Measuring Hotspot Size in SNSPDs

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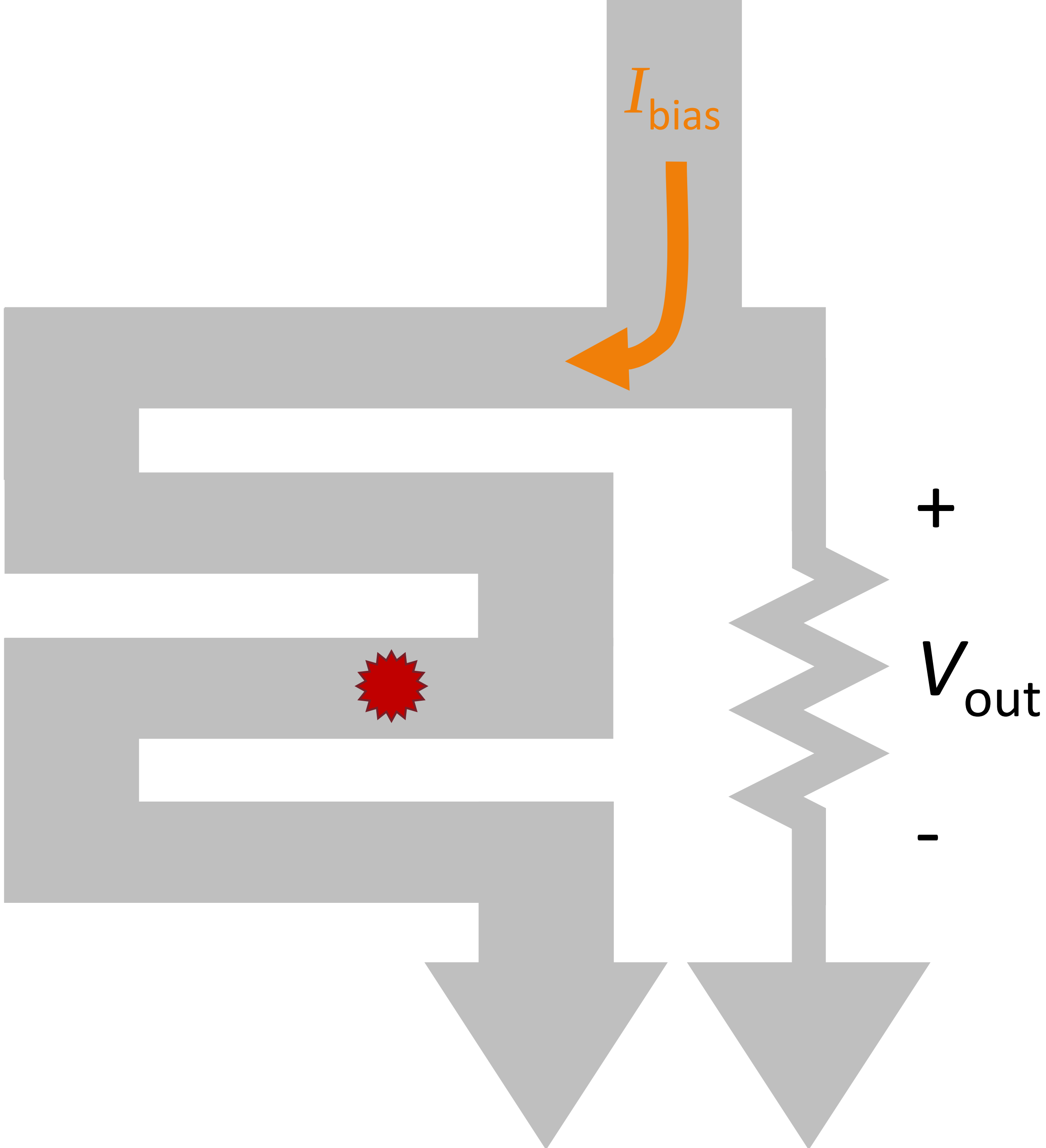
NIST
National Institute of Standards and Technology

JPL
Jet Propulsion Laboratory
California Institute of Technology

Lancaster University



1 photon absorbed:
Superconductivity suppressed
→ “Hotspot” formed

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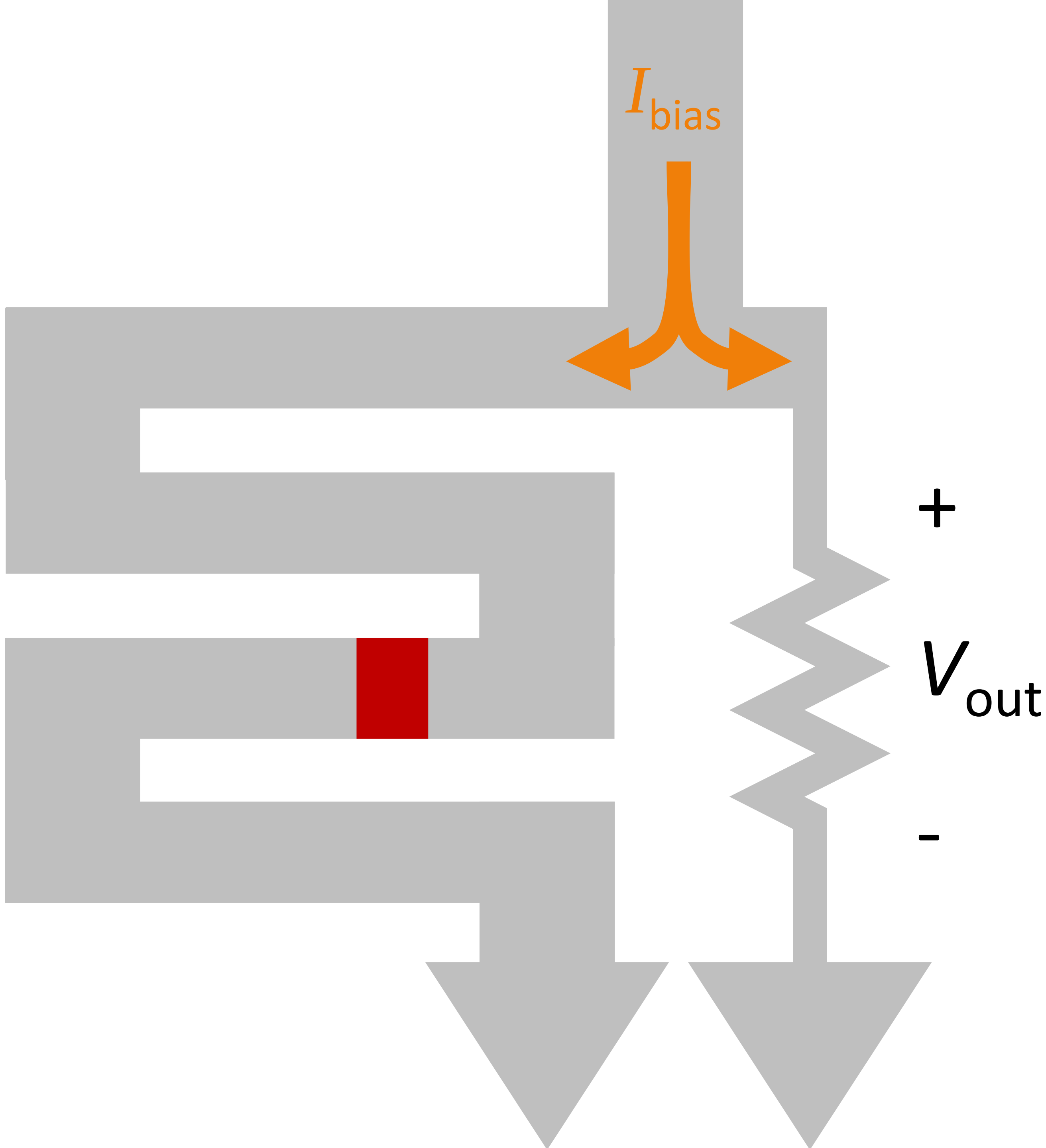

1 photon absorbed:
Superconductivity suppressed
→ “Hotspot” formed

When $I_{bias} \approx I_{crit}$, detector clicks

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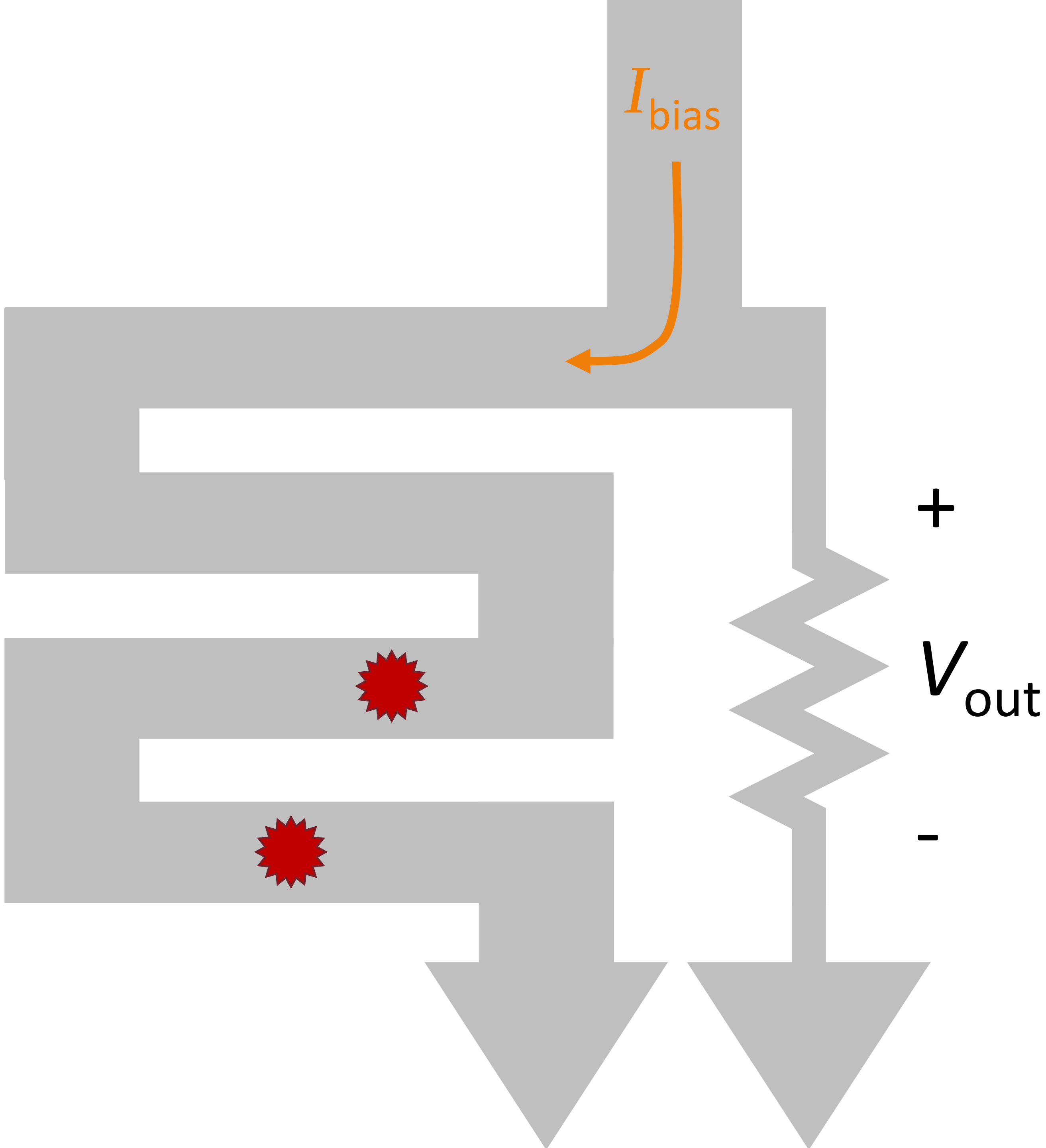

