Study of the excess noise and optimum operating conditions for LGAD detectors in high precision X-γ ray spectroscopy

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[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Milano, Via Celoria 16, Milan, Italy
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High Precision X-ray Measurements (HPXM) conference
Laboratori Nazionali di Frascati (INFN) 16-20 June 2025

Outline

Introduction and motivation

Performance of LGAD-based X-γ ray spectrometer

- Equivalent Noise Charge (ENC)
- Excess noise
- Optimum operating conditions

Ultra low-gain LGAD with state-of-the-art CSA

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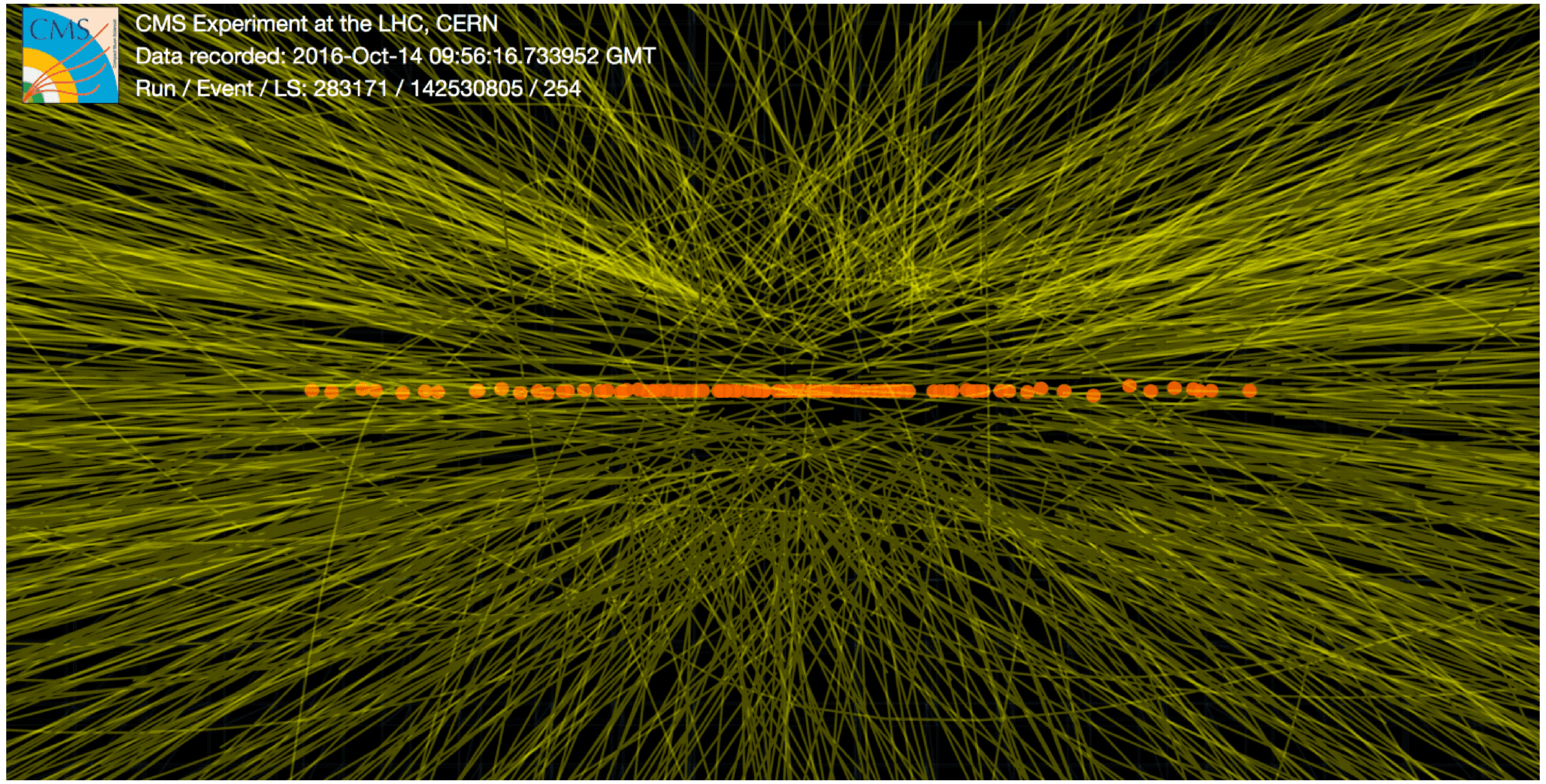
High Energy Physics



Source: Ritson, Sophie. "Creativity and modelling the measurement process of the Higgs self-coupling at the LHC and HL-LHC." Synthese 199.5 (2021): 11887-11911.

< 30 ps time resolution [1]

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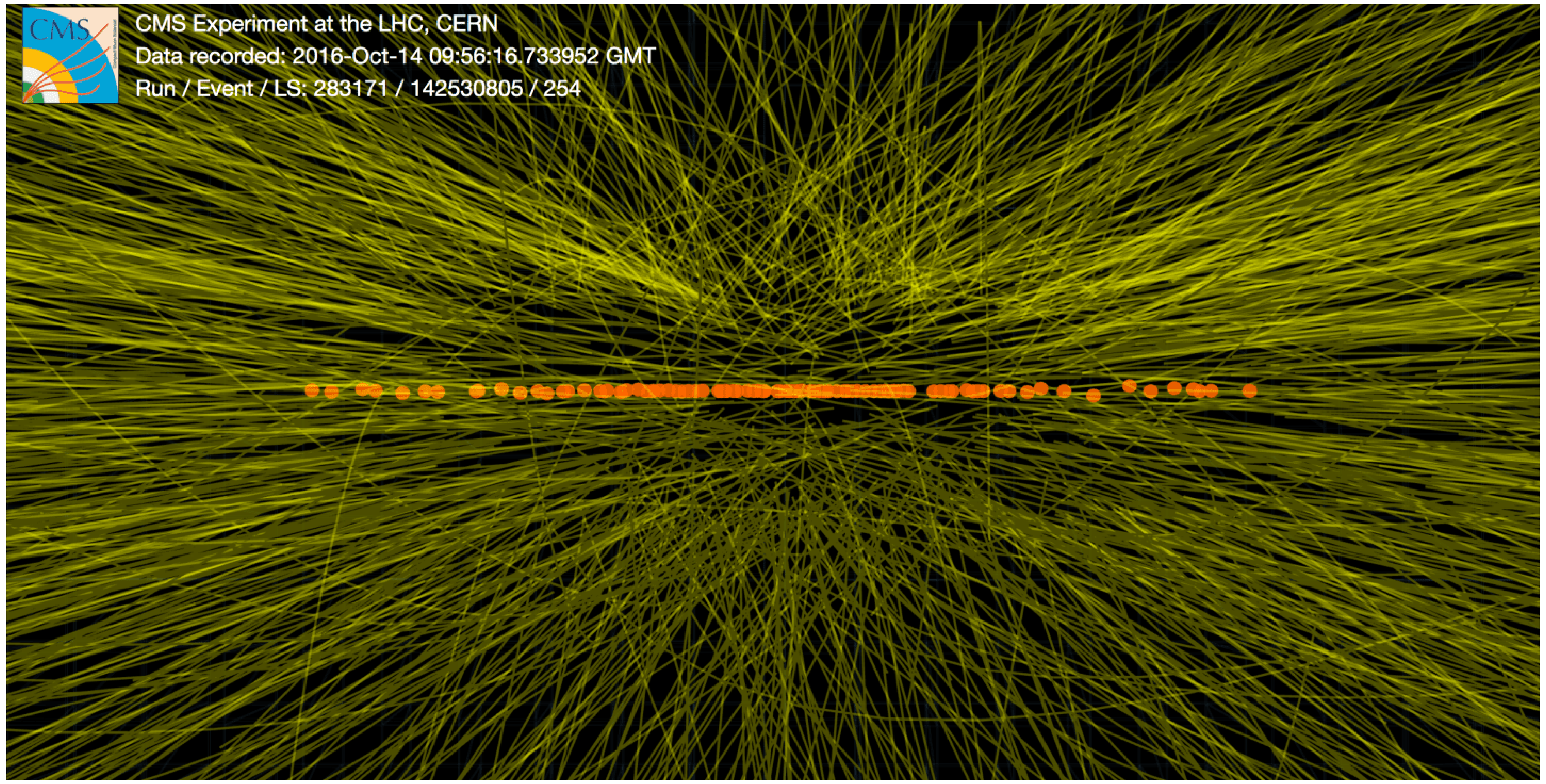

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Synchrotrons and FEL

3rd generation: The European Synchrotron Radiation Facility at Grenoble, France
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Soft-X-ray (down to 200 eV) [2,3]

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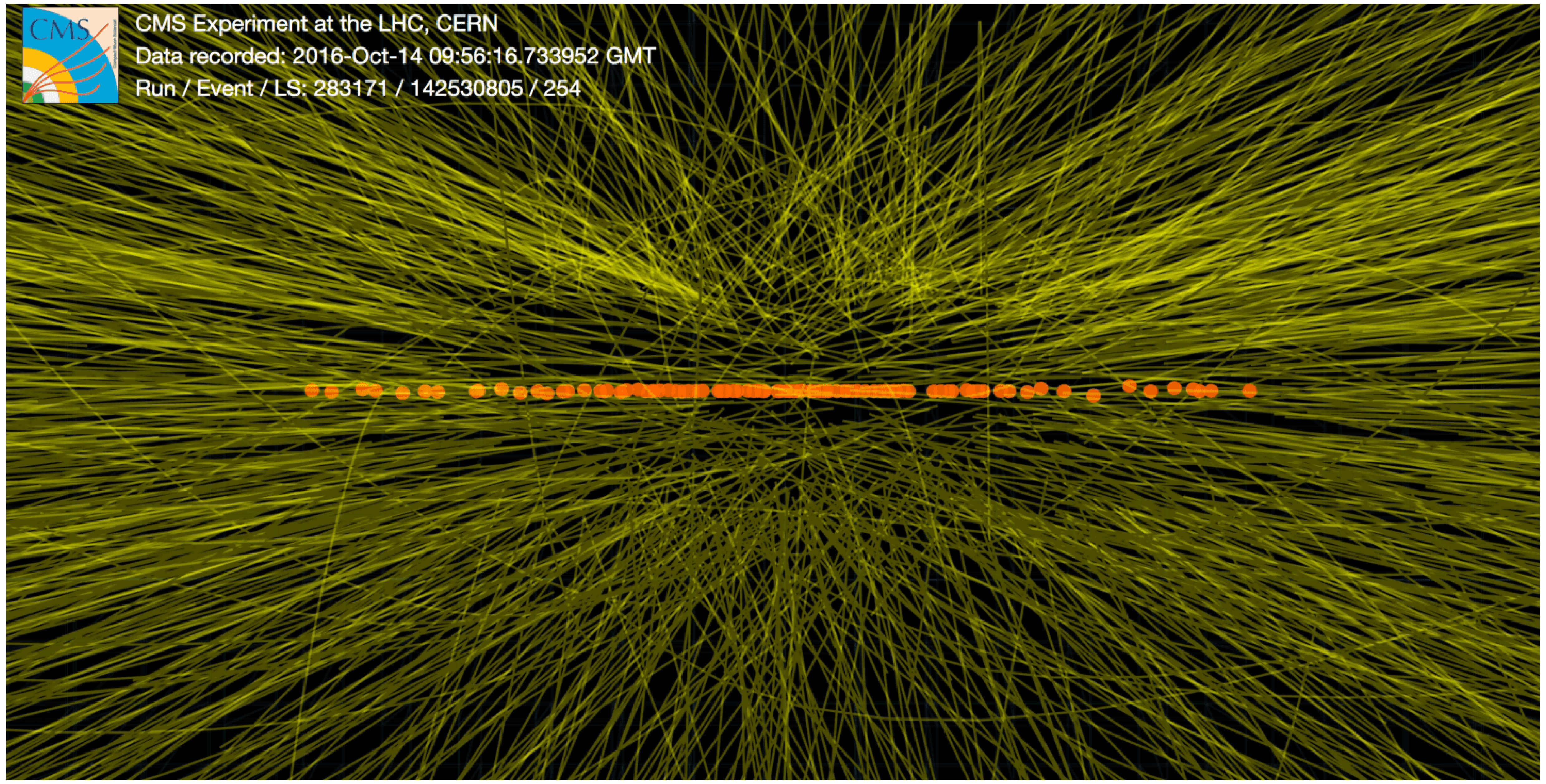

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Objective of the work: study of the **noise and energy resolution in LGADs**-based system for **X-ray spectroscopy**

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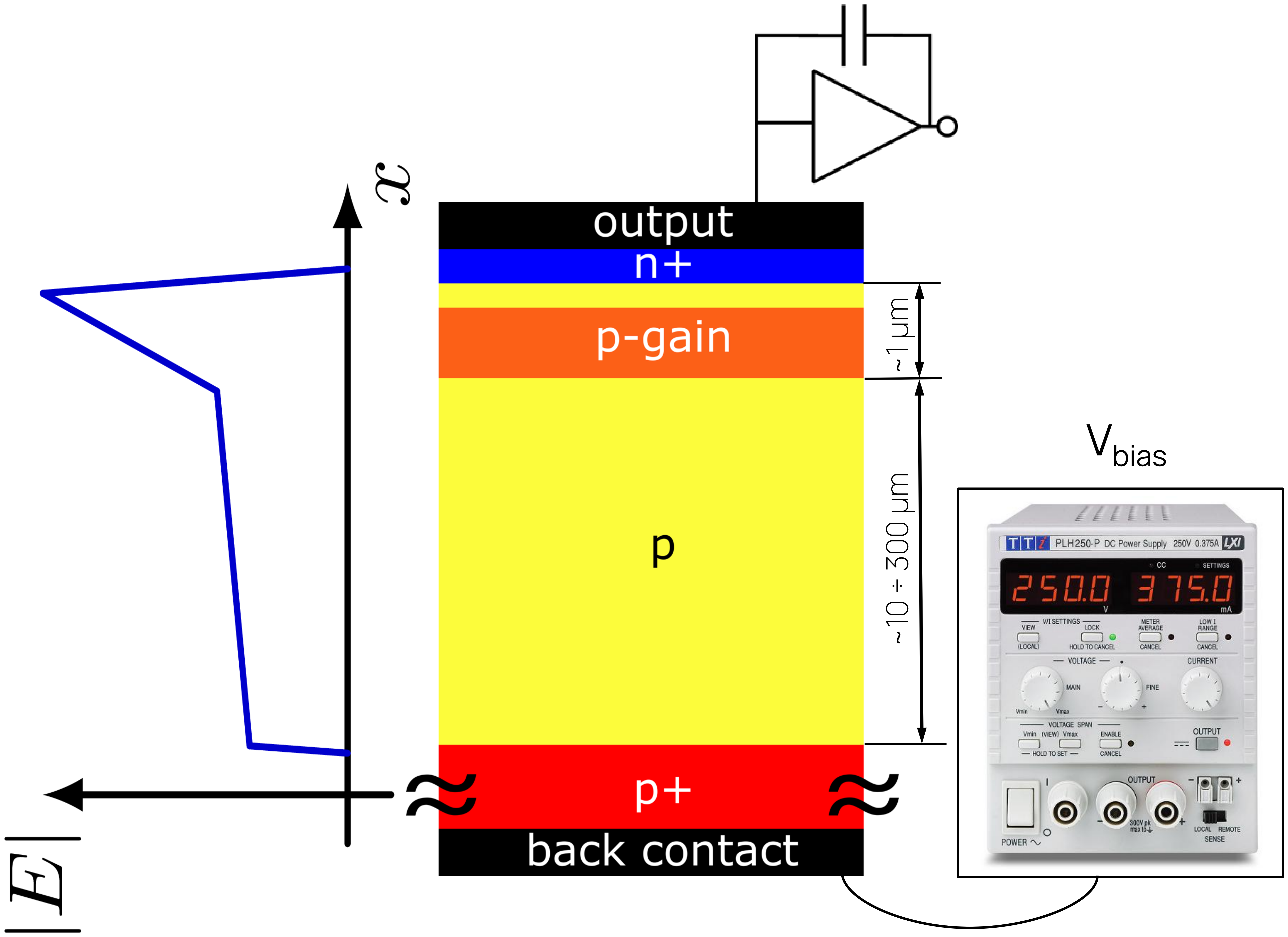
LGAD multiplication gain for photon science



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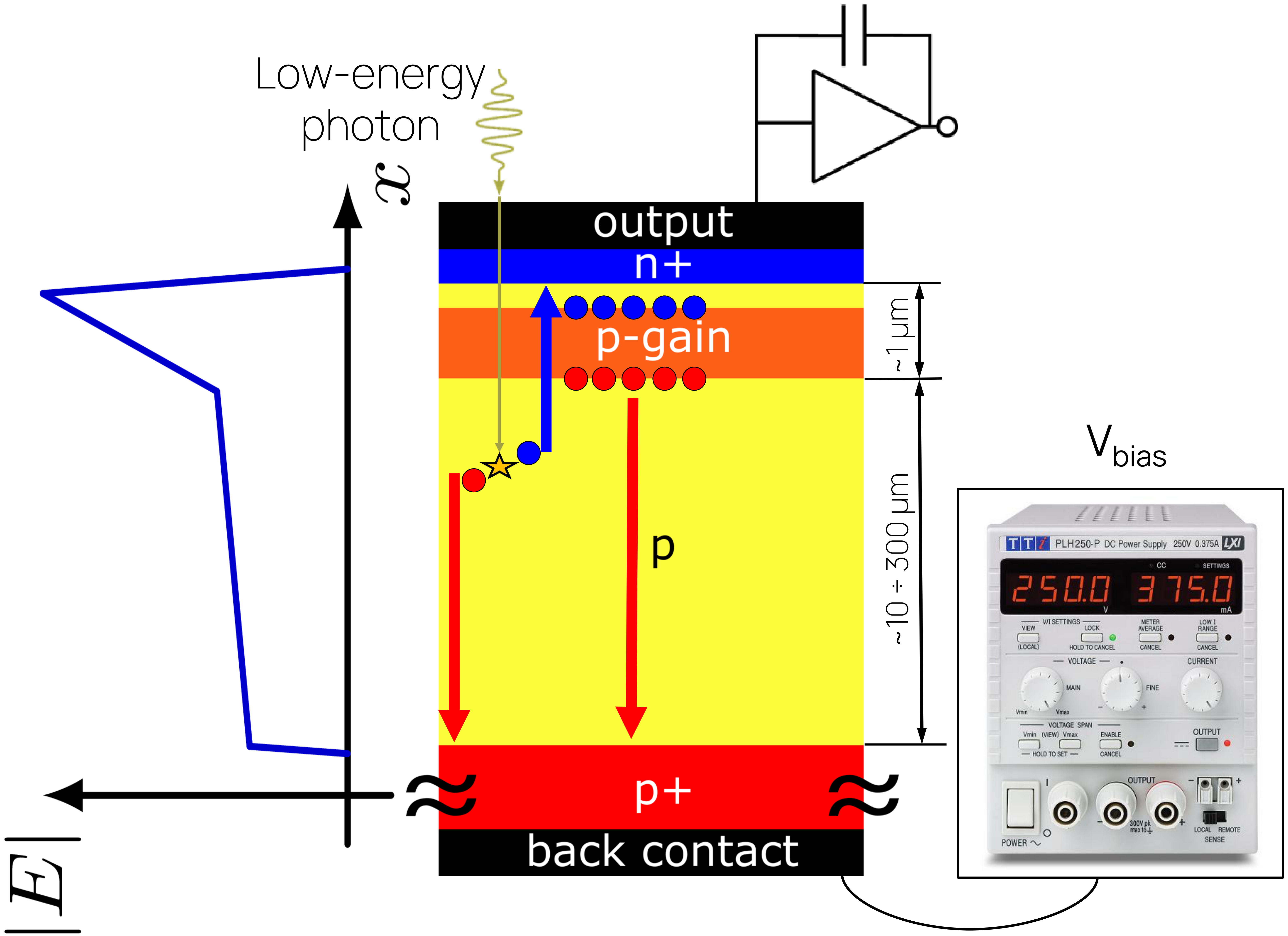

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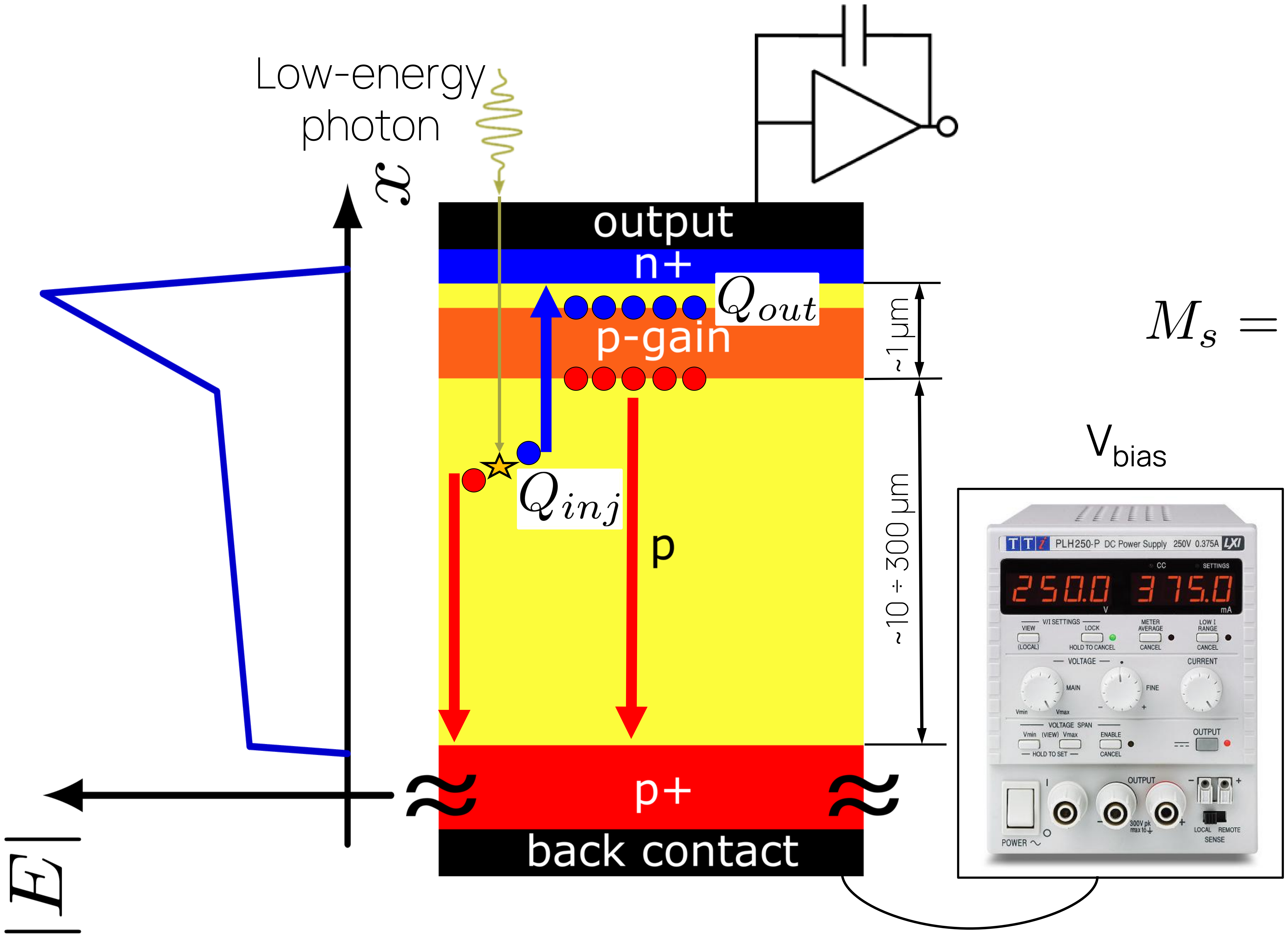

$$M_s = \frac{Q_{out}}{Q_{inj}} \ll 100$$

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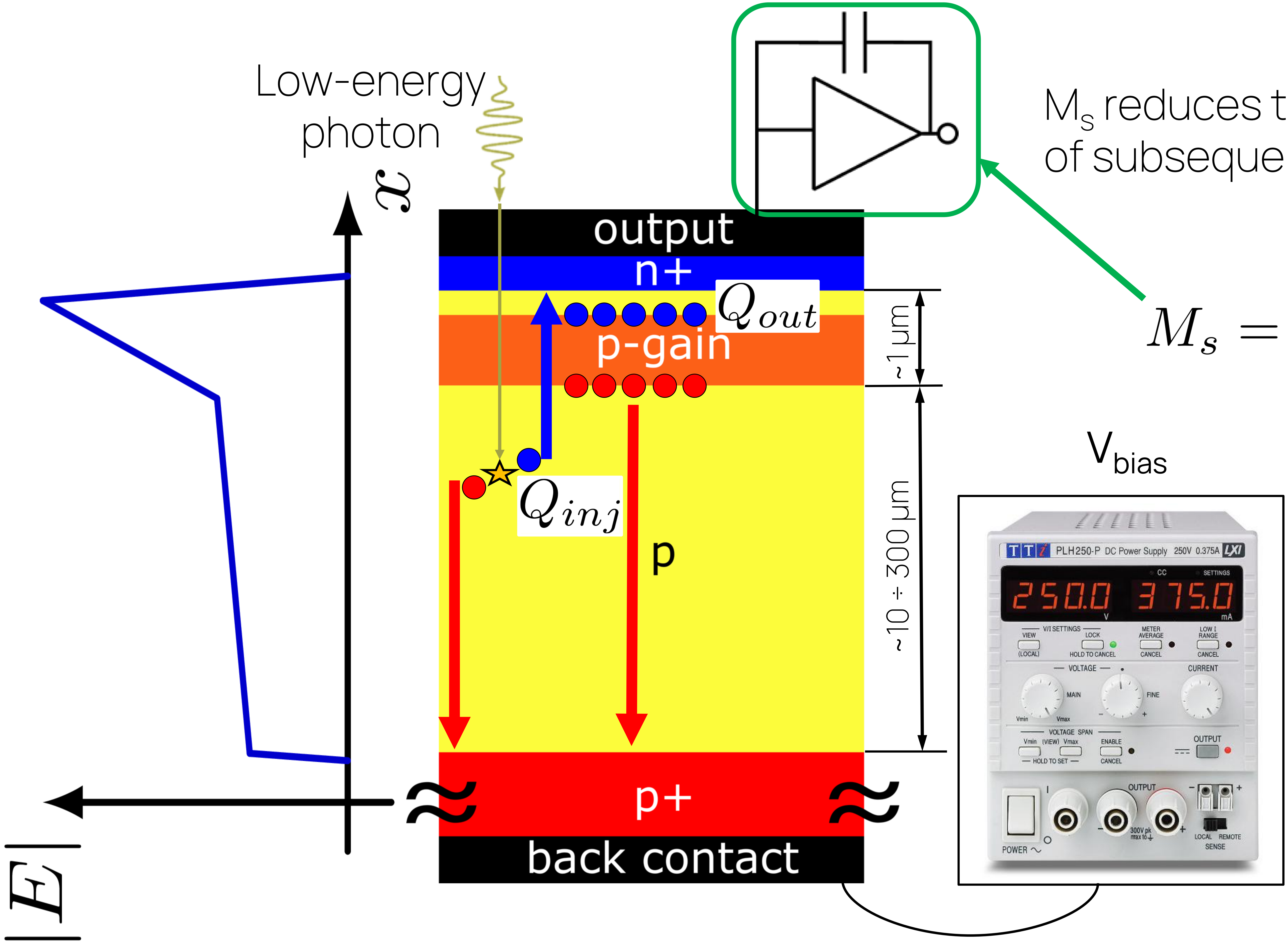

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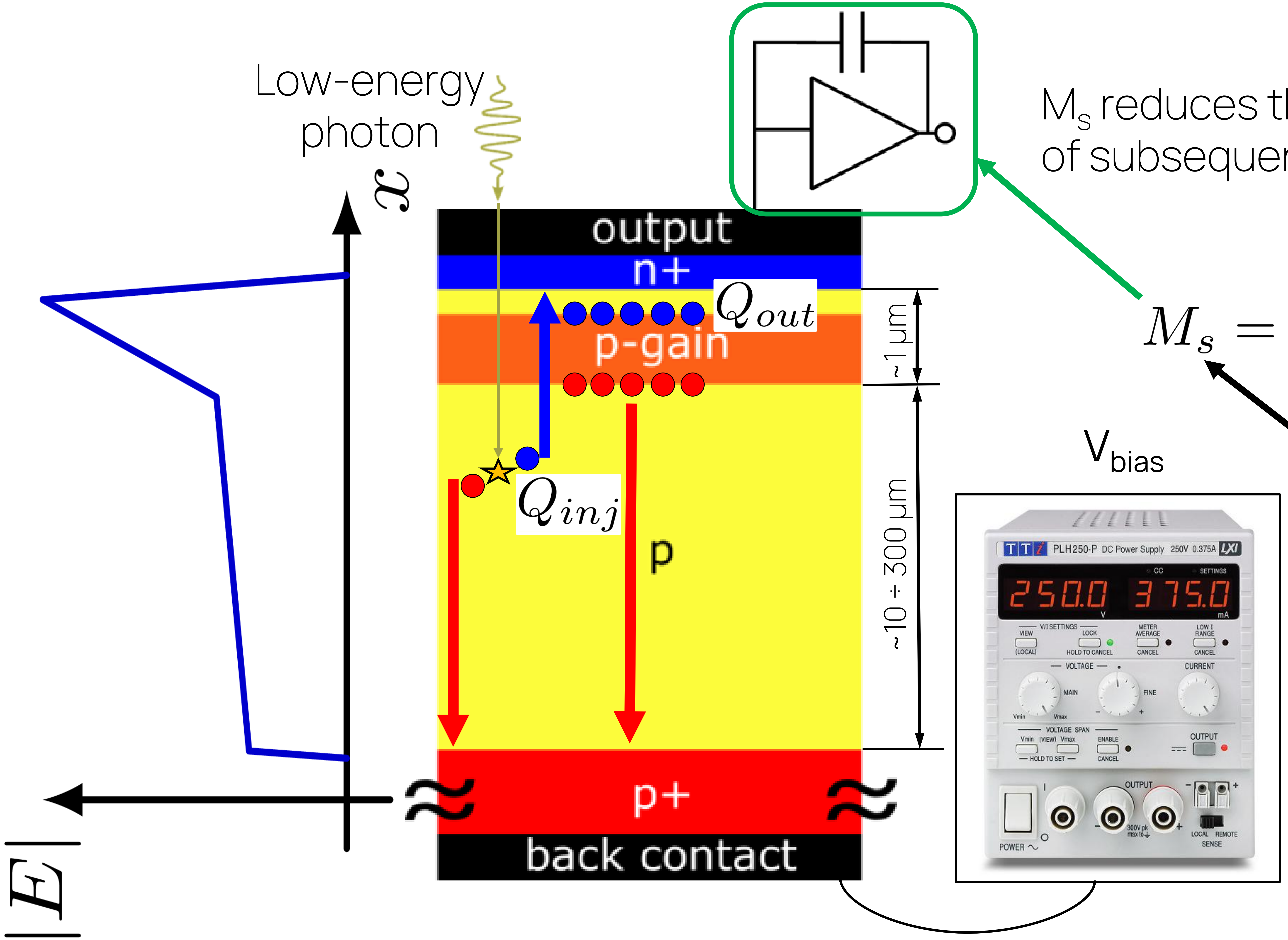

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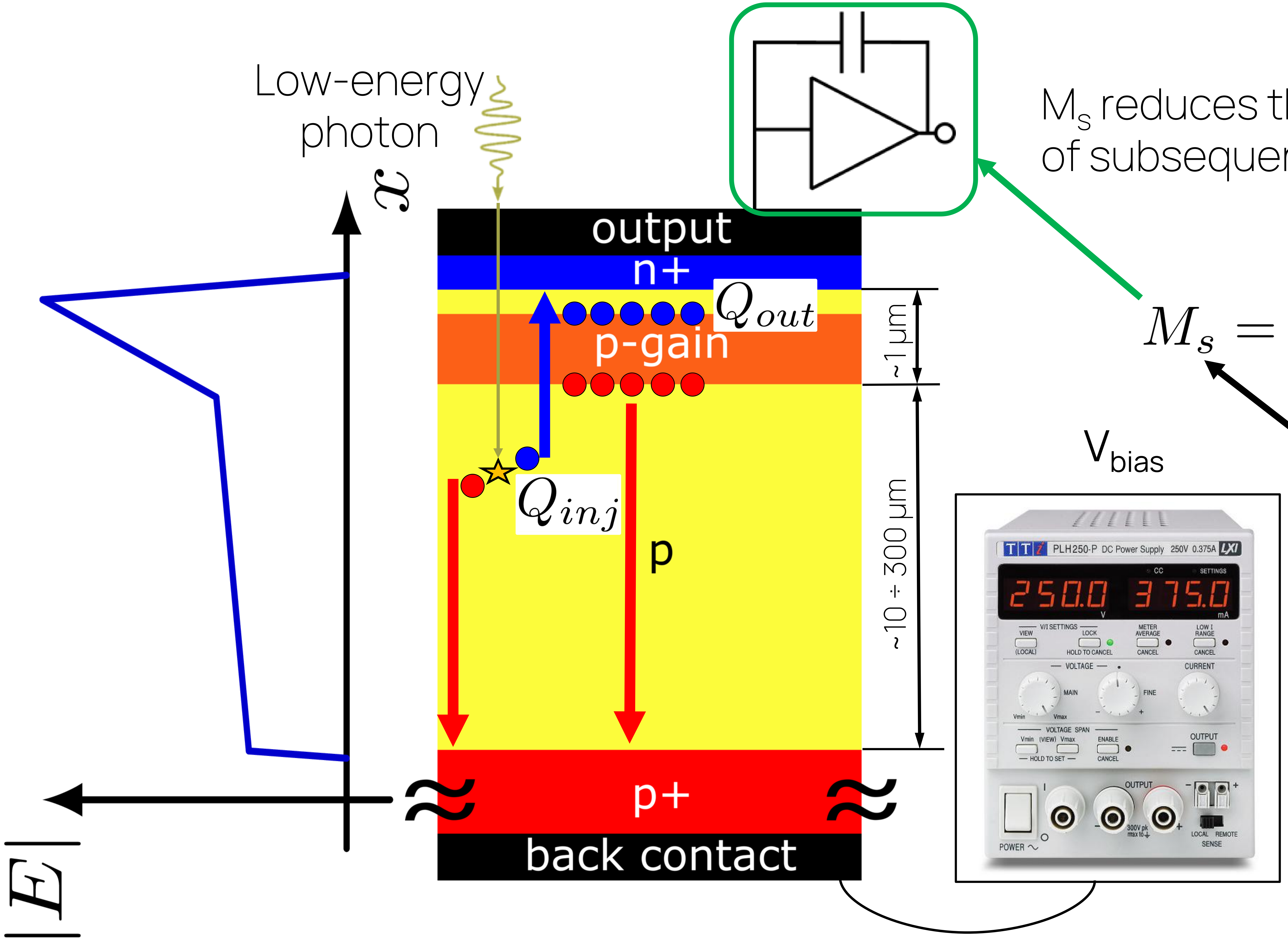

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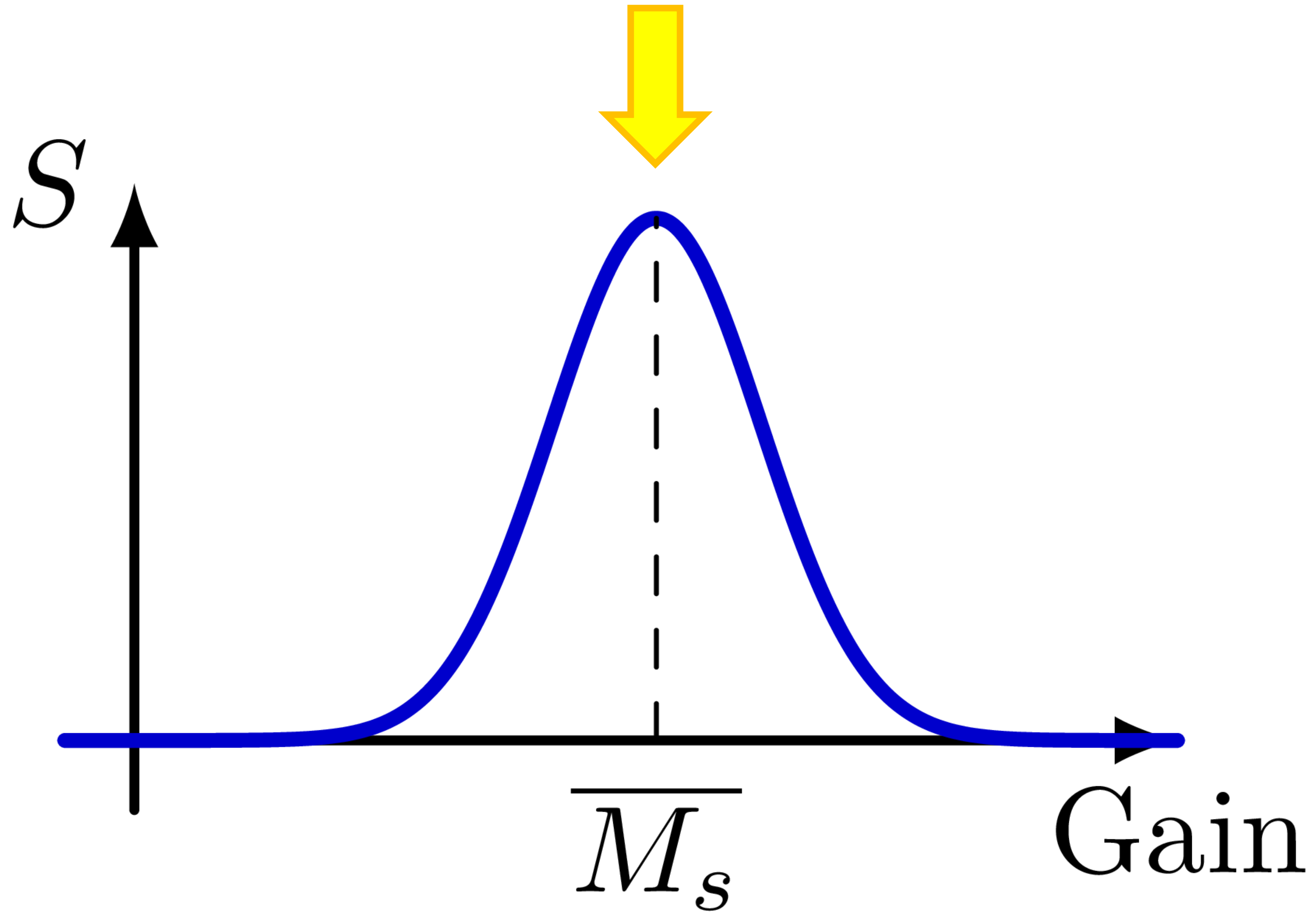

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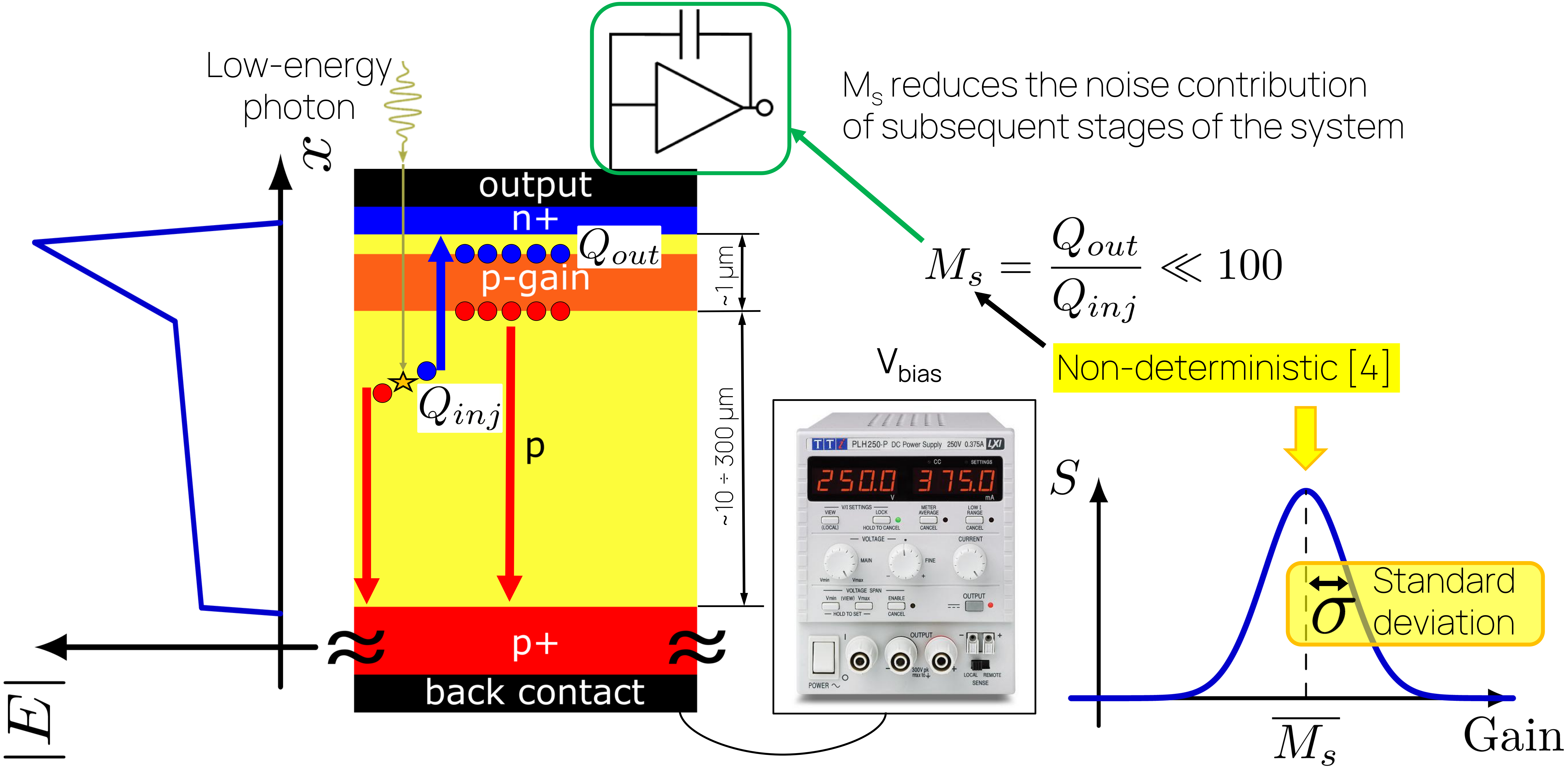

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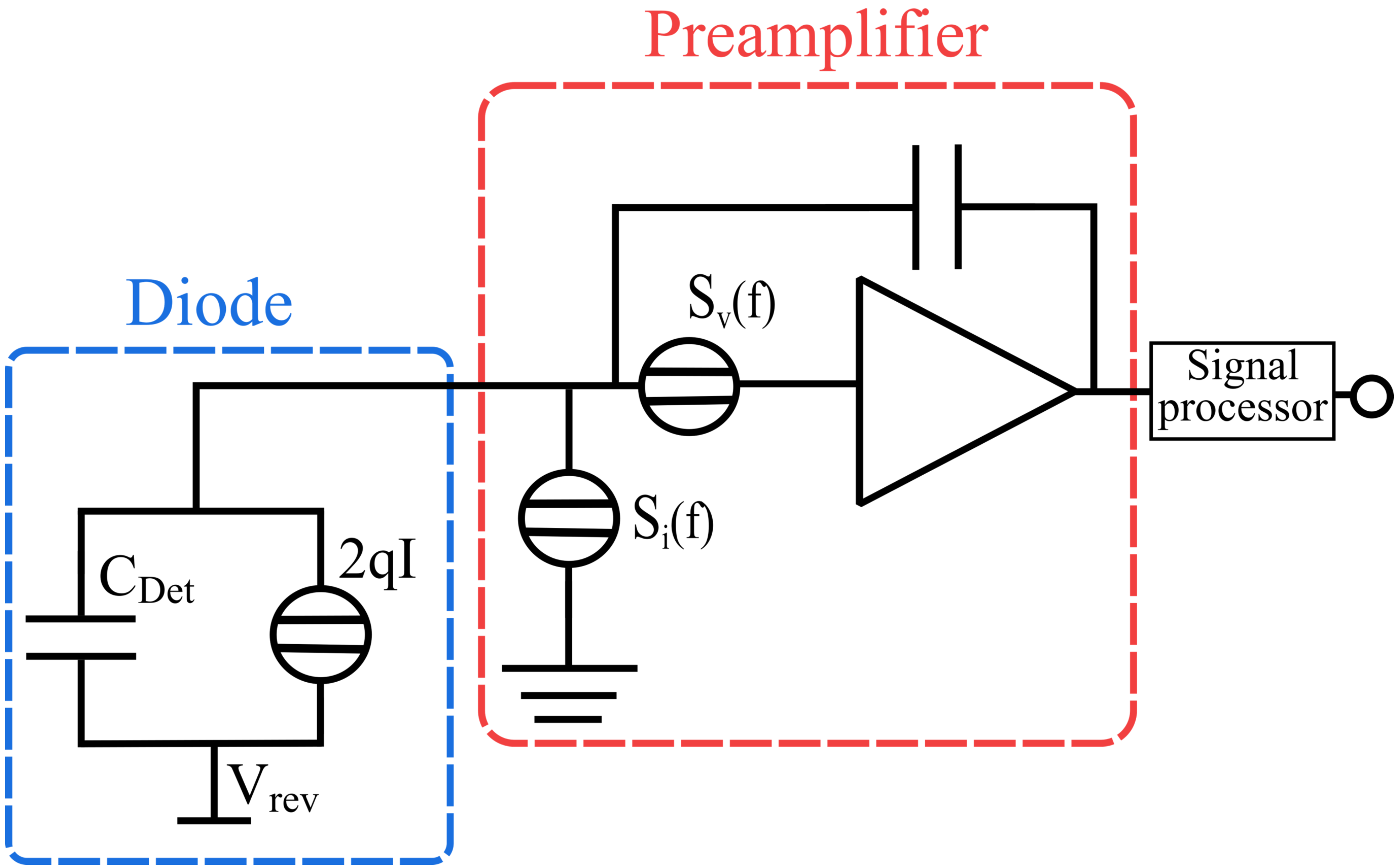

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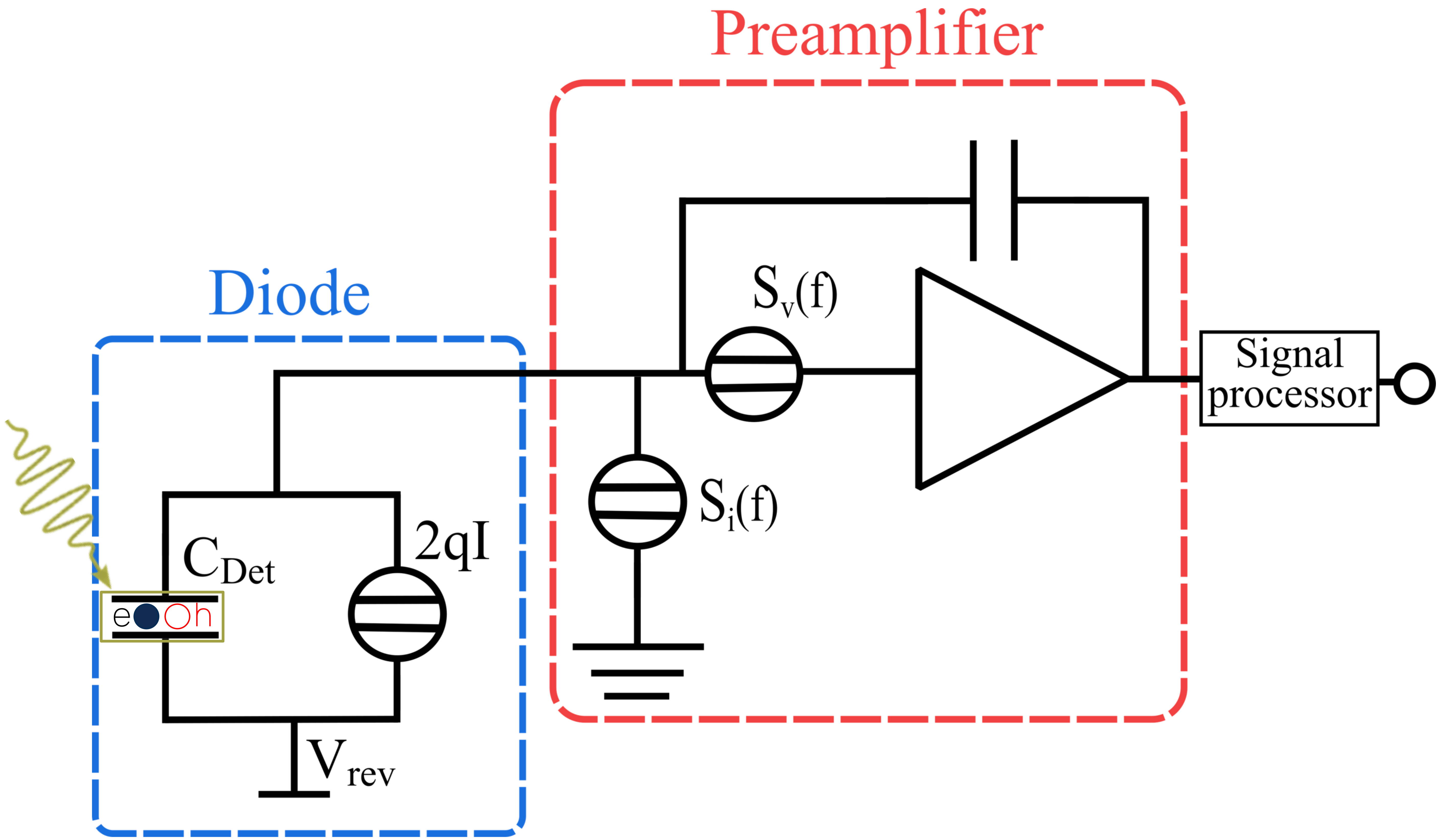

