Observation of unusual slow components in electroluminescence signal of two-phase argon detector

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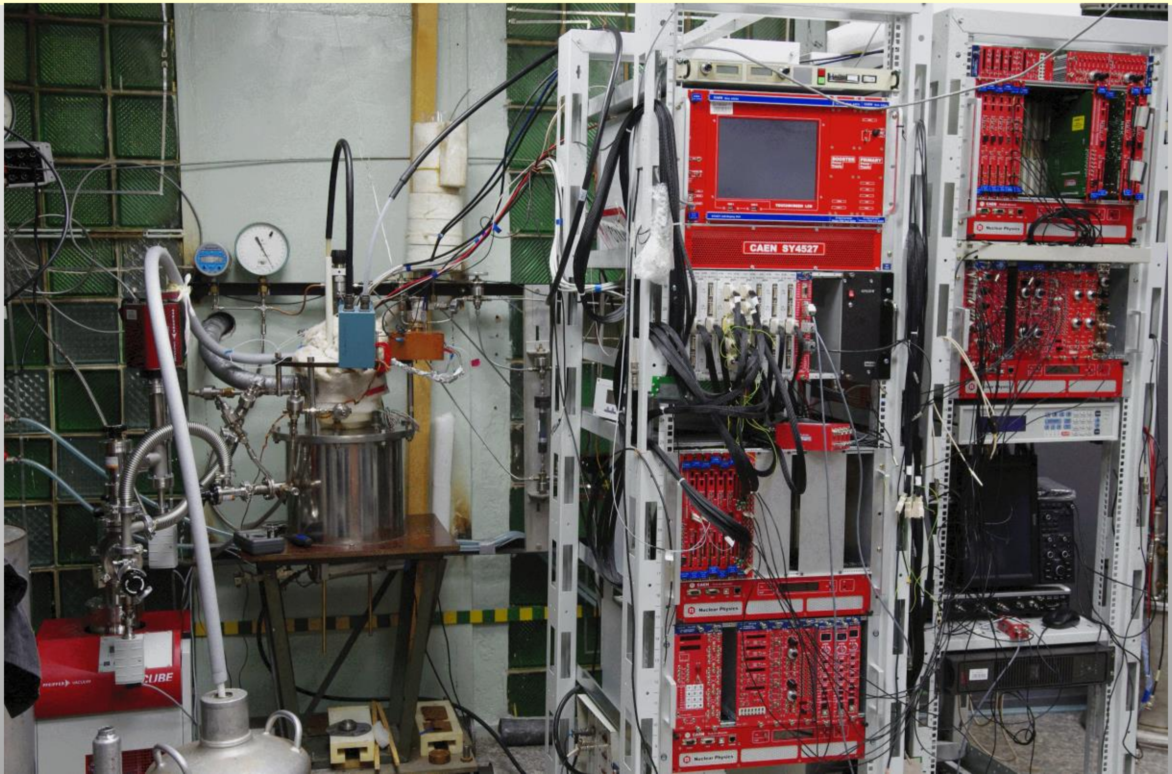
INSTR20, Novosibirsk

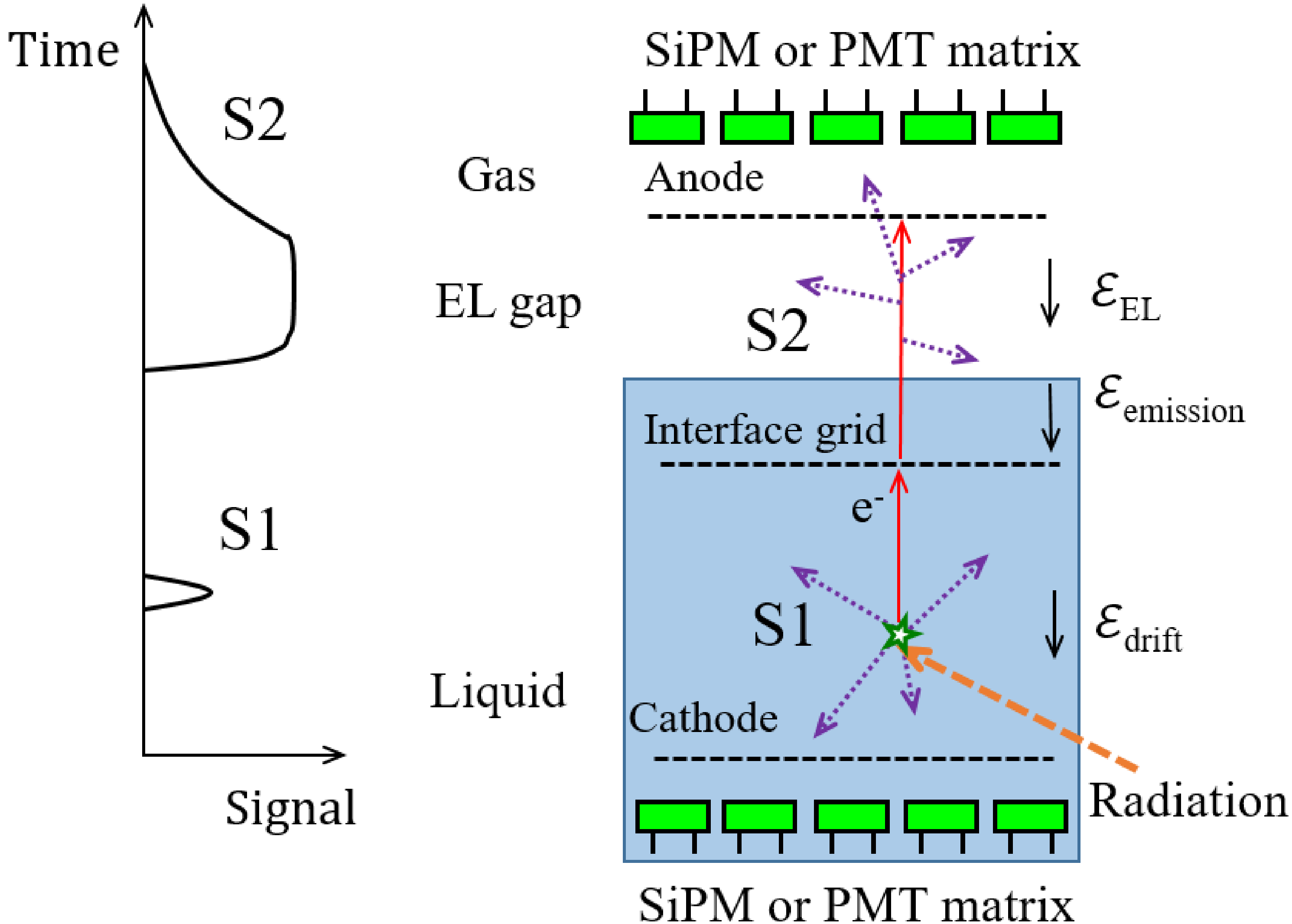
Novosibirsk group activity: development of two-phase Ar detectors for dark matter search experiments

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 (poster).**
- **Development of new readout techniques in two-phase Ar detectors using SiPM-matrices (paper in preparation).**
- **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.

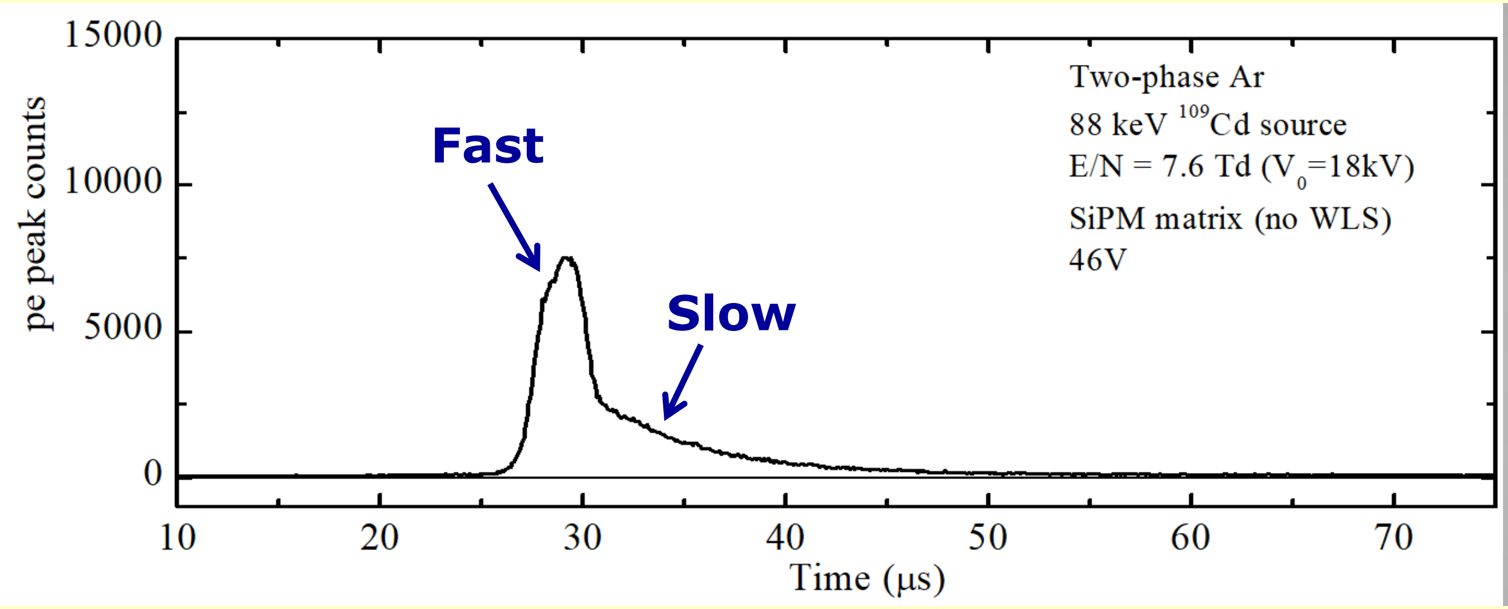
- To measure z-coordinate via electron diffusion (related to S2 fast component shape)

- To measure EL gap thickness using S2 shape

- To understand EL mechanisms

S2 slow component problem

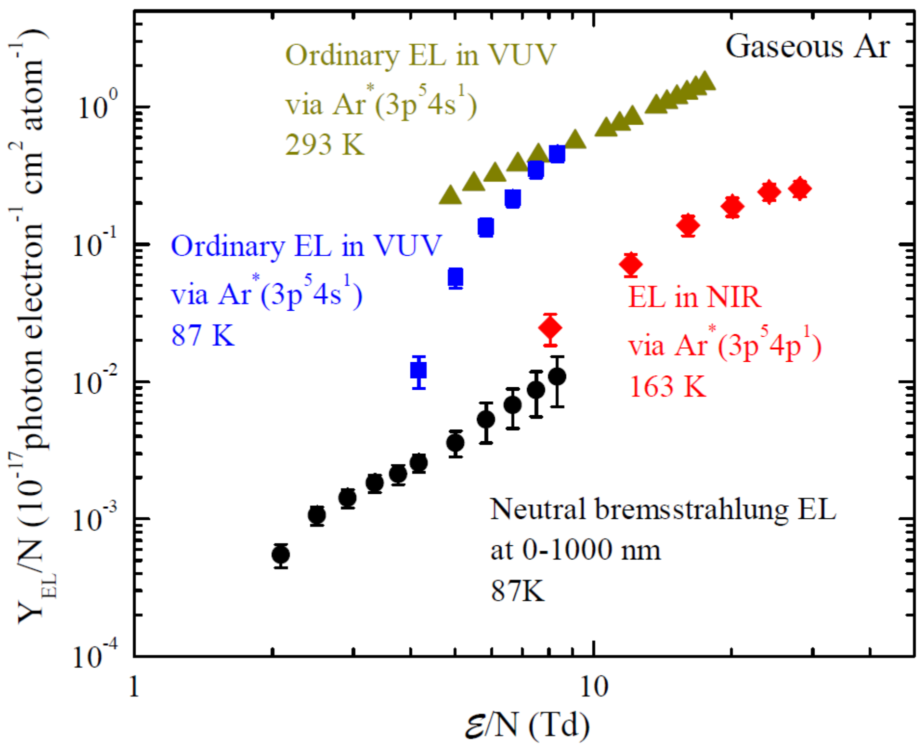
Electroluminescence pulse shapes in two-phase Ar have not been systematically studied in wide electric field range. This has been done in this work for the first time.

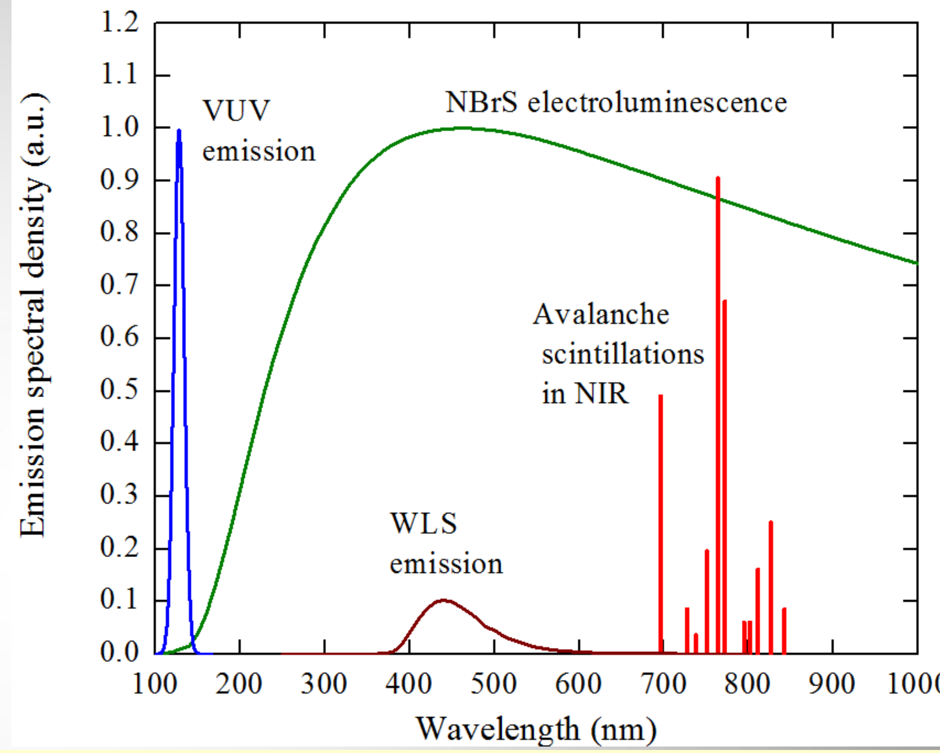


The slow component nature is not fully understood. There are few possible mechanisms:

- **Due to triplet excimer Ar_2^* ($^3\Sigma_u^+$) emission**
- **Due to thermionic emission of e^- through liquid-gas interface**
- **Other exotic mechanisms (TPB-related, delayed e^- emission, etc.)**

Electroluminescence mechanisms





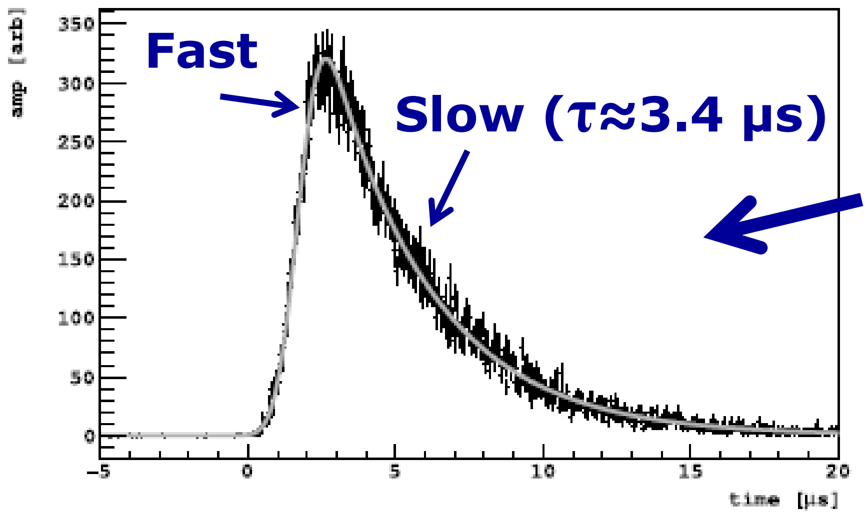
According to the current concept, there are three EL mechanisms:

- 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.