1 photon absorbed:
Superconductivity suppressed
→ “Hotspot” formed

When $I_{bias} << I_{crit}$, no click
→ 2 photons required

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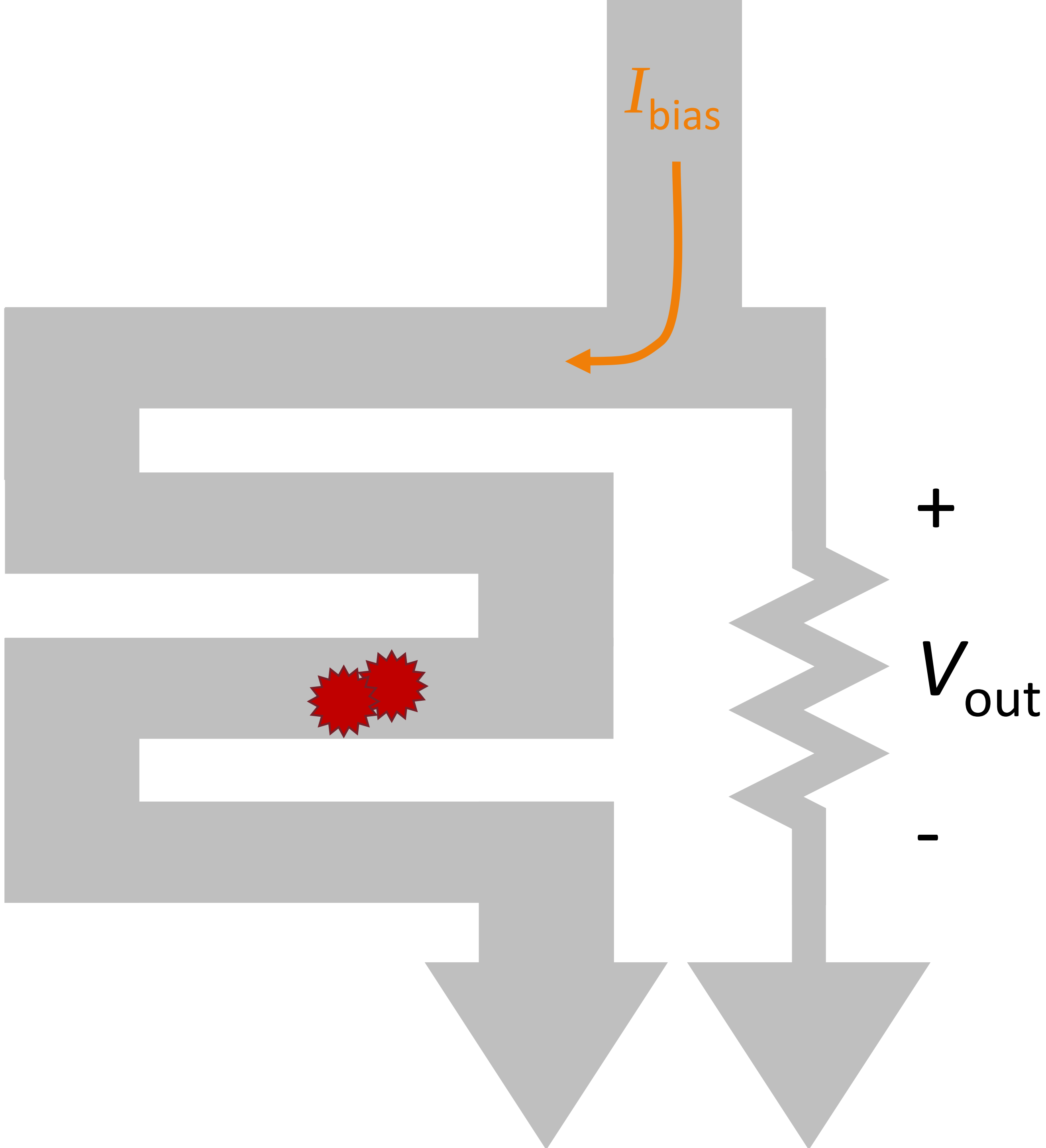

1 photon absorbed:
Superconductivity suppressed
→ "Hotspot" formed

When $I_{\text{bias}} \ll I_{\text{crit}}$, no click
→ 2 photons required
& hotspots must "overlap"

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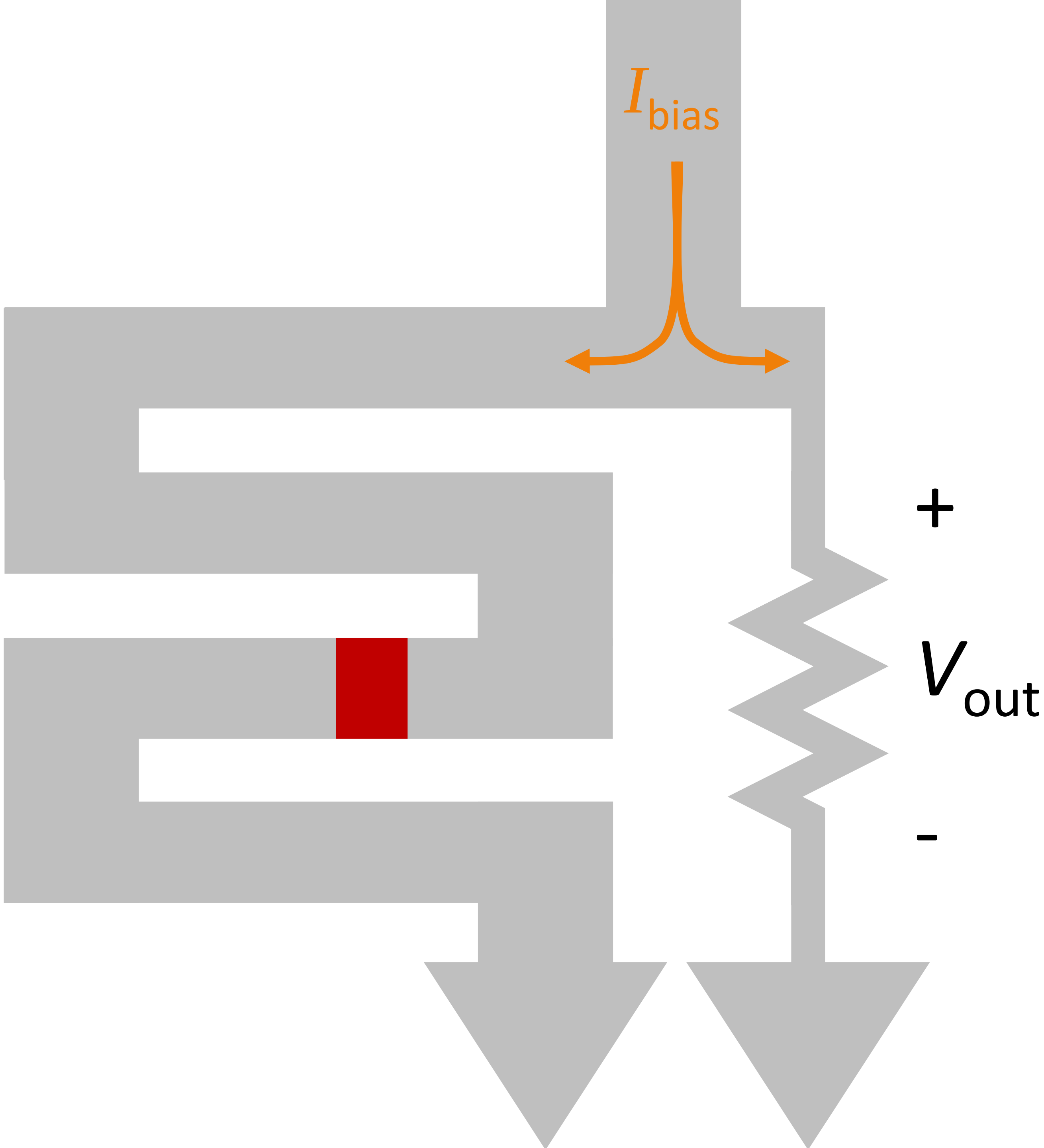

1 photon absorbed:
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When $I_{bias} << I_{crit}$, no click
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& hotspots must “overlap”

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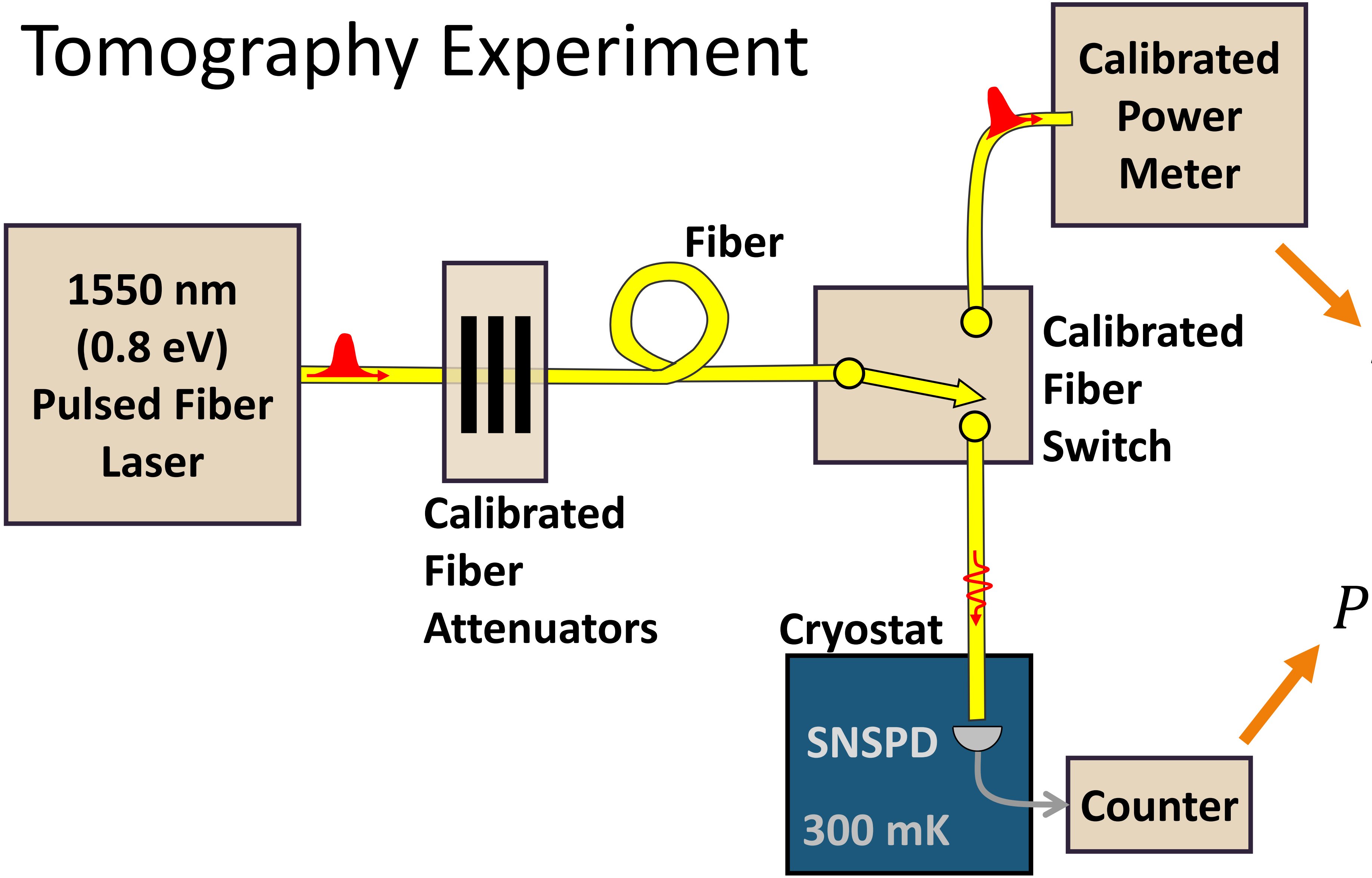
Tomography Experiment