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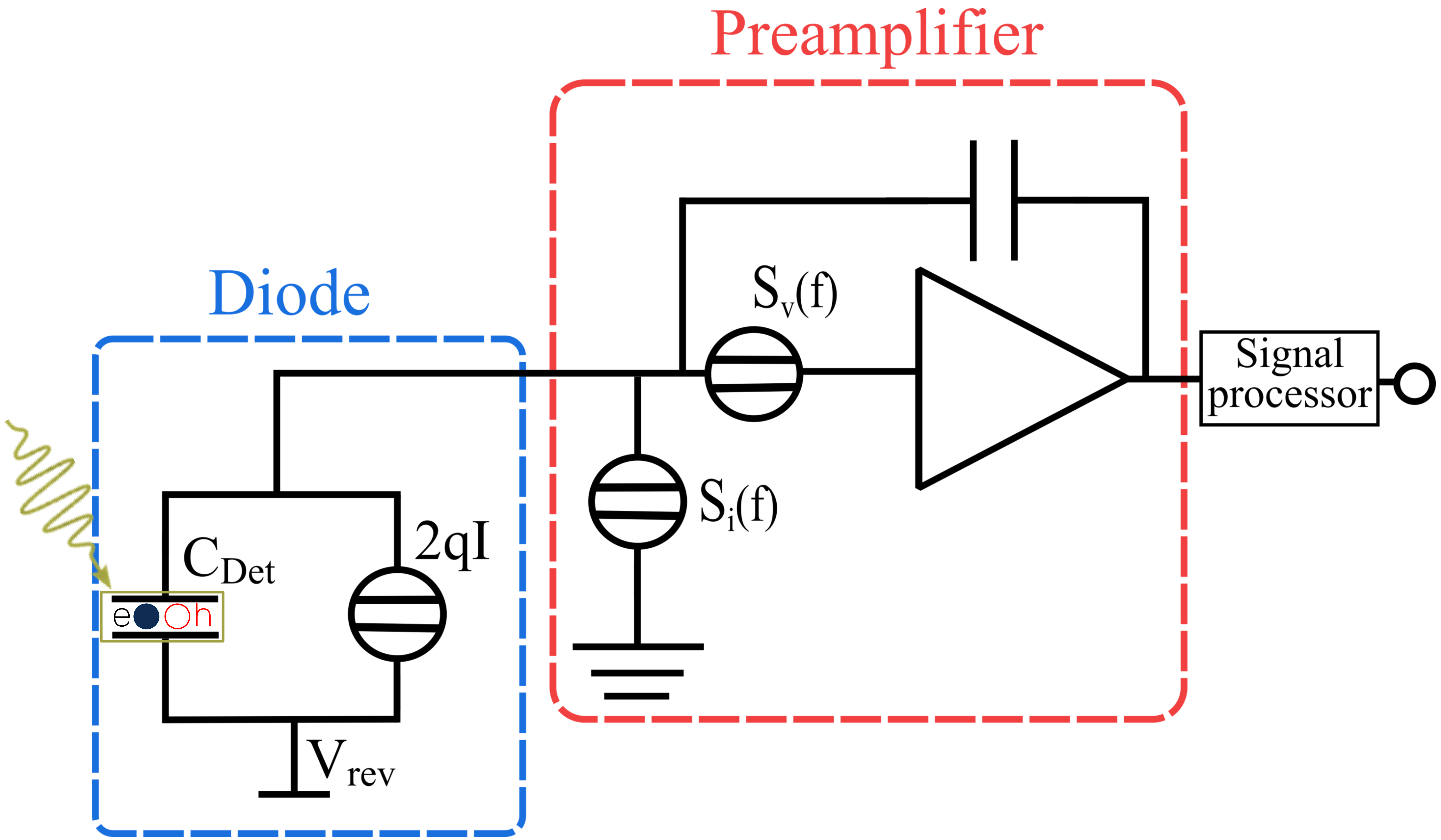
$$ENC = \sqrt{\frac{A}{\tau} + B + C\tau}$$



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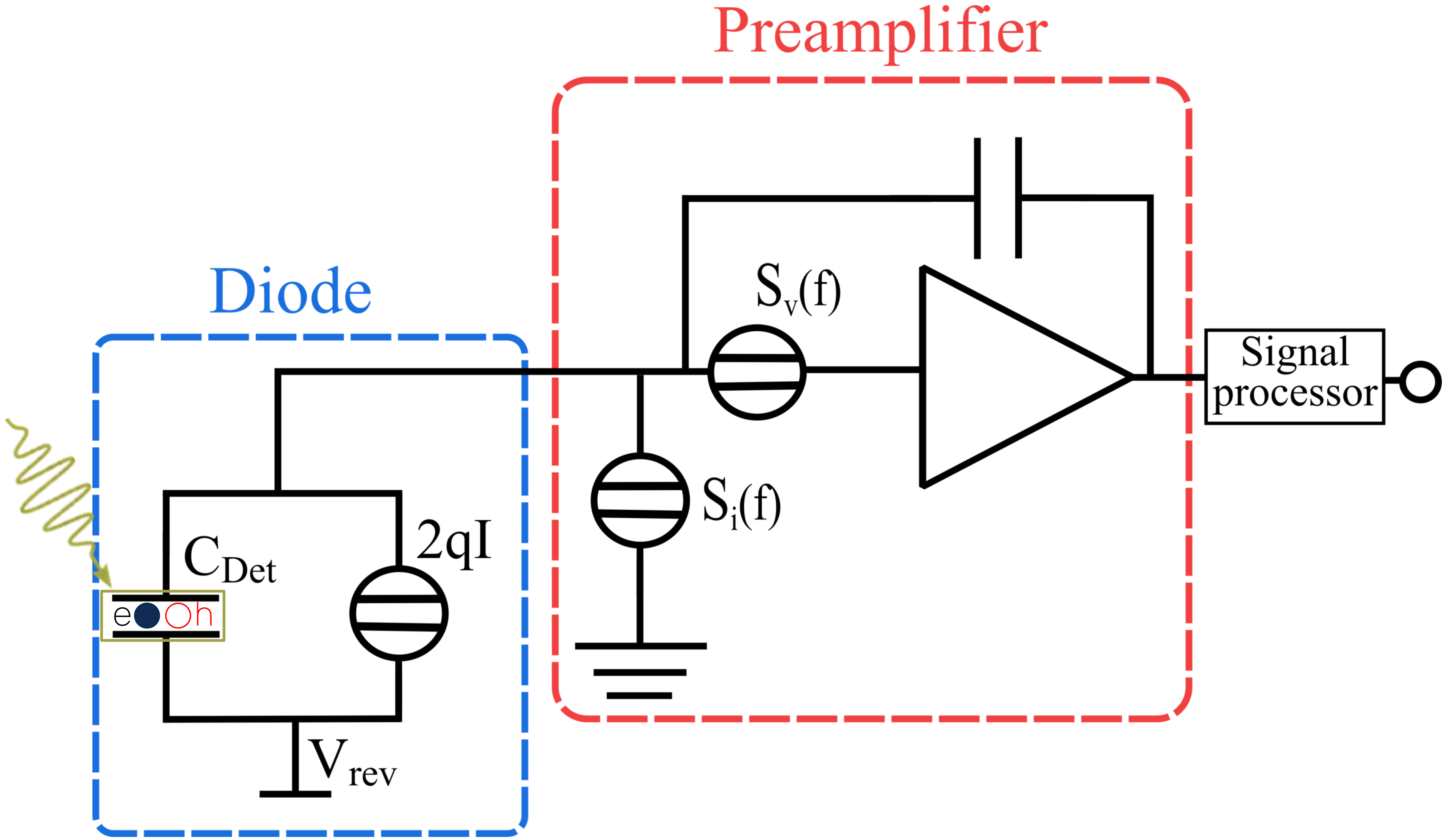

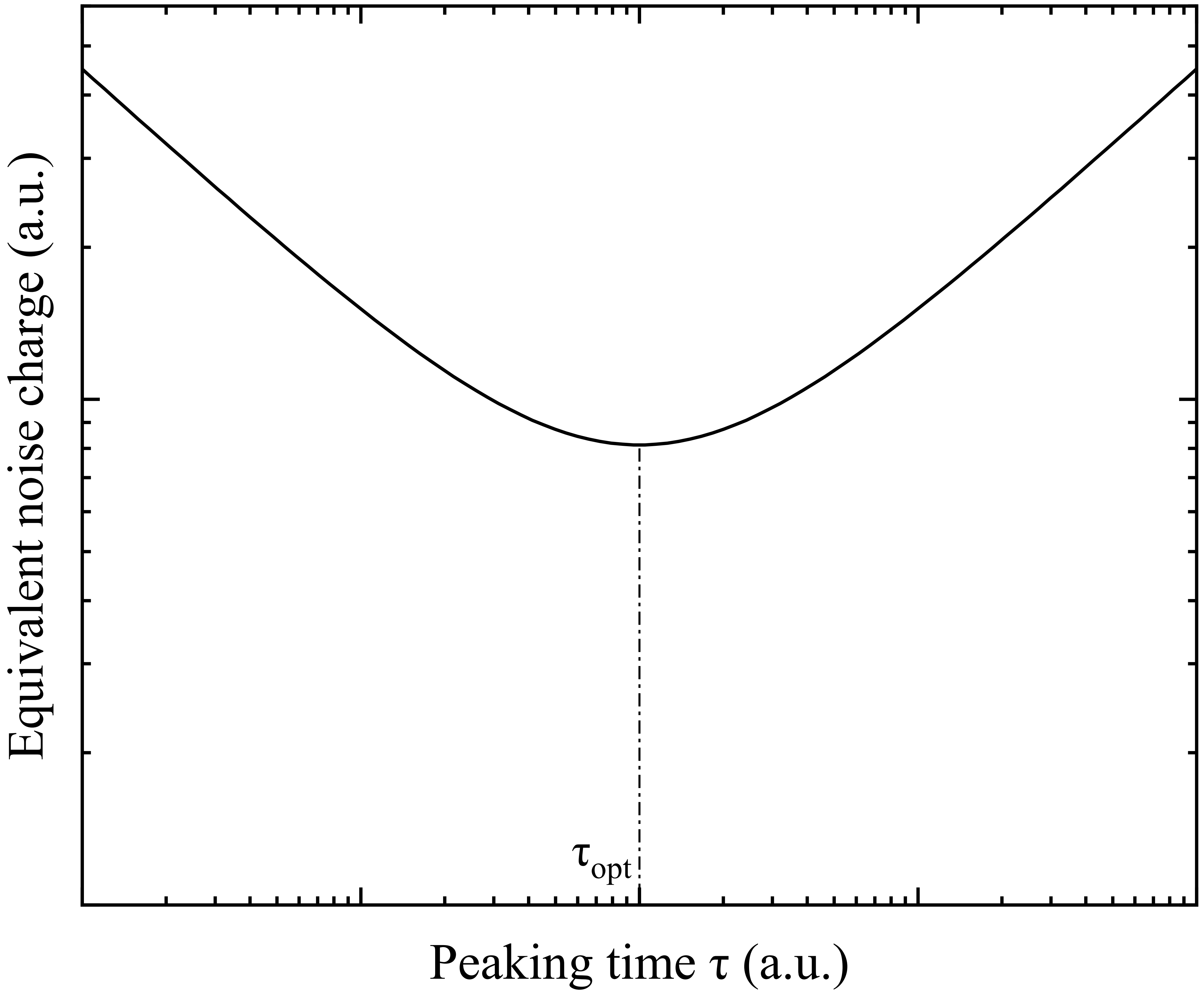

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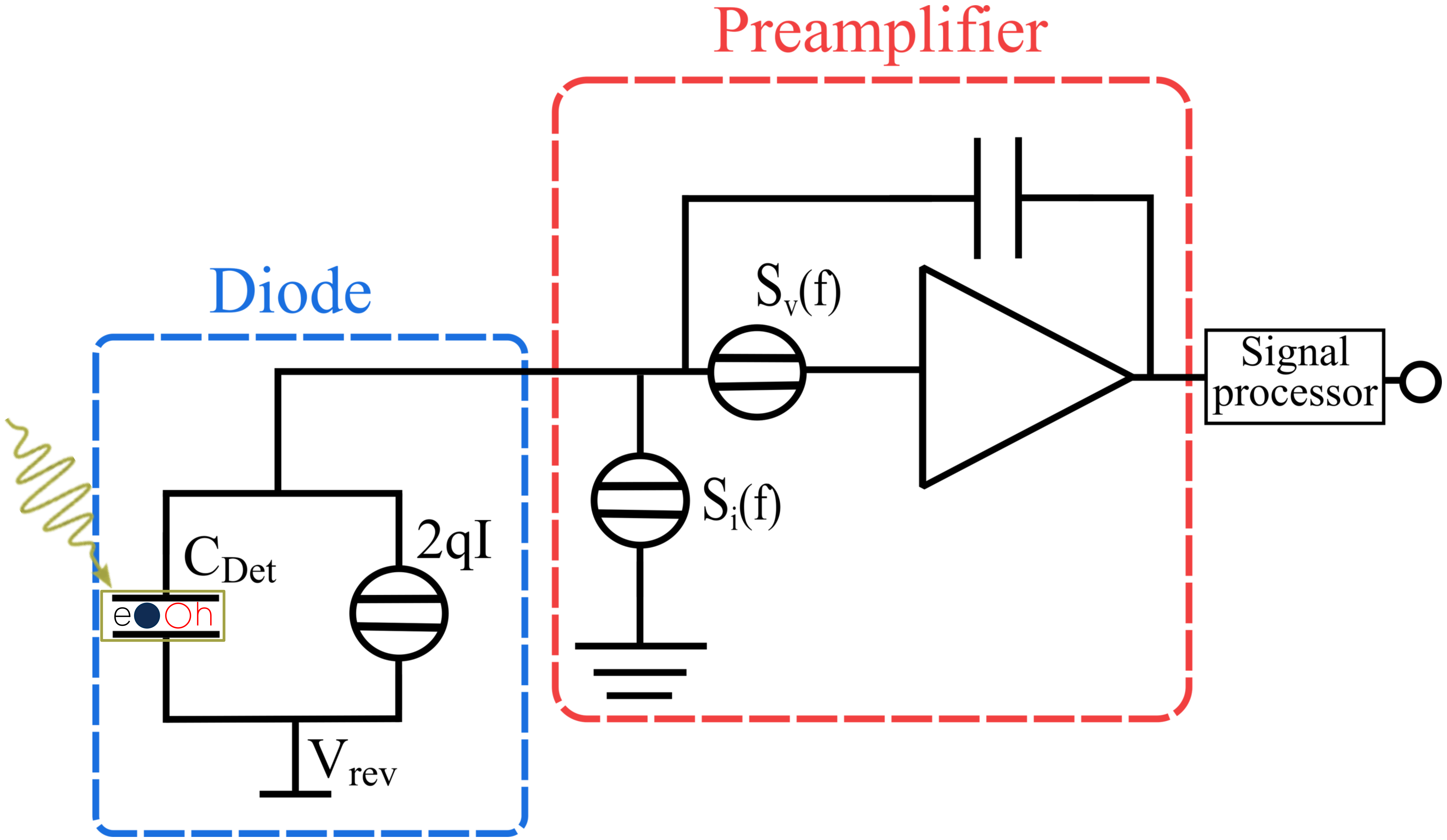

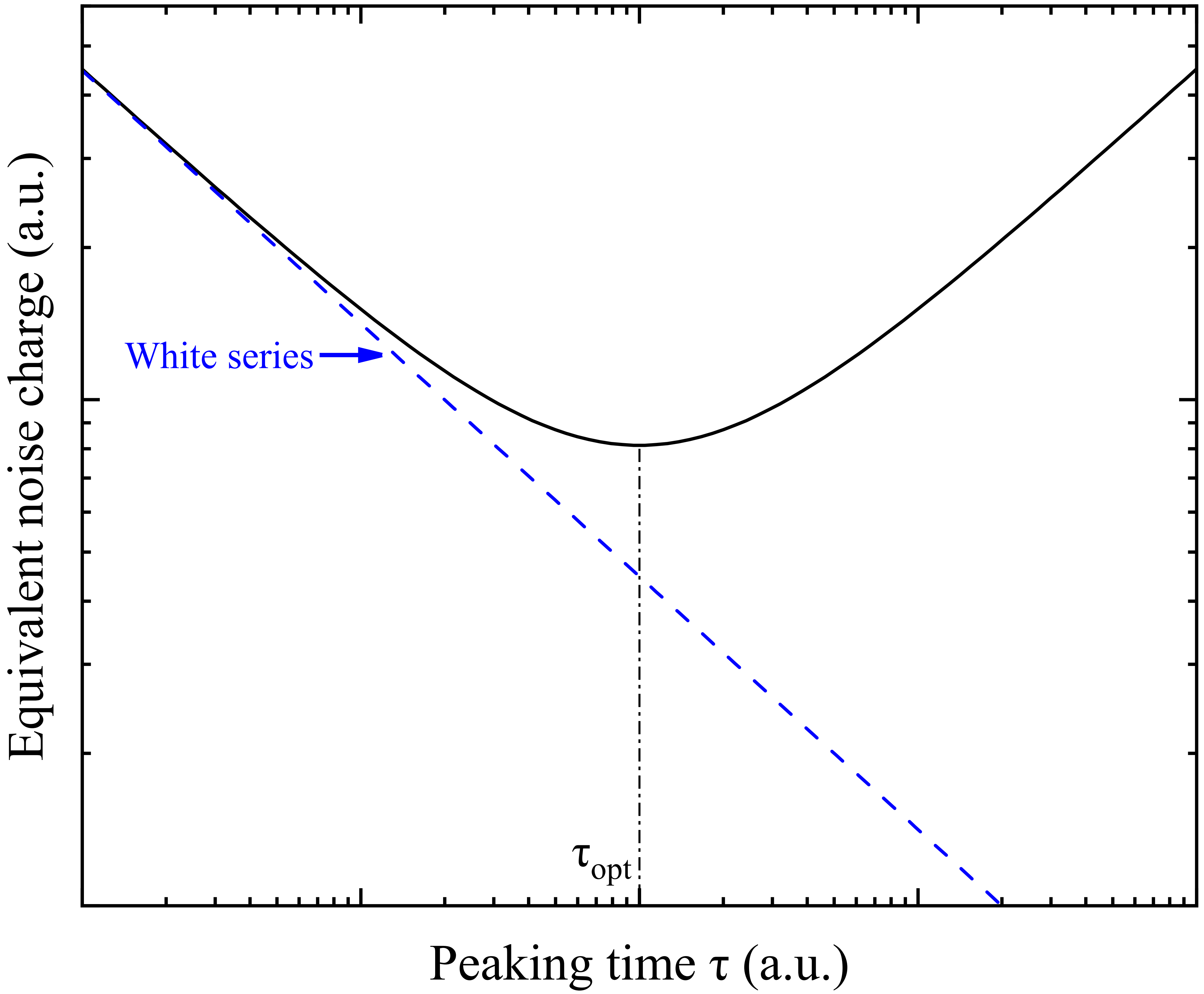

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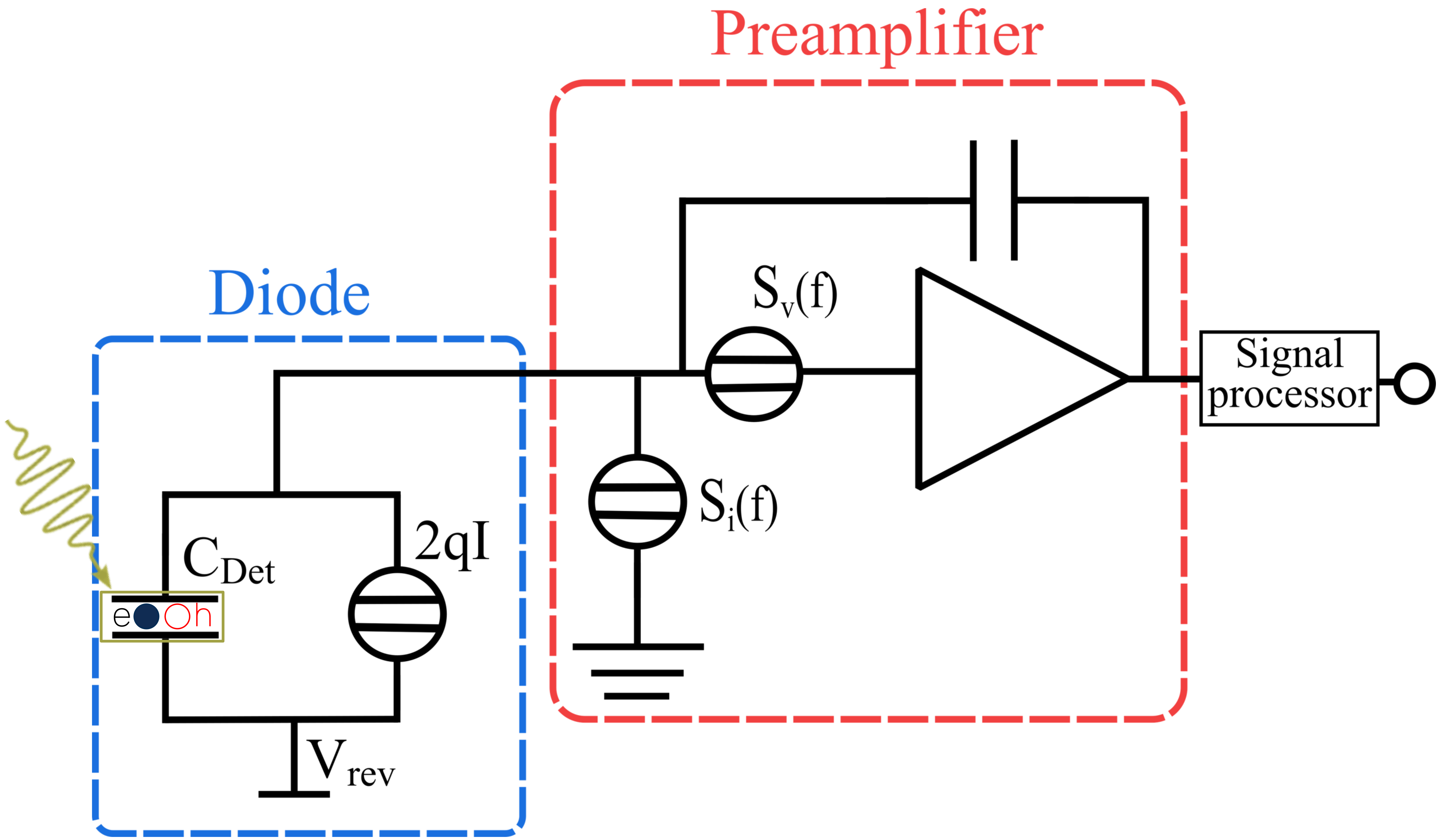
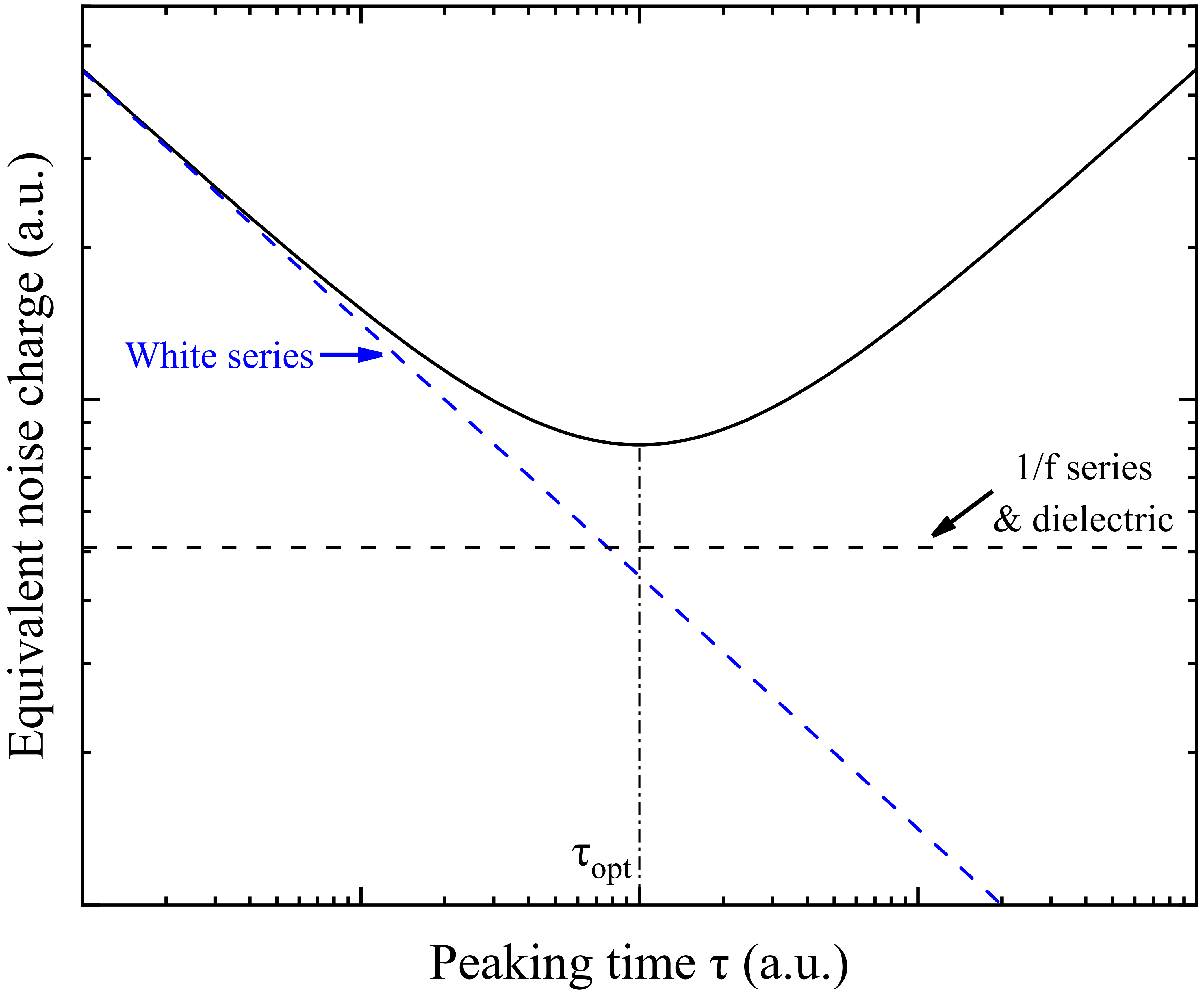
White series

Series 1/f and parallel dielectric





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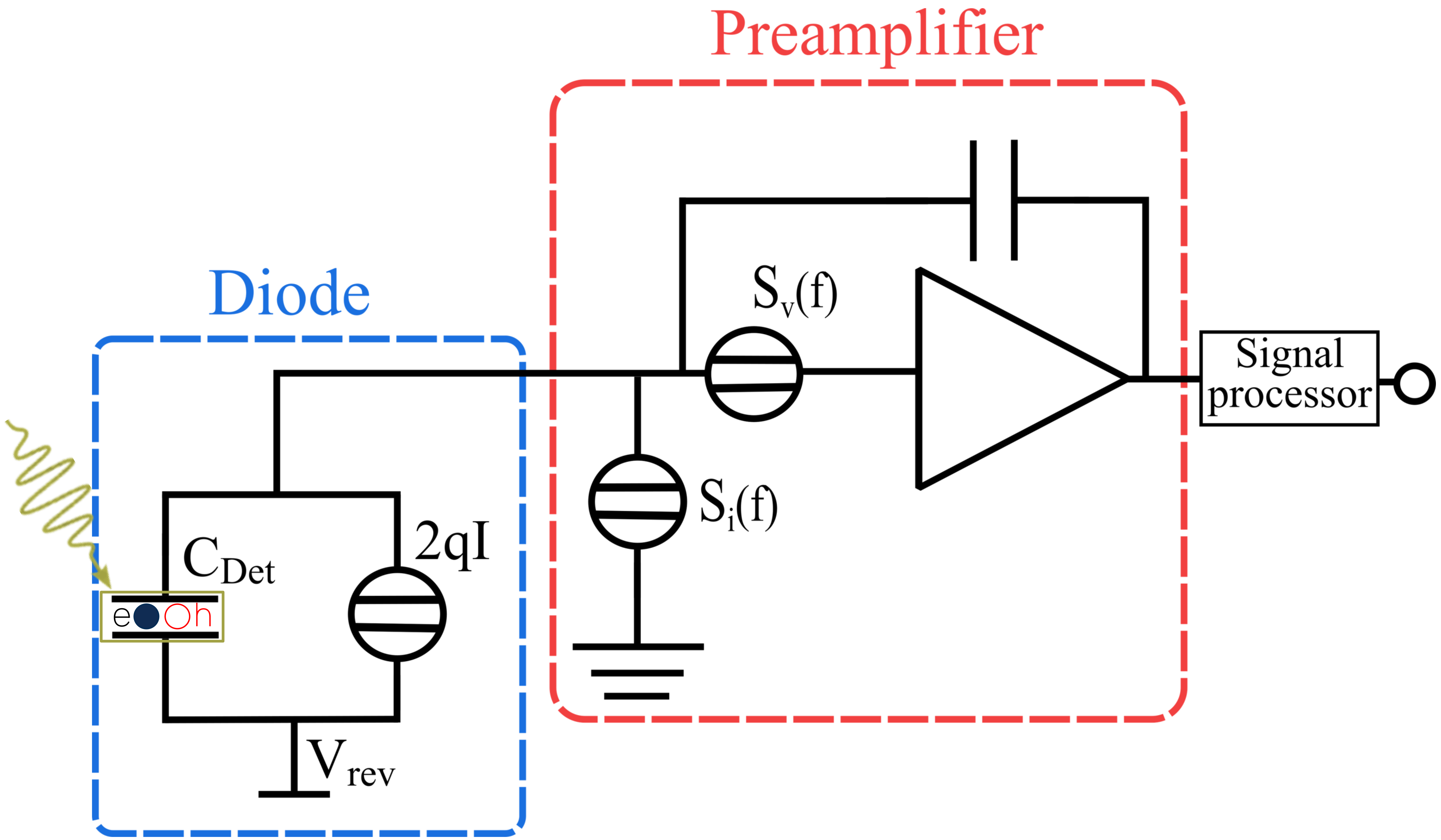

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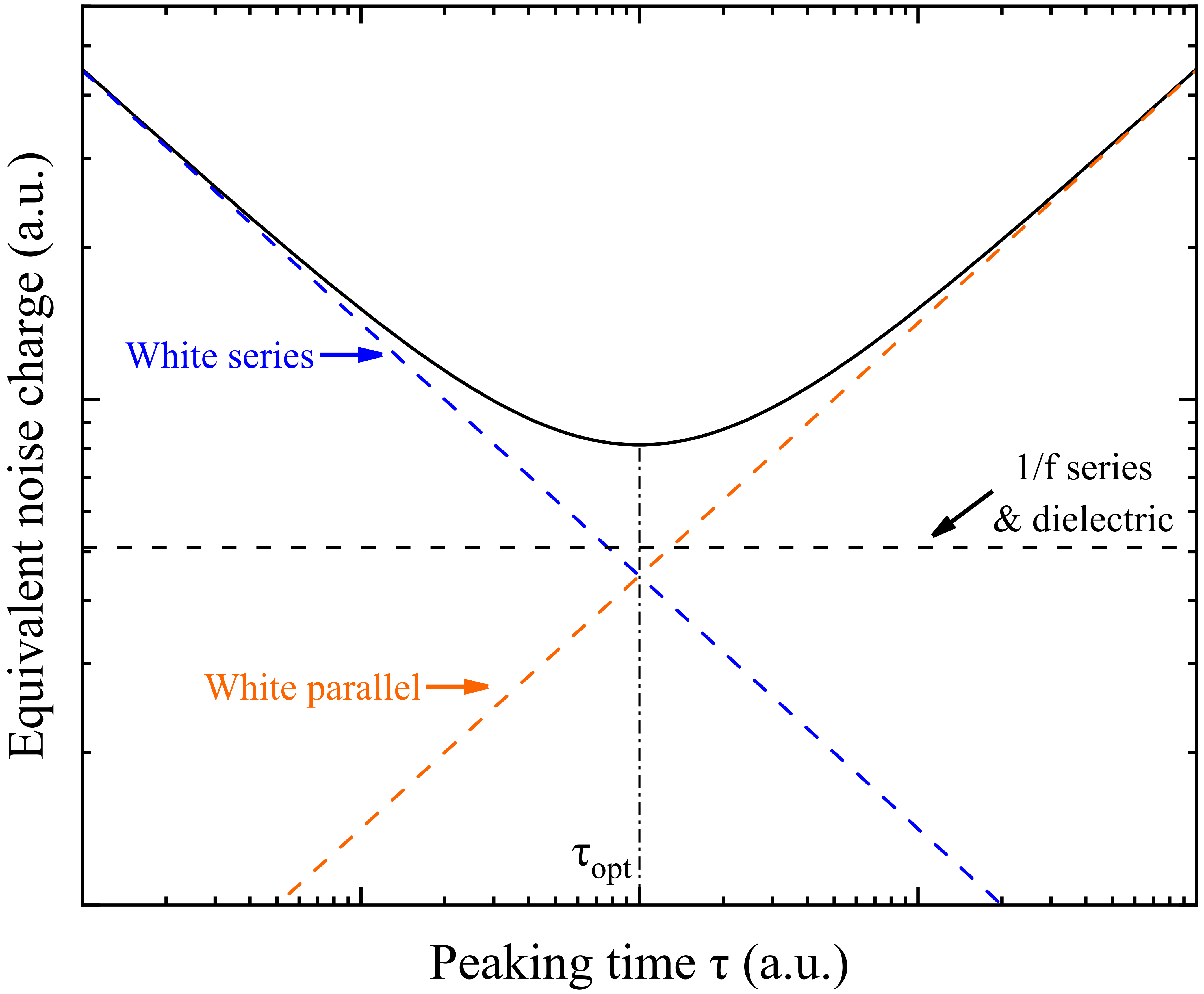
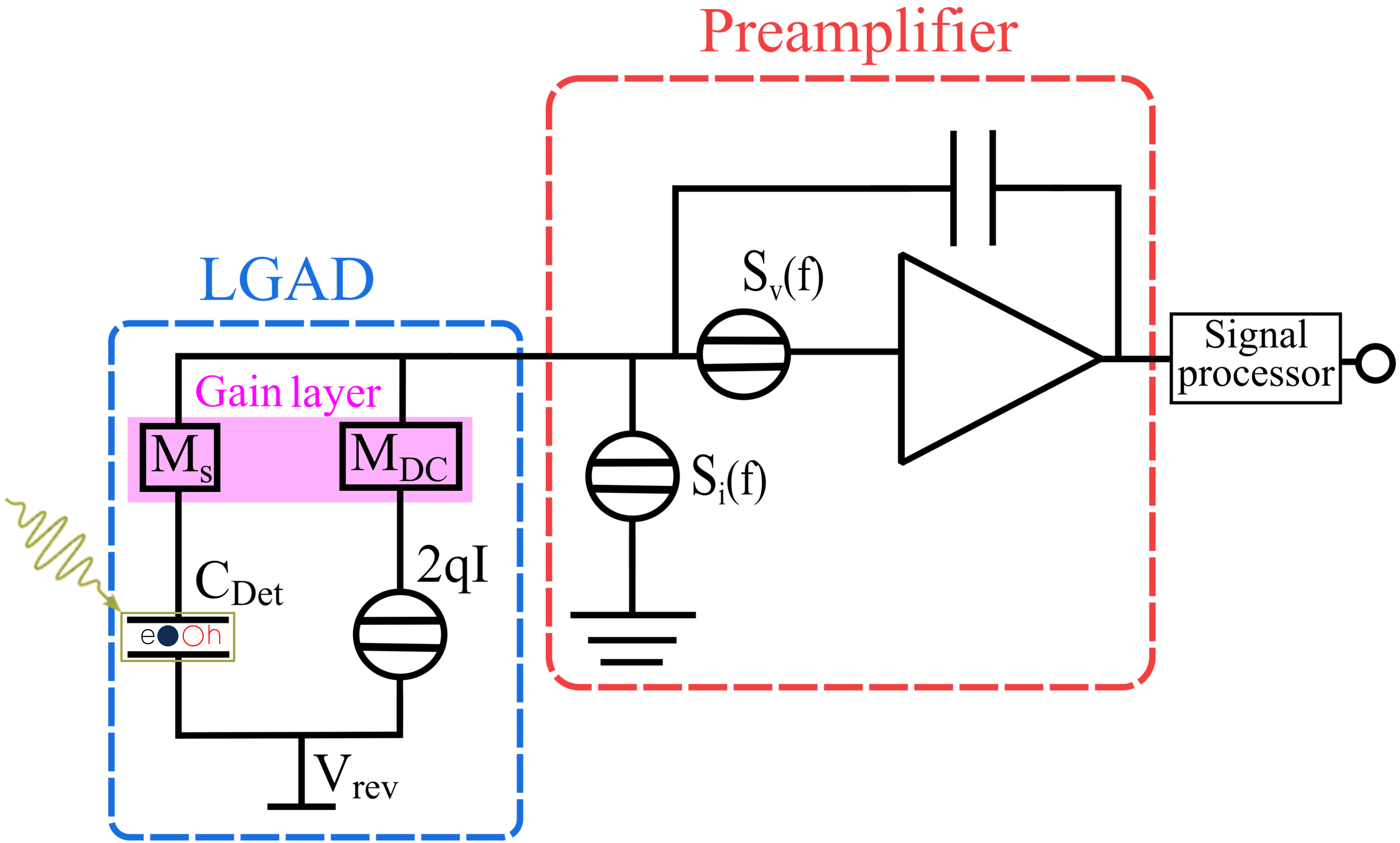
White Parallel $\propto 2qI + S_i(f)$



Equivalent Noise Charge of LGAD-based detection system



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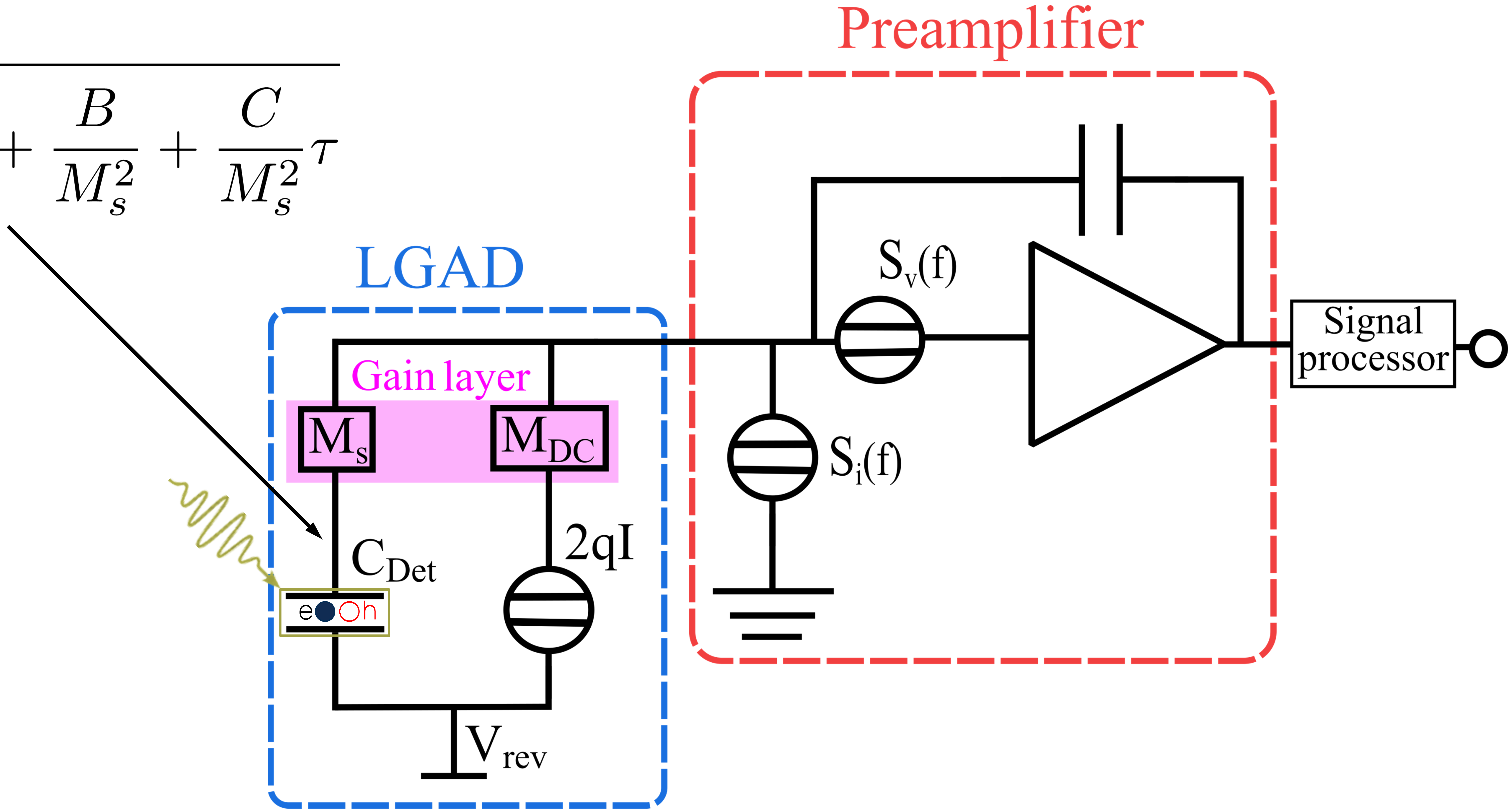

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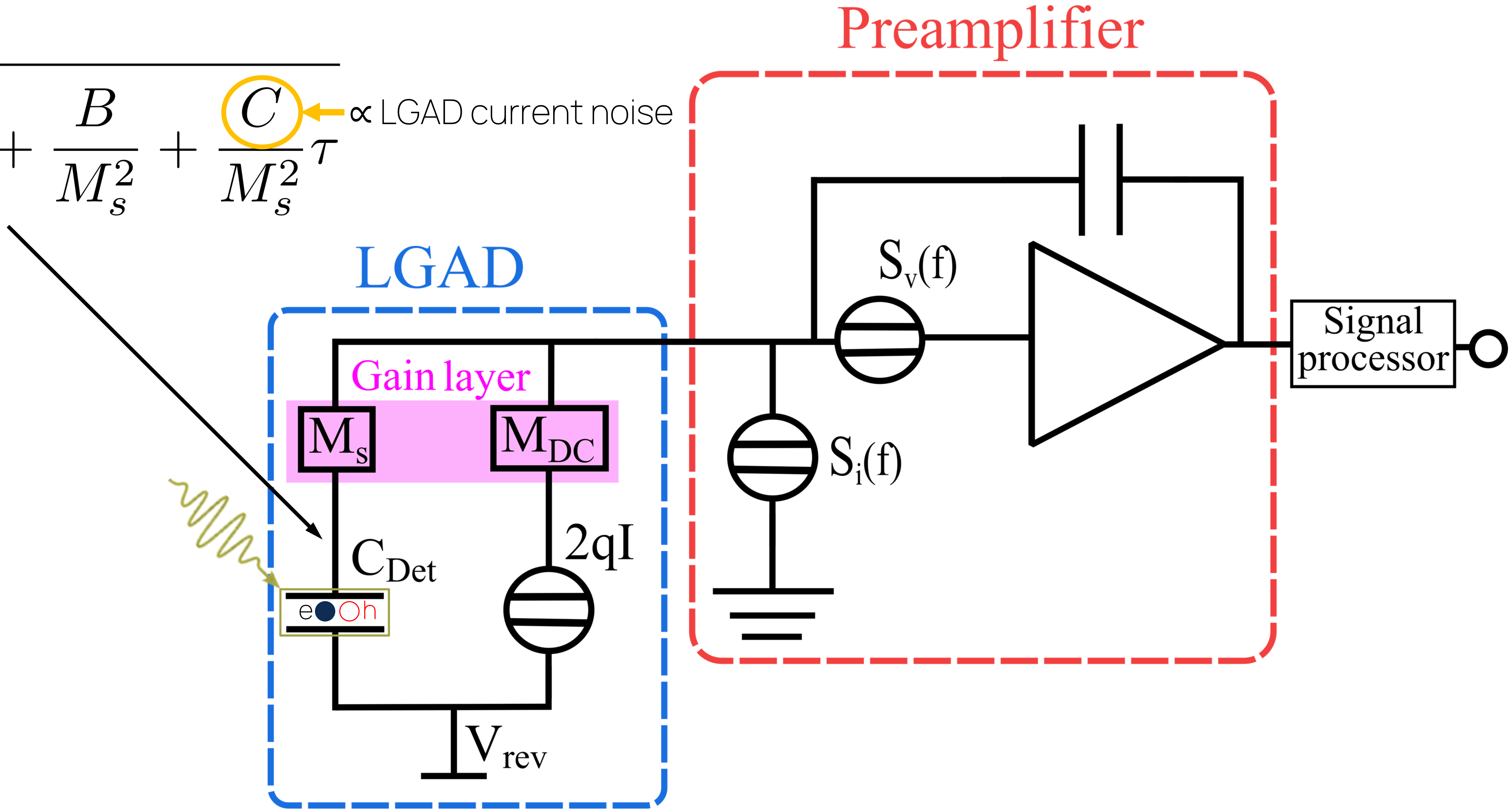
∝ LGAD current noise



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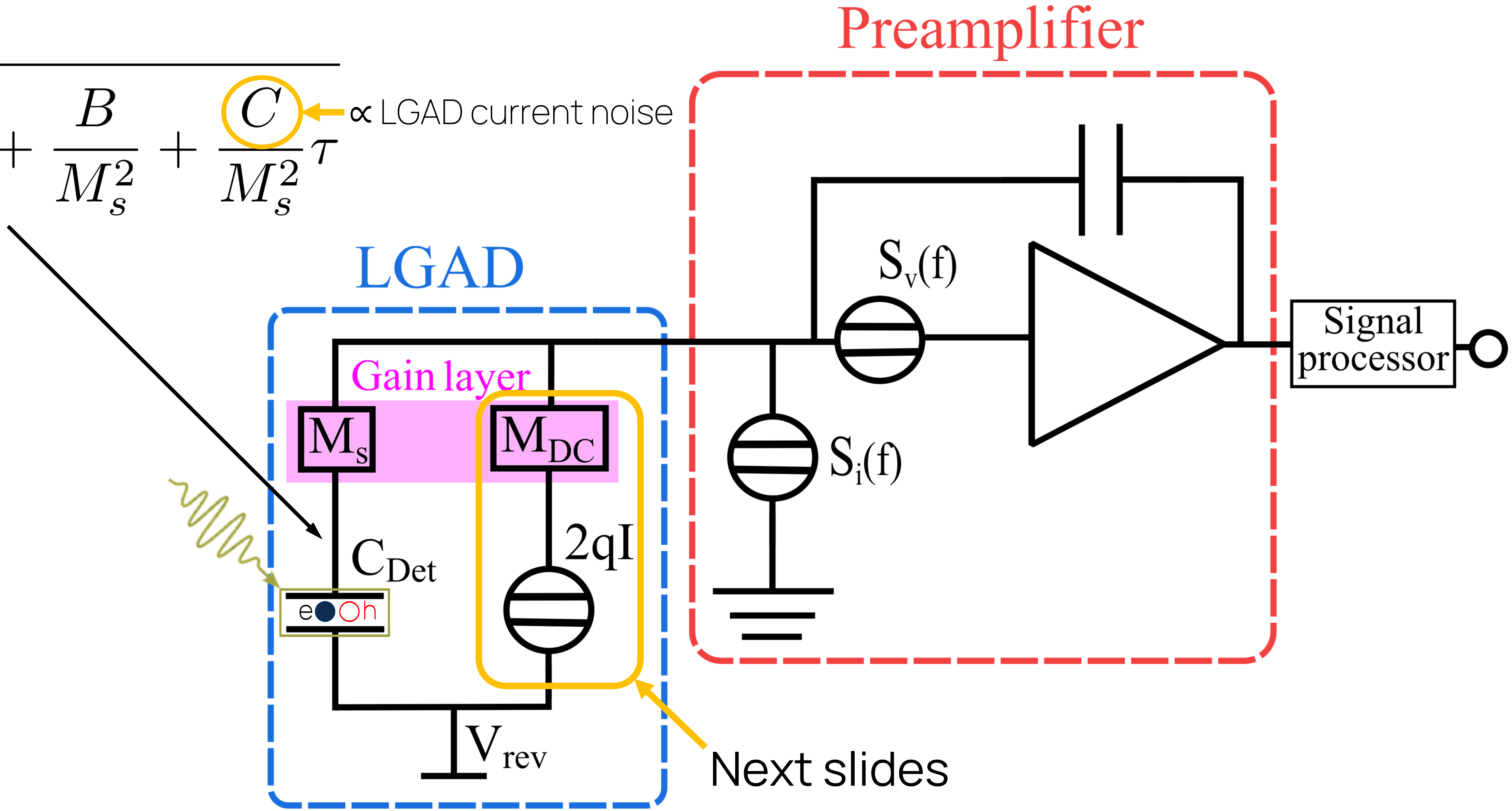

