Measurements of Argon-Scintillation and -Electroluminescence Properties for Low Mass WIMP Dark Matter Search

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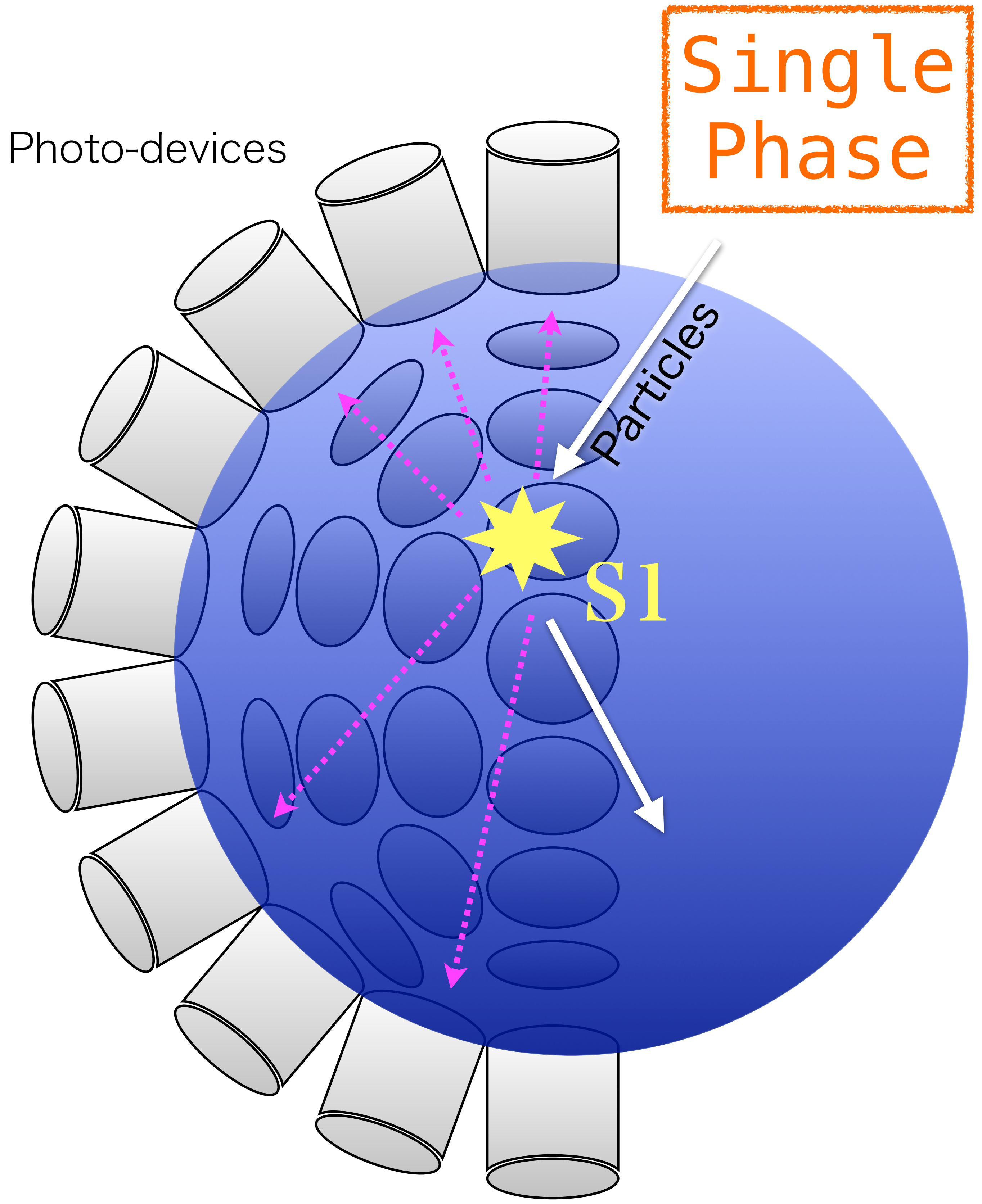
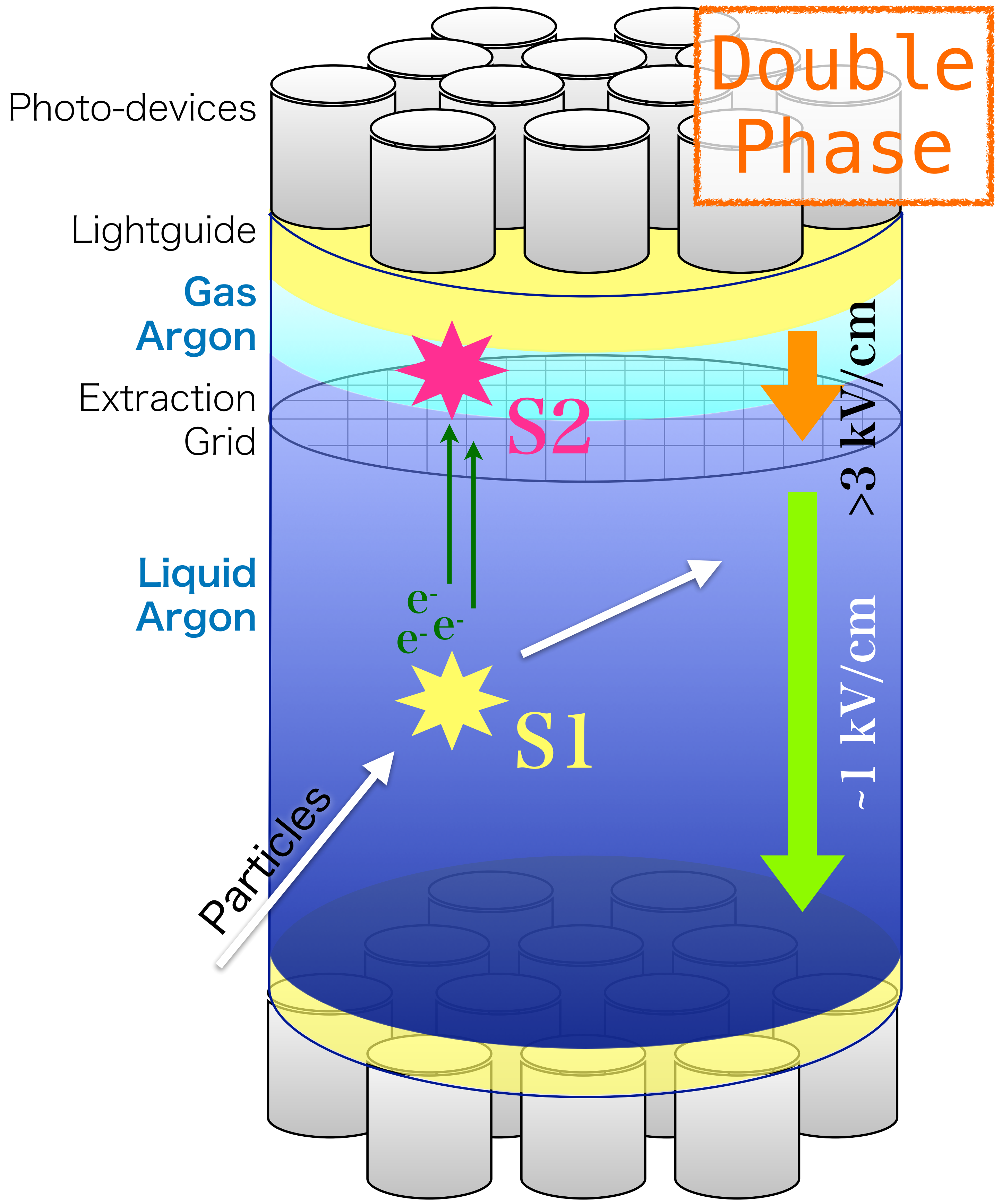
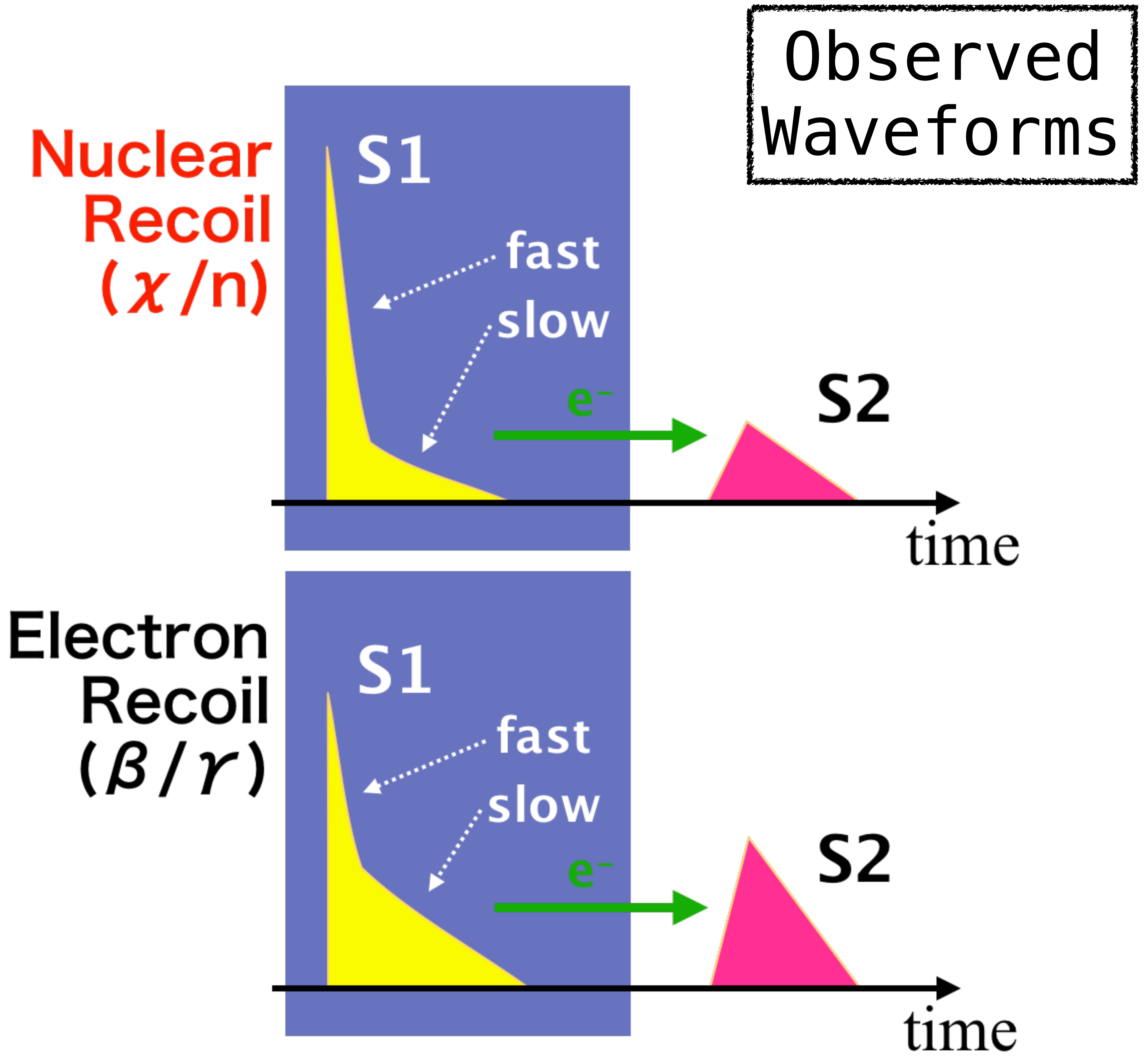
Liq.-Ar Scintillation Detectors

Attractive detector for WIMP search, ν-physics, ...

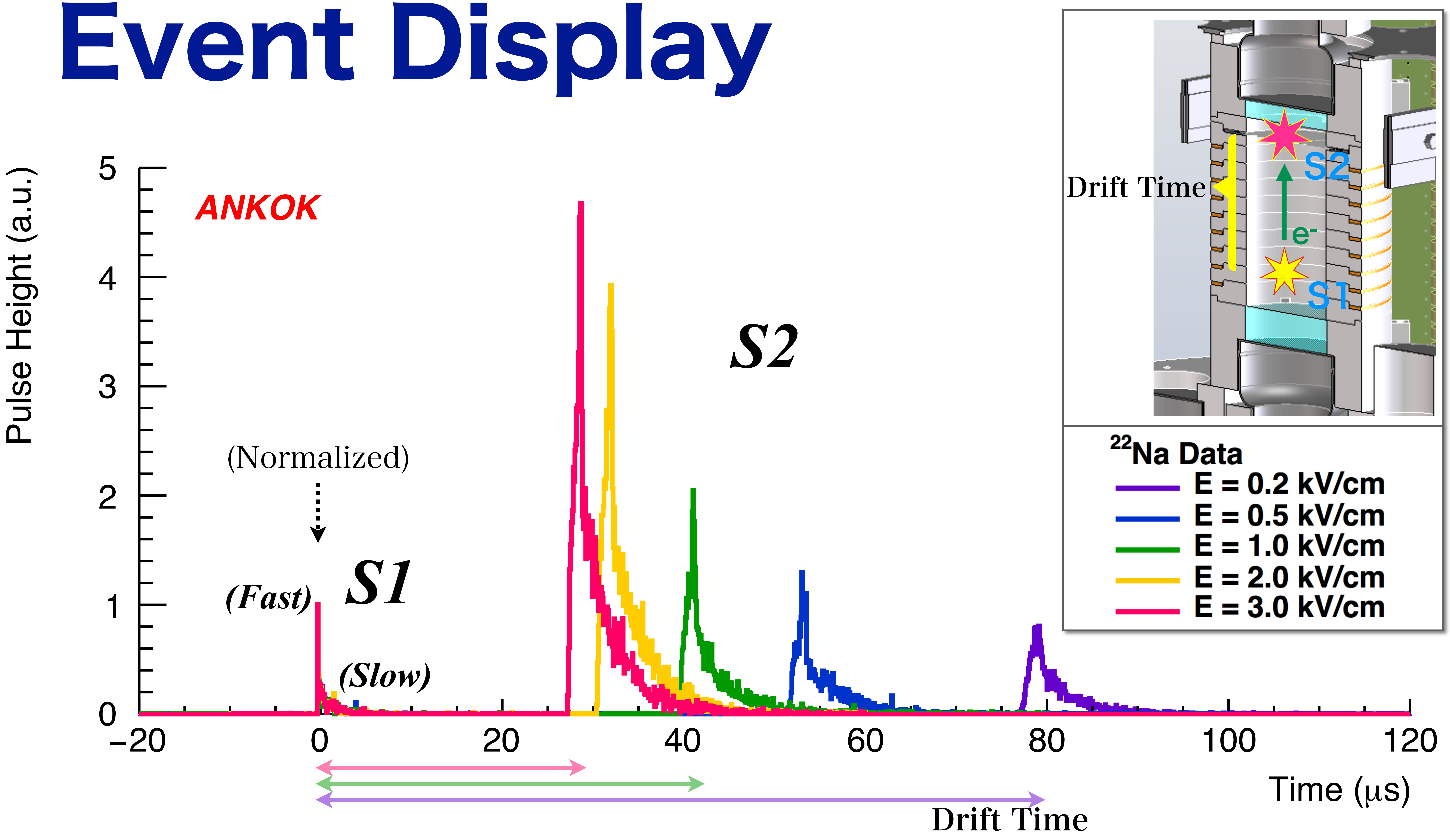
- **Efficient conversion of energy deposition** into scintillation (S1) and ionization (S2) signals.
- Powerful **pulse shape discrimination** (PSD) of nuclear recoils (NR) from electronic recoils (ER).
- **Cost effective detector** due to the availability of argon.





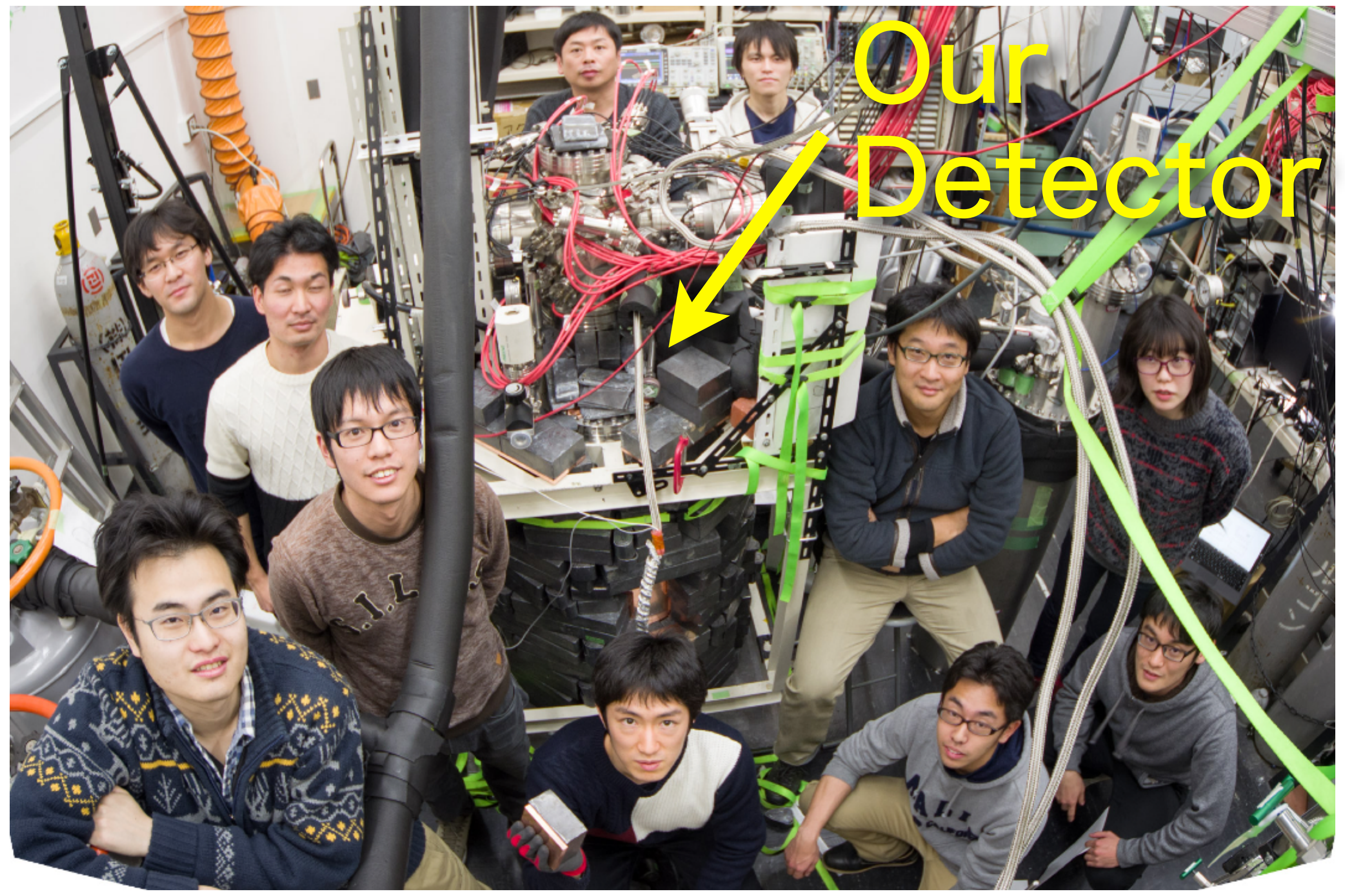


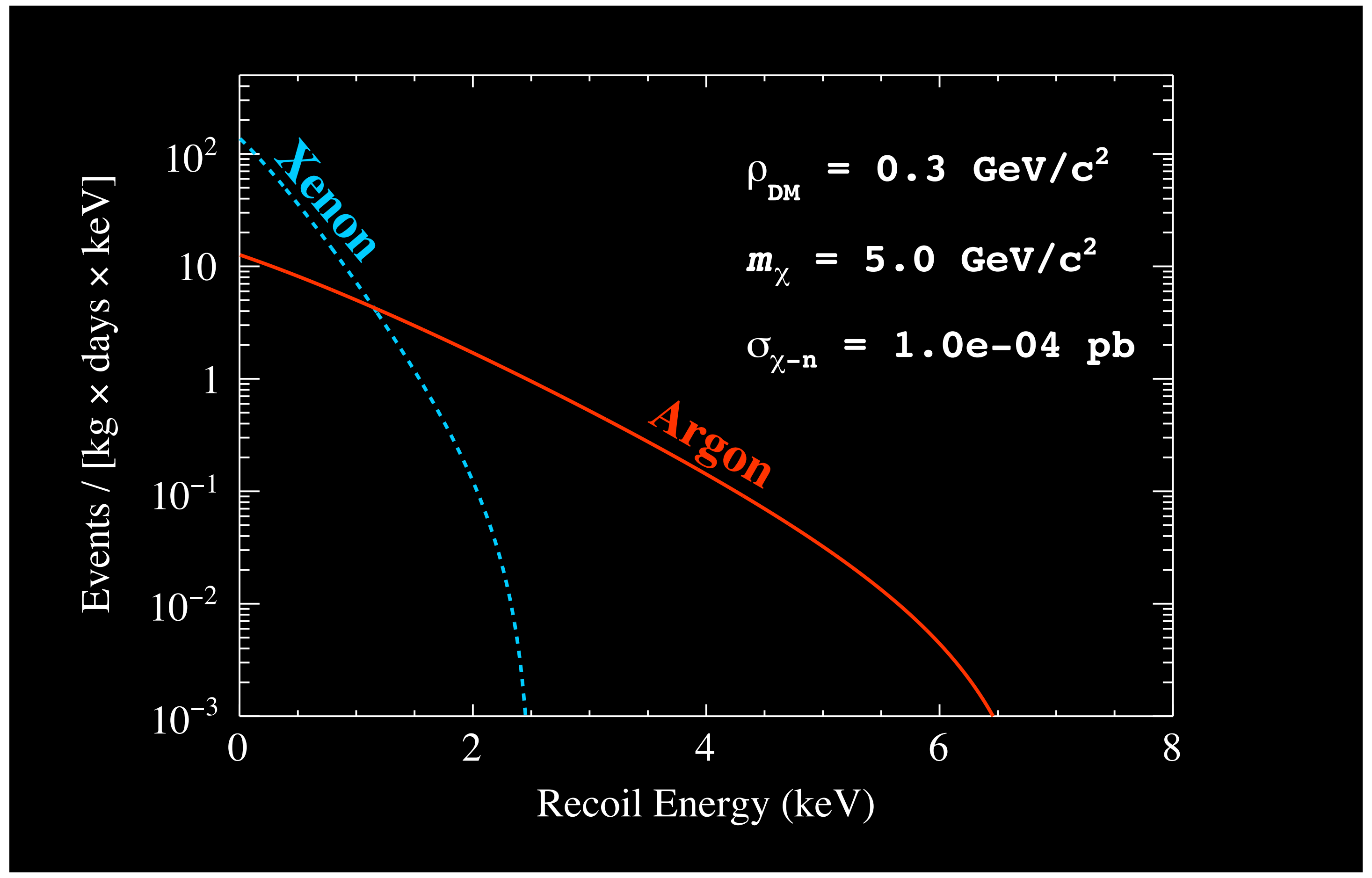
Event Display



Waseda LAr Group

- Launched in 2012, mainly focusing on
  Low-Mass WIMP Dark Matter Search
  - Relatively high recoil energy for WIMP-Ar scattering
  - Potential to "Zero-Background" search thanks to PSD
  - Potential to detect <GeV mass WIMP signal thanks to large signal yield





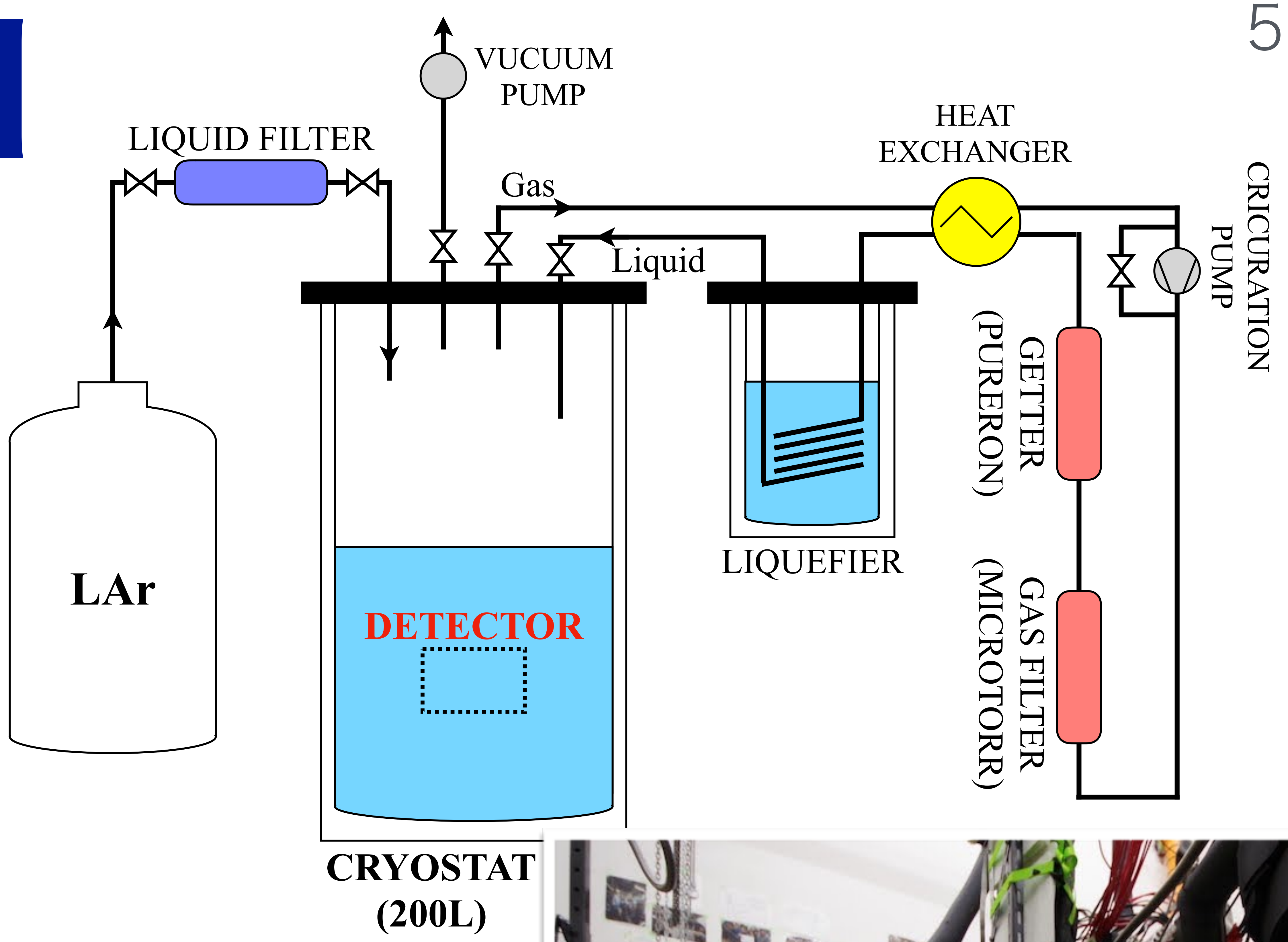
Current R&D topics

1. LAr response on NR under high electric field with a systematical response modeling (c.f. Liq.-Xe) ☞ PRD 100 (2019) 032002
2. LAr response on ER with optimized high light yield detector(s) ☞ will be submitted in this March.
3. Study on S2 luminescence mechanism and "Neutral Bremsstrahlung (NBrS)" using a dedicated Room-Temp. GAr TPC ☞ JINST Proc. (LIDINE2019) + Updates

