Unusual slow components in electroluminescence signal of two-phase argon detector: threshold behavior and temperature dependence

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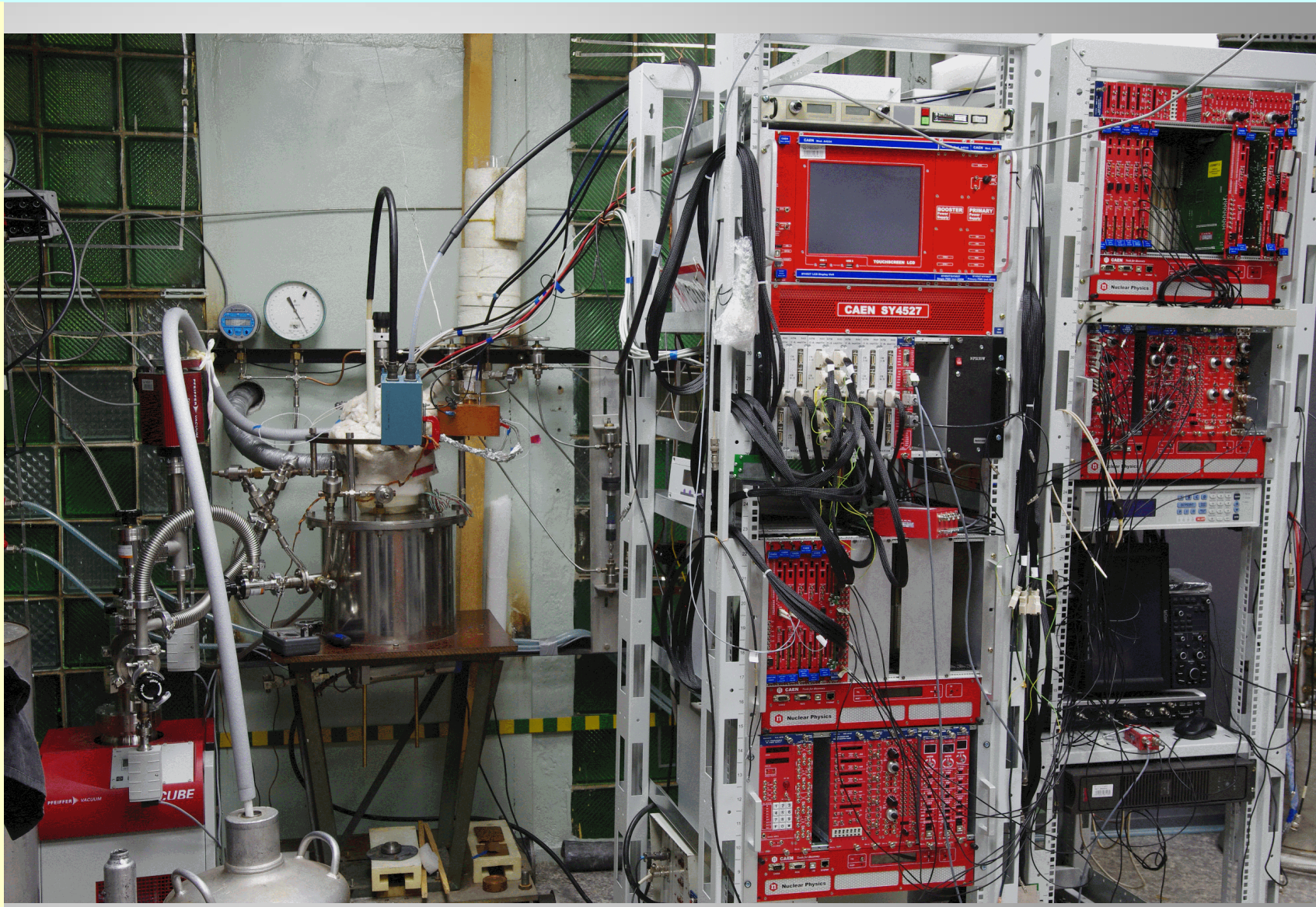
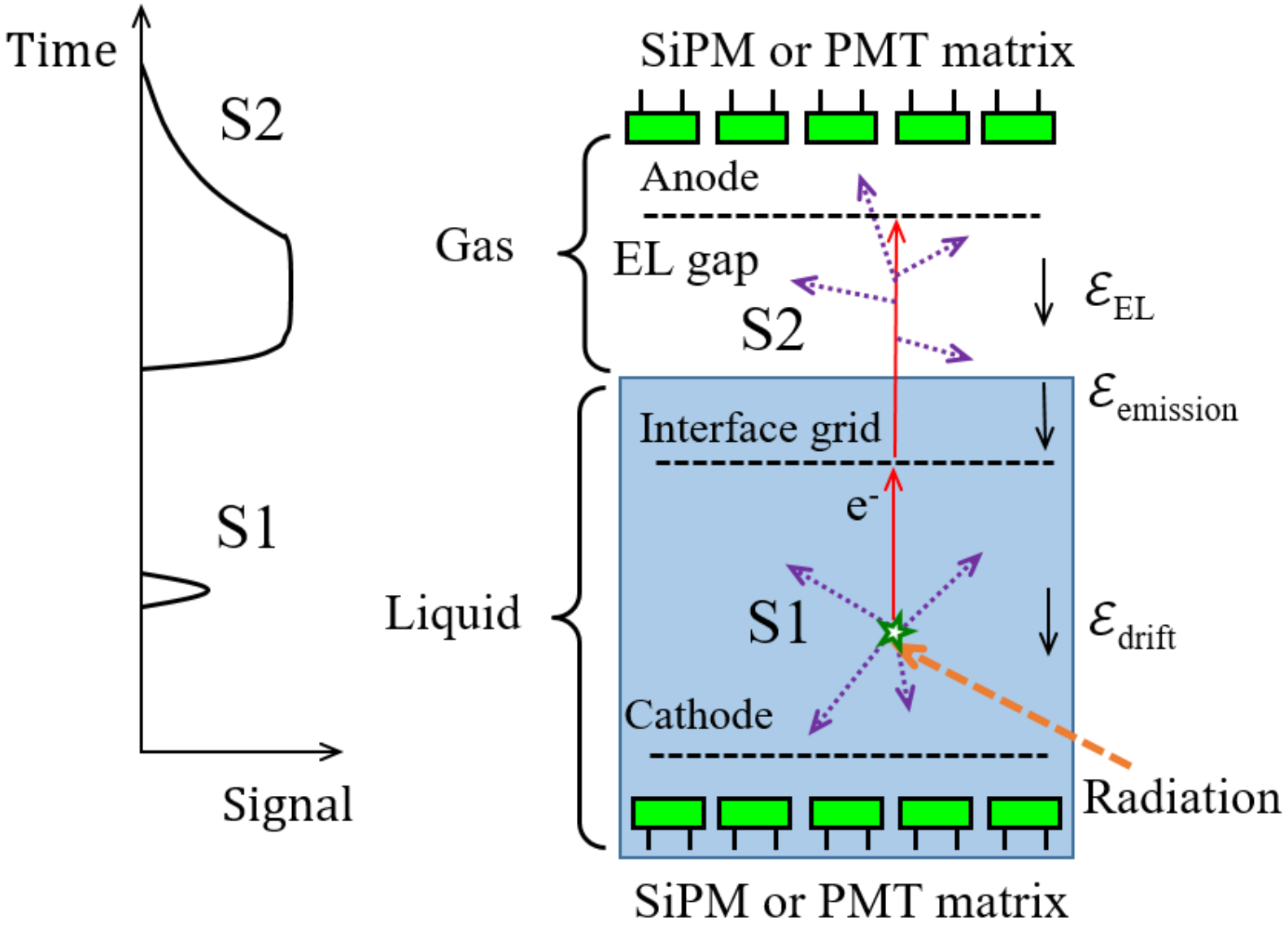
Novosibirsk group activity: development of two-phase Ar detectors for dark matter search experiments

Novosibirsk group is currently conducting researches in the frame of R&D program for DarkSide dark matter search experiment:

- **Study of electroluminescence phenomena in two-phase Ar (this talk).**
- **Study of primary scintillations in liquid Ar doped with CH4.**
- **Development of new readout techniques in two-phase Ar detectors using SiPM-matrices.**
- **Measurement of ionization yields of nuclear recoils in liquid Ar using neutron scattering technique.**



Concept of two-phase Ar detectors: introduction of electroluminescence (S2) signal



EL = Electroluminescence

S2 signal shape in two-phase detectors

Motivations to study S2 signal shape:

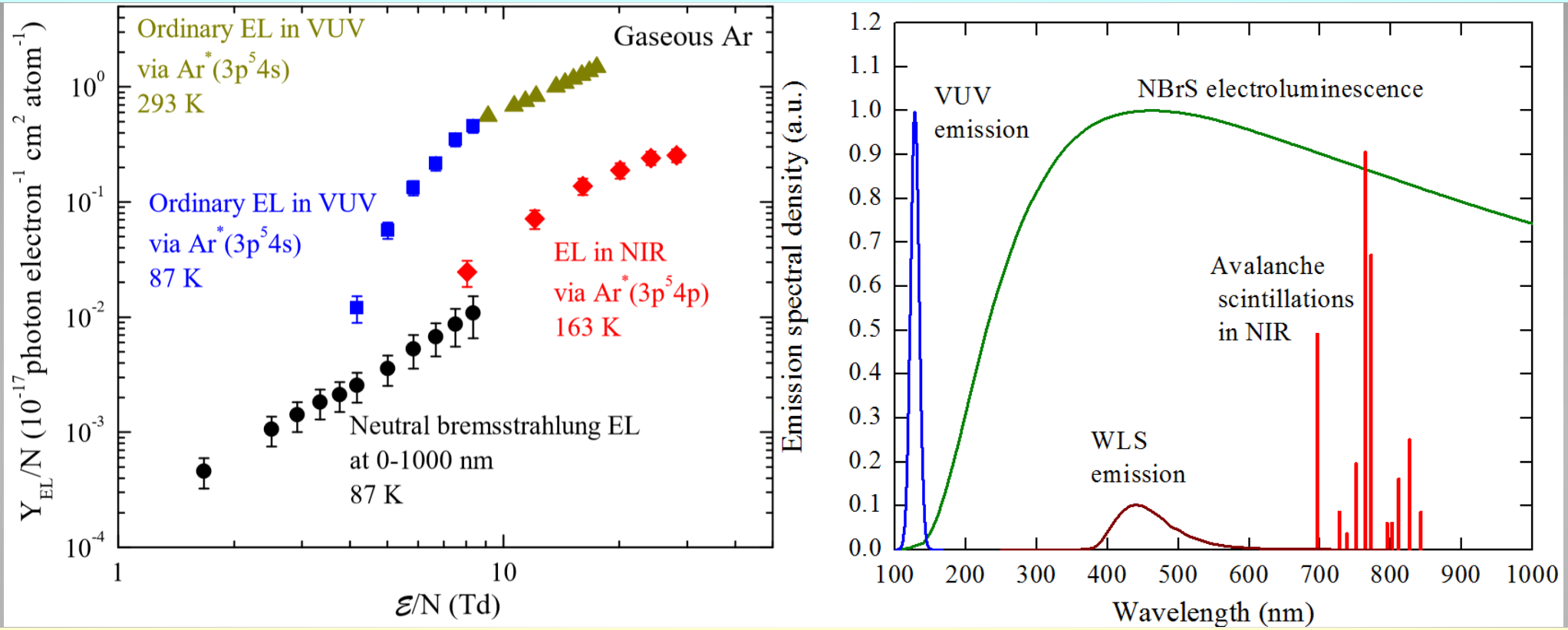
- Integration time to measure overall S2 amplitude.

- To measure z-coordinate via electron diffusion (related to S2 fast component shape)

- To measure EL gap thickness using S2 shape

- To understand EL mechanisms

Electroluminescence mechanisms



According to current concepts (A. Buzulutskov, Instruments (2020) 4), there are three EL mechanisms:

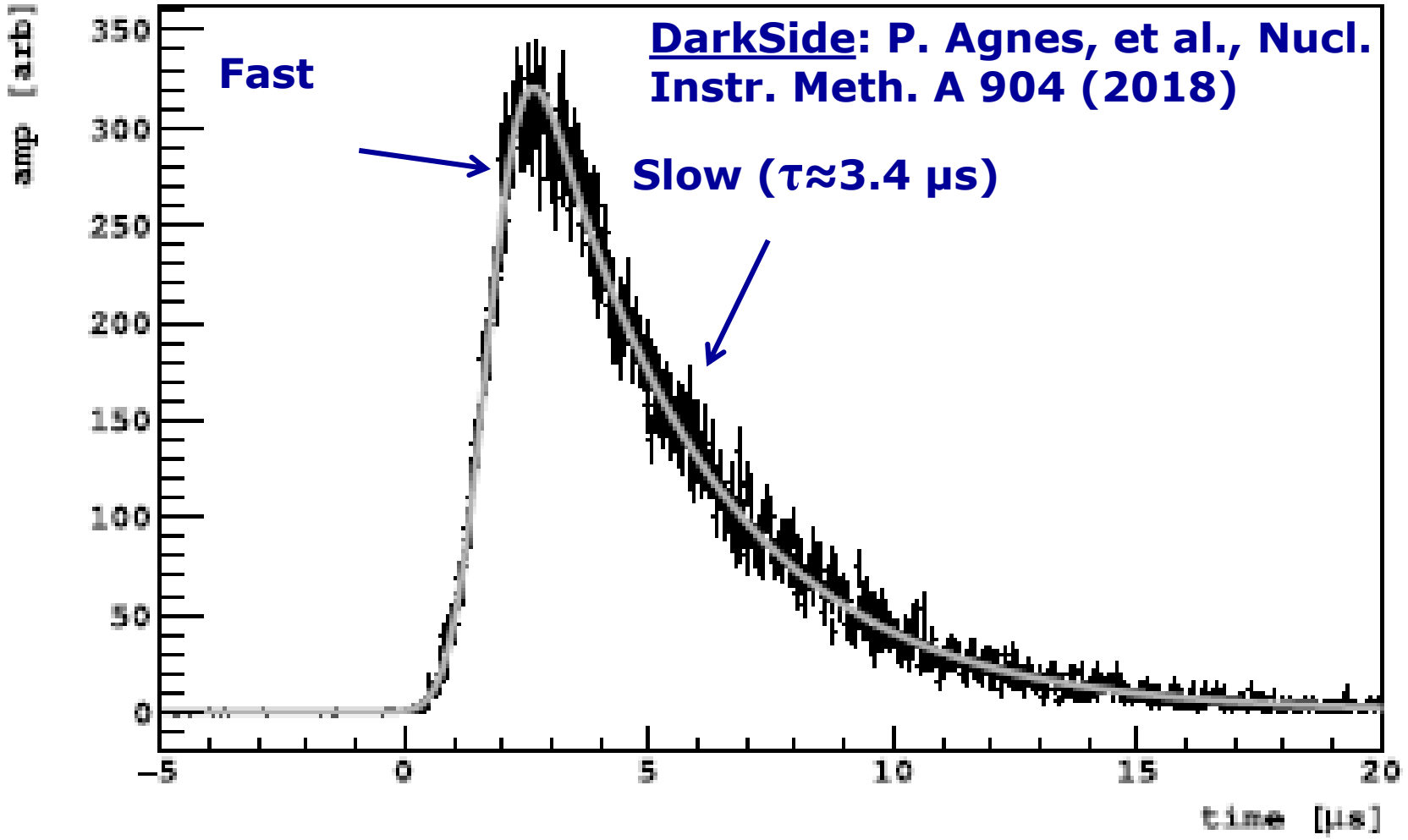
- Excimer (Ar_2*) emission in VUV (ordinary EL). It has fast (singlet) and slow (triplet) components with time constants of 4 ns and 3.2 μs respectively.

- Neutral bremsstrahlung (NBrS) in visible and NIR. It is fast.

