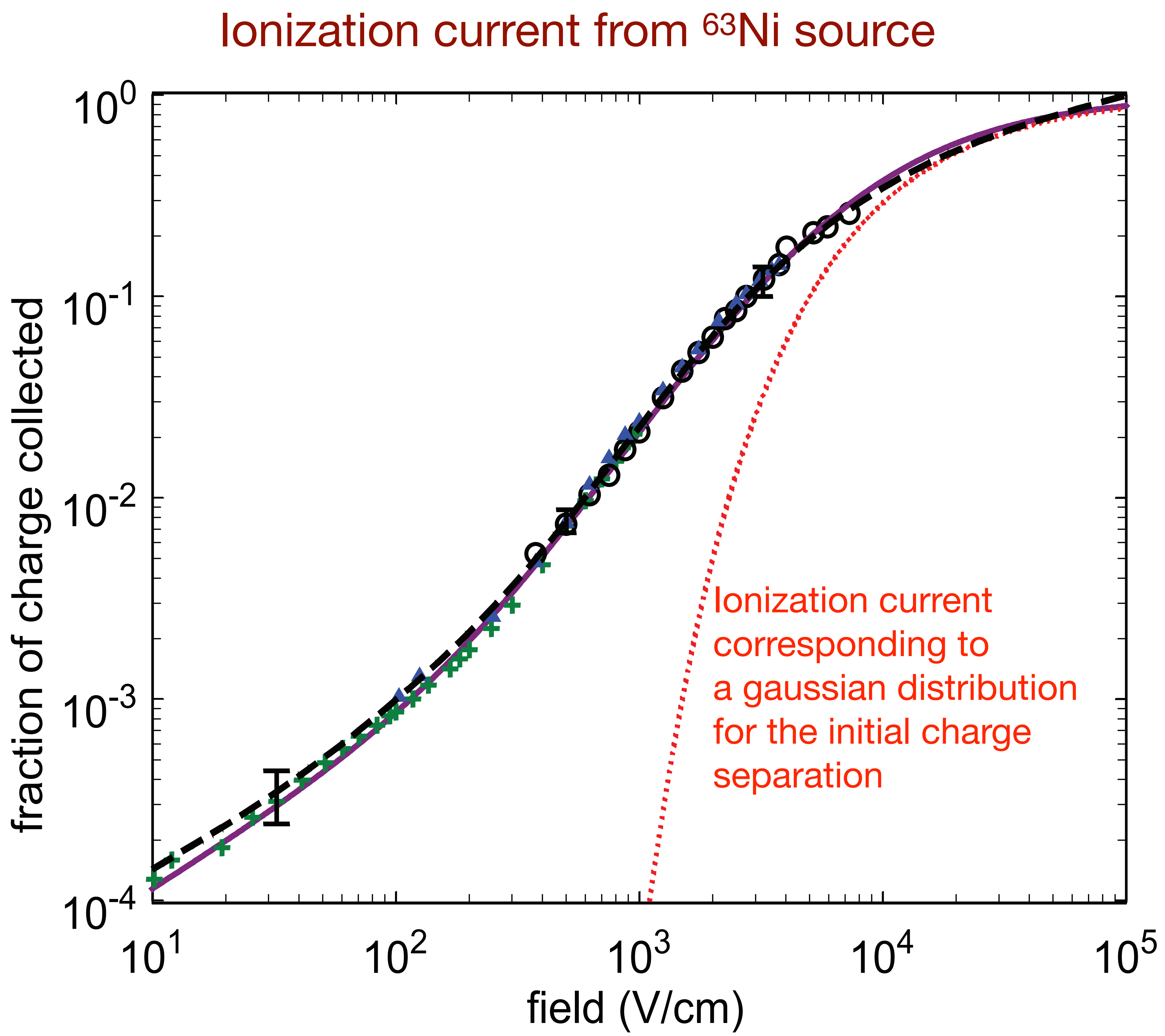
- If we know f_s for α induced scintillation, we can predict what f_s is for neutron capture reaction induced scintillation.
- For α induced scintillation, f_s = 0.47.
  - The fraction of the deposited energy going to the prompt scintillation is 10% whereas the expected value in the absence of quenching is 23%.
- f_s = 0.47 gives ξ=3.5.
  - This gives $\Upsilon_s = 2.3\times10^{-9}$ cm³/s.

