PROPERTIES OF CHARGE RECOMBINATION IN LIQUID ARGON

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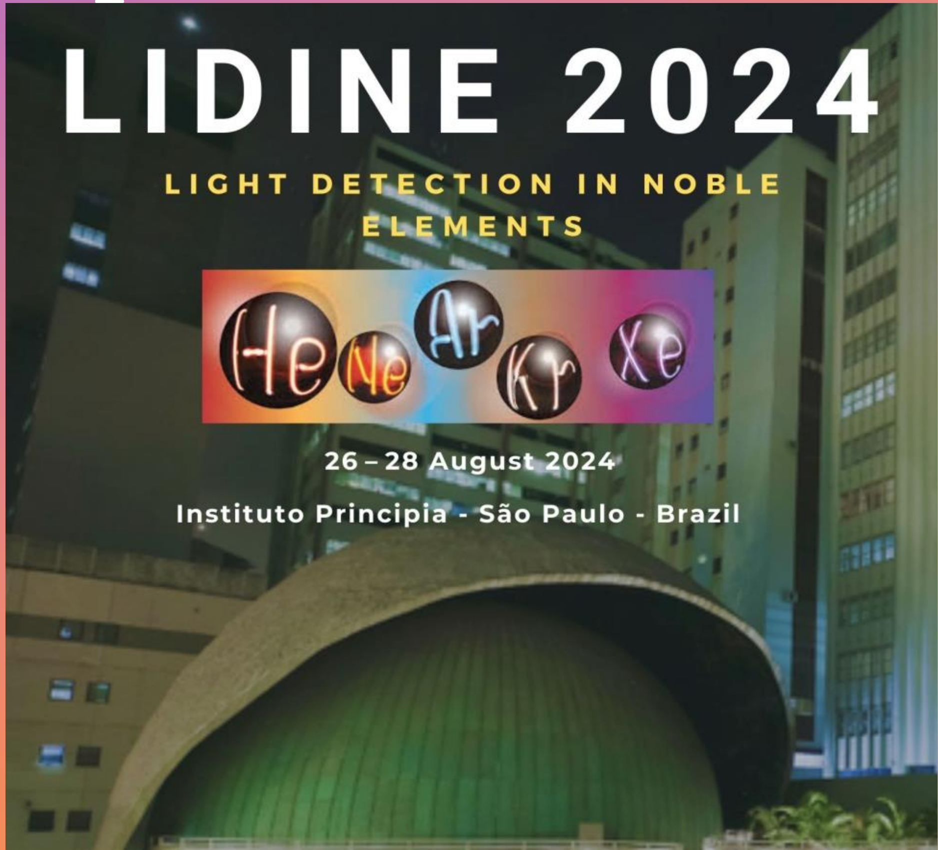

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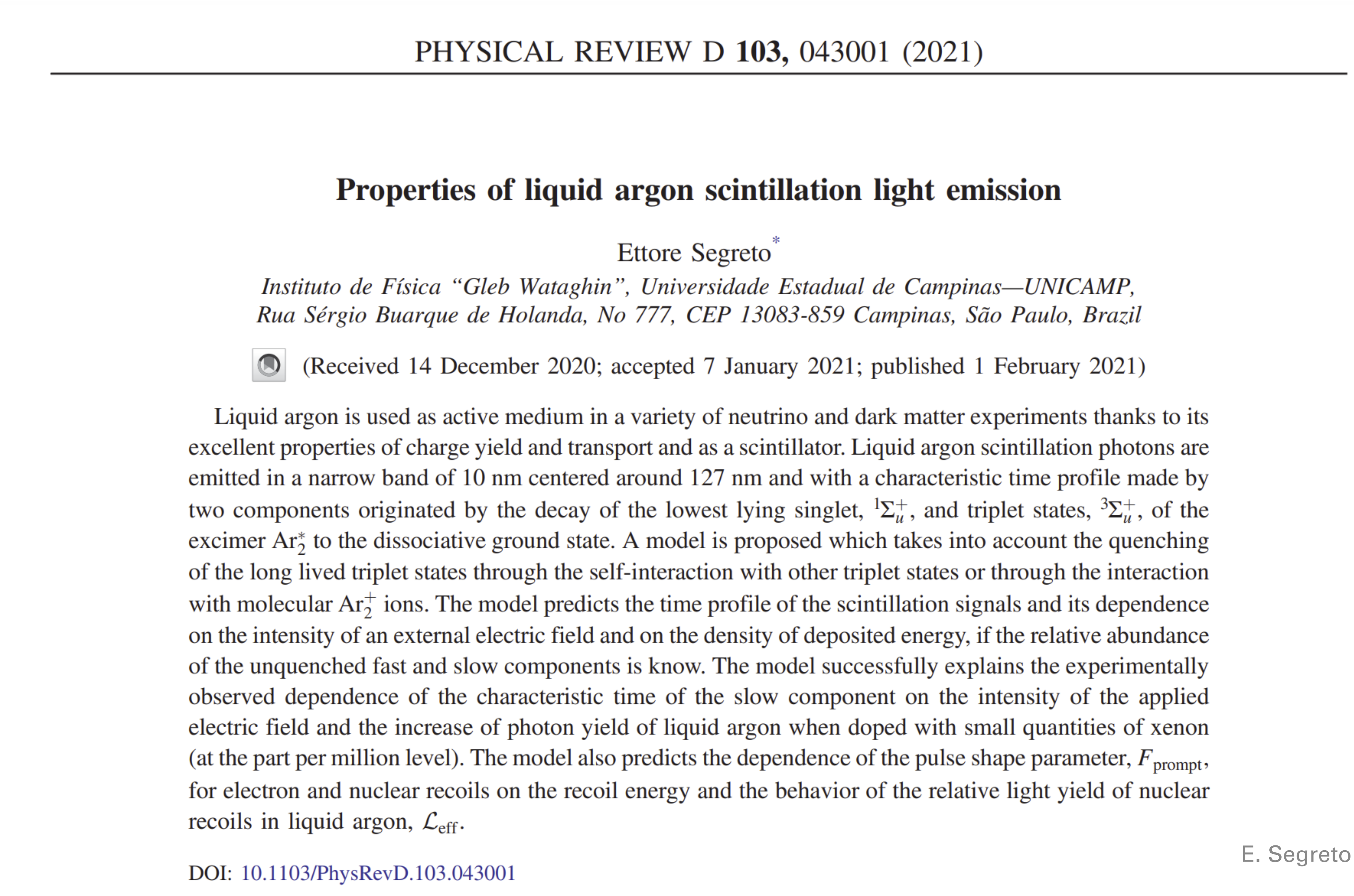
CHARGE RECOMBINATION IN LAR

- Charge recombination is a ***fundamental process for the operation of any LArTPC;***
- The application of *an external electric field*, ε, allows the extract **a fraction of the charge produced** by ionizing radiotion. It is used for doing **calorimetric meaurements** and **tridimensional reconstruction;**
- The rest of the ionization charge recombines and produces *scintillation photons* (together with the excited argon dimers).

