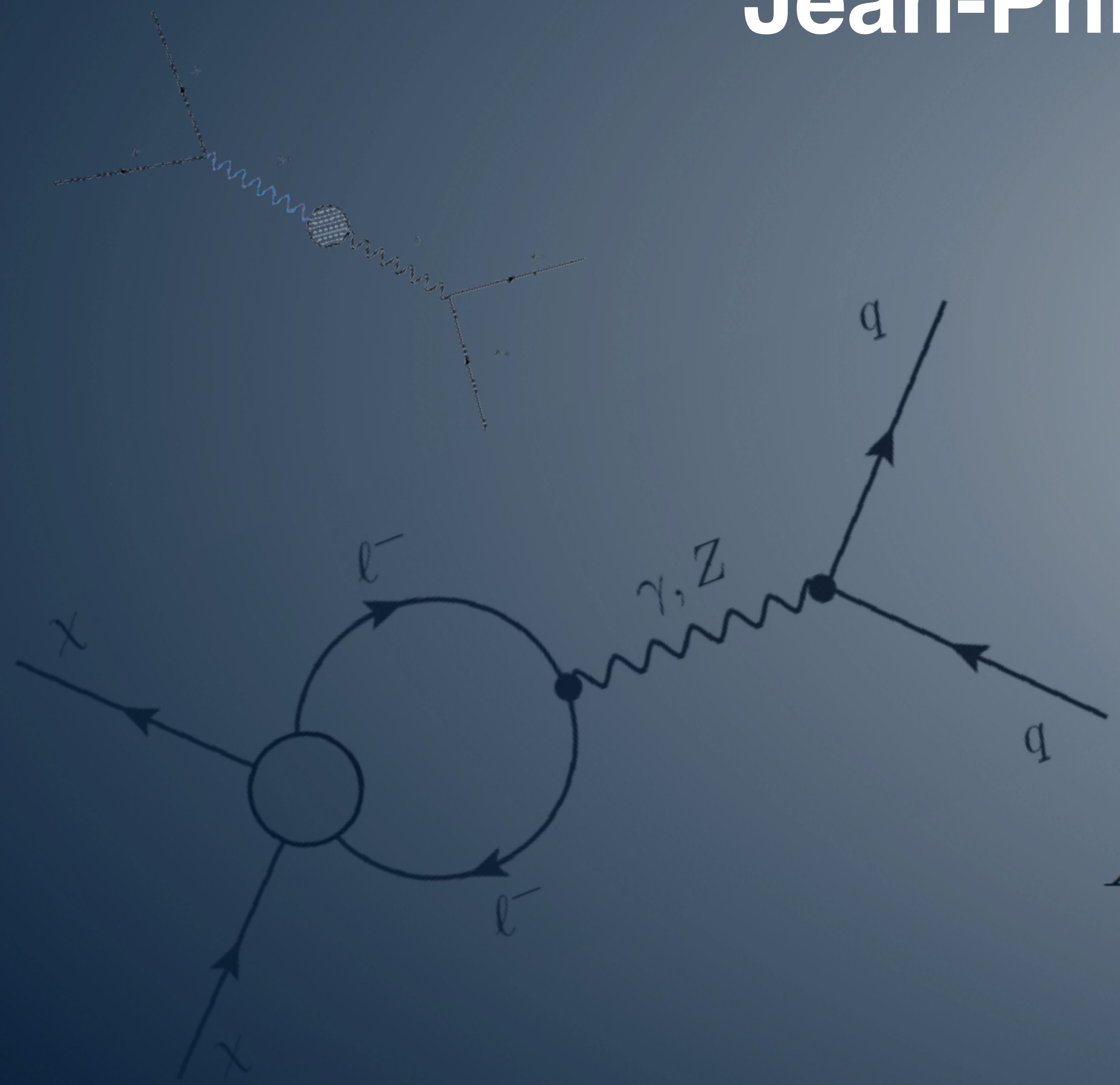
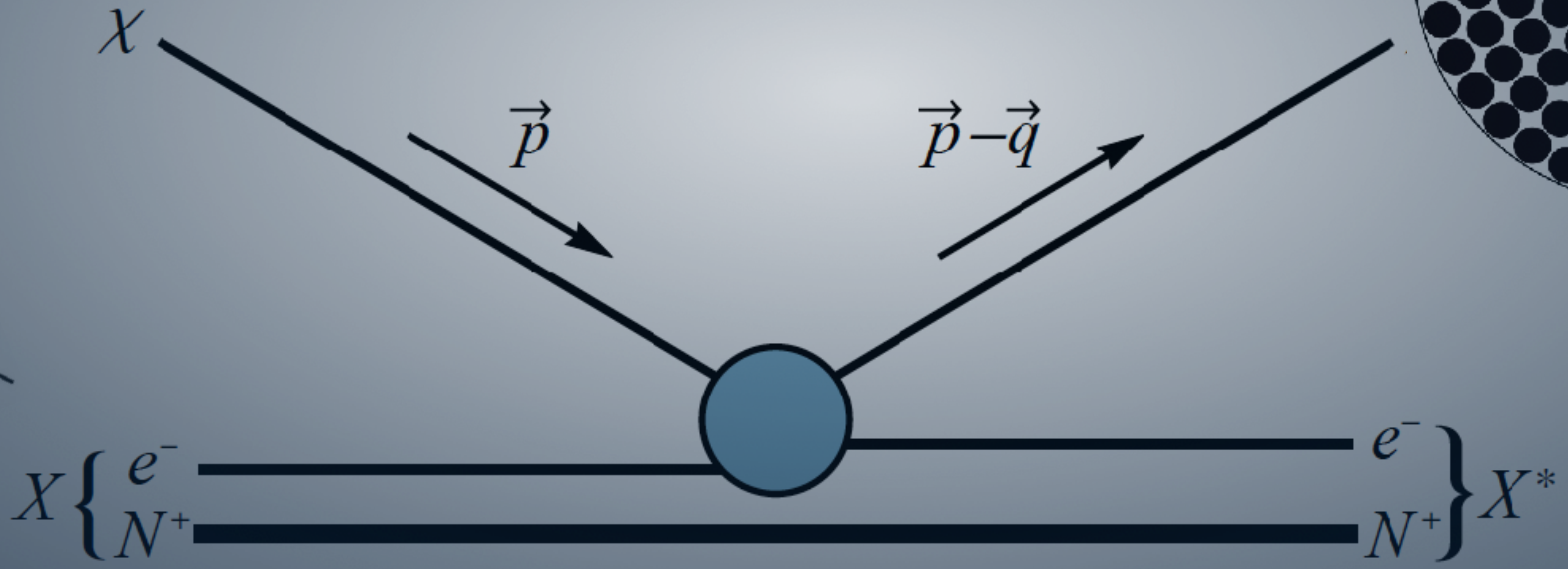
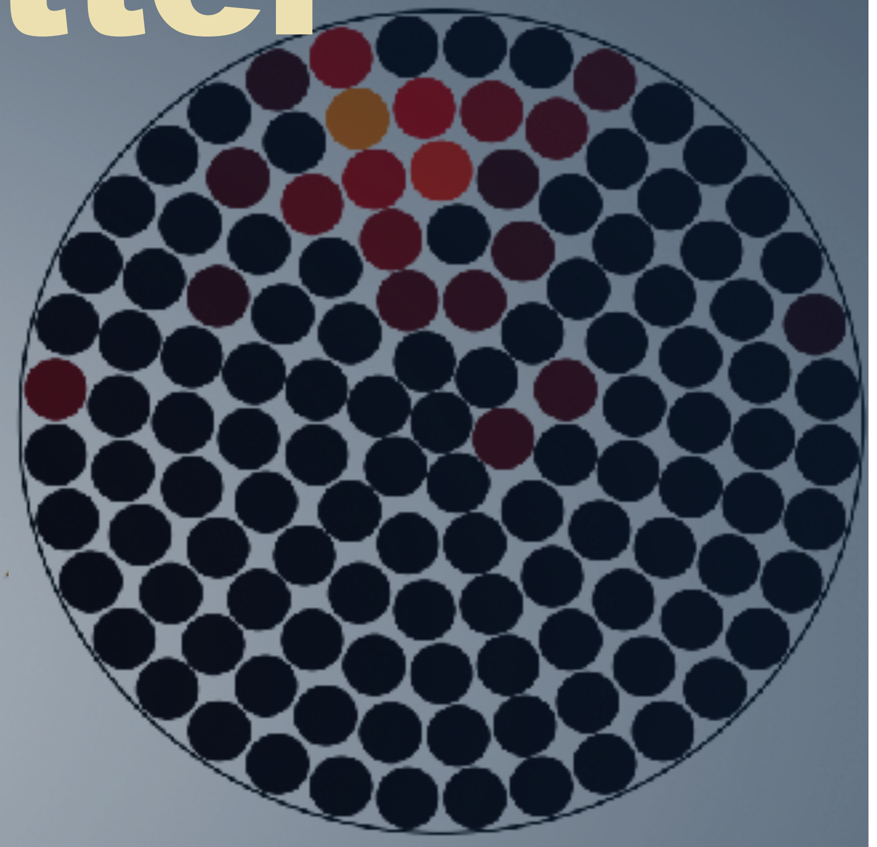
Emission of Single and Few Electrons in XENON1T and Limits on Light Dark Matter

Jean-Philippe Zopounidis







XeSAT conference
Coimbra 2022

The XENON1T detector (2016-2018)

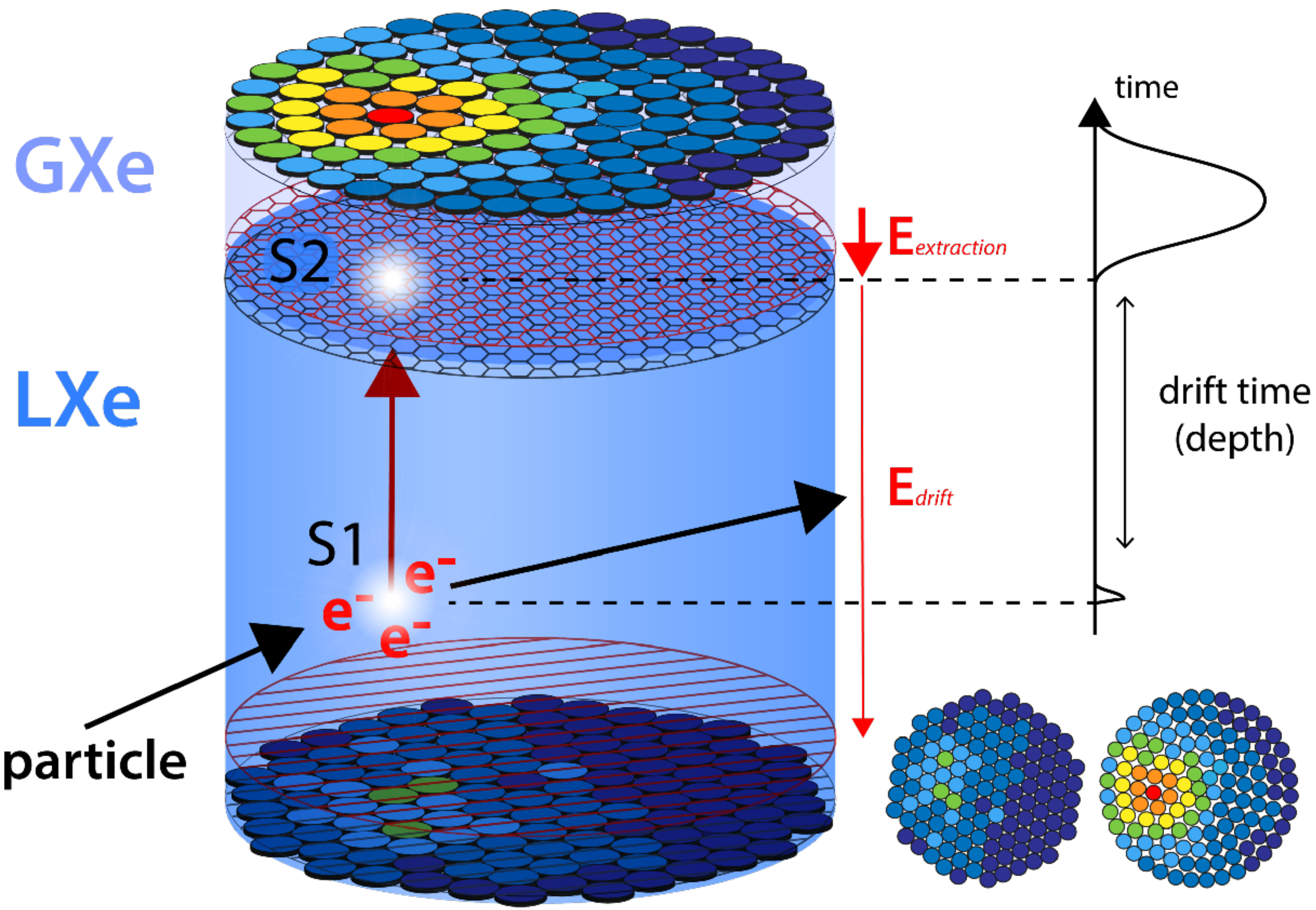
Double-phased TPC located at LNGS in Italy at an average depth of 3600m water equivalent.