Next slides

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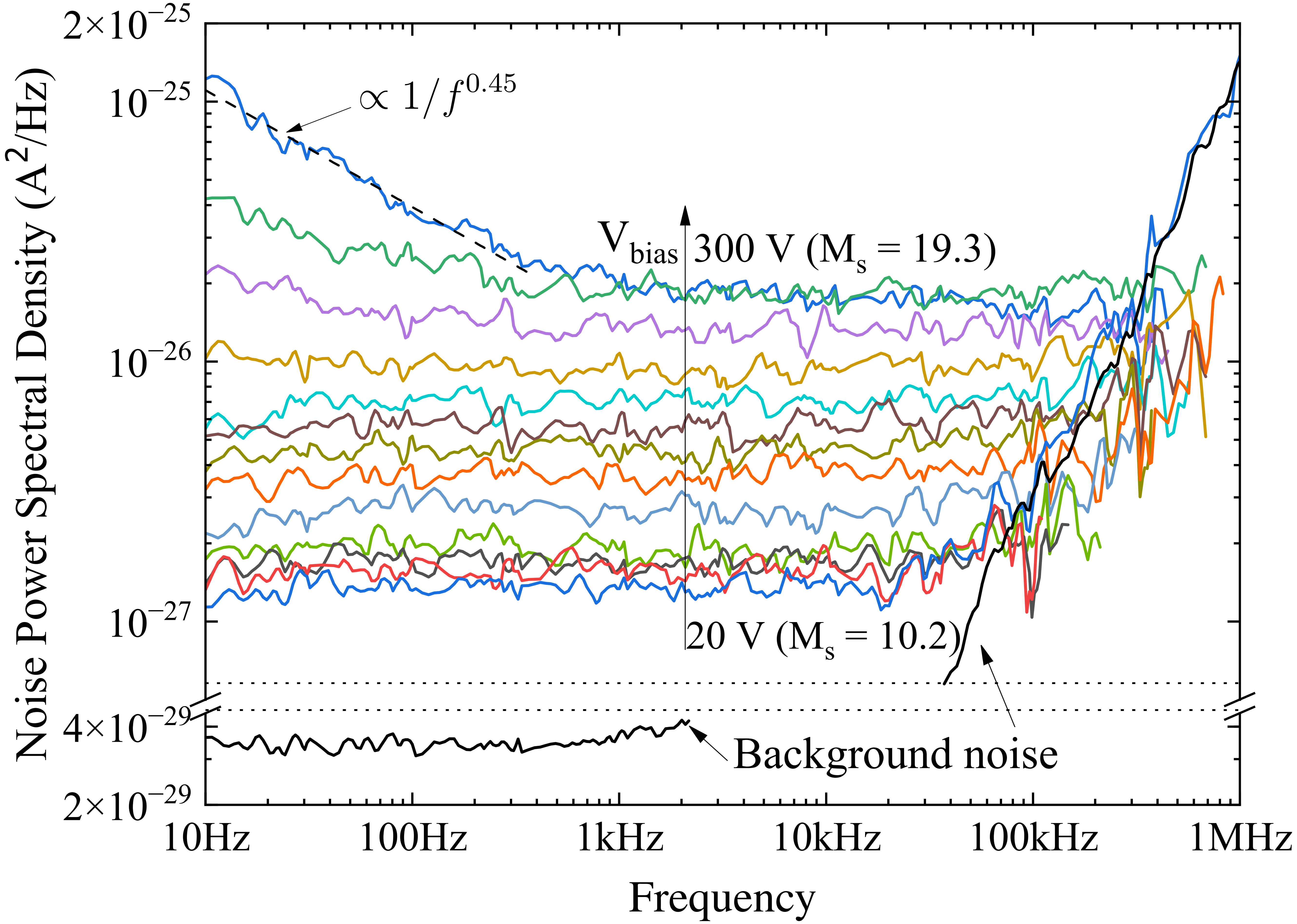
Current Noise Spectral Densities of LGAD

- LGAD NPSD are measured using the **custom transimpedance amplifier** [6,7] at different reverse bias voltages (V_{bias}) and temperature T = +20°C
- LGAD structure: 300 µm thick Float Zone p-bulk, provided by BNL



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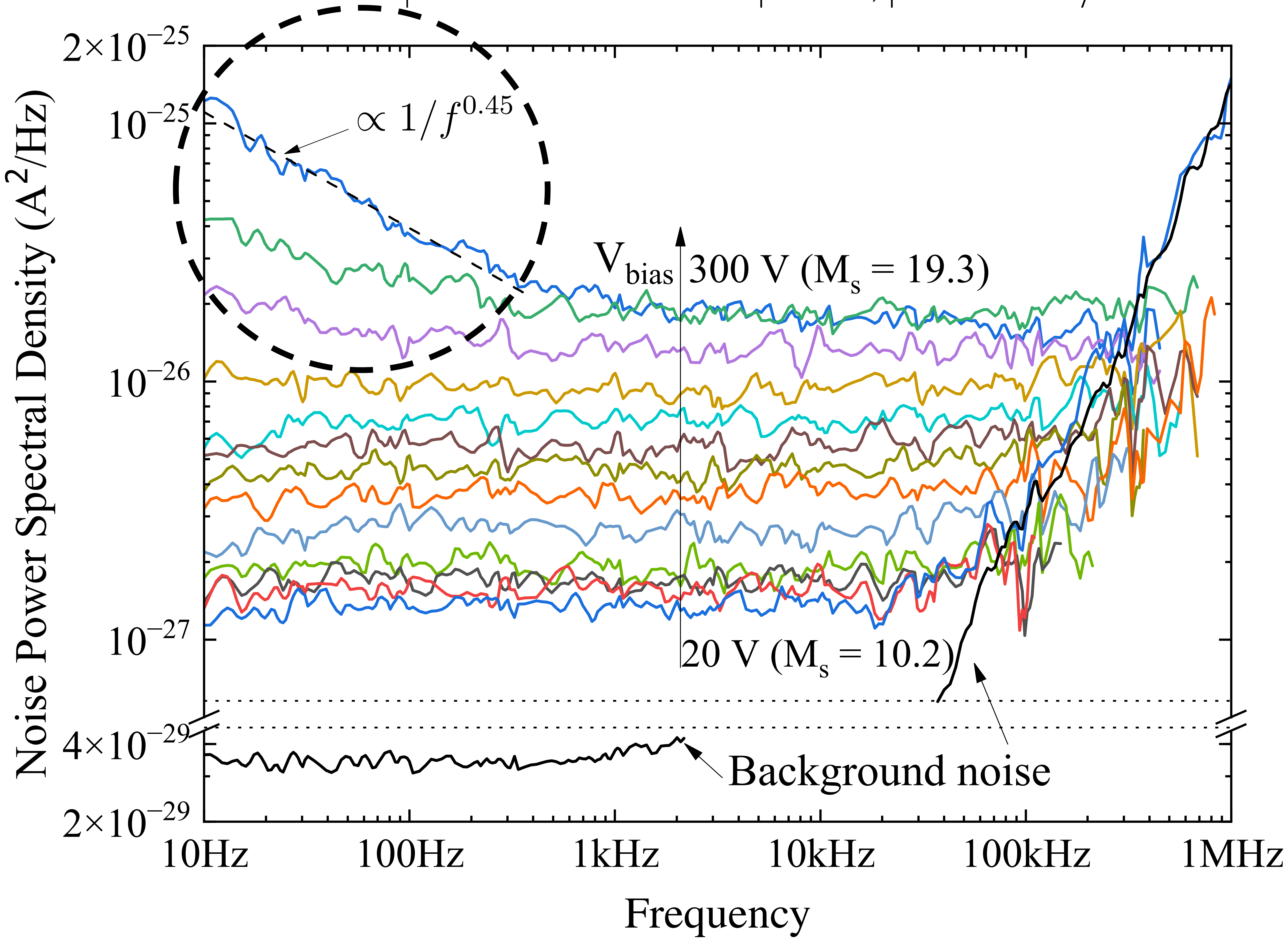

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1. **Low frequency (burst) noise** appears at V_{bias} >200 V due to the **charge traps** inside the high-electric field region [8]

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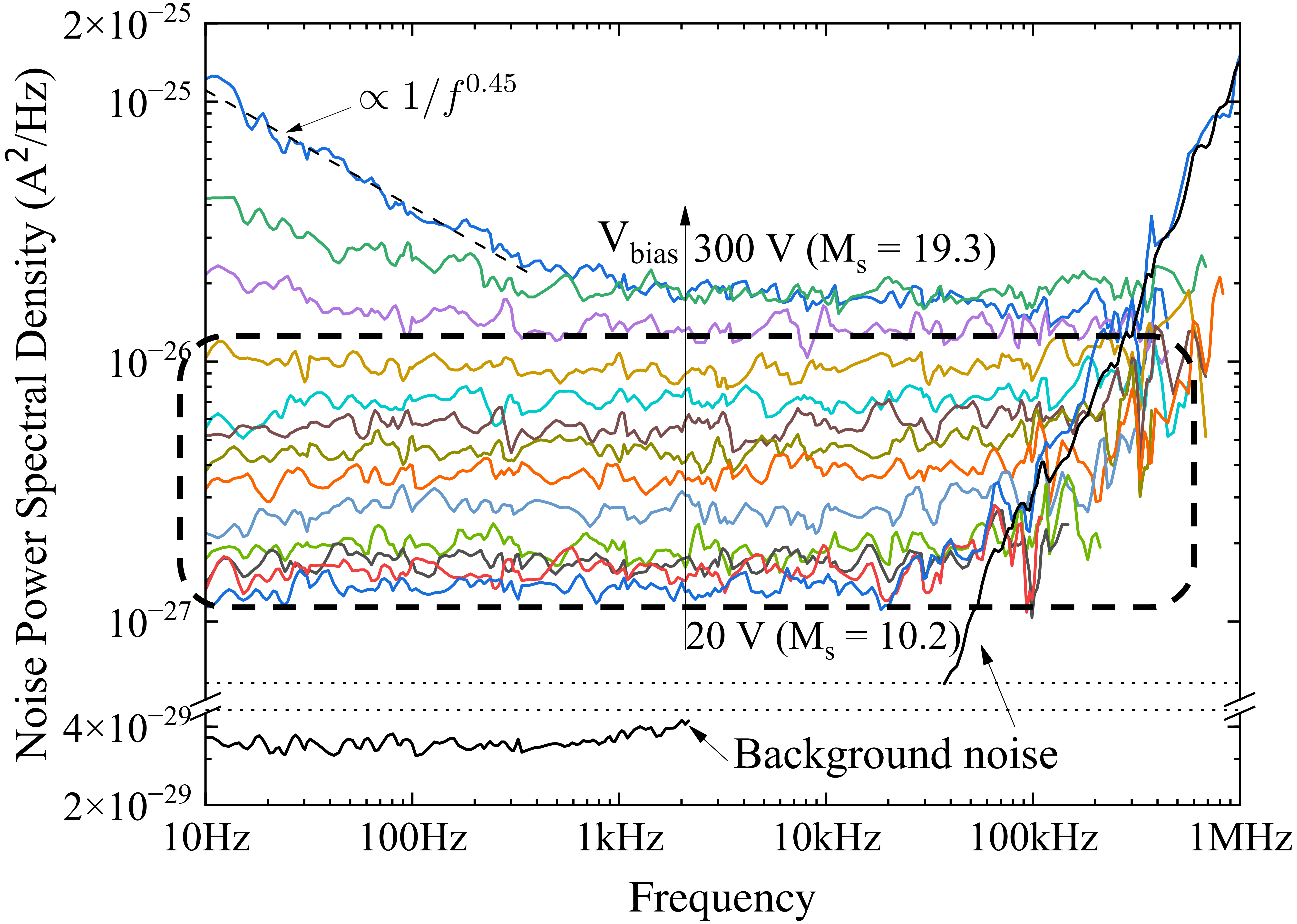

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$$NPSD_w = 2qI_{inj}M_{DC}^2\zeta$$

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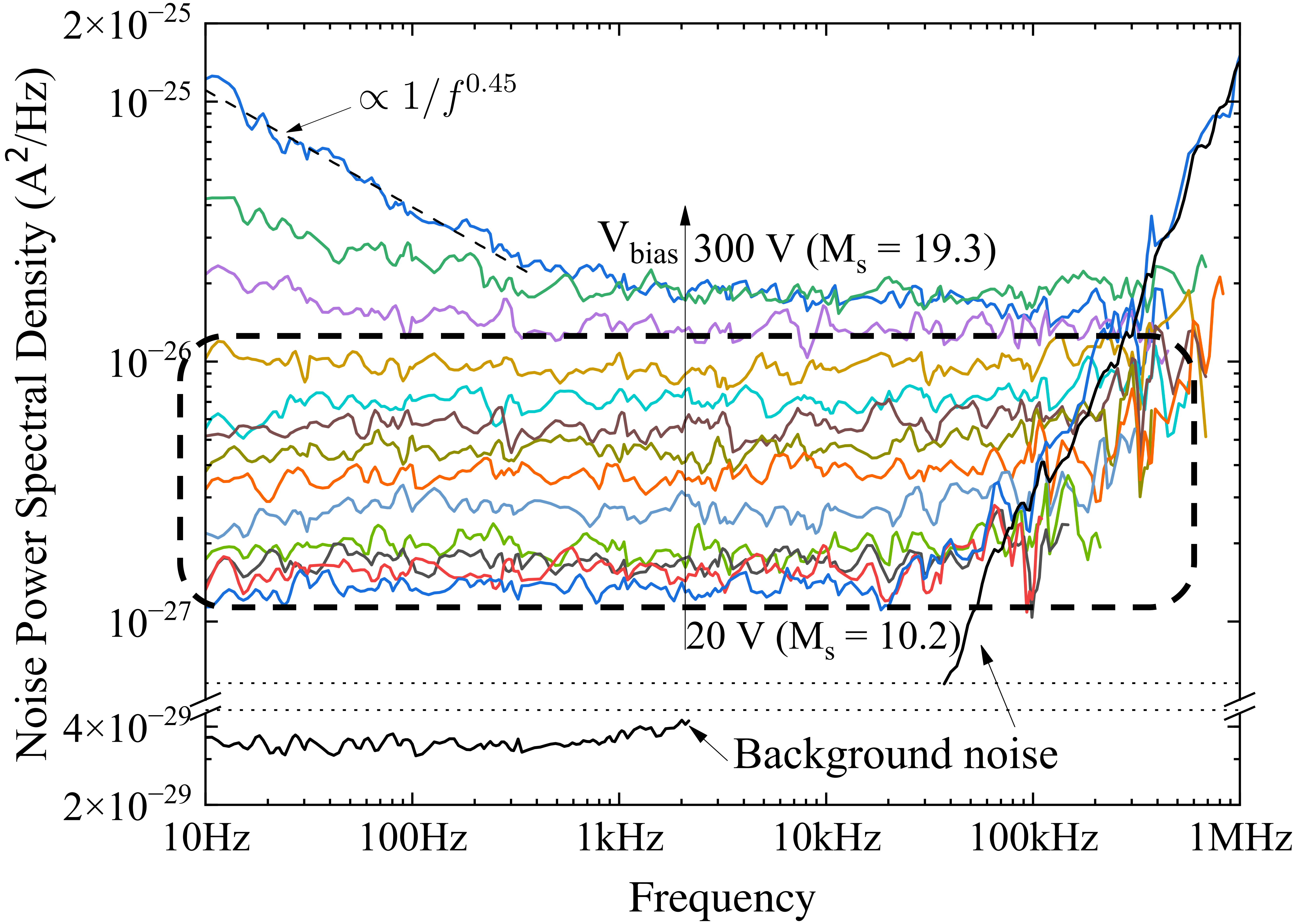

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Parallel noise referred to the gain layer input

$$\frac{NPSD_w}{M_s^2}$$

Signal charge multiplication gain

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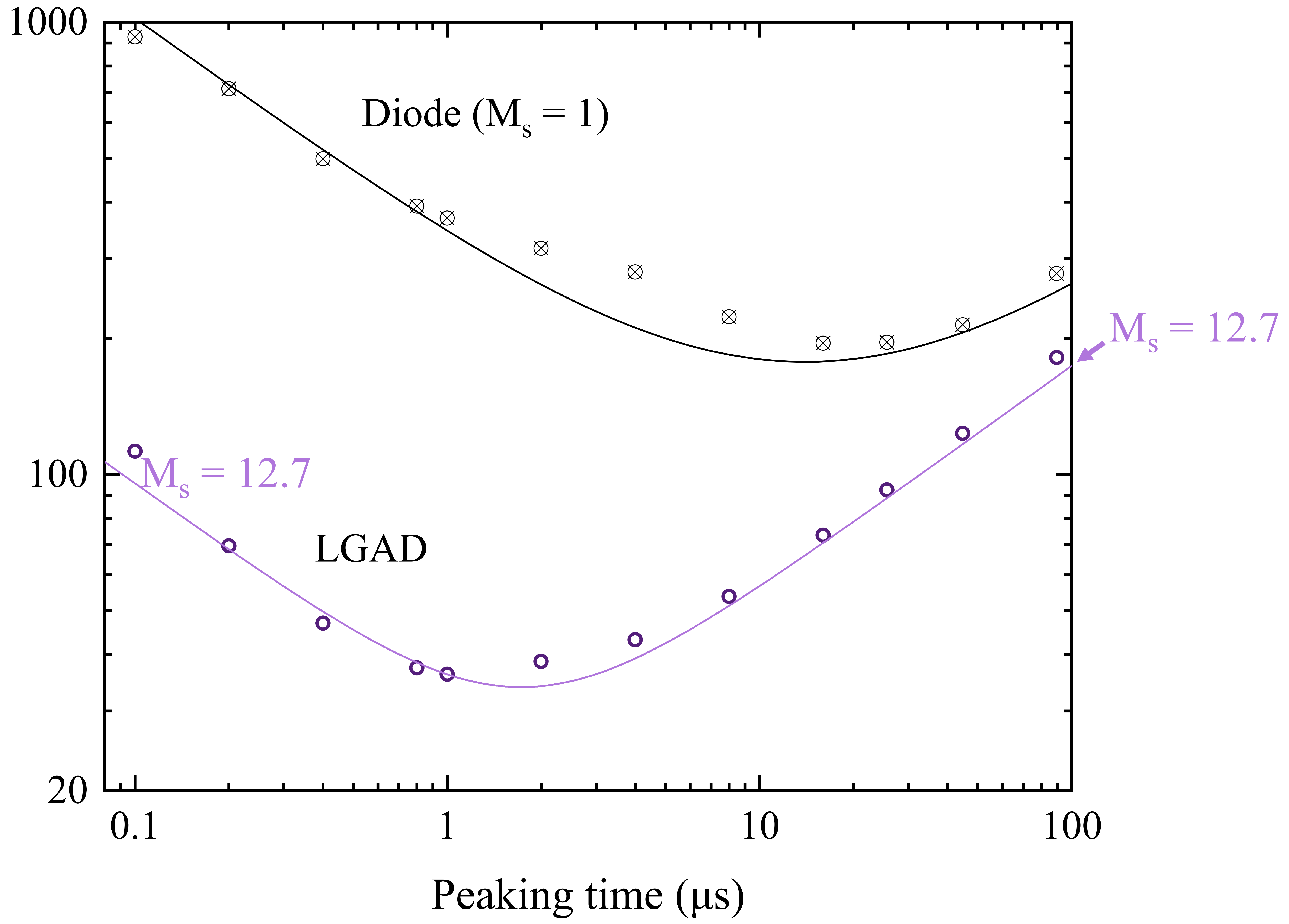

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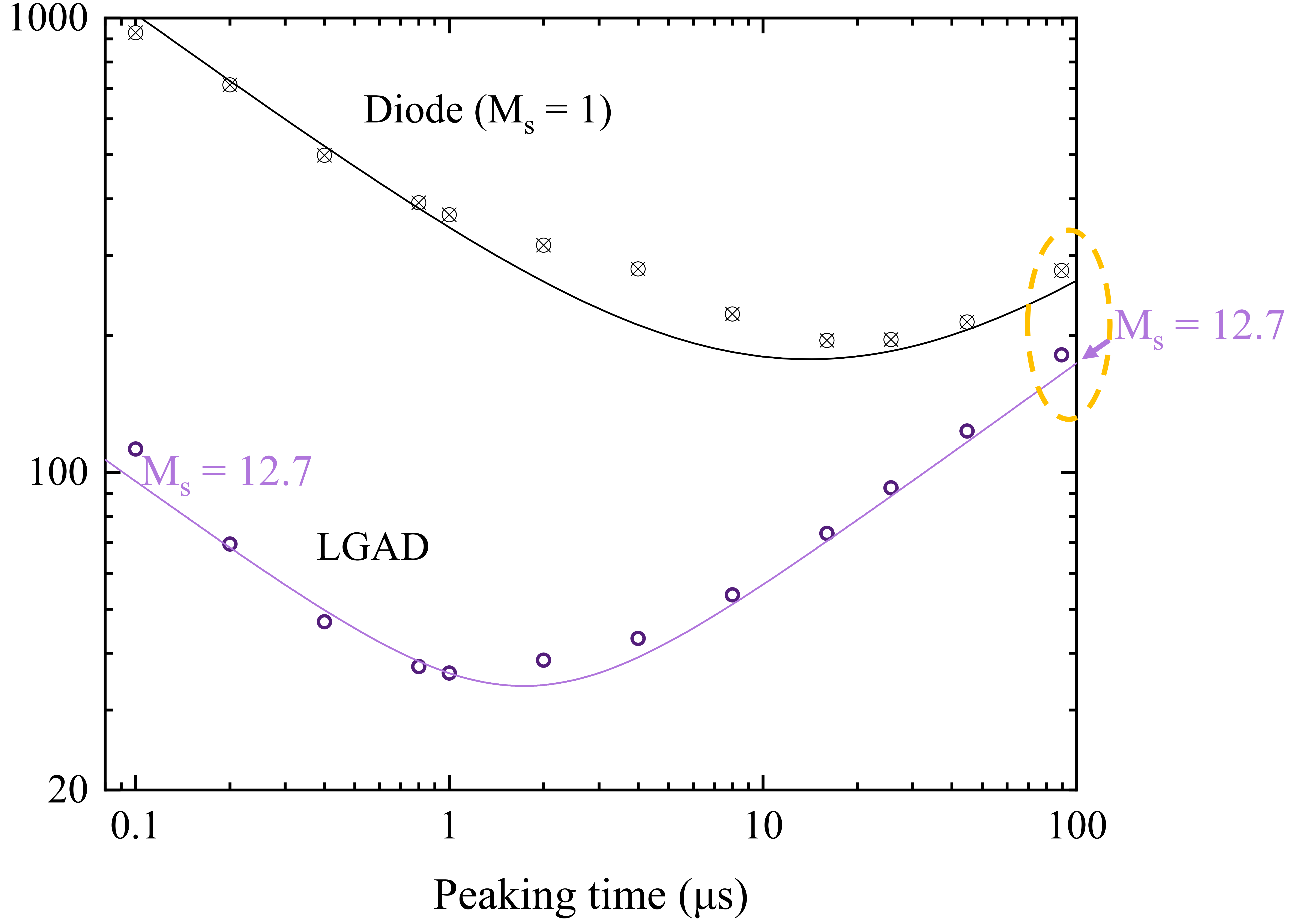

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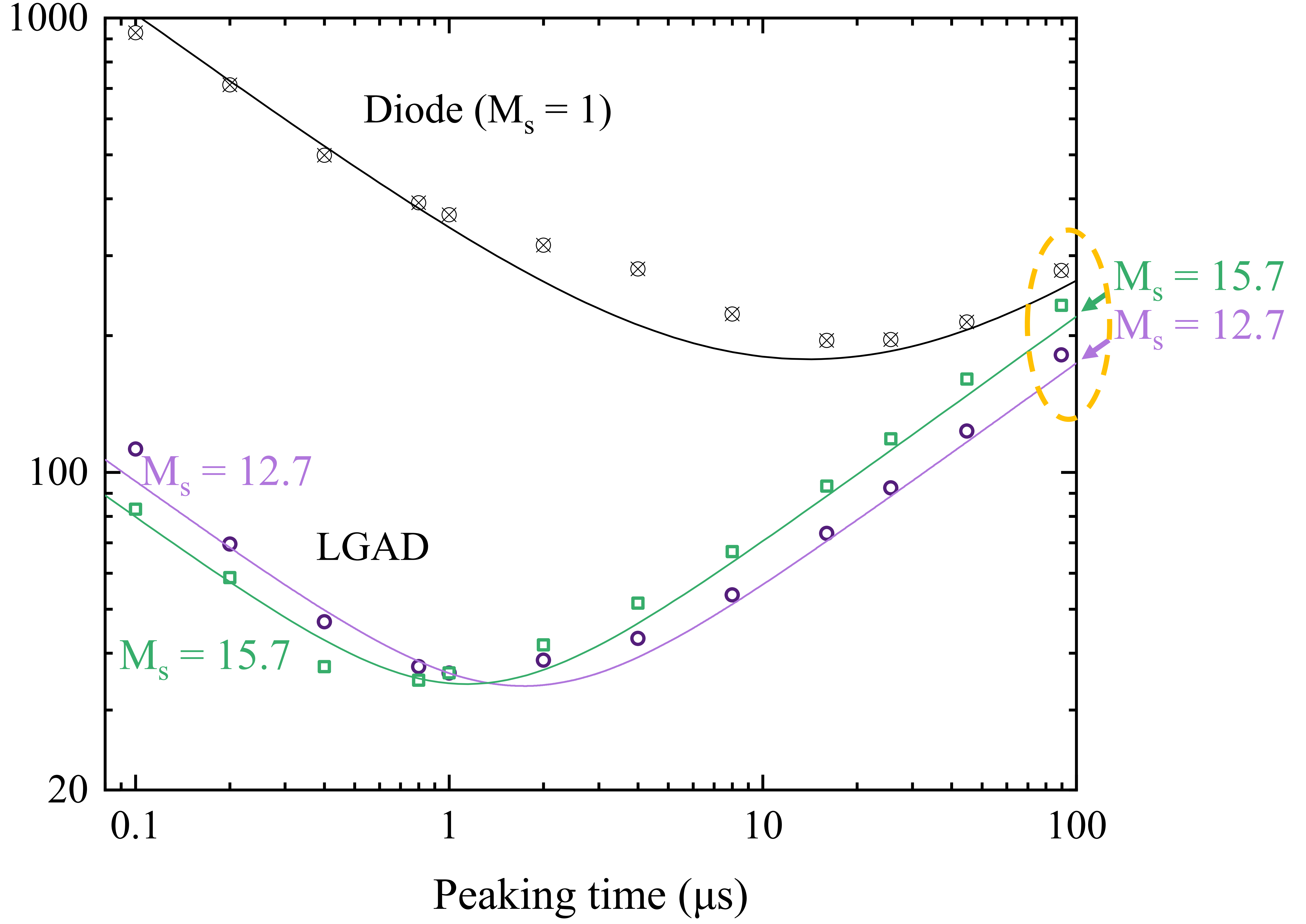

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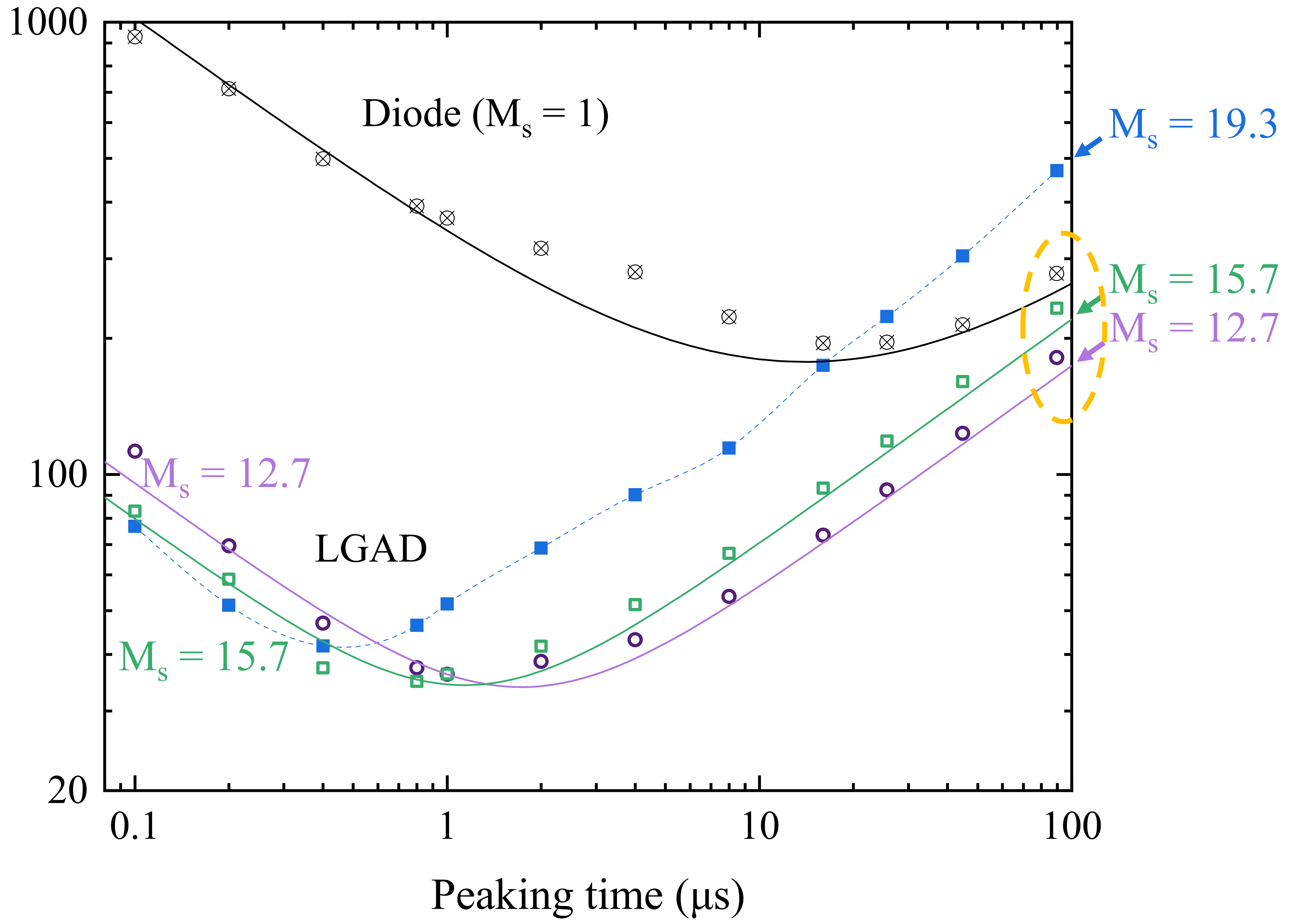

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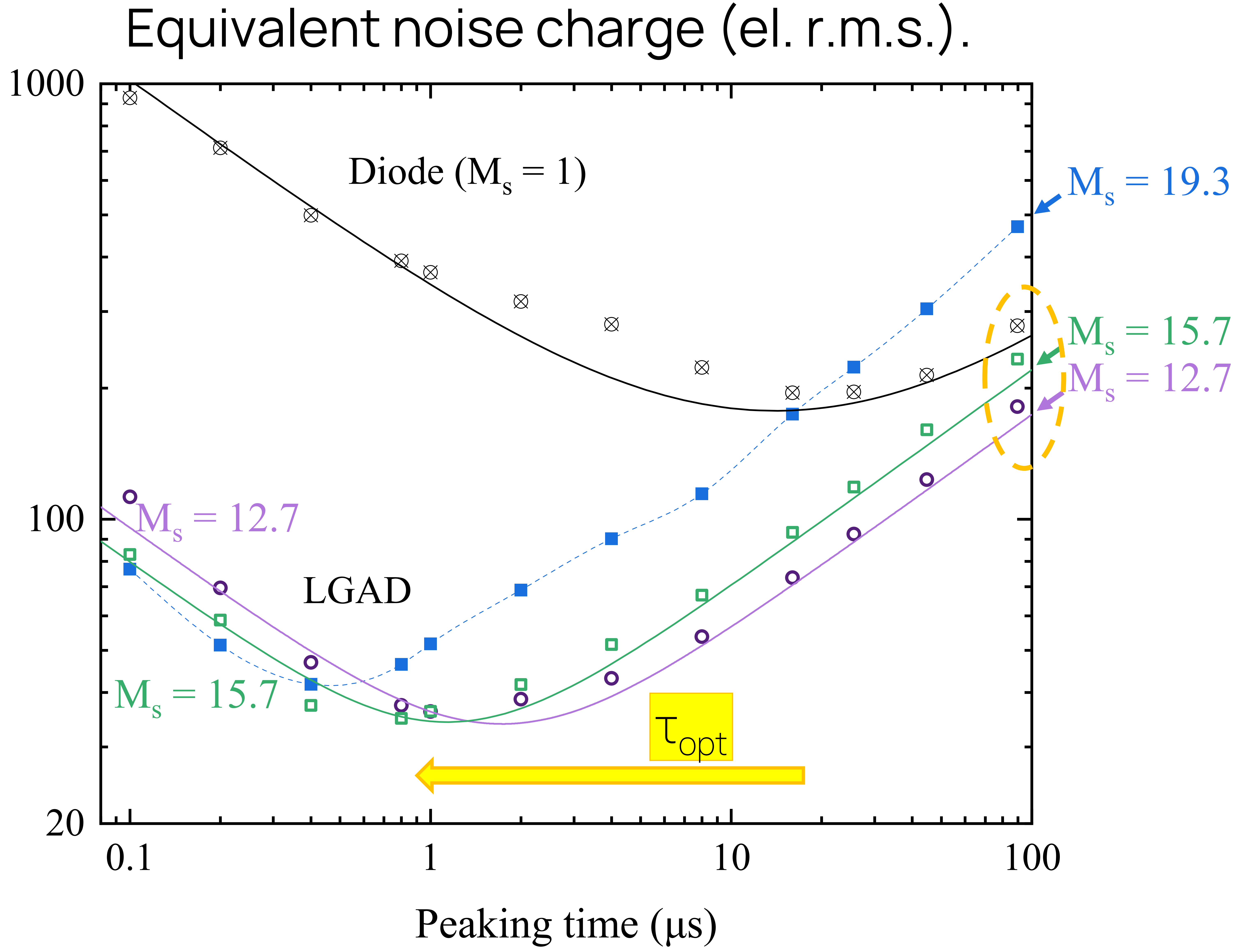
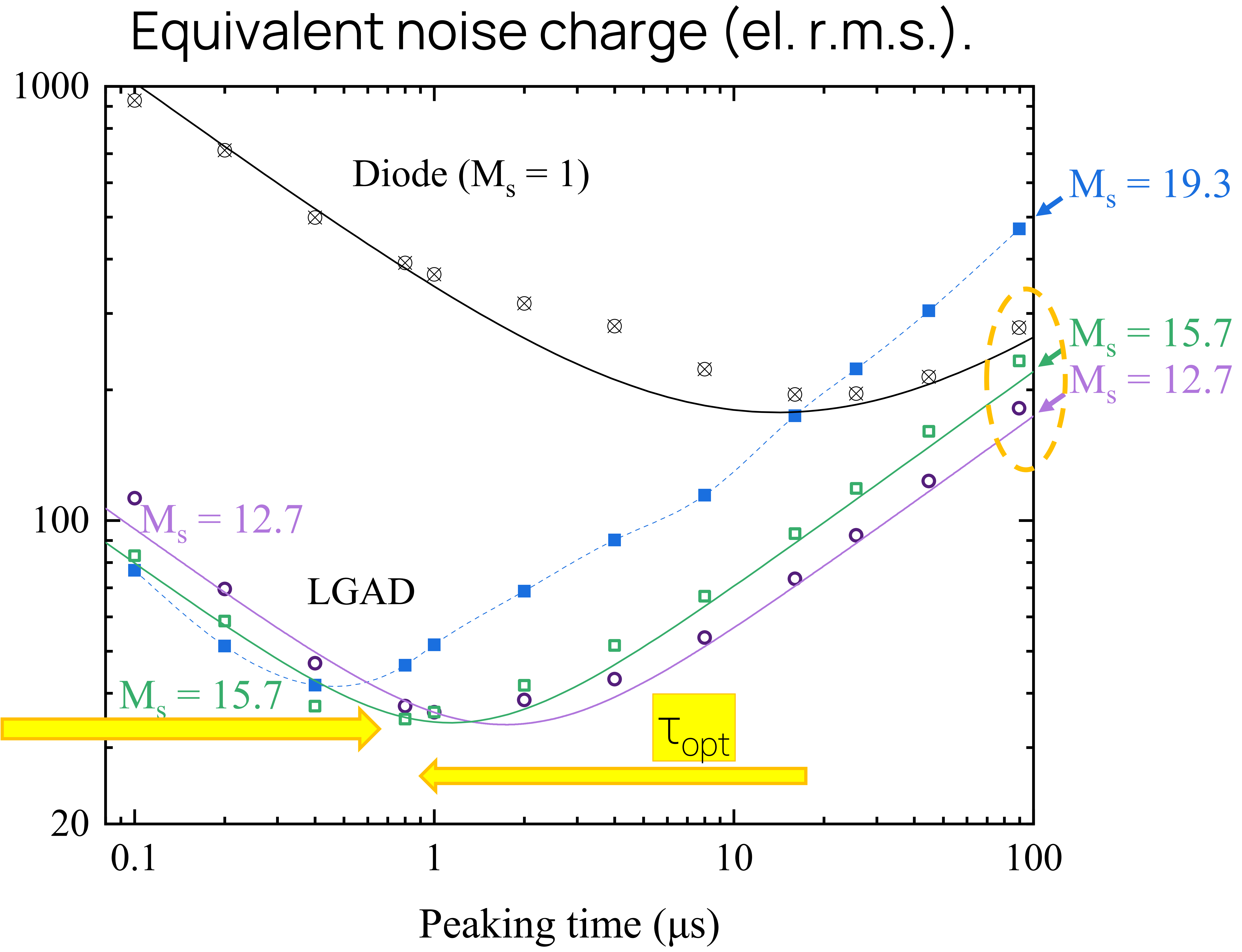


[7] Eremeev, Iurii A., et al. "Performance of an X-γ ray detection system based on a thick silicon LGAD." presented at TREDI2025 conference 4-6 Feb. 2025, Trento, Italy.

ENC of LGAD-based detection system

$$ENC_{M_s} = \sqrt{\frac{A}{M_s^2\tau} + \frac{B}{M_s^2} + \frac{\overset{\propto NPSD_w}{\boxed{C}}}{M_s^2}\tau}$$



$ENC_{opt} \approx$ const

τ_{opt}

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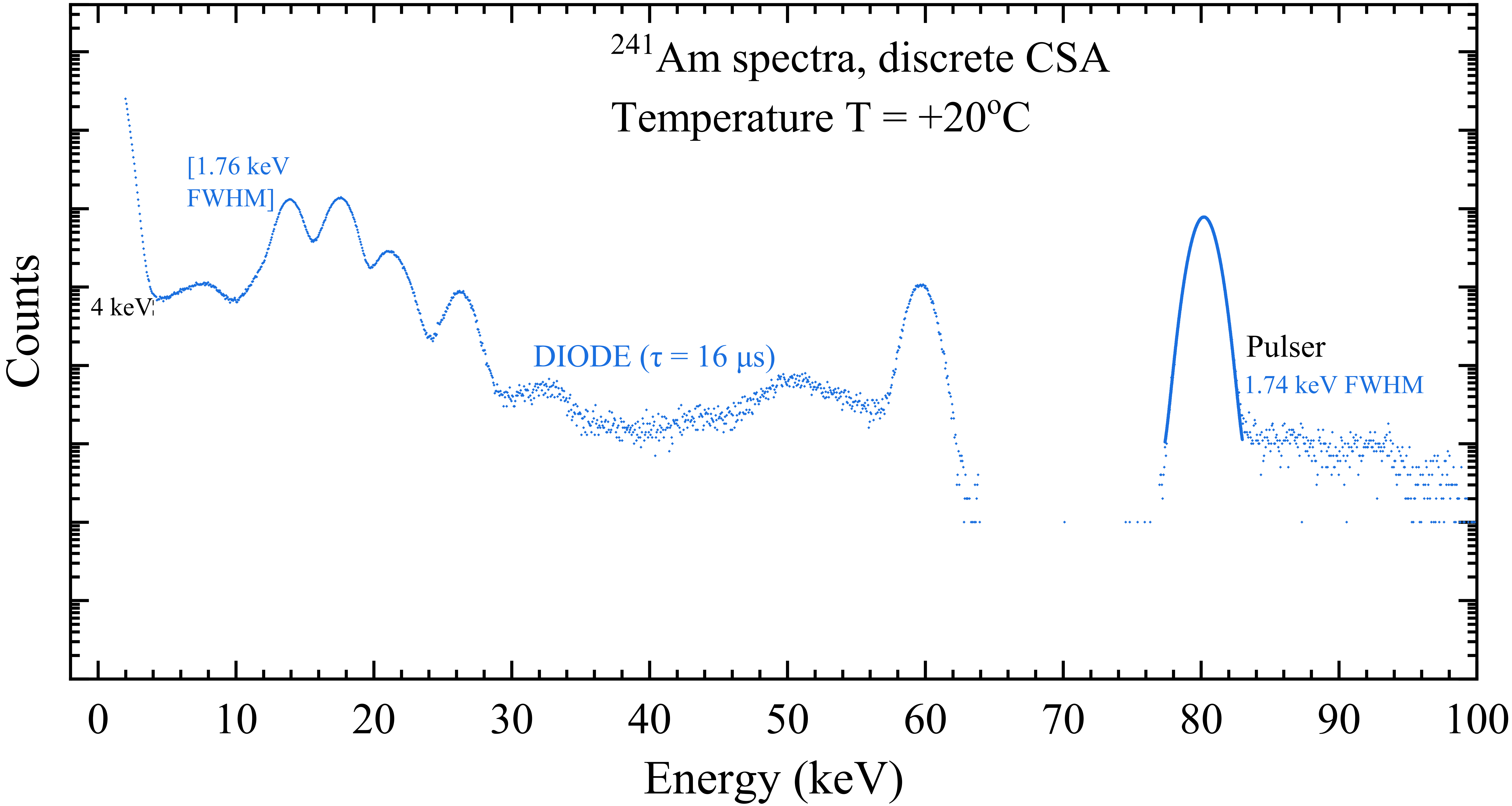
Spectral performance of LGAD and Diode detectors



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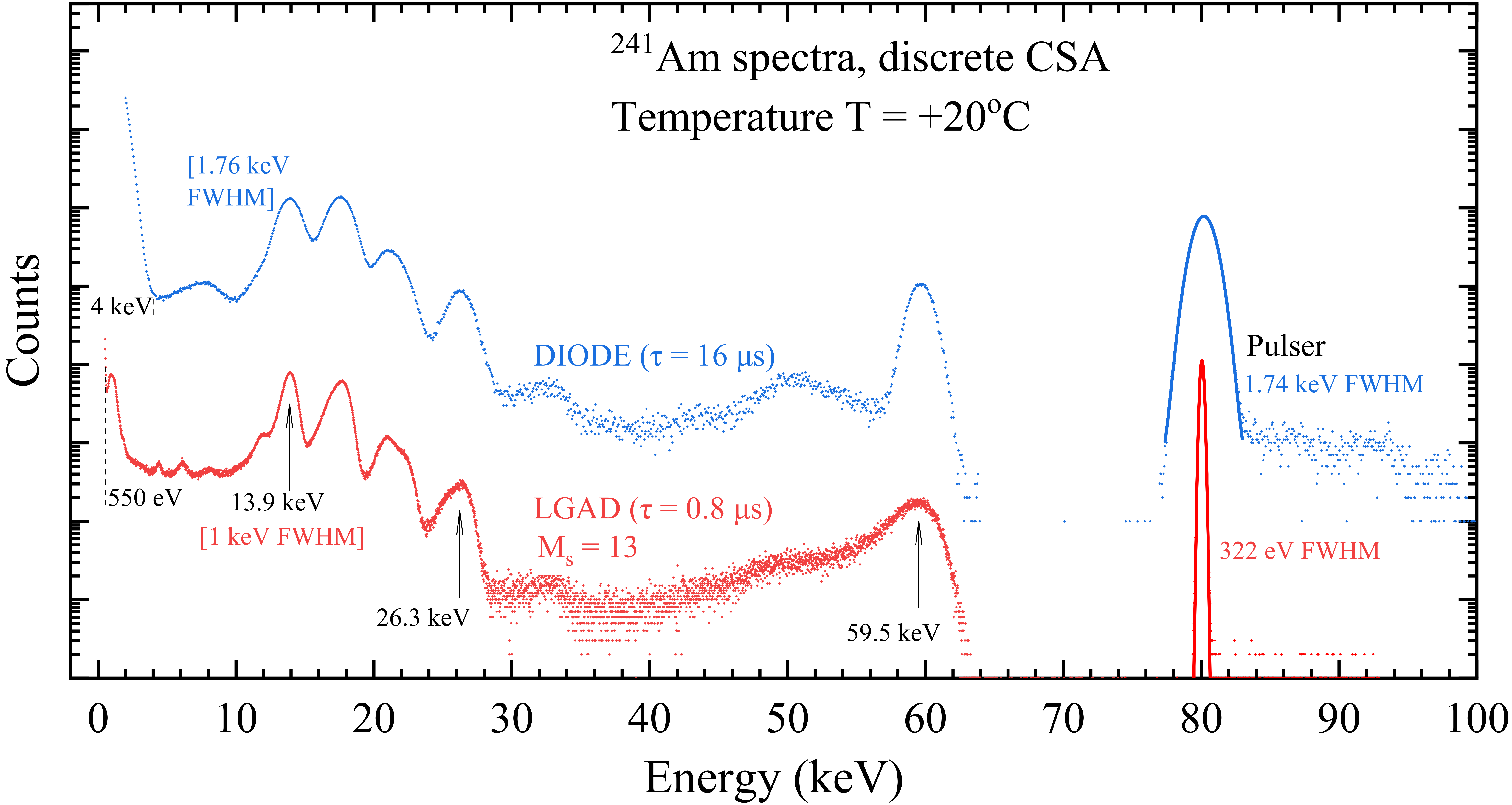

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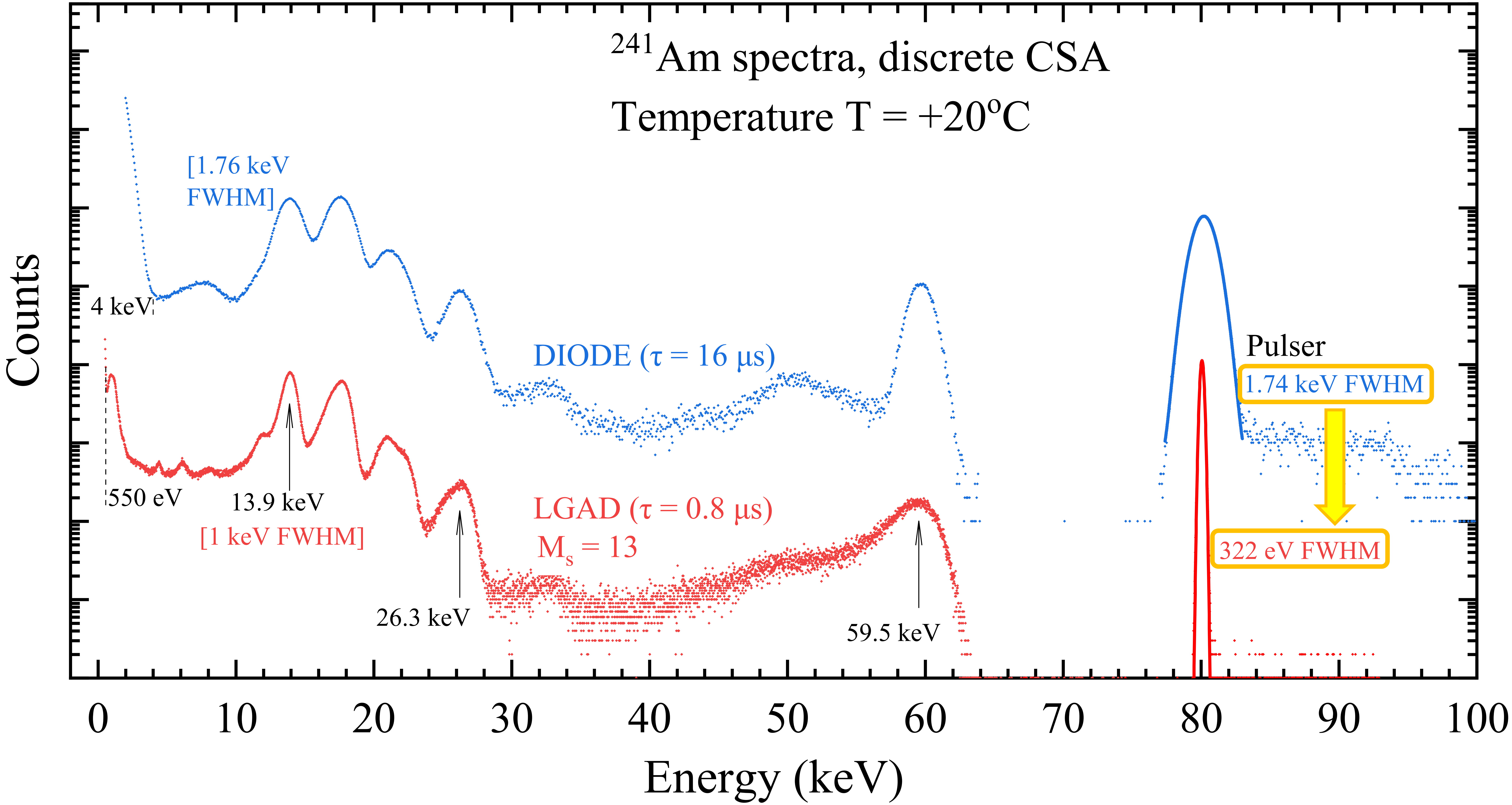

