Single-Photon Detection and Imaging by Using Superconducting Nanowires

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Funding Acknowledgement:
DARPA, NSF, AFOSR, MIT

HOW TO DETECT A PHOTON WITH A SUPERCONDUCTOR?

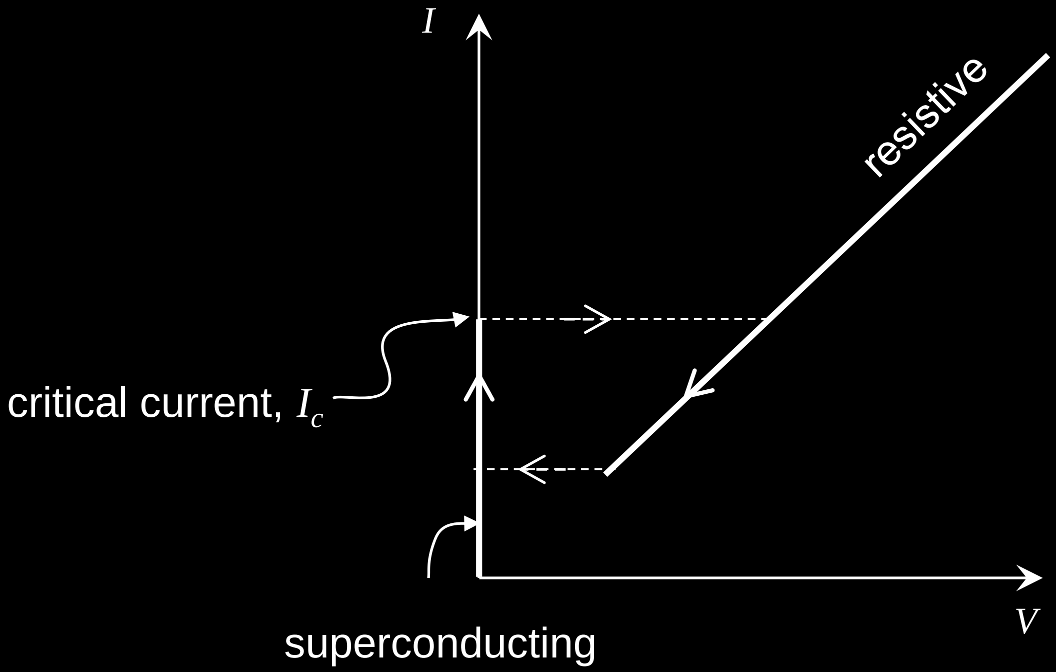
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity

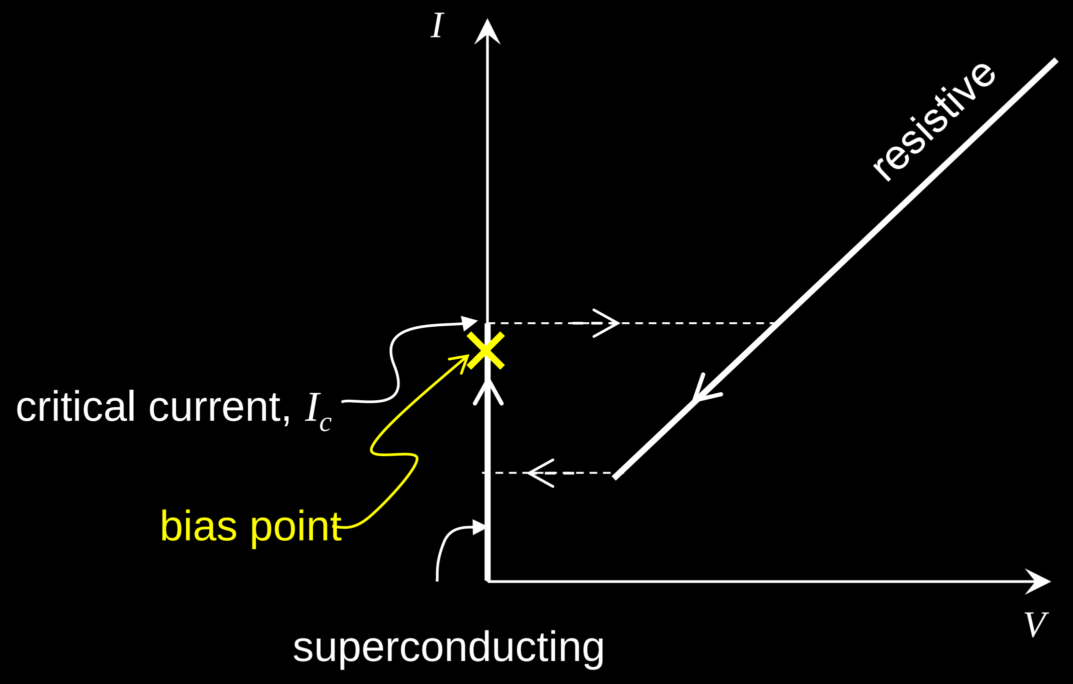
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity

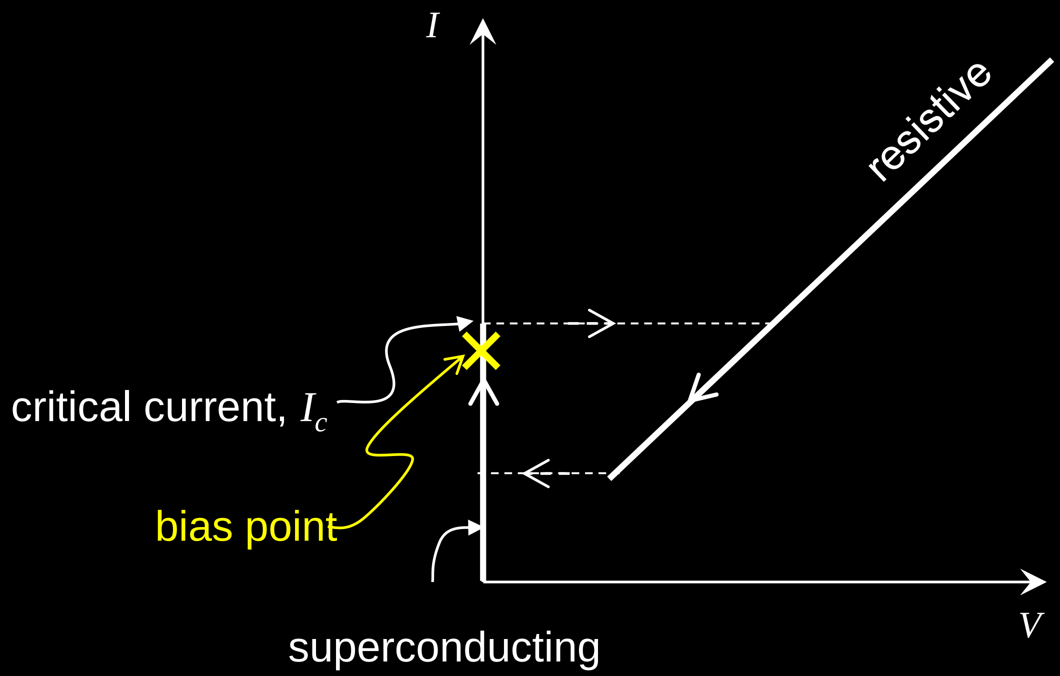
Comparison-Based Device

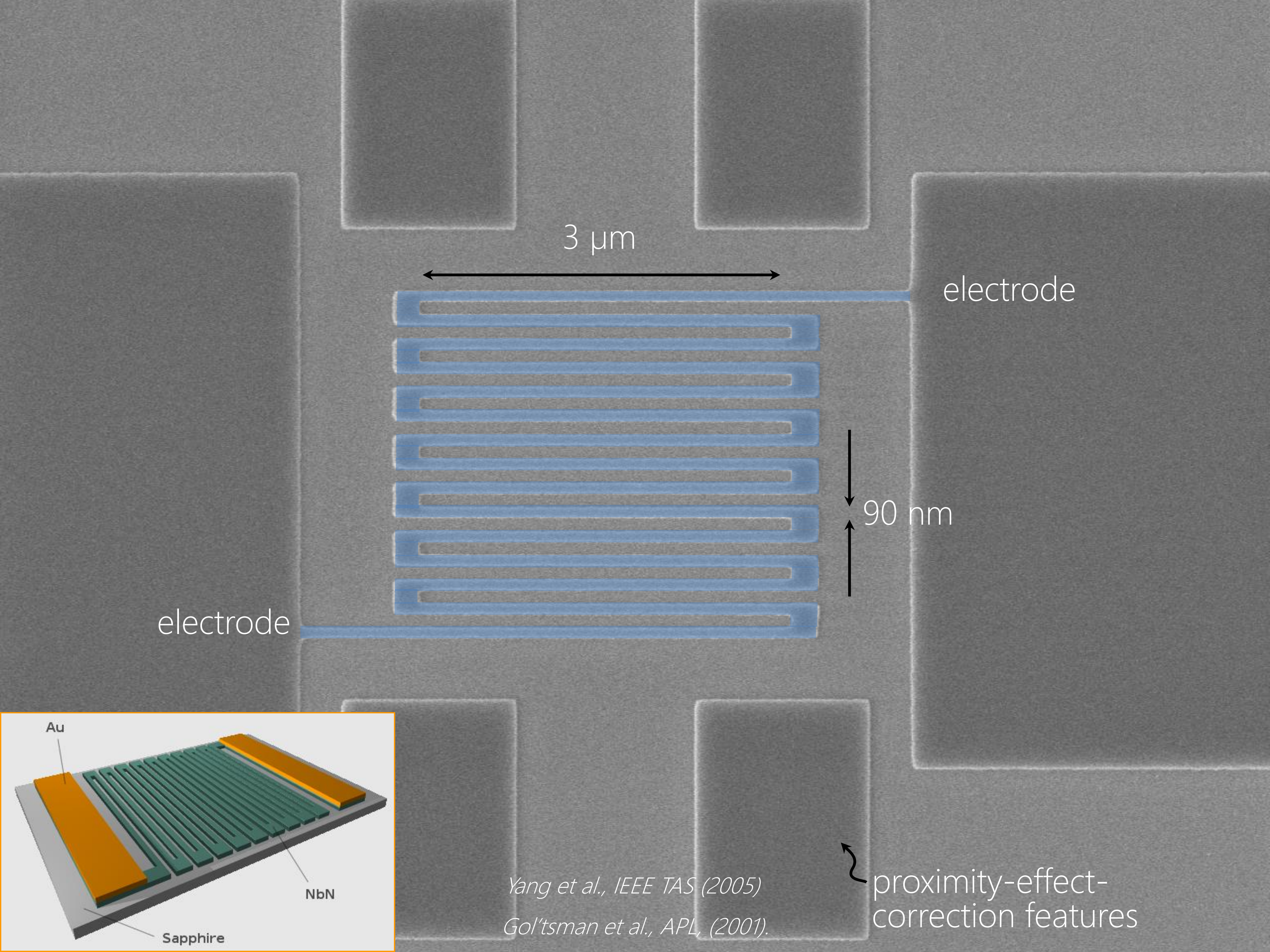


Comparison-Based Device



Comparison-Based Device

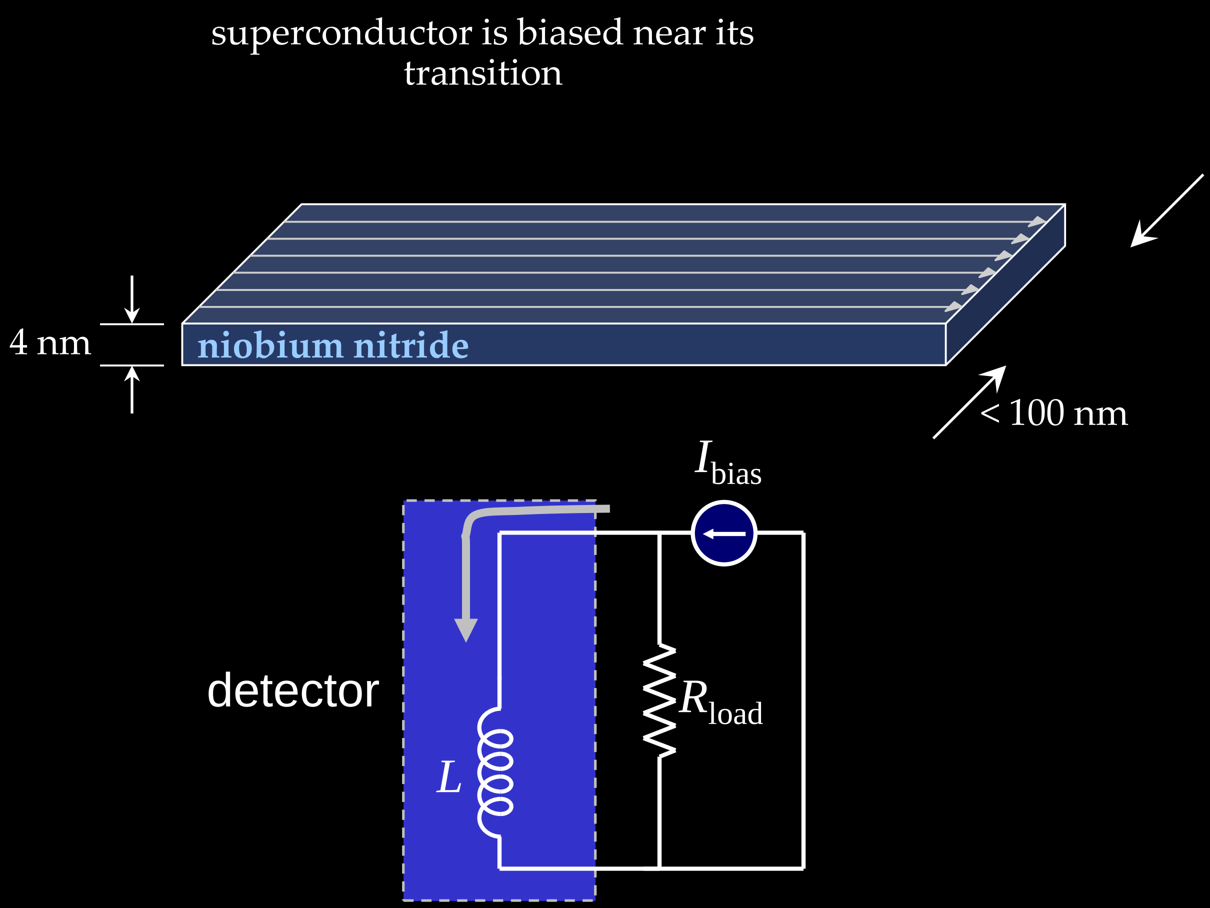



3 μm
electrode
90 nm
electrode
proximity-effect-
correction features
Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).
Au
NbN
Sapphire

DEVICE OPERATION

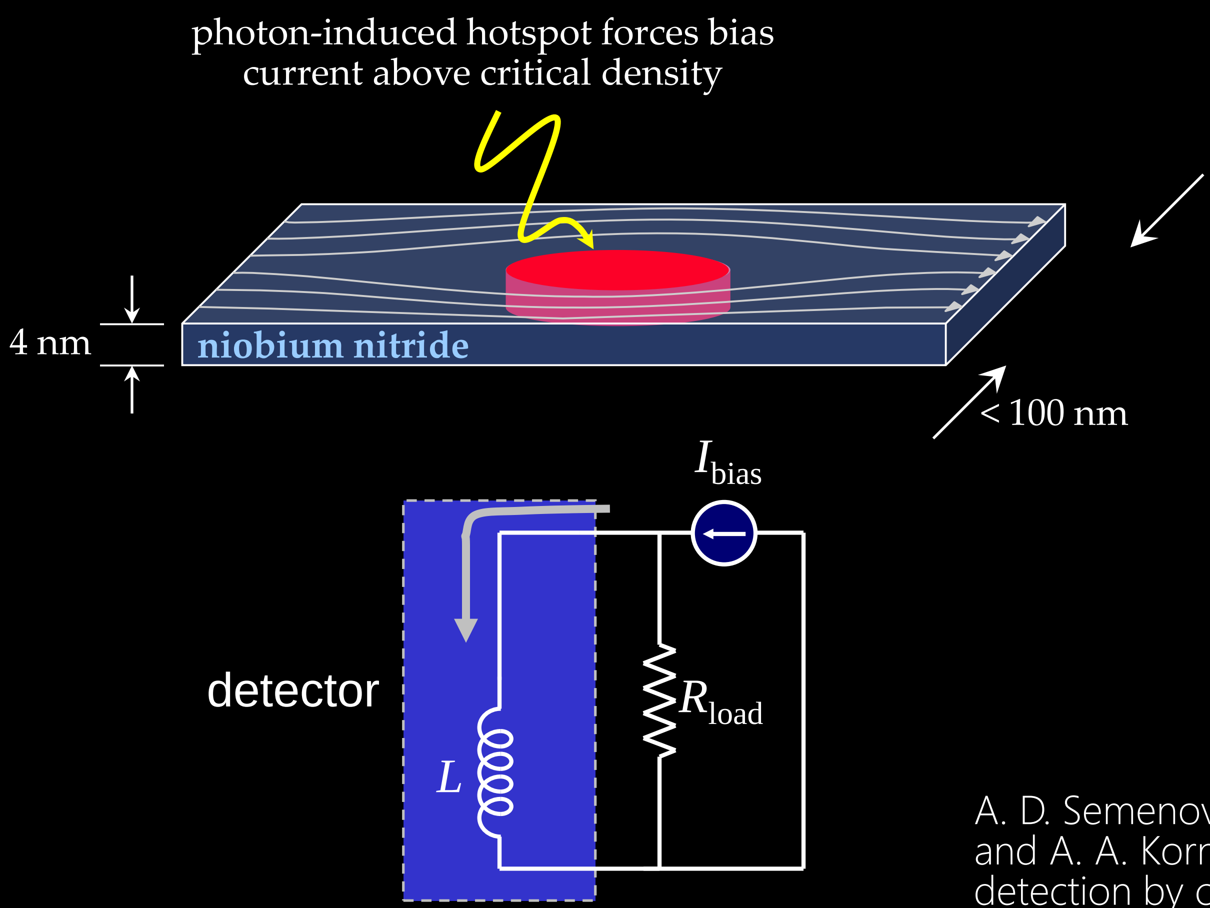
Detection Mechanism

Critical Temperature ~ 11 K



Detection Mechanism

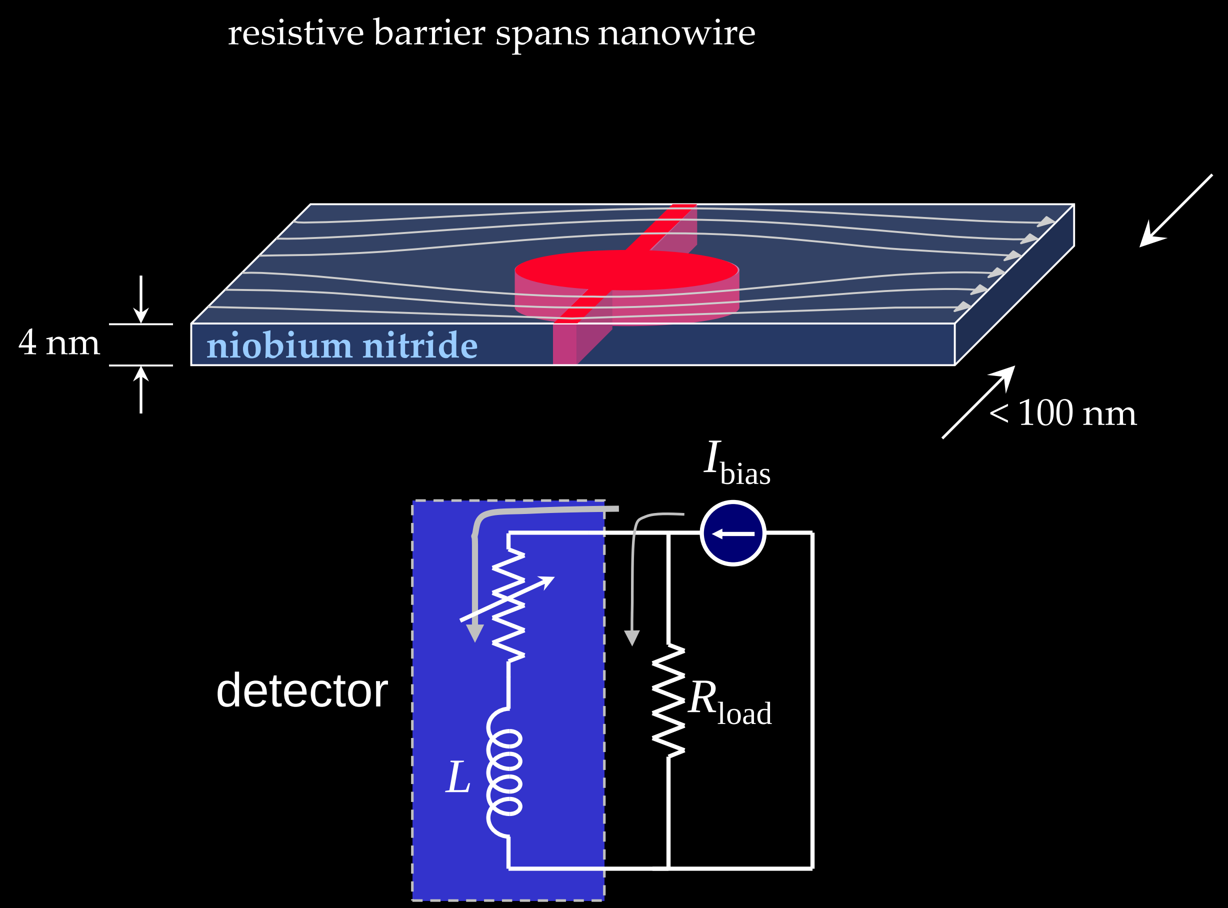
Critical Temperature ~ 11 K



A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C, vol. 351,* pp. 349–356, 2001.

Detection Mechanism

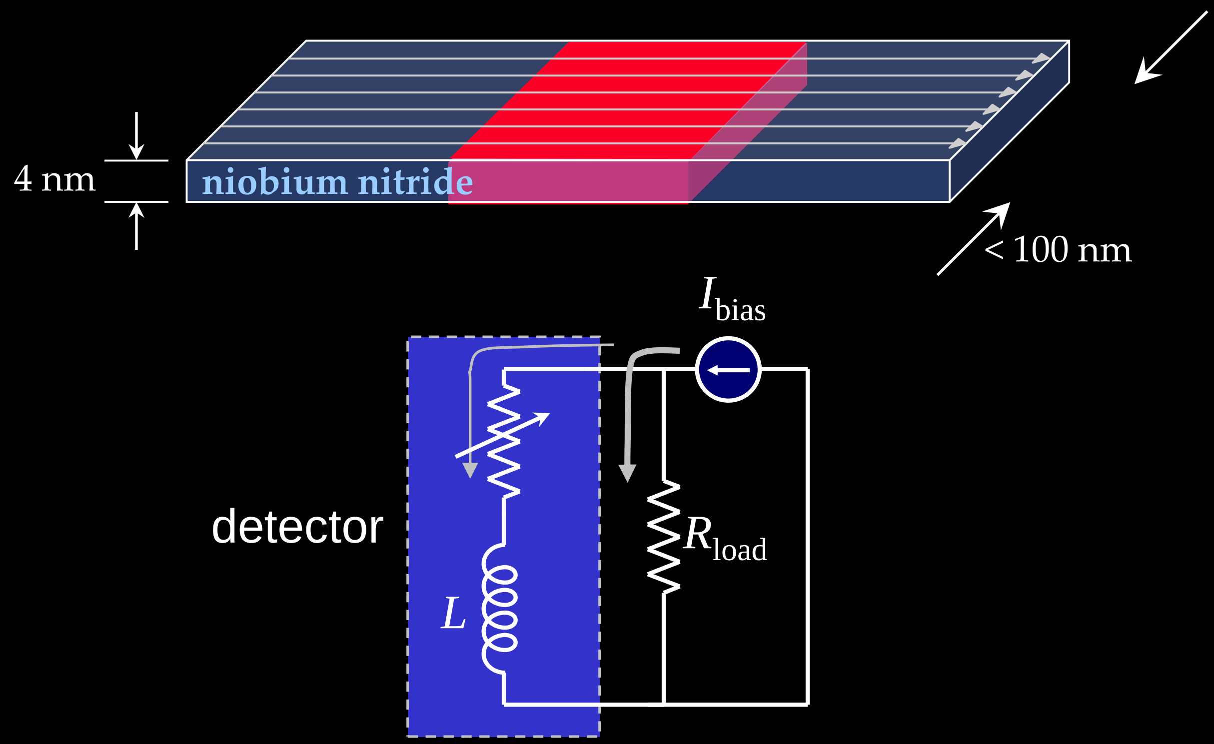
Critical Temperature ~ 11 K



Detection Mechanism

Critical Temperature ~ 11 K

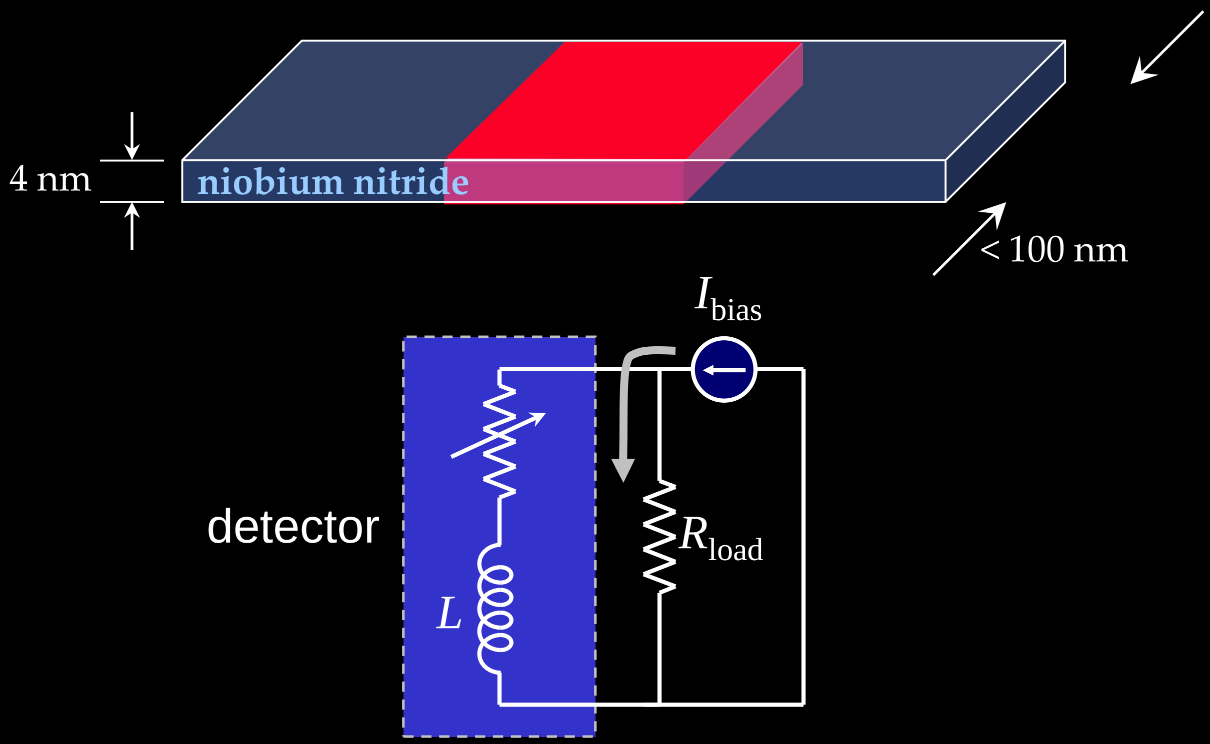
resistance grows from heating



Detection Mechanism

Critical Temperature ~ 11 K

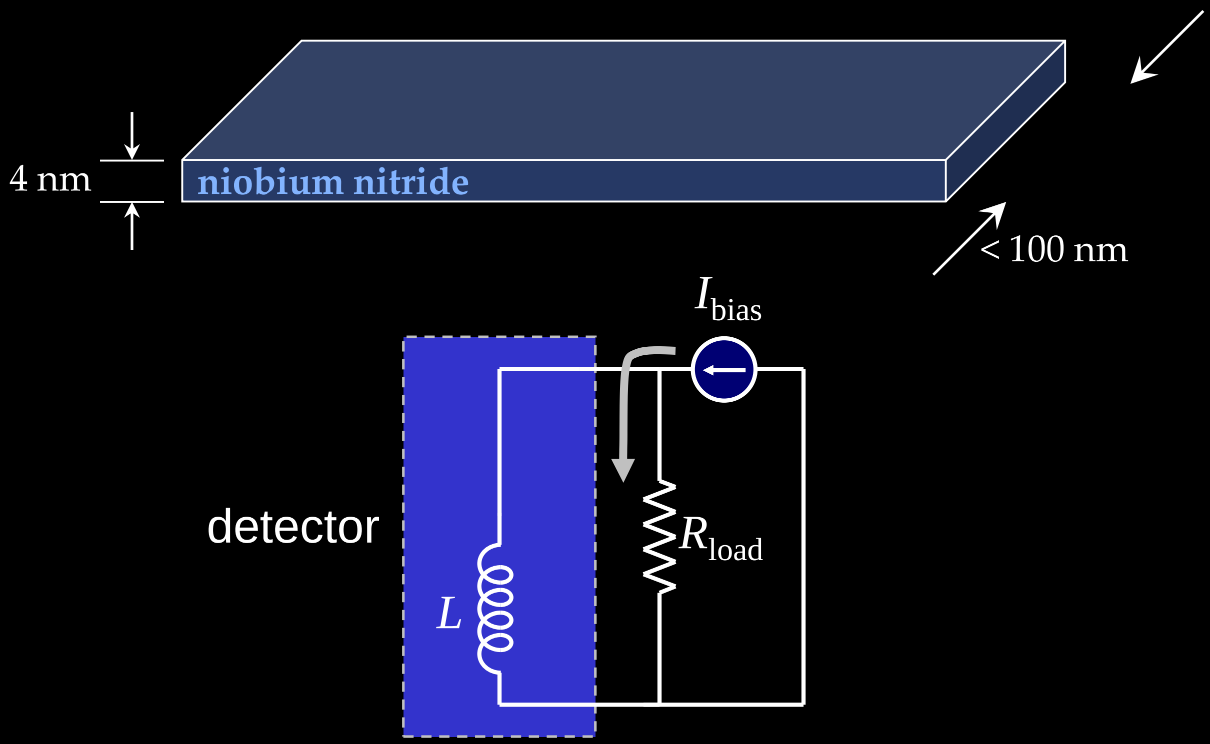
current is diverted



Detection Mechanism

Critical Temperature ~ 11 K

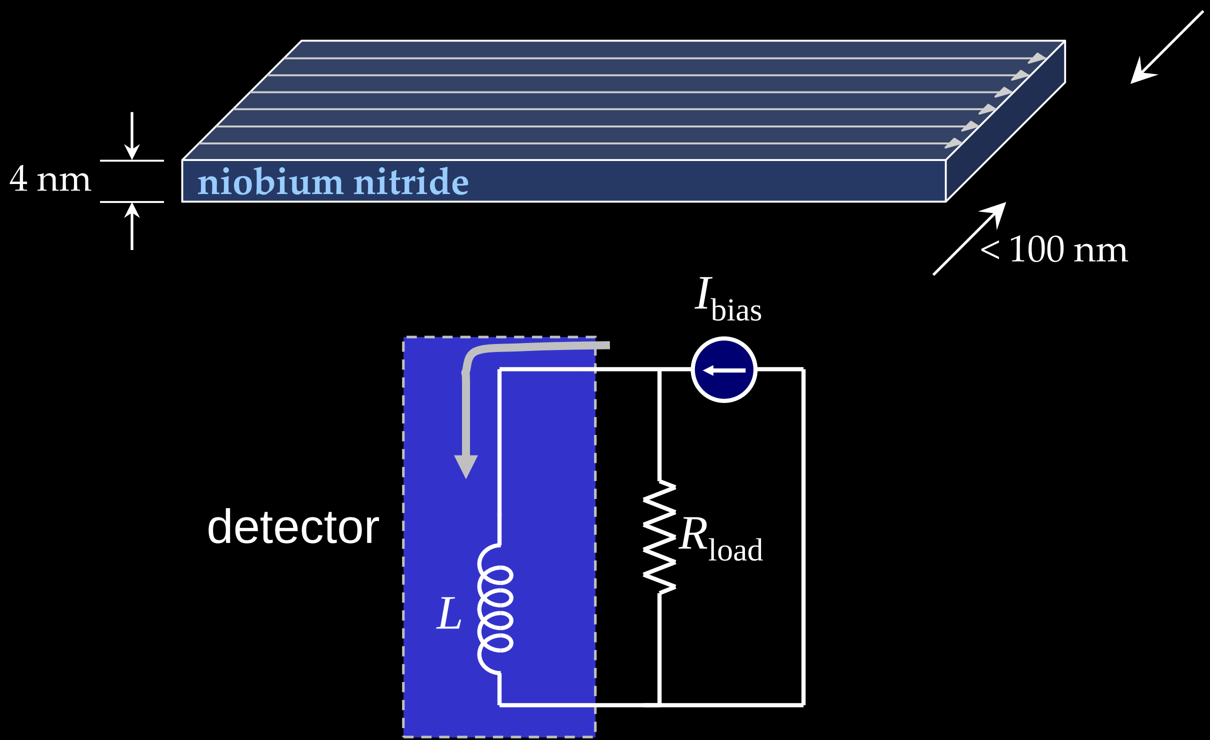
superconductivity is restored



Detection Mechanism

Critical Temperature ~ 11 K

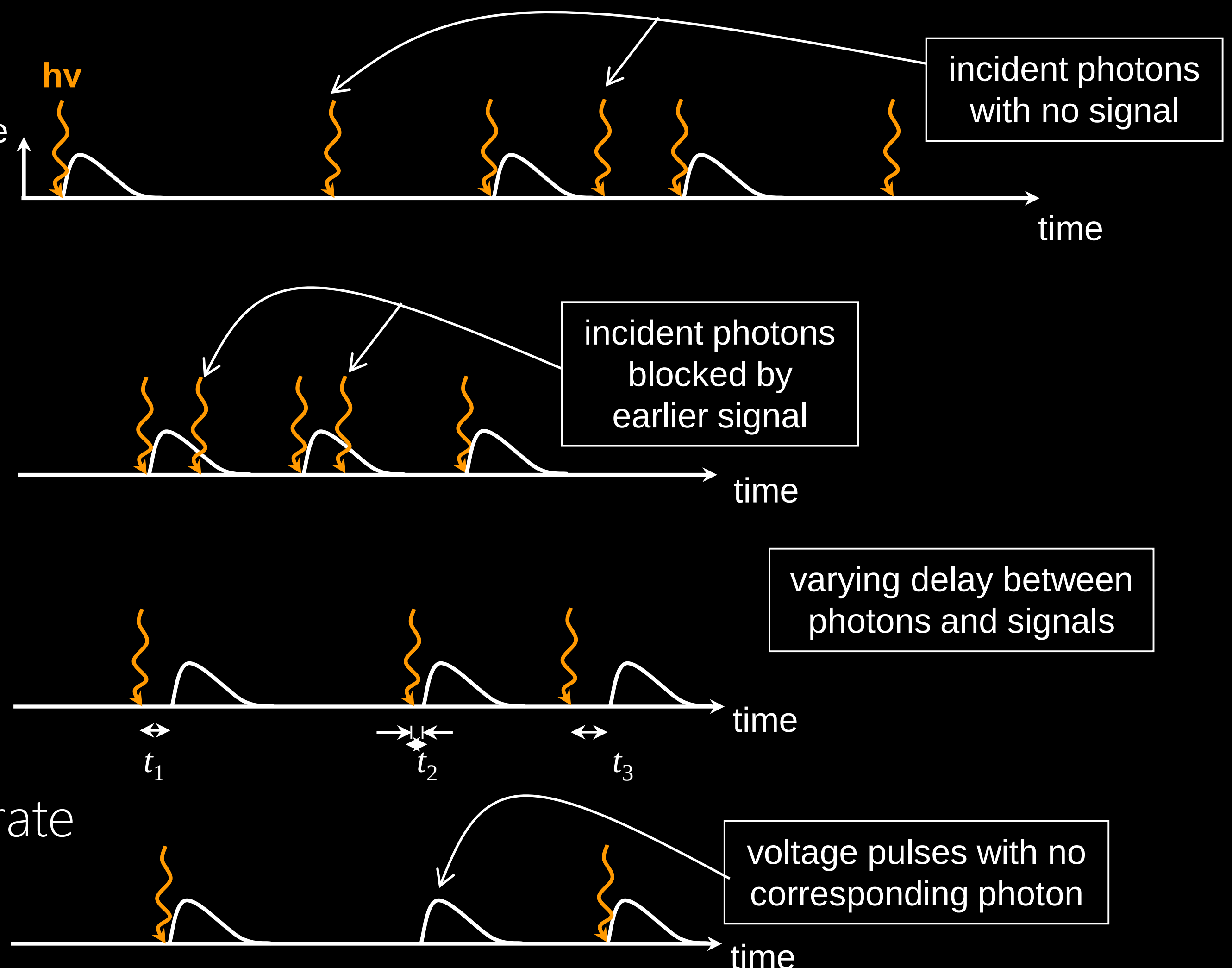
bias current is restored

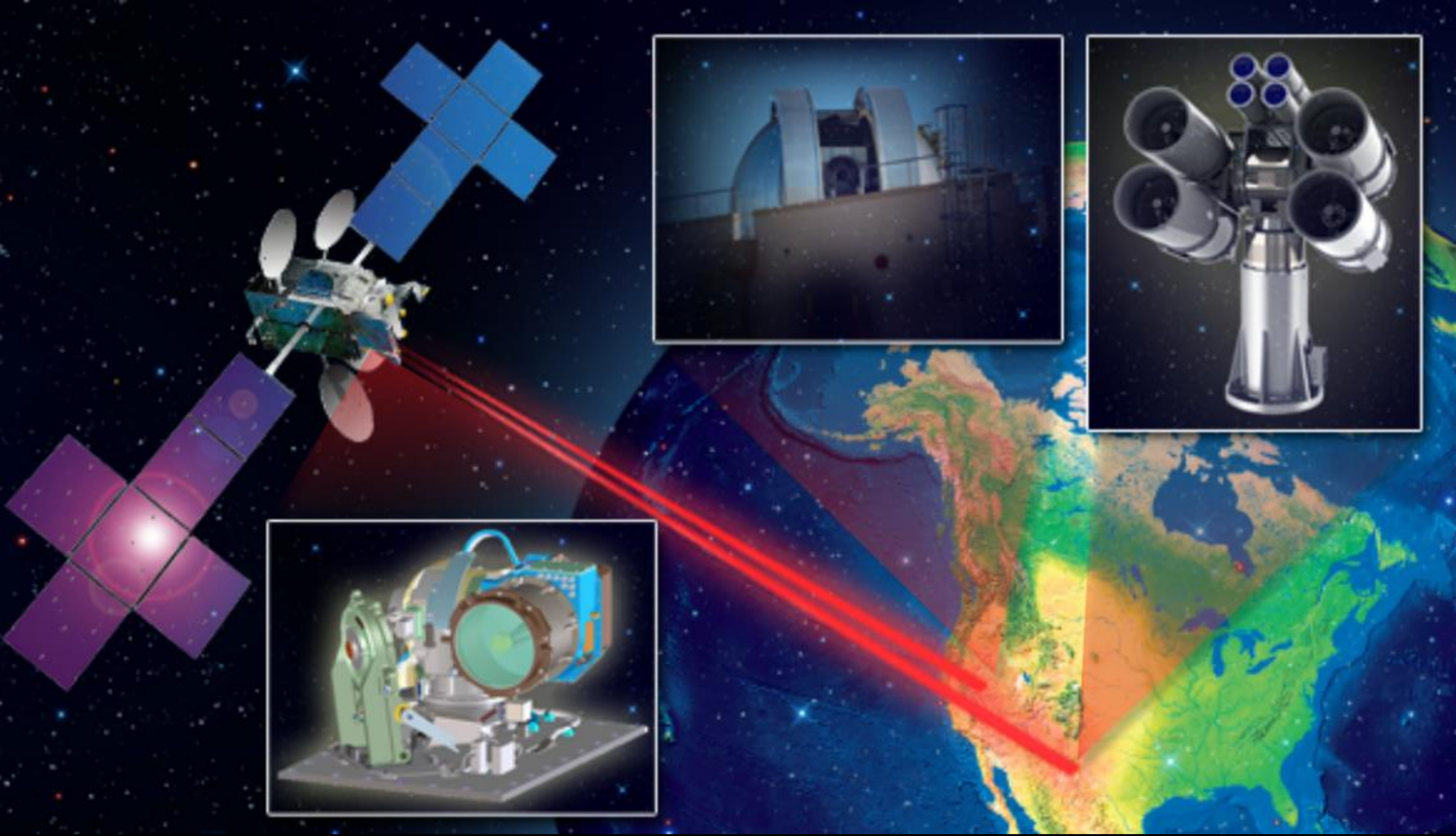


Kerman, Dauler, Keicher, Yang, KB, Gol'tsman, Voronov, *Applied Physics Letters*, (