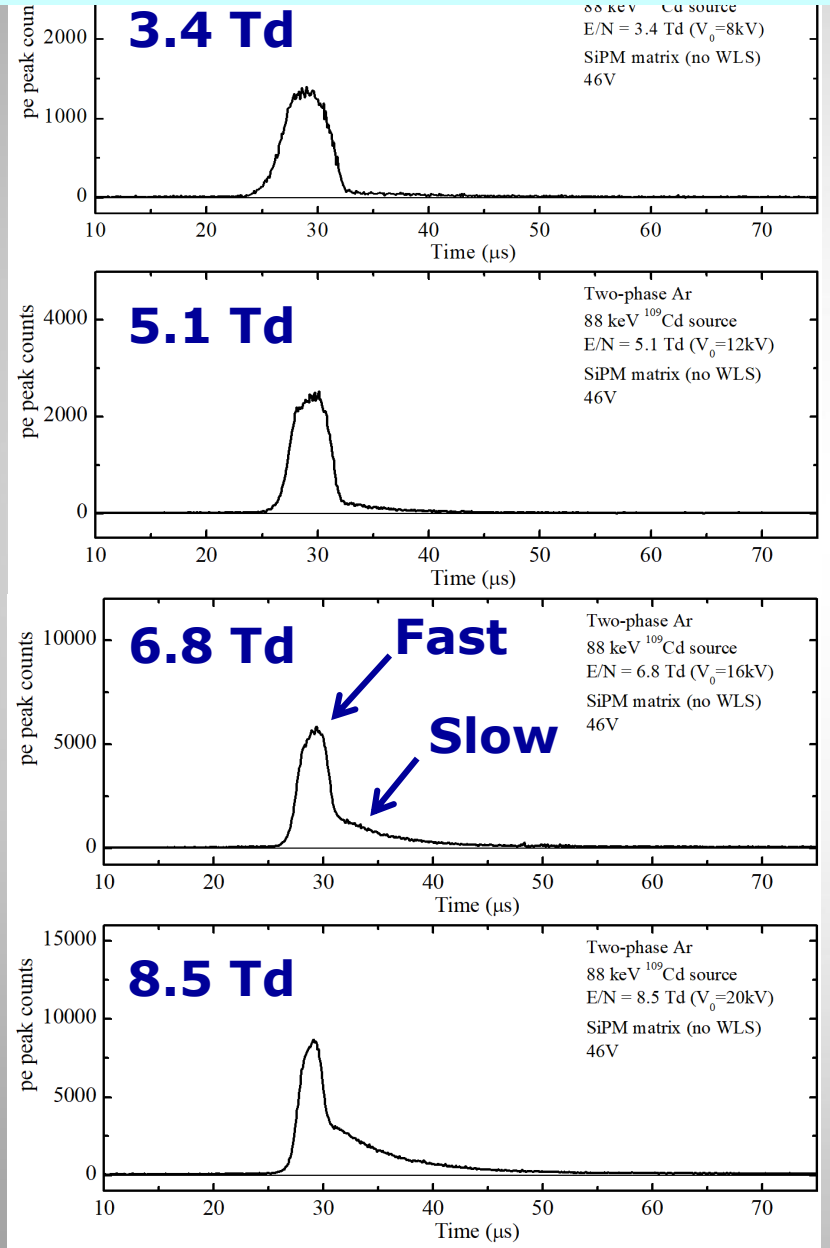
- Emission due to atomic transitions in NIR. It is fast.

"Usual" slow component in EL signal in two-phase Ar

Triplet component of Ar_2^* excimer emission results in slow component in VUV (128nm). Main feature is that time constant and contribution of this component do not depend on the electric field



Previous results on S2 signal shape in two-phase detectors (A. Bondar, et al., JINST 15 (2020) C06064)

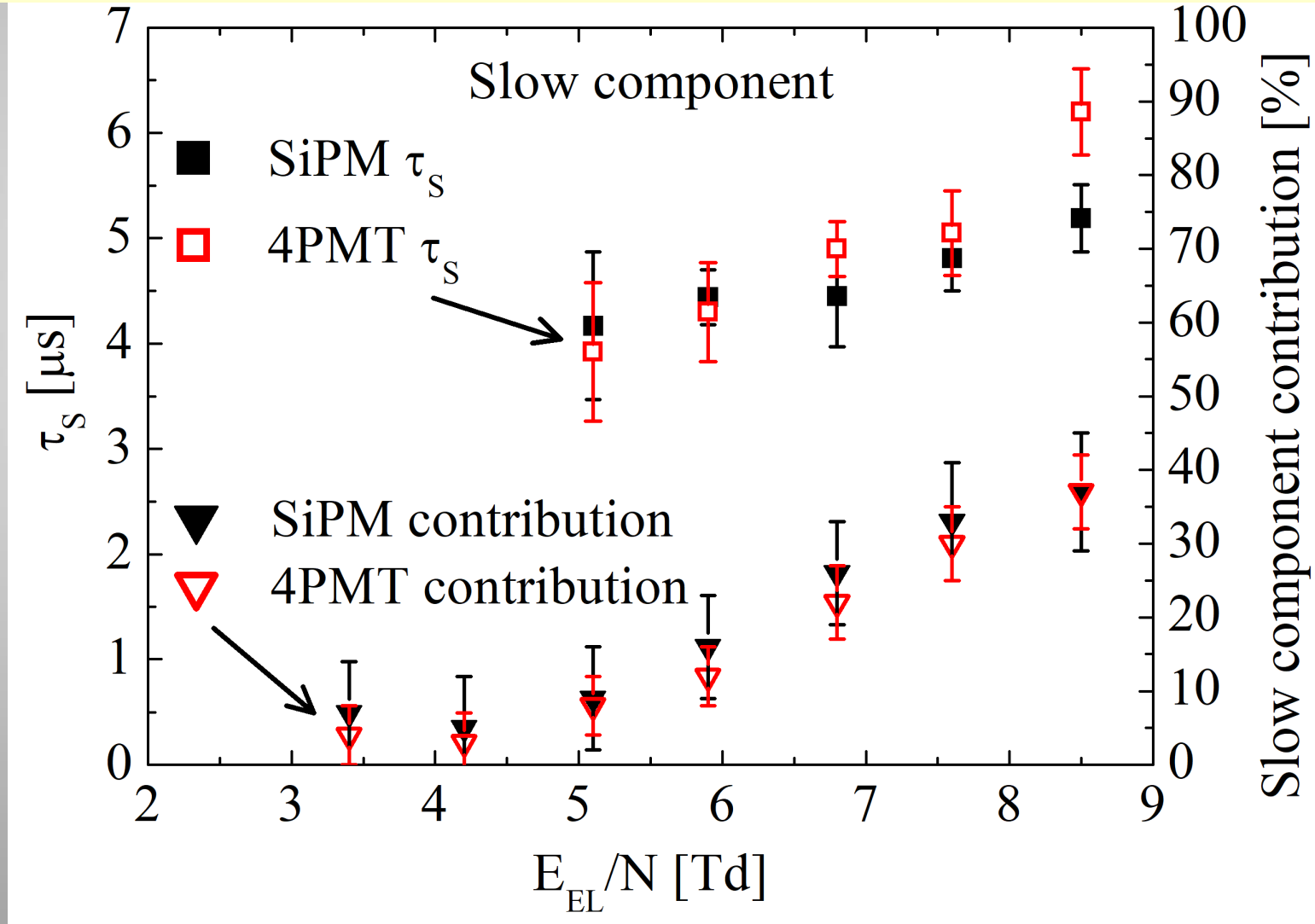


Current S2 slow component issue: unusual slow components were observed in visible range (NBrS)

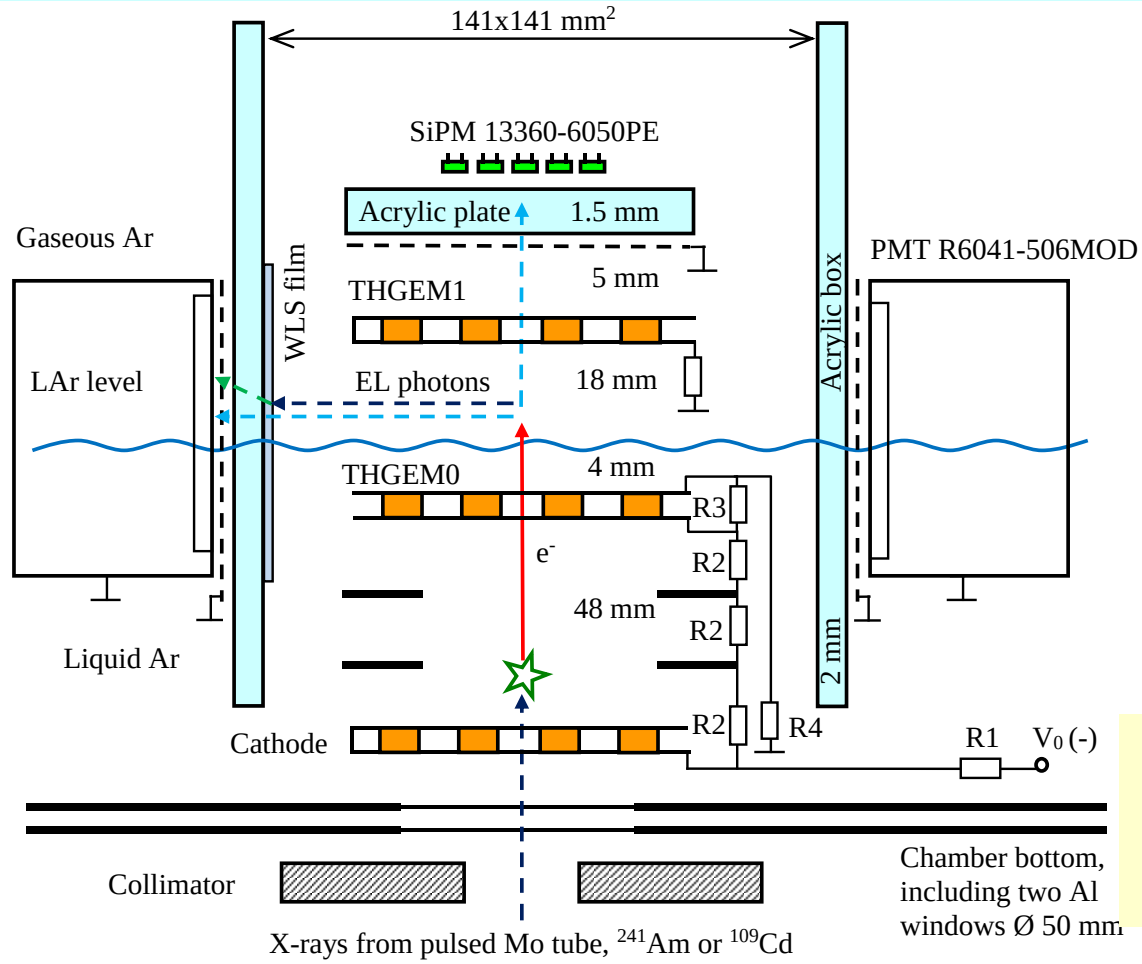
In this work, we further investigate S2 slow components. In particular, their threshold behavior and temperature dependence are studied.

Previous results on S2 signal shape in two-phase detectors (A. Bondar, et al., JINST 15 (2020) C06064)

The unusual slow components were observed in visible range (due to NBrS mechanism). The unusual property is that both time constant and contribution increase with electric field.

