A distributed superconducting nanowire single photon detector for imaging

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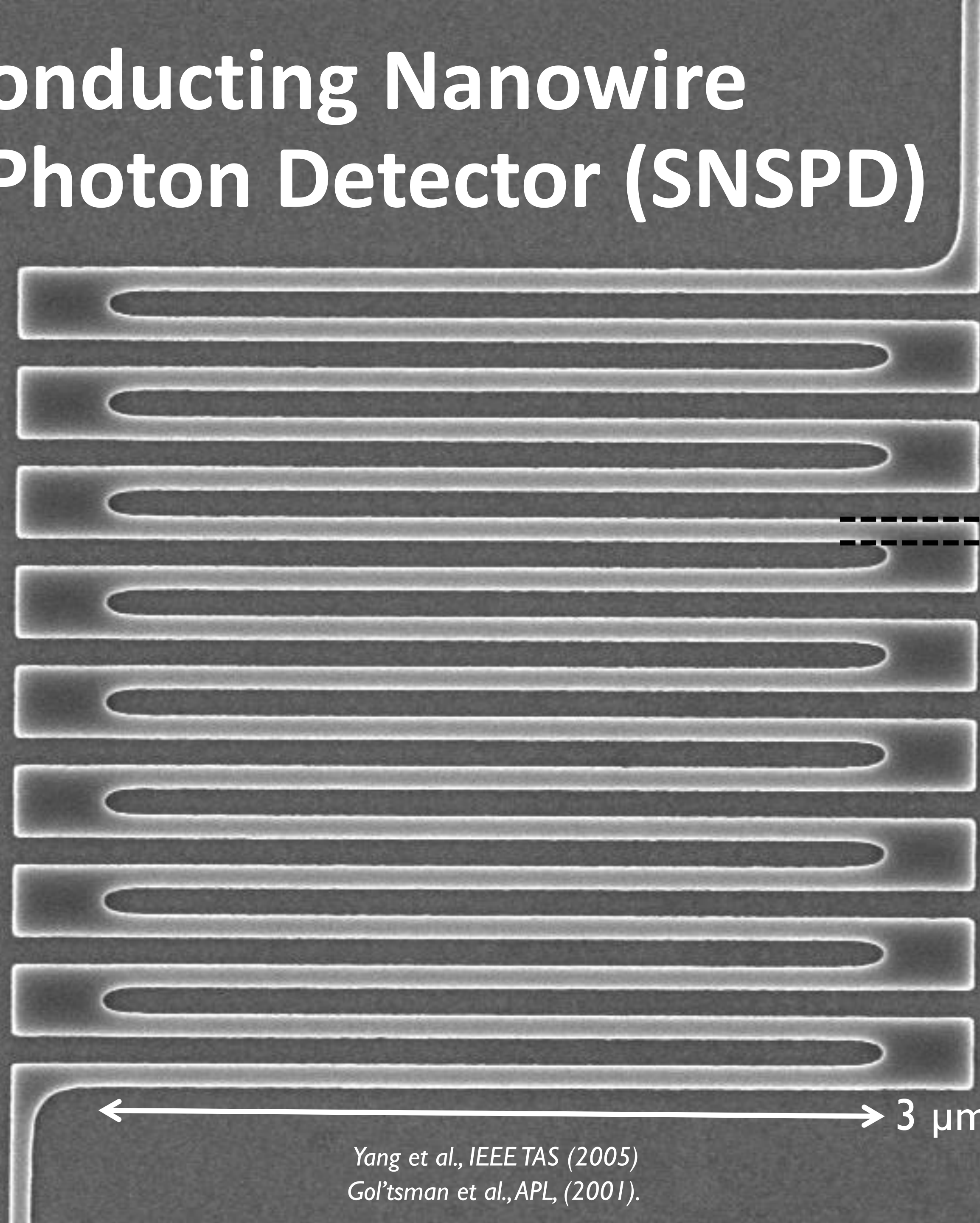
Acknowledgement::

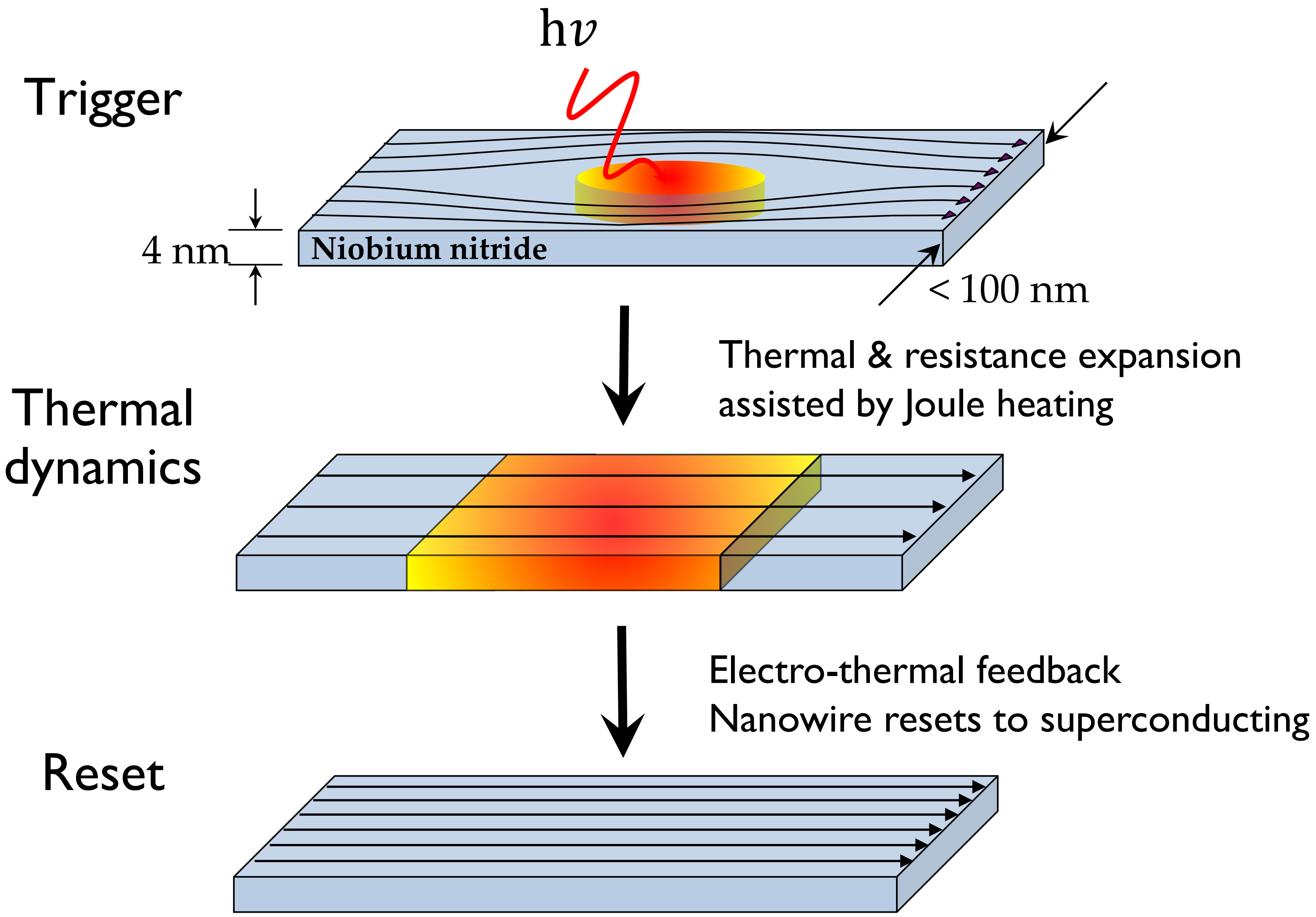
Superconducting Nanowire Single-Photon Detector (SNSPD)

NbN
@2.5 K

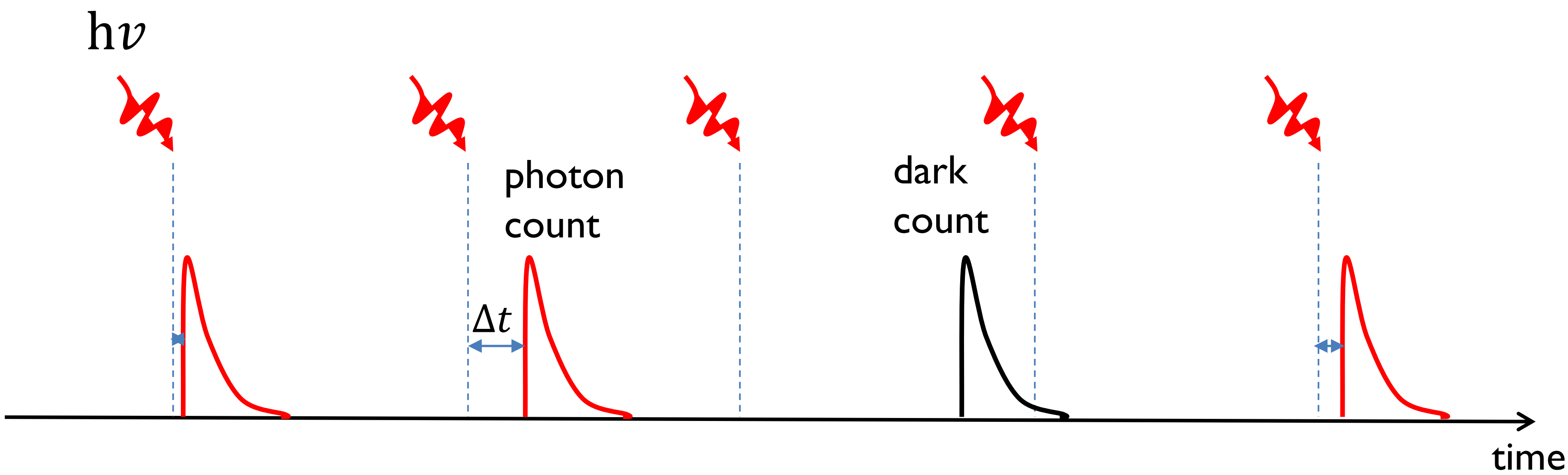


Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).

3 Detection mechanism



4 Detector performance



Single SNSPD performance		
Detection efficiency	N_{ph}/N_{in}	93% (WSi) [NIST 2012]
Timing jitter	FWHM of hist(Δt)	24 ps [MIT 2015]
Counting rate	N_{dt} per sec	~100 Mcps [MIT LL 2012]
Dark counts	N_{dcr} per sec	1 count / 10^3 sec [Kitami]

5

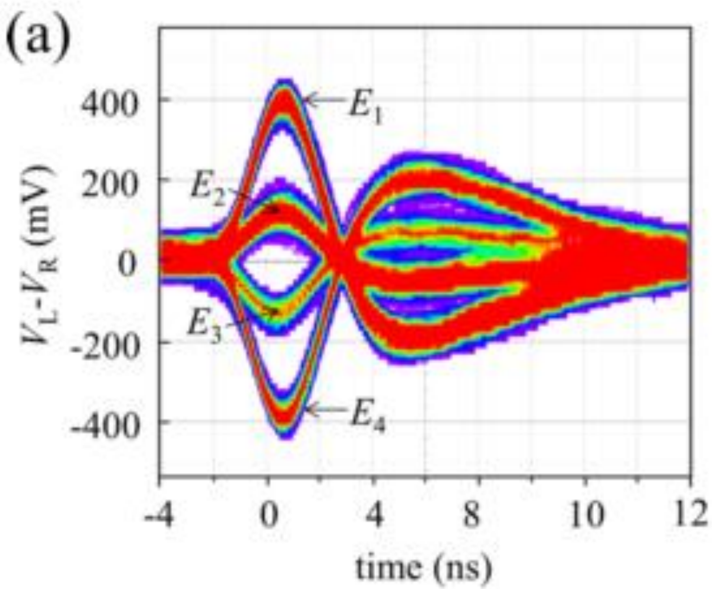
Constrains of an SNSPD

1. It has wide response spectrum, but cannot resolve photon energy

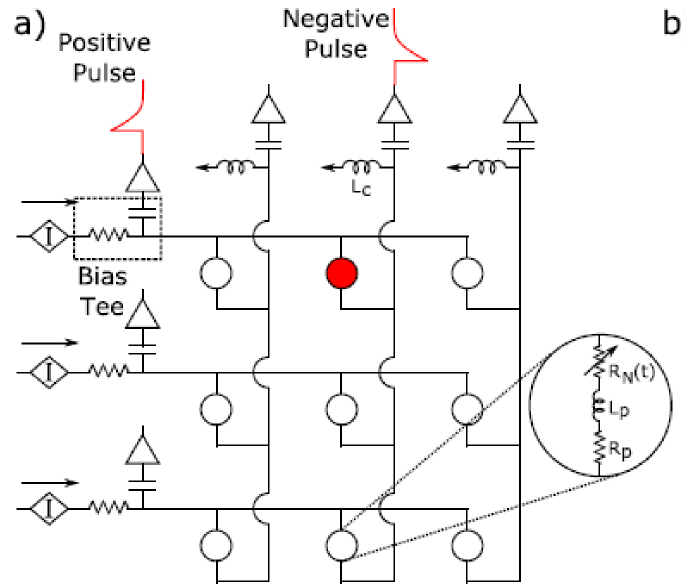
2. It is difficult to have a large SNSPD array ✓