$$\mu = \frac{\text{Photons/s}}{\text{Pulses/s}}$$

$$P_{\text{click}} = \frac{\text{Counts/s}}{\text{Pulses/s}}$$

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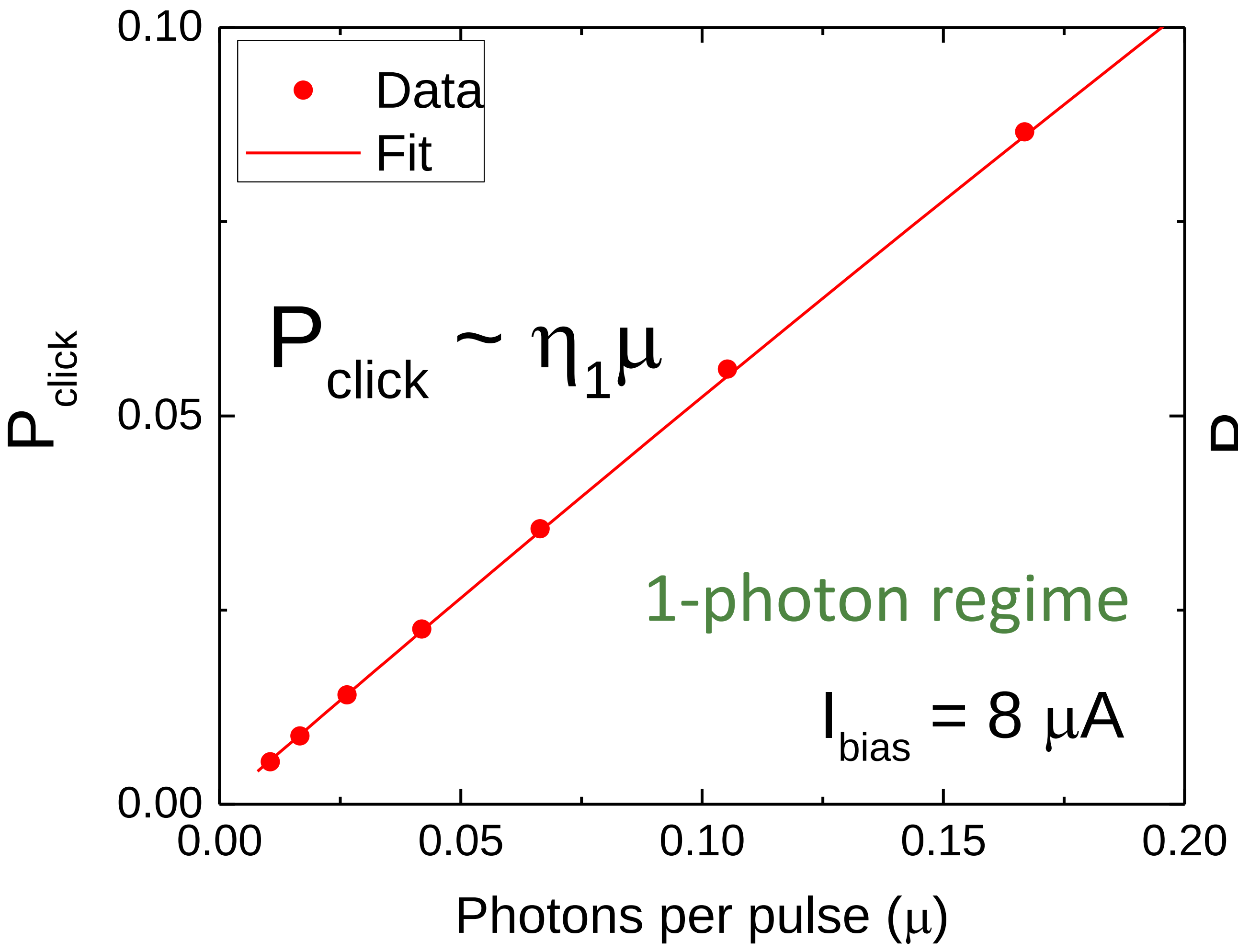
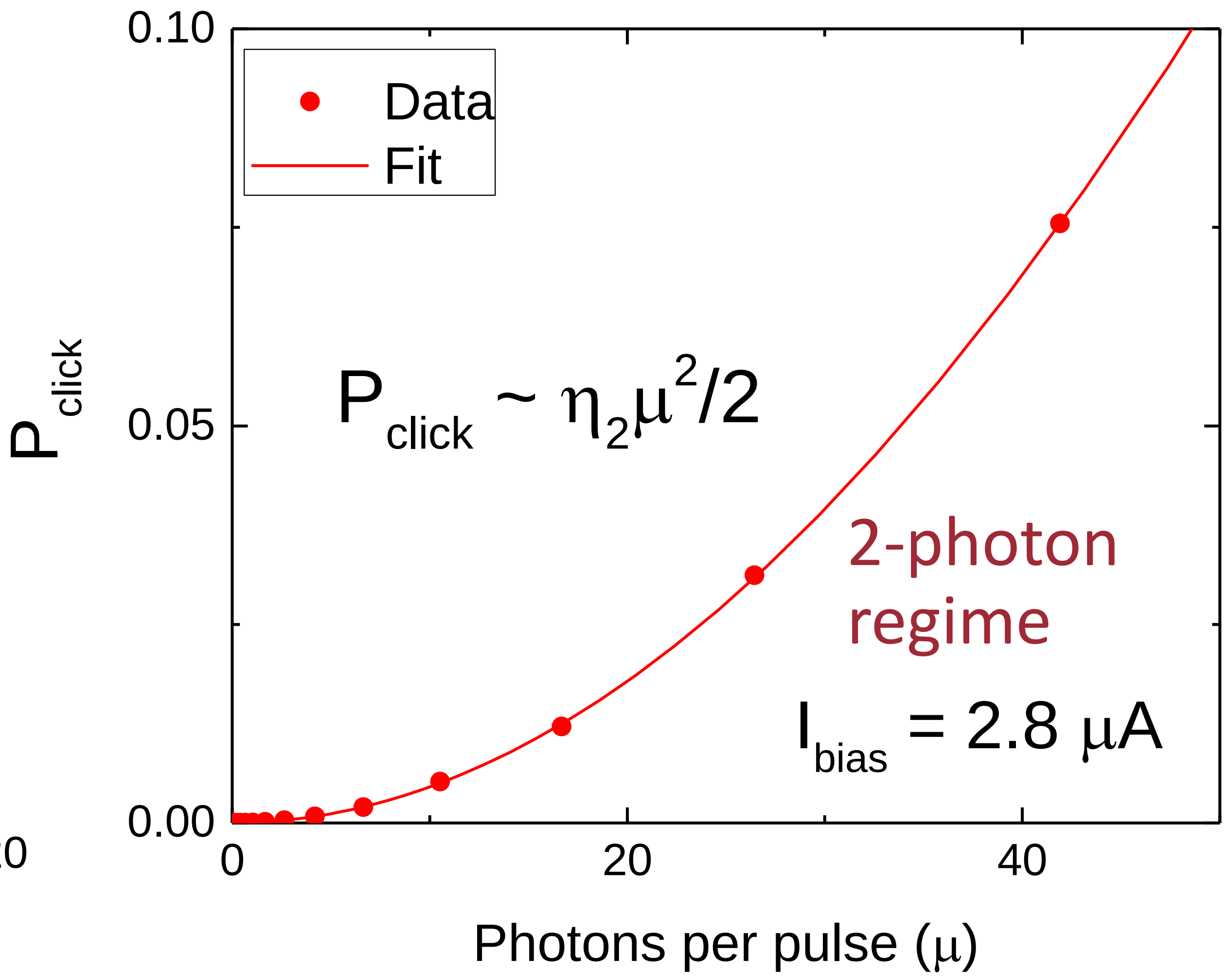
At each I_{bias}, fit P_{click} vs. μ data to extract η_1 & η_2





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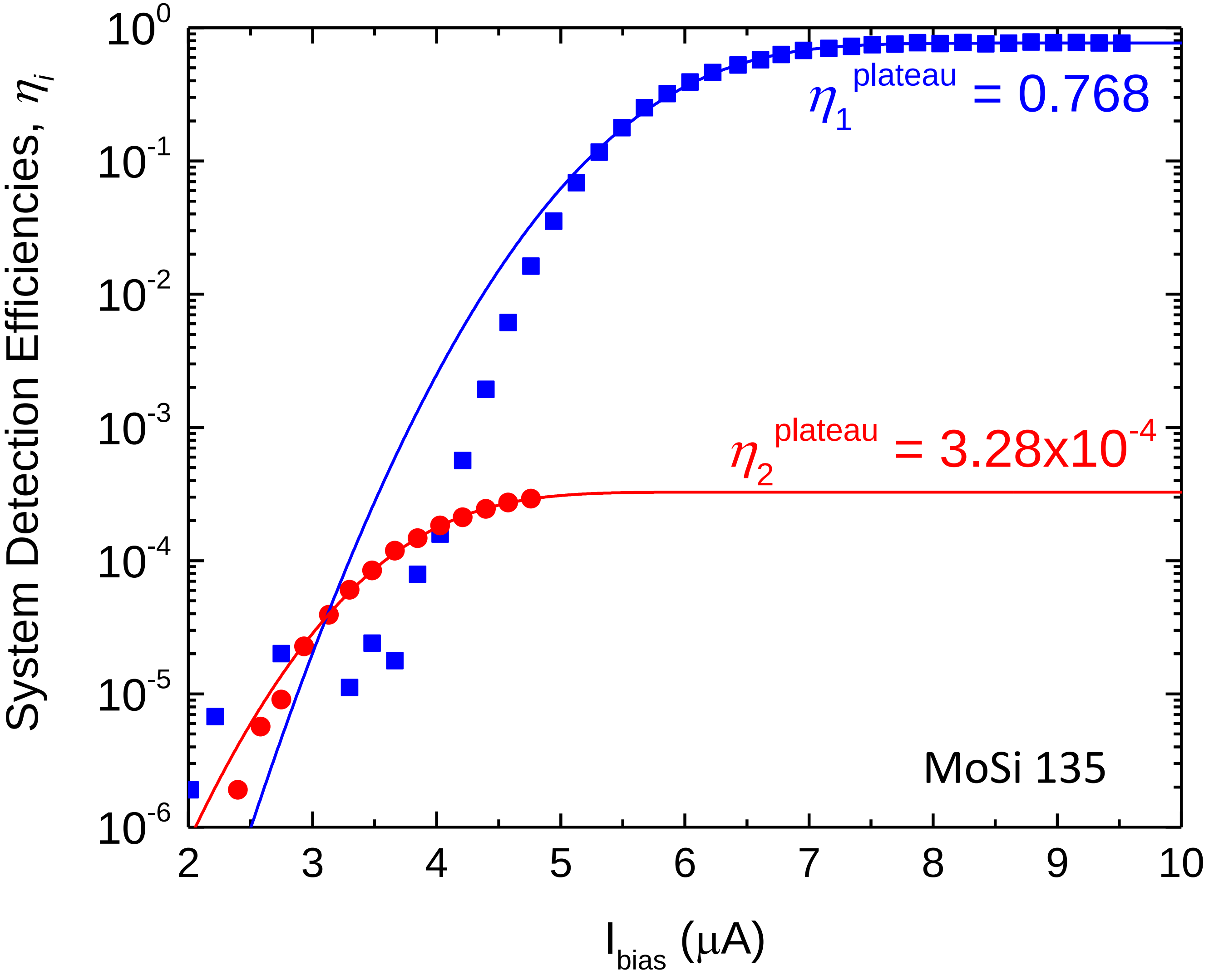