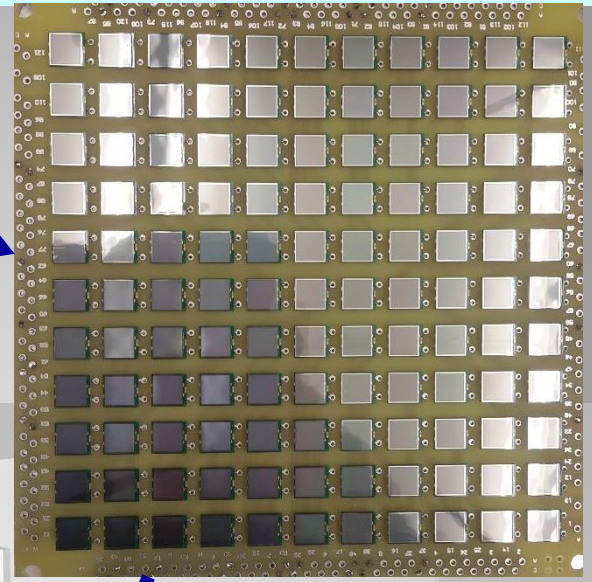


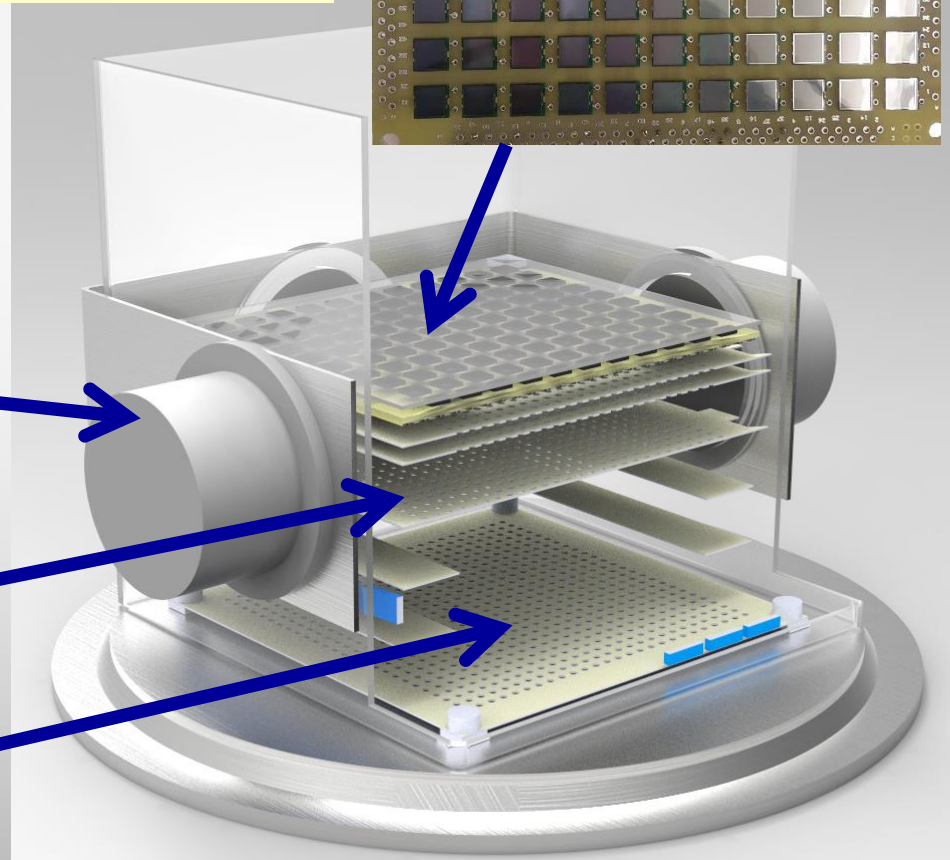
Experimental setup



Trigger is taken from S2: by threshold on sum of 4PMTs

Hamamatsu 13360-6050PE
6x6 mm²
5x5 matrix is used



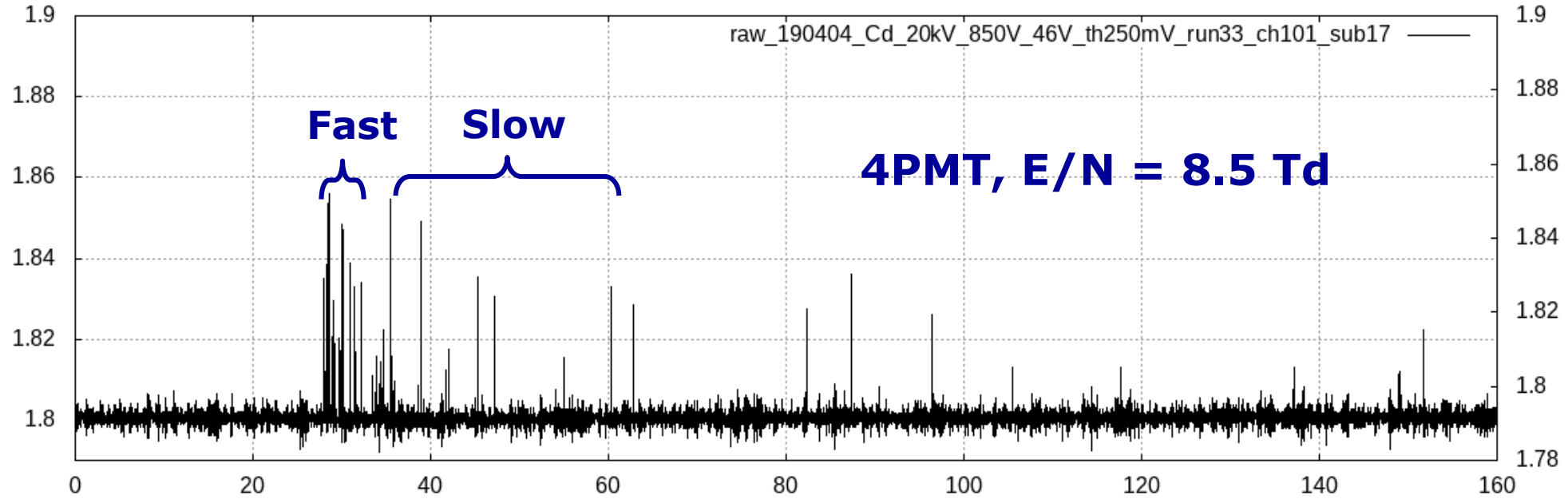


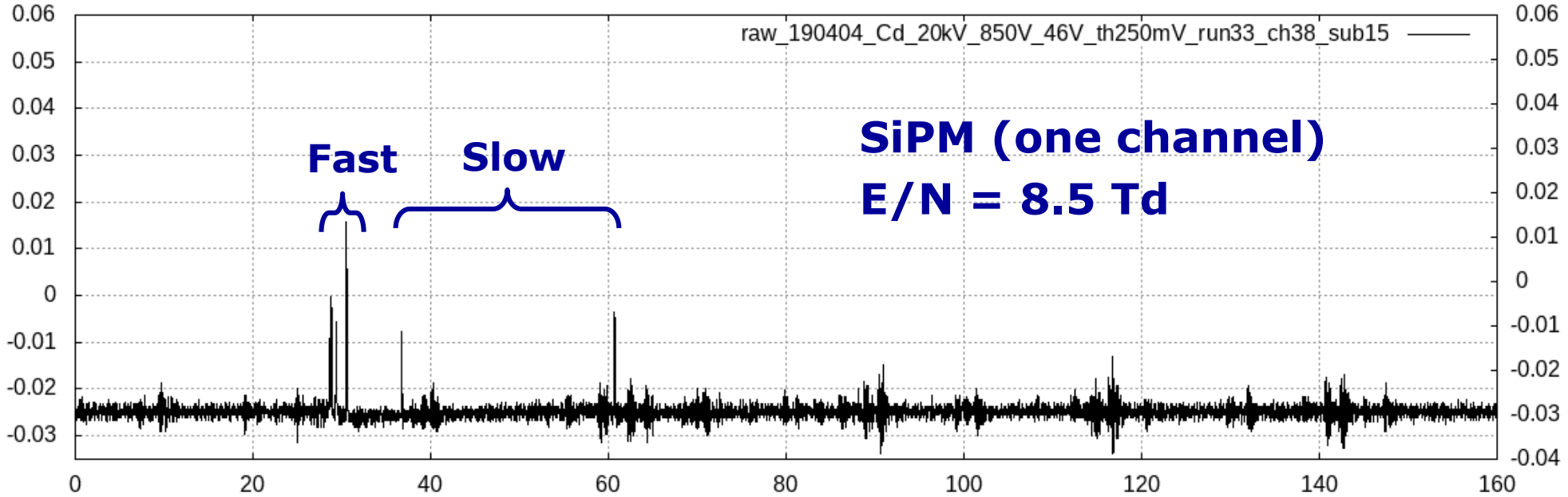
PMT R6041-506 MOD, Hamamatsu

EL gap

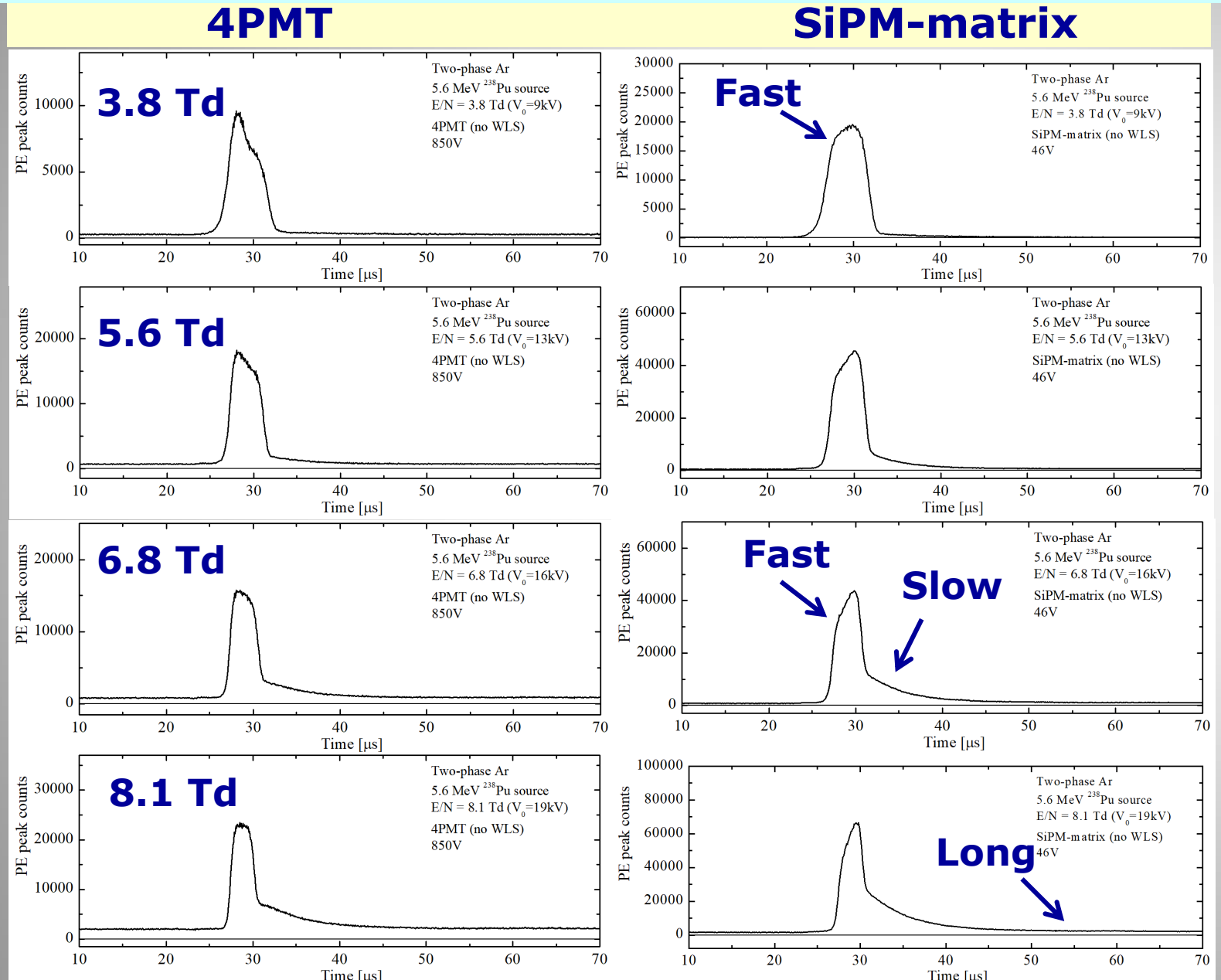
Drift region

PMT and SiPM signal waveforms (no WLS)





Observation of slow components (α-particles, PMTs and SiPMs, without WLS)

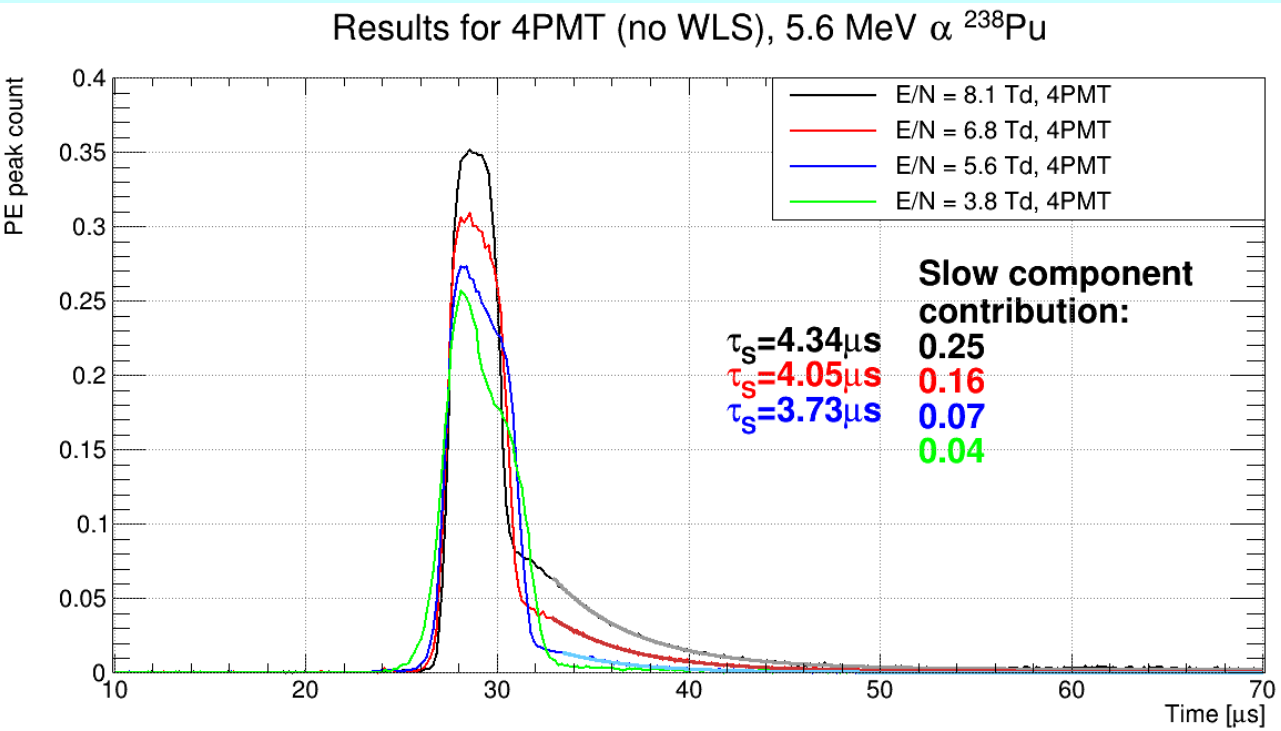


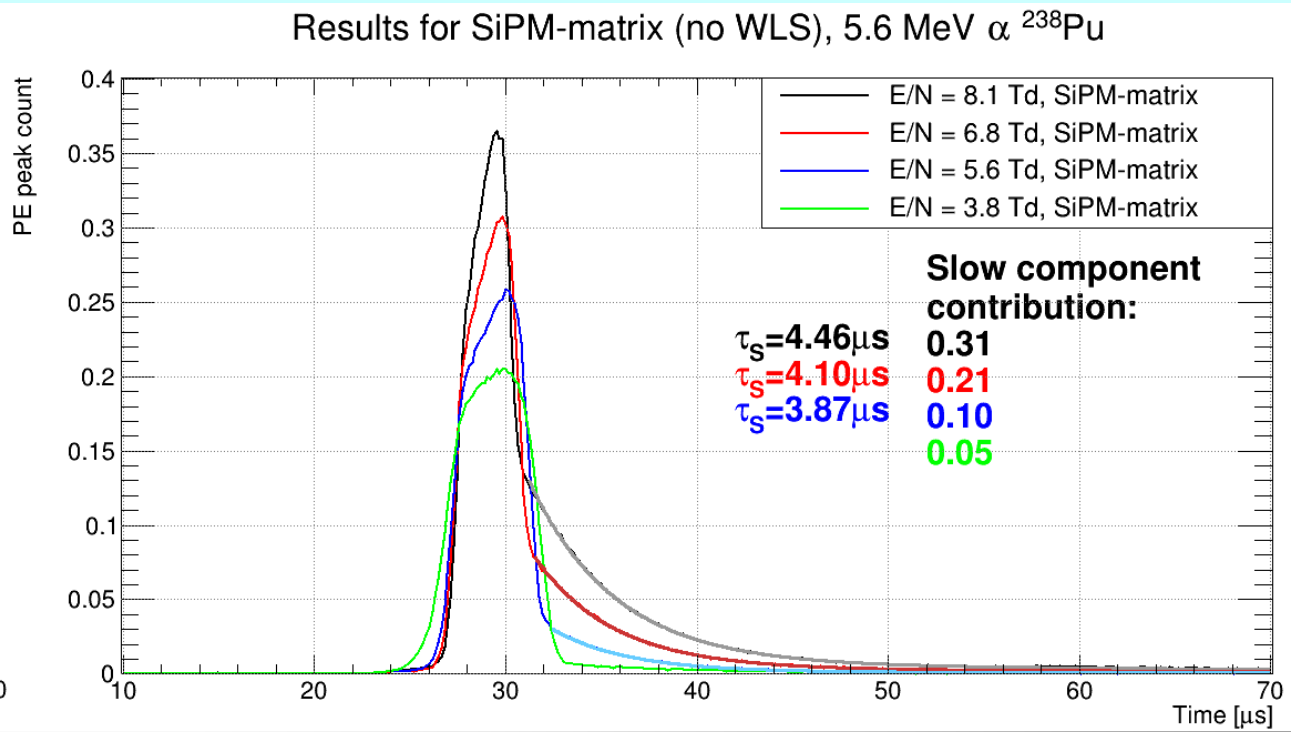
Low fields: only fast component is observed

Just above the 5 Td threshold: slow component has emerged but fast component still dominates

Middle and high fields: appreciable contribution of slow component

Observation of slow components (α-particles, PMTs and SiPMs, without WLS)