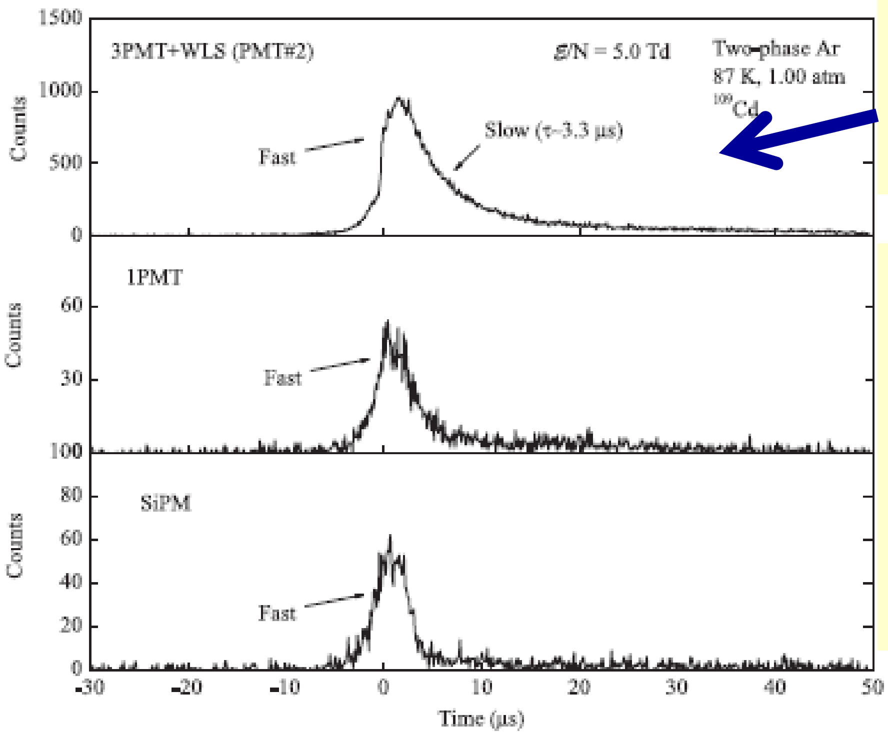
- Emission due to atomic transitions in NIR. It is fast.

“Usual” slow components in EL signal in two-phase Ar due to triplet component of Ar_2* excimer emission



DarkSide

P. Agnes, et al., Nucl. Instr. Meth. A 904 (2018)

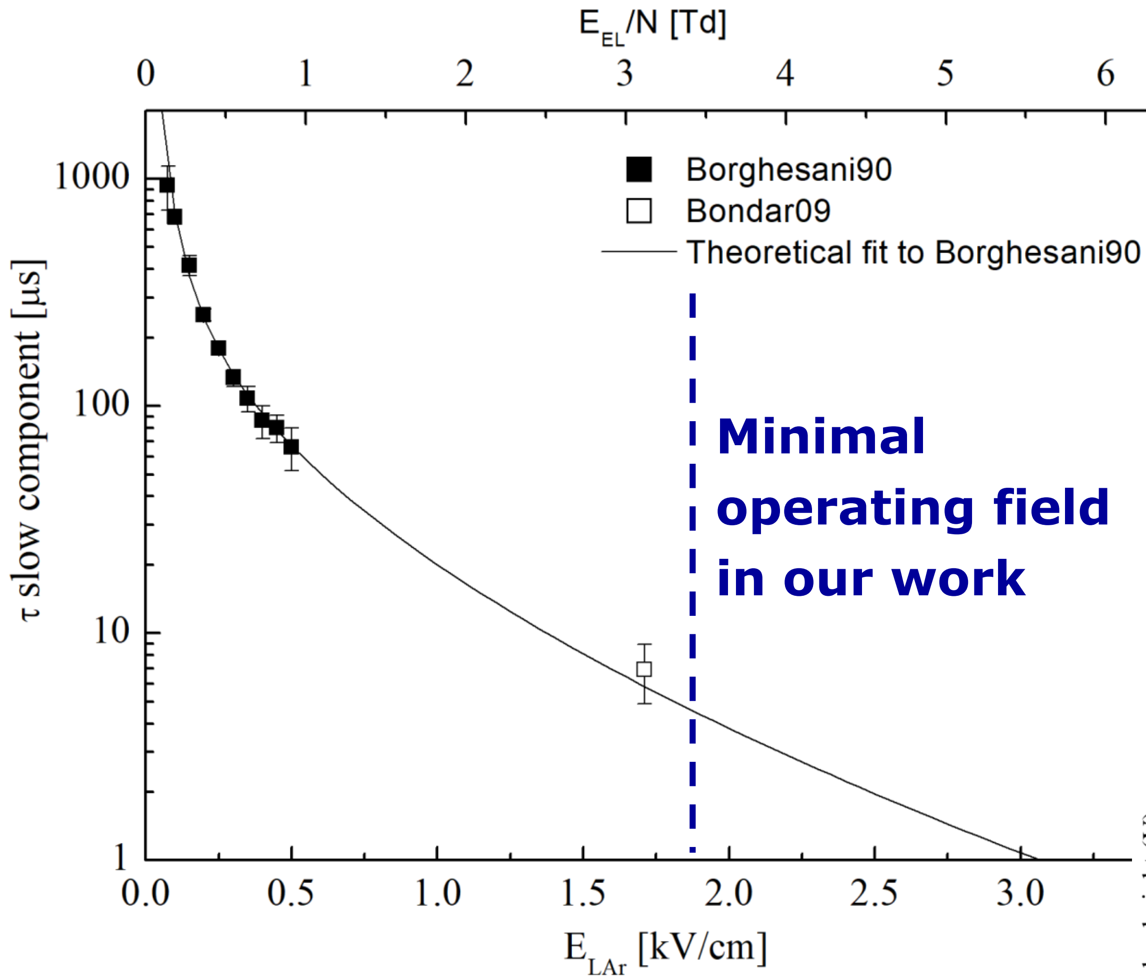


Our group

A. Buzulutskov, et al., Astroparticle Physics, 103 (2018)

Main feature: time constant and contribution of slow component should not depend on the electric field

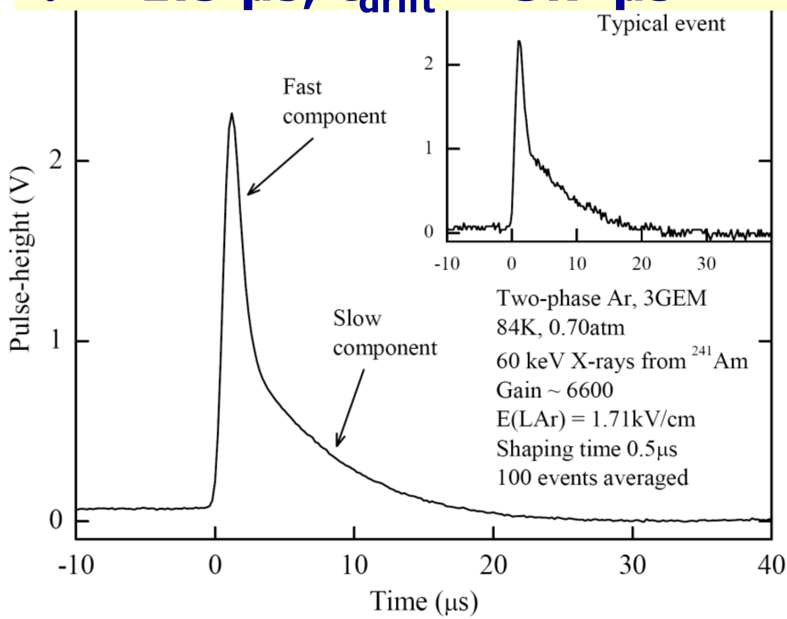
"Usual" slow component in EL signal in two-phase Ar due to electron emission effect at liquid-gas interface



- **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:

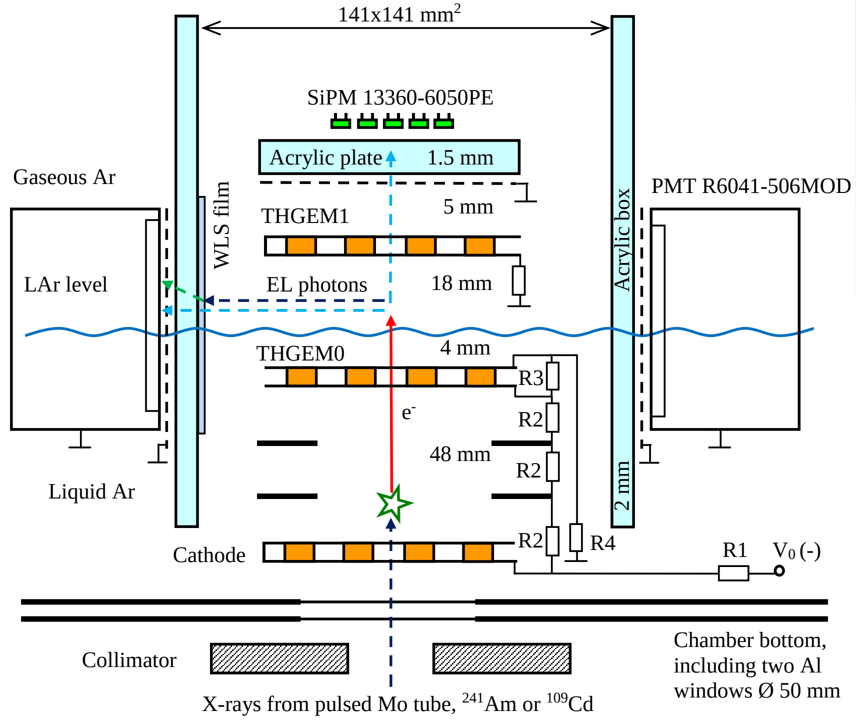
τ = 1.5 μs, t_{drift} = 3.7 μs



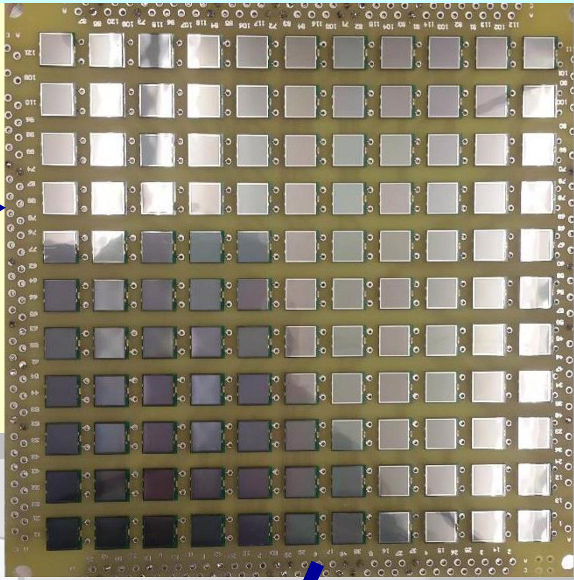
A. Borghesani, et al., Phys. Lett. A 149 (1990) 481

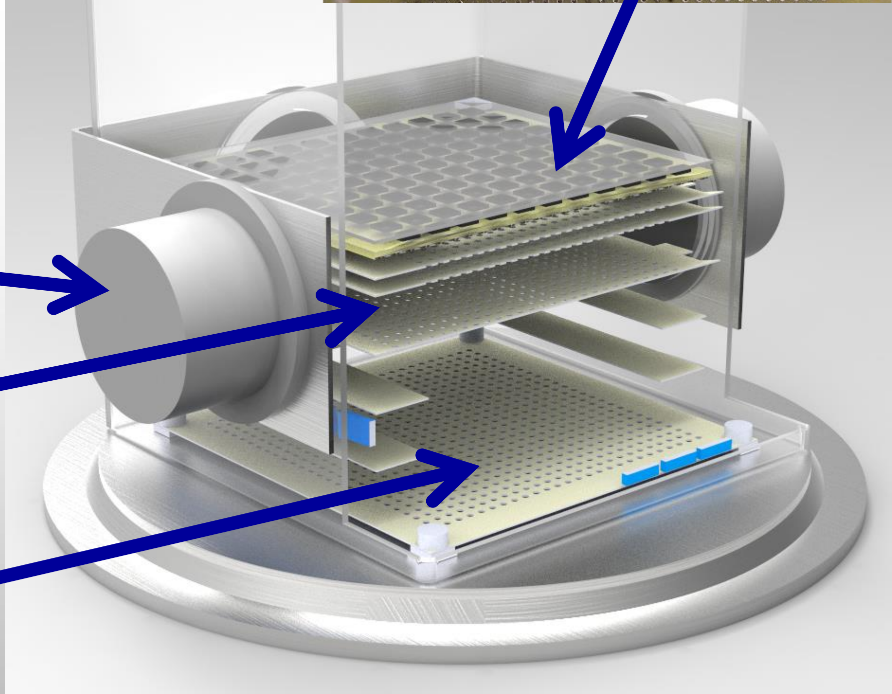
A. Bondar, et al., JINST 4 (2009) P09013

Experimental setup



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





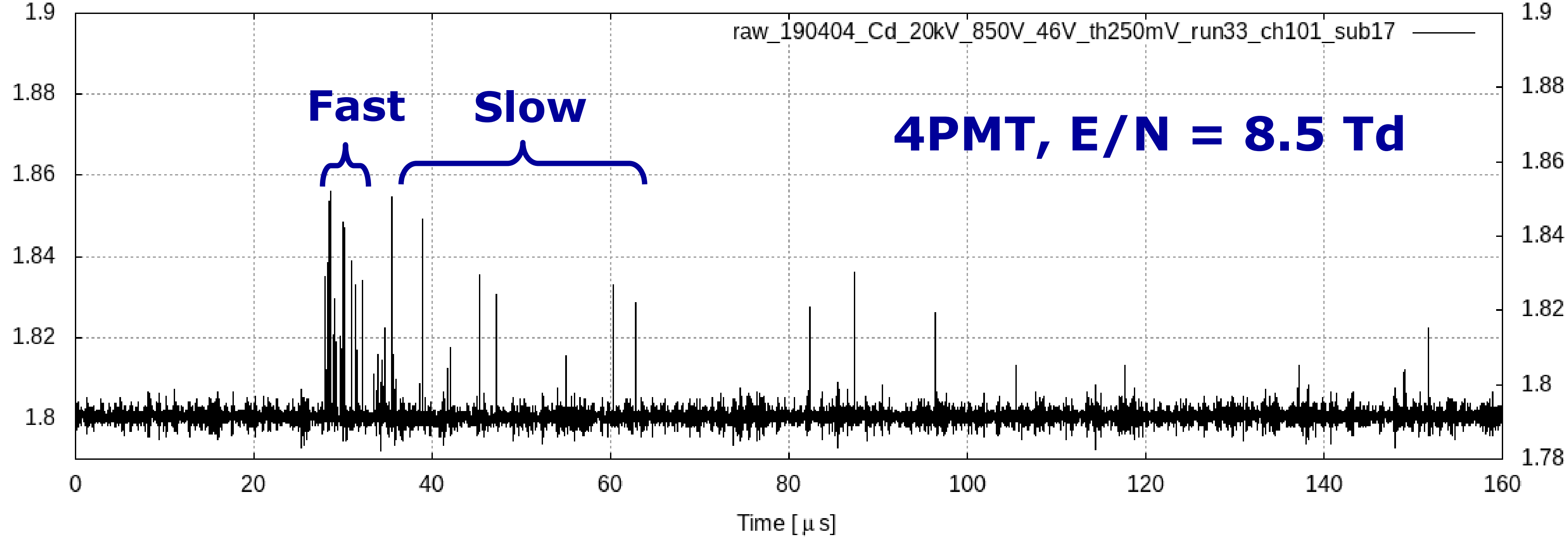
Trigger is taken from S2: by threshold on sum of 4PMTs

