Validation of Optical simulation

BULLKID simulation meeting 20/02/26

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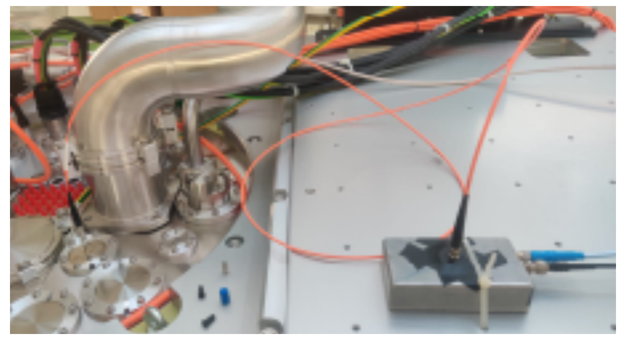
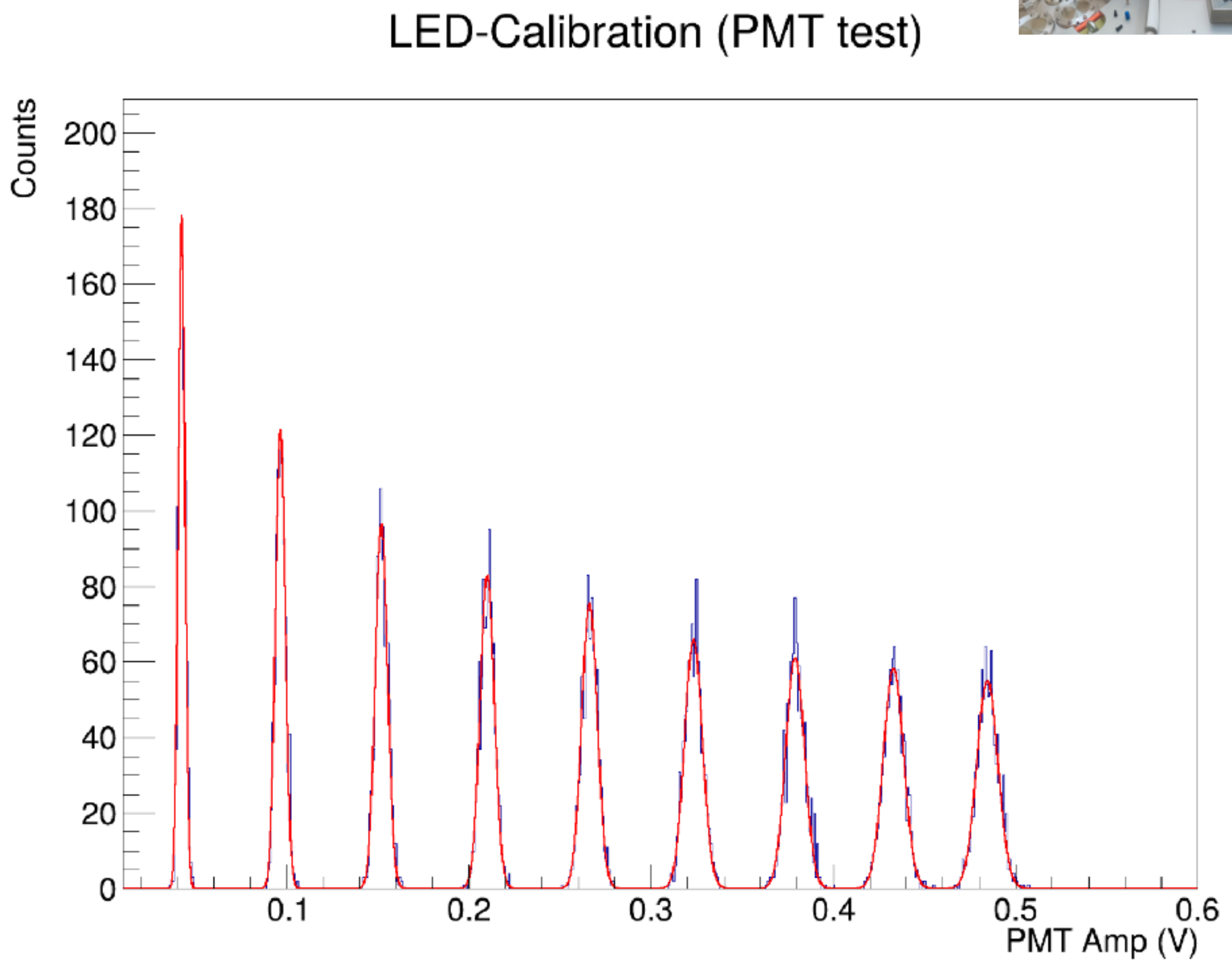
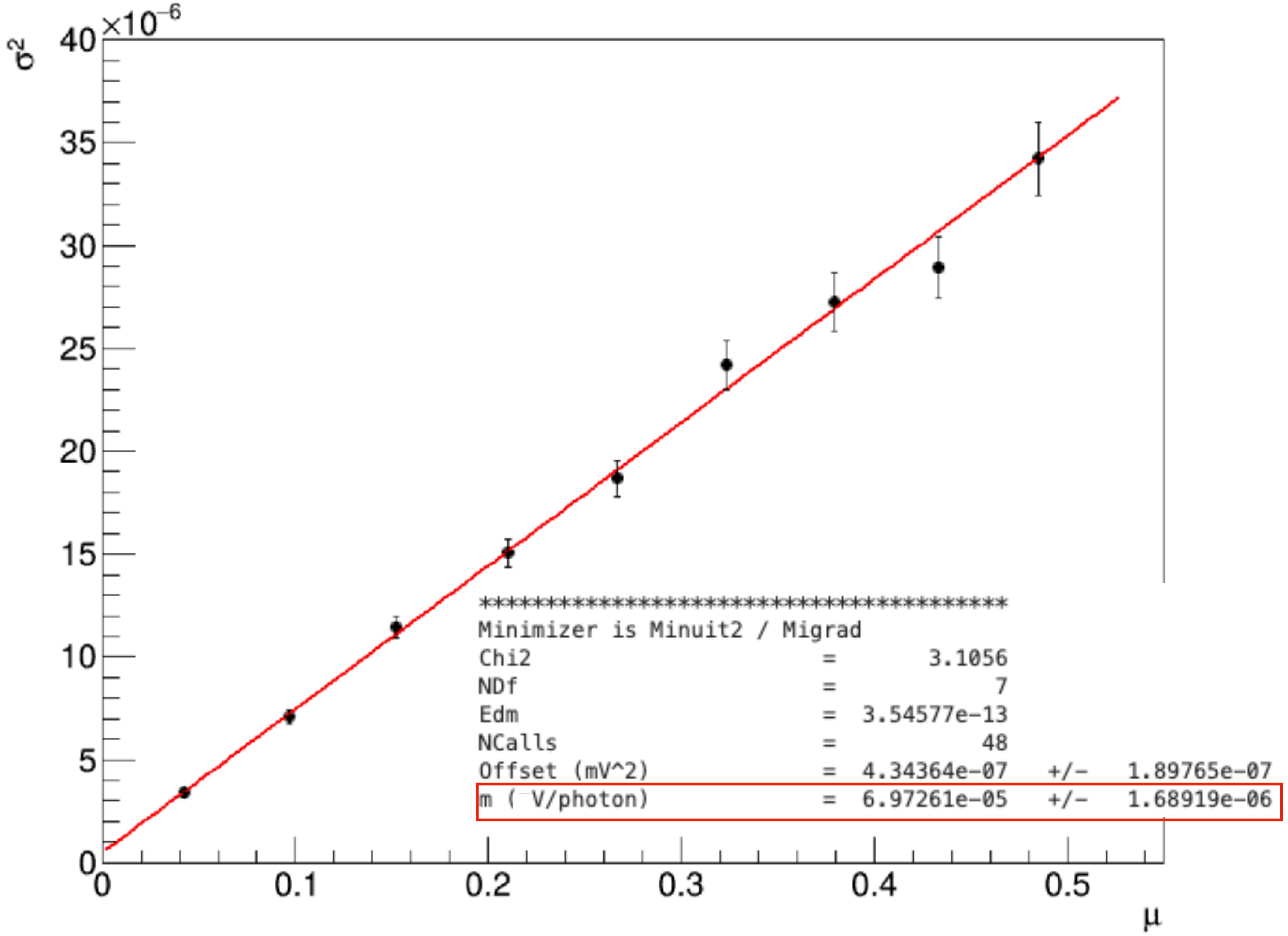
Calibration of PMT:

PMT Calibration

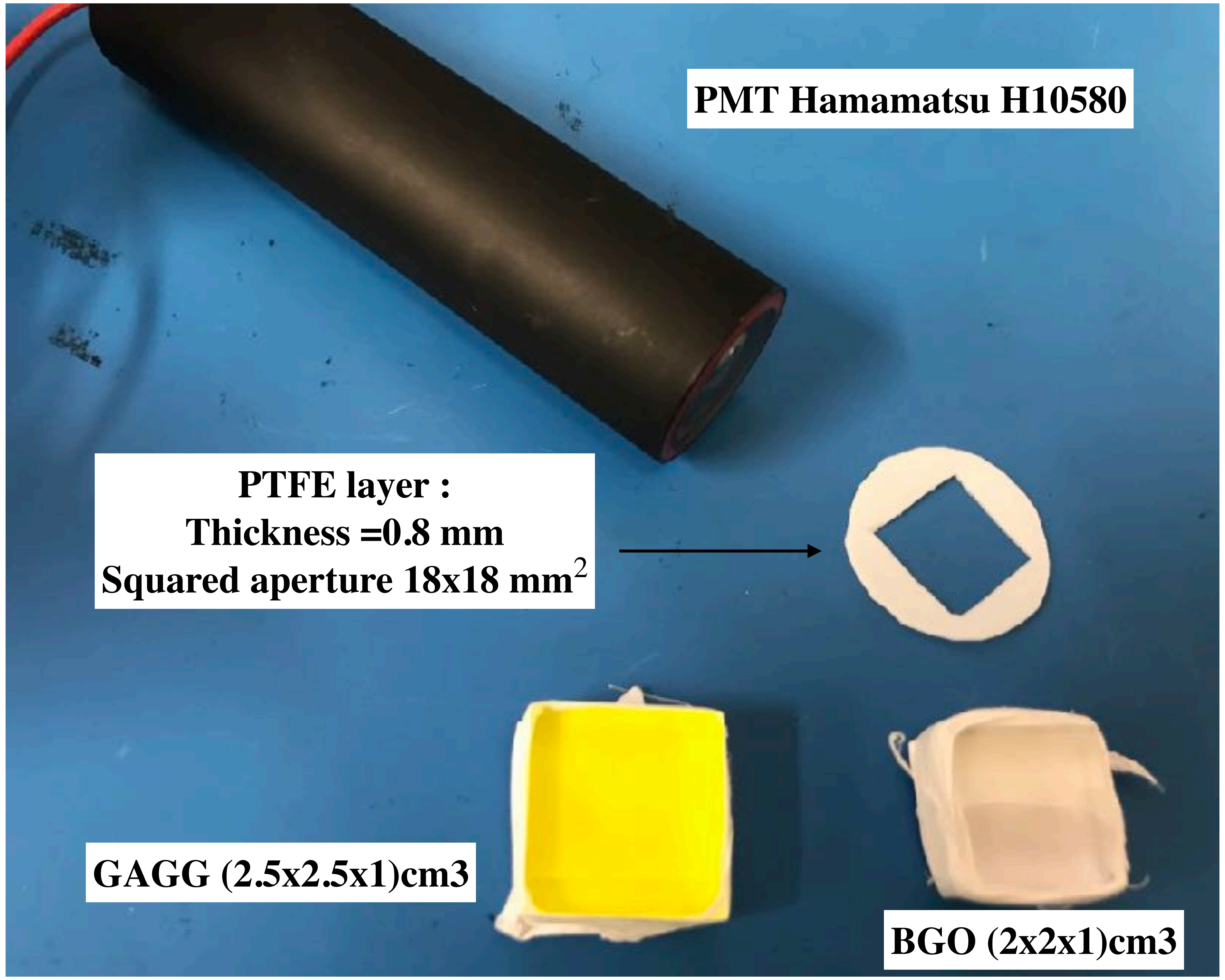


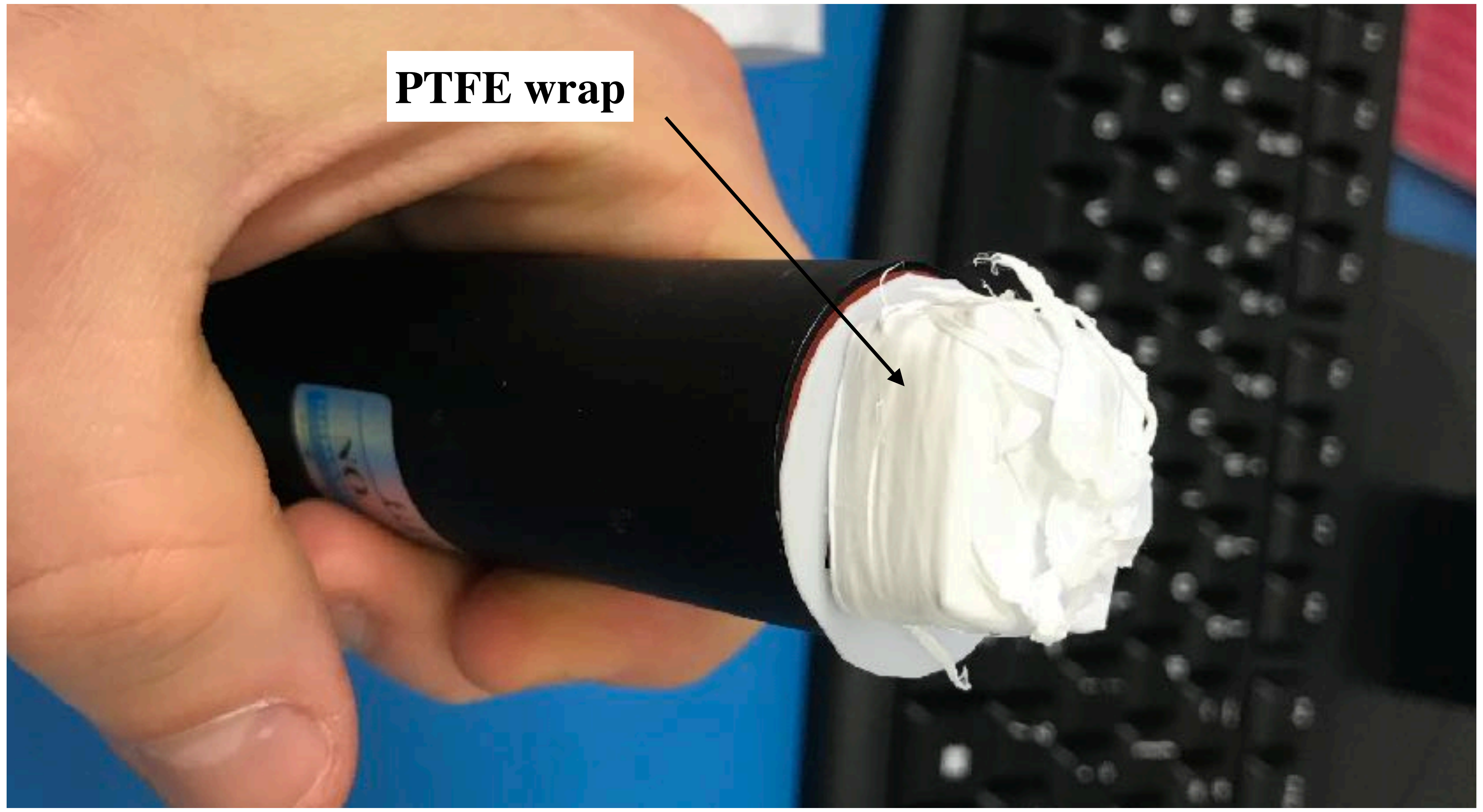




Warm tests of crystals:

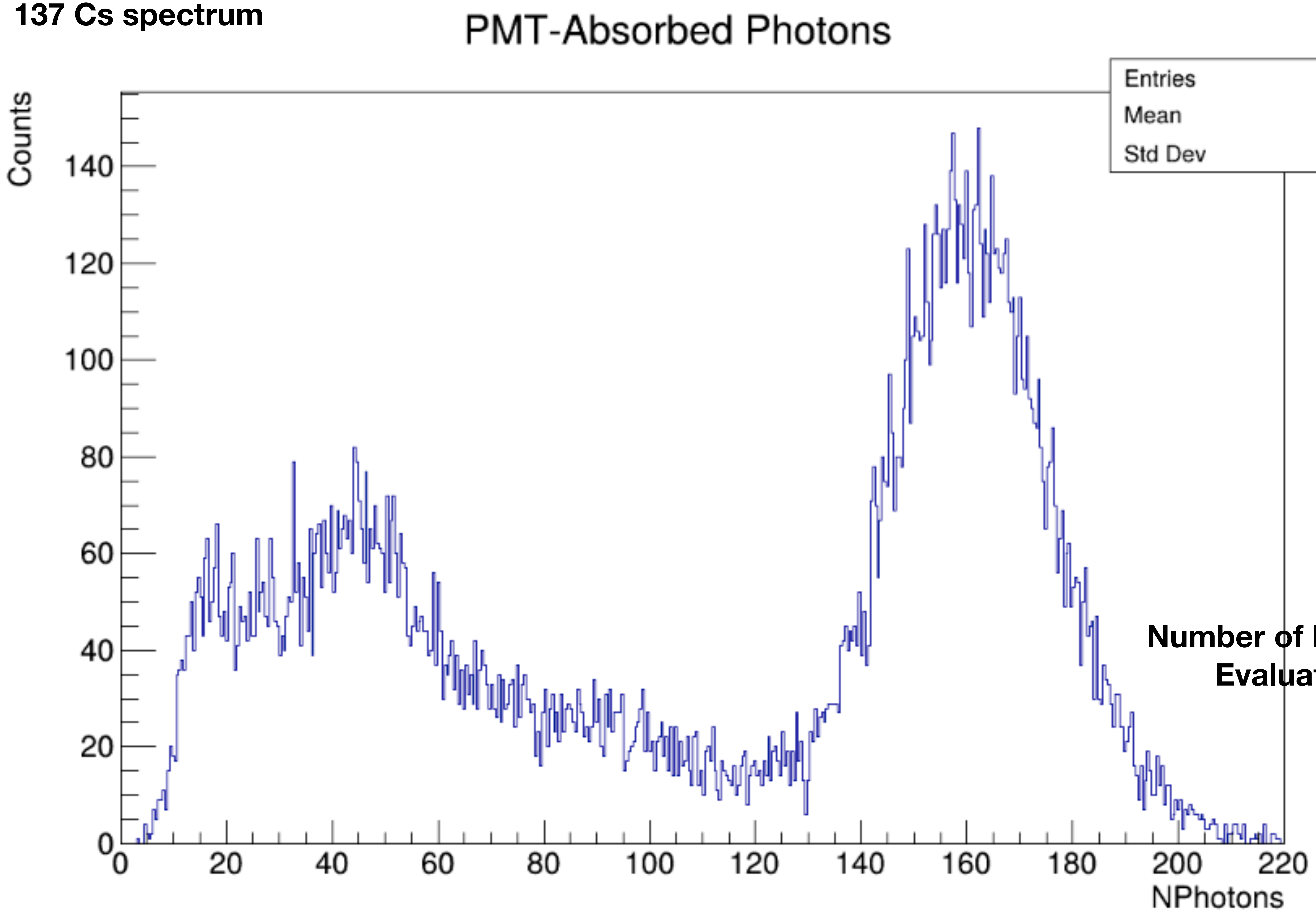
PMT+ crystals (BGO/GAGG)





Warm tests of crystals:

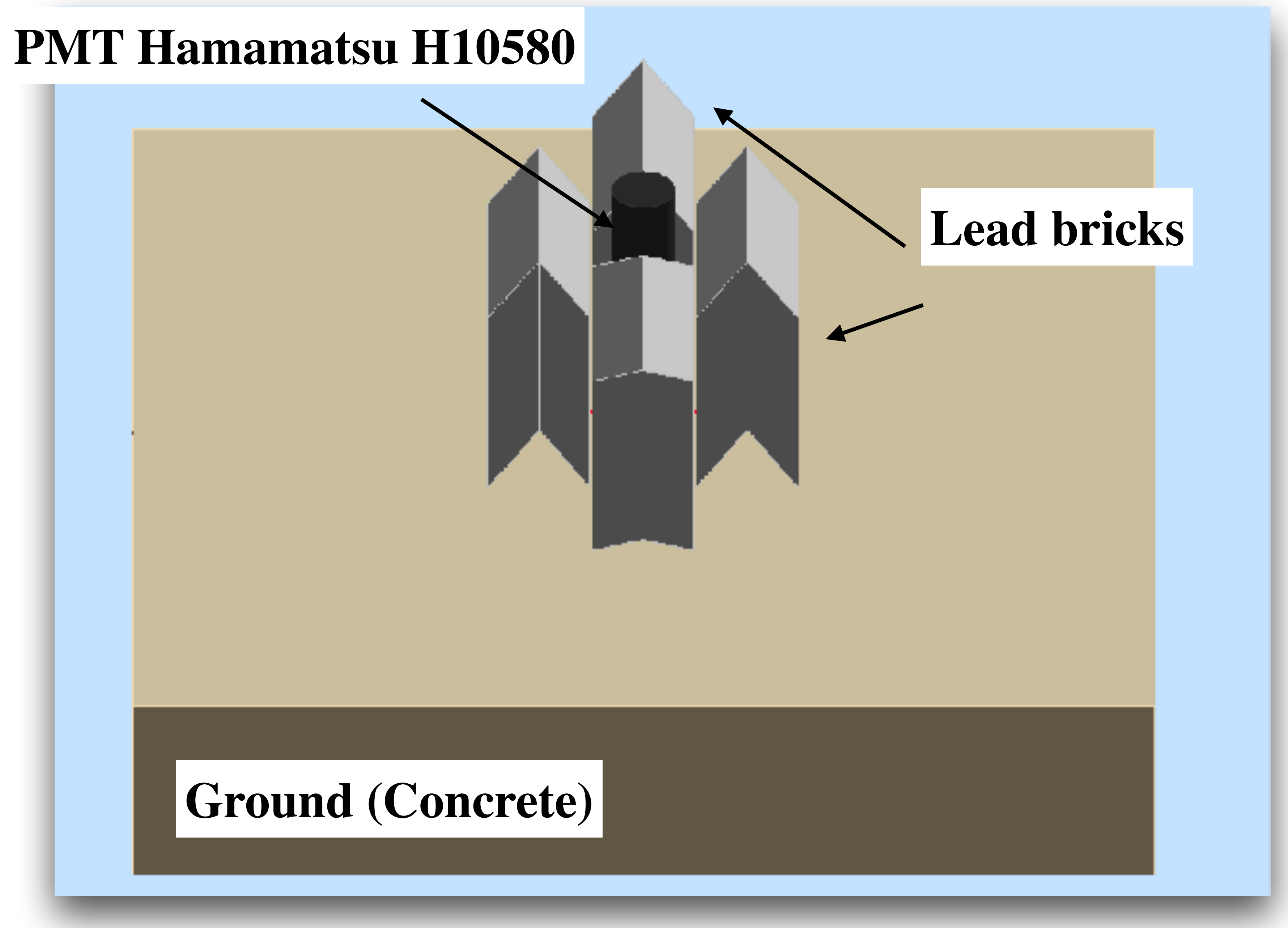
137 Cs spectrum

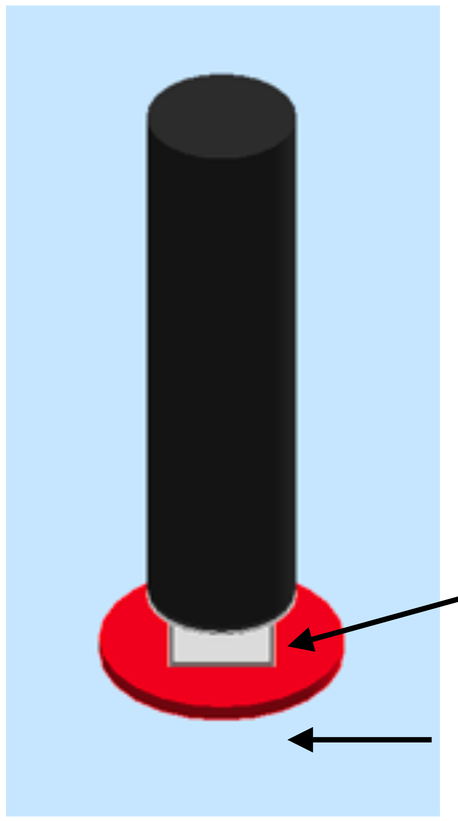


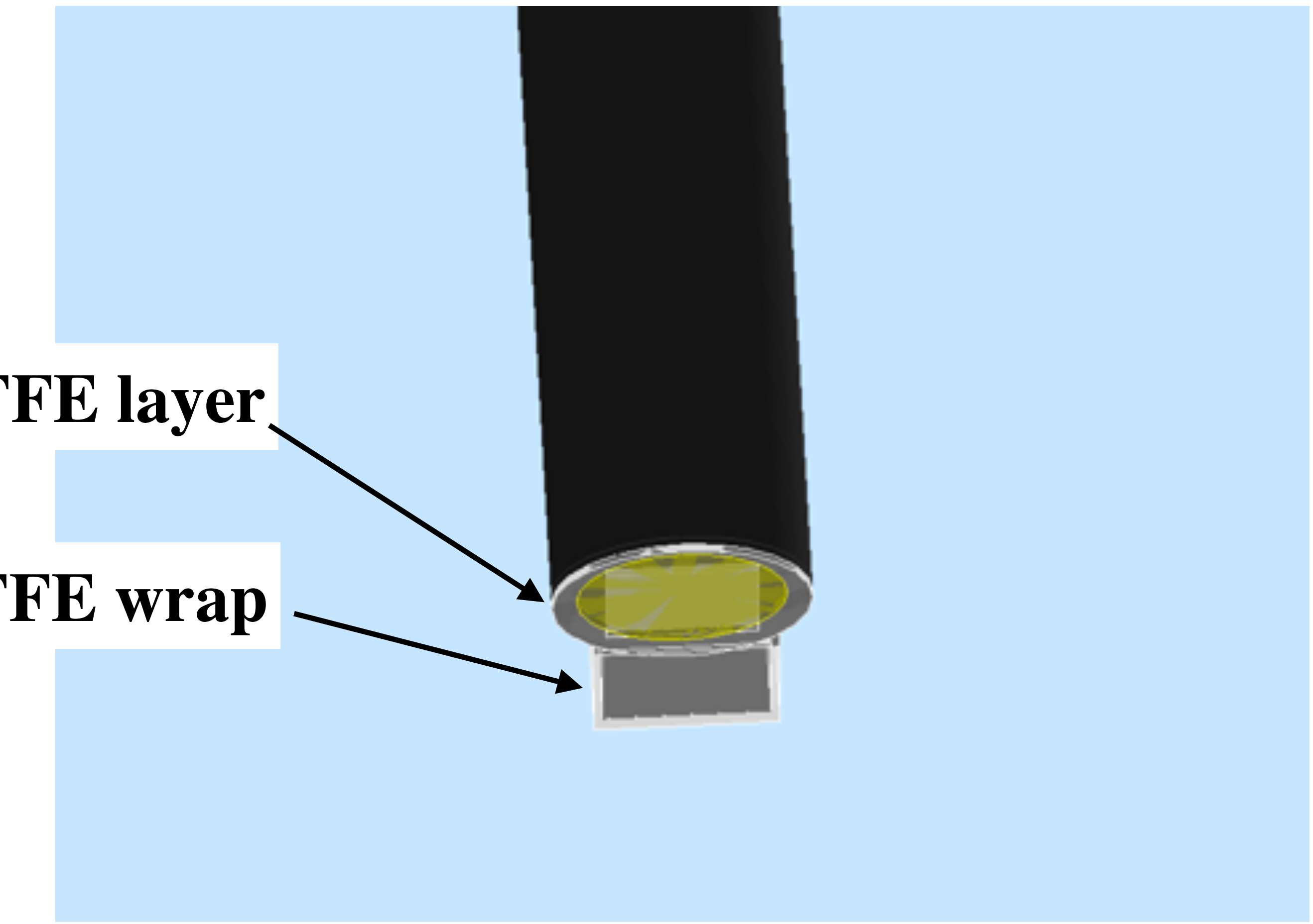
Number of Photons absorbed by the PMT
Evaluated using PMT calibration

Warm tests of crystals:

Simulation:





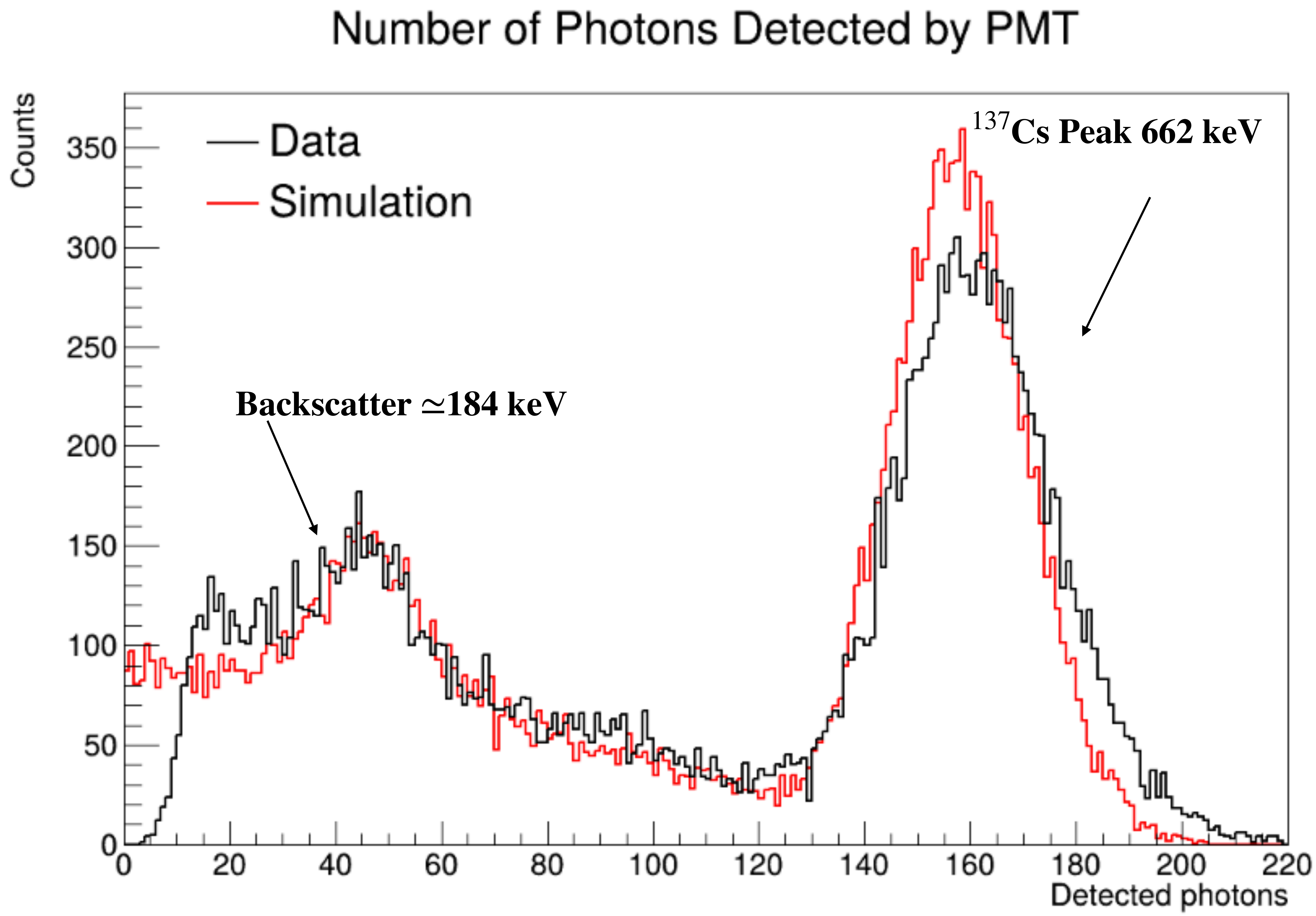


BGO LY	8000 ph/MeV
BGO absorption length	50 cm
PTFE surface	Lambertian refl. = 0.98
Distance PTFE wrap-crystal	1 um /no optical contact
PMT Quantum efficiency (data sheet value)	0.27

Detection of photons:
- PMT sensitive area:
  - Logical surface dielectric-metal
  - Detection efficiency=PMT Qe
- If (status=detection) {count the photon}