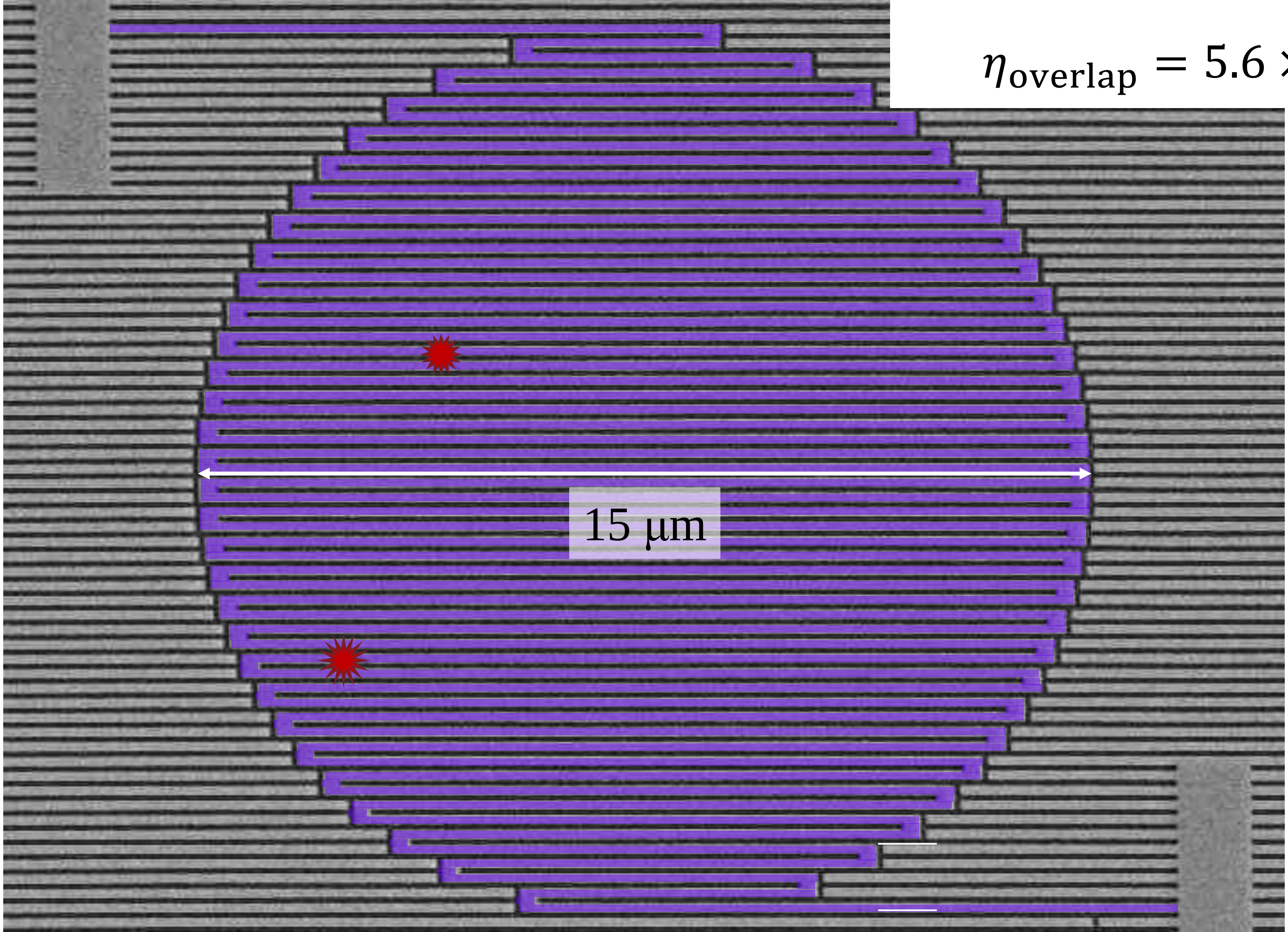
$$\eta_{\text{overlap}} = \frac{\eta_2^{\text{plateau}}}{\left(\eta_1^{\text{plateau}}\right)^2}$$

$$\eta_{\text{overlap}} = 5.6 \times 10^{-4}$$

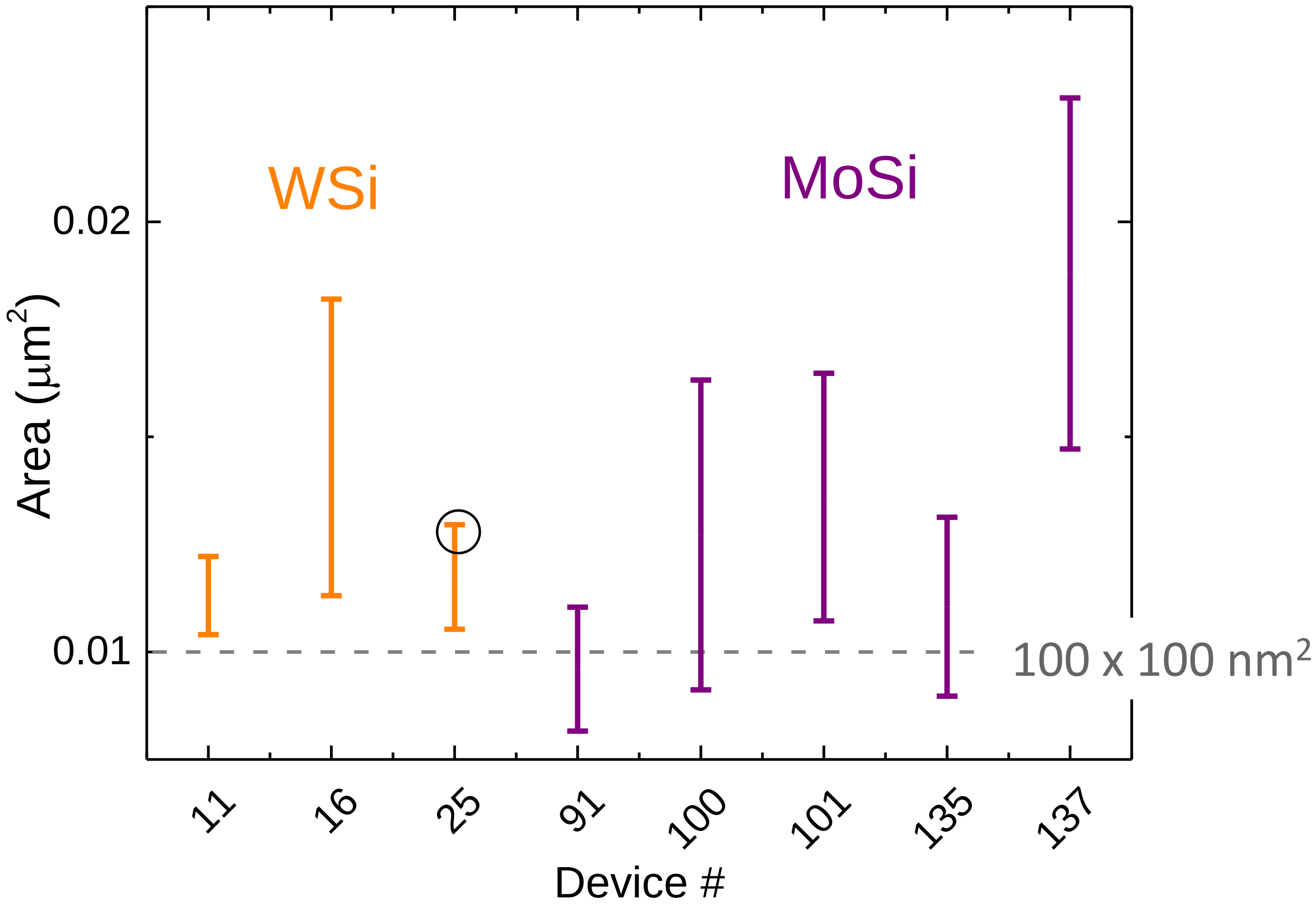
$$\eta_1(I_{bias}) = \eta_{couple} \times \eta_{absorb} \times \eta_{QE1}(I_{\text{bias}})$$

$$\eta_2(I_{bias}) = \left(\eta_{couple} \times \eta_{absorb}\right)^2 \times \eta_{\text{overlap}} \times \eta_{QE2}(I_{bias})$$

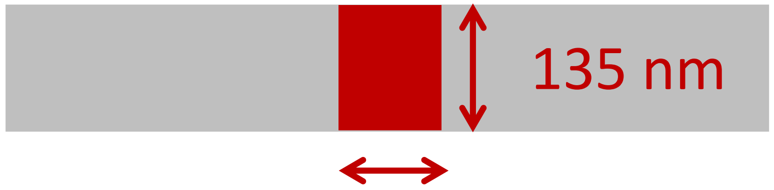
$\eta_{overlap} = 5.6 \times 10^{-4}$



Detector Tomography as a Probe of Hotspot Size in SNSPDs



In WSi & MoSi, 1 photon at 1550 nm generates a "hotspot" -- a region of suppressed (not broken) superconductivity approximately as wide as the wire



l_{HS} = 96 nm

Poster G1.41, Tuesday

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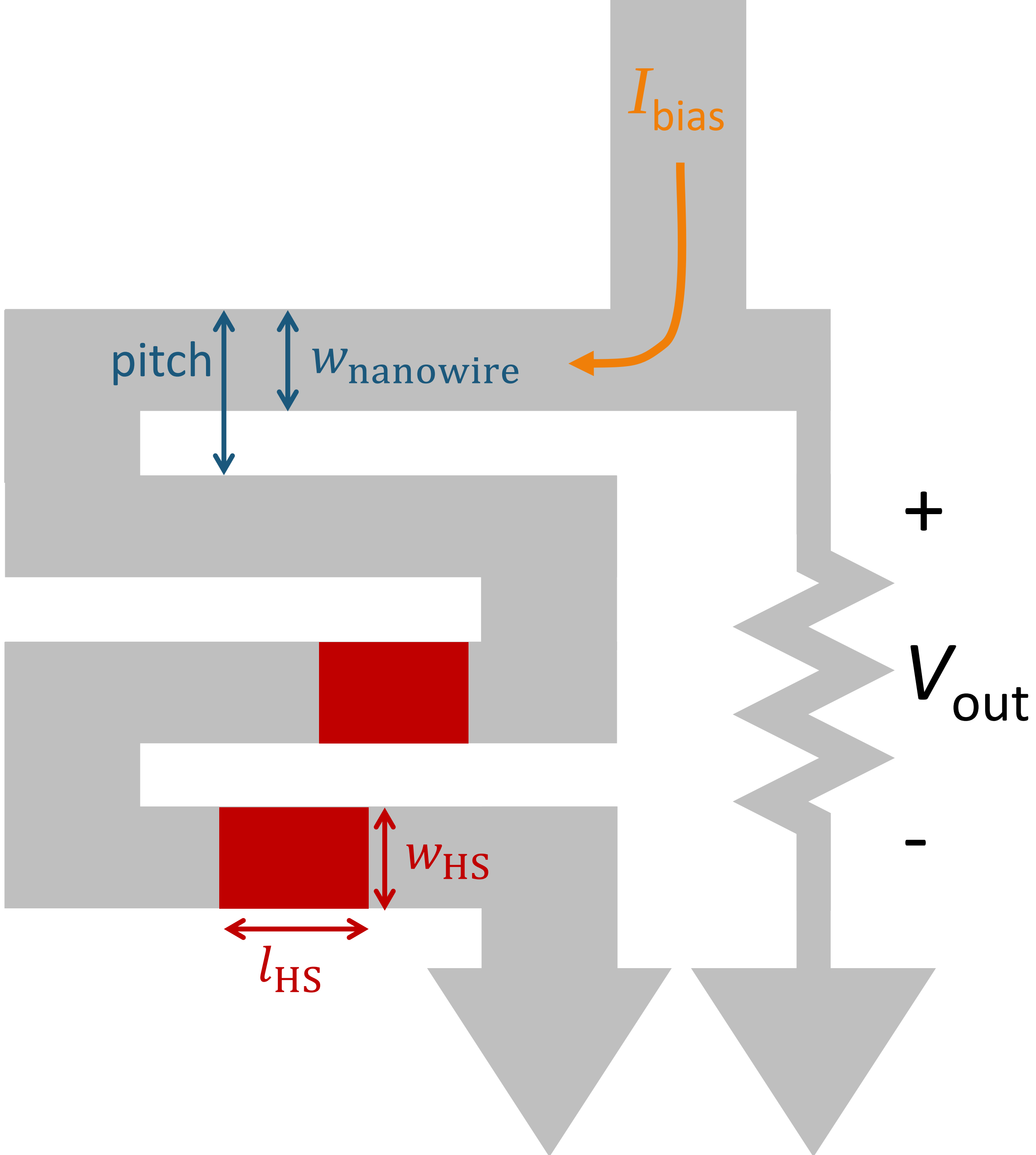