LAr Teststand

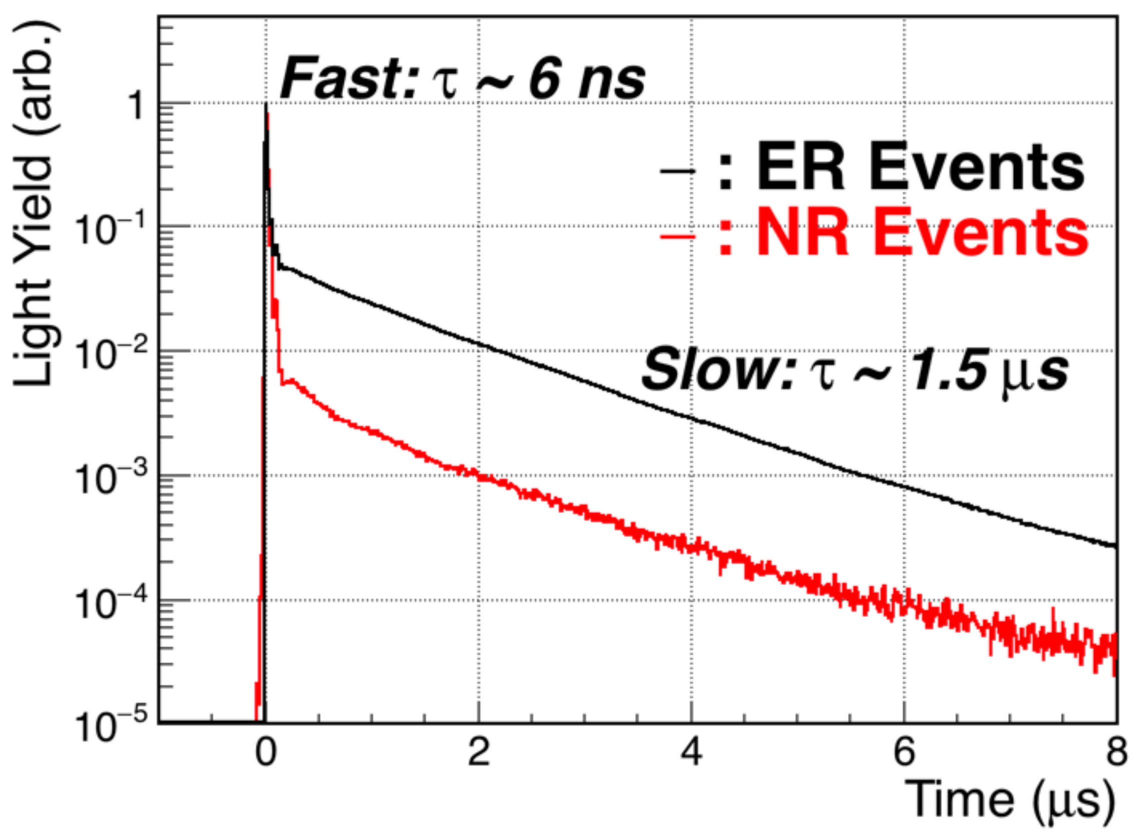
: Surface laboratory at Tokyo

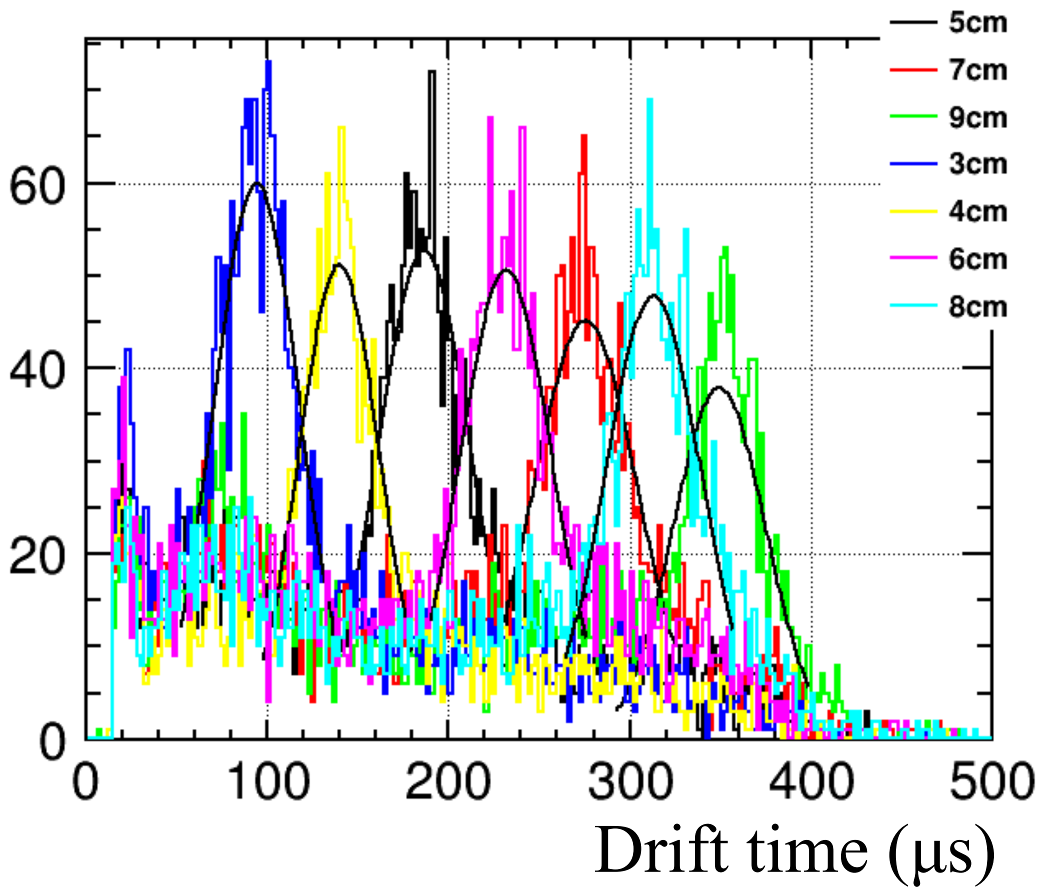
: 200L cryostat and liquefier, with filling and recirculation lines

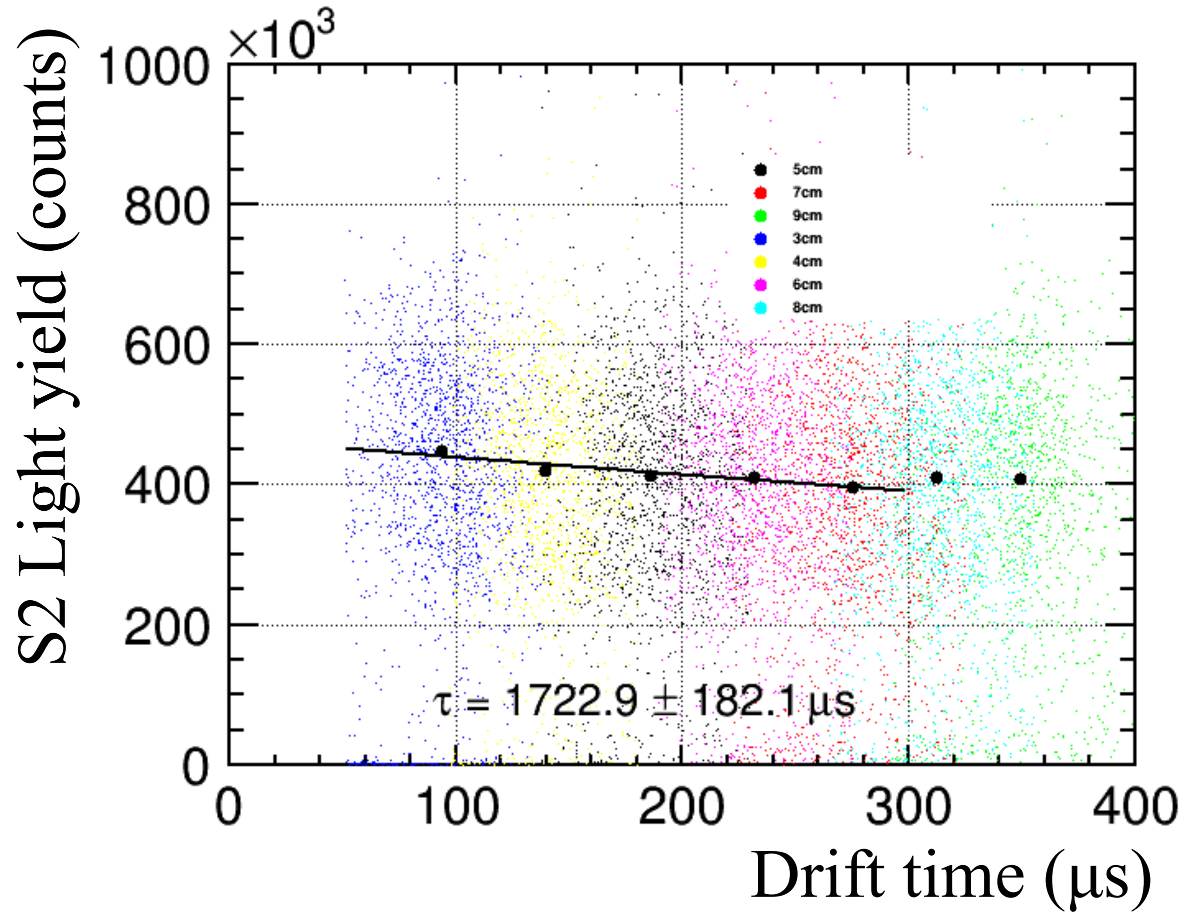


We have achieved...

- ~1 month of **stable operation**,
- 0.5 mm **liquid surface control**,
- **Contamination removal** from LAr. (Electron lifetime τ ~ 1.5 ms).

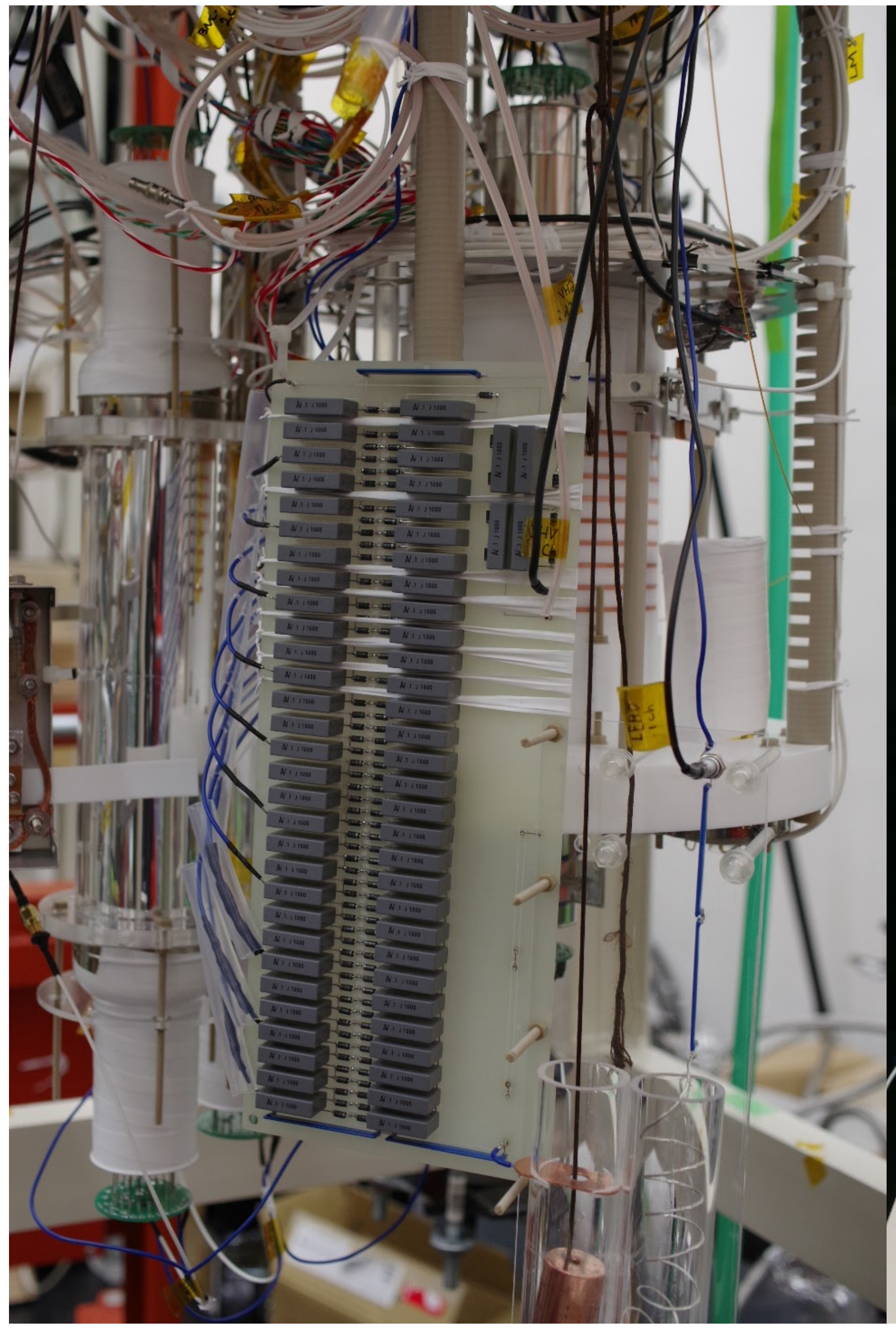






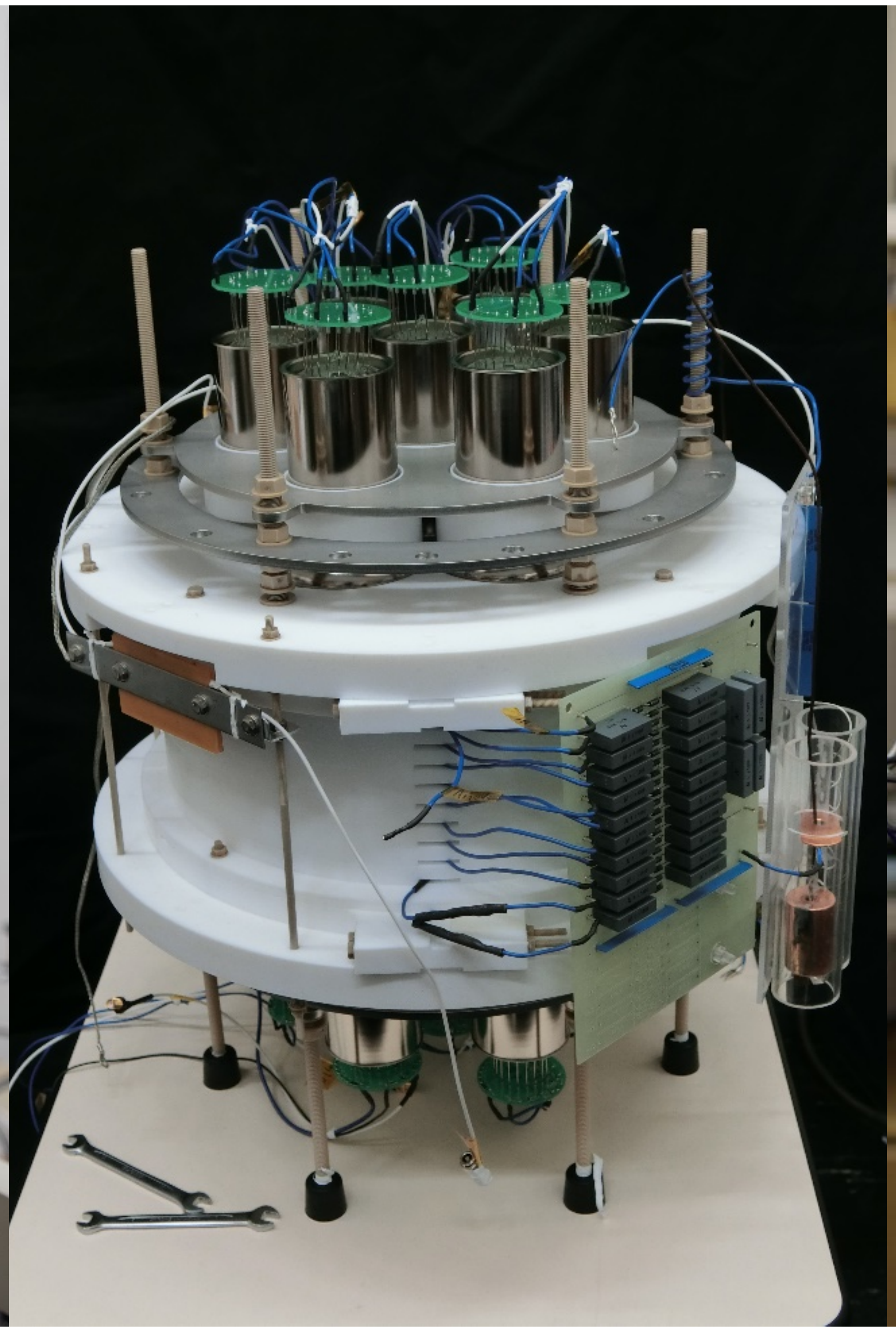
R&D Detectors

(2017)



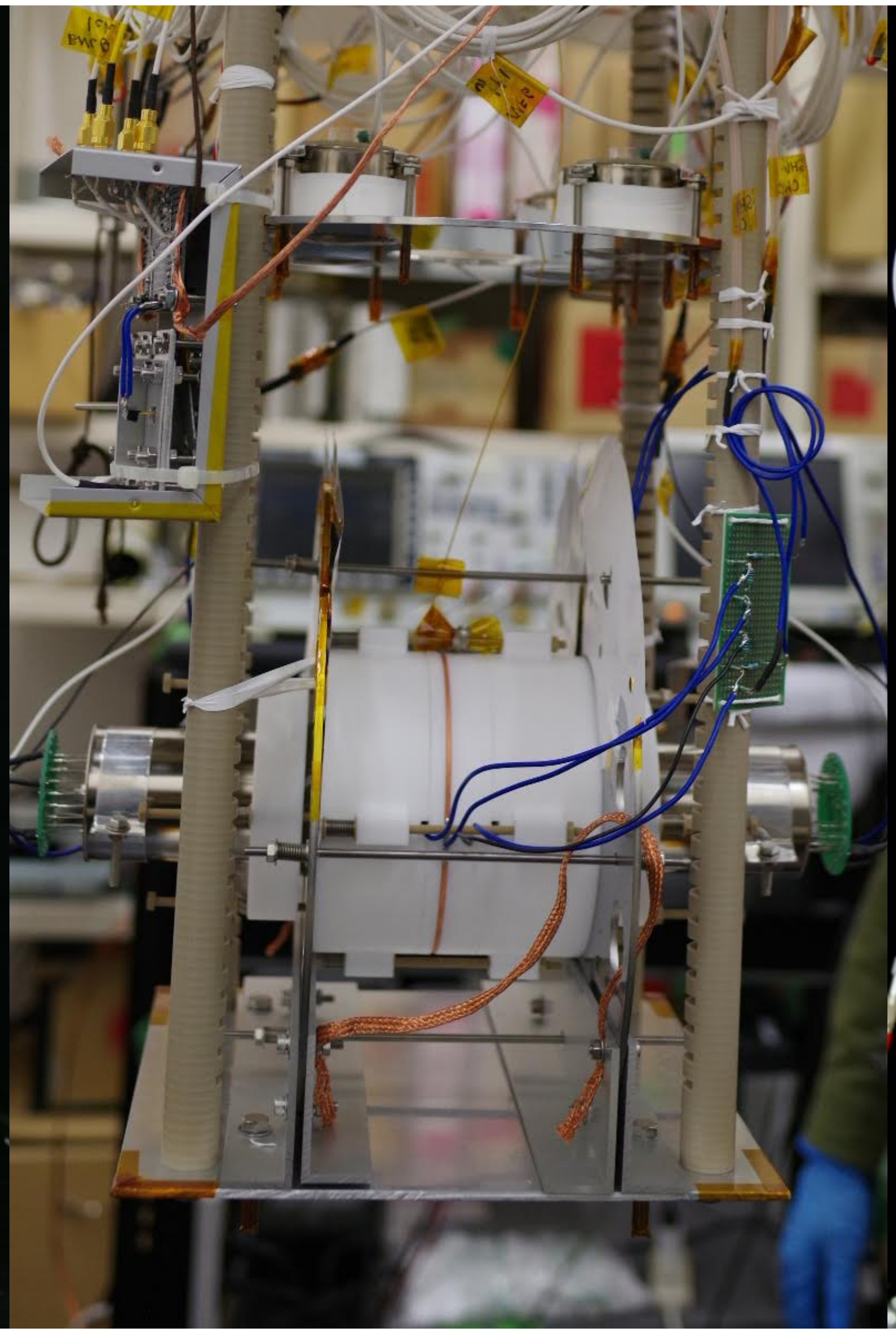
PMT x2,
Double-Phase,
High-Field

(2017-2018)



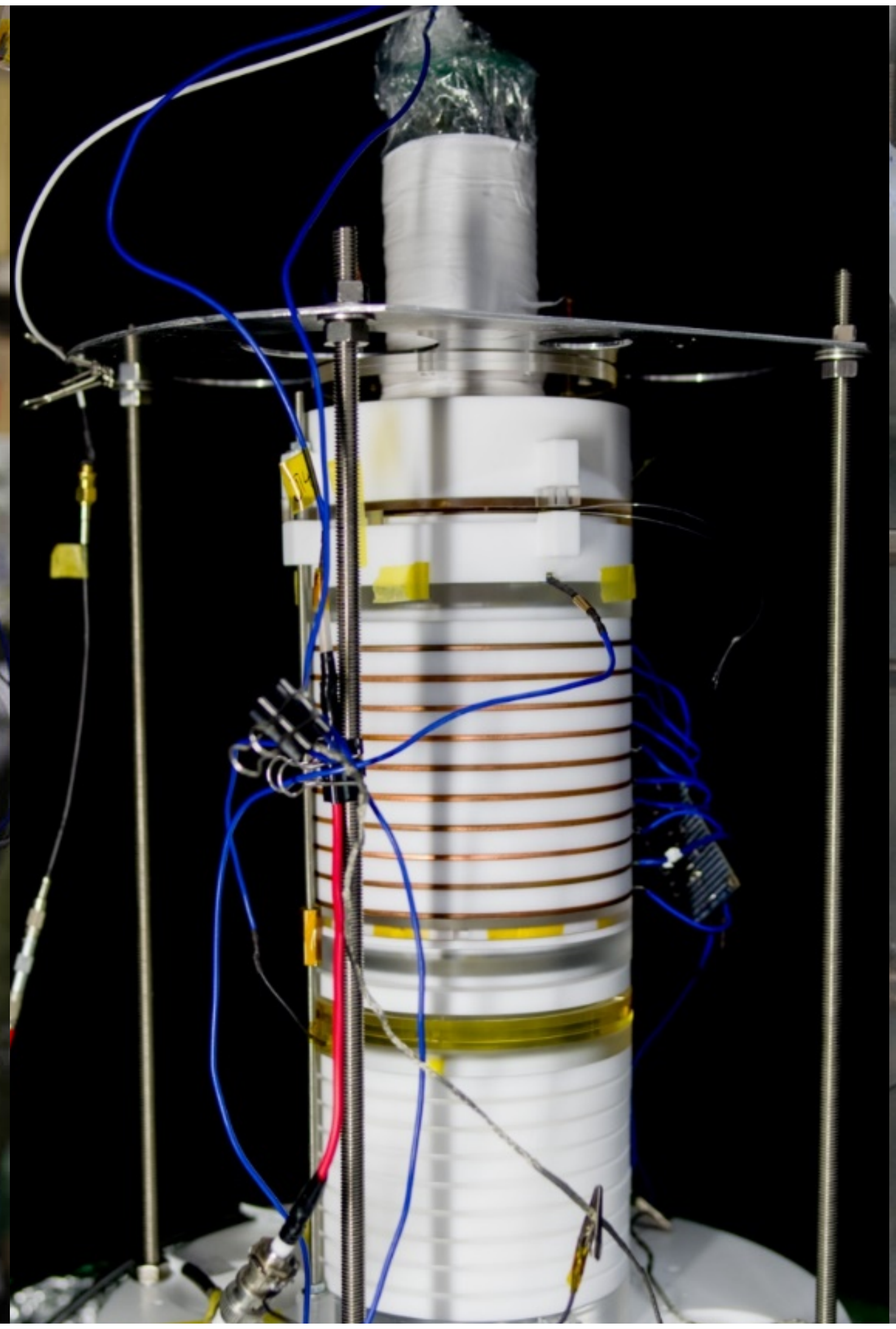
PMT x14,
Double-Phase,
Scale-up

(2018-2019)



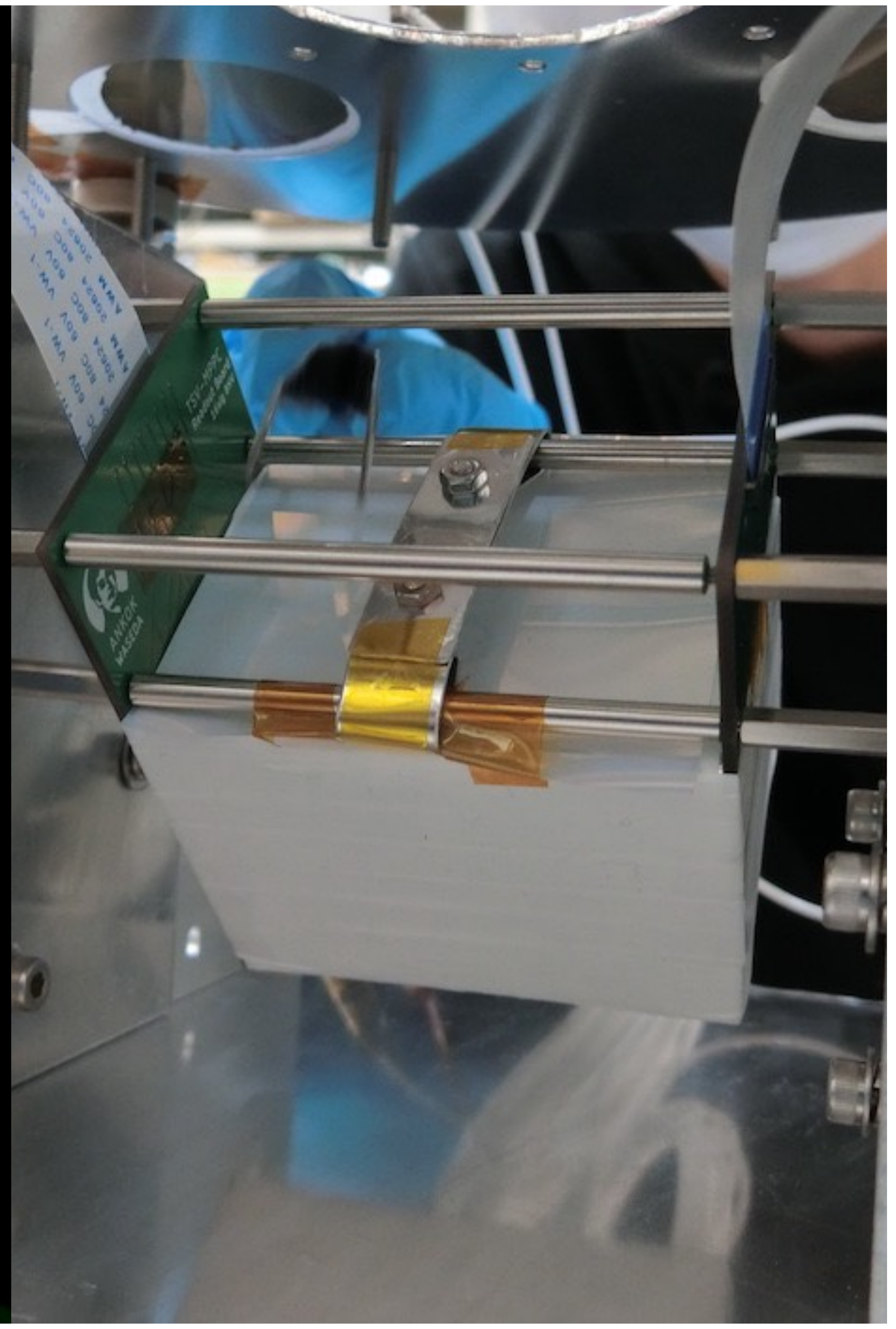
PMT x2,
Single-Phase,
High Light-Yield

(2019-2020)



PMT or
Spectrometer,
Gas-TPC,
S2 Study

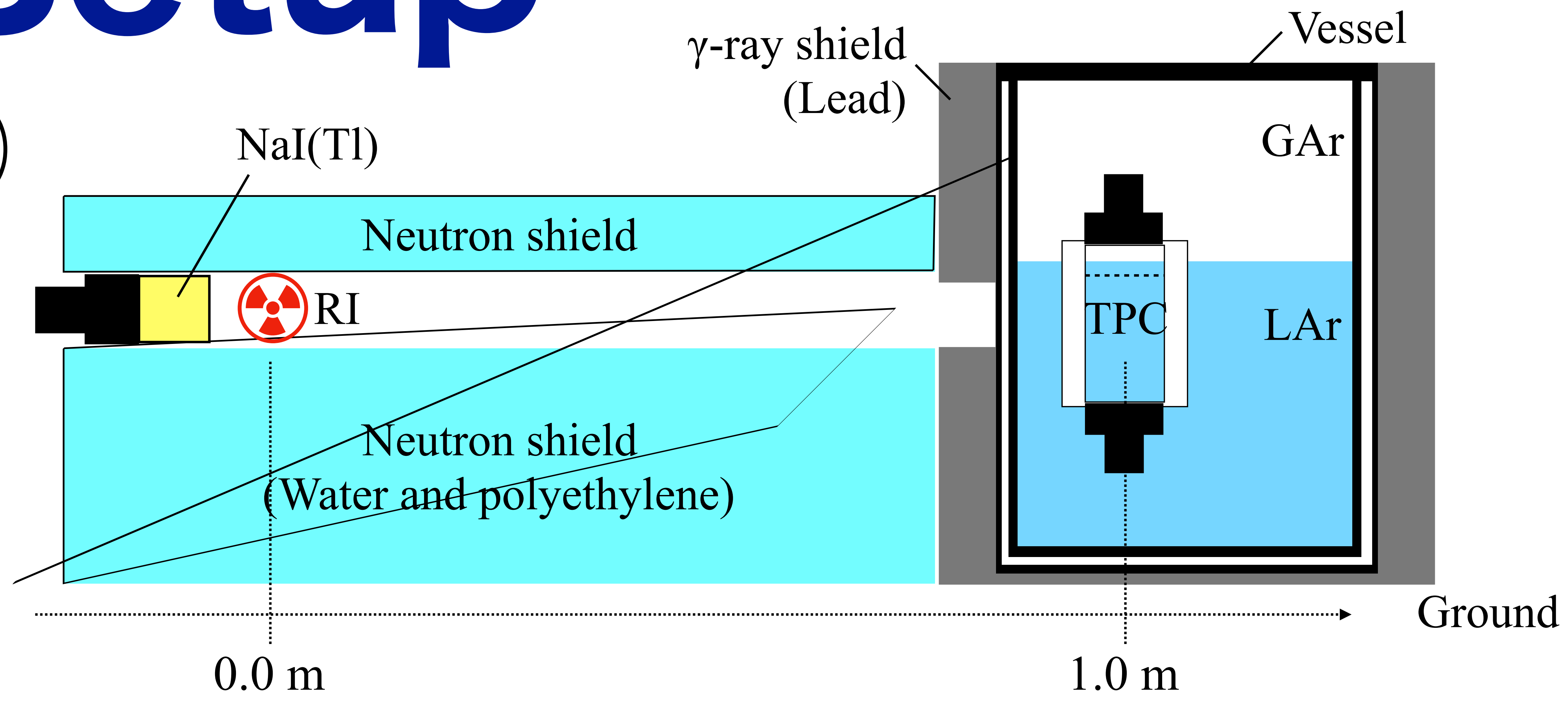
(2019-2020)