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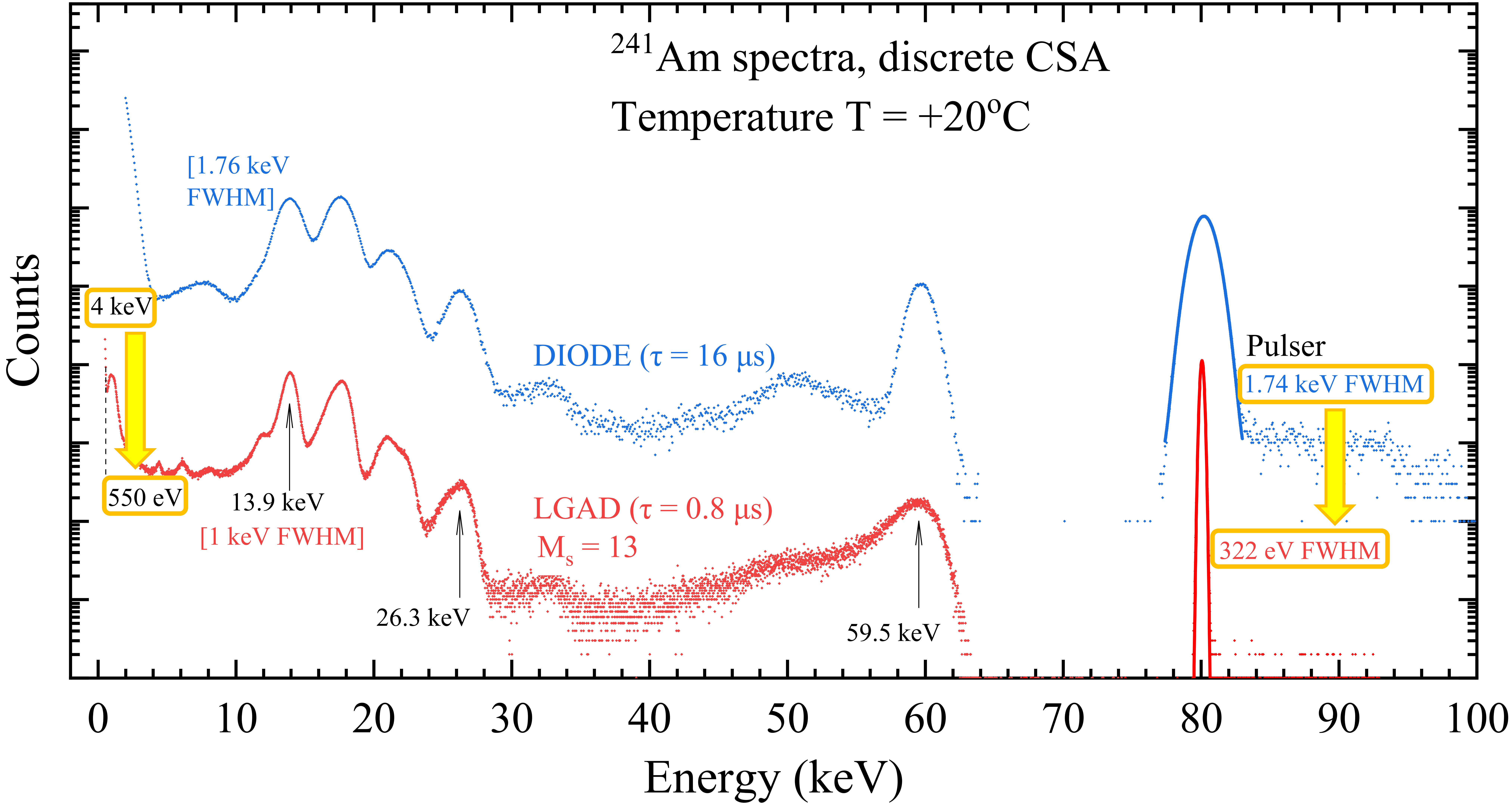

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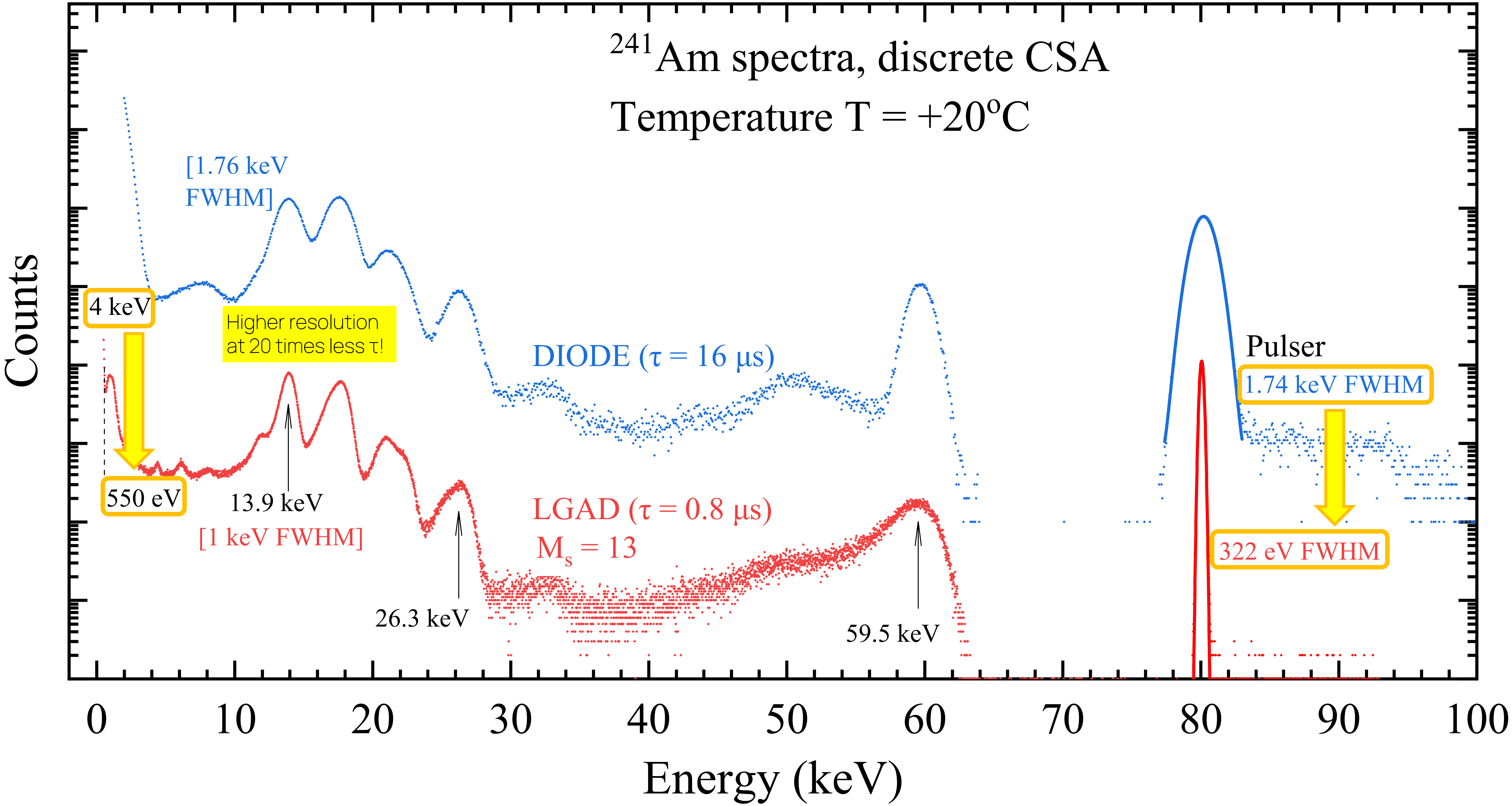

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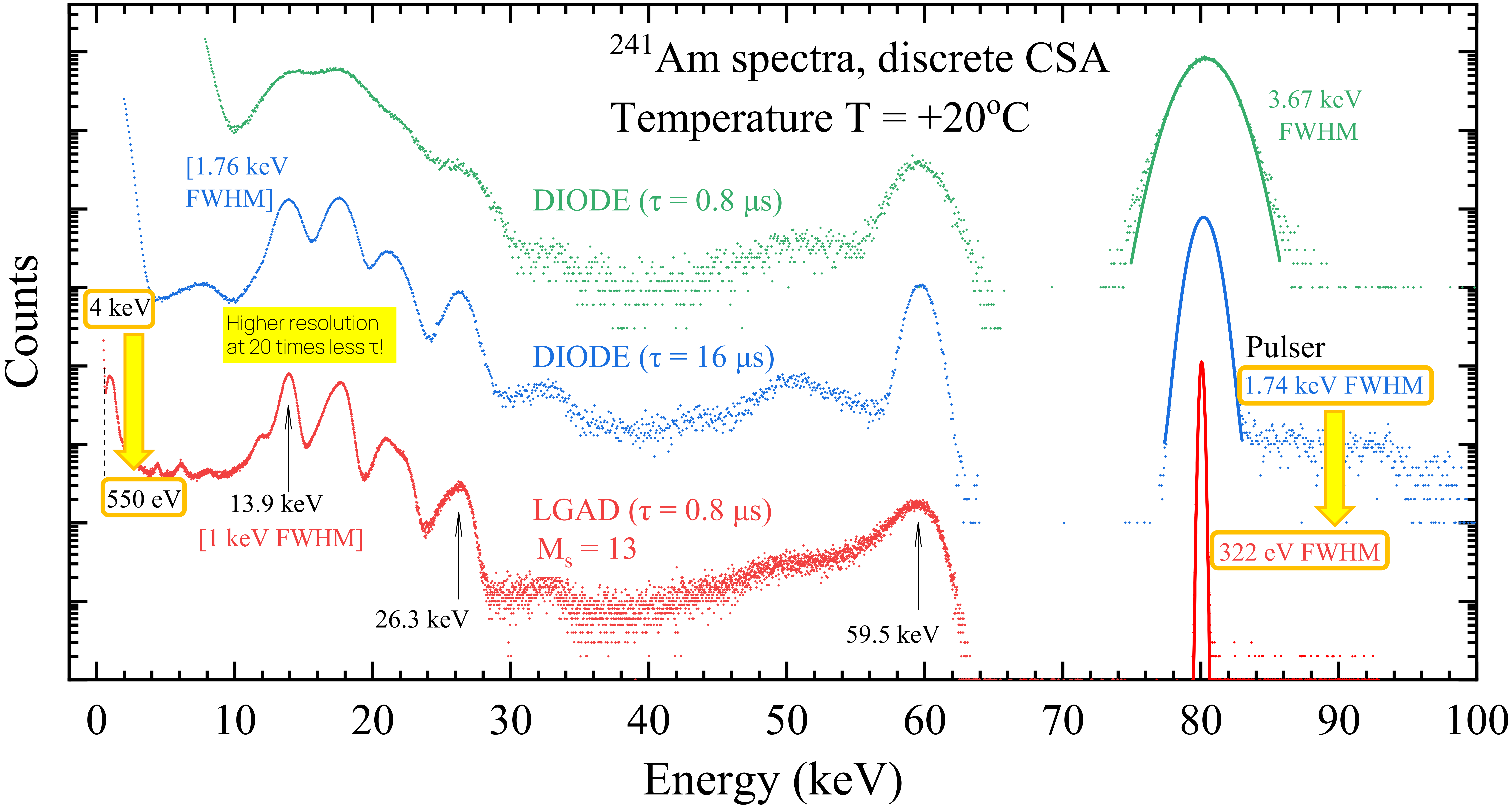

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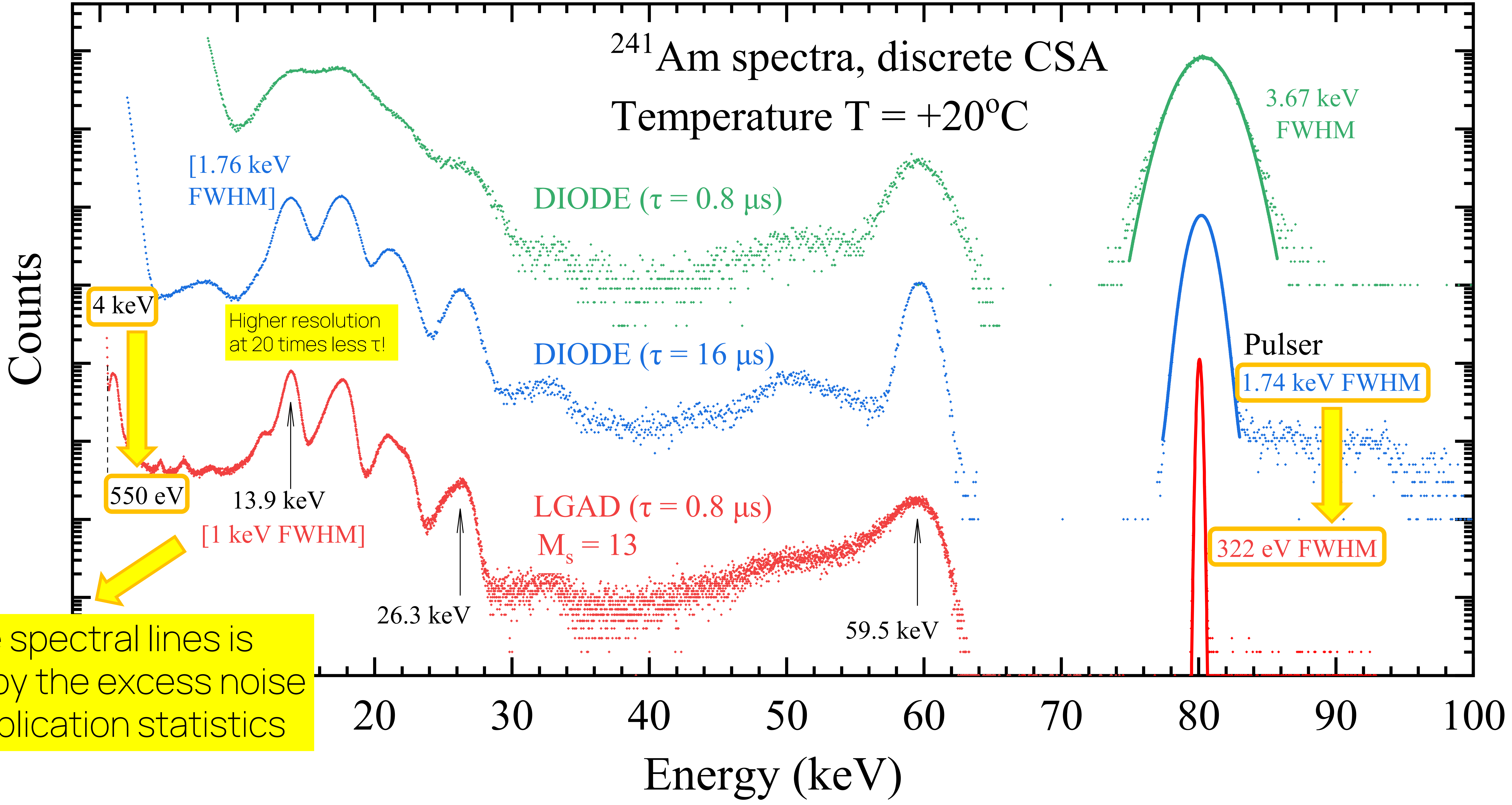
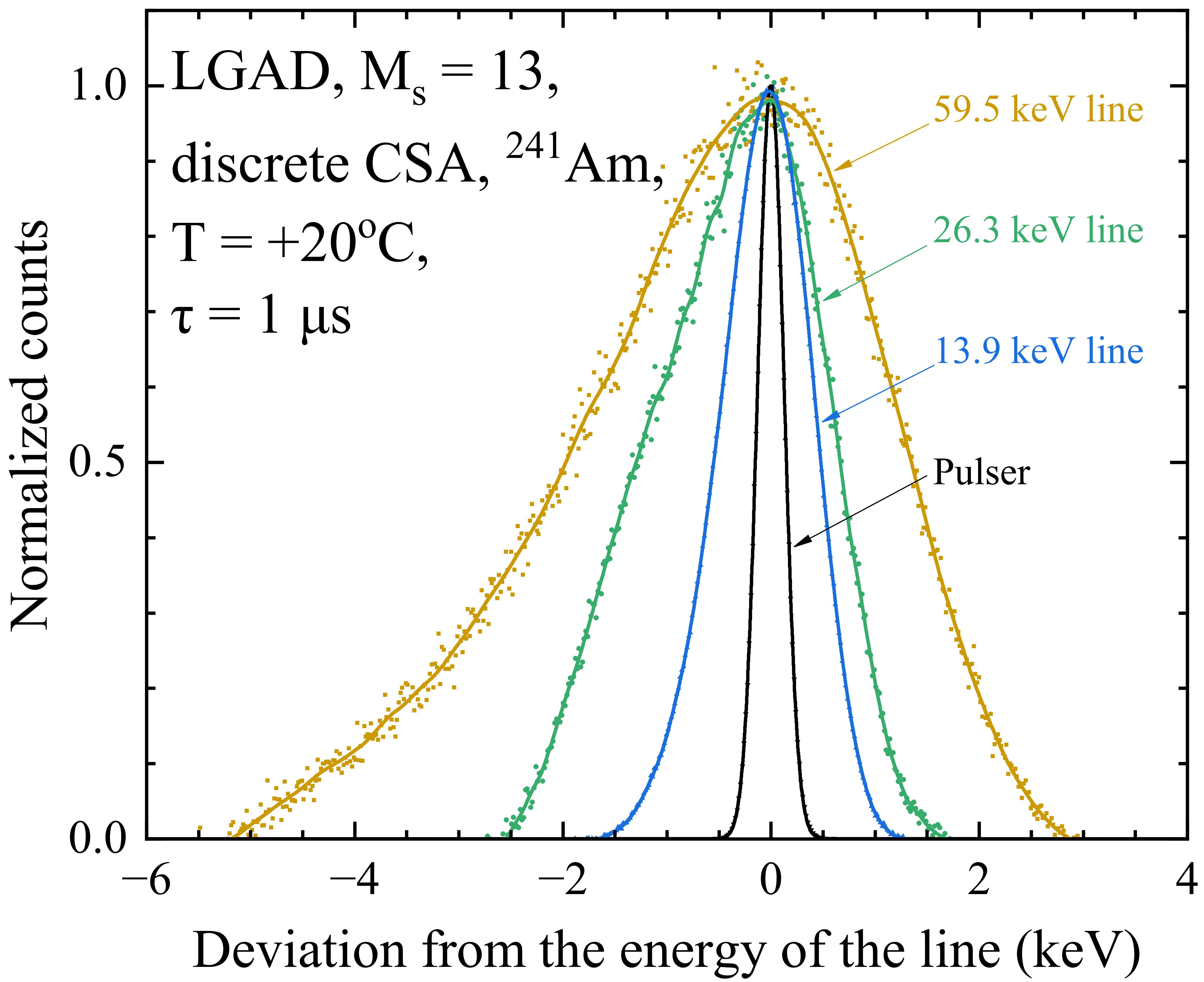


Higher resolution at 20 times less τ!

FWHM of the spectral lines is determined by the excess noise (EN) of multiplication statistics

Spectral lines measured with LGAD at M_s = 13



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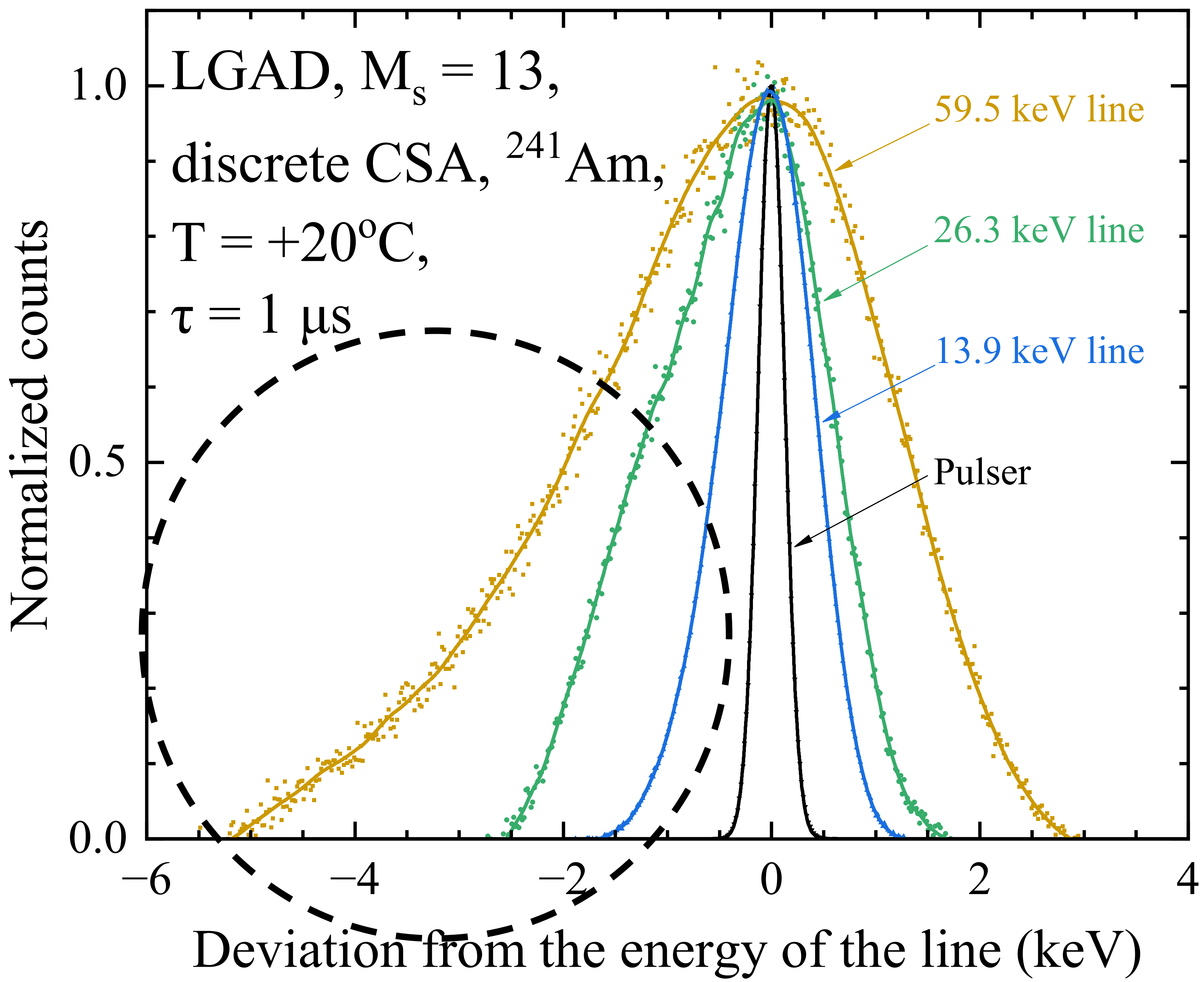

- Left-side tailing can be due to:

1. Charge-trapping inside the detector [10]
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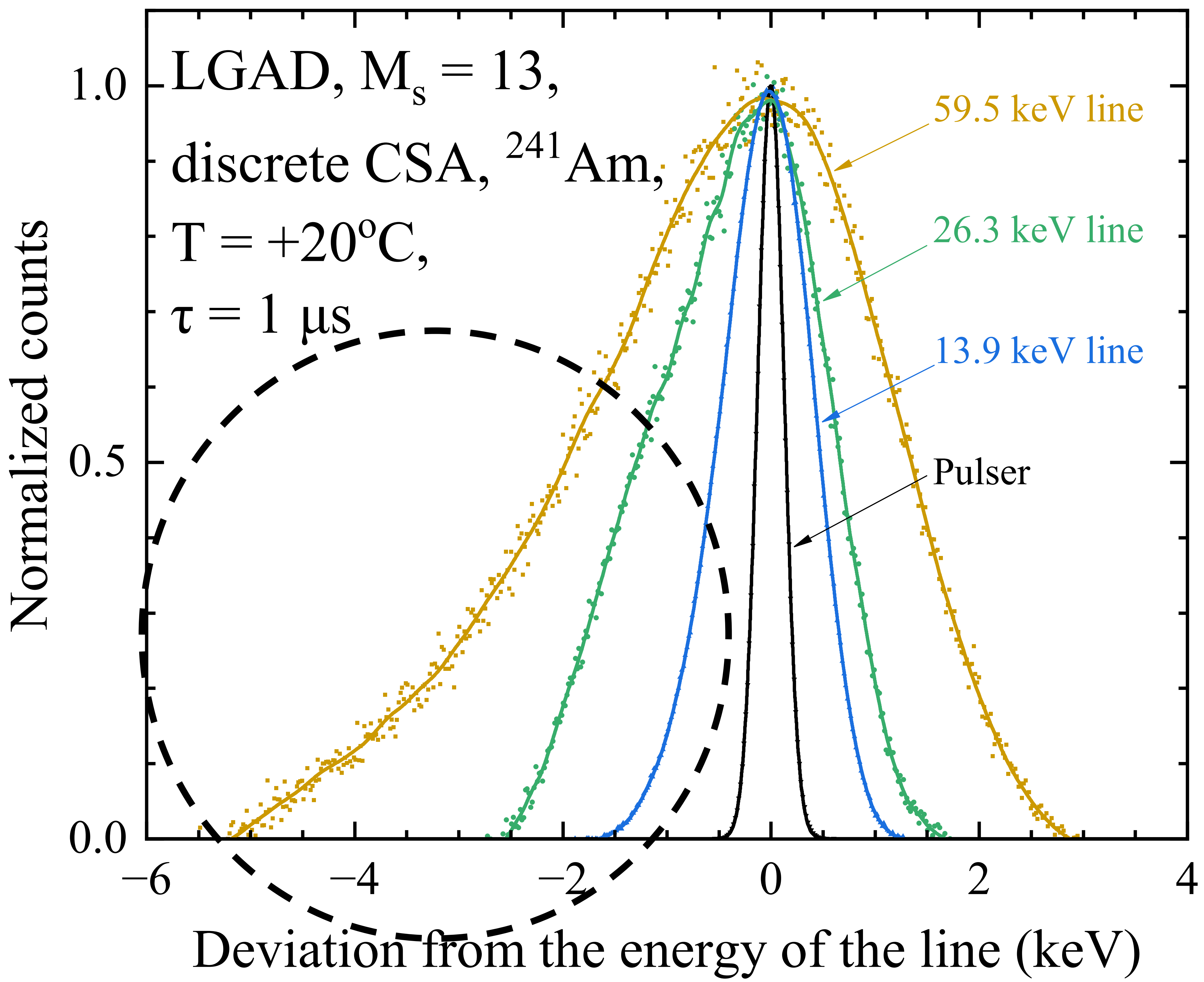

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$$FWHM_{line} = \sqrt{2.35^2 F E_{ph}\epsilon + (FWHM_{pulser})^2 + 2.35^2(\zeta - 1)E_{ph}\epsilon}$$

E_{ph}: photon energy; ε: electron-hole pair generation energy; F: Fano factor; $FWHM_{pulser}$ pulser width; ζ: excess noise factor.

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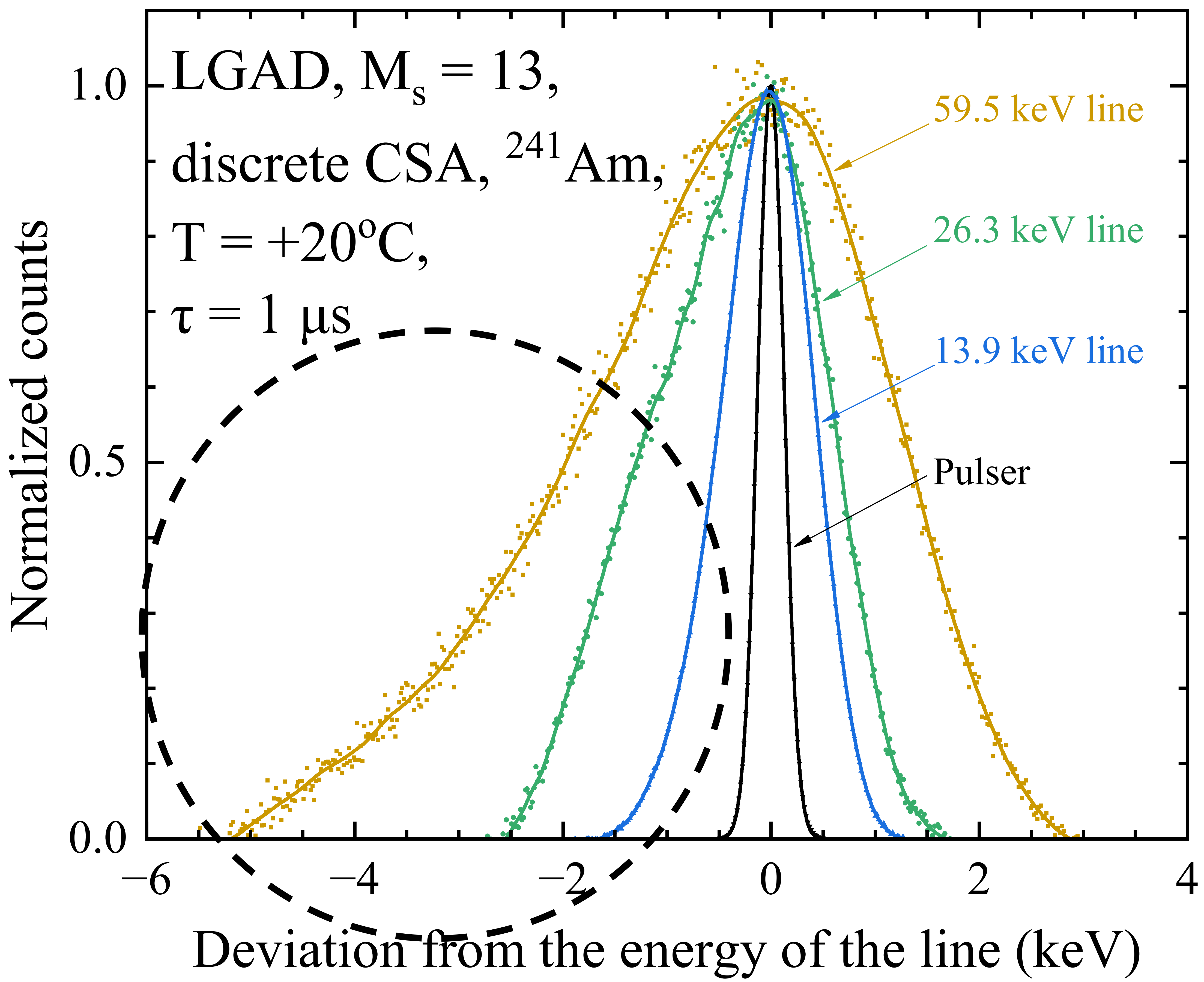

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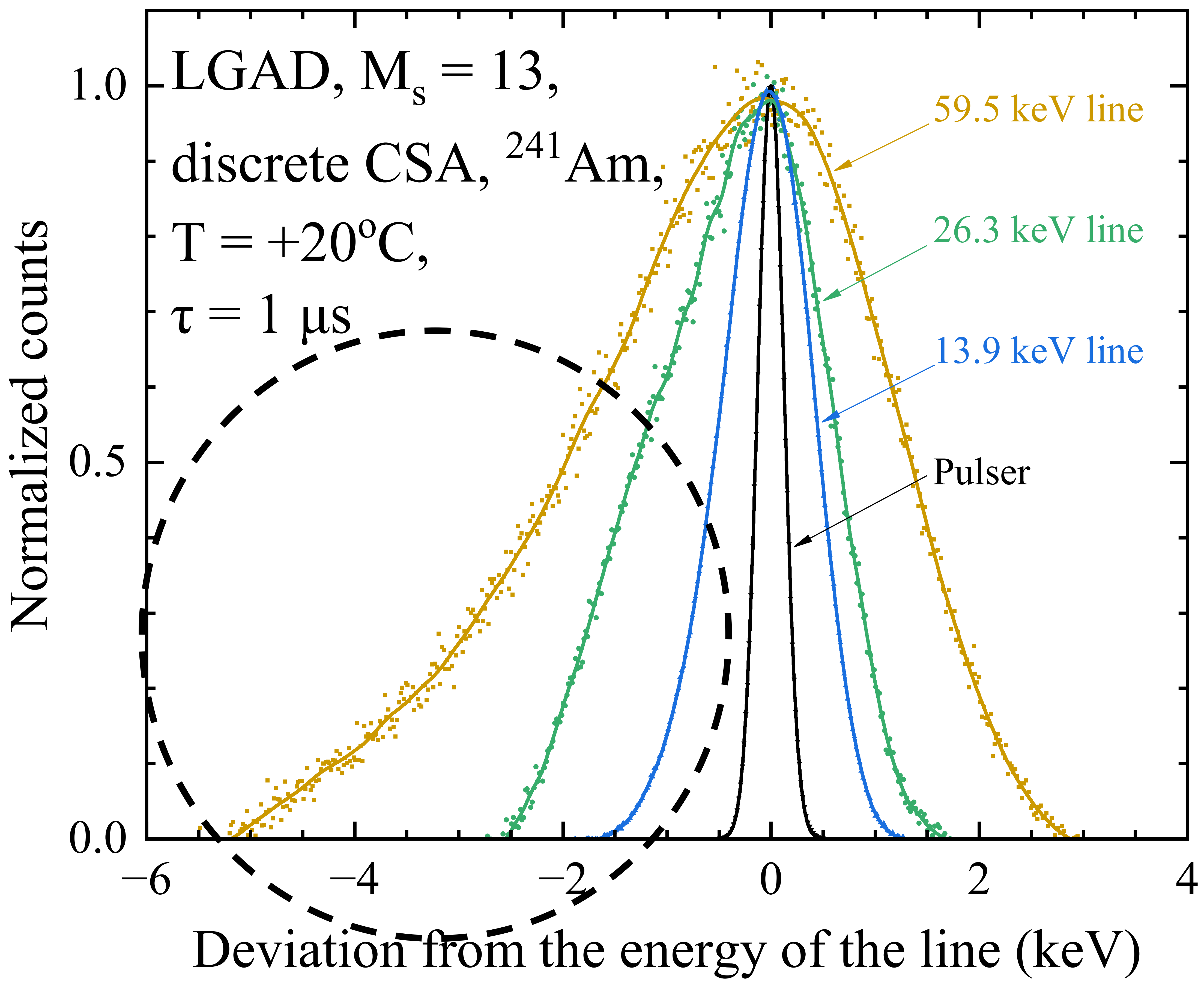

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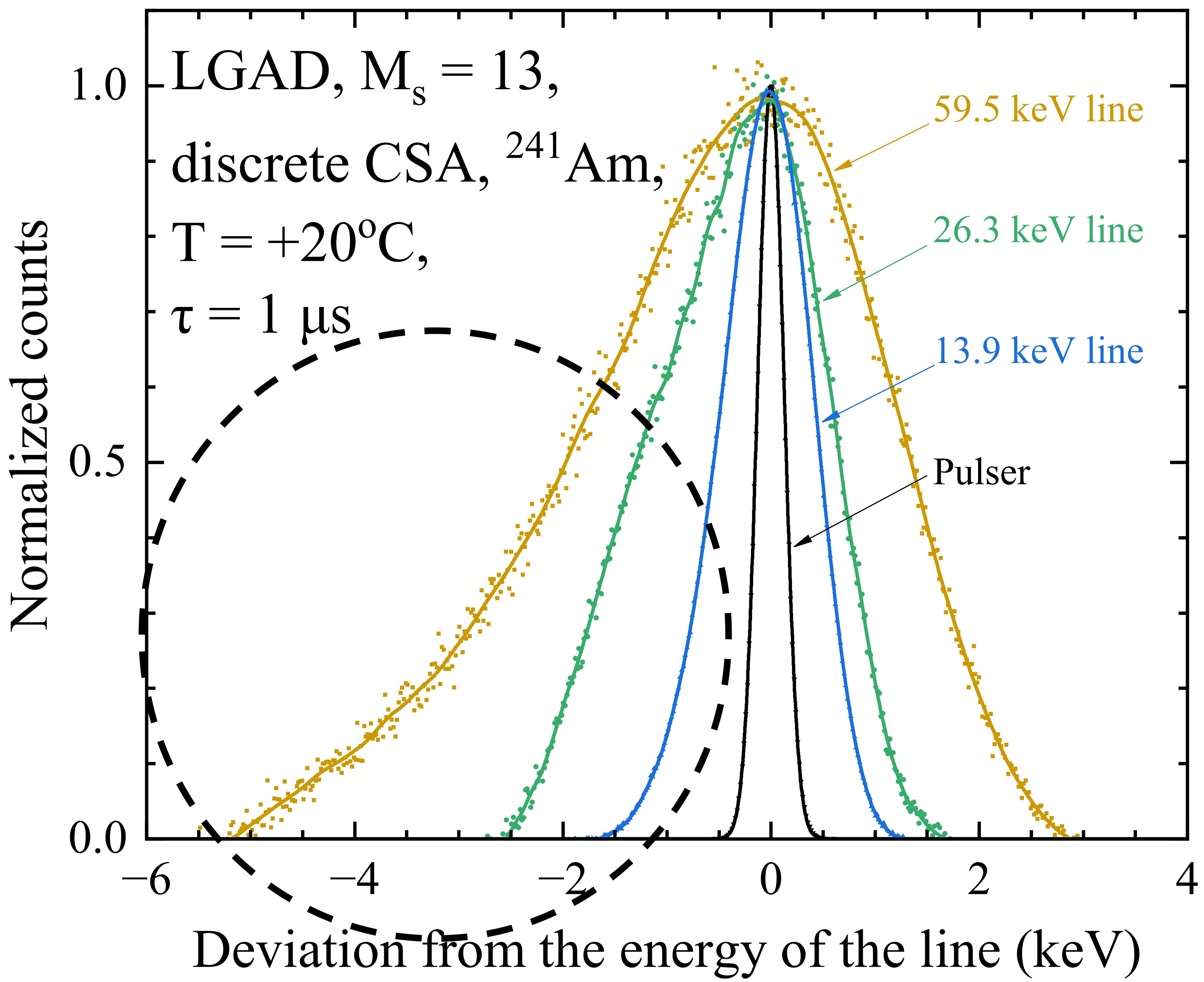

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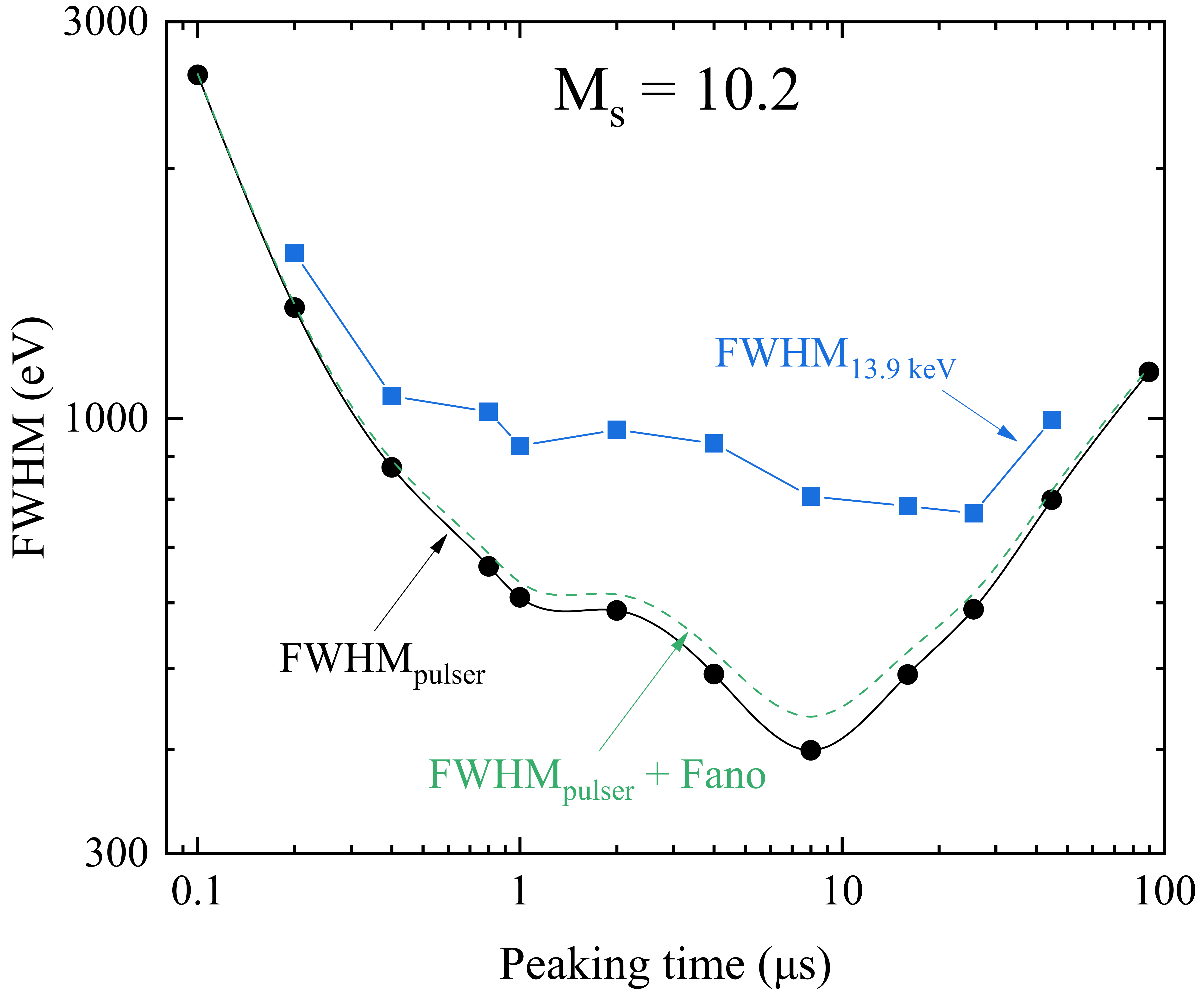
FWHM dependencies on peaking time



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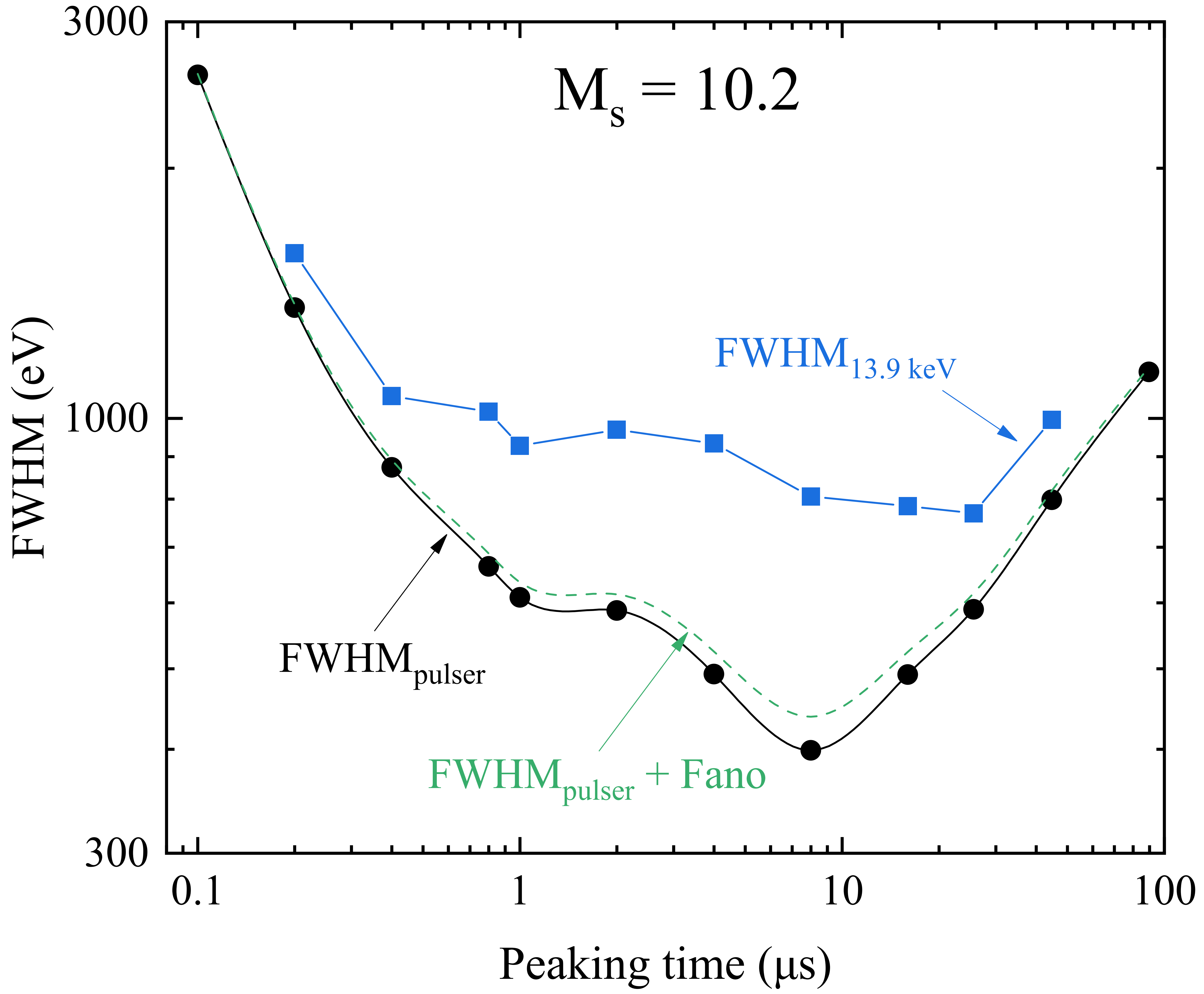
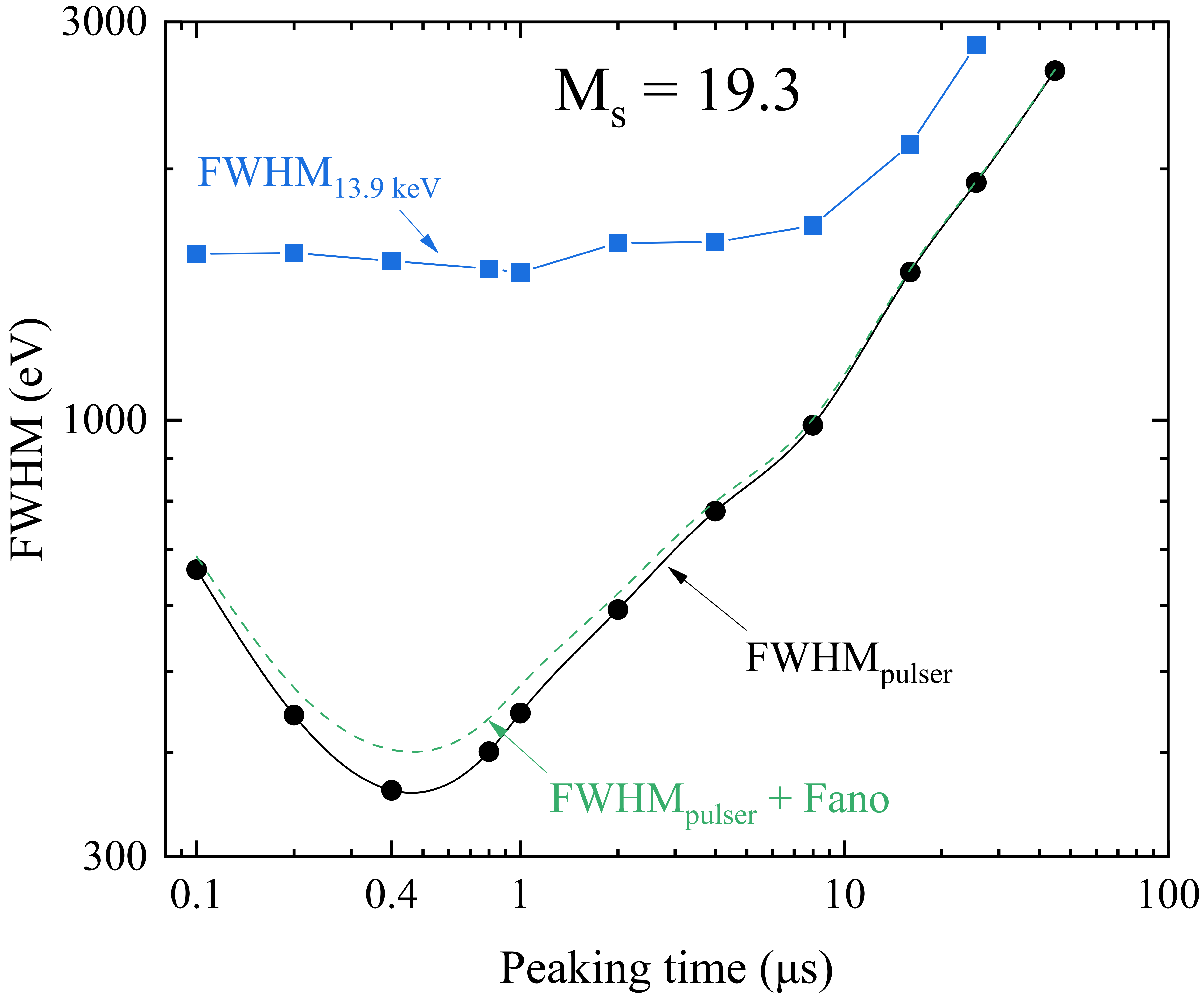
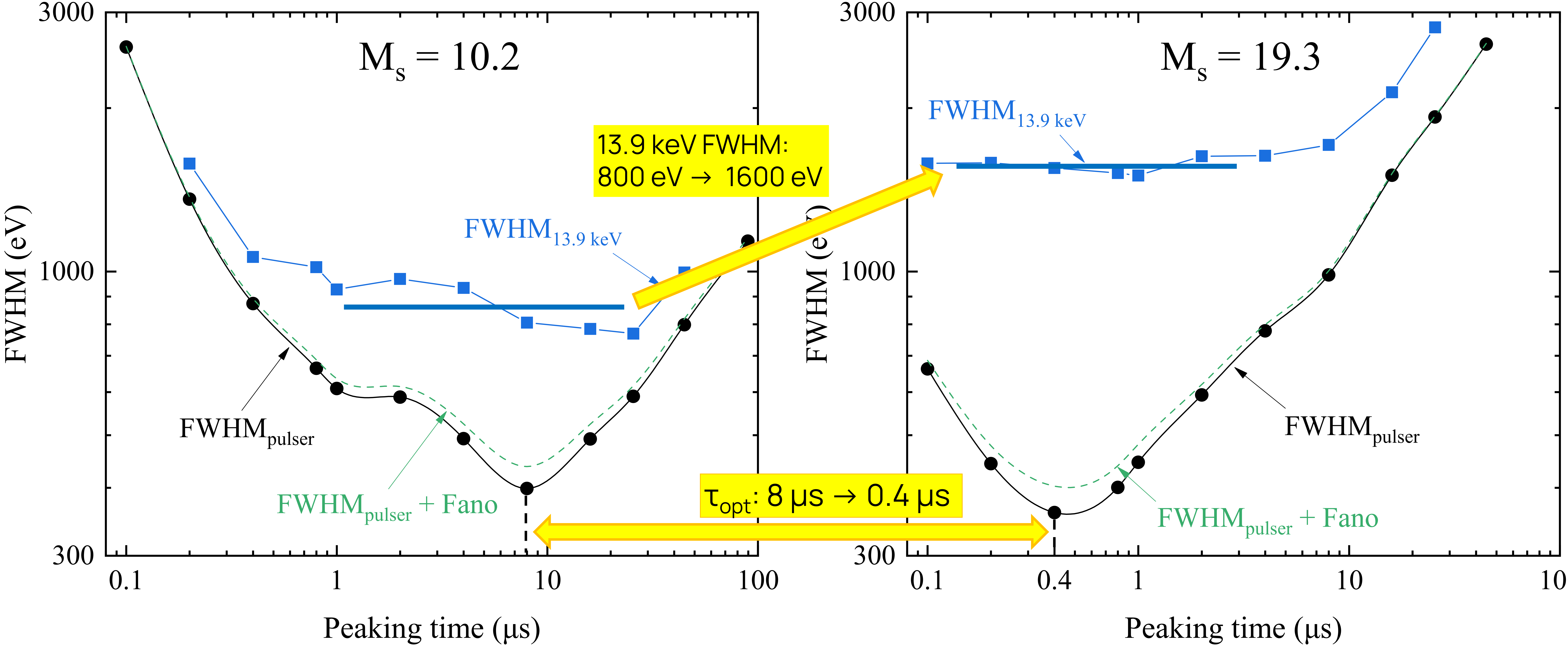