Two tonnes of LXe in the active target

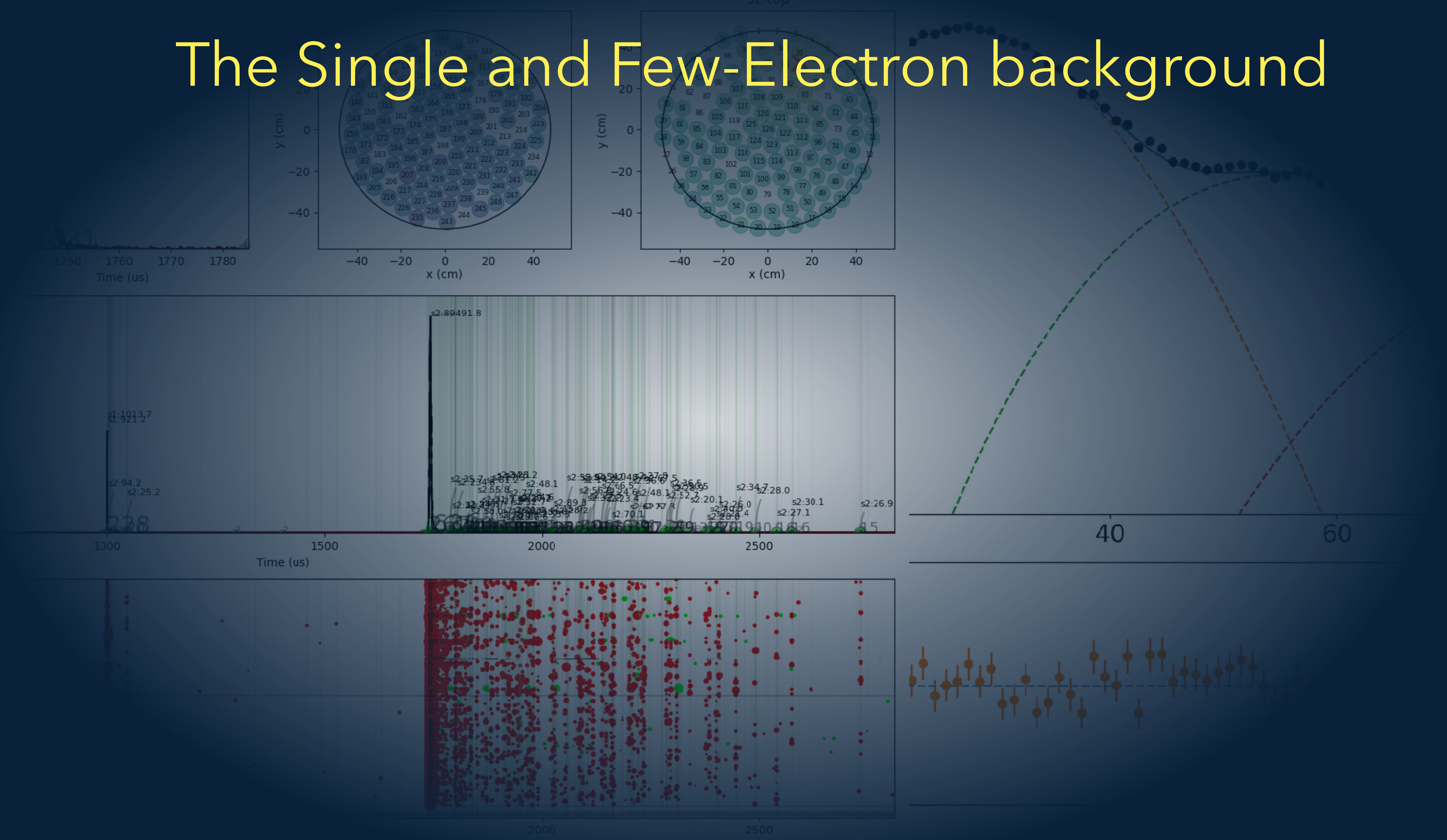
Drift region of 97 cm

Two arrays of PMTs observing the LXe target

The principle of detection with a double-phased TPC



The Single and Few-Electron background



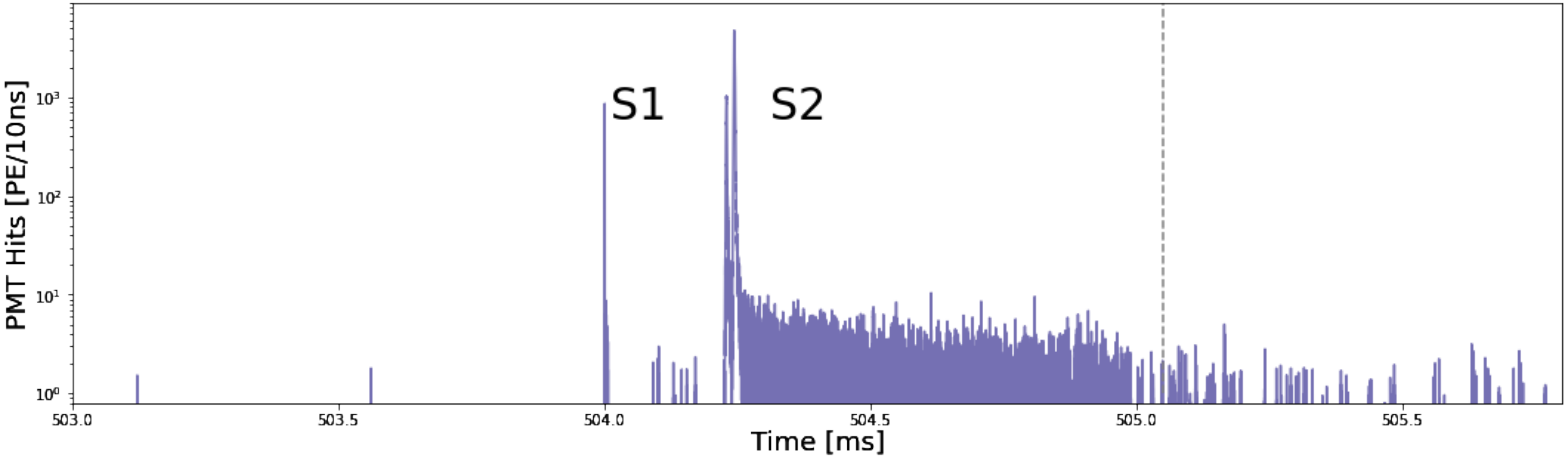
Single Electrons

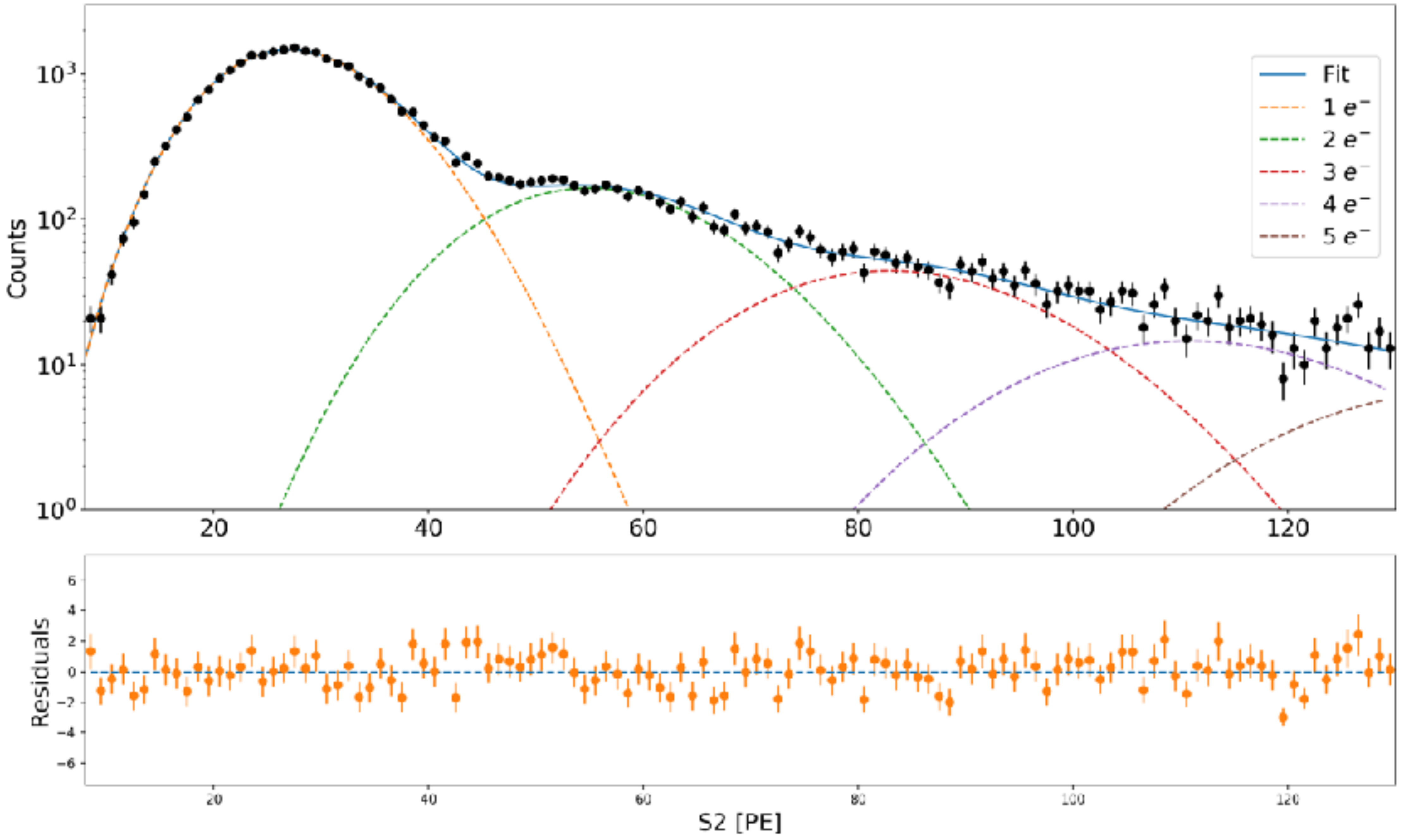
Possible interpretation

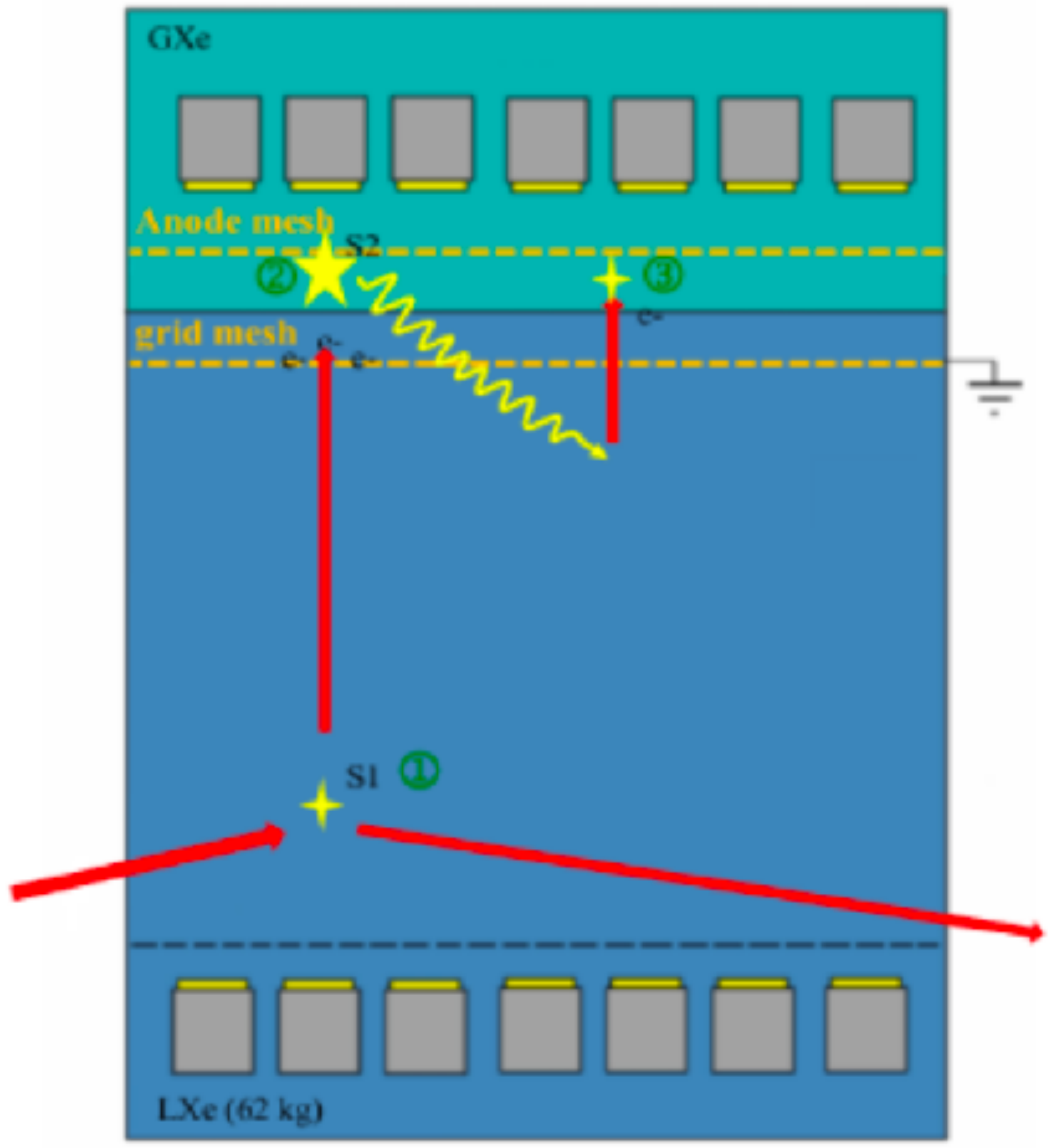
Few electrons immediately after a primary S2 can be attributed to single electrons and their pileups

These can be attributed to photoionization on metal surfaces and impurities from the primary S2 light