Characteristics of Photon Detectors

- Efficiency
- Reset time
- Jitter
- Dark count rate

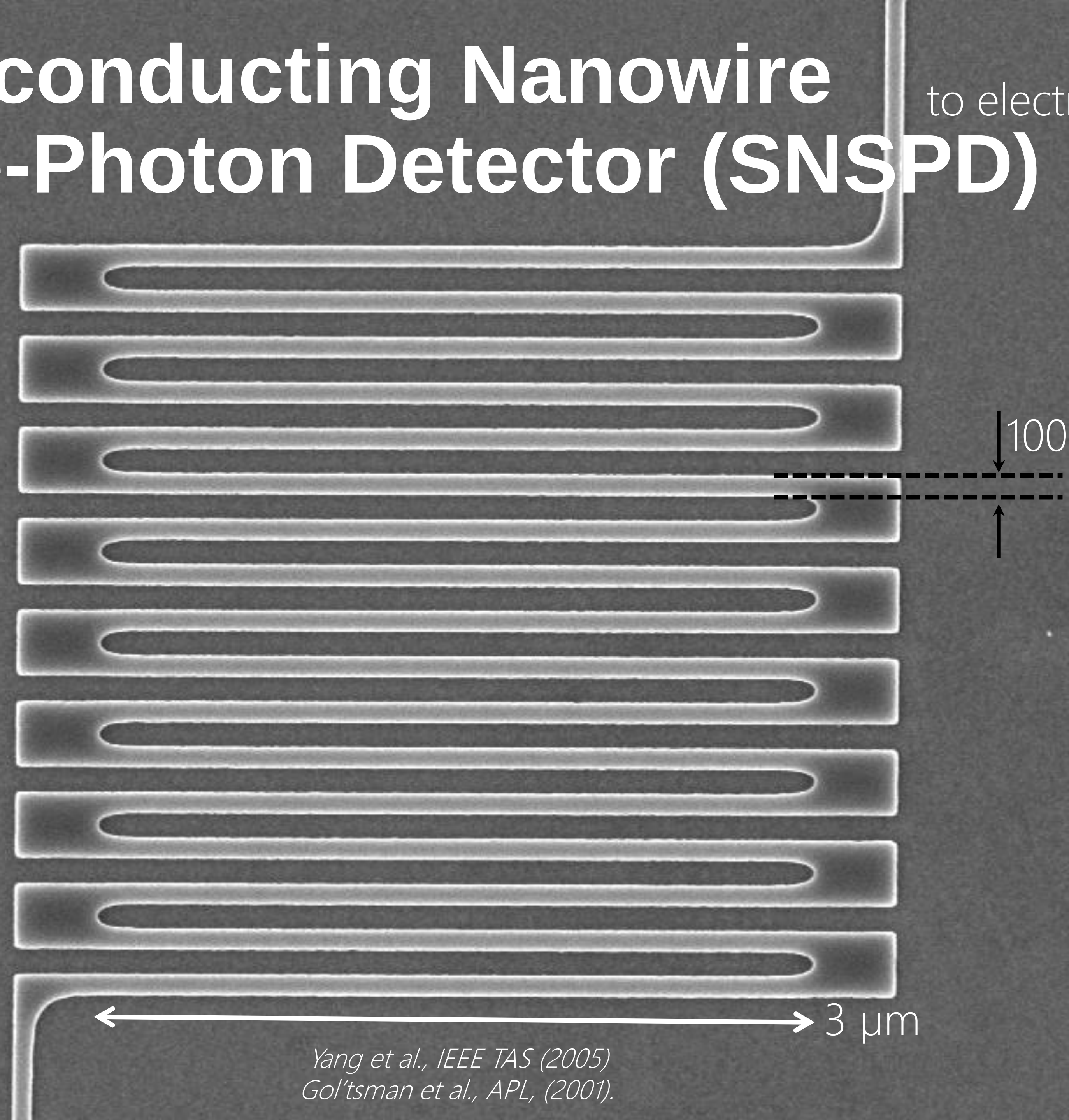




"LLCD will be the first high-rate space laser communications system that can be operated over a range ten times larger than the near-Earth ranges that have been demonstrated to date." from http://esc.gsfc.nasa.gov/267/271.html, enabled by nanowire detectors developed at MIT Lincoln Laboratory in collaboration with MIT campus.

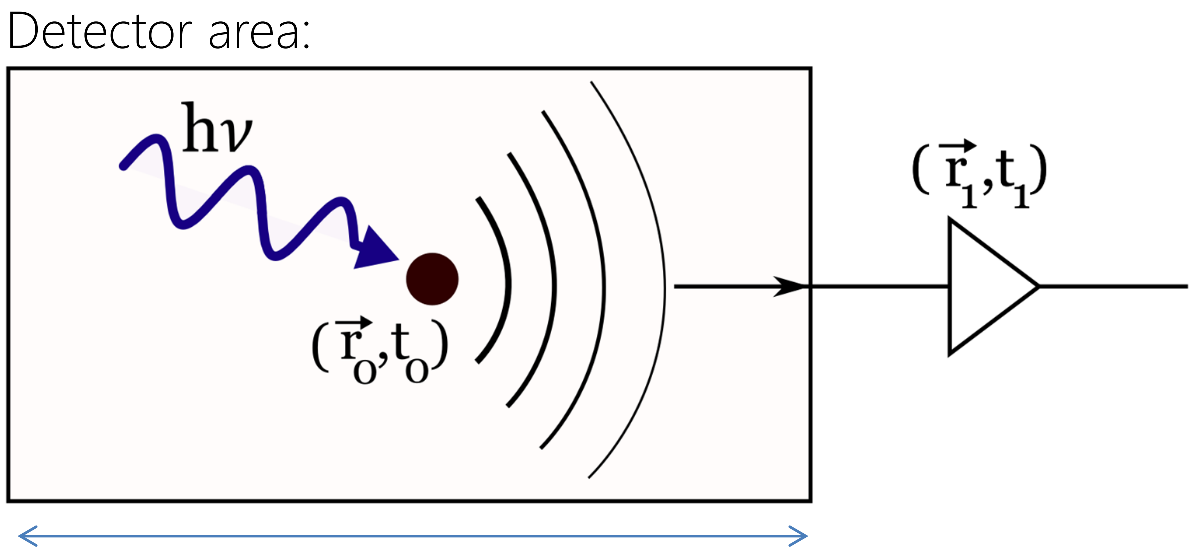
Superconducting Nanowire Single-Photon Detector (SNSPD)

NbN
@2.5 K



Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).

Geometric Jitter



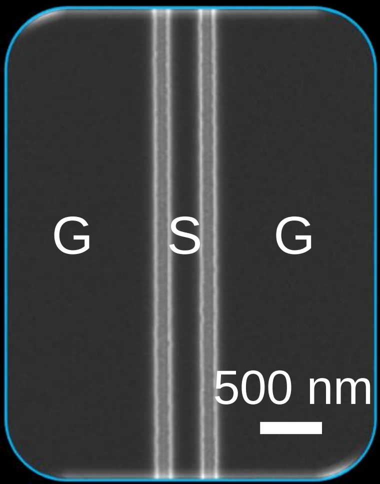
$$d = 10\,\mu\mathrm{m}$$

$$\text{Signal Speed} \equiv c' \sim \frac{c}{3} = 100\,\mu\mathrm{m\,ps}^{-1}$$

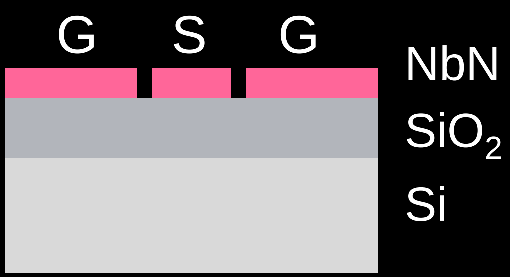
$$\Rightarrow \text{geometric jitter} \sim 50\,\mathrm{fs}$$

Kinetic Inductance: Superconductivity's Ugly Little Secret

Top view



Side view

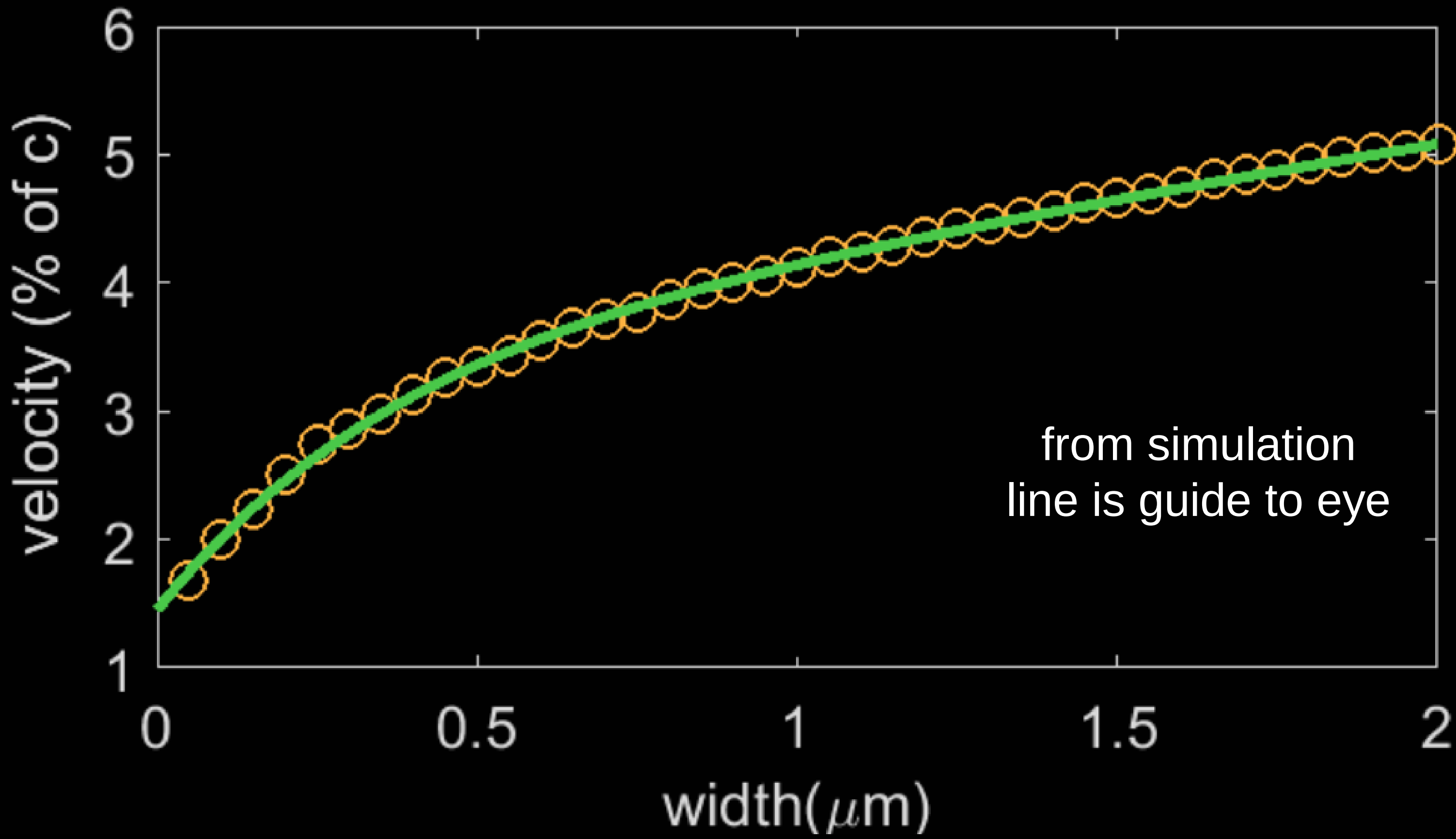


$$\text{Specific Inductance} \equiv L_{\mathrm{S}} = \mu_\circ \frac{\lambda^2}{\text{Area}} \approx 400\,\mathrm{pH}\,\mathrm{\mu m}^{-1}$$

$$\text{Specific Capacitance} \equiv C_{\mathrm{S}} \approx 3.3\epsilon_\circ \approx 30\,\mathrm{aF}\,\mathrm{\mu m}^{-1}$$

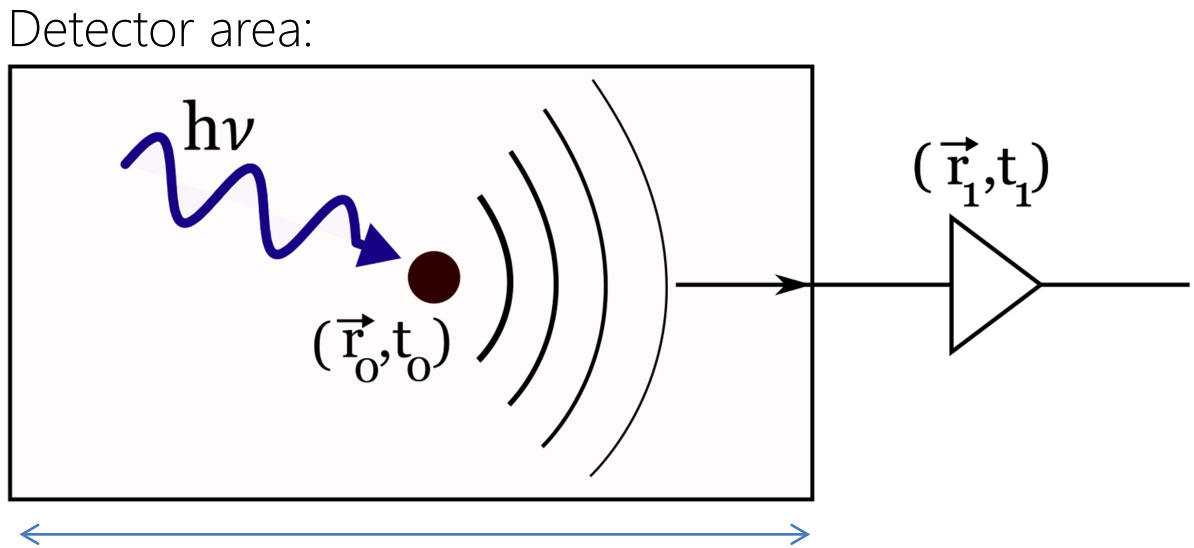
$$\text{Signal Speed} = c_{\text{eff}} = \frac{1}{\sqrt{C_{\mathrm{S}} L_{\mathrm{S}}}} \sim \frac{c}{30} = 3\%\,c$$

Kinetic Inductance: Superconductivity's Ugly Little Secret



Λ / d = 50 pH/square

Geometric Jitter



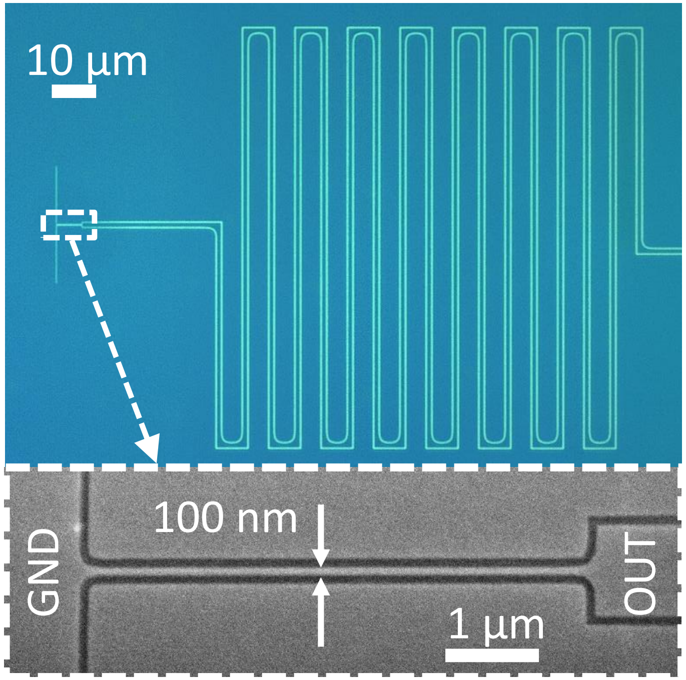
$$d = 10\,\mu\text{m}$$

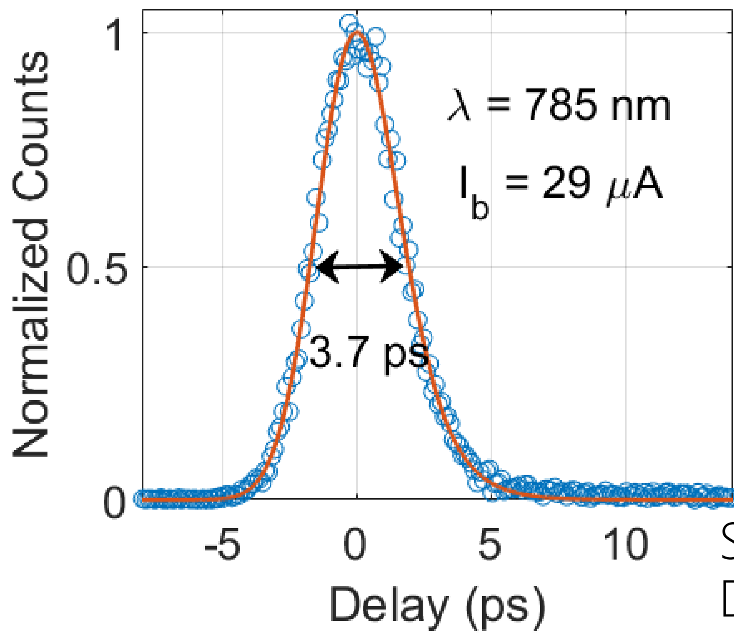
$$c_{\text{eff}} \sim \frac{c}{25} = 100\,\mu\text{m}\,\text{ps}^{-1}$$

$$\Rightarrow \text{geometric jitter} \sim 20\,\text{ps}$$

Ultra-High-Time-Resolution SNSPDs

Jet Propulsion Laboratory
California Institute of Technology

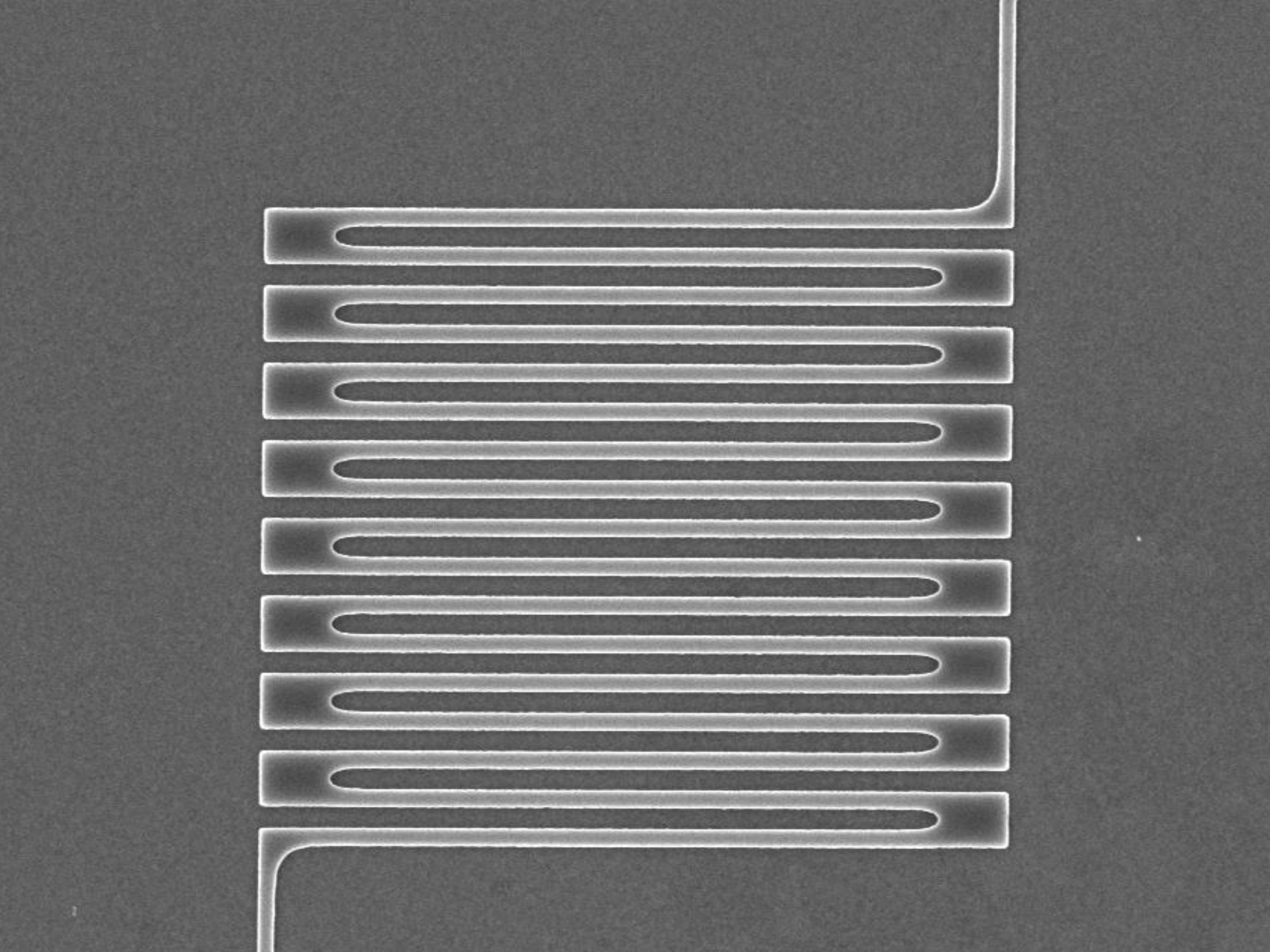


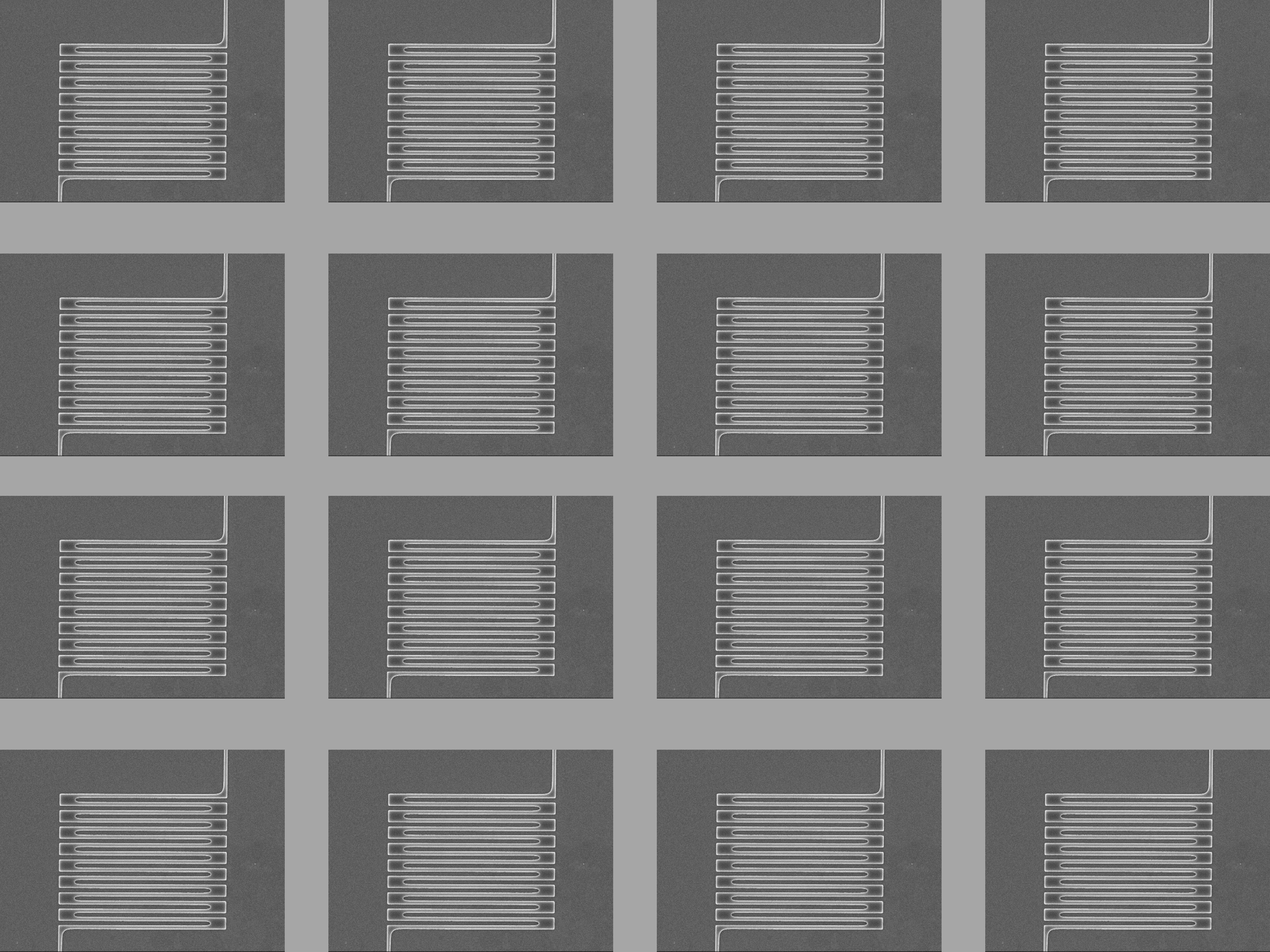


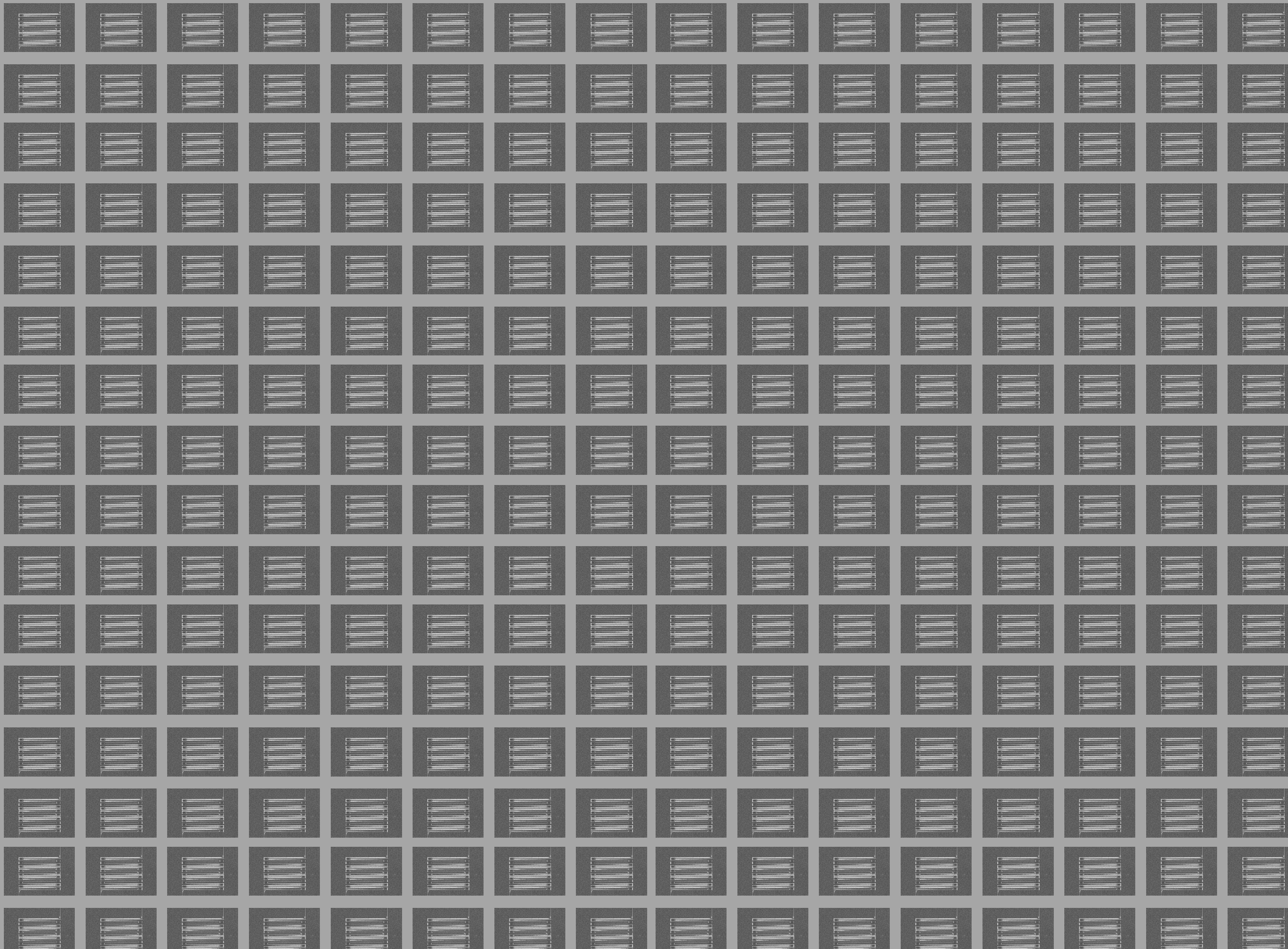
Supported by:
DARPA & NSF

- Single photon detection with 3.7 ps FWHM time resolution at 1550 nm
- 20 µm x 80 nm x 5 nm NbN nanowire, low-noise cryogenic amplifier
- Low jitter with larger active area may be practical using differential readout

JPL: Boris Korzh, Simone Frasca, Matthew Shaw MIT: Qing-Yuan Zhao, KKB
NIST: Thomas Gerrits, Marty Stevens, Richard Mirin, Sae Woo Nam

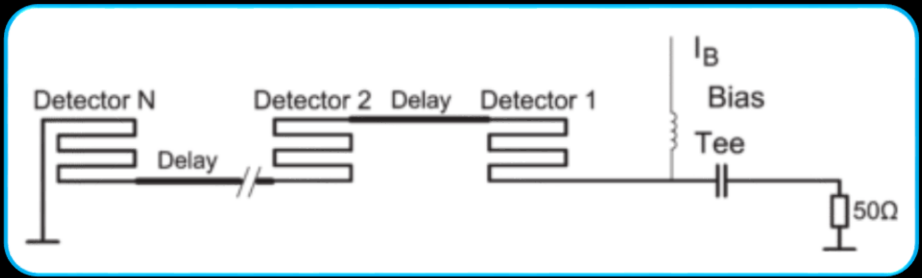






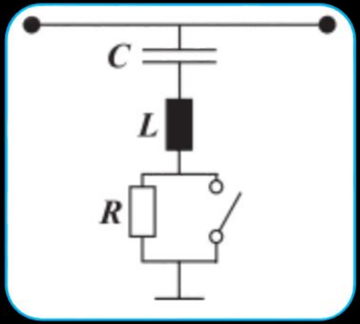
Existing SNSPD arrays

Time-domain multiplexing (2 pix)



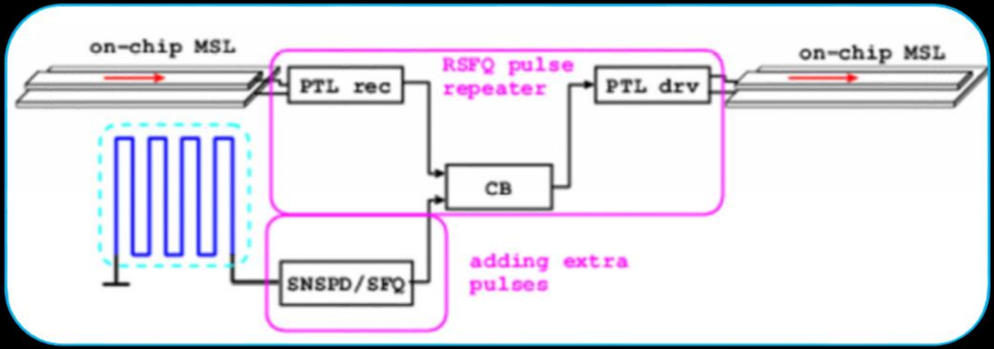
Hofherr, M. *et al. IEEE Trans. Appl. Supercond.* (2013).
Karlsruhe (proposal from Grenoble, also work at Delft)

Frequency-domain multiplexing (2 pix)



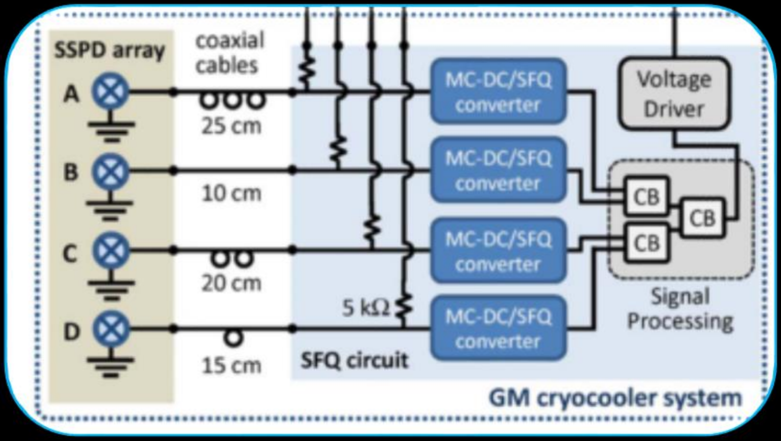
Doerner, S. *et al. IEEE Trans. Appl. Supercond.* (2016) (Karlsruhe)

SFQ readout (4 pix)



Hofherr, M. *et al. Opt. Express* (2012) (Karlsruhe)

SFQ readout (4 pix)