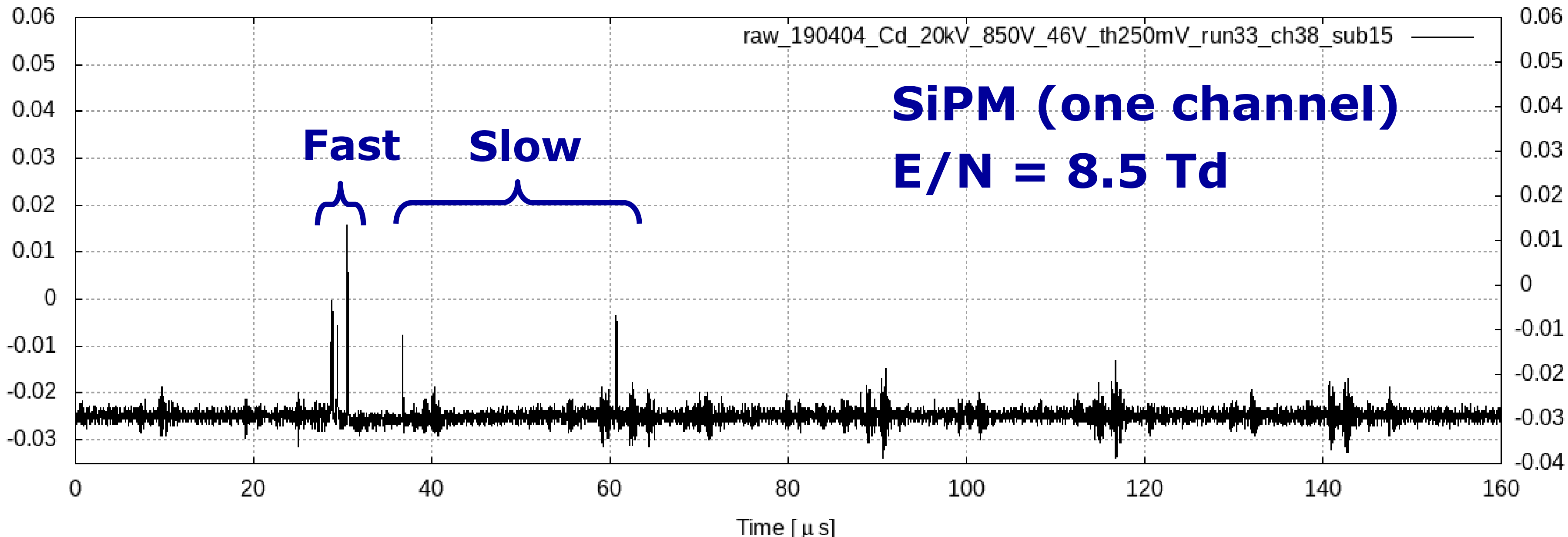
PMT R6041-506 MOD

EL gap

Drift region

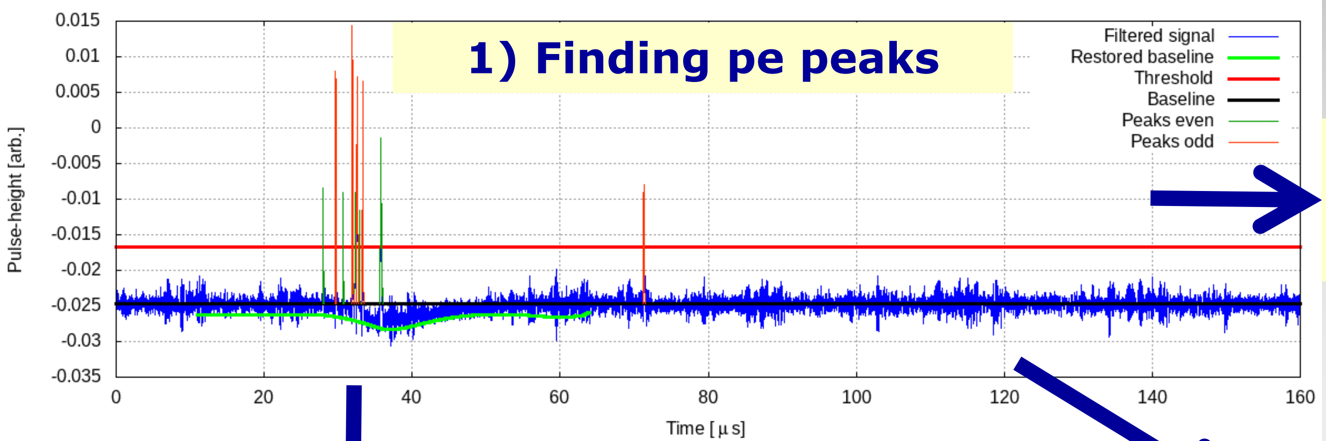
PMT and SiPM signal examples (no WLS)





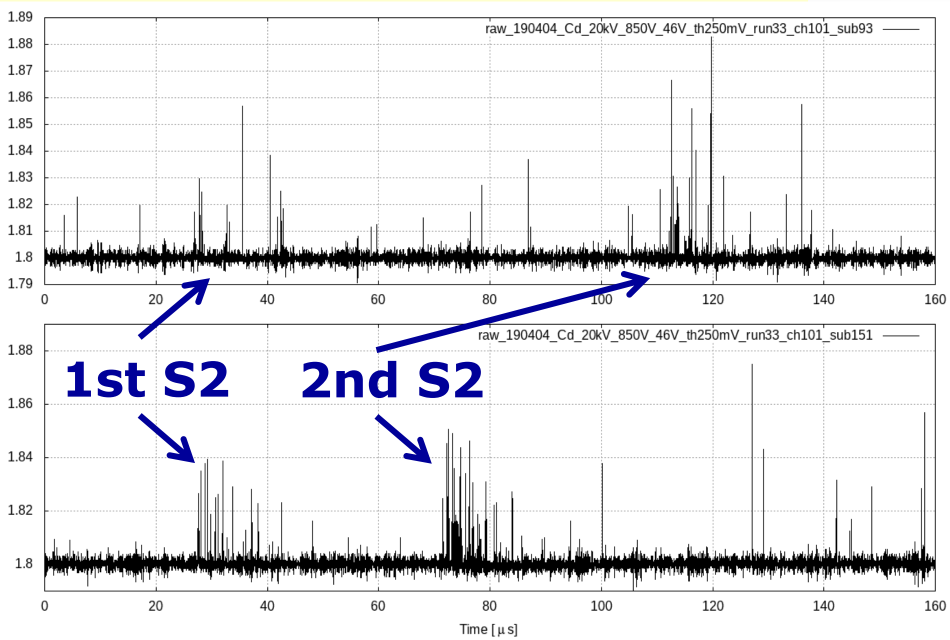
Analysis algorithm

1) Finding pe peaks

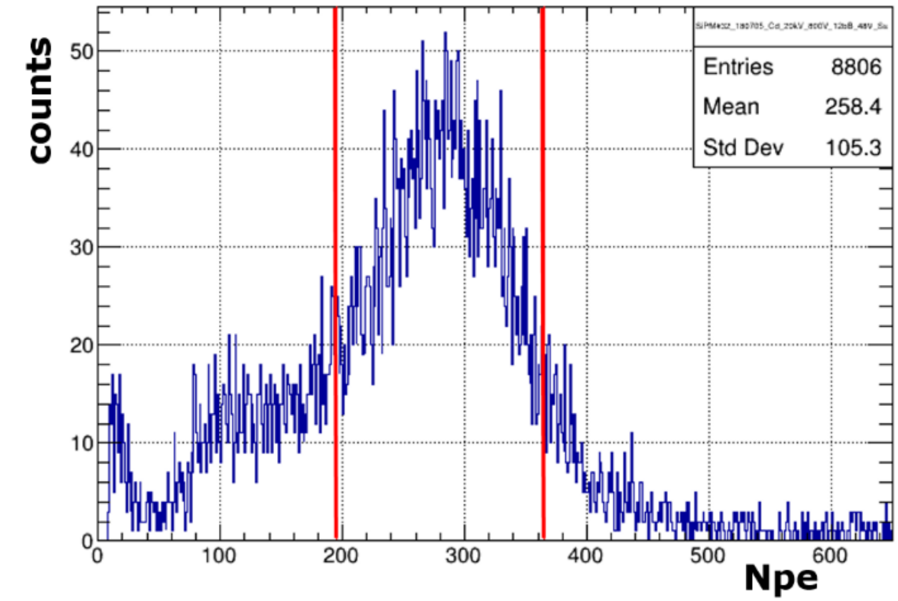


4) Building time histograms of pe peaks: pulse-shapes

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

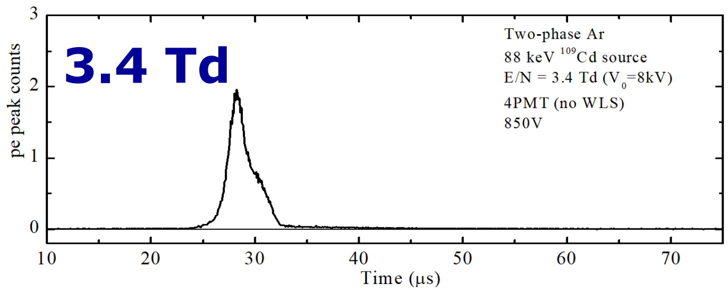


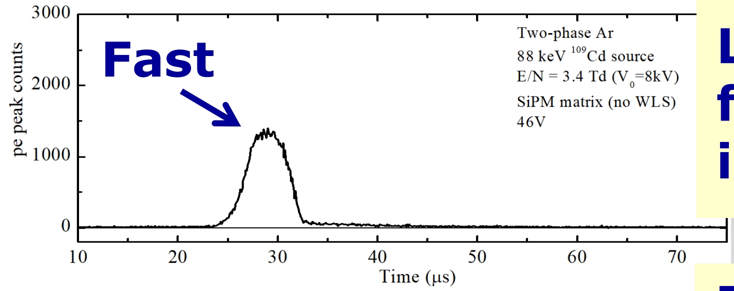
3) Selection of events from the 88 keV peak of ^{109}Cd



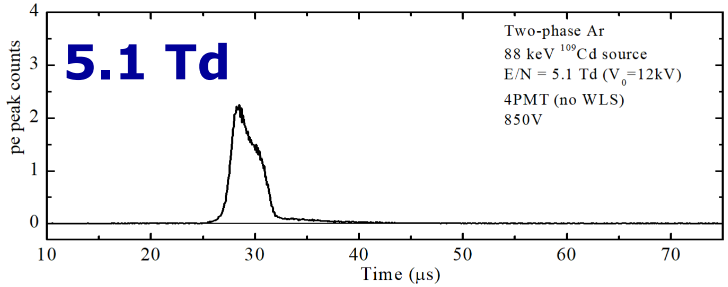
Results without WLS: PMT vs SiPM pulse-shapes (time histograms)

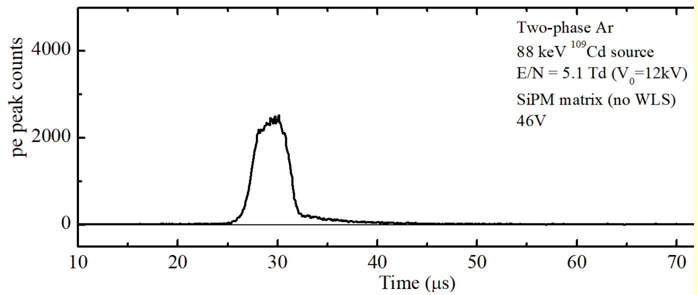
4PMT | SiPM-matrix



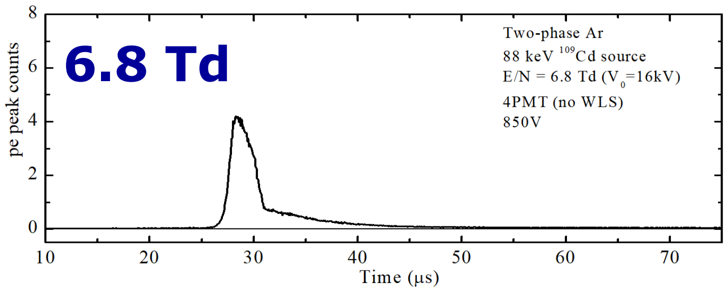


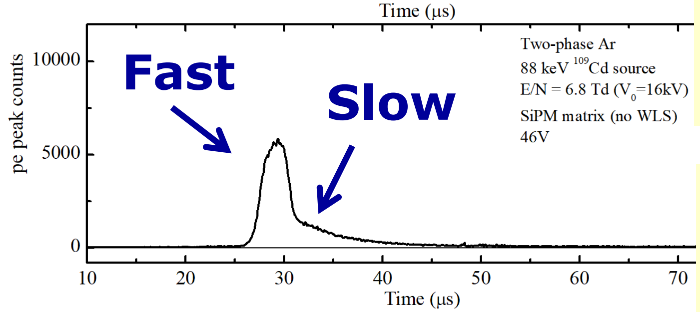
Low fields: only fast component is observed

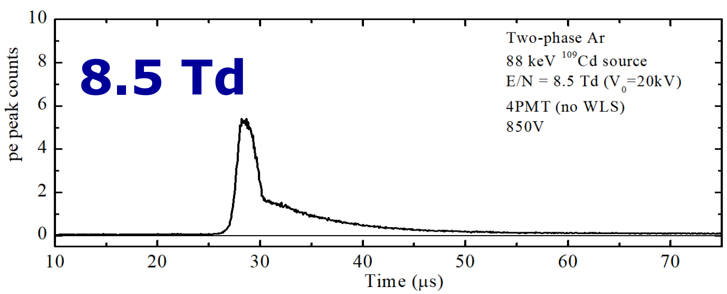


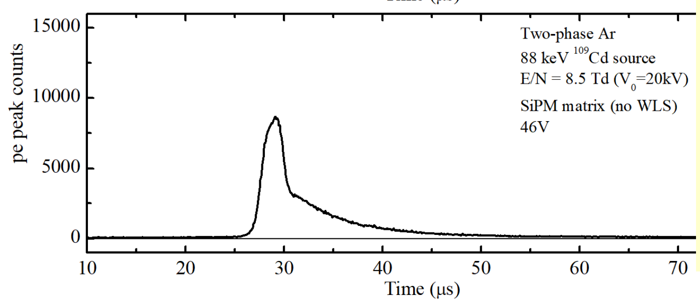


Just above the 4 Td EL threshold: slow component has emerged but fast component still dominates



