Electron emission in liquid argon detectors

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on behalf of the DarkSide-50 collaboration
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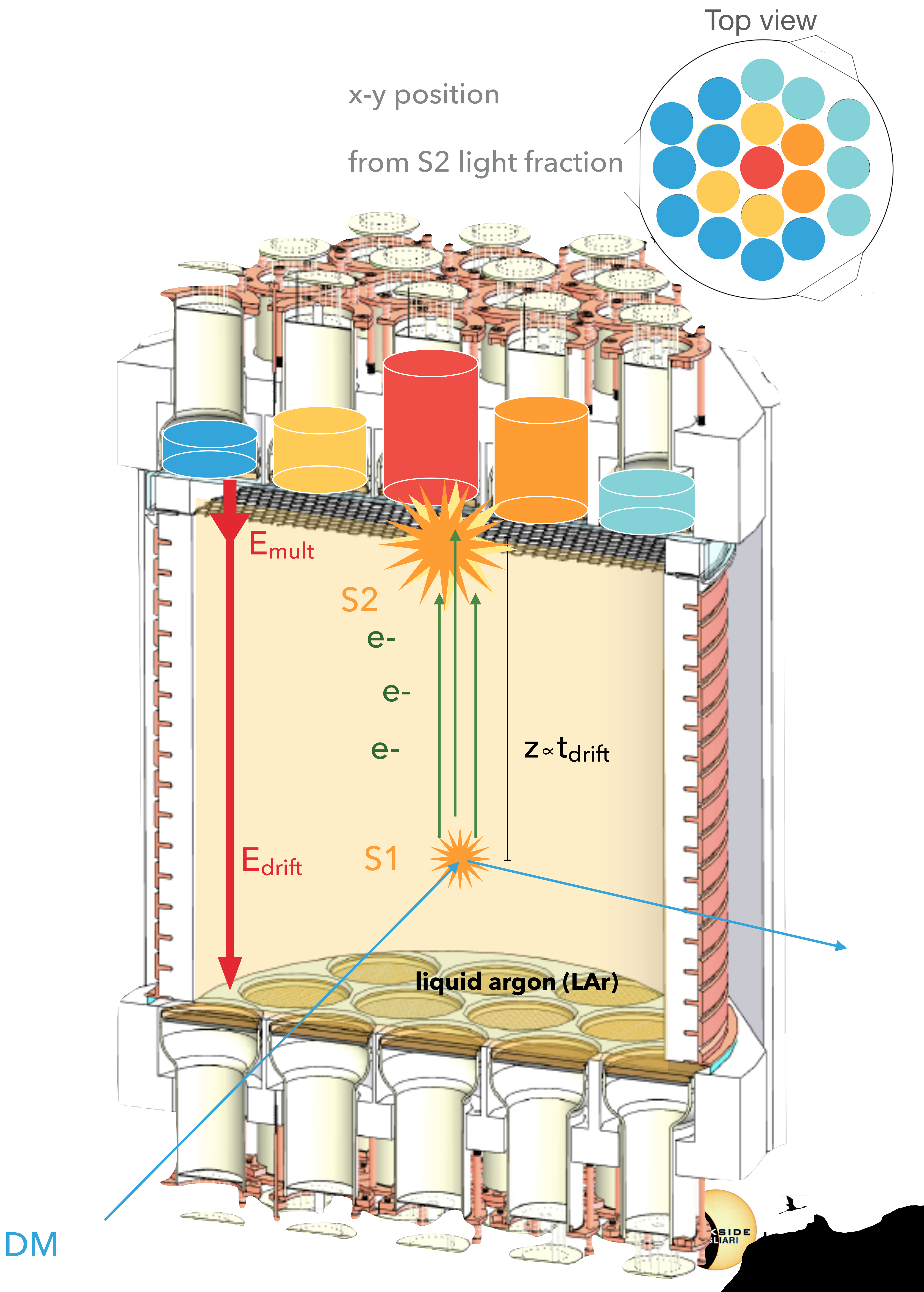
DS-50 Liquid Argon TPC

- Double-phase liquid argon TPC (see Physics Letters B 743, 456 (2015)).
- Readout S1 and S2 signals with PMTs.
- Trigger on two PMTs coincidence (0.6 PE) within 100 ns.
- Drift field is 200 V/cm.
- Multiplication field is ~5.6 kV/cm (at the x-y center) and 4.2 kV/cm (at the edge).
- Cathode and anode consist of ITO coated on fused silica instead of wires unlike in the Xenon TPCs.
- The hexagonal meshed grid at 5 mm below the liquid surface to apply the extraction filed of 2.8-3.7 kV/cm
- Argon is purified in gas phase by a hot getter and a Rn trap, then directly brought back in the TPC from a condenser.



Category of few electron signals in DS-50

preliminary

Few-electron events identified in DS-50 mainly by pulse shape and time info relative to other pulse.

- ***Delayed electrons*** (> the acquisition window, 440 μs, independently triggered events)
  - Spurious electrons ; paper in preparation
- ***Photo-ionization*** (within the acquisition window) see arXiv:2107.08015 for more details.
  - TPB photo-ionization (@ maximum drift time, 375 μs: S1or S2 echos)
  - Impurity photo-ionization? delayed electrons? (< maximum drift time)
- ***Not seen*** (or not identified) in DS-50, but reported in Xenon based TPCs
  - Clustered electron emission withing tens of ms after S2

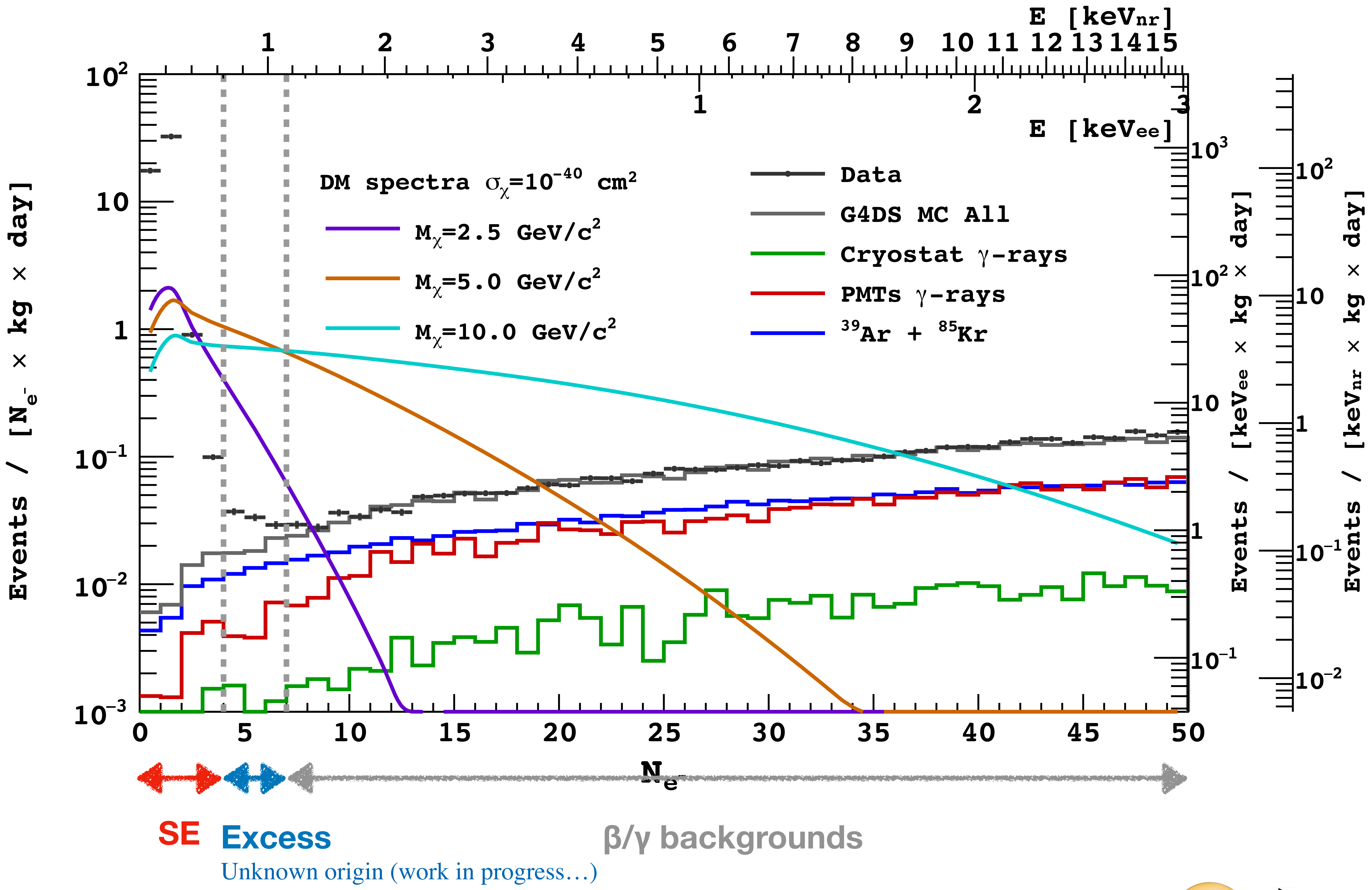
D.S. Akerib et al. Phys. Rev. D 102, 092004 (2020)
P. Sorensen and K. Kamdin JINST 13 P02032 (2018)
E Aprile et al. J. Phys. G: Nucl. Part. Phys. 41 035201 (2014)
Santos, E. et al. J. High Energ. Phys. 2011, 115

Delayed electrons

Low Energy Backgrounds in DS-50

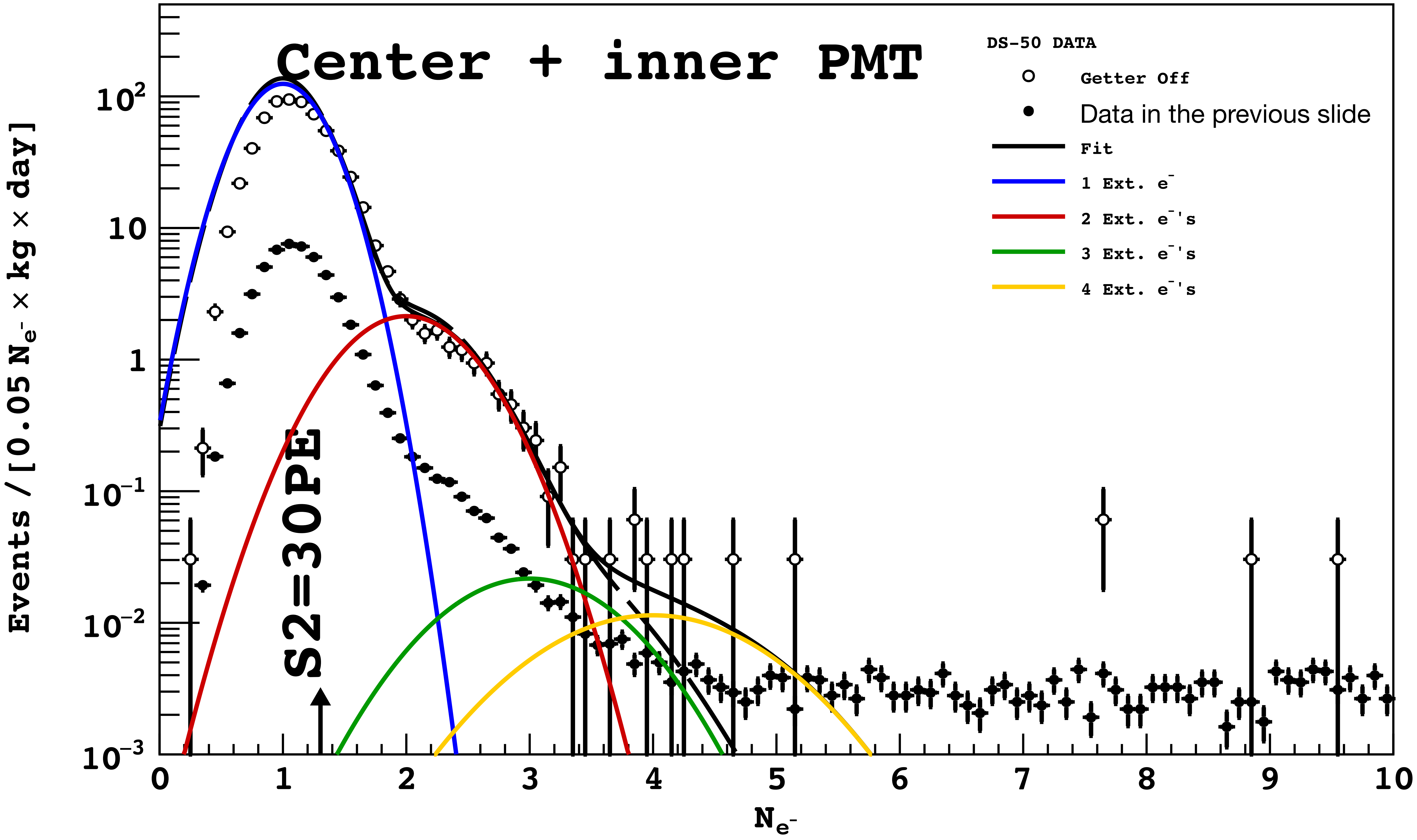
PRL 121, 081307 (2018)

- The analysis threshold was determined by the high rate events at 1-4 Ne.
- Limits our sensitivity to lower WIMP mass range.
- Need to understand the few electrons events, so called, spurious electrons (SE) events