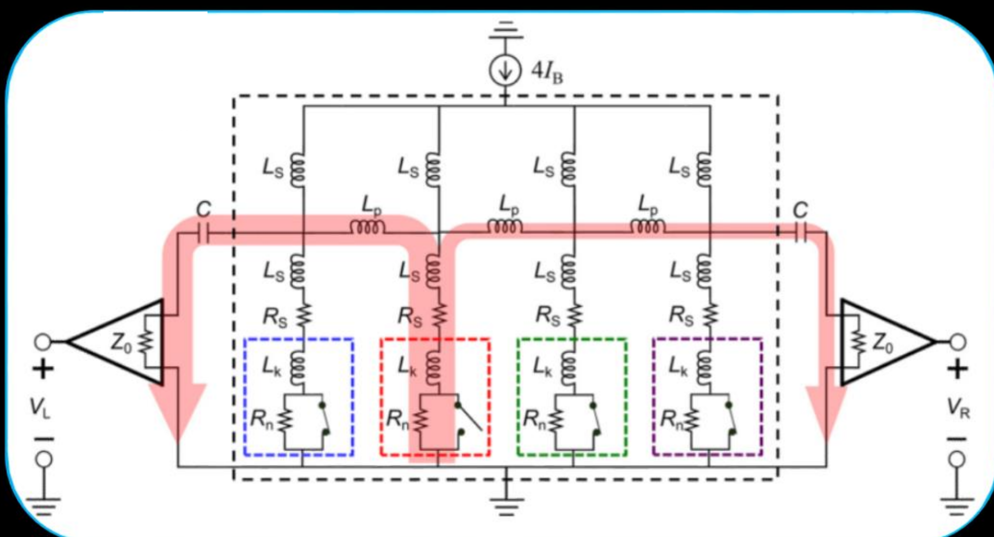


Yamashita, T.*et al. Opt. Lett.* (2012) NICT

Existing SNSPD arrays

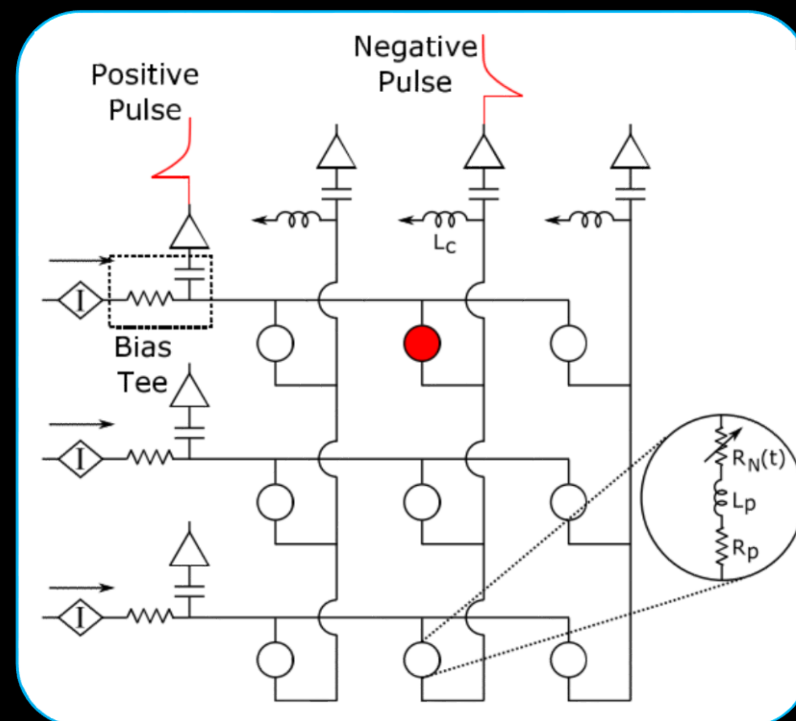
Modulate SNSPD's output

Inductive current splitting (4 pix)



Zhao, Q-Y. *et al. Appl. Phys. Lett.* (2013)
MIT

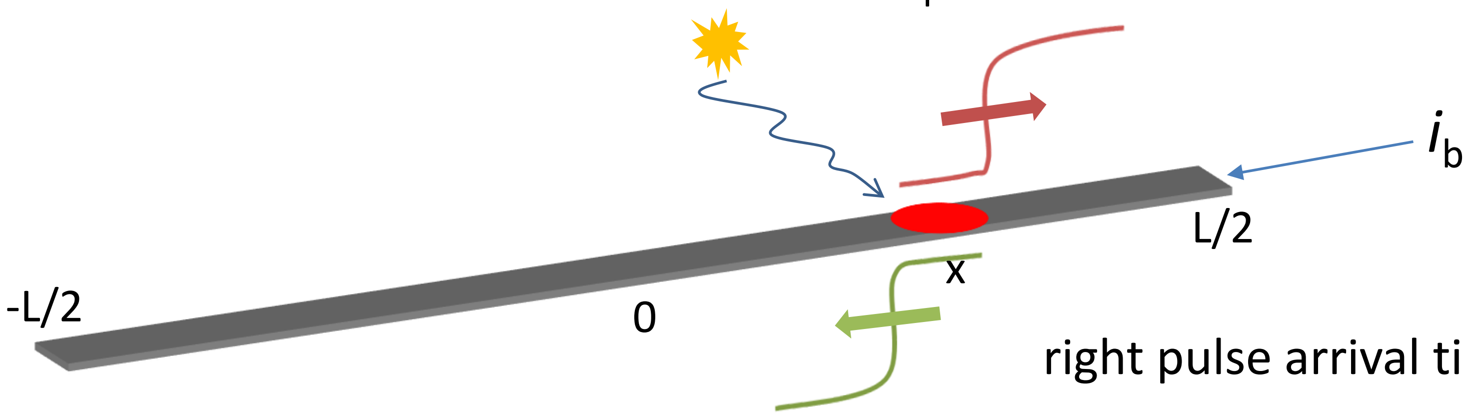
Row-column addressing (64 pix)



Allman, M. S. *et al. Appl. Phys. Lett.* (2015)
NIST, JPL

Spatial and temporal detection in a wire

Photon arrives at x, t_p



right pulse arrival time

$t_R = t_p + (L/2-x)/c'$

left pulse arrival time:

$t_L = t_p + (L/2+x)/c'$

Location: $x = (t_L - t_R)c'/2$

differential time

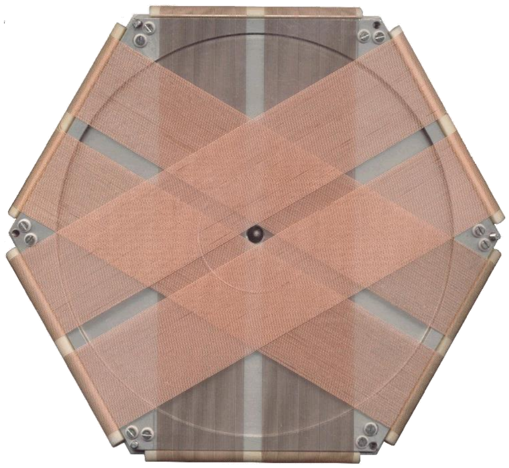
Time: $t_p = (t_L + t_R - L/c')/2$

sum time

Photon position and arrival time can be detected **simultaneously**!

Similar readout architectures in other detector arrays

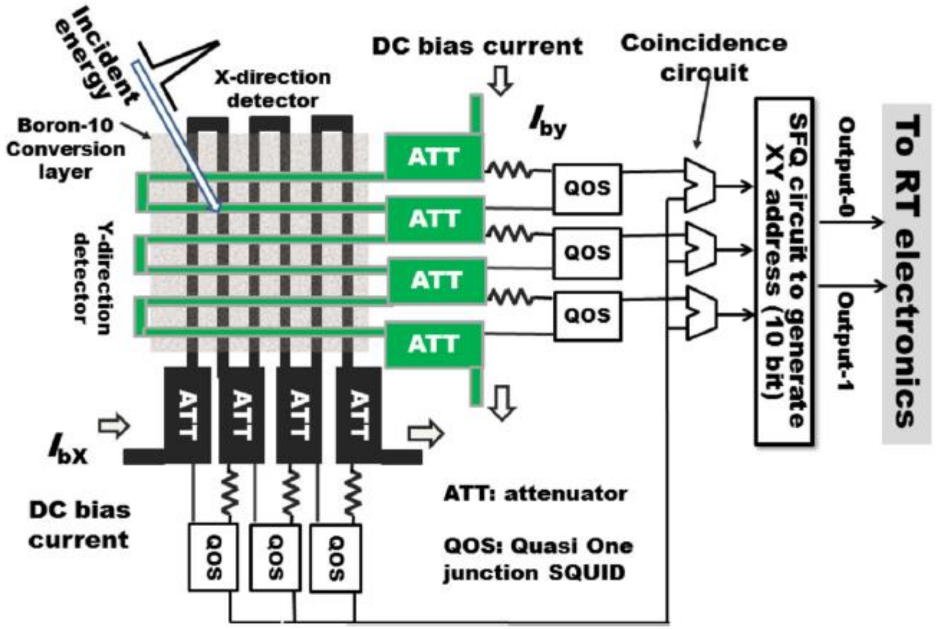
micro-channel plate (MCP) using delay lines for imaging



http://www.roentdek.com/

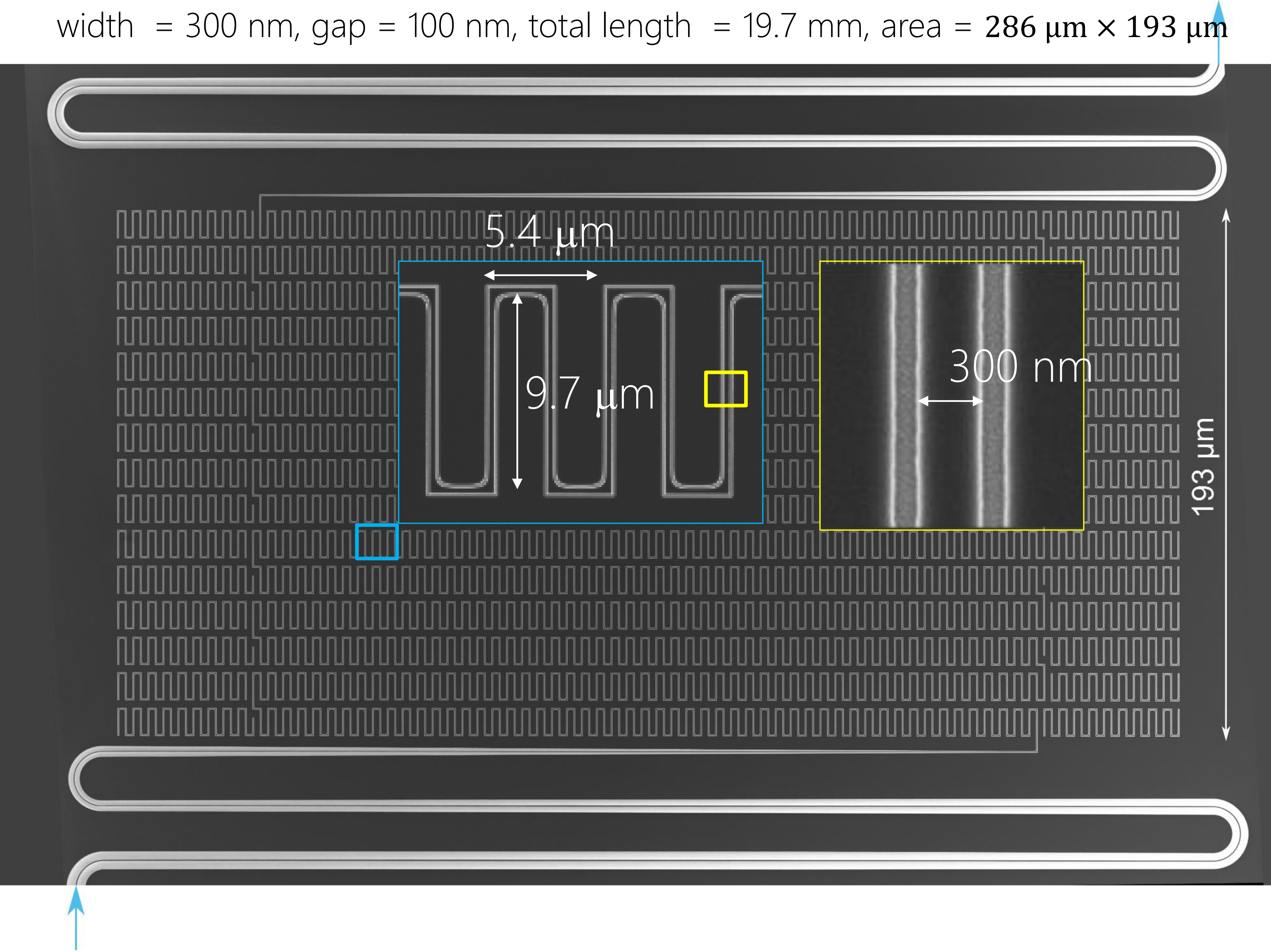
*O. Jagutzki *et al.*, *Nucl. Instruments Methods Phys. Res. Sect. A* **477**, 244–249 (2002)

Neutron imager using delay lines



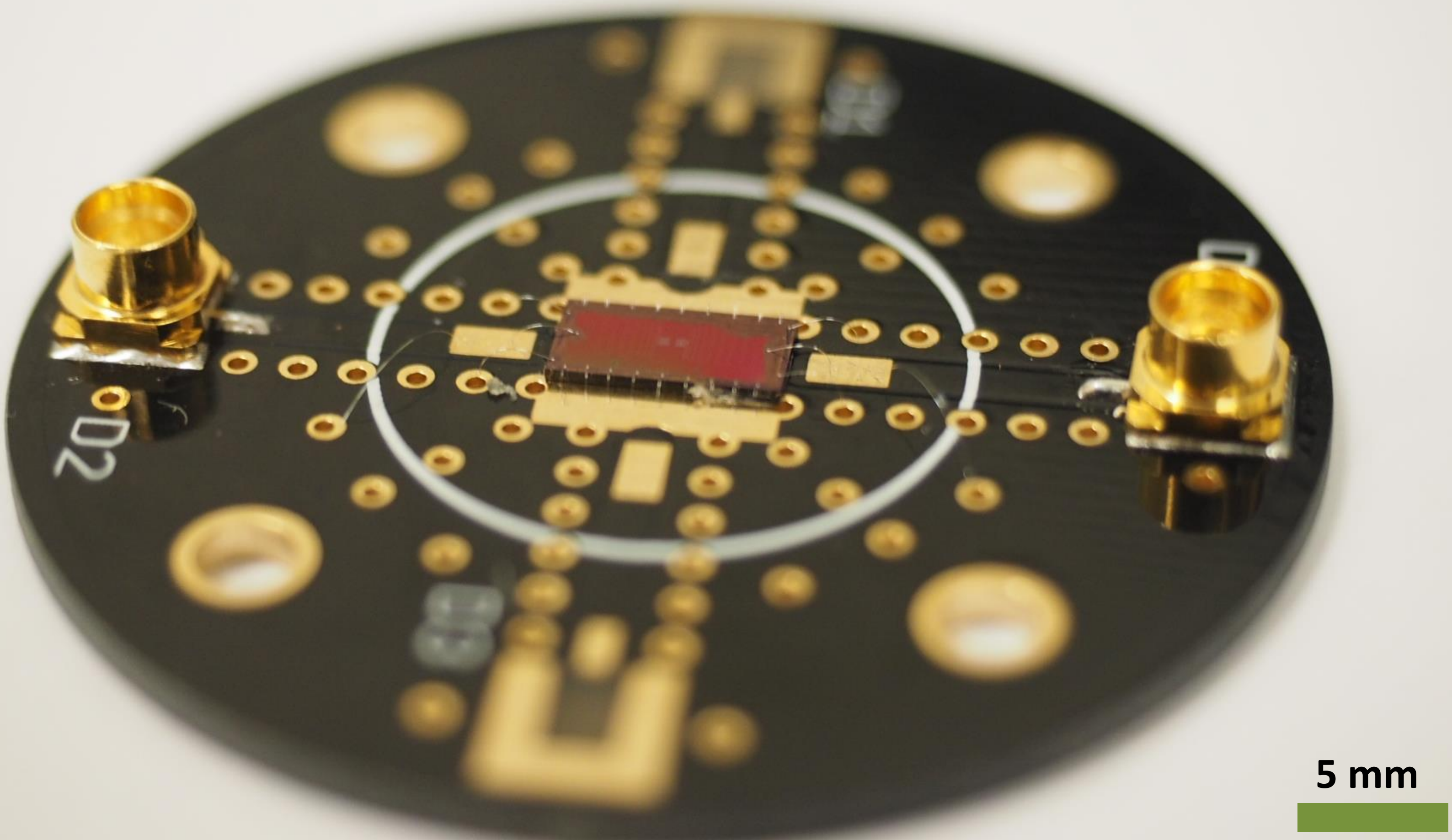
*T. Ishida, *et.al.*, *J. Low Temp. Phys.*, vol. 176, no. 3–4, pp. 216–221, 2014.

width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 µm × 193 µm



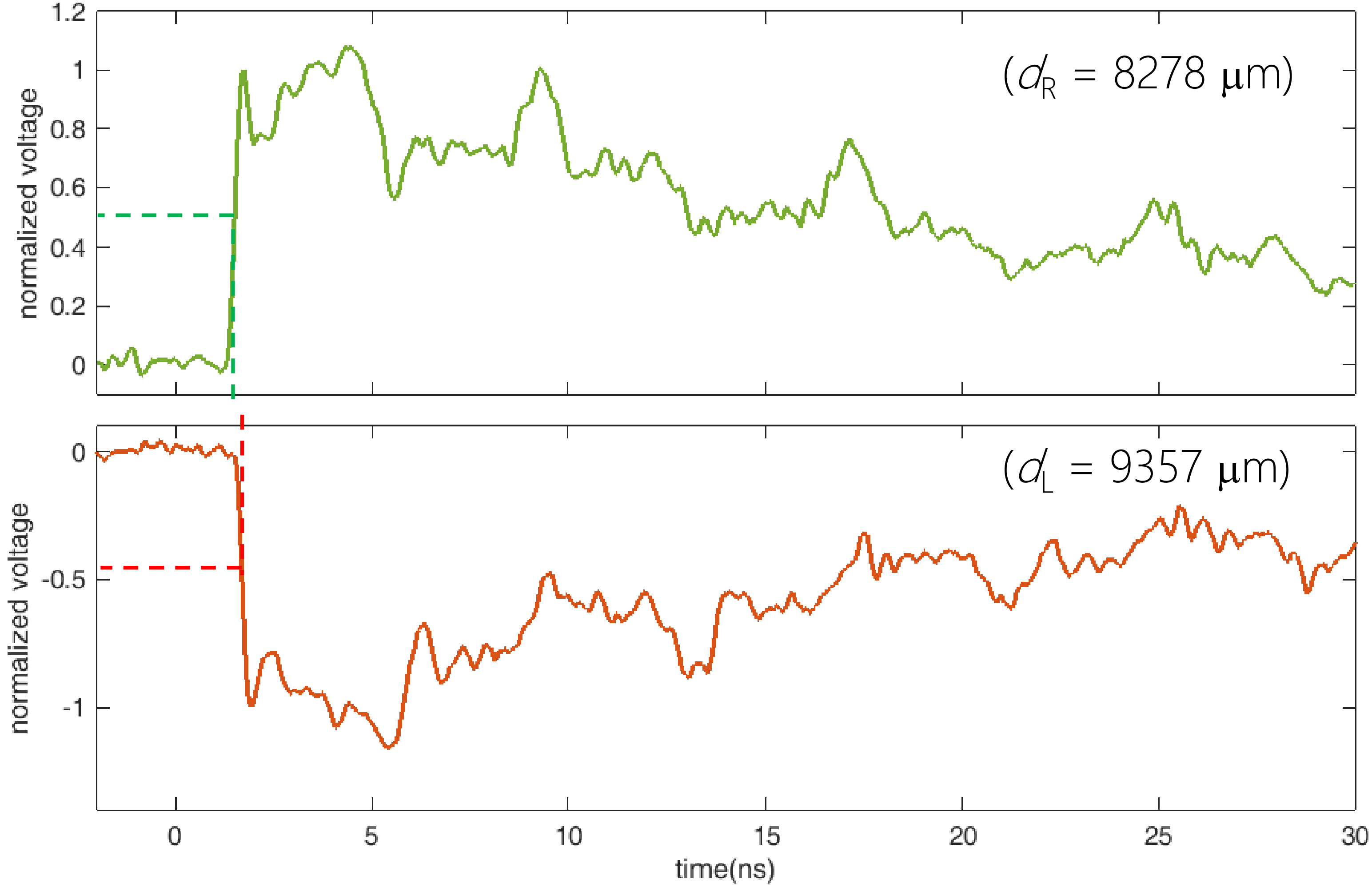
Two connectors for one imager (>500 pixels)

No cryogenic circuit is required



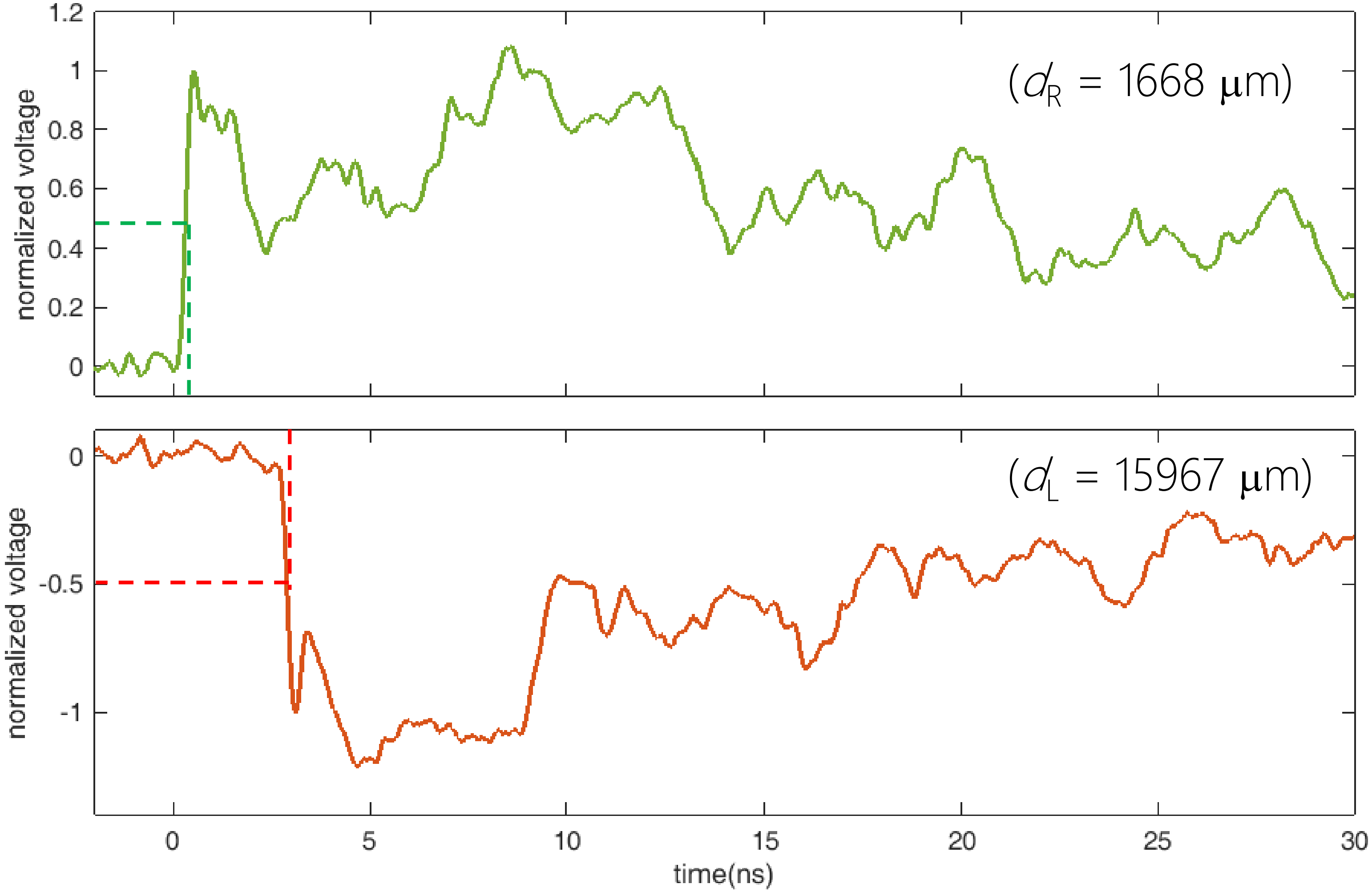
Output pulses from the SNSPI

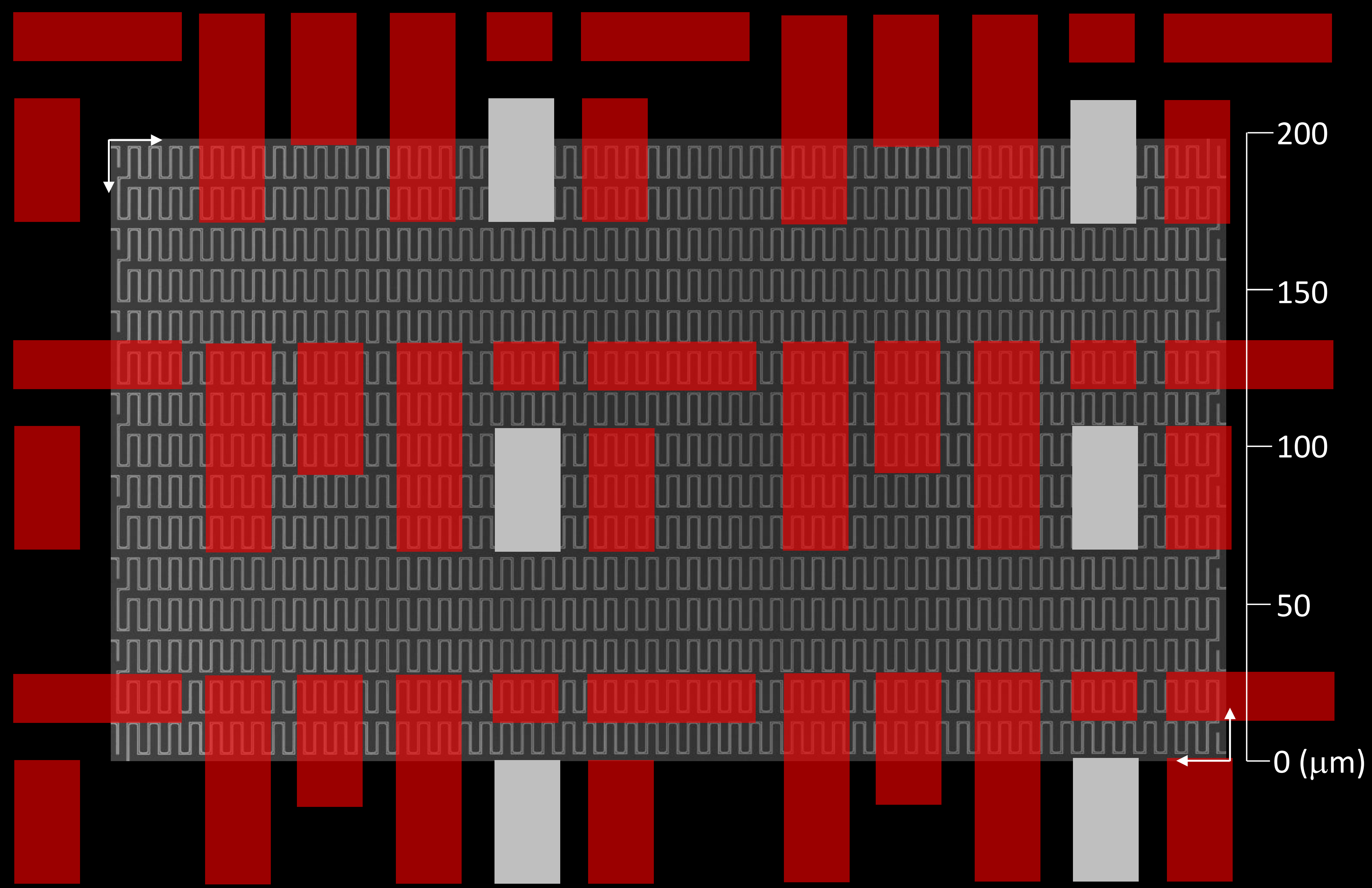
Photon lands near the middle



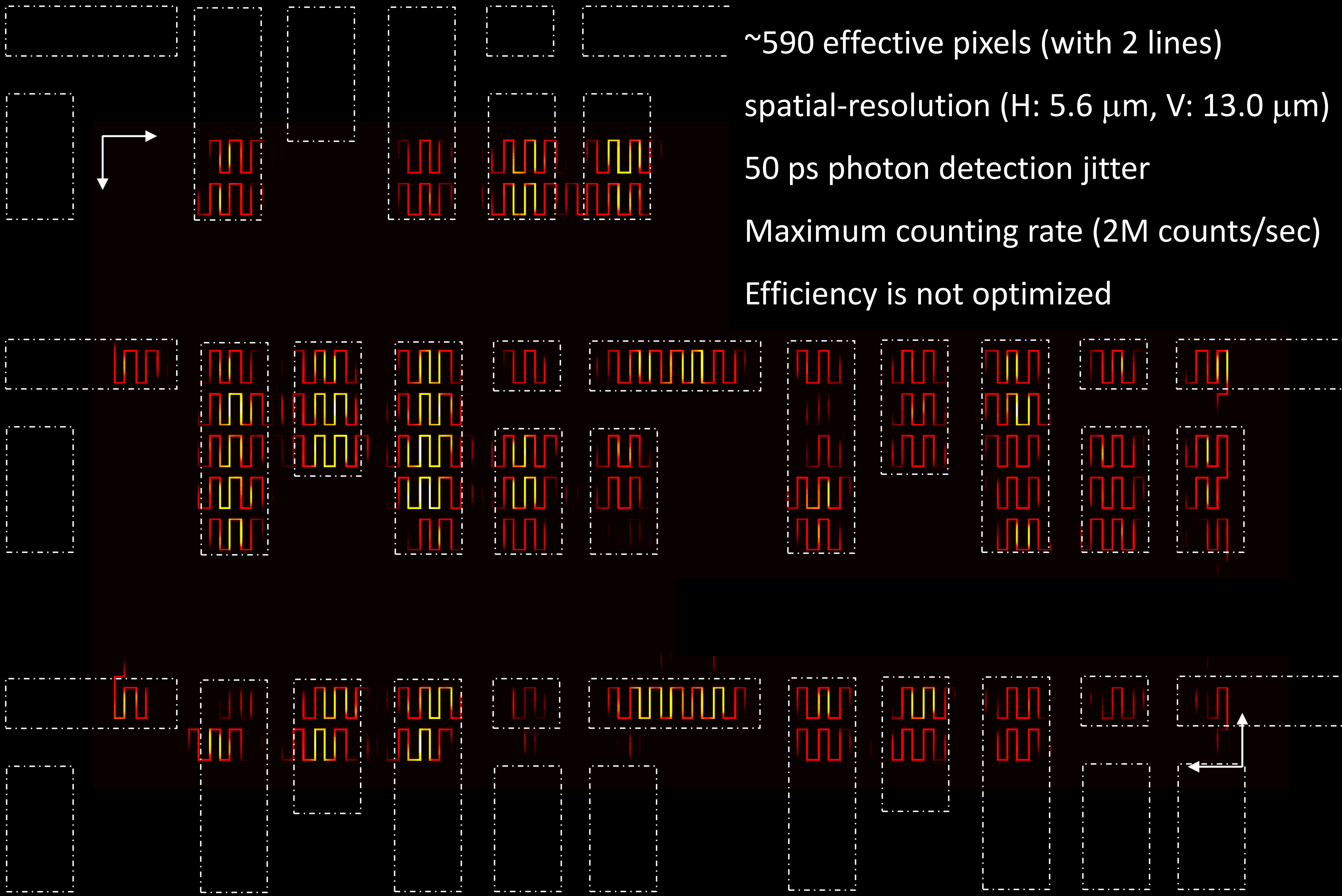
Output pulses from the SNSPI

Photon lands near the right end




200
150
100
50
0 (μm)

Mapping each photon position to form an image



~590 effective pixels (with 2 lines)

spatial-resolution (H: 5.6 μm, V: 13.0 μm)

50 ps photon detection jitter

Maximum counting rate (2M counts/sec)

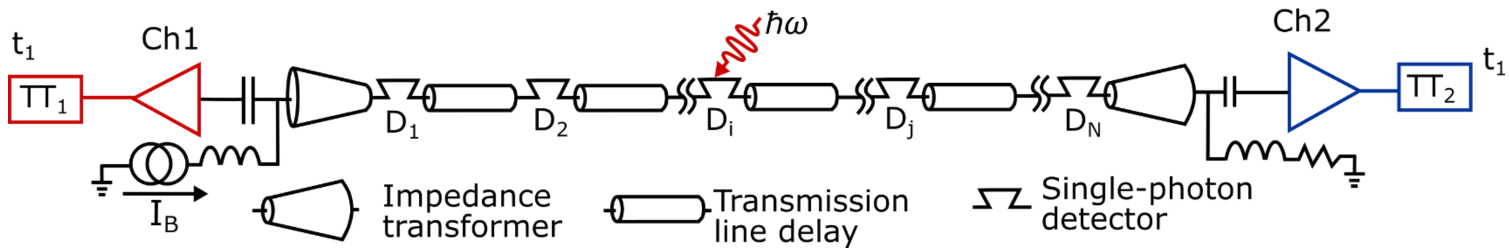
Efficiency is not optimized

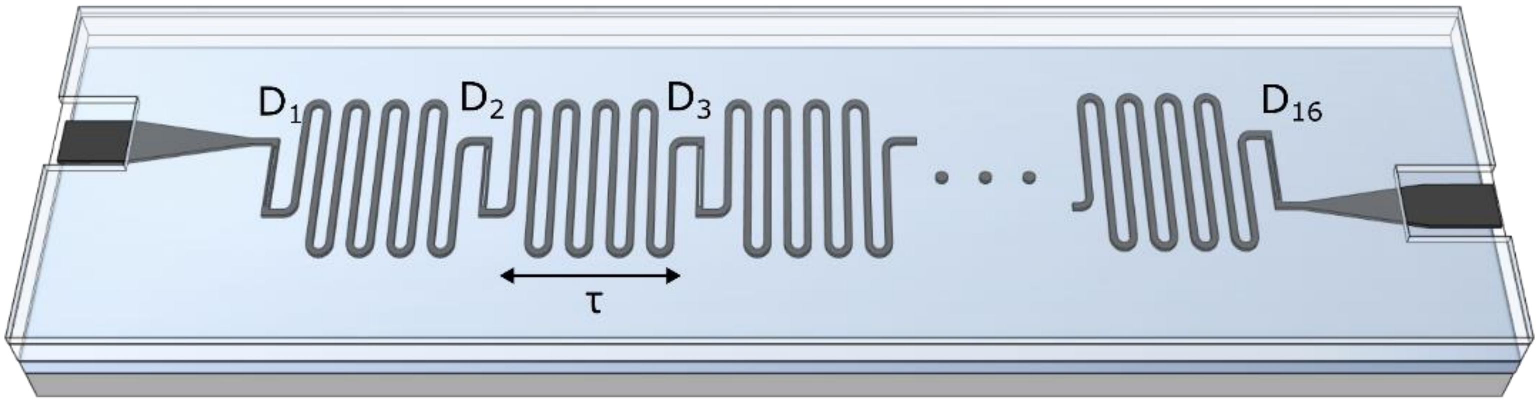
Q.-Y. Zhao, *et.al., “Single-photon imager based on a superconducting nanowire delay line”.* Nature Photonics 11 (4), 247-251

Can We Observe Two-Photon Coincidences?