FWHM dependencies on peaking time

τ_{opt}: 8 μs → 0.4 μs

FWHM dependencies on peaking time



13.9 keV FWHM:
800 eV → 1600 eV

τ_{opt}: 8 μs → 0.4 μs

FWHM dependencies on peaking time

13.9 keV FWHM:
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Excess Noise

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τ_{opt}: 8 µs → 0.4 µs

Excess noise vs multiplication gain

$$\mathrm{EN} = \sqrt{FWHM_{13.9keV}^2 - FWHM_{Pulser}^2 - \mathrm{FWHM}_{\mathrm{Fano}}^2}$$

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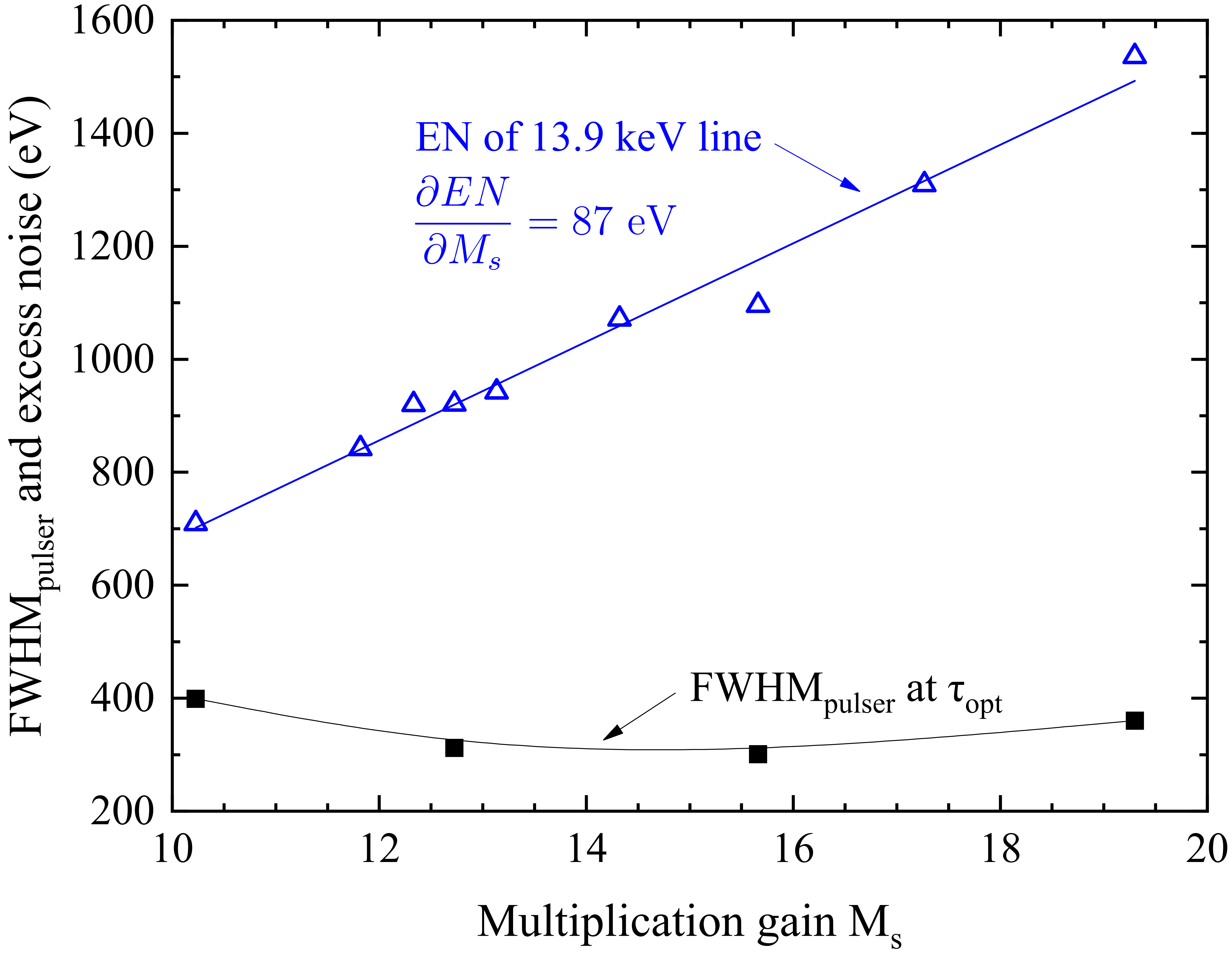

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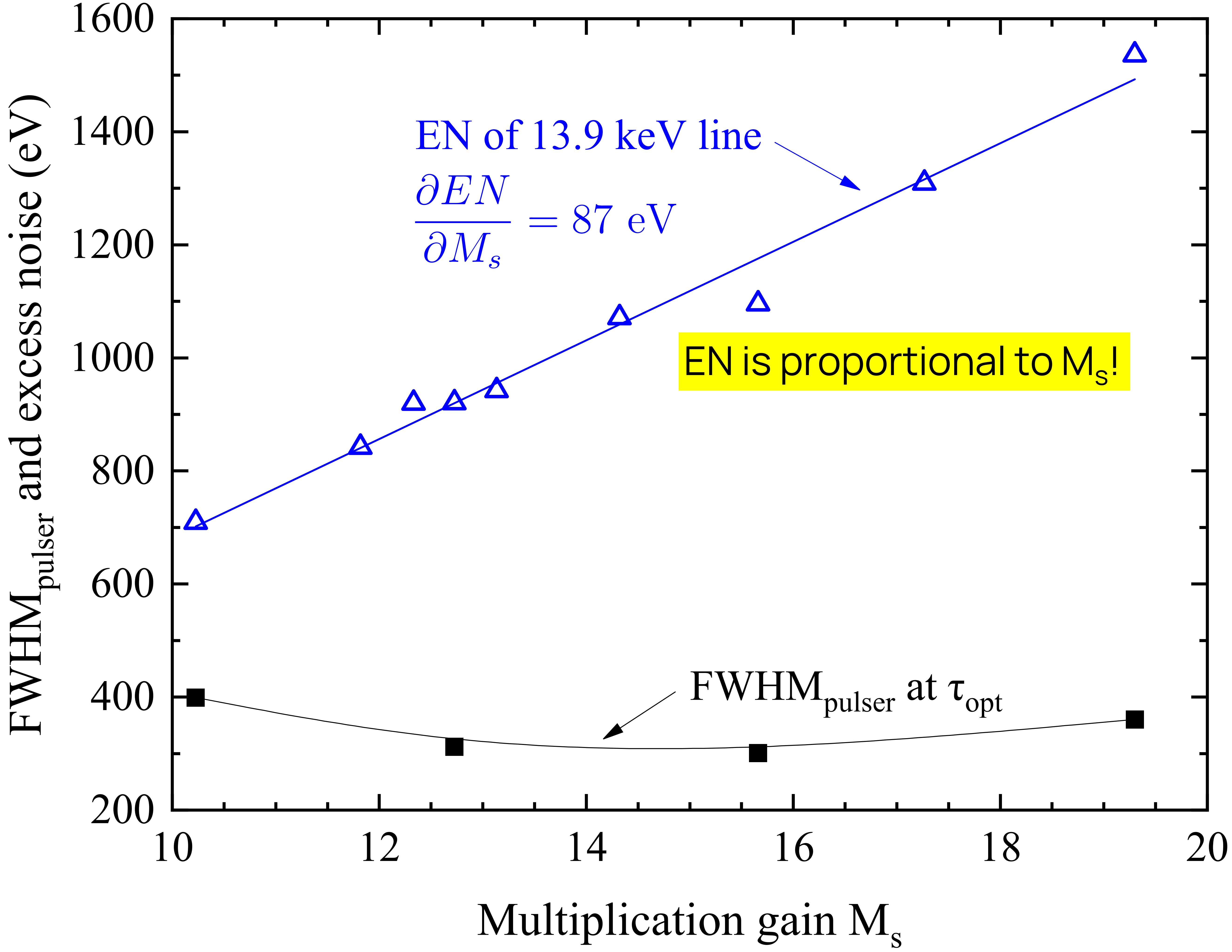

EN is proportional to M_s!

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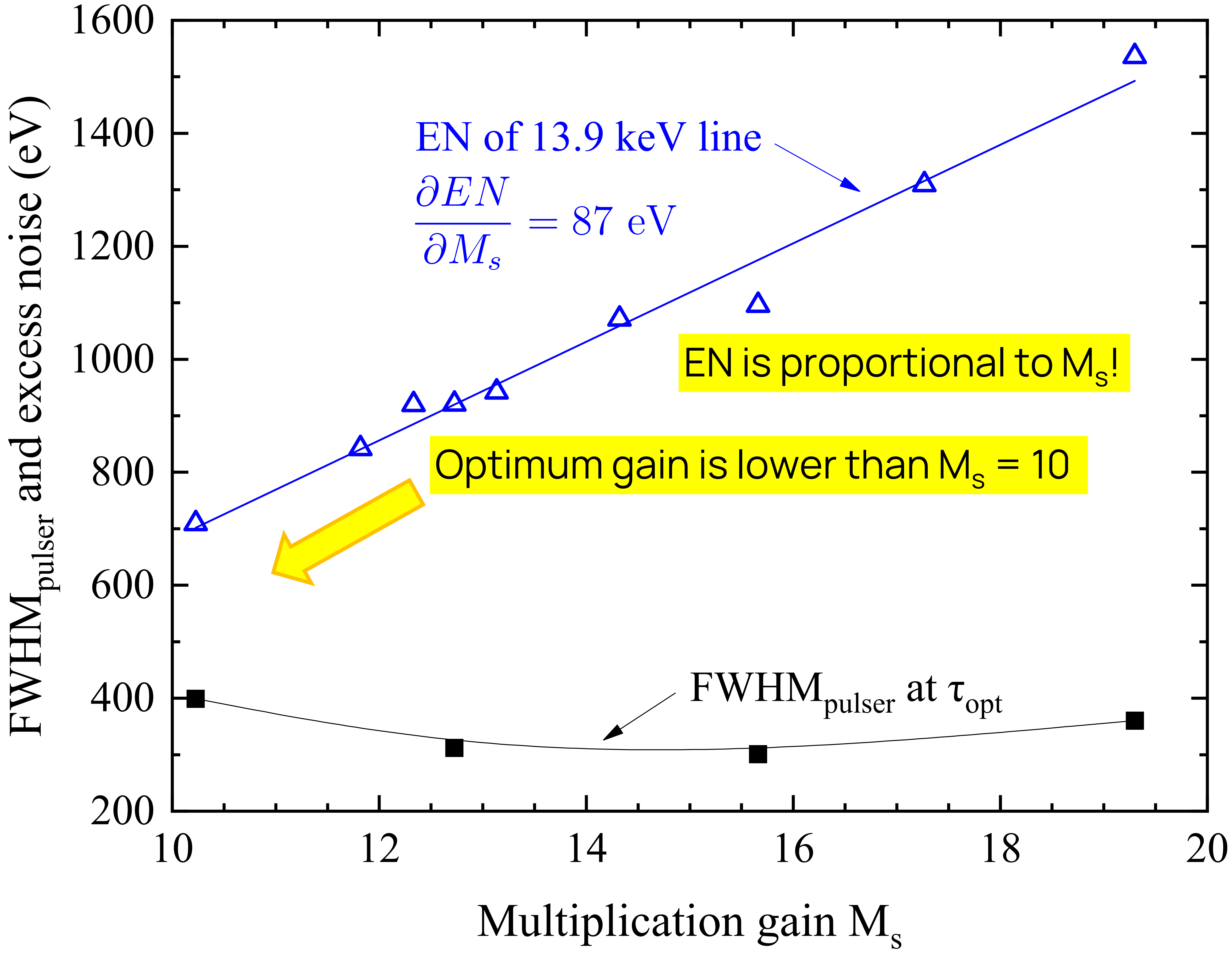

EN is proportional to M_s!

Optimum gain is lower than $M_s = 10$

Optimum gain for LGAD-based spectrometer

$$FWHM_{line} = \sqrt{\boxed{2.35^2 F E_{ph} \epsilon} + 2.35^2 \epsilon^2 \boxed{\left(\frac{A}{M_s^2 \tau} + \frac{B}{M_s^2} + \frac{C}{M_s^2} \tau \right)} + \boxed{EN}^2}$$

Fano noise

whites, 1/f and dielectric noises

Excess noise $\propto M_s$

E_{ph}: photon energy; ε: electron-hole pair generation energy; F: Fano factor.

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Dominant dielectric + 1/f noise : $FWHM_{line} = 2.35\sqrt{\epsilon^2 \frac{B}{M_s^2} + EN^2}$

$$\mathrm{Min}\left(FWHM_{line}\right) \text{ if } EN^2 = \epsilon^2 \frac{B}{M_s^2}$$

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Negligible dielectric + 1/f noise: $FWHM_{line,\tau_{opt}} = \sqrt{FWHM_{Fano}^2 + FWHM_{pulser,\tau_{opt}}^2 + EN^2}$

Optimum gain for LGAD-based spectrometer

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Independent on multiplication gain

Optimum gain for LGAD-based spectrometer

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EN should be as low as possible, so the multiplication gain!

Outline

Introduction and motivation

Performance of LGAD-based X-γ ray spectrometer

- Equivalent Noise Charge (ENC)
- Excess noise
- Optimum operating conditions

Ultra low-gain LGAD with state-of-the-art CSA

Conclusions

Spectroscopic performance of ultra low-gain LGAD + Sirio

- Ultra low-gain LGAD with $M_S = 1.2 \div 2$ from BNL is tested using Integrated CMOS preamplifier (Sirio [15])

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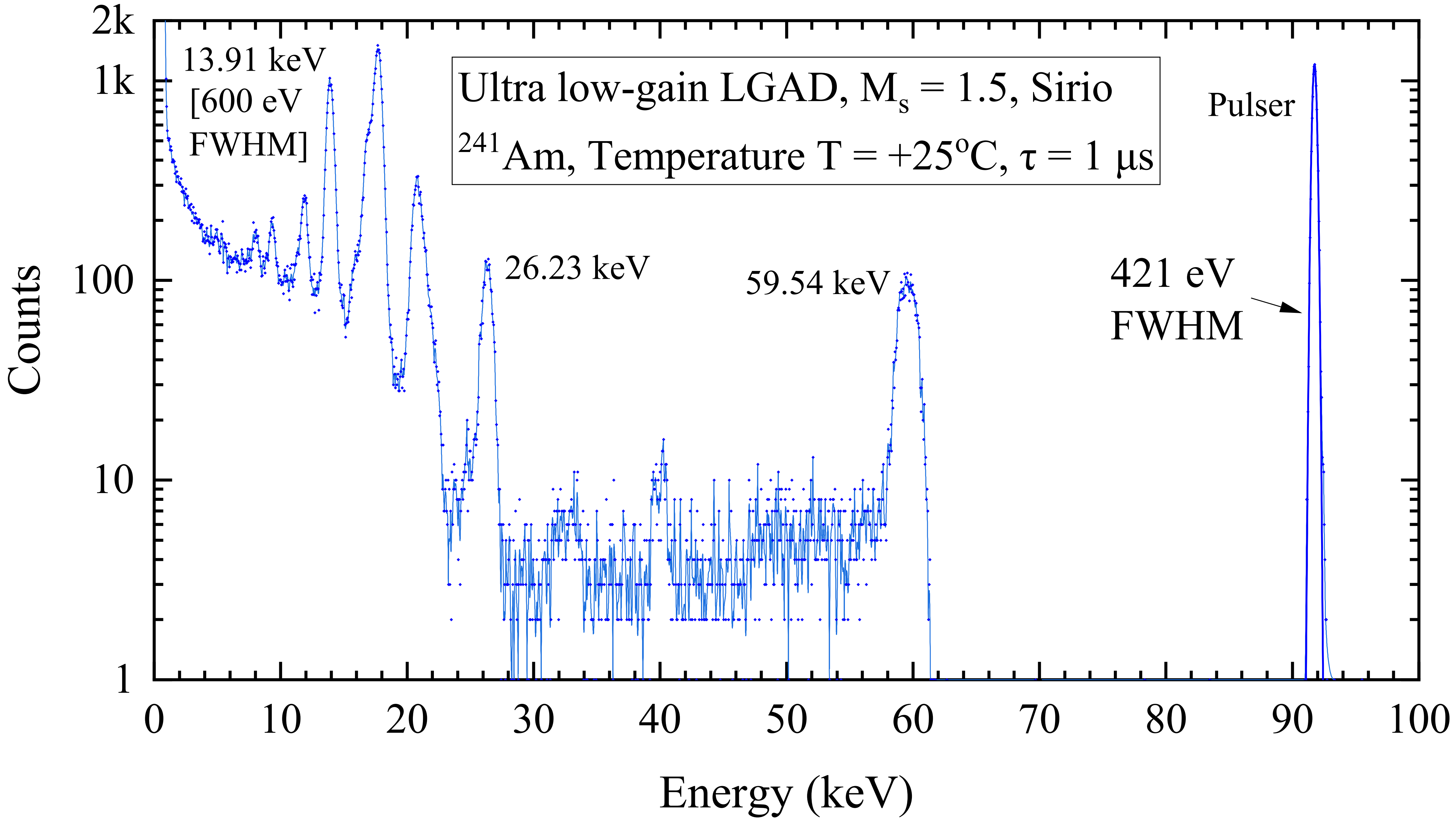

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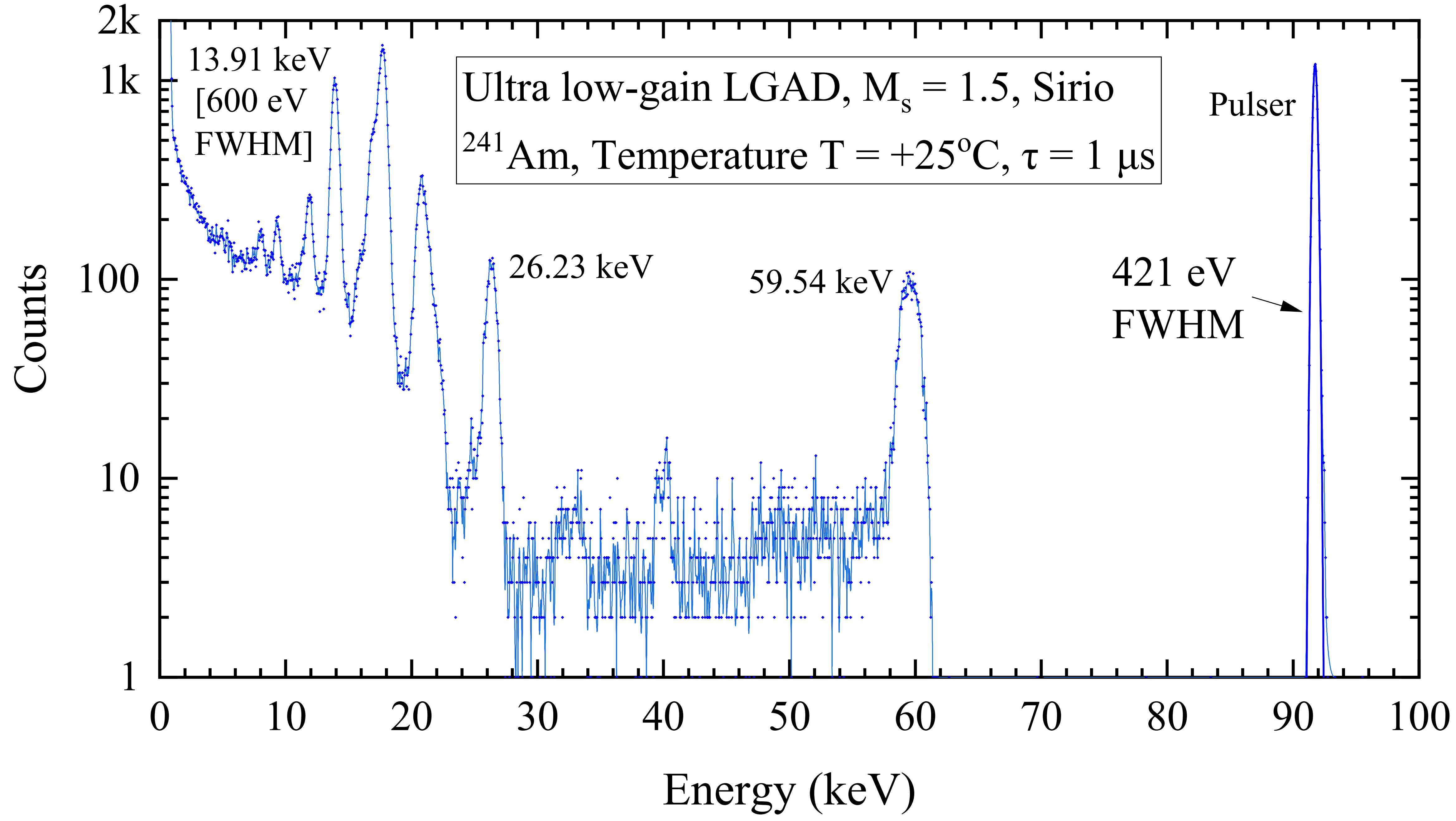

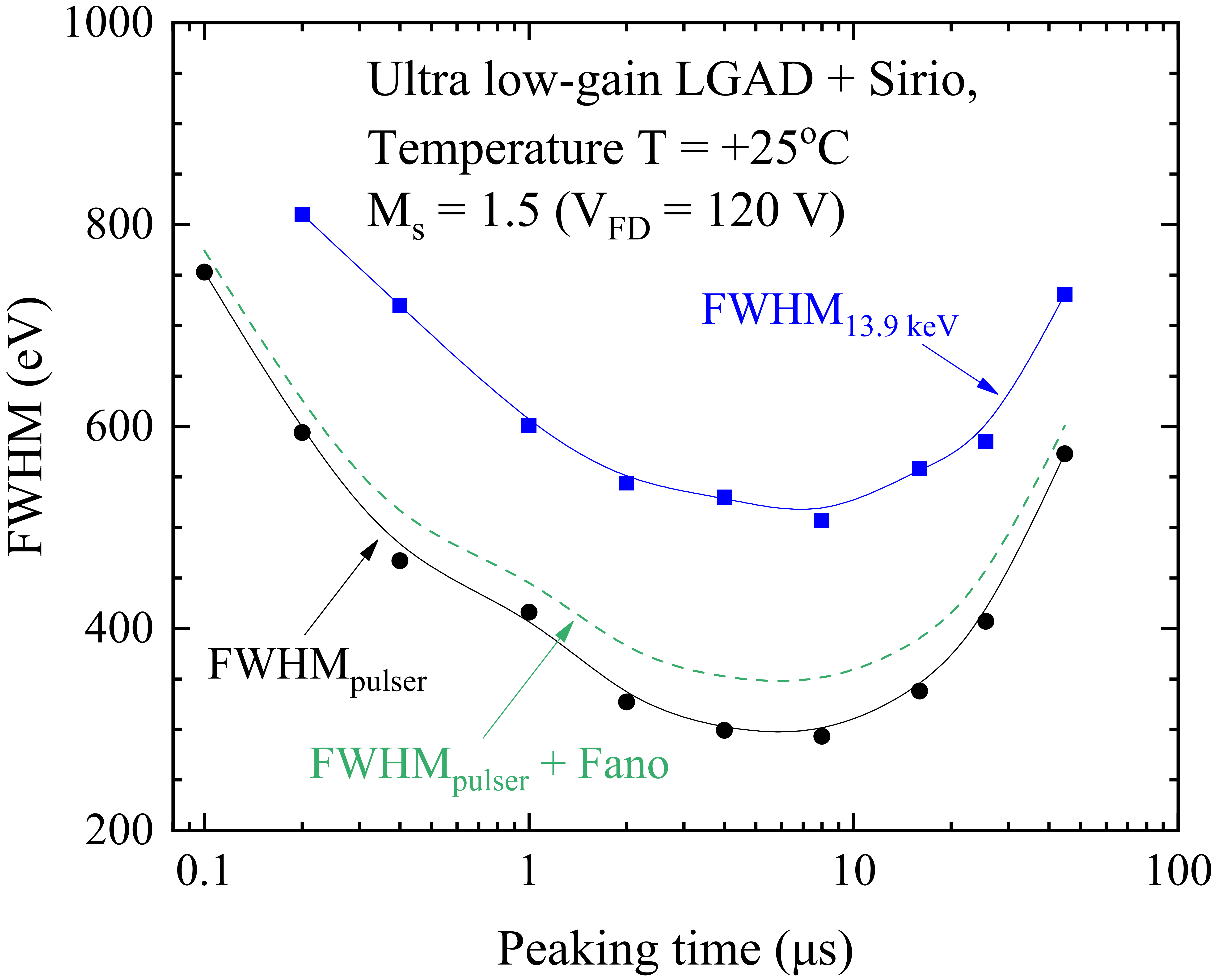

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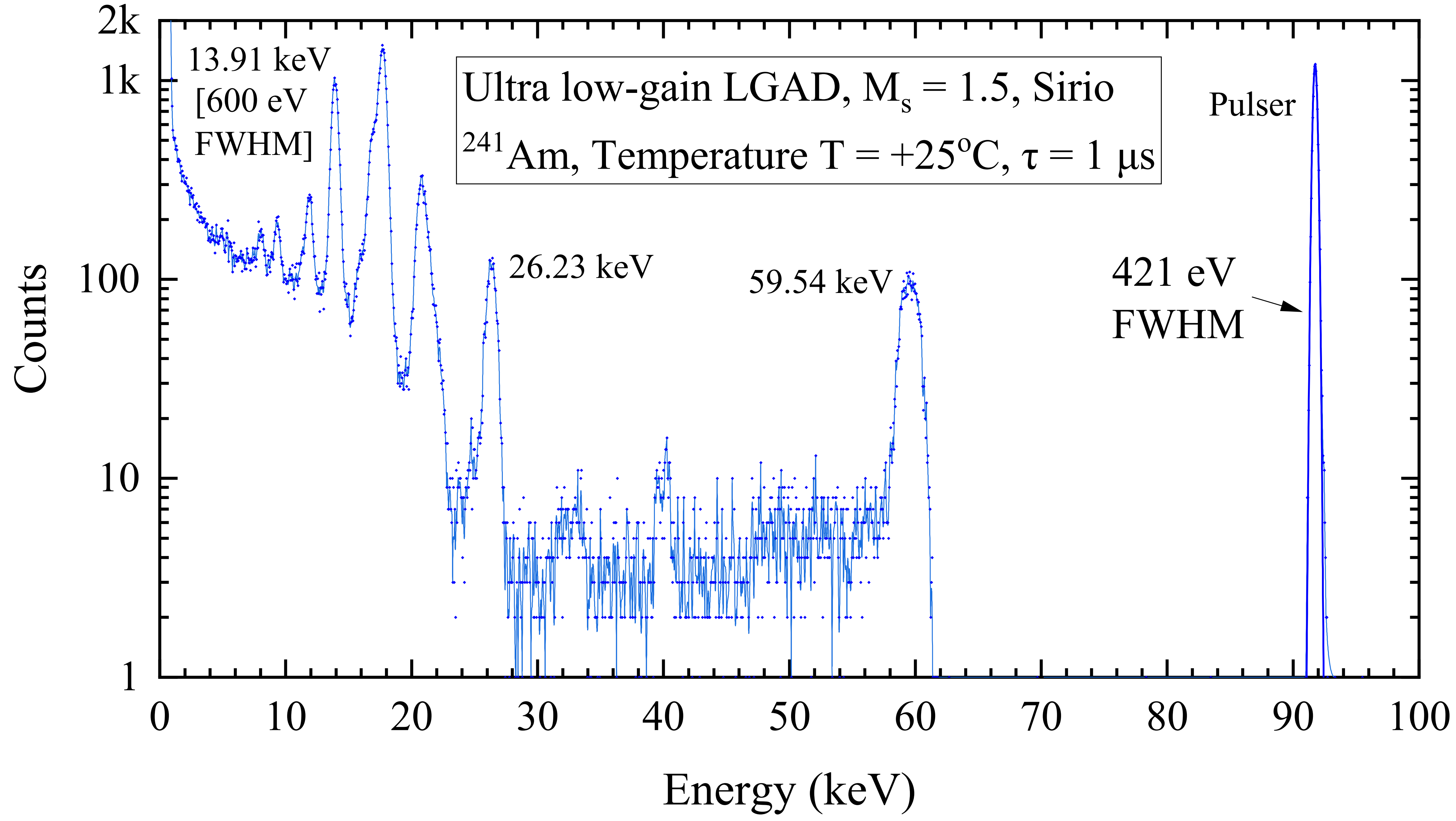
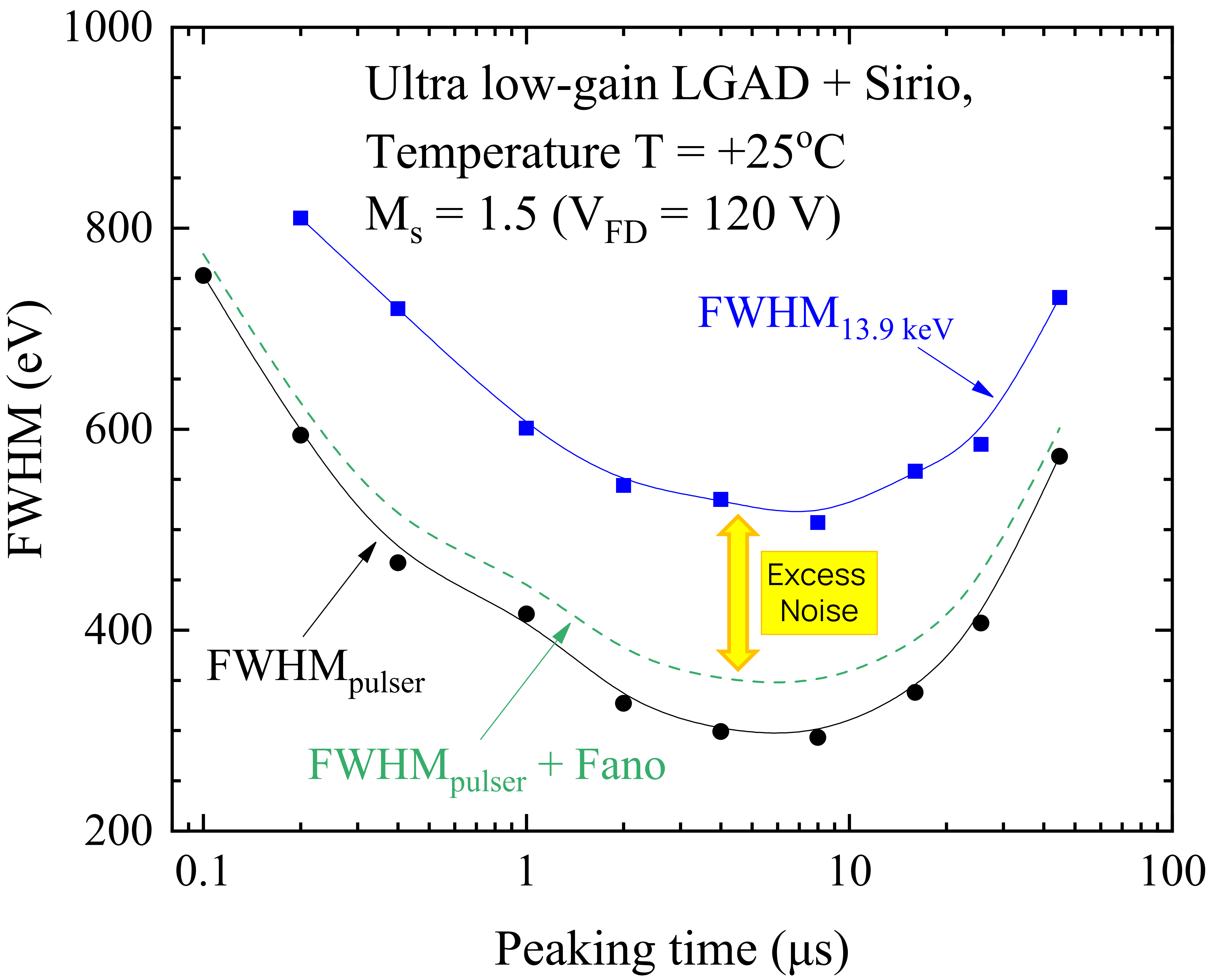
Spectroscopic performance of ultra low-gain LGAD + Sirio

- Ultra low-gain LGAD with M_s = 1.2 ÷ 2 from BNL is tested using Integrated CMOS preamplifier (Sirio [15])

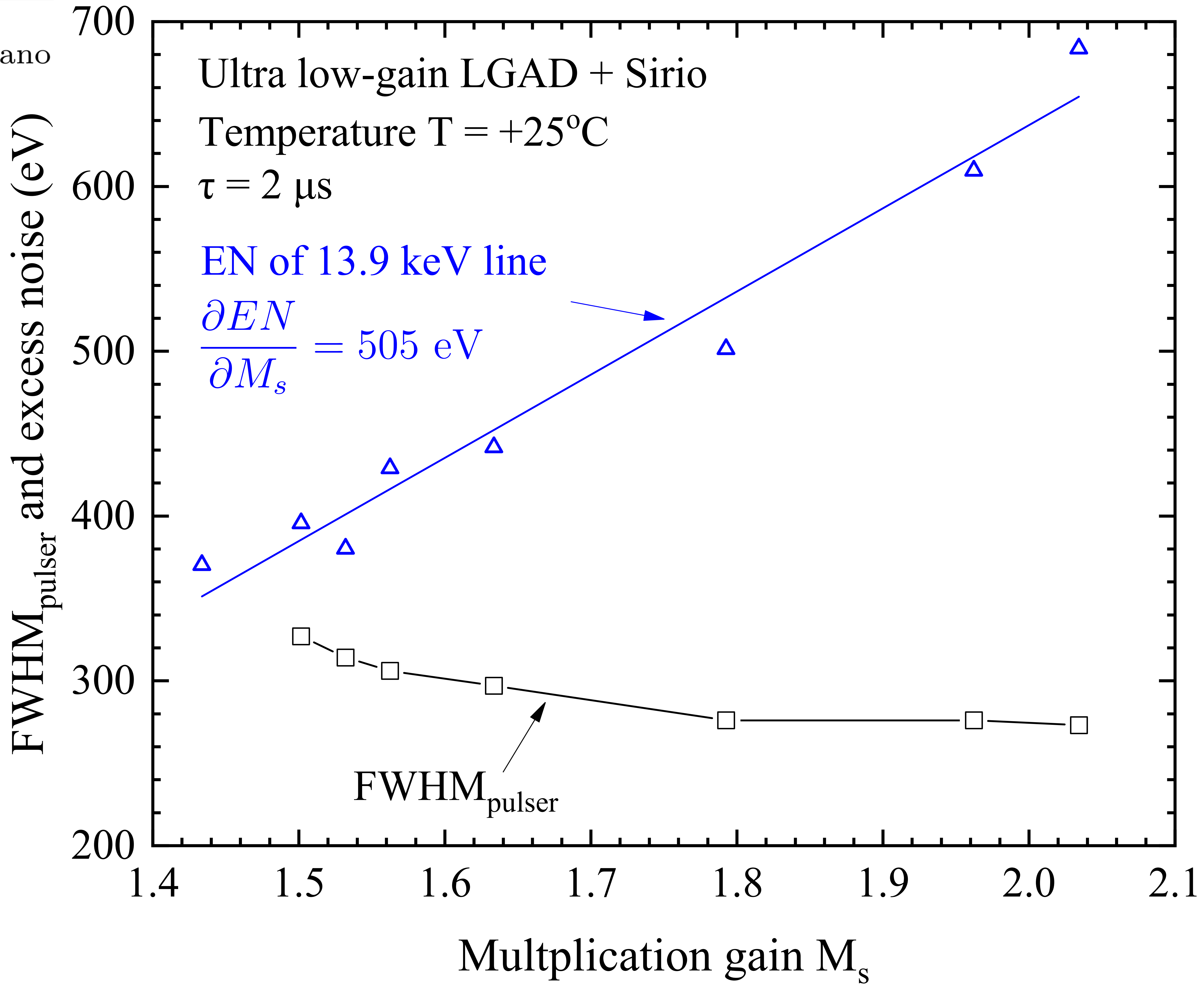




[15] Mele, Filippo, Massimo Gandola, and Giuseppe Bertuccio. "SIRIO: A high-speed CMOS charge-sensitive amplifier for high-energy-resolution X-γ ray spectroscopy with semiconductor detectors." IEEE Transactions on Nuclear Science 68.3 (2021): 379-383.

Excess noise vs multiplication gain (M_s < 2)

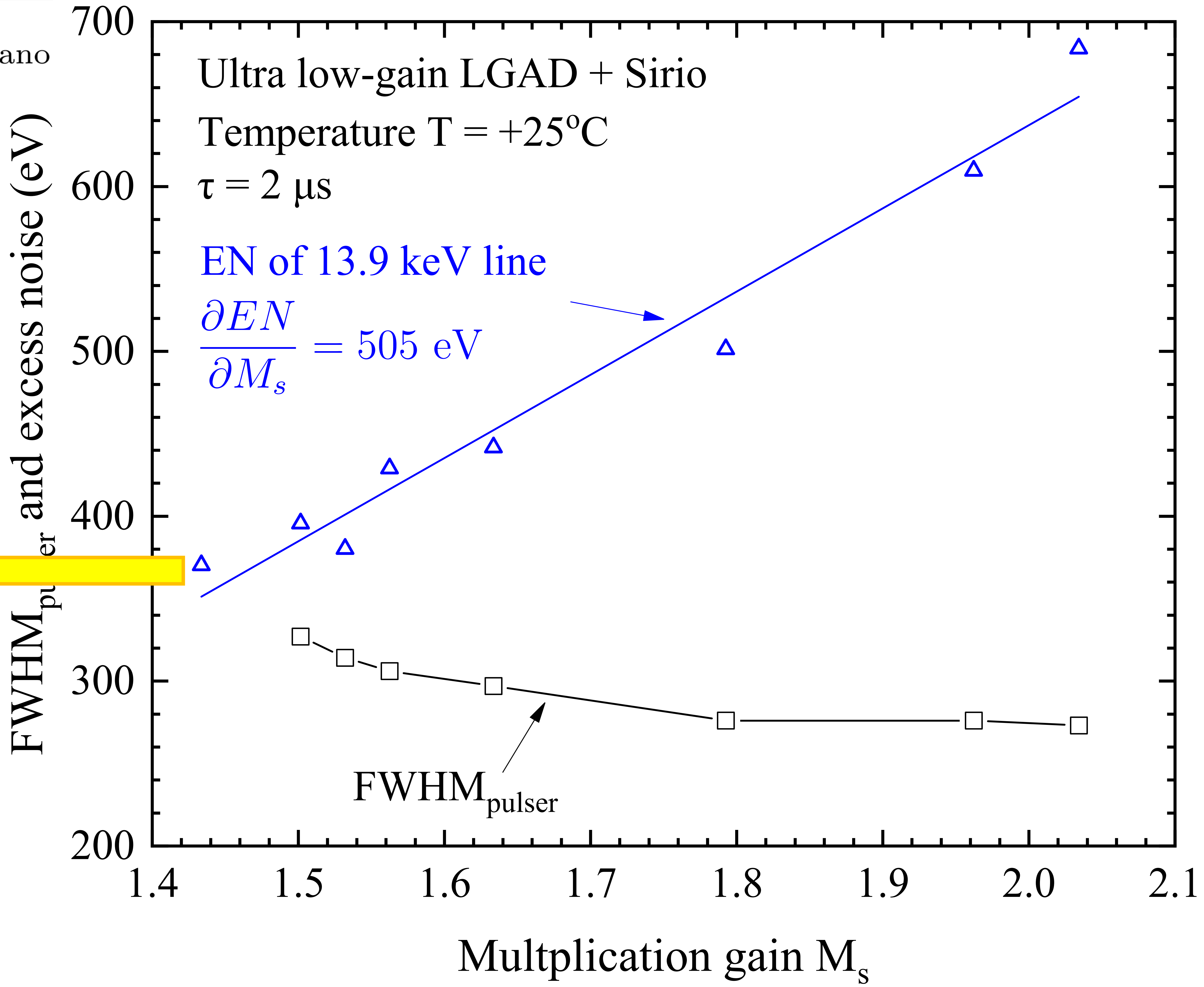
$$\mathrm{EN} = \sqrt{FWHM^2_{13.9keV} - FWHM^2_{Pulser} - \mathrm{FWHM}^2_{\mathrm{Fano}}}$$



Excess noise vs multiplication gain (M_s < 2)

$$\mathrm{EN} = \sqrt{FWHM^2_{13.9keV} - FWHM^2_{Pulser} - \mathrm{FWHM}^2_{\mathrm{Fano}}}$$

Excess noise of multiplication gain down to M_s=1.43 has been determined!



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Model for excess noise[14]: $\mathrm{EN} \propto \sqrt{E_{ph}}$

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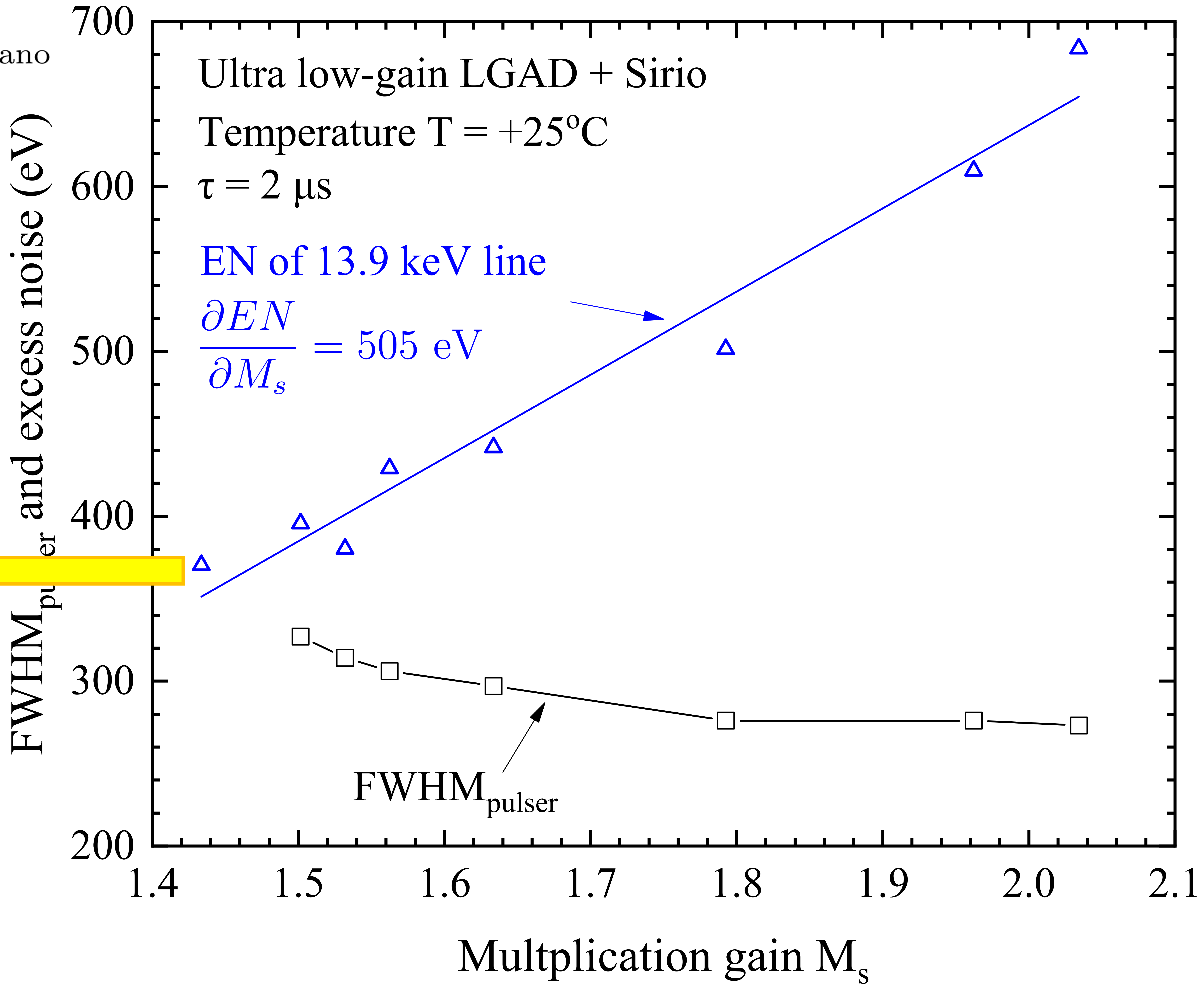

[14] Tan, Chee Hing, et al. "Avalanche gain and energy resolution of semiconductor X-ray detectors." *IEEE transactions on electron devices* 58.6 (2011): 1696-1701.

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$$\mathrm{EN} = \sqrt{FWHM^2_{13.9keV} - FWHM^2_{Pulser} - \mathrm{FWHM}^2_{\mathrm{Fano}}}$$

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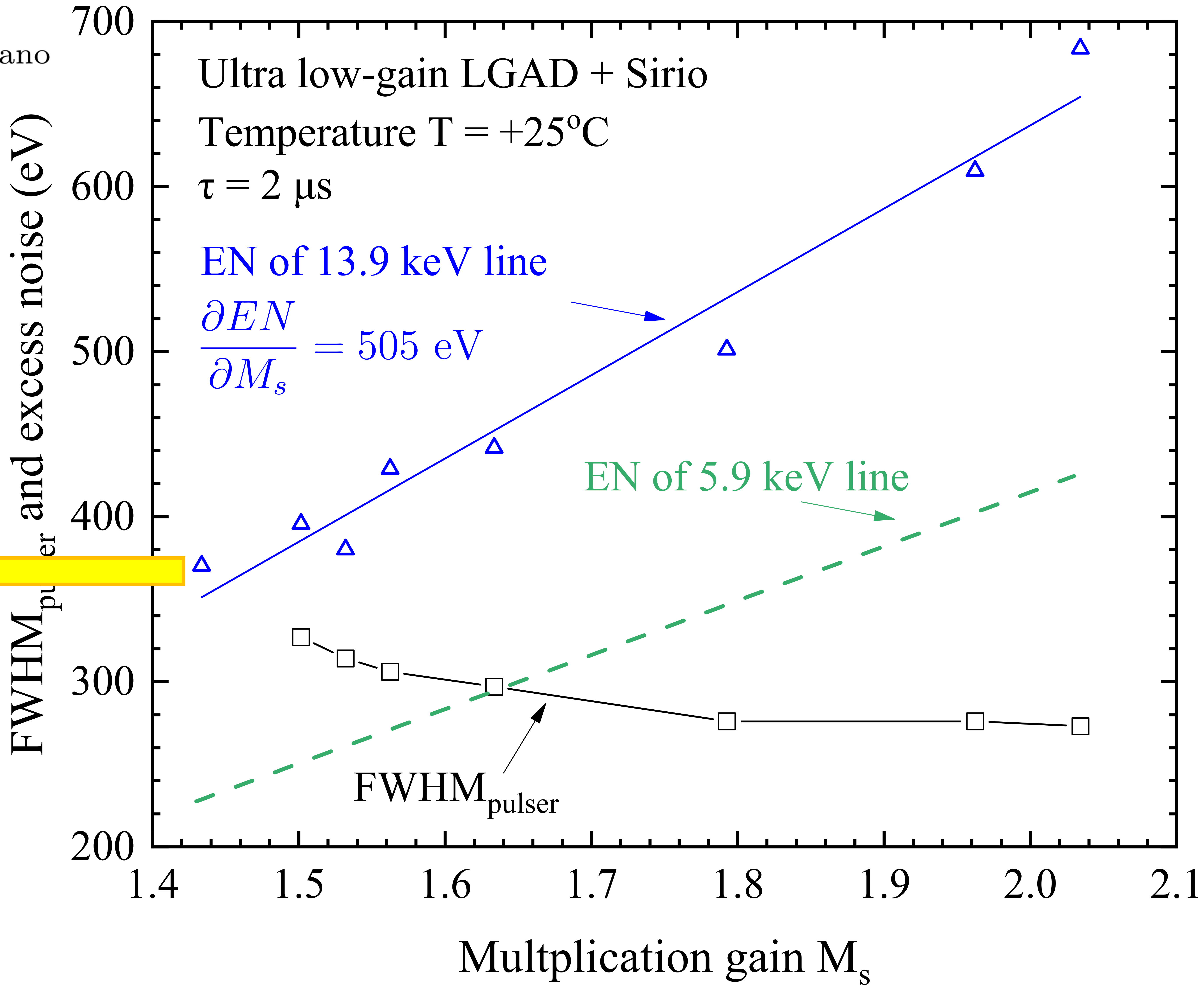

[14] Tan, Chee Hing, et al. "Avalanche gain and energy resolution of semiconductor X-ray detectors." *IEEE transactions on electron devices* 58.6 (2011): 1696-1701.