Model

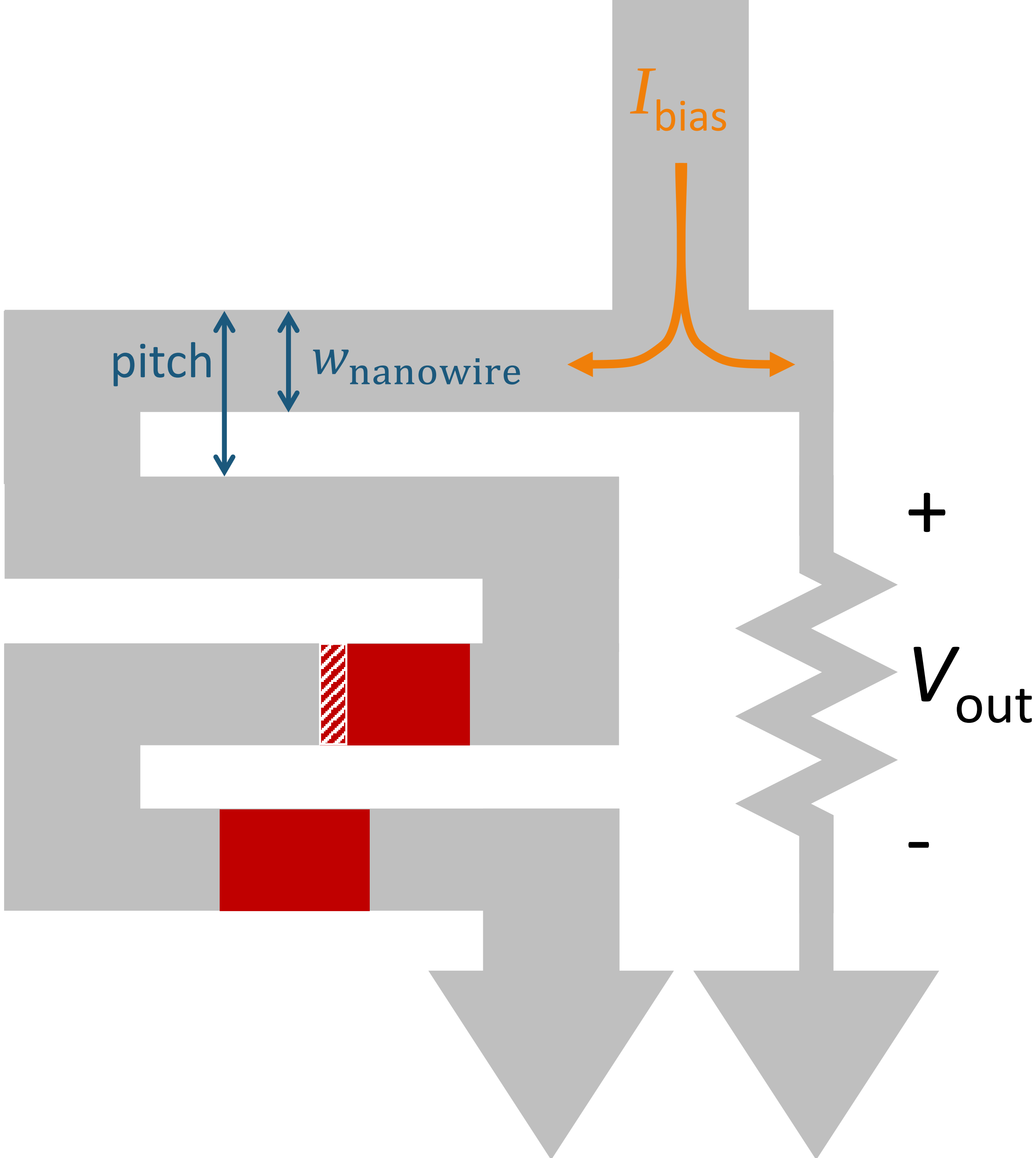
1. Treat “hotspot” as a rectangle of suppressed (not broken) superconductivity

2. Assume

$$w_{\text{HS}} = w_{\text{nanowire}}$$
$$l_{\text{HS}} = ?$$

3. Do hotspots overlap?

- no → no click
- yes → click



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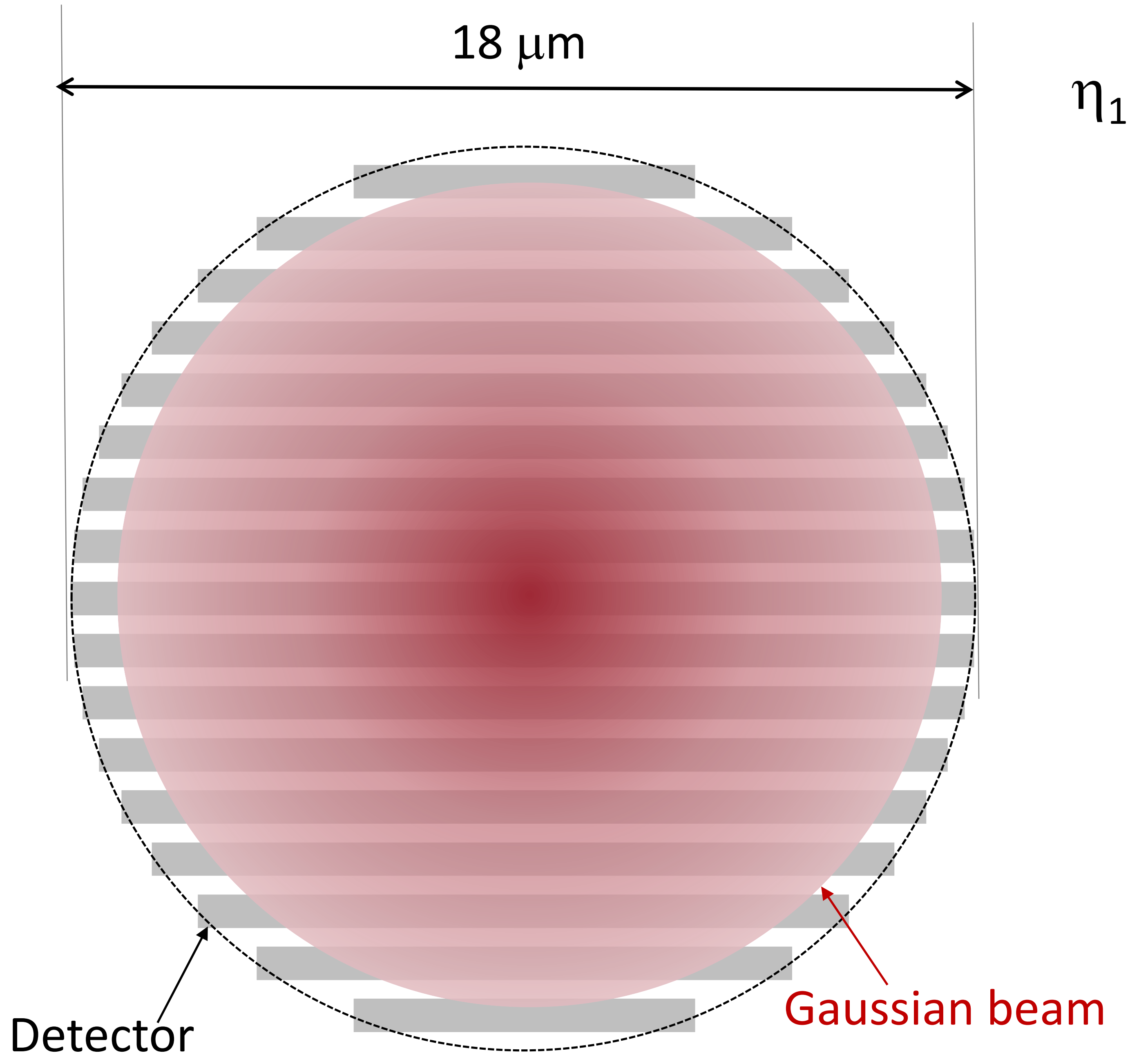
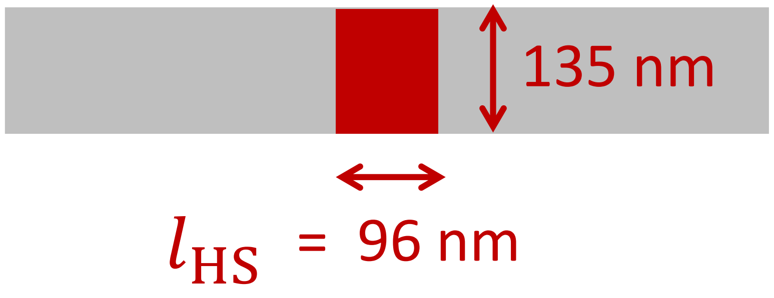
$\eta_1^{plateau} = 0.88$. $\eta_{overlap} = 9 \times 10^{-4}$



Upper limit:
Perfect alignment



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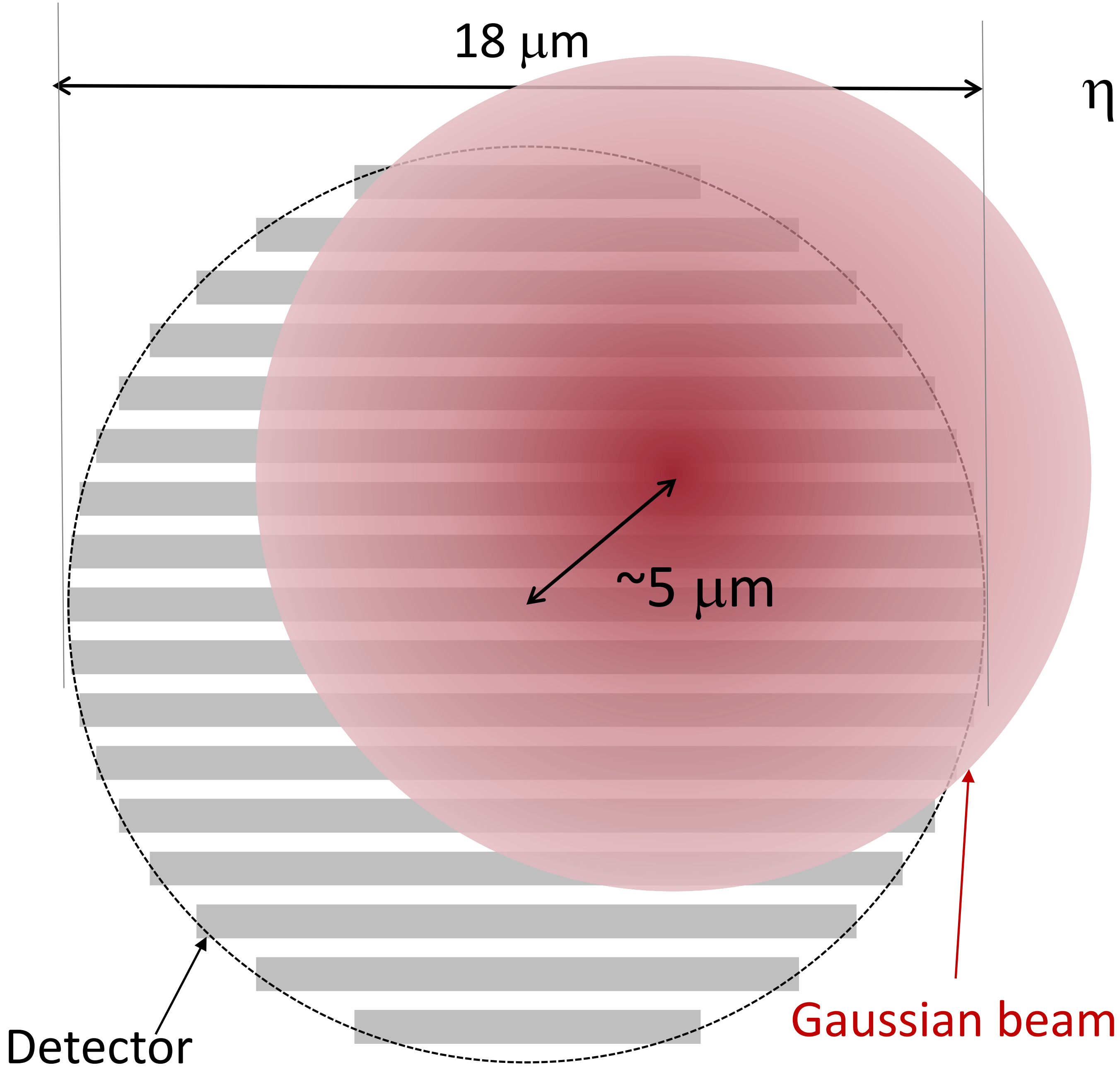