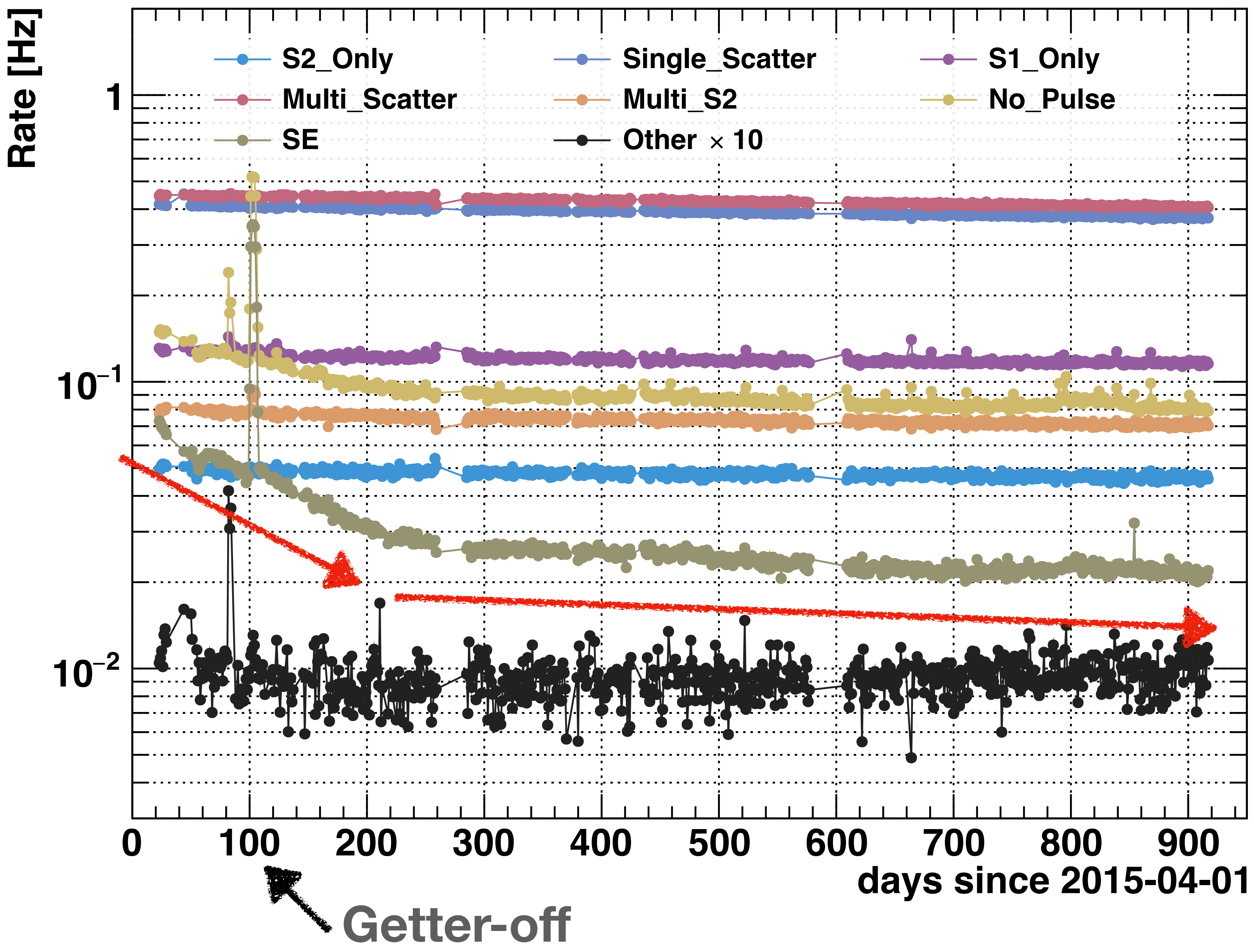


Zoom into the SE range

- Accounting for trigger efficiency, SE rates are consistent with Poisson statistics.
- That indicates two or more electrons events are pileup of single electrons.
- “Getter off” runs (open circle) saw increased rate of SE events.



Time Evolution of events in DS-50



Pulse identification by pulse shape and pulse size

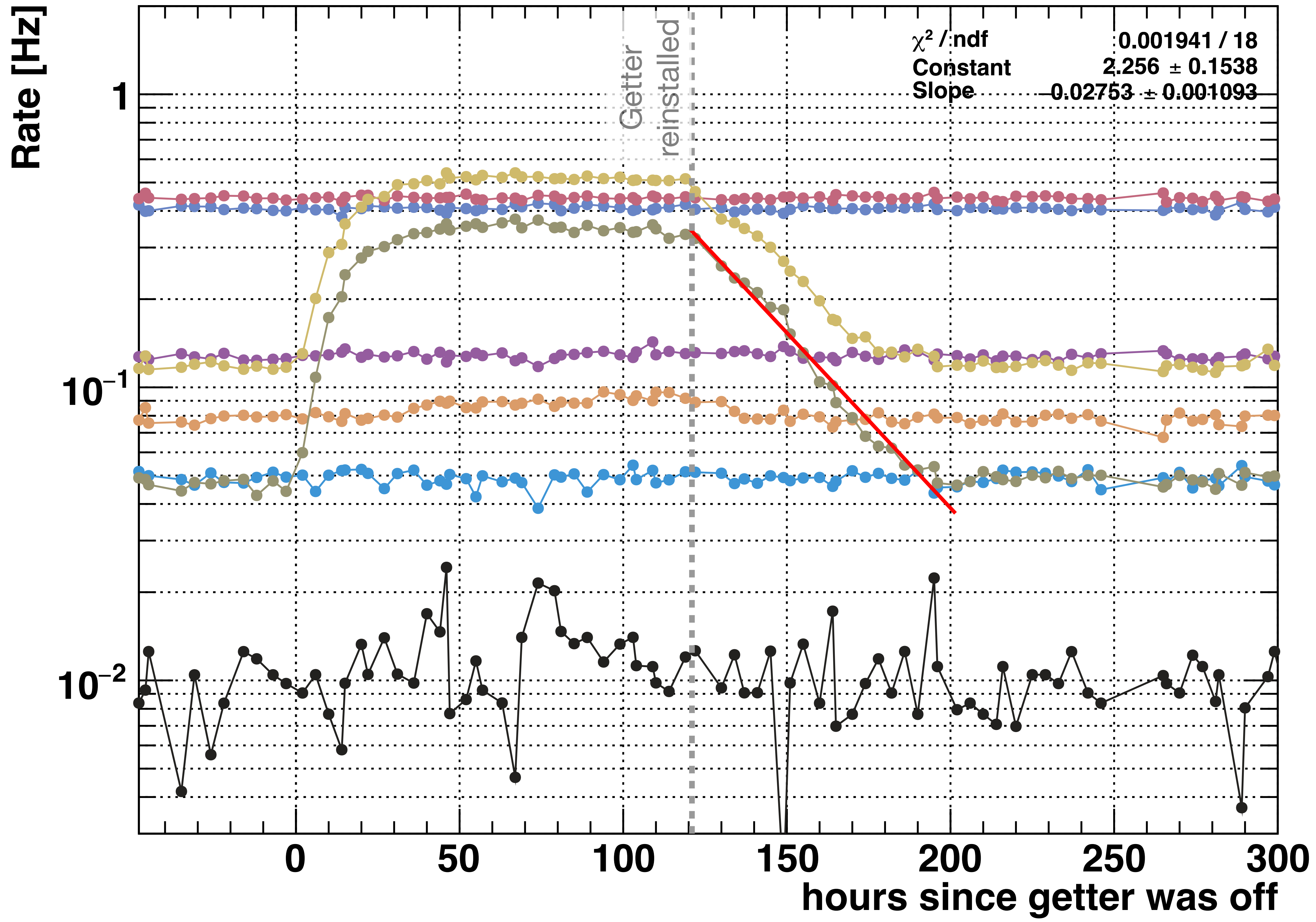
Event categorization based on the pulse id's and their temporal order

- *No pulse*: triggered, but pulse finder cannot find pulse including low Ne events that happen at the edge of the TPC (finder optimised for larger energies)
- *S1 only*: events don't have S2 or S2 too small (Cherenkov, wall effect, events in holes)
- *Single scatter*: normal events (S1+S2)
- *Multi scatter*: gamma events, random pileups
- *S2 only*: events don't have S1, or S1 too small for pulse finder (only Ne≥4)
- *SE*: *S2 only*, but Ne<4, most of them are delayed electrons
- *Multi S2*: Multi scatters with S1 and the first S2 pileup (due to low t_drift)
- *Other*: all the rest, 10^{-3} Hz (<0.1% of all events), for example, event with S2 + S1 + …

- Time evolution of each category from the underground Ar filling date (2015/04/01)
- Except *SE* and *No Pulse*, the rates are relatively flat. Stable operation over years.
- **In *SE* and *No Pulse*, two slopes: until 200 days and rest.**
- Getter-off runs are from 99 to108 days.

Getter Off runs

preliminary



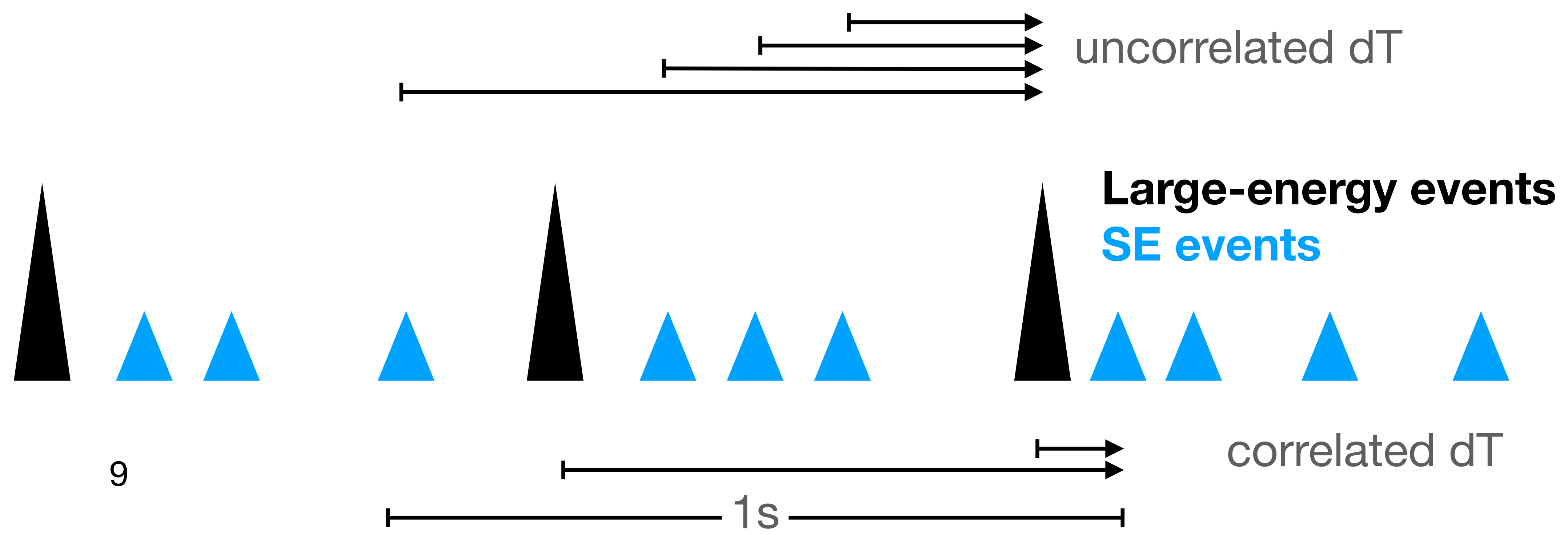
- For maintenance, the hot getter in the argon gas circulation system was removed for about 5 days.
- We noticed an increase in event rates with one pulse.
- Those events had a short livetime and small signal size.
- The elevated event rate was back to normal in 4 days after reinstallation of the getter.

- The increase in rates were seen only in *SE* and *No Pulse*.
- The decrease rate of the extra events had a time constant of 36 hours
- The rate increased in 2 days and stable until the getter was re-installed.
- This suggests that **impurities introduced by the absence of the getter are responsible for *SE* events** (and *SE* events too small to be found by the pulse finder, ie. *No Pulse*).