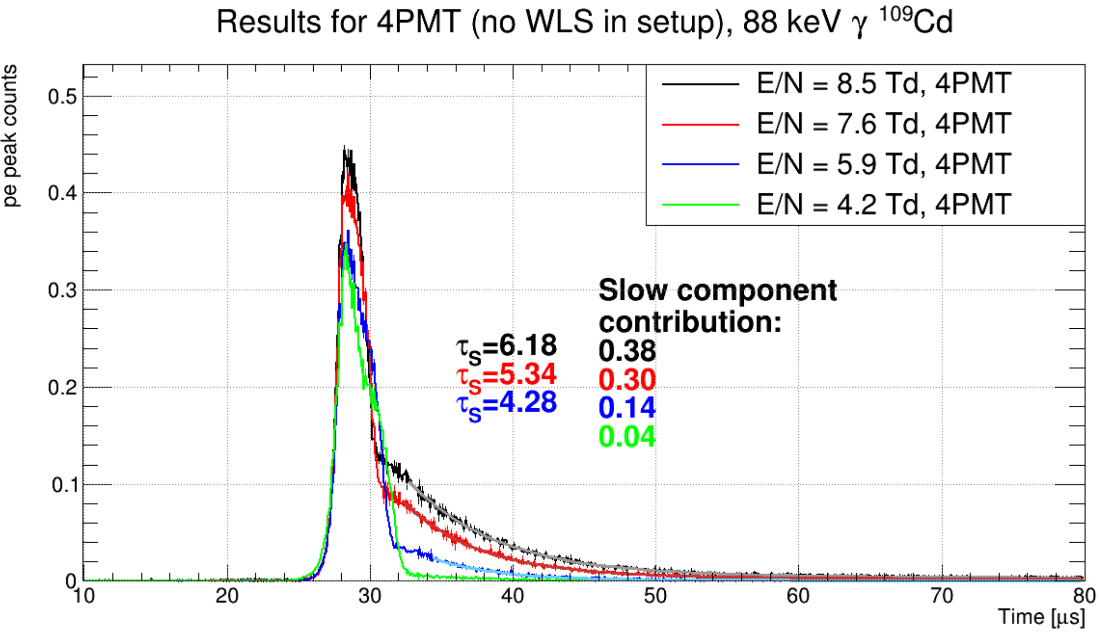


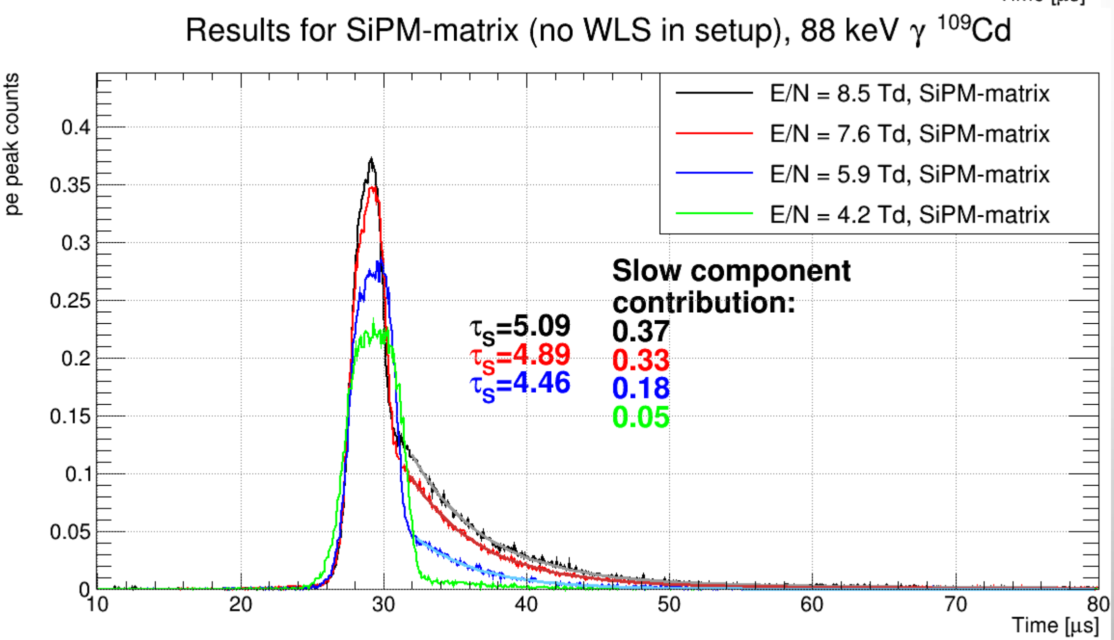




Middle and high fields: appreciable contribution of slow component

Results without WLS: PMT vs SiPM pulse-shapes (time histograms)





- **Slow component contribution increases with electric field**

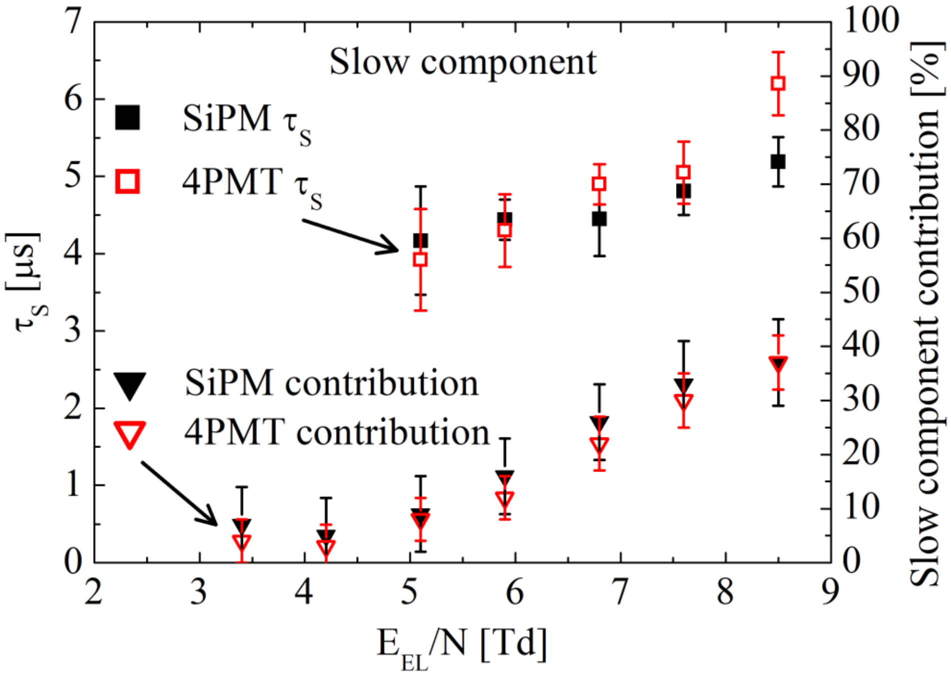
- **Slow component time constant τ_S increases with electric field as well**

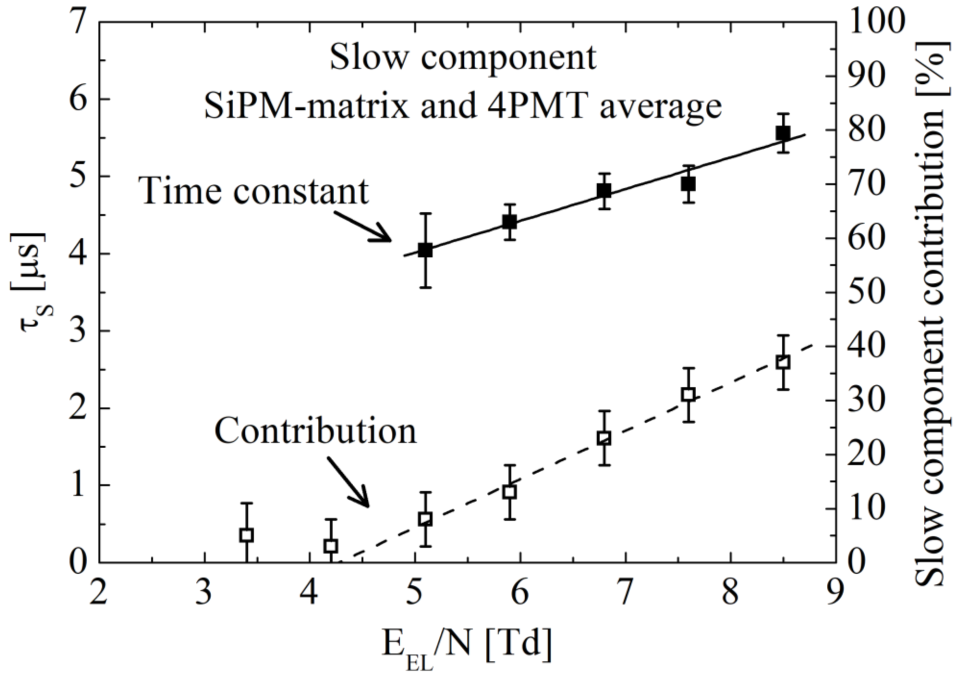
- **Fast component width, reflecting drift time across EL gap, decreases with field**

- **The SiPM-matrix and 4PMTs data are in good agreement**

(Histograms are normalized by area of the fast component)

Results without WLS: PMT vs SiPM
τ and contribution of slow component





Slow component has unusual character:

- Its contribution increases with electric field

- Its time constant τ_S increases with electric field as well

- The SiPM-matrix and 4PMTs data are in good agreement, despite having different spectral sensitivities

Two hypotheses of slow component nature

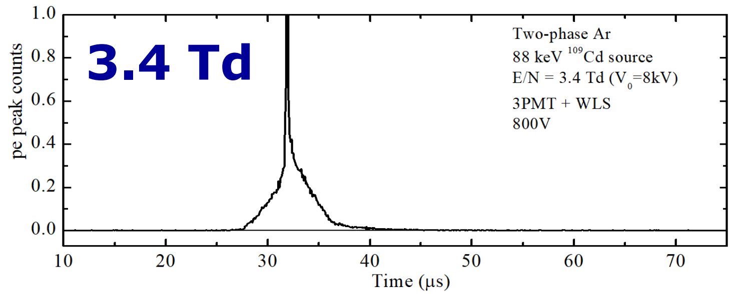
1) Due to new unknown EL mechanism

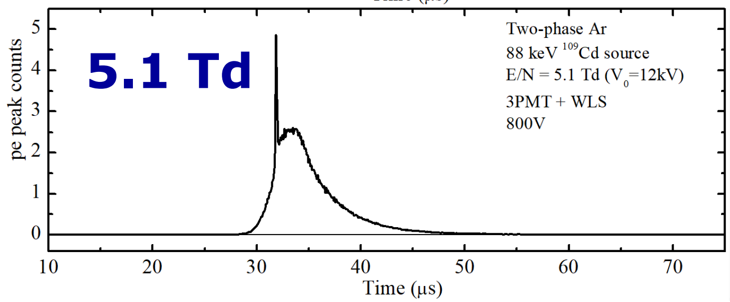
2) Slow component is present in charge signal itself

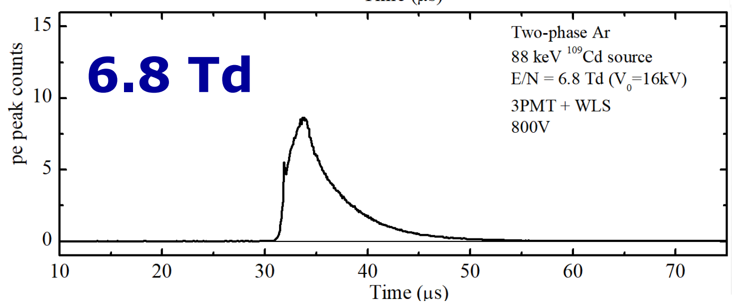
Measurements with WLS may shed light upon slow component nature

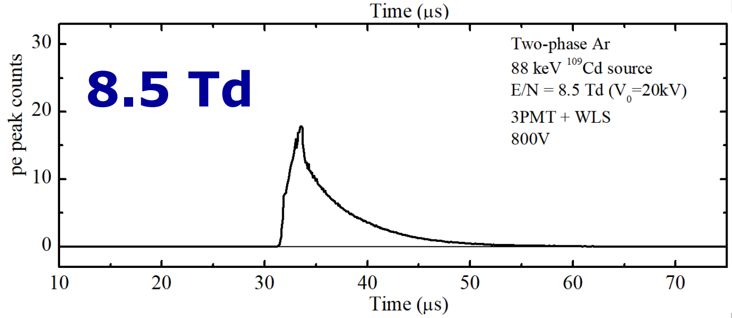
Results with WLS: PMT+WLS vs SiPM pulse-shapes

3PMT+WLS (sensitive to excimer component)

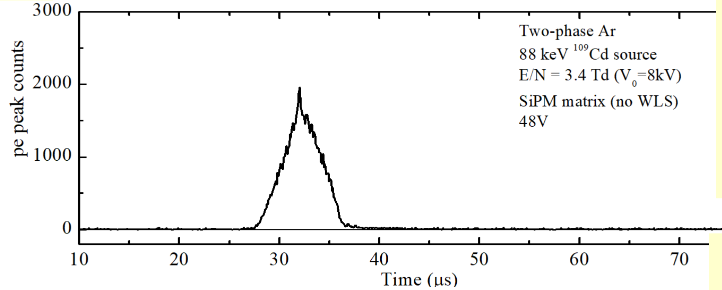


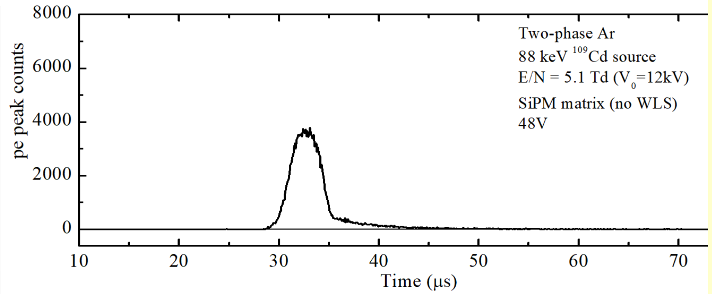


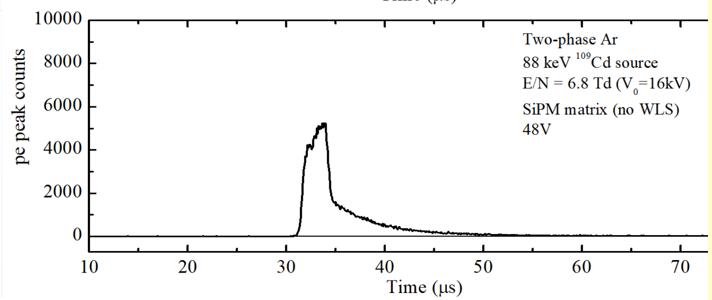


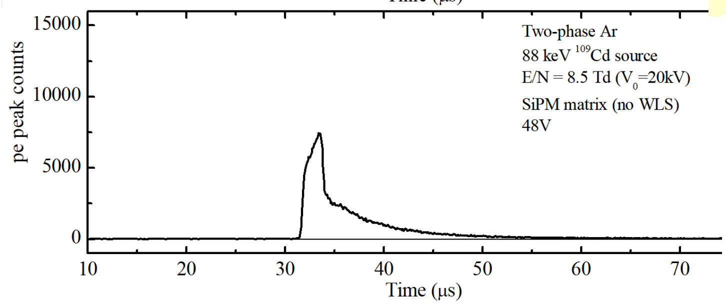


SiPMs (not sensitive to excimer component)