MOTIVATION AND INSPIRATION

- Started thinking to the problem of charge recombination while writing a paper on **scintillation light**;
- I found difficoult to navigate through the models available in the literature. ***Lacking of a common picture***
- *Some of the models are adaptations/modifications of other models to fit experimental data*
- Some of the hypotheses of these models ***do not represent very well the ionization track structure at microscopic scale***, at least in some cases
  - *Columnar theory (charge distribution, ion mobility)*
  - *Box model (charge distribution)*
  - *Doke Birks (semi-empirical model)*



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Properties of liquid argon scintillation light emission

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Liquid argon is used as active medium in a variety of neutrino and dark matter experiments thanks to its excellent properties of charge yield and transport and as a scintillator. Liquid argon scintillation photons are emitted in a narrow band of 10 nm centered around 127 nm and with a characteristic time profile made by two components originated by the decay of the lowest lying singlet, ${}^1\Sigma_u^+$, and triplet states, ${}^3\Sigma_u^+$, of the excimer Ar_2^* to the dissociative ground state. A model is proposed which takes into account the quenching of the long lived triplet states through the self-interaction with other triplet states or through the interaction with molecular Ar_2^+ ions. The model predicts the time profile of the scintillation signals and its dependence on the intensity of an external electric field and on the density of deposited energy, if the relative abundance of the unquenched fast and slow components is know. The model successfully explains the experimentally observed dependence of the characteristic time of the slow component on the intensity of the applied electric field and the increase of photon yield of liquid argon when doped with small quantities of xenon (at the part per million level). The model also predicts the dependence of the pulse shape parameter, F_{prompt}, for electron and nuclear recoils on the recoil energy and the behavior of the relative light yield of nuclear recoils in liquid argon, $\mathcal{L}_{\mathrm{eff}}$.

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PROPOSED RECOMBINATION MODEL

- **Local approach** to the recombination problem;
- Charge recombination ***driven by electrostatic interaction between the electronic cloud and the positive ion core;***
- Consider *the details of stopping power for different particles;*
- Consider *the dimension and shape of the electronic cloud* for different particles and in different ranges of energy;

RECOMBINATION MODEL

- The ***infinitesimal amount of charge*** extracted by an electric field ε, from a local energy deposition dE is given by:

$$\boldsymbol{dq = dq_i\, P(\varepsilon, \frac{dq_i}{dx}, Q_i, q_i, \ldots)}$$

$dq_i = dE/w_i$
$Q_i = E_{kin}/w$
w_i is the enery required to creat an electron ion pair

- The ***extraction probability*** is given by the general expression:

$$\boldsymbol{P = \frac{\varepsilon^{\alpha}}{\varepsilon_{1/2} + \varepsilon^{\alpha}}}$$

ε is the intensity of external E field
$\varepsilon_{1/2}$ and α are parameters

- *The recombination fator/charge yield is defined as:*

-

$$R = \frac{1}{Q_i}\int_0^{Q_i} dq$$

$$Q_y = \frac{1}{E_{kin}}\int_0^{Q_i} dq$$

ELECTRONIC RECOILS

- The charge distribution is assumed to have ***cylindrical symmetry*** and the extraction probability is:

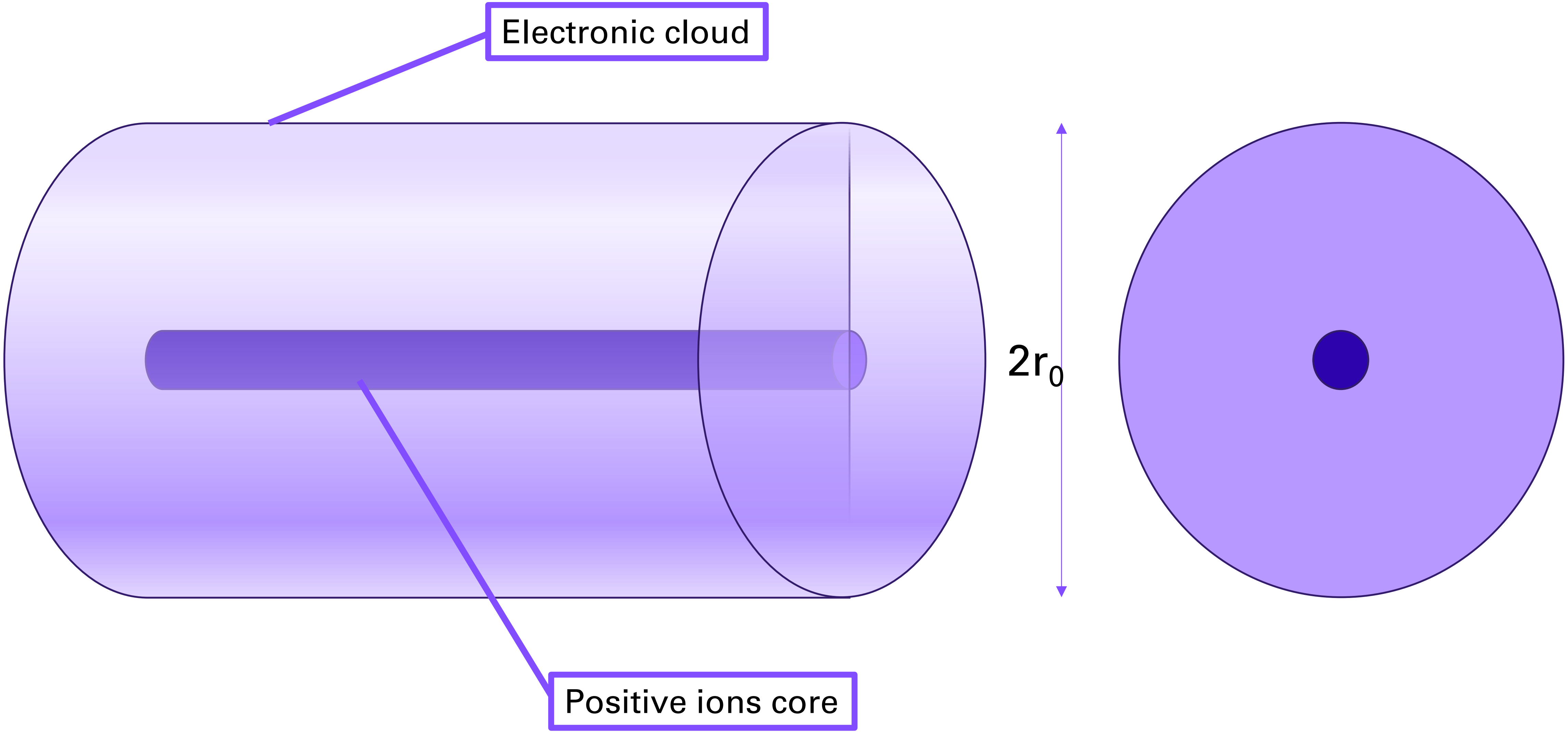
$$\boxed{P = \frac{\varepsilon}{k\,\frac{dq}{dx} + \varepsilon}}$$

$$\boxed{\begin{array}{l} \varepsilon_{1/2} = k\, dq_i/dx \\ a = 1 \end{array}}$$