Time correlation of SE with large-energy events

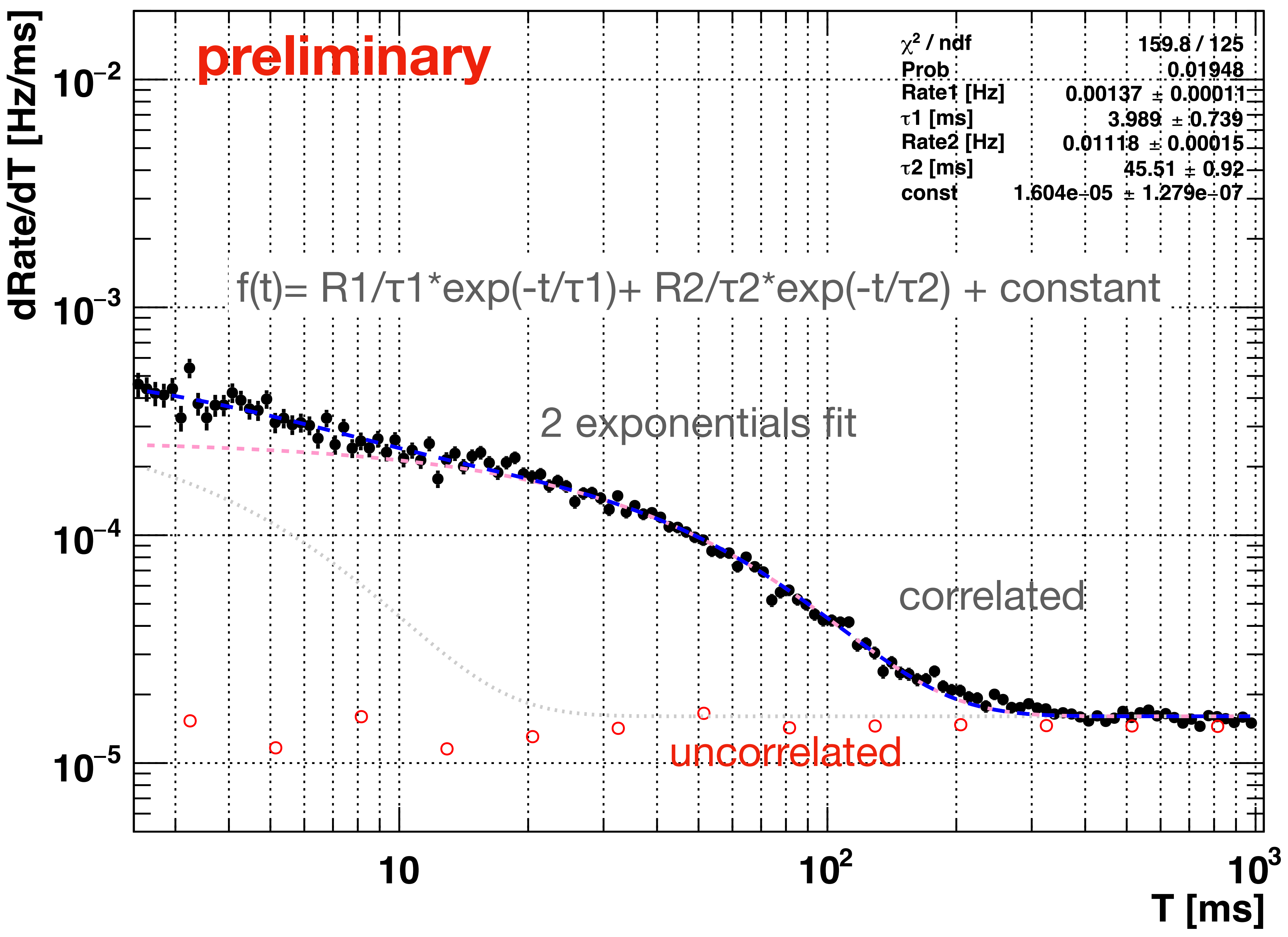
Time evolution of the time correlation

- large-energy events (parent events): S1>1000PE, t_drift defined (at least two pulses), and x-y position reconstructed.
- Register trigger time of events for large events and *SE* separately.
  - correlated ΔT: for each identified *SE*, fill time difference from all preceding large events within 1s from the *SE*.
  - uncorrelated ΔT: for each identified large event, fill time difference from all preceding *SE* events within 1s from the large event.
- uncorrelated ΔT helpings modeling the uncorrelated fraction that is present in the correlated ΔT

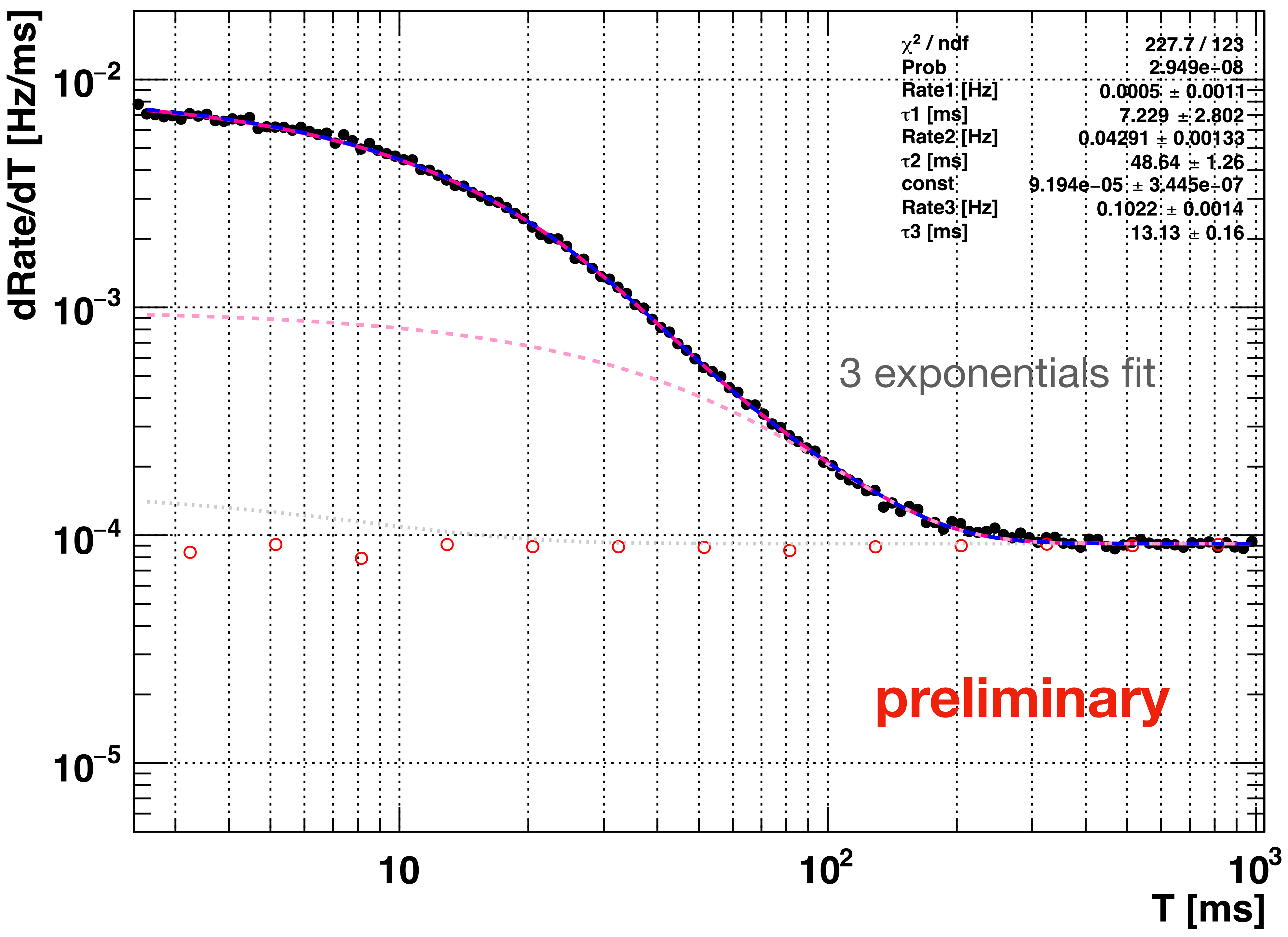


Time correlation

Normal runs (300-320 days)



Getter off data

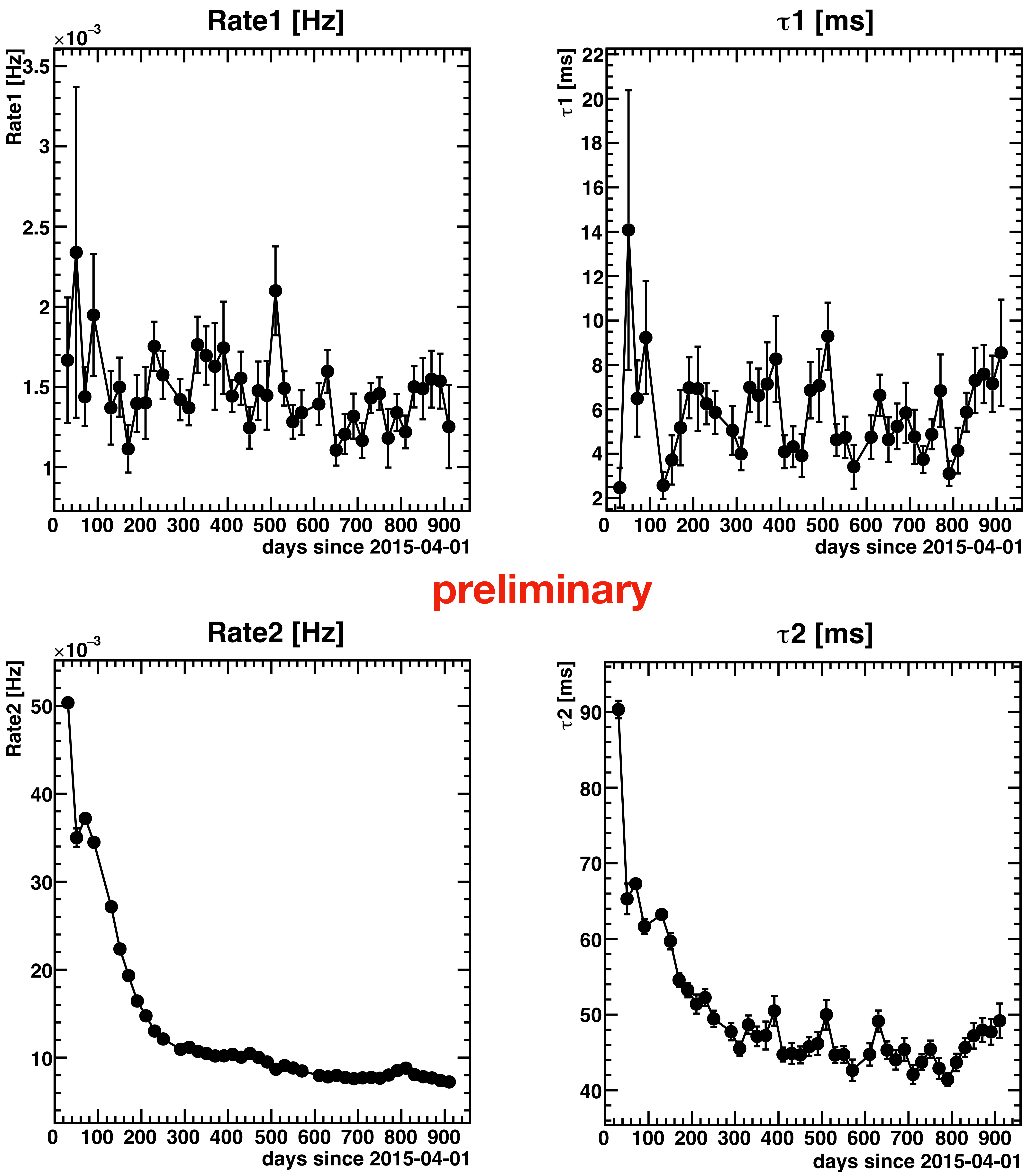


- At least two exponentials are necessary. Not power law unlike in Xenon based TPC.

D.S. Akerib et al. Phys. Rev. D 102, 092004 (2020)

- **In getter off data, an additional time constant of 13 ms appeared** and three exponentials are used.