Events from sub-GeV DM interacting with electrons are expected to consist of few electrons.





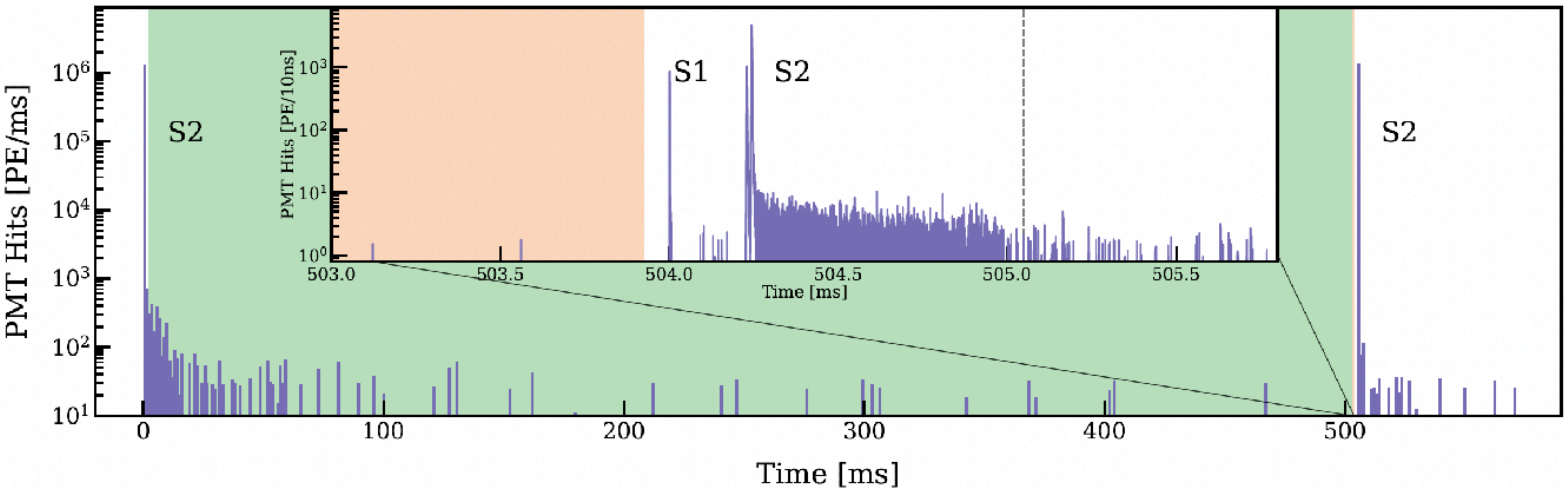


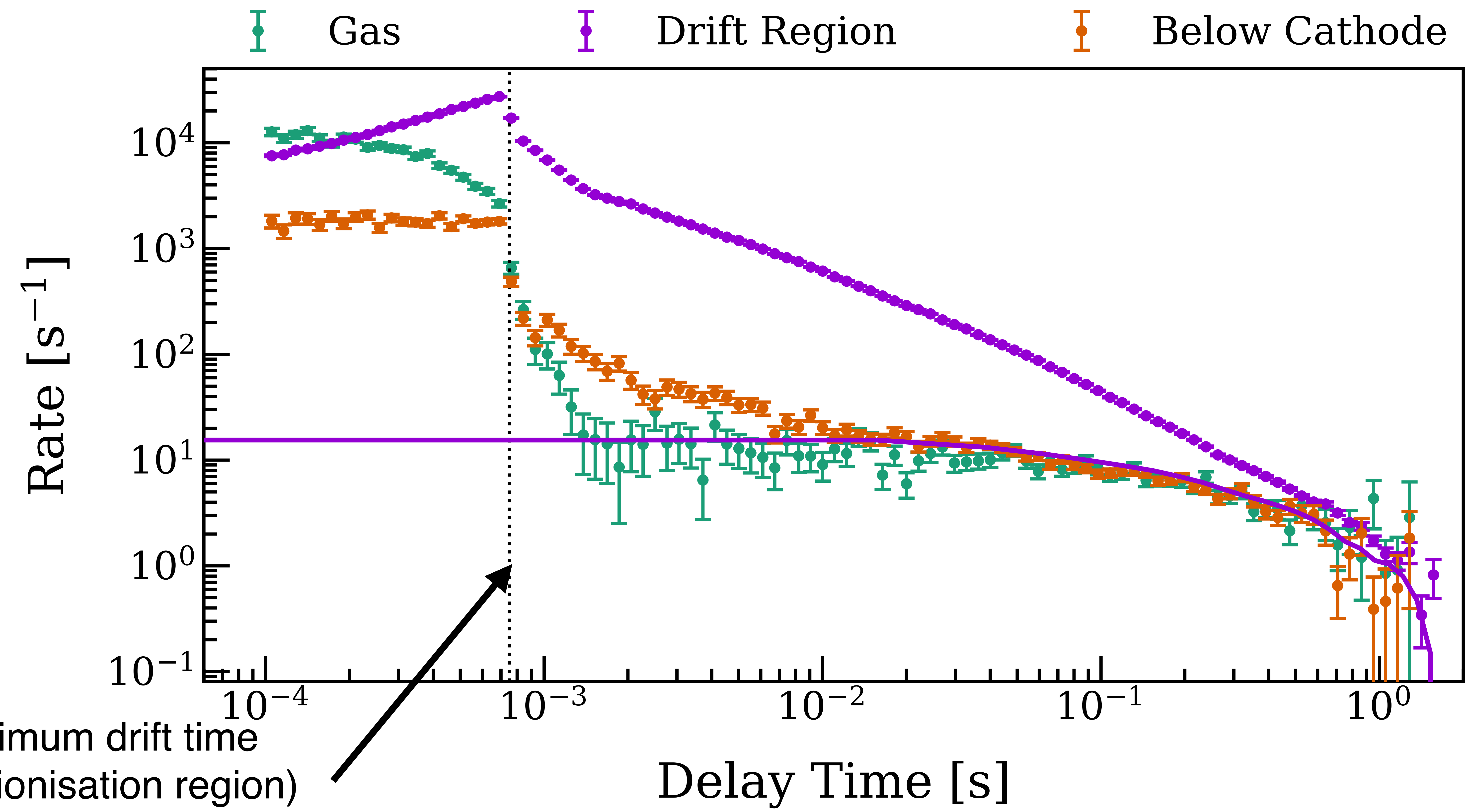
[E Aprile et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 035201]

Single electron trains

Dependence on Interaction Location

- It was observed that SE train appear many ms after a primary S2 event
- Three kind of primary interactions in XENON1T. Gaseous, drift, and below cathode events
- Investigation of the time dependance of few-electron trains as a function of the interaction