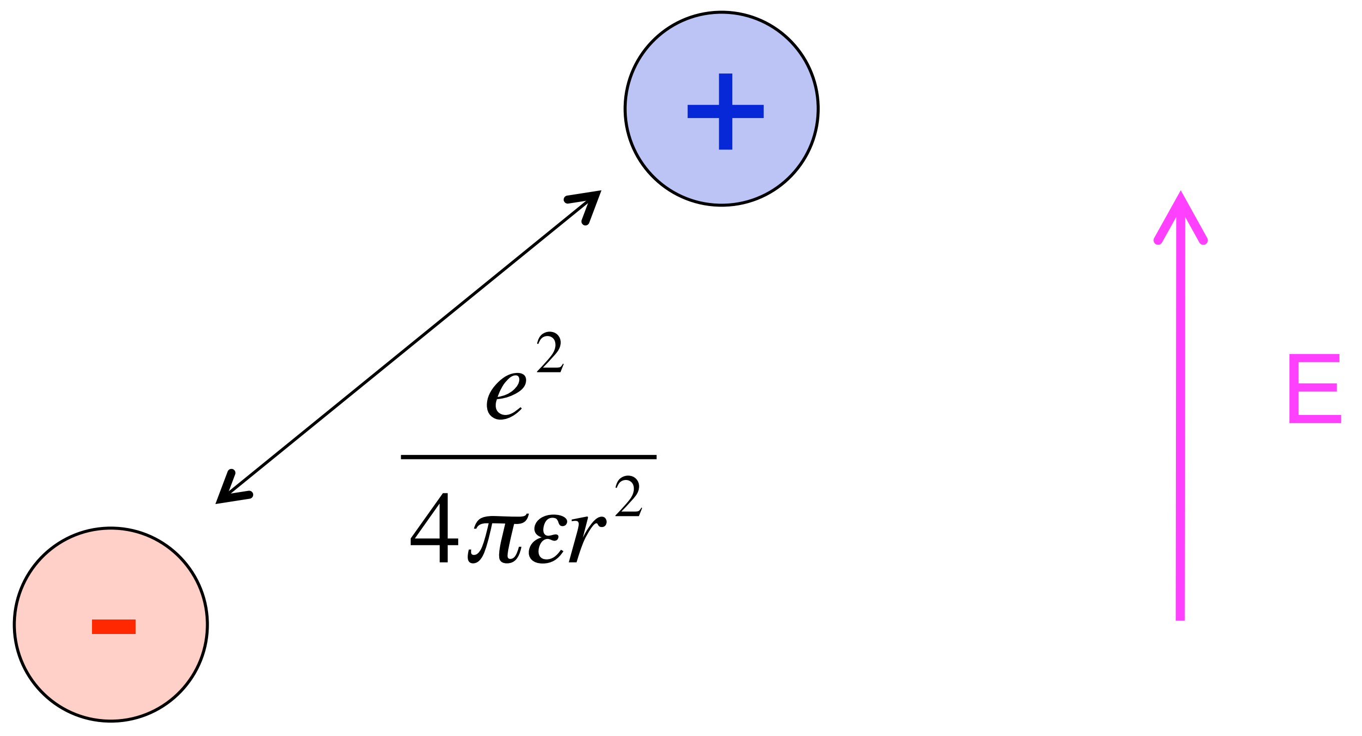
- Setting ξ=1.75 gives f_s = 0.58 for scintillation induced by the $^3He(n,t)^3H$ reaction products.
  - The fraction of the deposited energy that goes to the prompt scintillation is 13%.
  - The number of prompt EUV photons emitted per neutron capture event is ~ 6200 for E=0 kV/cm.