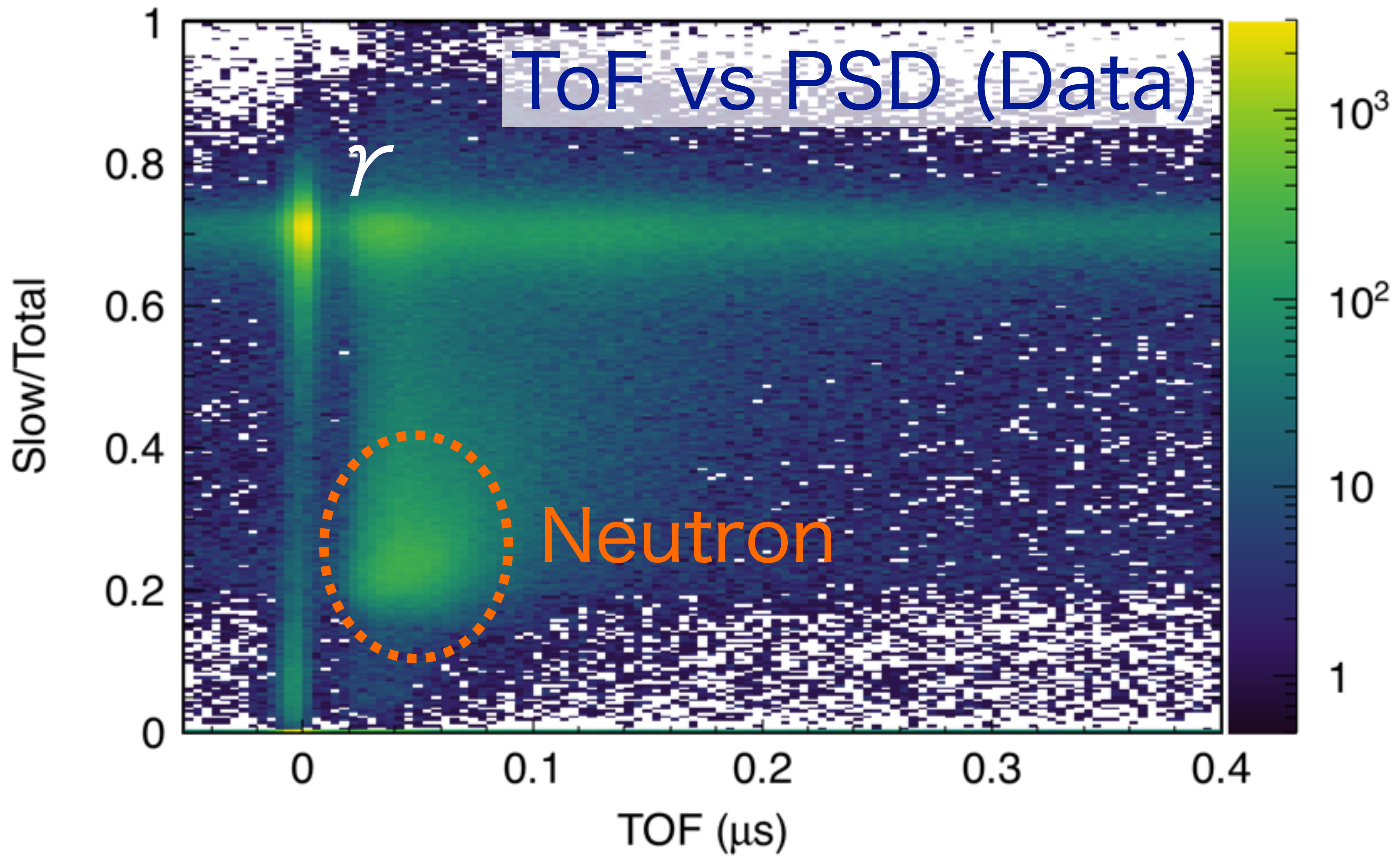


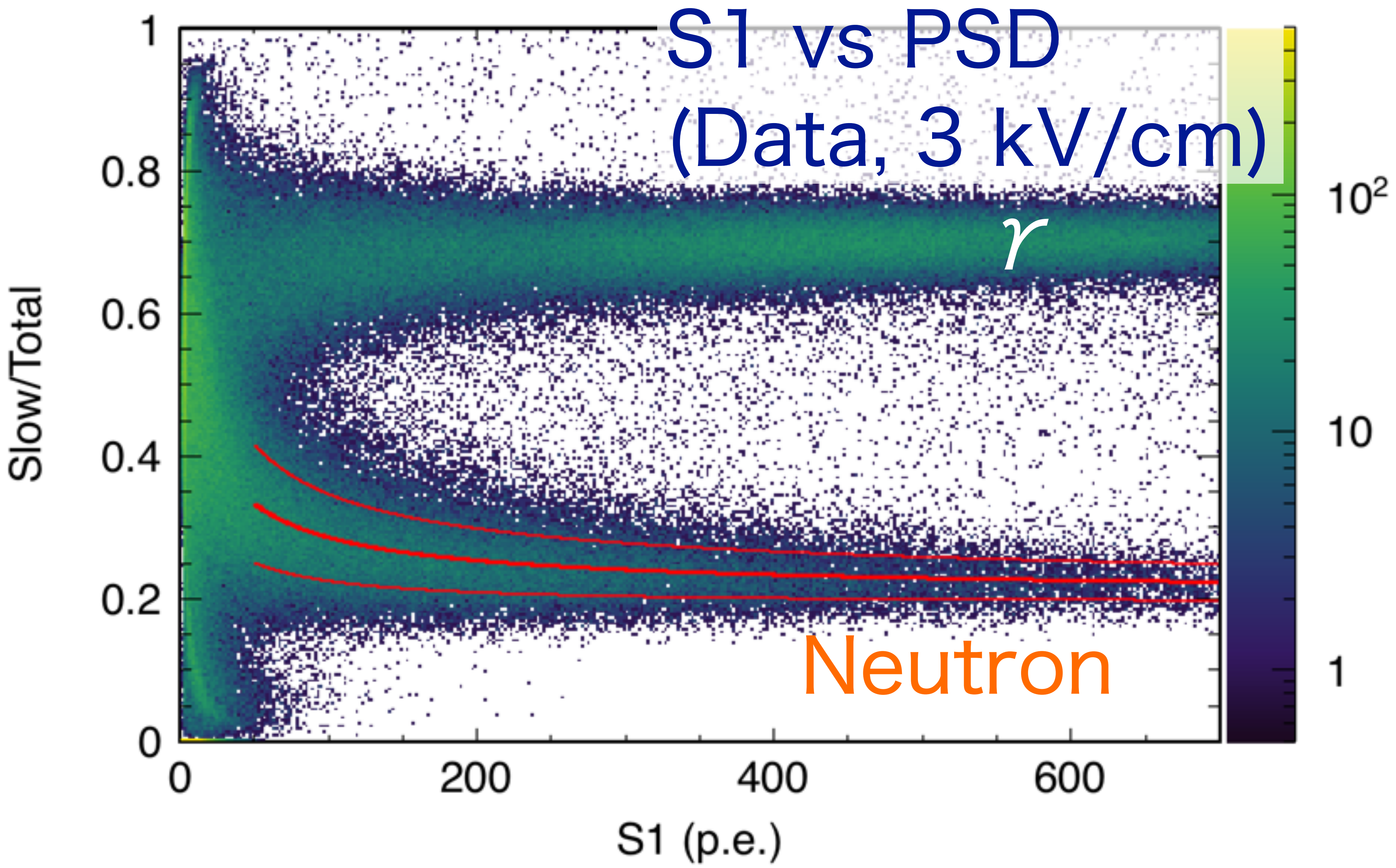
SiPM x128,
Single-Phase,
Improve Light-Yield

Experimental Setup

- Small size LAr-TPC (ϕ6.4 cm × h10 cm) with two 3-inch PMTs (R11065)
  - Drift field = **0.0 - 3.0 kV/cm**
- ^{252}Cf source + Time of Flight (TOF)
  - Reconstruct incident neutron energy, and then predict energy spectrum using Geant4 MC and response model.

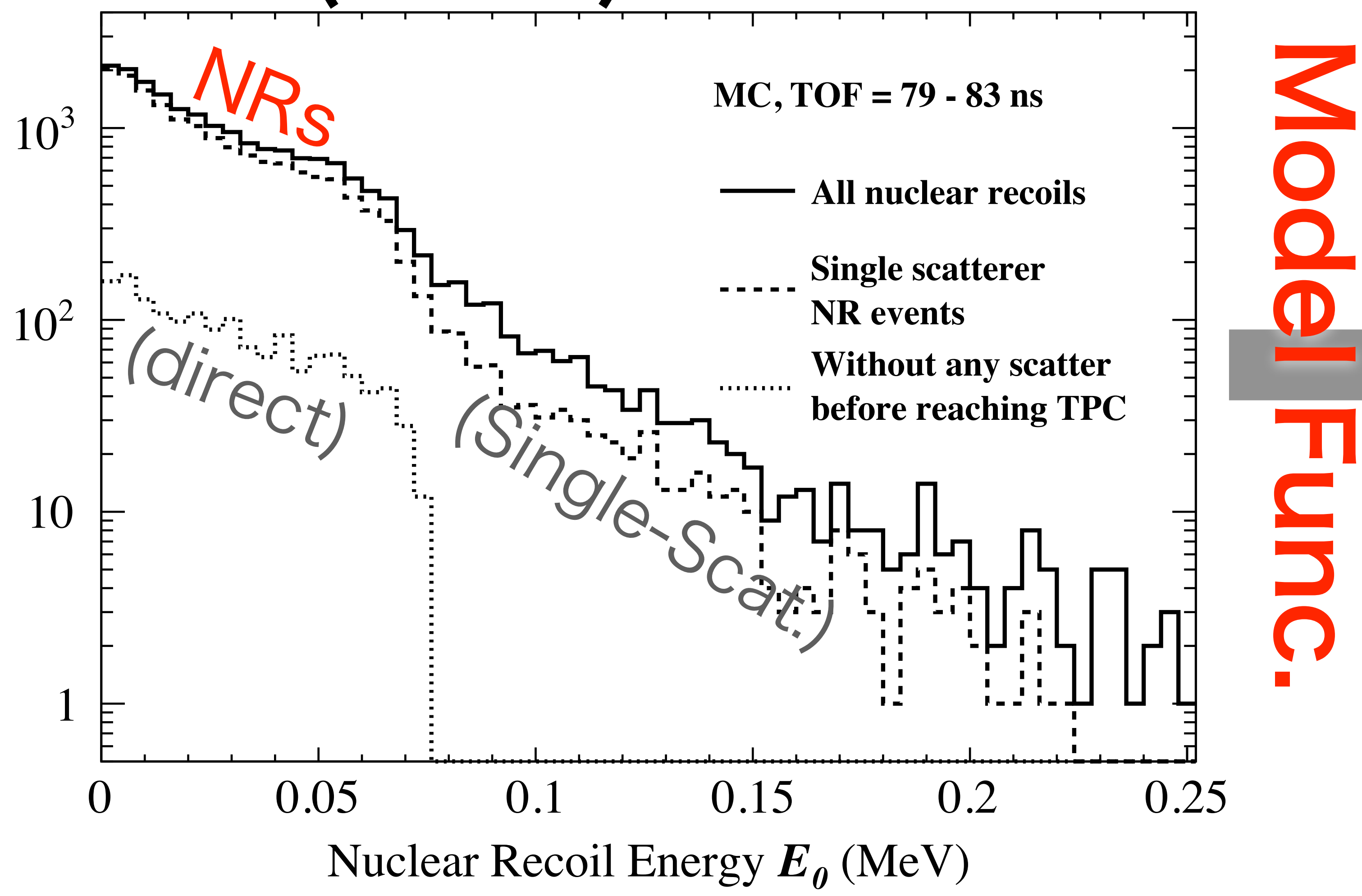


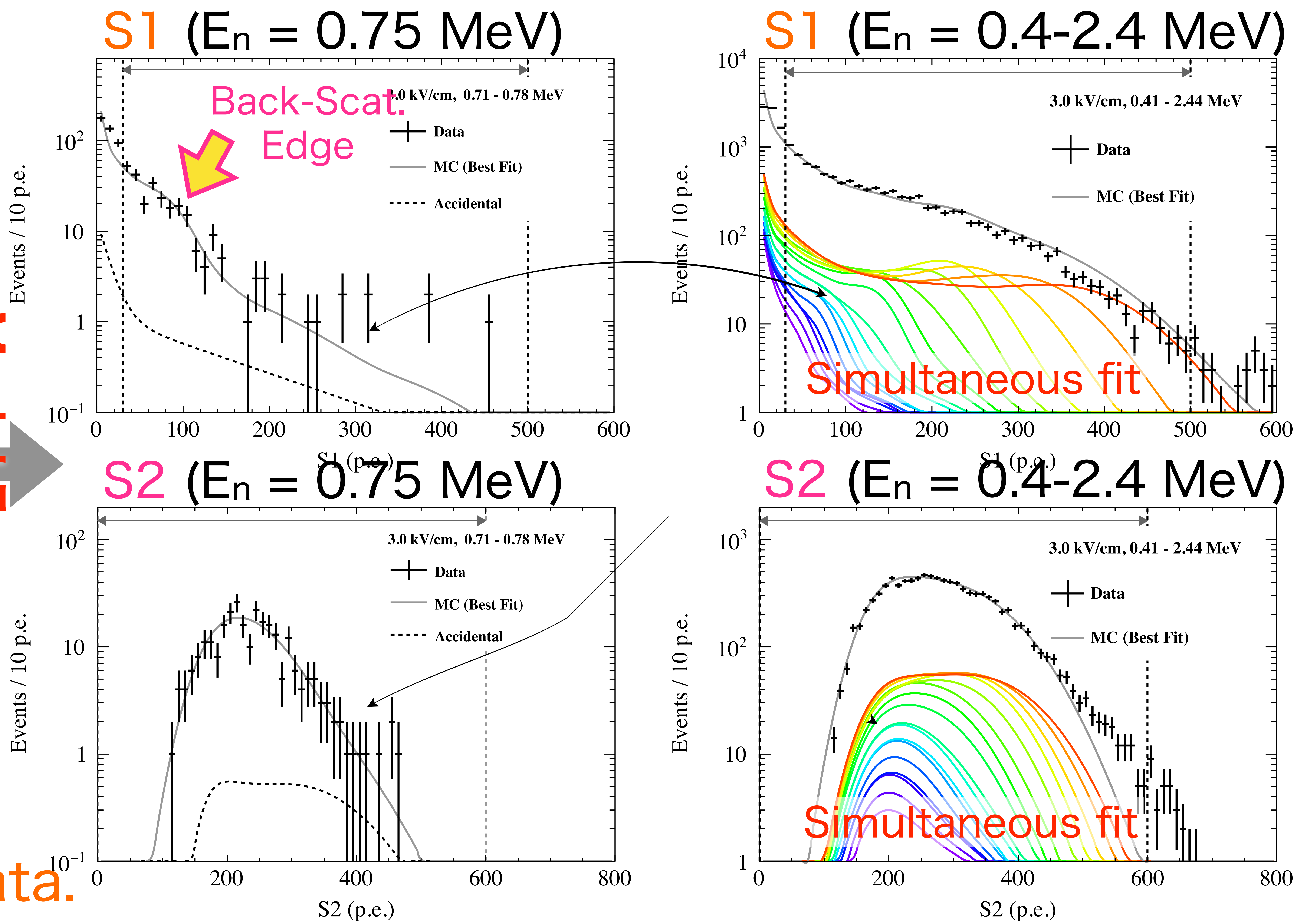




Fitting Analysis

MC (truth)





Simultaneous fit of data.

- Both S1 and S2 spectra of each TOF bin under all field points.
- Energy- and Field-sensitive due to the backscatter edges.

(Detailed in PRD 100 032002)

Result

The **model** and **a set of best fit parameters** describe **all spectra** well.

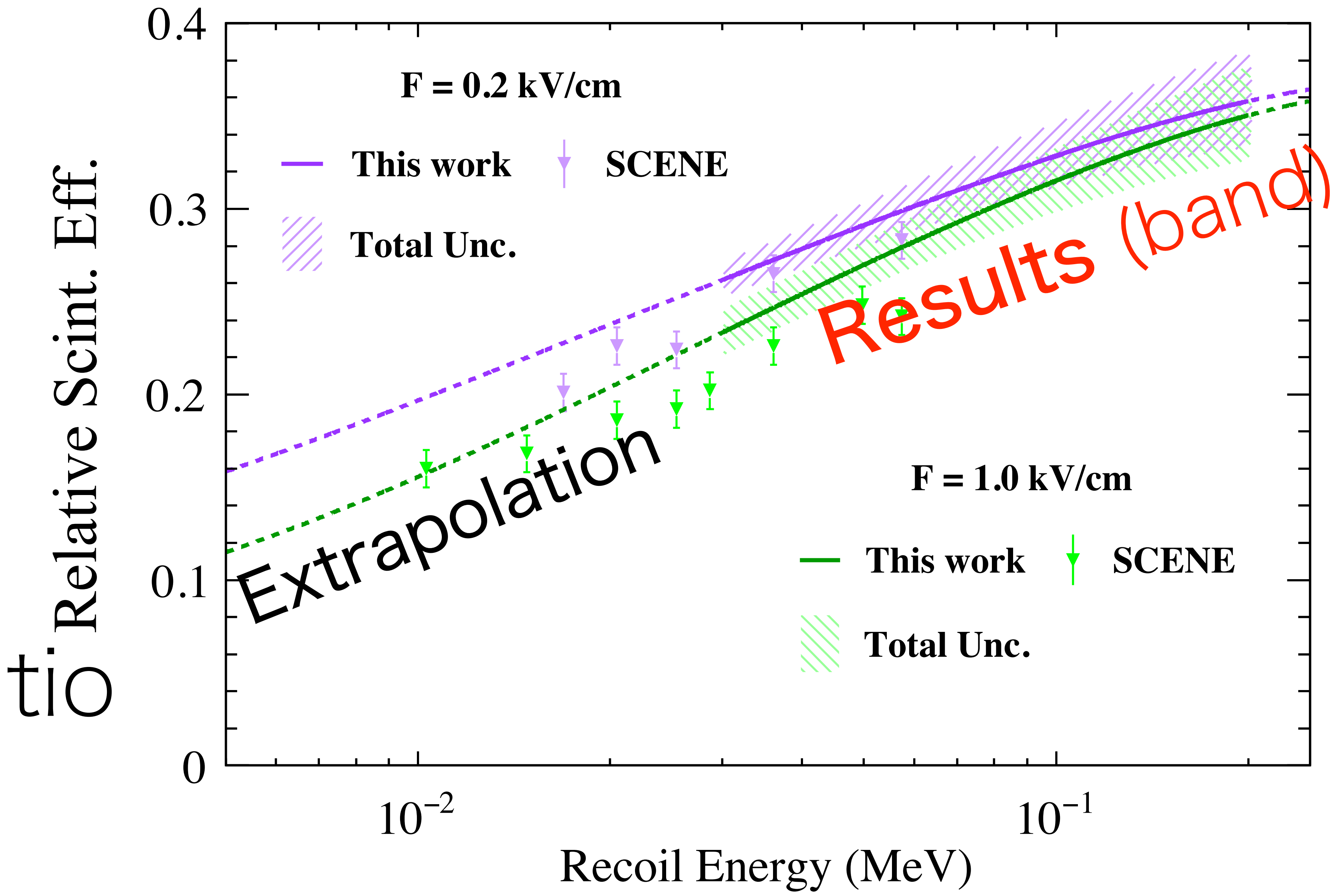
- Total 5 parameters of "Birks' law", "TIB model", and "Excitation-to-ionization" ratio

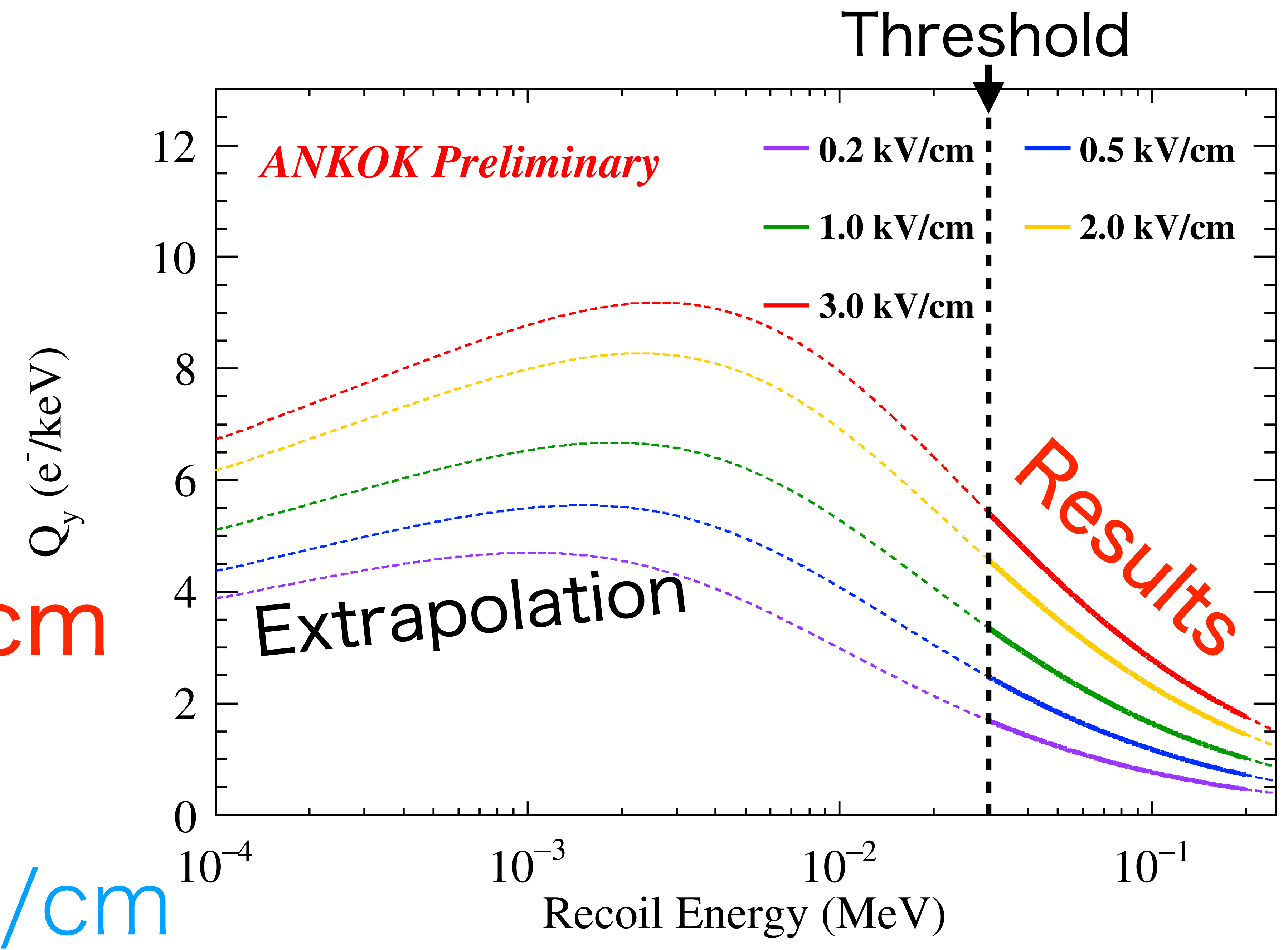
Parameter	Value
k_B [g/(MeV・cm^2)]	3.12×10^{-4}
α_0	1.0 (fixed)
D_α [(V/cm)$^{-1}$]	8.9×10^{-4}

Parameter	Value
γ [(V/cm)$^\delta$]	1.15
δ	5.76×10^{-1}

✦ Systematic functional modeling of LAr response on NRs under fields of 0-3 kV/cm

- Prediction ability for both S1 and S2 yields.
  e.g., x2 of Q_y for 1 keV NR @ 0.2 → 3.0 kV/cm

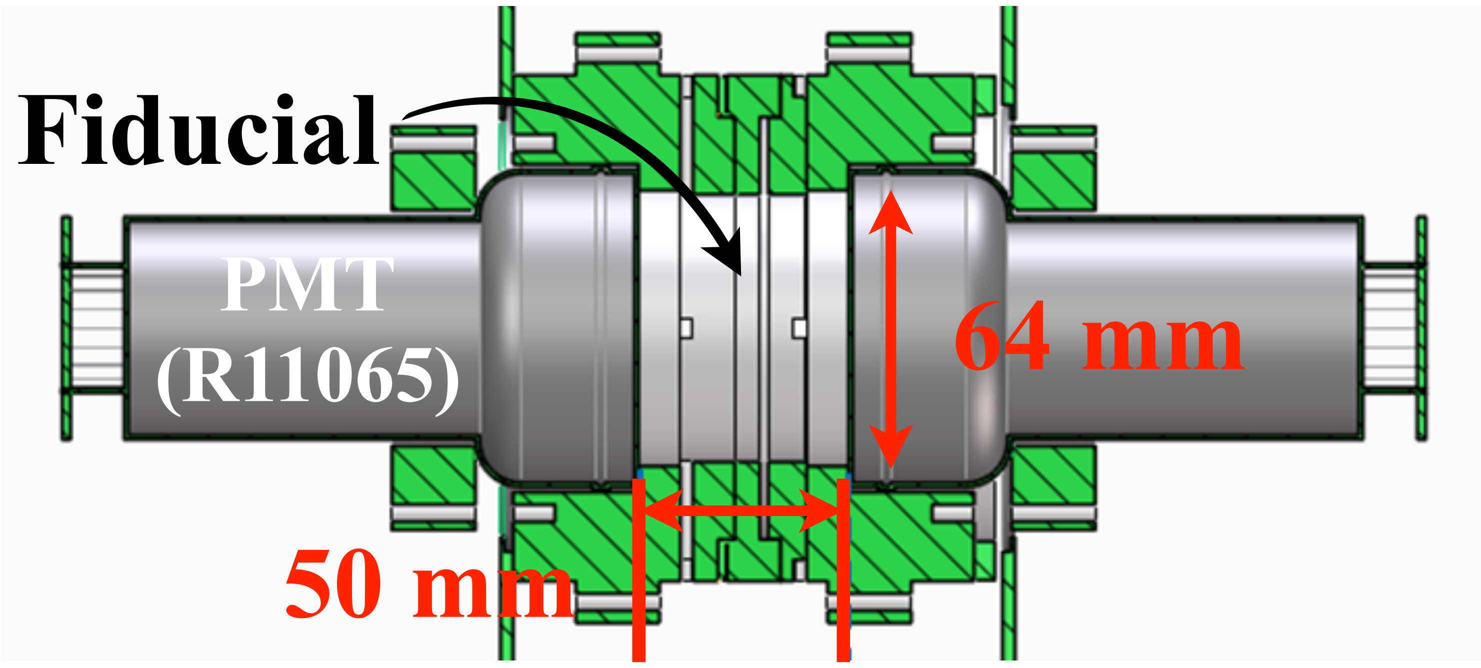




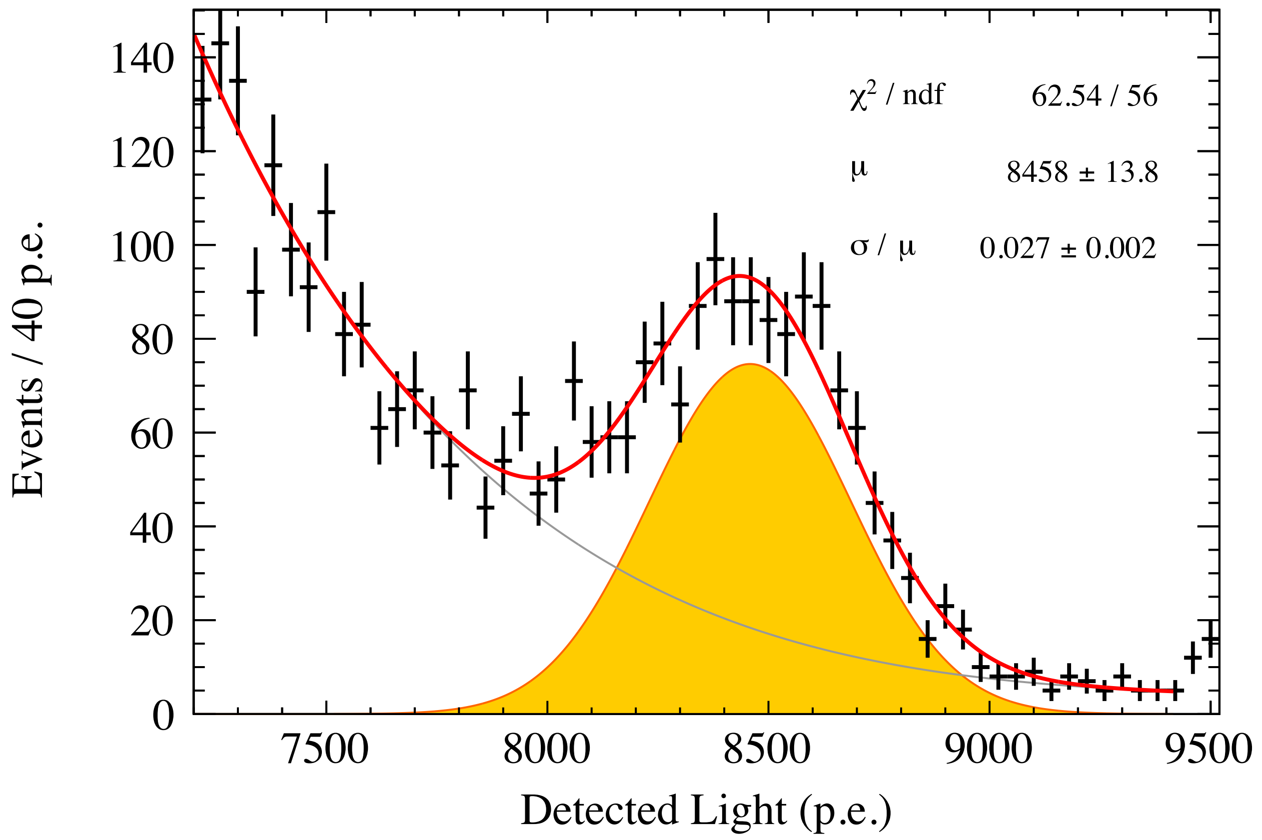
LAr-Scint. Detection : 128 nm @ 87 K

- High light yield ... Resulting to better BG discrimination & lower energy threshold
- Key Techniques ... Wavelength shifter (VUV to Vis.) & cryogenic photosensor