6 Move to detector arrays

1. Encode detector position on the amplitude of output pulses



Inductive splitting, MIT (4 pixel)

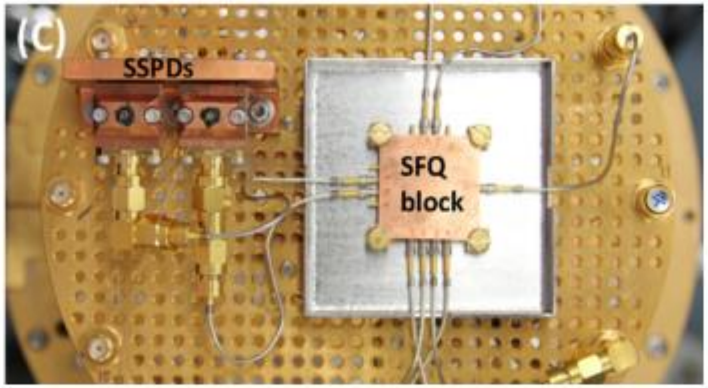


Resistive splitting, NIST&JPL (64 pixel)

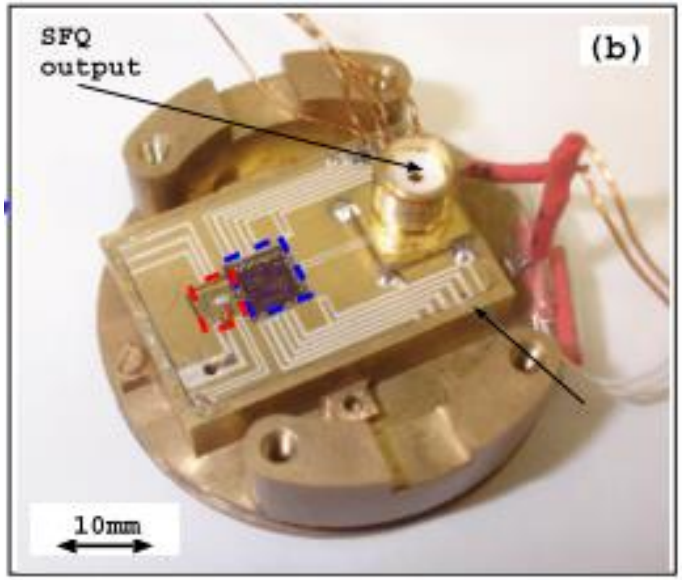
[1] Q.-Y. Zhao, *et. al.*, *Appl. Phys. Lett.*, vol. 103, no. 14, p. 142602, 2013.
[2] M. S. Allman, *et. al.*, *Appl. Phys. Lett.*, vol. 106, no. 19, 2015.

Move to detector arrays

2. Detector array + RSFQ readout circuits



NICT (4-pixel)

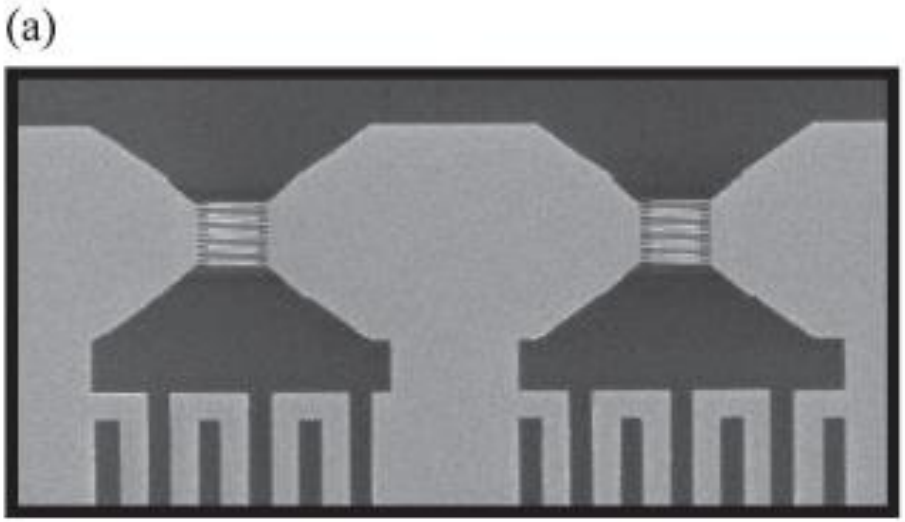


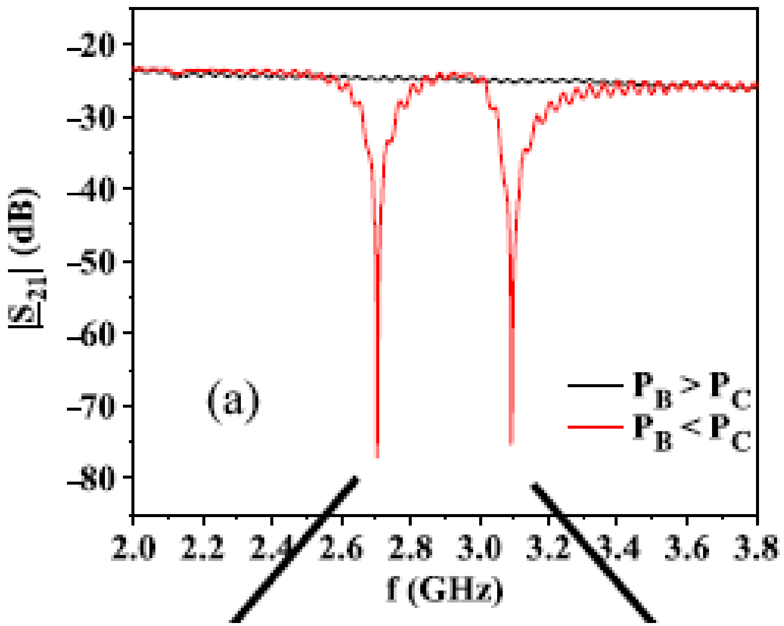
UCB & KIT (4-pixel)

[1] S. Miki, *et. al., Appl. Phys. Lett.*, vol. 99, no. 11, p. 111108, Sep. 2011.
[2] M. Hofherr, *et. al., Opt. Express*, vol. 20, no. 27, p. 28683, Dec. 2012.

Move to detector arrays

3. Frequency multiplexing



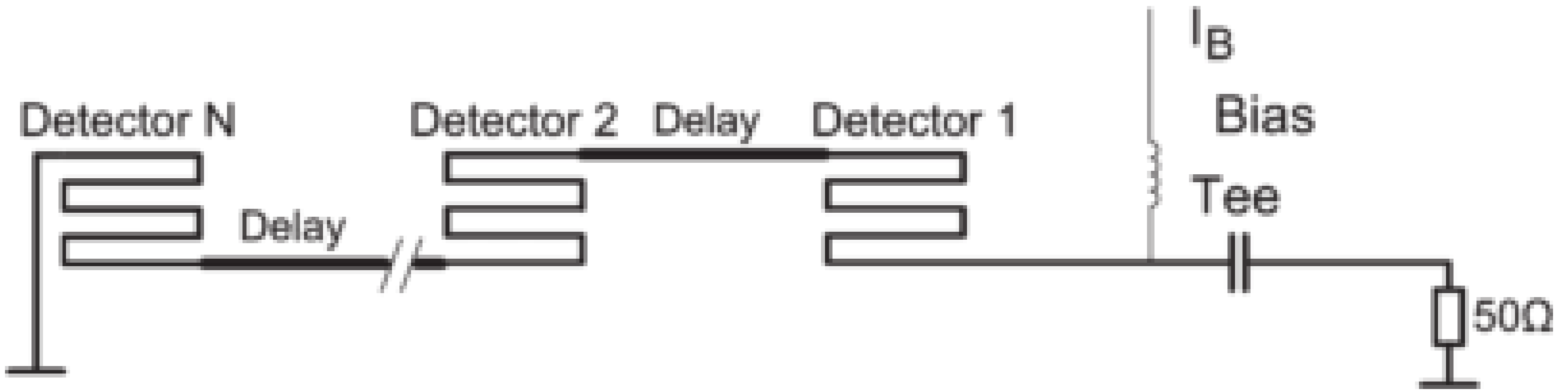


KIT (2-pixel)

[1] S. Doerner, *et. al., IEEE Trans. Appl. Supercond.*, vol. PP, no. 99, pp. 1–1, 2016.