Scintillation yield from n-3He capture in LHe



Ionization current from electron source and initial charge distribution



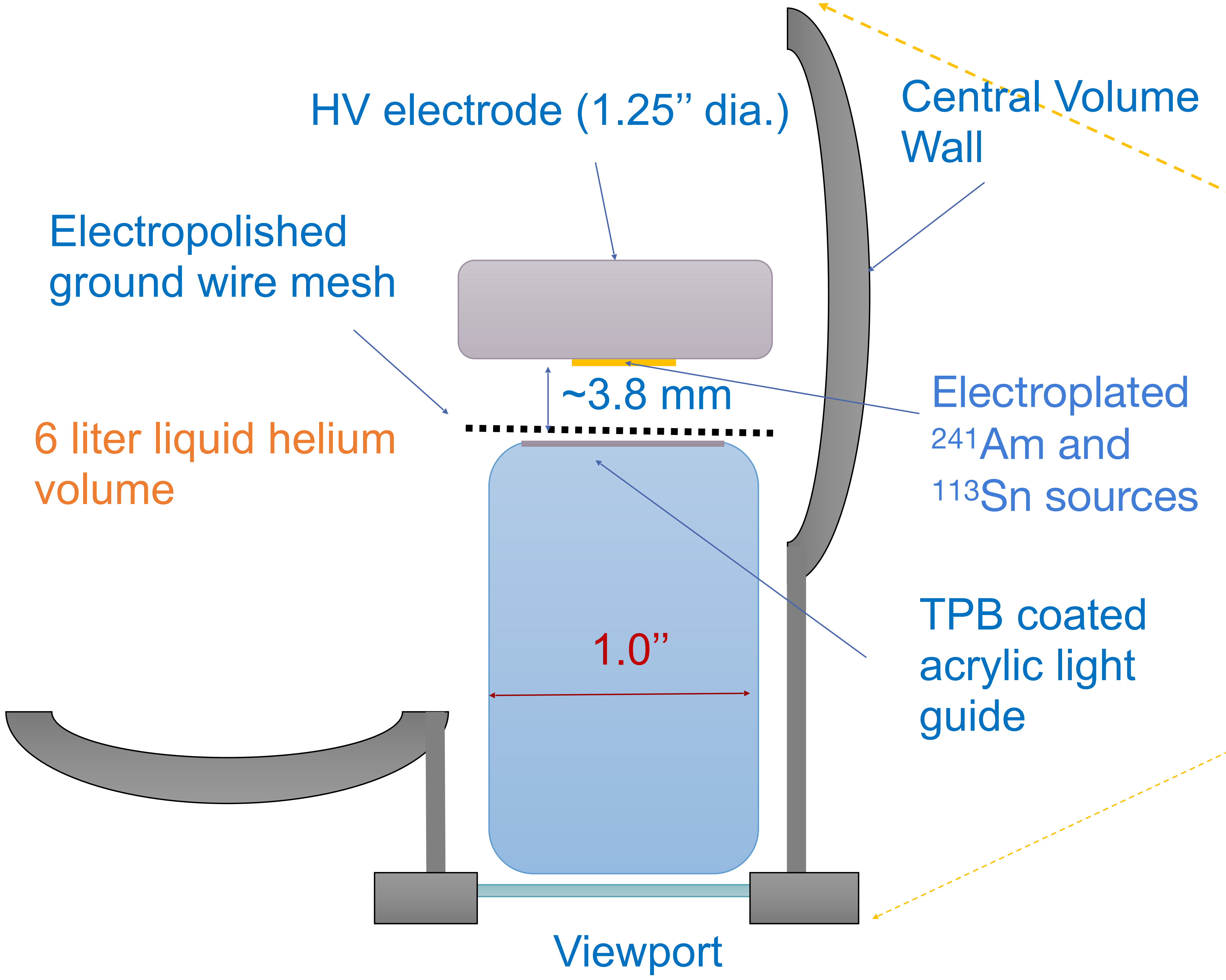


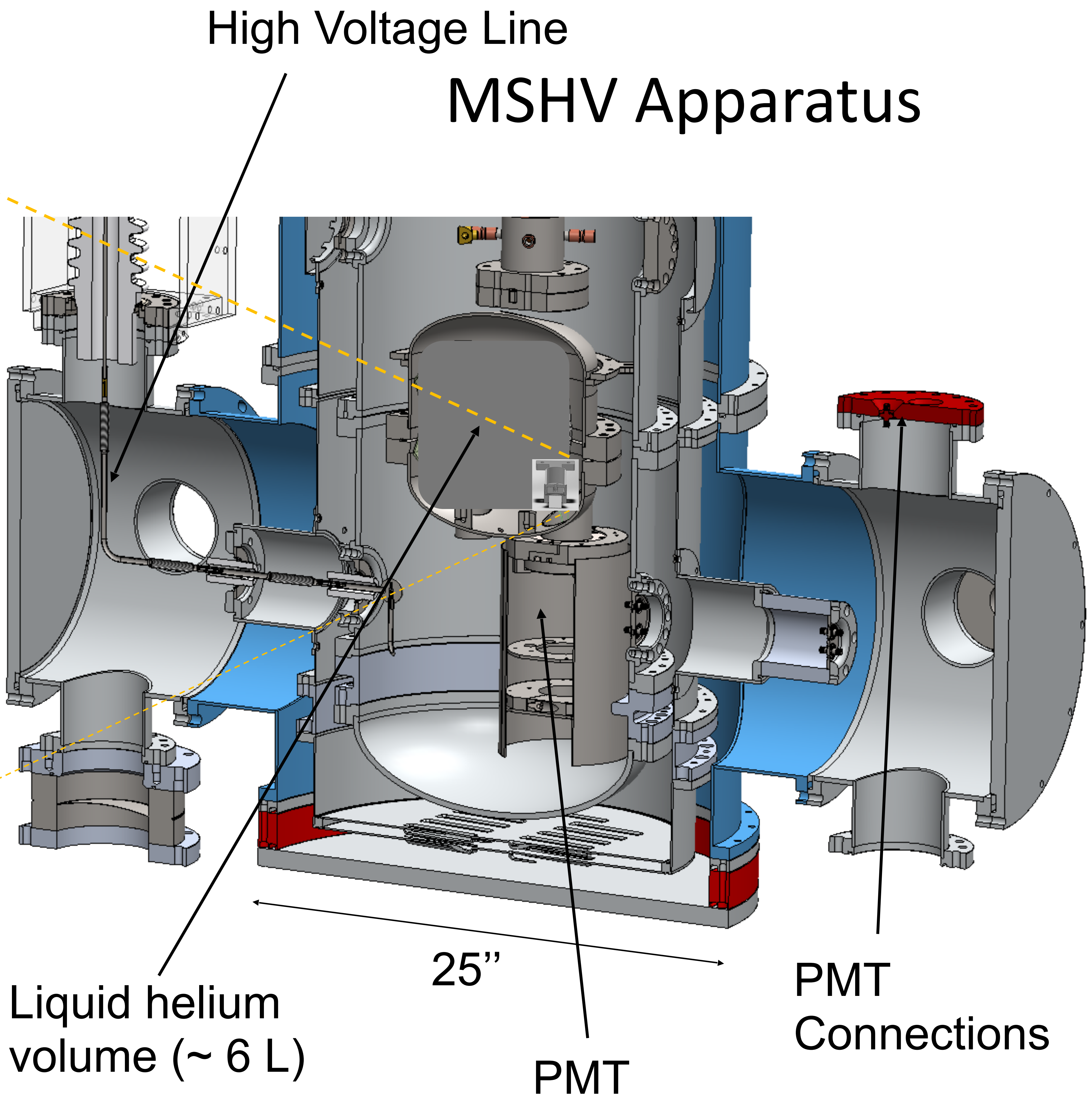
- Each ion-electron pair is spatially separated (geminate recombination).
- The electron and the ion are attracted by the Coulomb force while subject to the external electric field and Brownian motion.
- Condition for separation when no diffusion