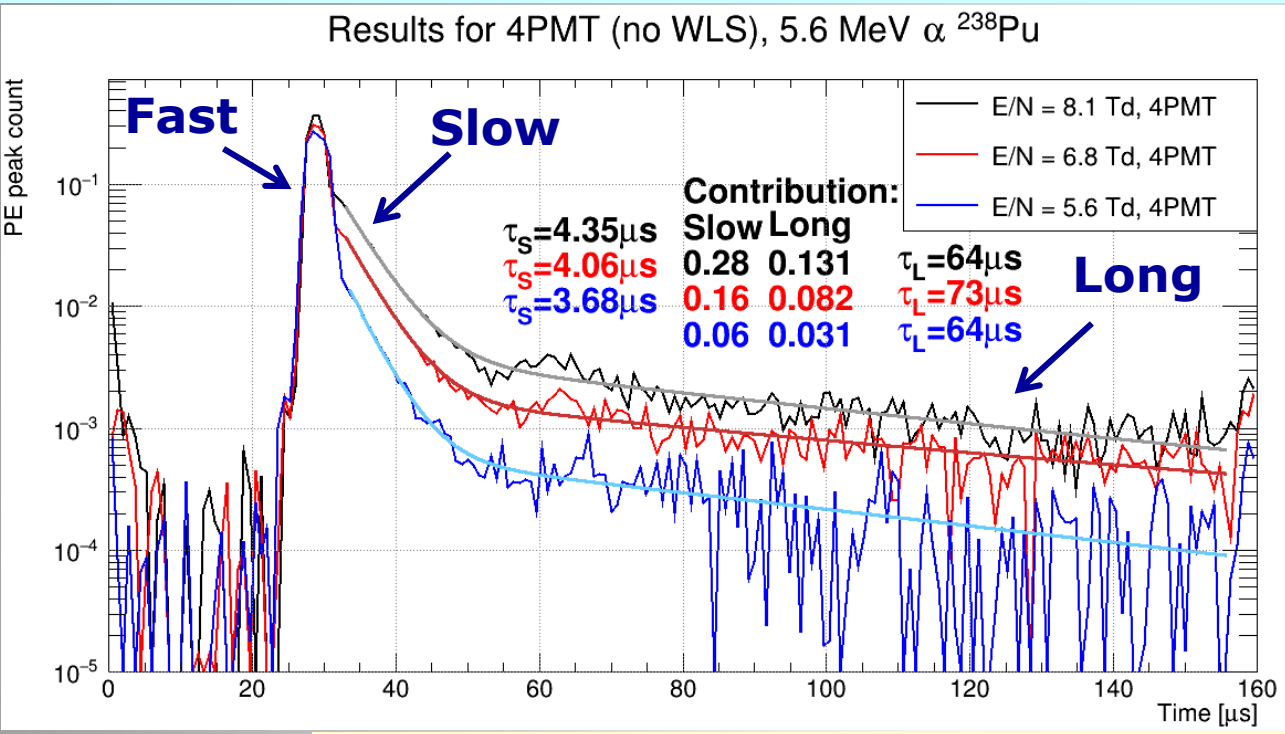


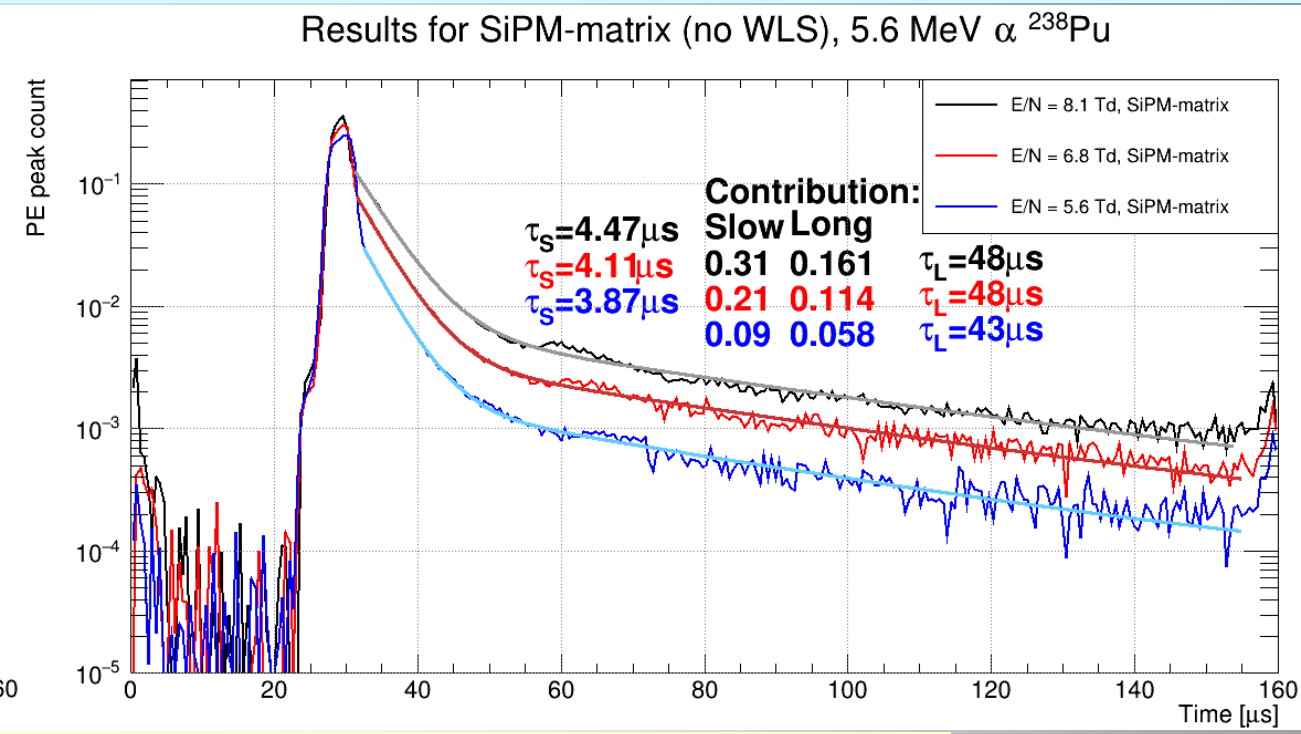


- Both slow component contribution and time constant increase with electric field
- Fast component width, reflecting drift time across EL gap, decreases with electric field
- The SiPM-matrix and 4PMTs data are in good agreement

(Histograms are normalized by area of the fast component)

Observation of slow components (α-particles, PMTs and SiPMs, without WLS)

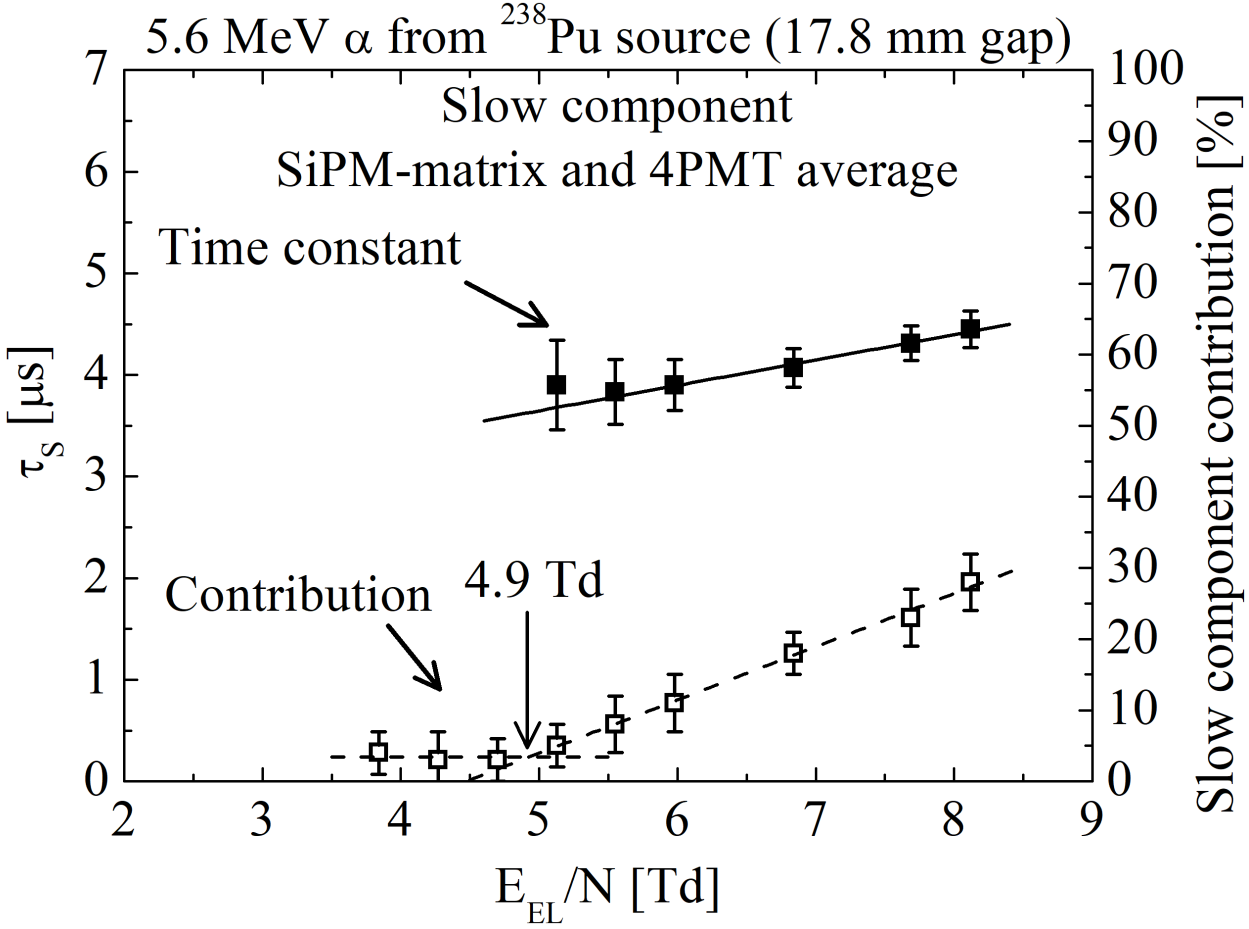


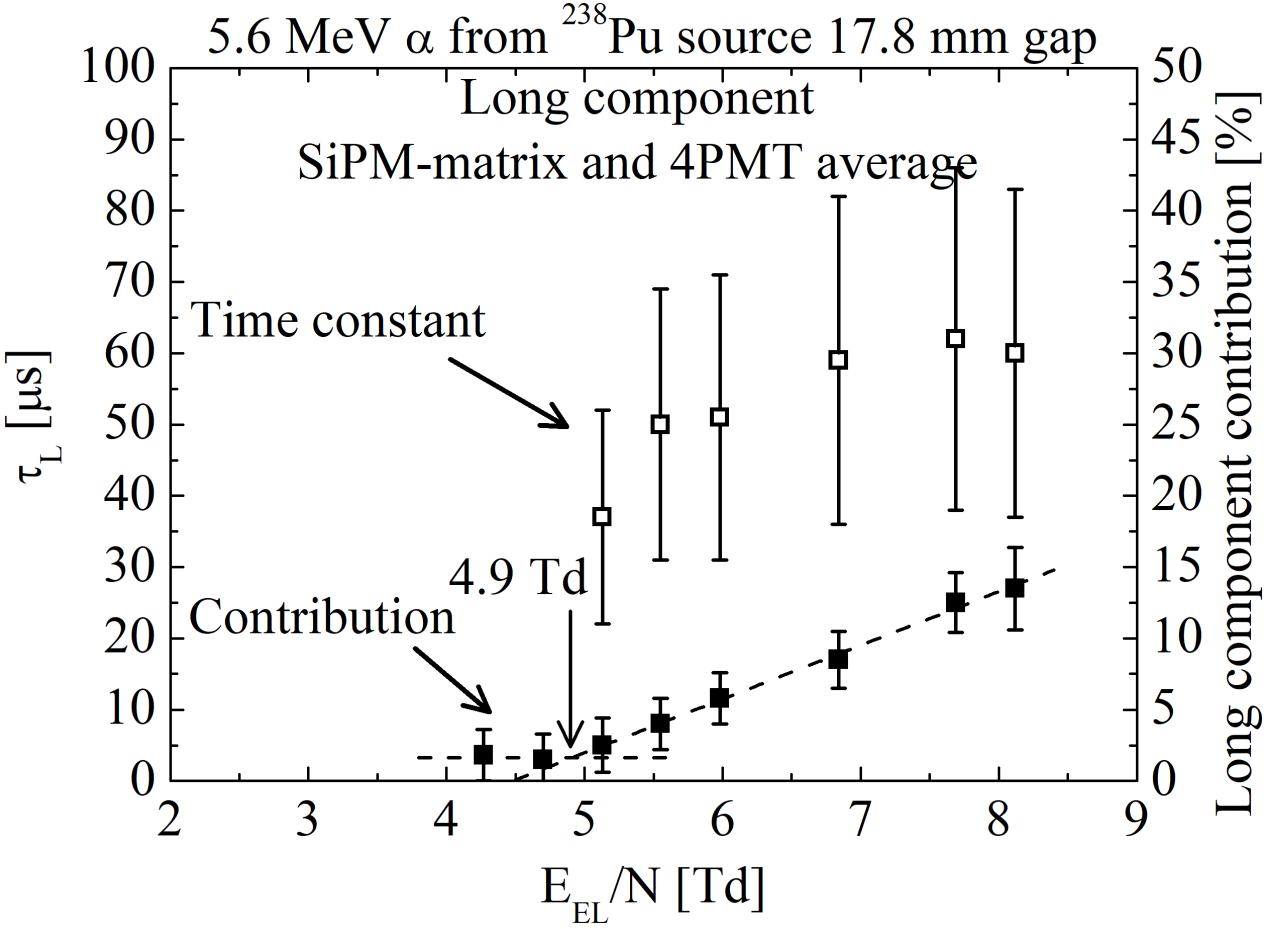


- An additional "long" component is distinctly seen on a logarithmic scale
- Time constants for slow and long components are 3.5-4.5 μs and 45-75 μs correspondingly
- Long component contribution increases with electric field
- Long component time constant is inconclusive

(Histograms are normalized by area of the fast component)