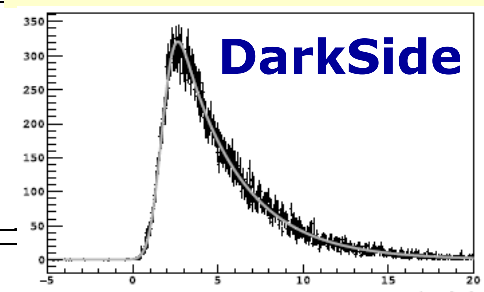




Low fields: only fast component is observed

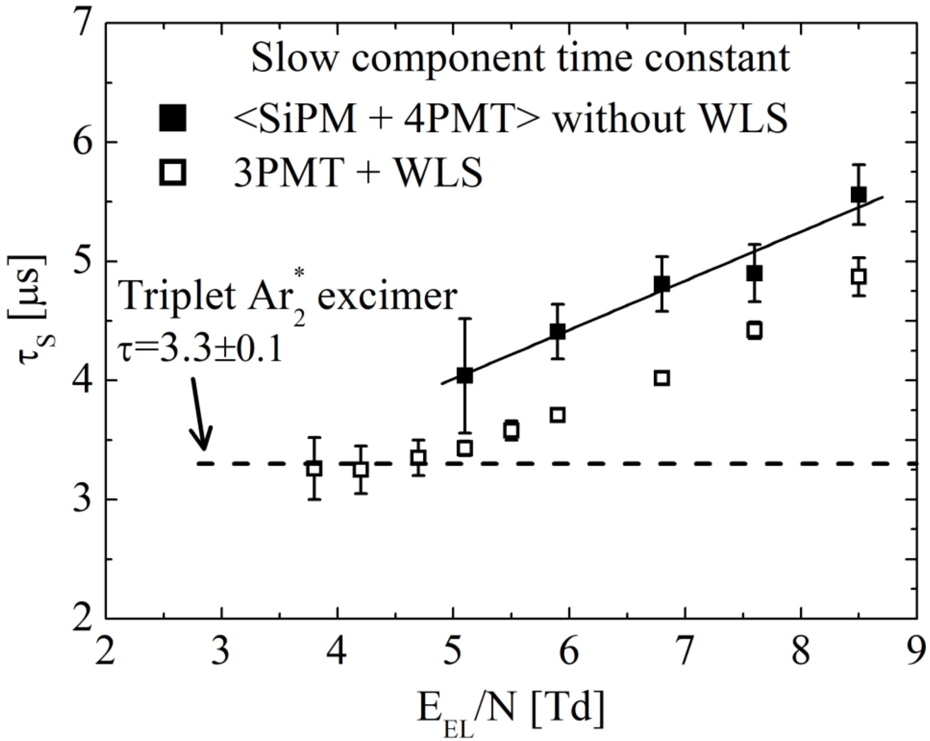
Above the 4 Td EL threshold: SiPM-matrix data match the data without WLS

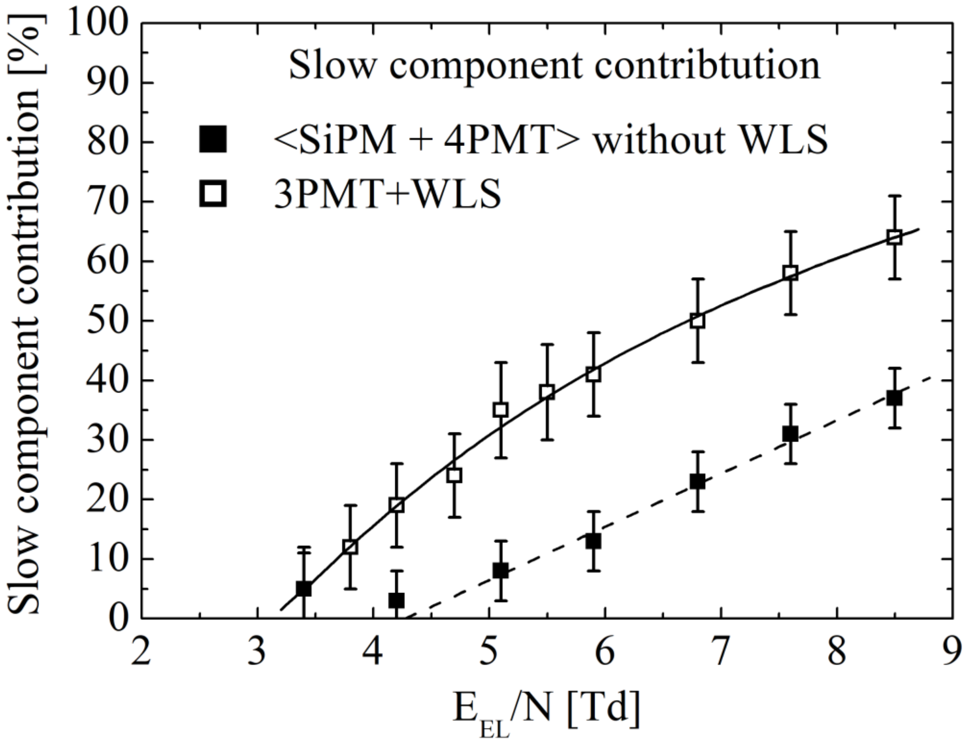
PMT+WLS are different, have shape expected from excimer mechanism



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

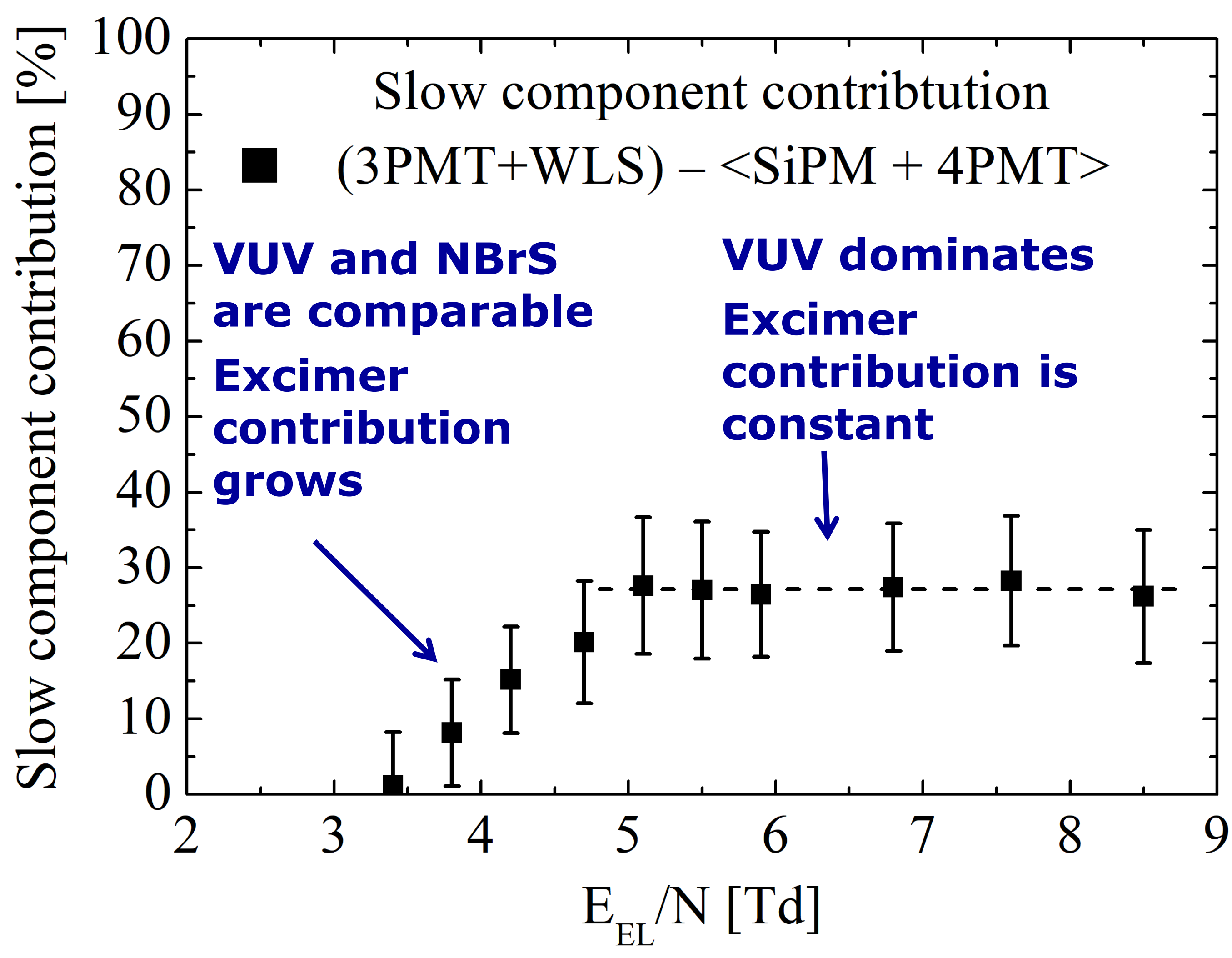
- Below 5 Td: no unusual slow component, only excimer one is observed by 3PMT+WLS
- Above 5 Td: the unusual slow component appears and increases, complicating 3PMT+WLS data





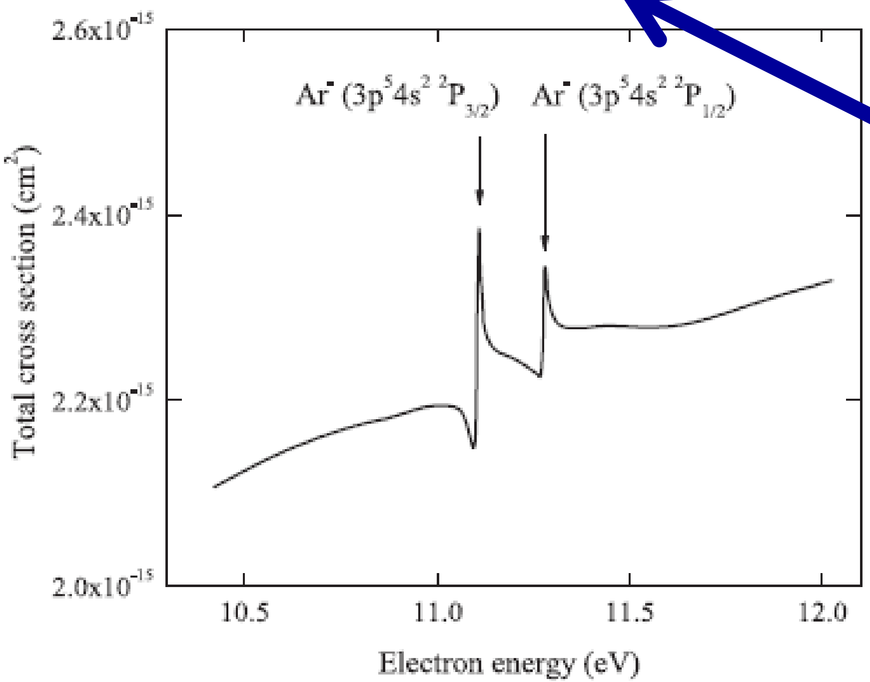
Confirmation of hypothesis of slow component in charge signal

If we subtract unusual slow component contribution from 3PMT+WLS data then it shows behavior expected from Ar_2^* excimer emission model



Discussion: hypothesis of slow component in charge signal

$$e^- + Ar \rightarrow Ar^-(3p^5 4s^2) \rightarrow e^- + Ar$$



Slow component in charge signal may appear if drifting electrons are delayed on metastable Ar- ions

Experimental cross section for e- scattering from Ar around Feshbach resonances

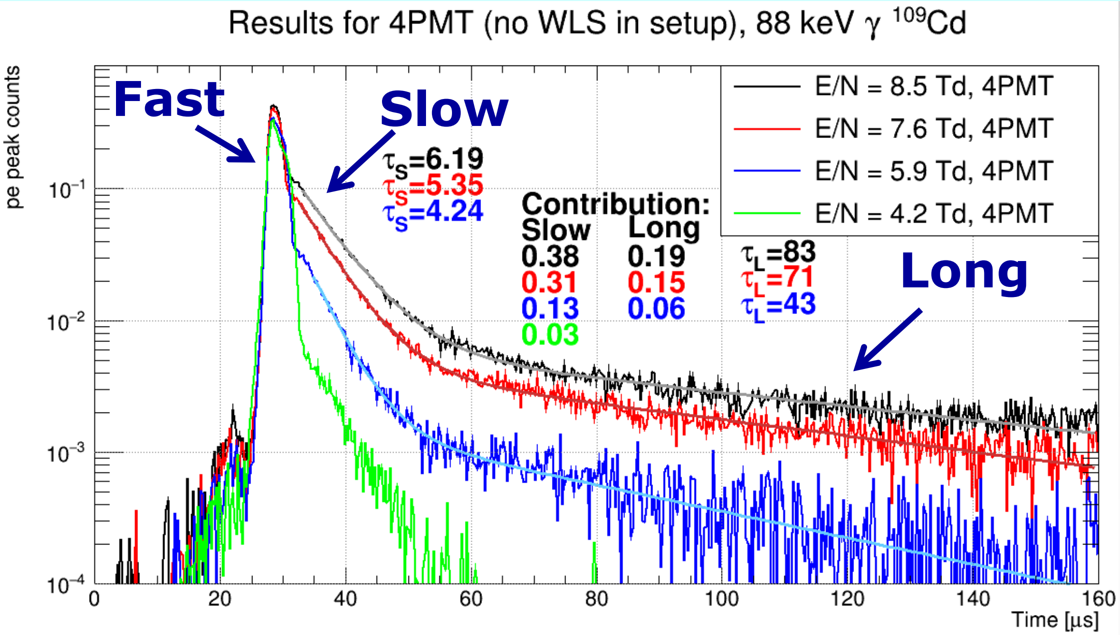
M. Kurokawa et al., Phys. Rev. A 84 (2011) 062717

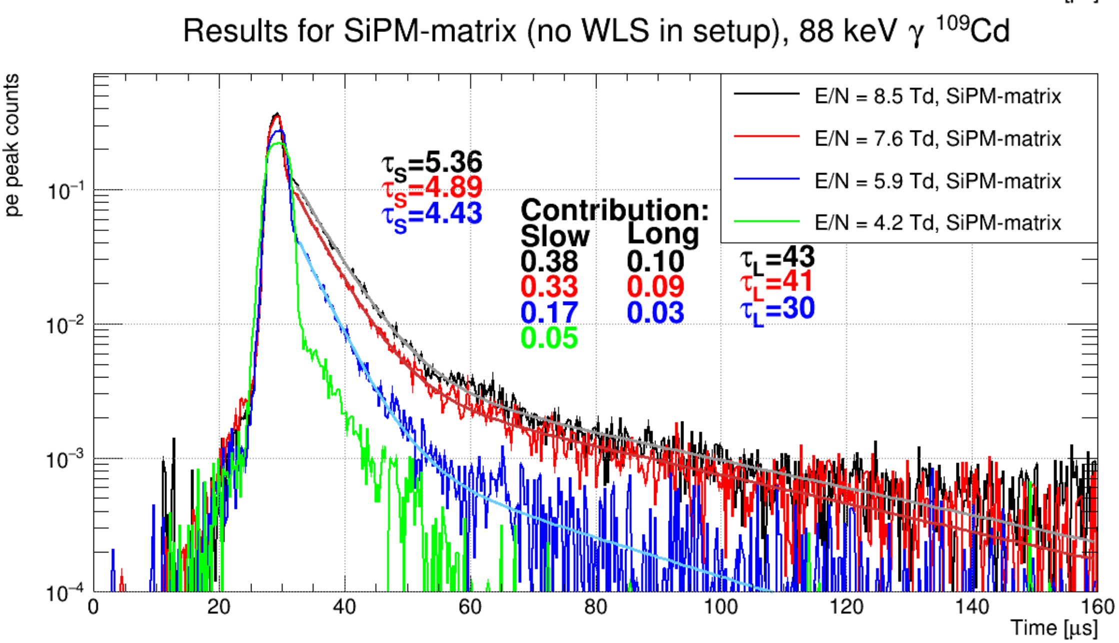
There is also Ar- ($3p^5 4s4p\ ^4S$) state with ~300 ns lifetime (from atomic beam experiments):

Y.K. Bae, et al., Phys. Rev. Lett. 54 (1985) 789

I. Ben-Itzhak, et al., Phys. Rev. A 38 (1988) 4870

Preliminary results on long component





Data without WLS

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

(Histograms are normalized by area of the fast component)

Conclusions

- The unusual slow component has been observed in electroluminescence signal of two-phase Ar, its time constant (~5μs) and contribution (~20%) increasing with electric field

- It was shown that this slow component might be due to the charge signal itself. We hypothesize that it is caused by drifting electron trapping on metastable ions.