$$r^2(1+\cos\theta_0) \geq \frac{2e}{4\pi\epsilon_0 E}$$

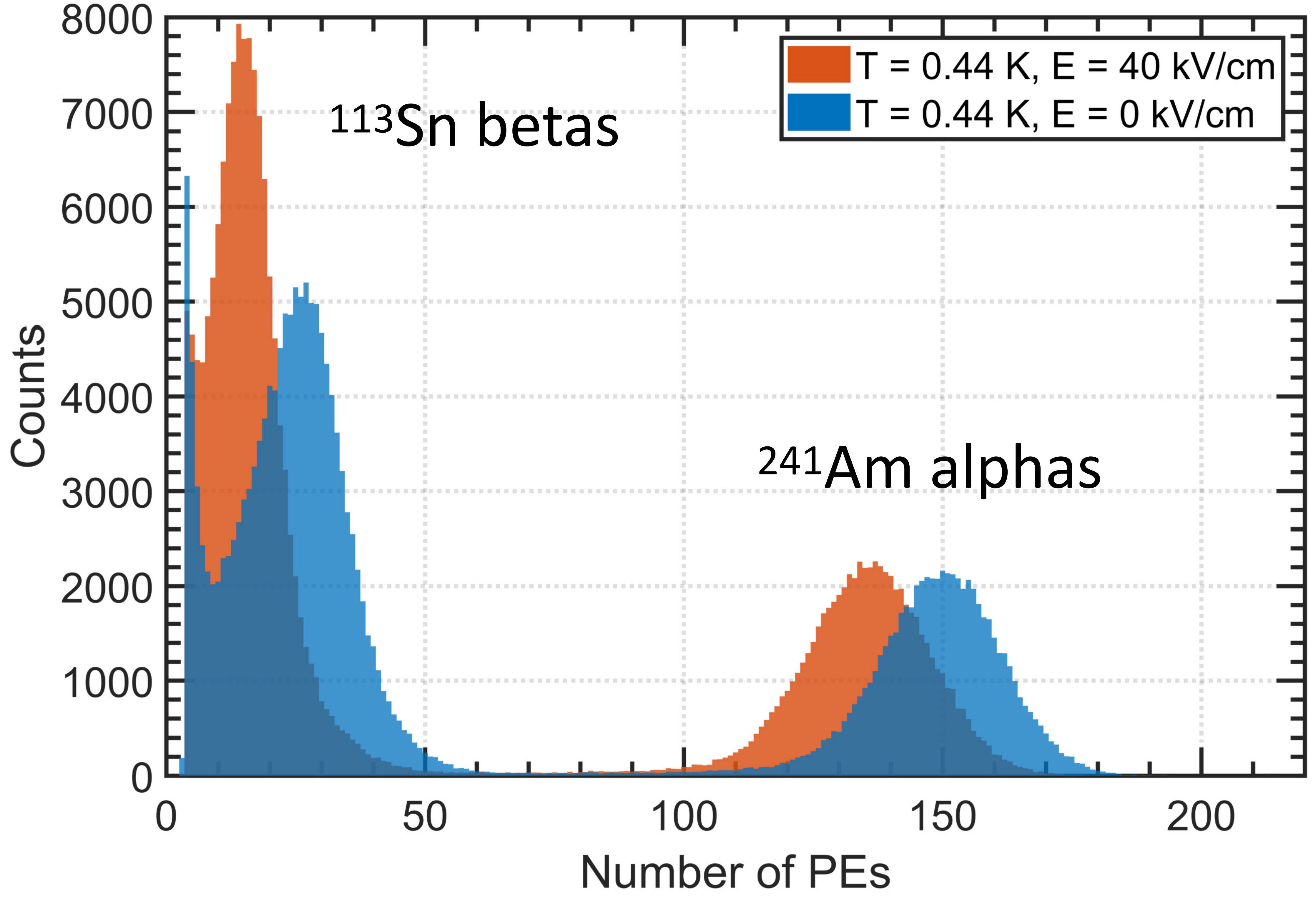
- Therefore, ionization current and the initial charge distribution have a 1-to-1 correspondence