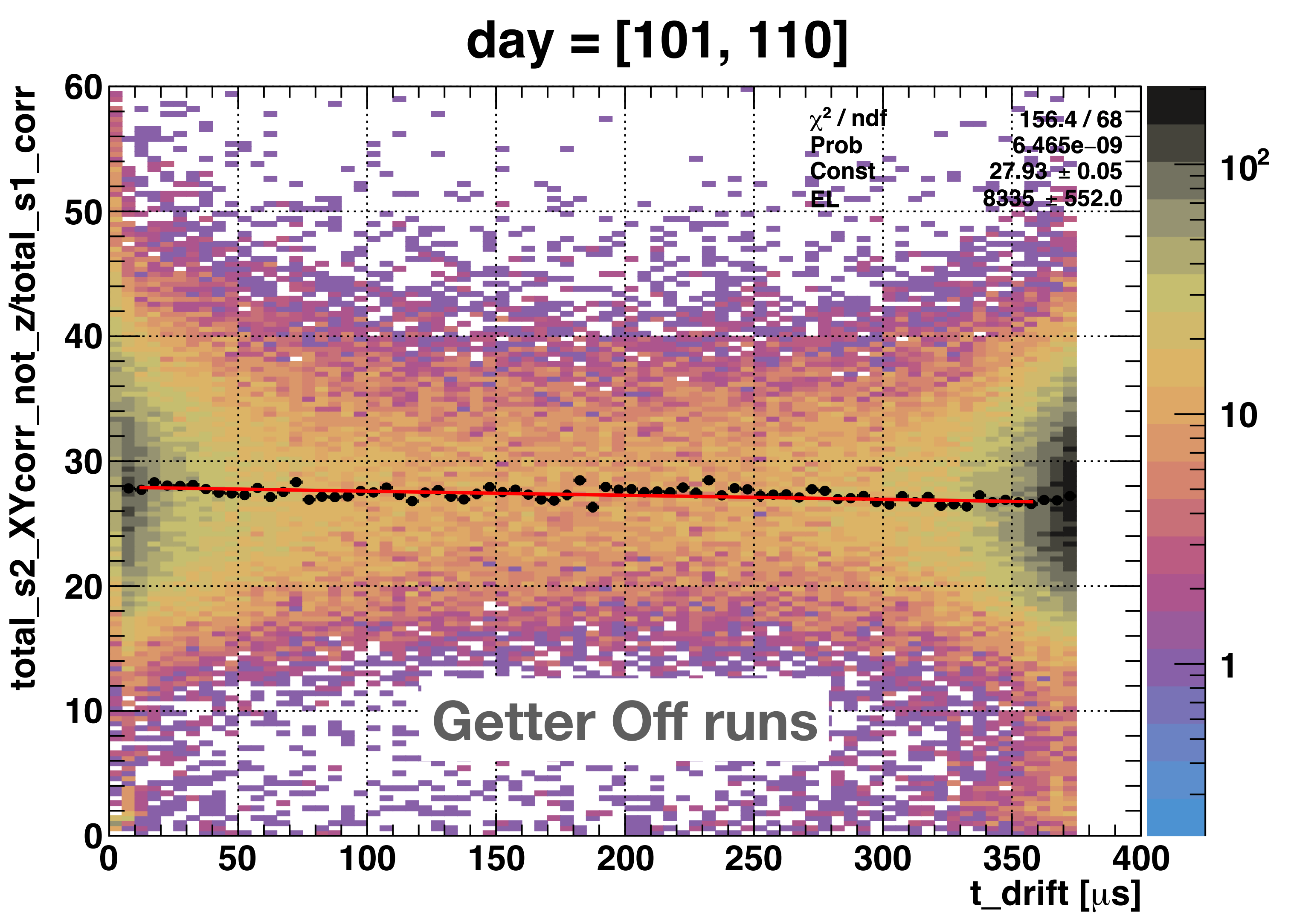
Time Evolution of Time Correlation



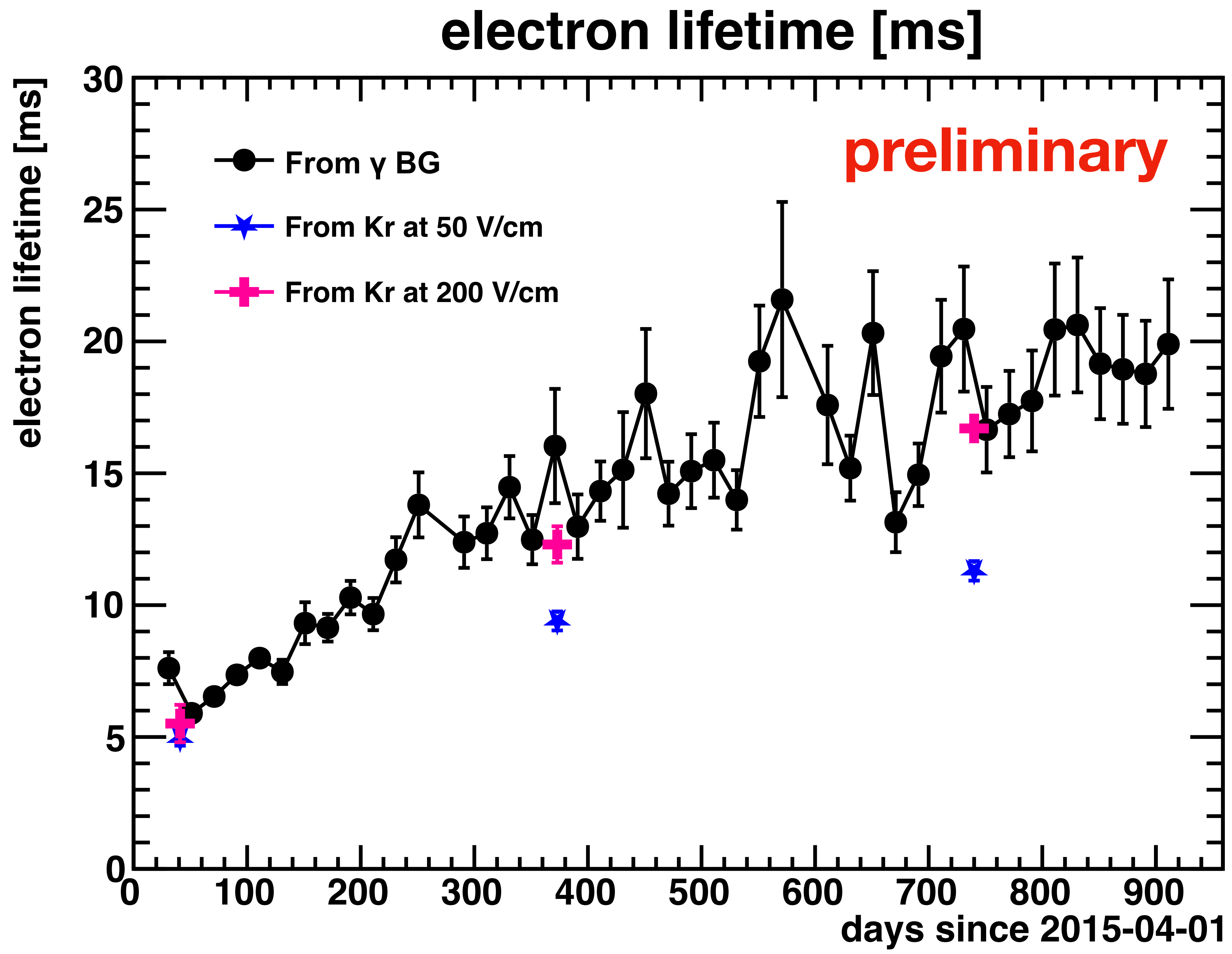
- Rate of the ~5 ms (τ1) component seems flat over time, ~1.5 mHz.
- Rate and time constant of the longer time constant (τ2) component decreased within the first 200 days.
- R_1 plus R_2 represent the correlated rates in SE events.
- We can explain 40% of the SE rate being correlated with well identified preceding events. Work underway to better quantify this.

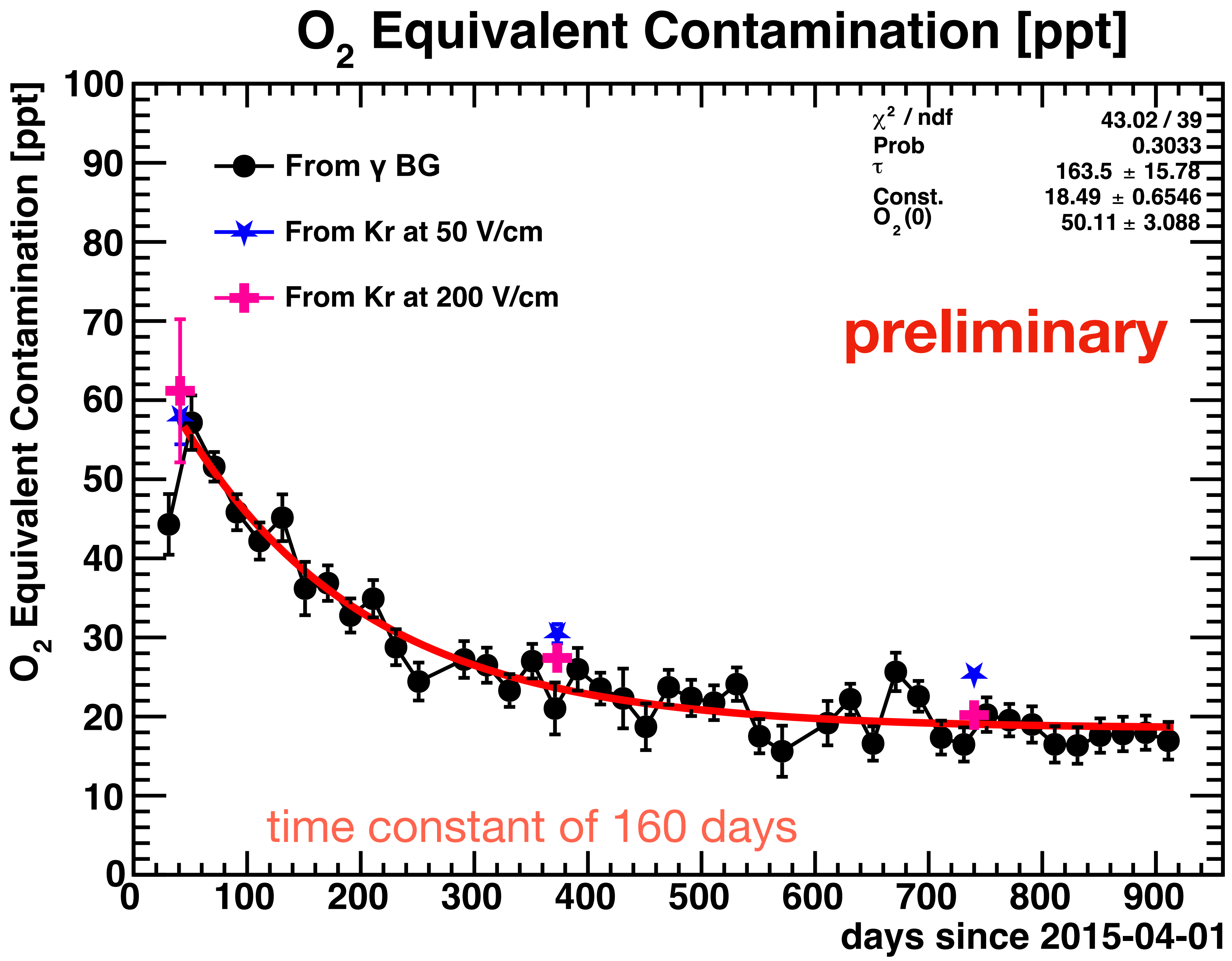
Getter off data is not included

Electron lifetime



- The electron lifetime is evaluated using normal data and Kr source data at 200 and 50 V/cm.





- The improvement trend of the electron lifetime is similar to the trend of the longer time correlation.
- The getter off runs did **not show degradation** of electron lifetime.
- **The impurity causing 13 ms time constant in the getter off is different from the impurity causing electron lifetime degradation.**

Spatial correlation

- Pearson's correlation coefficient is used.

$$Corr(x_a, y_b) = \frac{\sigma_{x_a y_b}}{\sqrt{\sigma^2_{x_a}\sigma^2_{y_b}}},$$ where

x_a (y_b) is 1 if channel a (b) is S2_max_chan in SE (parent) events.

$$\sigma_{x_a y_b} = \frac{1}{N}\sum_i^N \left(x_a^i - \langle x_a \rangle\right)\left(y_b^i - \langle y_b \rangle\right),\ \sigma^2_{x_a} = \langle x_a \rangle \text{, and } \sigma^2_{y_b} = \langle y_b \rangle .$$

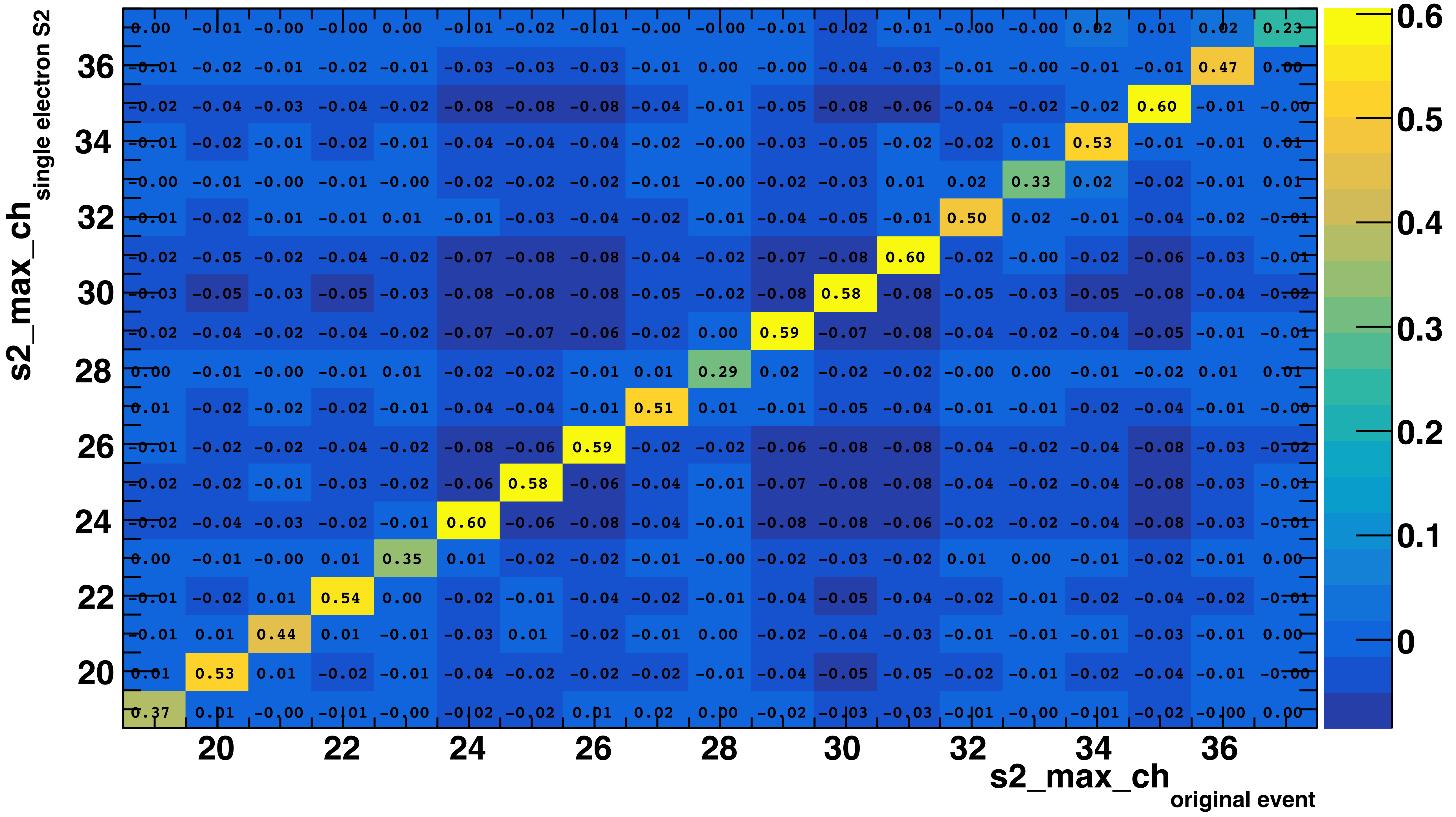
The mean values are used as approximation of variances since it is Poisson process.