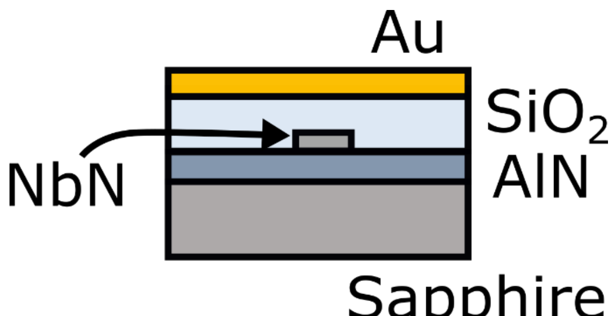
- Assume a pulsed source of photons (not continuous wave sources)
- Assume light will be coupled in via waveguides (not free space)

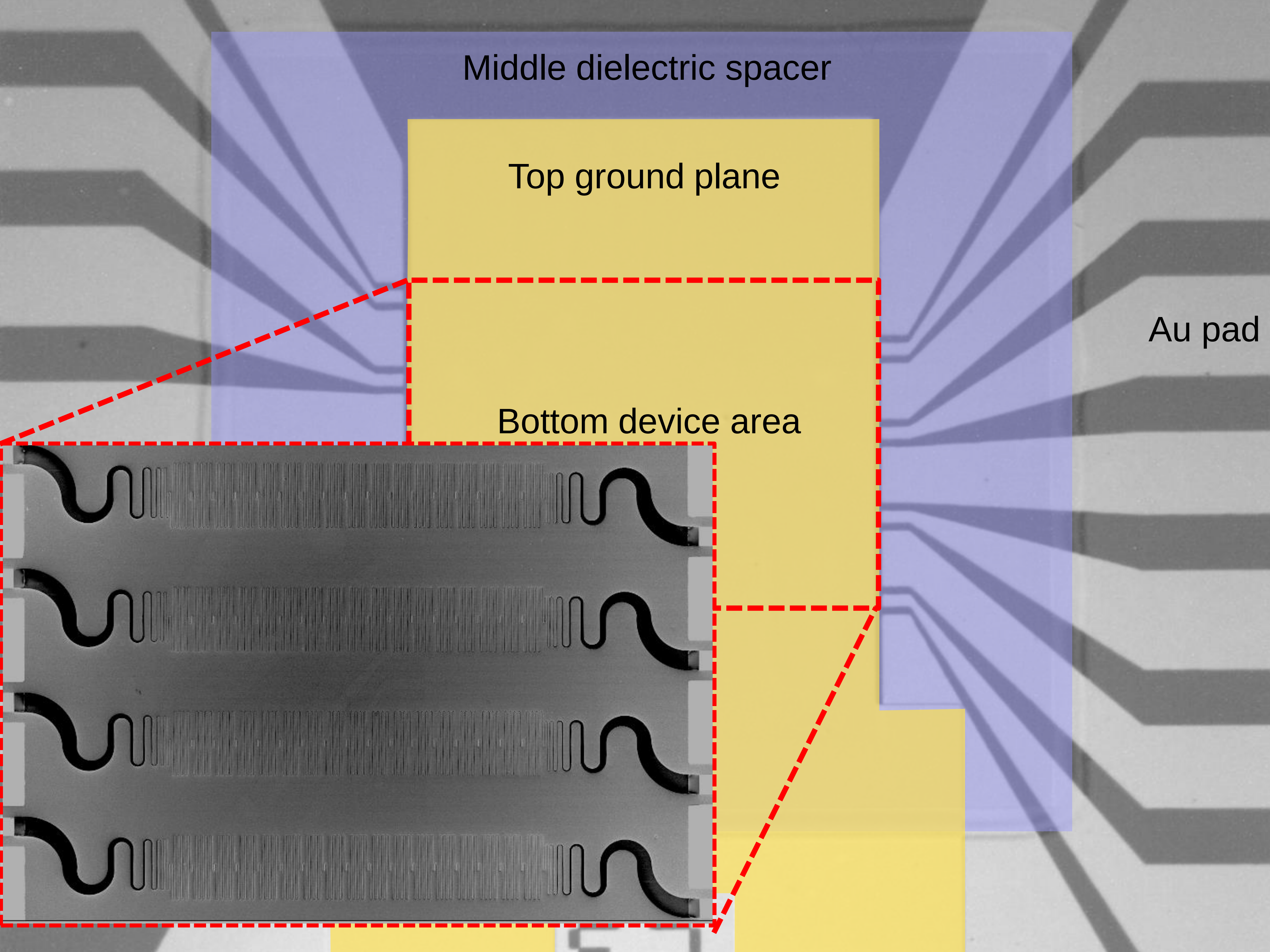
Delay-line Multiplexing



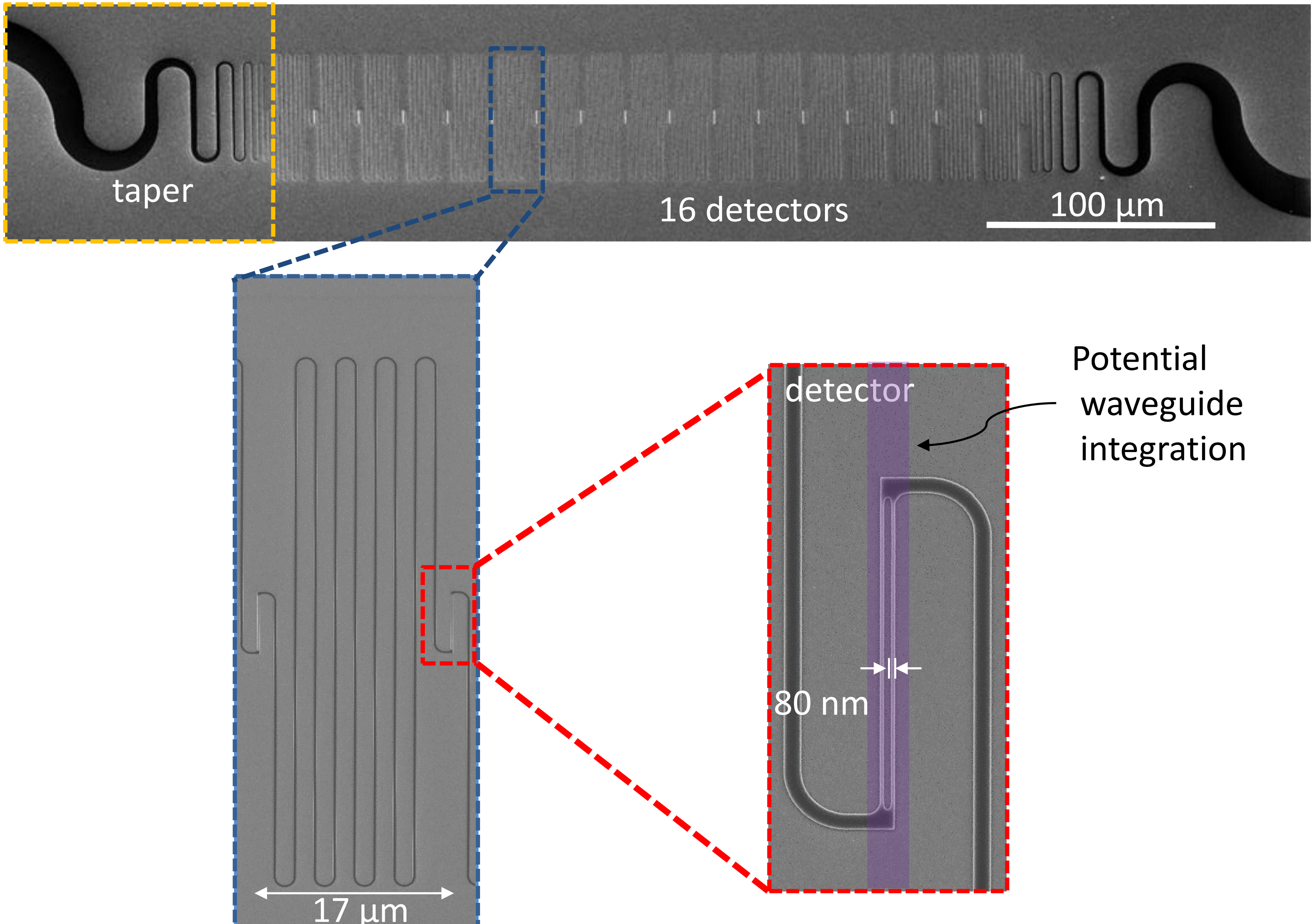


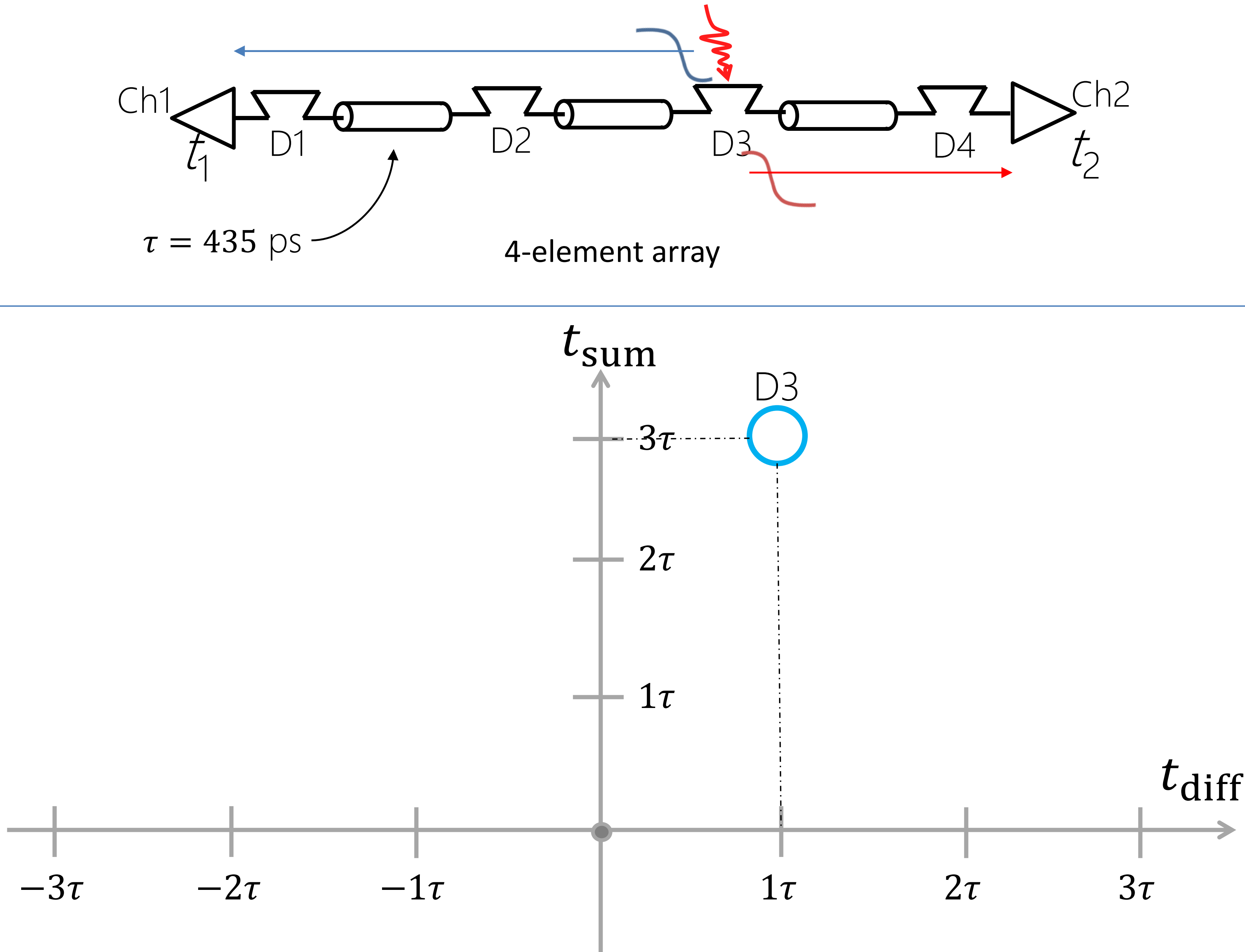
Nanowire microstrip transmission line

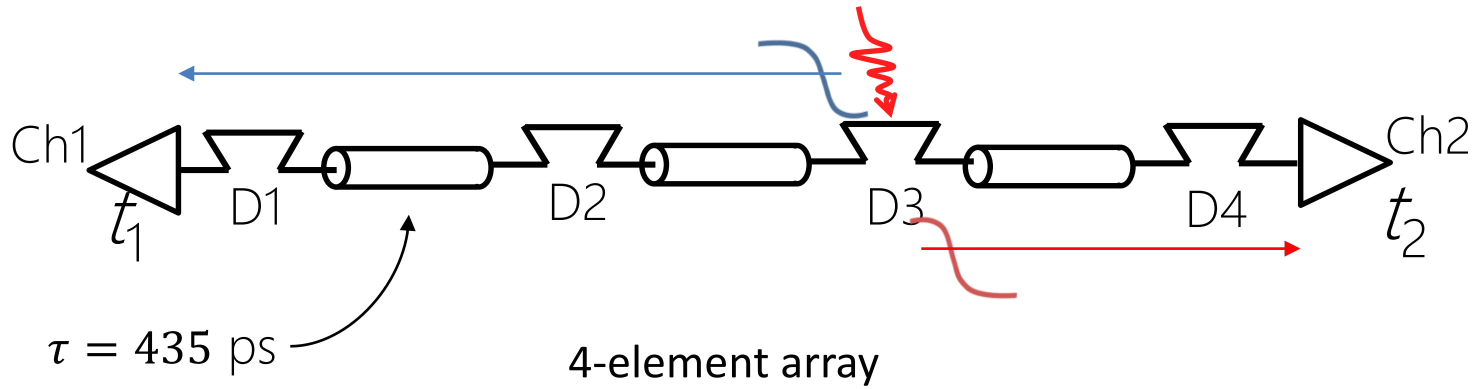



Middle dielectric spacer
Top ground plane
Au pad
Bottom device area

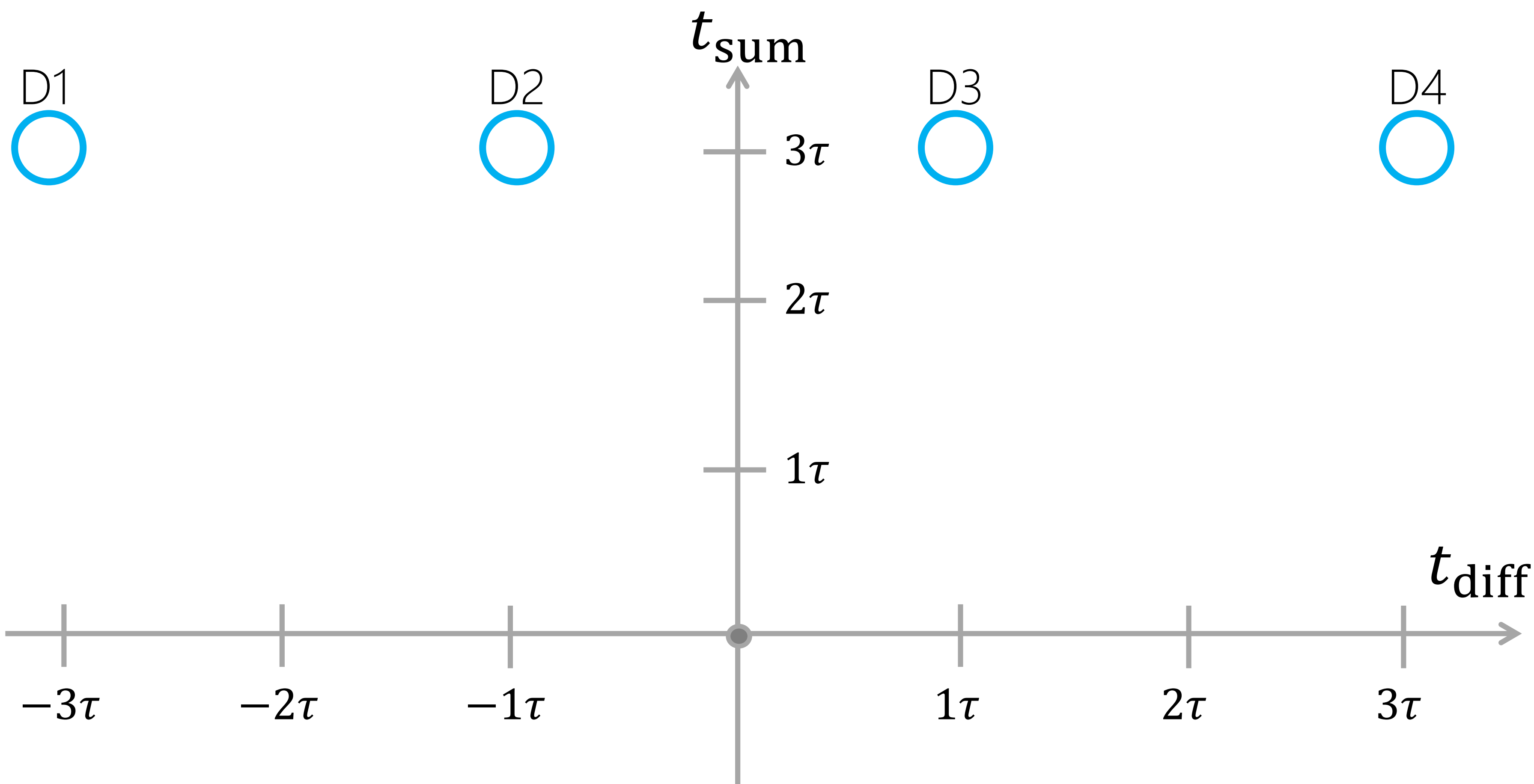
Delay line multiplexing



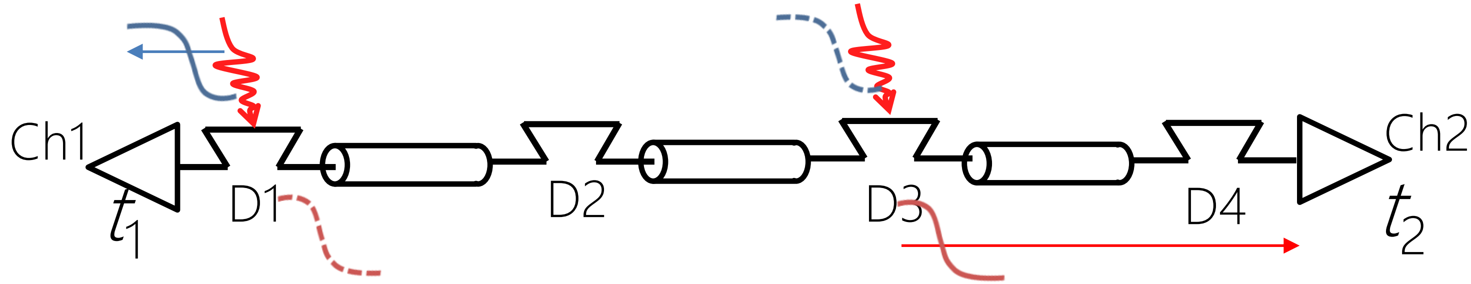

Ch1
Ch2
D1
D2
D3
D4
t_1
t_2
$\tau = 435$ ps
4-element array
t_{sum}
t_{diff}
D3
3τ
2τ
1τ
-3τ
-2τ
-1τ
1τ
2τ
3τ



Ch1
t_1
D1
D2
D3
D4
Ch2
t_2
$\tau = 435$ ps
4-element array

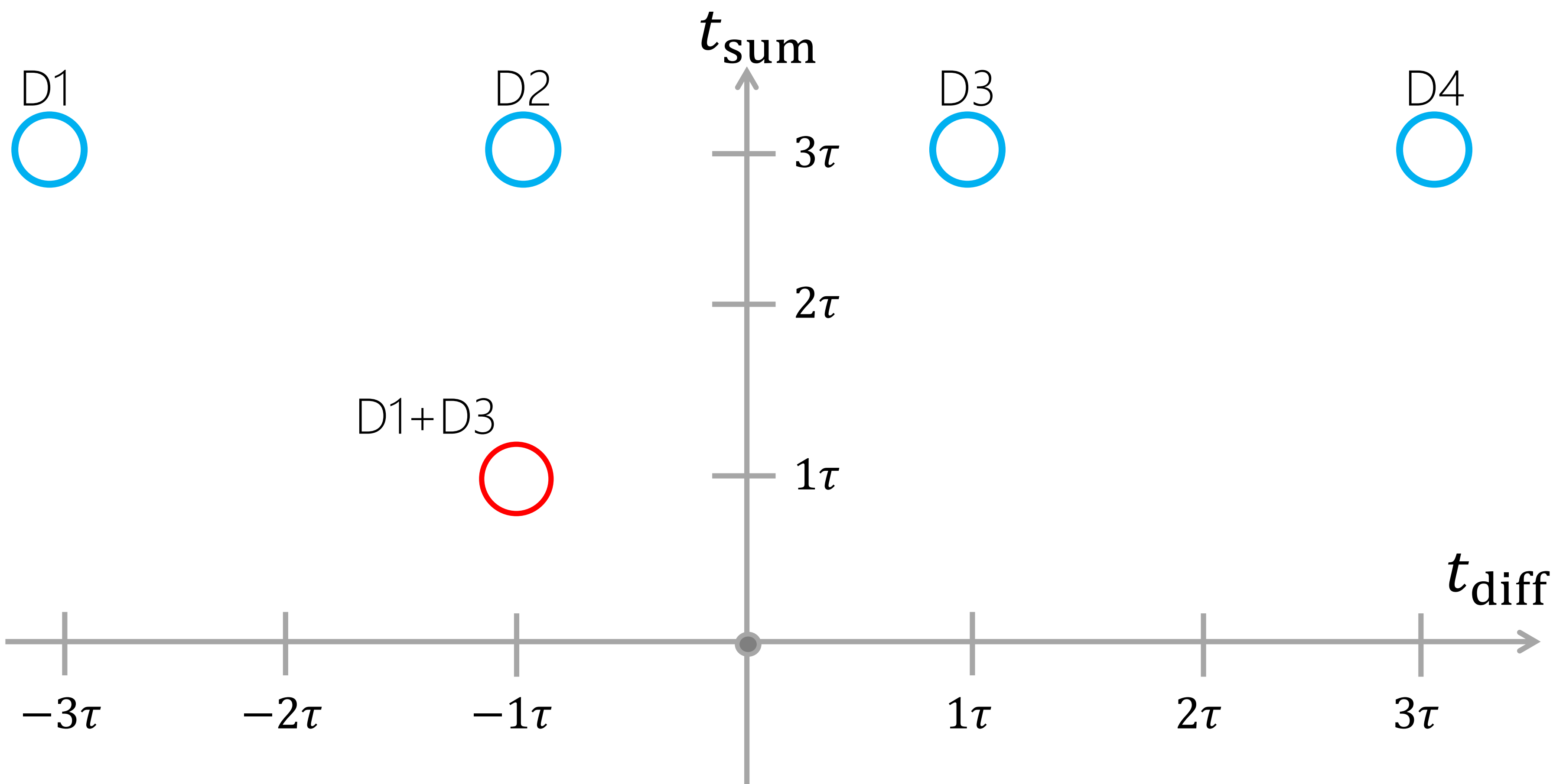


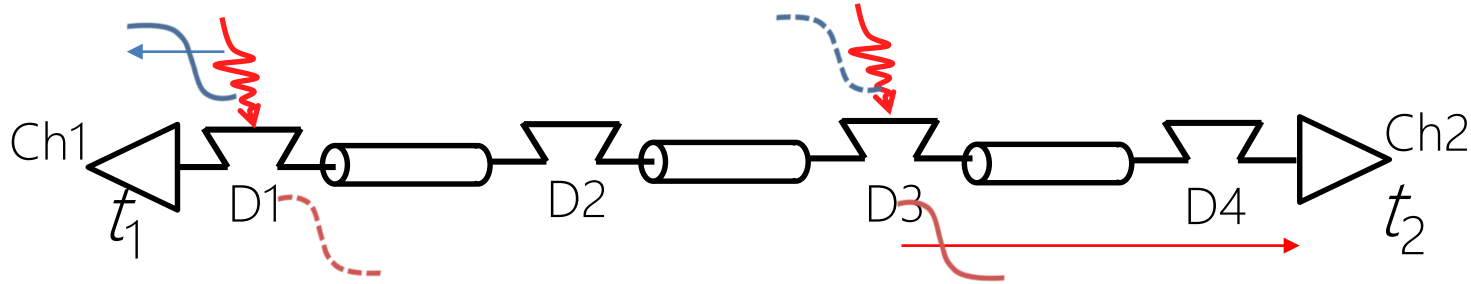
t_{sum}
D1
D2
D3
D4
3τ
2τ
1τ
t_{diff}
-3τ
-2τ
-1τ
1τ
2τ
3τ



4-element array

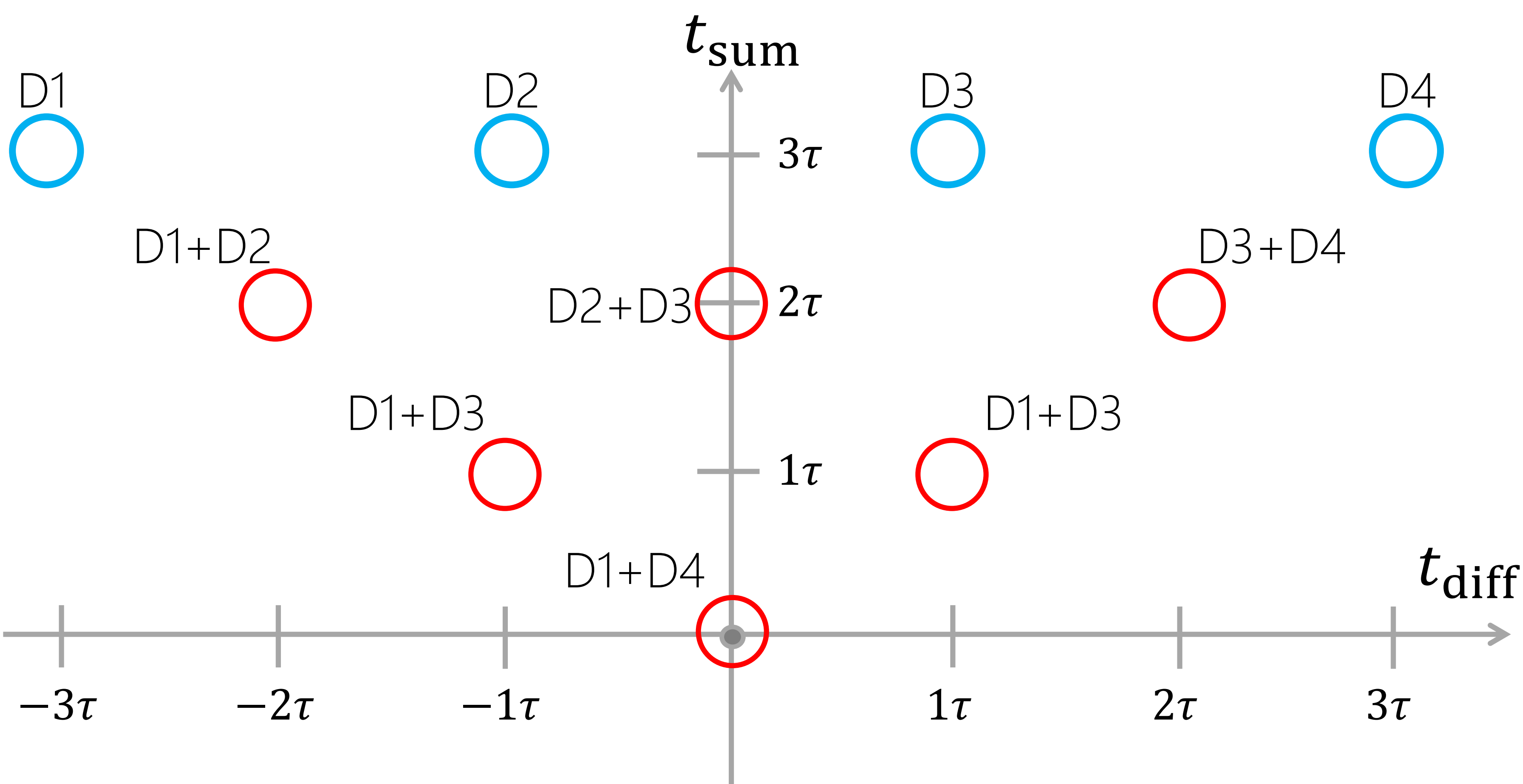
Only the first rising edge at each side is time-tagged

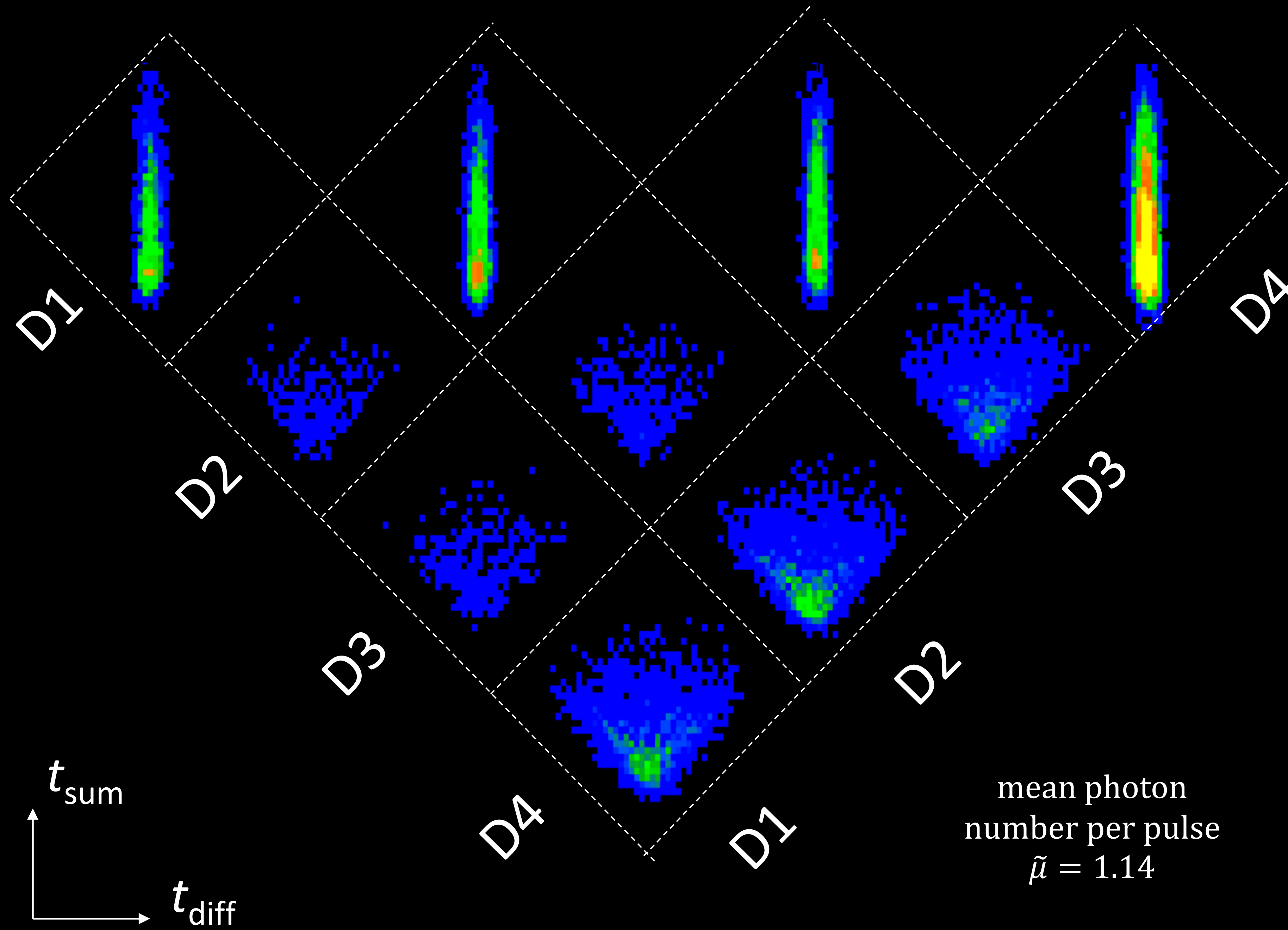




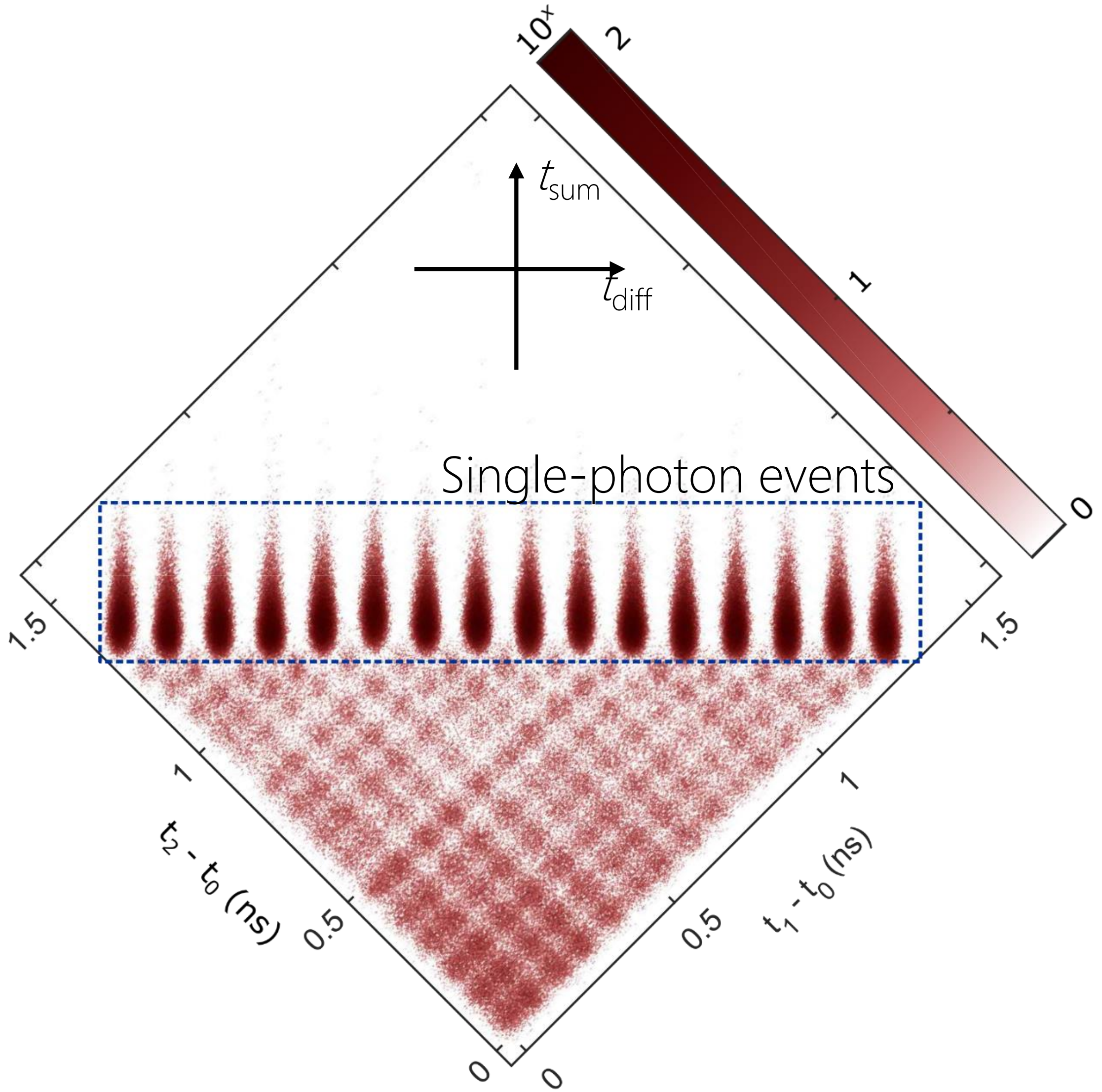
4-element array

Only the first rising edge at each side is time-tagged



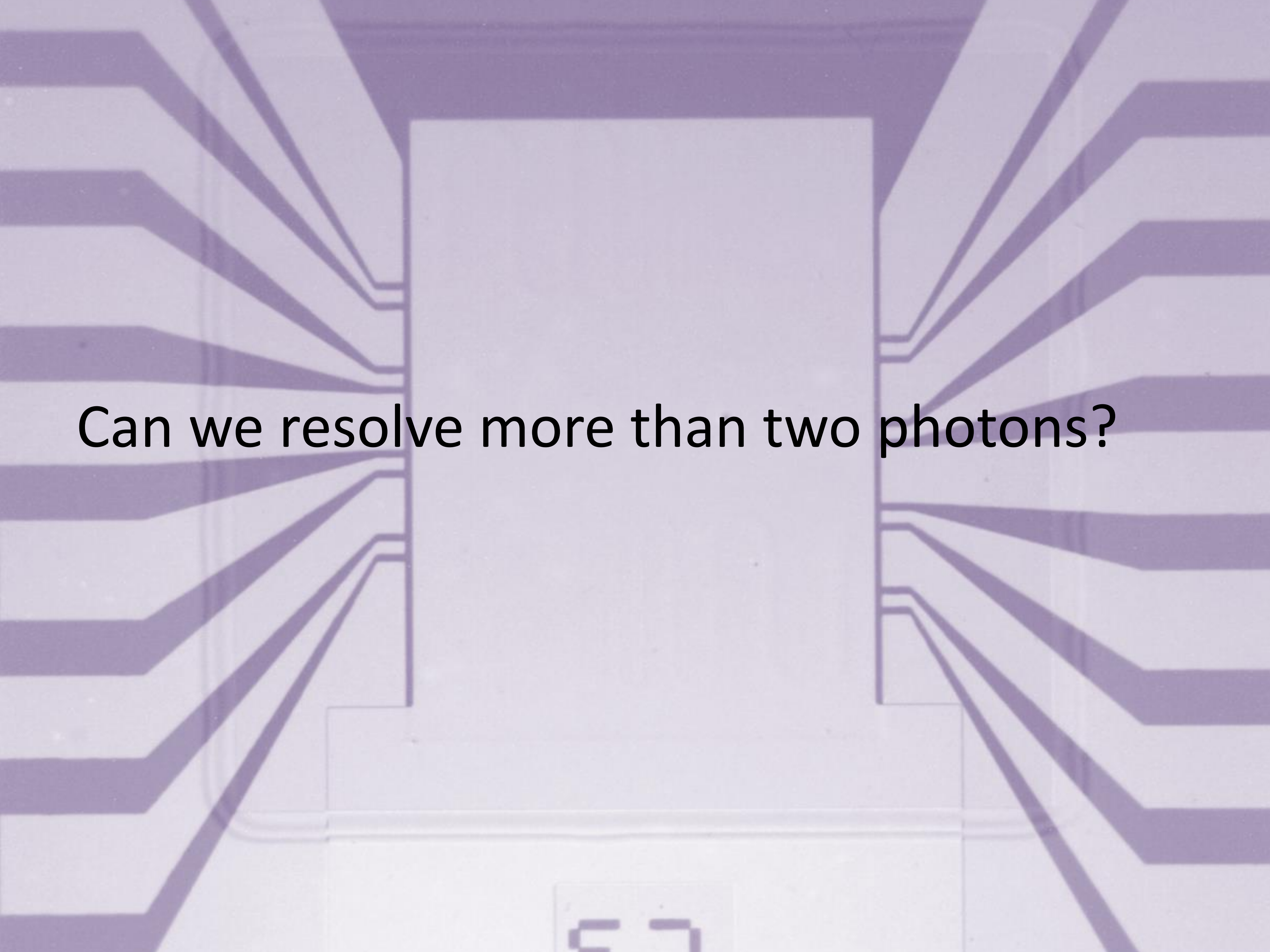

D1
D2
D3
D4
D4
D3
D2
D1
t_{sum}
t_{diff}
mean photon
number per pulse
$\tilde{\mu} = 1.14$

16-Element-detector chain



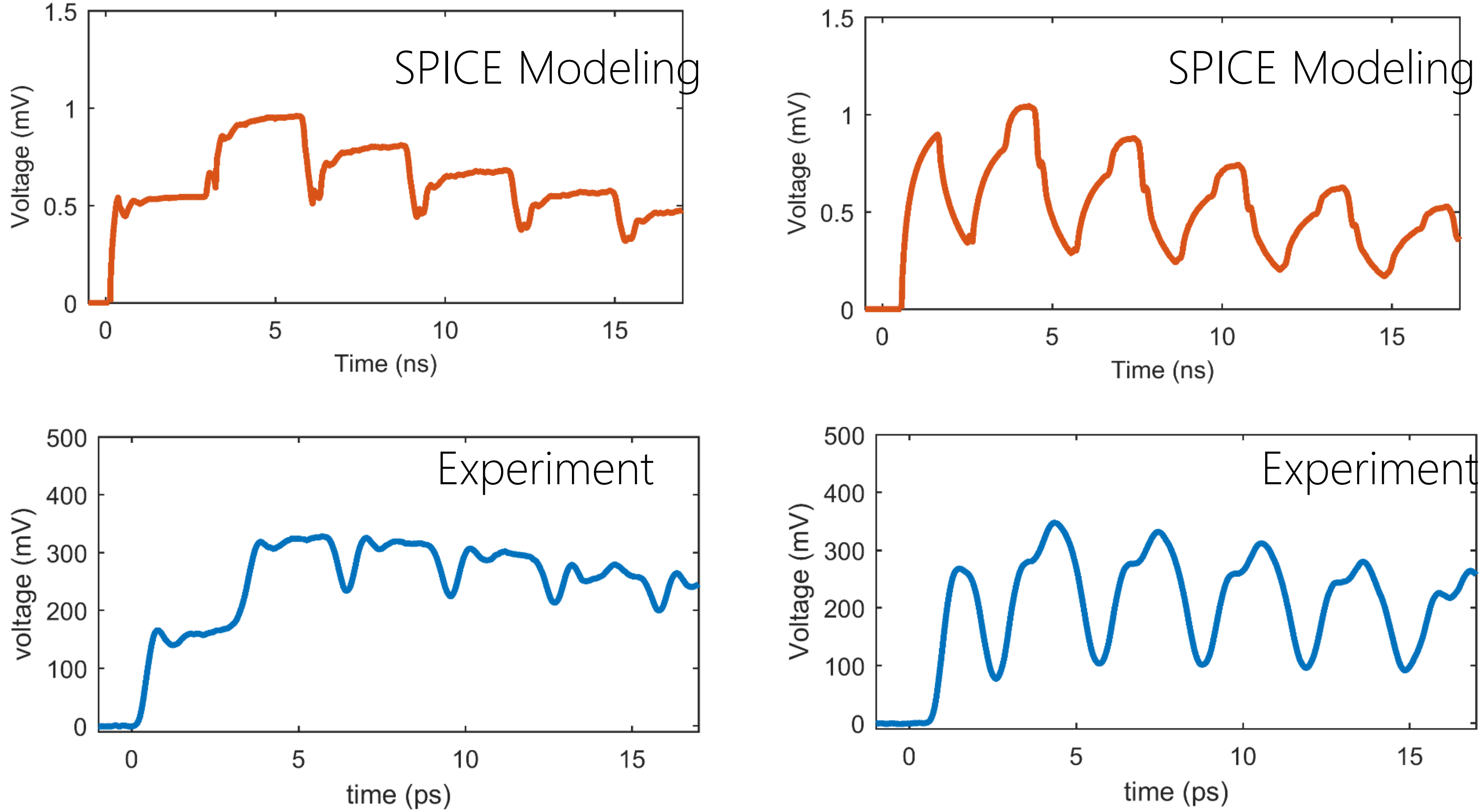
D Zhu, *et. al,* CLEO 2017: Applications and Technology, JTh5B. 4

Can we resolve more than two photons?