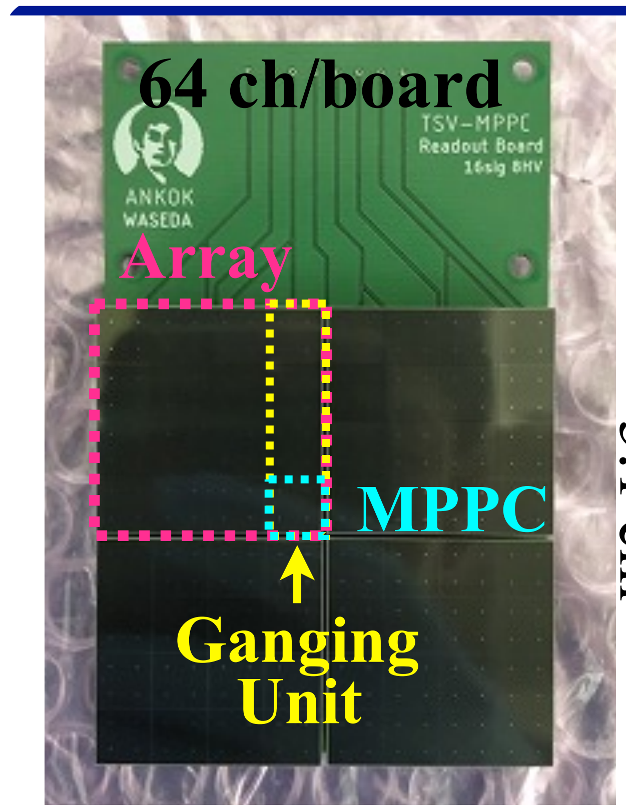
PMT Detector

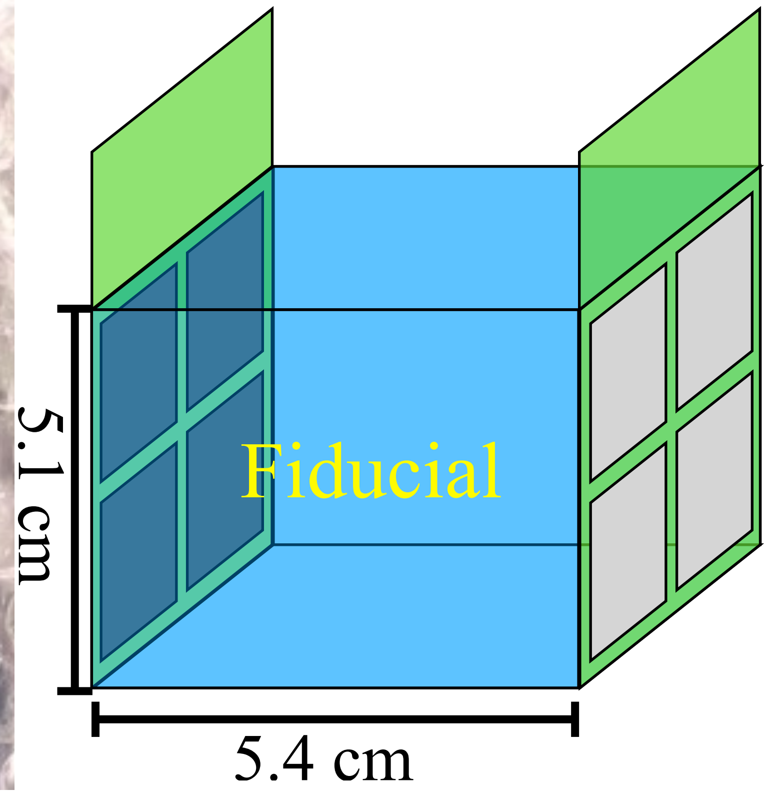


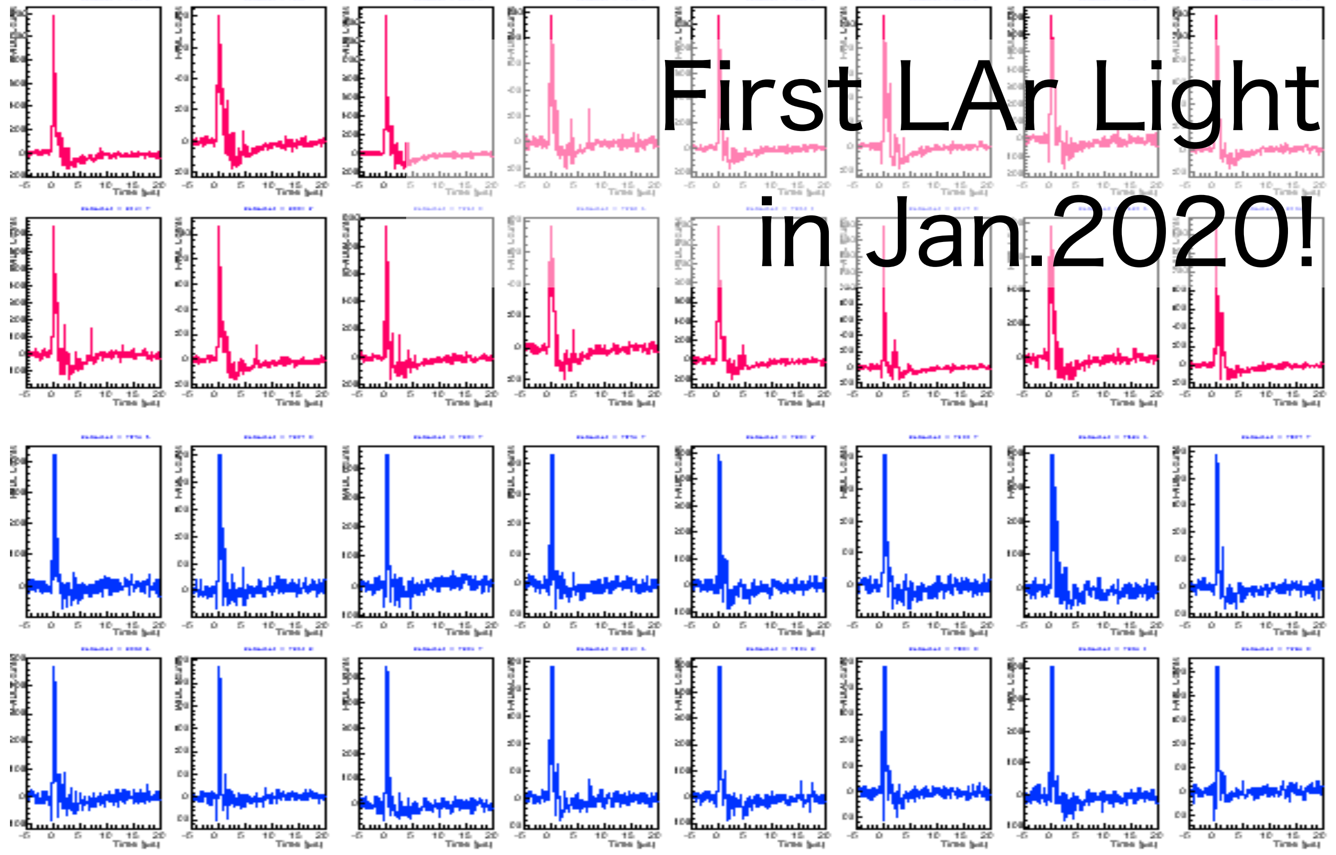
^{137}Cs 661.7 keV phot.-peak



MPPC Detector







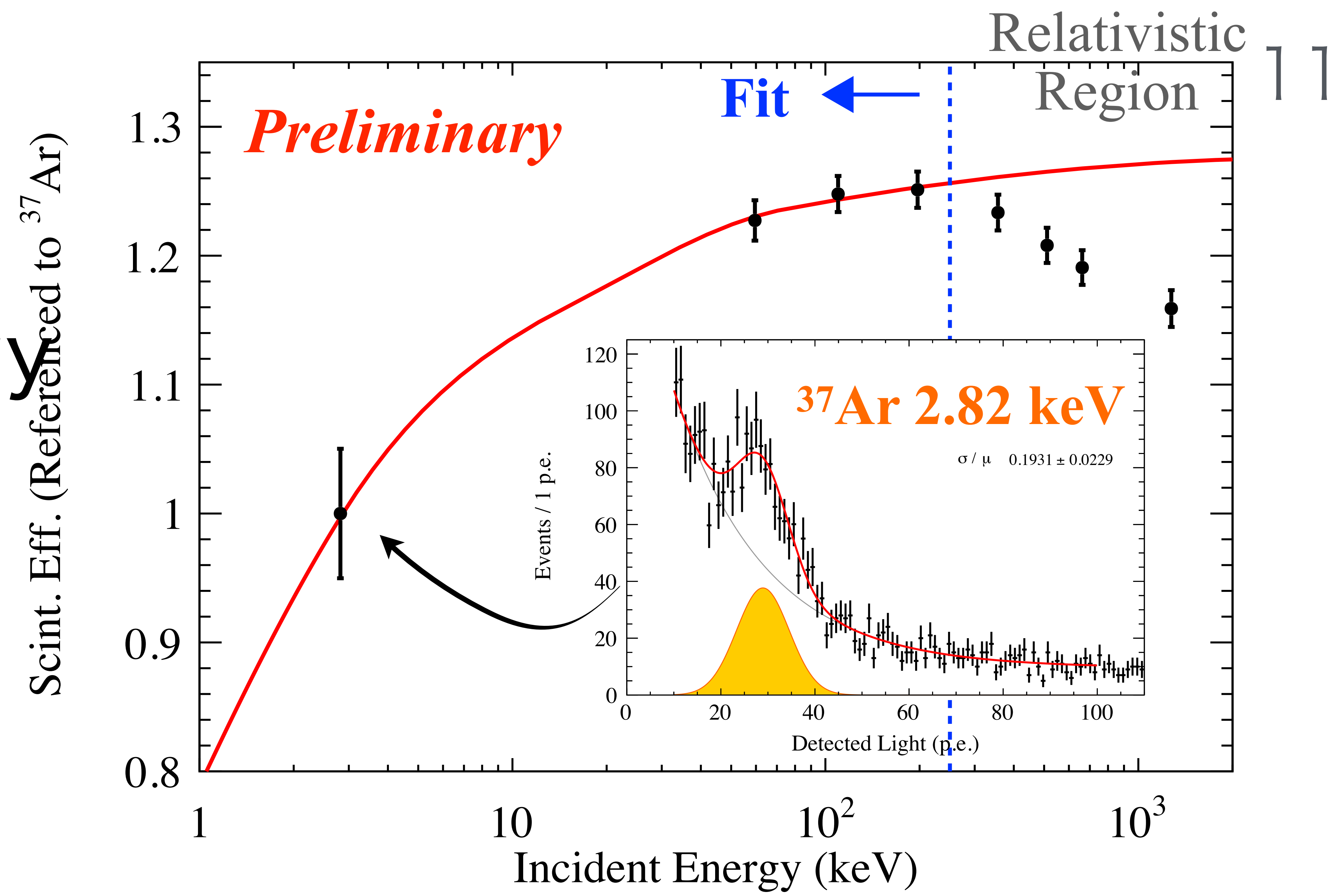
Project	L.Y. [p.e./keV]	Note
This work	11.1-12.6	PMT
This work	~25	MPPC (Very Rough Estimation)
DarkSide	9.1	[1]
DEAP	7.8	[2]
ARIS	6.4	[3]
SCENE	6.3	[4]

Confirm >10 p.e./keV by optimizations.

[1] Astropart.Phys. 49 44
[2] PRL 121 071801
[3] PRD 97 112005
[4] PRD 91 092007

Response on ER

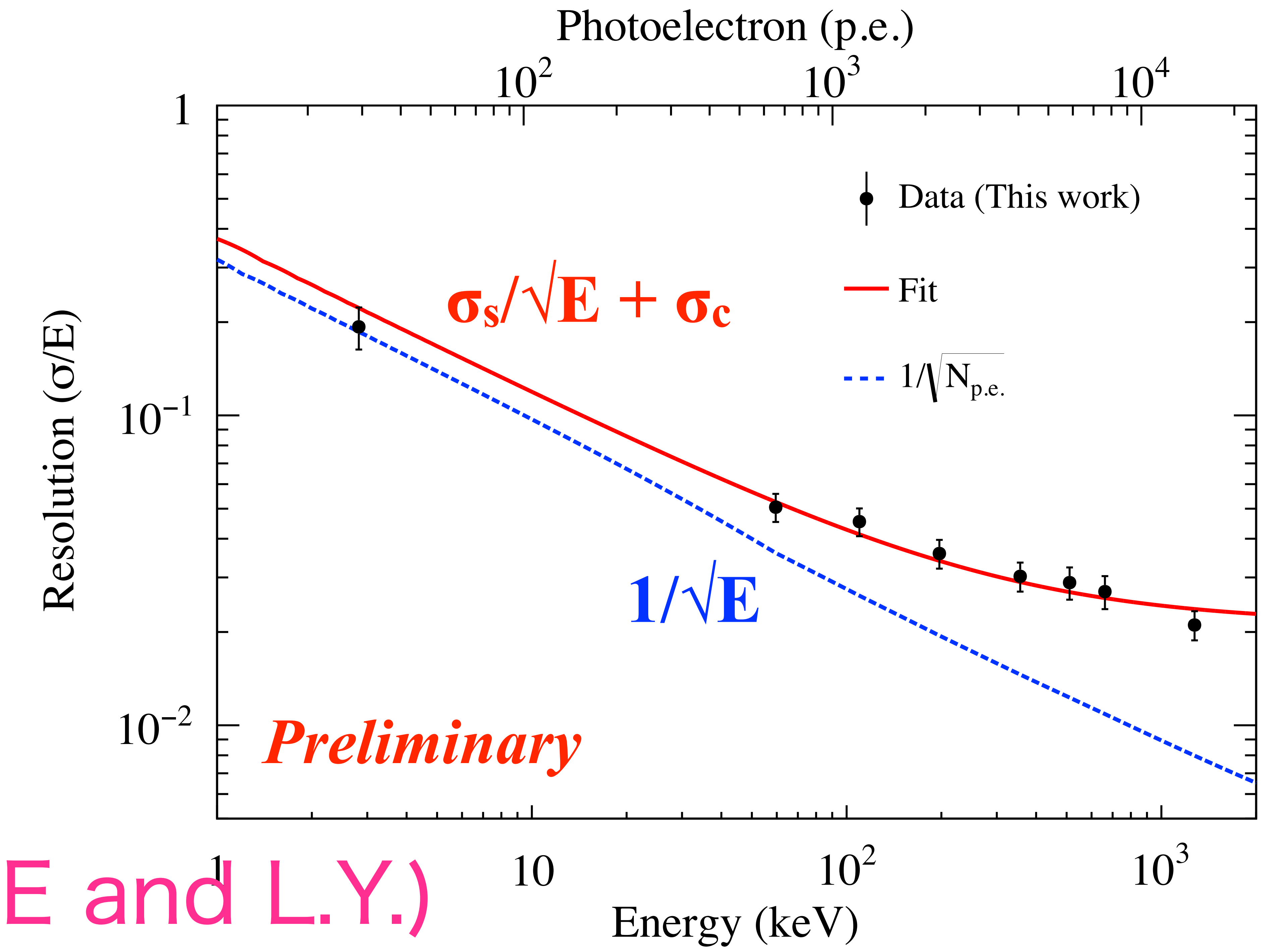
- Scint.-efficiency depending on the energy
  - Measured with 6 calibration sources, including 2.8 keV line of ^{37}Ar
  - Could be described with an analogy of that for NR : TIB model



- Energy resolution of the detector
  - Described as

$$\frac{\sigma}{E} = \frac{0.37}{\sqrt{E\ [\mathrm{keV}]}} \oplus 0.02 \quad \rightarrow \quad 2.6\,\%\ @\ 511\ \mathrm{keV}$$

  - PMT responses is a large contributor for the stochastic term.

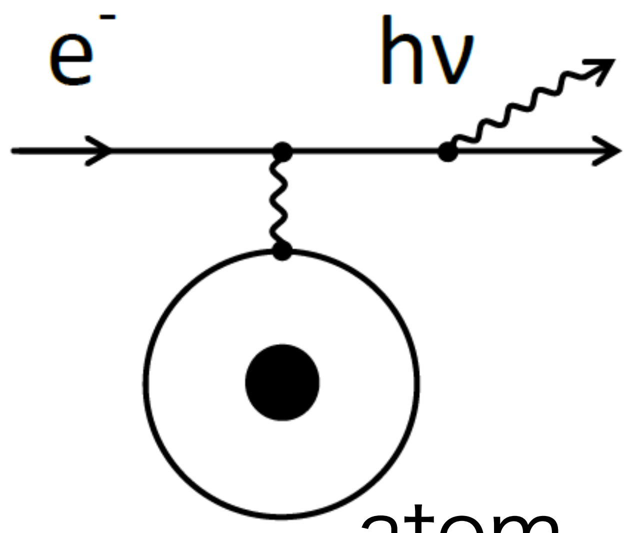


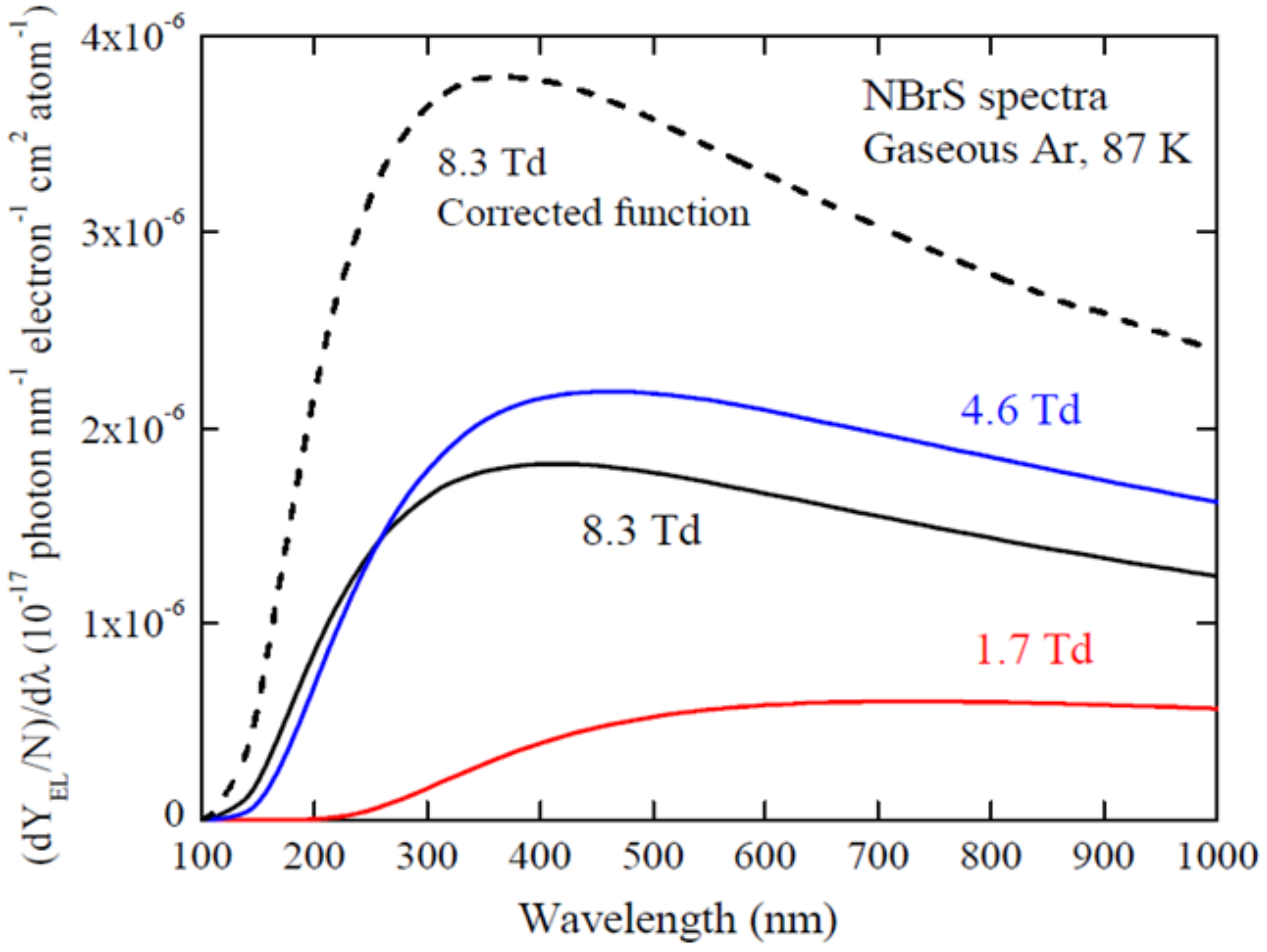
→ Possibly improved with SiPM (both σ/E and L.Y.)

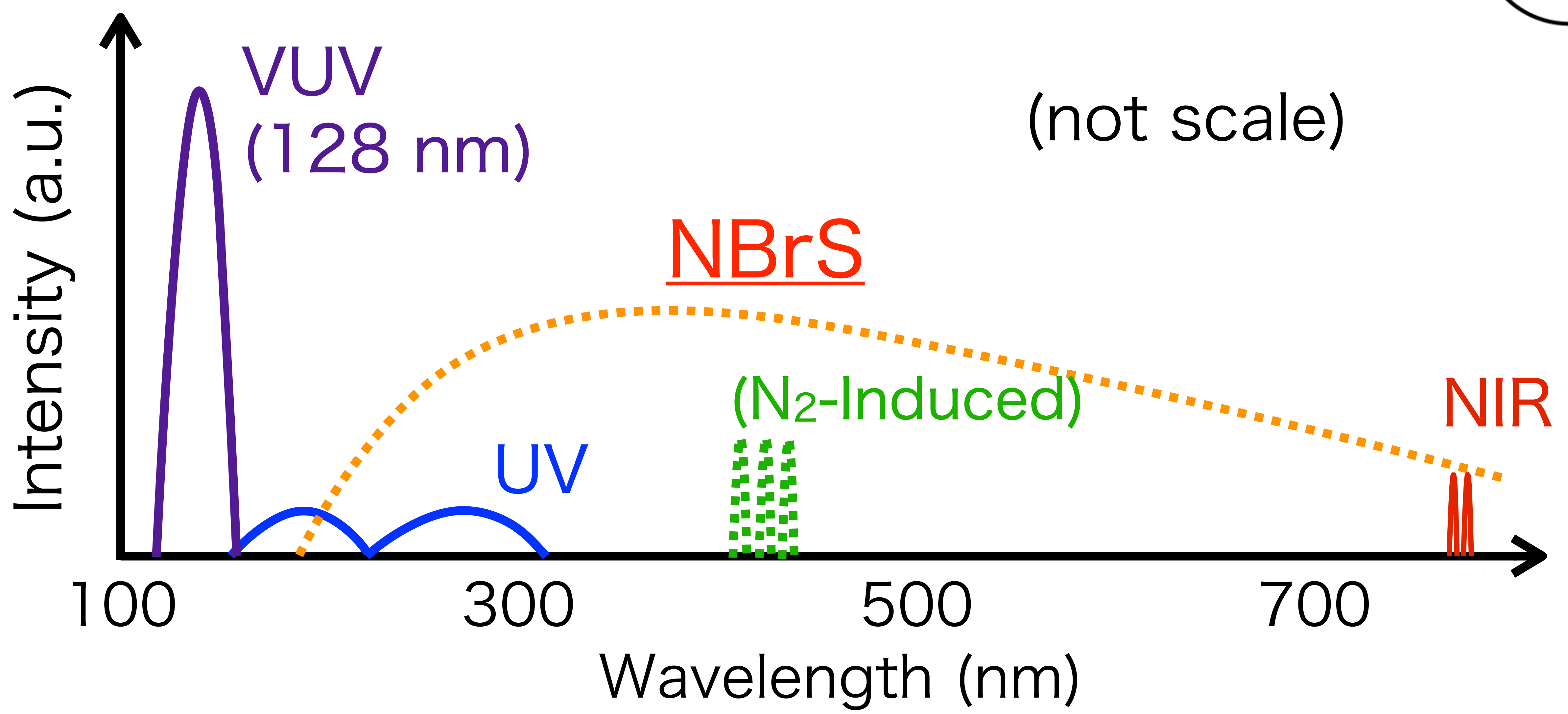
[5] Sov.Phys.JETP,12,1235
[6] Astropart.Phys. 103 29 & NIMA(2019)162432 (In Press)

S2 Mechanism : EL and NBrS

- **Electroluminescence (EL)** : Main (or only) component of S2 signal
  - Resulting from de-excitation of atoms excited by electrons under field
- Neutral Bremsstrahlung (NBrS)
  - Resulting from **slow electron** (~10 eV) (in-)elastically scattered on neutral atoms
  - Theoretically predicted[5], and recently experimentally suggested[6]
  - Perform further measurements, i.e., spectrum and field dependency