- *The stopping power*, for E < 1MeV, can be approximated as:

$$\boxed{\frac{dE}{dx} = \frac{\alpha_e}{E} + \beta_e}$$

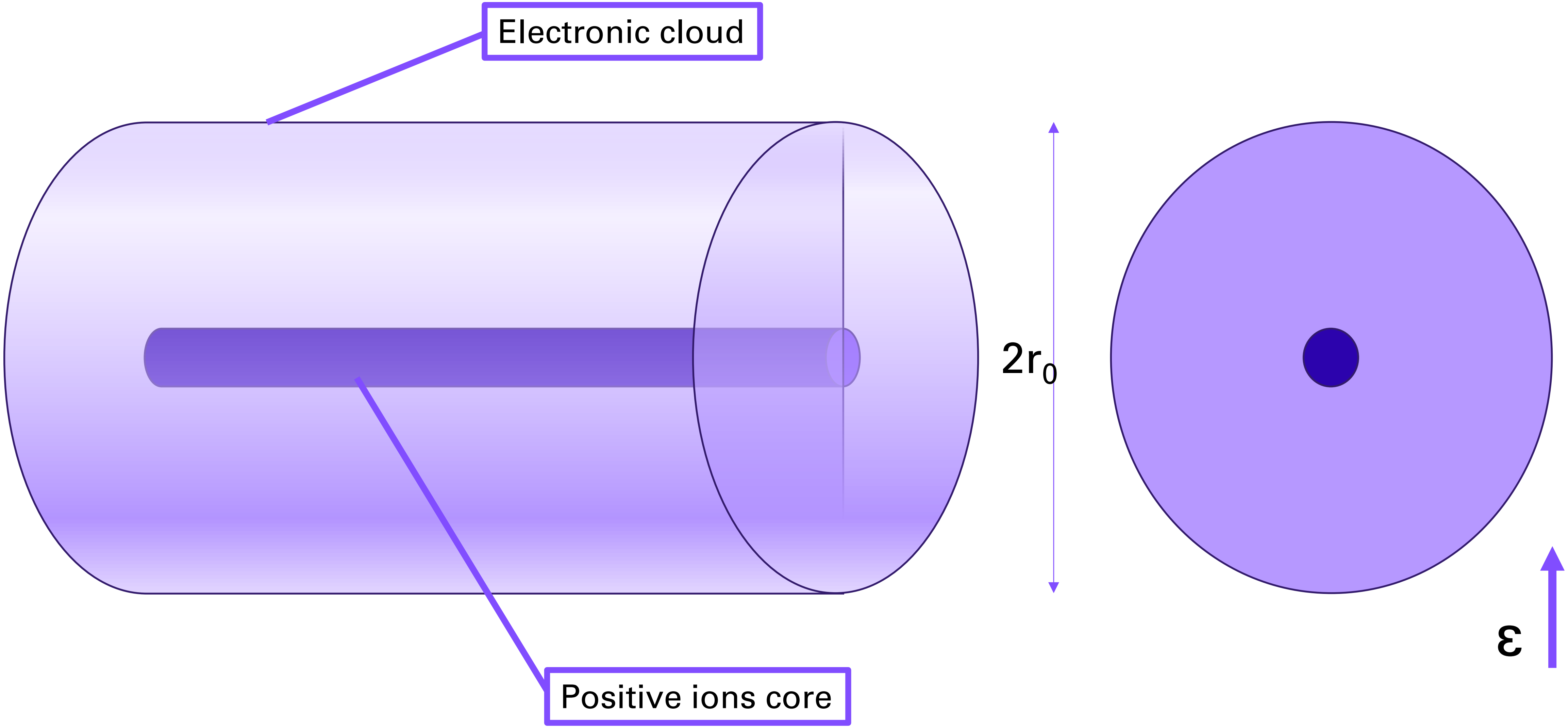
- And w_i is constant (~23.6 eV)



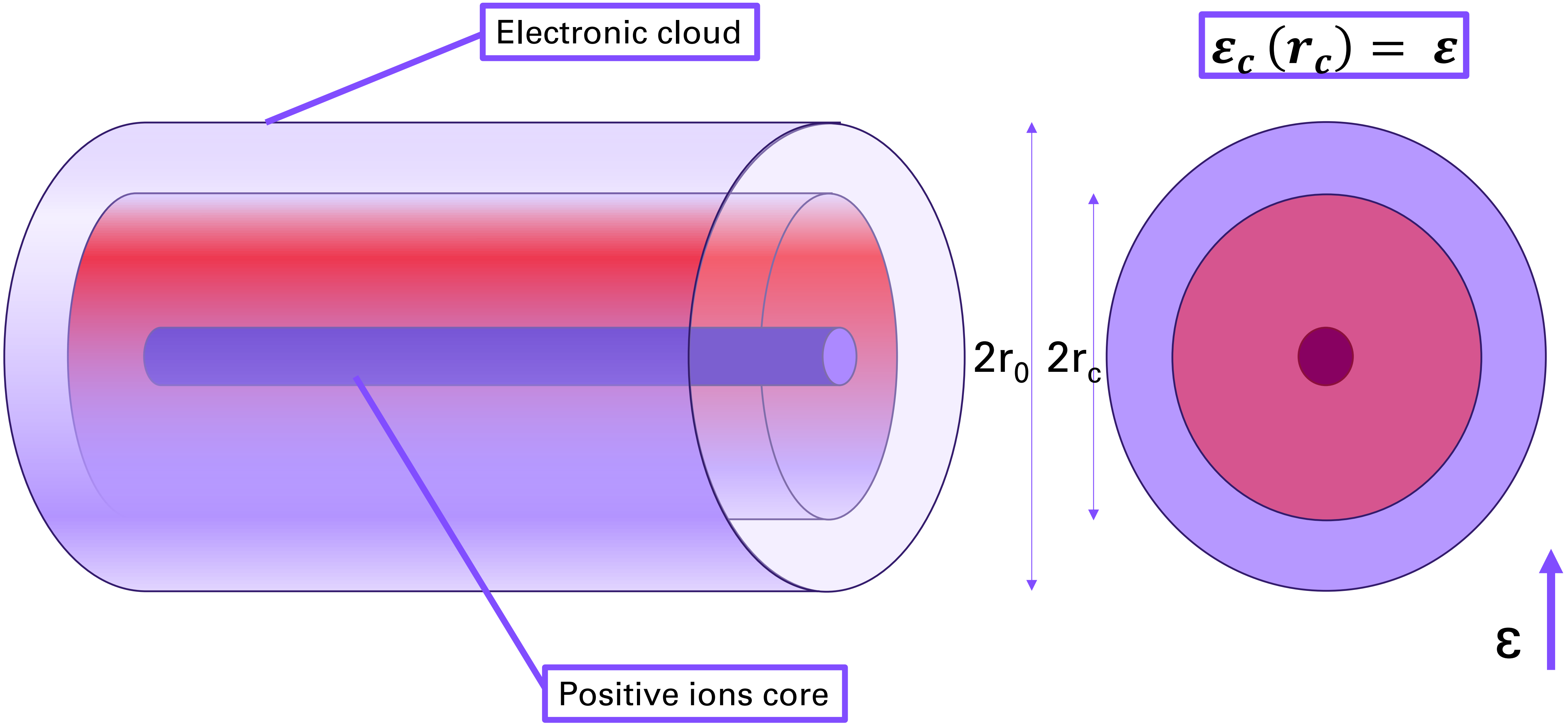
$$\varepsilon_c\,(r) = \frac{\lambda}{2\pi\epsilon}\left(\frac{1}{r} - \frac{1}{r_0}\right) = \varepsilon_0\left(\frac{r_0}{r} - 1\right)$$

$$\boxed{\boldsymbol{\varepsilon_0 = \frac{\lambda}{2\pi\epsilon r_0}}}$$

$$\boxed{\boldsymbol{\lambda = \frac{dq_{i\,*}e}{dx}}}$$



Consider the application of an external electric field



$$\boxed{\boldsymbol{\varepsilon_c(r_c) = \varepsilon}}$$

$$P = 1 - \frac{r_c}{r_0} \Rightarrow \frac{\varepsilon}{\varepsilon_0} = \frac{P}{1-P} \Rightarrow \boxed{\boldsymbol{P = \frac{\varepsilon}{k\,\frac{dq_i}{dx} + \varepsilon}}}$$

$$\boxed{\boldsymbol{k = \frac{e}{2\,\pi\,\epsilon\,r_0}}}$$

ELECTRONIC RECOILS

- Integrating ***the extracted charge*** between 0 and E_{kin}, gives:

$$\boxed{R = \frac{\varepsilon}{\varepsilon + \frac{k}{w_i}\beta_e}\left[1 - \frac{\log(1+z)}{z}\right]}$$