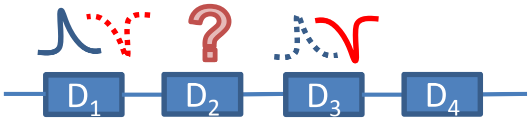
SPICE simulation for the pulse shapes

D_1 Ch1 | D_2 Ch1

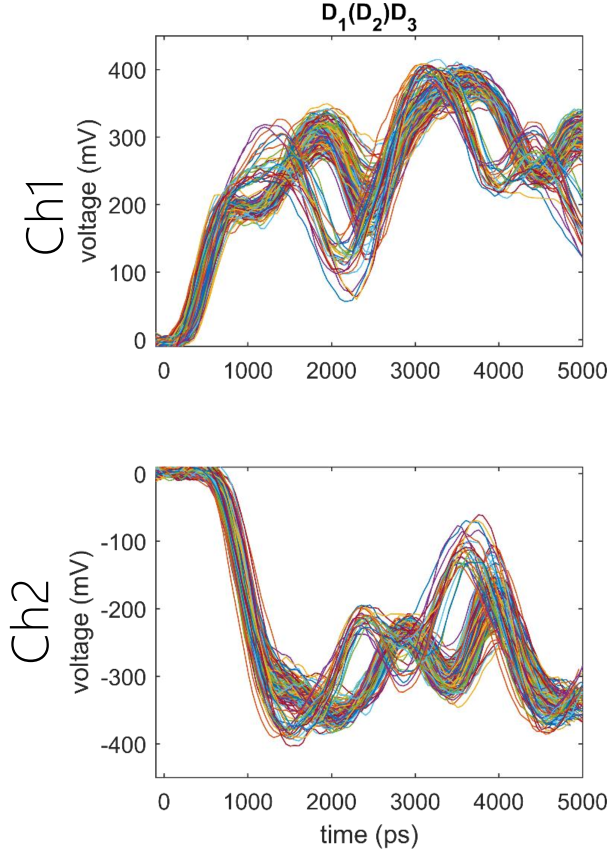


(SPICE modeling w/o amplifier gain and readout bandwidth)

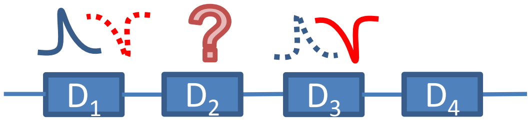
Ambiguous two-photon events



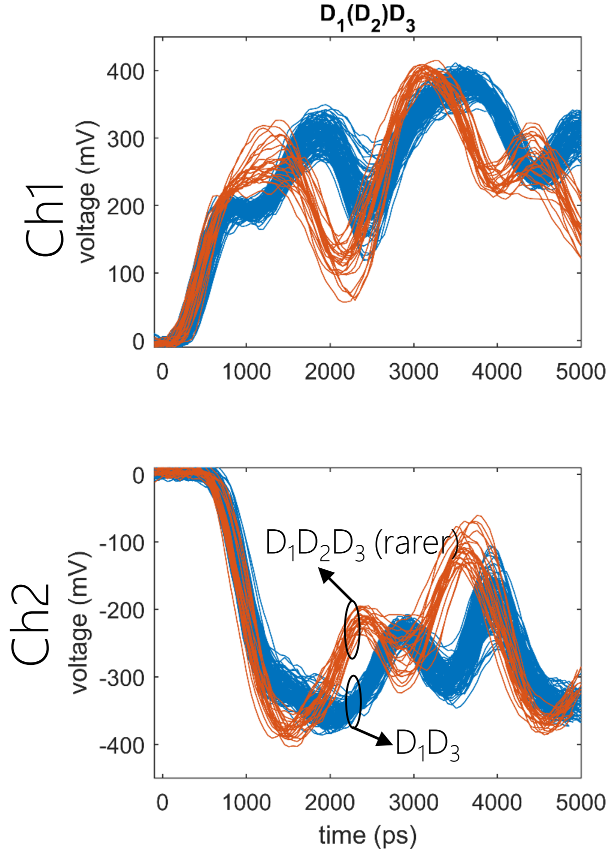
Same time tagging
Two pulse shapes



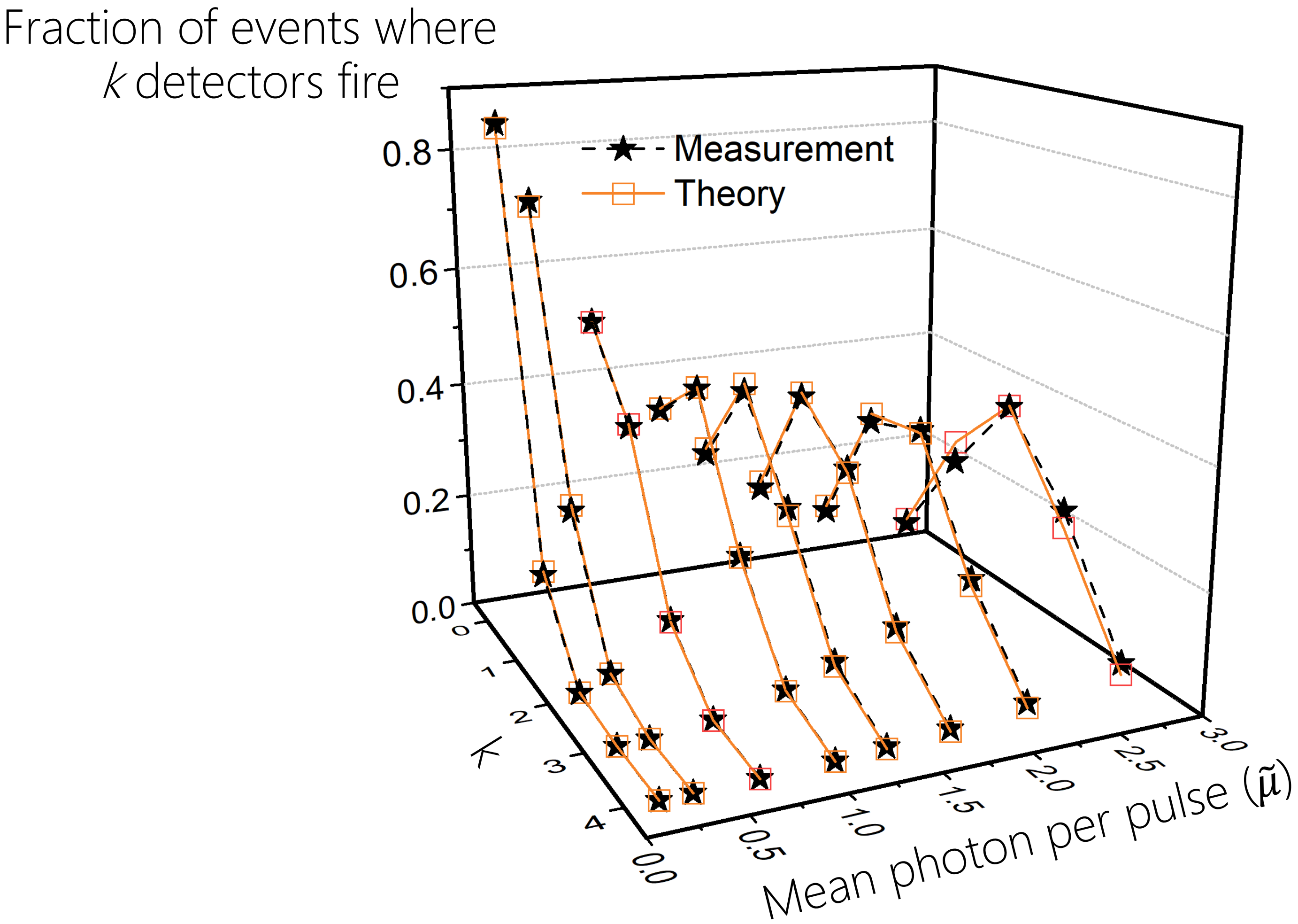
Ambiguous two-photon events



Same time tagging
Two pulse shapes

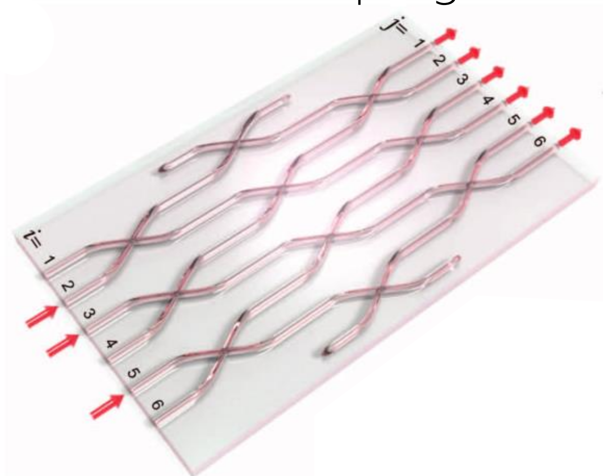


Photon number resolving



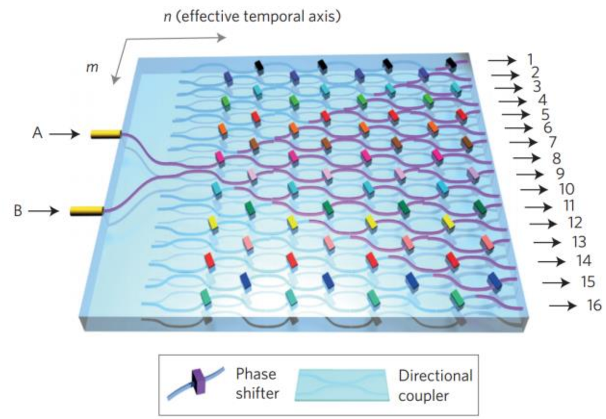
Applications

Boson sampling



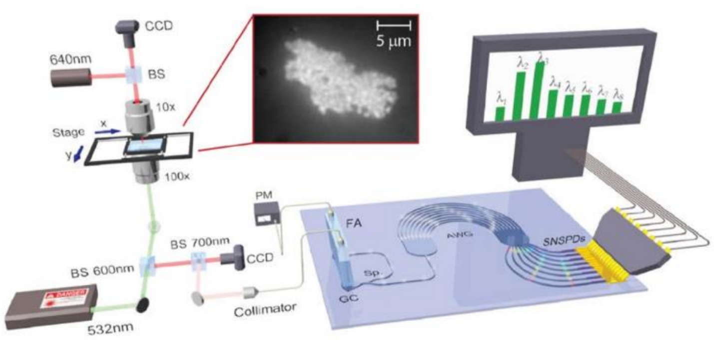
Spring, et al., Science 339 (6121), 798-801 (2013).

Quantum walk/simulation

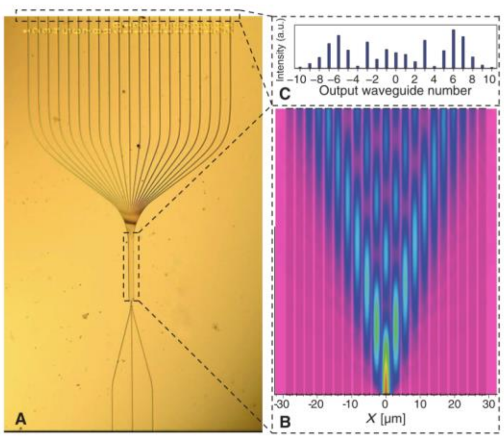


Crespi, et al., Nat. Photon 7, 322–328 (2013)

Single-photon spectrometer



Kahl, et al., arXiv:1609.07857 (2016)



Peruzzo, et al., Science 329 (5998), 1500-1503 (2010)

What Have We Learned?

1. SNSPDs should be treated as distributed elements
2. Speed of light is extremely slow in these materials

Where Are We Going?

1. Photon-number resolution
2. Large imaging arrays
3. Even-shorter jitter
4. Apply slow-light effect to other kinds of devices and applications

Superconductivity Team in QNN Group

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(Now Prof.,
Nanjing U.)

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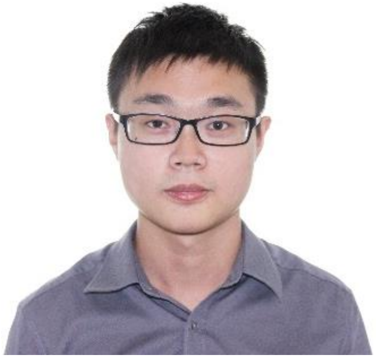
(NASA Fellow)

Reza Baghdadi
(Post-Doc)

Emily Toomey
(NSF Fellow)



Di Zhu
(A*Star Fellow)

Brenden Butters
(Grad Student)

Murat Onen
(Grad Student)

<u>Graduated/Former</u>

Nathan Abebe
Lucy Archer
Francesco Bellei
Ignacio Estay Forno
Niccolo Calandri
Yachin Ivry
Adam McCaughan
Faraz Najafi
Kristen Sunter
Hao-Zhu Wang


Thank you!

Backup slides!

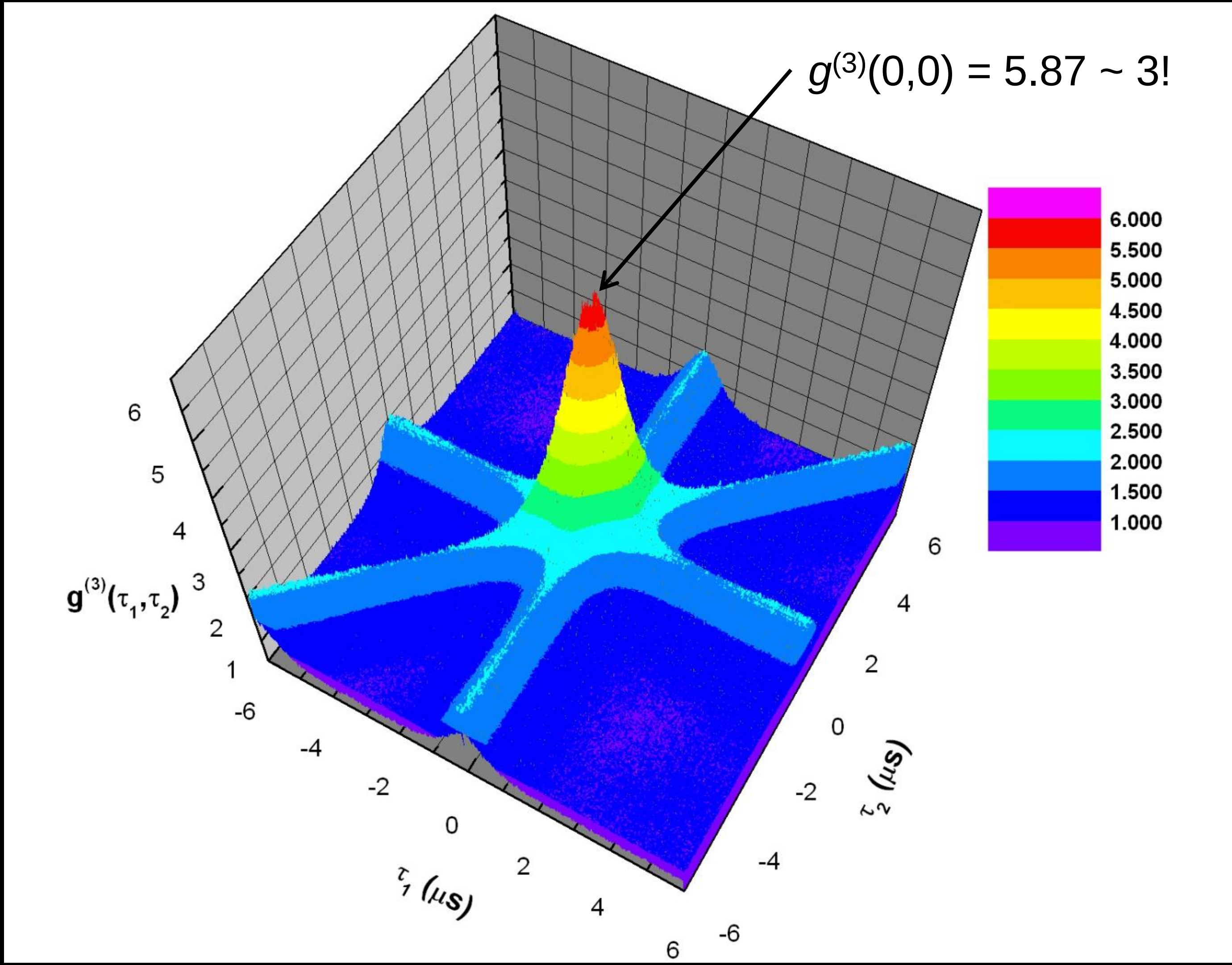
VLSI Circuit Evaluation

- VLSI circuit imaging and debugging
- SNSPD enables performance advances

Image courtesy of DCG Systems

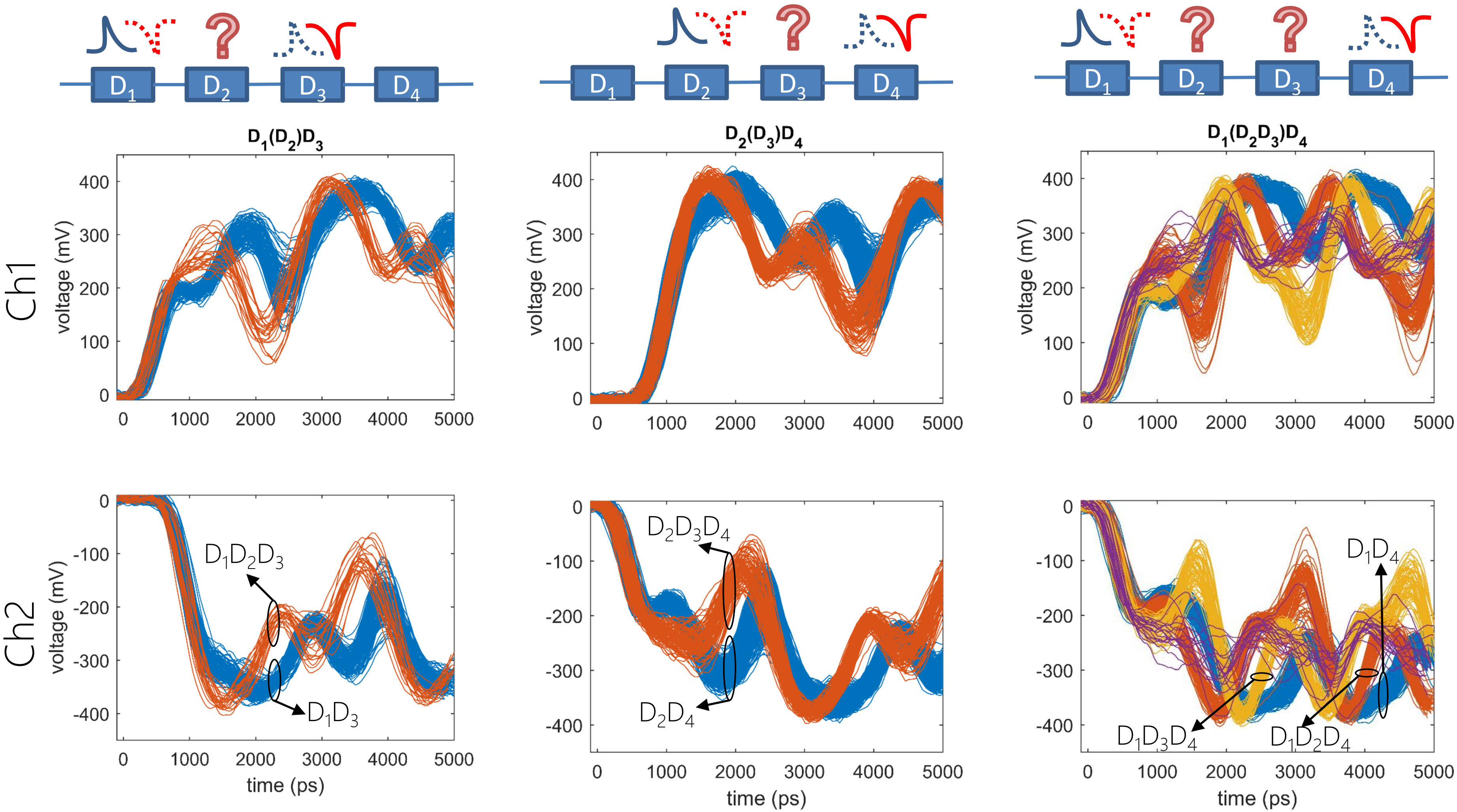
Collaboration between BU, DCG Systems, IBM, Photonspot, funded by IARPA

3rd-order Intensity Correlations

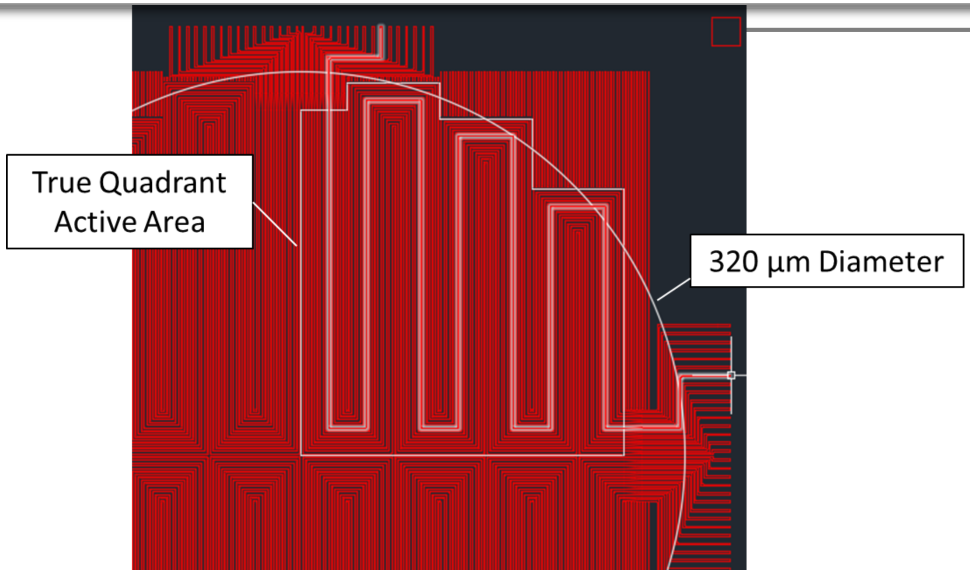


"High-order temporal coherences of chaotic and laser light", Stevens, Baek, Dauler, Kerman, Molnar, Hamilton, Berggren, Mirin, and Nam, *Optics Express, 18, 1430 (2010)*

Ambiguous two-photon events

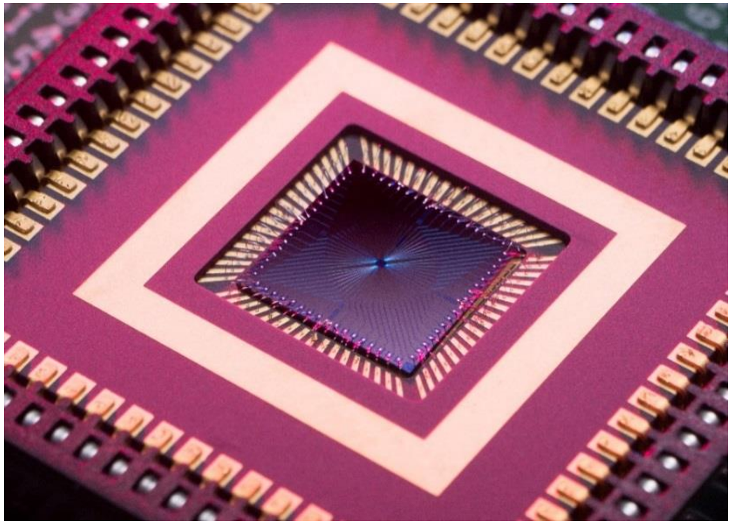


Large-Area 64-pixel SNSPD Arrays



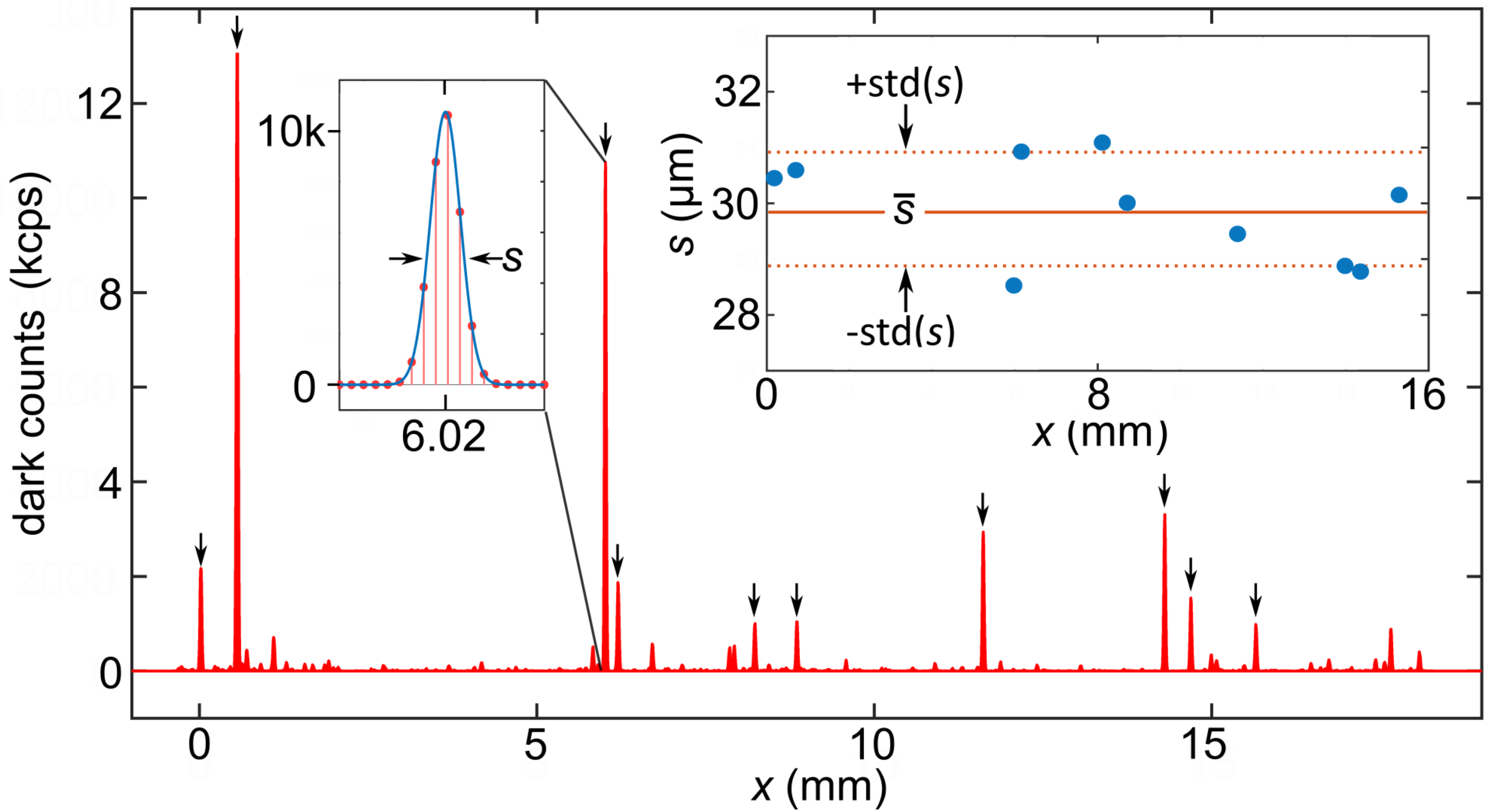
Work supported by NASA Deep Space Optical Communication Project

- 64 pixel WSi SNSPD array, 97% yield
- 320 µm diameter, free space coupling
- 74% System Detection Efficiency
- 1.1 Gcps maximum count rate
- < 150 ps FWHM timing jitter
- Background limited dark counts
- Interdigitated pixels offer pseudo-PNR

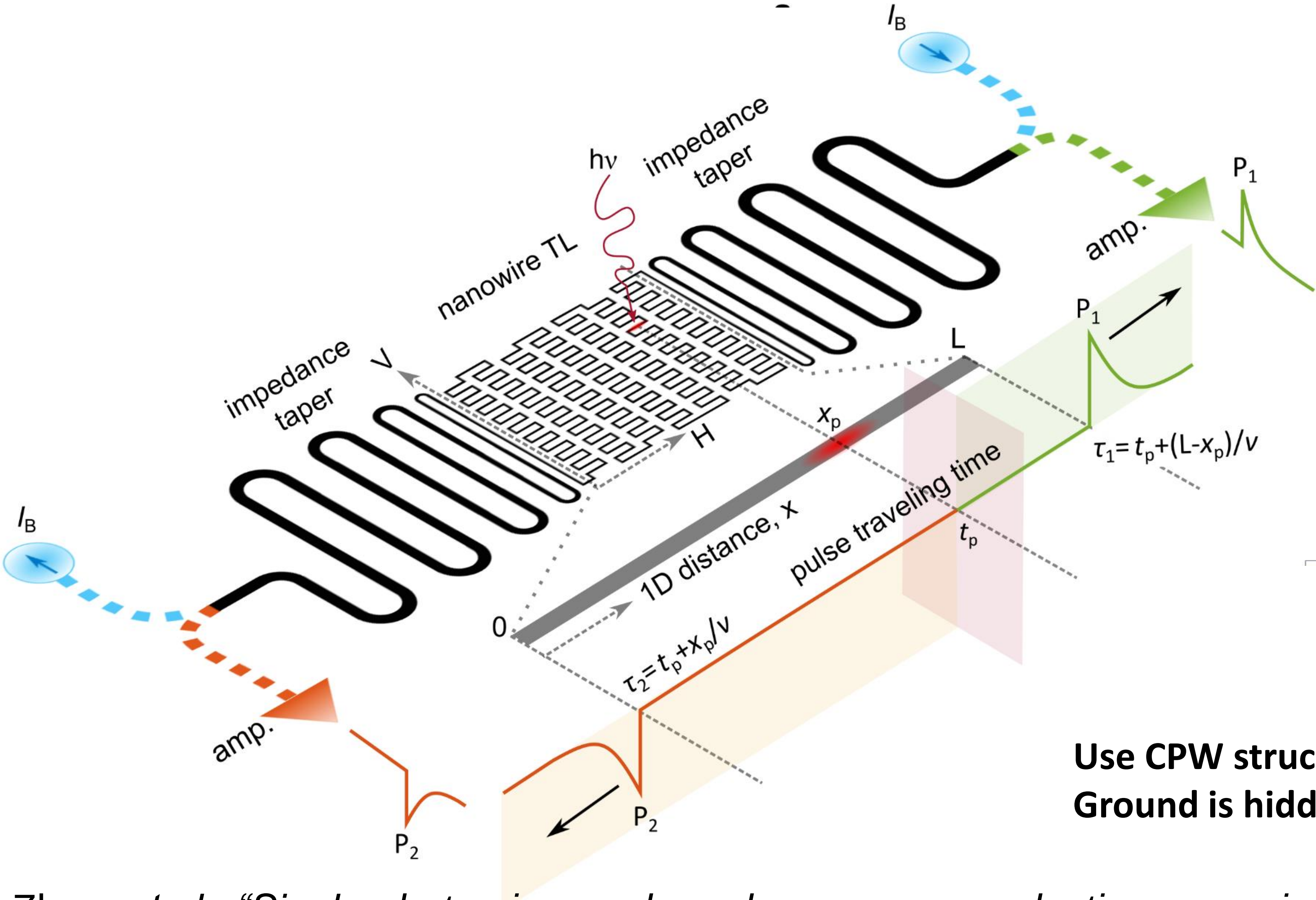


Jason Allmaras, Andrew Beyer, Ryan Briggs, Francesco Marsili, Bill Farr, and Matthew Shaw

Dark count map



SNSPI: superconducting nanowire single-photon Imager

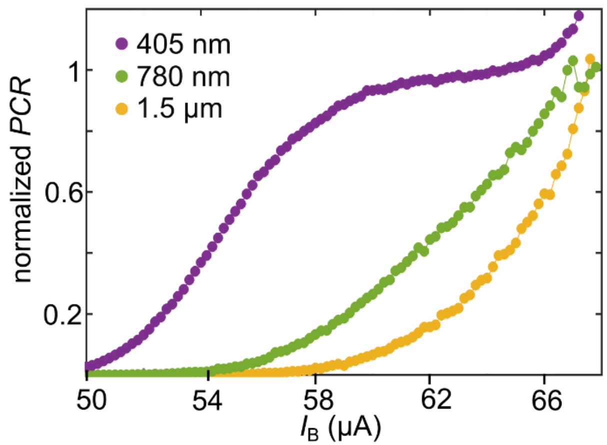


Use CPW structure
Ground is hidden

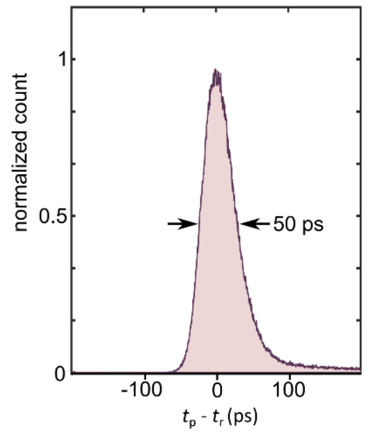
Q.-Y. Zhao, *et.al., "Single-photon imager based on a superconducting nanowire delay line".* Nature Photonics 11 (4), 247-251