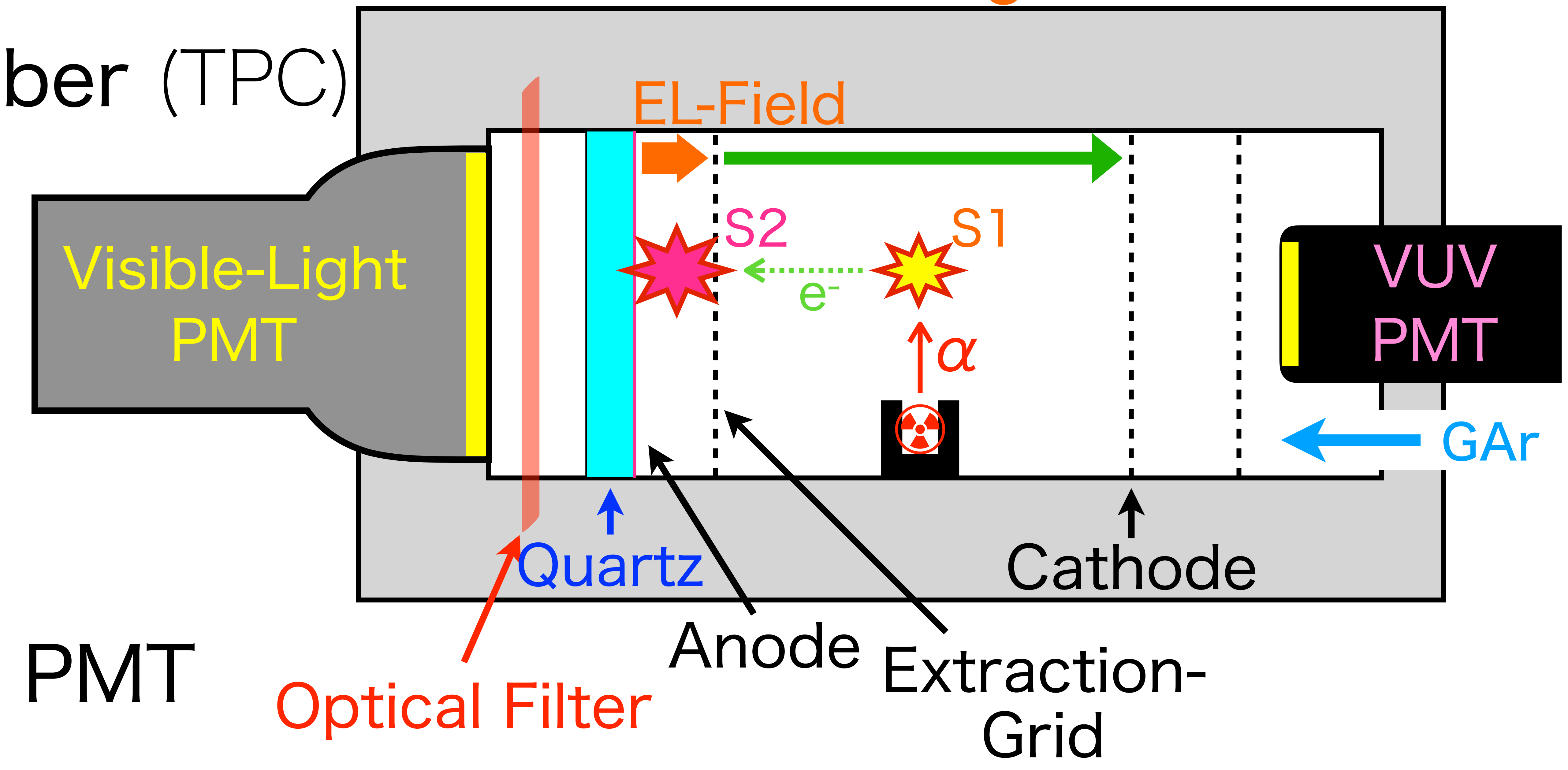


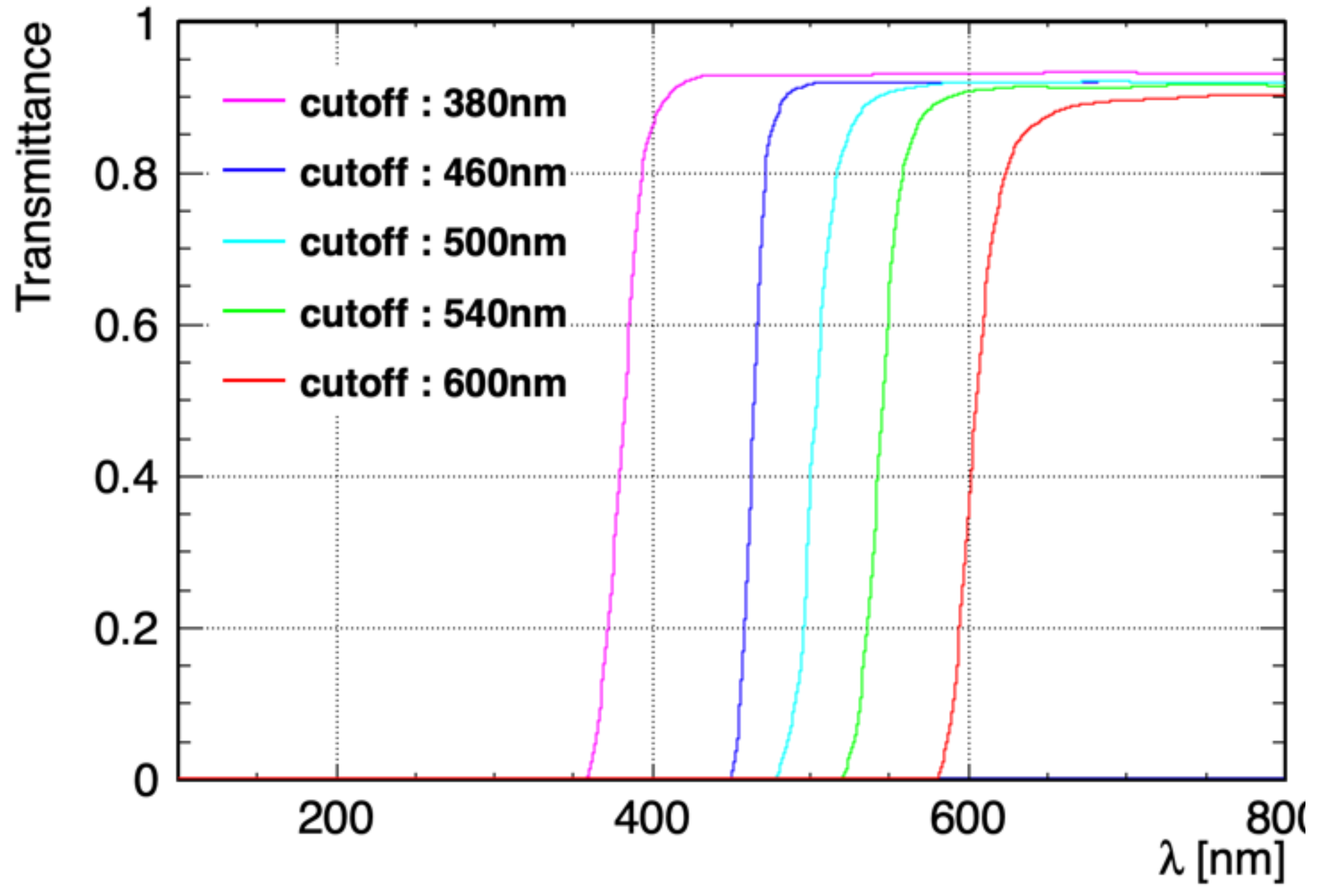


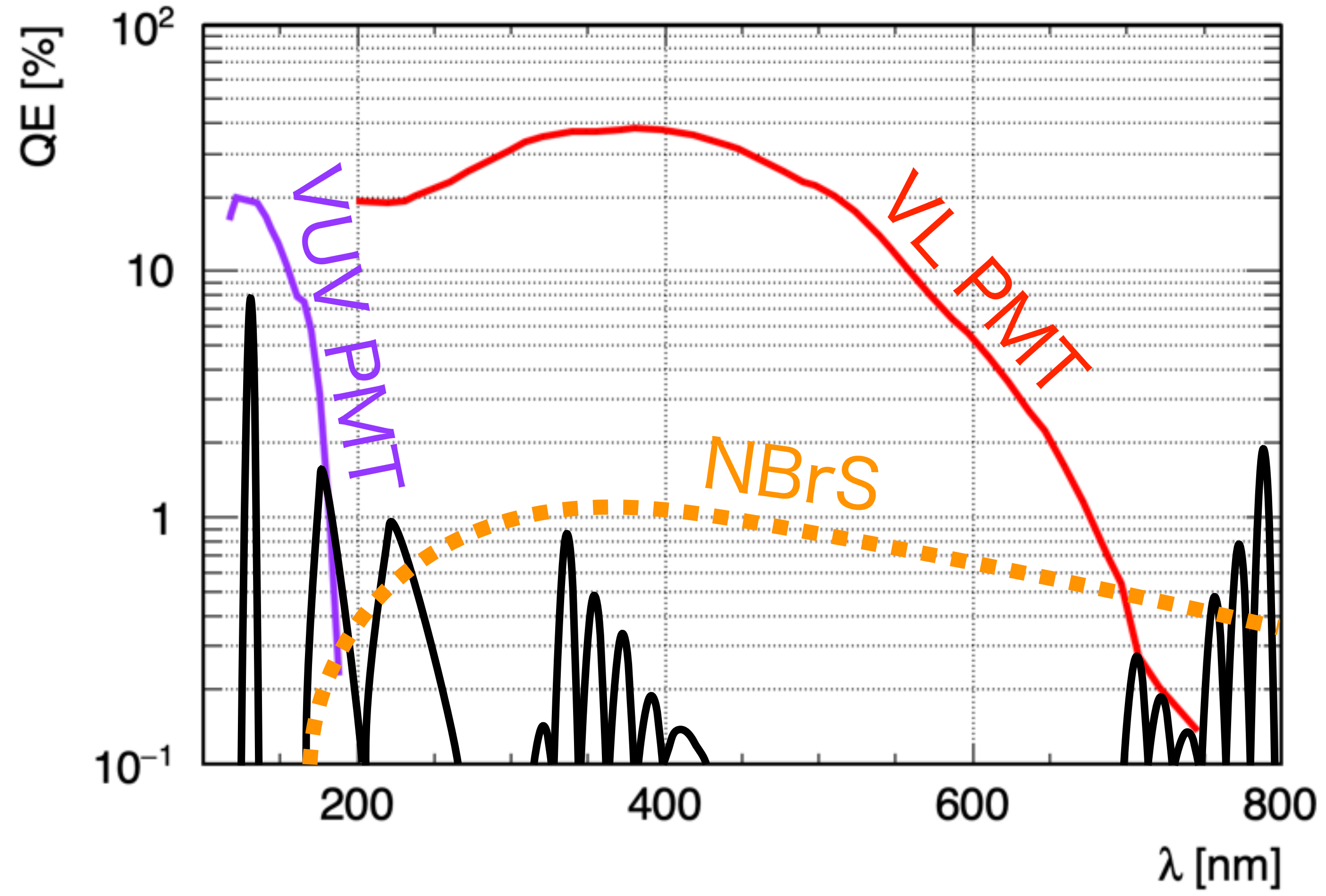
Experimental Setup

No Wavelength Shifter is used

- **Gas Argon Time Projection Chamber** (TPC) at room temperature
  - Both S1 and S2 observed
  - Trigger PMT and Measuring PMT
  - α-source in "drift region"
- **Optical filter between Quartz and PMT**
  - Approximately 50 nm step, allowing spectrum measurement
- **EL-Field = 1.7 - 8.3 Td** (= 0.42 - 2.0 kV/cm), Drift-Field = 0.1 kV/cm (fix)



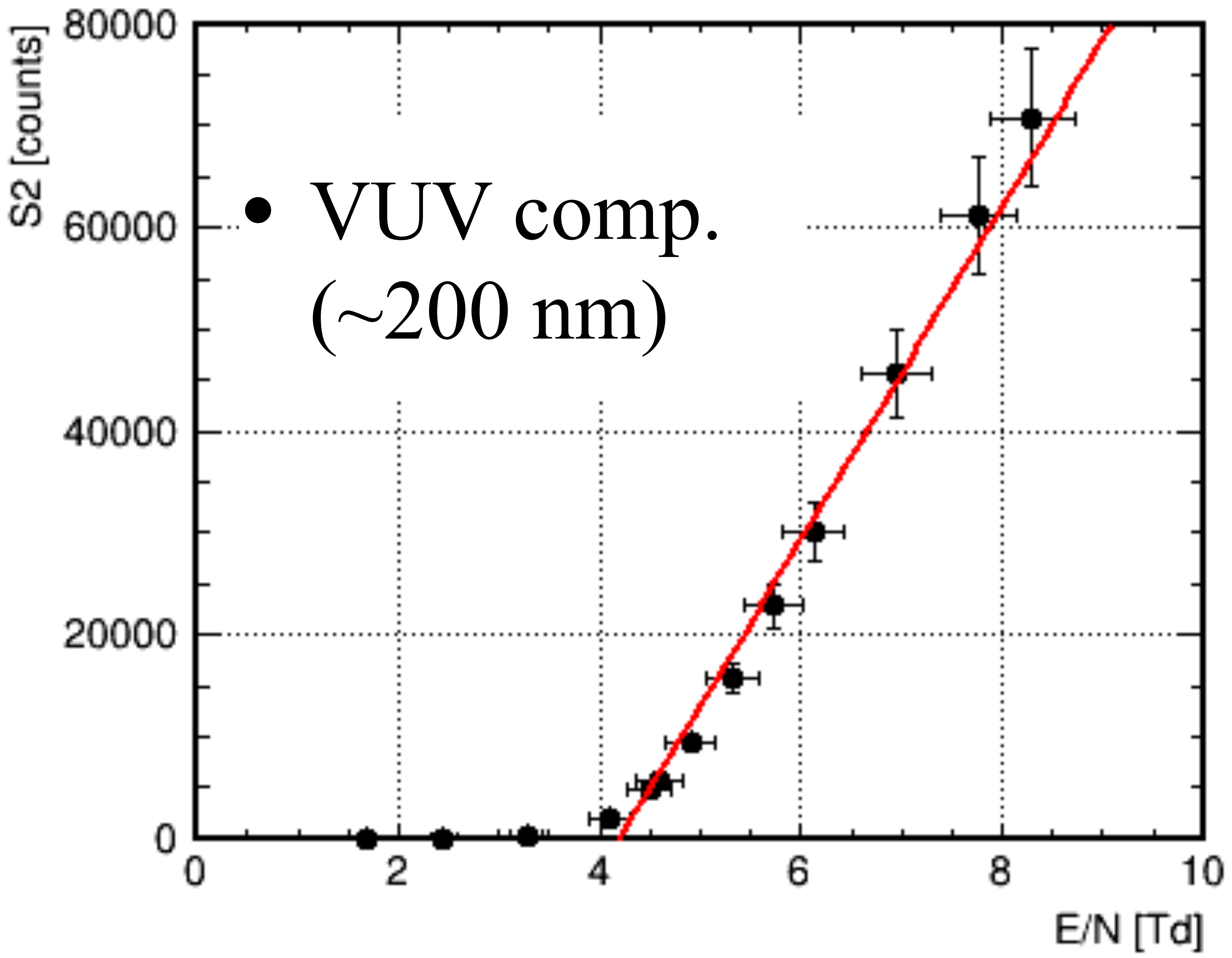




Field Dependence

: Measurement by changing luminescence field

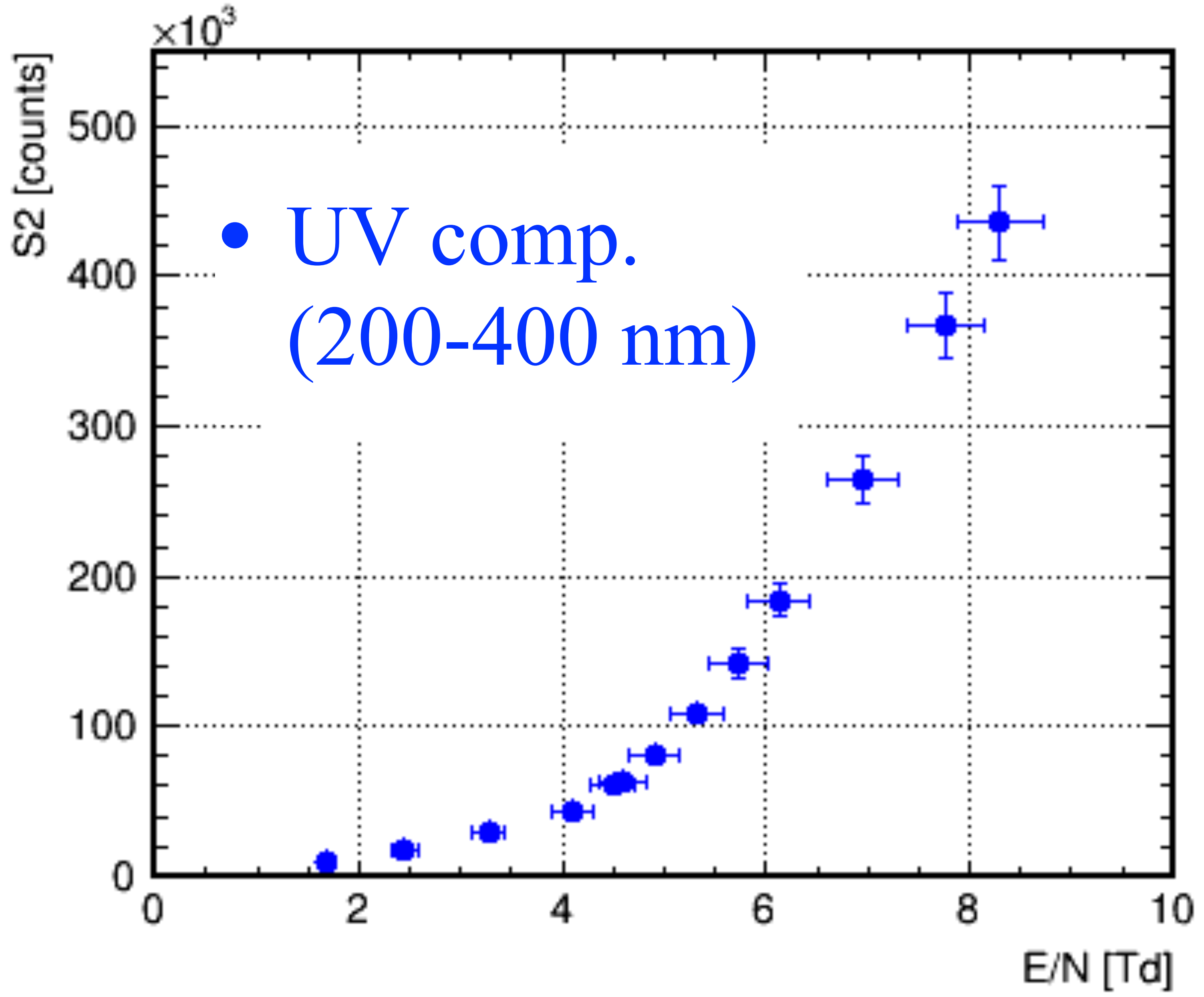
λ ~ 200 nm



Electroluminescence

- : Threshold around 4 Td
- : Linear dependence of the yield on the field

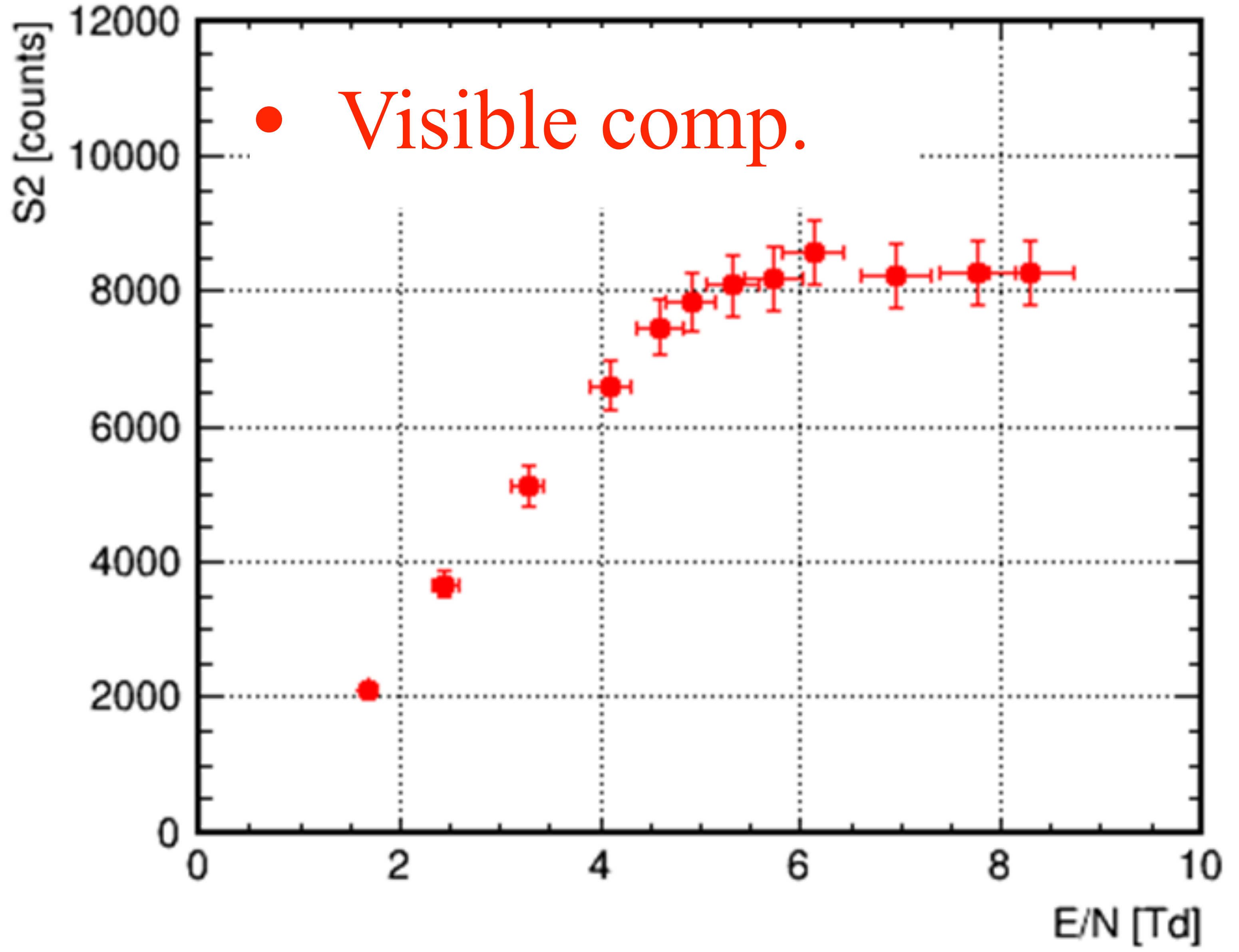
λ = 200-400 nm



Compound of

- : Electroluminescence,
- : Impurity-induced luminescence (Likely N_2),
- : and NBrS?

λ = 500-600 nm

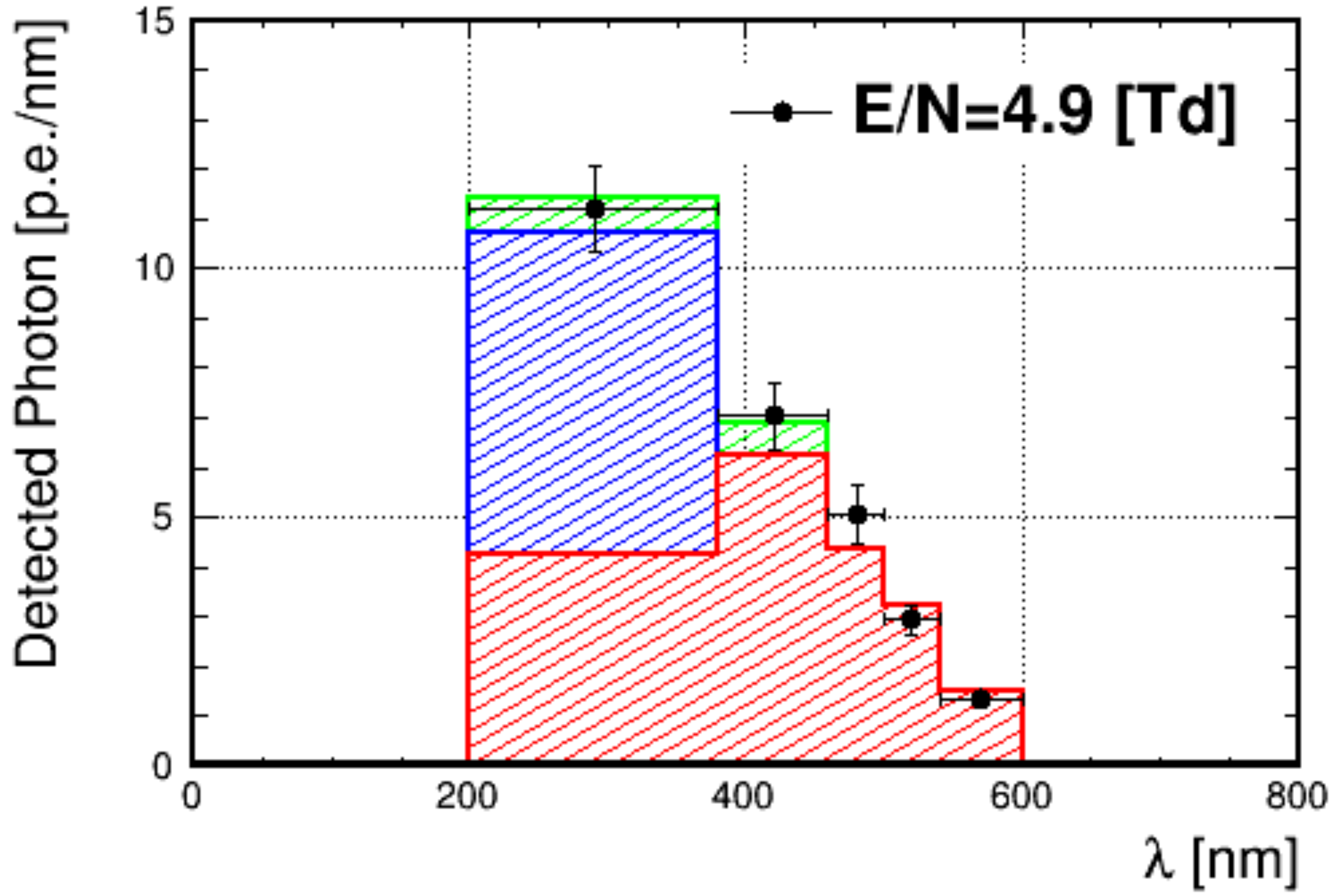


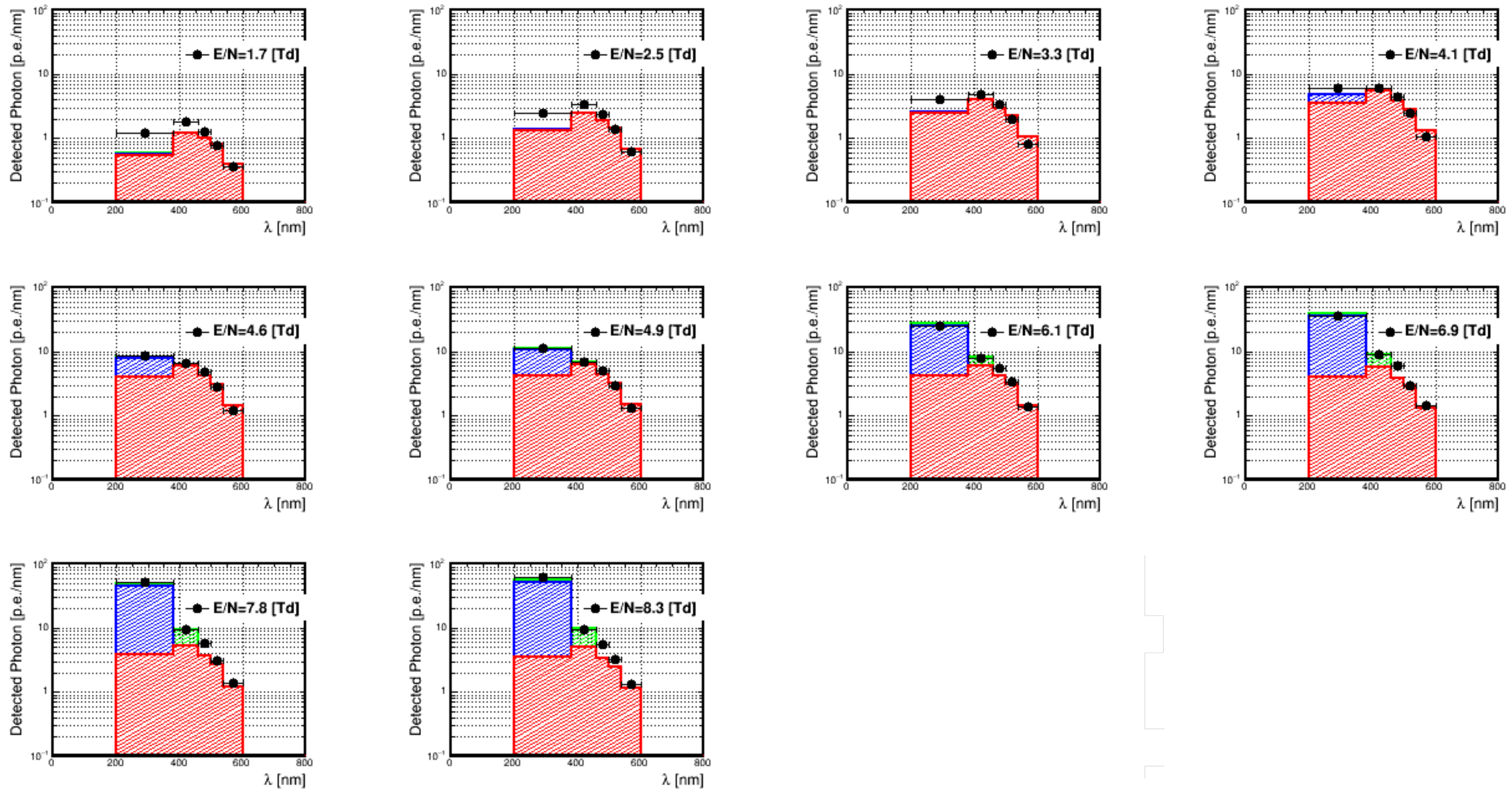
NBrS-Like

- : Visible-light component
- : Signal below EL-thre. field
- : Saturated at high field (theoretical prediction)

Spectrum Measurement

- Spectrum measurement by changing the optical filters
- Interpreting the spectra of each field as the sum of three components (Electroluminescence + N_2 (Impurity)-Induced + NBrS)

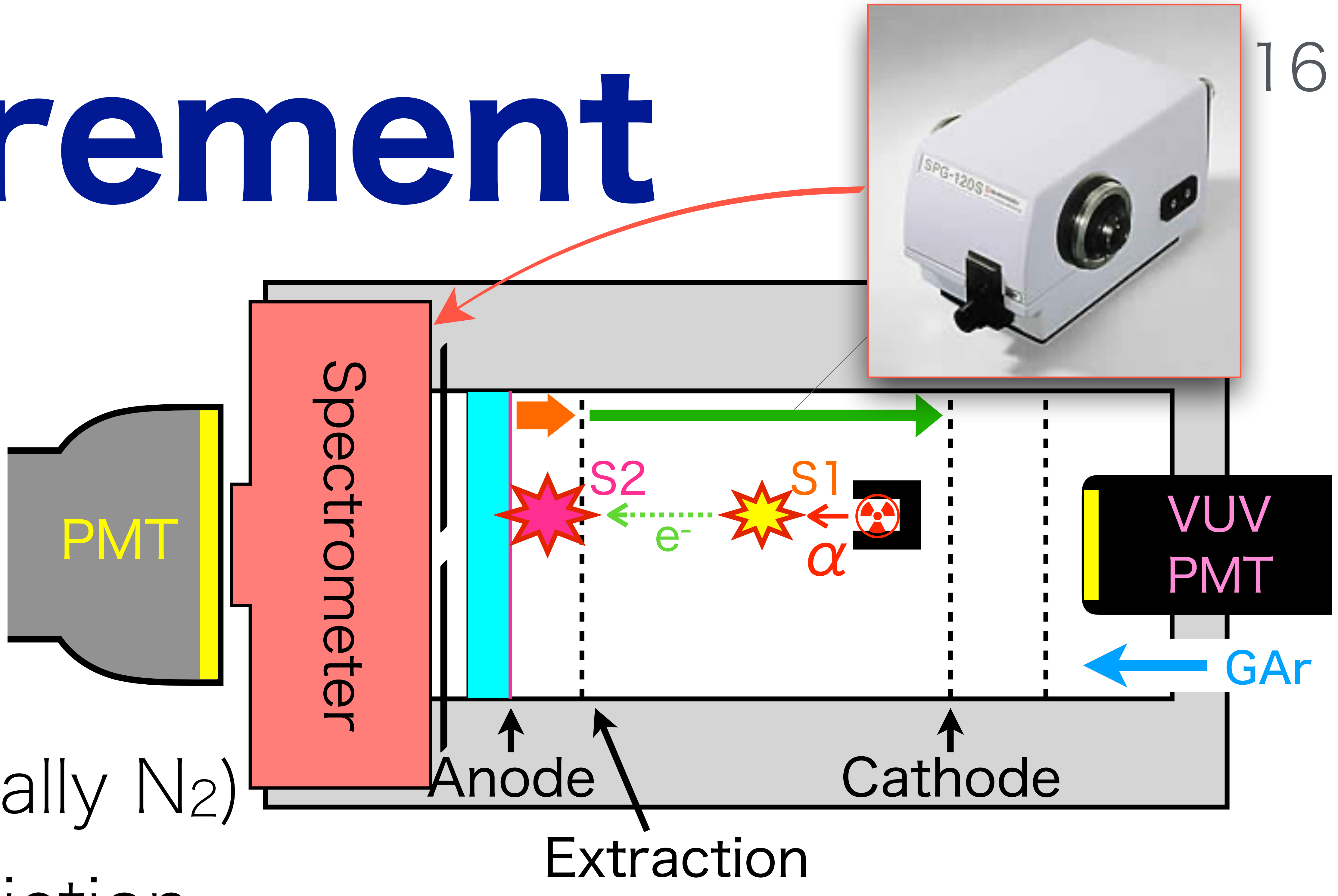


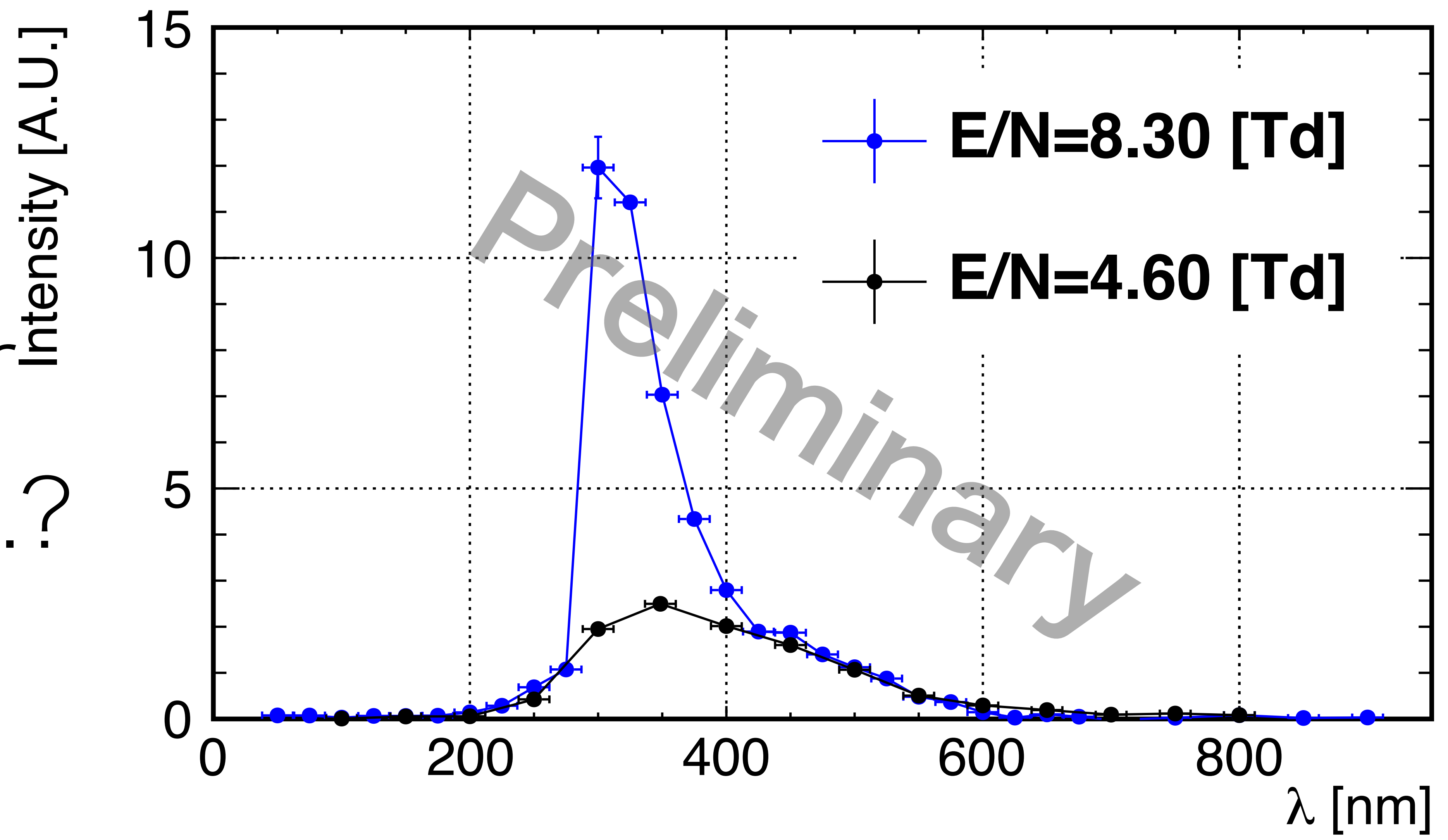


Observed spectra is consistent to the NBrS prediction within factor

Further Measurement

- Implementing a spectrometer just now (SHIMADZU SPG-120G)
- Further measurements are ongoing :
  - Update spectrum measurement
  - Estimate effects from impurity (especially N_2)
  - Quantitative comparison with the prediction
  - Any directionality or not?
- Application to the experiments
  - Observable with vis.-light sensitive detector
  - Position reconstruction, purity monitor, etc.?
  - Work also in liquid?