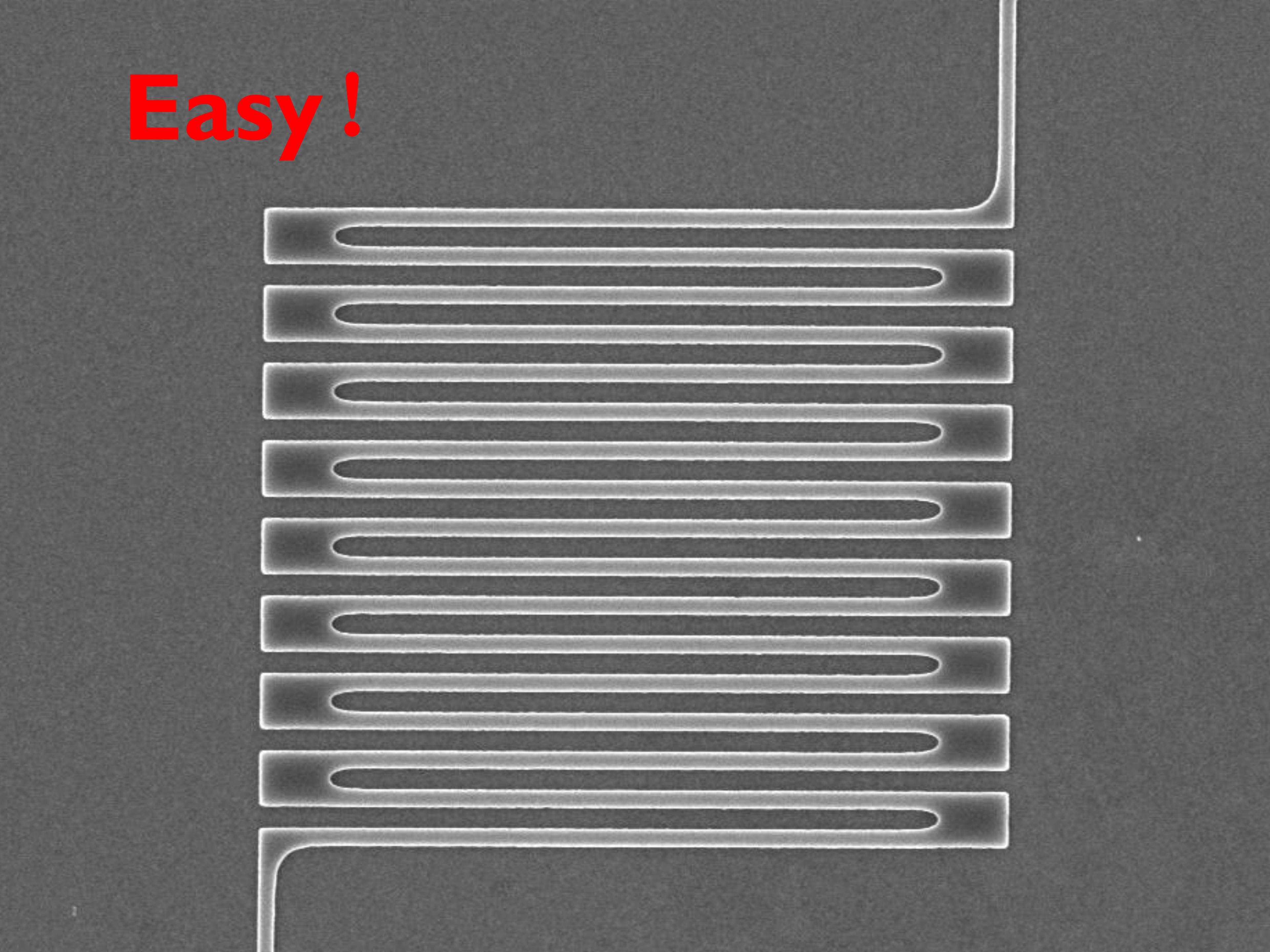
Move to detector arrays

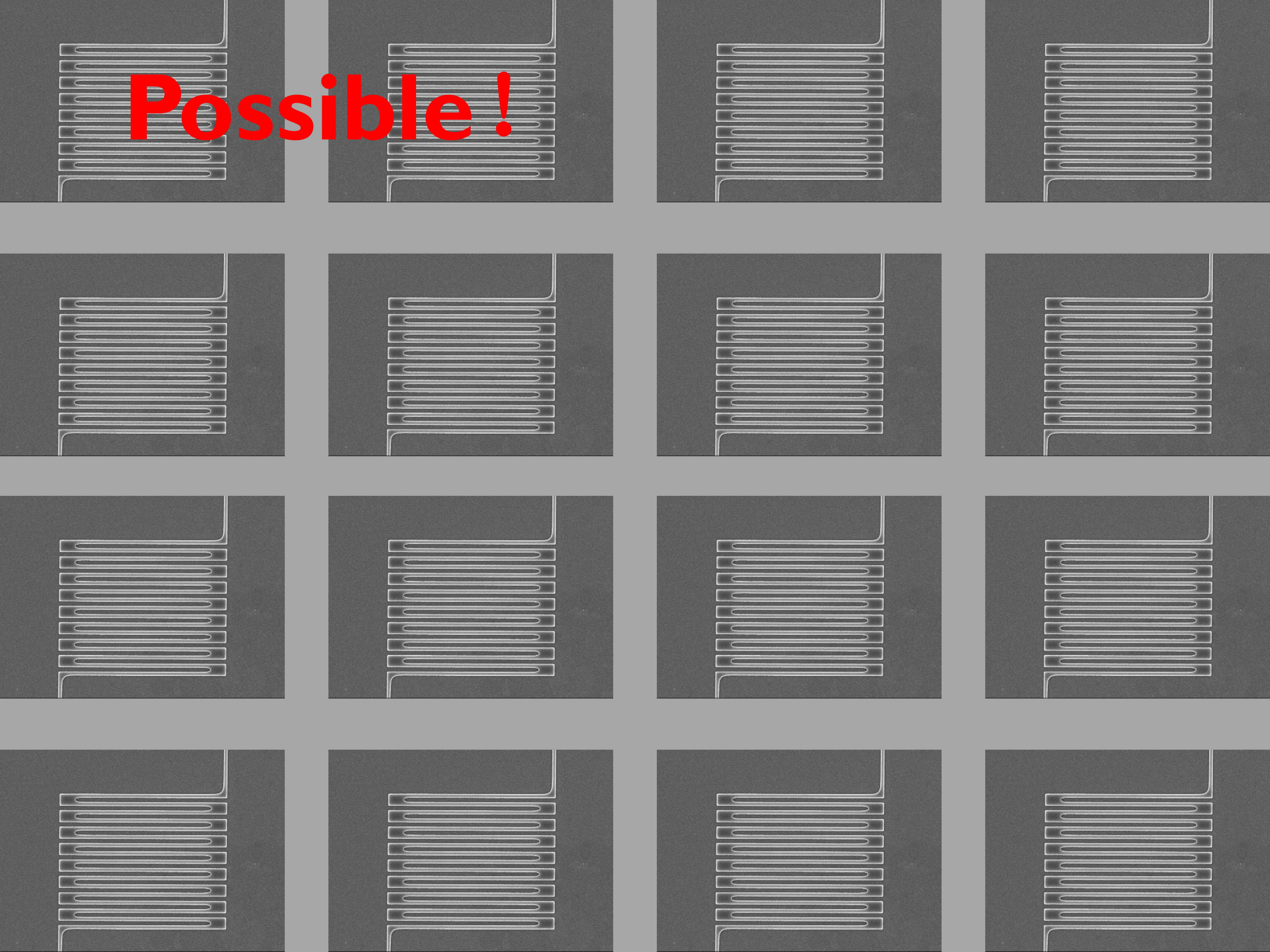
4. Time multiplexing



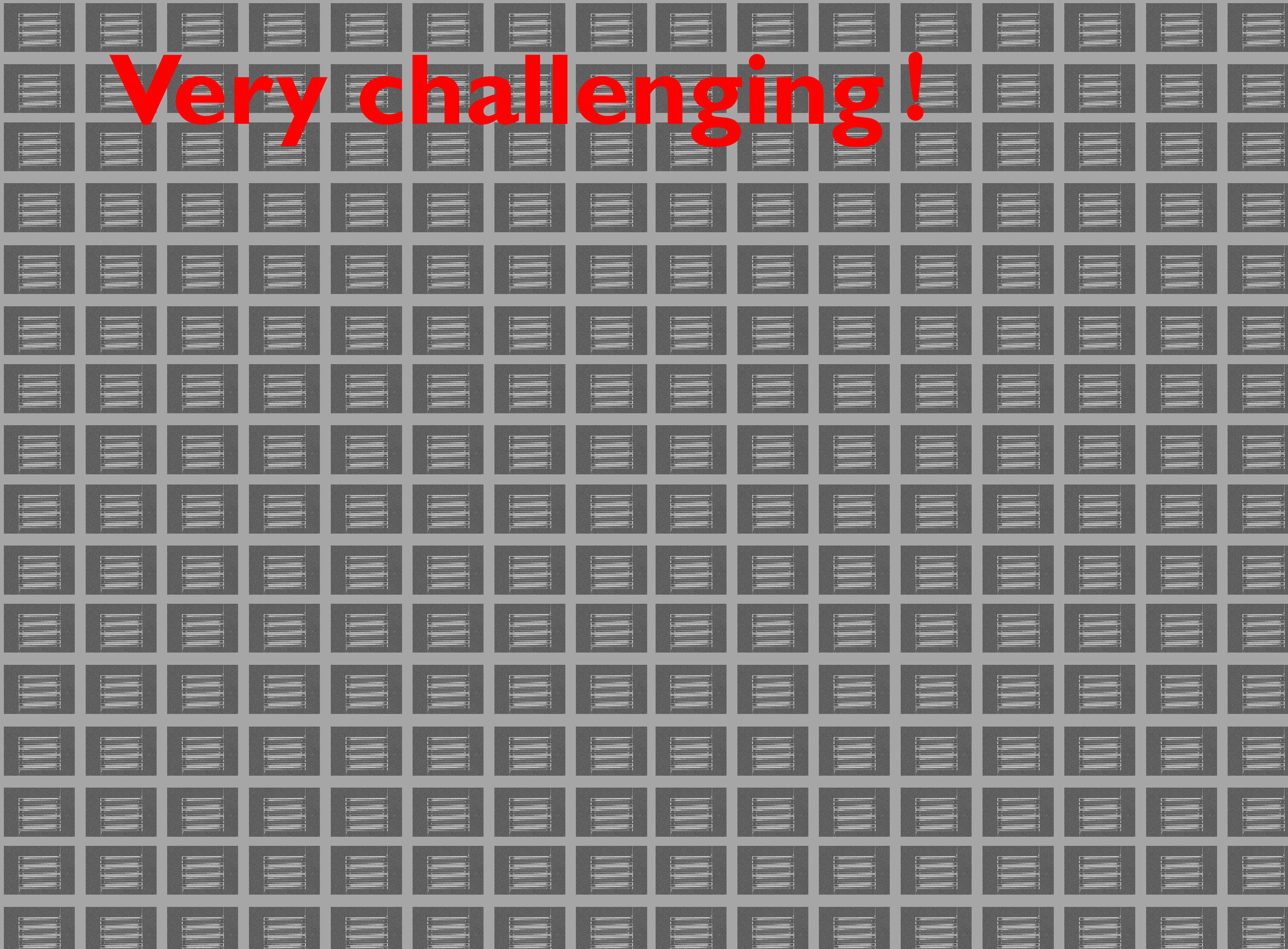
KIT (2-pixel)

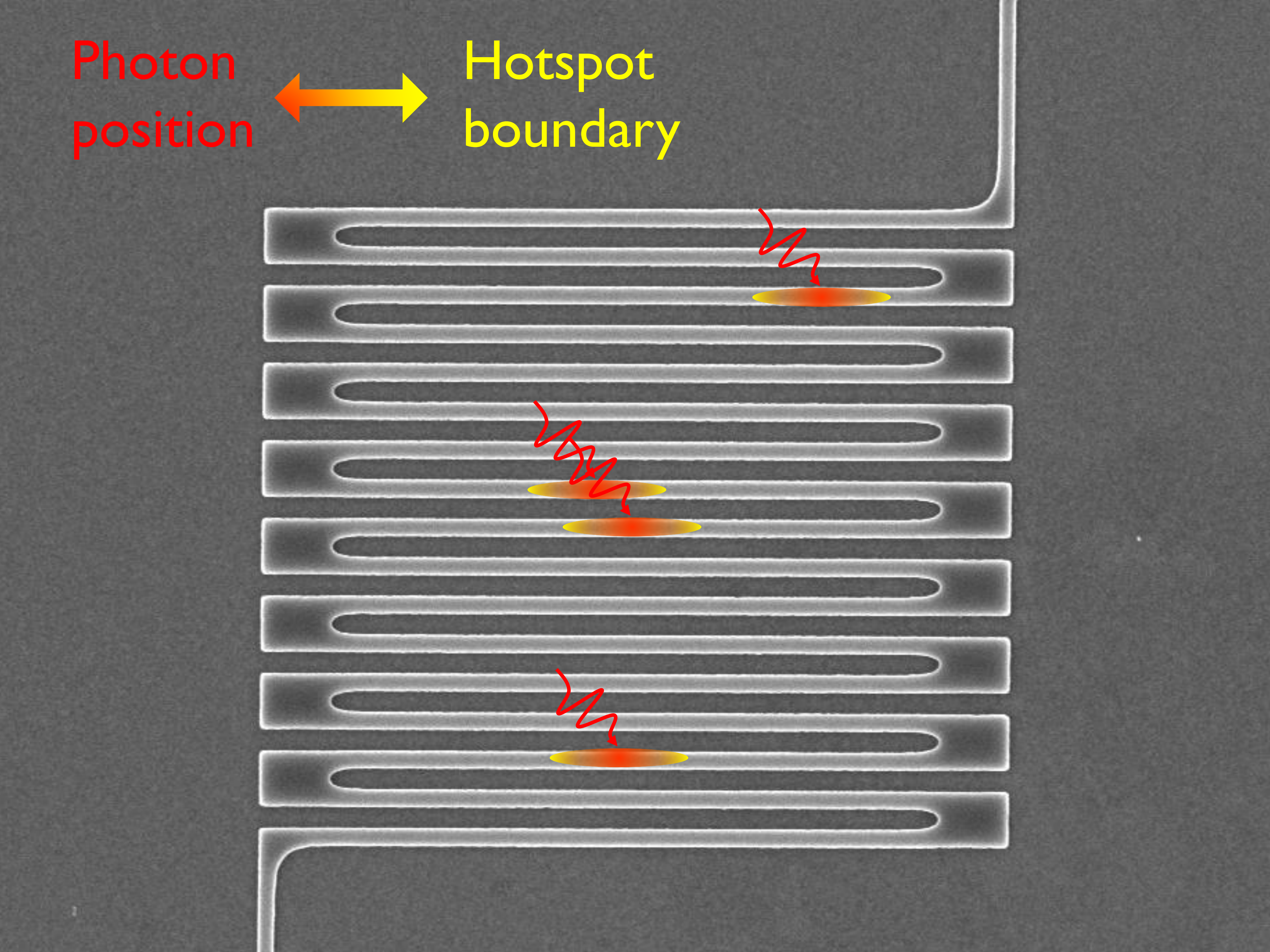
[1] M. Hofherr, *et. al.,* *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, 2013.


Easy !

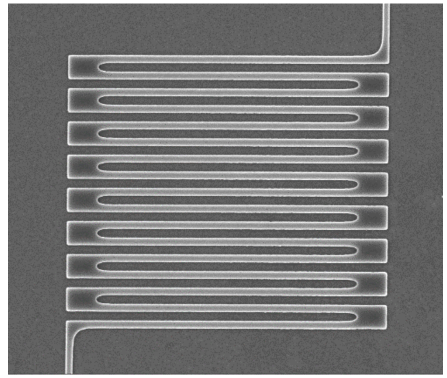

Possible !

Very challenging!



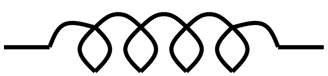

Photon position
Hotspot boundary

Q: what is the equivalent circuit model of an SNSPD?