This coefficient is 0 if there is no correlation, 1 for perfect correlation and -1 for perfect anti-correlation.

- Only single scatter parent events (well-defined event positions) are used
- Only SE events <200ms from single scatter parent events are used.
- The correlation coefficients are about (0.60/0.51/0.34) at (center, middle, edge) PMTs.
- **Strong correlations** are observed between S2_Max_chan of SE and its parent events. The correlation with other channels are basically 0, no correlation.

The first 120 days including Getter-Off runs

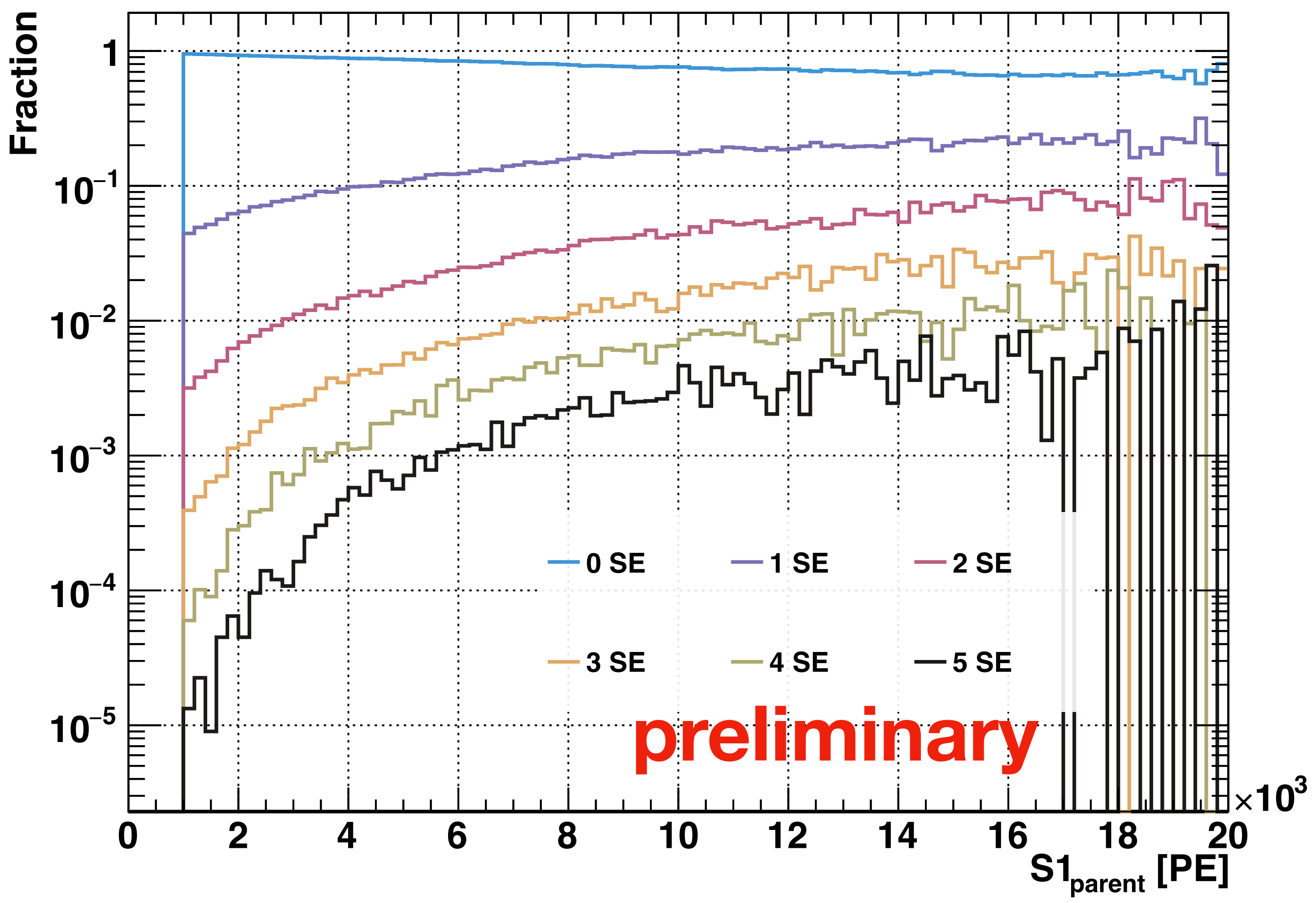
preliminary



Correlation w/ Parent's energy and z-position

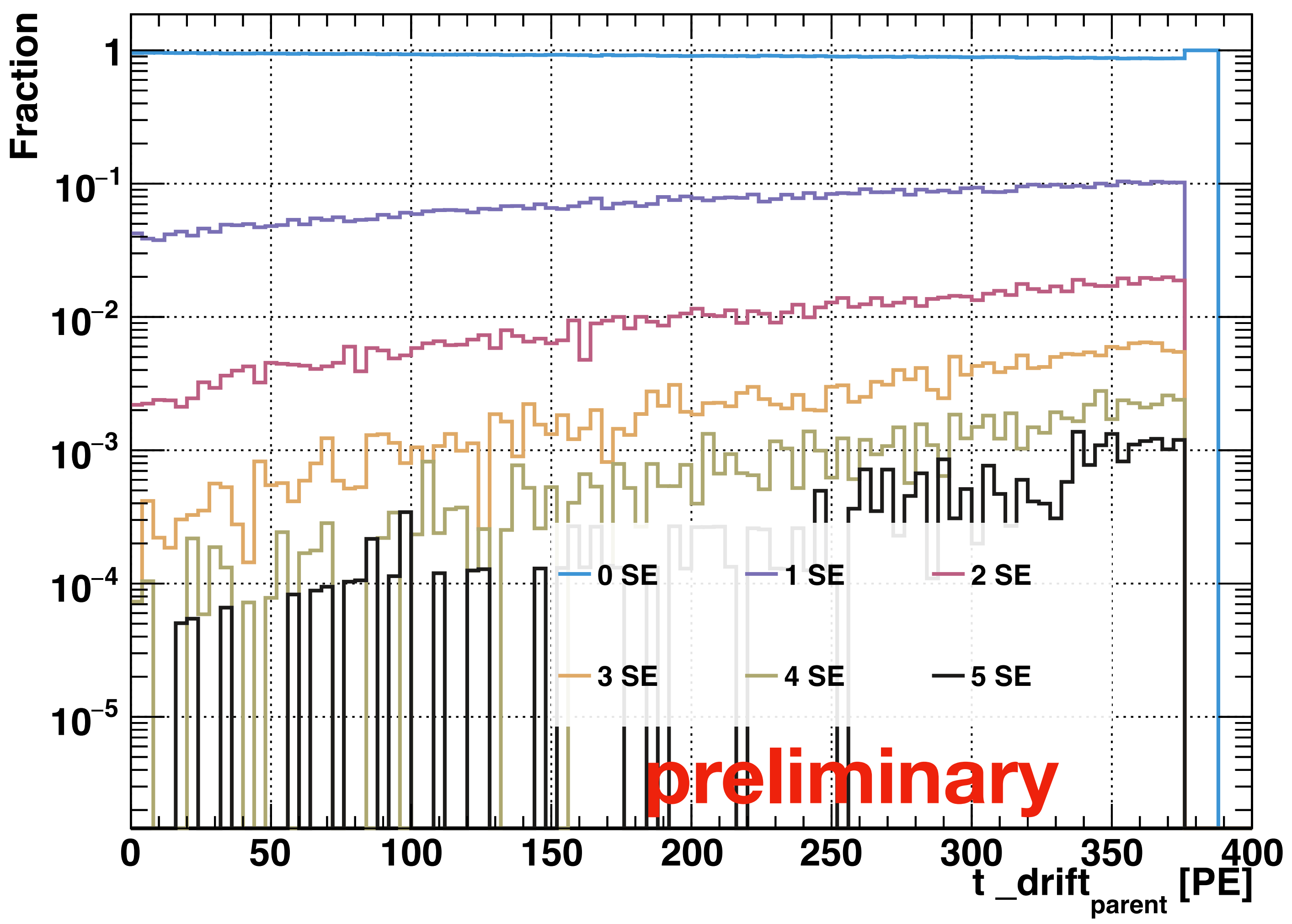
- For all parent events, count how many SE events follow until next parent event.
- The fraction of parent events with no SE events, one SE event, two SE events, so on, is calculated as a function of parent S1.
- **Large energy events create more SE events.**

The first 120 days including Getter-Off runs



- Only single scatter events as parent to have a well-defined z-position.
- Clear linear relationship with z-position of parent. -> **The longer the drift time, the higher the chance of electrons to be captured.**
- This is consistent with the expected behavior of the correlated events, which originates from the charge released in previous interactions drifting along the field and being trapped along the route.

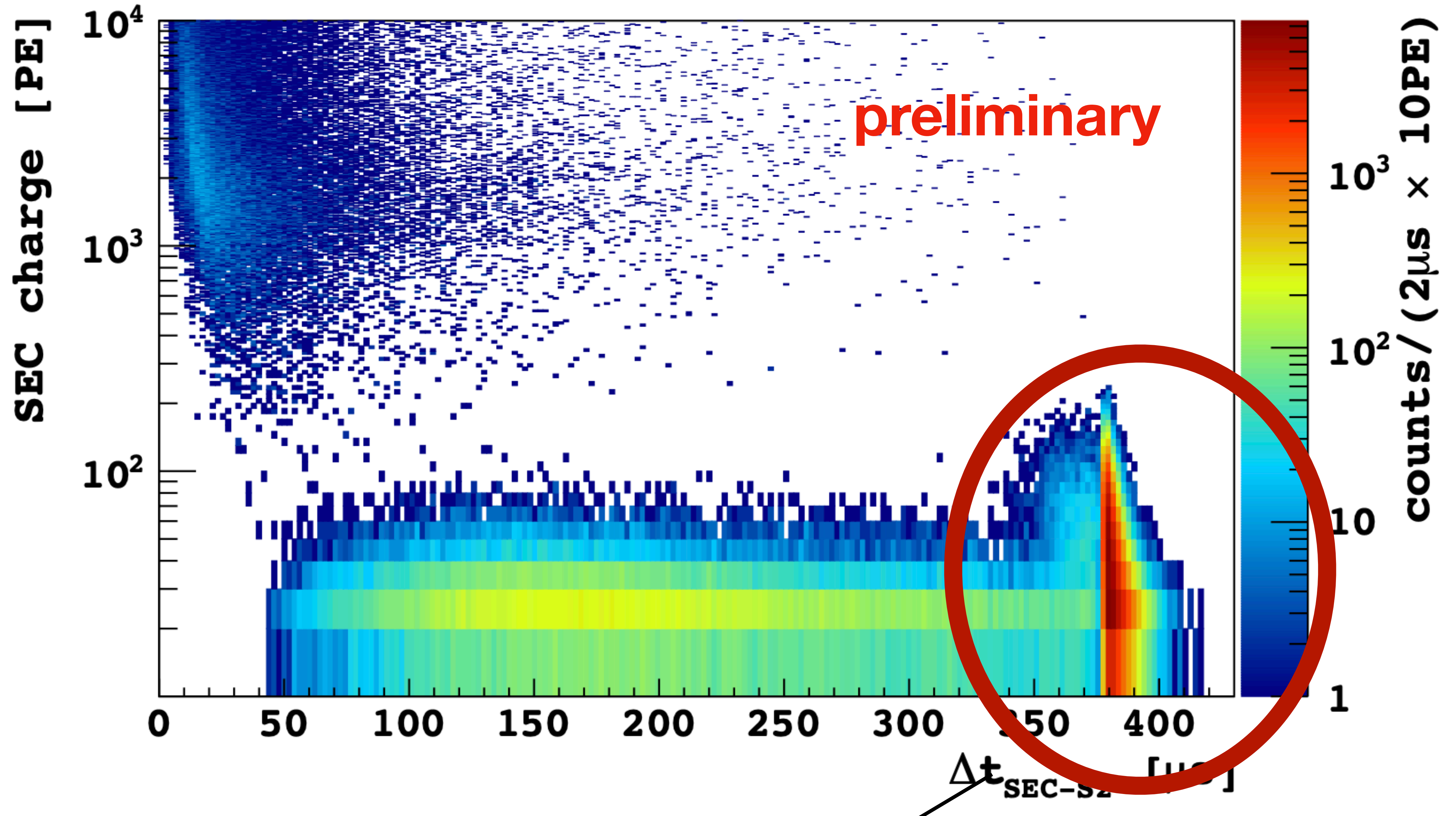
The first 120 days including Getter-Off runs