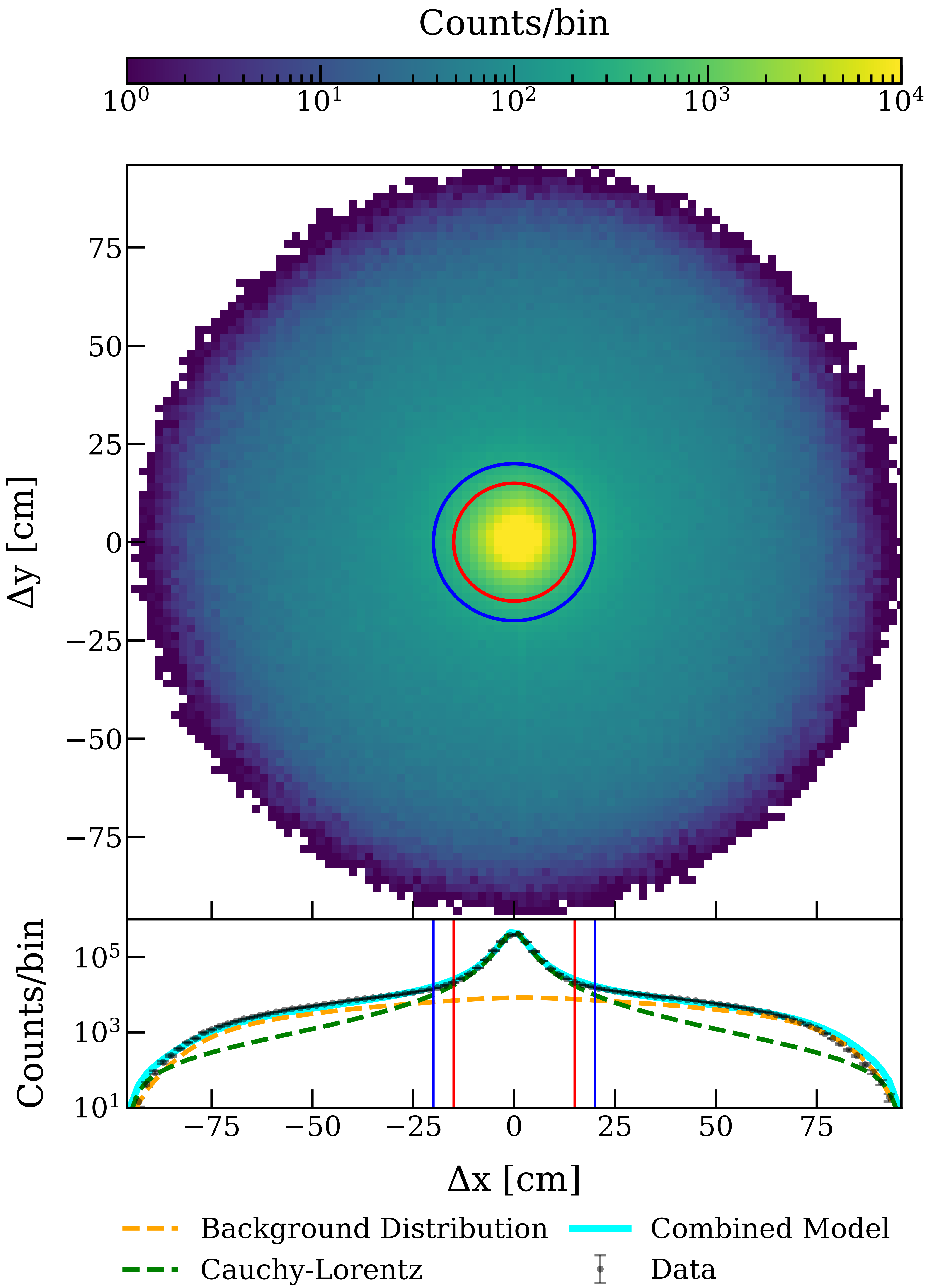


Maximum drift time
(photoionisation region)

Single electron trains
X-Y Position Dependence

Investigation of the spatial separation between the primary S2 and its subsequent delayed electrons

We observe a Cauchy-Lorentz + flat background describing the $(\Delta x, \Delta y)$ distribution of delayed SE trains



Displacement of delayed electrons in x-y relative to the most recent primary S2

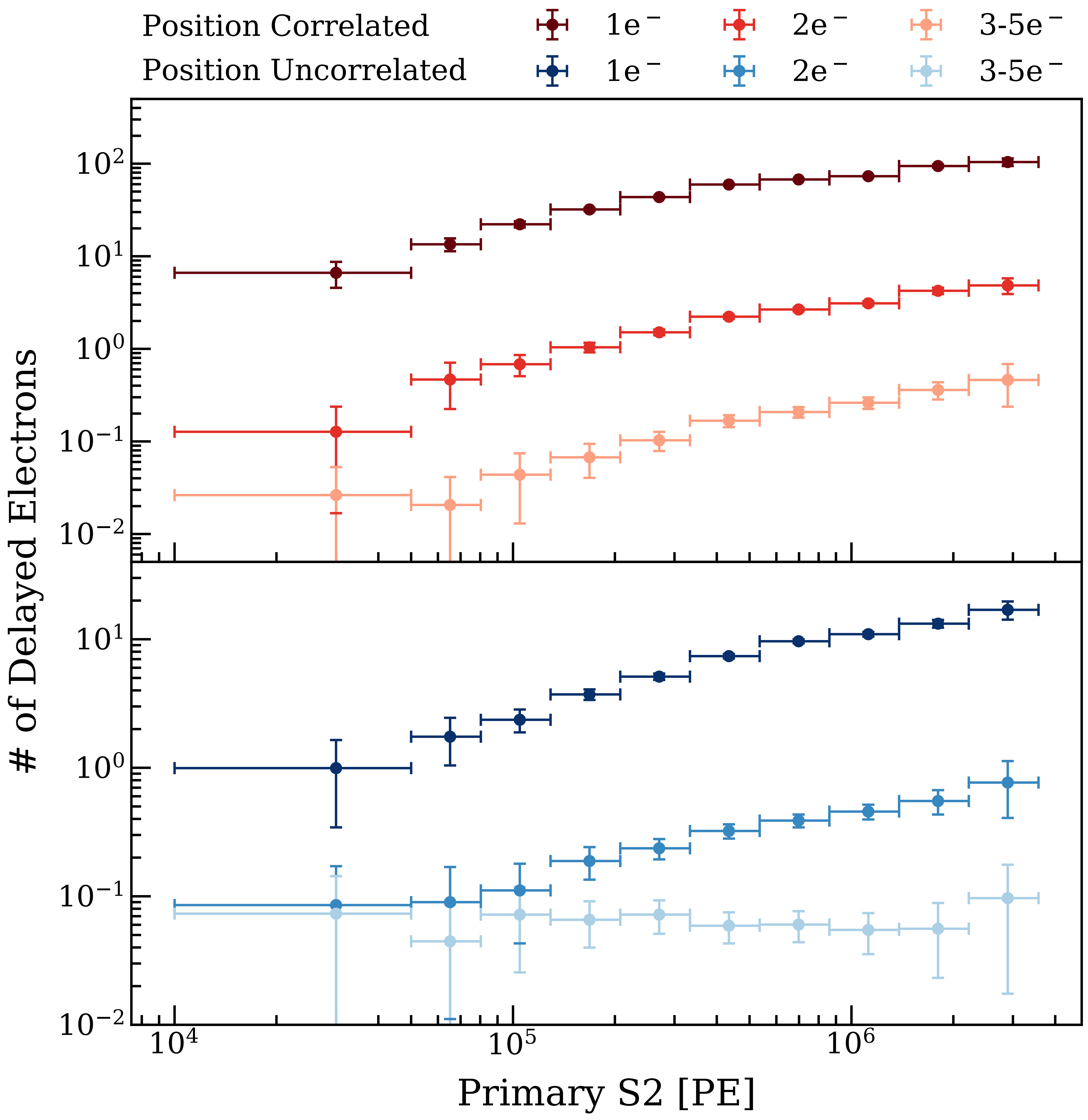
Excess in data indicating position correlation between the primary S2 and delayed electron emission, best described by a Cauchy-Lorentz distribution

Position correlated $R \leq 15cm$
Position uncorrelated $R \geq 20cm$

Single electron trains

Dependence on Interaction Size

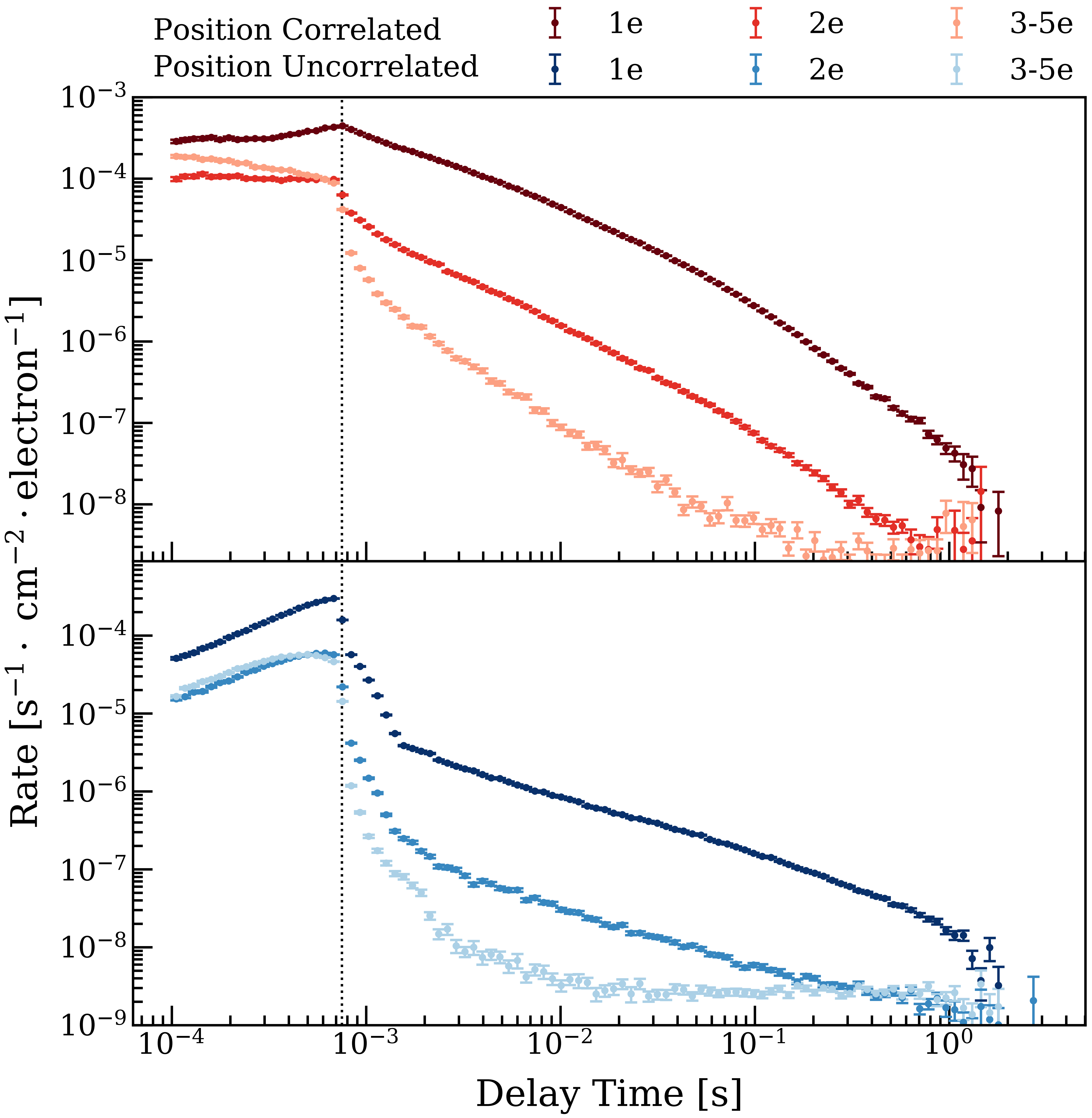
- We observe that the number of SE trains **increases** with the intensity of the primary S2, but not proportionally
- Same increasing trend for position correlated electrons.
- This is due to **residual contamination** in the uncorrelated population by correlated few-electrons