Inductor

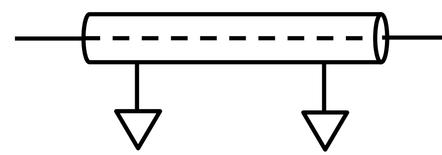
L_K



Lumped device
SNSPD

Transmission line

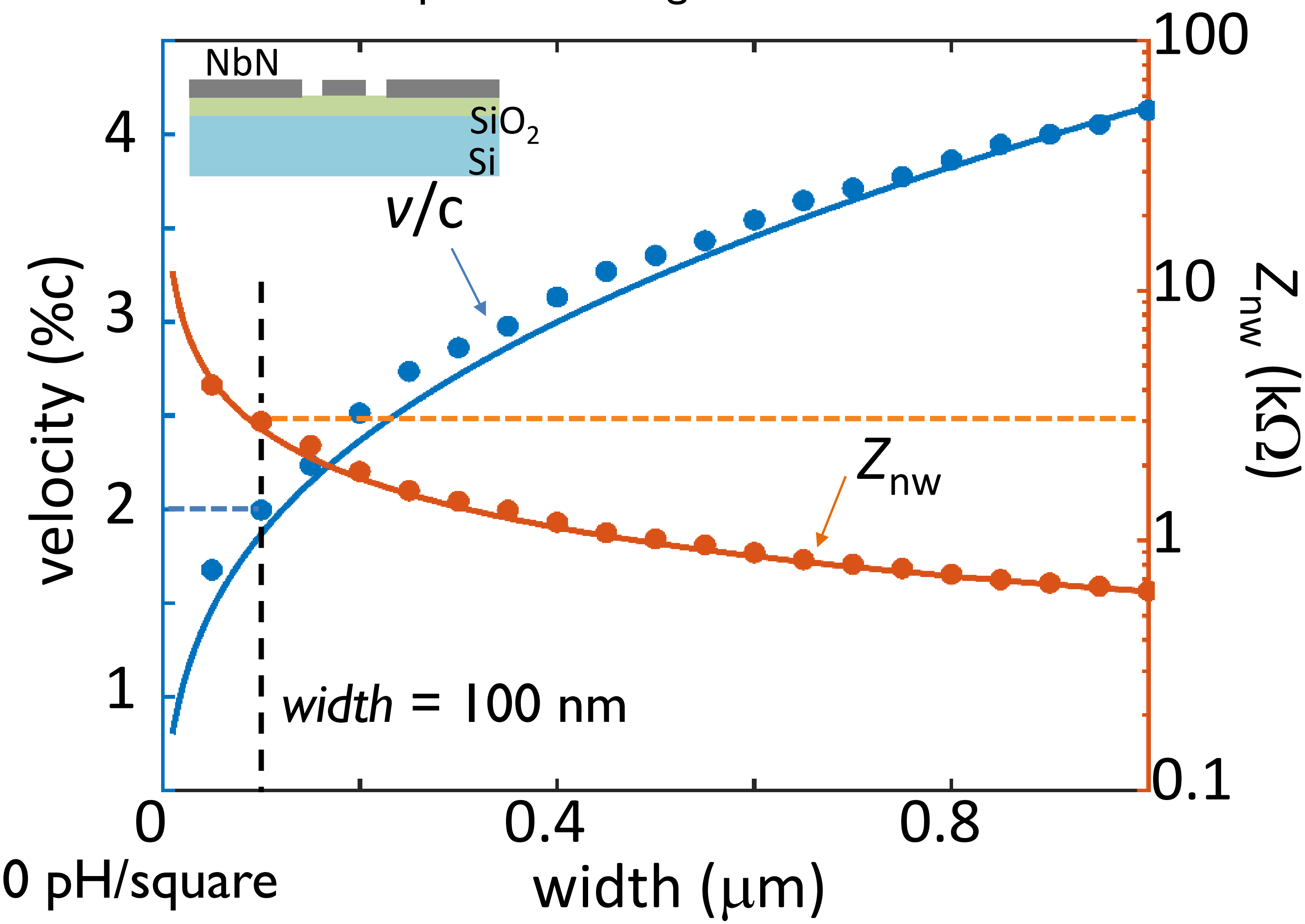
L, Z_n, V_n



Distributed device
Imager

Design a superconducting nanowire into a CPW

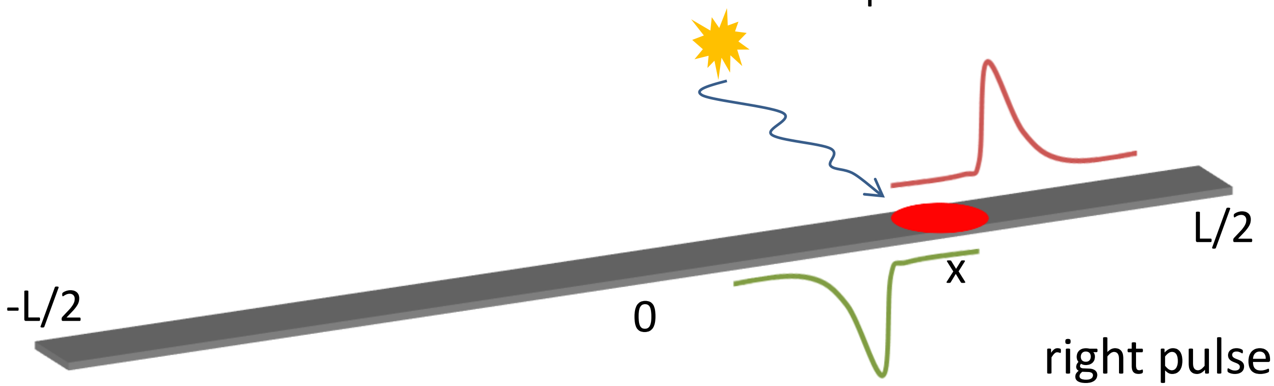
Simulation a superconducting nanowire transmission line



Lk = 50 pH/square

Spatial and temporal detection in a wire

Photon arrives at t_p



right pulse arrival time

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

left pulse arrival time:

$t_L = t_p + (L/2+x)/v$

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

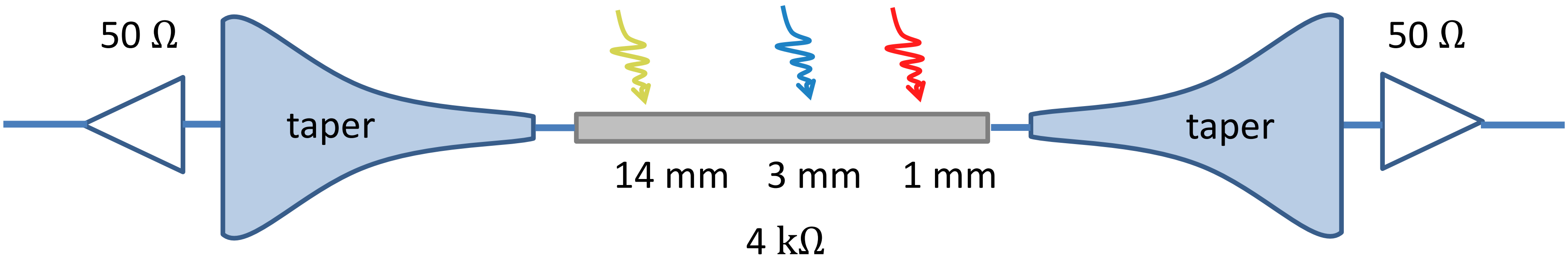
differential time

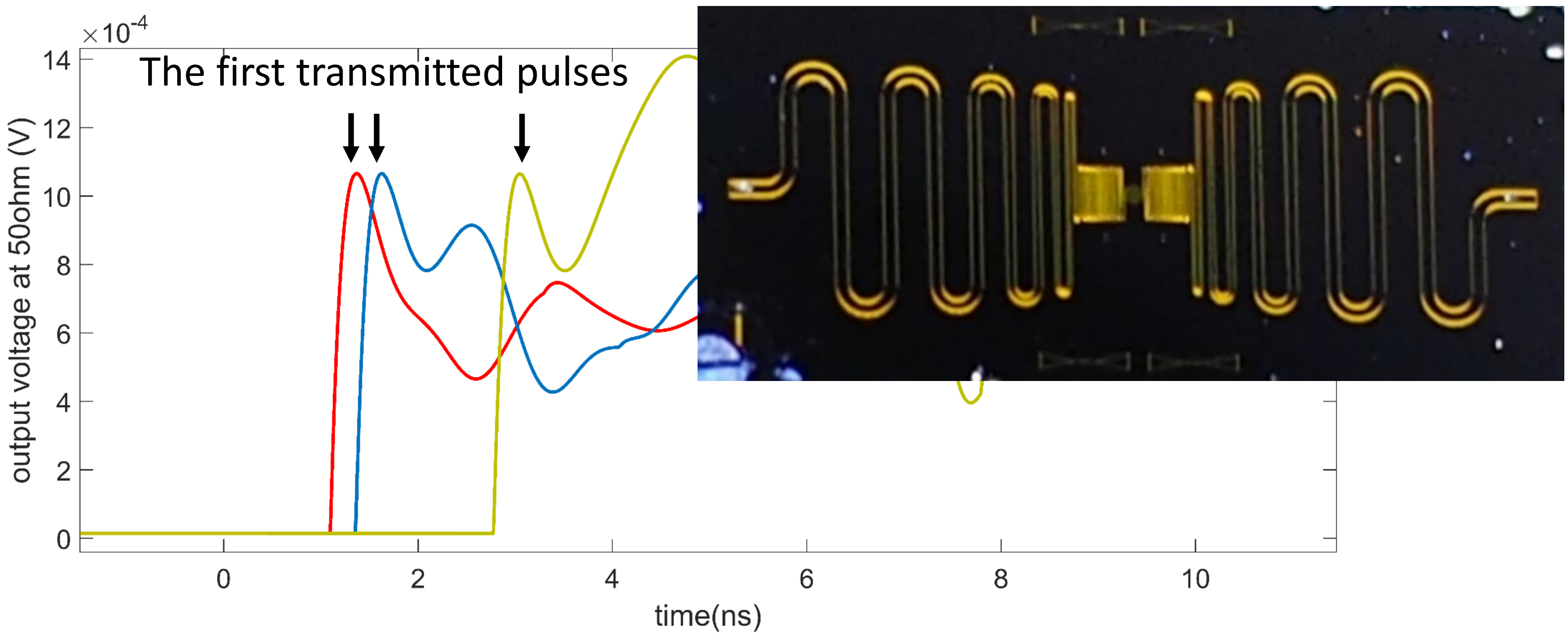
Time: $t_p = (t_L + t_R - L/v)/2$

sum time

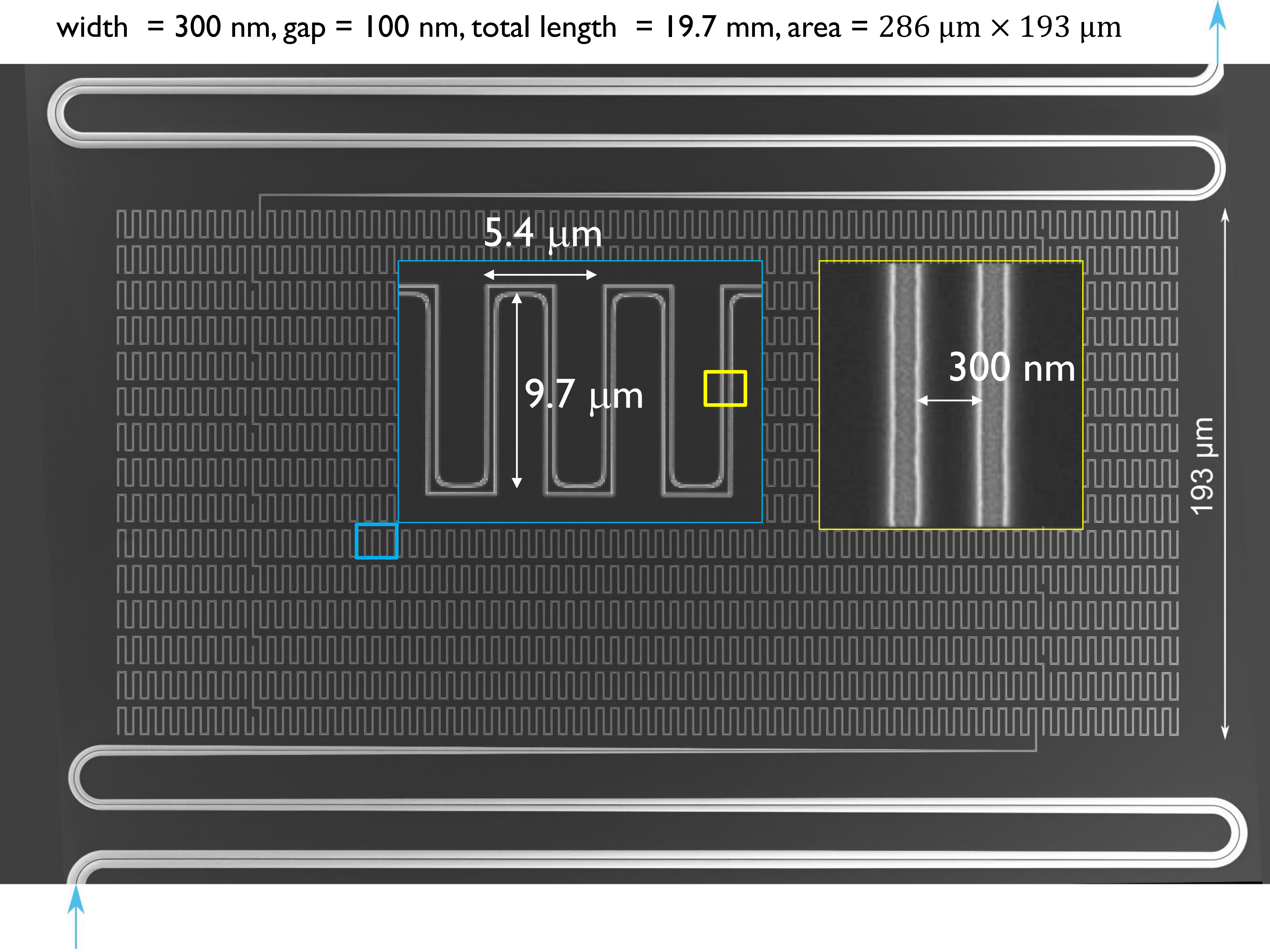
Photon position and arrival time can be detected **simultaneously**!