Detection performance

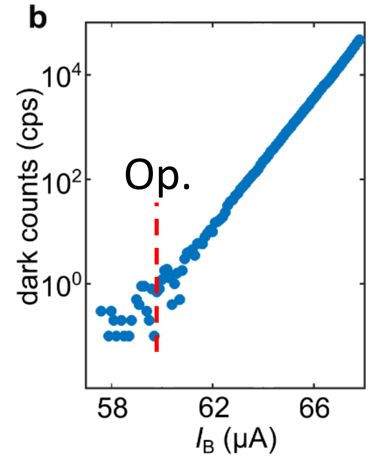
SNSPD-like *DE*



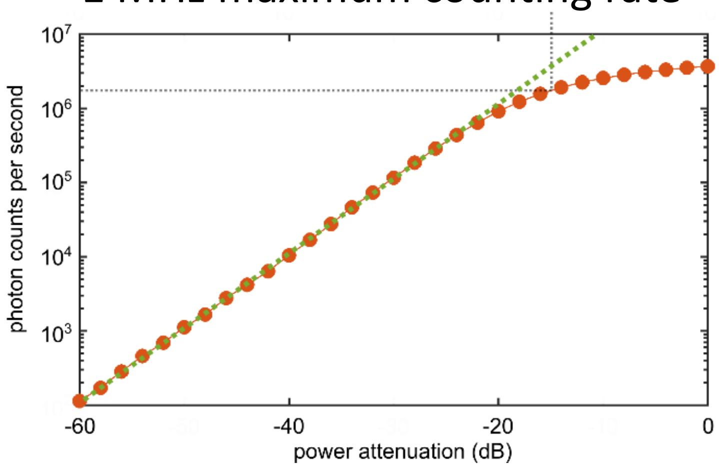
50 ps detection jitter



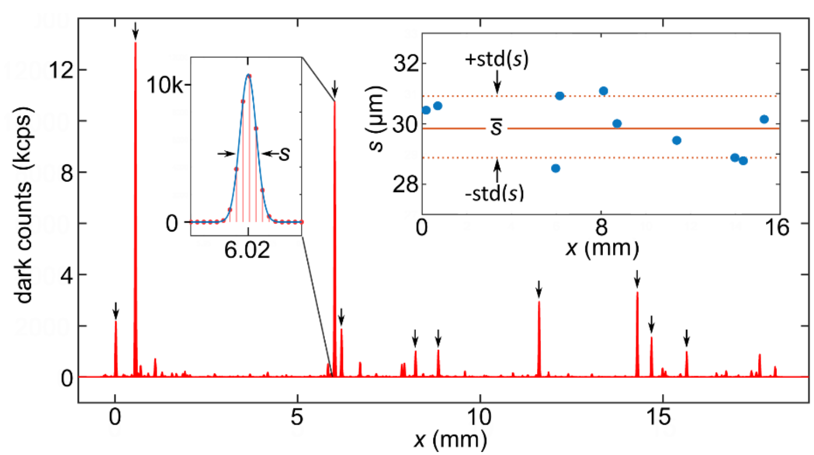
1 cps dark count



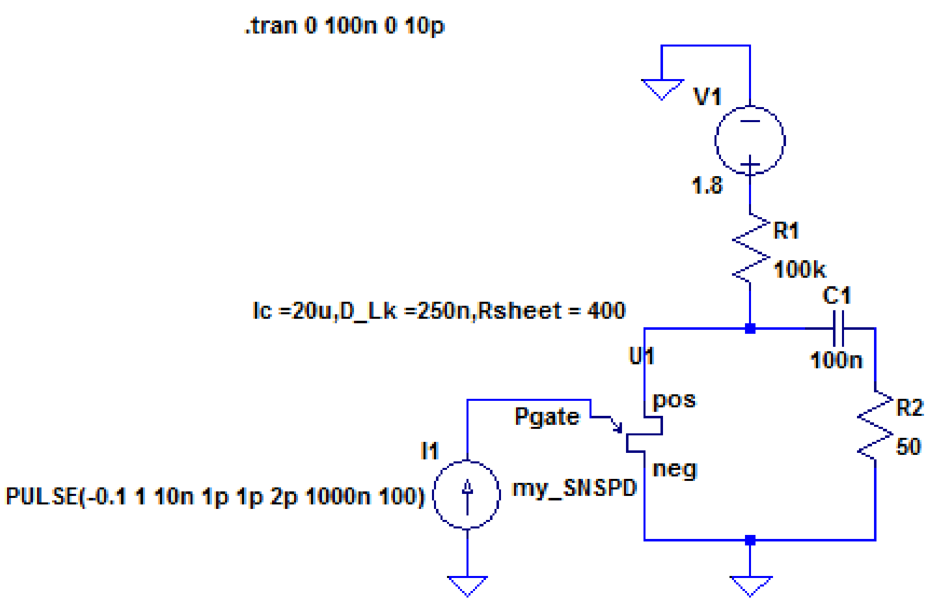
1 MHz maximum counting rate

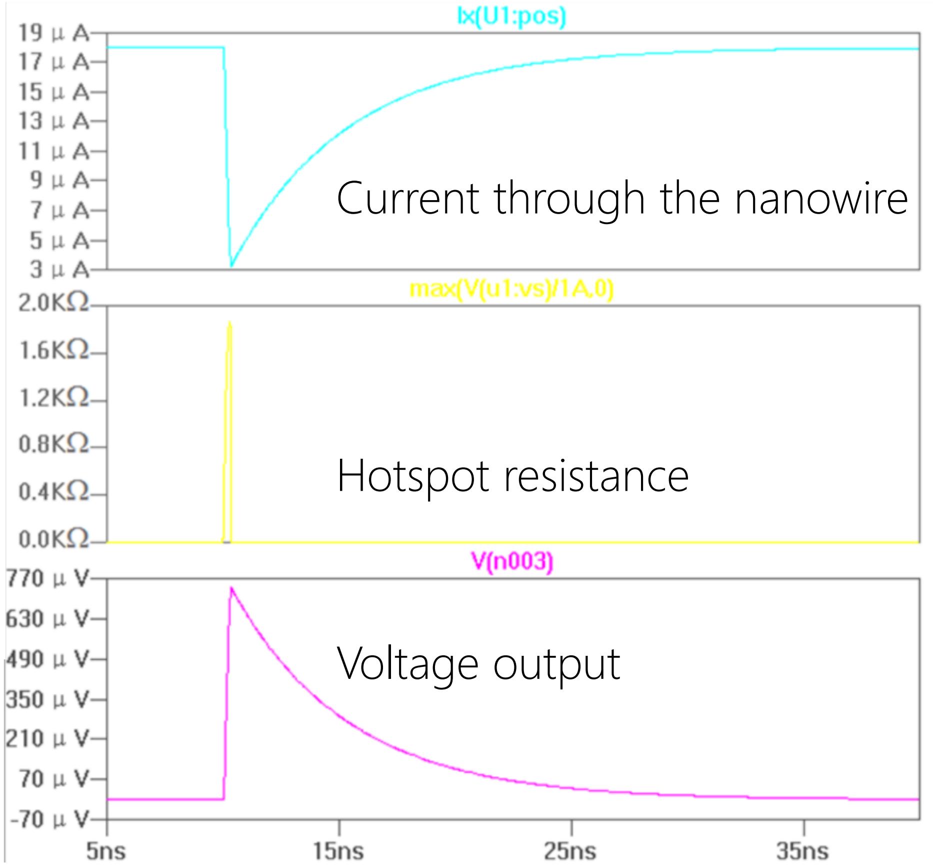


Fewer constrictions contributing for DCR



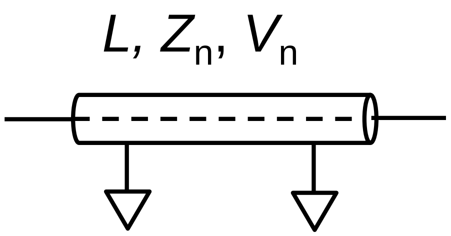
SPICE circuit simulation including simplified eletrothermal model





The device is treated as a lumped device. It gives NO information of the photon hit location.

Low velocity and high impedance superconducting nanowire transmission/delay line



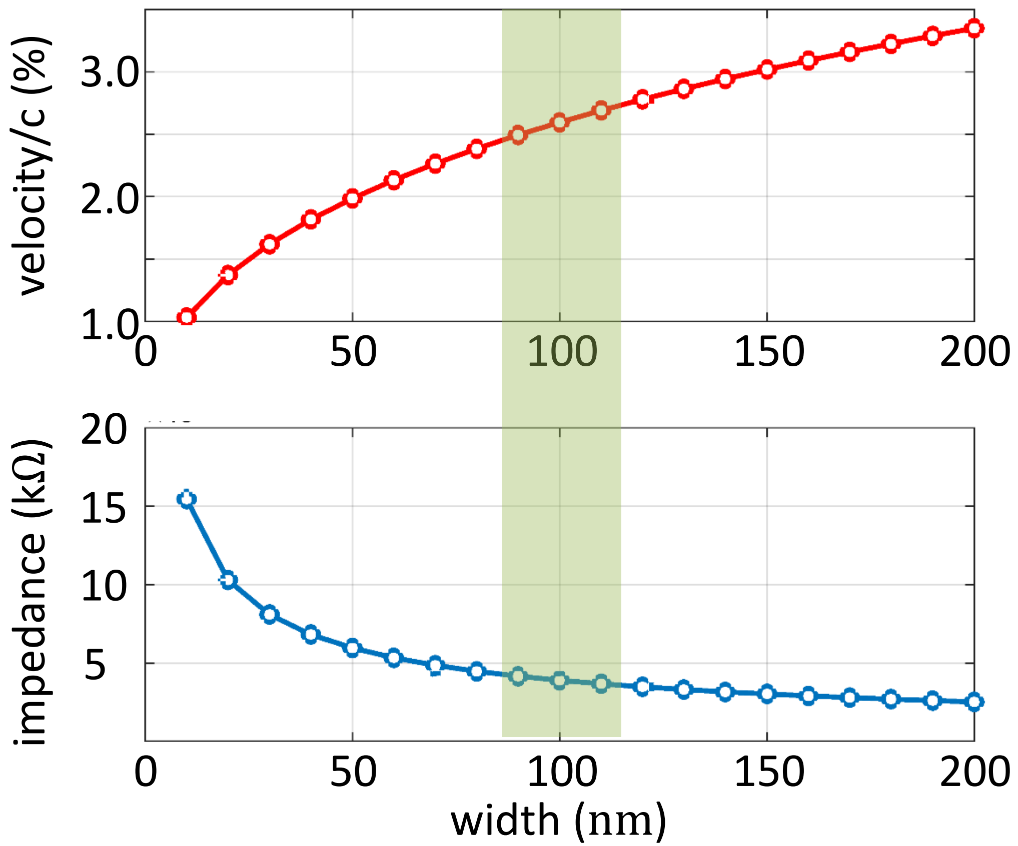
Lumped model of transmission lines

$$v = \sqrt{\frac{1}{LC}} \qquad Z = \sqrt{\frac{L}{C}}$$

$$L = L_K + L_G \cong L_K$$

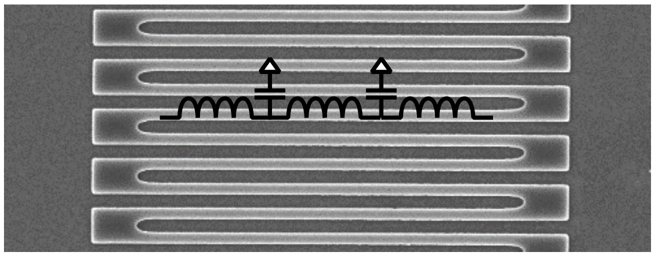
velocity = 2.5%c = 7.5 μm/ps

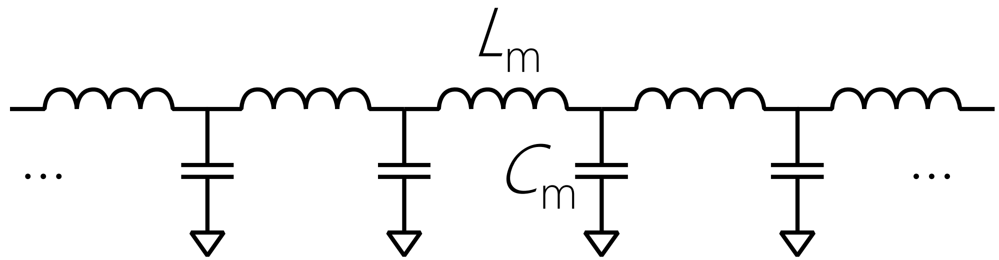
impedance = 4 kΩ



NbN nanowire: 100 nm wide, 50 pH/square

Microwave transmission line





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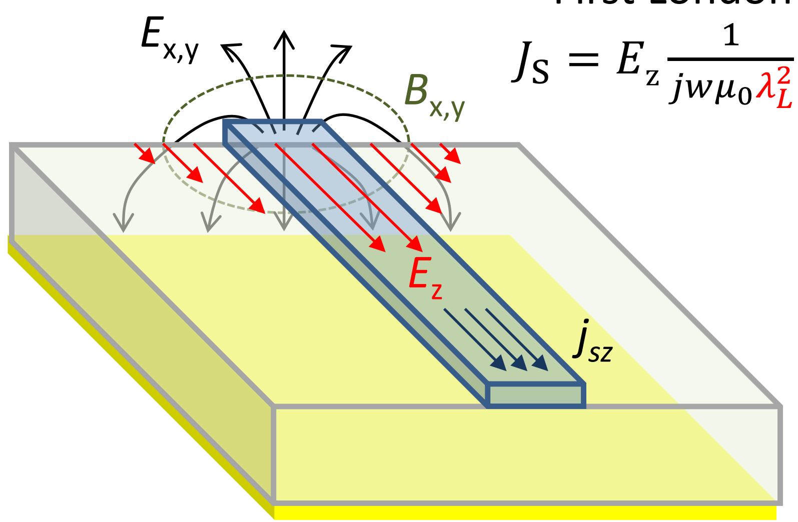
First London equation

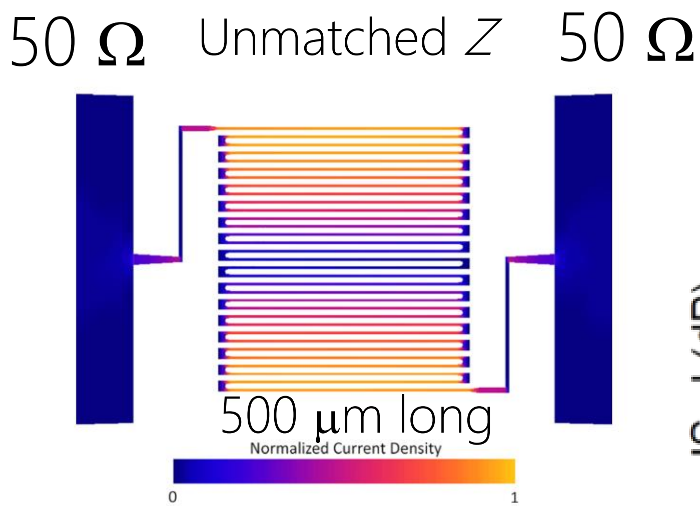
$$J_S = E_z \frac{1}{jw\mu_0\lambda_L^2} = E_z \frac{1}{jwL_{kS}d}$$

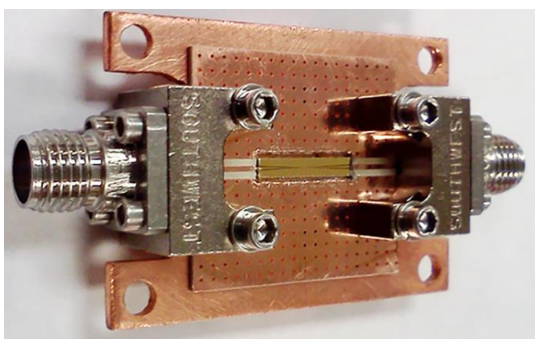


Questions?

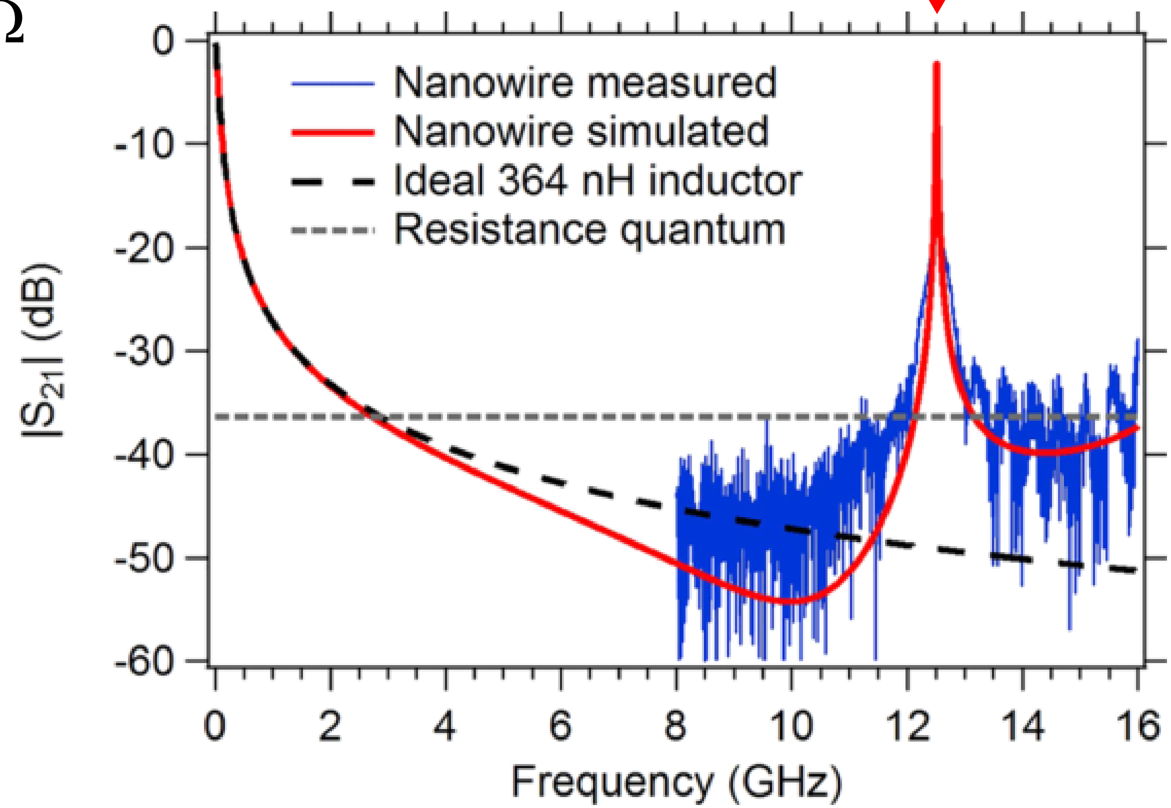
Transmission line effects, evidence 1

T.L. Impedance





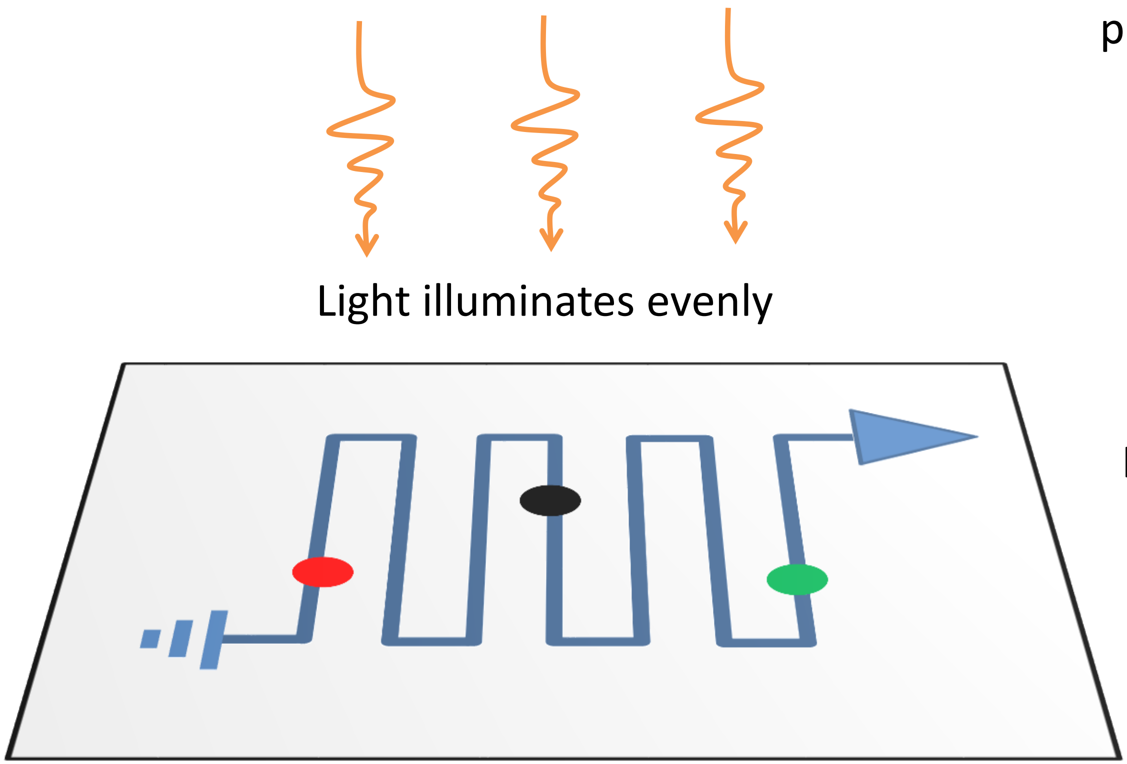
$\frac{\lambda}{2}$ Resonance indicates V_p = 4.2%c

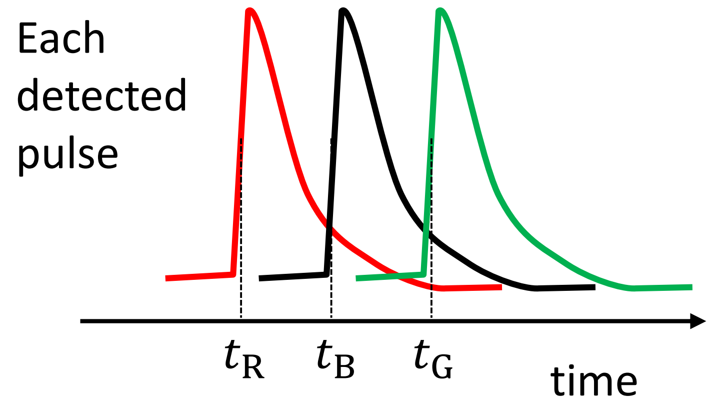


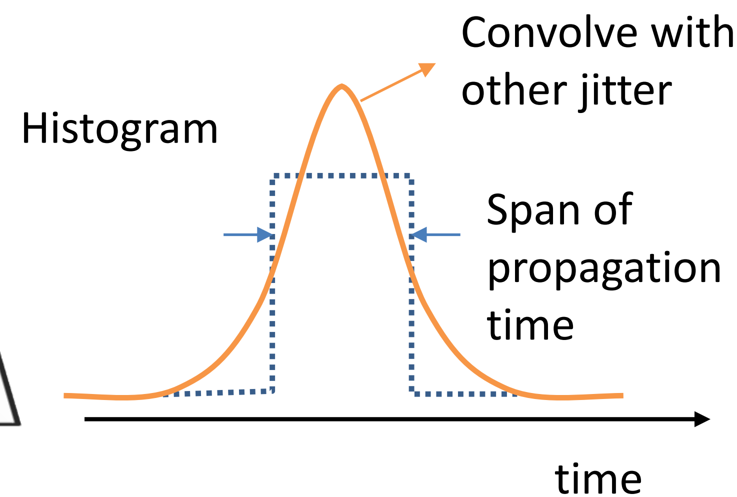
Santavicca, D. F., et.al, *J. Appl. Phys.* **119,** 234302 (2016).

Transmission line effects, evidence 1I

Geometry jitter / propagation jitter in SNSPD

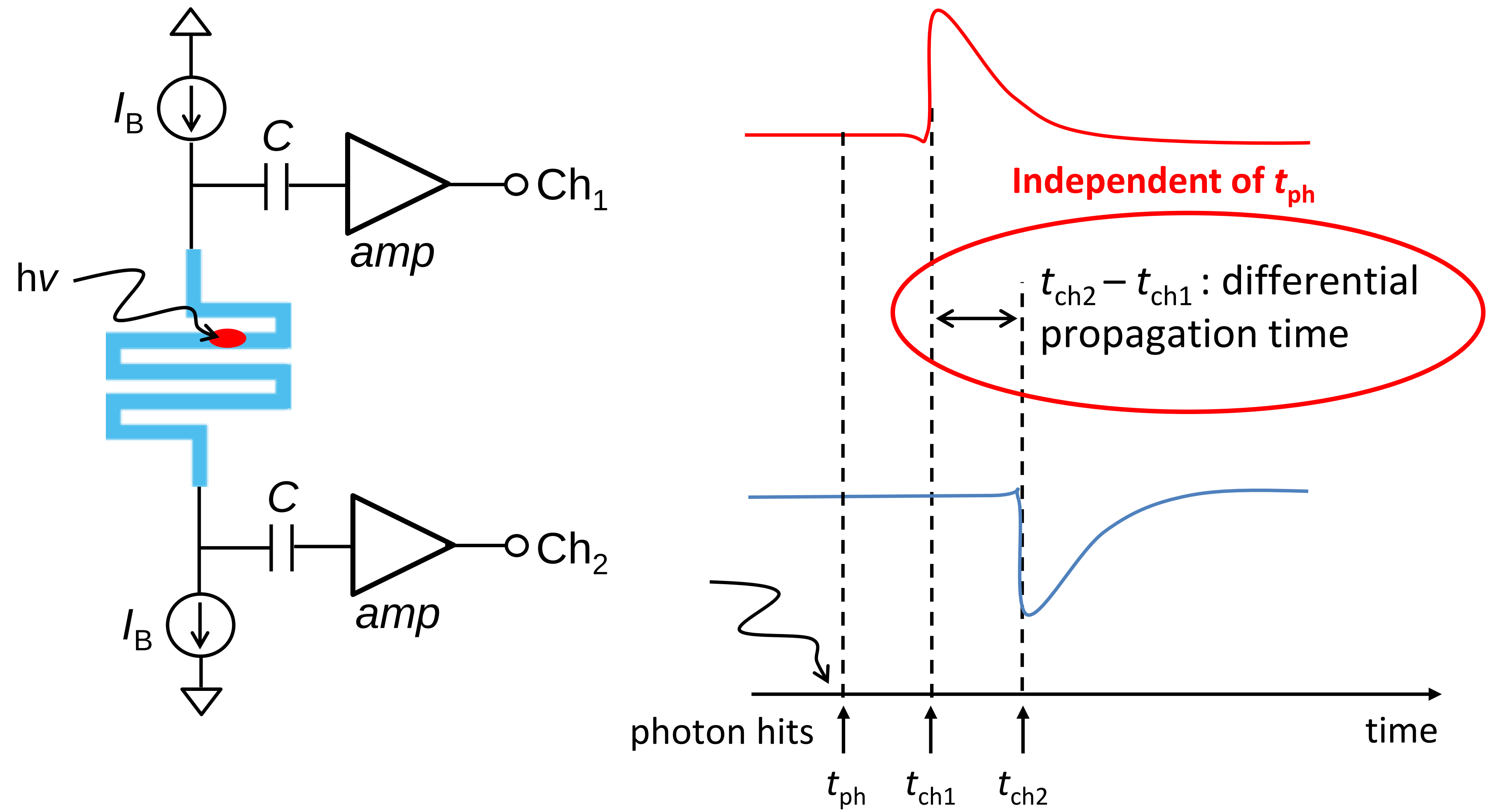




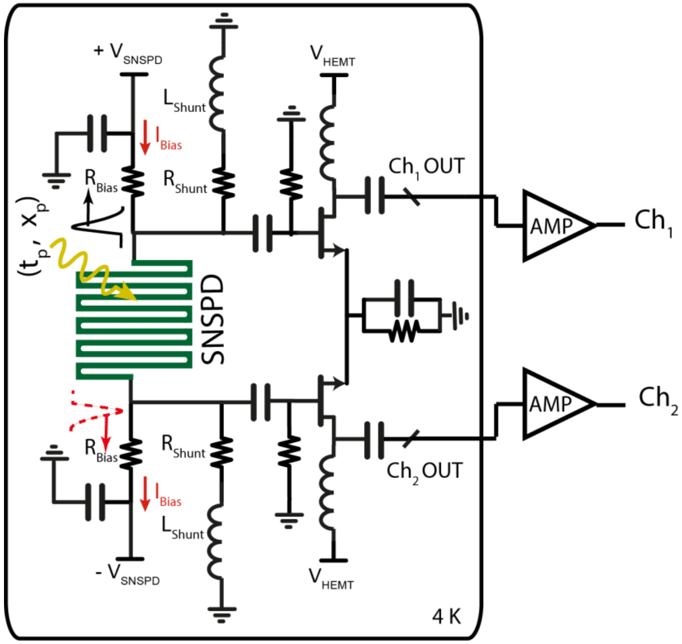


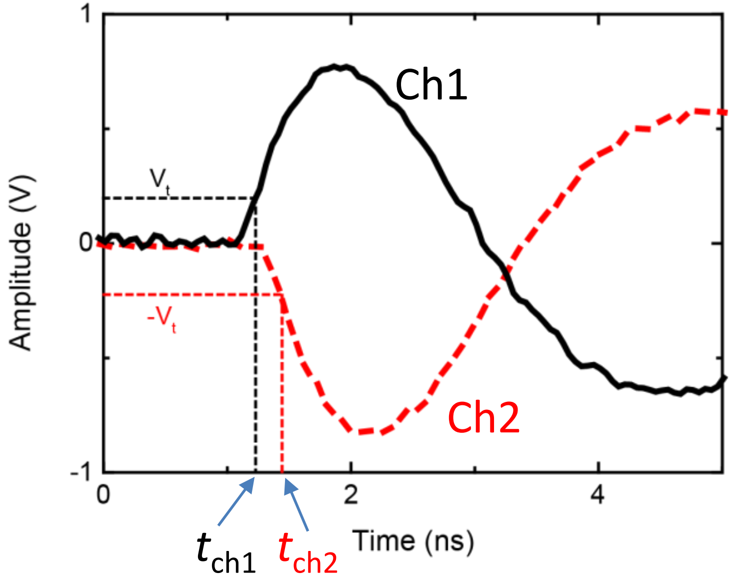
Spatial distribution of incident photons contributes to propagation jitter

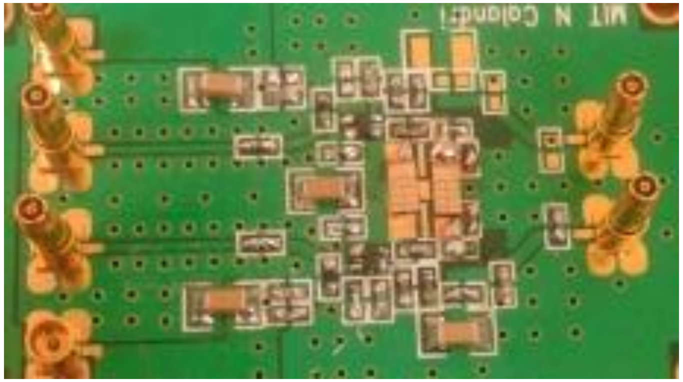
Measured propagation time independently to photon detection time



Timing differential cryogenic amplifier







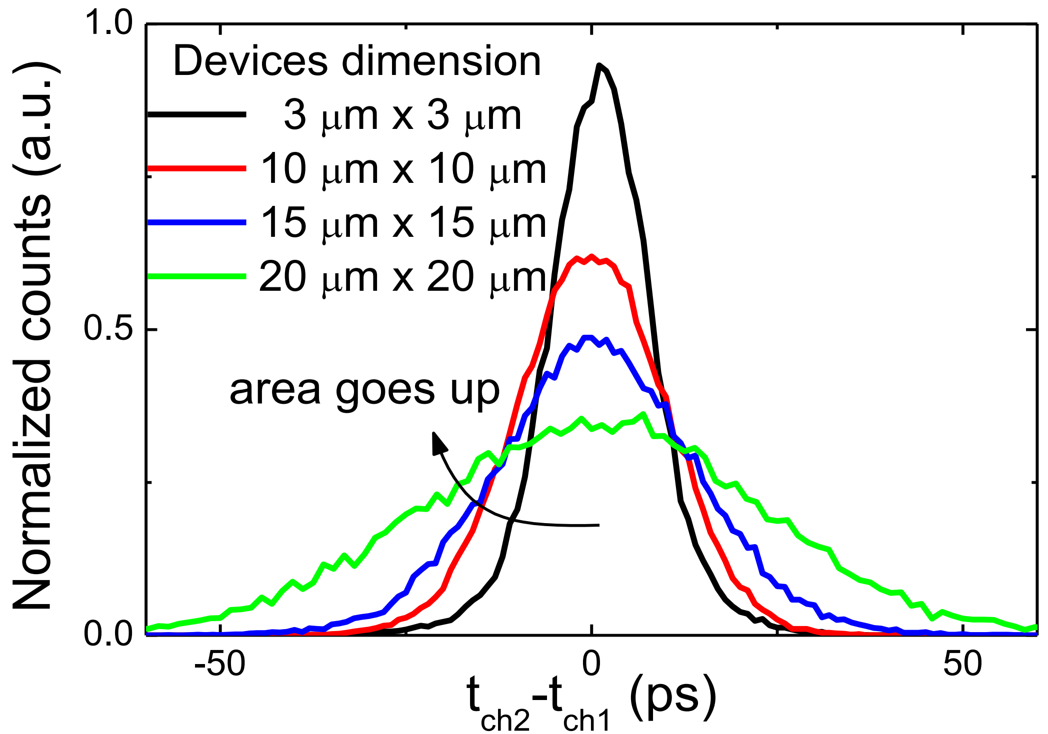
Set discrimination level lower to have less effects from reflections

N. Calandri, et. al.,. ***arxiv:1607.06713***, 0–8 (2016).

Propagation time in SNSPDs of different area

Standard SNSPD of different area

Jitter of (tch2 – tch1) increases as the area goes up

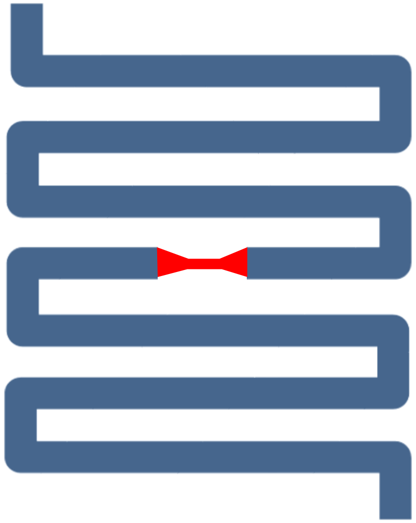


Calandri, N., et. al, *Appl. Phys. Lett.* **109,** (2016).

Single constriction SNSPDs

Standard SNSPD of different area

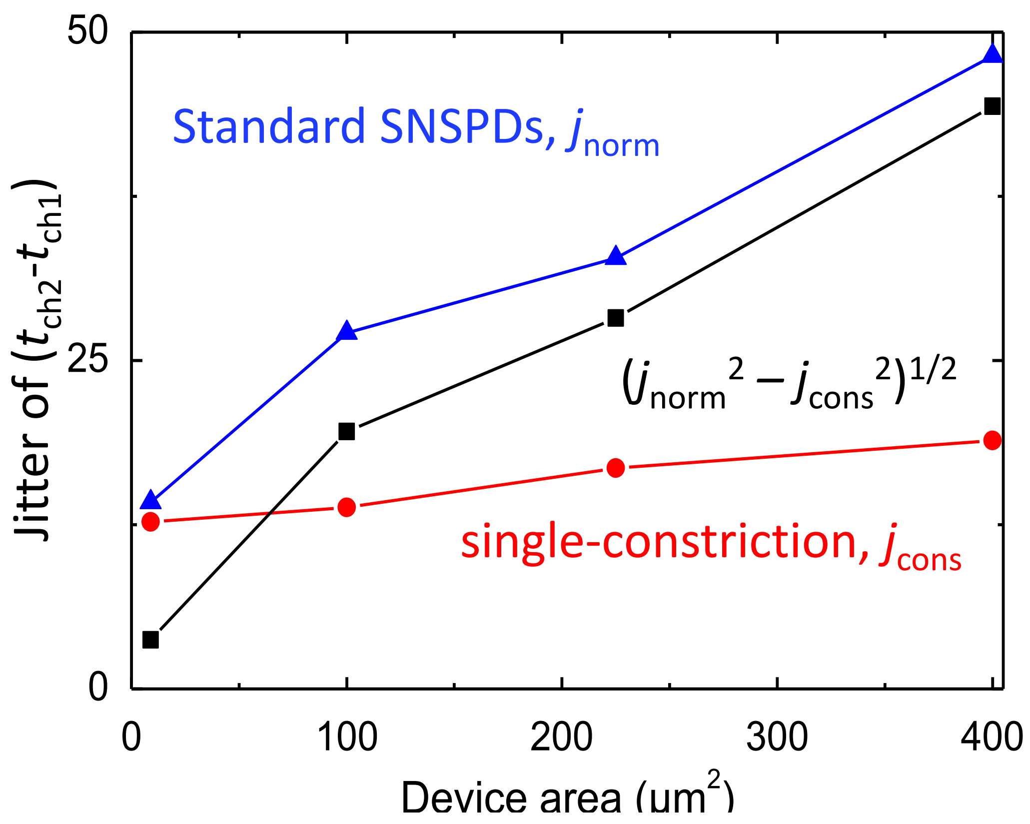
Only a short wire at the center can respond to photons



No variation in propagation time. The jitter measured is mostly from electrical noise.

Calandri, N., et. al, *Appl. Phys. Lett.* **109,** (2016).