Single electron trains

Temporal Dependence

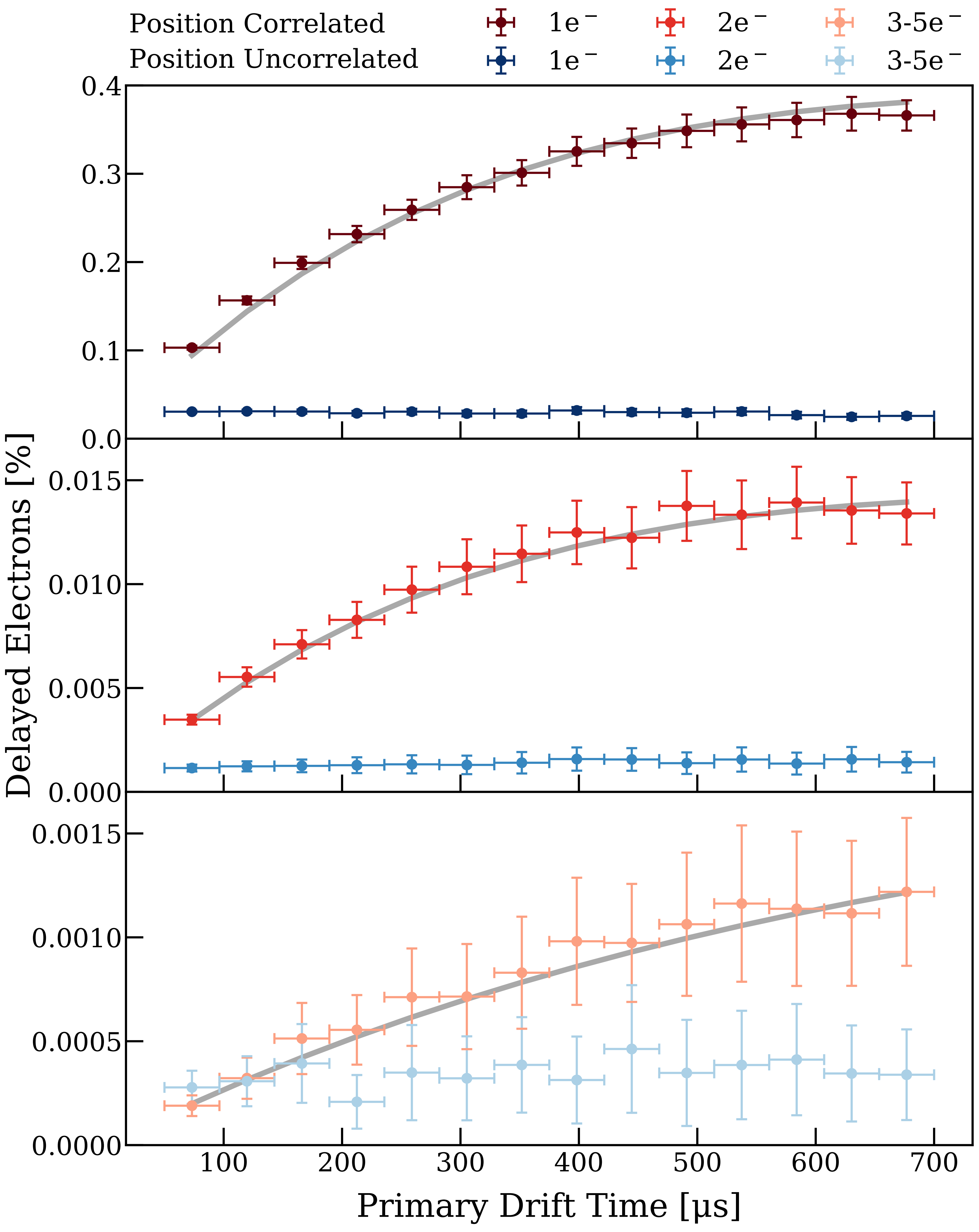
- The evolution in time of the SE trains rate follows a power-law.
- The fitted power law for 1, 2 and 3-5 position correlated electrons gives similar values
- The rate of position uncorrelated electrons drops sharply beyond the maximum drift time and/or reduces more slowly in time (presence of contamination from position correlated SEs)



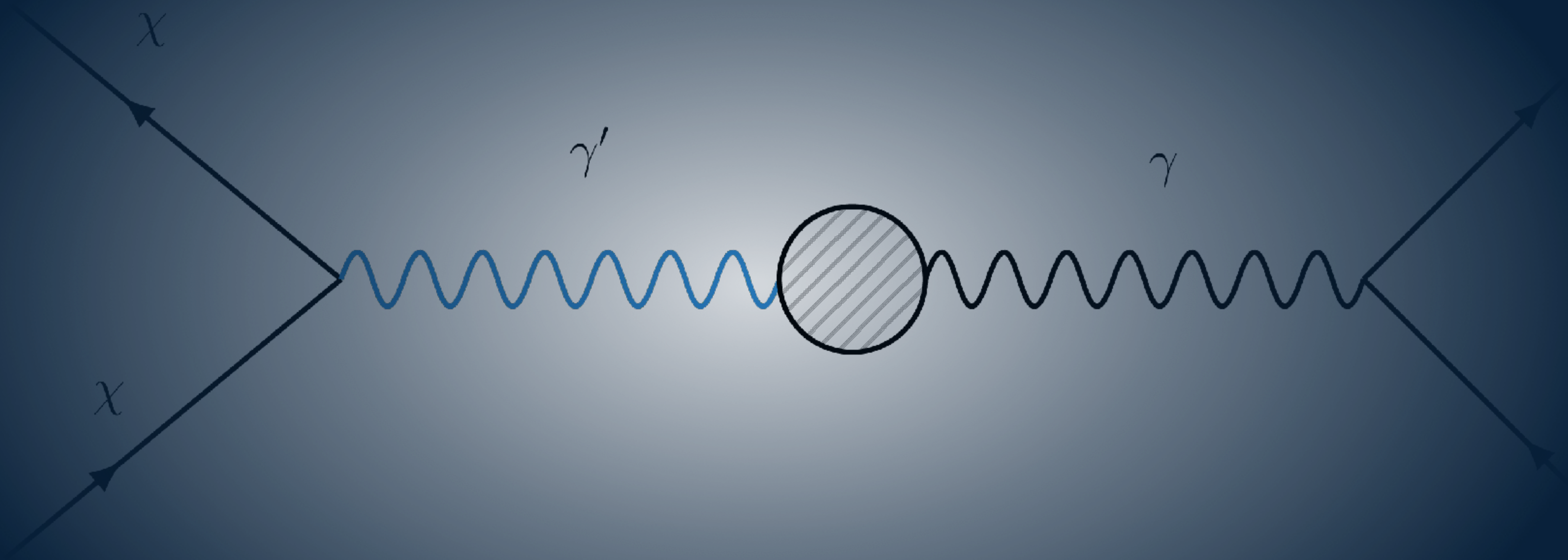
Single Electron trains

Drift Time Dependence

- We examine the dependence on drift time of the primary S2
- We calculate the number of delayed SEs as a percentage of the original primary S2 (electron-lifetime corrected)
- Position correlation presents a totally different behaviour wrt position uncorrelated
- Observation consistent with the theory that delayed electron emission is a byproduct of impurities in the LXe



Search for Sub-GeV Dark Matter

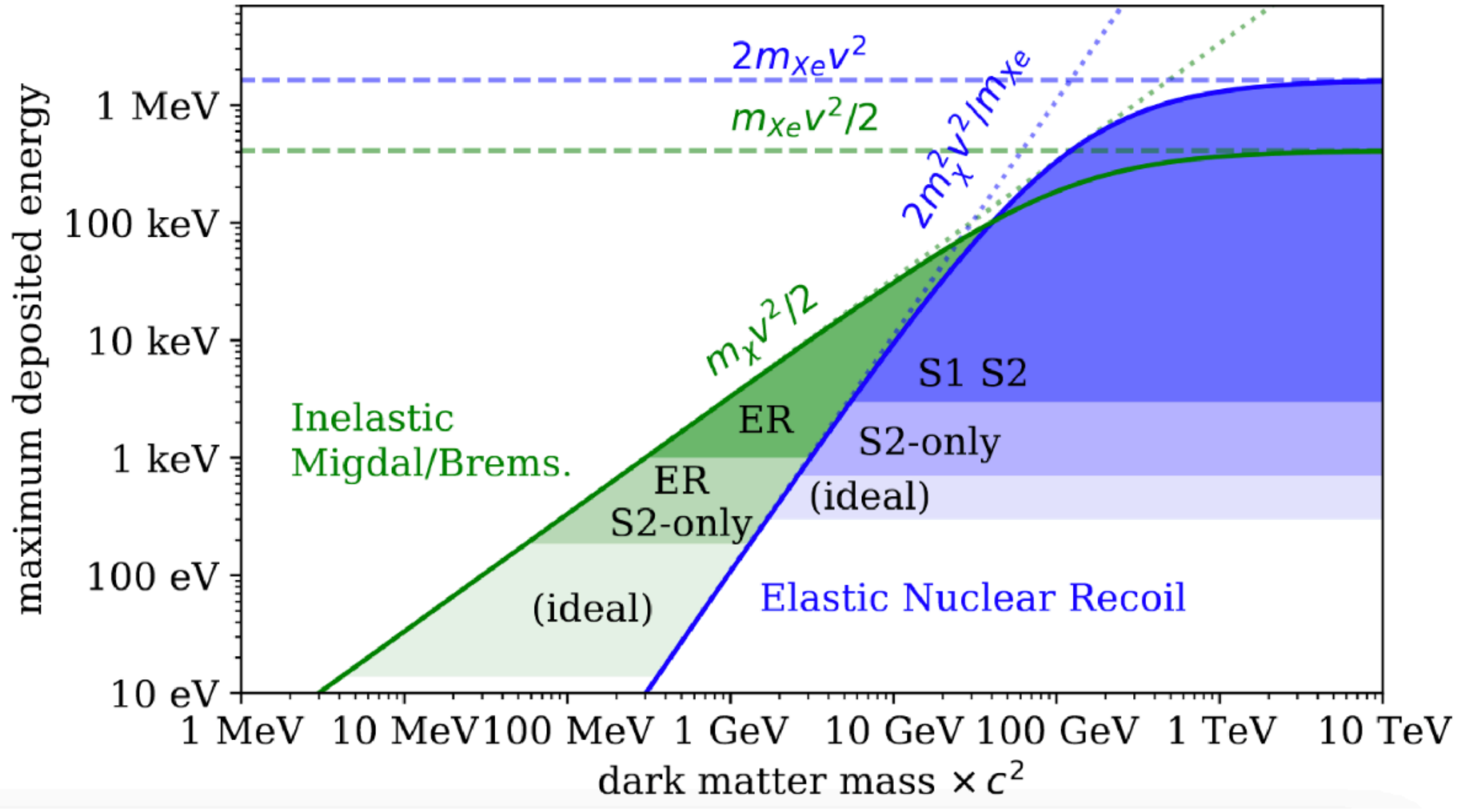


Sub-GeV Dark Matter search

NRs or ERs below O(1 keV) give S1 light below the low energy threshold.

S2-only analysis: Drop the requirement for an S1 (mild unmodelled backgrounds)

Aggressive S2-only analysis: Go below the minimum energy for which a measurement of the charge yield exists (Huge unmodelled backgrounds)



S2-only

Few-Electrons-S2-only

Aprile et al. Light Dark Matter Search with Ionization Signals in XENON1T Phys. Rev. Lett. 123, 251801 (2019)

Aprile et al. Emission of Single and Few Electrons in XENON1T and Limits on Light Dark Matter (2021) arxiv.2112.12116

Sub-GeV Dark Matter

In the absence of a Direct Detection of WIMP DM a variety of theories predicting sub-GeV DM particles with leptonic interactions gained interest