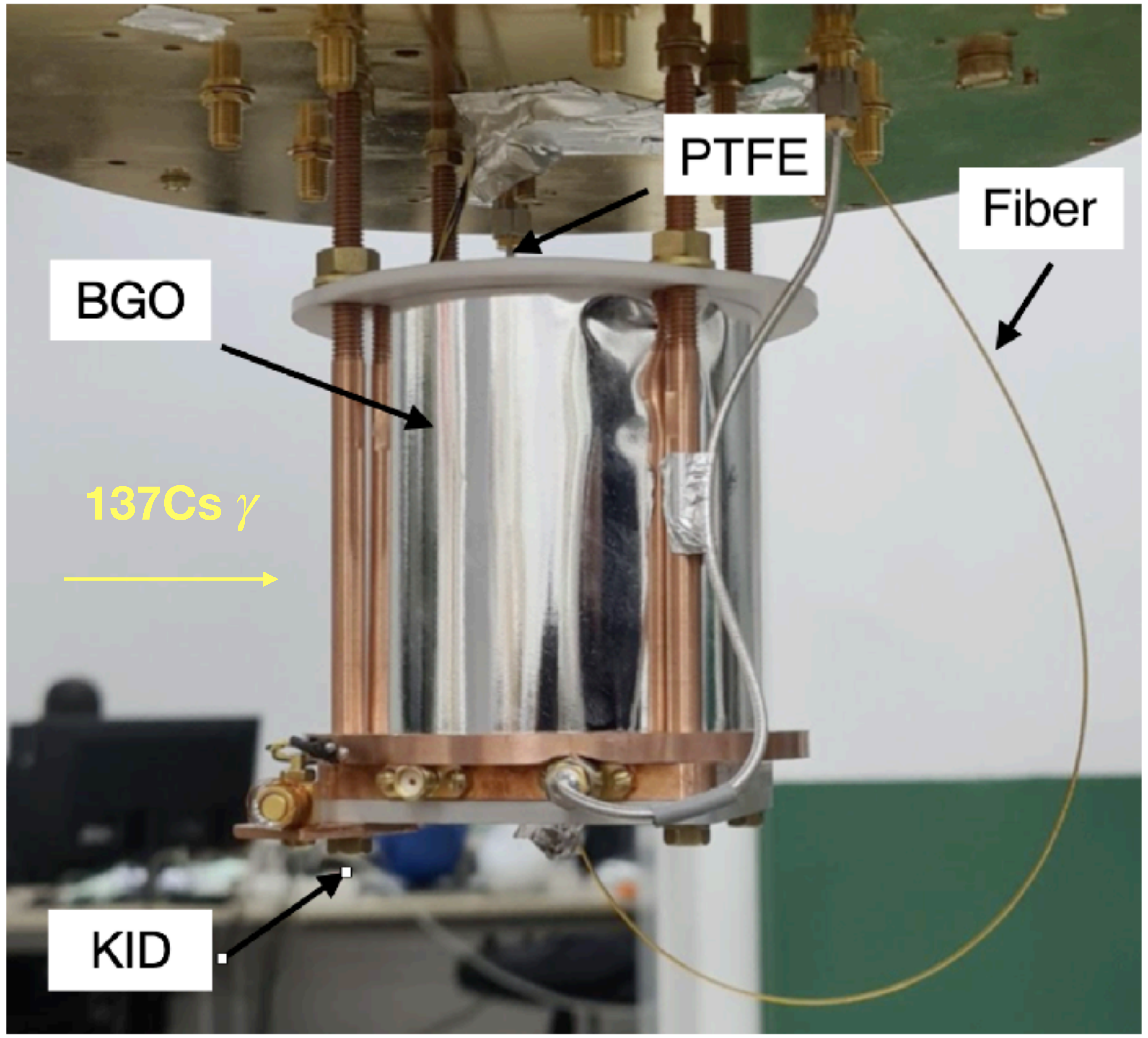
137Cs Source:
- Isotropic emission

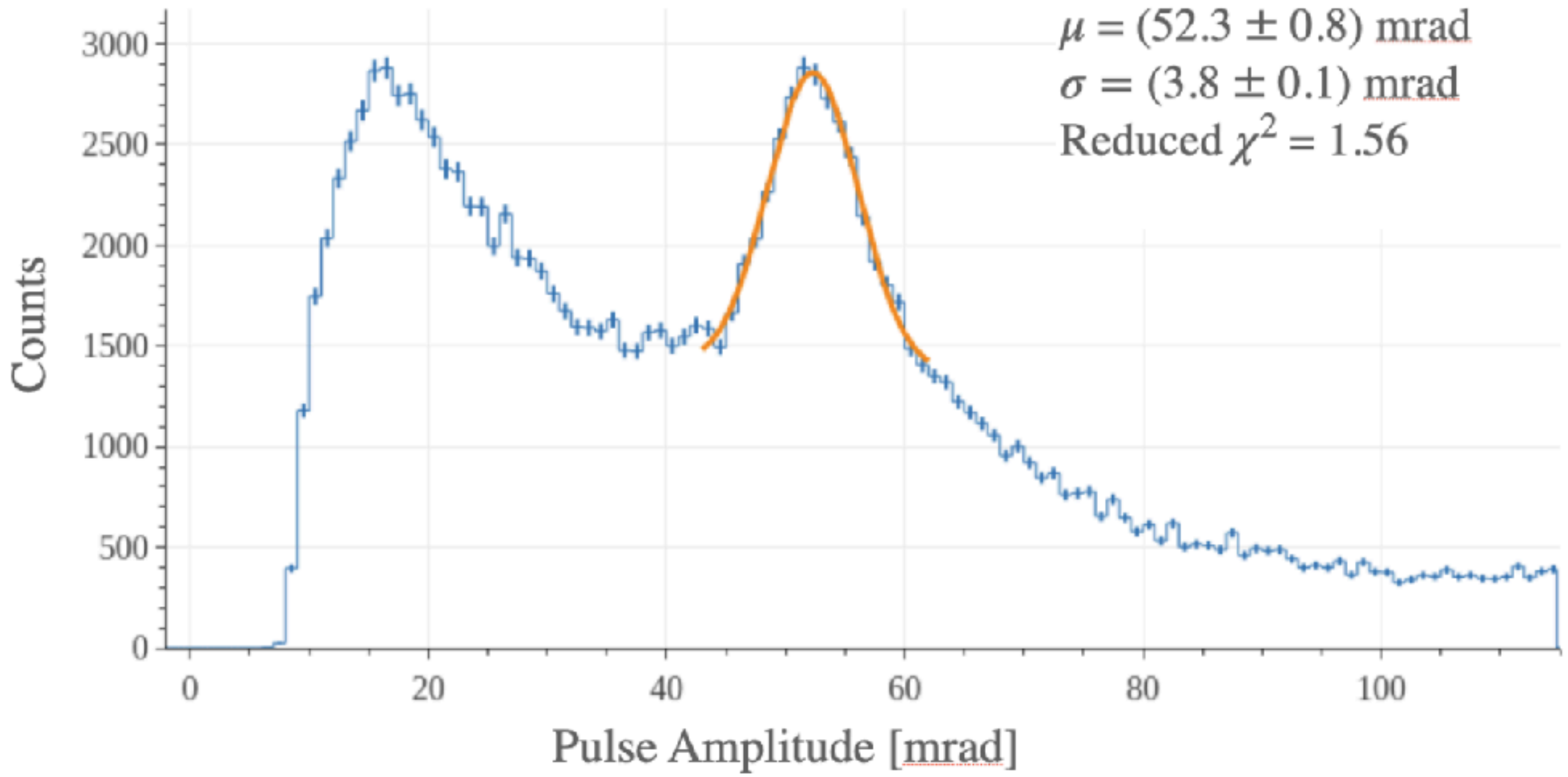
Warm tests of crystals:



Simulation: BigBGO tests

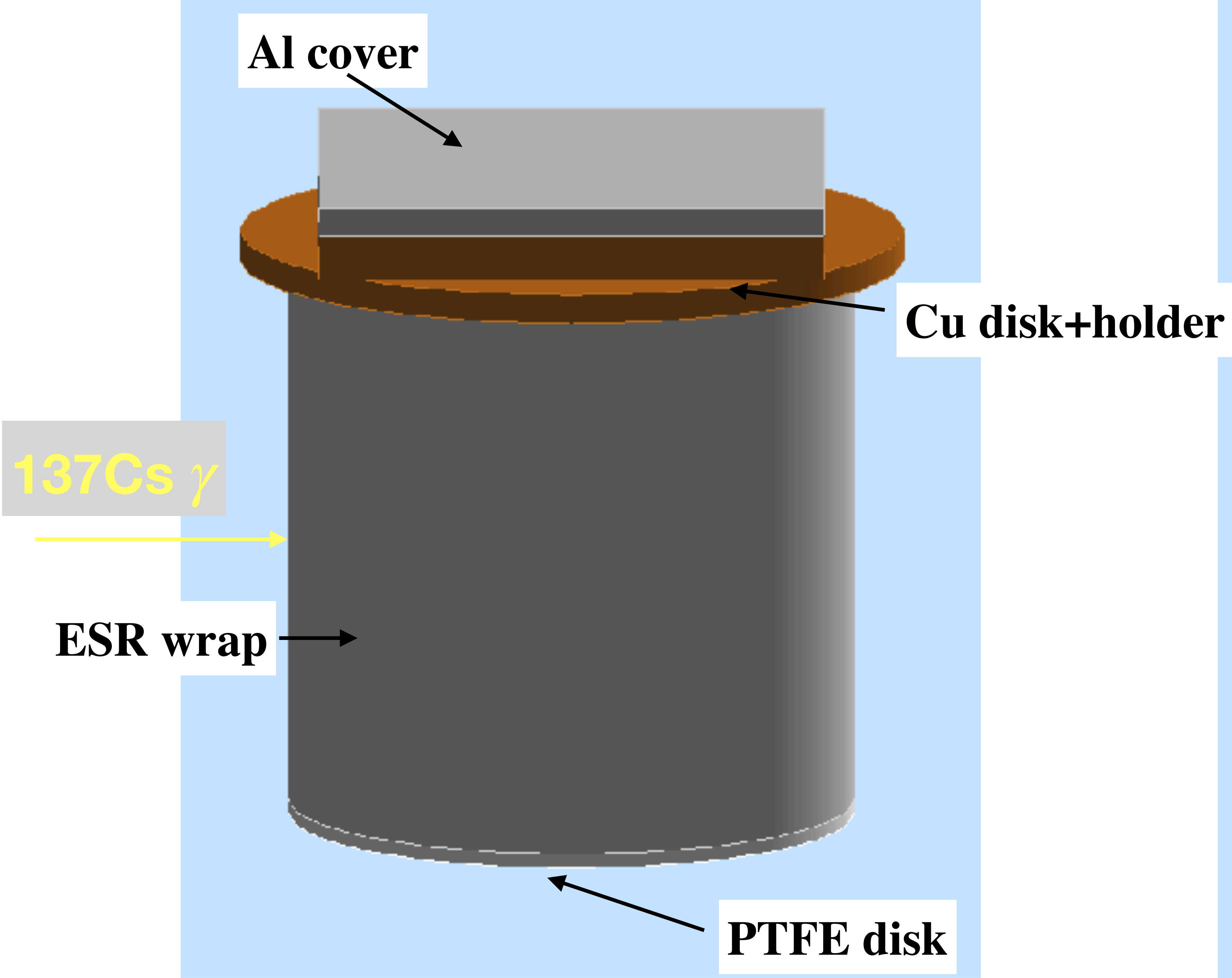
BGO + 5x5 cm2 KID

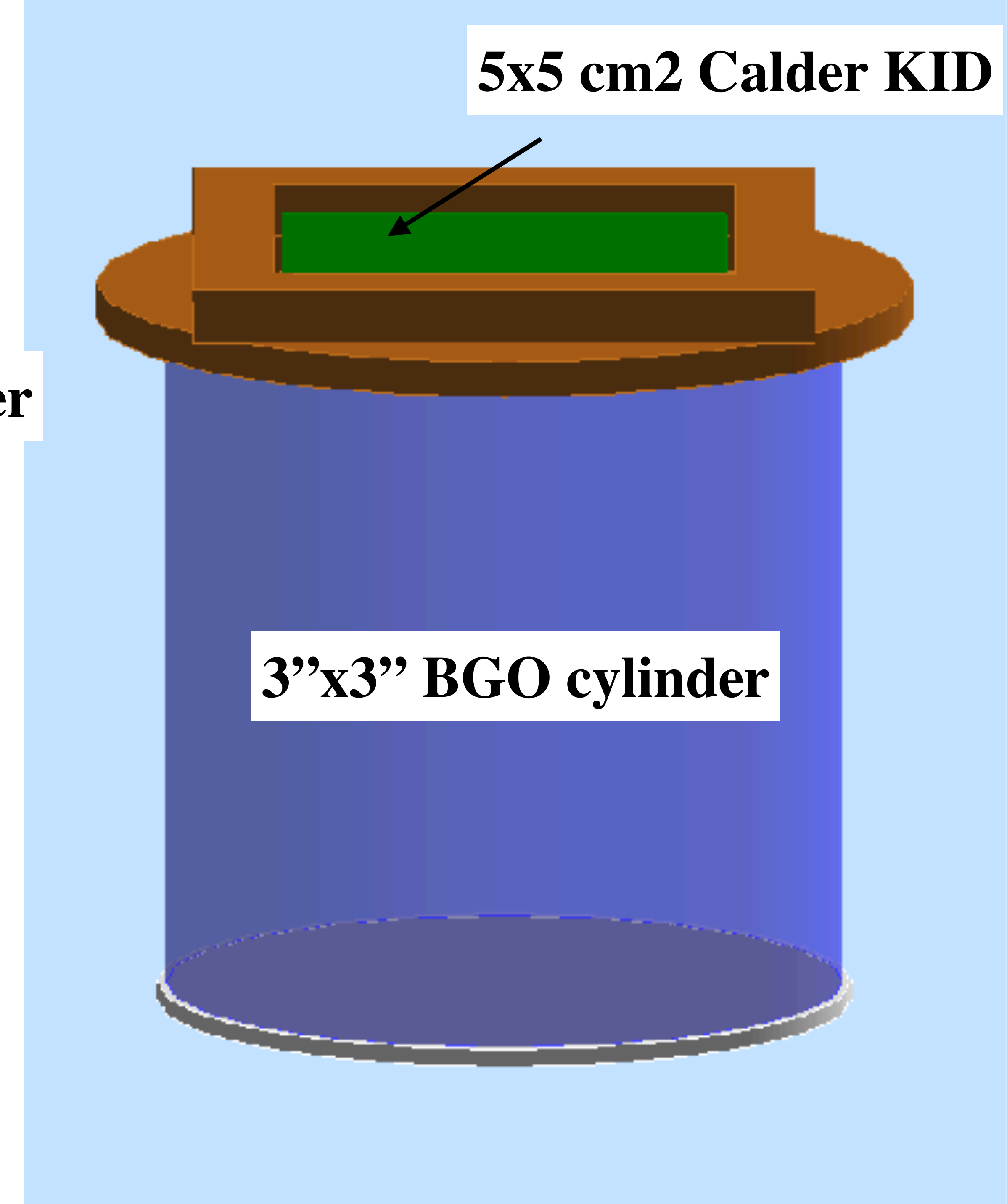




Simulation: BigBGO tests

BGO + 5x5 cm2 KID Simulation





Detection of photons:

- KID wafer:
  - Polished Si
  - Phonons interact at the vacuum-Si surface following Fresnel laws
- If (photon enter the Si)
  { -Count the photon
  -Retrive the energy
  -Kill the photon}

137Cs Source:

- Source Emits in a 11 deg cone at a distance of 30 cm from the crystal

BGO LY	8000 ph/MeV x 4 (see later)
BGO absorption length	155cm (see later)
PTFE surface	Lambertian refl. = 0.98
Distance PTFE wrap-crystal	1 um /no optical contact
PMT Quantum efficiency (From data sheet)	0.27
ESR surface	Mirror-like refl. = 0.99
Cu surface	Finish=raw + Complex and real Refr. Index
Al surface	Finish=raw + Complex and real Refr. Index
Distance ESR-Crystal	1 mm

Refr Index Cu

```
static G4double CU_N[NUM] =
{
  0.326, 0.314, 0.334, 0.454, 0.696, 0.930, 1.046,
  1.093, 1.126, 1.155, 1.180, 1.212, 1.247, 1.288
};

static G4double CU_K[NUM] =
{
  3.4000, 3.0830, 2.8150, 2.5100, 2.2930, 2.2380, 2.2440,
  2.2150, 2.1540, 2.0830, 1.9980, 1.9070, 1.8180, 1.7055
};
```

Refr Index Al

```
static G4double AL_N[NUM] =
{
  1.5580, 1.3664, 1.2623, 1.1796, 1.1140, 1.0611, 1.0176,
  0.9811, 0.9502, 0.9230, 0.8994, 0.8789, 0.8613, 0.8407
};

static G4double AL_K[NUM] =
{
  7.7124, 7.4059, 7.1855, 6.9706, 6.7772, 6.5970, 6.4294,
  6.2707, 6.1246, 5.9864, 5.8561, 5.7335, 5.6198, 5.4700
};
```

Photon Energy

```
stat                D [NU
{
  1.9077*eV,  // 650 nm
  2.0000*eV,  // 620 nm
  2.0667*eV,  // 600 nm
  2.1379*eV,  // 580 nm
  2.2143*eV,  // 560 nm
  2.2963*eV,  // 540 nm
  2.3846*eV,  // 520 nm
  2.4800*eV,  // 500 nm
  2.5833*eV,  // 480 nm
  2.6957*eV,  // 460 nm
  2.8182*eV,  // 440 nm
  2.9524*eV,  // 420 nm
  3.1000*eV,  // 400 nm
  3.3067*eV   // 375 nm
};
```

Simulation: BigBGO tests

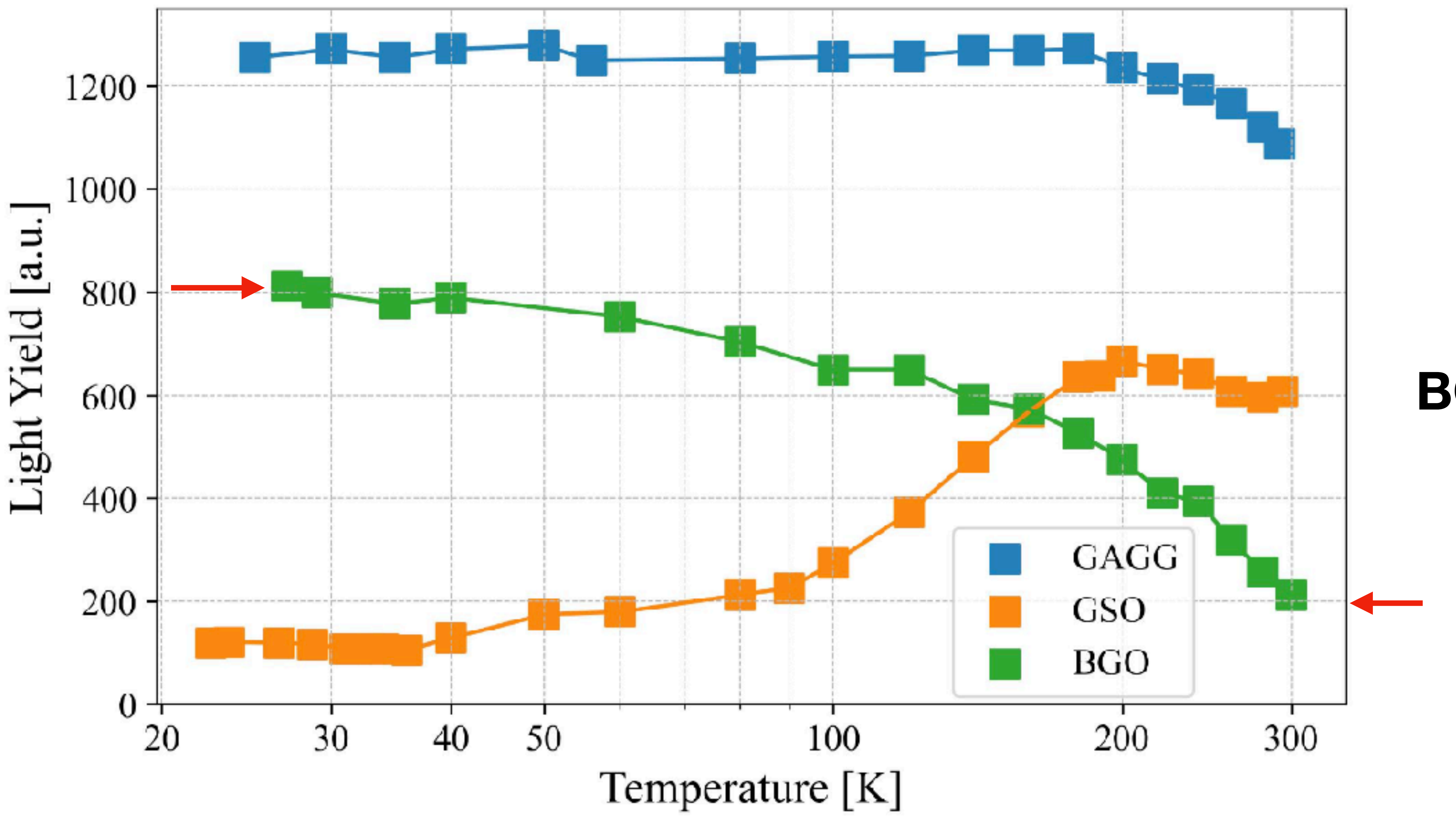


Fig. 2. Light yield of GAGG, GSO and BGO in temperature range [20-300] K. The light yield is mesured with a PMT placed at room tempertaure and by stimulating the crystals with a ^{241}Am α-source.

BGO L.Y. ⟶ (BGO L.Y.) x 4

Simulation: BigBGO tests

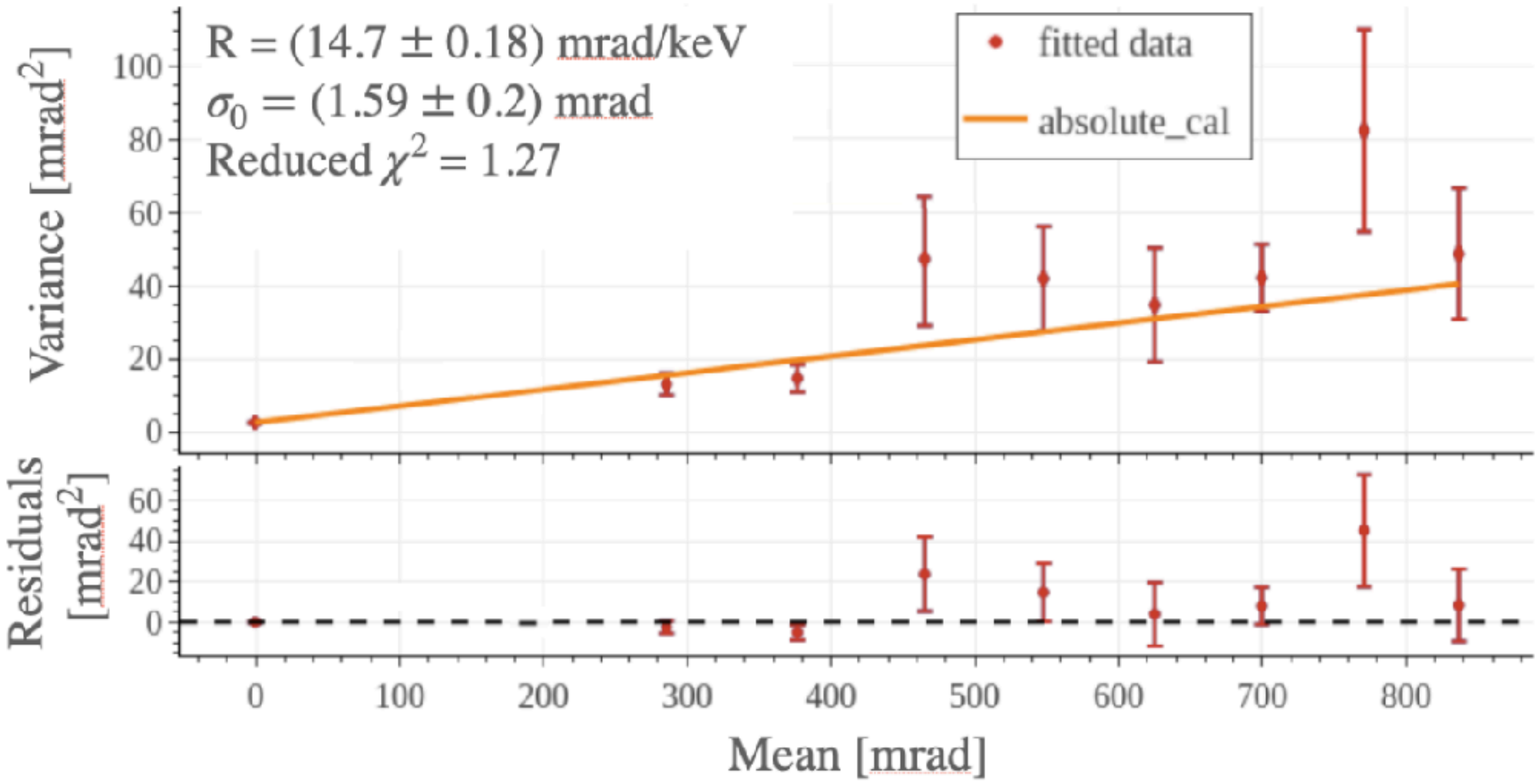
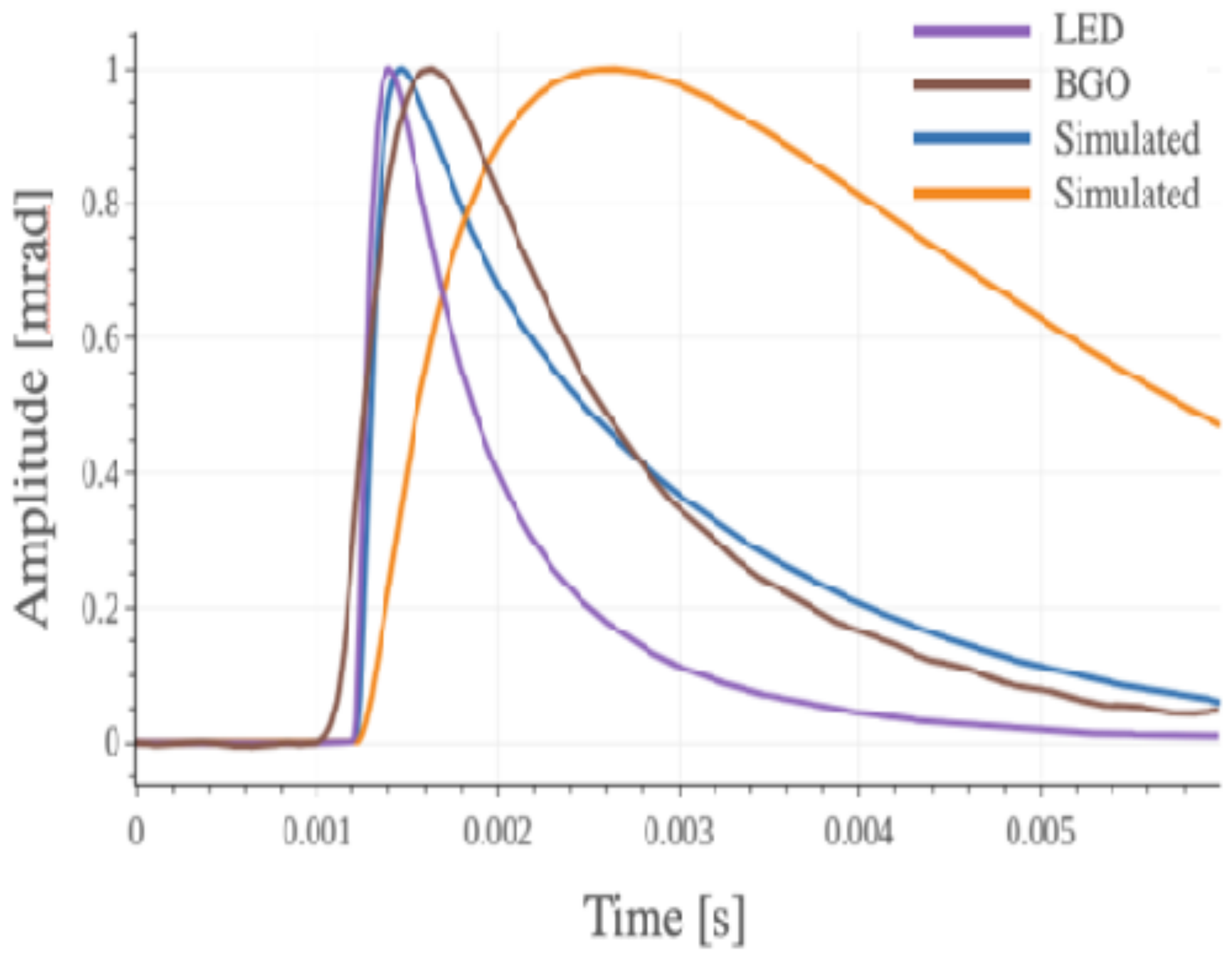