Read out the propagation delay without reflections



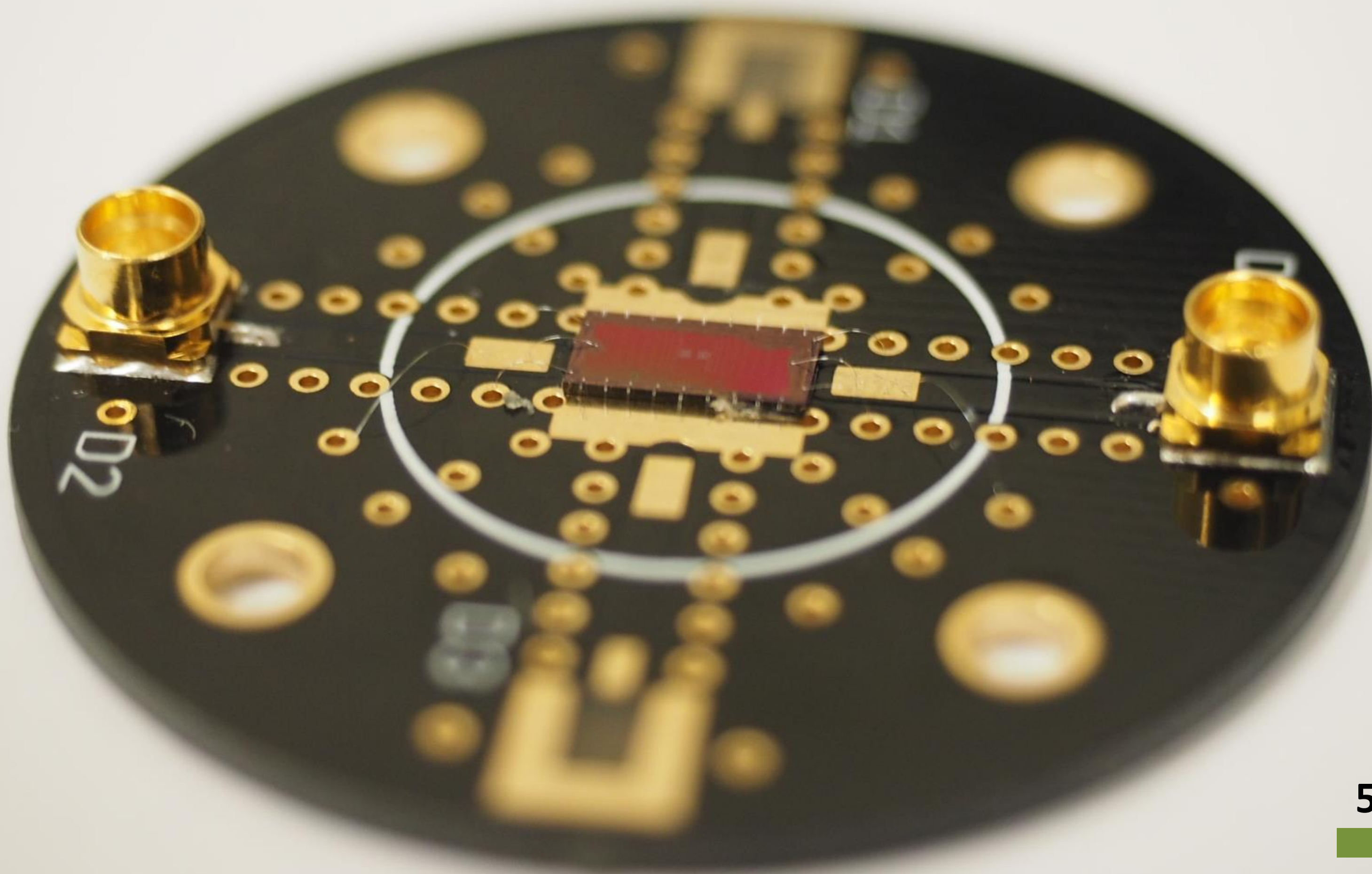


width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 μm × 193 μm



Two connectors for one imager (>500 pixels)