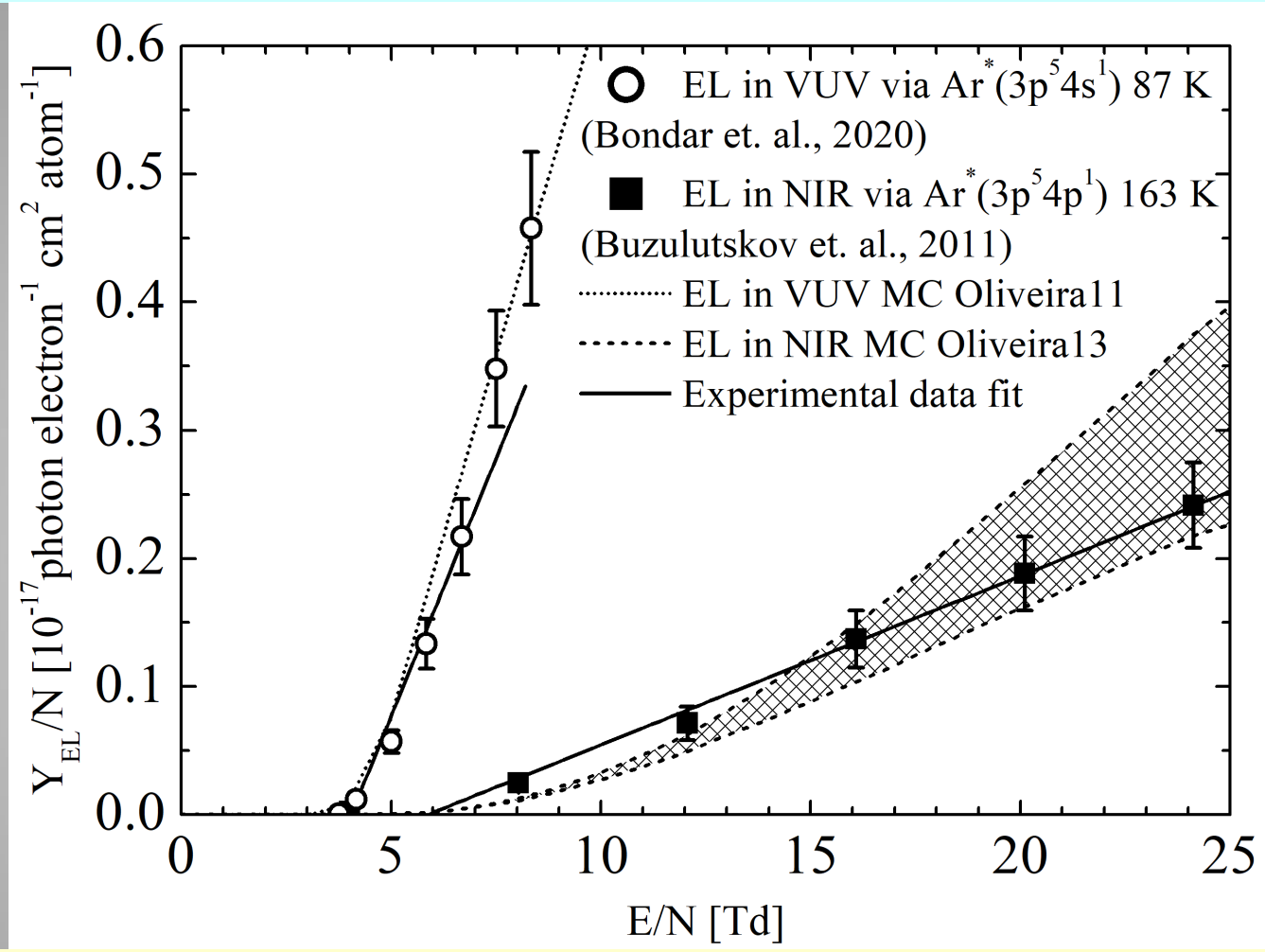
Threshold behavior of slow components

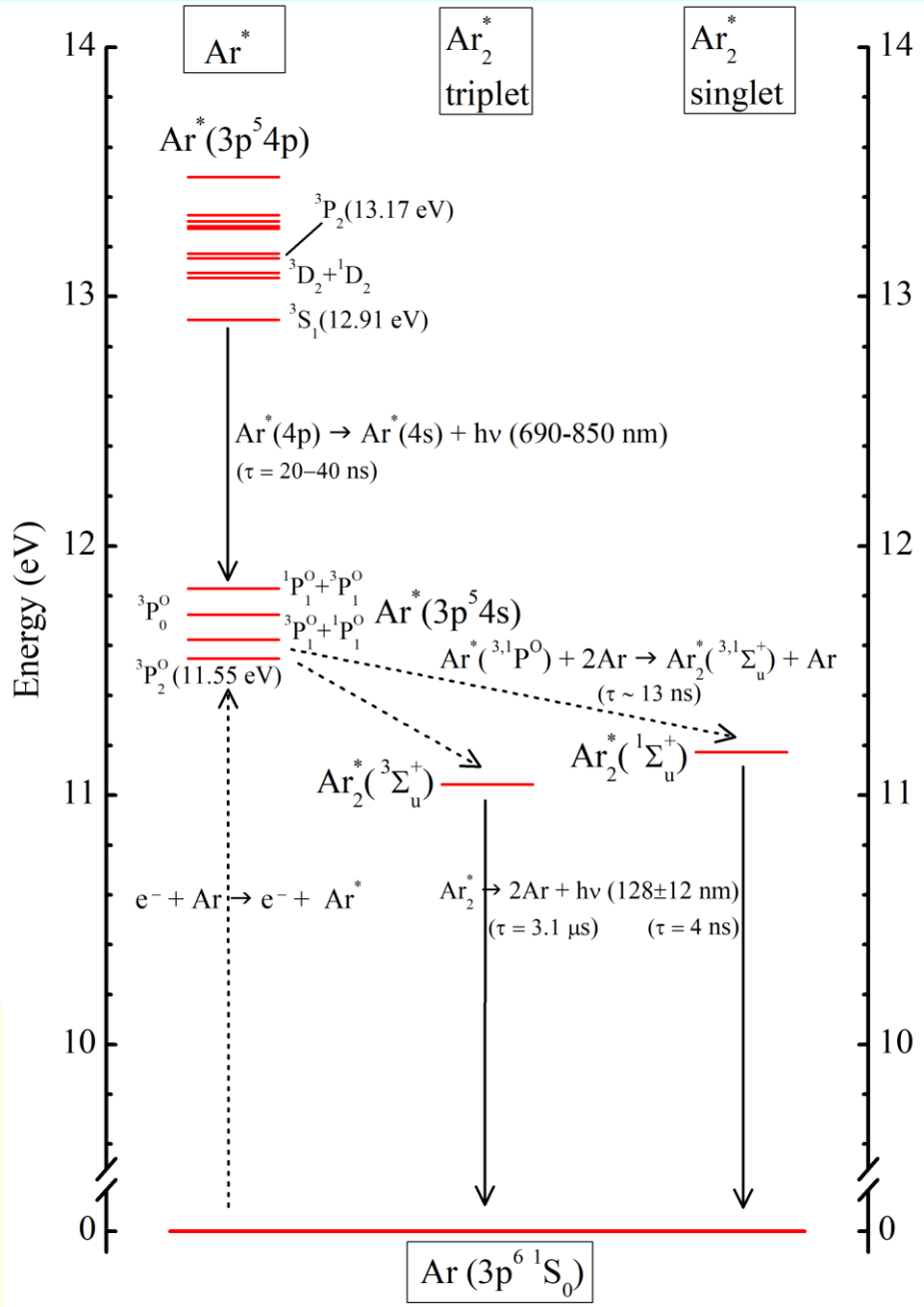




Contribution of both components have threshold behavior. Both components have threshold at ~5 Td which is 1 Td higher than threshold for standard EL. This threshold seems to be the same as for the NIR electroluminescence observed earlier.

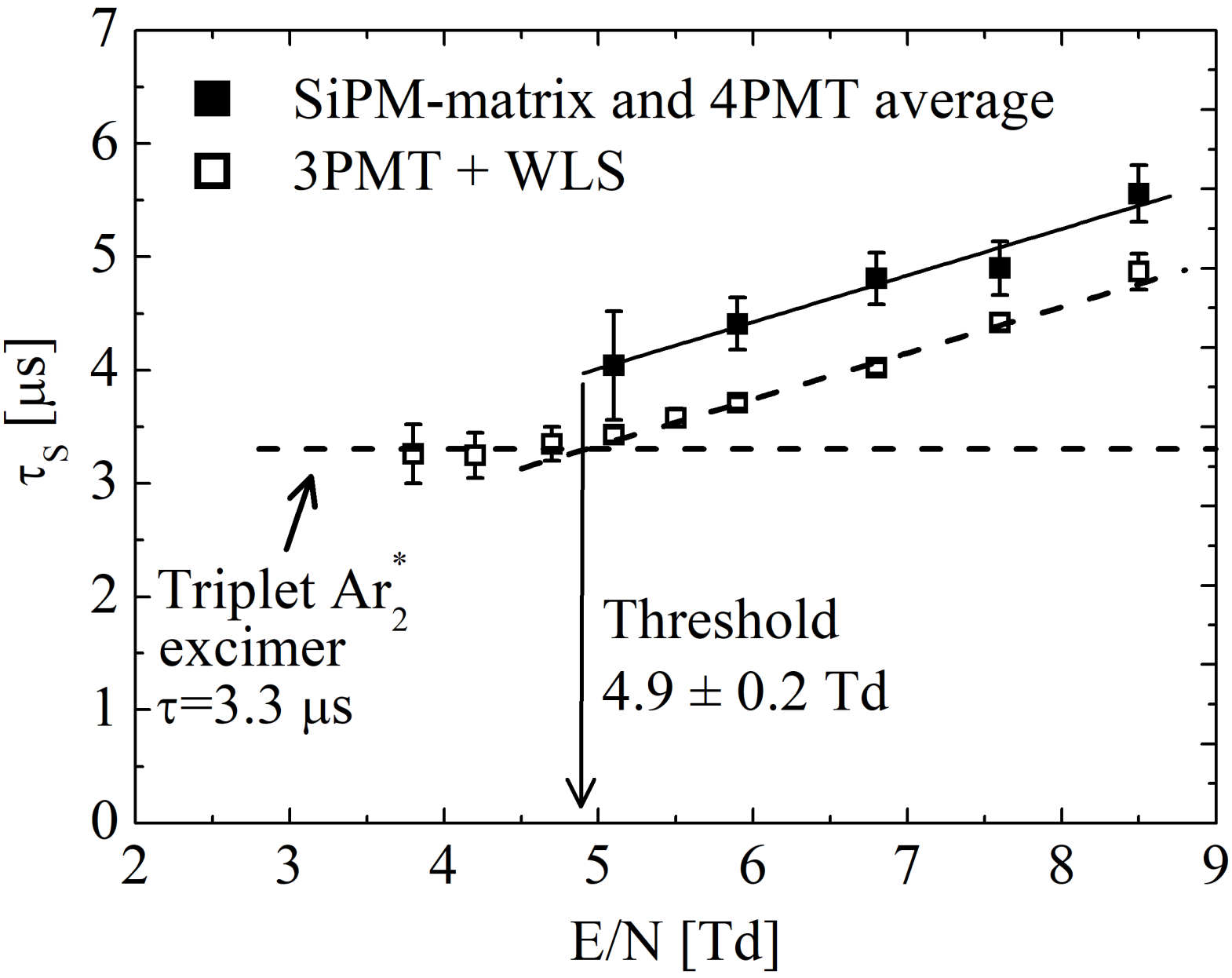
EL mechanism thresholds





Thresholds in VUV and NIR electroluminescence are due to Ar*(3p54s) and Ar*(3p54p) states at ~4 and 5-6 Td.

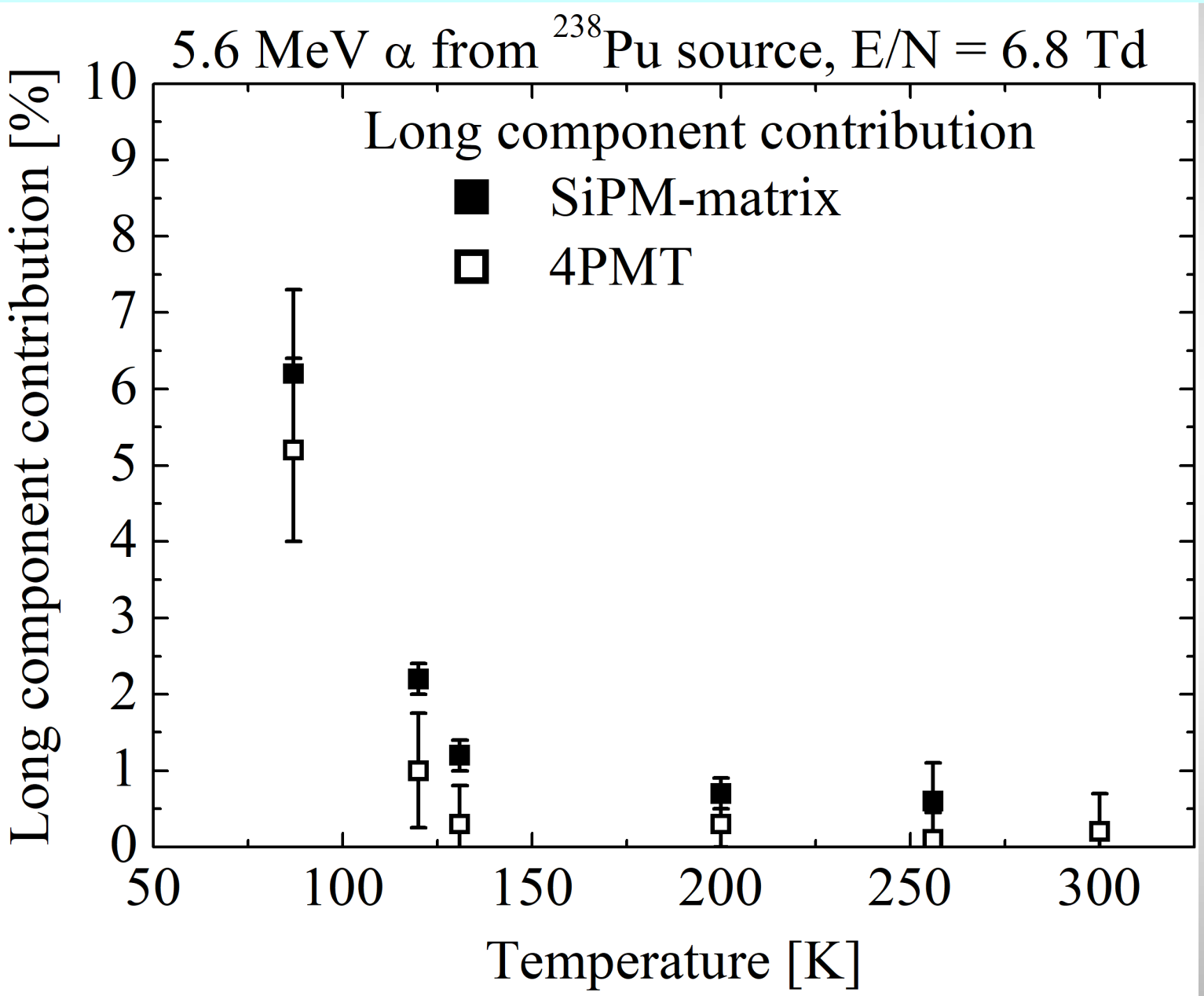
Threshold behavior of time constant using WLS



Threshold behavior was also confirmed using time constant for PMT+WLS configuration (sensitive to VUV). Below 5 Td, standard excimer 3.3 μs component is observed. Above 5 Td, unusual slow component is mixed with triplet one, leading to increase of time constant.

It should be remarked that DarkSide did not see unusual slow components as their nominal field is only 4.6 Td.

Temperature dependence of long component contribution



Long component contribution decreases with temperature and disappears above ~150K

- 87K: two-phase Ar measurements at 1 atm. pressure, α-particle source in LAr (55 μm mean free path)

- Other temperatures: gas only, same concentration as 1.5 atm. at 300K. α-particle source is in gas (3.1 cm mean free path)

Conclusions

- The unusual slow and long components have been observed in electroluminescence signal of two-phase Ar detector, their time constants (~4μs & ~50μs) and contributions increasing with electric field, overall contribution reaching 50%.

- Both components have threshold behavior. The threshold is the same for both components and is about 5 Td (1 Td higher than standard EL threshold) which corresponds to higher excited states $Ar^*(3p^54p)$.

- Long (and presumably slow) component contribution decreases with temperature and disappears above around 150K.

- Slow and long components are most probably due to the charge signal itself. We propose that it is caused by trapping of drifting electrons on metastable negative Ar ions.

- Slow components are present in real EL signals and thus should be considered when analyzing data of dark matter search experiments.