- The unusual long (~50 μs) component has also been observed. Its nature is yet unclear.

Prospects

- Direct charge measurement

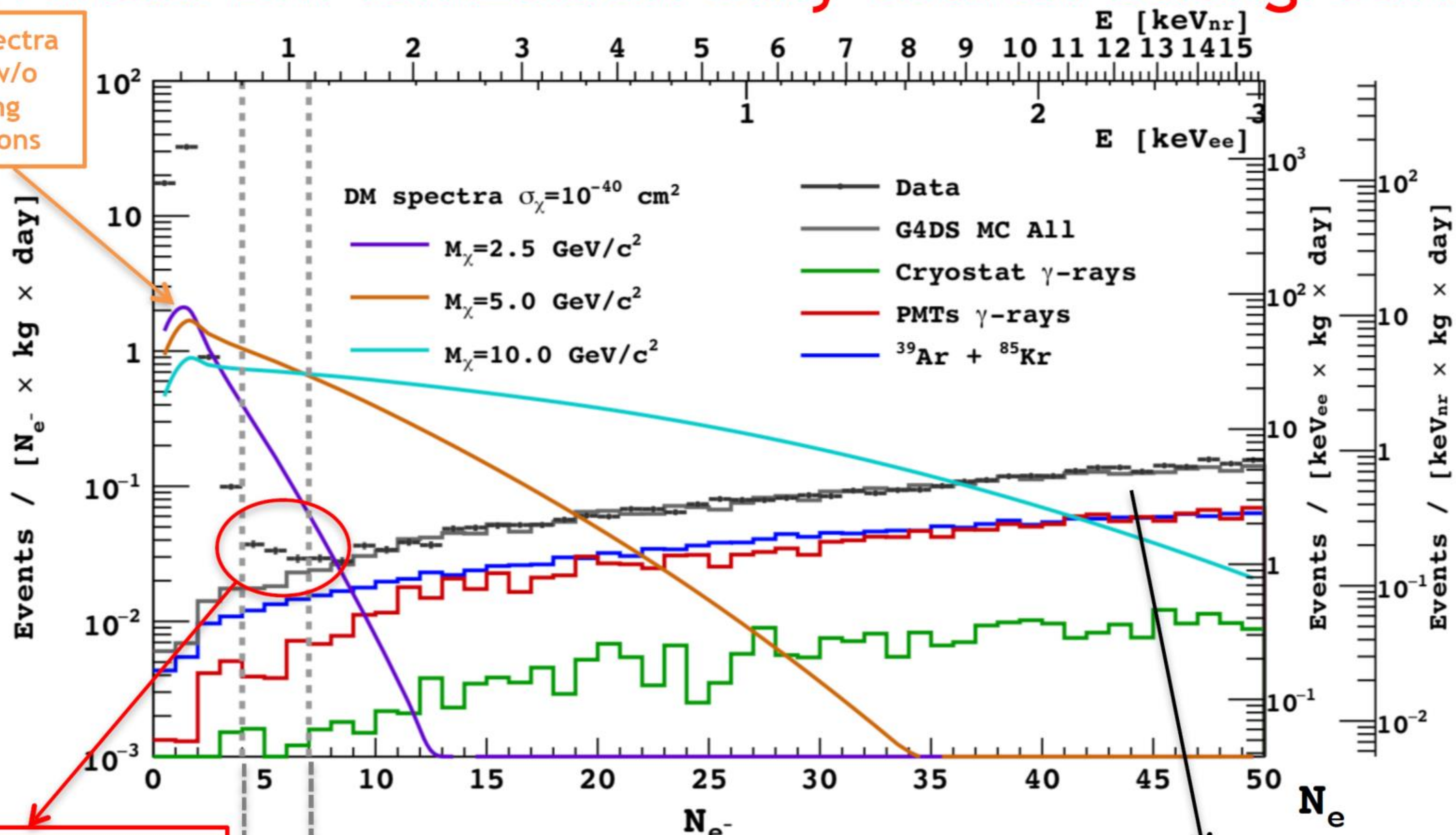
- Measurements with different EL gap thicknesses

- Getting rid of trigger-related signal shape distortion

Practical application for DarkSide

Low Mass DM ionization only search background

WIMP spectra plotted w/o quenching fluctuations



Excess of events wrt to background prediction due to trapped/delayed electrons peak.

Also seen by XENON100. Further studies ongoing.

N_e > 7 analysis threshold for Mχ > 3.5 GeV in Data-MC good agreement region.

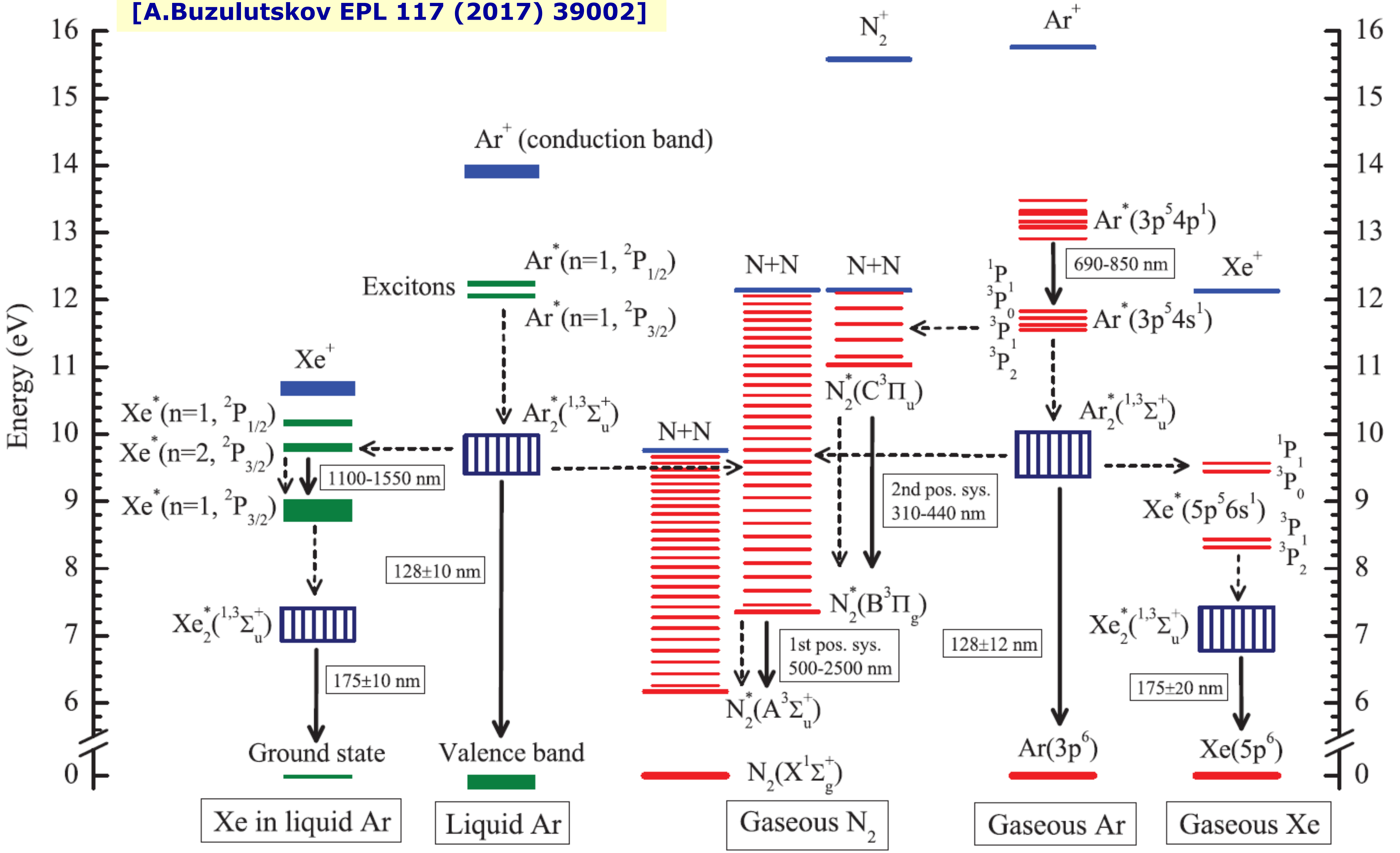
N_e > 4 analysis threshold for Mχ < 3.5 GeV. Region dominated by excess of Data over MC

In high N_e region, dominant ER backgrounds, level prediction with extrapolation from high energy spectrum MC fit, in very good agreement with data (at % level).

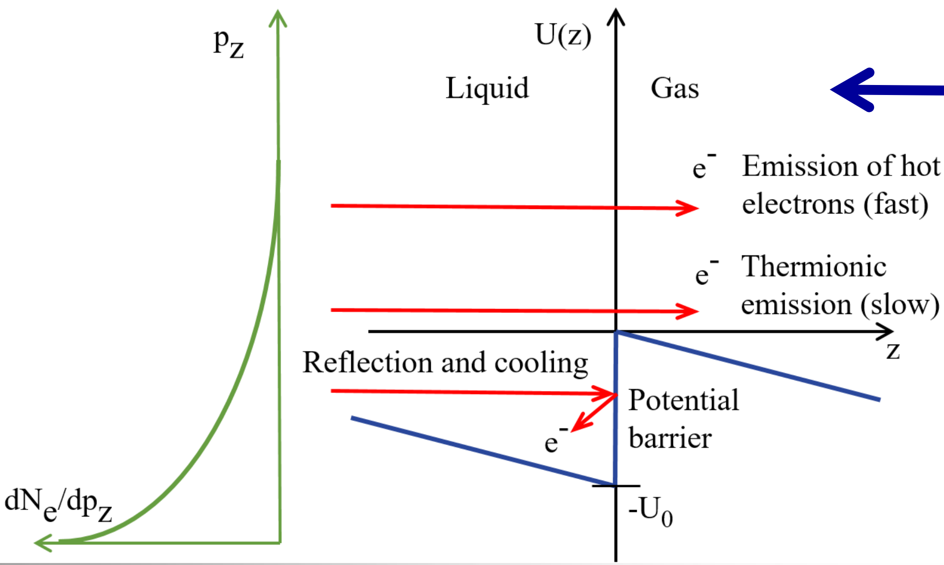
BACKUP

Photon emission and collisional processes in two-phase Ar doped with Xe and N_2

[A.Buzulutskov EPL 117 (2017) 39002]



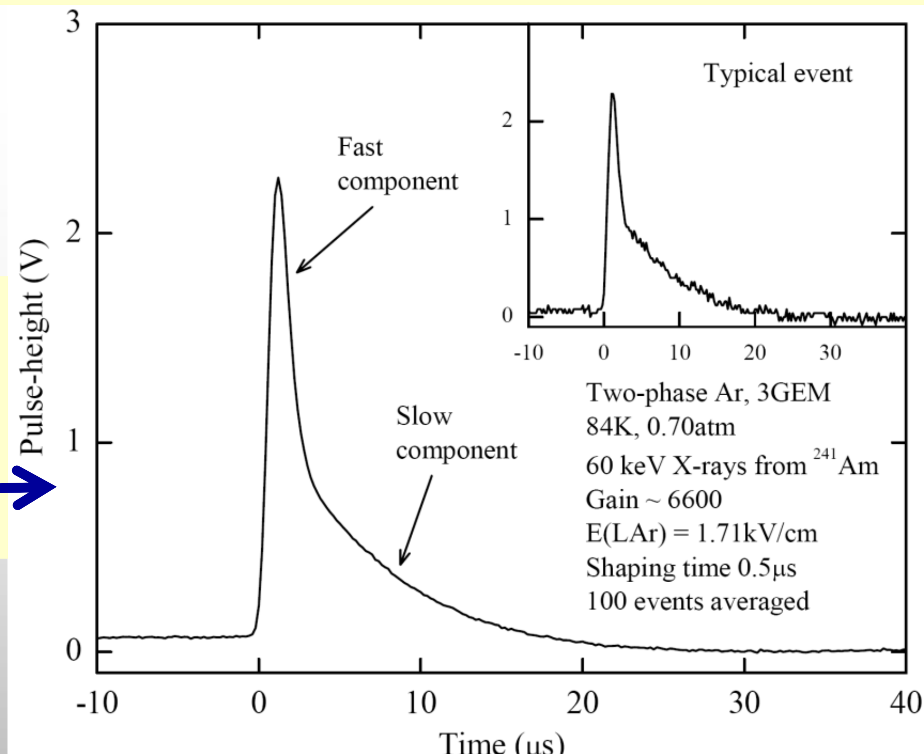
"Usual" slow component in EL signal in two-phase Ar due to electron emission effect at liquid-gas interface



- **Fast component – e^- has enough energy to pass the barrier**
- **Slow component - e^- acquires necessary energy after multiple scatterings and recoils**

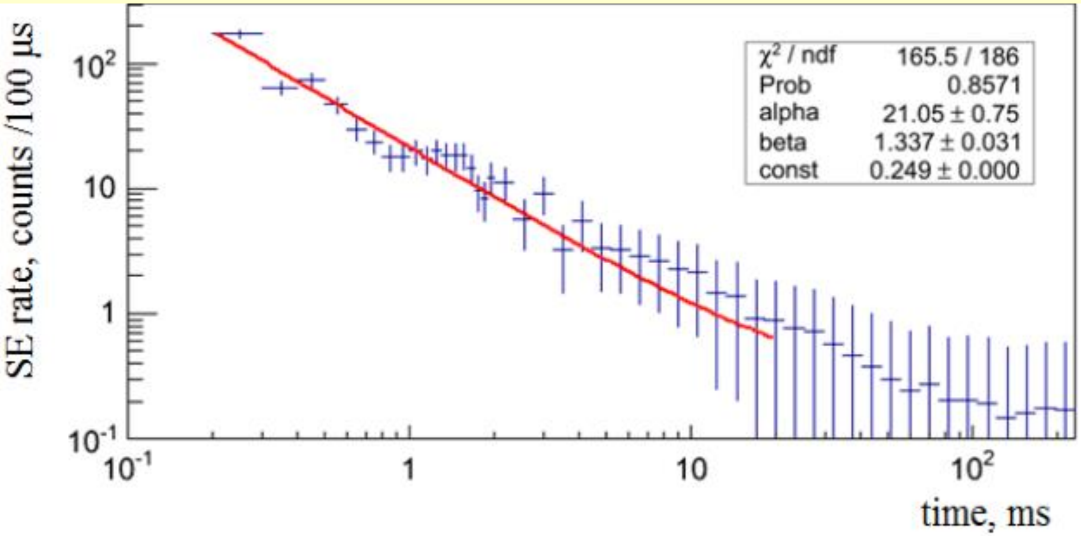
<u>Charge</u> signal at 1.7 kV/cm in LAr after extraction from the liquid