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Upper limit:
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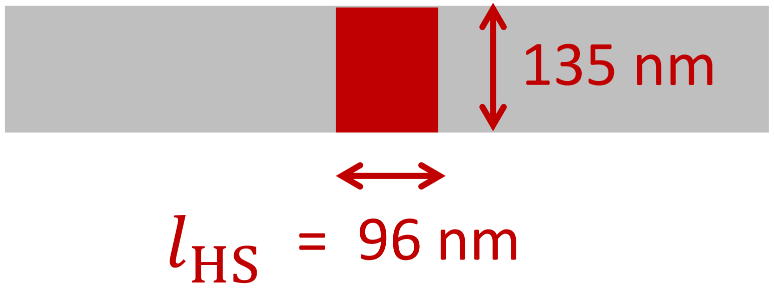
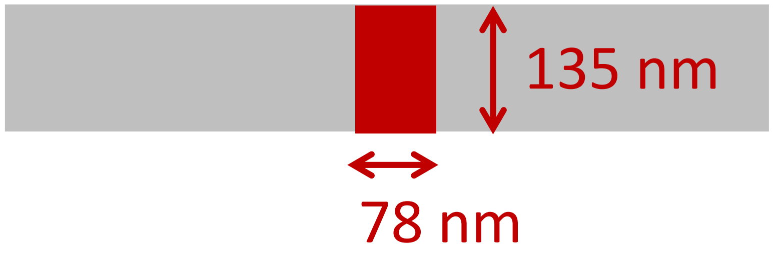


Lower limit:
Worst-case alignment



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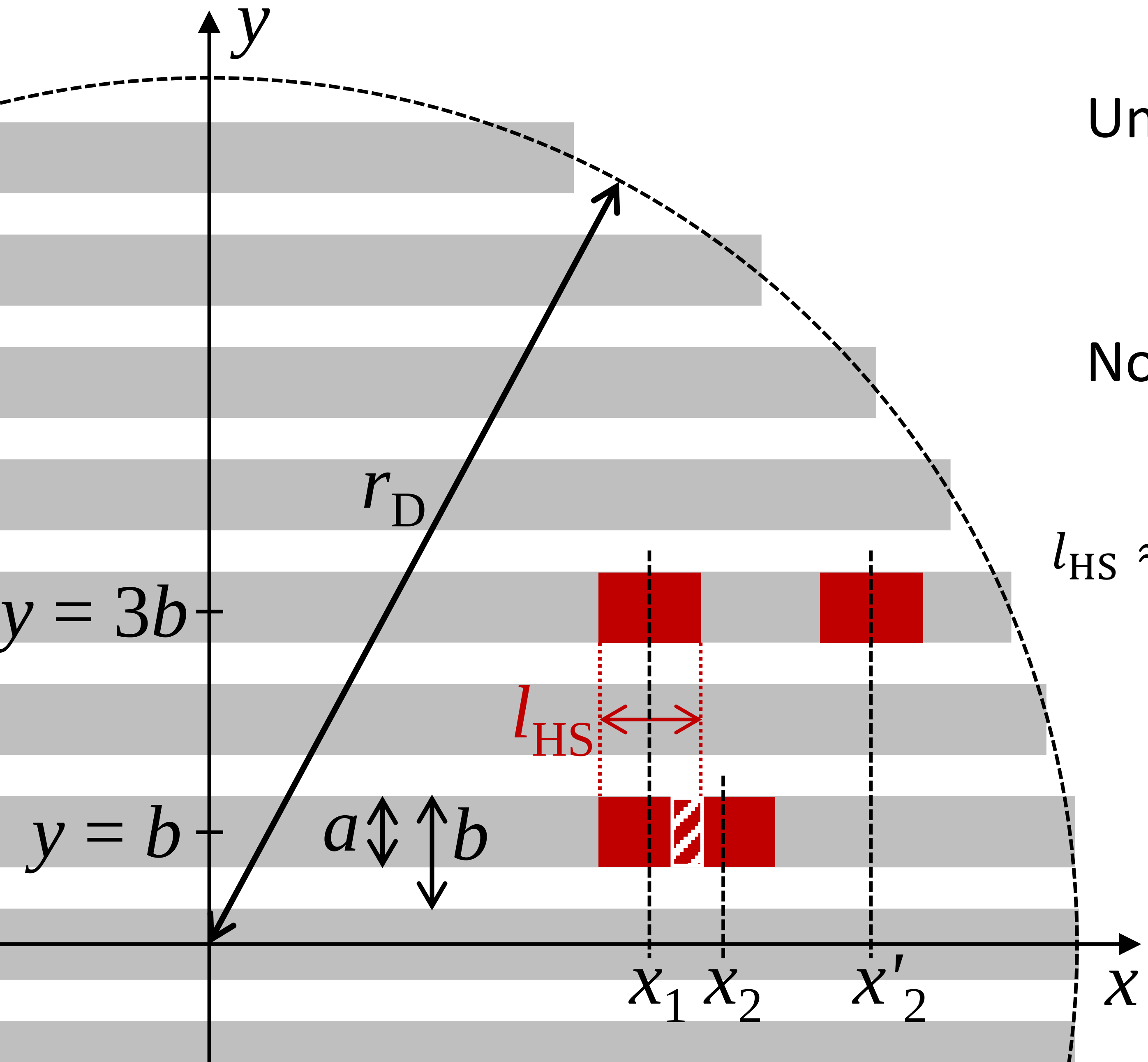
Model SNSPD as series of wires



Uniform illumination:

$$l_{HS} = \eta_{overlap} \sum l_n$$

Non-uniform illumination:

$$l_{HS} \approx \frac{\eta_2^{plateau}}{2\left(\eta_1^{plateau}\right)^2} \frac{\left[\sum_{n=-N}^{N} \int_{-l_n/2}^{l_n/2} \mathcal{E}(x, nb)dx\right]^2}{\sum_{n=-N}^{N} \int_{-l_n/2}^{l_n/2} [\mathcal{E}(x, nb)]^2 dx}$$

Electric field amplitude

→ l_{HS} depends on alignment

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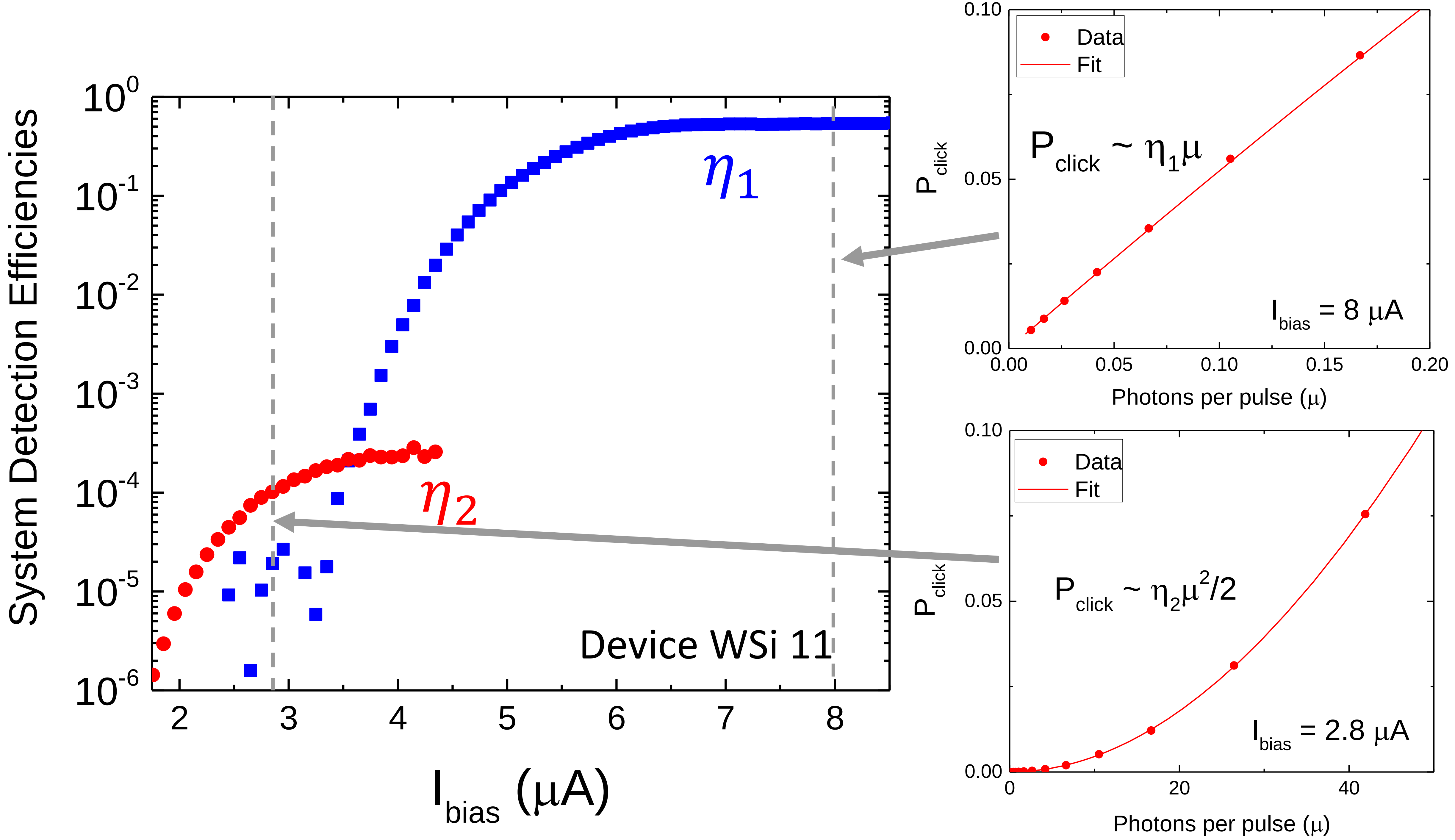

System Detection Efficiencies
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
3
4
5
6
7
8
I_{bias} (μA)
η_1
η_2
Device WSi 11
P_{click}
Data
Fit
$P_{click} \sim \eta_1 \mu$
I_{bias} = 8 μA
0.00
0.05
0.10
0.15
0.20
Photons per pulse (μ)
P_{click}
Data
Fit
$P_{click} \sim \eta_2 \mu^2/2$
I_{bias} = 2.8 μA
0.00
0.05
0.10
0
20
40
Photons per pulse (μ)

Nonlinearity in single photon detection: modeling and quantum tomography

Mohsen K. Akhlaghi,[1,*] A. Hamed Majedi,[1,2] and Jeff S. Lundeen[3]

2011 / Vol. 19, No. 22 / OPTICS EXPRESS 21305

"Standard" tomography:

e.g., Feito *et al.*, NJP **11**, 093038 (2009)

$$P_{\text{click}}(\mu) = 1 - e^{-\mu}\sum_{n=0}^{\infty}\frac{\mu^n}{n!}(1-\eta_1)^n(1-\eta_2)^{n(n-1)/2}$$

1- & 2-photon detection efficiencies

$$P_{\text{click}}(\mu) = 1 - e^{-\mu}\sum_{n=0}^{\infty}\frac{\mu^n}{n!}\left(1-p_{\text{click}|n}\right)$$