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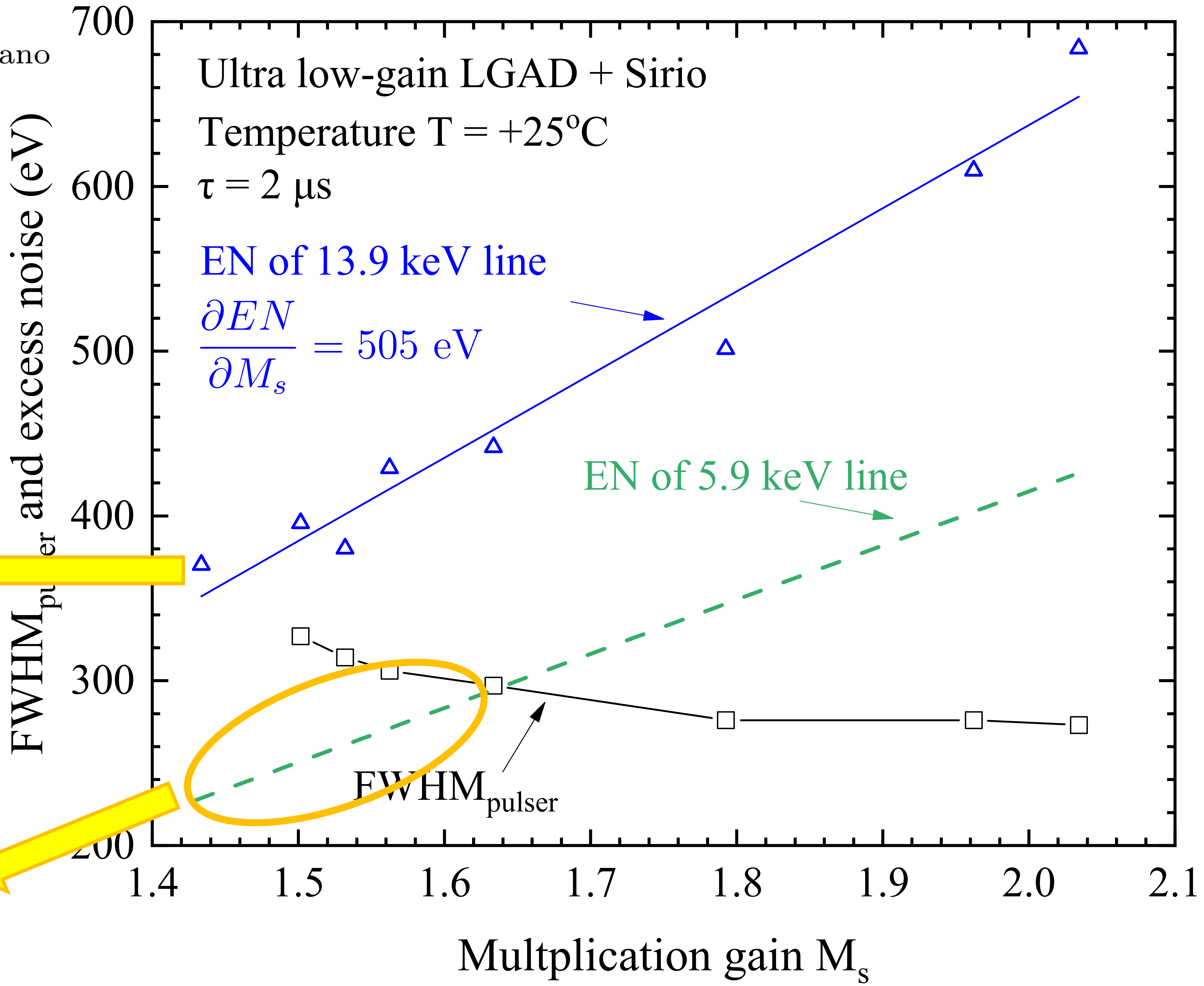


Excess noise of multiplication gain down to M_s=1.43 has been determined!

EN < FWHM$_{\mathrm{pulser}}$ at low E$_{\mathrm{photon}}$ and low M_s!

[14] Tan, Chee Hing, et al. "Avalanche gain and energy resolution of semiconductor X-ray detectors." *IEEE transactions on electron devices* 58.6 (2011): 1696-1701.

Conclusions

1. **LGAD** detector **improves the energy resolution** of X-γ ray detection system **at low photon energies** (E_{ph} < 30 keV) under specific conditions.

2. **LGAD gain** reduces the optimum peaking time in X-γ ray spectroscopy, improving the **high-rate capability.**

3. **The statistical noise of LGAD multiplication gain** has been **determined** at the different signal charge multiplication gain (**from M_s = 1.4 to M_s = 19.3**) and **shows a linear dependence on multiplication gain value.**

4. **Improving X-ray energy resolution** implies EN < $FWHM_{pulser}$ + Fano, achievable at **very low M_s**

Thank you for your attention!

<u>I. A. Eremeev</u>[1*], F. Mele[1,2,3], W. Chen[4], G. Giacomini[4] and G. Bertuccio[1,2]

[1] Politecnico di Milano, Department of Electronics, Information and Bioengineering, Via Anzani 42, Como, Italy
[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Milano, Via Celoria 16, Milan, Italy
[3] Istituto Nazionale di Astrofisica e Planetologia Spaziali (INAF-IAPS), Via del Fosso del Cavaliere 100, Rome, Italy
[4] Brookhaven National Laboratory, Instrumentation Division, Upton, NY 11973 USA
* email: iurii.eremeev@polimi.it

website: https:\\deib.polimi.sdiclab.it

High Precision X-ray Measurements (HPXM) conference
Laboratori Nazionali di Frascati (INFN) 16-20 June 2025

Backup

Explanation for the linear dependence of excess noise on gain M_s

The model for excess noise of multiplication gain [14]

$$EN = 2.35\sqrt{(\boxed{\zeta} - 1)E_{ph}\epsilon}$$

McIntyre model [9]: $\zeta = kM_s + \left(2 - \frac{1}{M_s}\right)(1-k)$

High M_s: $\zeta \propto kM_s$

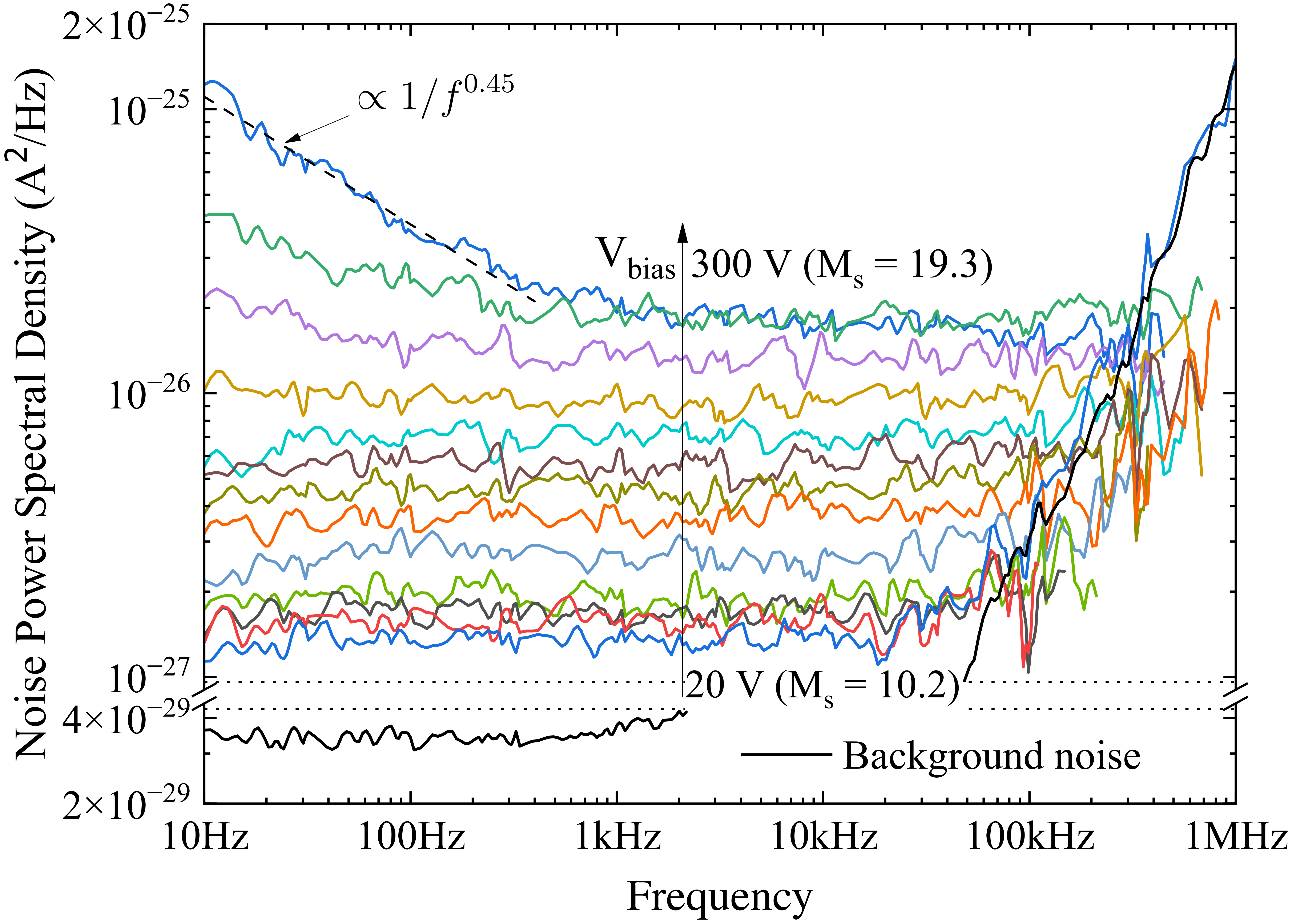
$$EN \propto M_s \text{ if } k \propto M_s$$

---

[9] McIntyre, R. J. "Multiplication noise in uniform avalanche diodes." *IEEE T-ED* 1 (1966): 164-168.

[14] Tan, Chee Hing, et al. "Avalanche gain and energy resolution of semiconductor X-ray detectors." *IEEE transactions on electron devices* 58.6 (2011): 1696-1701.

NPSD of high-gain LGAD



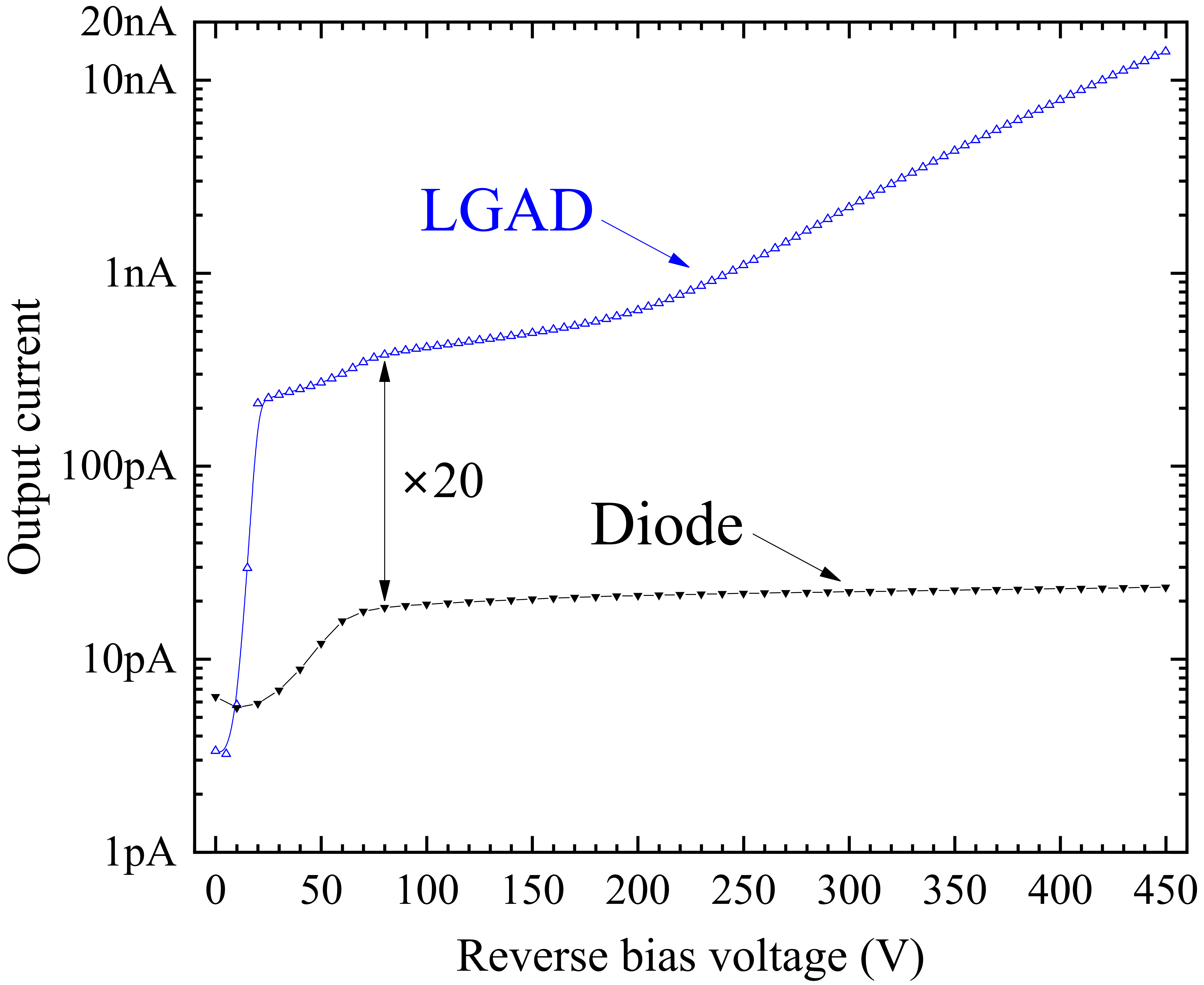
$$NPSD_w = 2qI_{inj}M_{DC}^2\zeta$$

$$M_{DC} = M_s$$

$$I_{inj} \times M_{DC} = I_{LGAD}$$

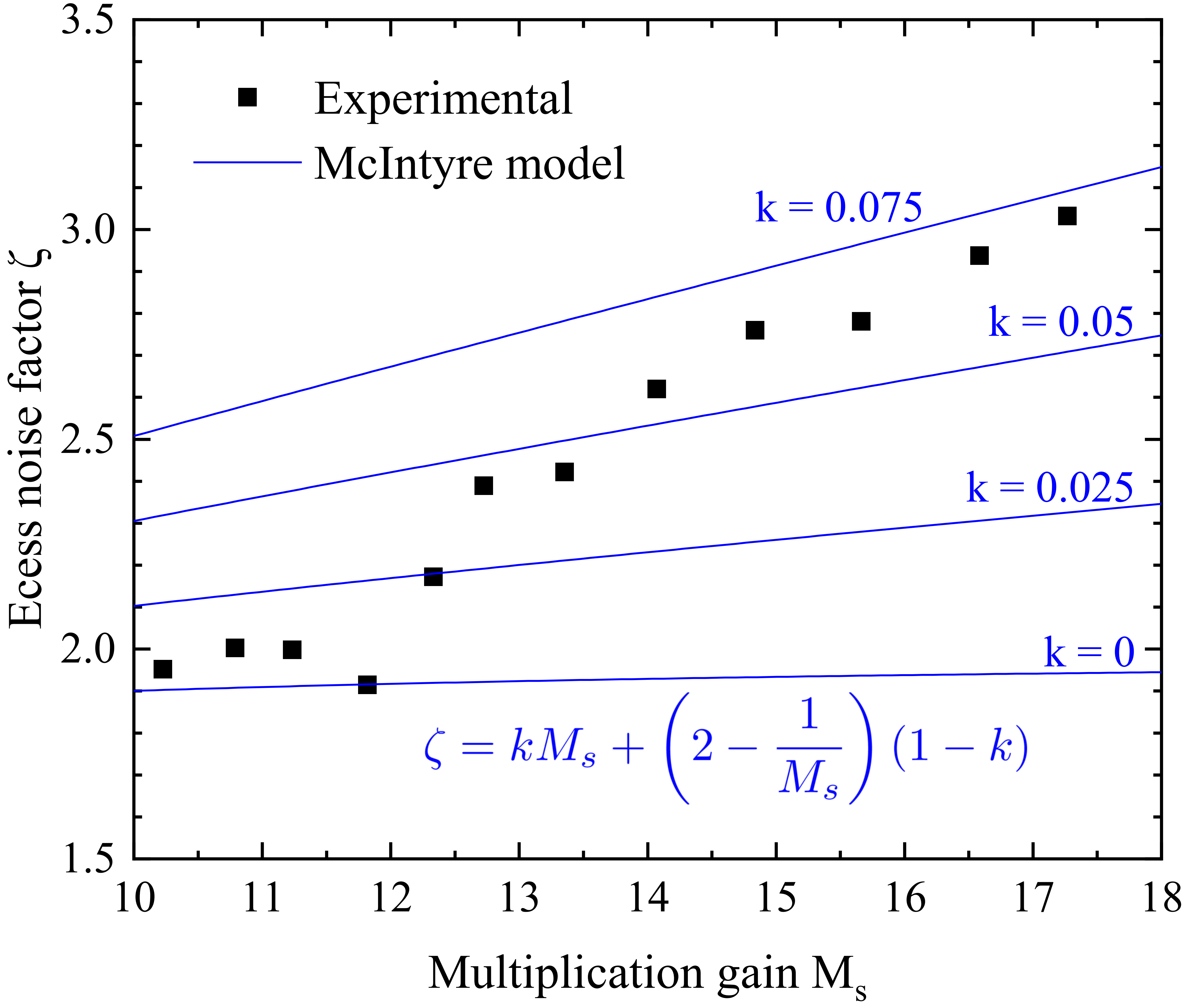
$$\boxed{\zeta = \frac{NPSD_w}{2qI_{LGAD}M_{DC}}}$$

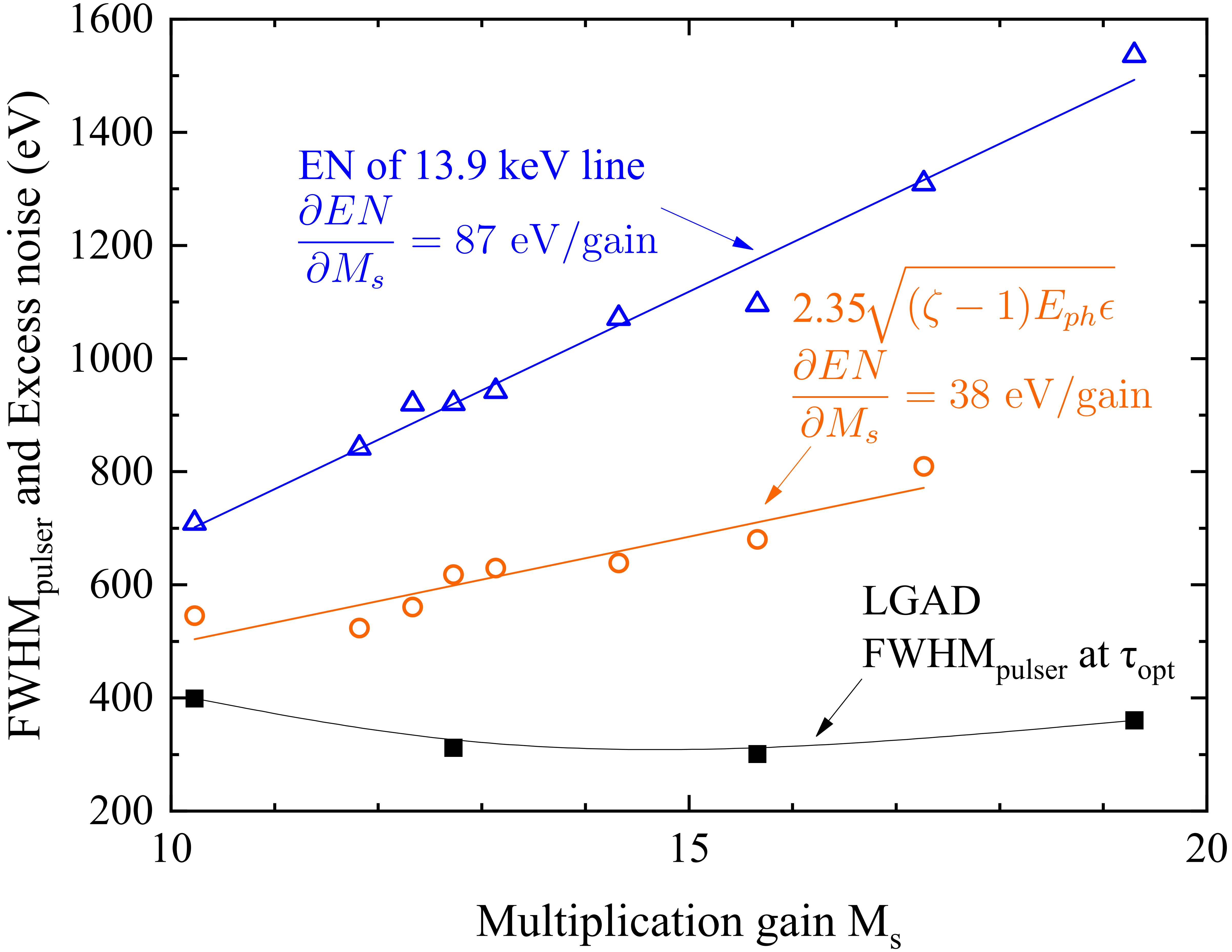
DC current of high-gain LGAD and Diode



Excess noise of the spectral lines calculated using excess noise factor

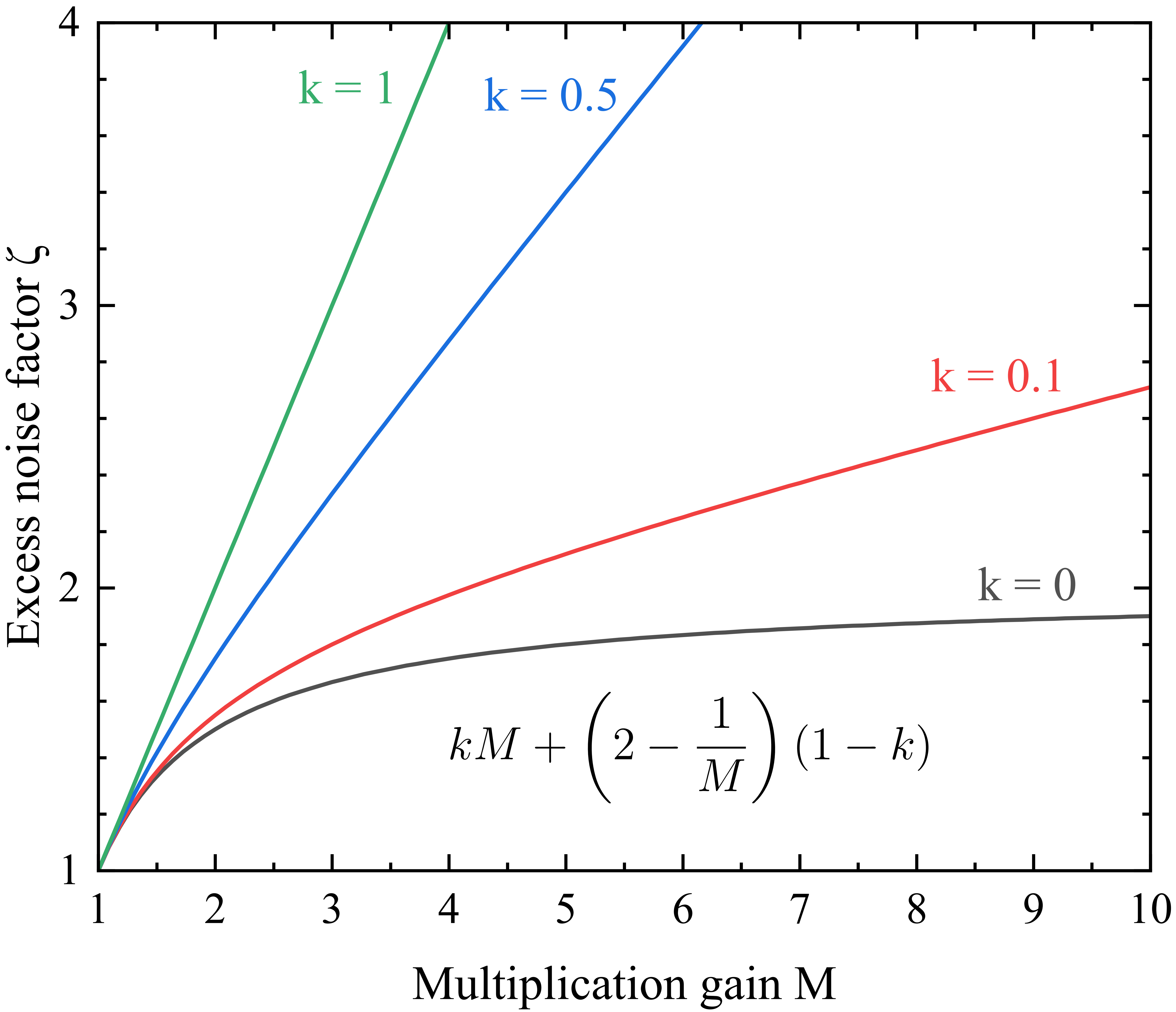
$$\zeta = \frac{NPSD_w}{2qI_{LGAD}M_{DC}} \longrightarrow EN = 2.35\sqrt{(\zeta - 1)E_{ph}\epsilon}$$





Theoretical dependence of excess noise factor of multiplication gain

$$\mathrm{EN} \propto \sqrt{\zeta}$$



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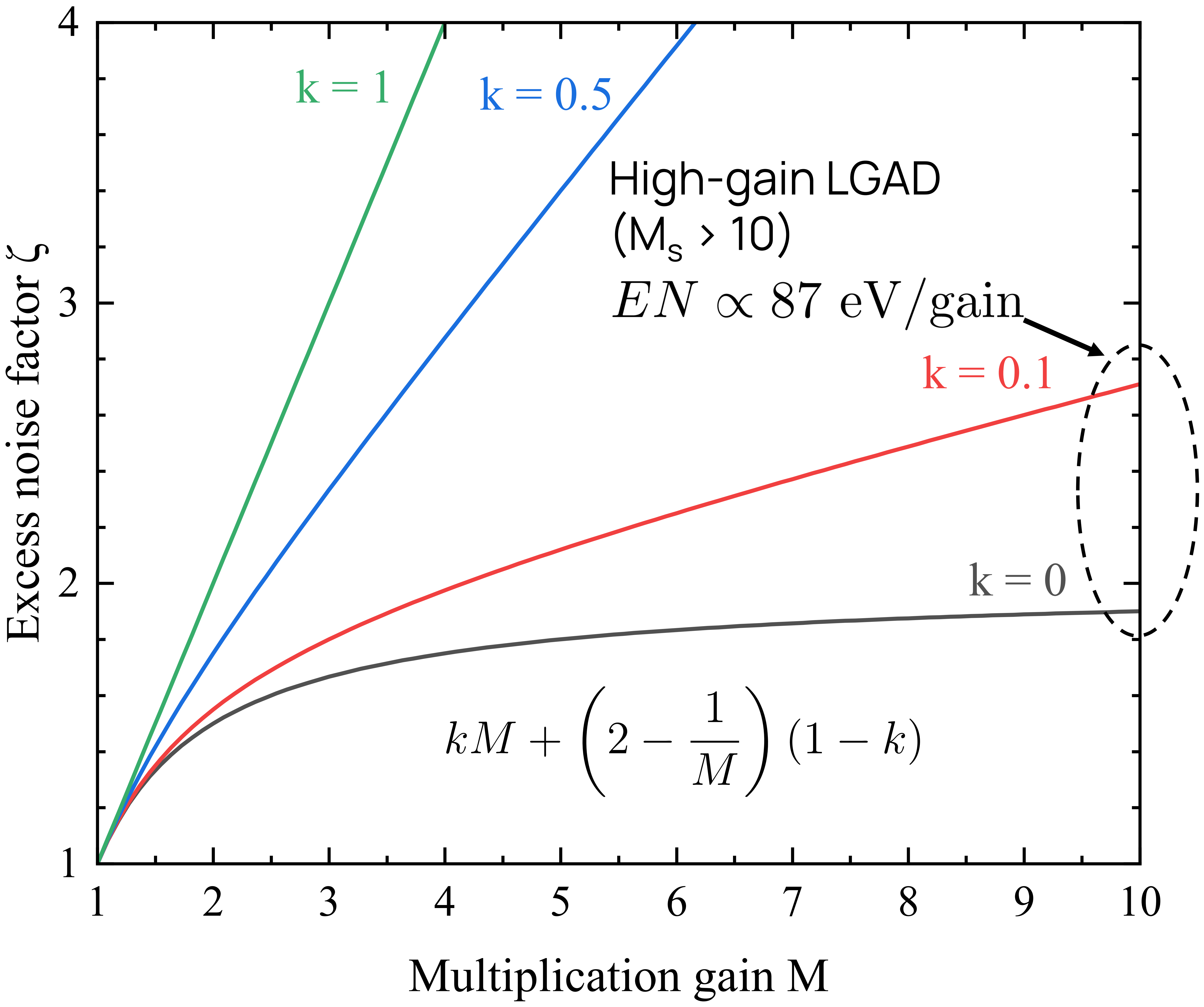

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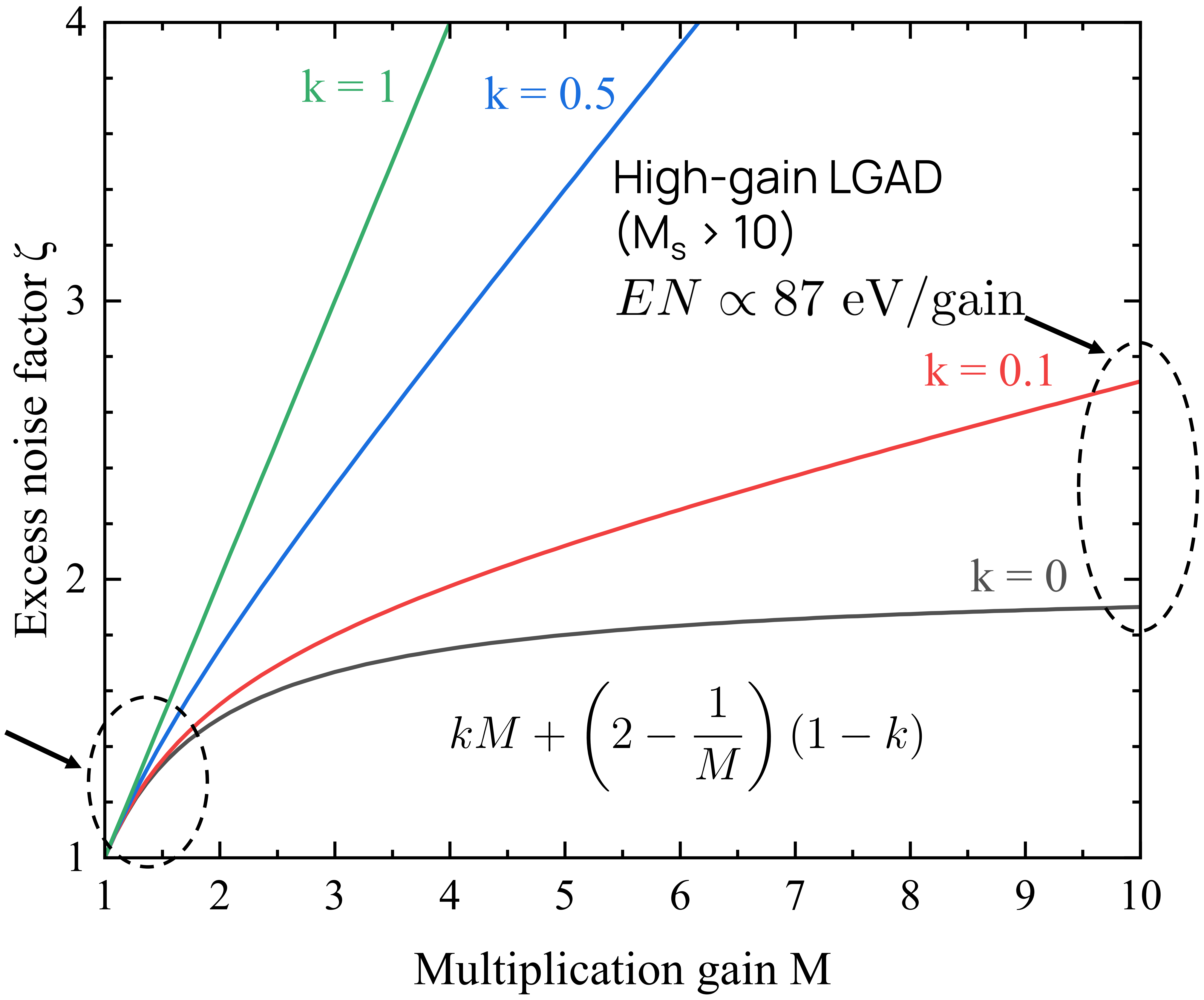


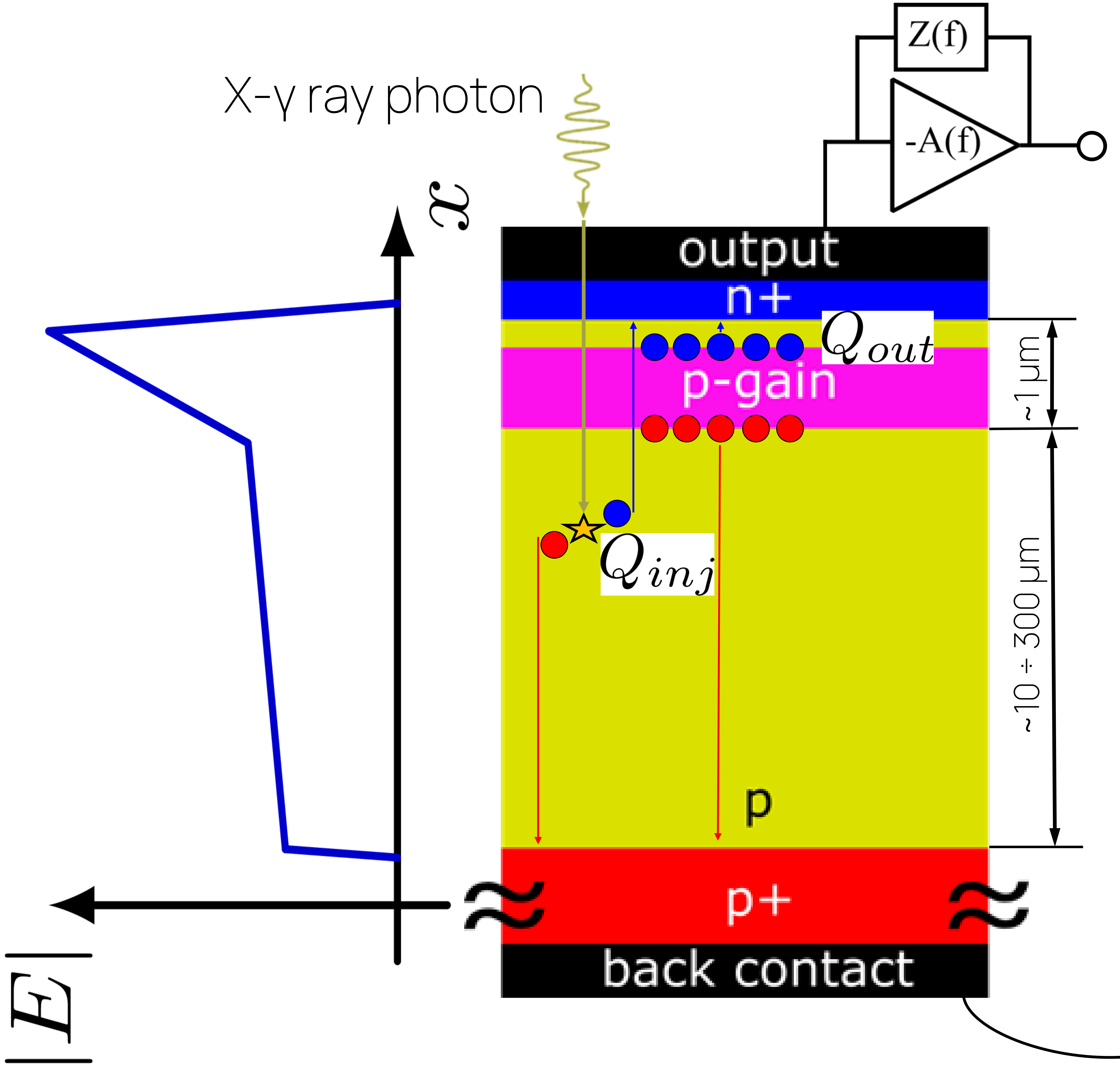
$$kM + \left(2 - \frac{1}{M}\right)(1 - k)$$

High-gain LGAD
(M_s > 10)
$EN \propto 87$ eV/gain

Ultra low-gain LGAD
(M_s < 2)
$EN \propto 505$ eV/gain

- Additional contribution of non-uniform electric field distribution

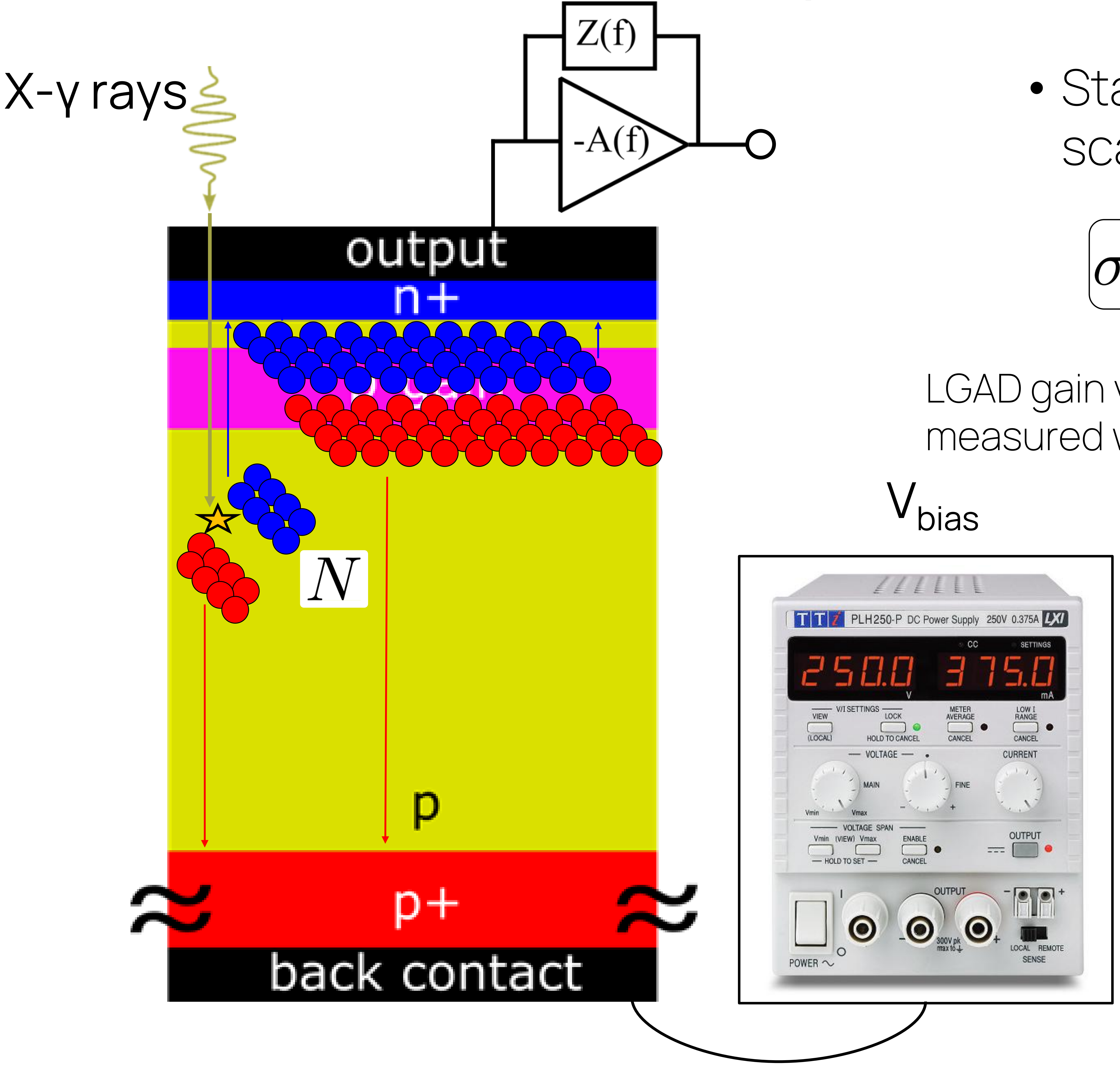
Excess noise of LGAD signal gain



$$M_s = \frac{Q_{out}}{Q_{inj}} \lesssim 100$$

V$_{bias}$

LGAD noise study in X-γ ray spectroscopy



- Statistical noise of multiplication gain scales with the number of carriers [13]

$$\boxed{\sigma_N^2} \propto N\boxed{\sigma^2_{single\ charge}}$$

LGAD gain variance measured with X-γ rays

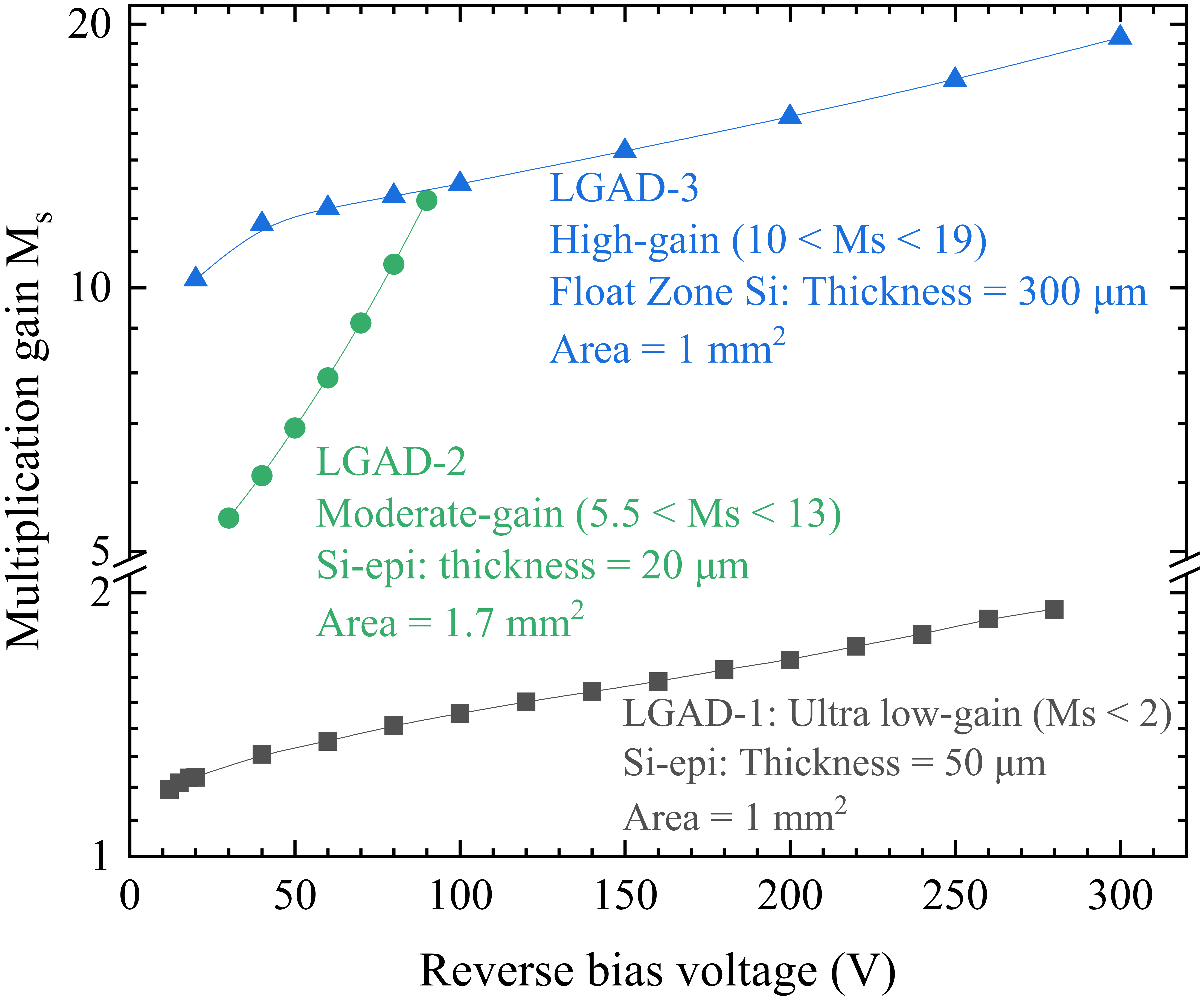
Gain variance for single charge

Study of excess noise (EN) using **X-γ rays** allows determination of EN for **single charge since N is known**

---

[13] Tan, Chee Hing, et al. "Avalanche gain and energy resolution of semiconductor X-ray detectors." *IEEE transactions on electron devices* 58.6 (2011): 1696-1701.