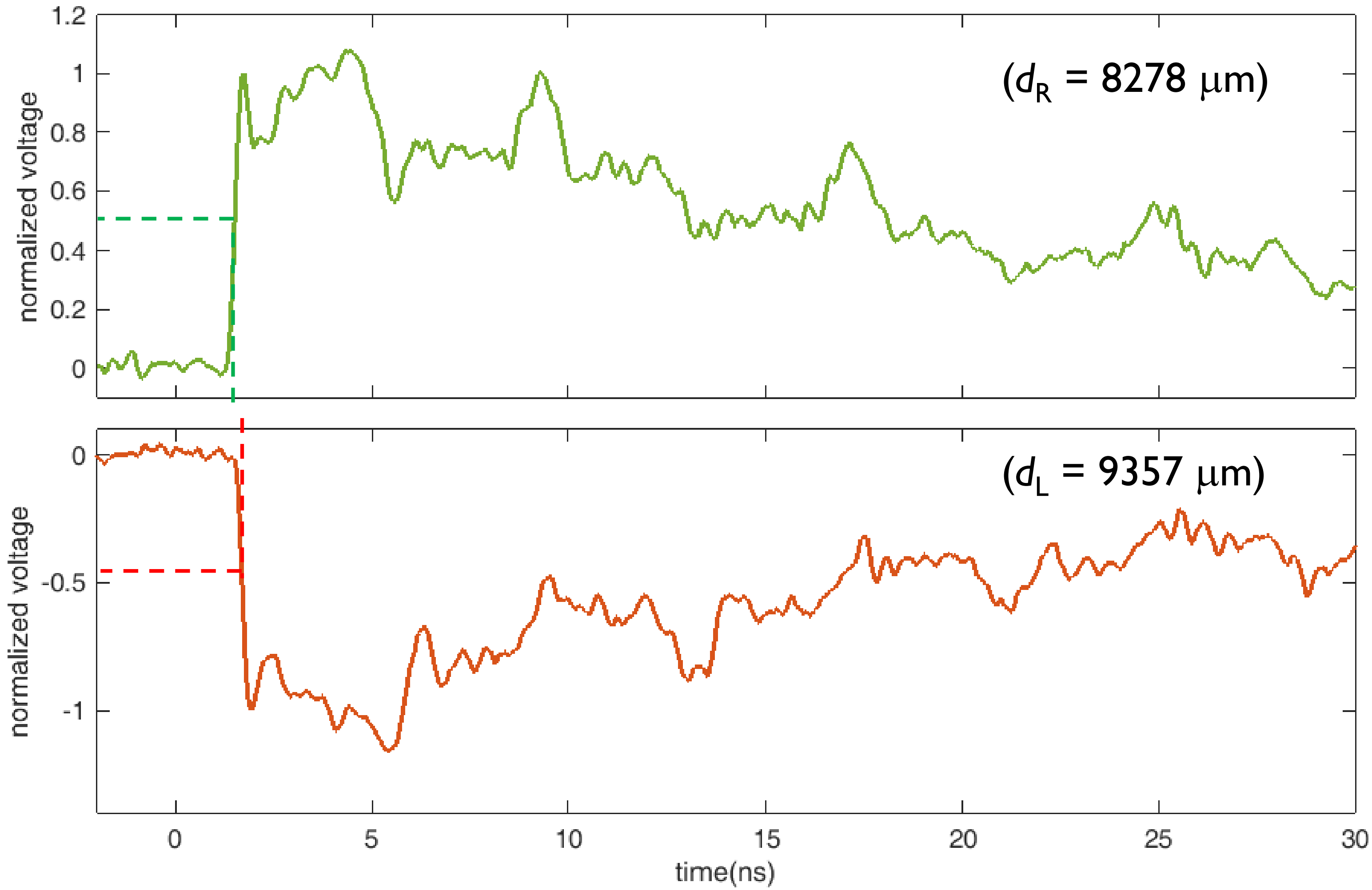
No cryogenic circuit is required



5 mm

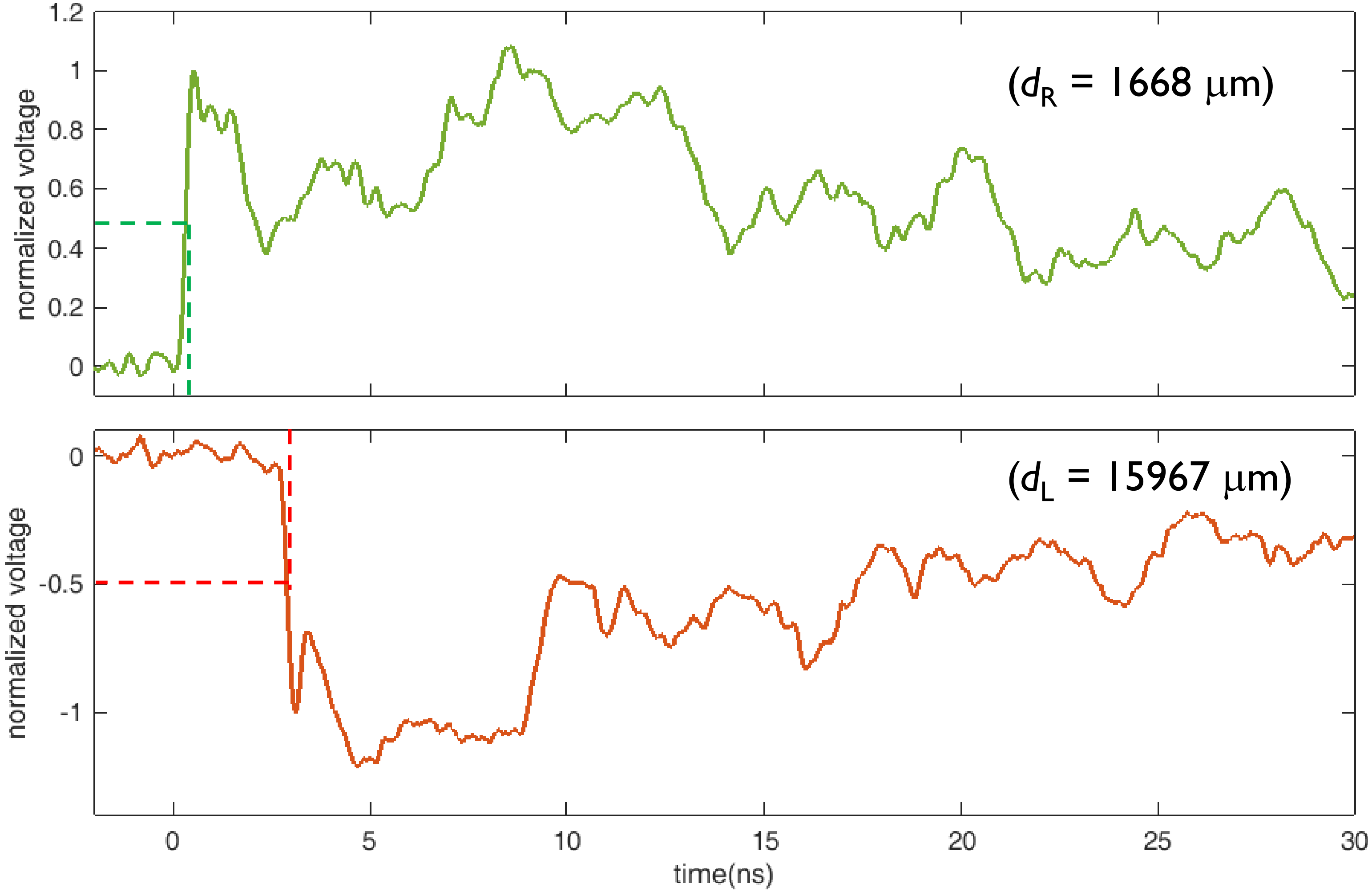
Output pulses from the SNSPI

Photon lands near the middle



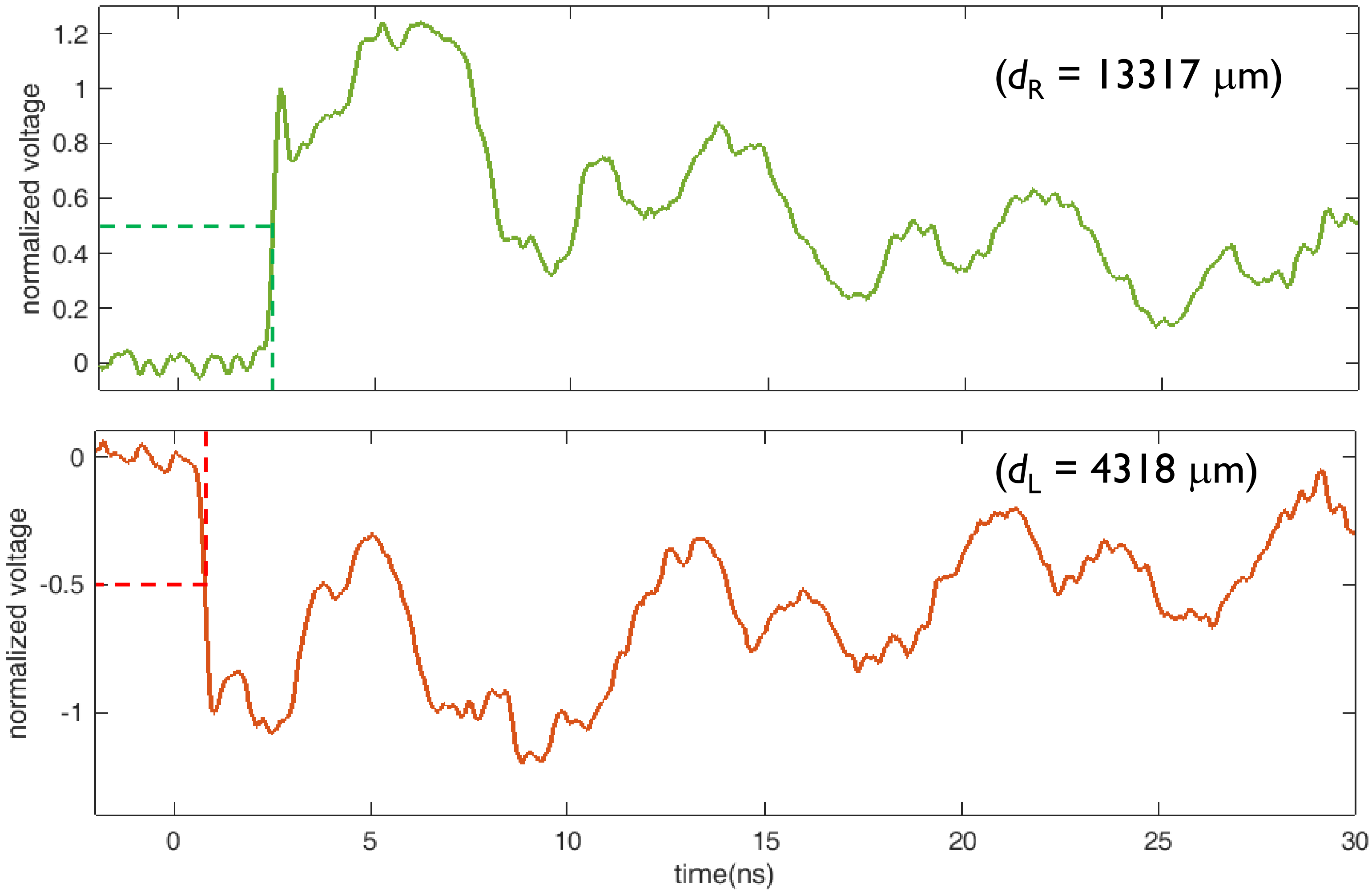
Output pulses from the SNSPI

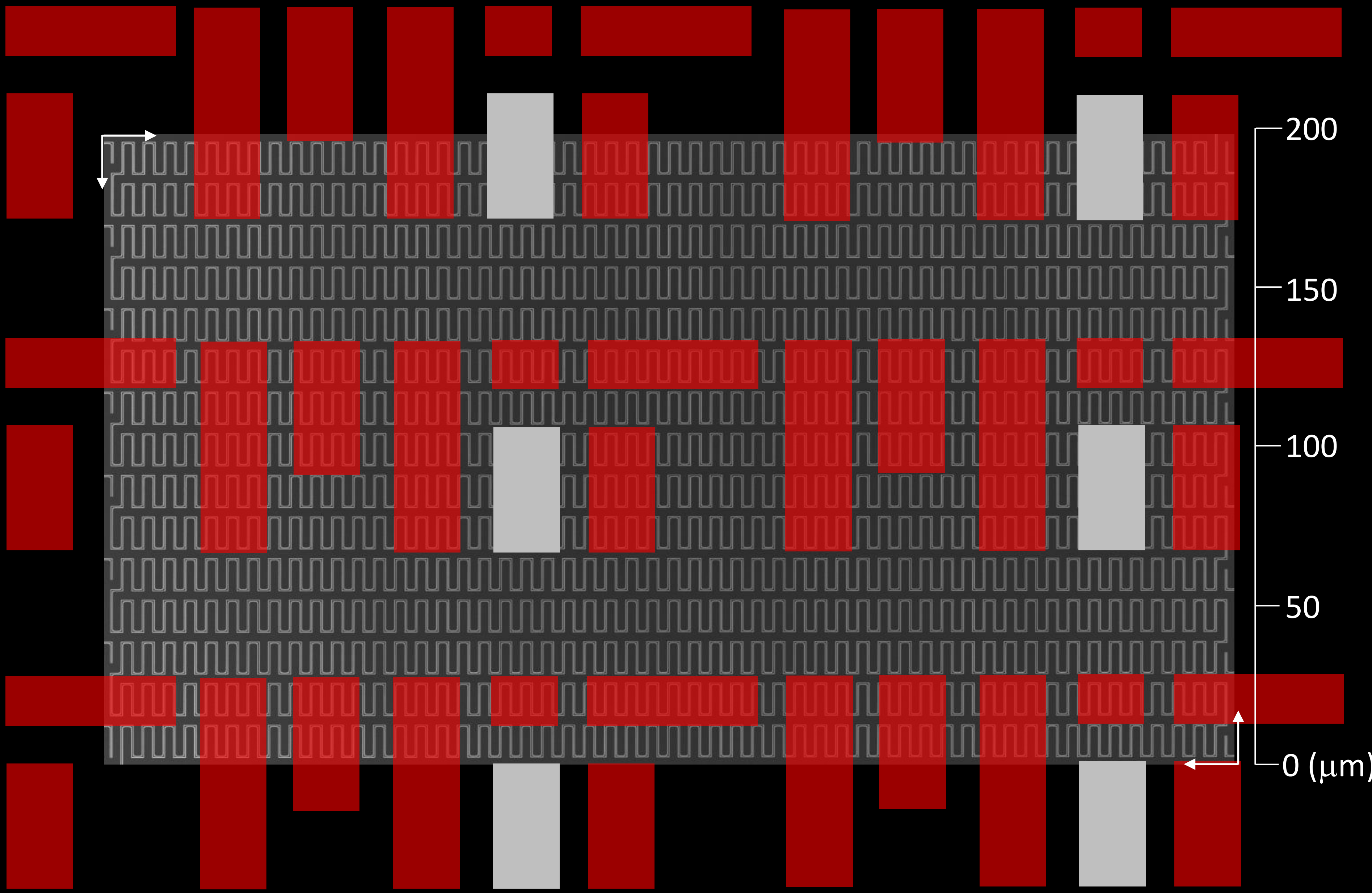
Photon lands near the right end



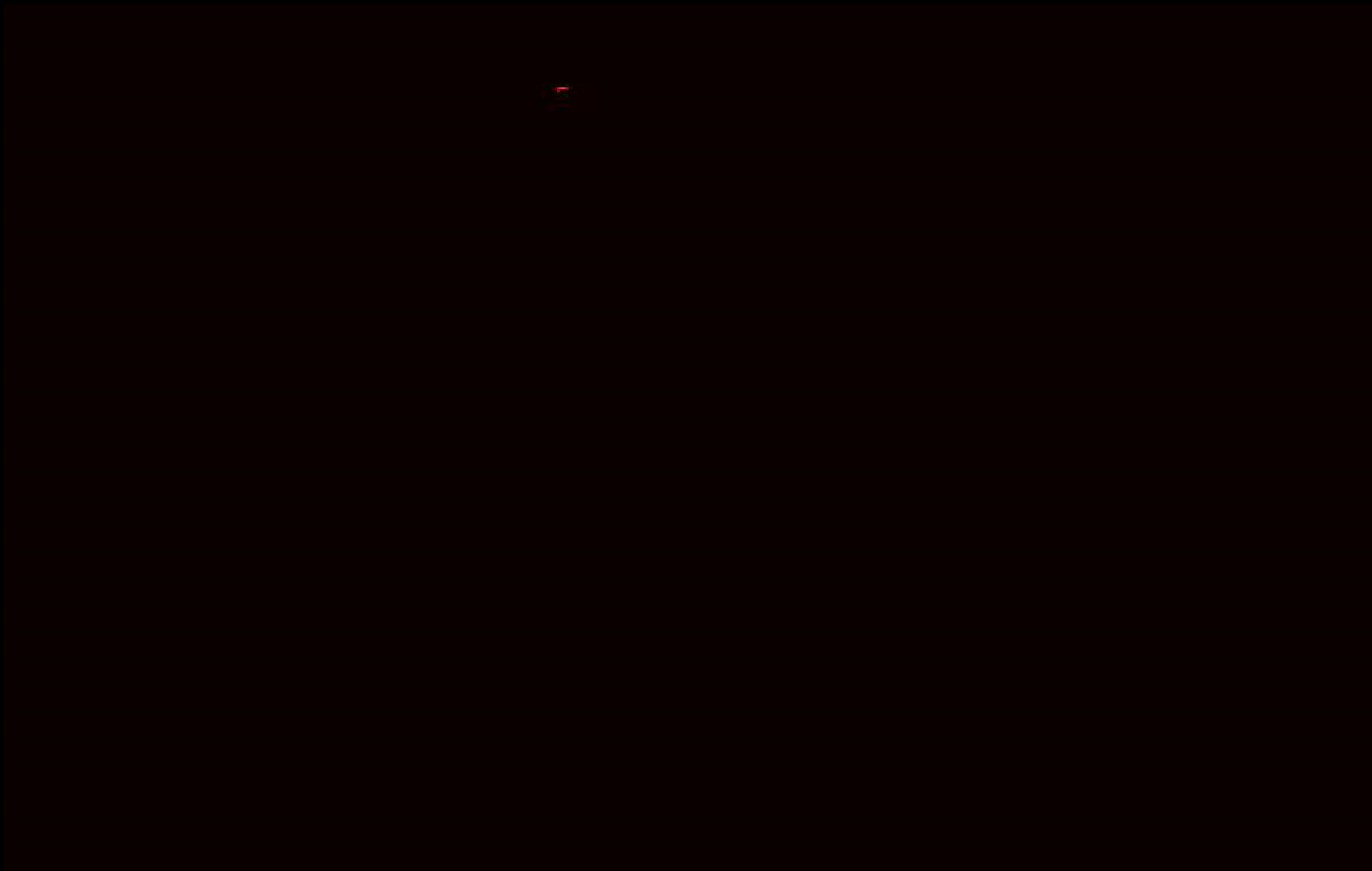
Output pulses from the SNSPI

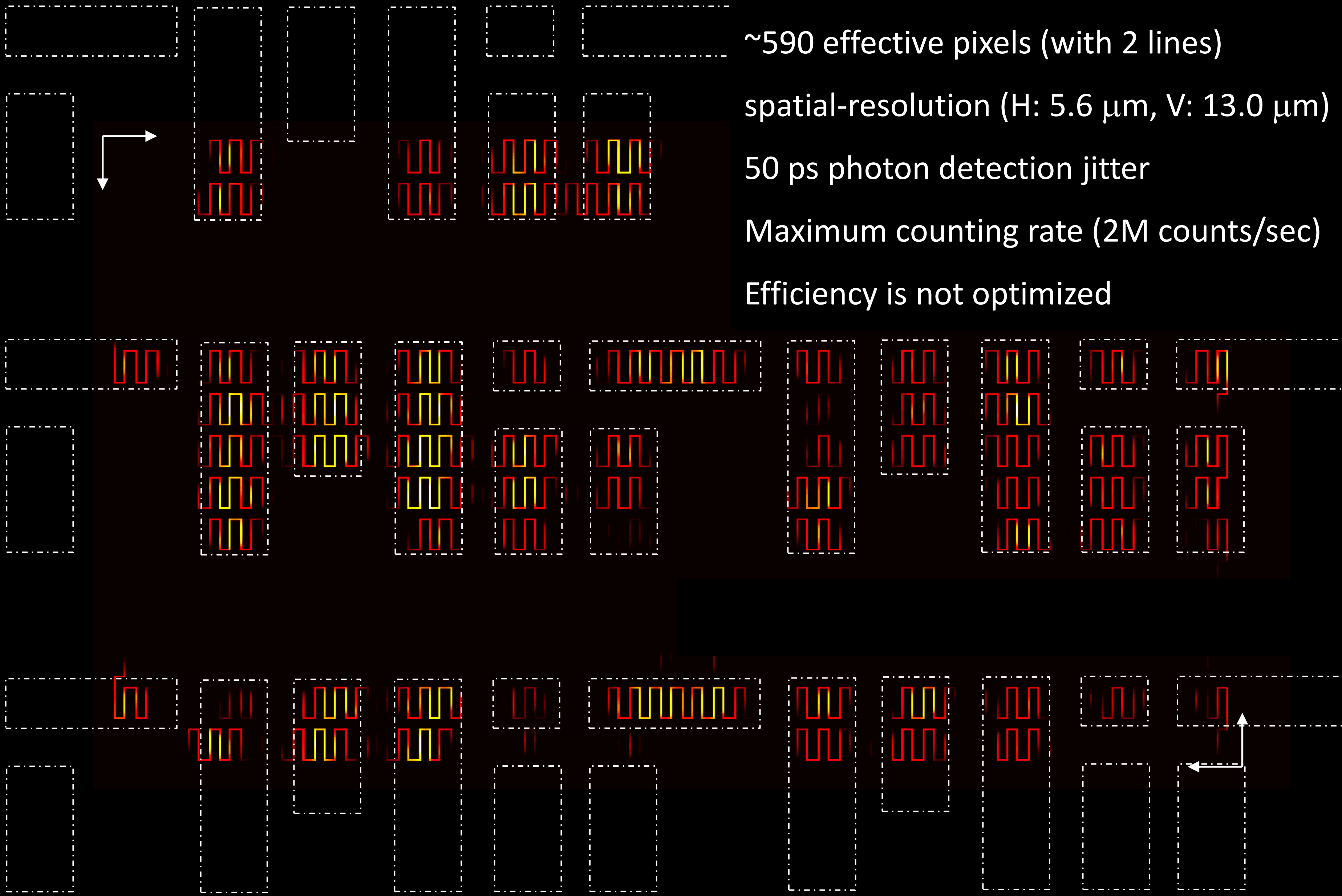
Photon lands near the left end




200
150
100
50
0 (μm)

Mapping each photon position to form an image





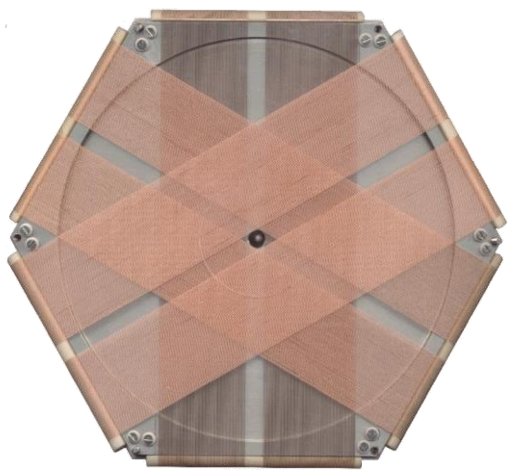
- ~590 effective pixels (with 2 lines)