Summary

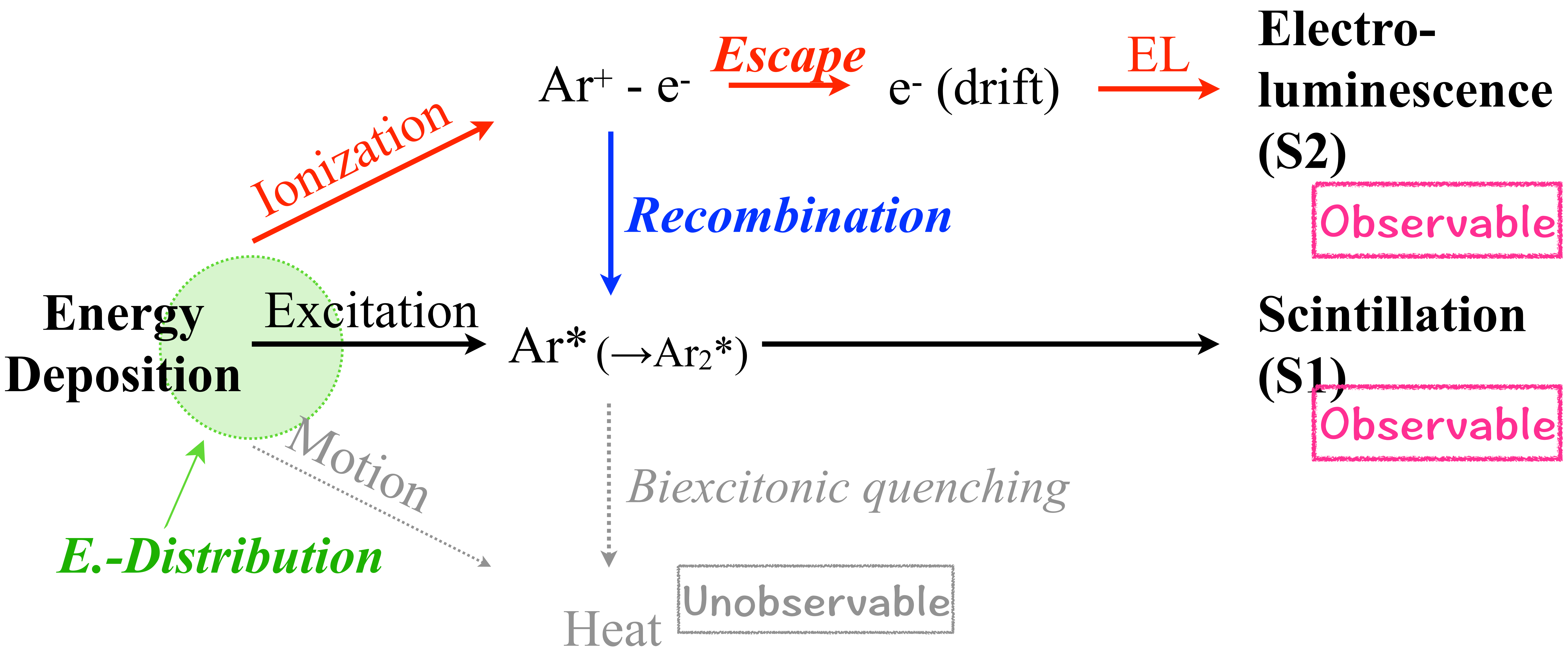
- Liquid argon scintillation detector
  - Attractive to search for WIMP dark matter, as well as other various physics experiments
  - Large signal yield, Powerful PSD, Availability at cheap cost, …
- R&D efforts of the detector in Waseda Univ., Japan
  - Construction of high field or high light yield detector
  - Measurements of liquid argon scintillation and ionization response under fields and basic properties of the detector
  - Basic study of a new "S2" component, Neutral Bremsstrahlung
- Helpful informations for not only our experiment but also current and future LAr projects.

Backup

WASEDA University

Response on Nuclear Recoils

- ✓ Essential process in WIMP search and CNNES measurements.
- ✓ The scheme should be common to ERs **except** each parametrizations.



— Parametrization for NRs —

- NR quenching ($N_i + N_{ex} = \frac{E}{W} \times L_{\mathrm{eff}}^{\mathrm{Mei}}$) : Mei model ············ $L_{\mathrm{eff}}^{\mathrm{Mei}} = L_{\mathrm{eff}}^{\mathrm{Lindhard}} \times \frac{1}{1 + k_B \frac{dE}{dx}}$
- Excitation-to-Ionization ratio : Empirical function ······ $\alpha = \frac{N_{ex}}{N_i} = \alpha_0 \exp(-D_\alpha F)$
- Recombination prob. : Thomas-Imel box (TIB) model ··· $R = 1 - \frac{\ln(1 + N_i \varsigma)}{N_i \varsigma}, \ \varsigma = \gamma F^{-\delta}$

Analysis Method

- Define the "Scintillation Efficiency" $\mathcal{L}_{eff}(E_0, F)$ as,

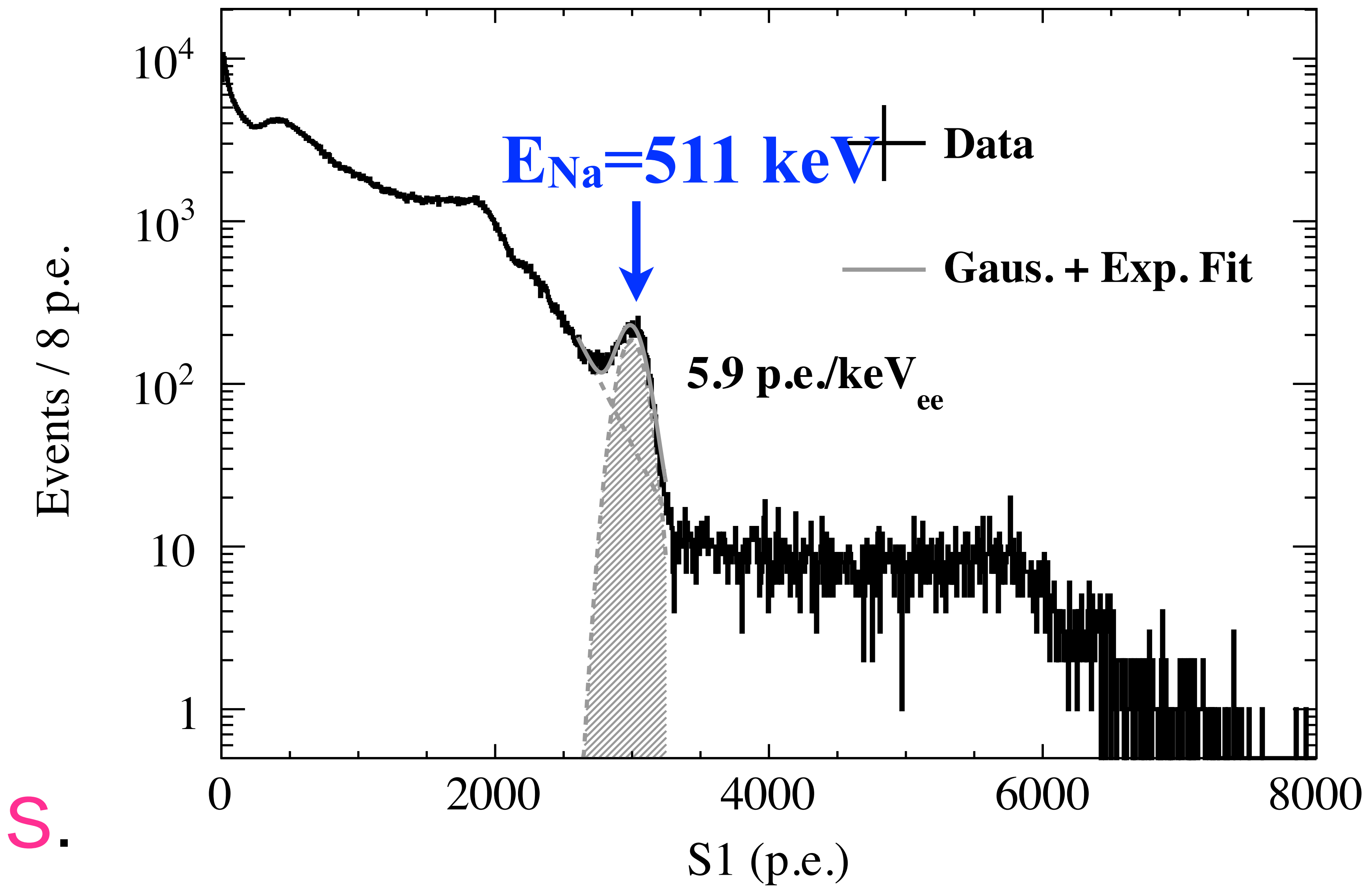
$$\mathcal{L}_{eff}(E_0, F) = \frac{\text{S1 per NR Energy}}{\text{S1 per ER Energy}} = \frac{\text{S1}/E_0\ [\text{p.e./keV}_{nr}]}{\text{S1}_{Na}/E_{Na}\ [\text{p.e./keV}_{ee}]}$$

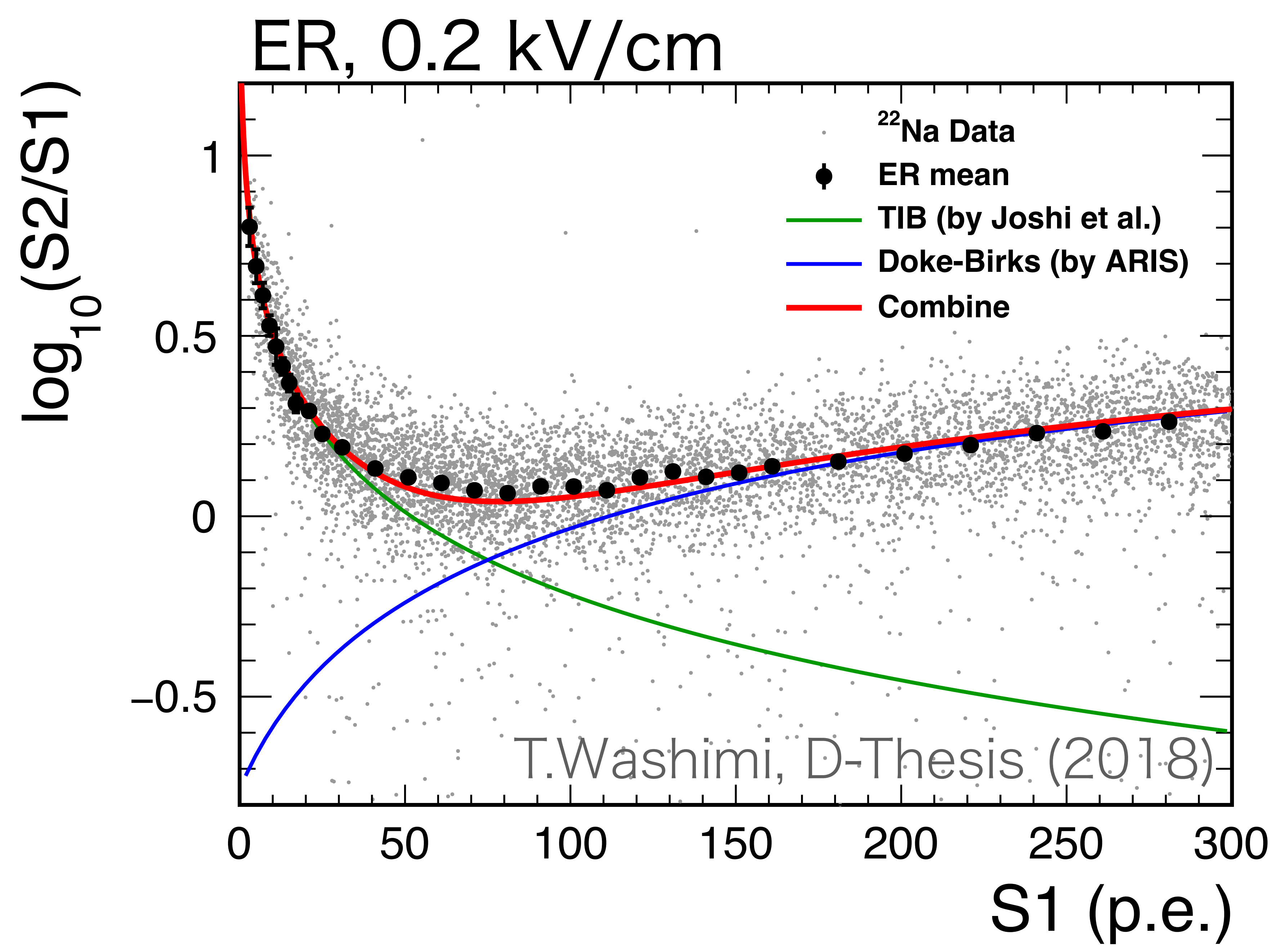
(Referenced to 511 keV γ-ray line)

- Express the $\mathcal{L}_{eff}(E_0, F)$ value using model functions.

$$\mathcal{L}_{eff}(E_0, F) = \frac{n_{ph}}{W/E_0} = L_{eff}^{Mei} \times \left[1 - \frac{1-R}{1+\alpha}\right]$$

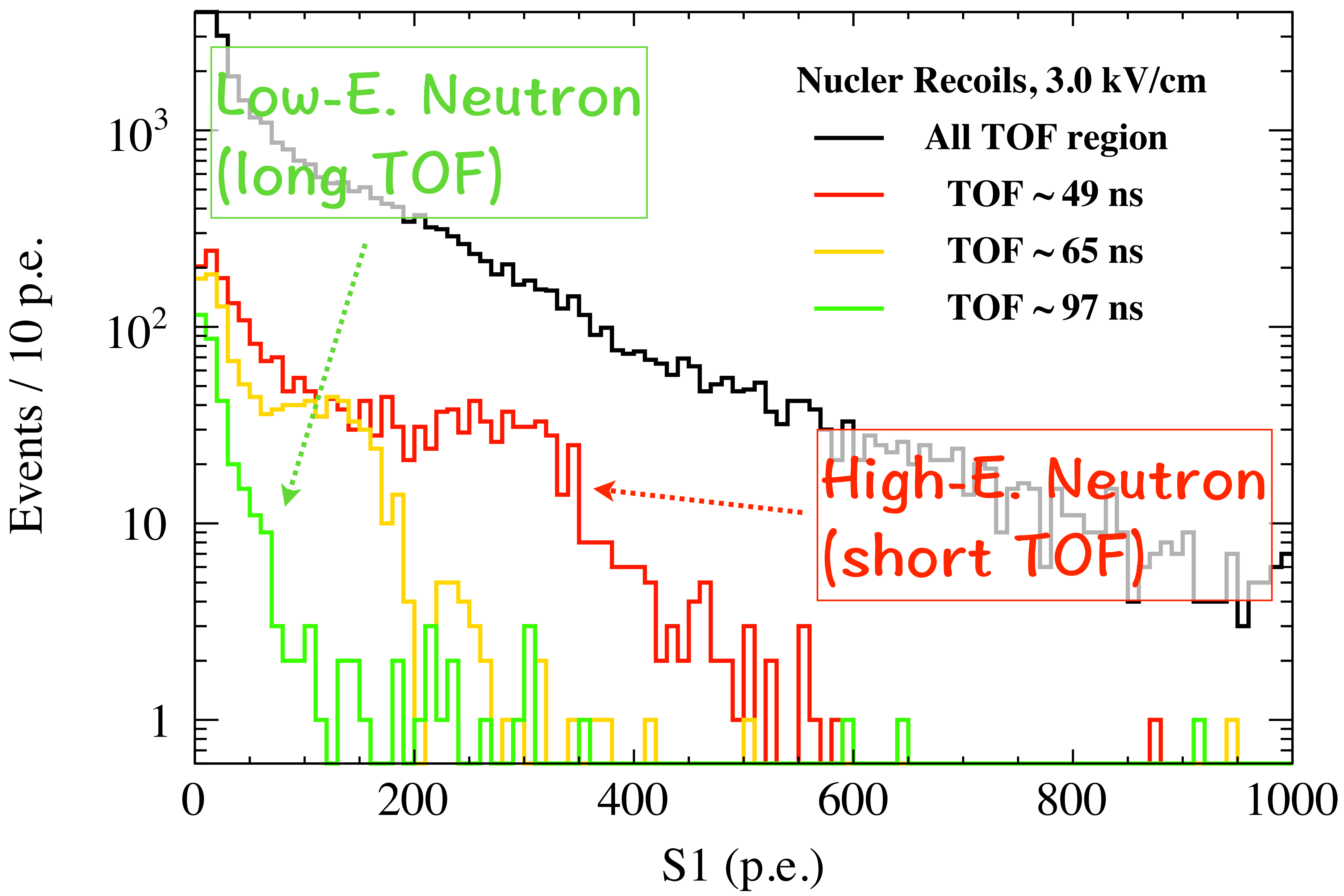
- Fit the data with the MC and the functions.
  - Determine k_B from null field data, and then D_α, γ, and δ from E-fields data set.
  - (Use the S2-gain "g_2" [p.e./e-] derived from the ER events under lower filed.)



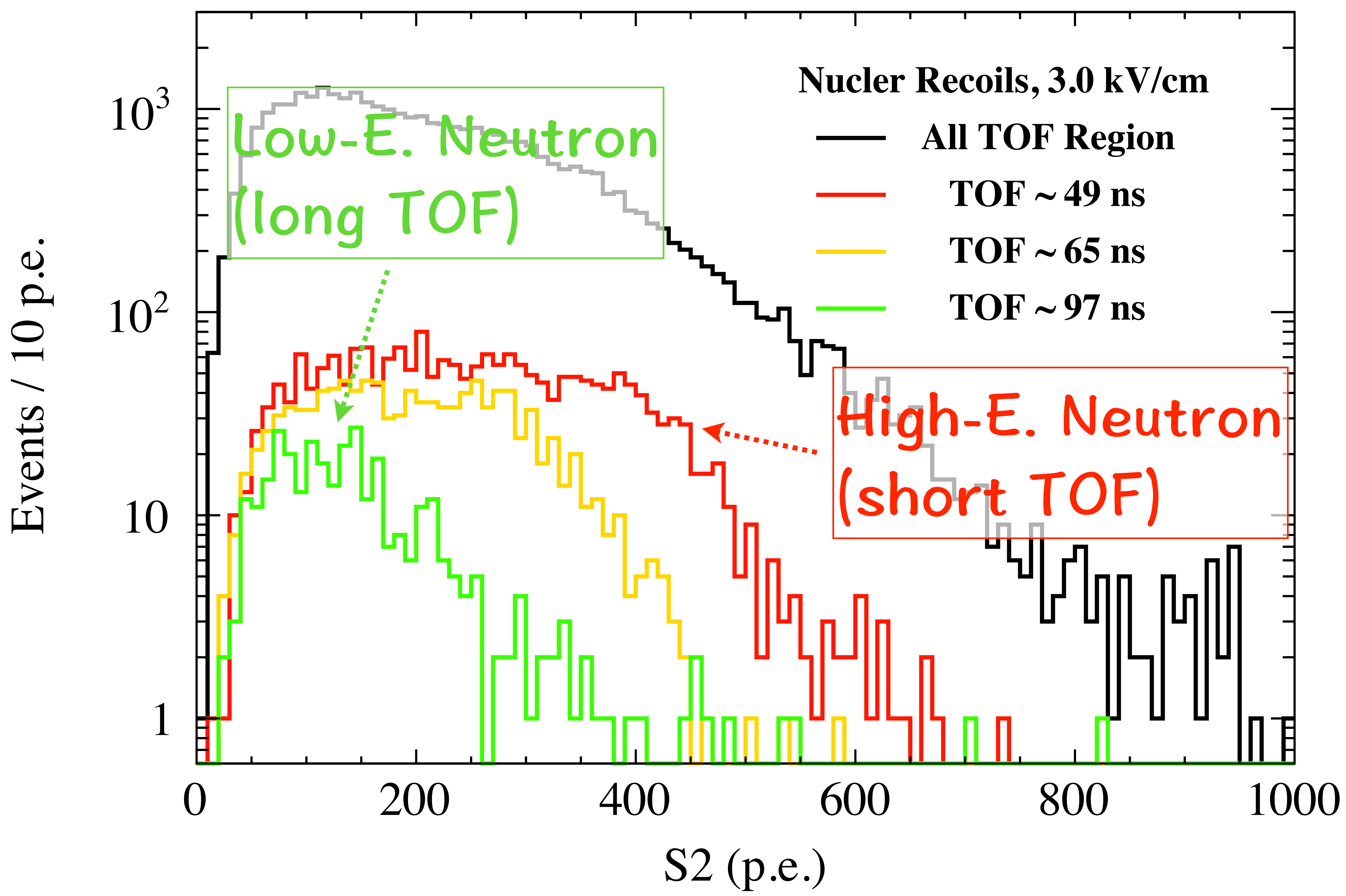


Observed Spectra from NRs

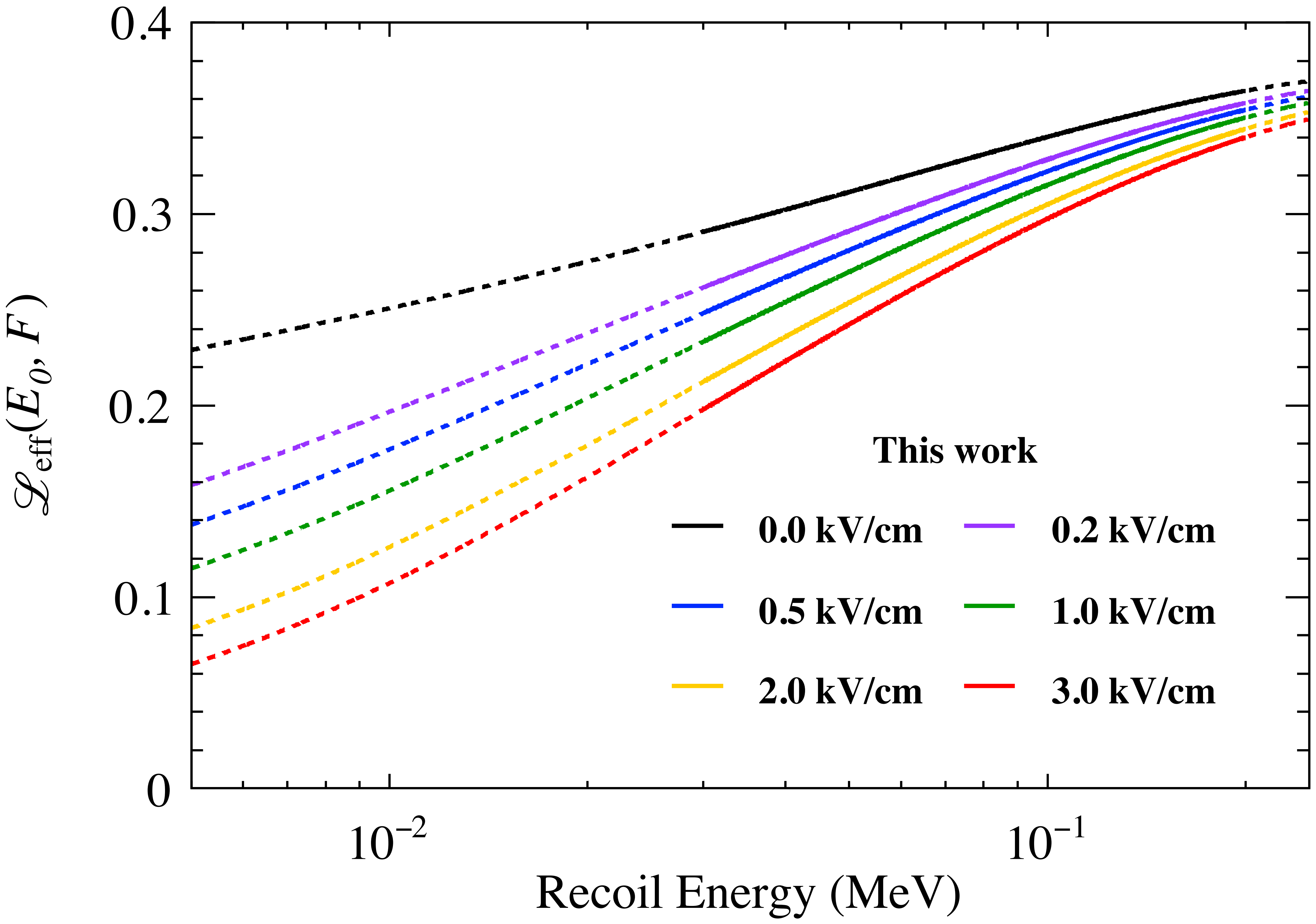
S1 (3 kV/cm)