- Where:

$$\boxed{z = \frac{\varepsilon + \frac{k}{w_i}\beta_e}{\frac{k}{w_i}\alpha_e}E_{kin}}$$

ELECTRONIC RECOILS – ESCAPING ELECTRONS

- A fraction of ***ionization electrons escapes recombination*** even in the *absence of an electric field*;
- Defining de **escaping probability** as:

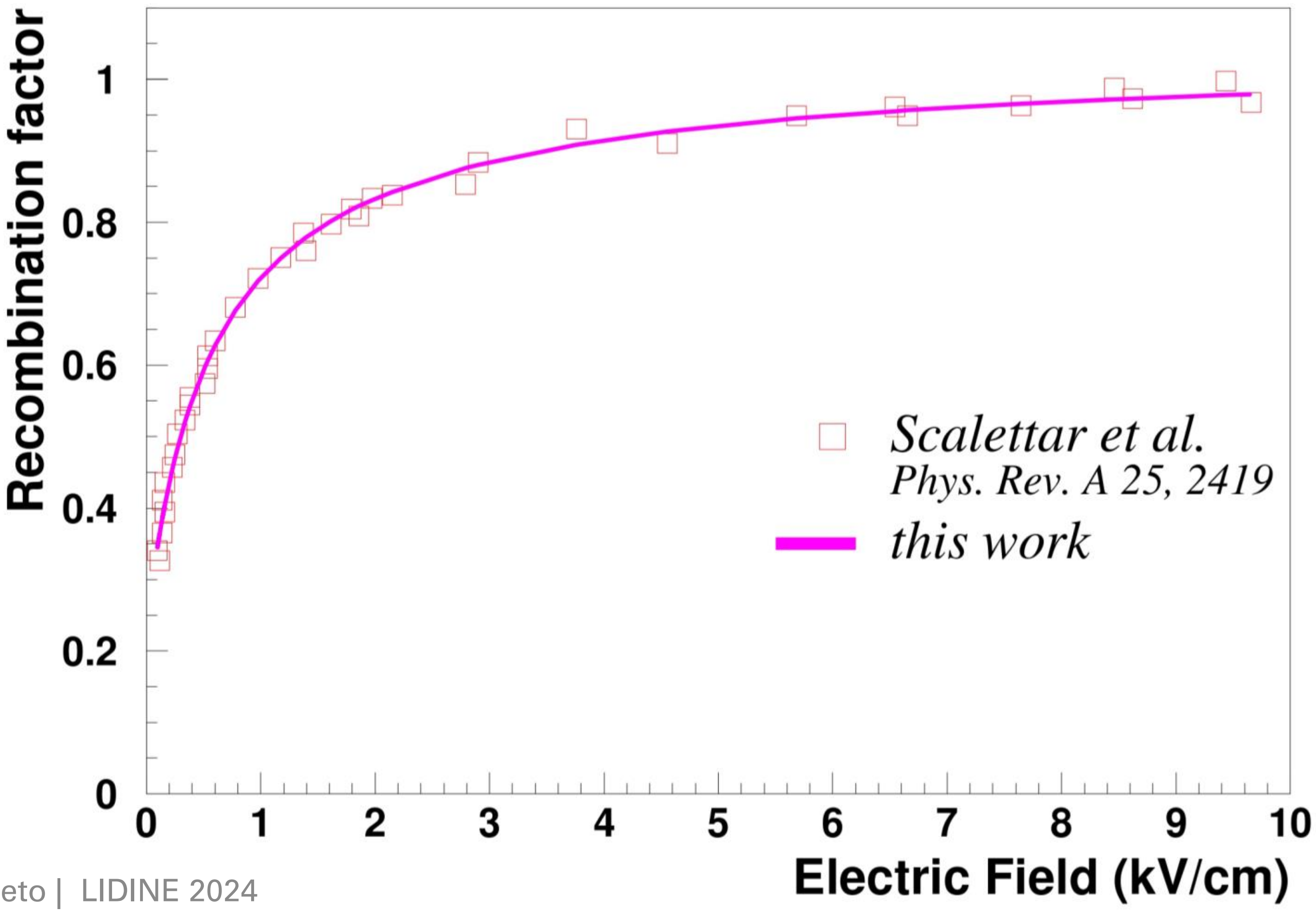
$$S = \frac{1}{1 + \frac{1}{\gamma}\frac{dq}{dx}}$$

R depends on two parameters: k and γ

- ***The recombination factor becomes:***

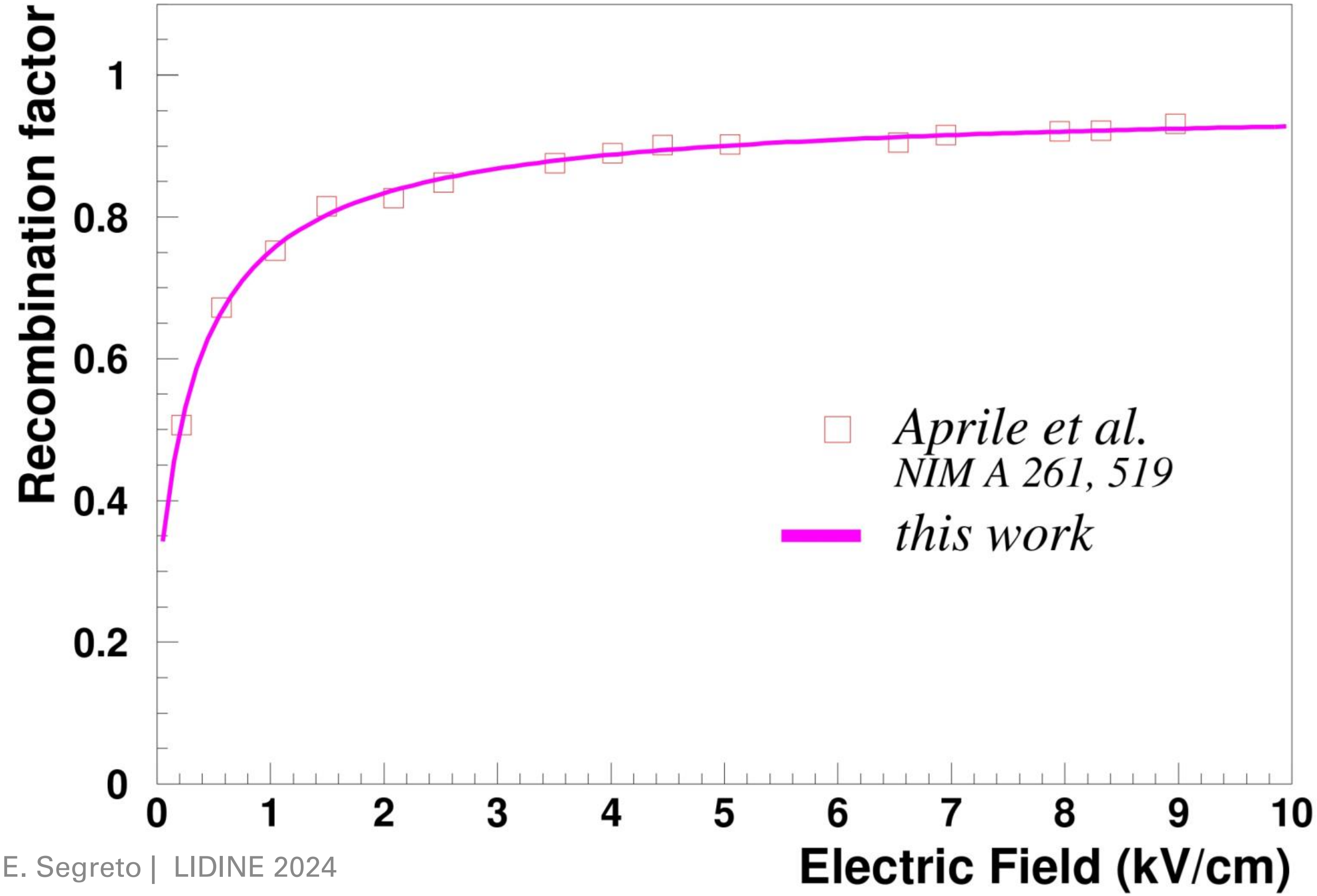
$$\boxed{R_e = R \, * \left(1 + \frac{k\,\gamma}{\varepsilon}\right)}$$