Experimental setup for electron scintillation measurements

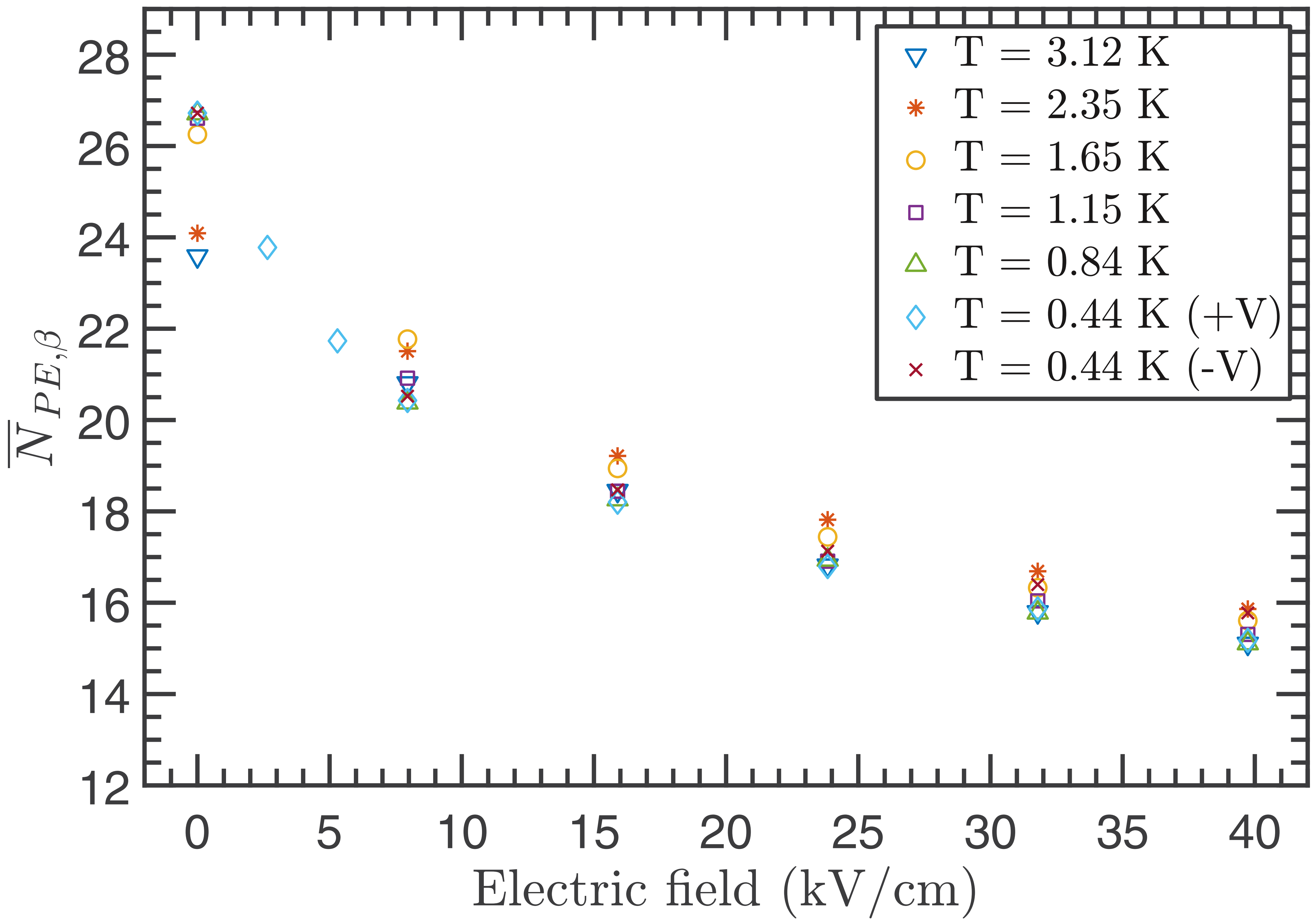




Results for prompt signal (first 100 ns)