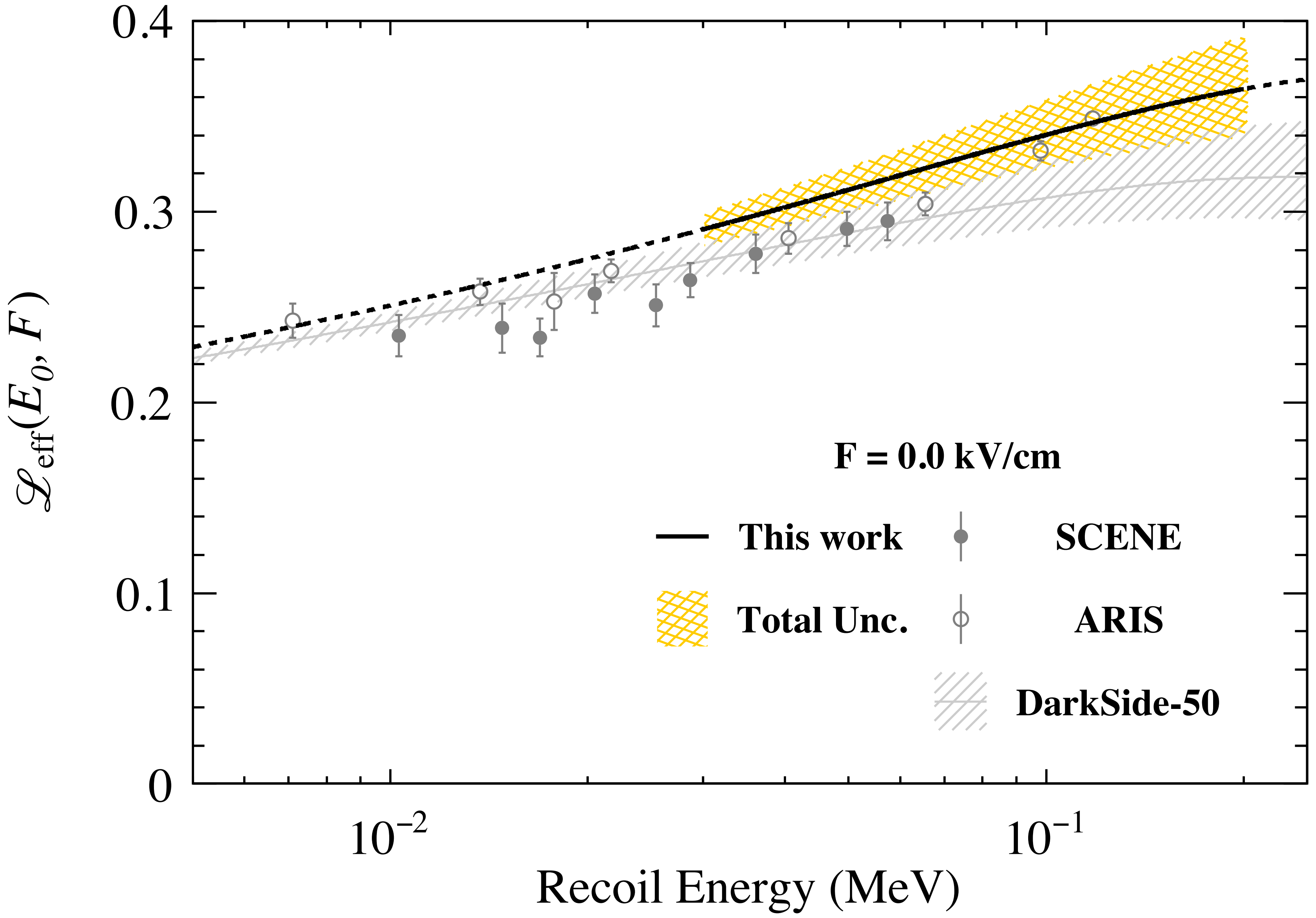
S2 (3 kV/cm)



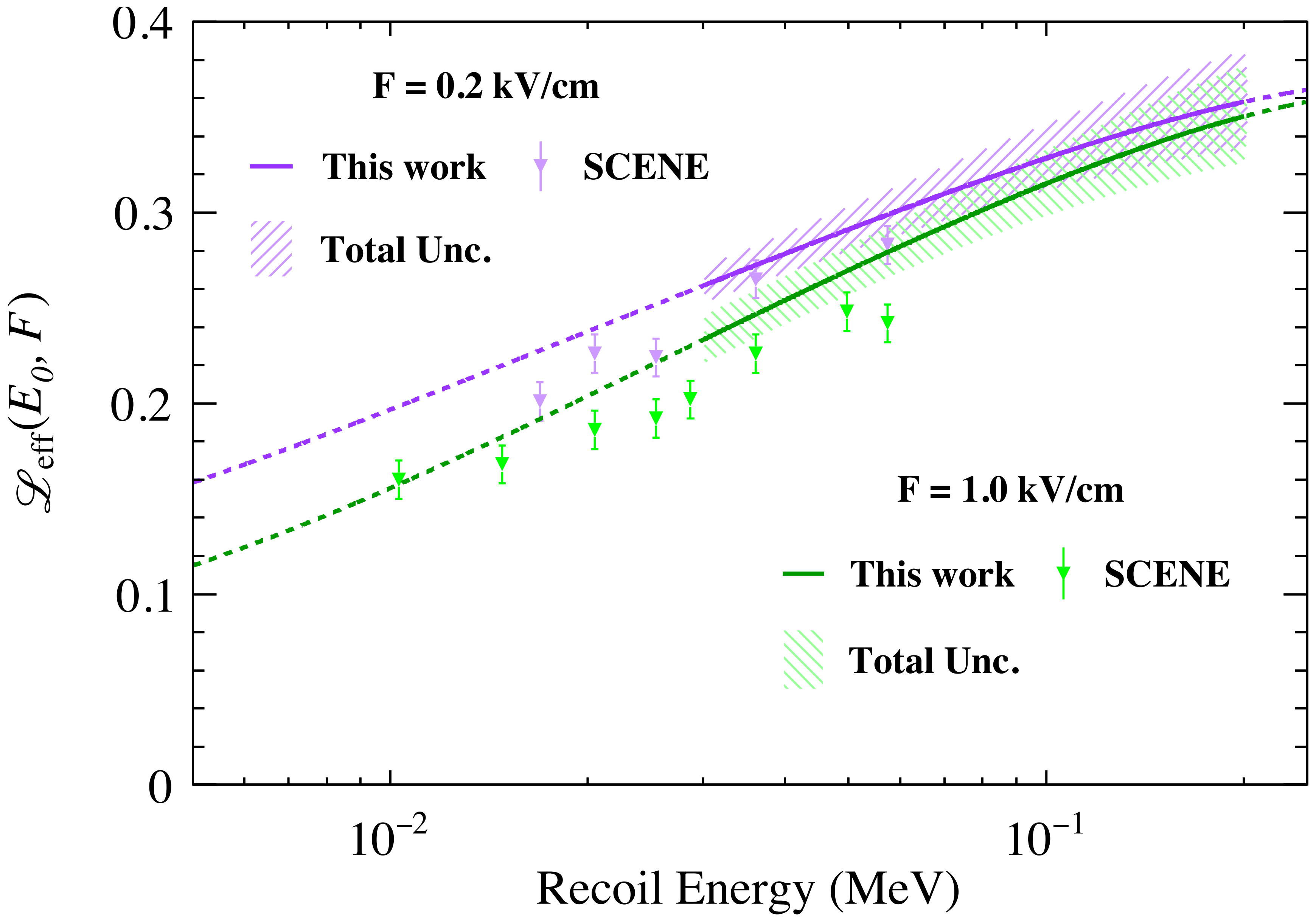
- ✓ Successfully operating the LAr-TPC and taking the data at 3.0 kV/cm.
- ✓ Reconstructed incident neutron energy by the TOF method.



0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
Recoil Energy (MeV)
$\mathscr{L}_{\rm eff}(E_0, F)$
This work
0.0 kV/cm
0.2 kV/cm
0.5 kV/cm
1.0 kV/cm
2.0 kV/cm
3.0 kV/cm

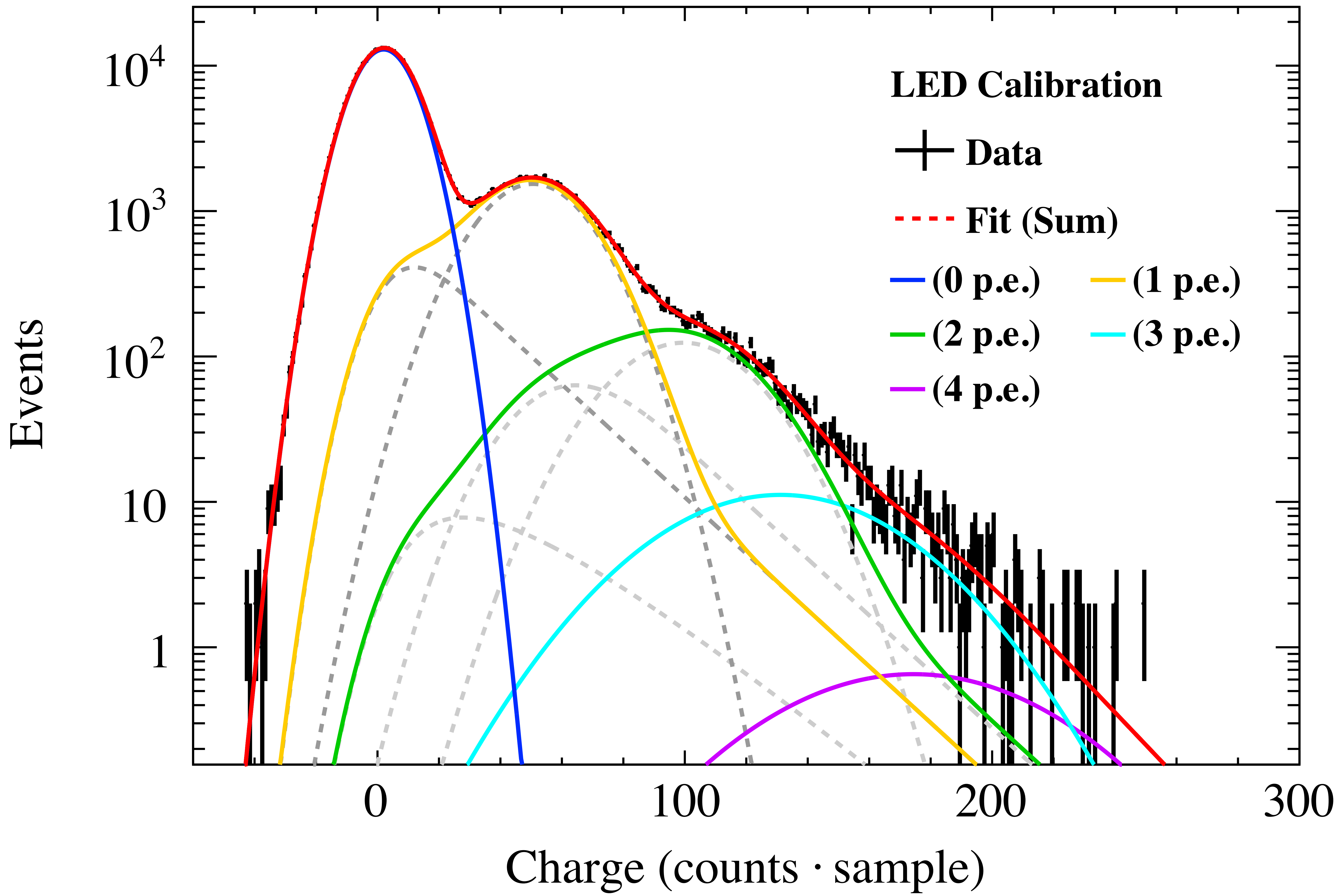


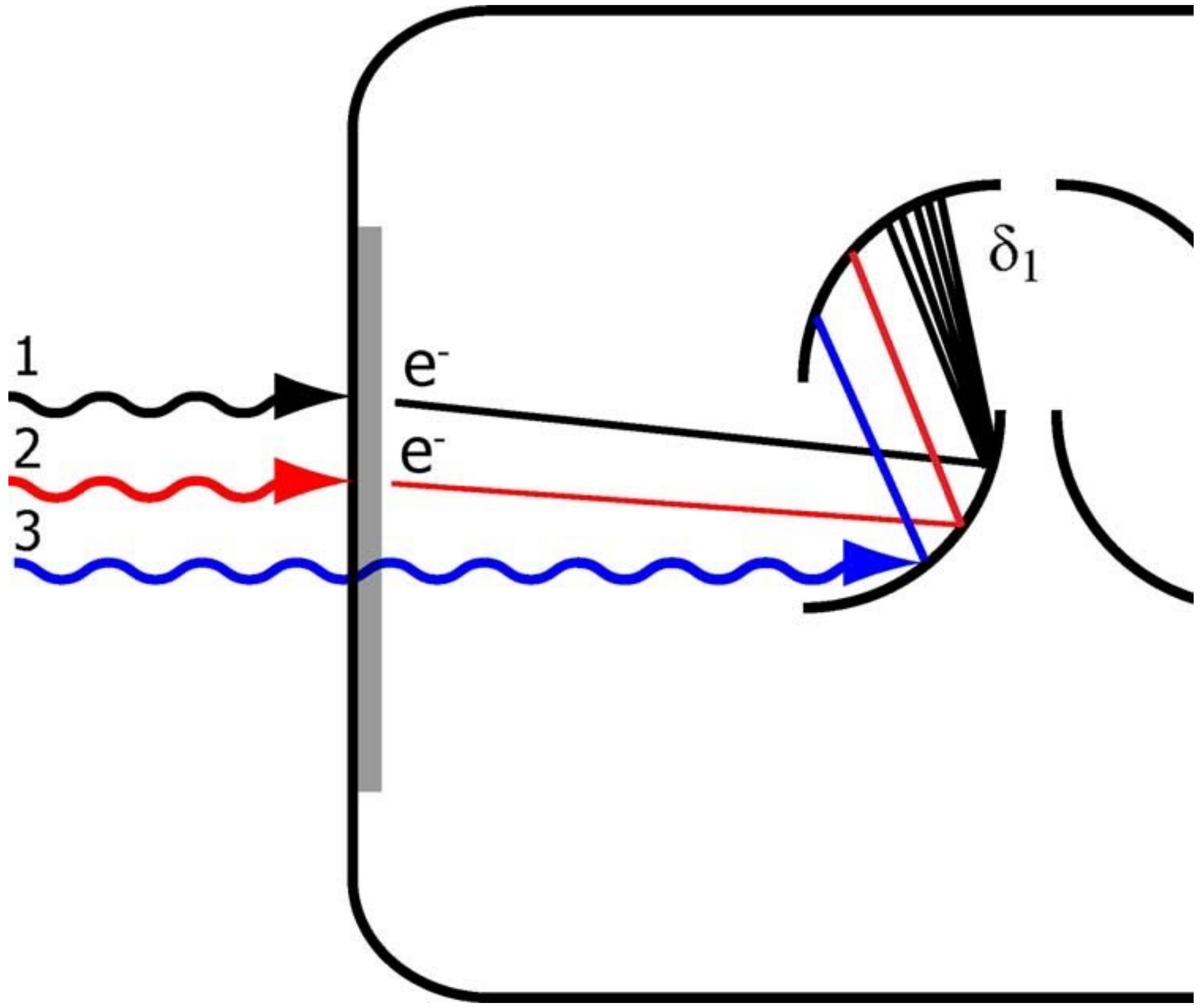
0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
Recoil Energy (MeV)
$\mathscr{L}_{\rm eff}(E_0, F)$
F = 0.0 kV/cm
This work
SCENE
Total Unc.
ARIS
DarkSide-50



0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
Recoil Energy (MeV)
$\mathscr{L}_{\rm eff}(E_0, F)$
F = 0.2 kV/cm
This work
SCENE
Total Unc.
F = 1.0 kV/cm
This work
SCENE
Total Unc.

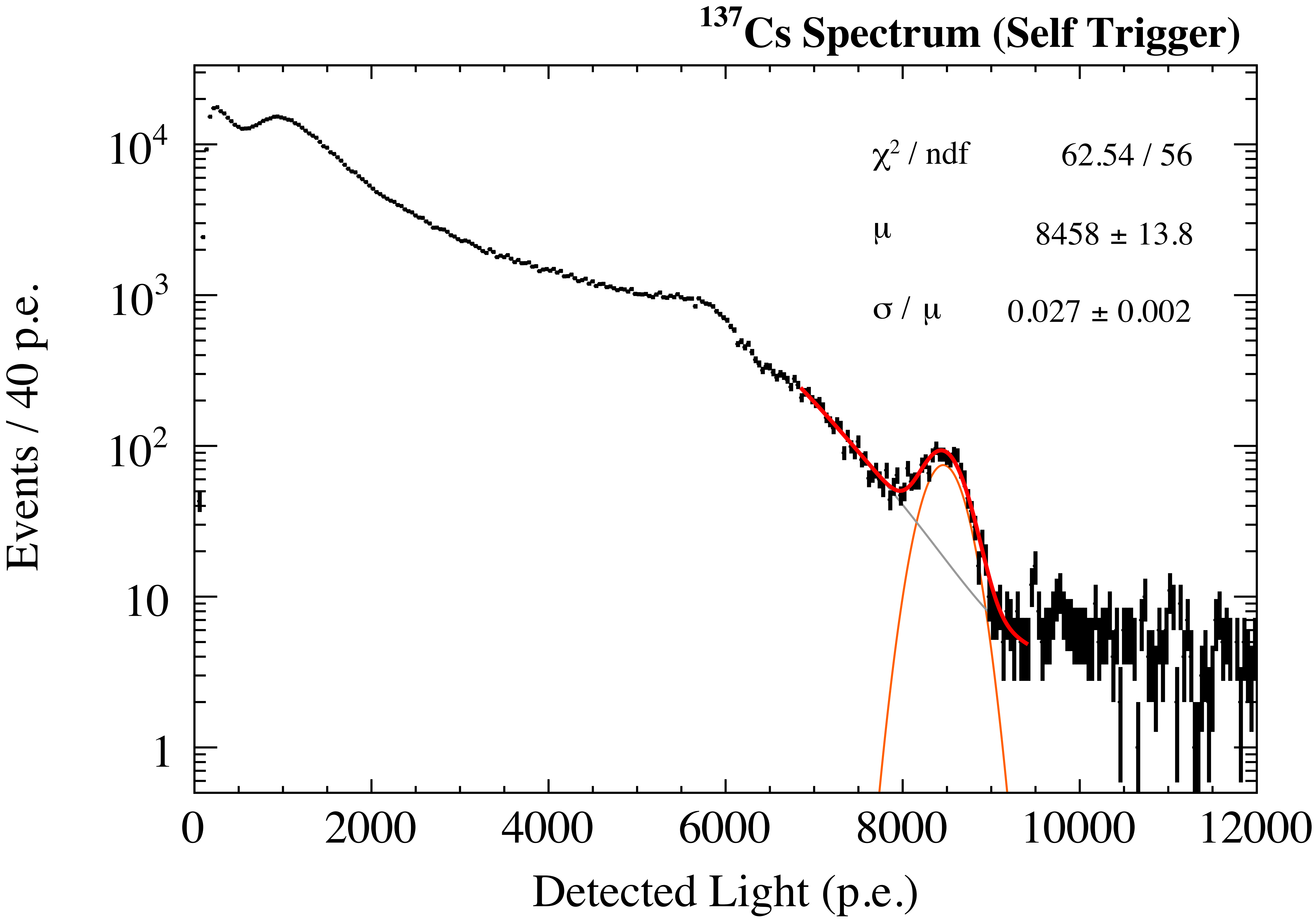
PMT Gain





IEEE Tracns. Nucl. Sci. 58, 1290

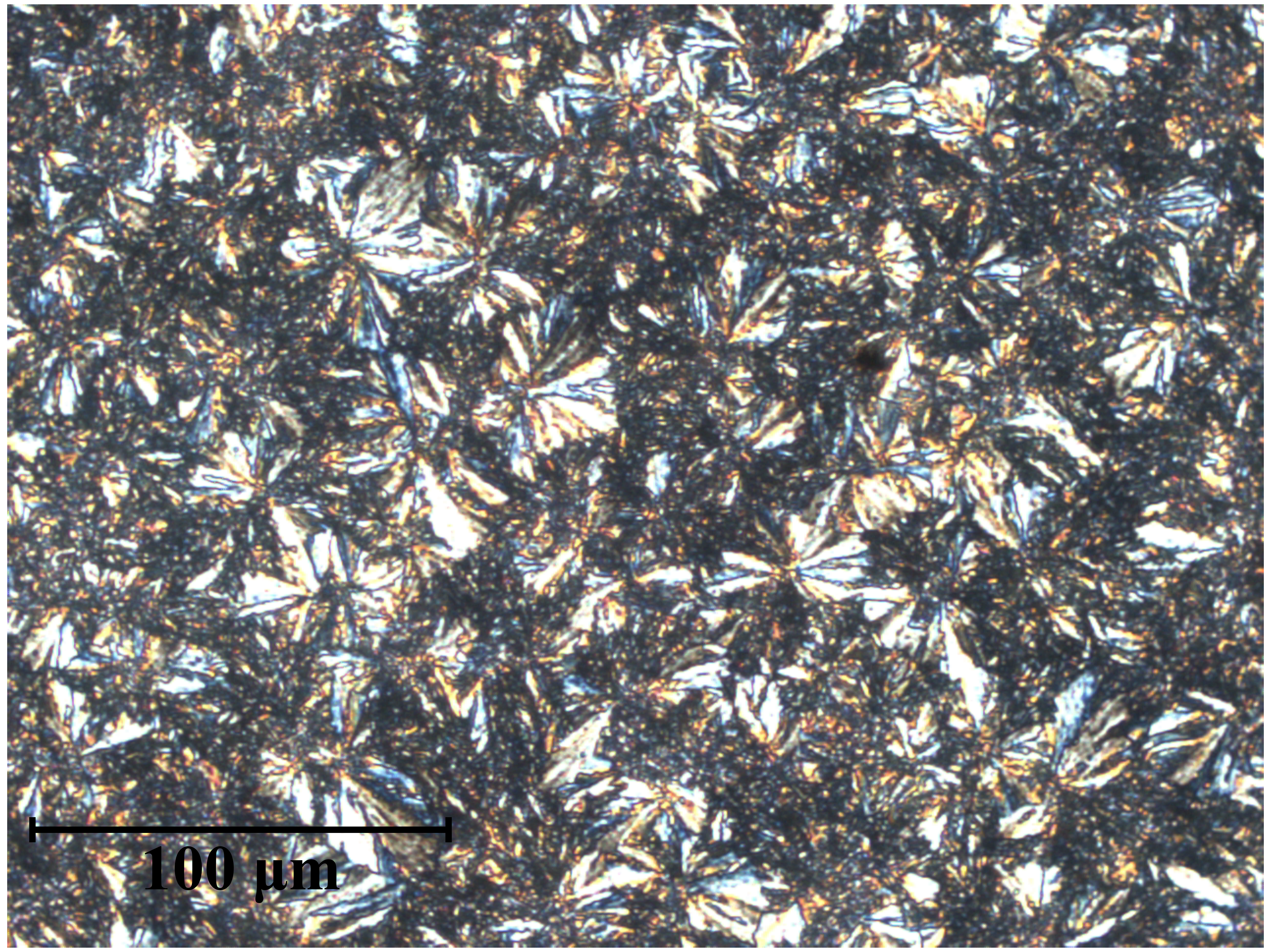
Phot.-Peak



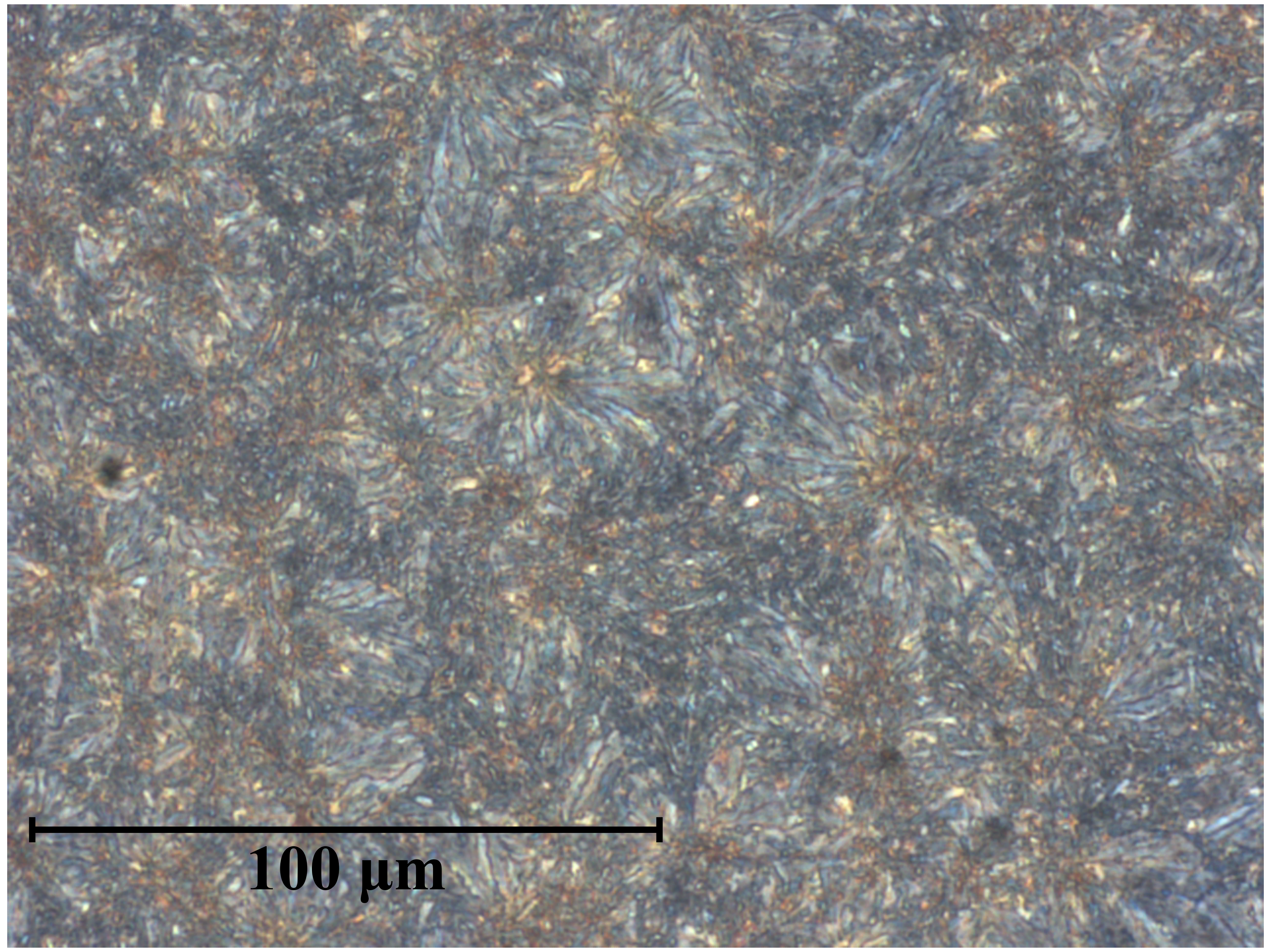
^{137}Cs Spectrum (Self Trigger)
χ^2 / ndf 62.54 / 56
μ 8458 ± 13.8
σ / μ 0.027 ± 0.002
Events / 40 p.e.
Detected Light (p.e.)
0
2000
4000
6000
8000
10000
12000
1
10
10^2
10^3
10^4

TPB Surface

Polarizing Microscope



Phase-Contrast Microscope



Thickness ~ 1 um (30-40 ug/cm^2)

Experimental setup

☐ Spectrometer

Spectroscopic method
- w/diffraction grating

Measureable Wavelength region
- 200~900nm

☐ Measurement

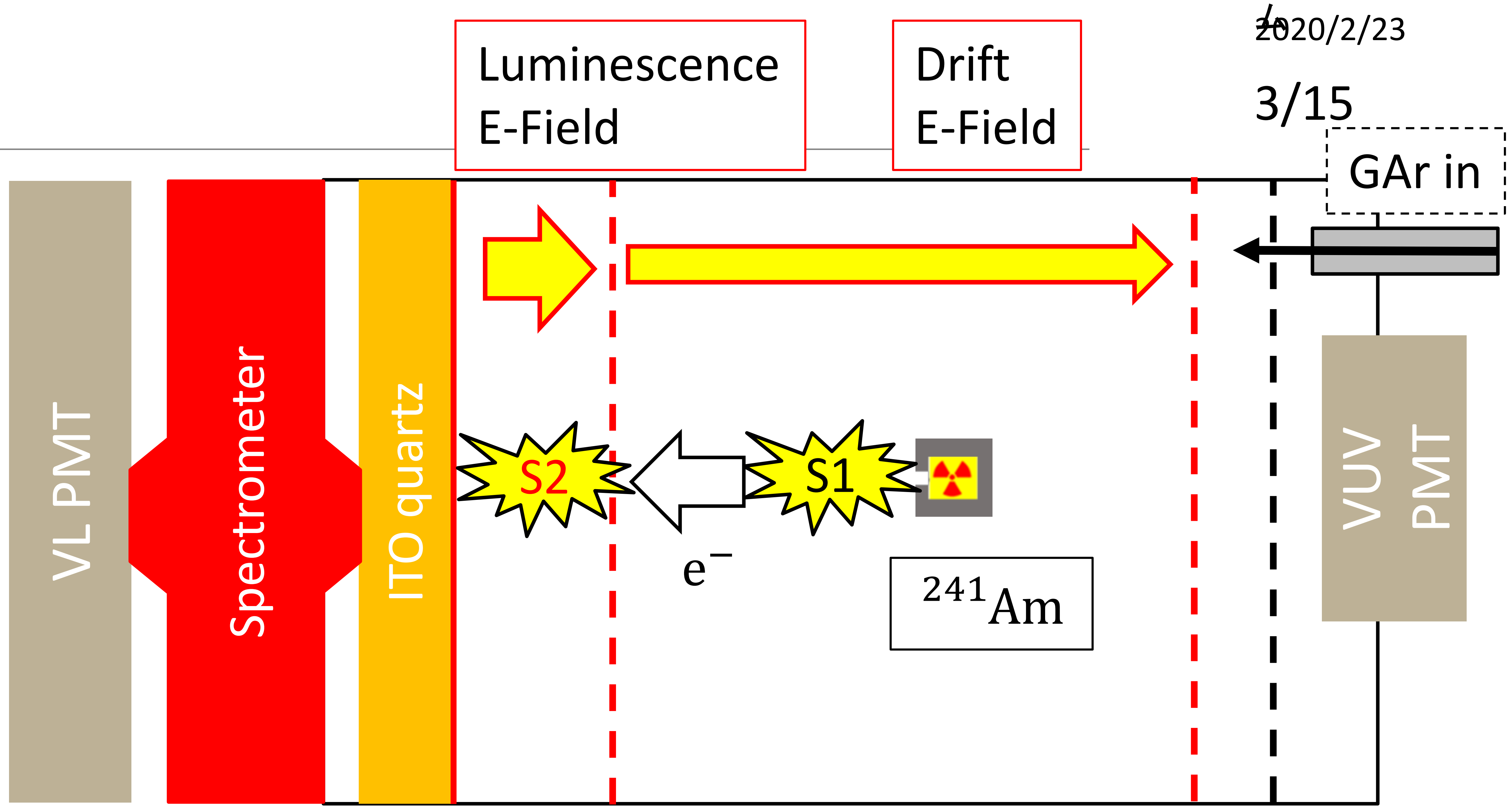
Gas Flow
- After 3hours gas inflow, start data taking for spectrum measurement.