- spatial-resolution (H: 5.6 μm, V: 13.0 μm)
- 50 ps photon detection jitter
- Maximum counting rate (2M counts/sec)
- Efficiency is not optimized

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

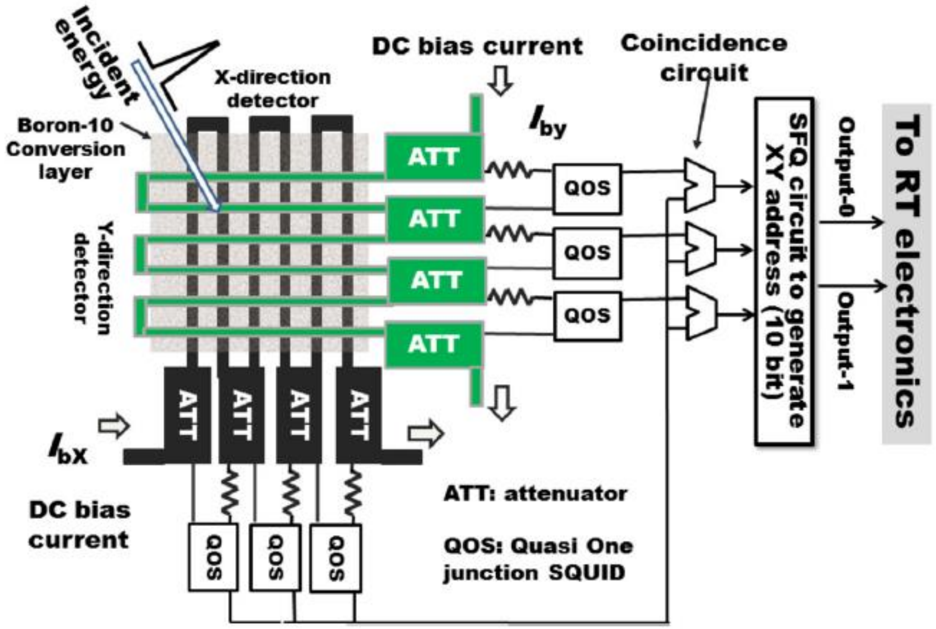
Similar readout architectures in other detector arrays

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

Neutron imager using delay lines



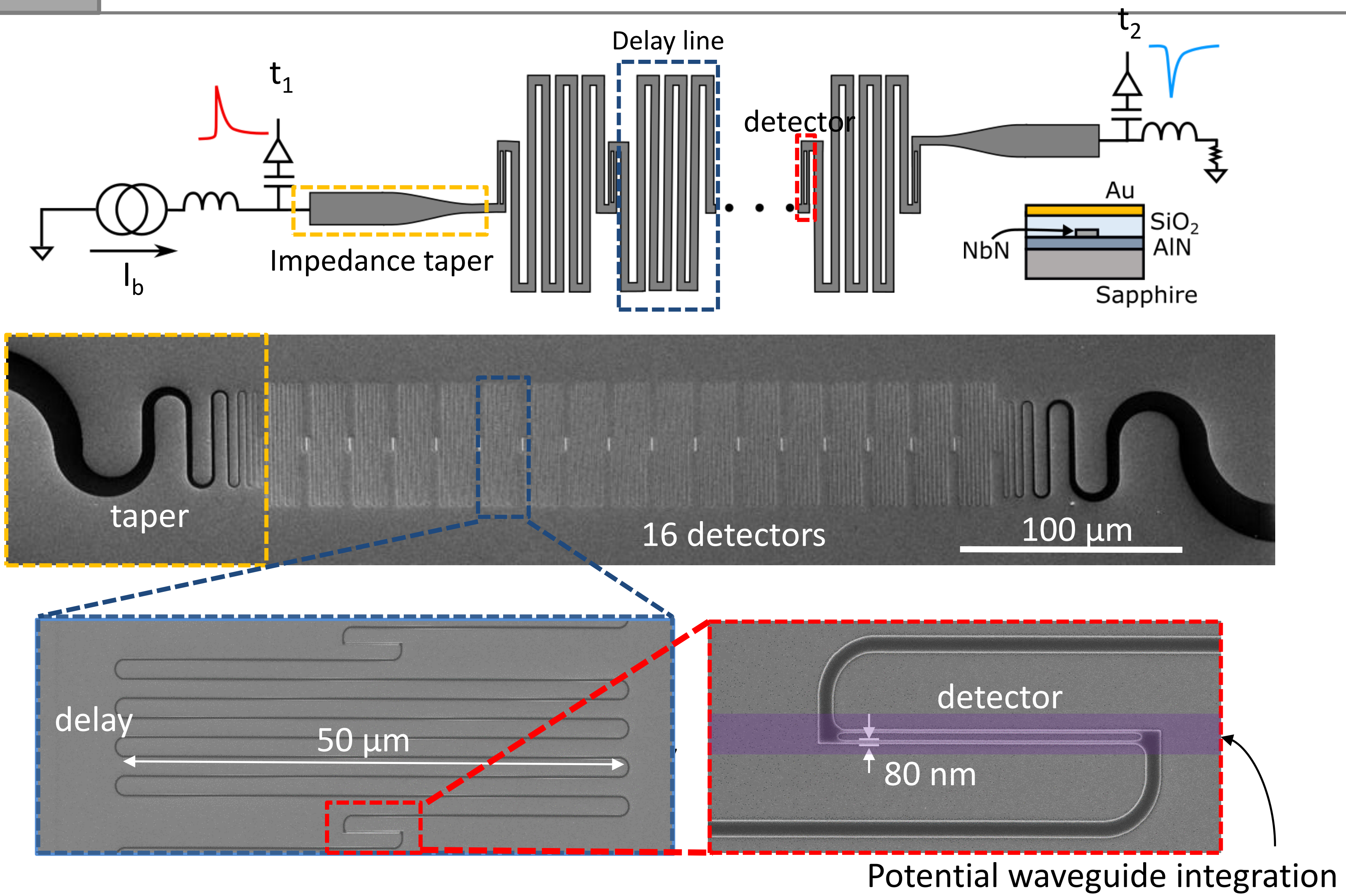
http://www.roentdek.com/



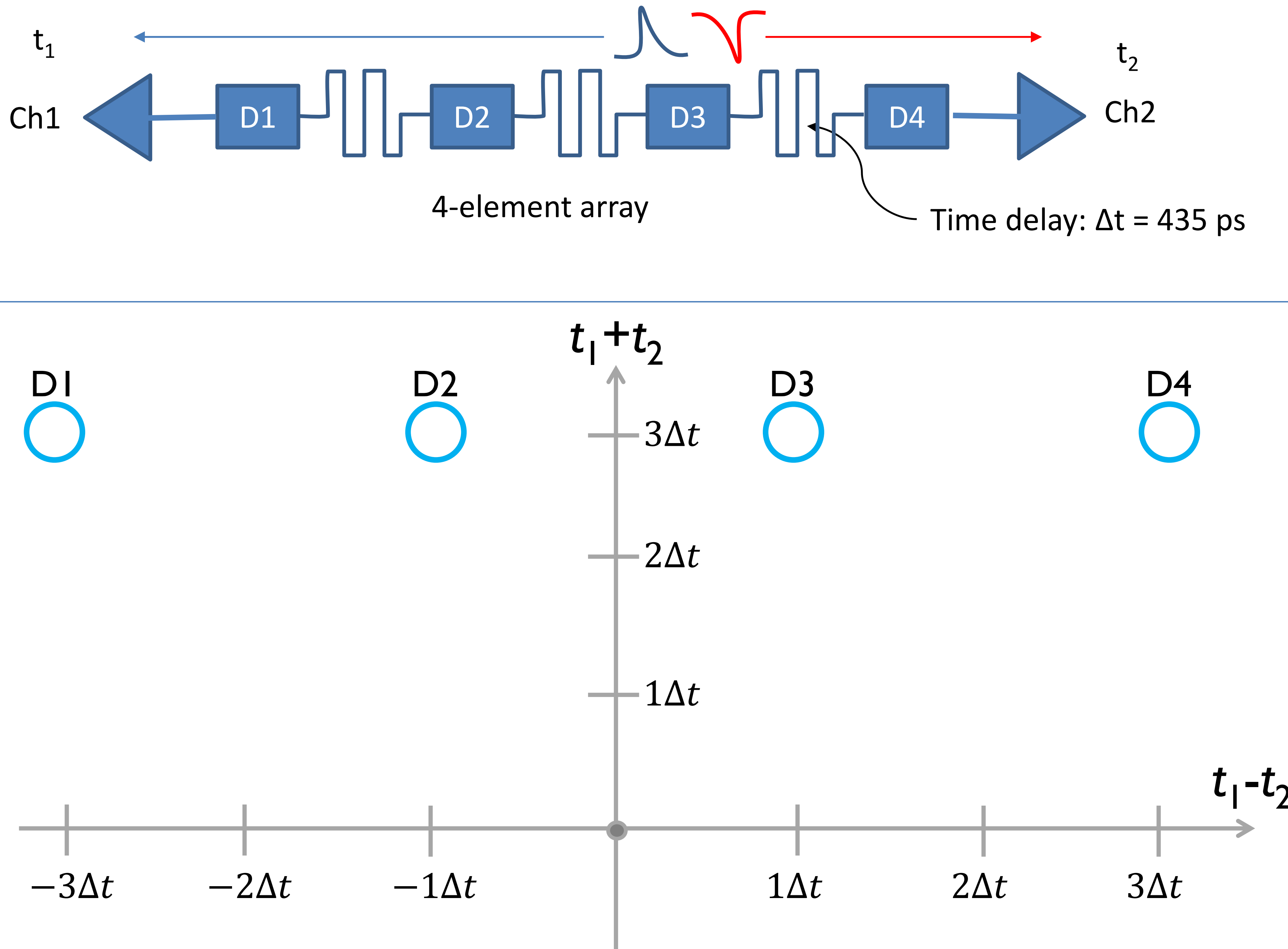
*O. Jagutzki *et al.*, *Nucl. Instruments Methods Phys. Res. Sect. A* **477**, 244–249 (2002)