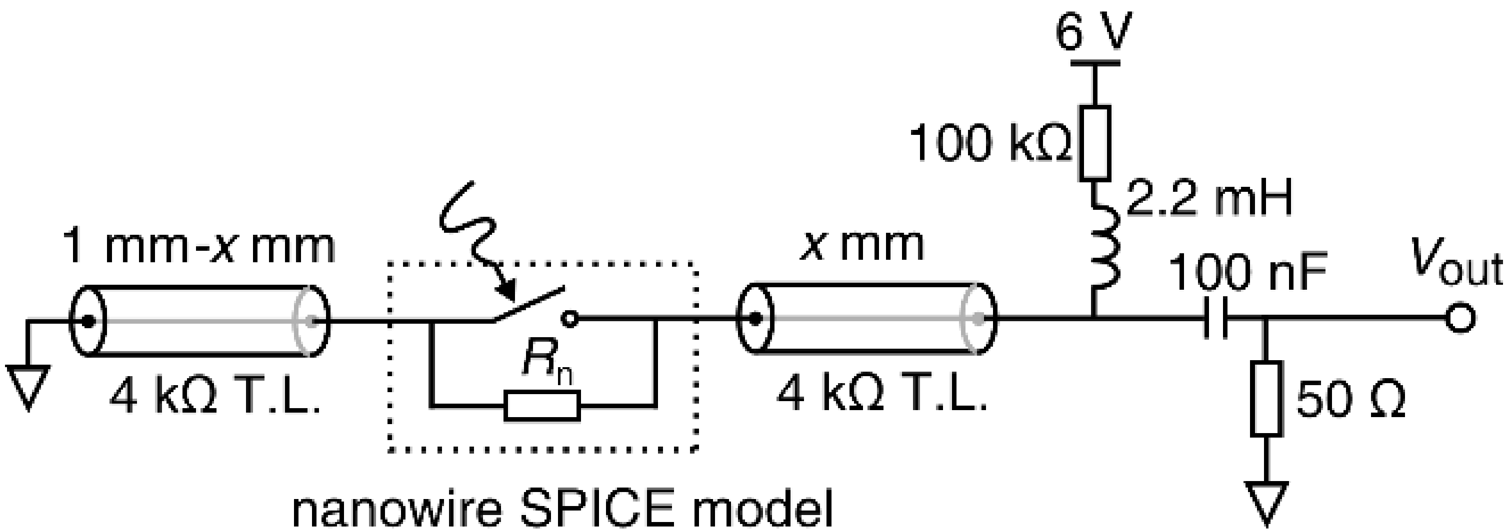
Estimate jitter attributed to signal propagation time



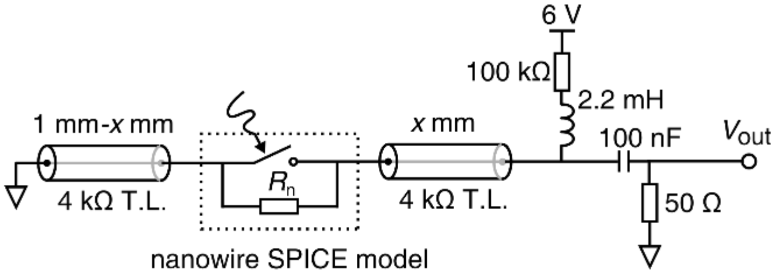
- Larger area detectors will have jitter attributed to propagation time variation
- If location is well known, the overall jitter can be reduced by removing the propagation time

Simulation of a transmission line in a normal SNSPD

SPICE simulation of an ideal nanowire transmission line at different firing location x

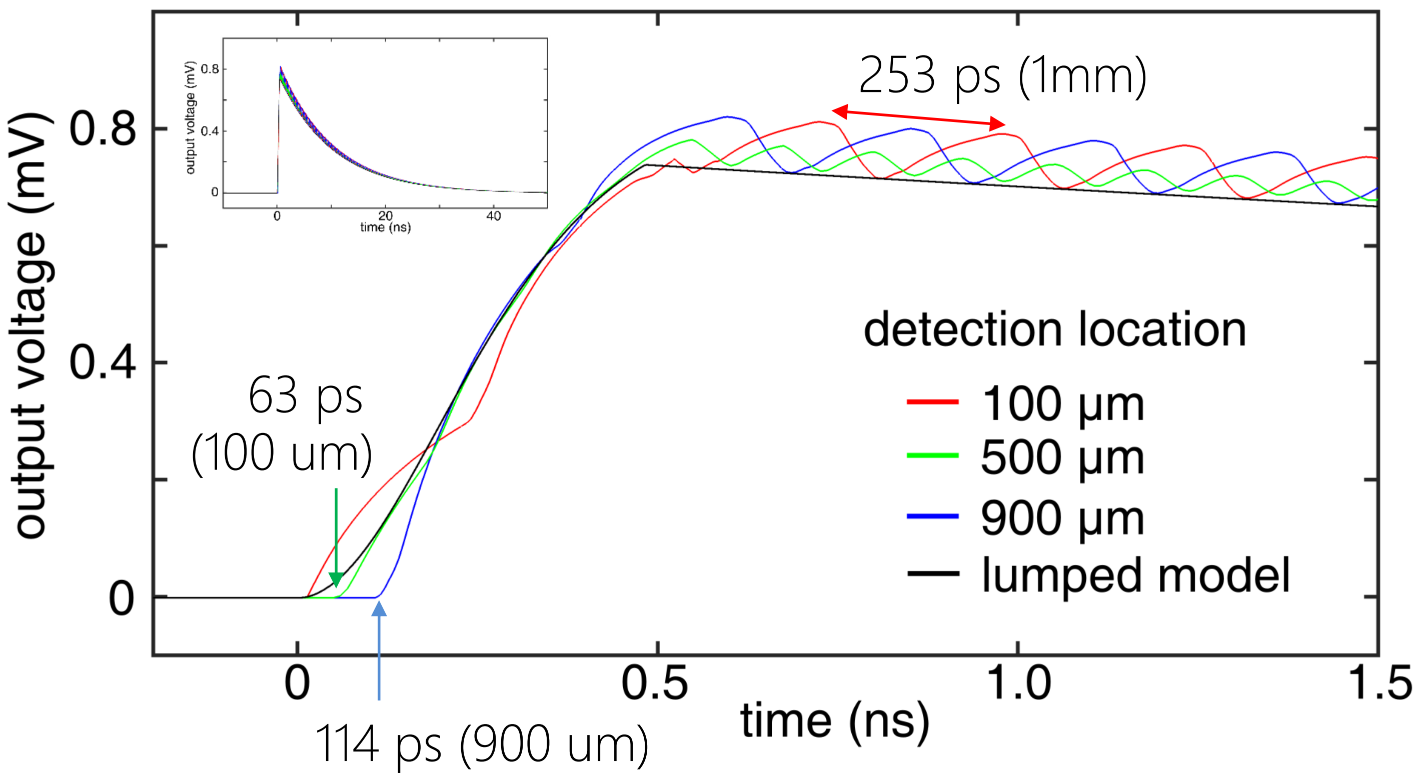


Reflections inside an meander wire



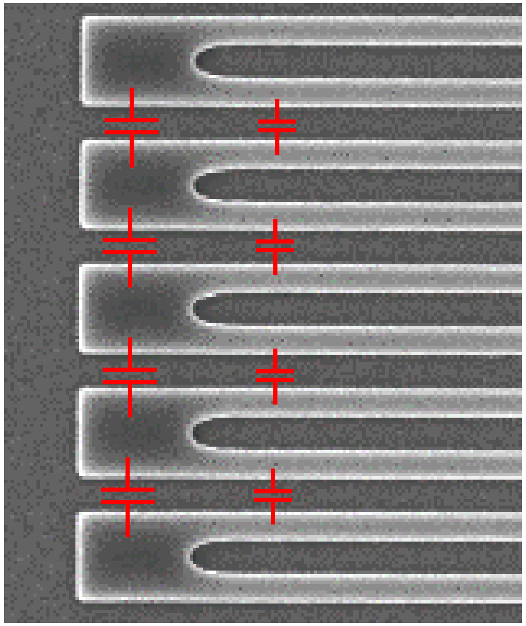
$$v = \sqrt{\frac{1}{LC}} = 7.9\ \mu\text{m/ps}$$

$$Z = \sqrt{\frac{L}{C}} = 4\ \text{k}\Omega$$

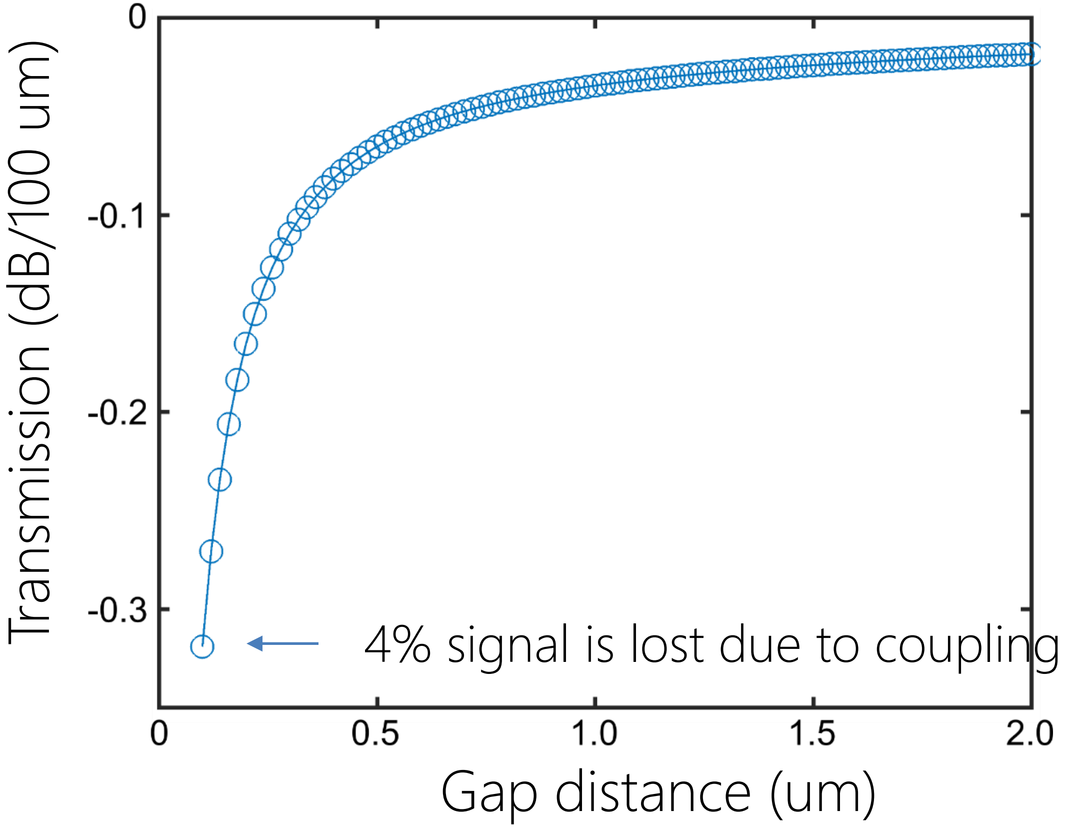


Crosstalk (coupling) between adjacent wires

Capacitive coupling in a meandered SNSPD



RF simulation of the transmission at 5 GHz



What we have learned?

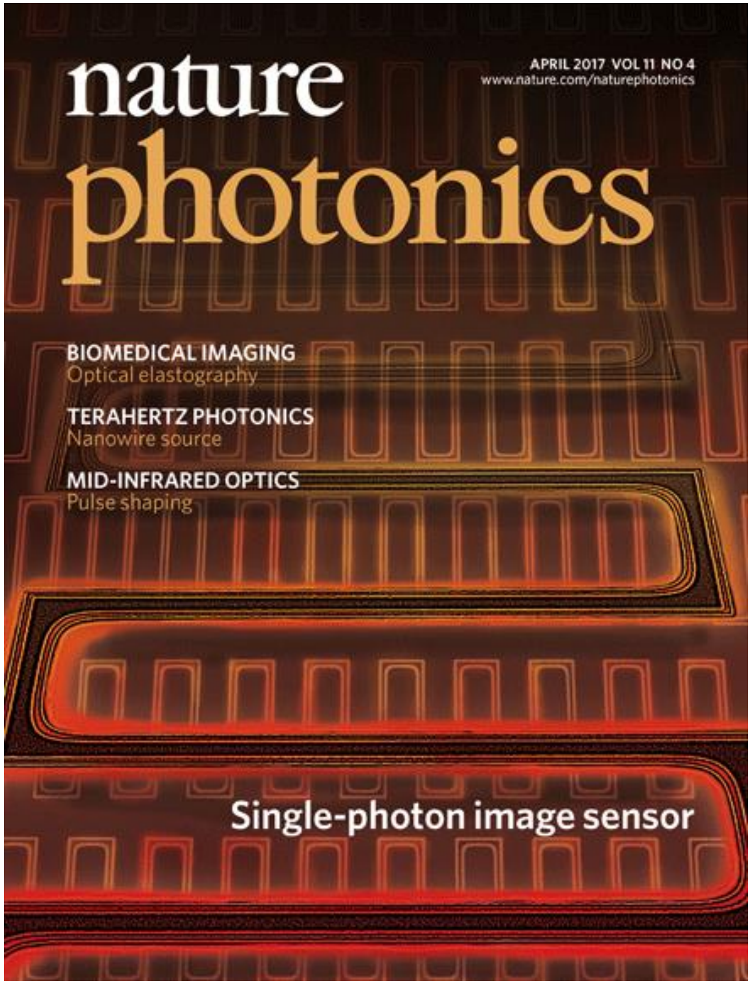
1. SNSPDs do have T.L. effects
2. The T.L. effects are not well exhibited in normal SNSPDs,

due to:

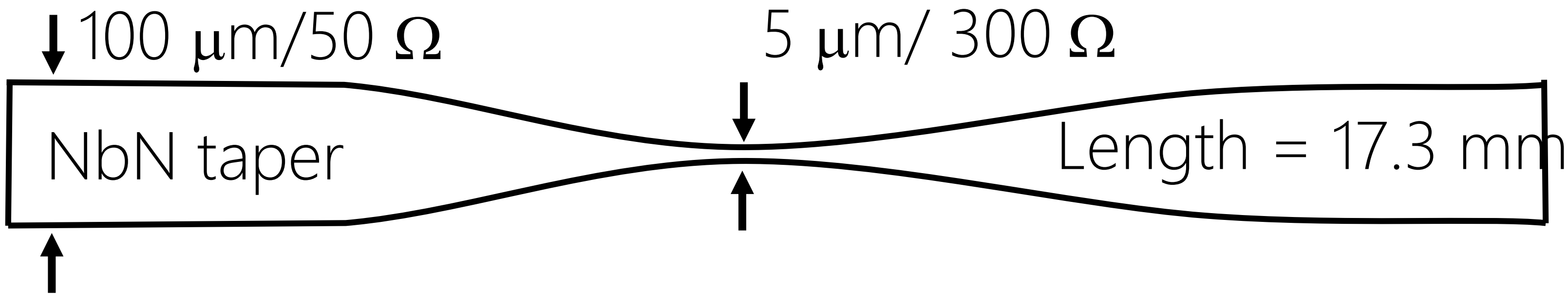
- The wire is not long enough
- The impedance too high
- Not designed for a good microwave transmission line

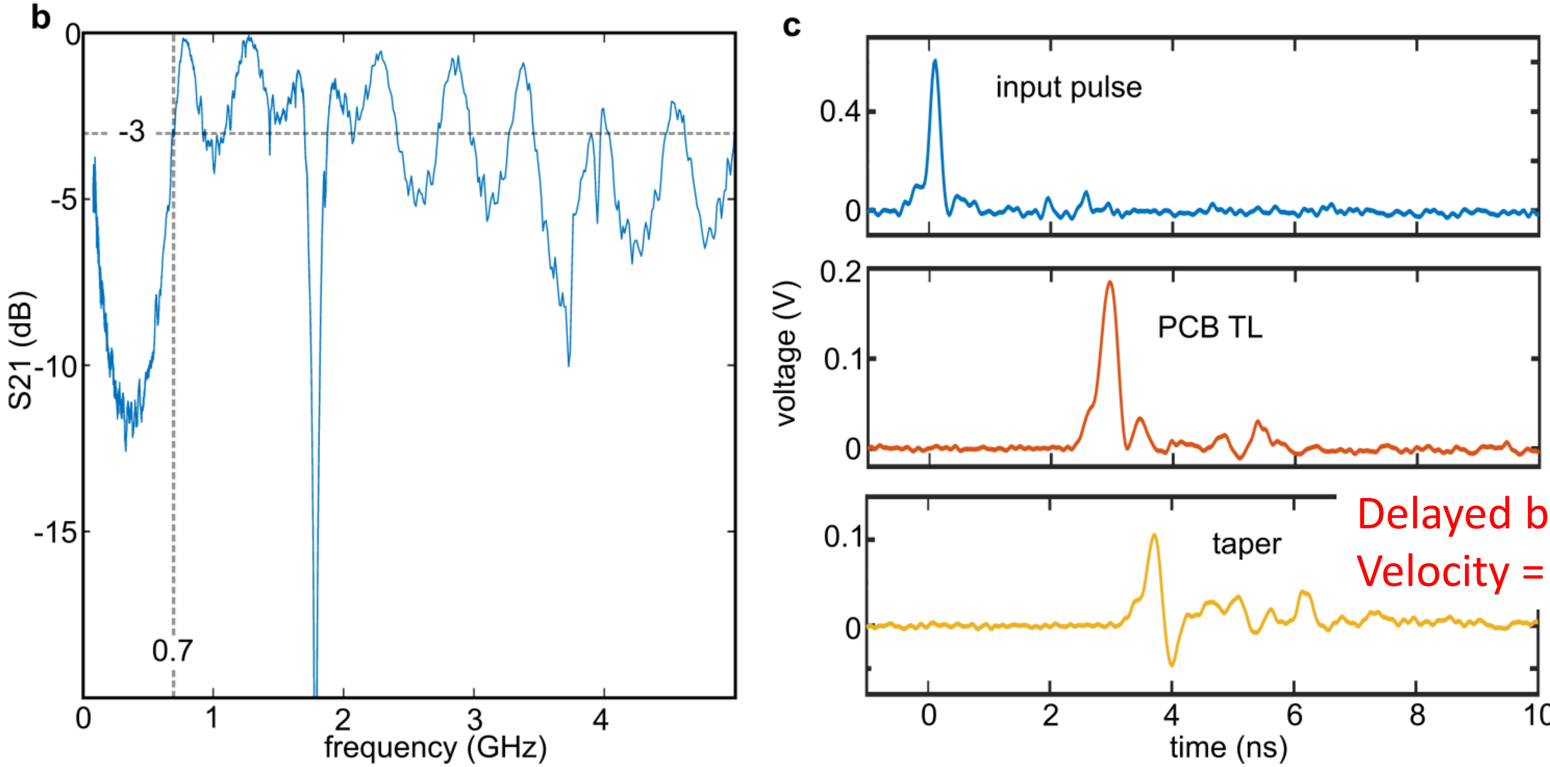
Application of a distributed SNSPD:

Single-photon Imager



Microwave taper for transforming impedance

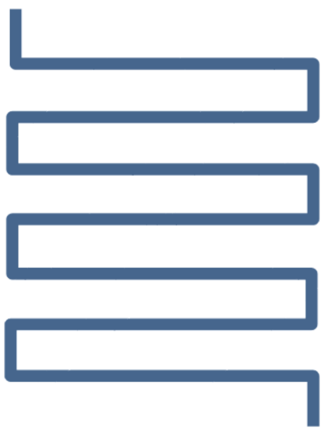




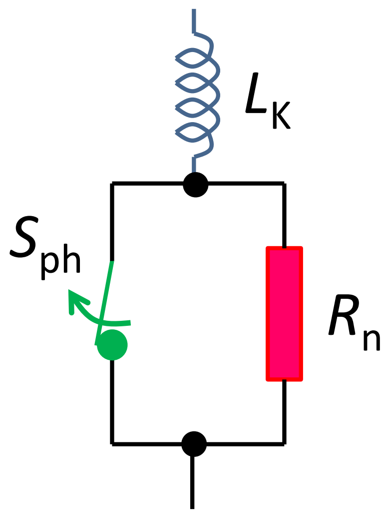
Delayed by 666 ps
Velocity = 8.7%c

From a lumped inductor to a transmission line

Meandered SNSPD



Electrical model of an SNSPD



S_{ph}: ideal switch triggered by photon detection

$$L_K = \mu_0 \lambda_{Leff}^2 \times \frac{L}{wd}$$

$$R_n(t) = R_s \times \frac{l_{hp}(t)}{wd}$$

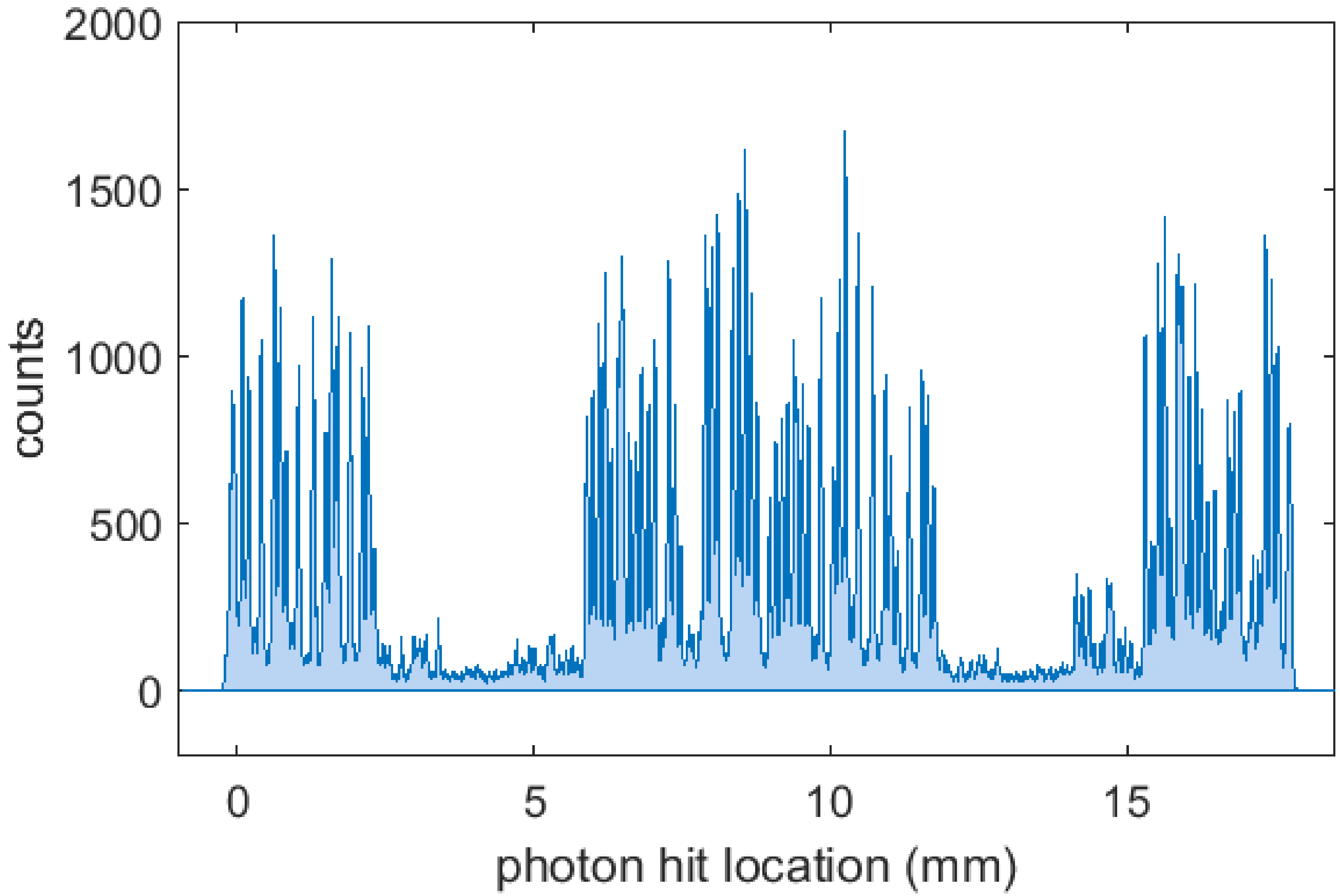
Typical values:
L = 500 μm, w = 100 nm, d = 5 nm
L_{ks} = 50 pH/square, R_s = 400 Ω/square
I_C = 20 μA

$$L_K = 250 \text{ nH}$$

$$\text{Max}\,(R_n(t)) \cong 1 \text{ k}\Omega$$

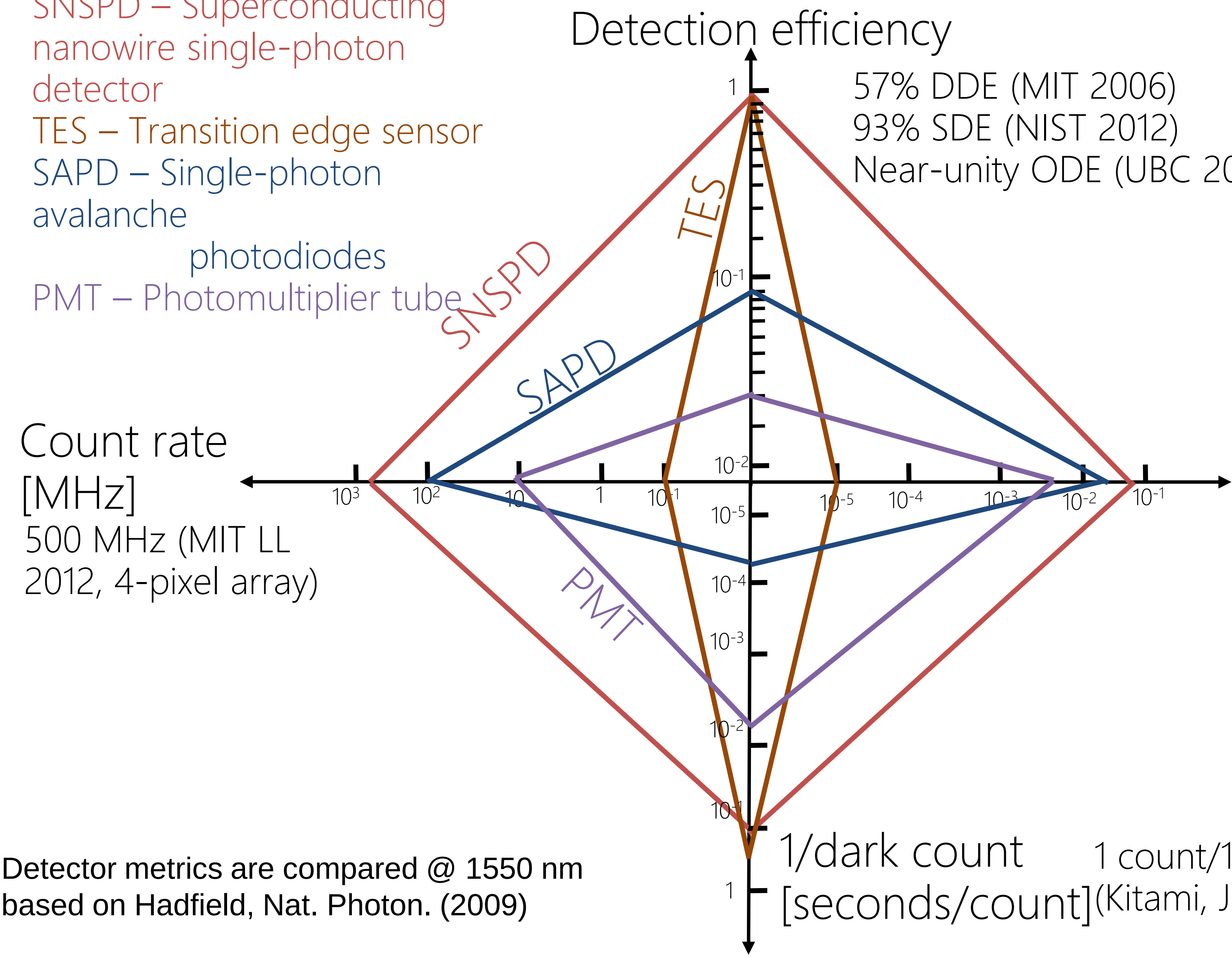
Yang, J. *et al. IEEE Trans. Appl. Supercond.* **17,** 581–585 (2007).

Histogram of pulse arrivals



Detector metrics

SNSPD – Superconducting nanowire single-photon detector
TES – Transition edge sensor
SAPD – Single-photon avalanche photodiodes
PMT – Photomultiplier tube



57% DDE (MIT 2006)
93% SDE (NIST 2012)
Near-unity ODE (UBC 2015)

500 MHz (MIT LL 2012, 4-pixel array)

1/(18 ps) (Yale 2012)
1/(24 ps) (MIT 2015)

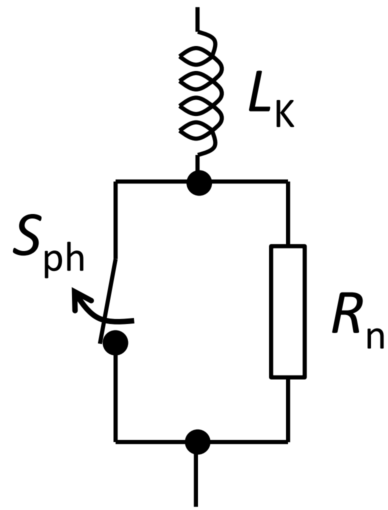
1 count/10^3 seconds (Kitami, Japan 2015)

Detector metrics are compared @ 1550 nm based on Hadfield, Nat. Photon. (2009)

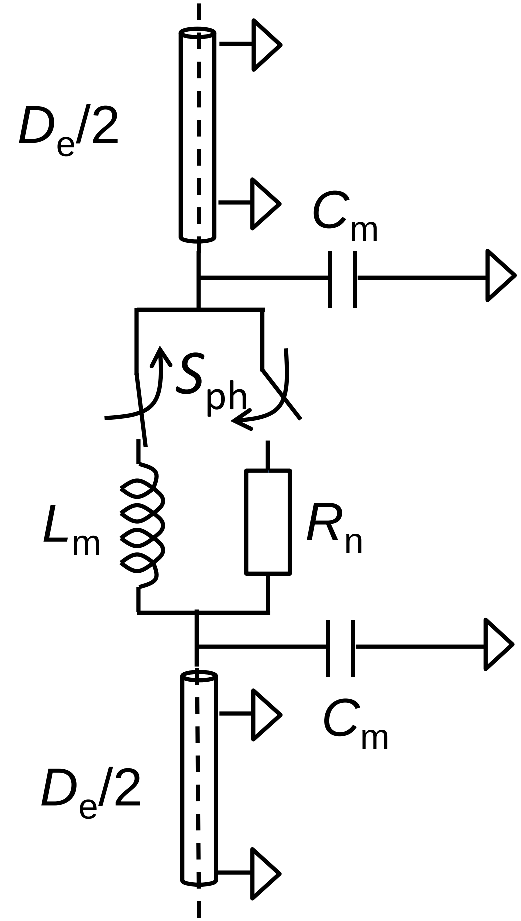
From a lumped inductor to a transmission line

Meandered SNSPD

Lumped model



Distributed model

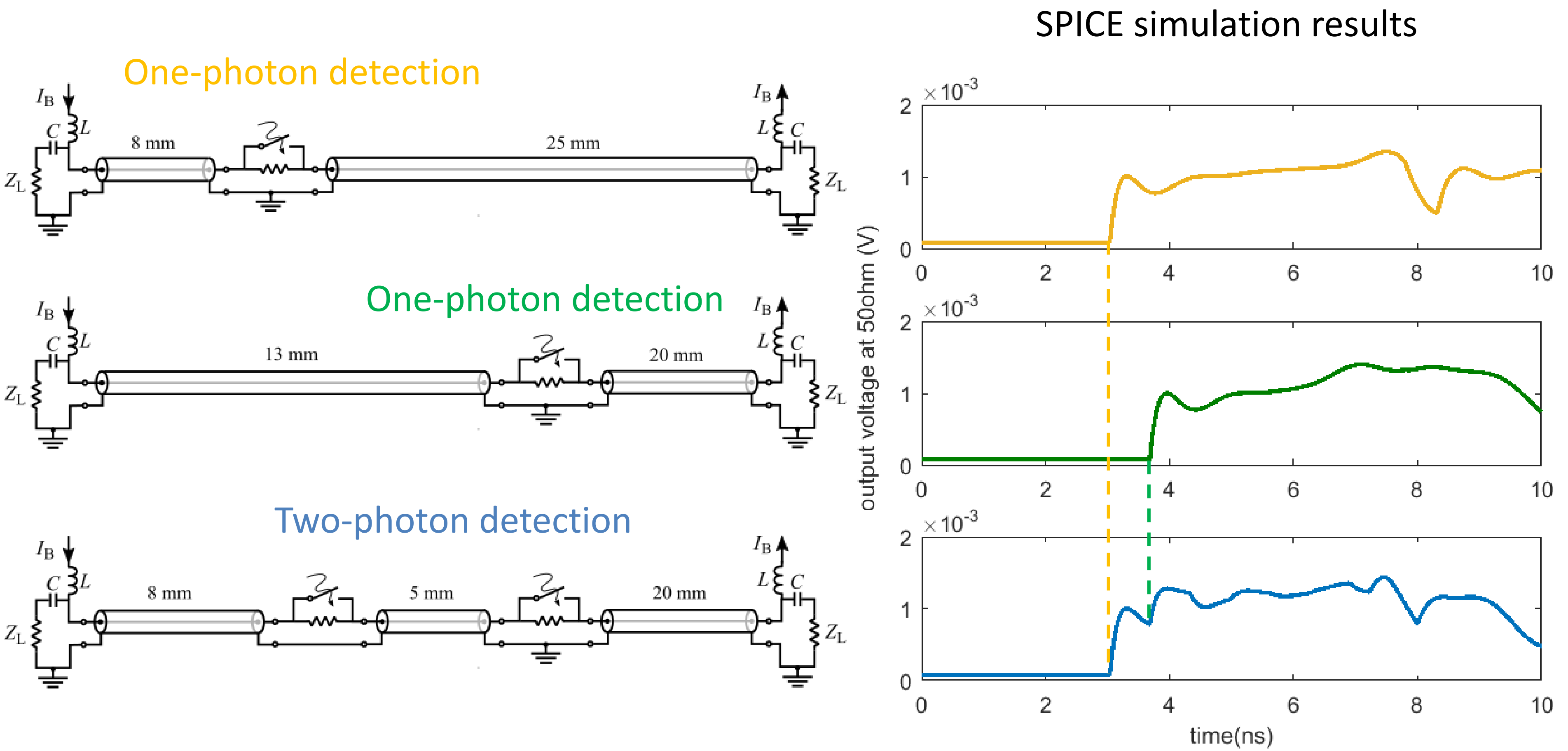


D_e: electrical length

L_m: inductance per unit length

C_m: capacitance per unit length

Multiple detection events

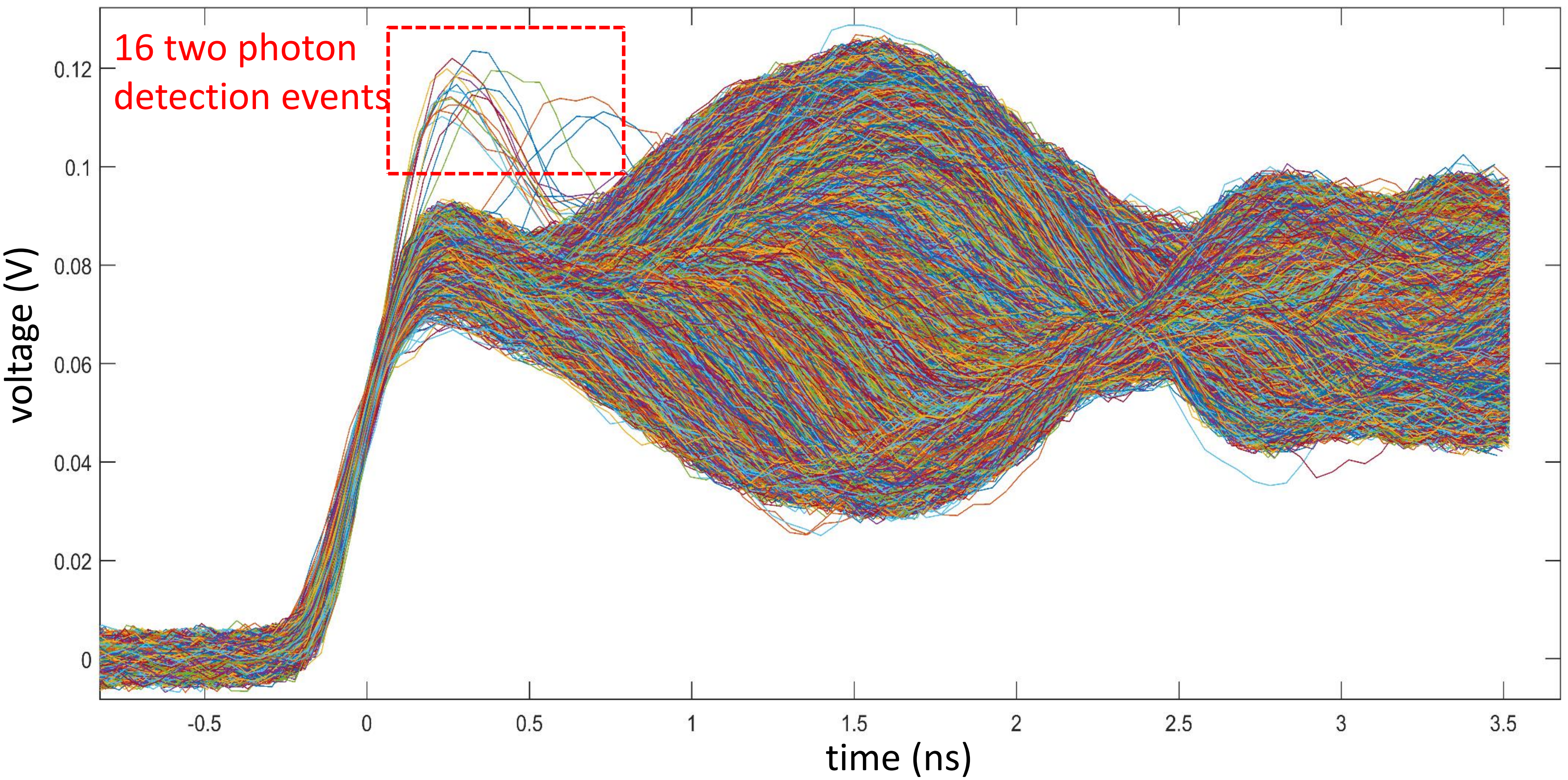


Details of the pulse shape could give a full information of

photon numbers, arrival times and locations

Detecting two-photon-firing events

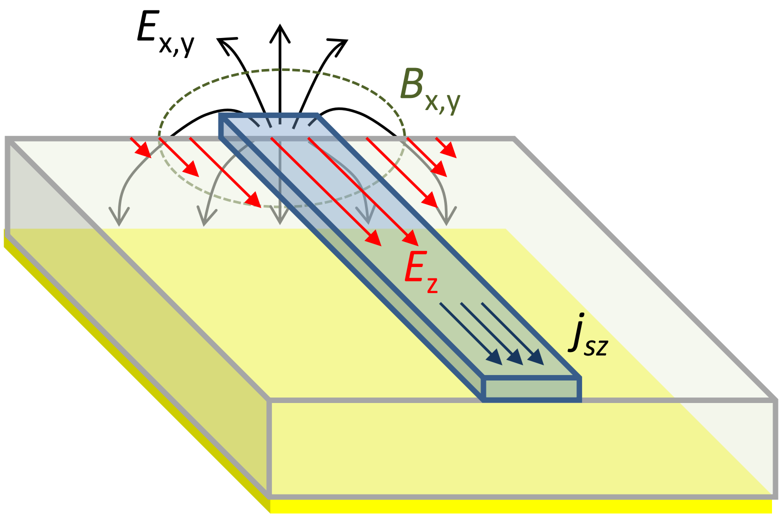
16 two-photon firing events among 50,000 photon detection events
(flood illumination over the entire area)