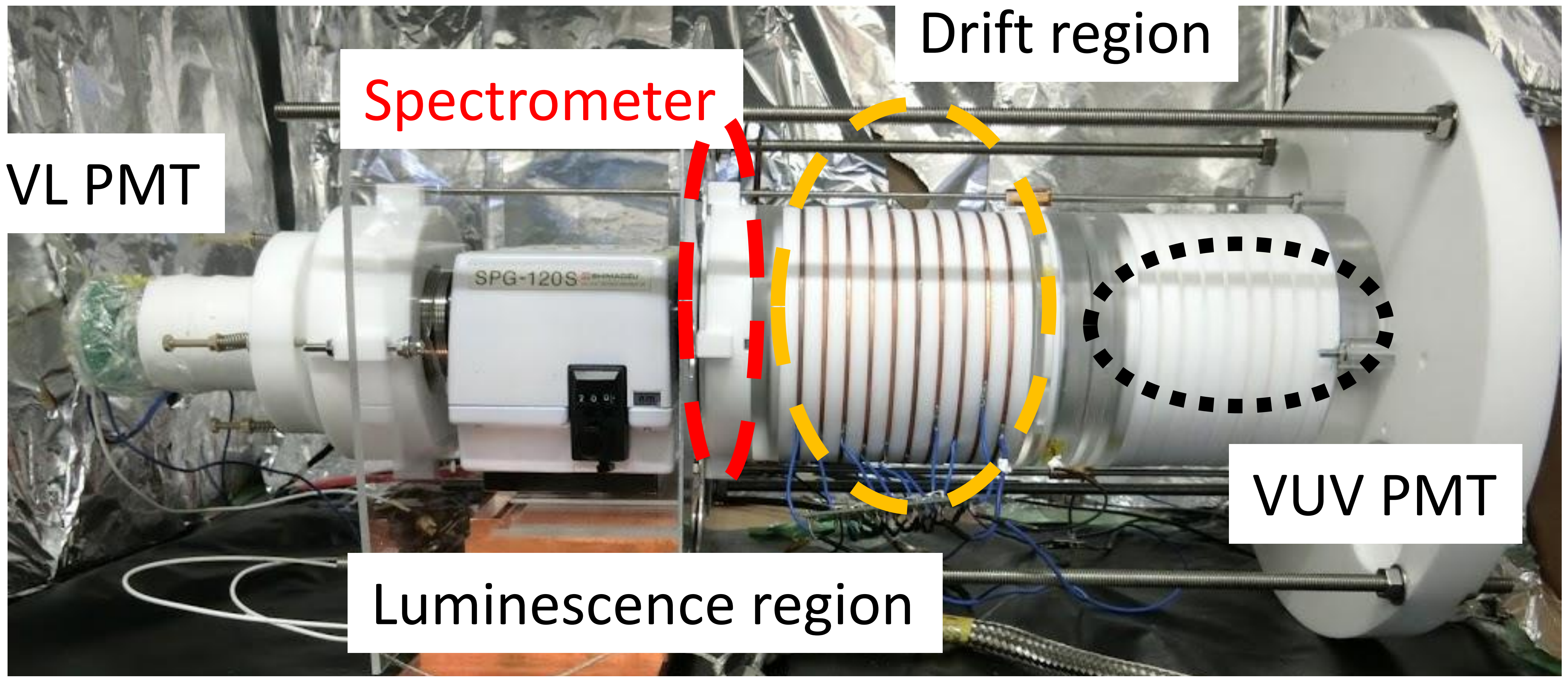
Luminescence E-Field
- 4.6, 8.3Td(1.125, 2.03kV/cm @300K)

Drift E-Field
- 0.1kV/cm (fixed)

Wavelength resolution
- ~30nm

Measured Time
- 15min/meament point
(α ray event rate : ~50Hz)





analysis

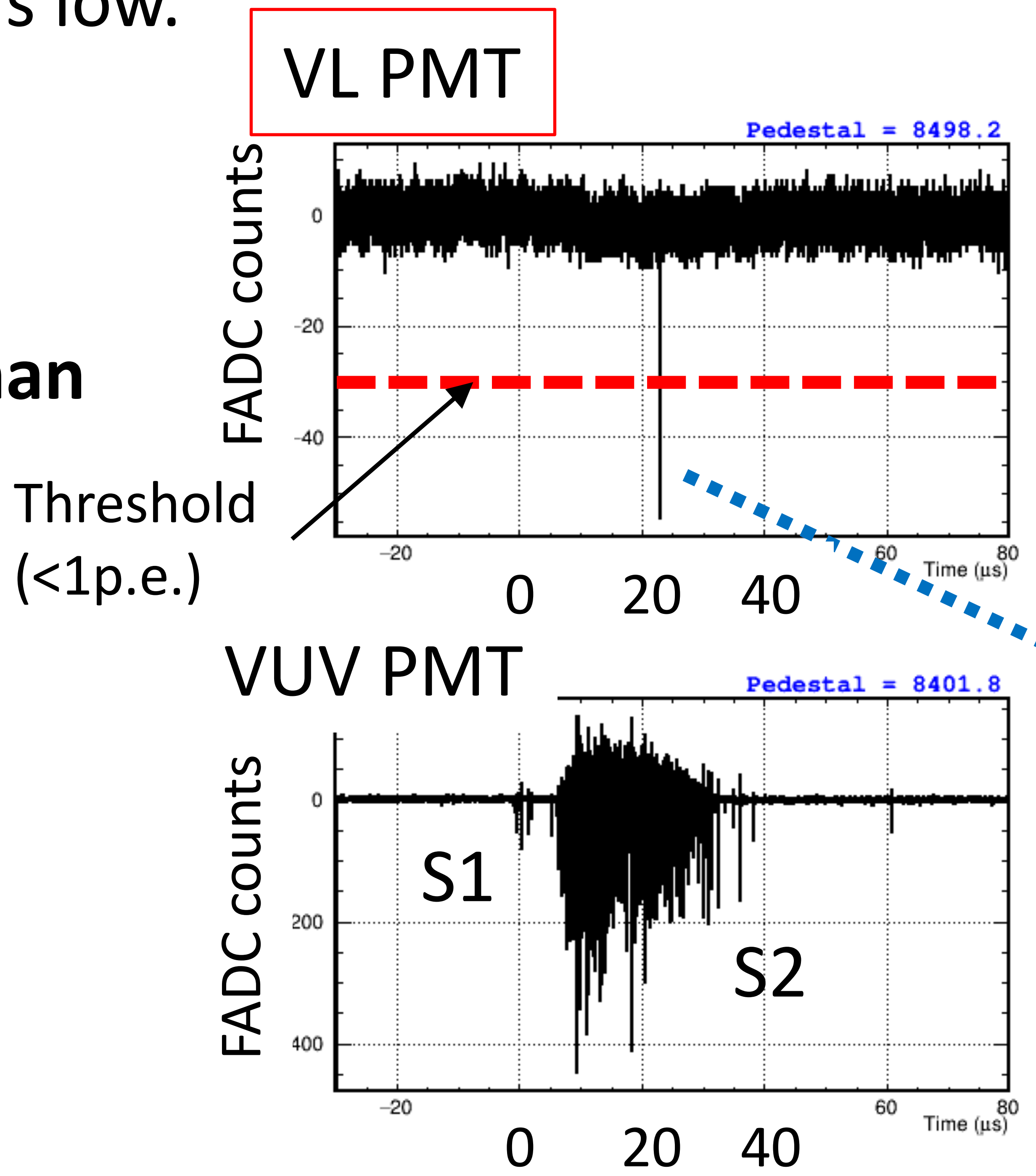
S2 light yield that passed through the spectrometer is low.

Ex) Original : $O(10^4)$ photons.

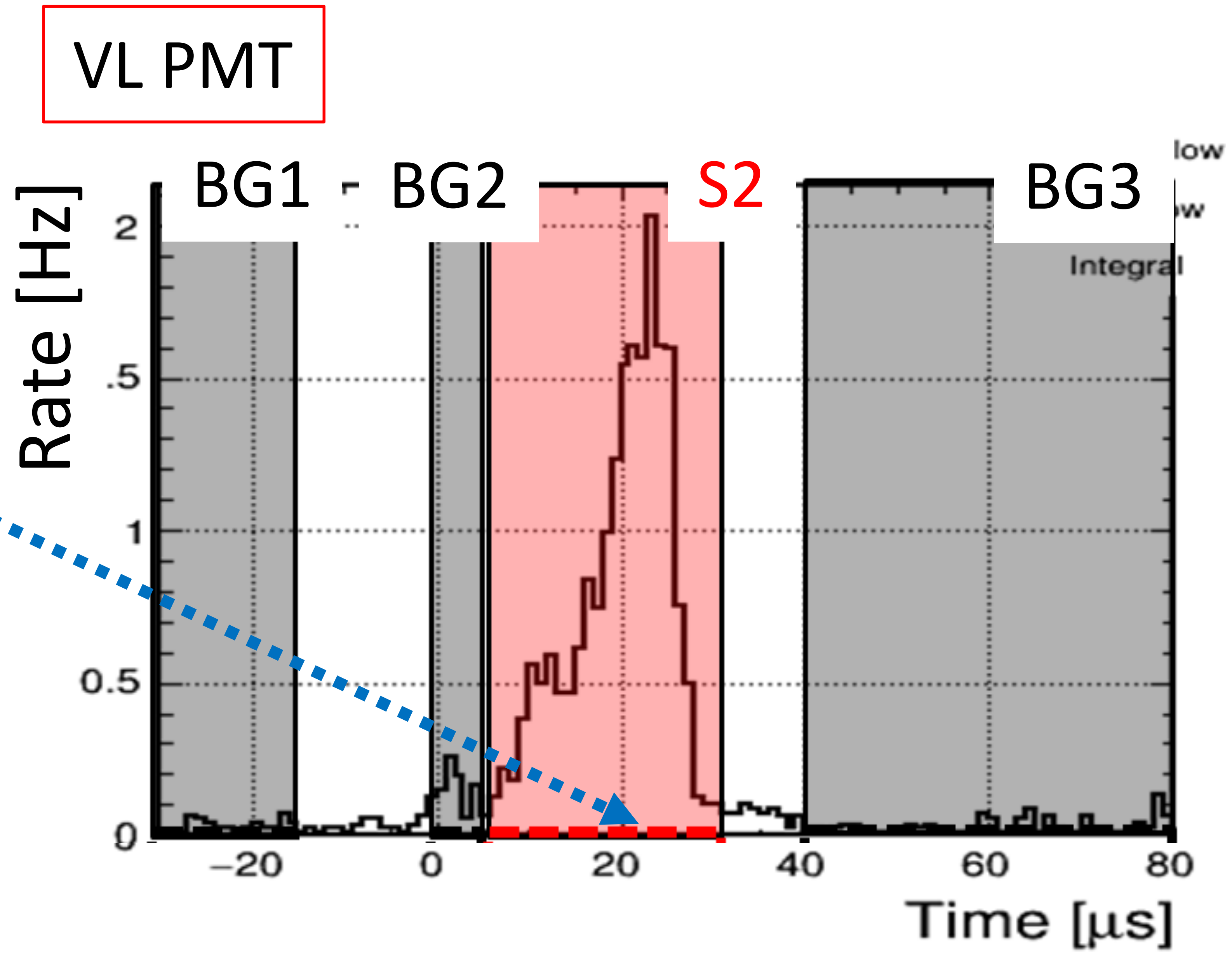
- After spectroscopy : $O(10^{-1})$ photons.

- **Count the event detected by VL PMT for more than one photons, and calculate the event rates at each wavelength.**

- Waveform(1event)



- Waveform($O(100)$event)
  (Add bins that exceed threshold.)



☐ background subtraction

Define a signal region(S2 region) and
3 back ground region(BG1,2,3 region).

- Subtract BG event with below equation.

$$S2_{cor} = S2 - \frac{\left(BG1 * \frac{25}{15} + BG2 * \frac{25}{5} + BG3 * \frac{25}{45}\right)}{3} \text{ [Hz]}$$

Integral region	Integral time window
S2 region	$[5\mu s, 30\mu s]$
BG1 region	$[-30\mu s, -15\mu s]$
BG2 region	$[0\mu s, 5\mu s]$
BG3 region	$[35\mu s, 80\mu s]$

Accidental rate

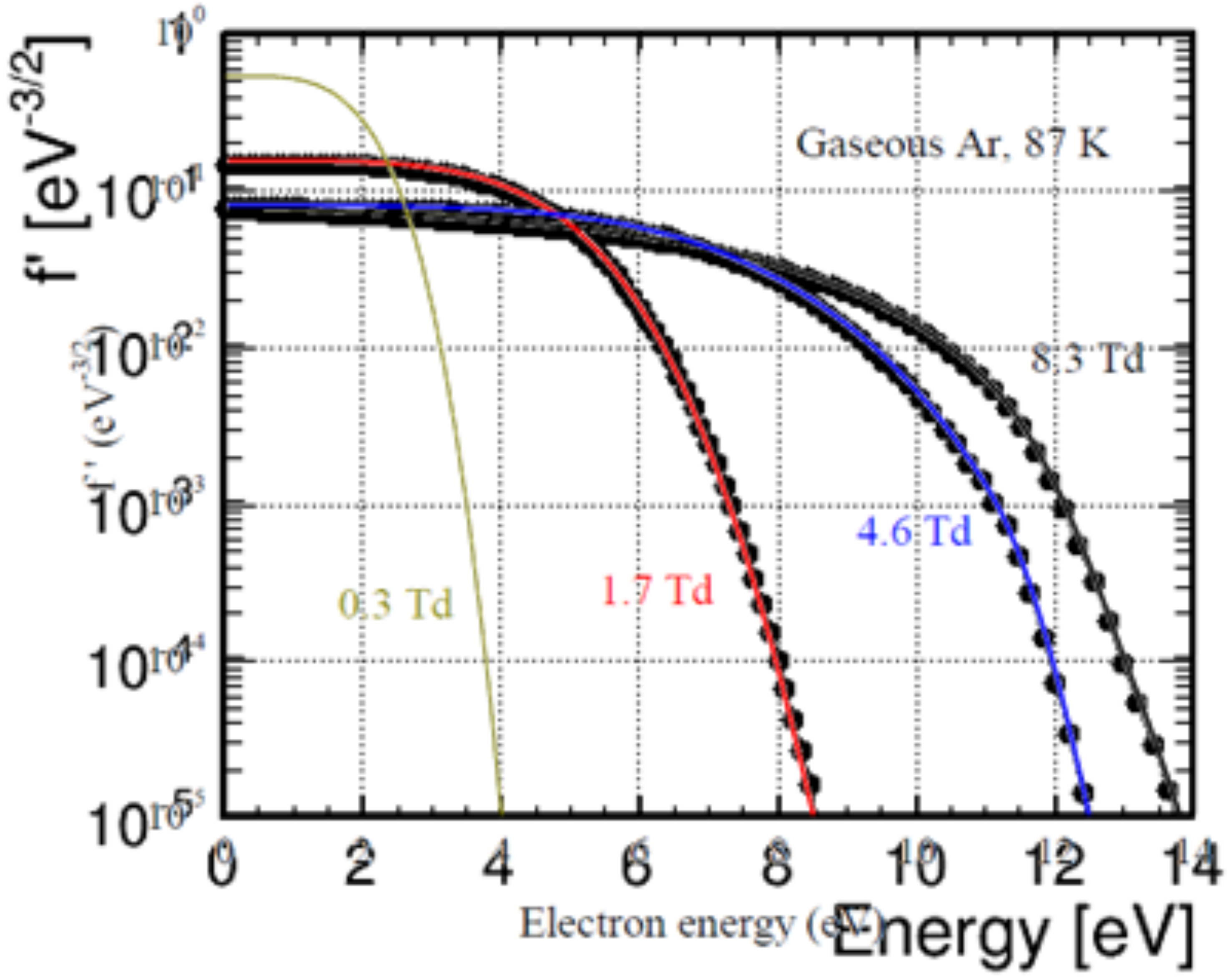
(The rate when the light exit of the spectrometer is closed.)

$S2_{cor} = (0.35 \pm 1.5) \times 10^{-2}$[Hz]→0 consistent

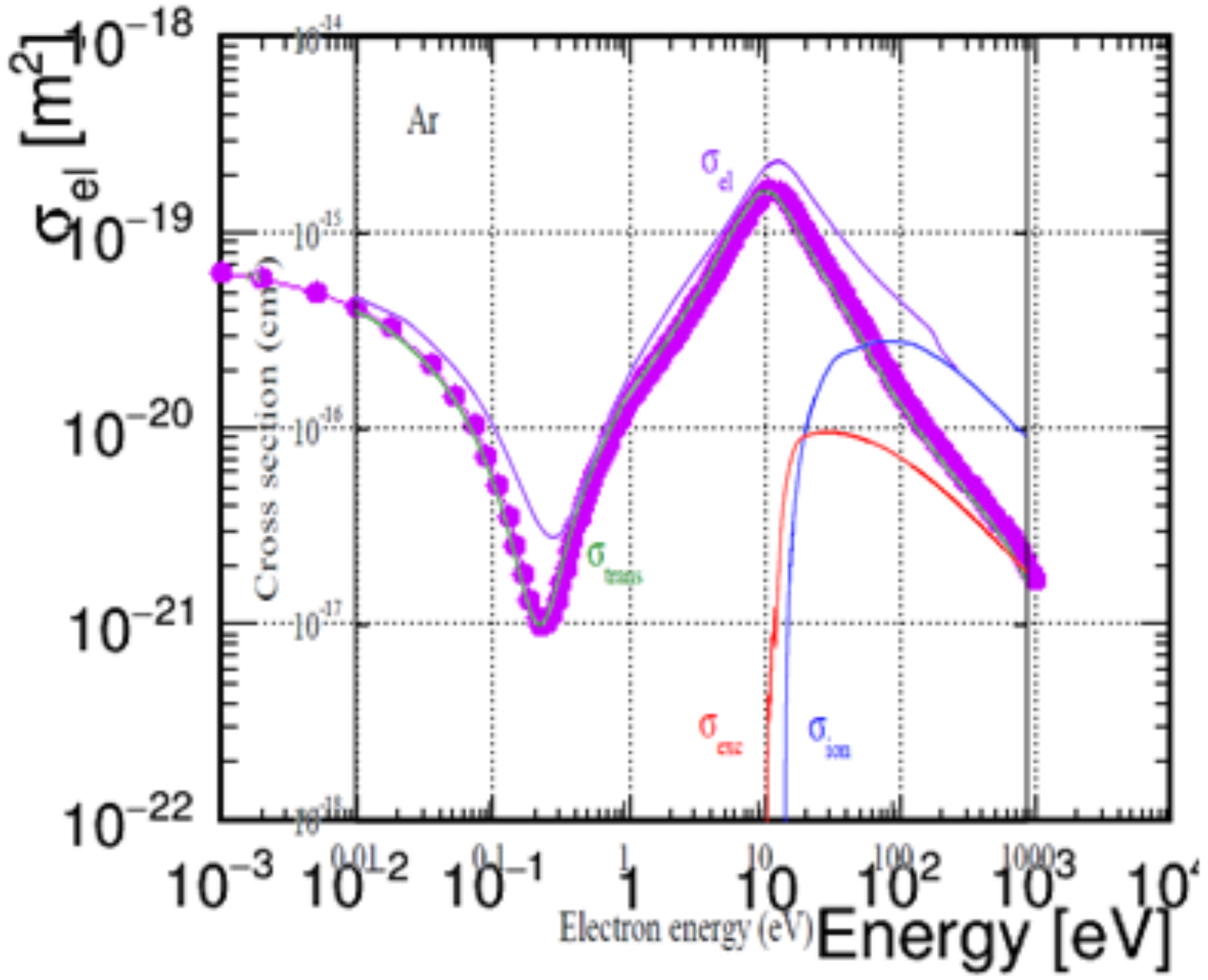
NBrS Calculation

- Based on "Neutral bremsstrahlung in two-phase argon electroluminescence: further studies and possible applications"
- Use "Bolsig+" and "Magboltz".

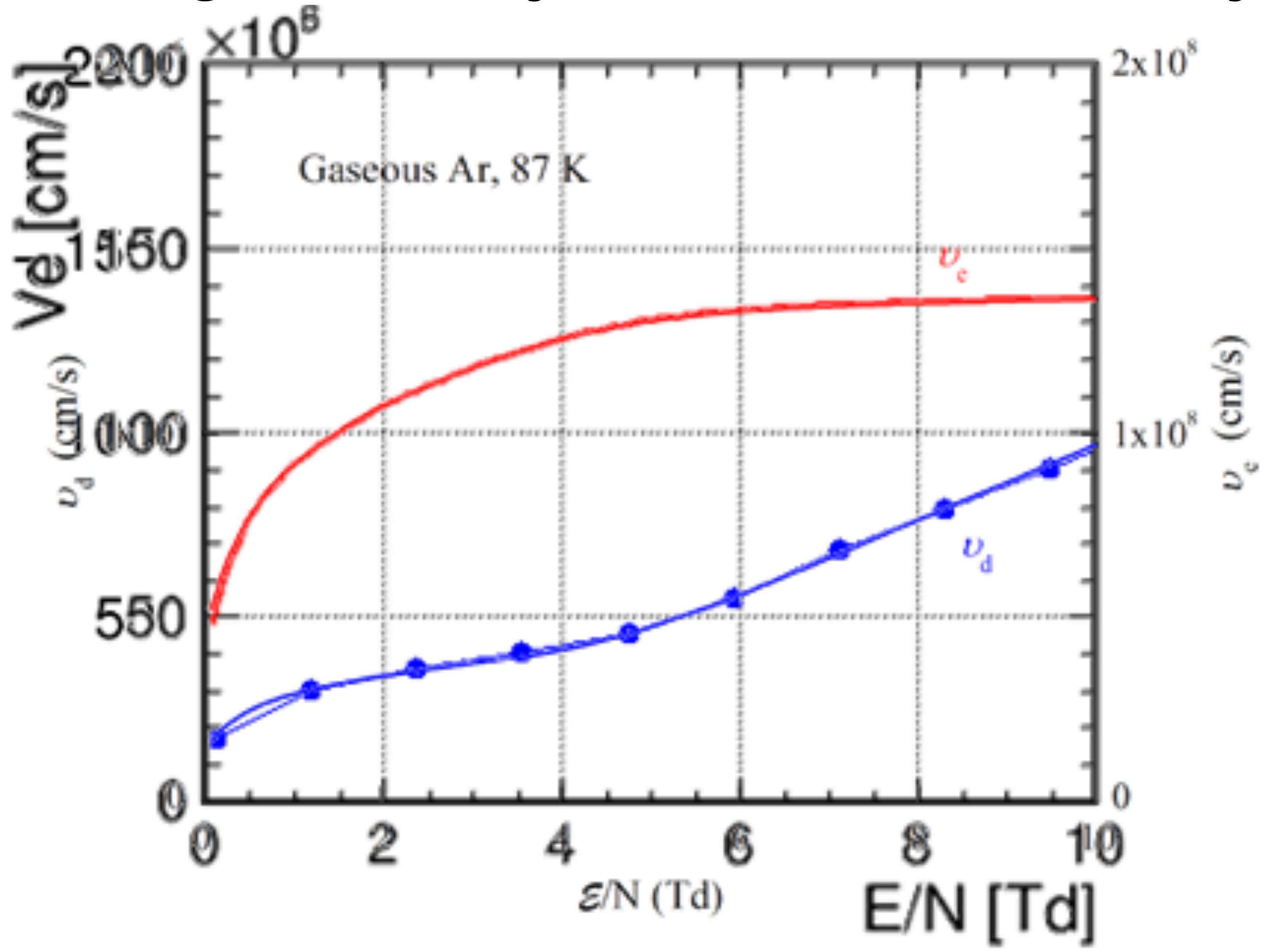
Electron Energy

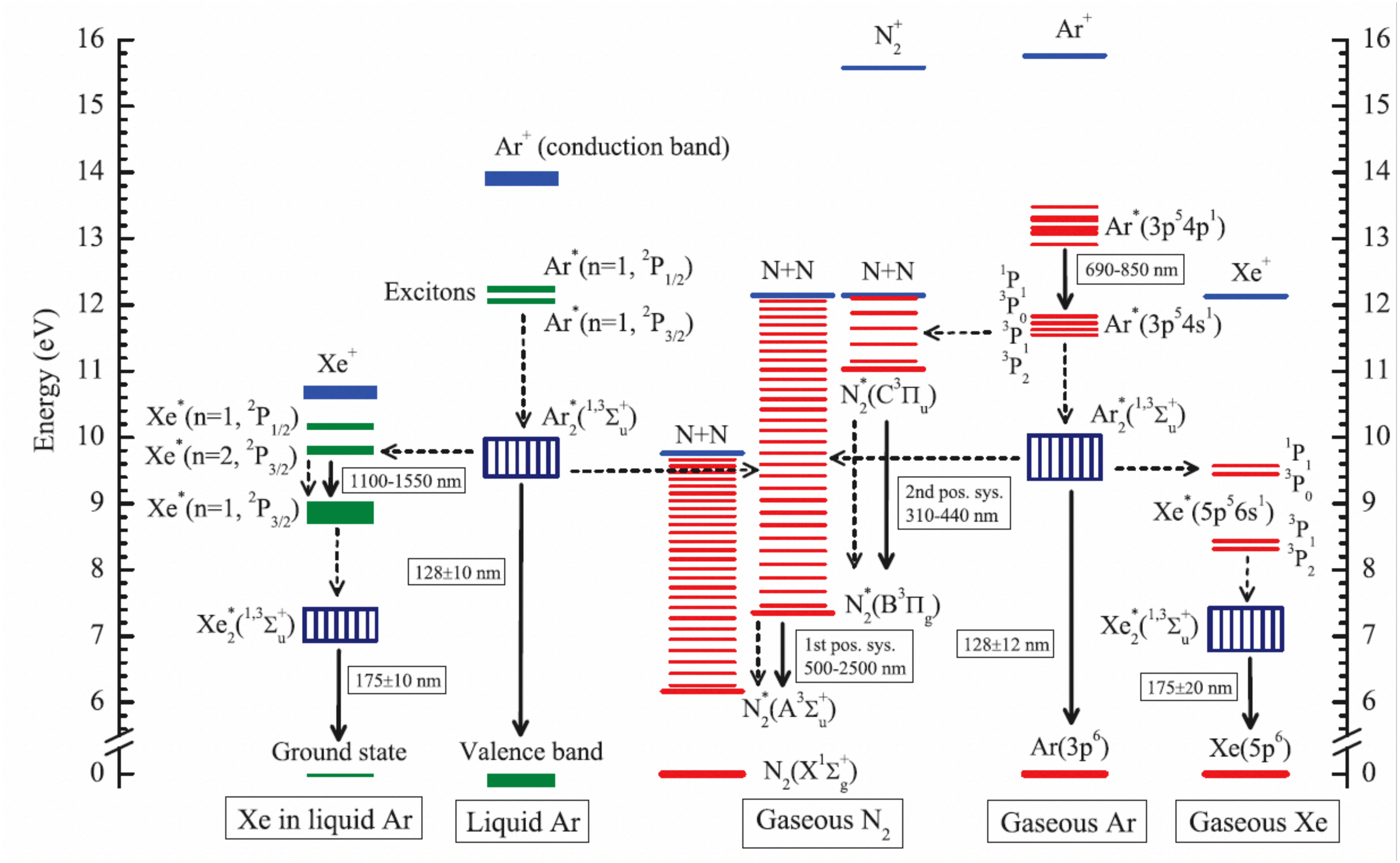


Cross Section



Average Velocity (Red), Drift Velocity (Blue)




Energy (eV)
Ar+ (conduction band)
Excitons
Ar*(n=1, 2P1/2)
Ar*(n=1, 2P3/2)
Xe+
Xe*(n=1, 2P1/2)
Xe*(n=2, 2P3/2)
Xe*(n=1, 2P3/2)
1100-1550 nm
Ar2*(1,3Σu+)
128±10 nm
Xe2*(1,3Σu+)
175±10 nm
Ground state
Valence band
N2+
Ar+
N+N
N+N
N+N
N2*(C3Πu)
2nd pos. sys.
310-440 nm
N2*(B3Πg)
1st pos. sys.
500-2500 nm
N2*(A3Σu+)
N2(X1Σg+)
Ar*(3p54p1)
690-850 nm
1P1
3P0
3P1
3P2
Ar*(3p54s1)
Ar2*(1,3Σu+)
128±12 nm
Ar(3p6)
Xe+
1P1
3P0
Xe*(5p56s1)
3P1
3P2
Xe2*(1,3Σu+)
175±20 nm
Xe(5p6)
Xe in liquid Ar
Liquid Ar
Gaseous N2
Gaseous Ar
Gaseous Xe

Ar　アルゴン　　高純度ガス

製品規格		G1	G2	G3
純度		＞99.9999　vol.%	＞99.9995　vol.%	＞99.999　vol.%
不純物	N_2	＜0.3　vol.ppm	＜0.5　vol.ppm	—
	O_2	＜0.1　vol.ppm	＜0.2　vol.ppm	＜0.2　vol.ppm
	H_2	＜0.1　vol.ppm	＜0.5　vol.ppm	＜1　vol.ppm
	CO	＜0.1　vol.ppm	＜0.2　vol.ppm	—
	CO_2	＜0.1　vol.ppm	＜0.2　vol.ppm	＜1　vol.ppm
	THC	＜0.1　vol.ppm	＜0.2	＜1　vol.ppm
	H_2O	＜−80　℃	＜−80　℃	＜−70　℃
容器		3.4L／10L／47L		
充填量		14.7MPa		
容器弁		JIS.W22−14R		

SHIMADZU SPG-120S

- Range 200 - 900 nm
- Diffraction Eff. >50%
- Accuracy +/- 1.5 nm
- Resolution 1 nm
- F-Value F = 3
- https://www.shimadzu.co.jp/products/opt/products/mono01-12-02.html

E [keV]	Source	Note
2.82	^{37}Ar	Diffused
59.54	^{241}Am	α -tagging
109.8	^{19}F (n, n' γ)	γ from PTFE
197.1	^{19}F (n, n' γ)	γ from PTFE

E [keV]	Source	Note
356.0	^{133}Ba	
511.0	^{22}Na	Back-to-back
661.7	^{137}Cs	
1274.6	^{22}Na