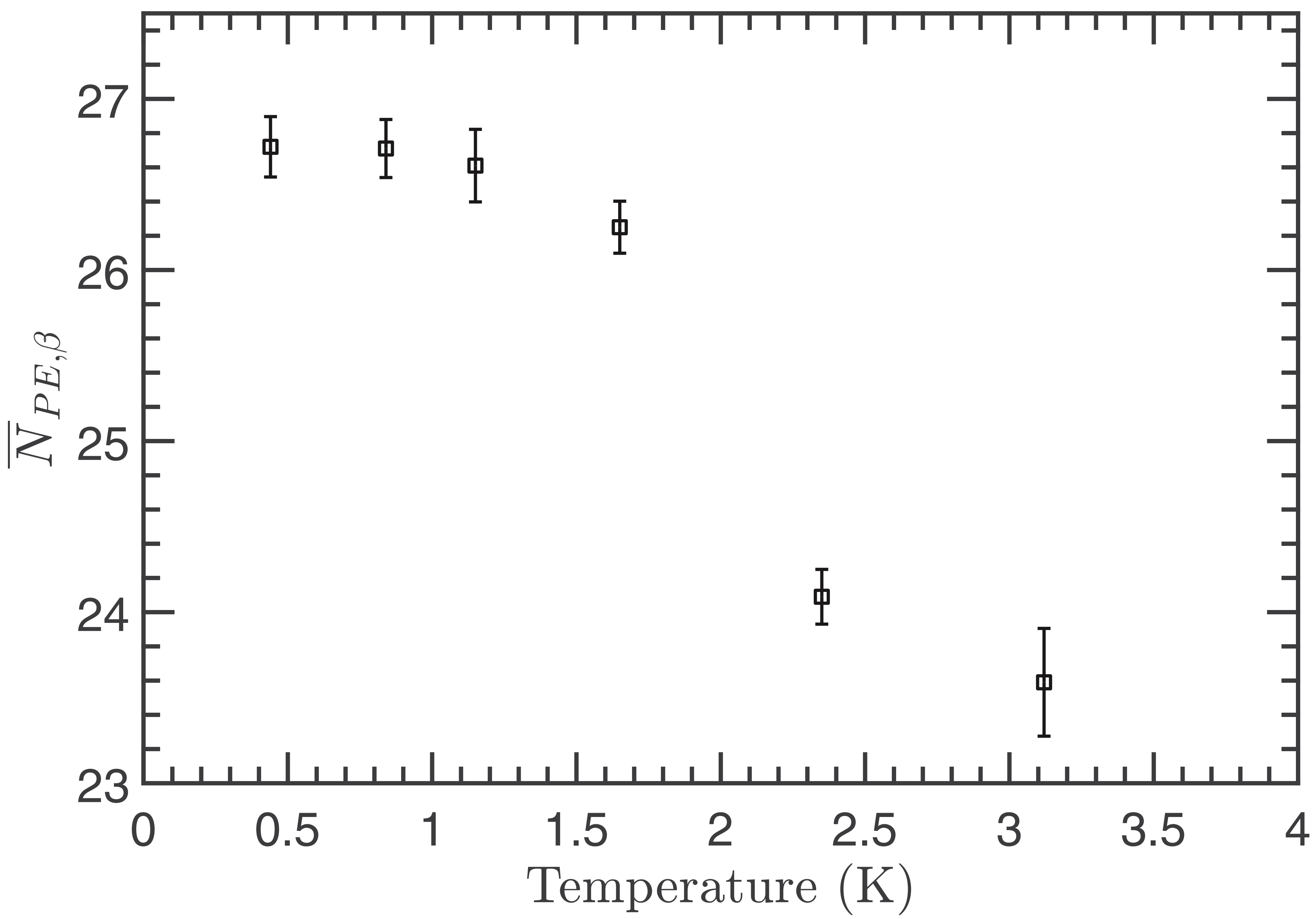


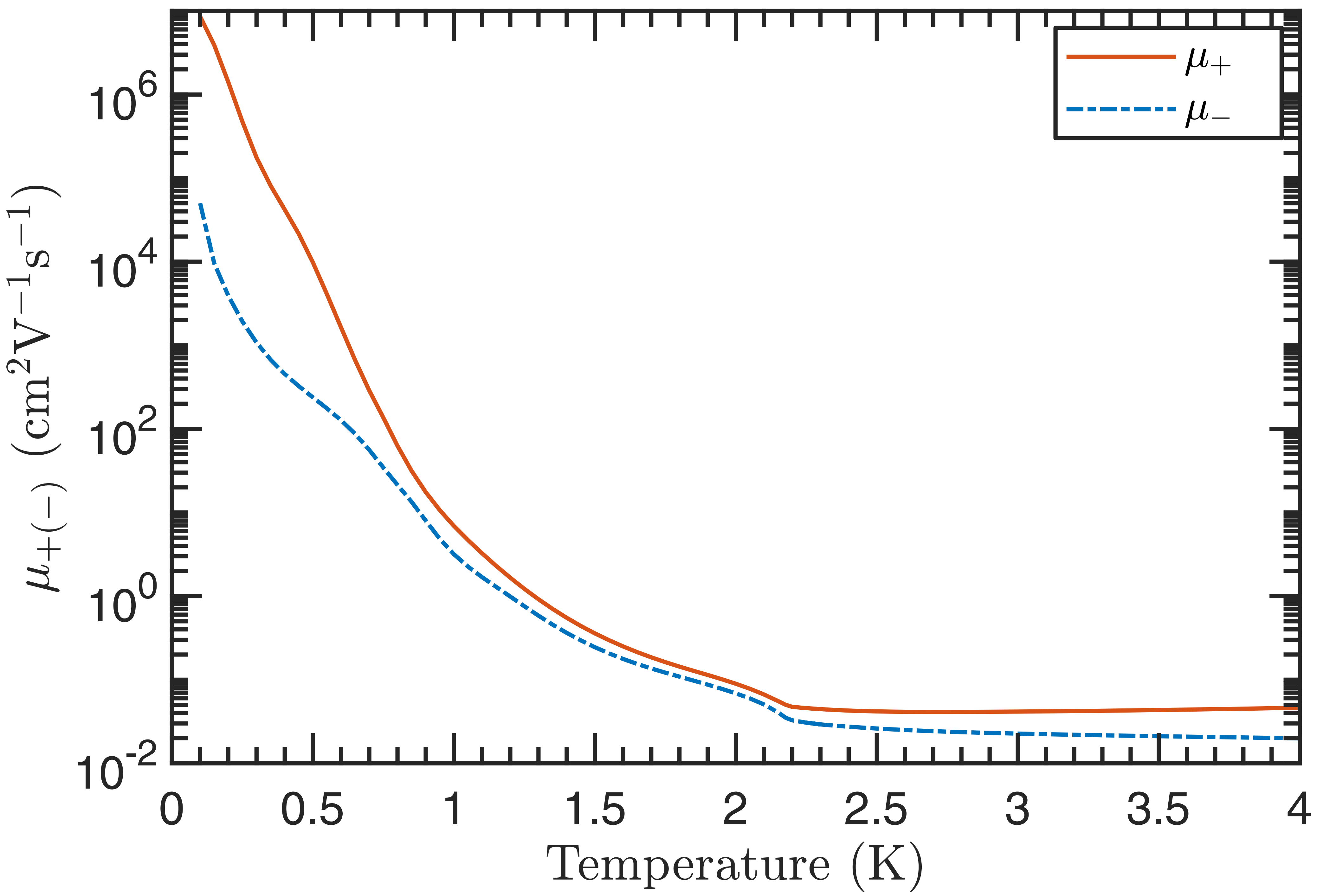
Electrons



- The results for alphas are consistent with our previous results.
- For electrons, the electric field dependence for low temperature data are consistent with what is expected from the ionization current measurement.
- The low field data points for higher temperature data for electrons appear to be at odds with other data points.