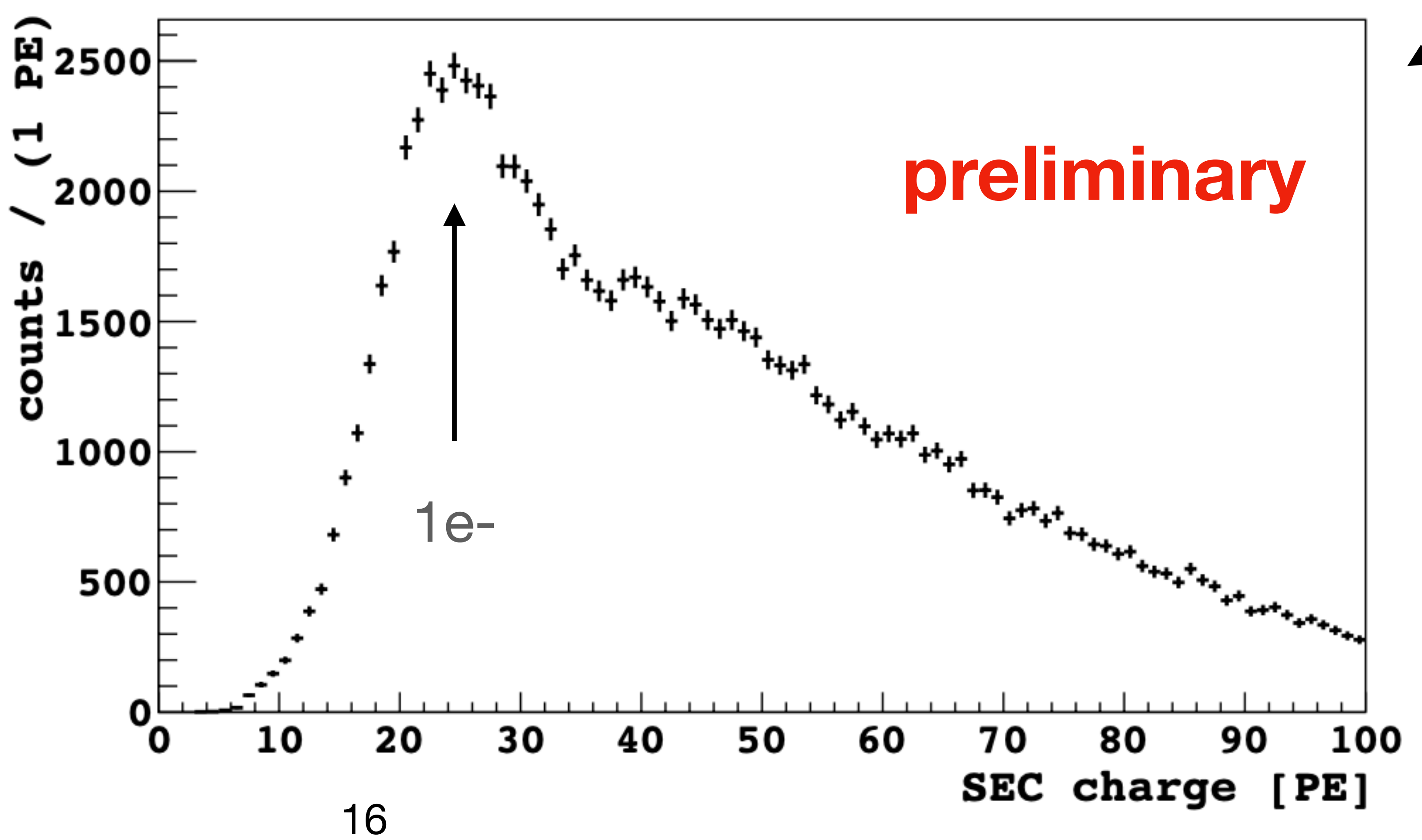


Photoionization electrons

Events with S1 followed by two S2's

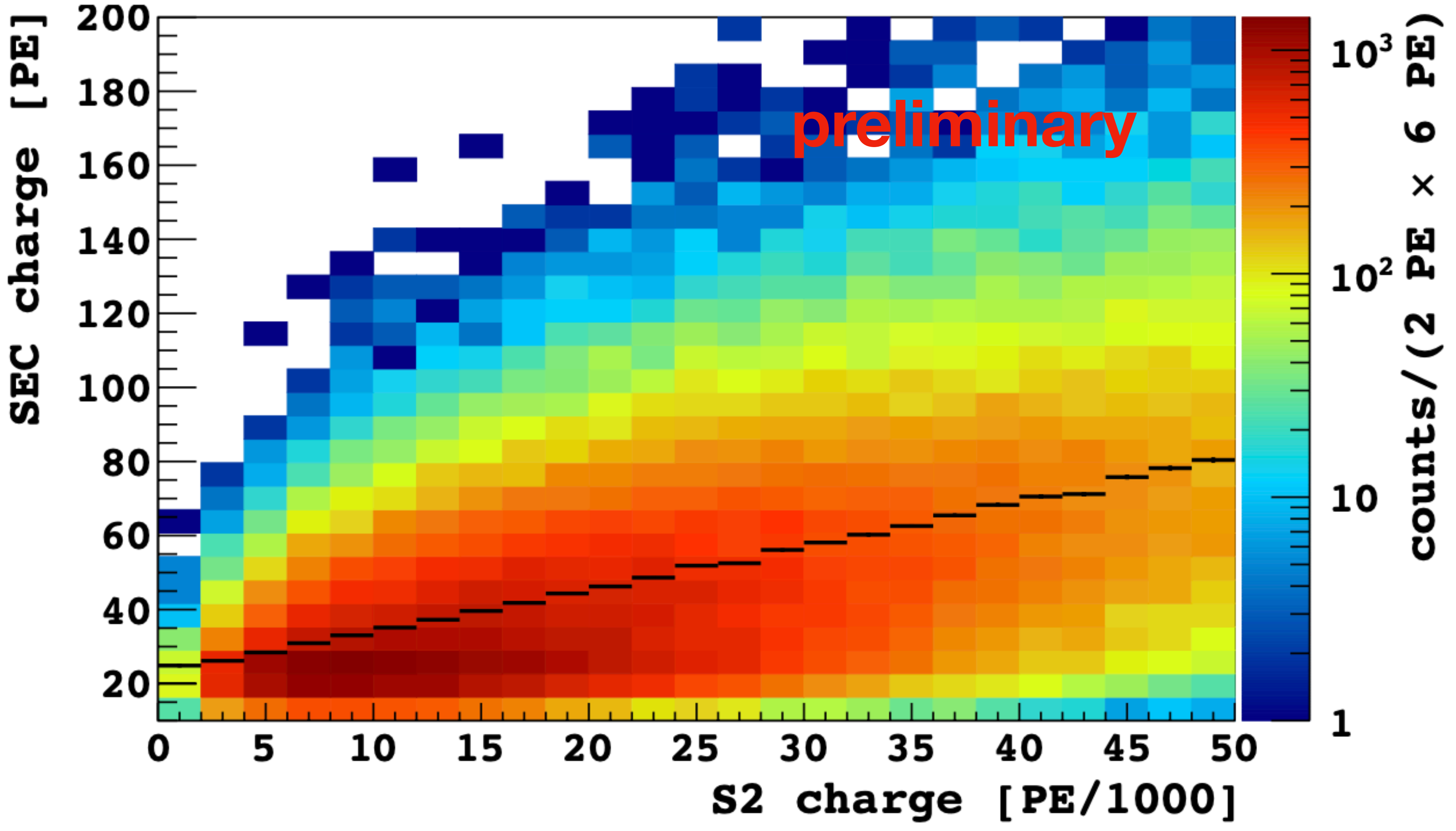
- The second S2 we called SEC
- For SEC only central PMT
- 3 populations
  - One max drift time after S2

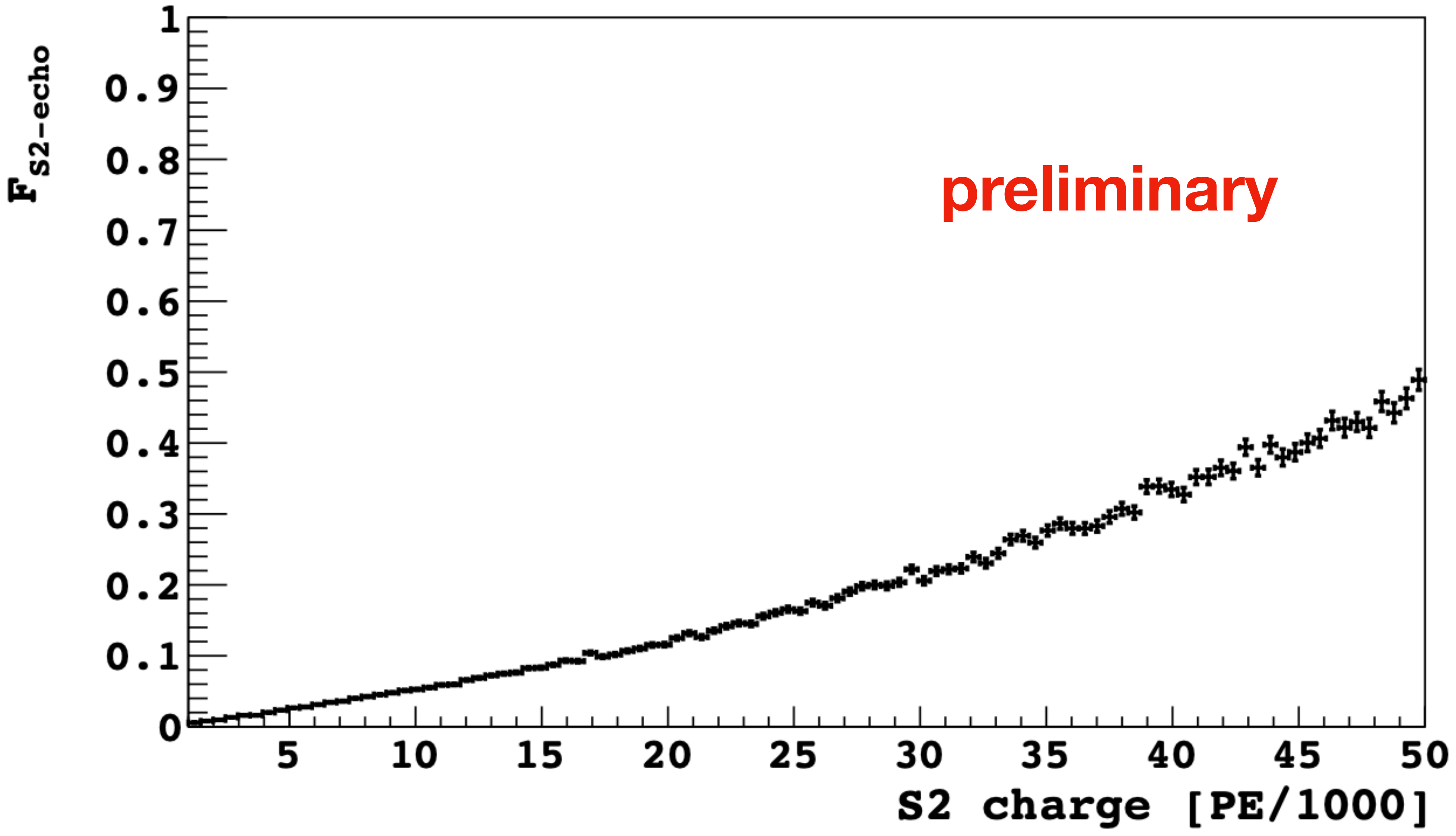




Interpretation:

Photoioinisation of the cathode by S2 UV photons: “S2-echo”