ELECTRONIC RECOILS – COMPARISON WITH DATA



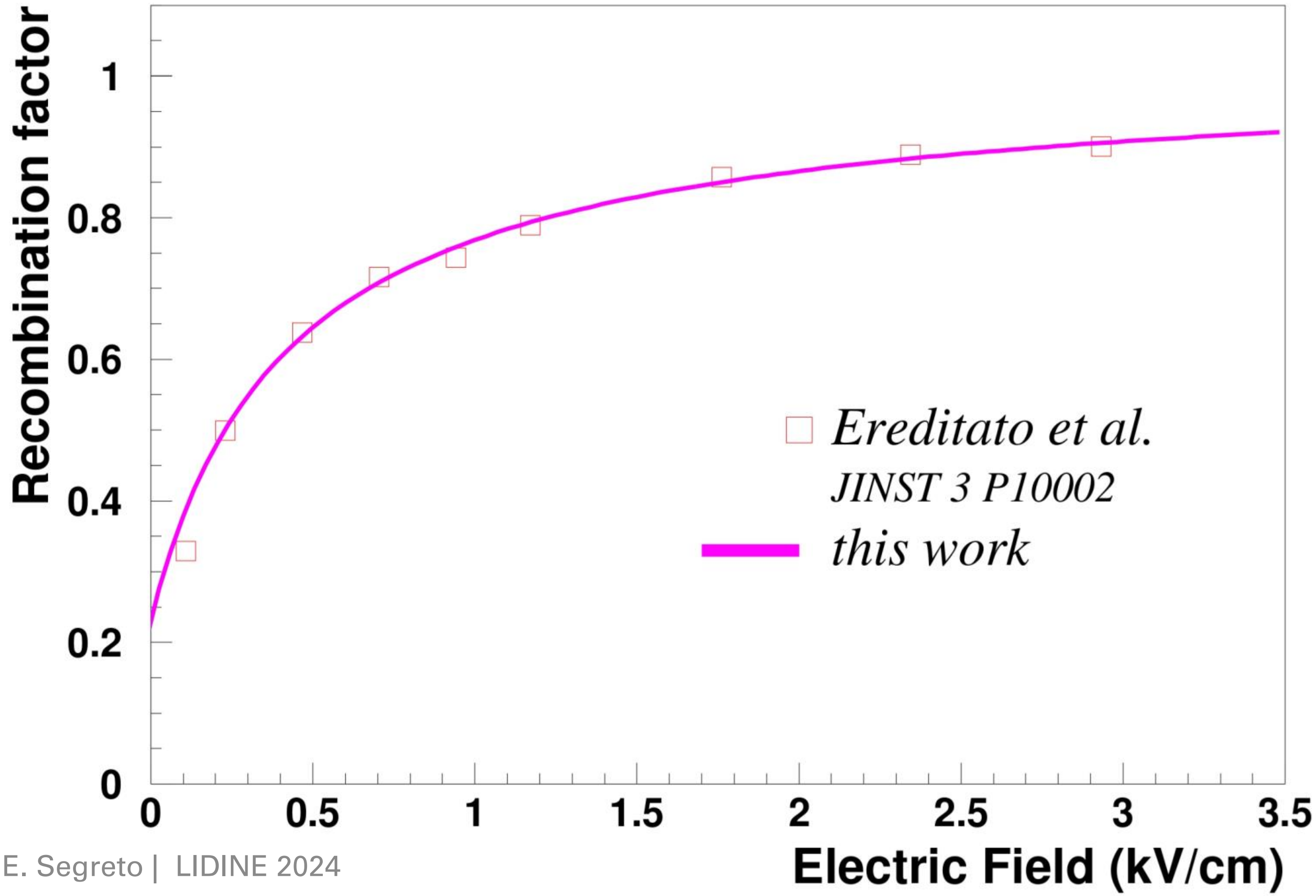
Electrons from a ^{113}Sn source (364 keV)

ELECTRONIC RECOILS – COMPARISON WITH DATA



Electrons from a ^{207}Bi source (976 keV)

ELECTRONIC RECOILS – COMPARISON WITH DATA



Compton electrons from ^{60}Co γ scattering (~ 1 MeV)