Prospects

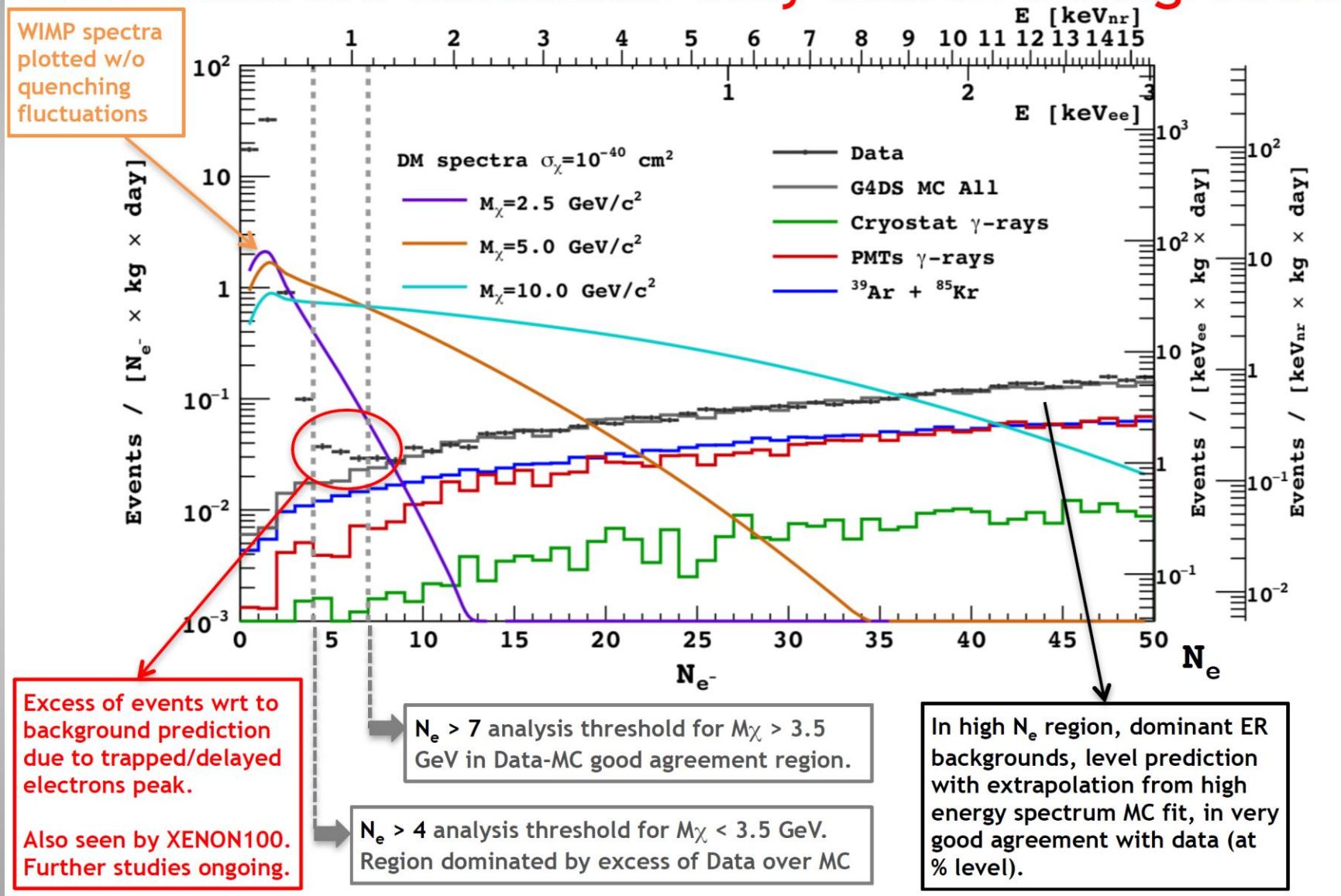
- Direct charge measurement

- Measurements with different EL gap thicknesses

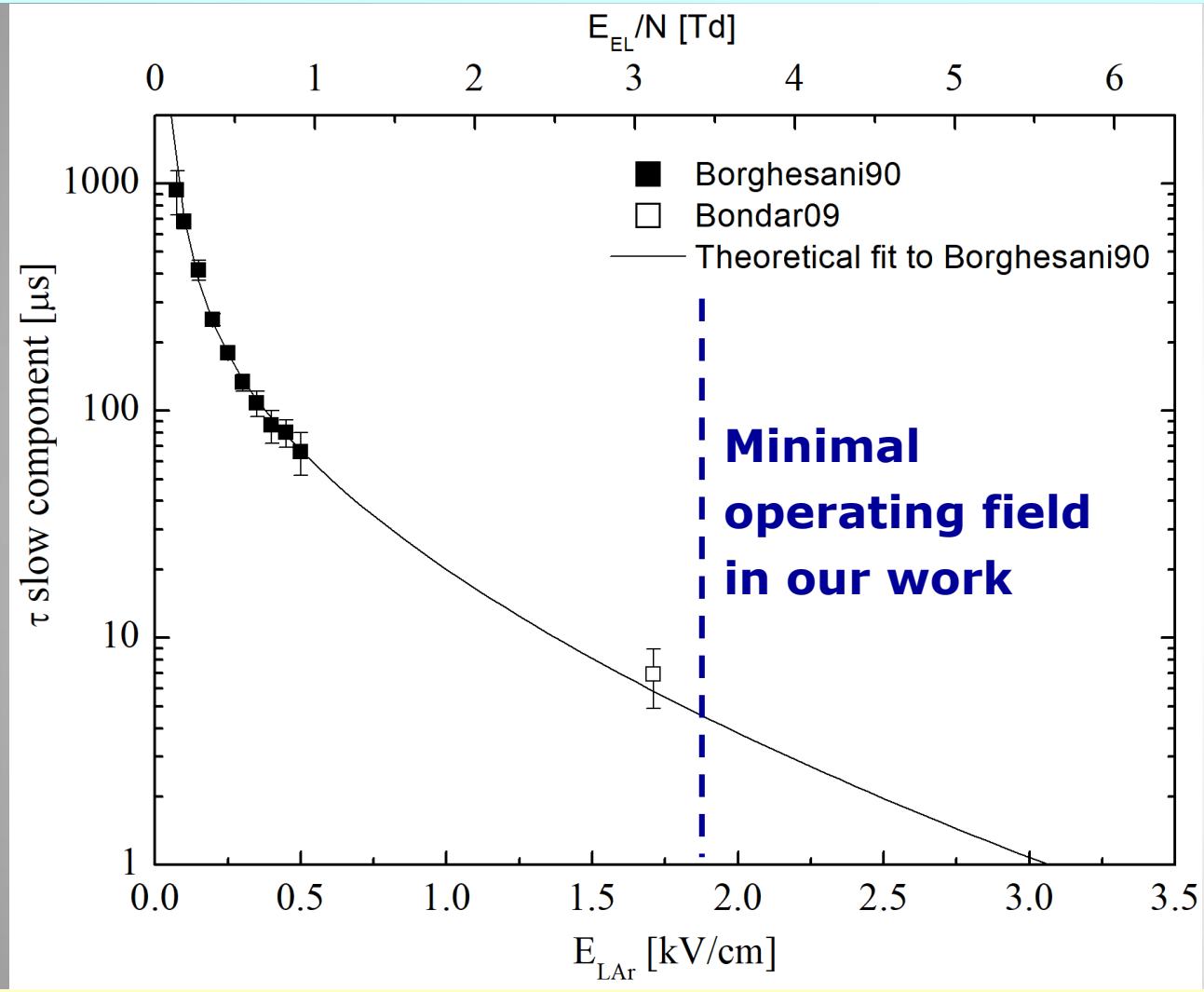
BACKUP

Practical application for DarkSide

Low Mass DM ionization only search background



"Usual" slow component in EL signal in two-phase Ar due to electron emission effect at liquid-gas interface

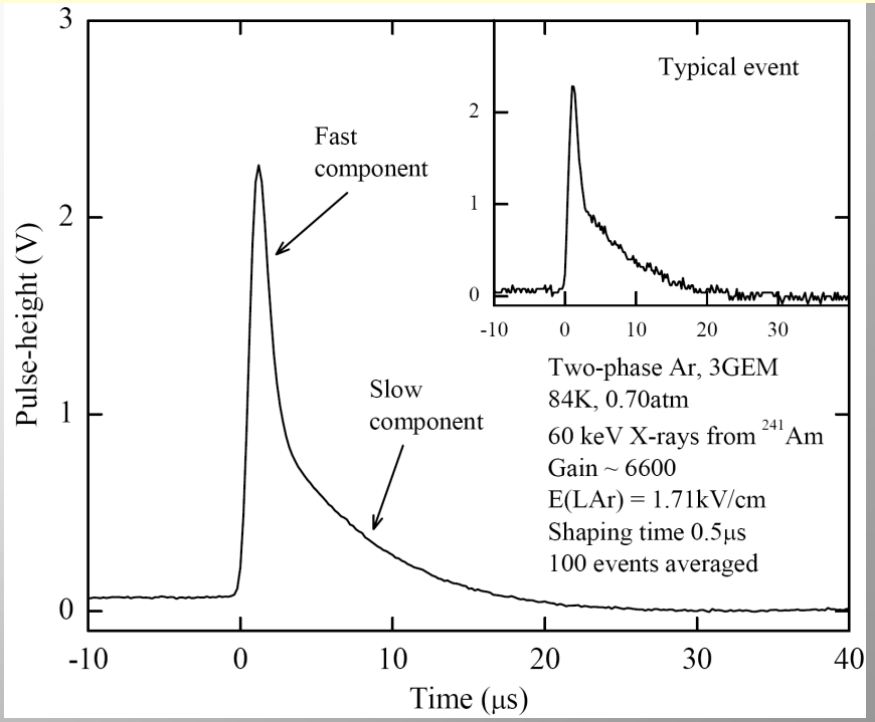


- Both time constant τ and contribution of slow component decrease with electric field
- Emission slow component is virtually undetectable since

$t_{drift} > \tau$ for all fields in our work.

E.g. at 5.1 Td:

τ = 1.5 μs, t_{drift} = 3.7 μs

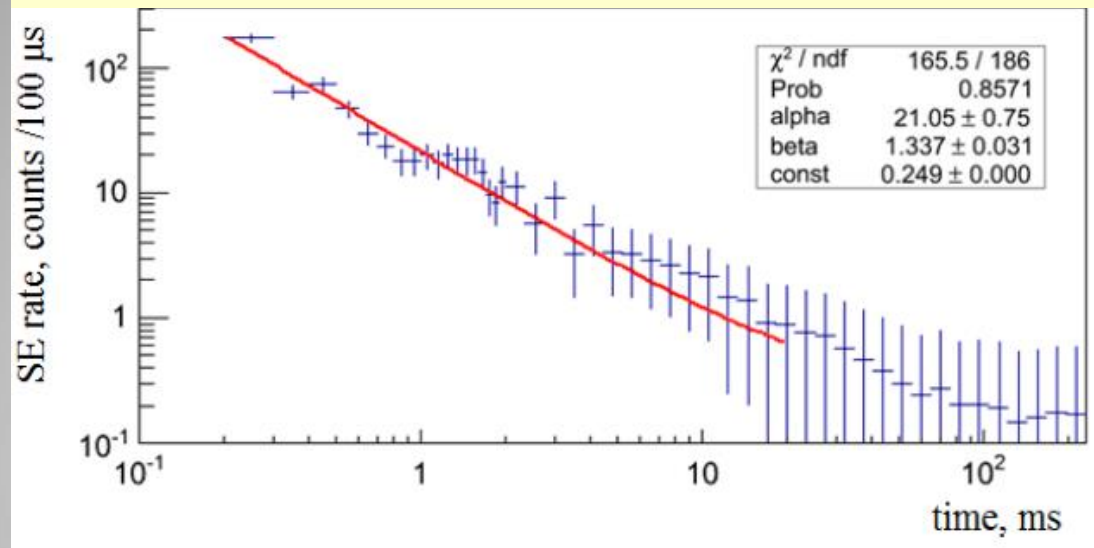


A. Borghesani, et al., Phys. Lett. A 149 (1990) 481

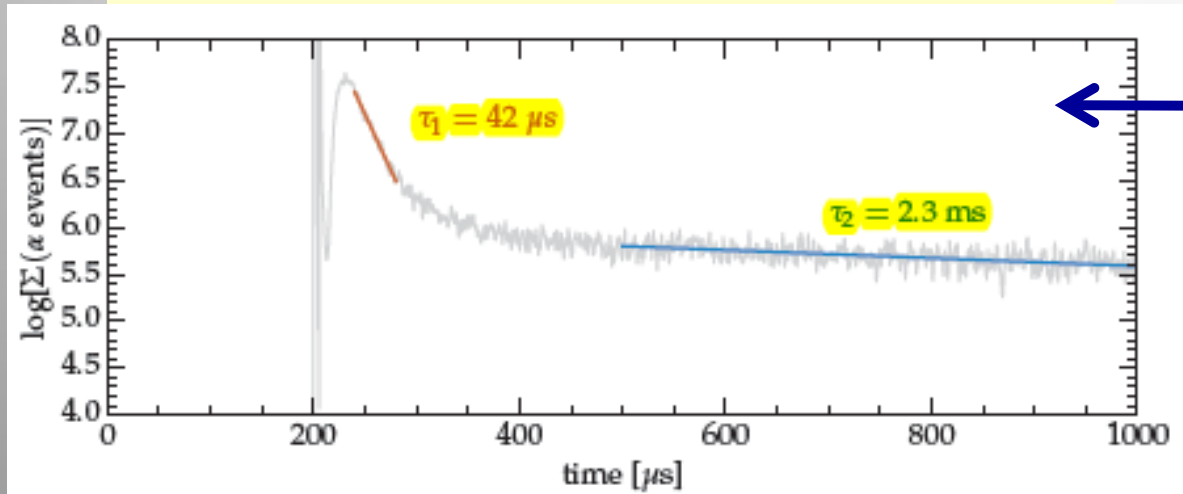
A. Bondar, et al., JINST 4 (2009) P09013

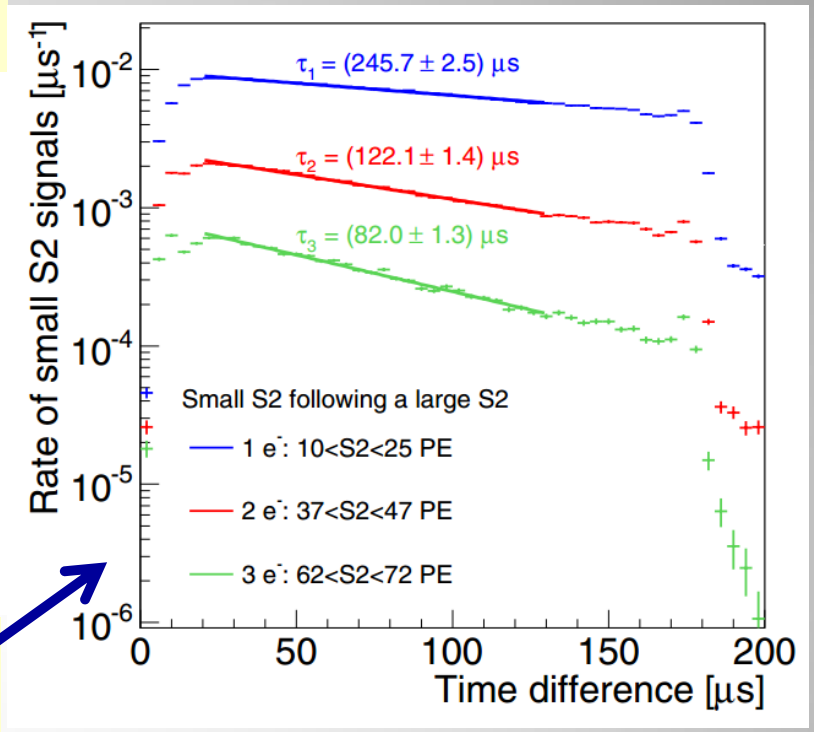
Slow components in EL signals in two-phase Xe (e- train background)