Temperature dependence for zero field electron data





- This unexpected temperature dependence for low field data was the reason for the discrepancy seen for low field, high temperature data.

- This, in turn, was caused by the finite recombination time, which has a strong temperature dependance due to the temperature dependent ion mobility

Finite recombination time for zero field scintillation yield

Temperature dependent germinate recombination is described by the Debye-Smoluchowski equation.

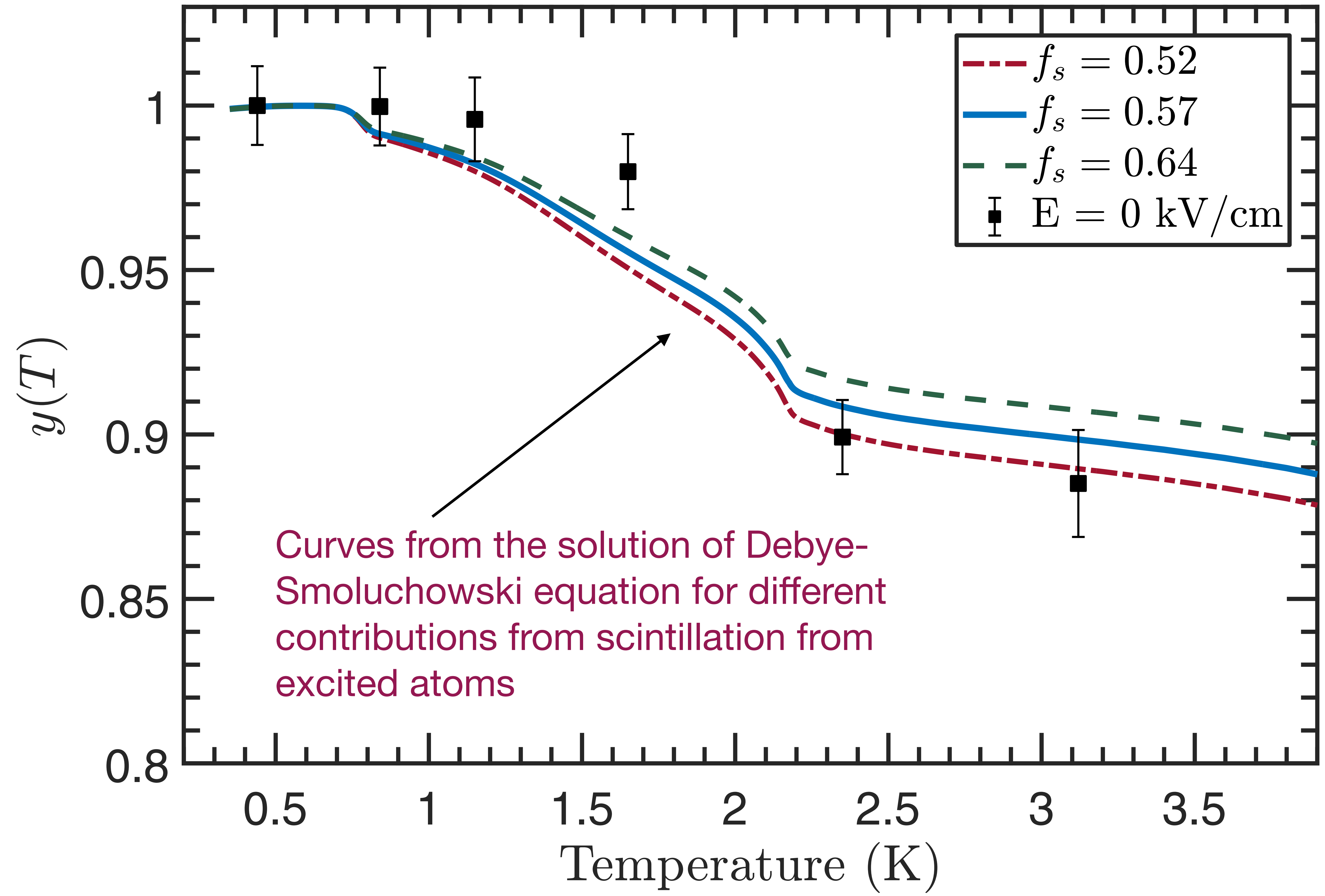
$$\frac{\partial \rho(\vec{r},t)}{\partial t} = \nabla D \bullet \left(\nabla \rho + \frac{\rho}{kT} \nabla U \right)$$