ELECTRONIC RECOILS - RESULTS

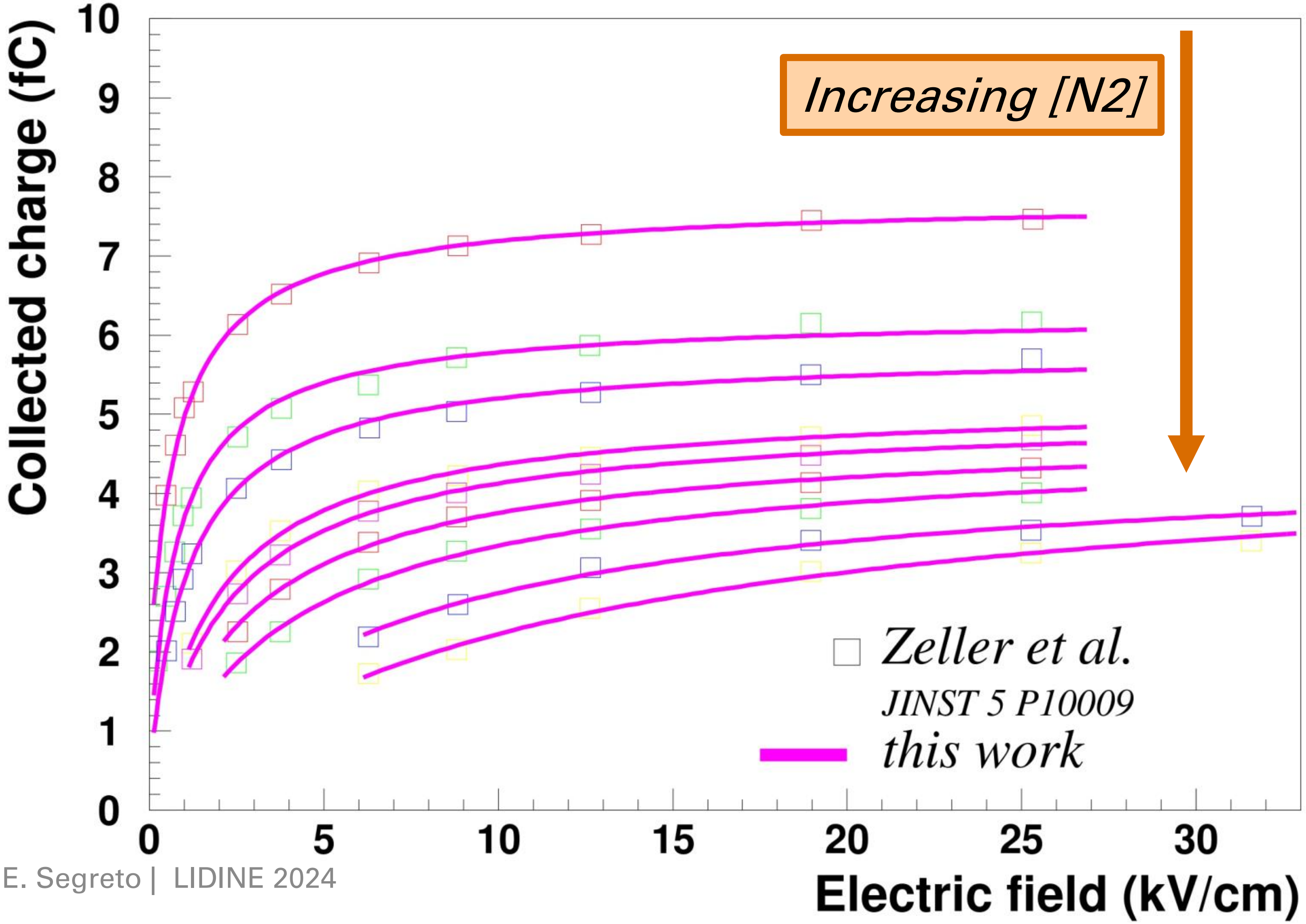
	Energy (keV)	K (mV)	γ (μm^{-1})
Scalettar	364	3.9 ± 0.2	3.0 ± 0.2
Aprile	976	3.7 ± 0.3	2.8 ± 0.3
Ereditato	1004	4.2 ± 0.4	2.3 ± 0.5
All		**3.8 ± 0.2**	**2.8 ± 0.2**

Using the value ok k = 4 mV it is possible to estimate the radius od the electronic cloud. $r_0 = e / 2\pi\varepsilon k \sim 500\ nm$

ELECTRONIC RECOILS – NITROGEN DOPED LAR

- **Interesting test of the model**: N_2 molecules have *vibrational states that can absorb efficiently the energy of the ionization electrons* (~10 eV) => **reduction of the theramlization length** => **increase of the factor k**
- The **thermalization length decreases exponentially** with the N_2 concentration => **k needs to increase exponentially**
- ***$K = K_0 exp(h*[N2])$***, with *K_0 and h independent of [N2]*
- w and γ left as free parameters which depend on [N2]

ELECTRONIC RECOILS – NITROGEN DOPED LAR



Increasing [N2]

From pure LAr to 14.9% of N2 (1%, 3%, 5.6%, 6.4%, 7.9%, 9.9%, 12.4%, 14.9%)

The model **describes well the data**. H ~ 20.8

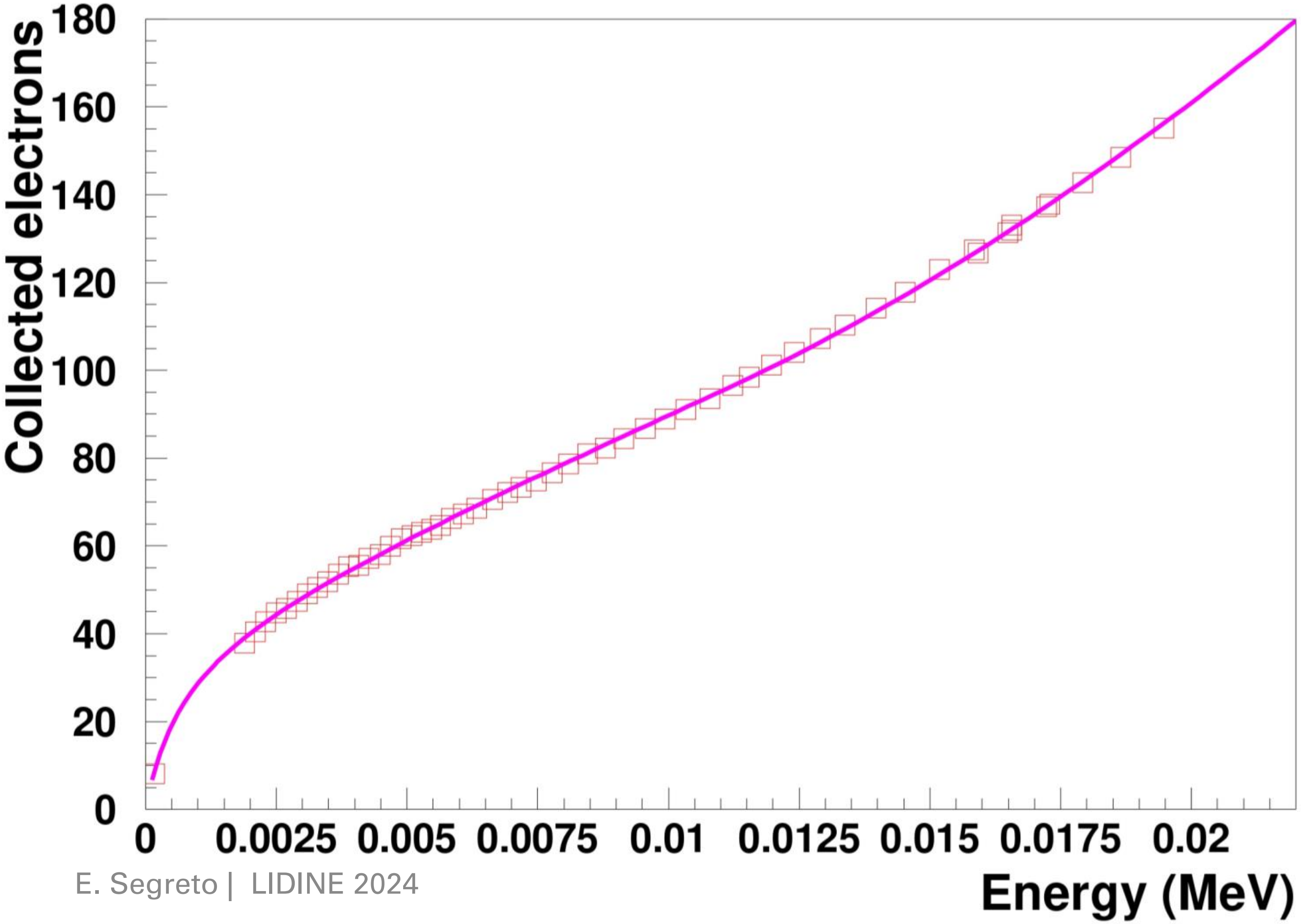
w increases from 23.6 eV up to 39.0 => *some quenching mechanism at production stage*

ELECTRONIC RECOILS – LOW ENERGY LIMIT

- When the energy of the primary electron ***drops below a certain limit***, *the spatial extension of the free electrons' cloud exceeds the length of the positive ions' track and takes an approximately spherical shape*;
- This limit is reached when approximately $E_{kin} = \sqrt{4\,\alpha_e r_0} \approx 7\,keV$
- The **extraction probability** is given by:

$$\boxed{P = \frac{\varepsilon}{k_l\,Q_i + \varepsilon}}$$

ELECTRONIC RECOILS – LOW ENERGY LIMIT



Data set from the DarkSide Collaboration for recoil energies <20 keV

The fit estimates the limit between low and high energy regimes. It results to be E_{bd} ***~10 keV.***