Probability of a click if n photons incident

(Considering only 1- & 2-photon processes)

$$p_{click|1} = \eta_1$$

$p_{click|2}$ includes η_1 & η_2 contributions

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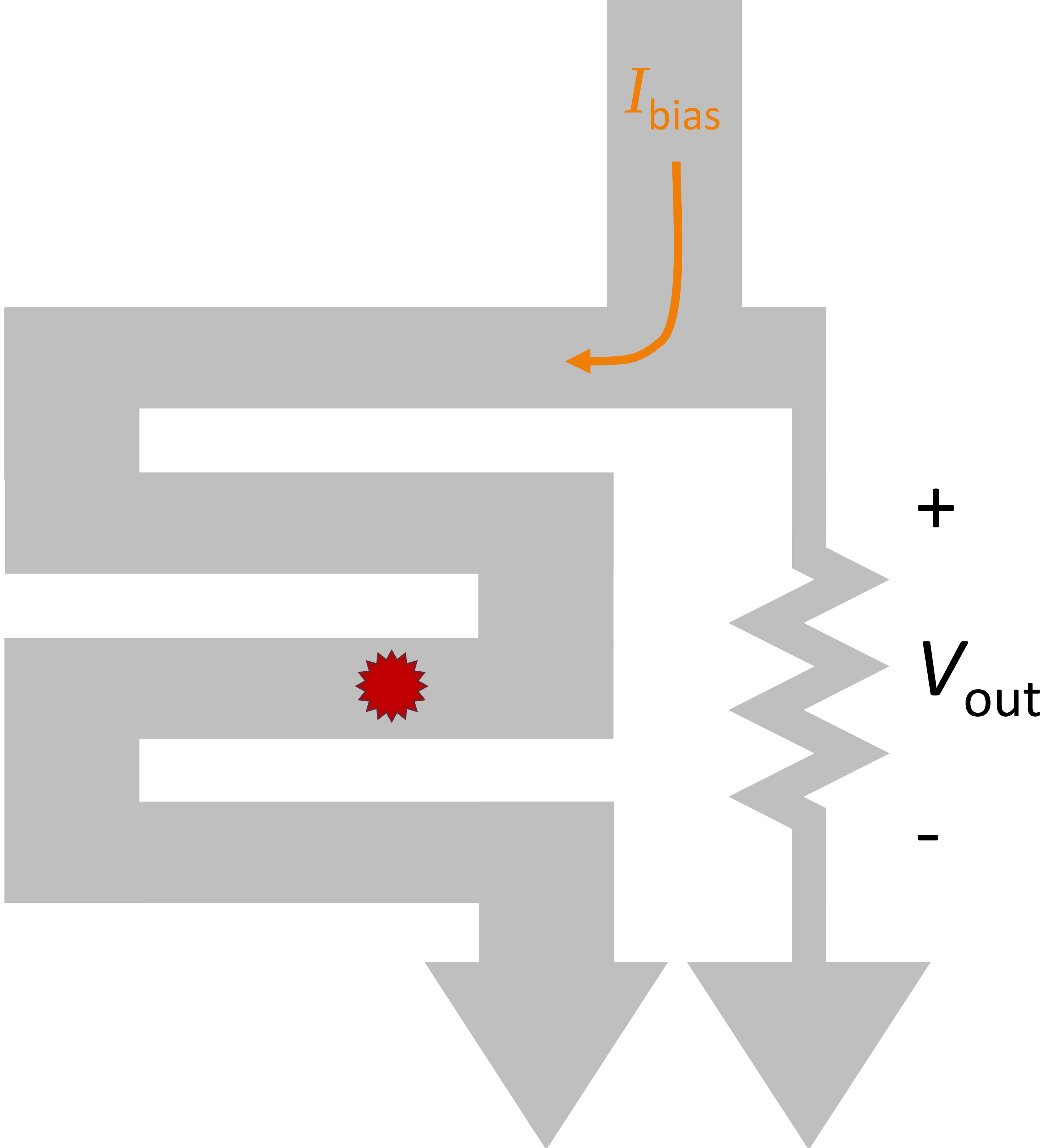

1 photon absorbed:
Superconductivity suppressed
→ "Hotspot" formed

When $I_{bias} << I_{crit}$, no click
→ 2 photons required

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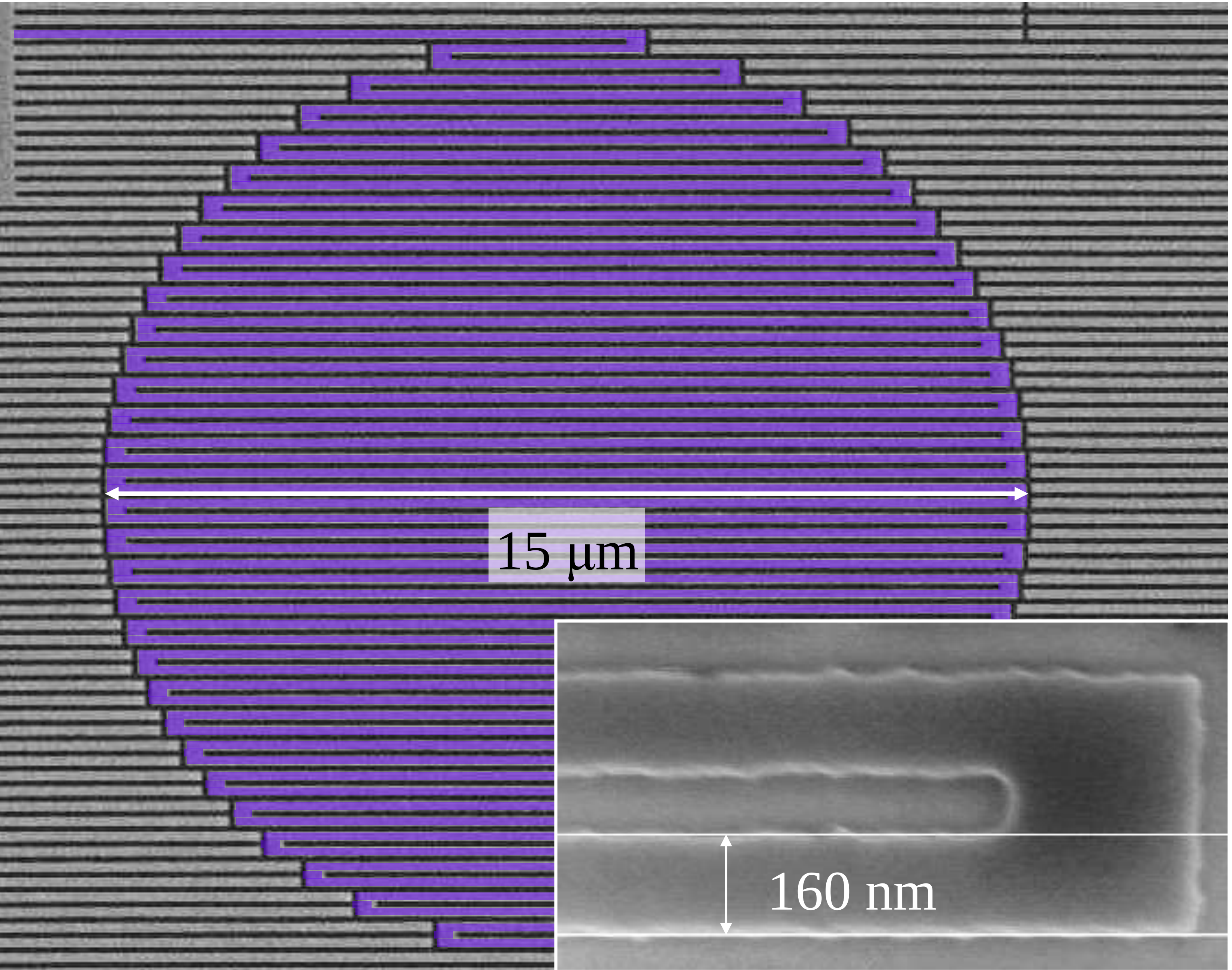
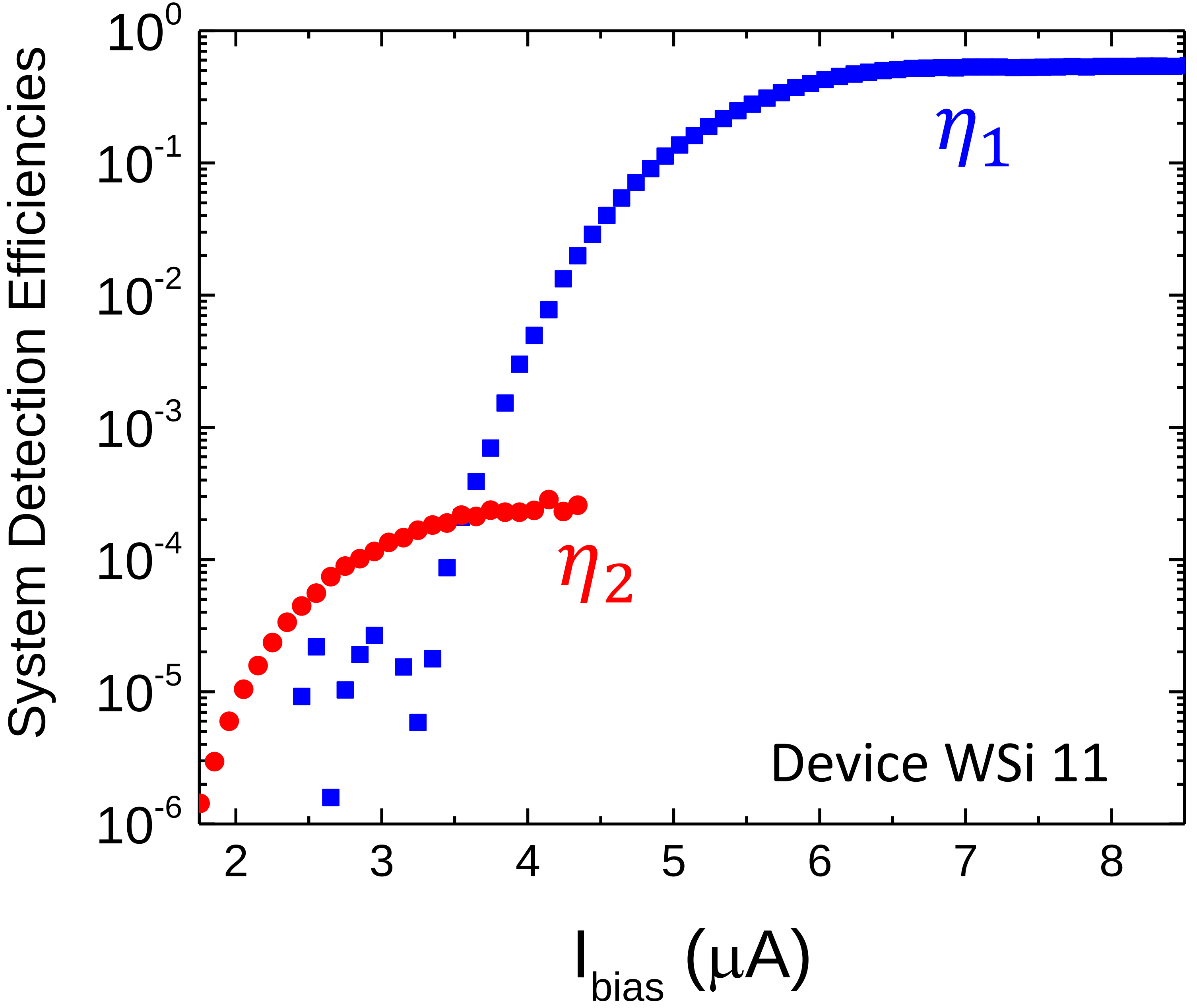


What's new?