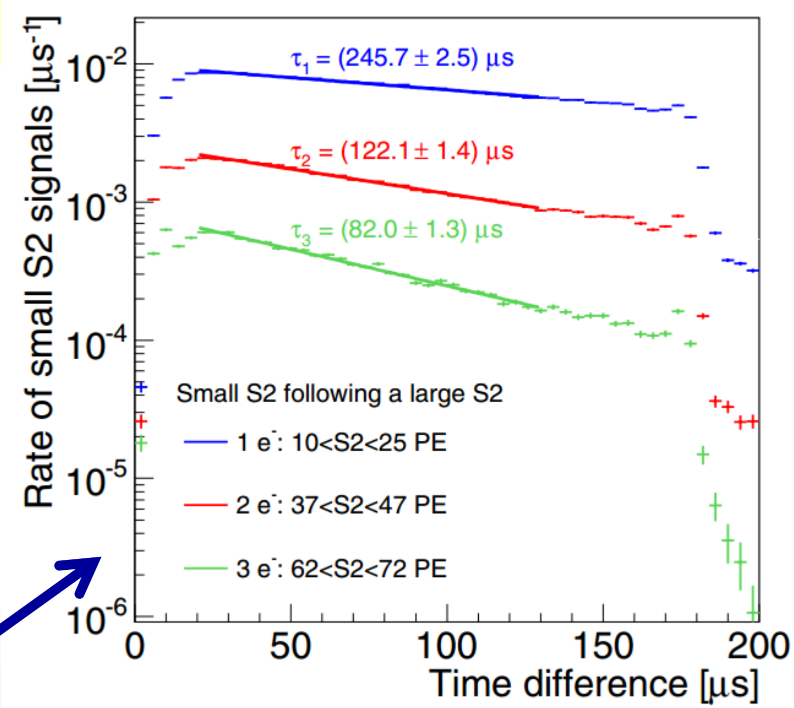
A. Bondar, et al., JINST 4 (2009) P09013



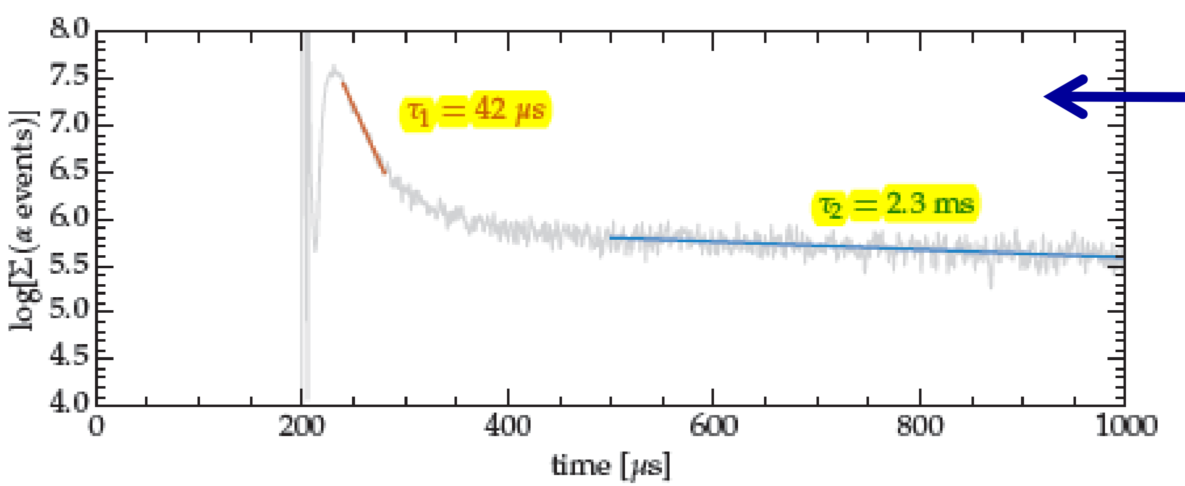
Slow components in EL signals in two-phase Xe (e- train background)

D. Akimov et al., 2016 JINST 11 C03007





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

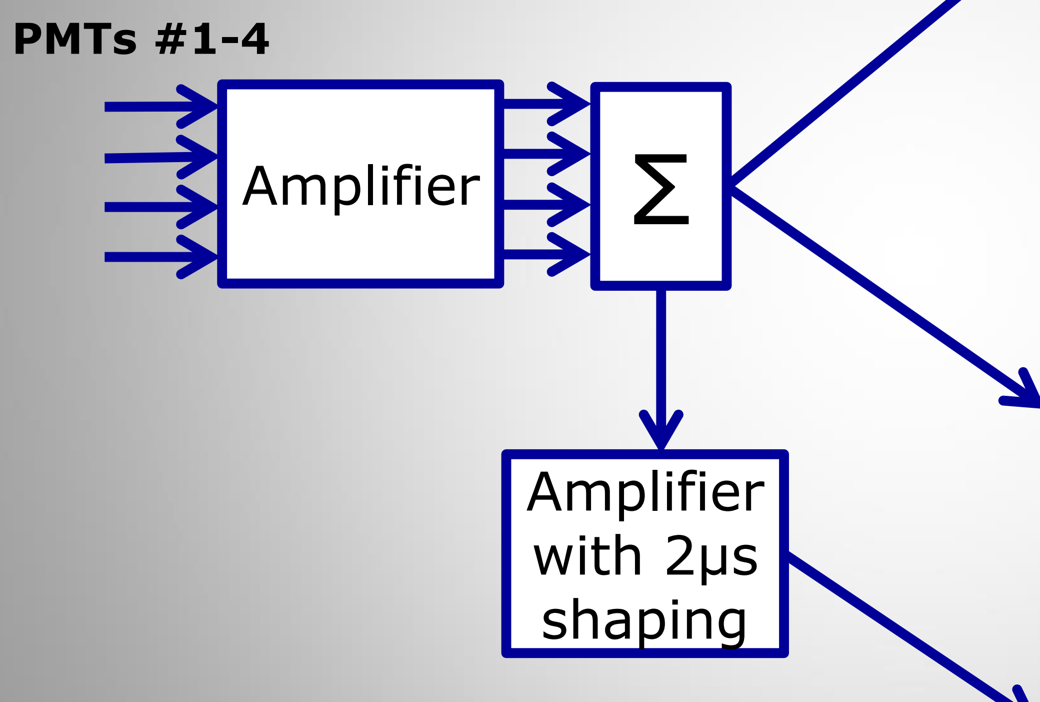


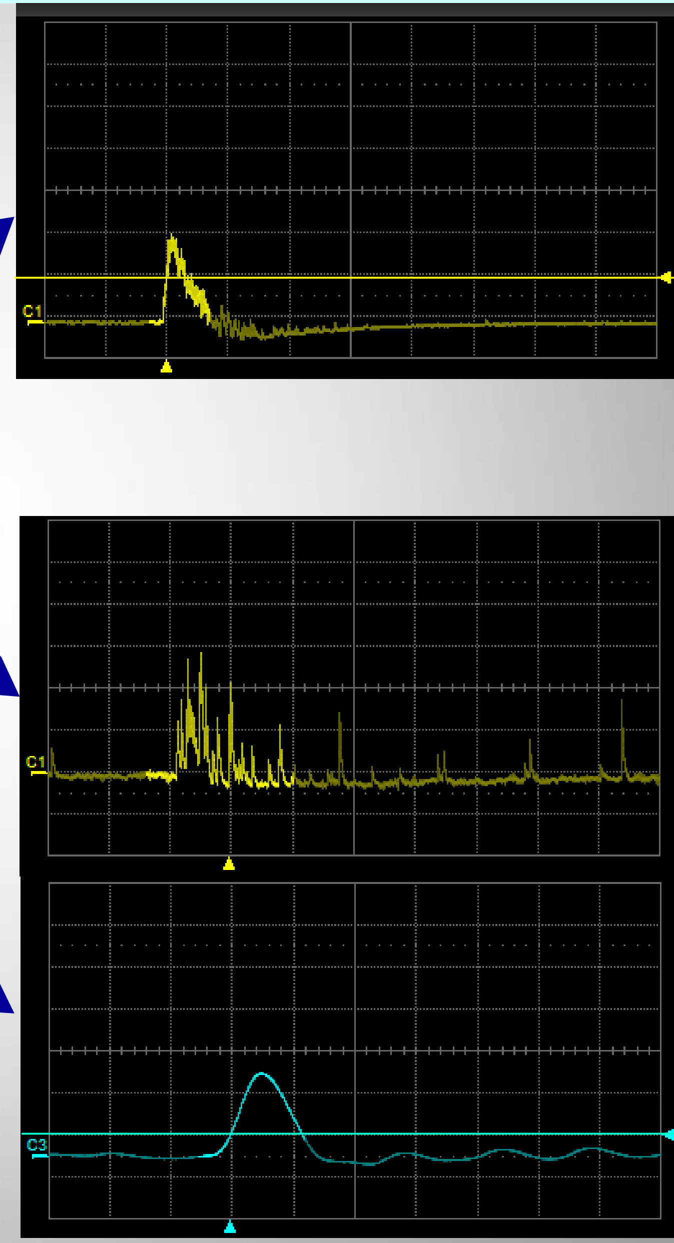
Abnormal slow components: time constants grow with electric field

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

Trigger for ^{109}Cd S2 signal

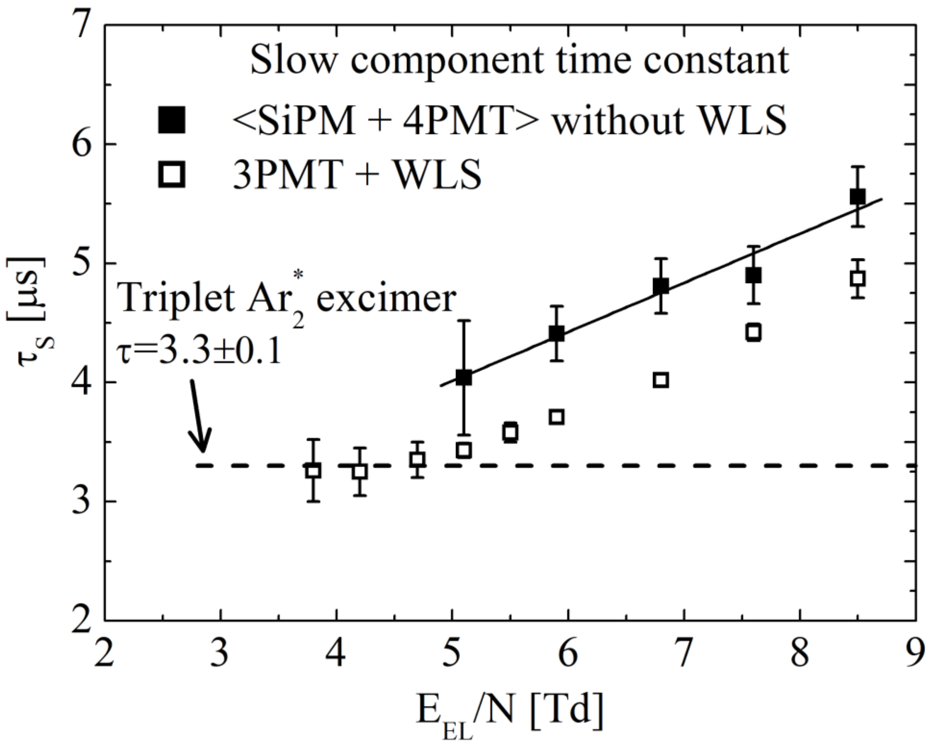
Experiments with WLS: large signal

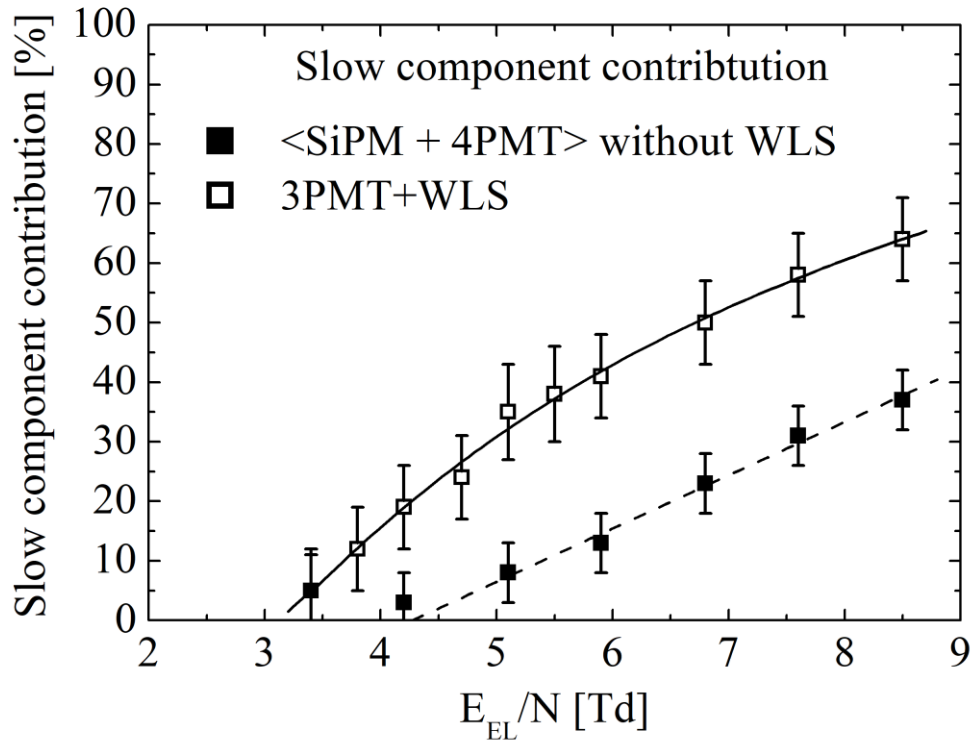




Experiments without WLS: small signal leads to issues with 1pe noise

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





This work: triplet τ = 3.3±0.1μs.