NUCLEAR RECOILS

- Nuclear recoils with **E_{kin} < 100 keV produce ionization tracks < 200 nm**
- It is reasonable to assume that ***the electronic cloud assumes an approximately spherical shape around the positive ions' core.*** Similar to the case of low energy electrons
- The difference is that *the speed of the recoiling Ar nucleus is much smaller than that of the emitted ionization electrons*
- The ***electronic cloud evolves in a sort of onion structure of overlapped shells***, *where each shell feels the electric field of the entire positive ions' track, screened by the innermost shells*

NUCLEAR RECOILS

- ***The extraction probability depends on the residual energy of the recoiling nucleus*** and is given by:

$$\boxed{\boldsymbol{P = \frac{1}{\frac{k_n\, q_i}{\varepsilon^{\alpha}} + 1}}}$$

- And the ***recombination factor*** is:

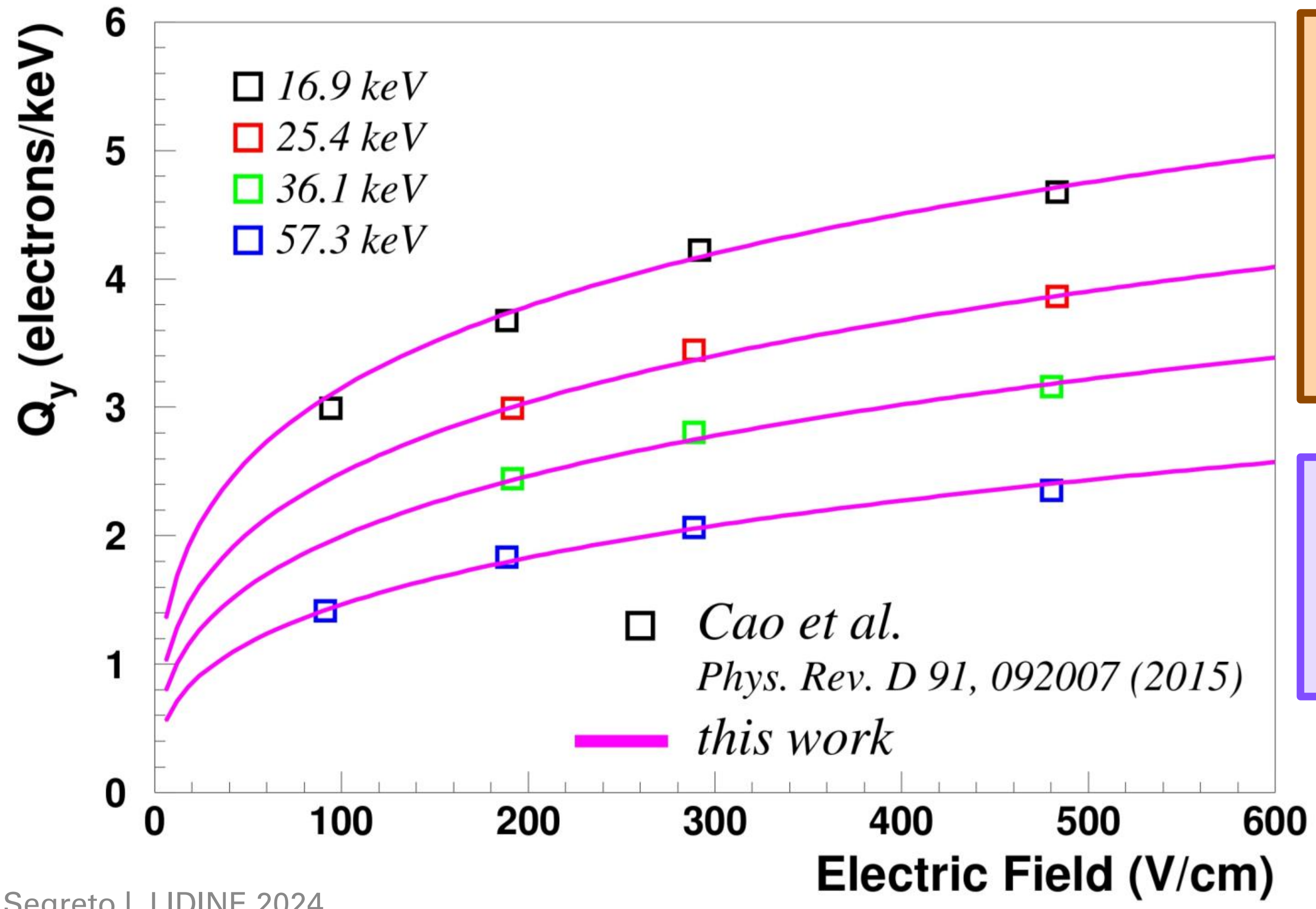
$$\boxed{\boldsymbol{R^n = \frac{1}{z_n} \log(1 + z_n)}}$$

$$\boxed{z_n = k_n \frac{Q_i}{\varepsilon^{\alpha}}}$$

$$\boxed{Q_i = \frac{\eta(\xi)}{w_i C_\xi} = \frac{0.427 * (C_\xi\, E_{kin})^{1.193}}{w_i\, C_\xi}}$$