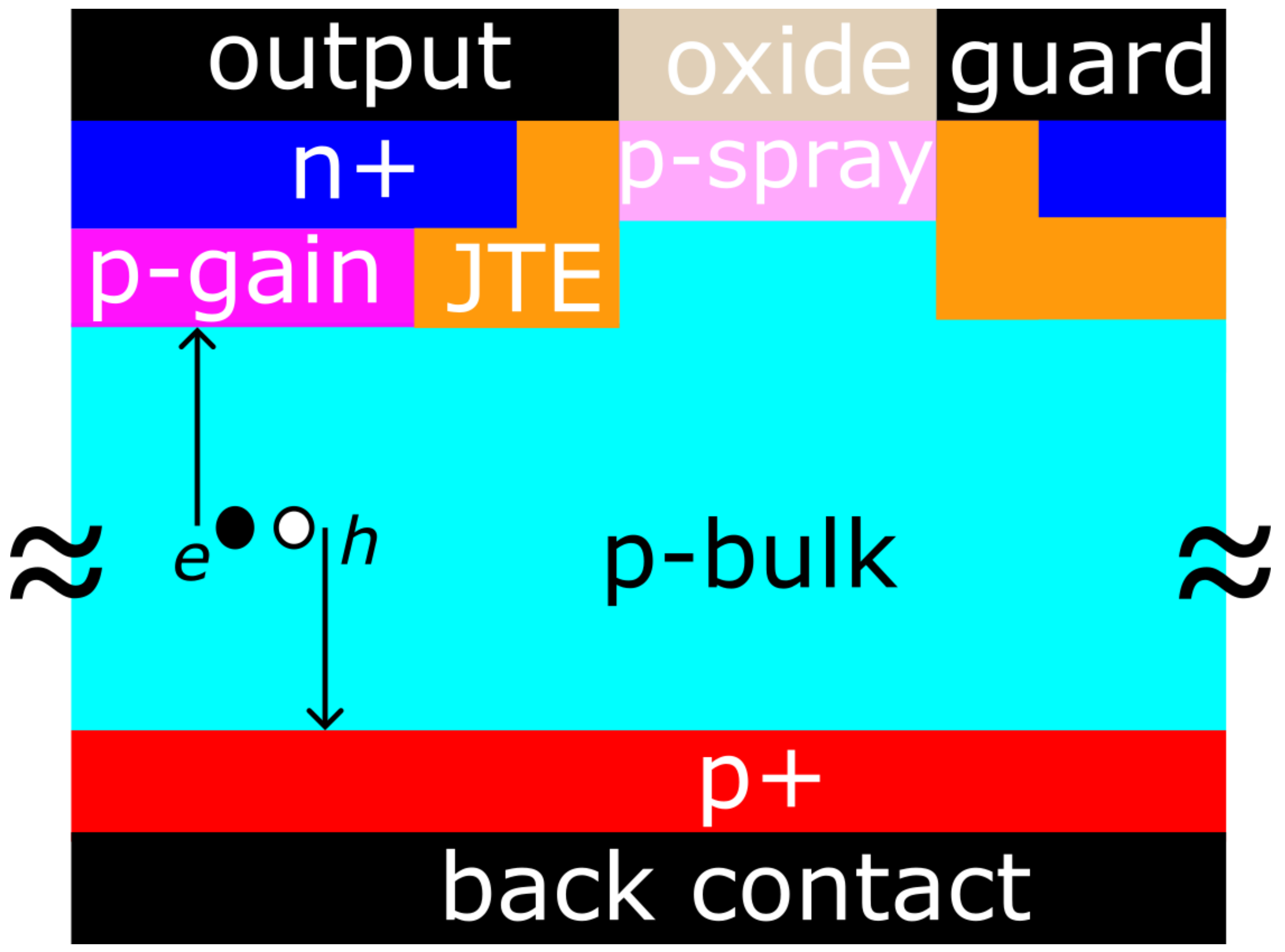
Studied LGAD structures



Doping profile of moderate and high-gain LGAD structures

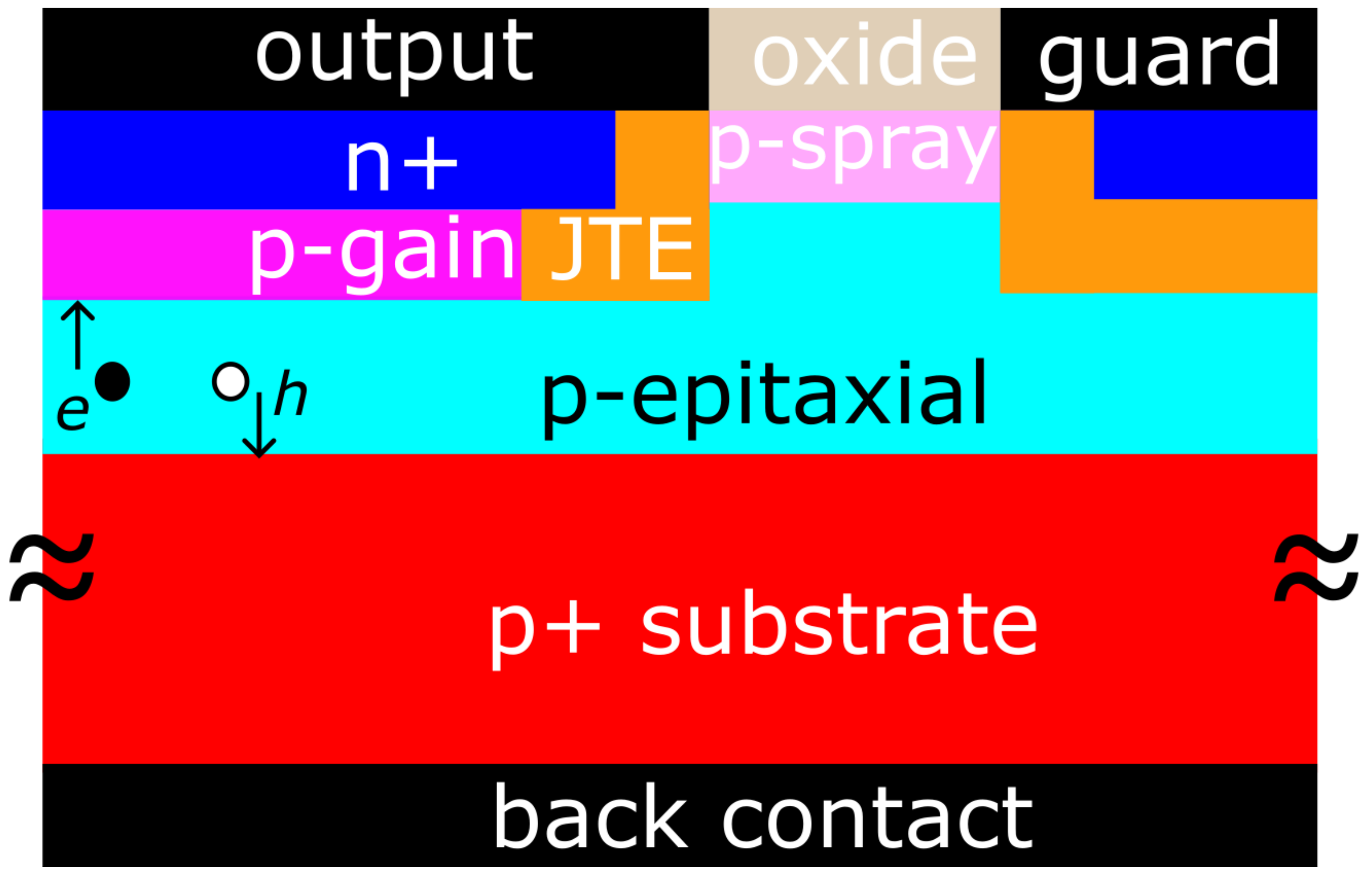
High gain LGAD (M_S = 10.2 – 19.3)

- Float zone 300 µm p-bulk
- Output contact area A = 1 mm^2

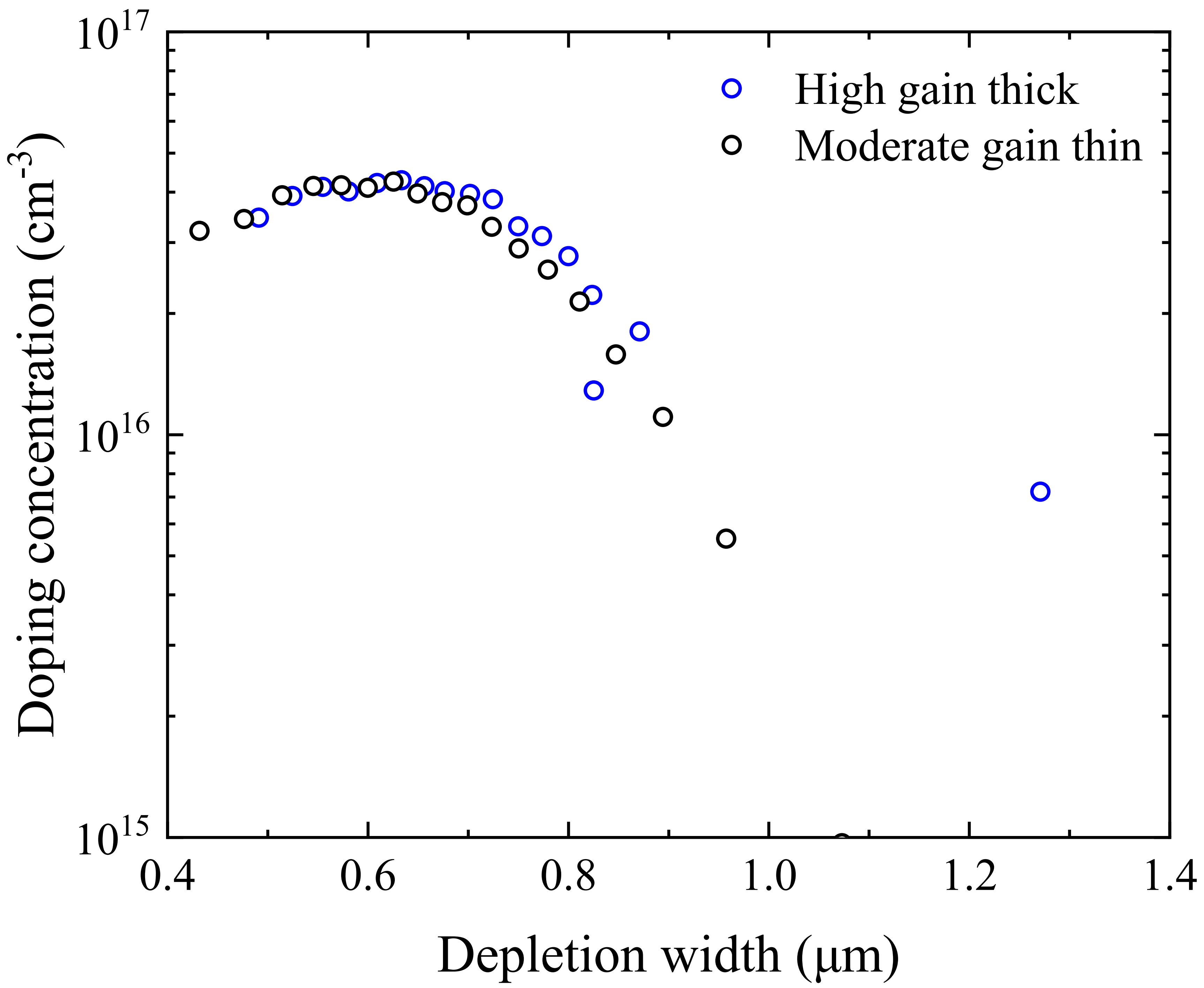


Moderate gain LGAD (M_S = 5.5 - 12.6)

- 20 µm epi-Si
- Output contact area A = 1.3×1.3 mm^2



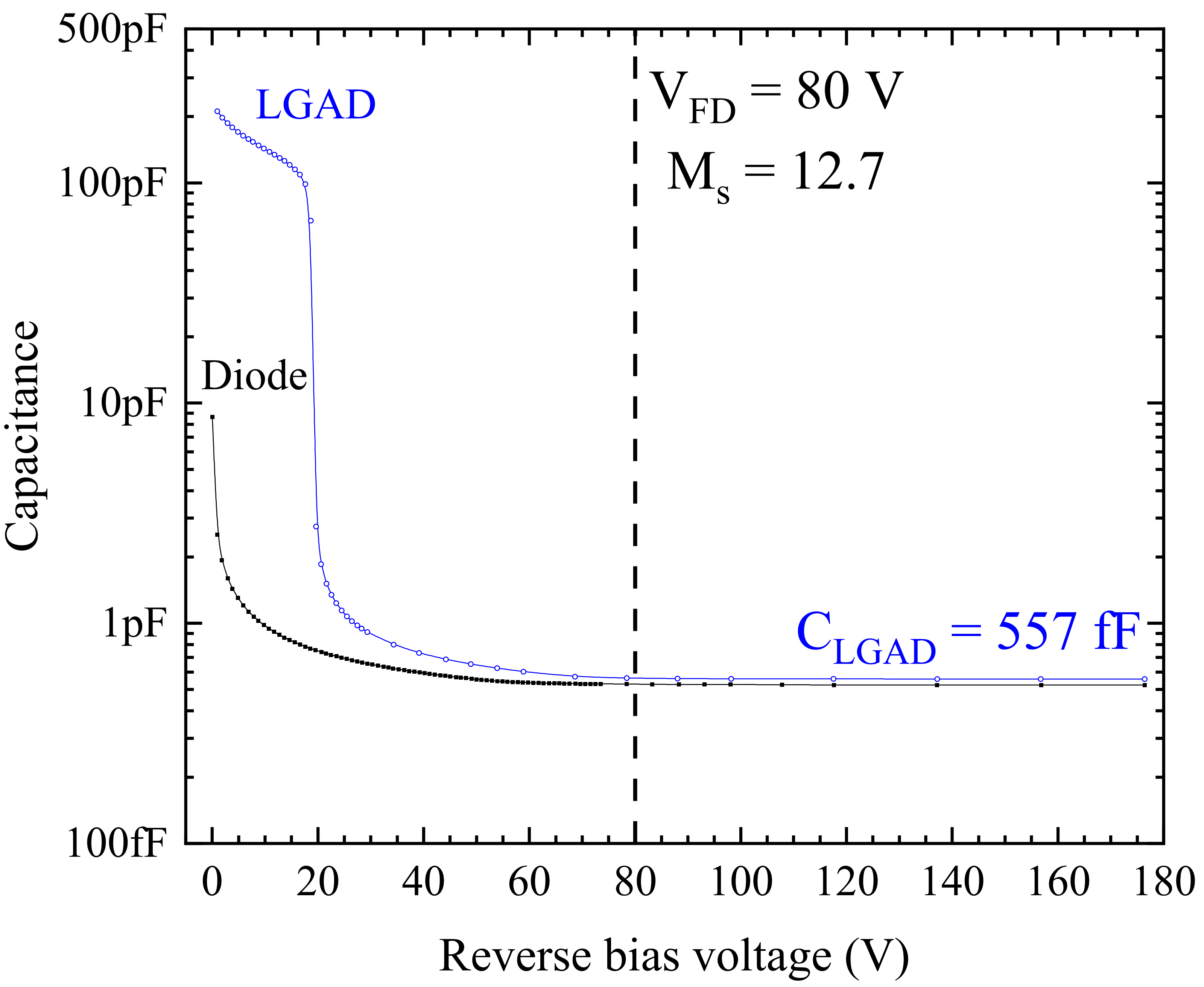
Measured doping profiles



LGAD capacitance

High-gain LGAD (M_s = 10.2 – 19.3)

- Float zone 300 μm p-bulk
- Output contact area A = 1 mm^2



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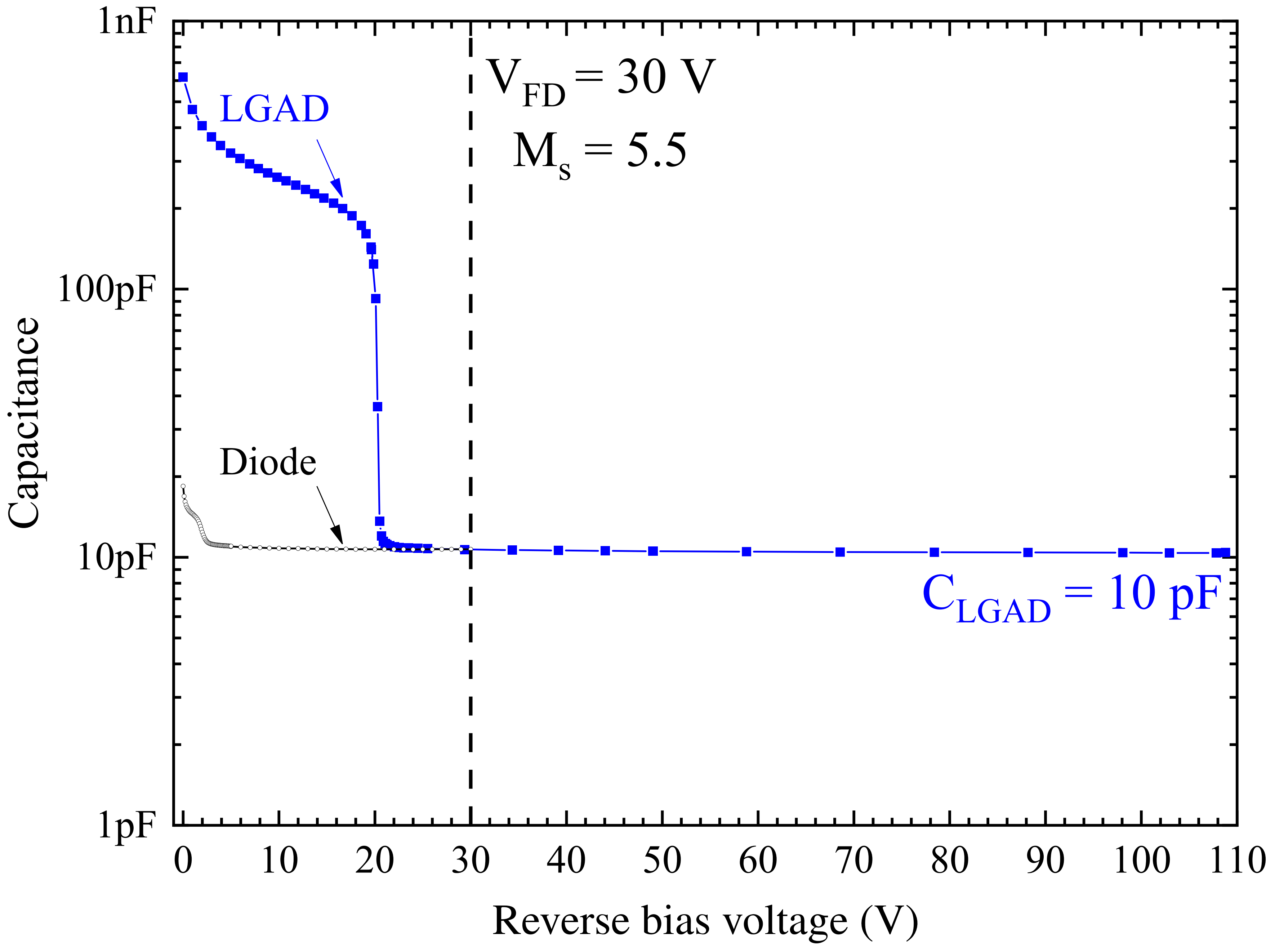
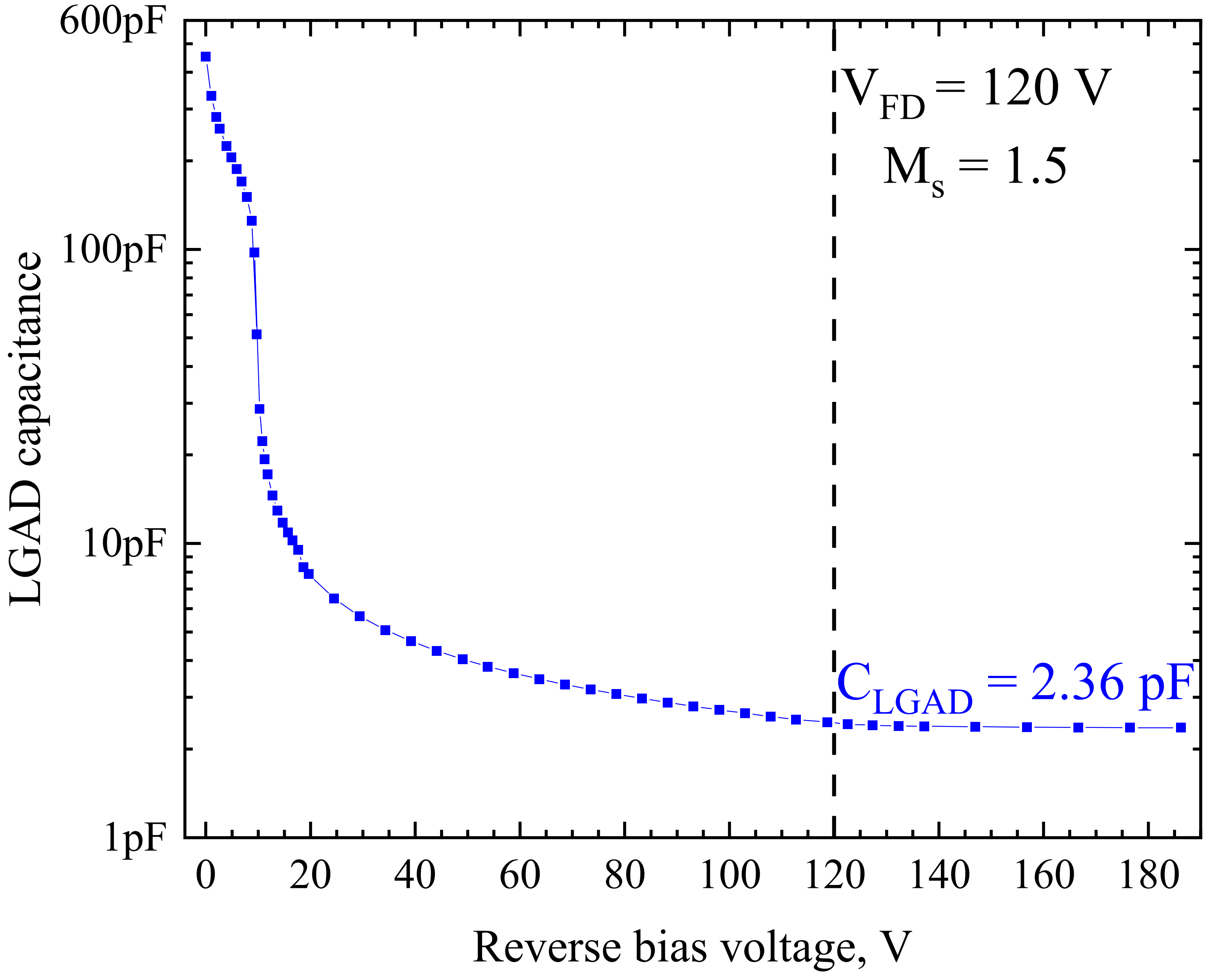
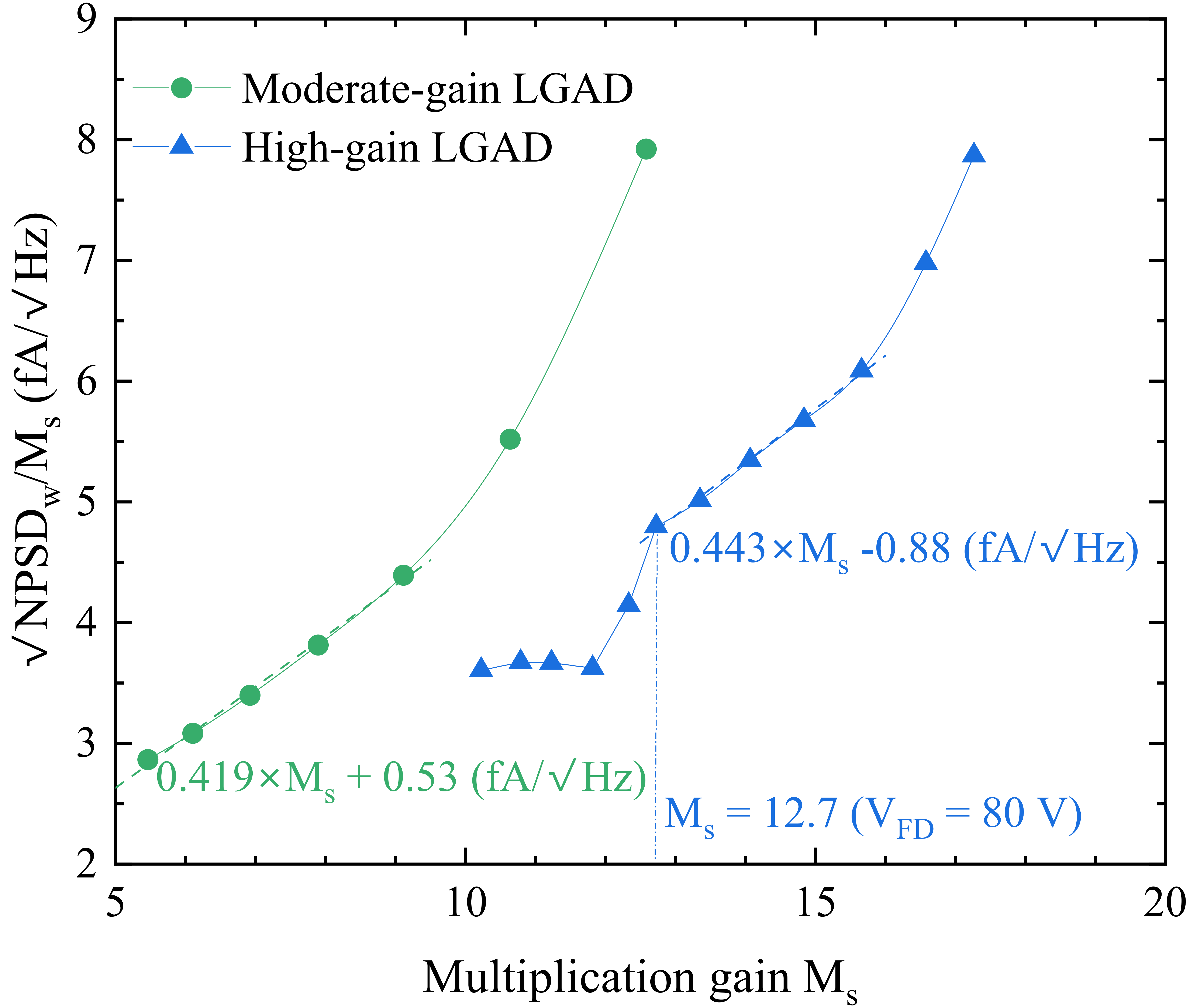


Ultra low-gain LGAD (M_s < 2)

- 50 μm epi-Si
- Output contact area A = 1 mm^2

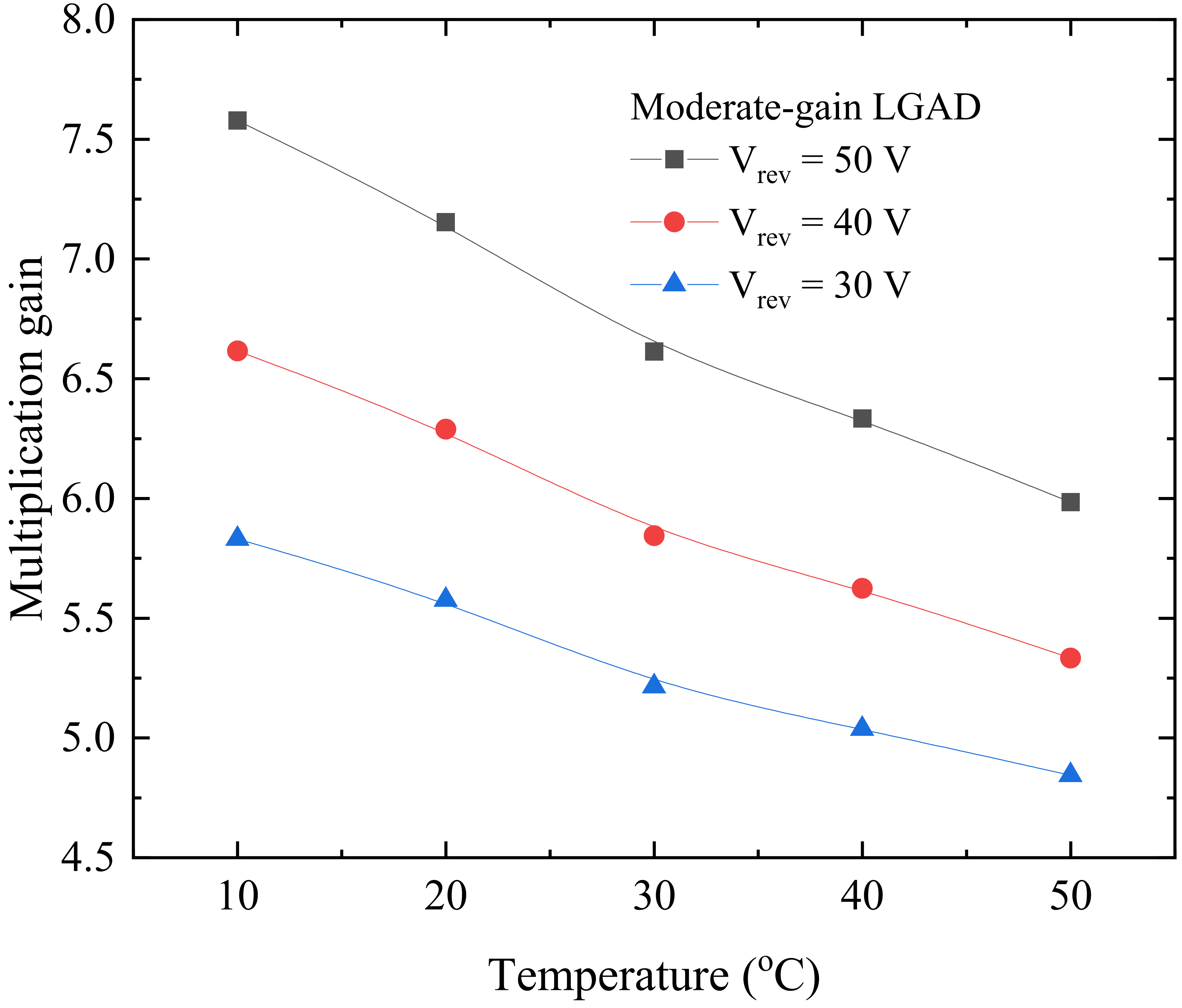


Dependence of the white LGAD current noise on multiplication gain

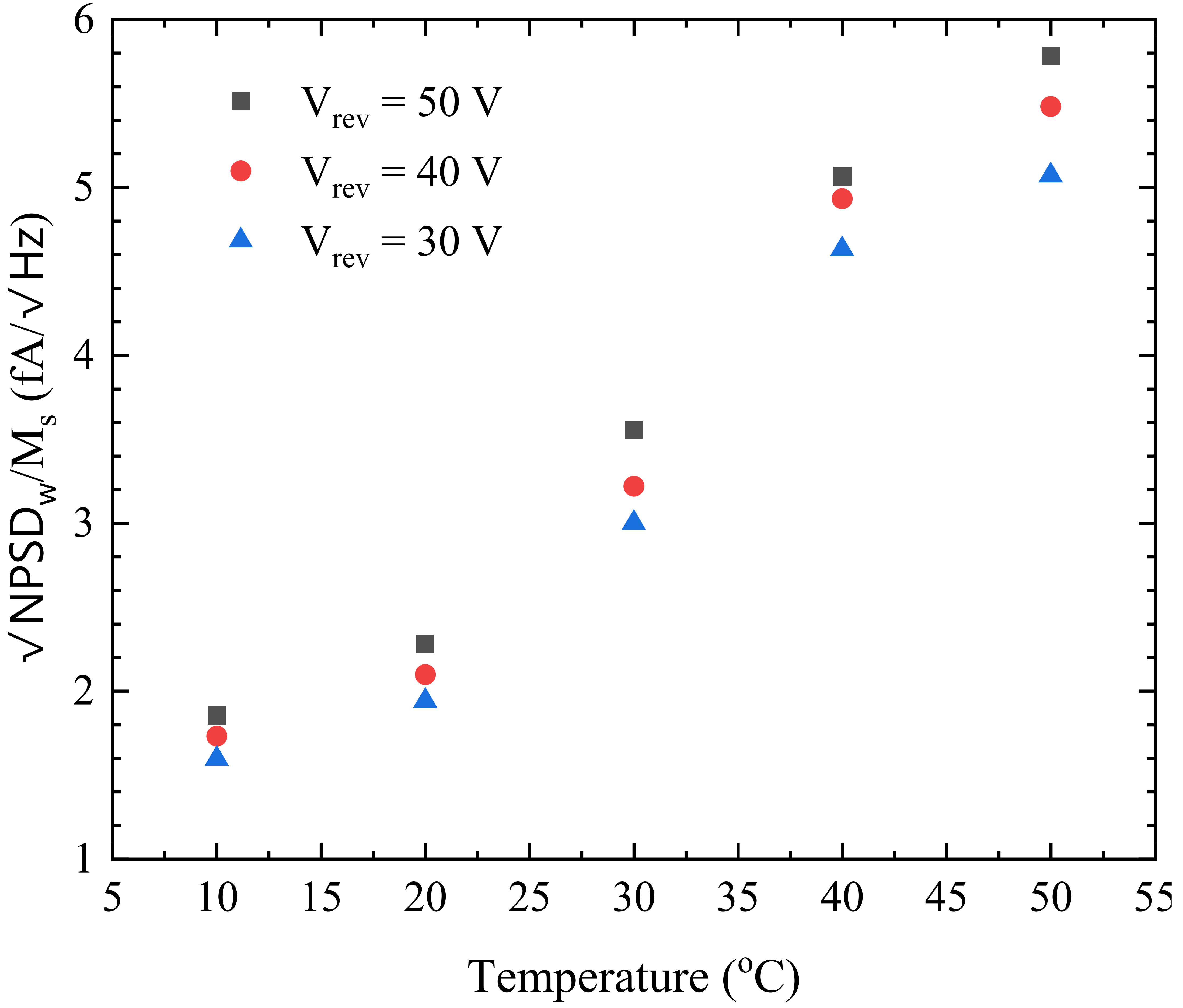


Dependence of parallel noise component on temperature

- A slight decrease of LGAD multiplication gain with temperature [15]



- Parallel noise component referred to the gain layer input increases with temperature

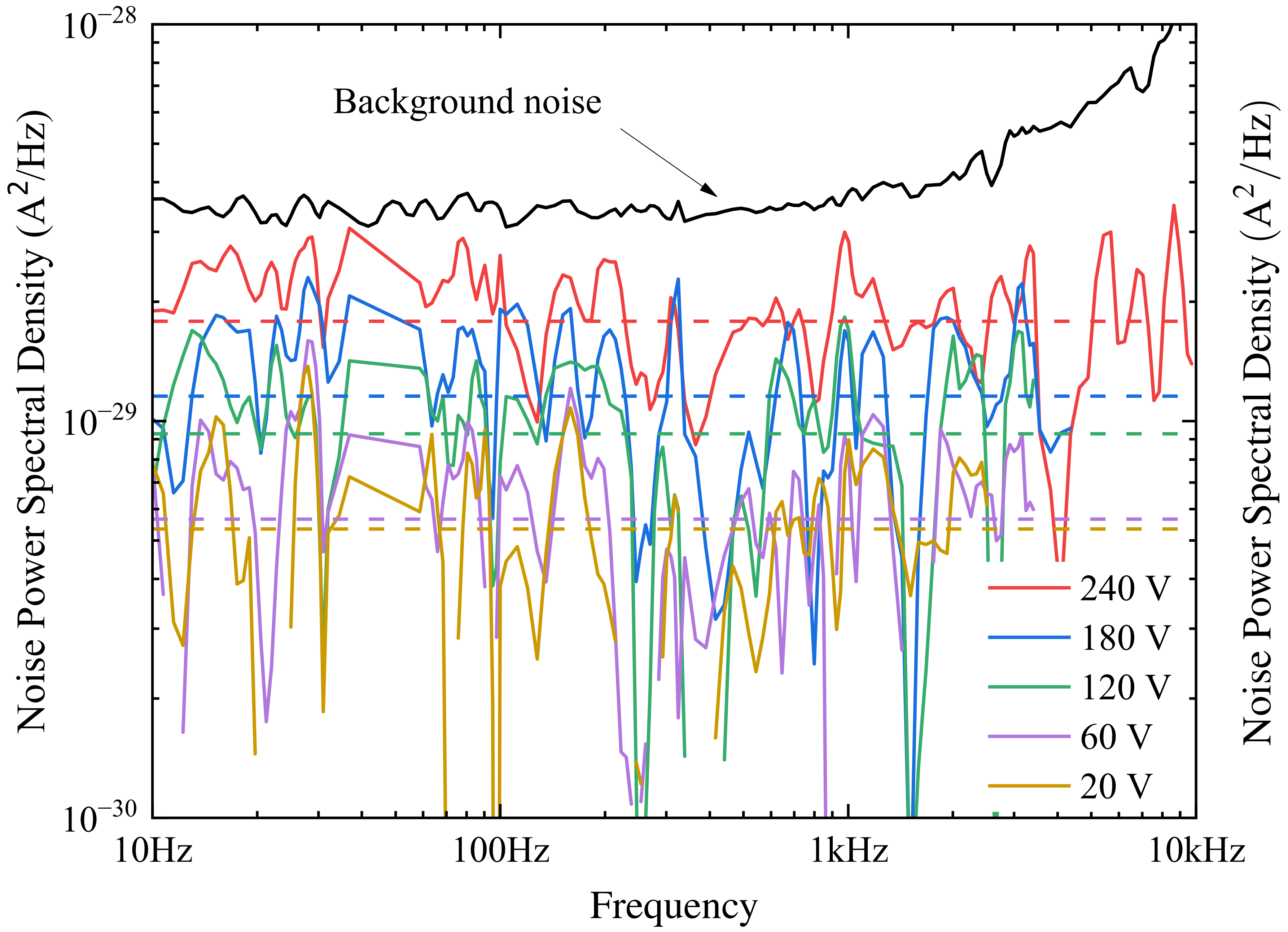


[15] Massey, D. J., J. P. R. David, and G. J. Rees. "Temperature dependence of impact ionization in submicrometer silicon devices." *IEEE Transactions on Electron Devices* 53.9 (2006): 2328-2334.

Measured LGAD noise power spectral densities

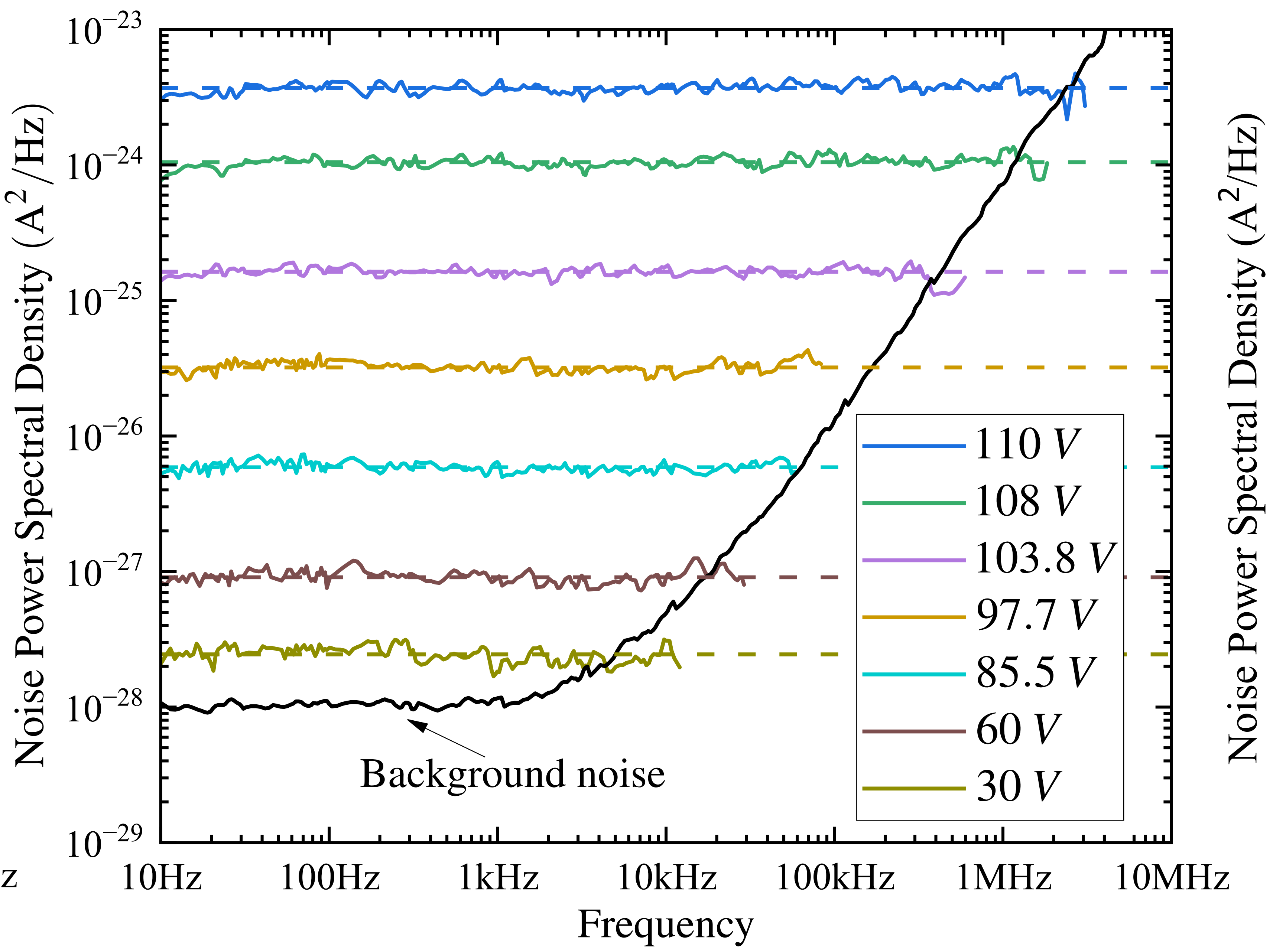
Ultra **low-gain** LGAD

- $M_S = 1.2 - 1.9$



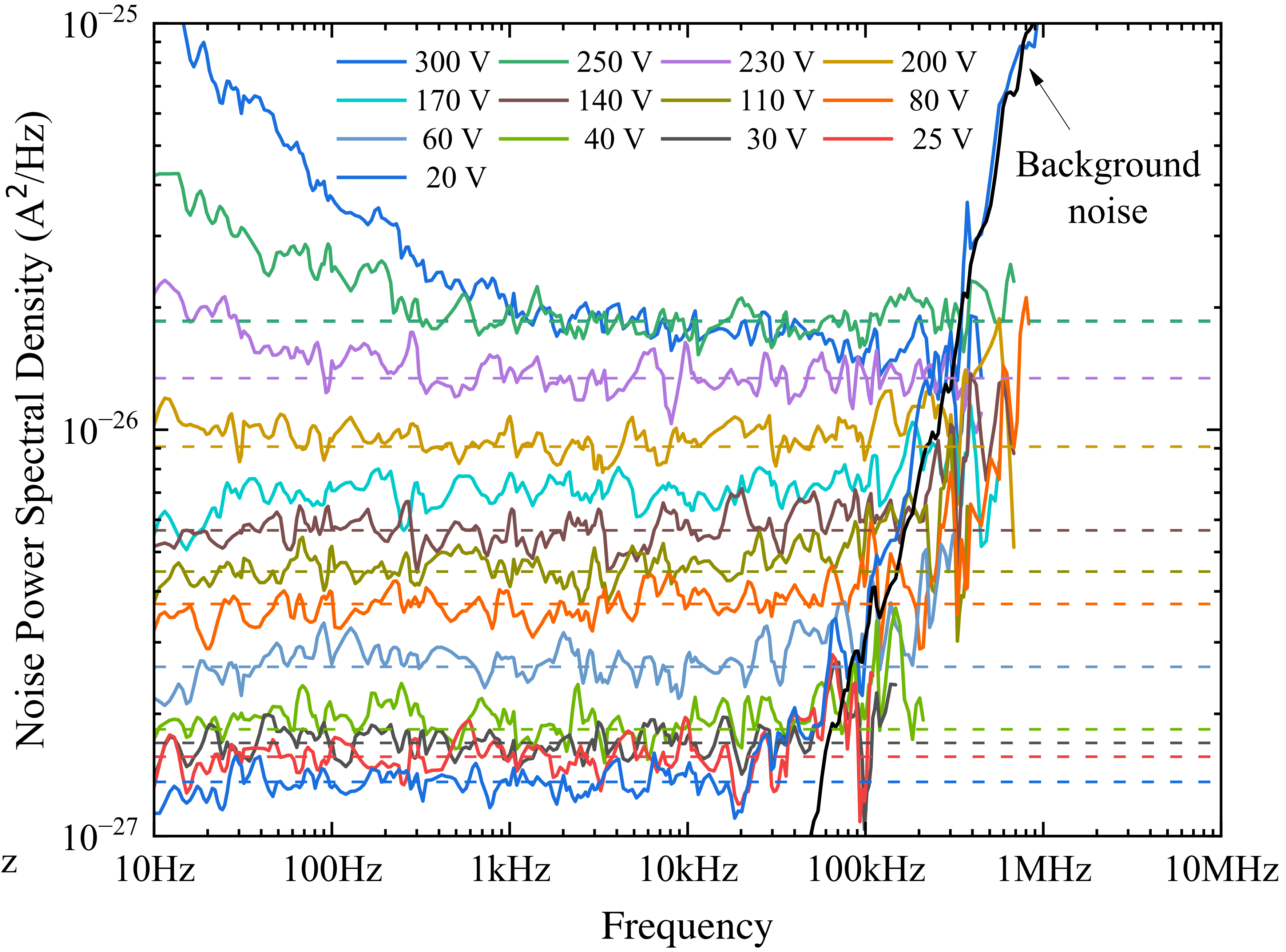
Moderate gain LGAD

- $M_S = 5 - 13$



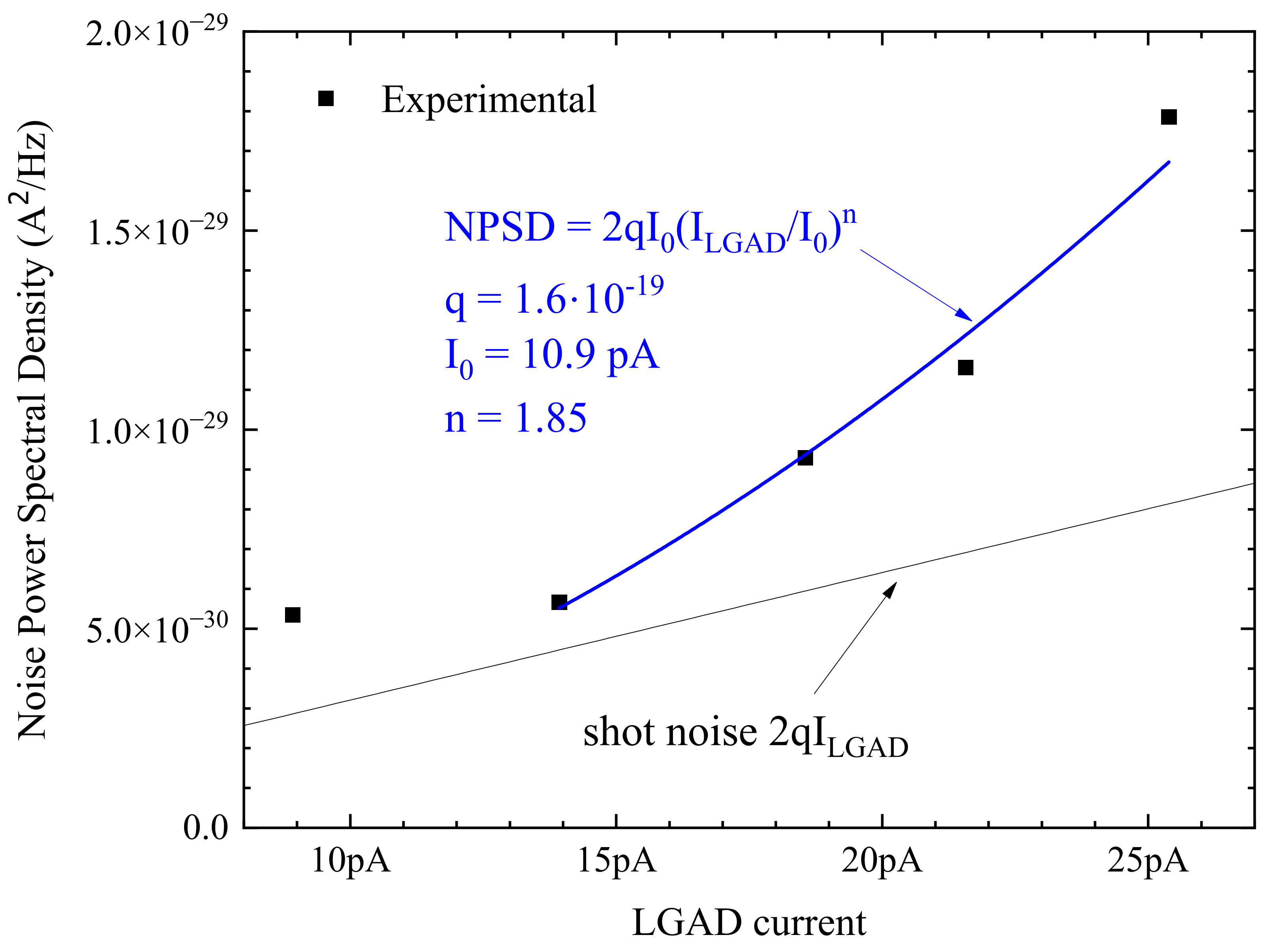
High gain LGAD

- $M_S = 10 - 20$

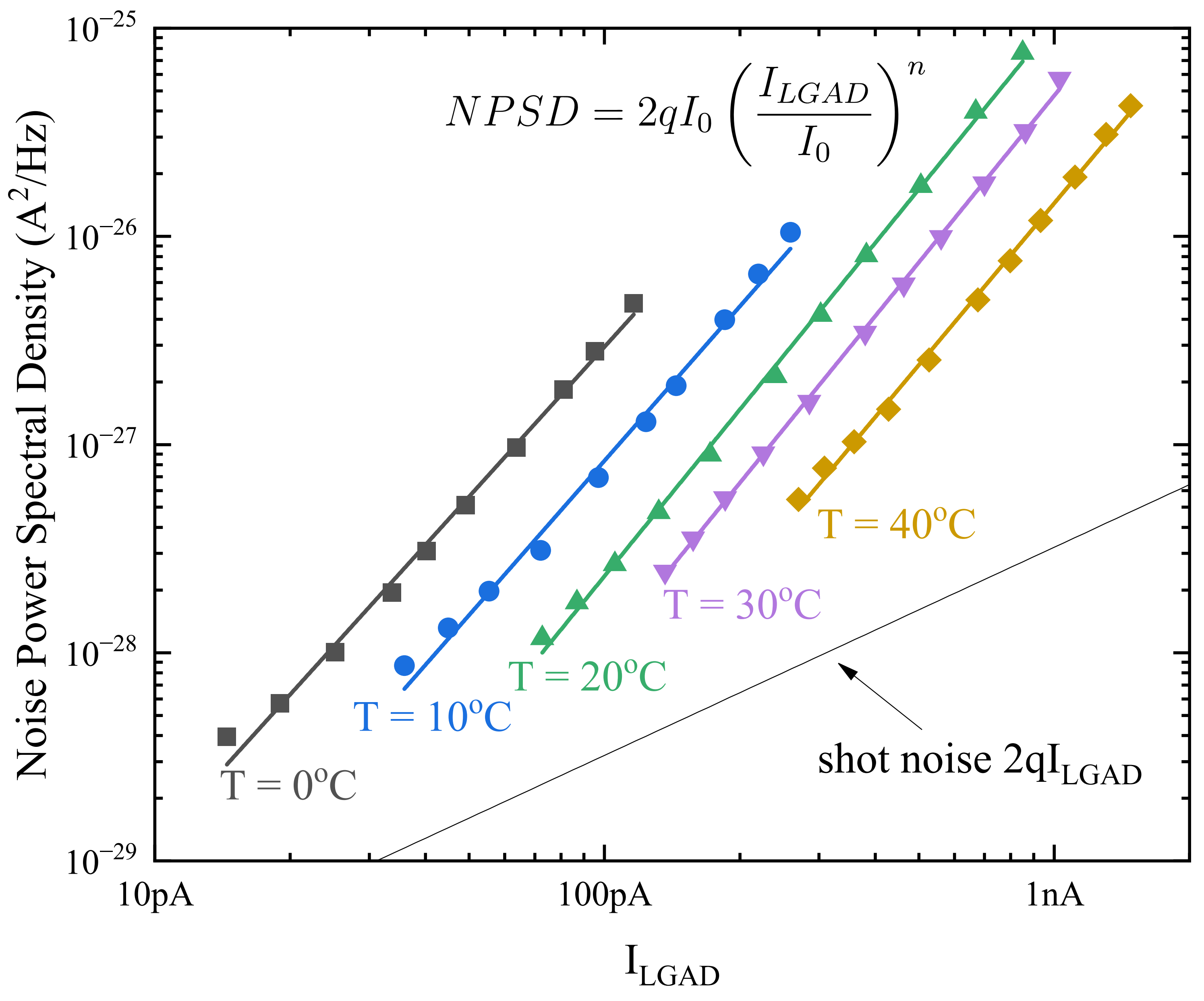


$NPSD_W$ dependencies on DC current

Ultra **low-gain** LGAD
- $M_S = 1.2 - 2$
- T = 25 °C

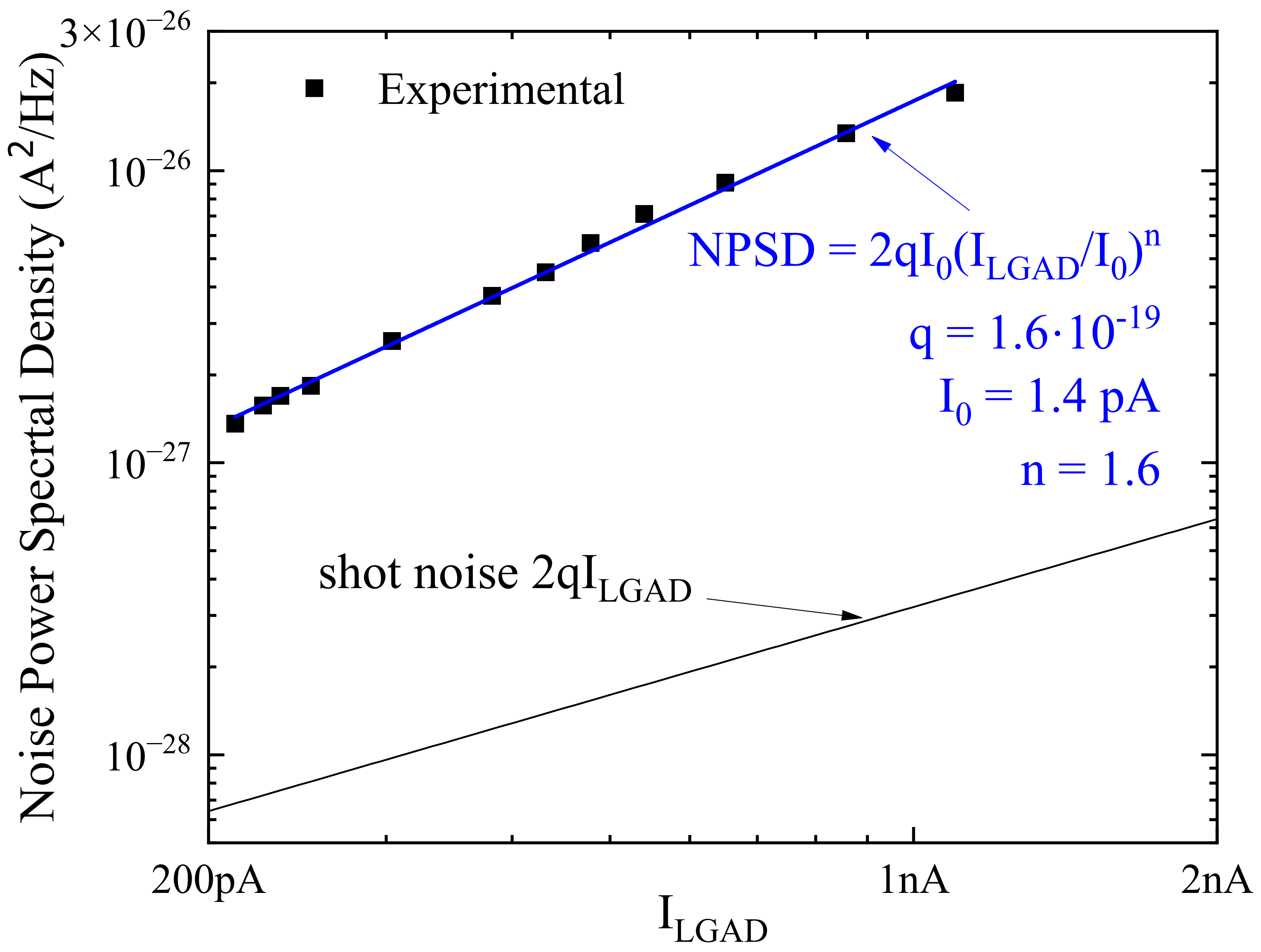


Moderate-gain LGAD
- $M_S = 5.5 - 12.7$
- T = 0 – 40 °C



Temperature, °C	n	I_0, pA
0	2.389	3.86
10	2.463	10.79
20	2.658	30.25
30	2.662	49.49
40	2.581	90.06