D. Akimov et al., 2016 JINST 11 C03007



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

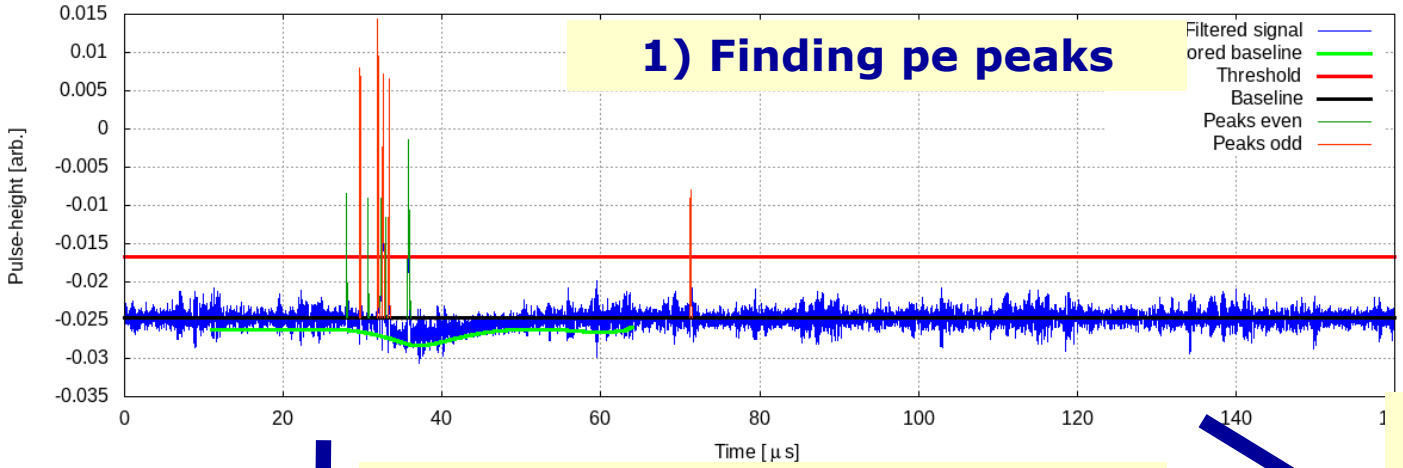




Abnormal slow components: time constants grow with electric field

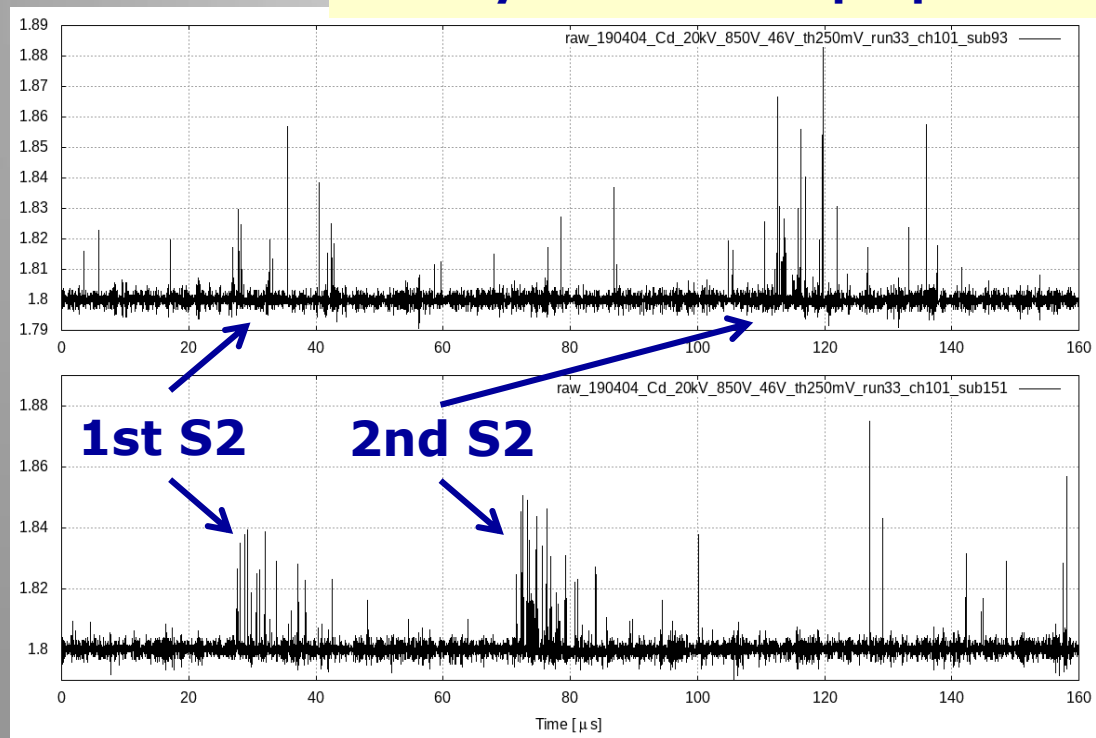
P. Sorensen and K. Kamdin, 2018 JINST 13 P02032

Analysis algorithm

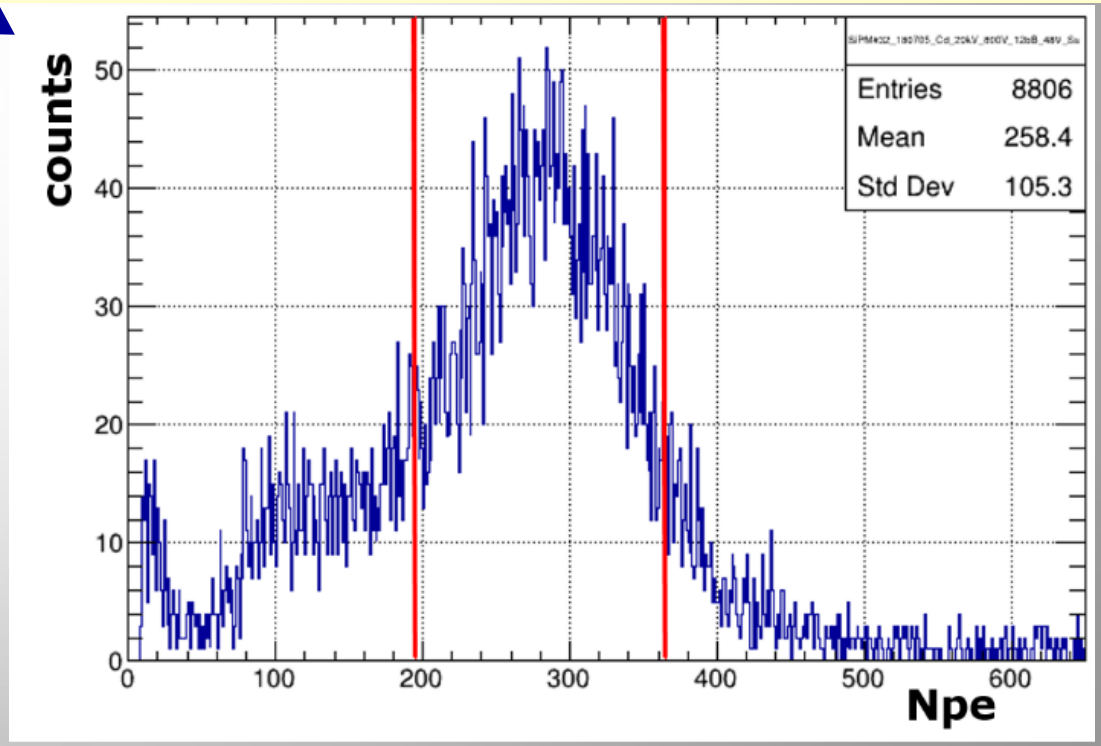


4) Building time histograms of PE peaks: pulse-shapes

2) Rejection of bad events. Mostly due to S2 superposition



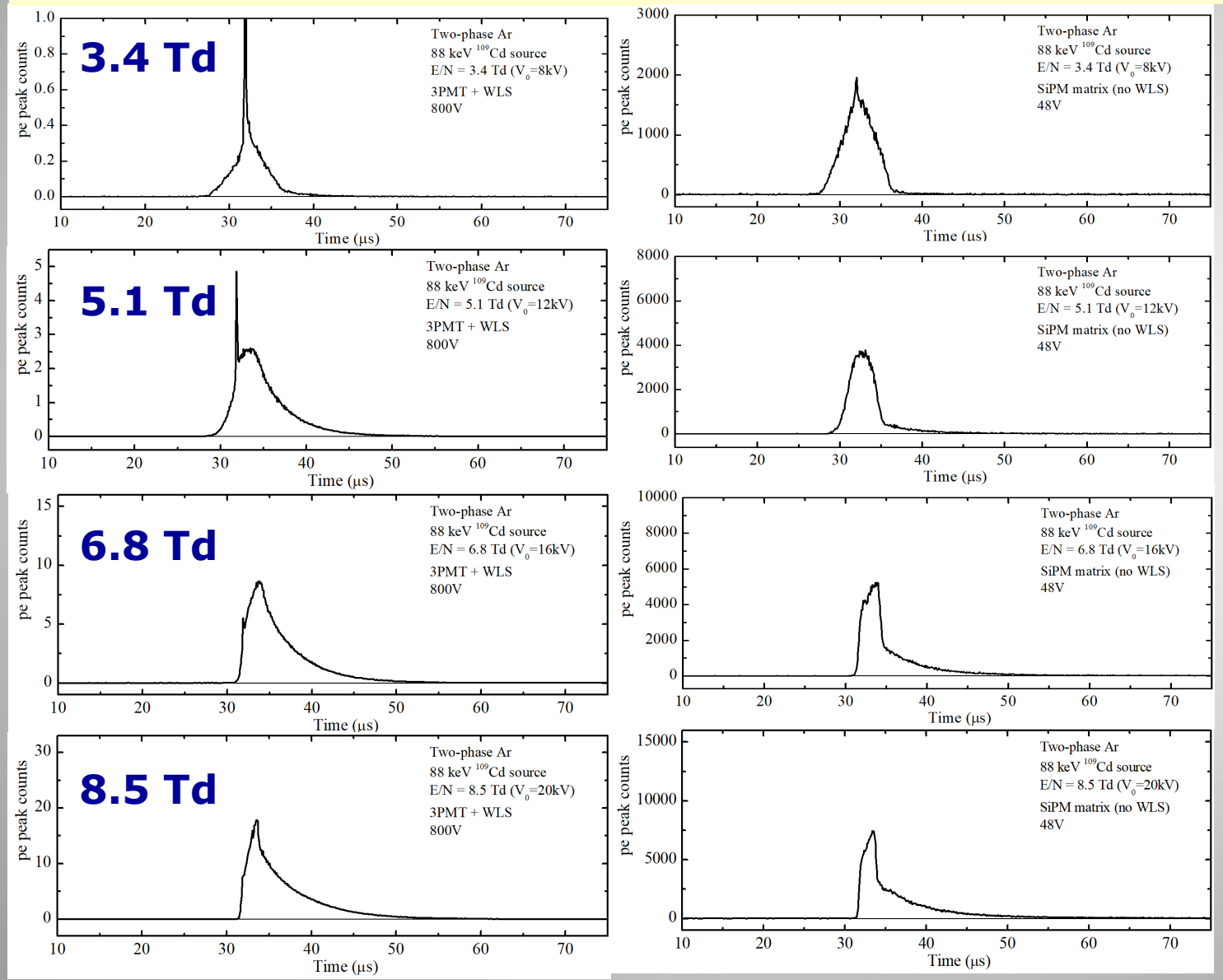
3) Selection of events from the 88 keV peak of ^{109}Cd or 5.6 MeV peak of ^{238}Pu



Results with WLS: PMT+WLS vs SiPM pulse-shapes

3PMT+WLS (sensitive to excimer component)

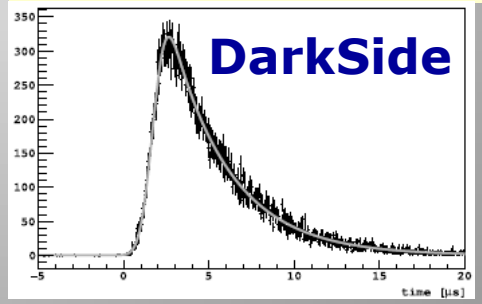
SiPMs (not sensitive to excimer component)



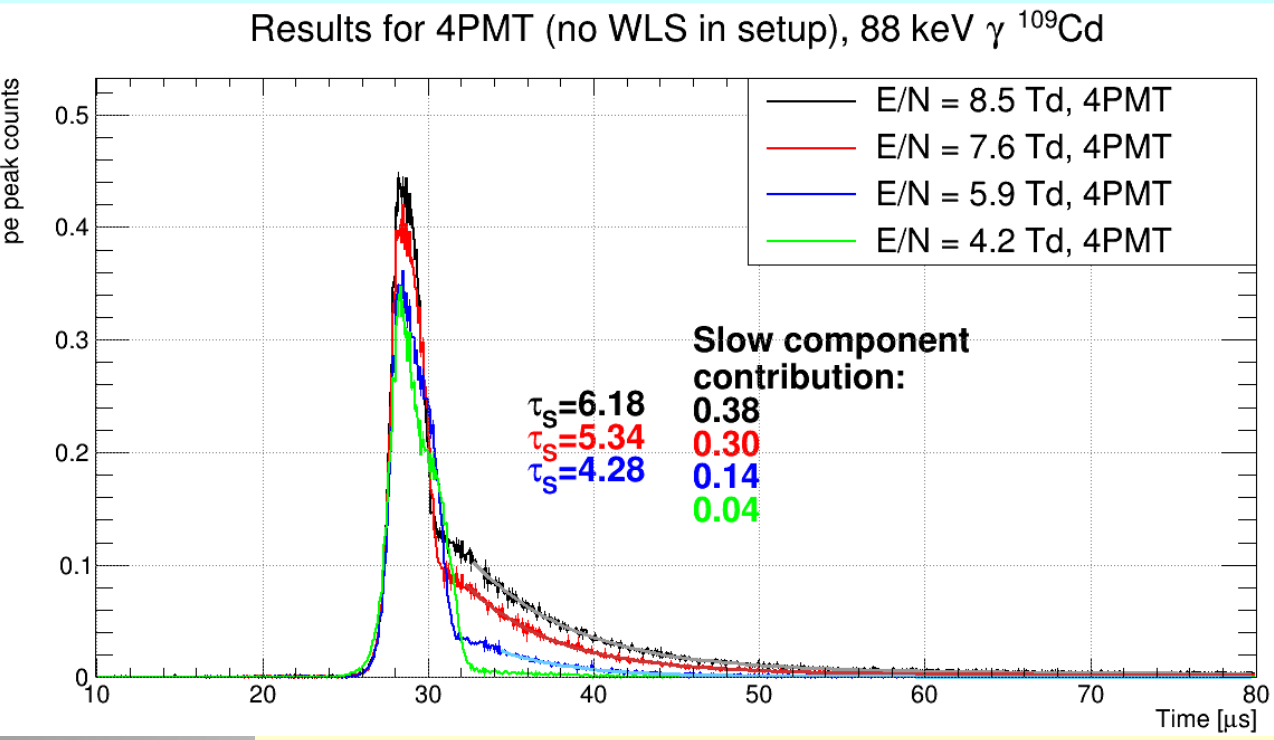
Low fields: only fast component is observed

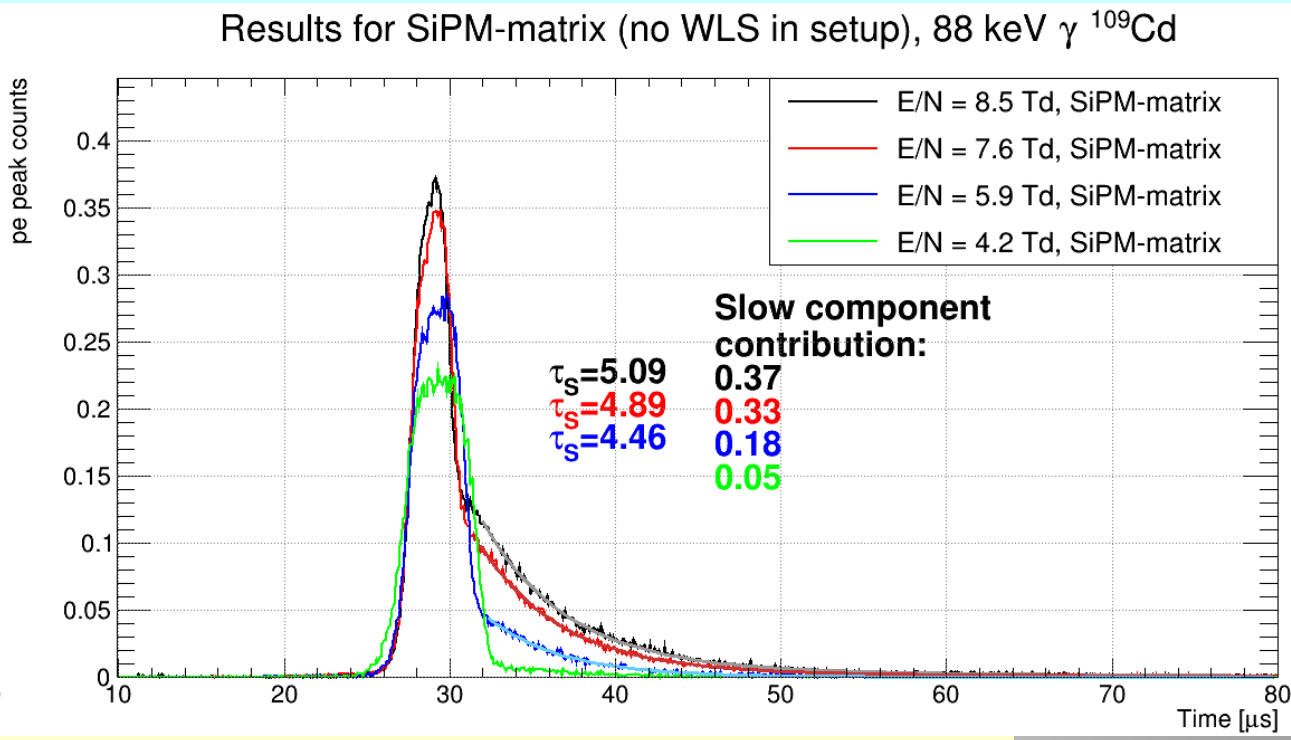
Above the 5 Td threshold: SiPM-matrix data match the data without WLS