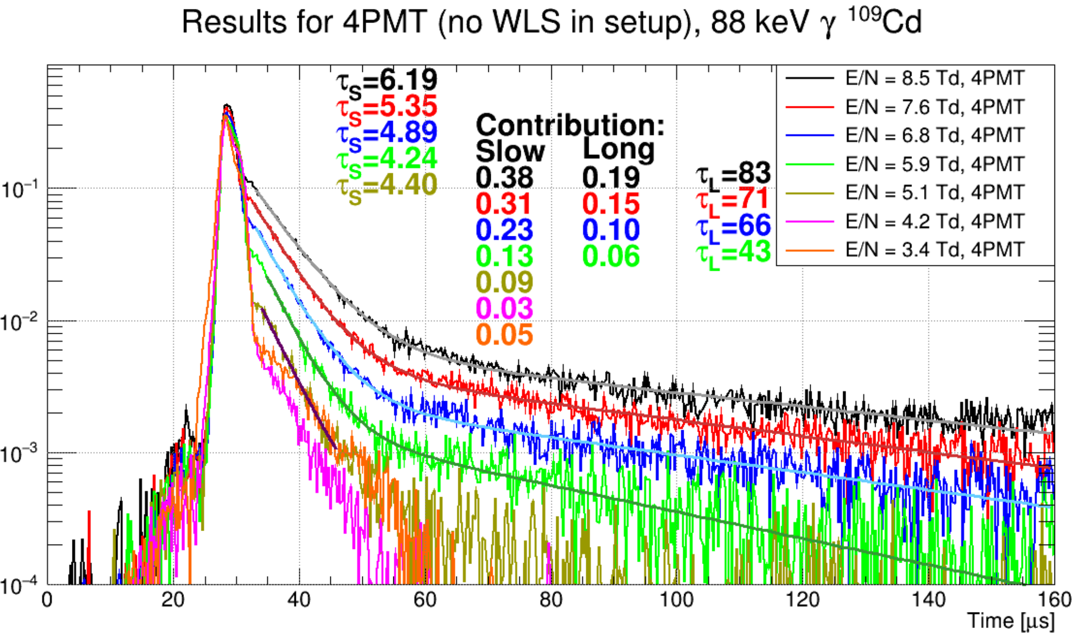
[1]: 3.2±0.3μs [2]: 3 μs [3]: 3.43 μs (at 4.5 Td)

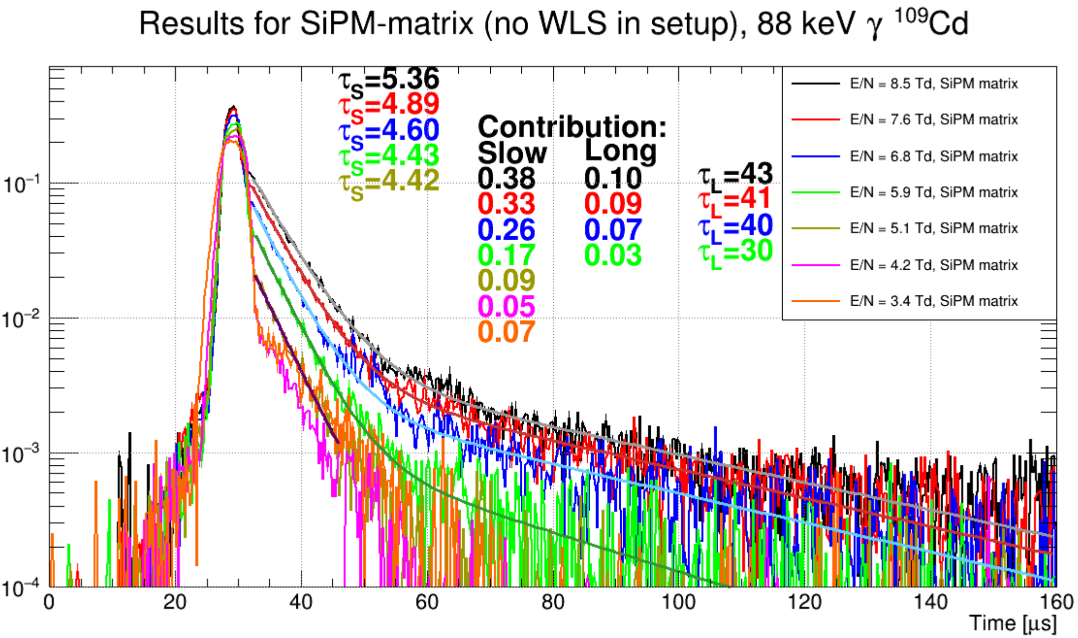
[1] Keto J.W. et al., Phys. Rev. Lett., 33 (1974) 1375

[2] Suzuki M. et al., Nucl. Instr. Meth., 192 (1982) 565

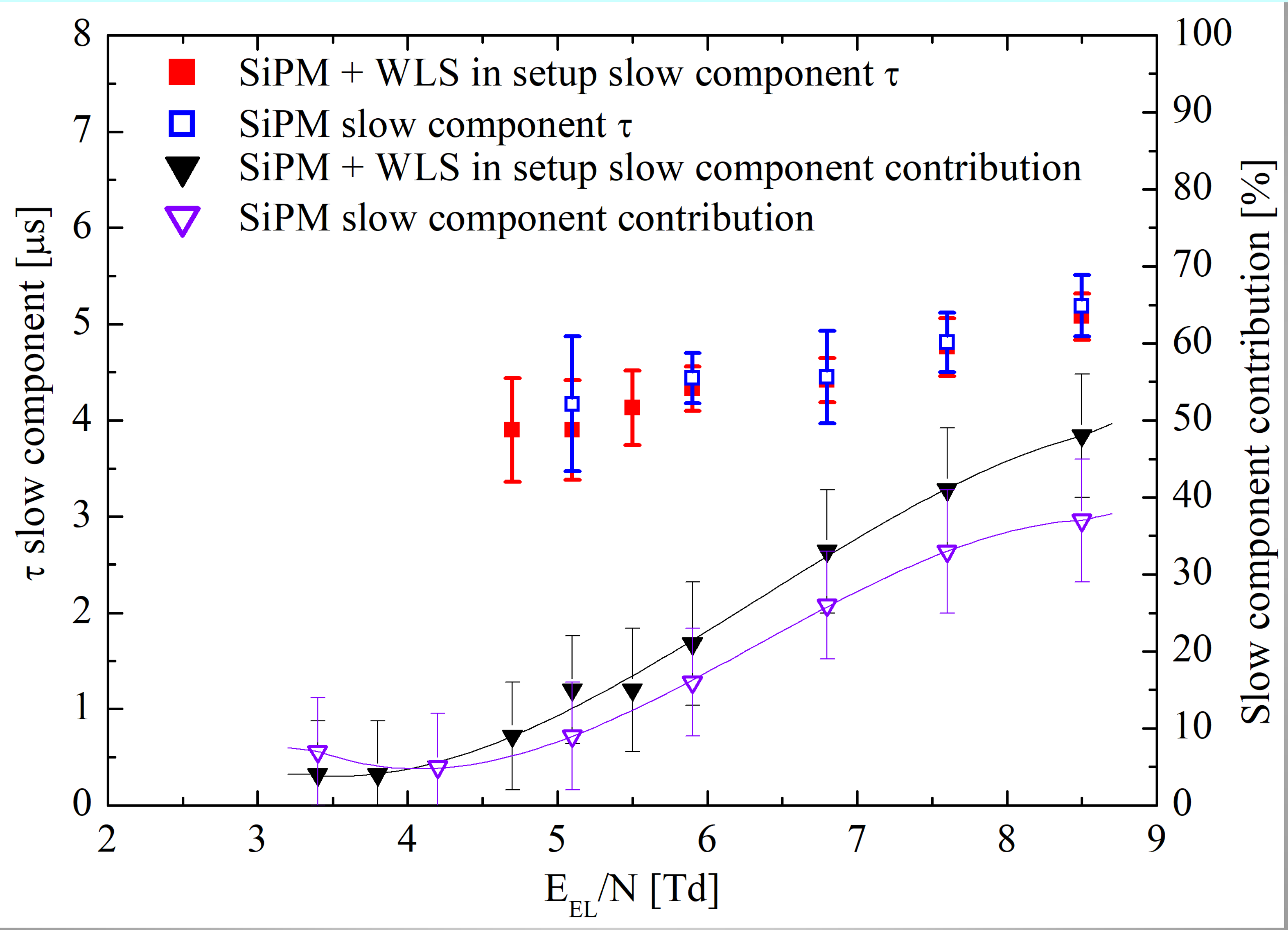
[3] P. Agnes, et al., Nucl. Instr. Meth. A 904 (2018)

Results without WLS: PMT vs SiPM pulse-shapes (time histograms)

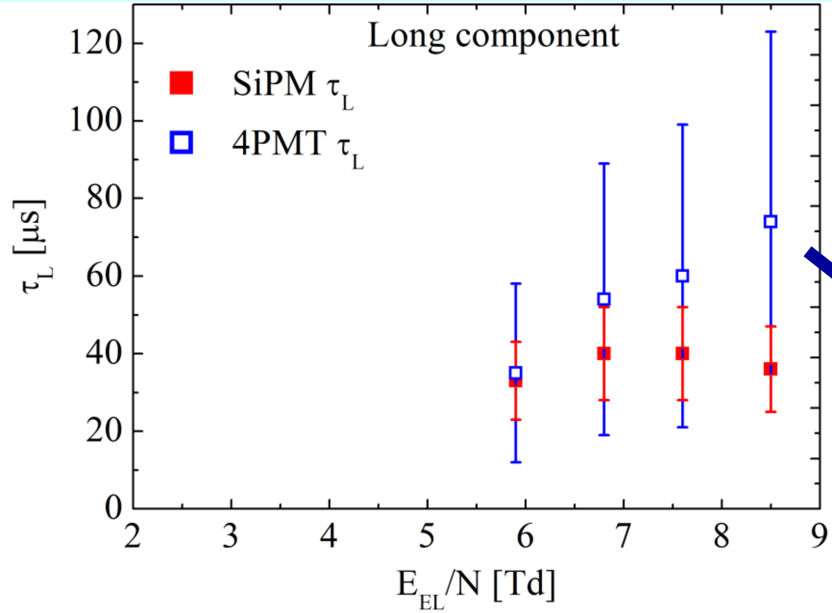


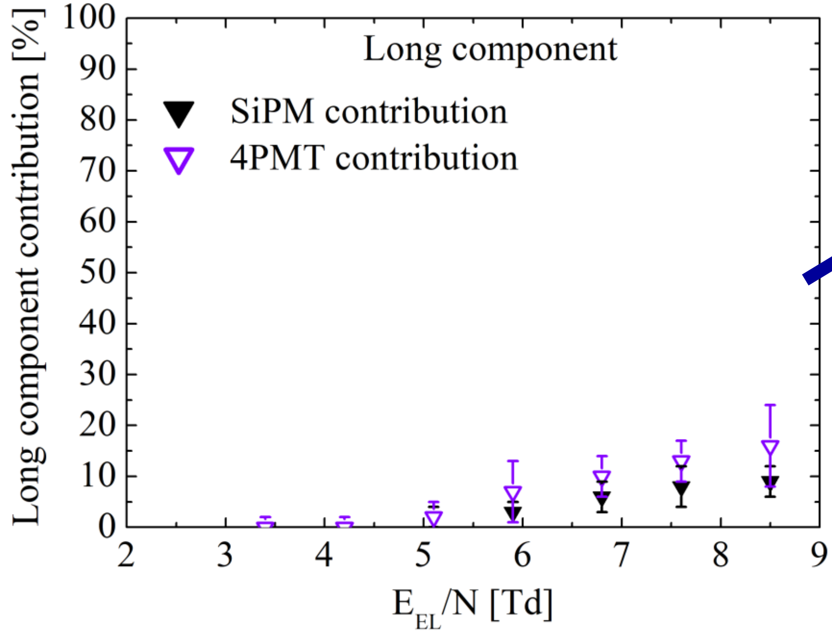


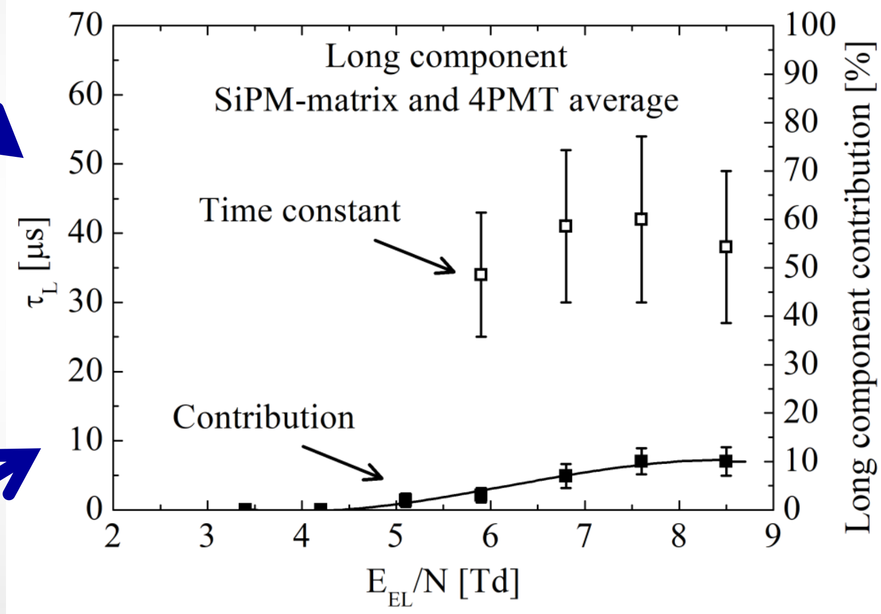
Results for SiPM with and without WLS in setup



Results without WLS: PMT vs SiPM
τ and contribution of long component

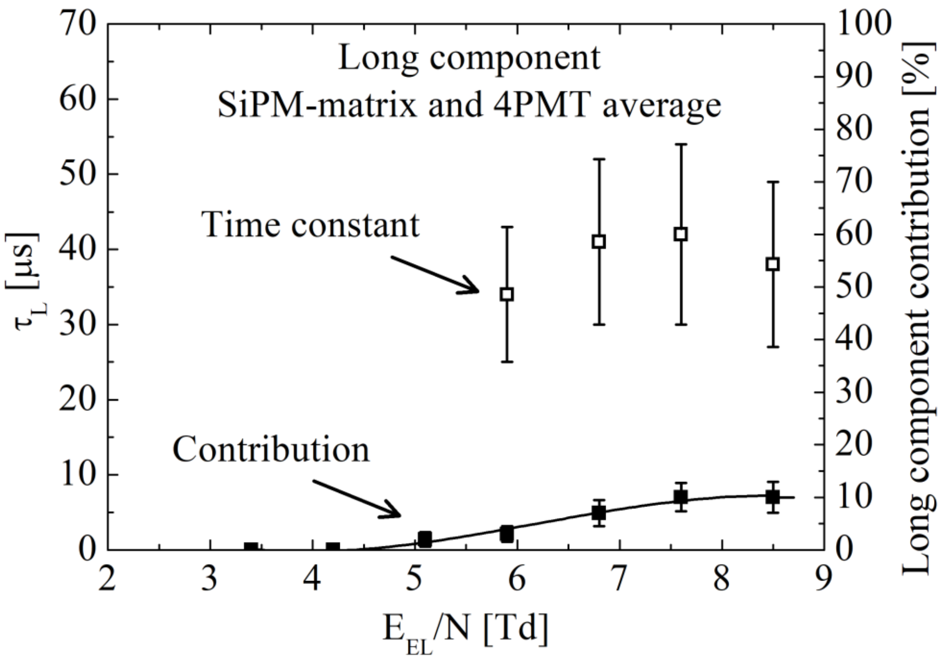




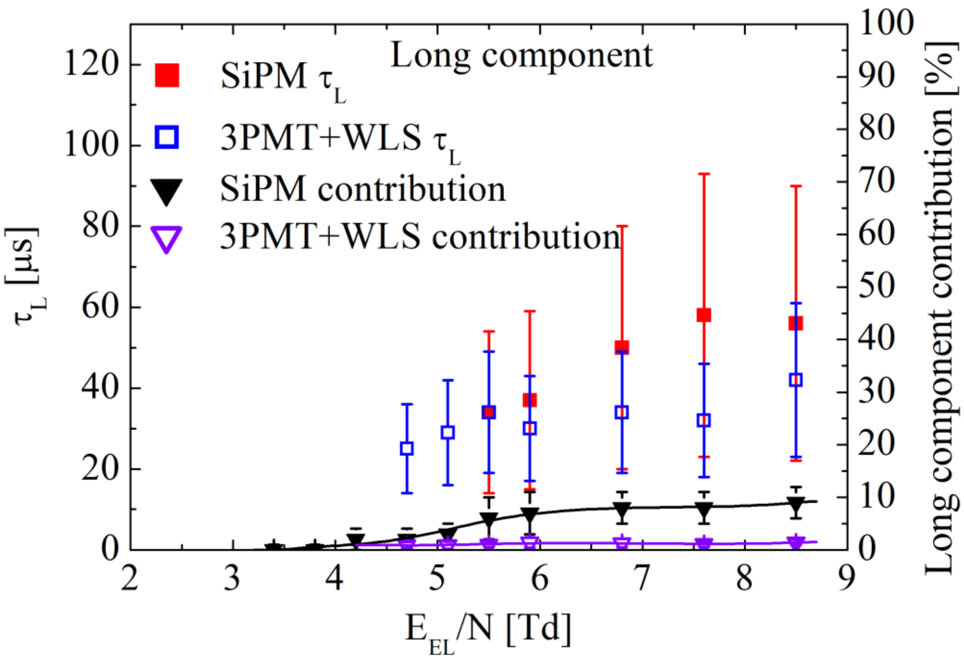


Long component results: Data comparison with and without WLS

Without WLS



With WLS



Results with fast component: EL gap thickness measurements