Physics channels

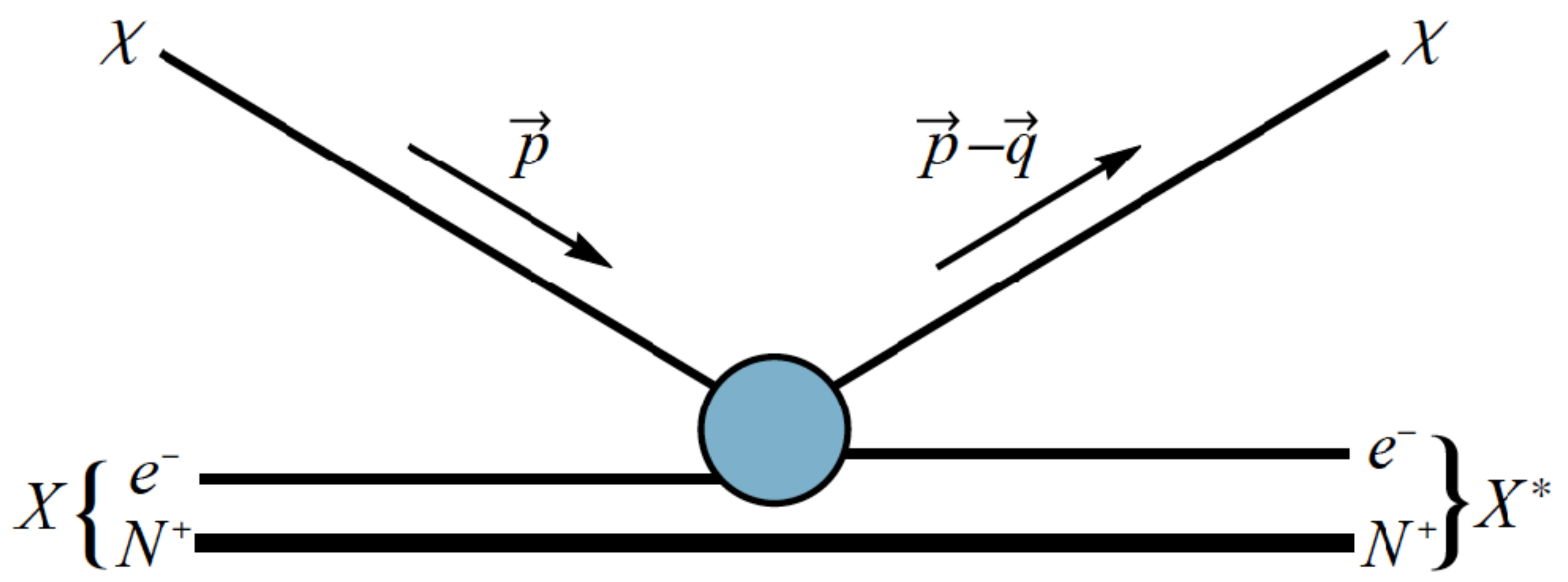
- DM-electron scattering
- Dark Photon absorption
- ALP absorption
- Solar Dark Photons

Particle candidates for a light dark matter

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

A hypothetical massive vector boson A' of a broken (dark) gauge group $U(1)_D$ that kinetically mix with the SM hypercharge. At low energies the mixing is between A' and a photon

The Dark Sector interacts with the SM via the gauge boson A'.
DM particles can scatter off bound electrons of the Xe atom via A' exchange.



$$\frac{dR_{ion}}{d\ln E_{er}} \sim \frac{d\langle\sigma^{nl}_{ion}u\rangle}{d\ln E_R} = \frac{\bar{\sigma}_e}{8\mu^2_{\chi,e}}\int q|f^{nl}_{ion}(p',q)|^2|F_{DM}(q)|^2\eta(u_{\min})dq$$

The rate depends on the initial and final state of the electron, the particular interaction and the Halo model

Two cases are of interest

- $F_{DM}(q) = 1$, heavy mediator, $(m_{A'} \gg \alpha m_e)$
- $F_{DM}(q) = (\alpha m_e/q)^2$, ultra-light vector mediator. $(m_{A'} \ll \alpha m_e)$

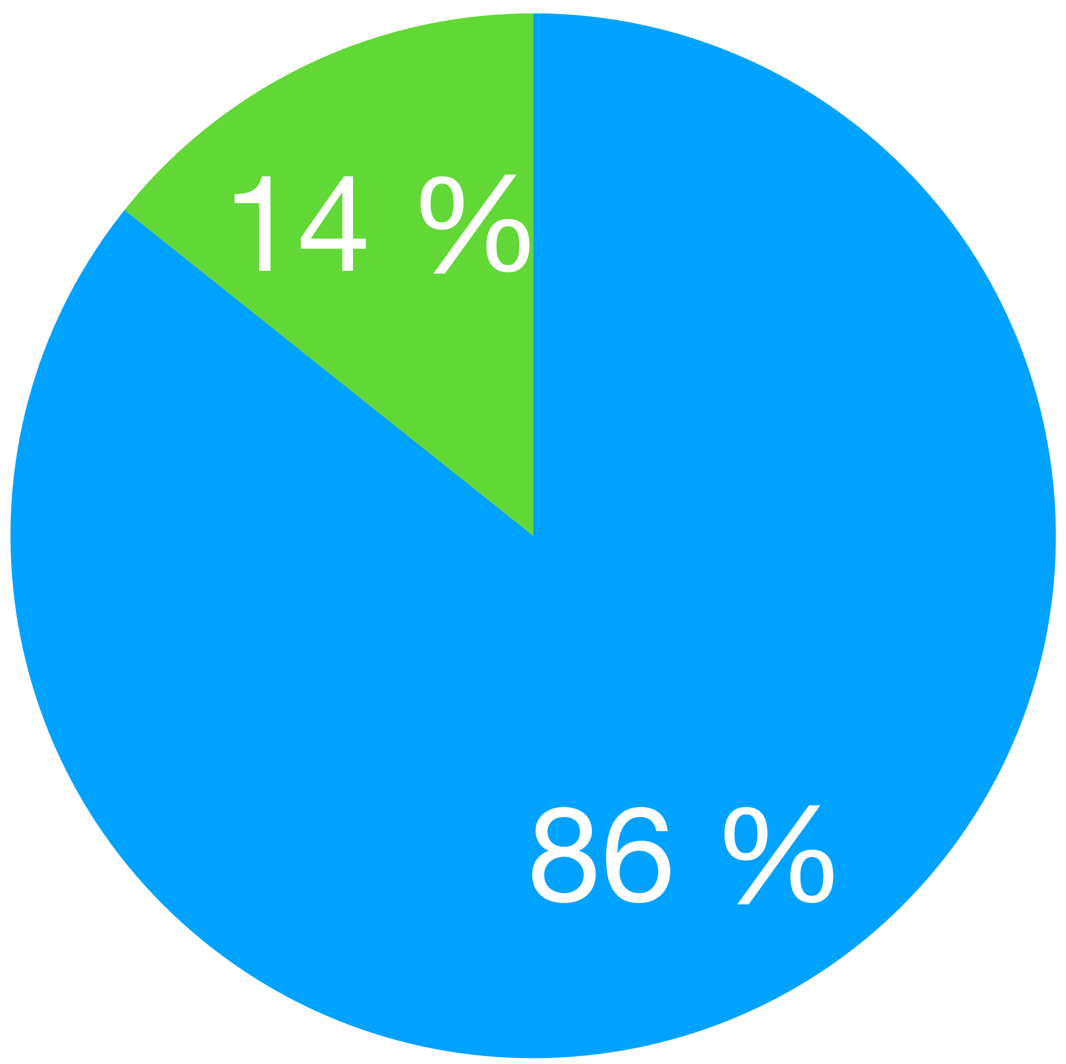
- Special cases of more general EFT models

Sub-GeV Dark Matter search

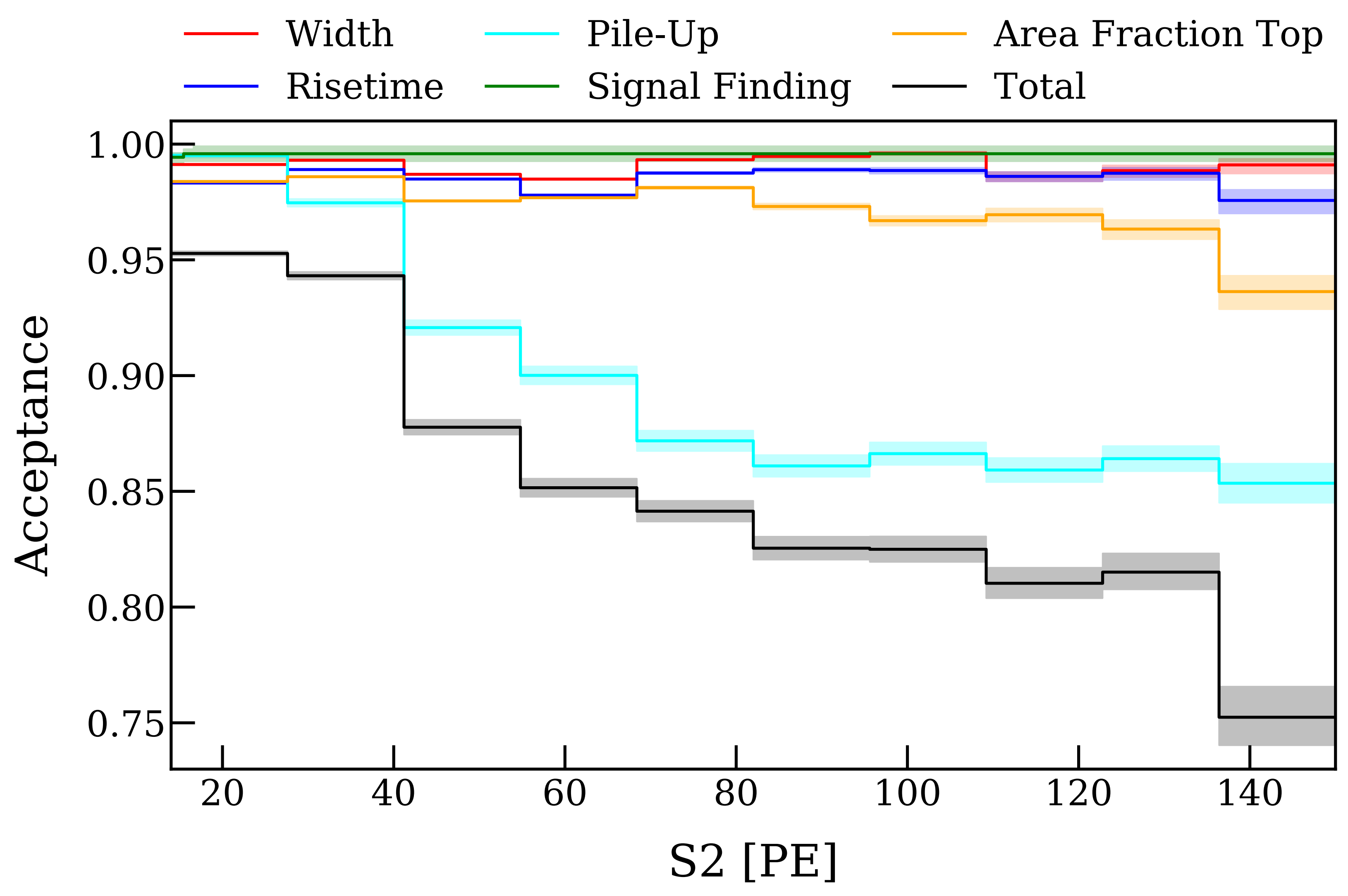
- We select S2s in the region [14, 150] PE corresponding to 1-5 observed electrons

- We developed a number of hard cuts in order to minimise the delayed electron background in a control data-set.