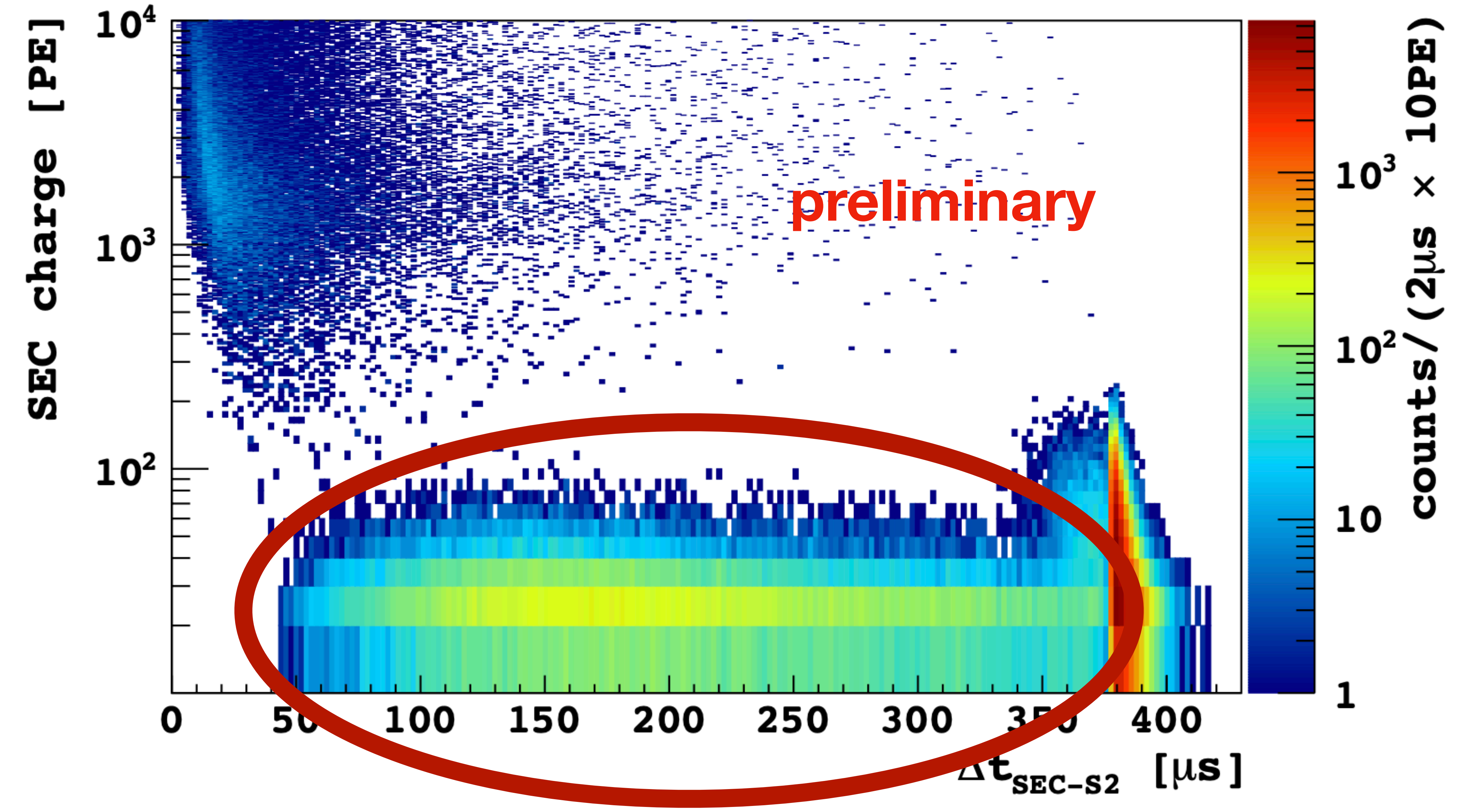


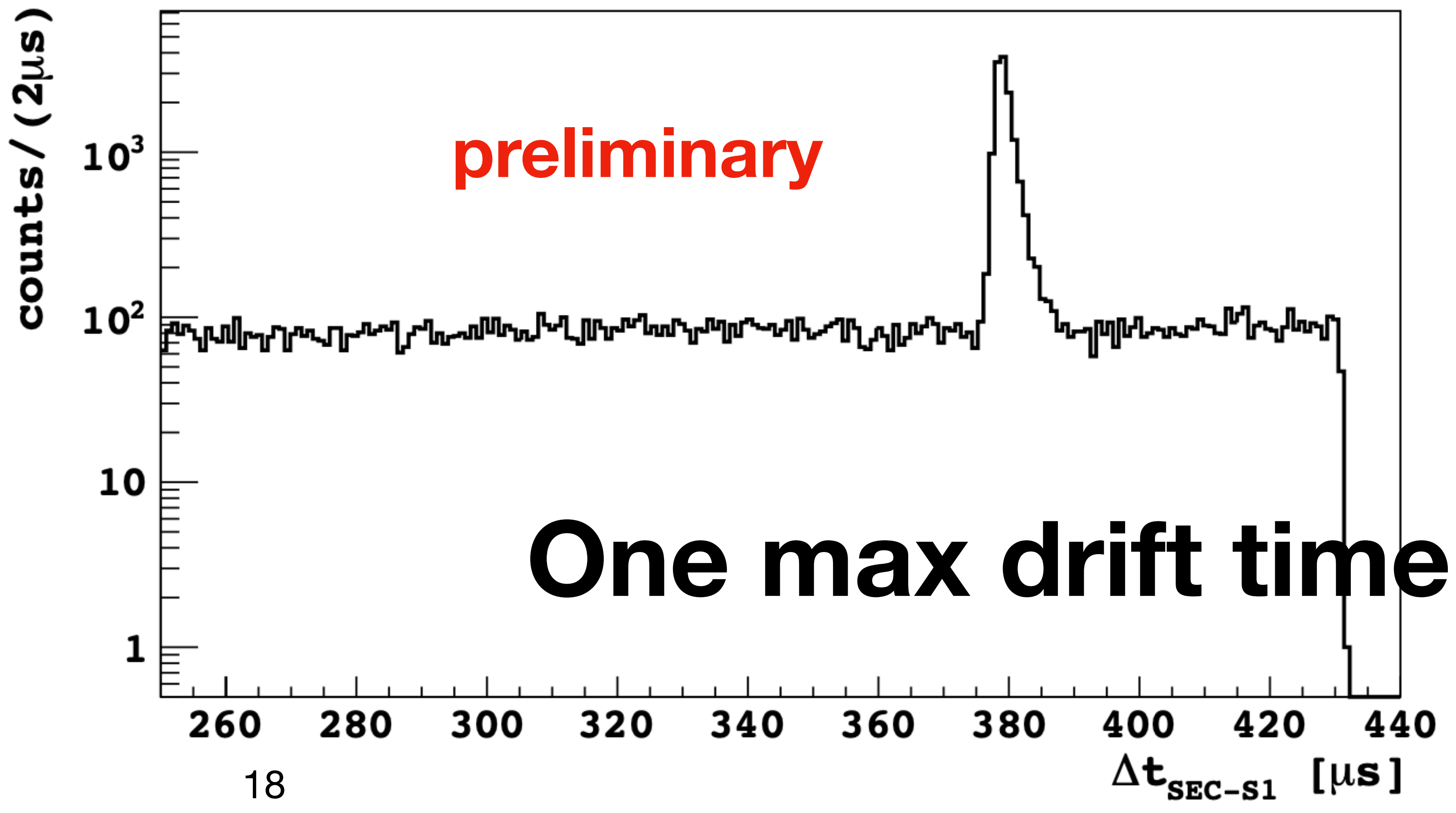


- Correlation of SEC charge and SEC occurrence with S2 charge

Events with S1 followed by two S2's

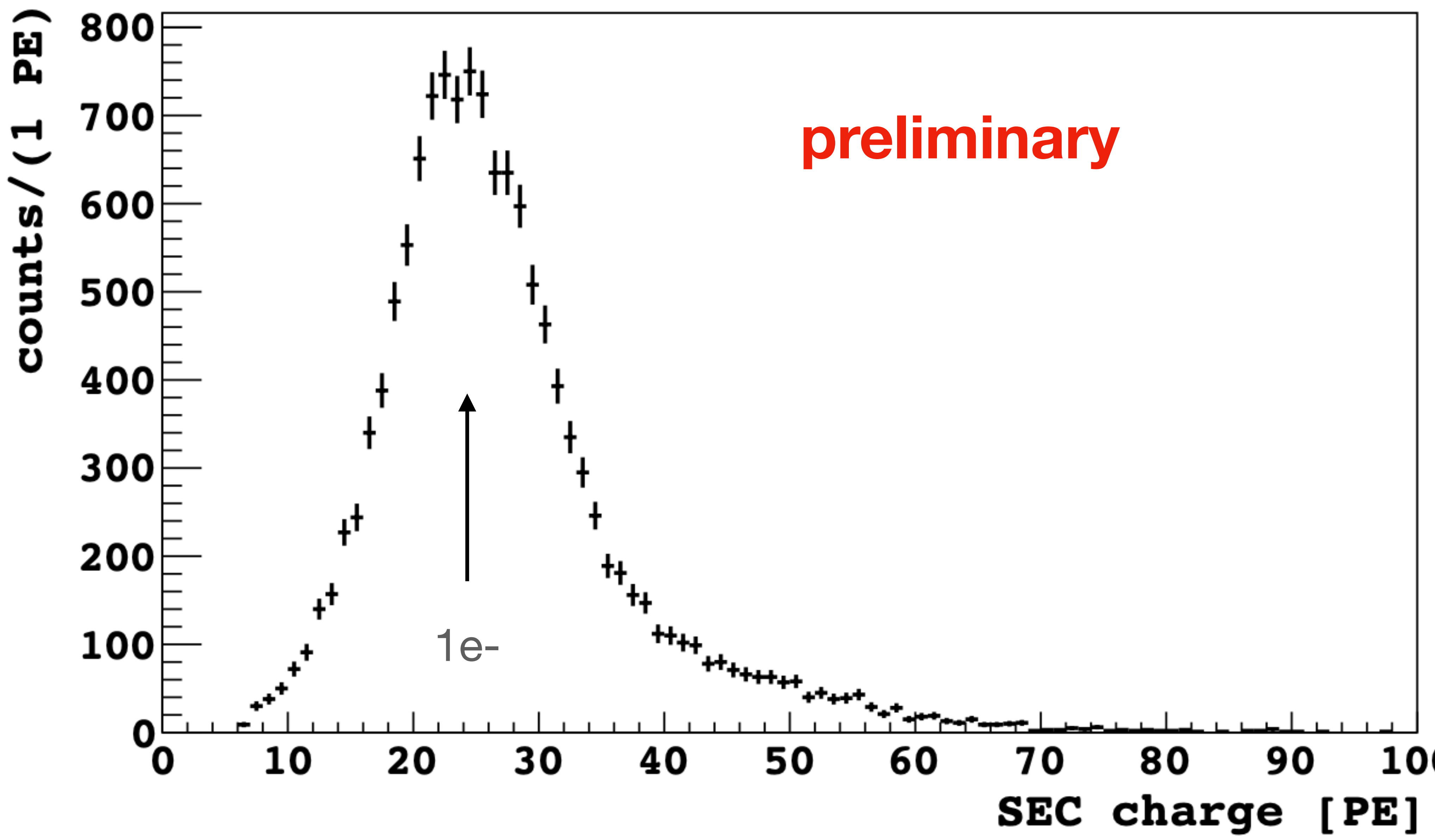
- The second S2 is called SEC
- For SEC only central PMT
- 3 populations
  - One max drift time after S2
  - Less than one max drift time after S2

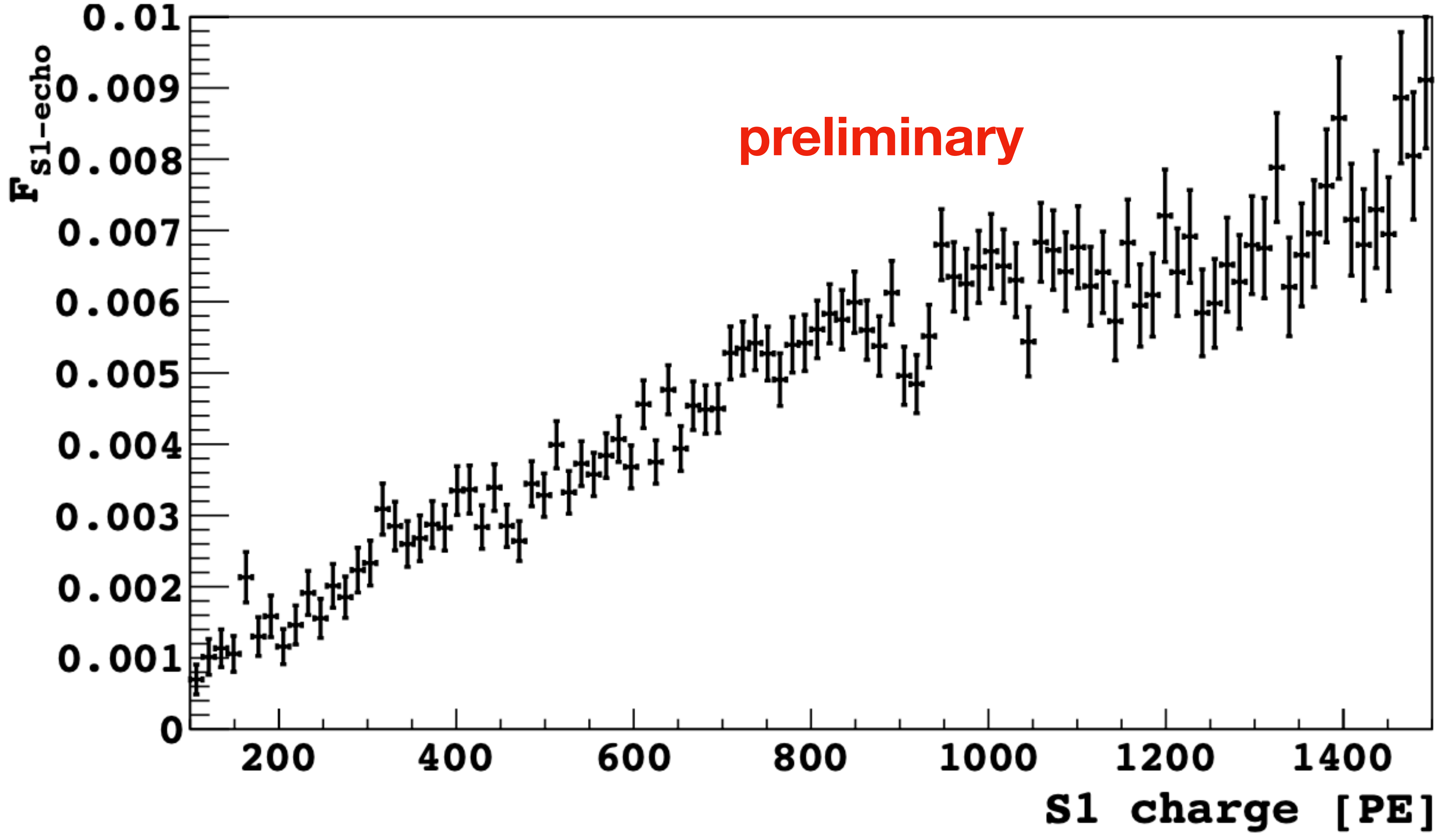




Interpretation:

Photoionisation of the cathode by S1 UV photons: “S1-echo”