PMT+WLS are different, have shape expected from excimer mechanism



Observation of slow components γ-particle source, PMT and SiPM, without WLS

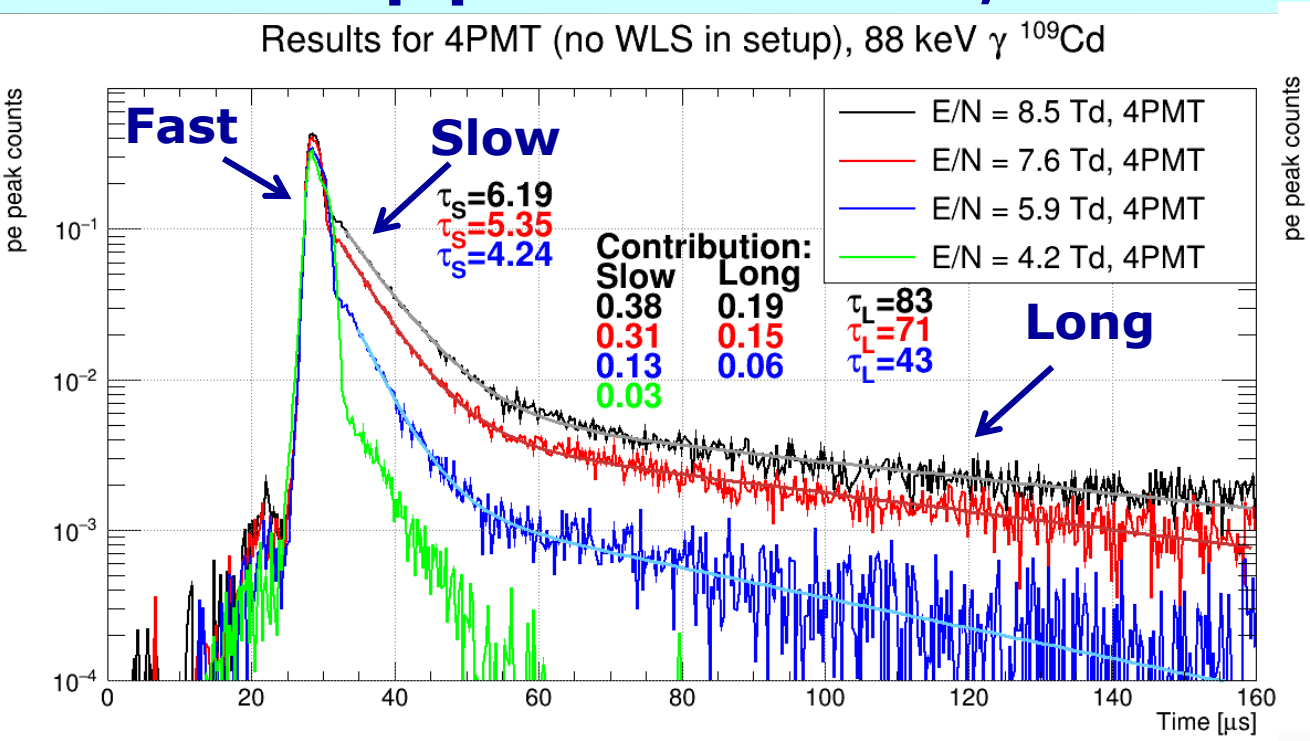


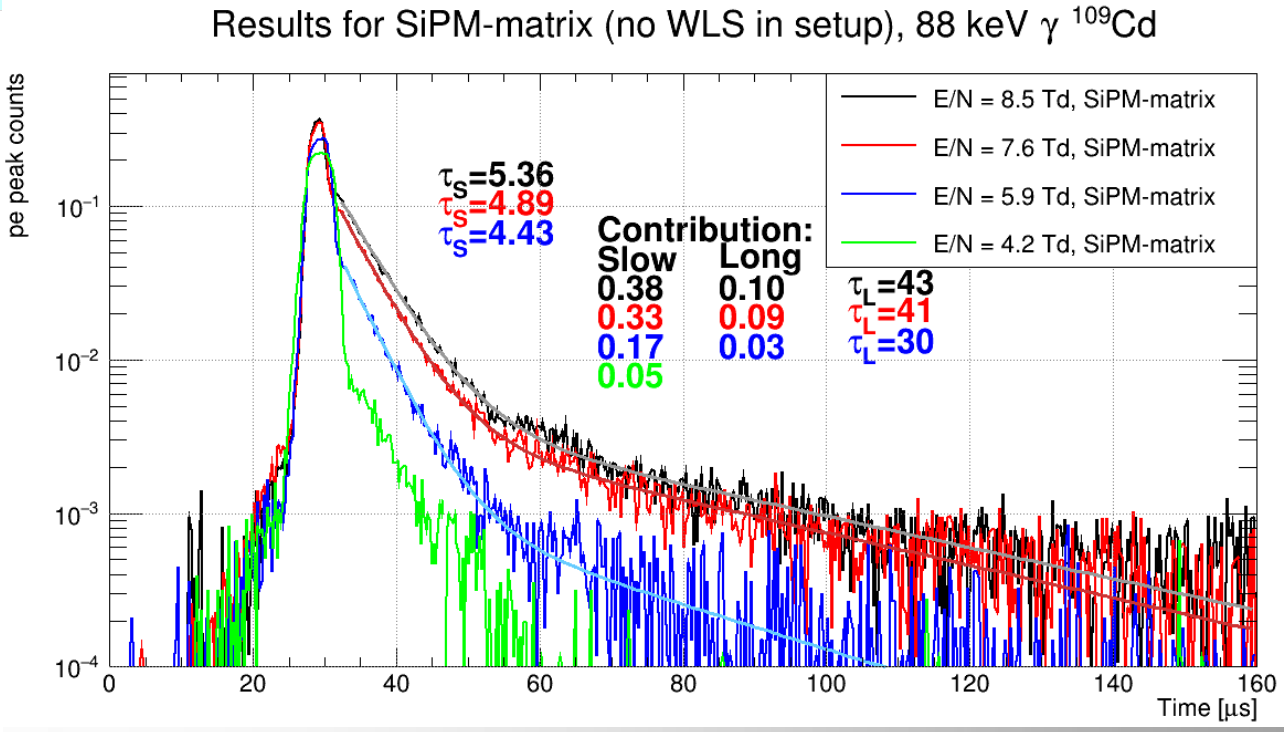


- Slow component contribution increases with electric field
- Slow component time constant τ_s increases with electric field as well
- Fast component width, reflecting drift time across EL gap, decreases with field
- The SiPM-matrix and 4PMTs data are in good agreement

(Histograms are normalized by area of the fast component)

Observation of slow components γ-particle source, PMT and SiPM, without WLS



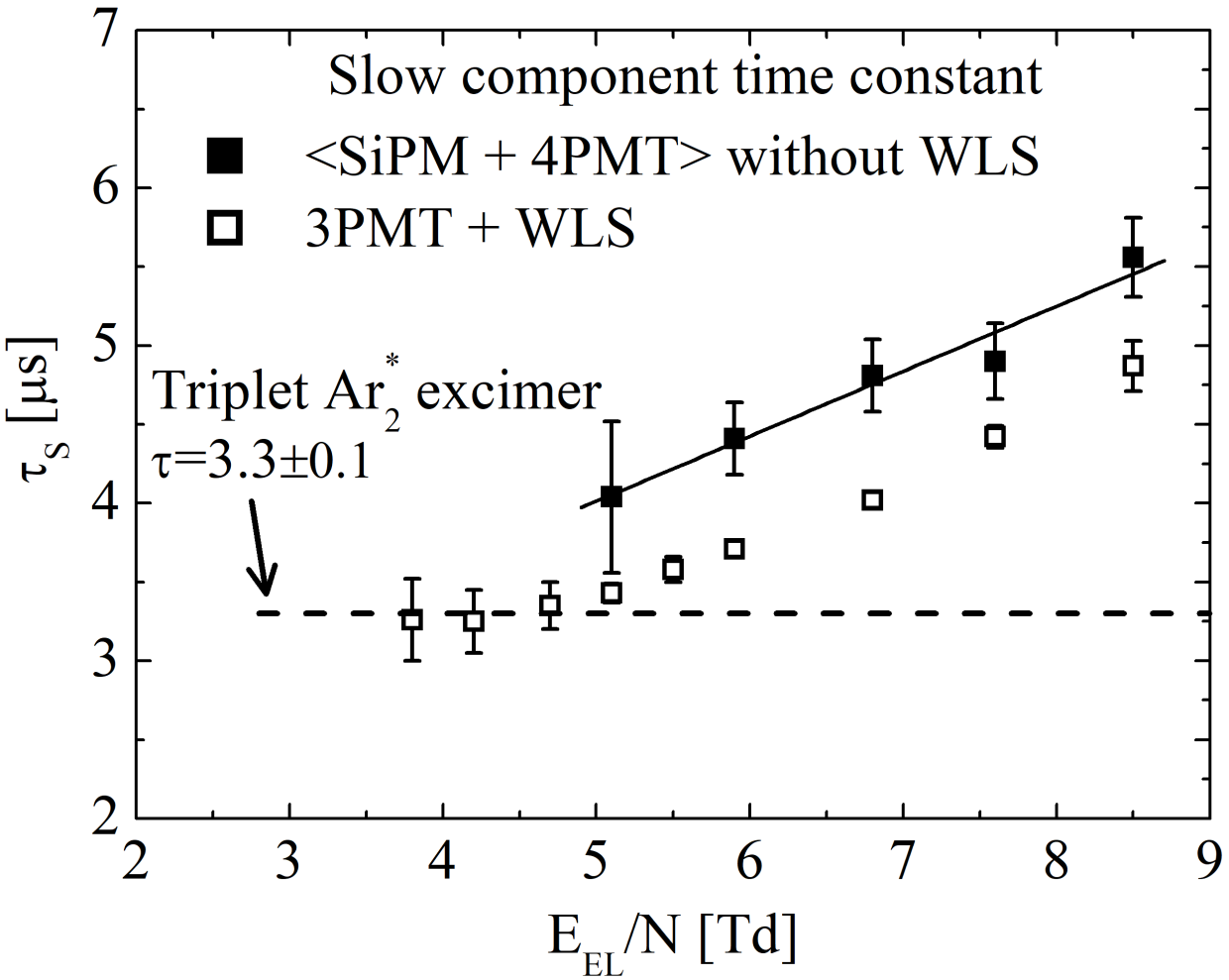


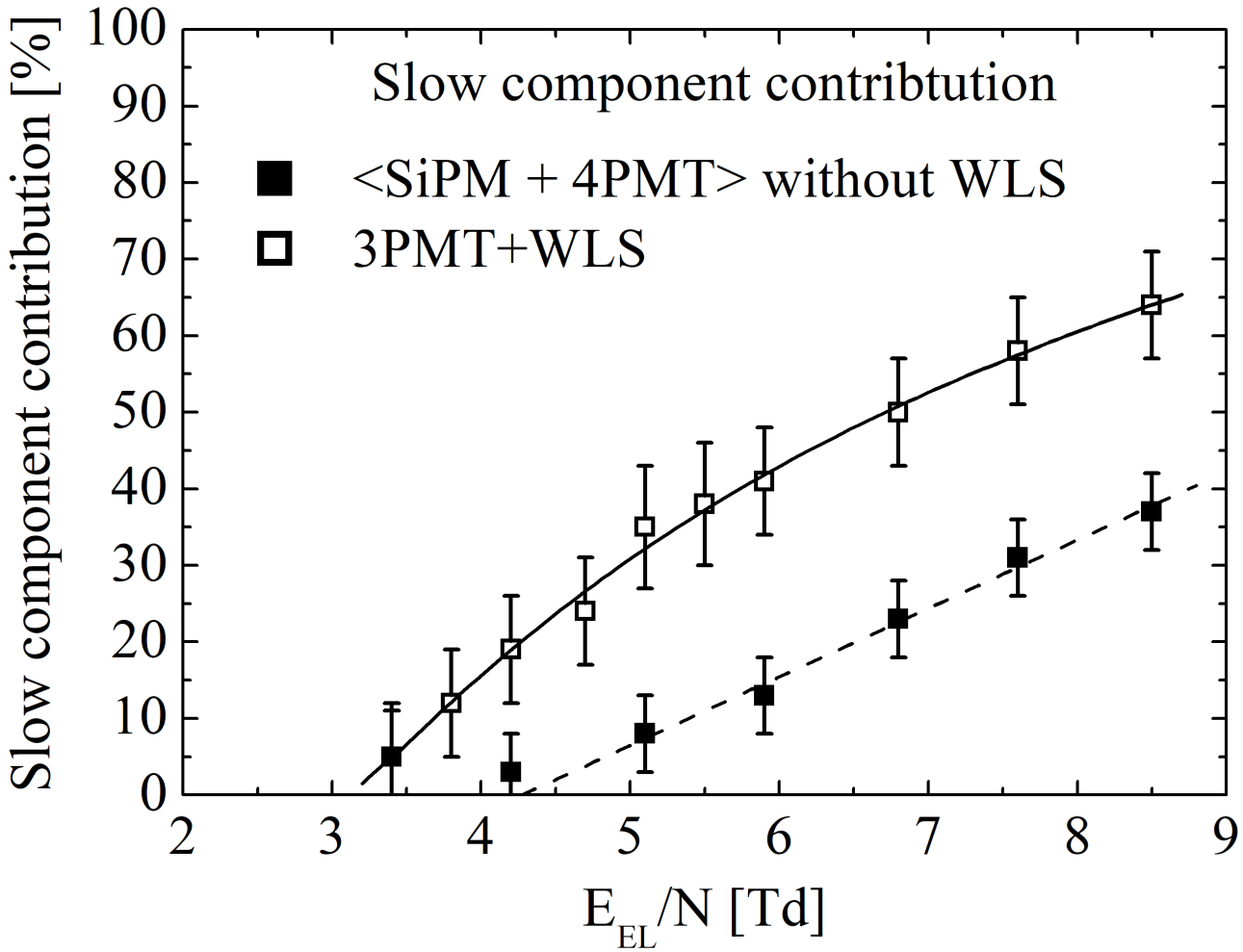
- An additional "long" component appears on a logarithmic scale

(Histograms are normalized by area of the fast component)

Results with WLS vs results without WLS: τ and contribution of slow component

- Below 5 Td: no unusual slow component, only excimer one is observed by 3PMT+WLS
- Above 5 Td: the unusual slow component appears and increases, complicating 3PMT+WLS data





Results with fast component: EL gap thickness measurements