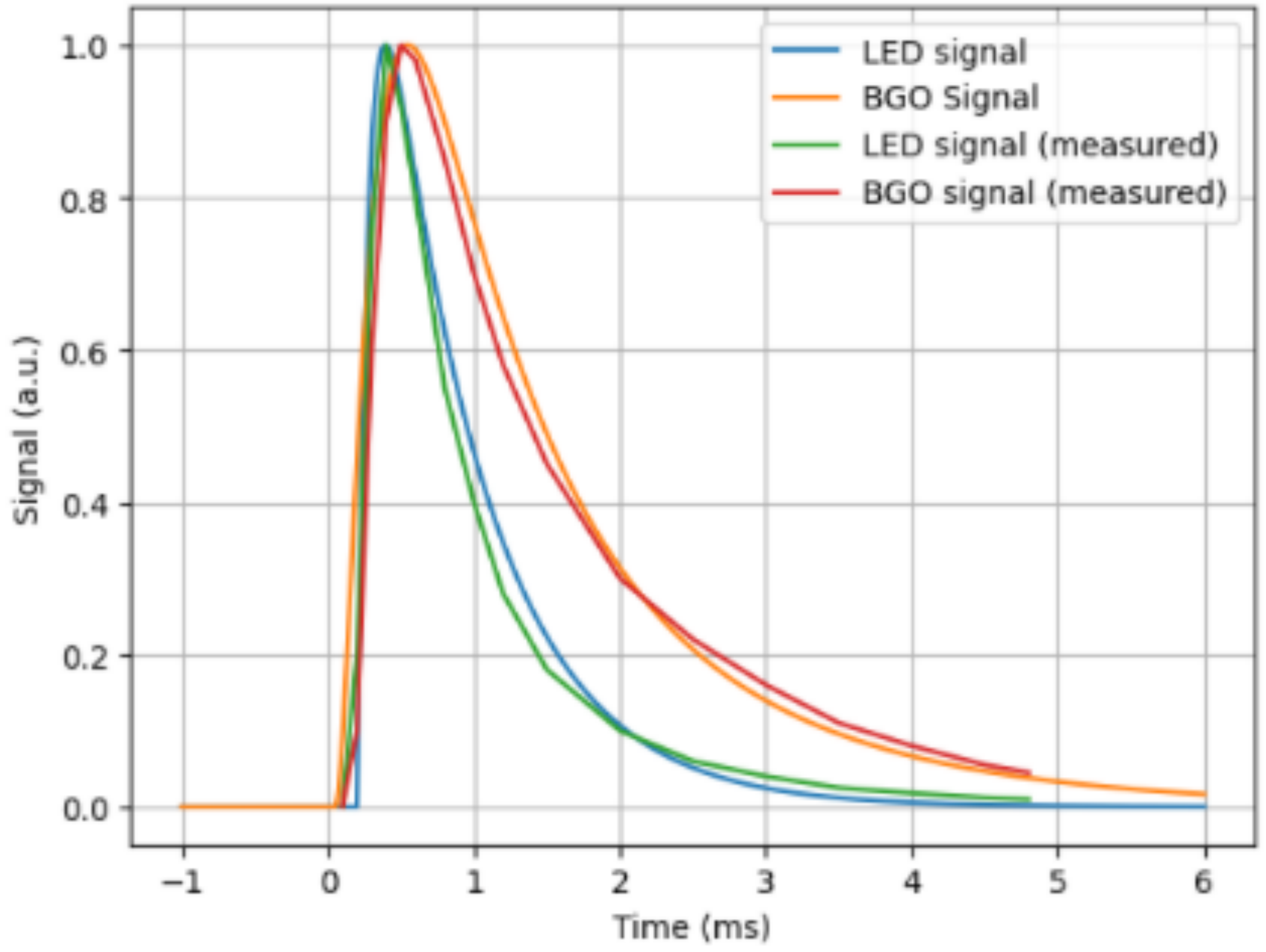
Fig. 7. Optical calibration of the light detector, obtained by a linear fit of variance vs mean of the light detector's signal amplitudes at increasing intensity of LED bursts. Since the number of photons in a burst N follows a

Calibration:
Amp (mrad)=Energy in Si wafer (keV) x 14.7 (keV/mrad)

Simulation: BigBGO tests

Impact of BGO slow down:





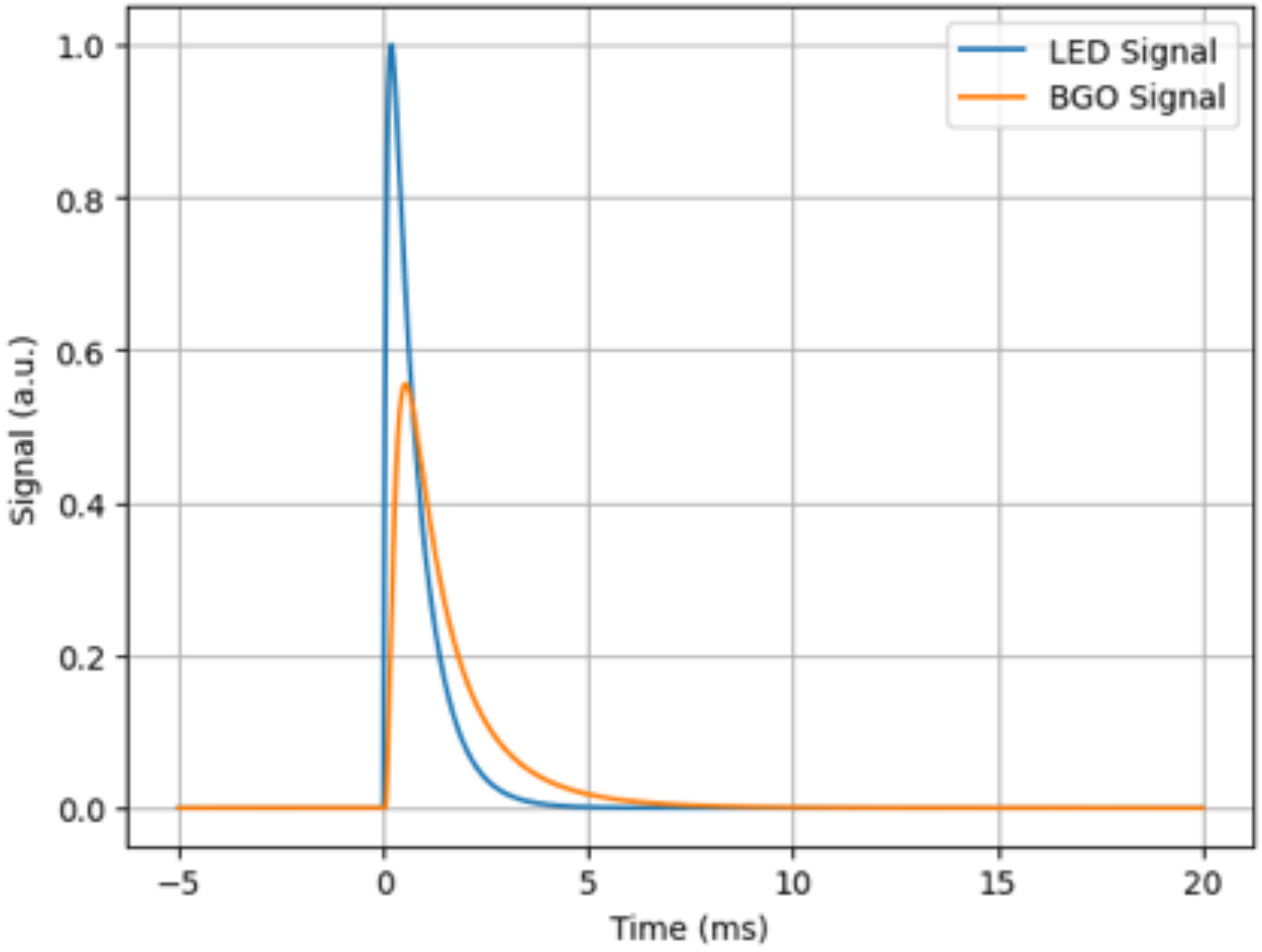
tau ring	0.08 ms
tau qp	680 us
tau light LED	0.0001 ms
tau light1 BGO	200 us
tau light2 BGO	1.5 ms
alpha	0.59

$$f_3(t,\tau_{\text{ring}},\tau_{\text{qp}},\tau_{\text{light}}) = \left[\frac{\tau_{\text{ring}}}{(\tau_{\text{qp}}-\tau_{\text{ring}})(\tau_{\text{light}}-\tau_{\text{ring}})}e^{-t/\tau_{\text{ring}}} + \frac{\tau_{\text{qp}}}{(\tau_{\text{ring}}-\tau_{\text{qp}})(\tau_{\text{light}}-\tau_{\text{qp}})}e^{-t/\tau_{\text{qp}}} + \frac{\tau_{\text{light}}}{(\tau_{\text{qp}}-\tau_{\text{light}})(\tau_{\text{ring}}-\tau_{\text{light}})}e^{-t/\tau_{\text{light}}}\right]\Theta(t)$$

$$f_4(t,\tau_{\text{ring}},\tau_{\text{qp}},\tau_{\text{light},1},\tau_{\text{light},2},\alpha) = \alpha f_3(t,\tau_{\text{ring}},\tau_{\text{qp}},\tau_{\text{light},1},1) + (1-\alpha) f_3(t,\tau_{\text{ring}},\tau_{\text{qp}},\tau_{\text{light},2},1)$$

Simulation: BigBGO tests

Impact of BGO slow down:

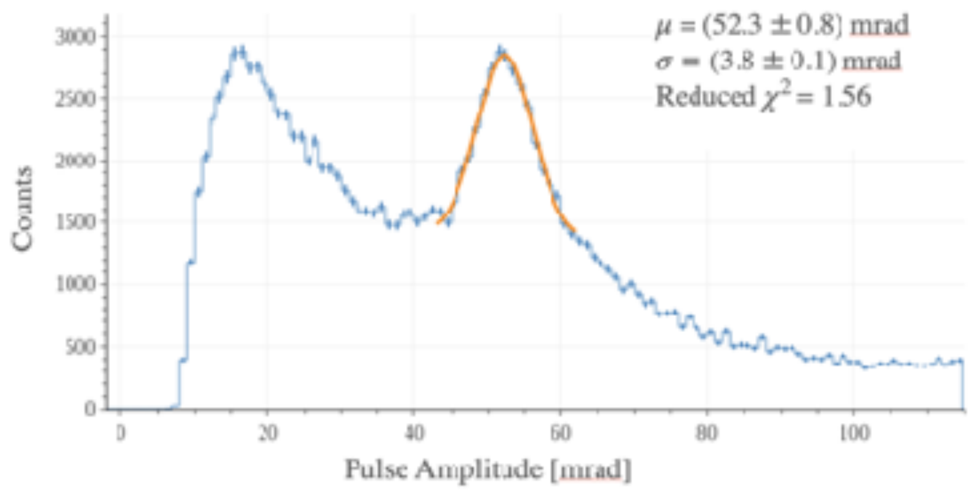


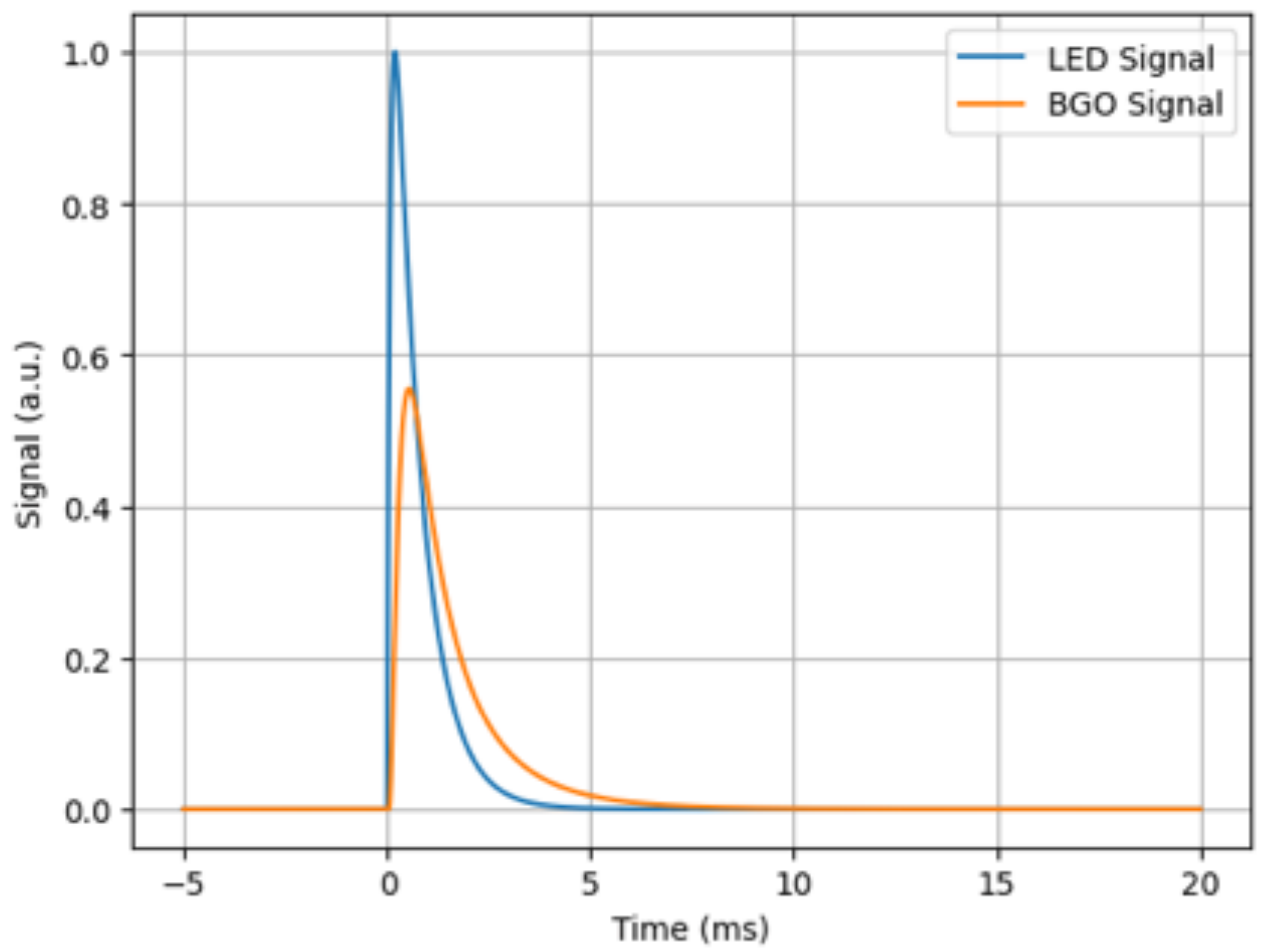
Same light output (Area)
-> lower amplitude of BGO signal (about 0.55)

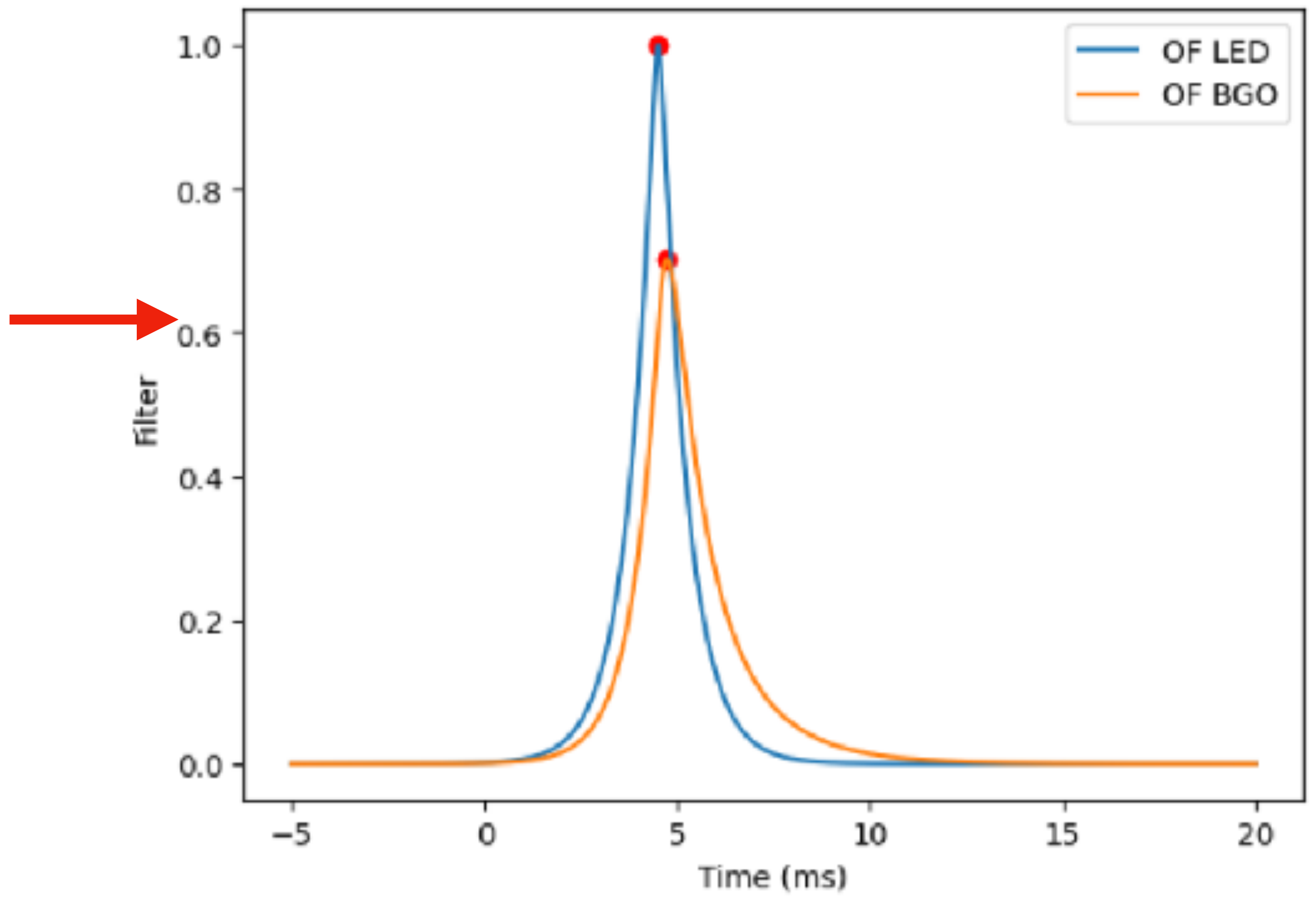
tau ring	0.08 ms
tau qp	680 us
tau light LED	0.0001 ms
tau light1 BGO	200 us
tau light2 BGO	1.5 ms
alpha	0.59

Simulation: BigBGO tests

Impact of BGO slow down:



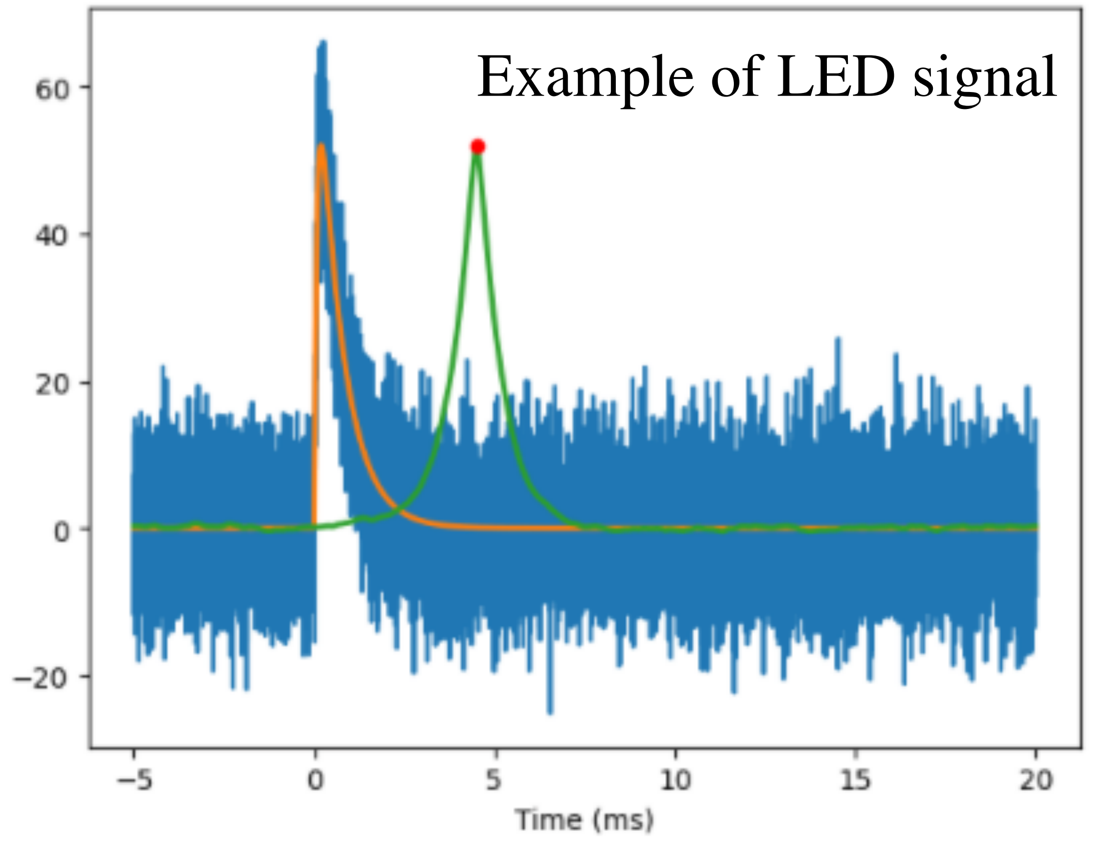


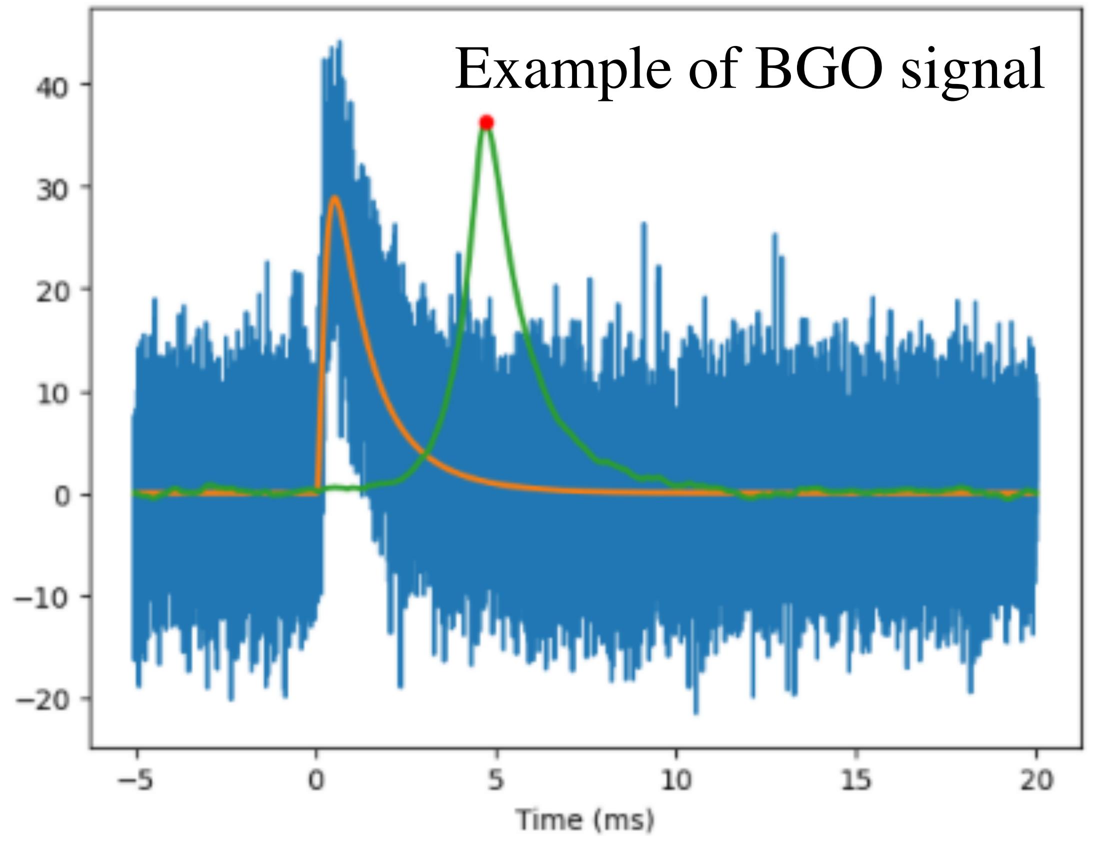


OF AmplitudeBGO/OF AmplitudeLED = 0.7015196185795922

- In the analysis the signal amplitude is evaluated using Optimum filter
- The filter is constructed using the LED pulse as template

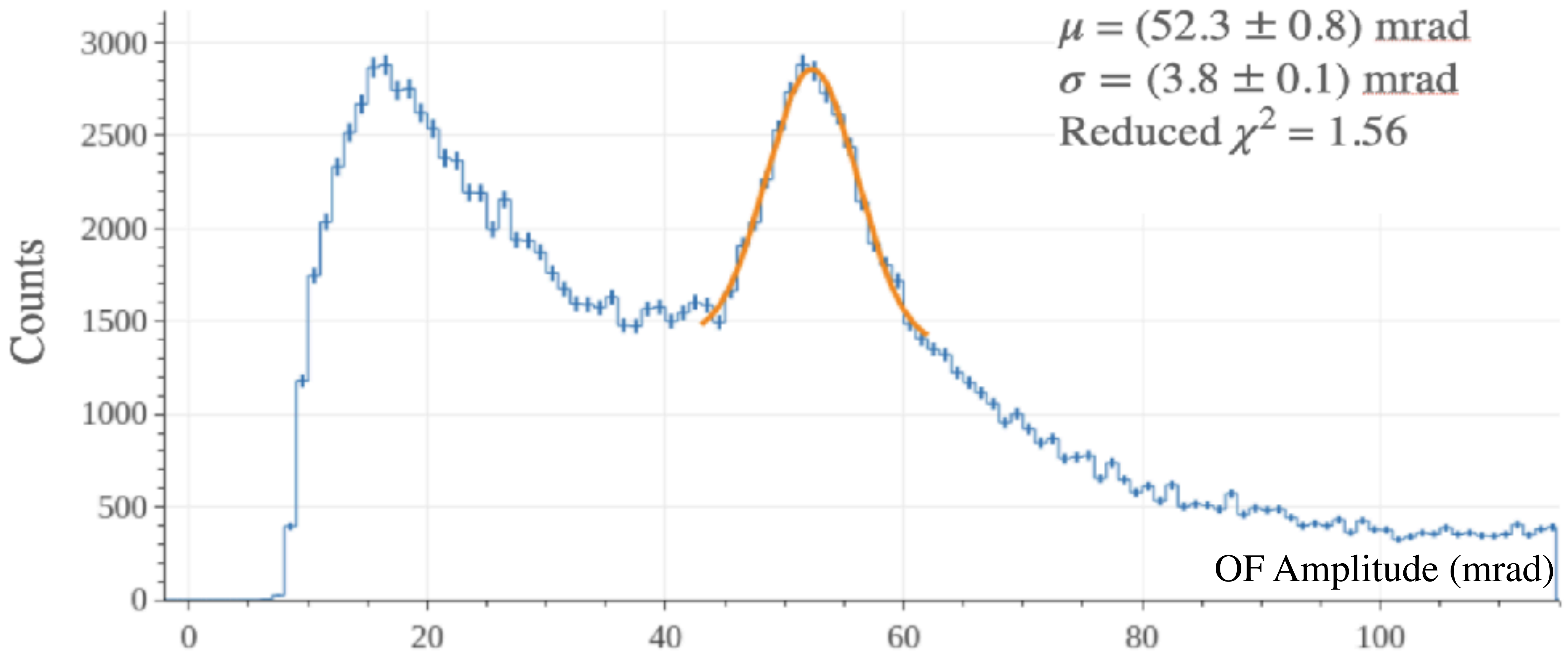
For signals containing the same number of photons (equal area), the amplitude of the BGO signal is 0.702 times the amplitude of the LED signal.

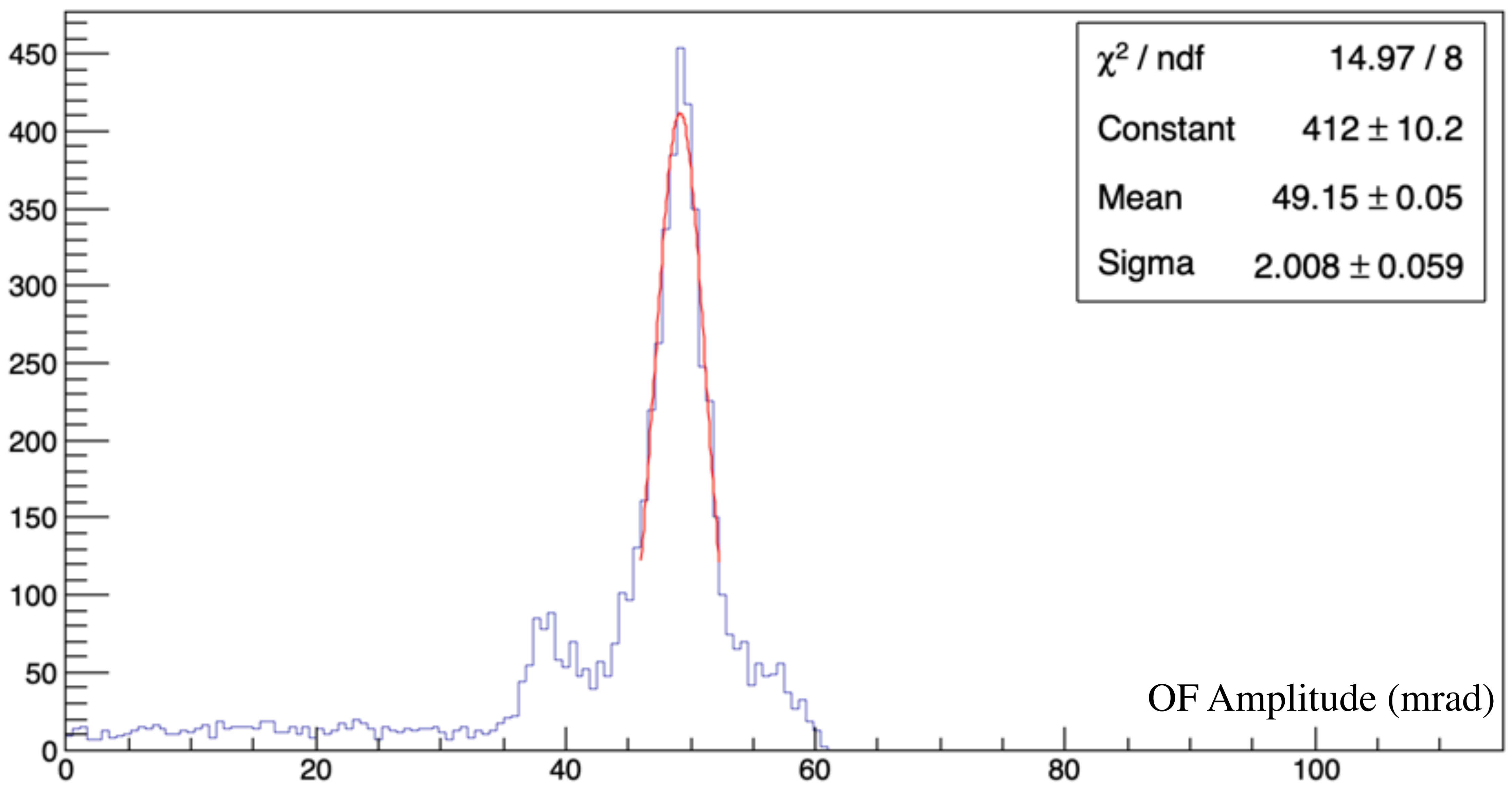




Calibration + Slow down:
Amp (mrad)=Energy in Si wafer (keV) x 14.7 (keV/mrad) x 0.702

Simulation: BigBGO tests





Comparison:

- Peak position: very good agreement
- Peak width:
  - In the simulation the sigma of the peak is lower than in the data: ~ 2 vs 3.8
  - Also if detector resolution is included, the value of the peak sigma is still lower: $\sqrt{2^2 + 1.59^2} = 2.55$

From calibration data

"Tuning" of absorption length:

- A wide range of absorption length (λ) values for BGO can be found in the literature (from 50 cm to 5 m).
- In the simulation, that better reproduce the data is $\lambda = 155$cm[1]
- λ has a negligible impact for small crystals, since the absorption length is significantly larger than the crystal size

Wei, Y., Zhang, Z., Zhang, Y., Wang, C., Wen, S., Dong, J., Li, Z., Wang, X., Xu, Z., Huang, G. and Liu, S., 2016. Performance of the BGO detector element of the DAMPE calorimeter. *IEEE Transactions on Nuclear Science*, *63*(2), pp.548-551.

$\lambda = 155$cm[1]

Ciabattoni, A., Fioretti, V., Tomsick, J.A., Zoglauer, A., Patel, P., Mitchell, L., Bulgarelli, A., Jean, P., Panebianco, G., Parmiggiani, N. and Vignali, C., 2025. Benchmarking of Geant4 simulations for the COSI Anticoincidence System. *Experimental Astronomy*, *60*(1), p.9.

$\lambda = (5 \pm 1)$m

Simulation: Modeling Veto Demonstrator