ρ: probability density of the ion-electron distance

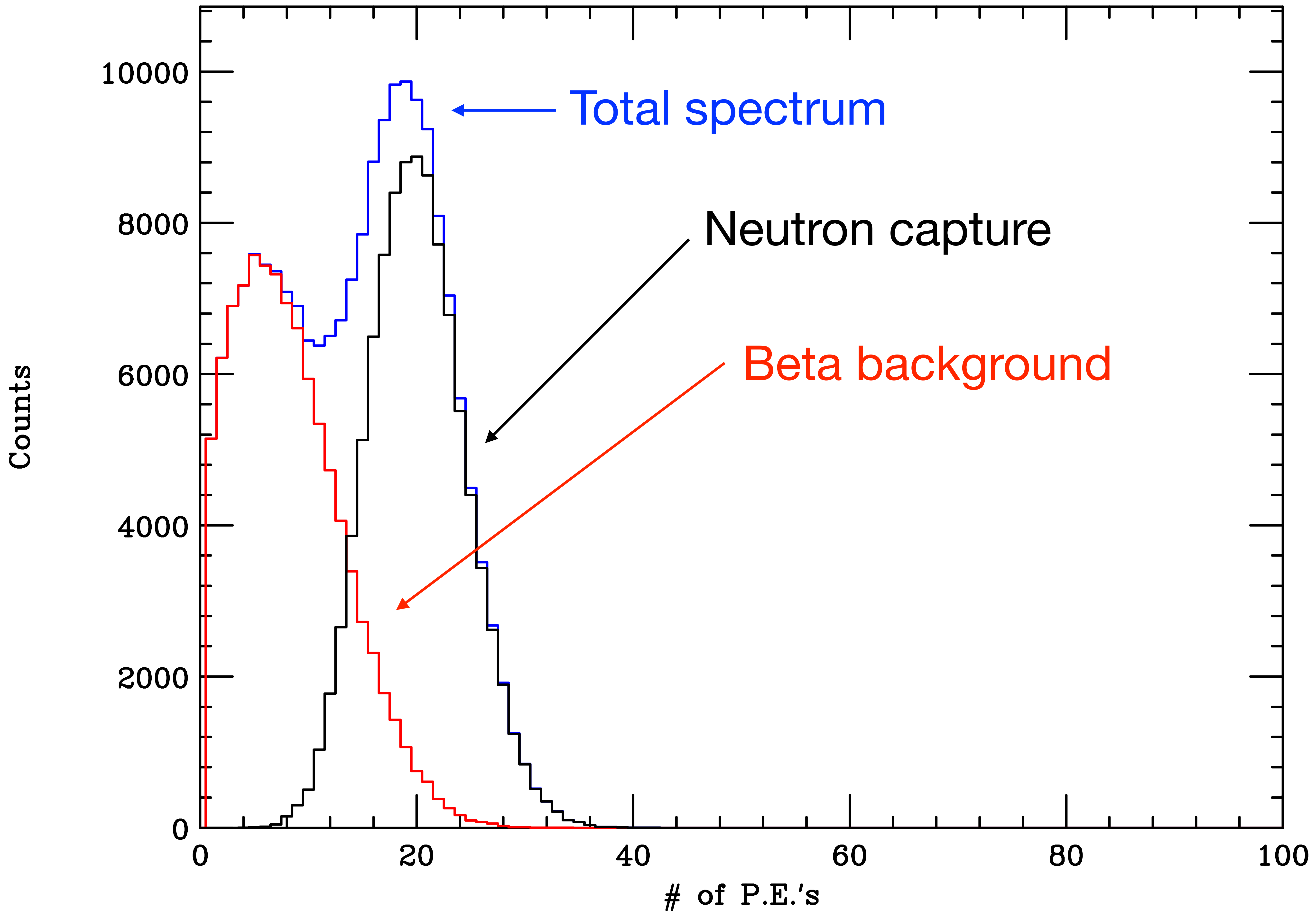
D: diffusion coefficient

U: interaction energy between electron-ion pair

Onsager's theory corresponds to the solution of this equation in the limit of $t \rightarrow \infty$



Simulated spectrum at E = 75 kV/cm



Input/assumptions

Neutron capture

- We expect ~20 PE from V. Cianciolo's light collection R&D
- ~10% of deposited energy is emitted as prompt scintillation light at 75 kV/cm from our measurement with alphas and our model.
  - For alphas, 10% of energy is emitted as prompt from Adams, et al Phys. Lett. B 341, 431 (1995)

For beta background

- α/β ratio = 0.45 from our measurement
- The prompt scintillation light from neutron beta decay is reduced by 48% at 75 kV/cm compared to the zero field value from our measurement.

Summary

- We have measured the electric field dependence of the prompt LHe scintillation yield from alphas and electrons.
- The results from alphas can be well described by the columnar theory of recombination.
- The results from electrons are consistent with our ionization current measurement.
- We observed for the first time the effect of finite recombination time for electrons.
- The results from alphas and our model for quenching predict that for n-3He capture events, ~10% of deposited energy to be emitted as prompt scintillation light at 75 kV/cm.
- The results from electrons indicate that the prompt scintillation light from neutron beta decay is reduced by 48% at 75 kV/cm compared to the zero field value.

References

- T. M. Ito, S. M. Clayton, J. Ramsey, M. Karcz, C.-Y. Liu, J. C. Long, T. G. Reddy, and G. M. Seidel, Phys. “Effect of an electric field on superfluid helium scintillation produced by α-particle sources,” Rev. A **85**, 042718 (2012).

- G. M. Seidel, T. M. Ito, A. Ghosh, and B. Sethumadhavan, “Charge distribution about an ionizing electron track in liquid helium,” Phys. Rev. C **89**, 025808 (2014).

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