Continuous readout data of SR1



Used for limit setting
Used for hard cut tuning



Event selection

Cut	*Efficiency*
Primary S2 in the drift region	Hard cut (reduction in exposure)
Selected S2 in the drift region	>95%
Neural Network cut removing spatial pileups	Dependend on S2 (>75%)
Cut on observed radius	Hard cut (reduction of exposure)
Cut of correlated delayed electrons	Hard cut (reduction of exposure)
Cut on time separation from primary S2	Hard cut but a function of the intensity of the primary S2

Sub-GeV Dark Matter

Detector response

- We must take into account the response of LXe to ionisation
- Drift and extraction of ionisation electrons
- Reconstruction effects

The reconstruction effects are taken into account by folding the theoretical signal plus the LXe response with the

$n^{(1)} + n^{(2)}$ quanta produced

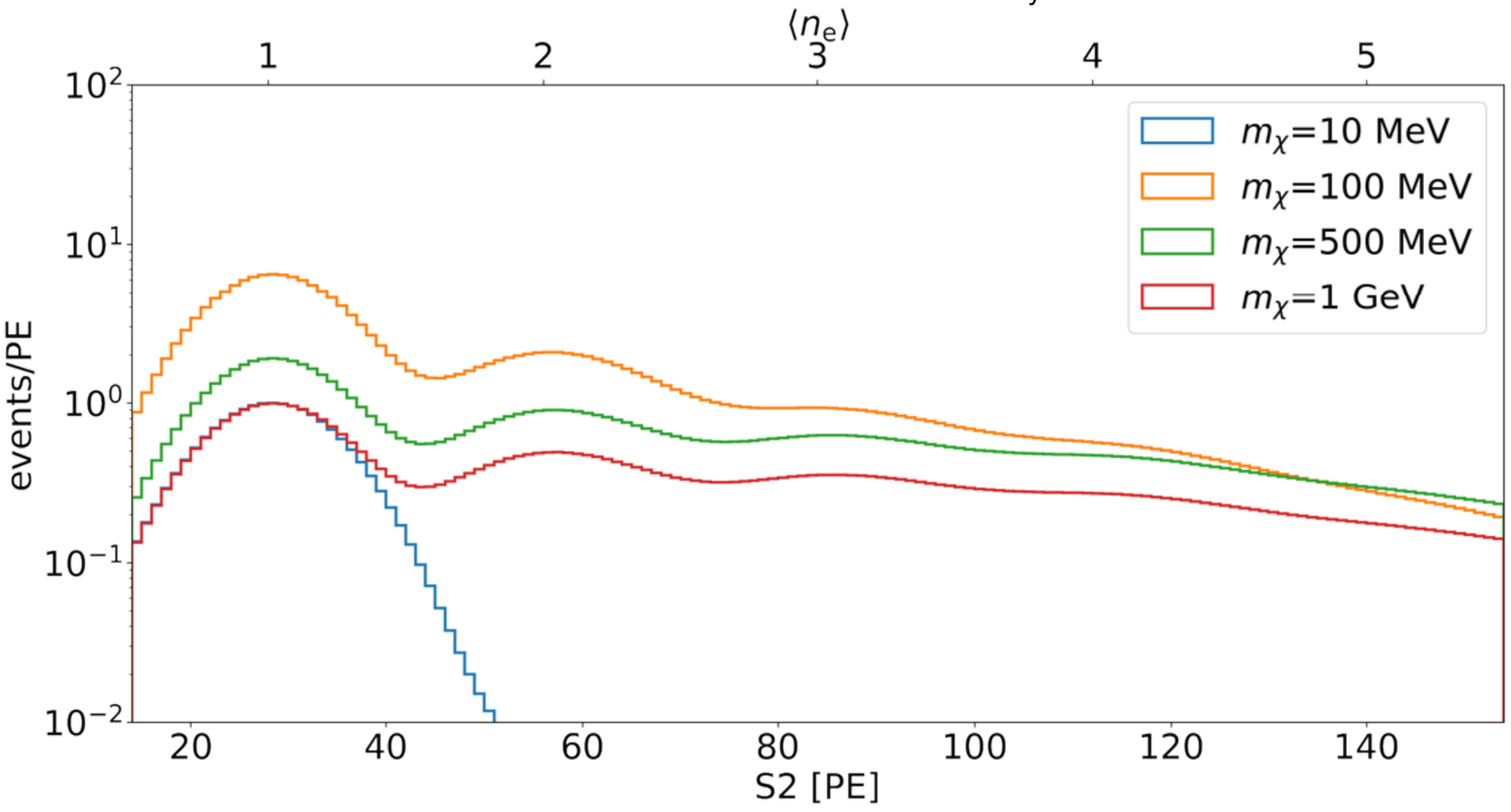
k ionisation electrons start drifting

n electrons producing S2 light

$$r_d(S2) = \sum_n \int \frac{dR}{dE} dE \sum_k P(k\,|\,n^{(1)}, n^{(2)}, f_e, f_R)\,\mathrm{Binom}(n\,|\,k, P_{\mathrm{drift}}(\tau_e) \times P_{\mathrm{extr}})\,\mathrm{Normal}(S2\,|\,n\mu, \sqrt{n}\sigma)$$

These are giving k electrons

n electrons are finally extracted

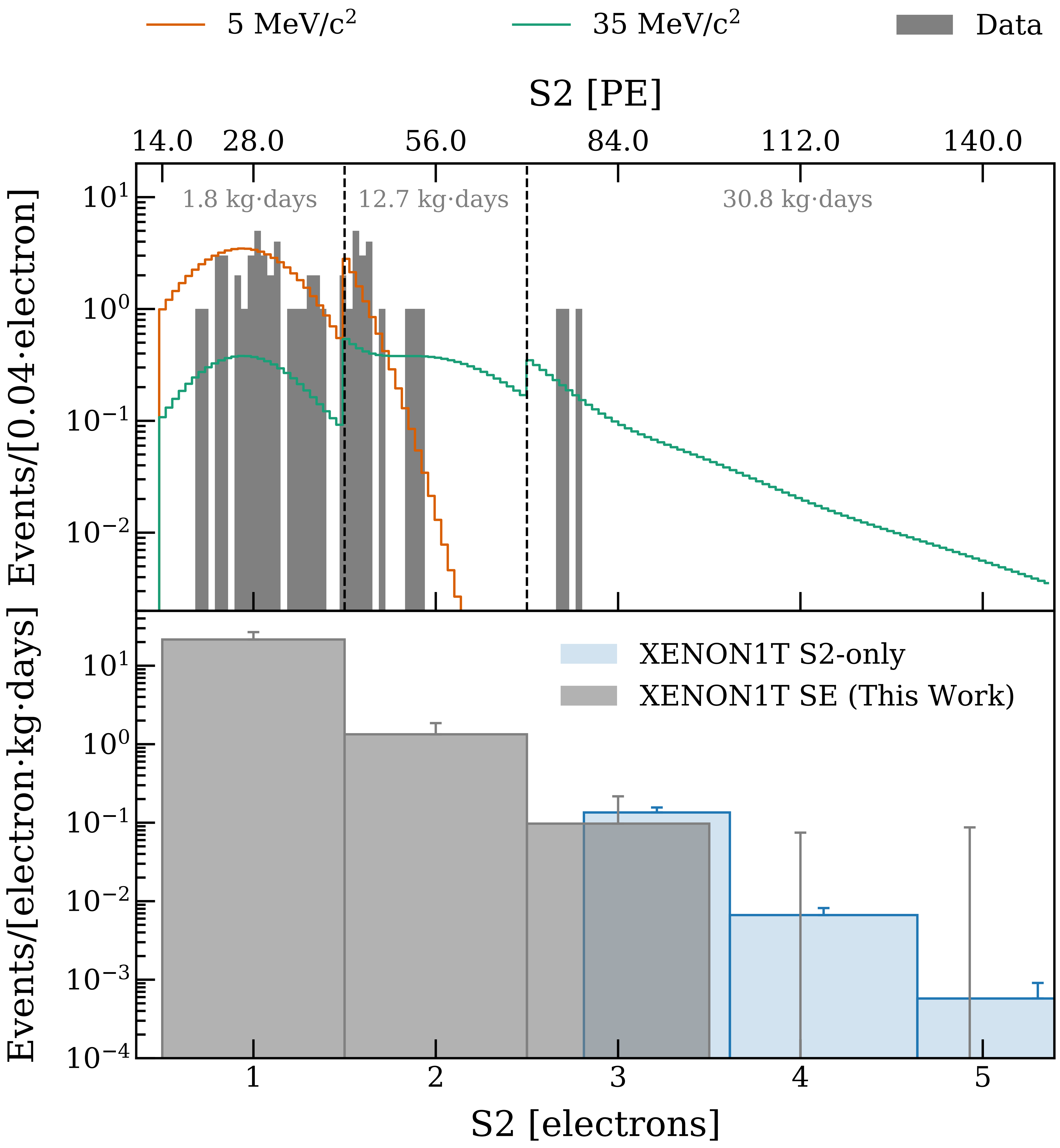


Rate as a function of S2

Sub-GeV Dark Matter

Limit setting

- We use the 86% of the available exposure of continuous readout data
- We use the optimum interval method
- We require a 0.9 value of the test statistic corresponding to a 90% C.L. upper limit in the coupling constant fro each model



Cross section fixed at the derived 90% C.L. for the case of a heavy mediator

Shown are spectra for $m_\chi = 5$ MeV and $m_\chi = 35$ MeV

The exposure due to the time-separation cut from the primary S2, as a function of the S2 size is [1.8, 18.7, 30.8] kg days for 1,2 and 3-5 electrons

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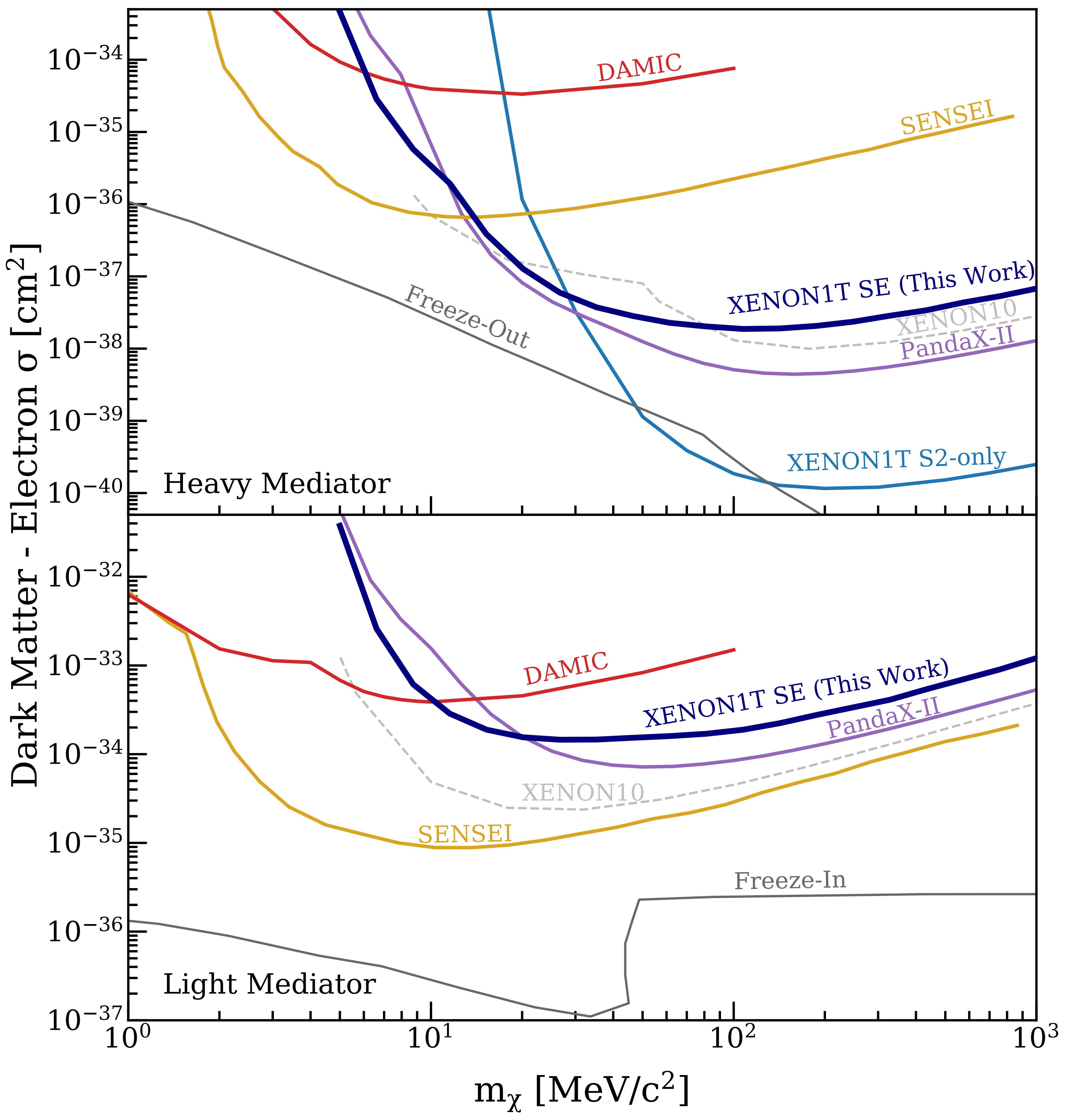