Where k_n depends on the size of the spherical electronic cloud distribution

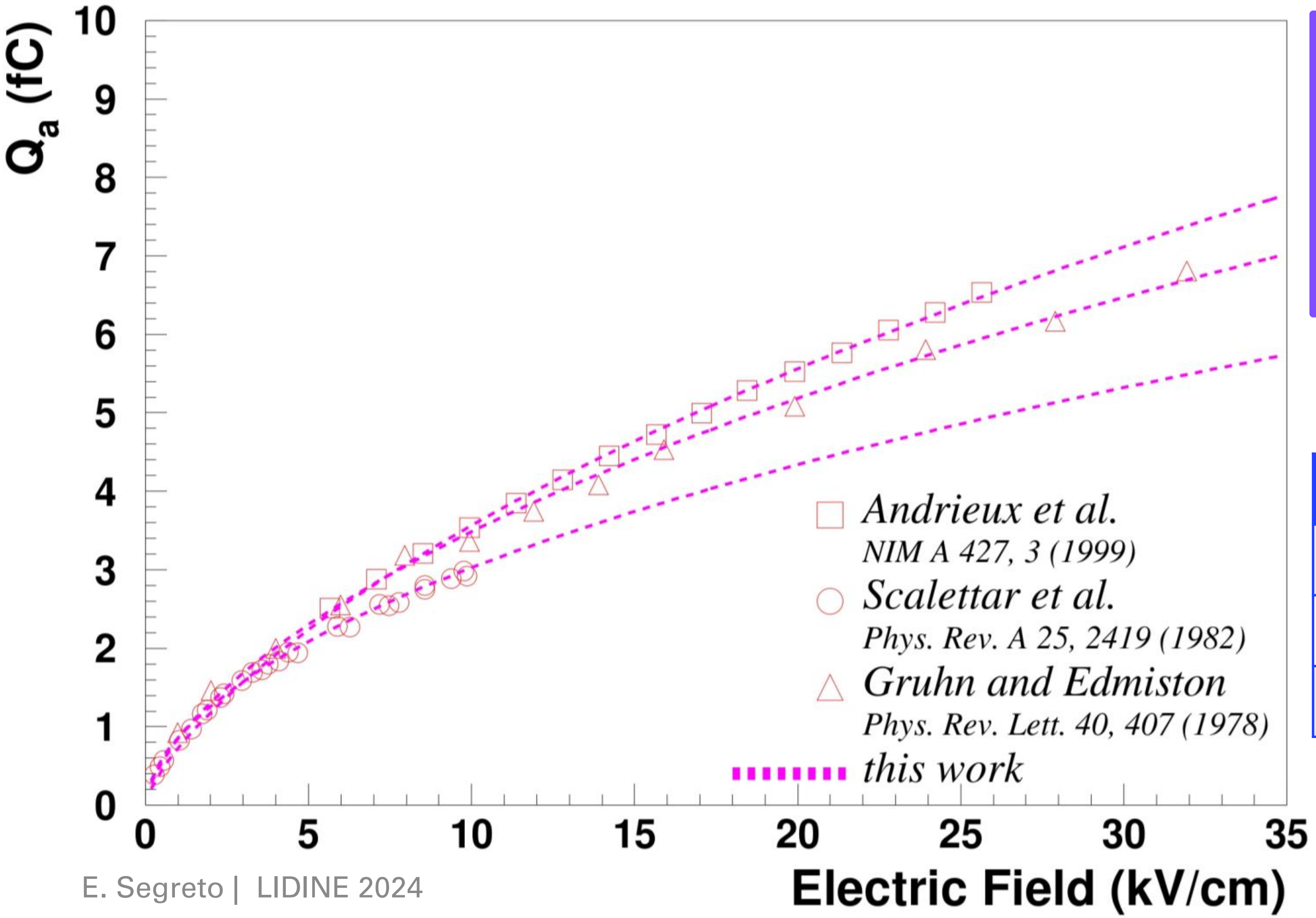
NUCLEAR RECOILS – COMPARISON WITH DATA



The model disfavors the dependence of w_i from the energy of the recoiling nucleus and points to a value ~ 24 eV

K_n = 3.7 ± 0.1 V/cm
α = 0.44 ± 0.02
w_i = 24.1± 0.9 eV

ALPHA PARTICLES



The model is applicable to alpha particles. These three datasets refer to 5.5 MeV alpha particles from ^{241}Am

	K (mV)	α
Scalettar	2.3±0.1	0.60±0.01
Grun	2.3±0.1	0.67±0.01
Andrieux	2.6±0.1	0.76±0.01

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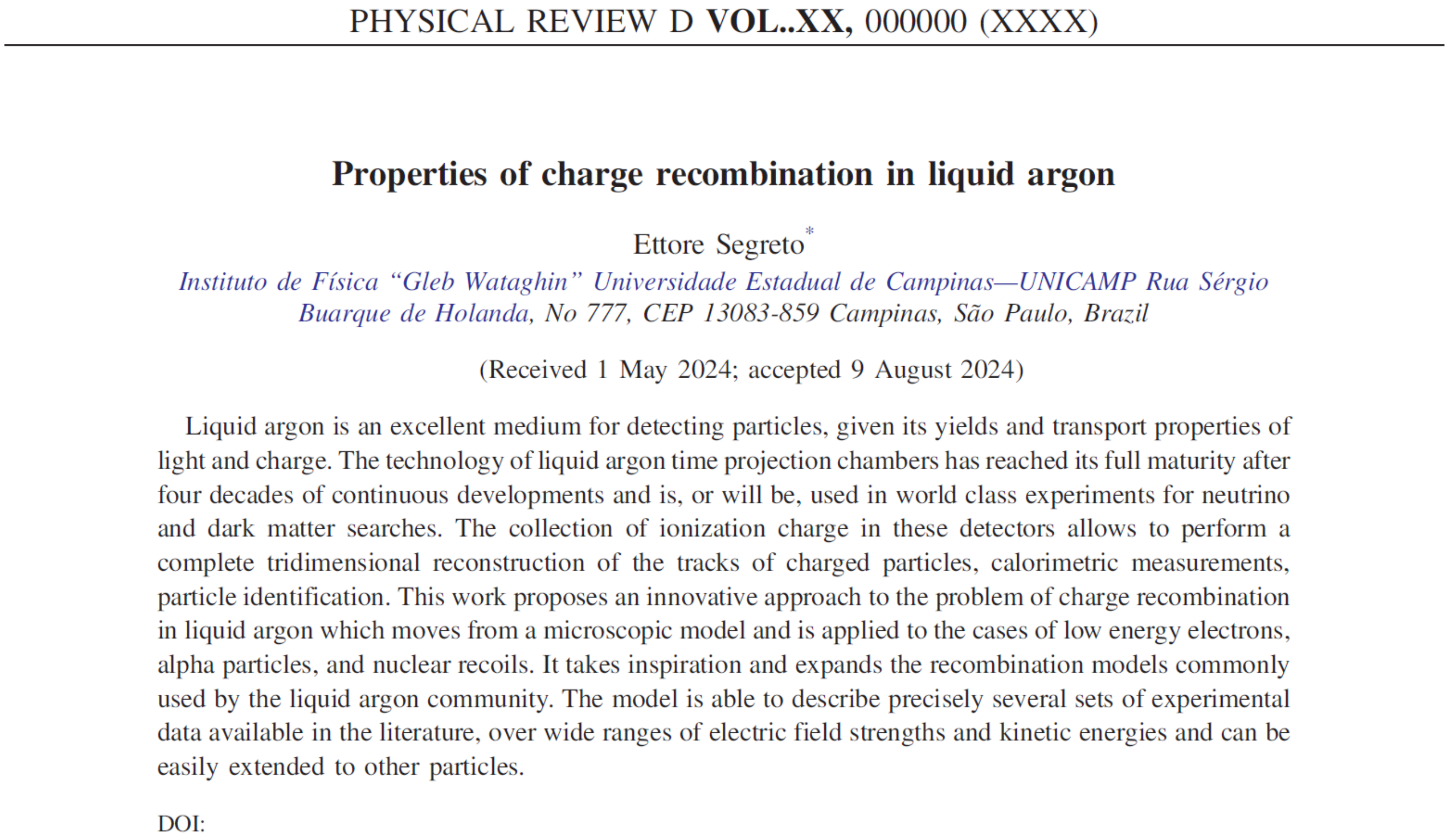

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Liquid argon is an excellent medium for detecting particles, given its yields and transport properties of light and charge. The technology of liquid argon time projection chambers has reached its full maturity after four decades of continuous developments and is, or will be, used in world class experiments for neutrino and dark matter searches. The collection of ionization charge in these detectors allows to perform a complete tridimensional reconstruction of the tracks of charged particles, calorimetric measurements, particle identification. This work proposes an innovative approach to the problem of charge recombination in liquid argon which moves from a microscopic model and is applied to the cases of low energy electrons, alpha particles, and nuclear recoils. It takes inspiration and expands the recombination models commonly used by the liquid argon community. The model is able to describe precisely several sets of experimental data available in the literature, over wide ranges of electric field strengths and kinetic energies and can be easily extended to other particles.

DOI:

CONCLUSIONS

- A new approach to the problem of charge recombination in LAr is proposed
- It is tested with success to the cases of low energy electrons (E < 1MeV), nuclear recoils and alpha particles
- The model takes inspiration (and incorporates) the existing models and offers the possibility of having a common picture for different particles and in different ranges of energy.

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