SN: a slow-wave and high Z transmission line

First London equation

$$J_S = E_z \frac{1}{jw\mu_0\lambda_L^2} = E_z \frac{1}{jwL_{kS}d}$$



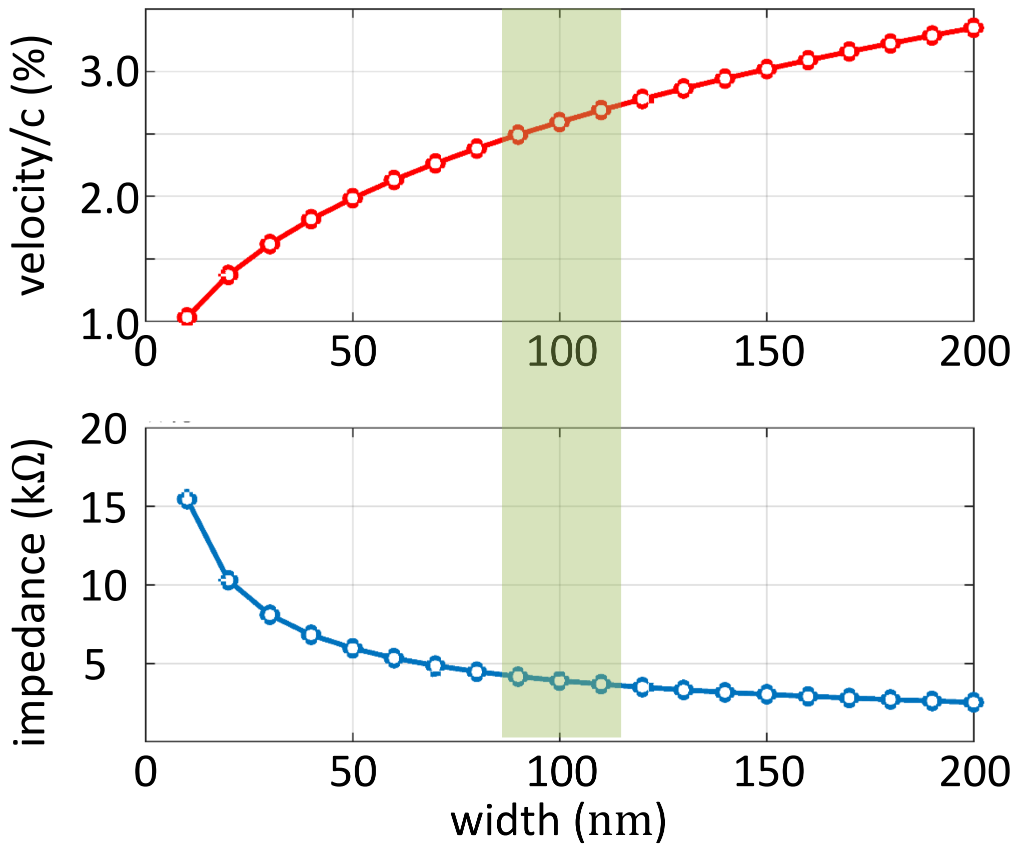
Lumped model of transmission lines

$$v = \sqrt{\frac{1}{LC}} \qquad Z = \sqrt{\frac{L}{C}}$$

$$L = L_K + L_G \cong L_K$$

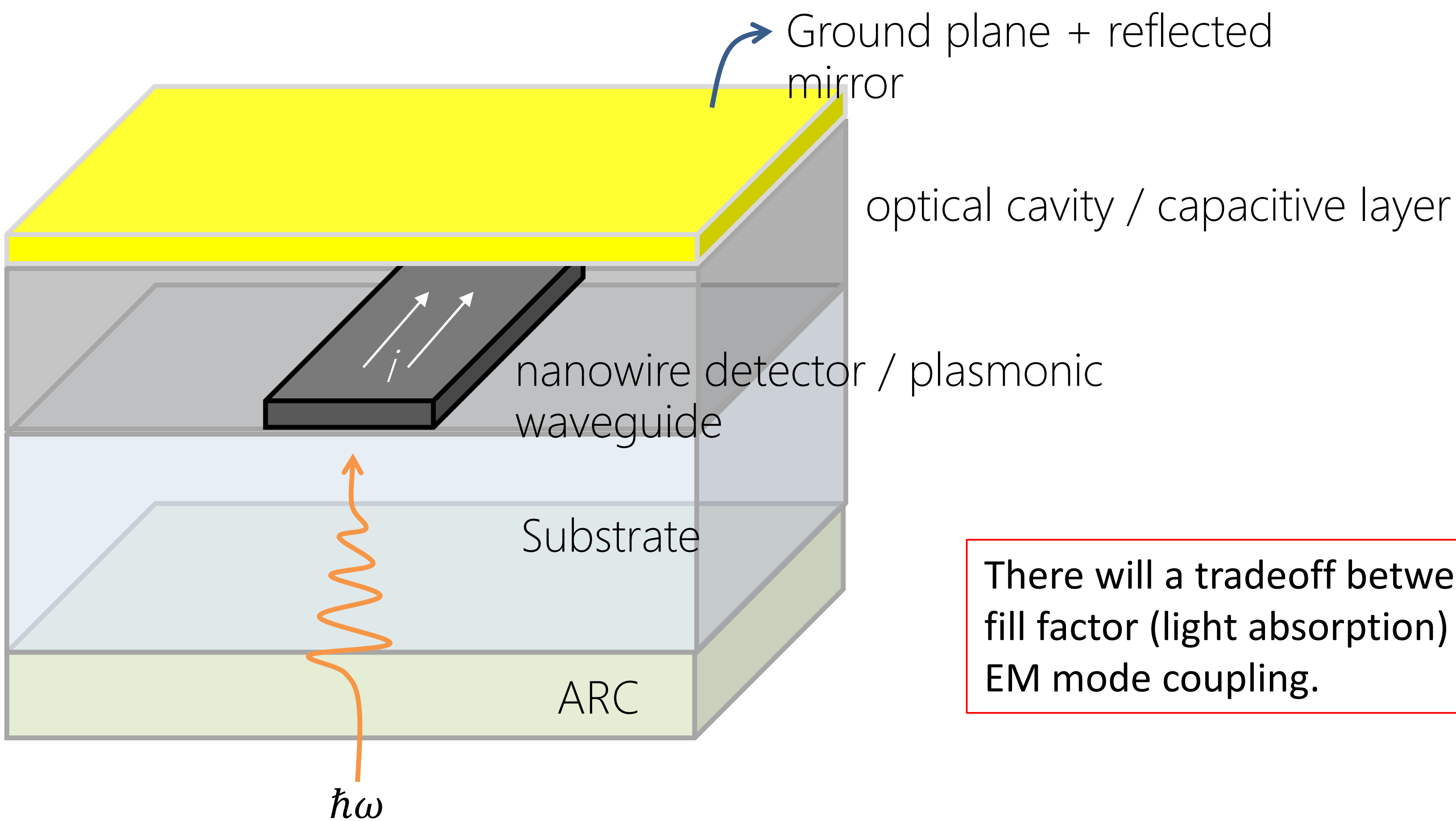
velocity = 2.5%c = 7.5 μm/ps

impedance = 4 kΩ



NbN SNSPD 100 nm wide, 50 pH/square

Microstrip-based SNSPI



There will a tradeoff between fill factor (light absorption) and EM mode coupling.

High efficiency, improved readout and avoid propagation jitter

Detection timing jitter is not affected

Location:

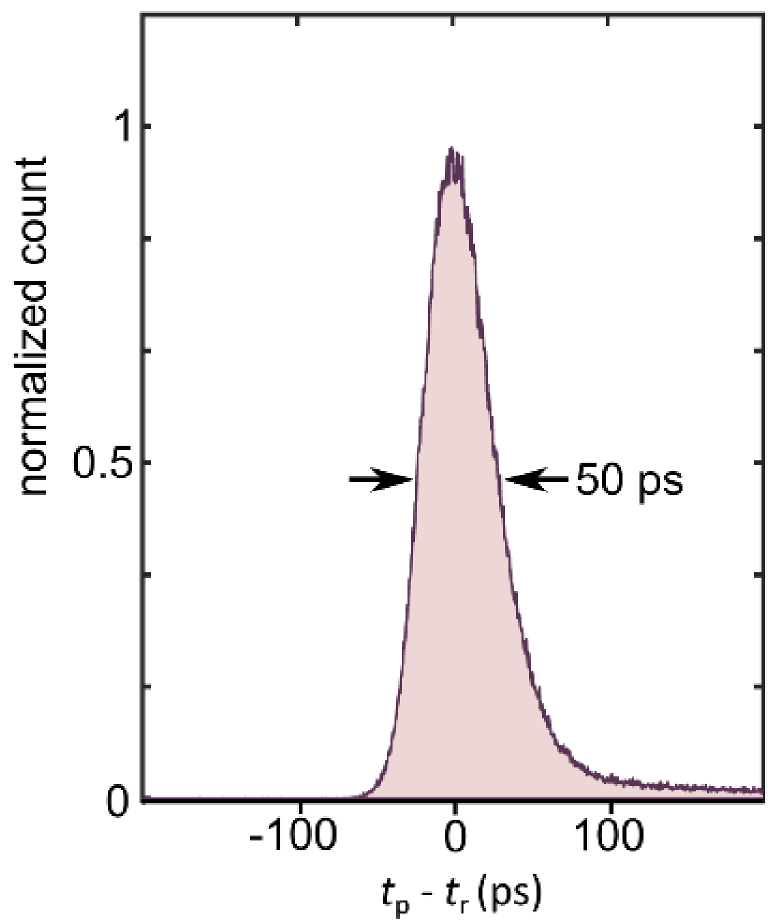
$$x = \frac{(t_L - t_R) \times v}{2}$$

Time:

$$t_p = \frac{t_L + t_R - L/v}{2}$$

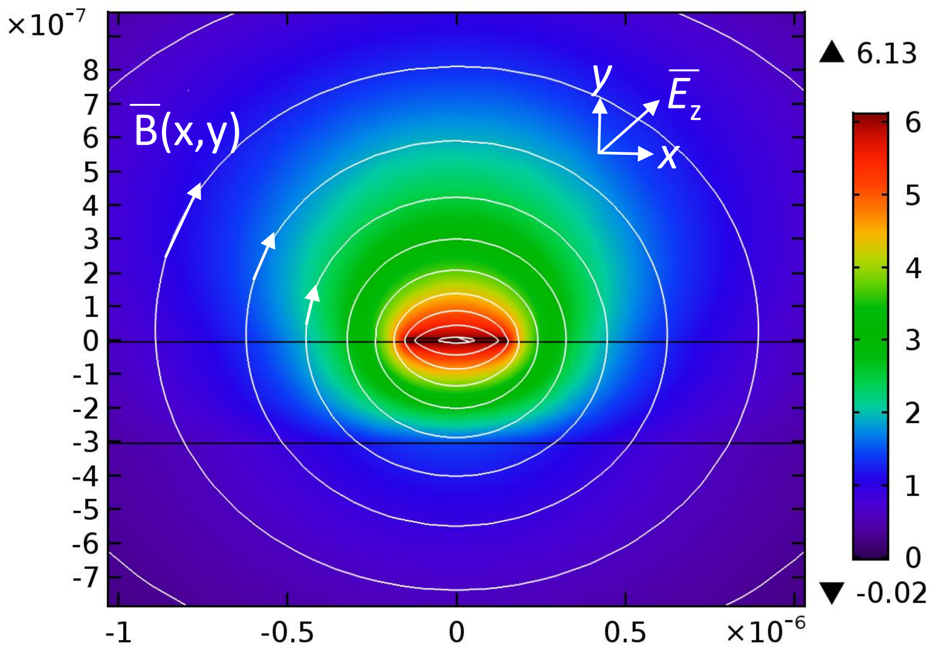
Position and time are simultaneously detected !

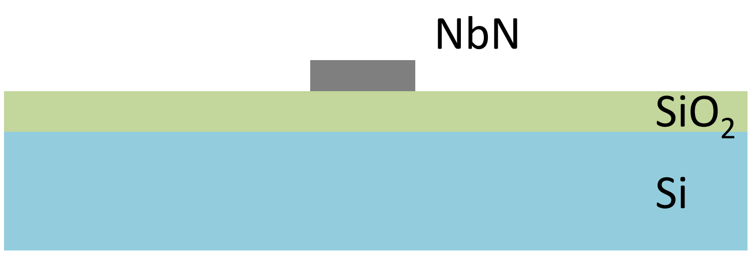
50 ps detection jitter



Superconducting nanowire: a plasmonic waveguide

Mode pattern at 5 GHz





First London equation asks for a longitudinal *E* to drive the kinetic inductance

$$J_S = E_z \frac{1}{jw\mu_0\lambda_L^2} = E_z \frac{1}{jwL_{kS}d}$$

Complex permittivity:

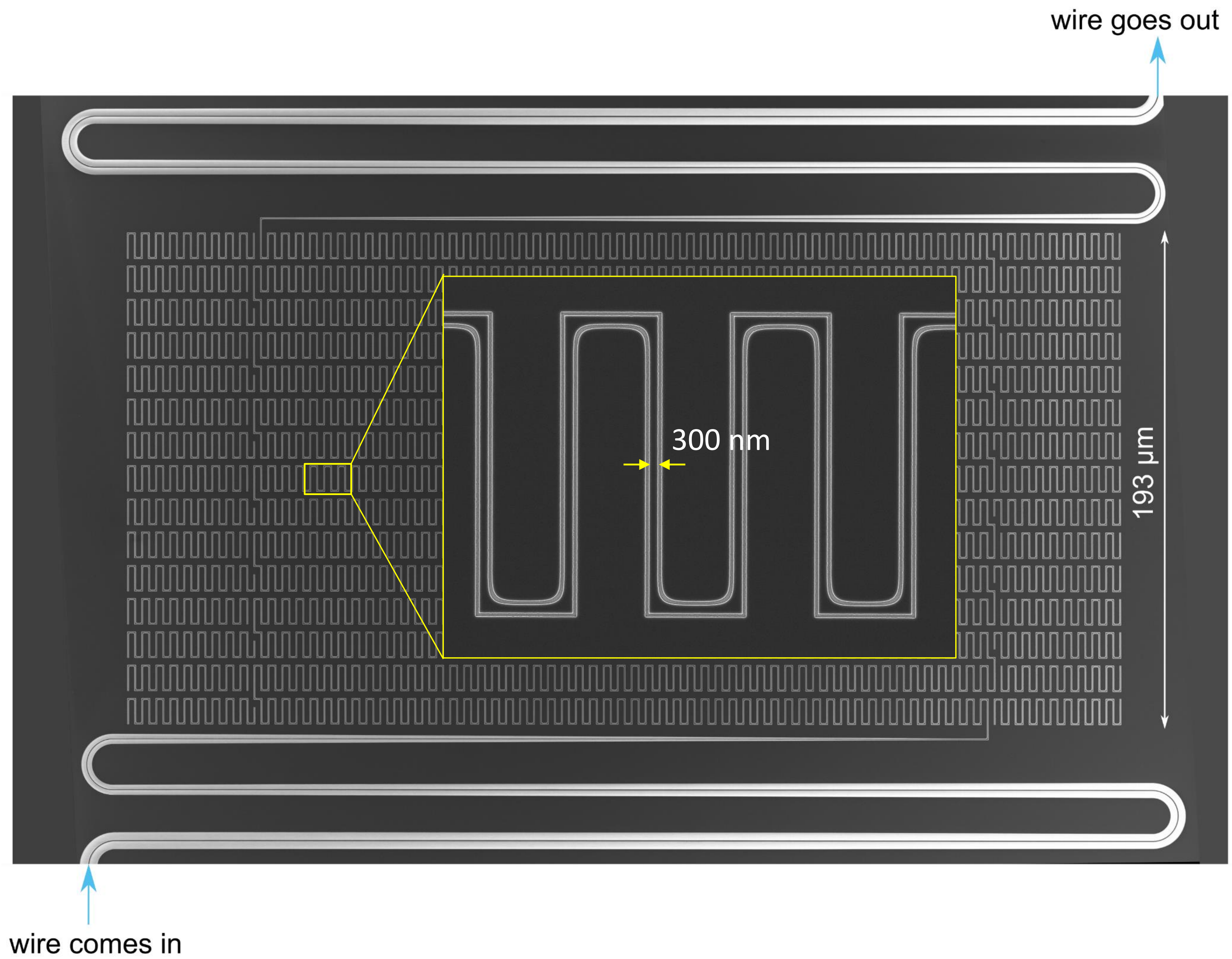
$$\varepsilon = \varepsilon_0 - \frac{1}{w^2\mu_0\lambda_L^2}$$

Kinetic energy:

$$E_K = \frac{1}{2} L_k I^2$$

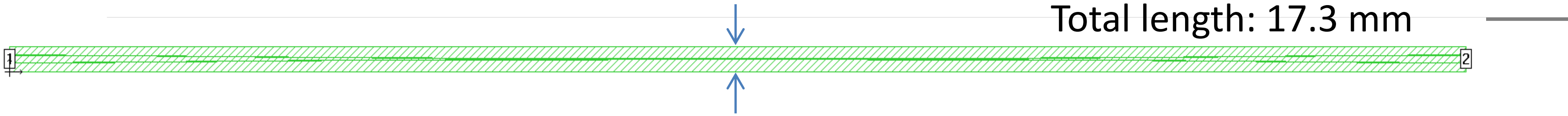
<u>Analogous to plasmonic waveguides:</u>

- Large negative dielectric constant
- Dominant kinetic resistance


wire goes out
300 nm
193 µm
wire comes in

Minimum width: 5um/10um

Total length: 17.3 mm

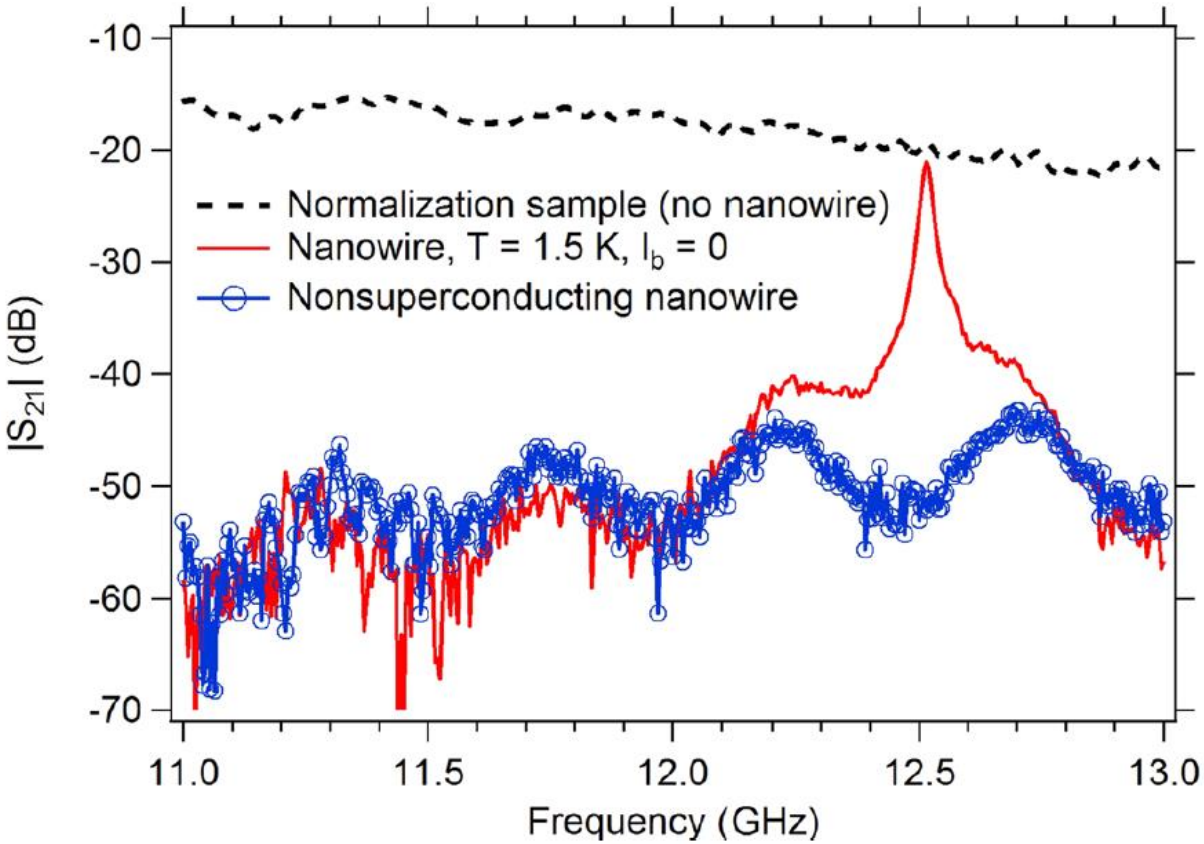


Tested wire: Fabricated by Heidelberg (Laser direct writing).

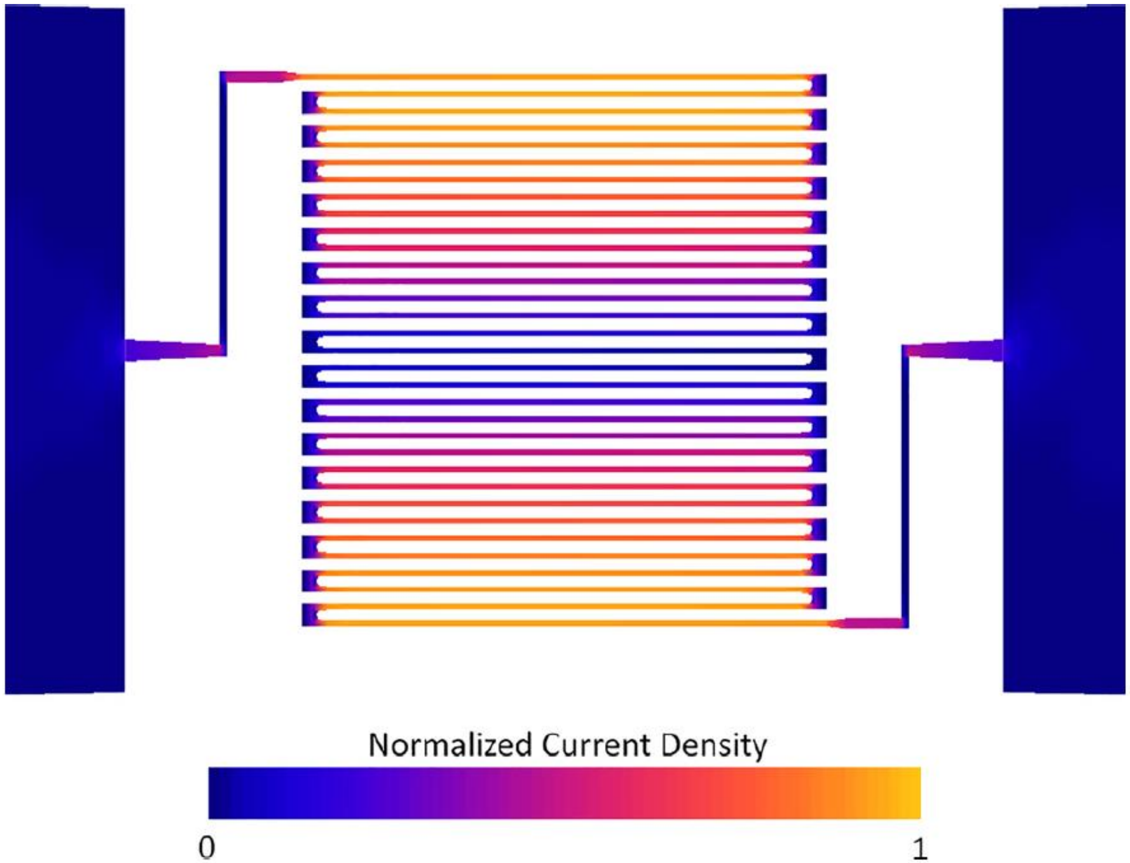
Port 4-8: 10 um wide, 3um gap CPW, Rn = 0.43 Mohm (Ic = 400 uA)
The wire coming out is narrower than 10 um, probably about 6 um, with gap increasing to 5 um.

Update:

1. Diced the chip and tested in a transmission line holder.
2. Removed the ripples in frequency domain that were caused by a bad SMA connector
3. Time domain measurement and find the velocity to be 17.3mm/(755ps-96ps) = 8.8%*c.
4. The experimental velocity from S parameter is about 8.3 %*c
5. The Sonnet simulated velocity is 13.7% at Lk = 50 pH/sq

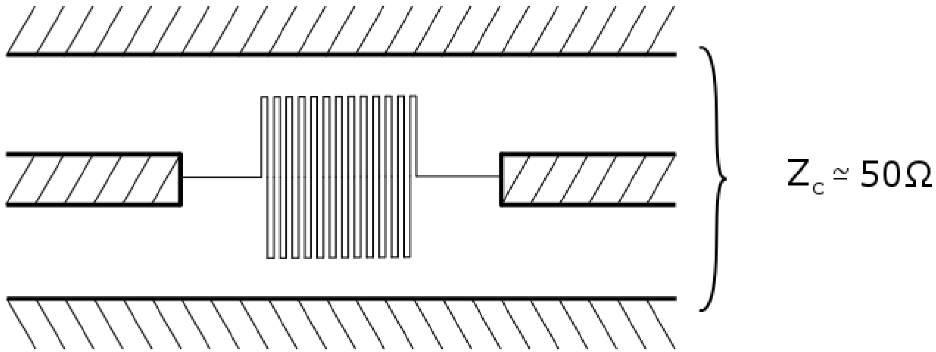


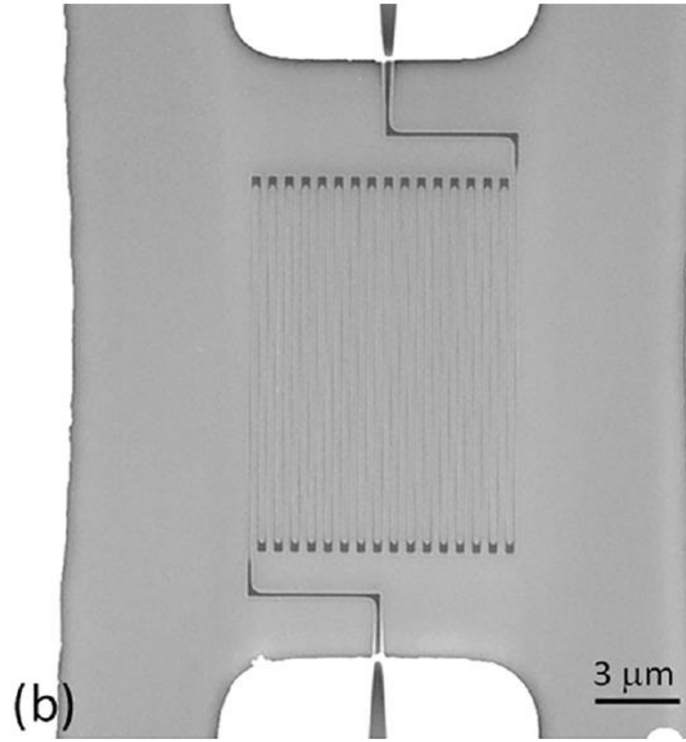
1%2E4954068.pdf - Adobe Acrobat Pro DC

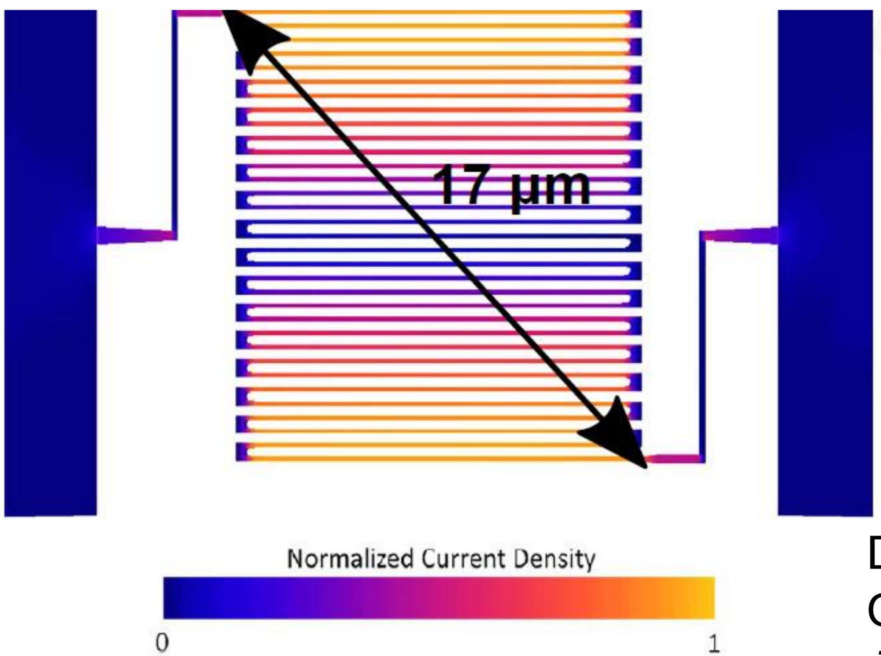


1%2E4954068.pdf - Adobe Acrobat Pro DC

First Clue: Self-Resonance







Estimate frequency of self-resonance:

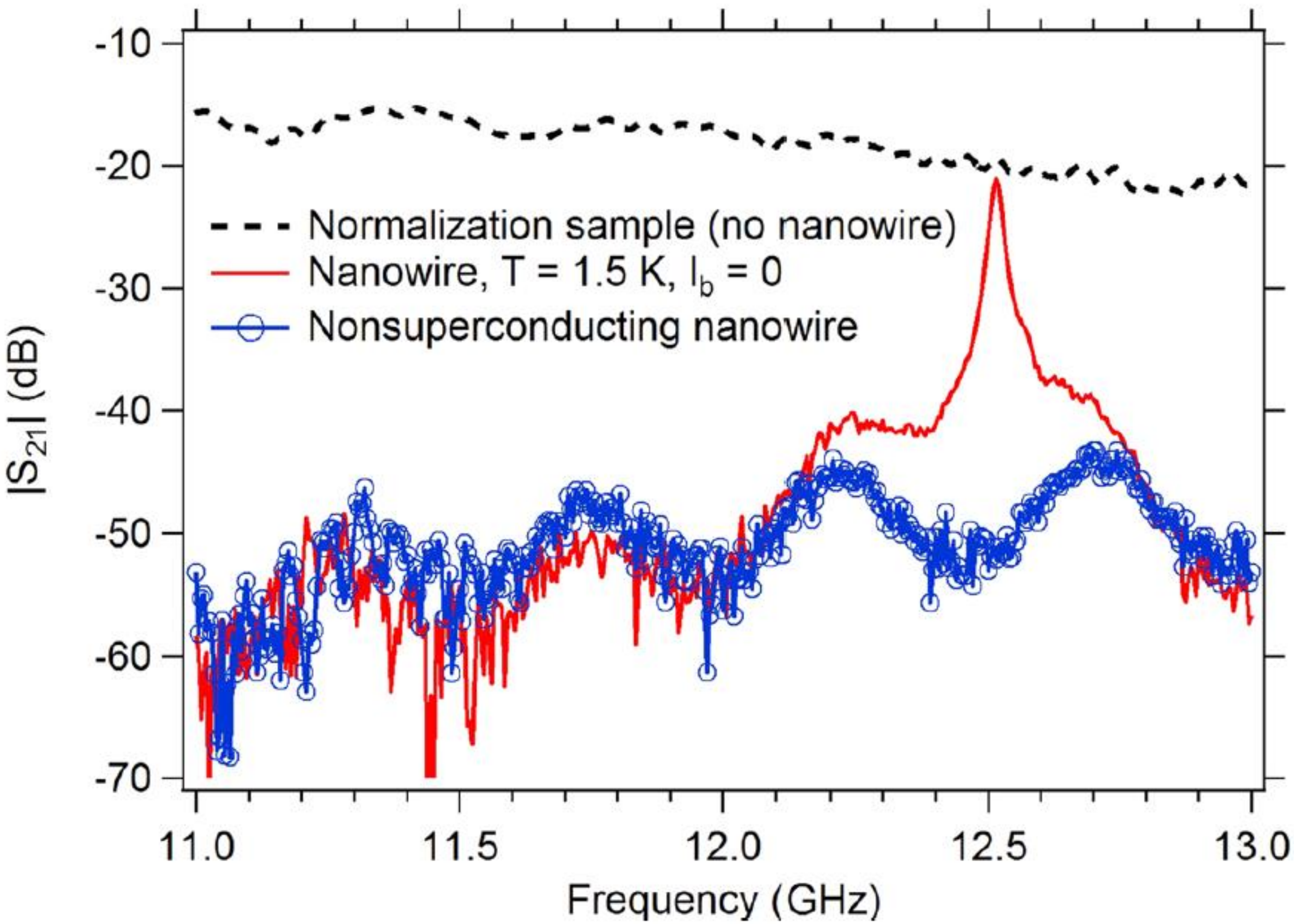
$\lambda \approx 34\,\mu\text{m}$

$\Rightarrow f_{\text{res}} \approx \frac{(c/3)}{\lambda} \approx 3\ \text{THz}$

Daniel F. Santavicca; Jesse K. Adams; Lierd E. Grant; Adam N. McCaughan; Karl K. Berggren; *Journal of Applied Physics* **2016,** 119

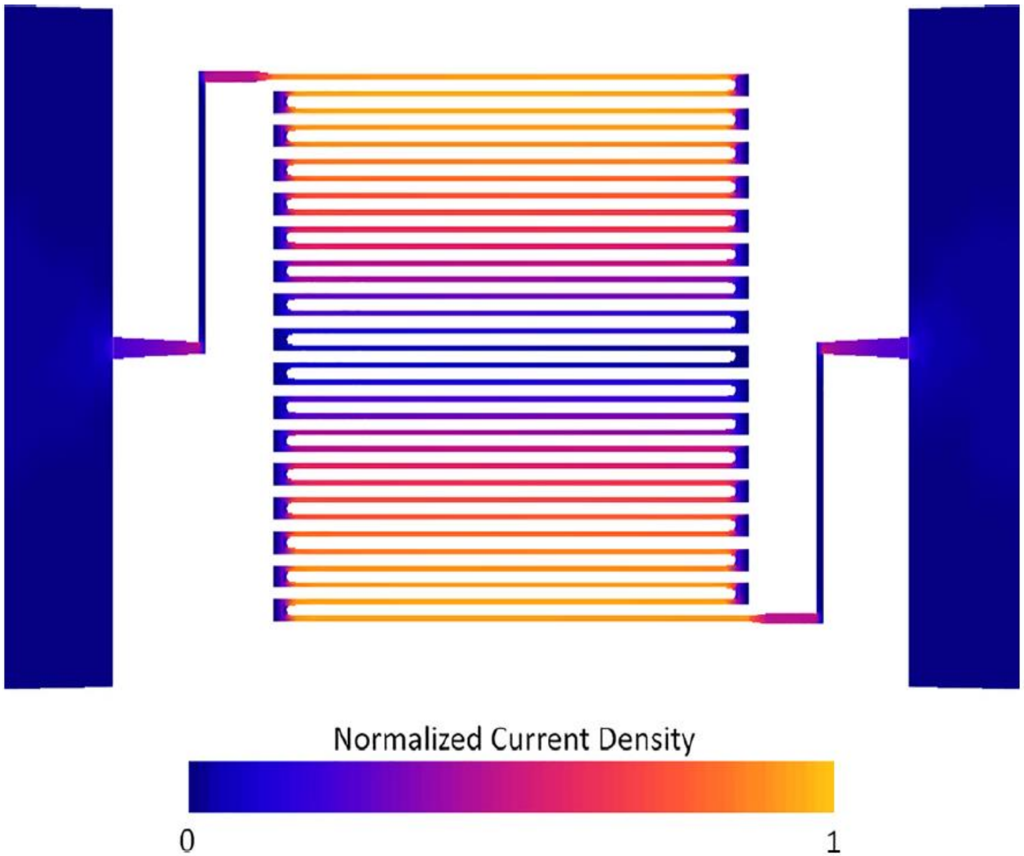
A ``Slight'' Discrepancy

Predicted self-resonance: 3 Thz



Self-resonant frequency is off by a factor of **240 x**

Almost There...



Use device length of 462 µm instead

$$\Rightarrow \lambda \approx 924\ \mu m$$

$$\Rightarrow f_{\text{self}-\text{res}} \approx 109\ \text{GHz}$$

Now only off by factor of 8.7

If $c' \sim c/26$ problem would be resolved...

Timing jitter FWHM vs. area