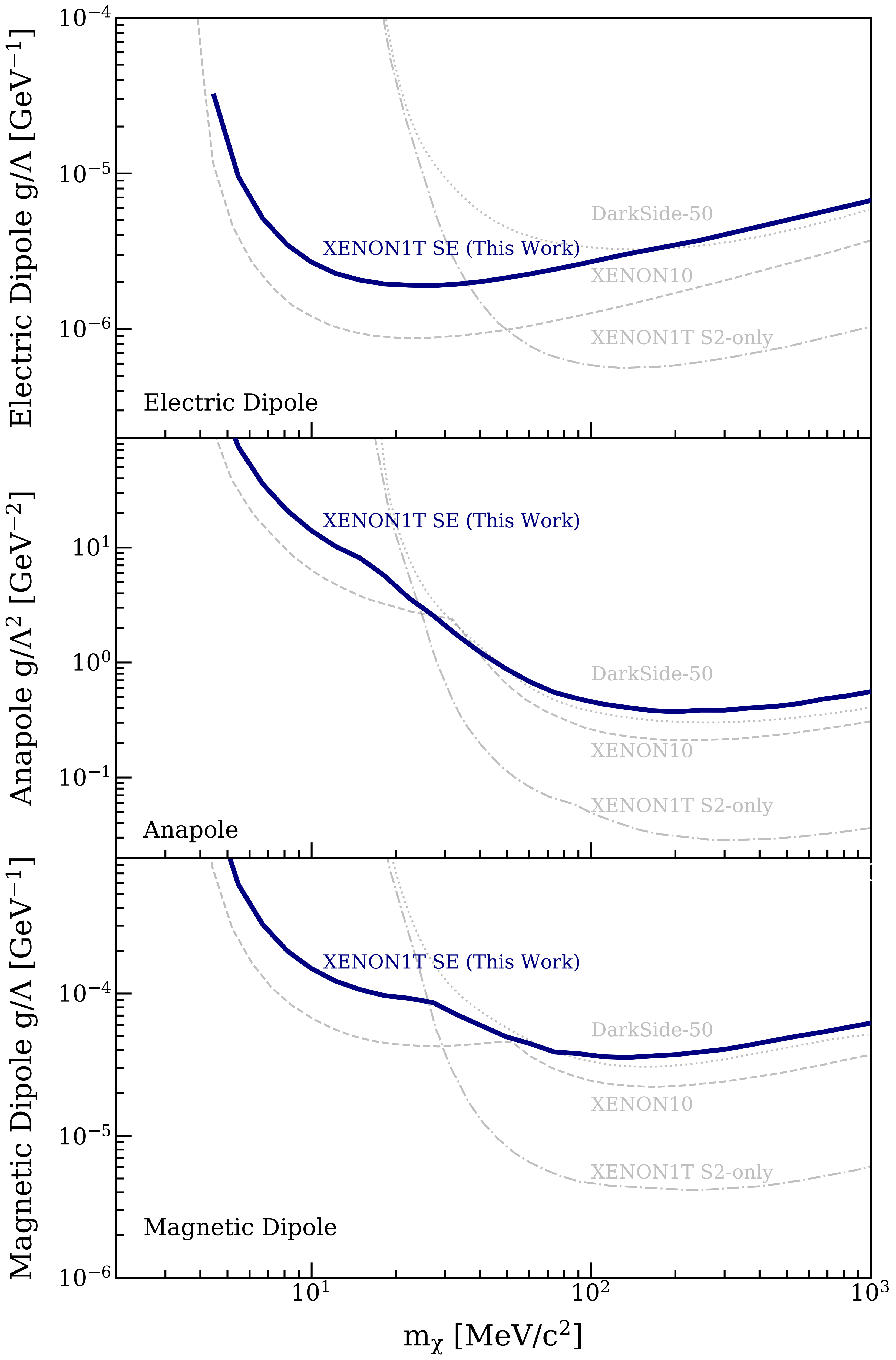

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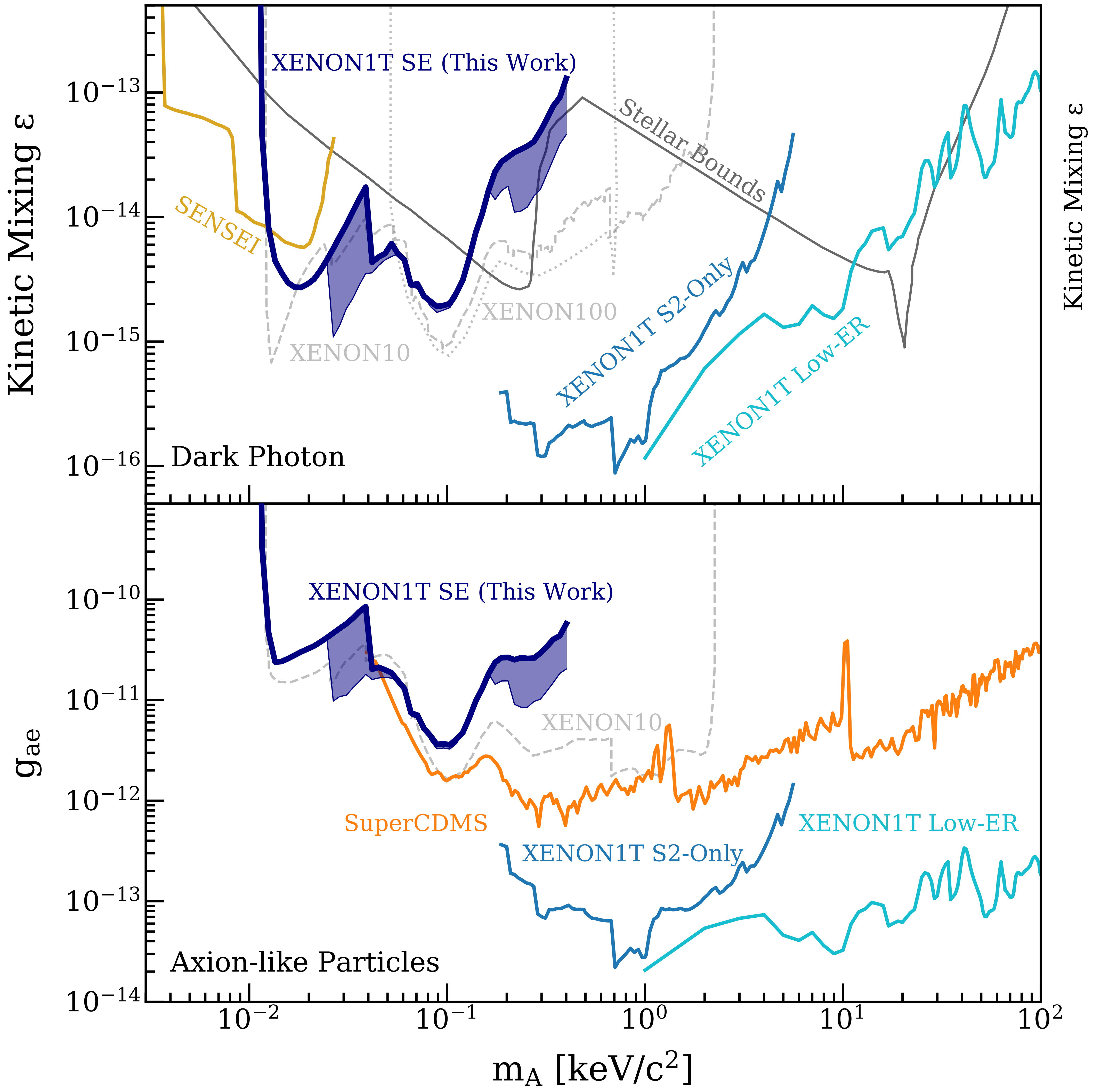

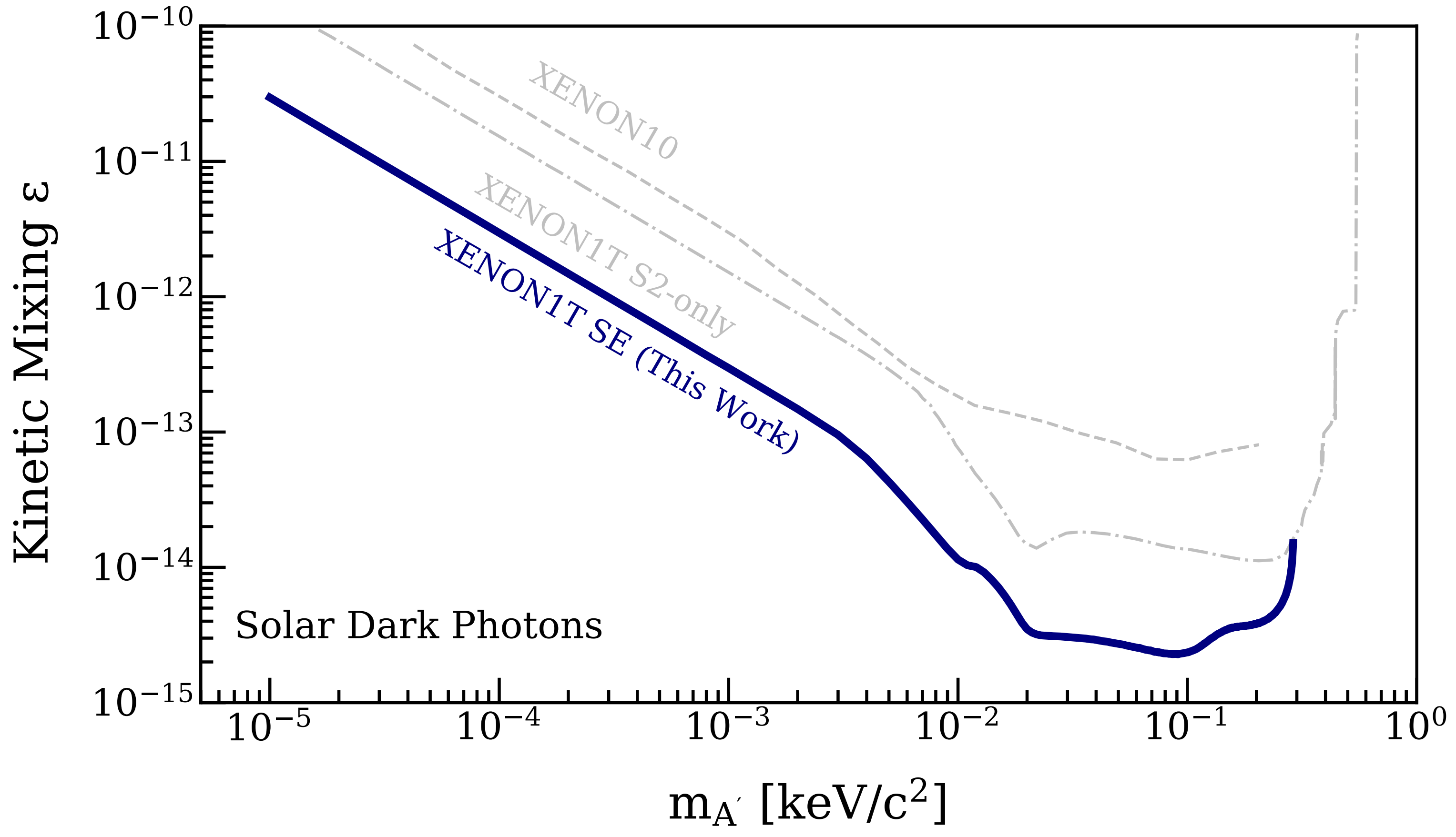

Conclusion

- Study of the low energy S2-spectrum and the Few electron background.

  Analysis of the phenomenology of the few-electron backgrounds

- Using the sensitivity of the detector to small charge signals for the search of a light dark matter interacting leptonically

  Large dual-phase liquid xenon detectors haven't reach the limit of their scientific potential for the search of light dark matter → R&D is needed to develop a background model for SE or to eliminate it in a hardware manner.

- For example the Xe-Lab of LPNHE is a project to conduct a thorough investigation of the few electrons background in a Xe TPC.