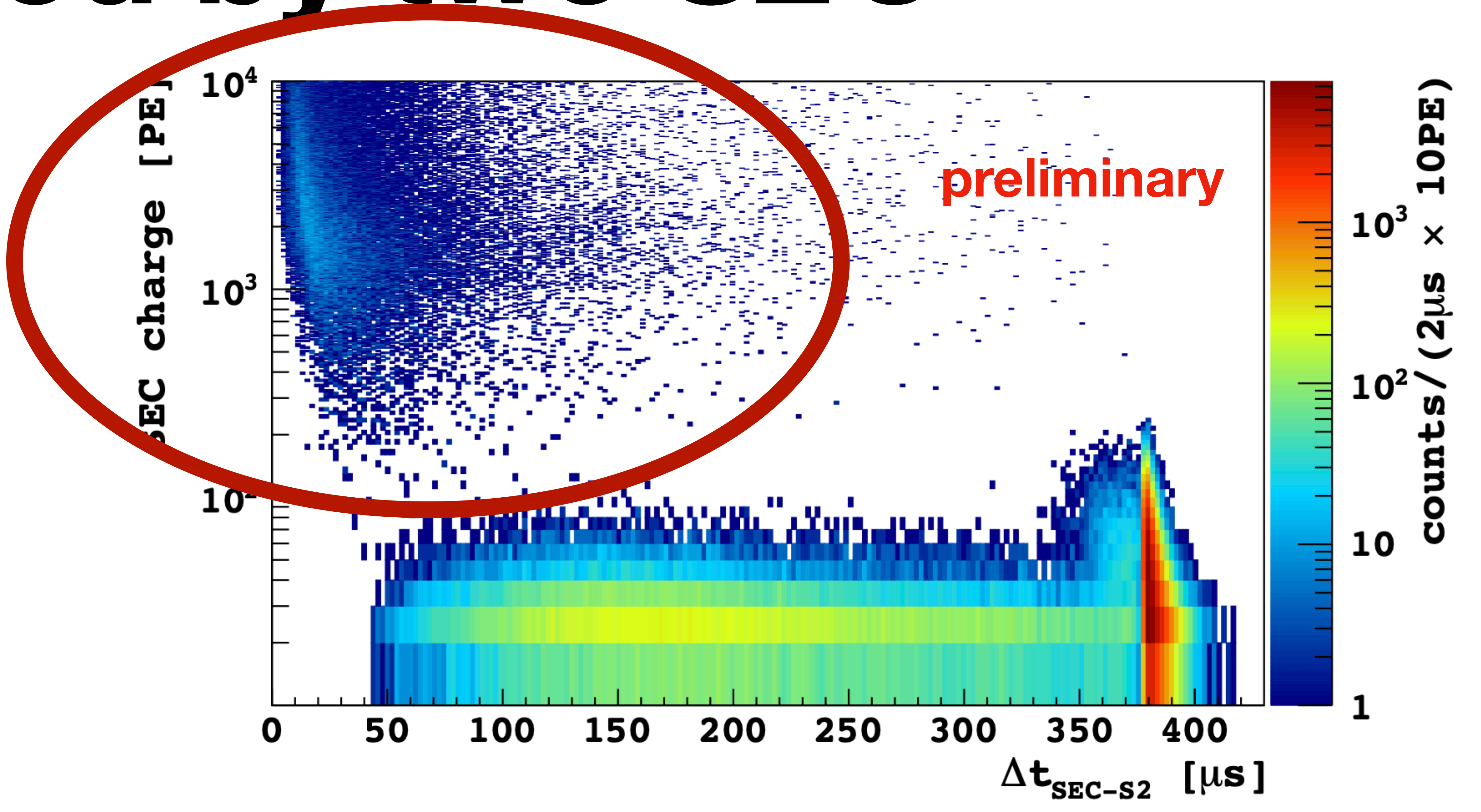


- SEC charge spectrum.

SEC occurrence with S1 charge

Events with S1 followed by two S2's

- The second S2 is called SEC
- For SEC only central PMT
- 3 populations
  - One max drift time after S2
  - Less than one max drift time after S2
  - Standard multi-site Compton scattering background



Calculation of cathode TPB quantum efficiency

First time ever

$$QE_{\mathrm{S1}} \sim \langle F^{\epsilon}_{\text{S1-echo}} \rangle \frac{g_1}{\langle S1 \rangle_e} \langle N_{el} \rangle_{S1}$$

- The fraction of echo events is corrected for the geometric efficiency vs z

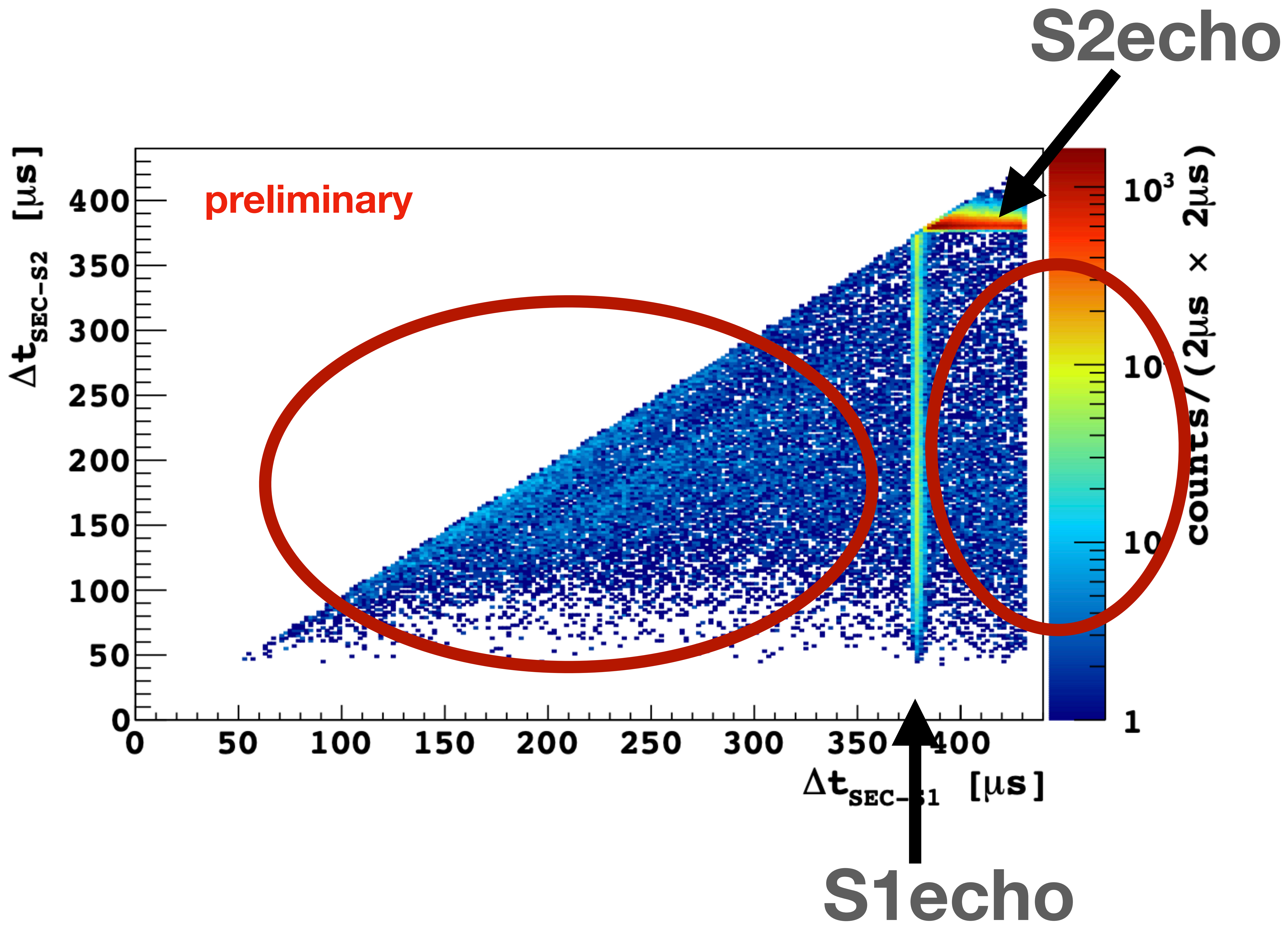
$$QE_{\mathrm{S2}} \sim \frac{\langle F_{\text{S2-echo}} \rangle}{\hat{\epsilon}_{\mathrm{S2}}} \frac{g_2}{\langle S2 \rangle_e} \langle N_{el} \rangle_{S2}$$

- g1 g2 are taken from MonteCarlo g1 and g2~ 0.16 PE/γ the average number of photoelectrons per UV photon

- Values in agreement within factor of 2.   QE ~ 3 × 10-4/γ

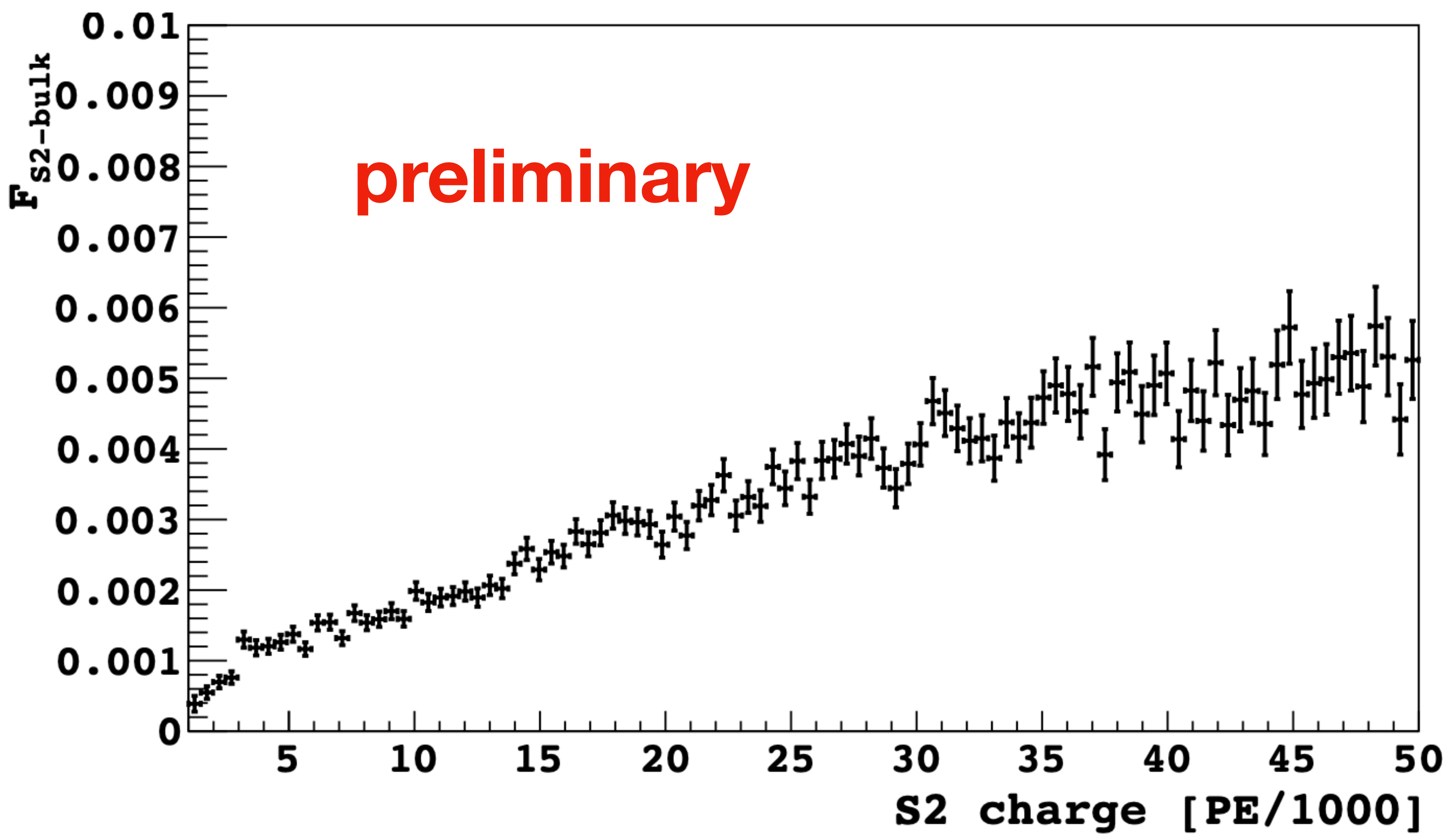
Another event set

Interpretation: Photoionisation of the liquid by S2 UV photons



N(el)SEC<1

Photoionisation in the liquid



- Calculation of probability of photoelectric extraction from the liquid per unit length and per UV photon

$$PEP_{S2} = \frac{1}{\hat{L}_{\mathrm{S2}}} \frac{g_2}{\langle S2 \rangle_b} \langle F_{\mathrm{S2\text{-}bulk}} \rangle$$

- LS2 taken from MonteCarlo. PEP = 3x 10-6 /γ/m about one order of magnitude less than LUX (D.S.Akerib et al. Phys.Rev.D 102, 092004 (2020))

- Nature of contaminant not clearly identified. Increase by 35% of these events with getter-off.

Conclusion

- In DS-50 TPC, we observed a few electrons (SE) emission, which set an unfortunate threshold for low mass dark matter search.
- Observation of strong correlations between parent events and following SE events in event positions, time, and energy —> 1) understanding or origin 2)cuts can be used to partially suppress the background
- Correlation with the presence of impurities but the mechanism of releasing electrons from impurity is unknown.
- Observation of photoionisation of both cathode and bulk as in liquid xenon
- Quantitative measurements of extraction probabilities
- Full understanding of delayed emission (and photoionisation of the liquid) for mitigation in future experiments would require dedicated test experiments

The end

Backup

Summary

- In DS-50 TPC, we observed a few electrons emission, which set a threshold for low mass dark matter search.
- The SE event rates decrease with time constant of 36 hours for the getter off impurity, which is much shorter than the time scale of the electron lifetime improvement (~160 days). This impurity should have lower boiling temperature than Ar, such as N^2, which has boiling temperature of 77K (87K for Ar) and is one of gases removed by the hot getter.
- There are strong correlations between parent events and following SE events in event positions, time, and energy.
- In the time correlation study, the time constants change with time: the short component ~5 ms stable, the long component evolve from 90 to 45 ms. With getter-off, an additional component is necessary, maybe sign of different type of impurities.
- No clear correlation with the impurity causing electron lifetime degradation.
- The SE rate decreased with a time constant of ~65 days.
- Another longer decreasing trend with time constant of ~8 years. Another impurity? or correlate with the decrease of the total event rate?
- The rate of SE shows a hint of correlation with the temperature of the Rn trap.
- The mechanism of releasing electrons from impurity is unknown.