1. Amorphous superconductors:
   WSi & MoSi

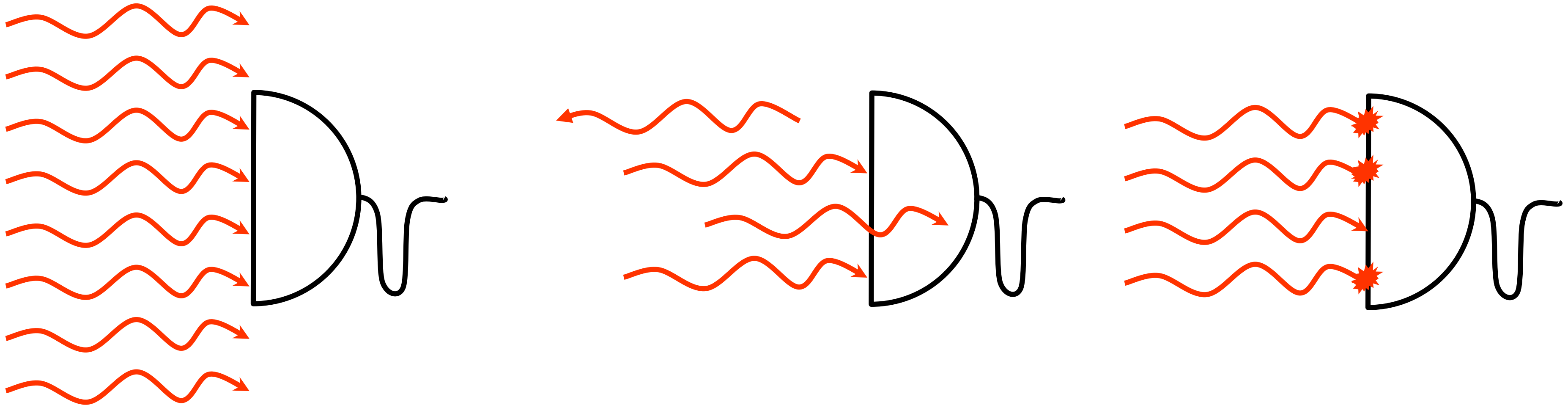
2. High-efficiency meander devices



System Detection Efficiencies
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
3
4
5
6
7
8
I_{bias} (μA)
η_1
η_2
Device WSi 11

Deconstructing System Detection Efficiency

Coupling Efficiency × Absorption × Internal Quantum Efficiency



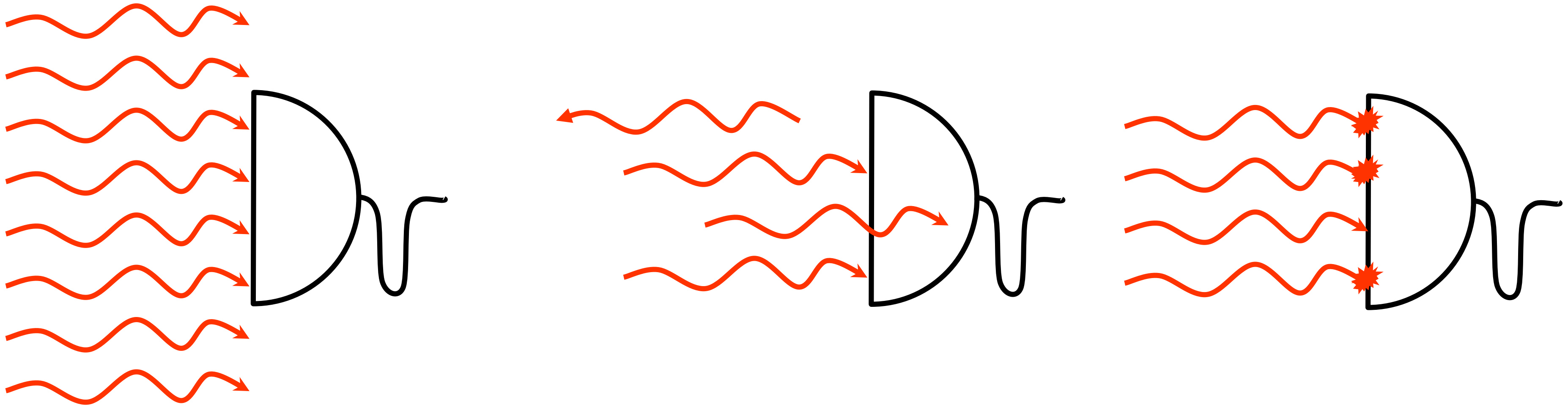
$$\eta_1(I_{\text{bias}}) = \underbrace{\eta_{\text{couple}} \times \eta_{\text{absorb}}} \times \underbrace{\eta_{\text{QE1}}(I_{\text{bias}})}$$

Probability that a photon creates a hotspot

Probability that a hotspot causes a click

Deconstructing System Detection Efficiency

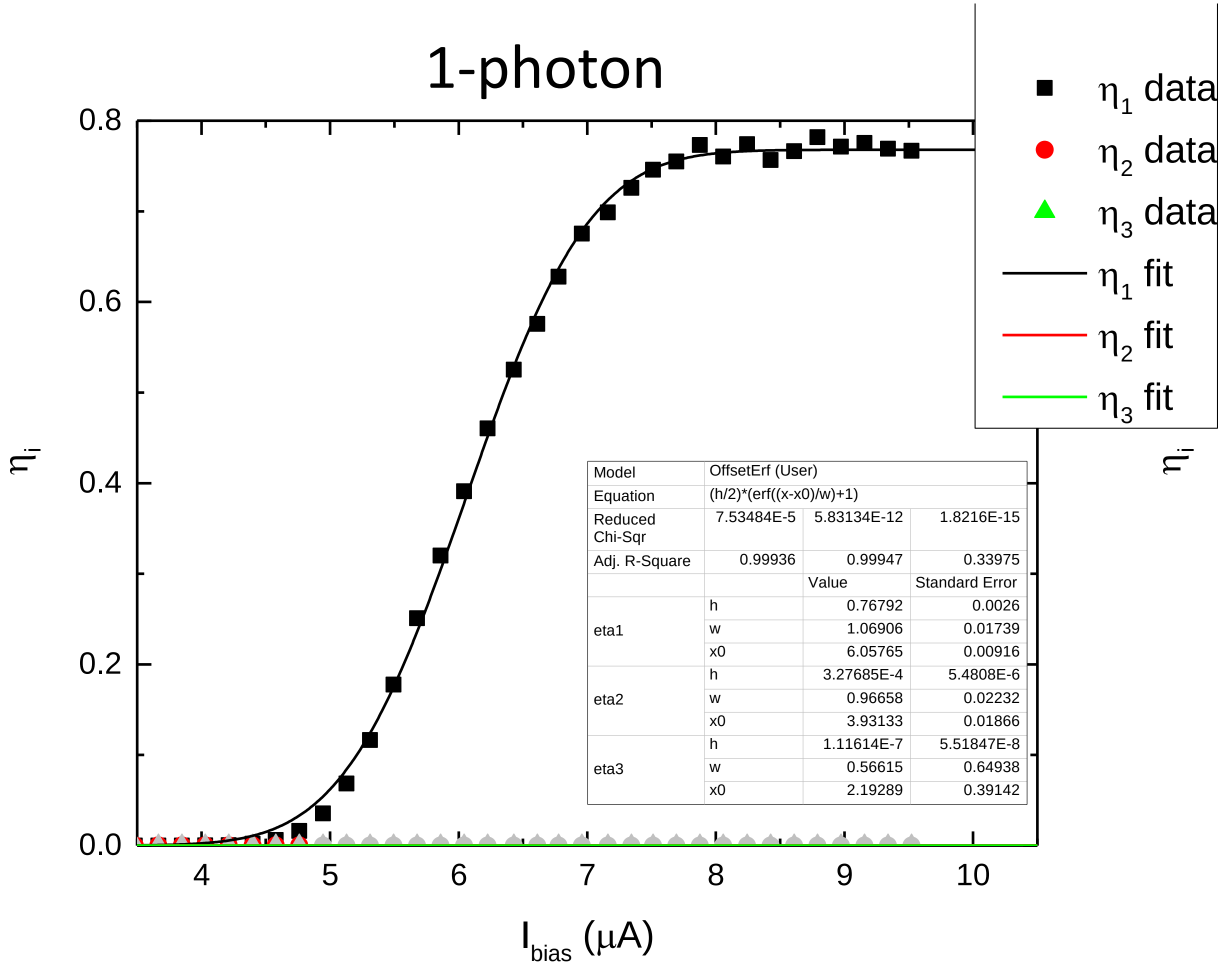
Coupling Efficiency × Absorption × Internal Quantum Efficiency

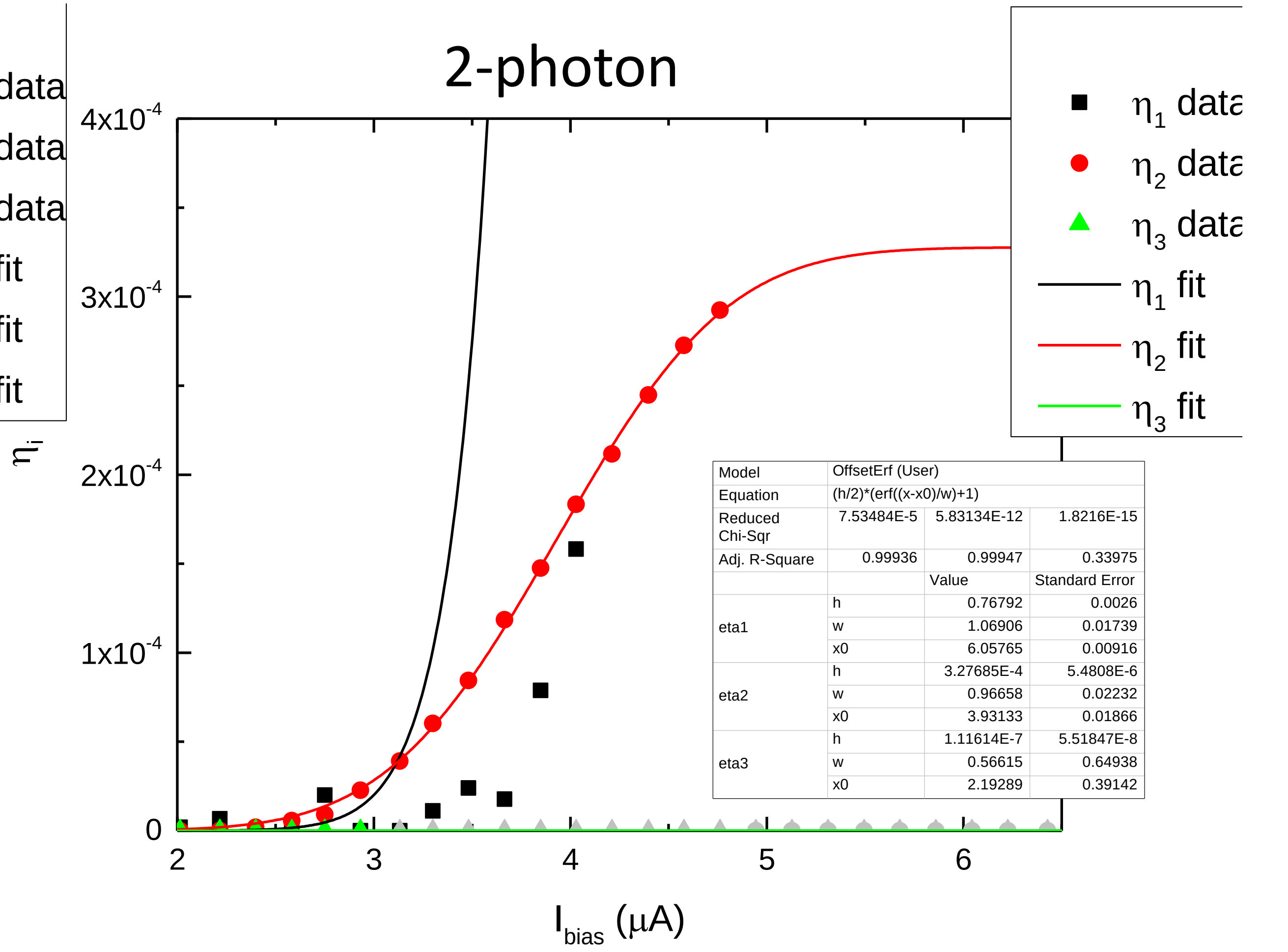


$$\eta_1(I_{\text{bias}}) = \eta_{\text{couple}} \times \eta_{\text{absorb}} \times \eta_{\text{QE1}}(I_{\text{bias}})$$

$$\eta_2(I_{\text{bias}}) = \underbrace{\left(\eta_{\text{couple}} \times \eta_{\text{absorb}}\right)^2}_{\text{Probability of creating 2 hotspots}} \times \underbrace{\eta_{\text{overlap}}}_{\text{Probability they overlap}} \times \underbrace{\eta_{\text{QE2}}(I_{\text{bias}})}_{\text{Prob. that overlapping hotspots cause a click}}$$

Same plots, linear scale





Fits to erfc() → Fano fluctuations