High-gain LGAD
- $M_S = 10.2 - 19.3$
- T = 20 °C



Optimum peaking time of LGAD -based detection system

$$ENC = \sqrt{\frac{A}{\tau} + B + C\tau}$$

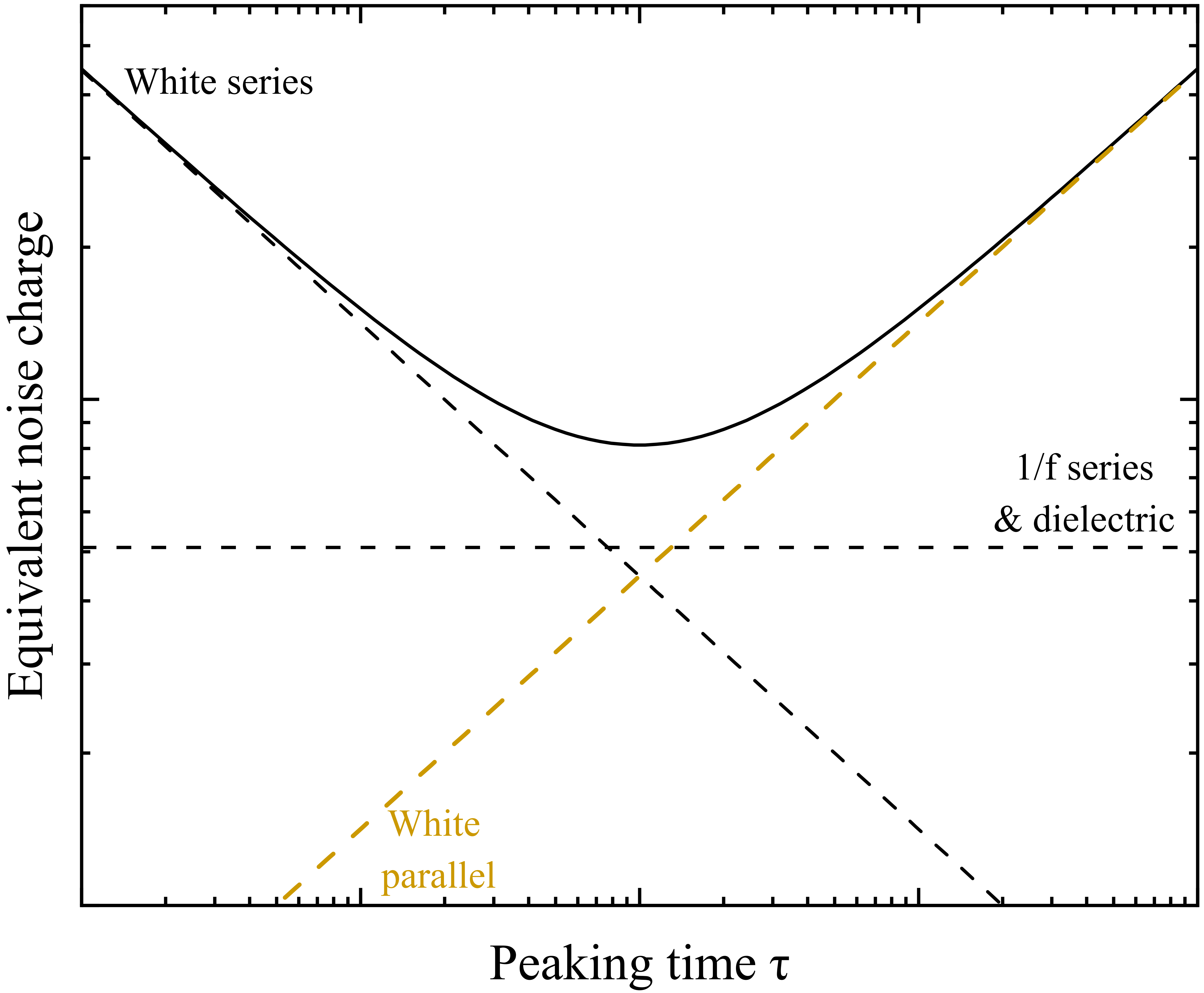
$$ENC_{M_s} = \sqrt{\frac{A}{M_s^2\tau} + \frac{B}{M_s^2} + \frac{C}{M_s^2}\tau}$$

Parallel noise increases proportionally to charge signal multiplication gain

$$\frac{C}{M_s^2} = (K_1 \times M_s)^2$$

$$\tau_{opt} = \frac{\sqrt{A}}{K_1}\frac{1}{\boxed{M_s^2}}$$

τ_{opt} decreases with $(M_s)^2$



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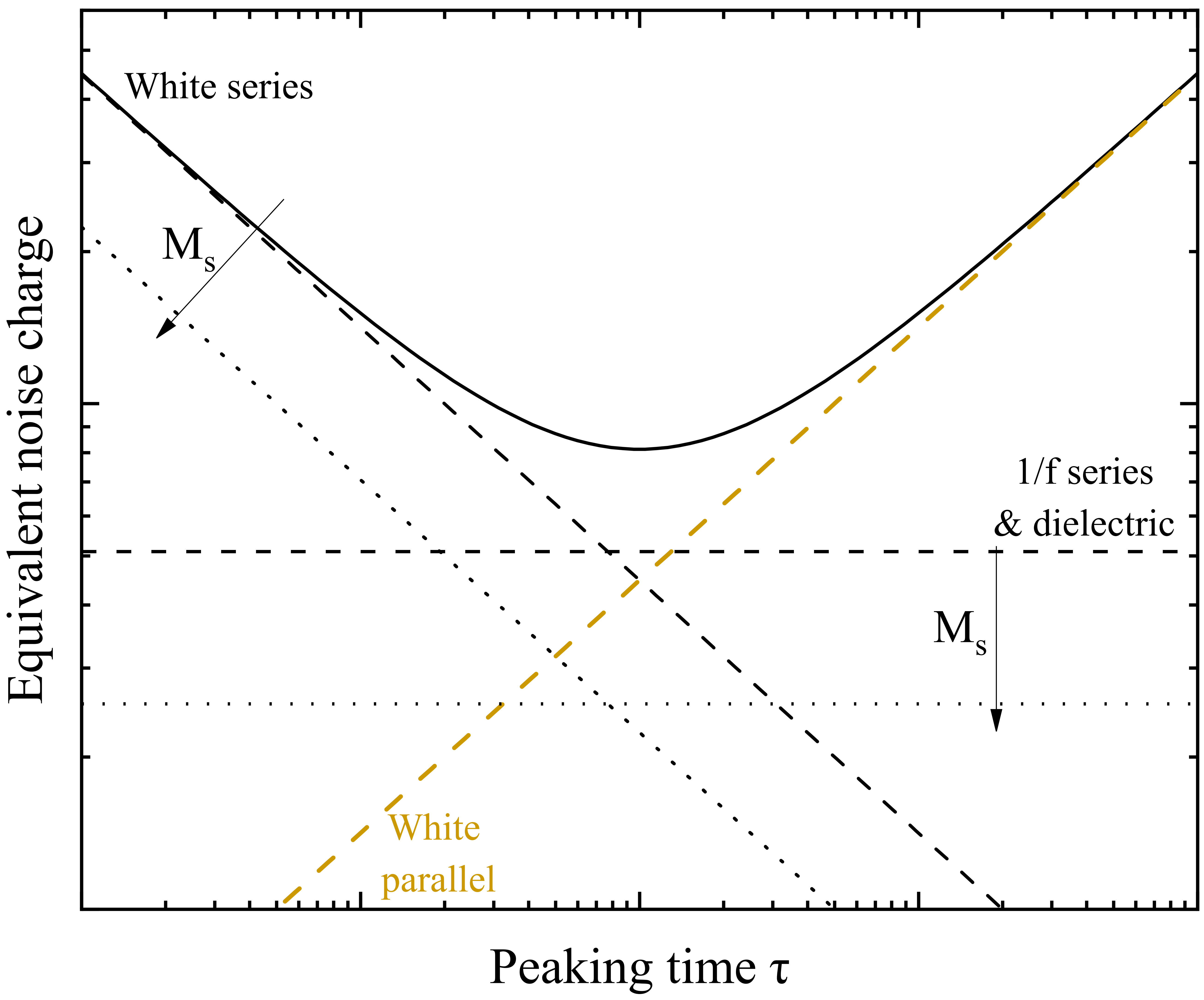

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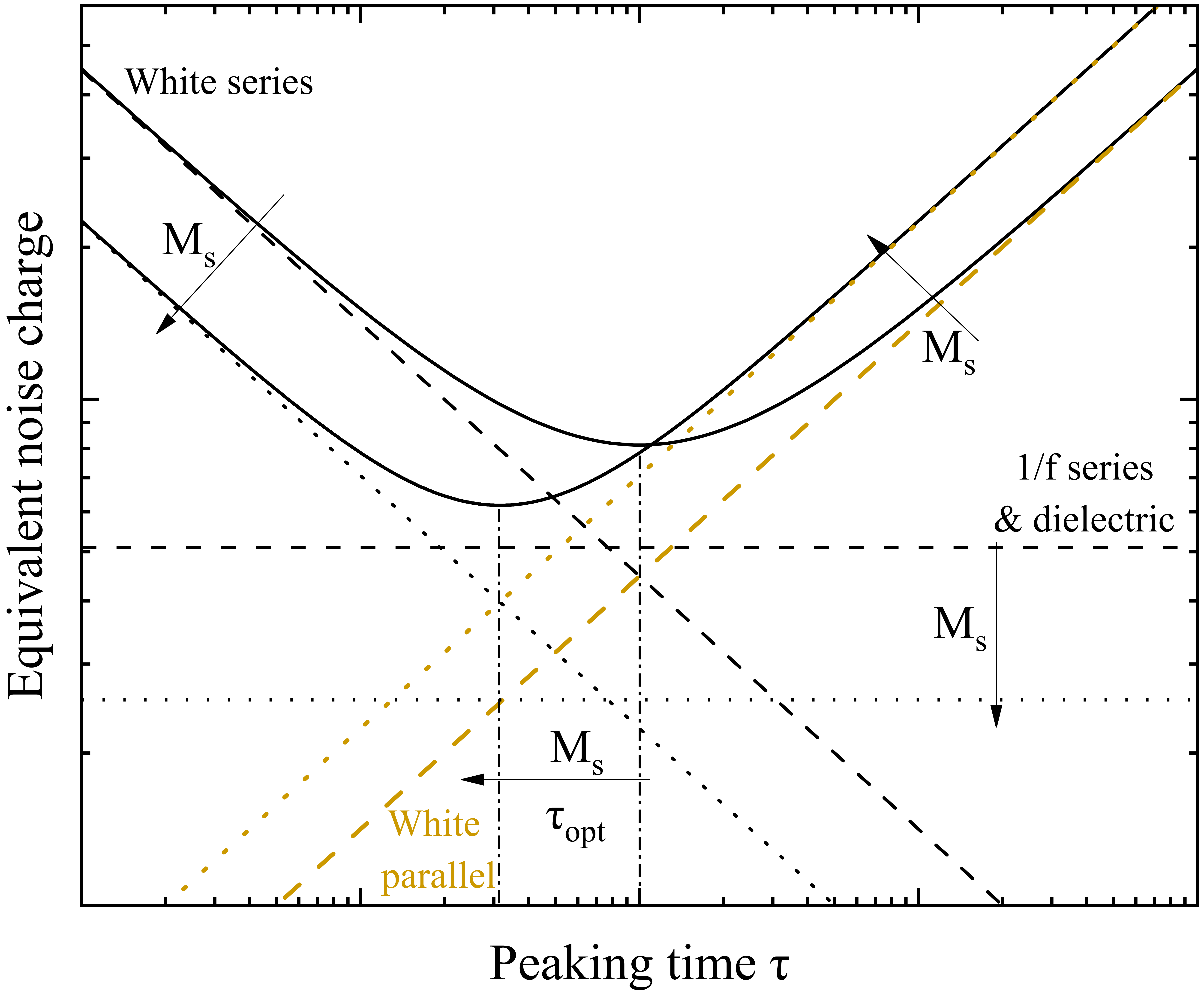
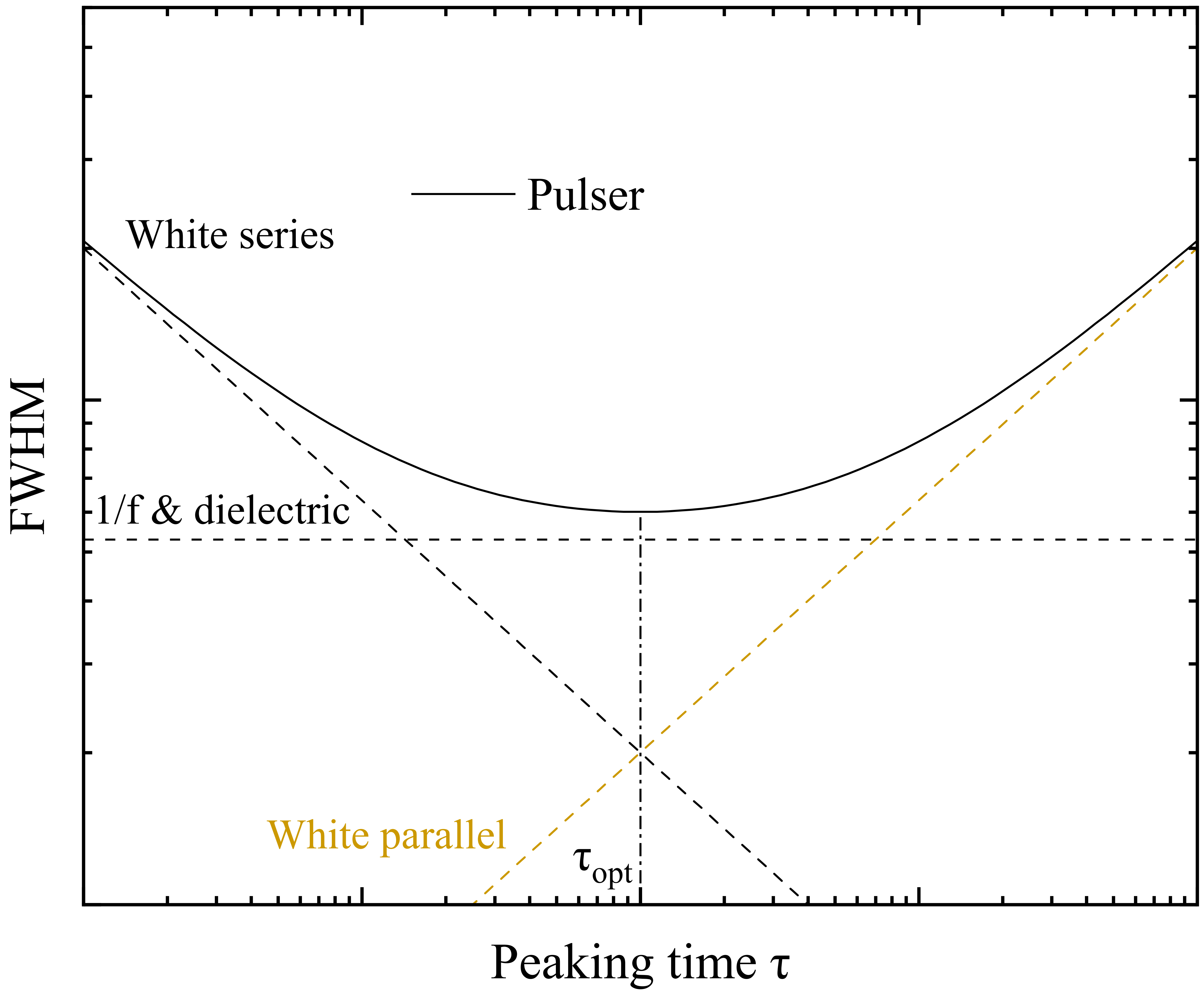


Optimum LGAD gain when operating with discrete preamplifier

$$FWHM_{line,\tau_{opt}} = 2.35\sqrt{EN^2 + \epsilon^2 \frac{B}{M_s^2}}$$



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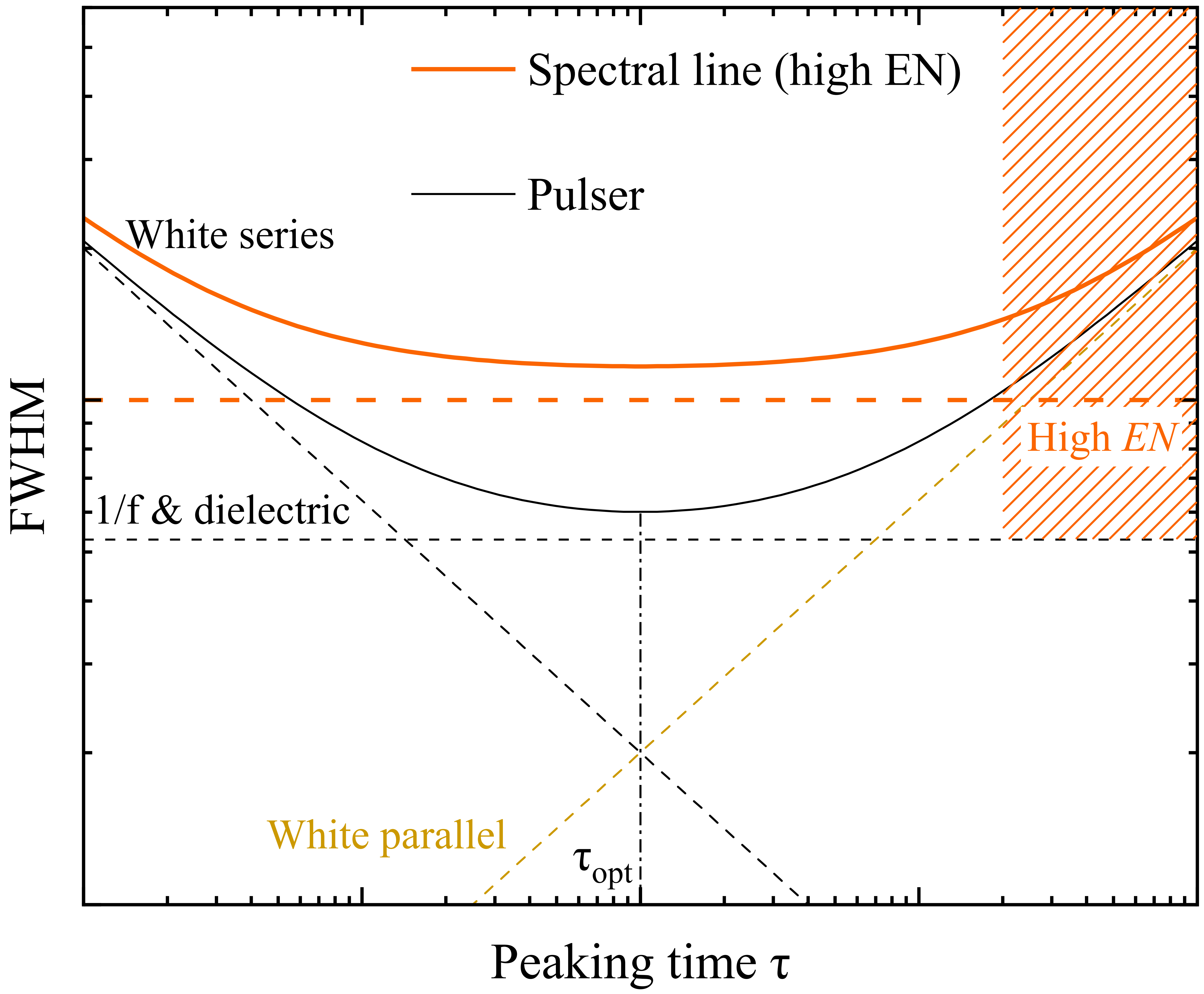

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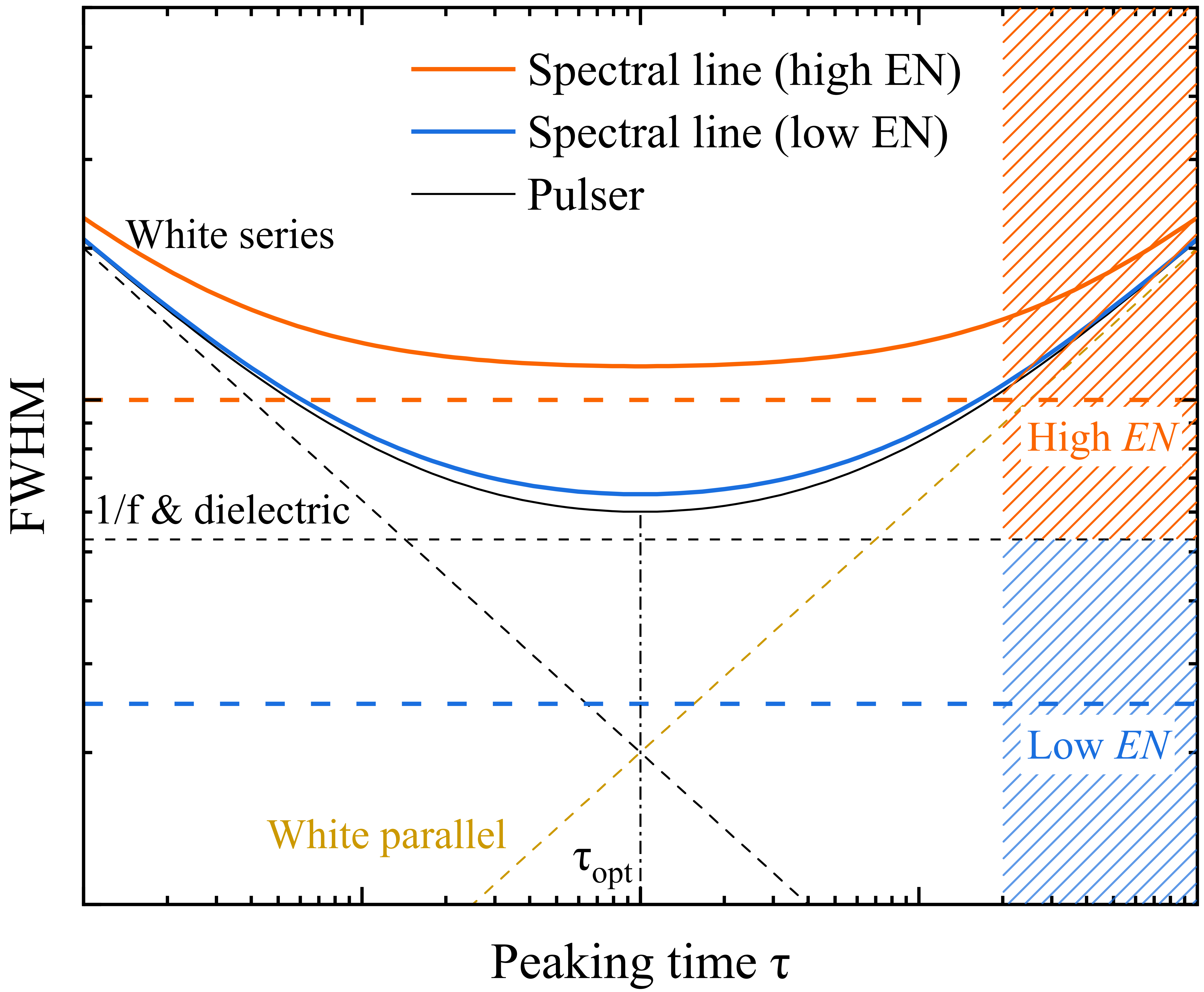

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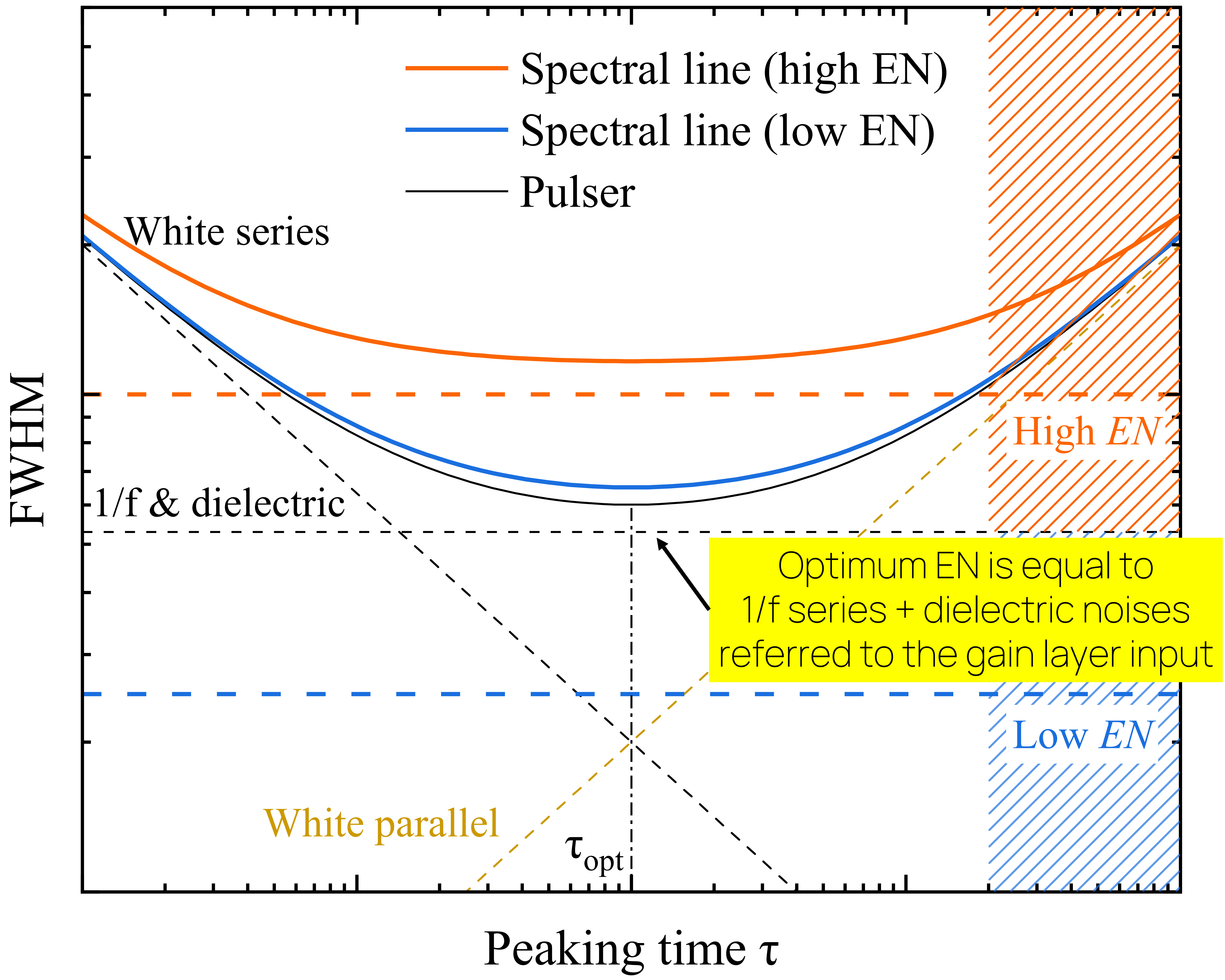
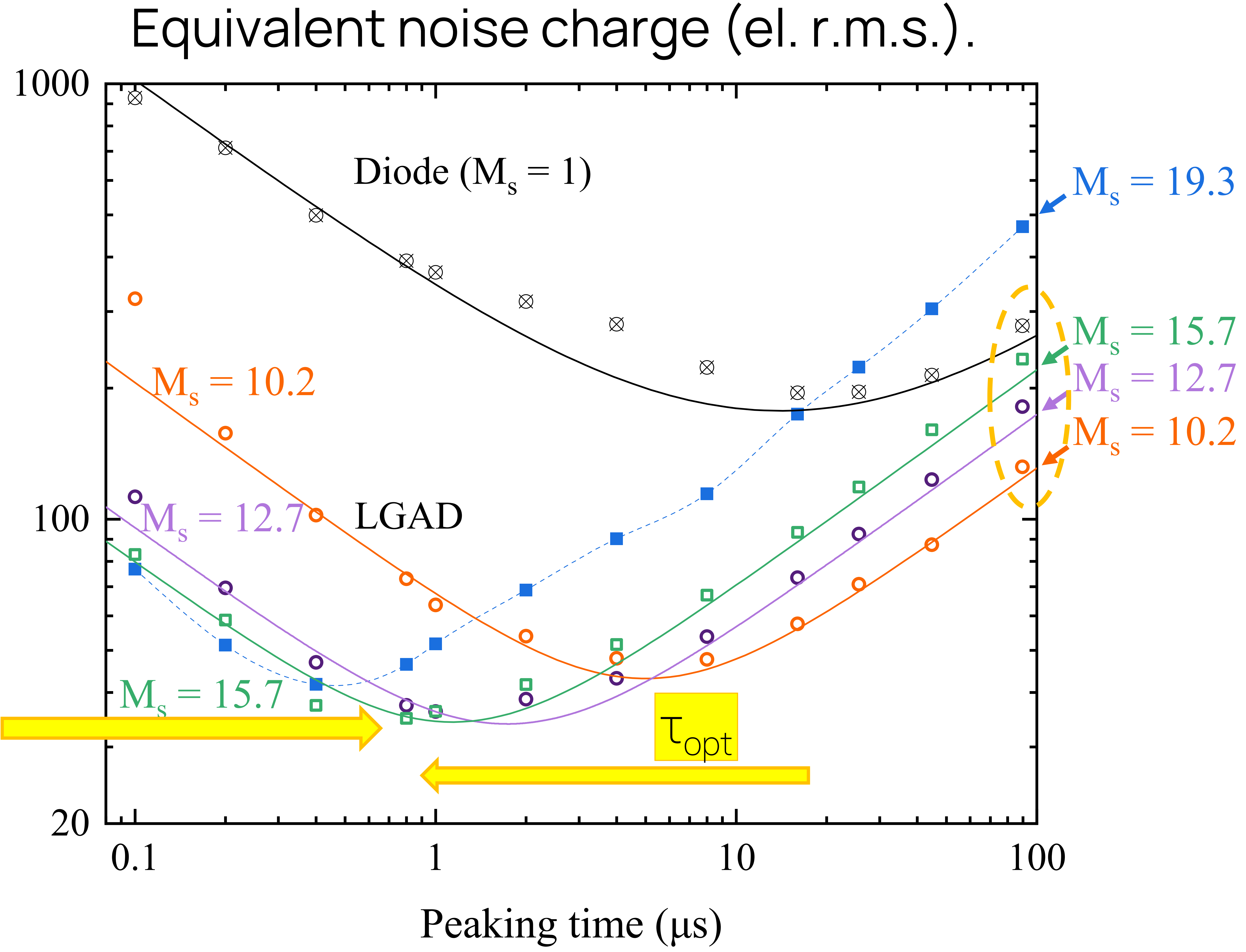


Optimum EN is equal to 1/f series + dielectric noises referred to the gain layer input

ENC of LGAD-based detection system

$$\propto NPSD_w$$

$$ENC_{M_s} = \sqrt{\frac{A}{M_s^2 \tau} + \frac{B}{M_s^2} + \frac{\boxed{C}}{M_s^2}\tau}$$

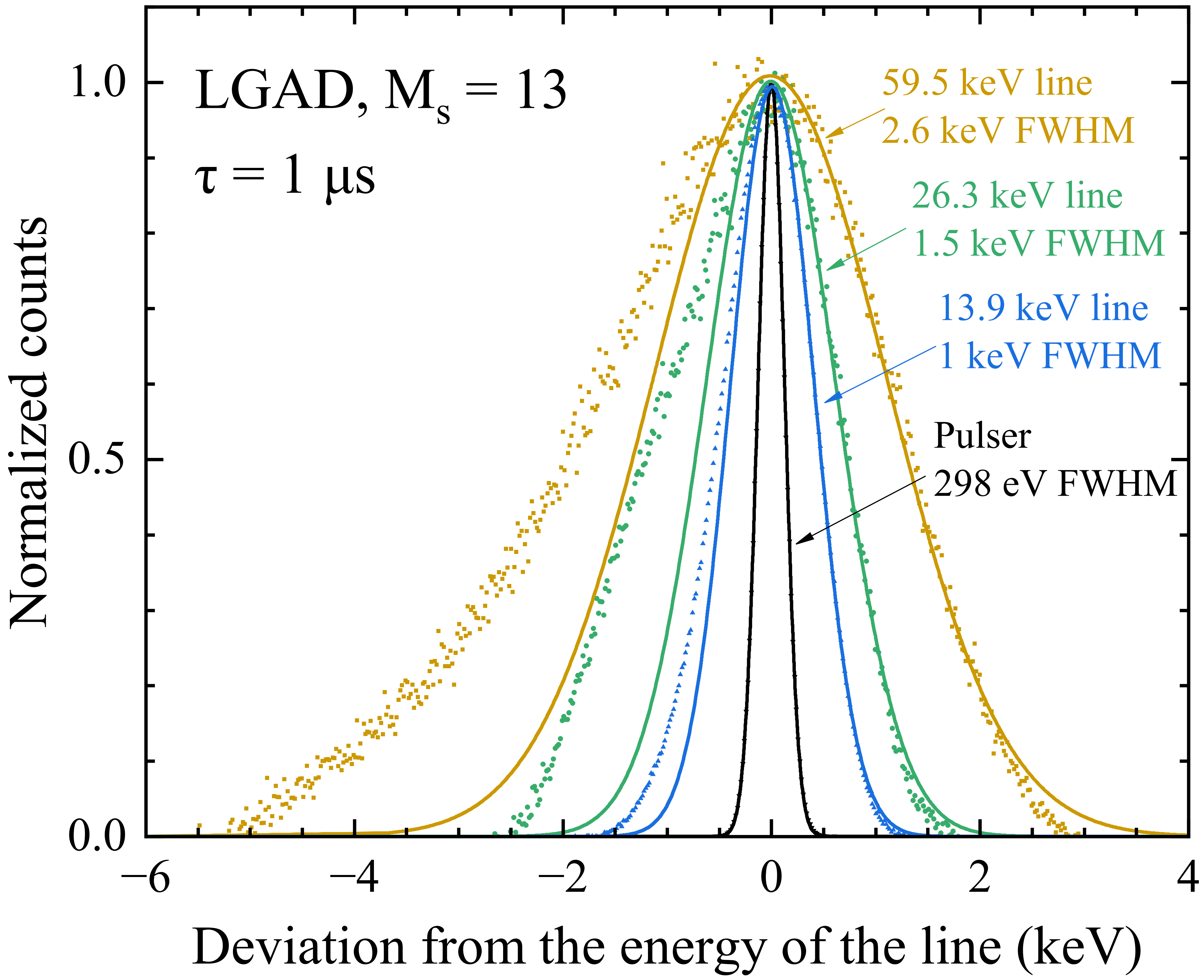


ENC_{opt} ≈ const

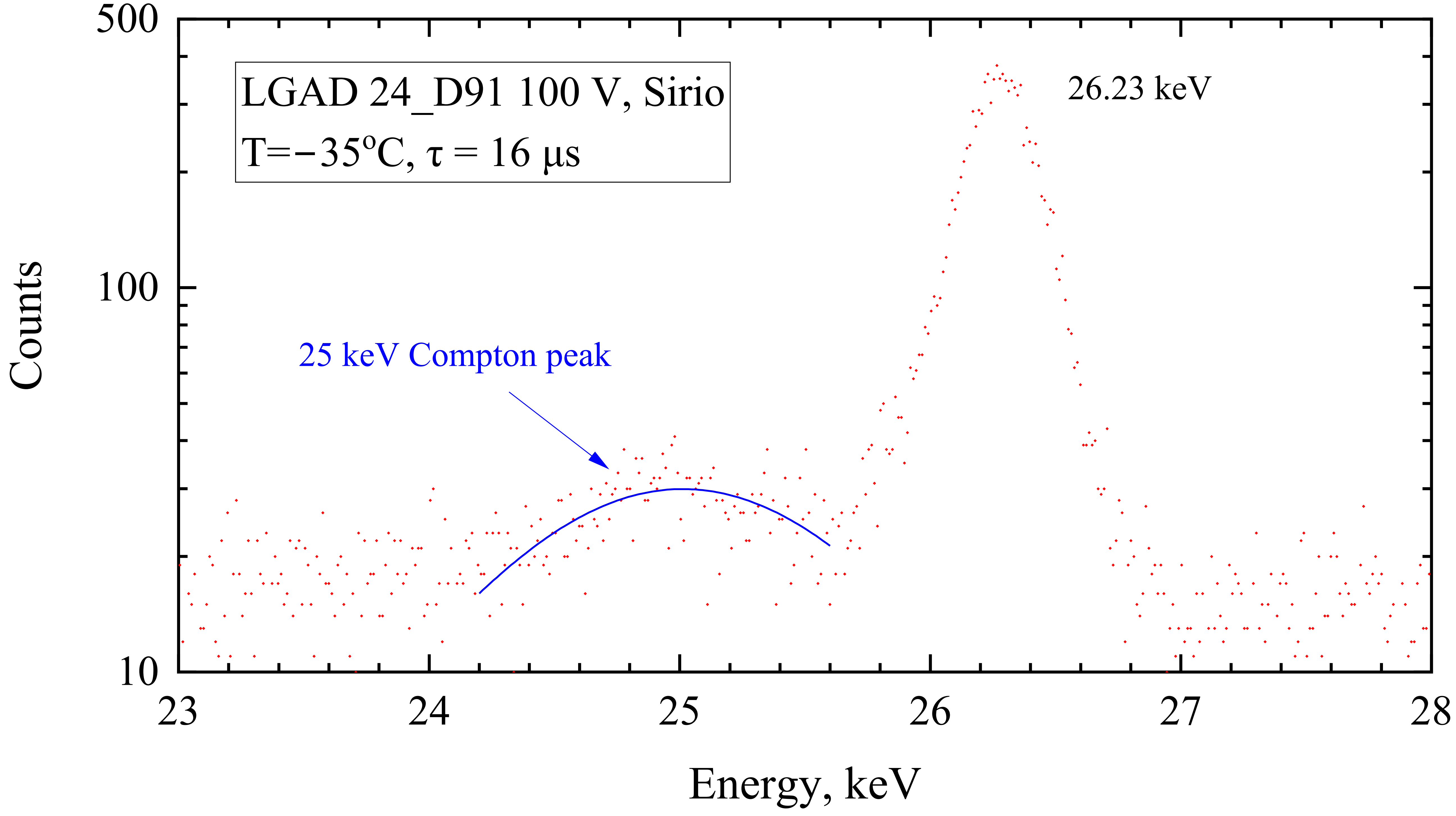
[7] Eremeev, Iurii A., et al. "Performance of an X-γ ray detection system based on a thick silicon LGAD." presented at TREDI2025 conference 4-6 Feb. 2025, Trento, Italy.

Gaussian fit of the Am spectral lines measured with LGAD

- Discrete CSA, temperature T=+20°C



- Compton peak at 25 keV measured with Diode+ Sirio due to 90° photon scattering in plastic backing [16]



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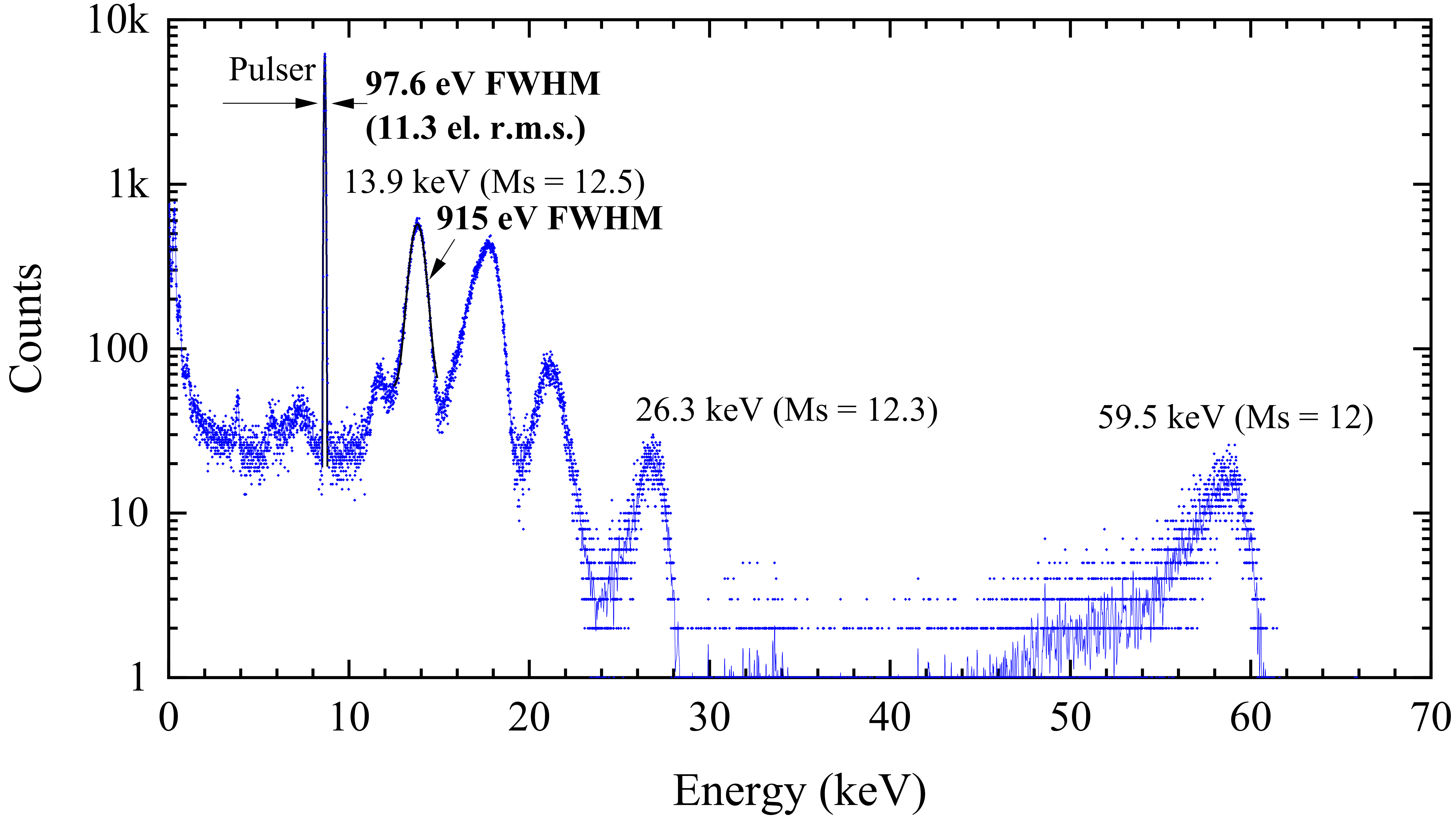
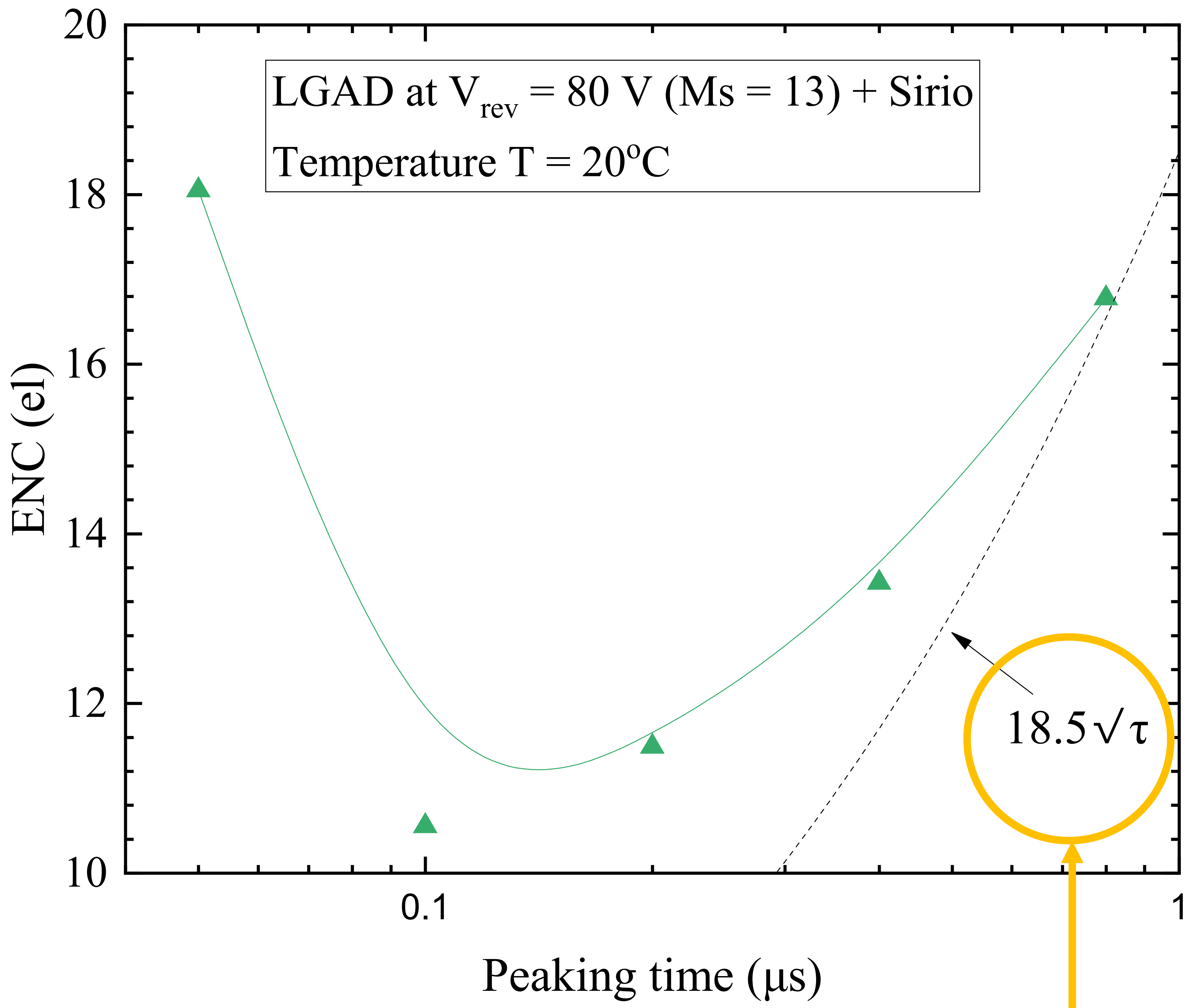
[16] Cohen, David D. "X-rays from an 241Am source and their relative intensities." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 267.2-3 (1988): 492-498.

Spectroscopic performance of high-gain LGAD + Sirio

^{241}Am spectrum acquired at the temperature T = 20°C and the peaking time τ = 0.1 us





Measured with Discrete CSA