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

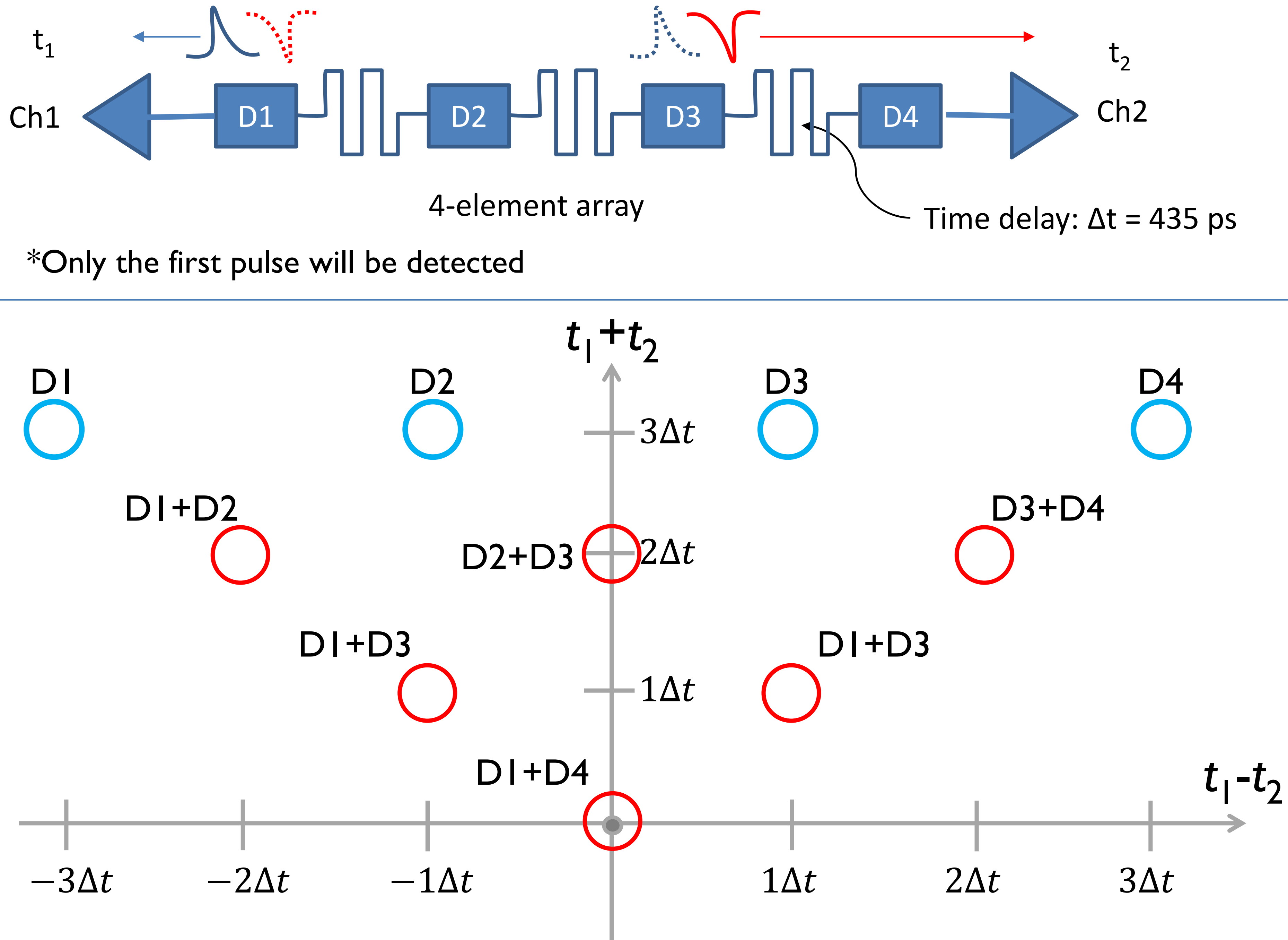
Delay line multiplexing of waveguide SNSPDs



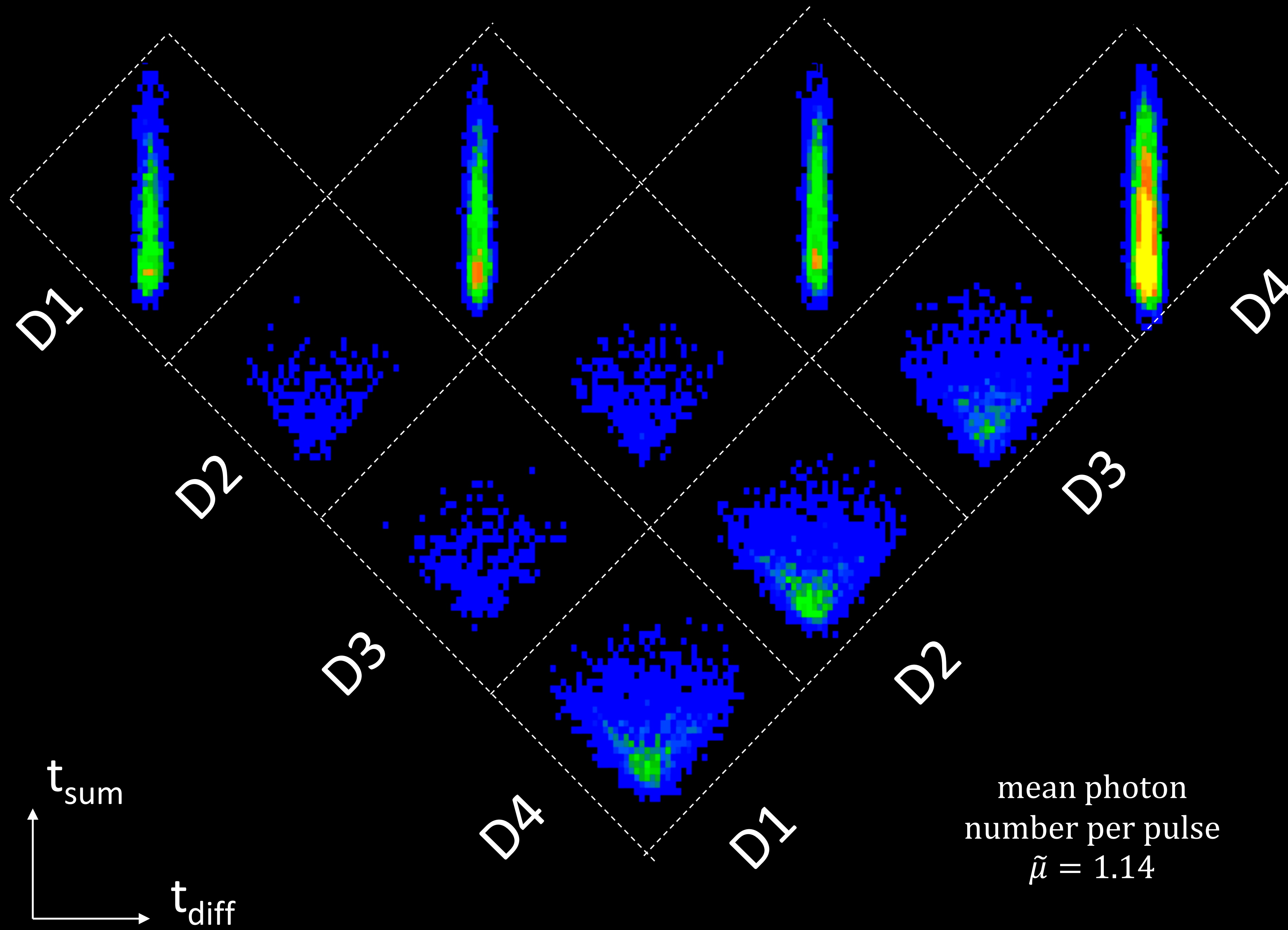
D Zhu, *et. al,* CLEO 2017: Applications and Technology, JTh5B. 4



t1
t2
Ch1
D1
D2
D3
D4
Ch2
4-element array
Time delay: Δt = 435 ps
t1+t2
3Δt
2Δt
1Δt
t1-t2
−3Δt
−2Δt
−1Δt
1Δt
2Δt
3Δt



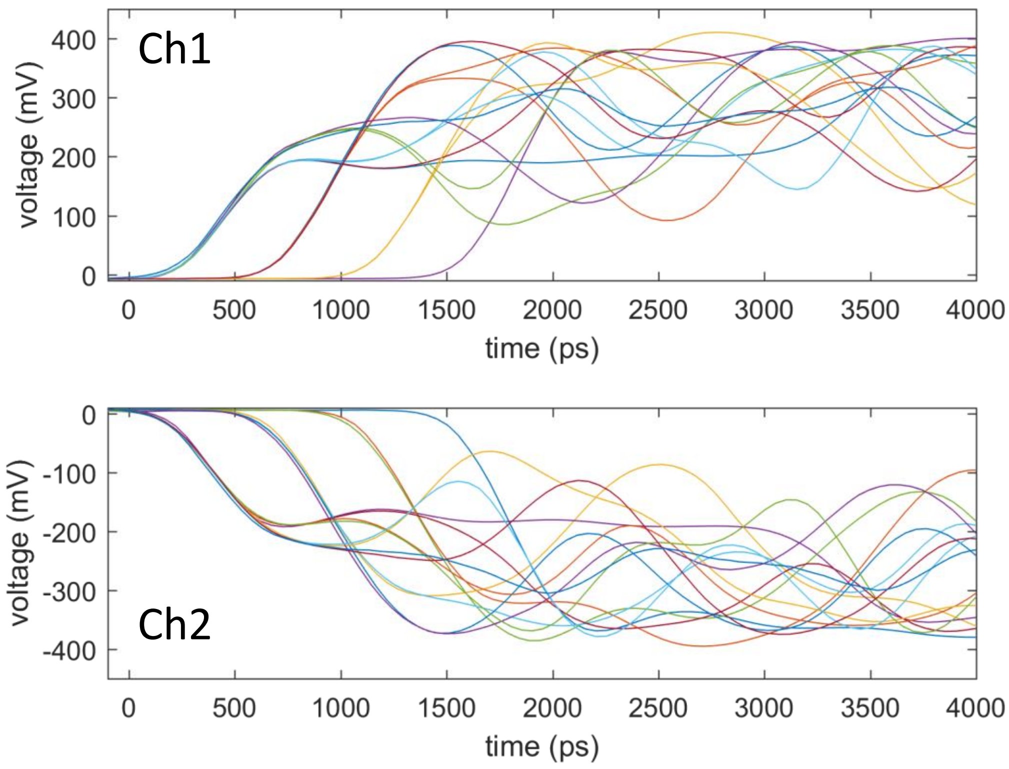
t1
t2
Ch1
Ch2
D1
D2
D3
D4
4-element array
Time delay: Δt = 435 ps
*Only the first pulse will be detected
t1+t2
t1-t2
D1
D2
D3
D4
D1+D2
D3+D4
D2+D3
D1+D3
D1+D3
D1+D4
3Δt
2Δt
1Δt
−3Δt
−2Δt
−1Δt
1Δt
2Δt
3Δt

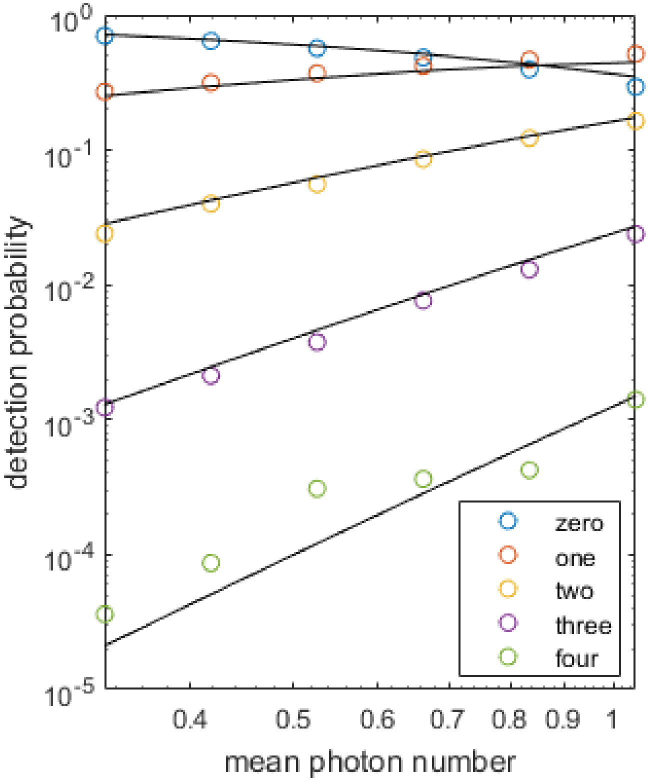

D1
D2
D3
D4
D4
D3
D2
D1
t_{sum}
t_{diff}
mean photon
number per pulse
$\tilde{\mu} = 1.14$

Multi-photon detection

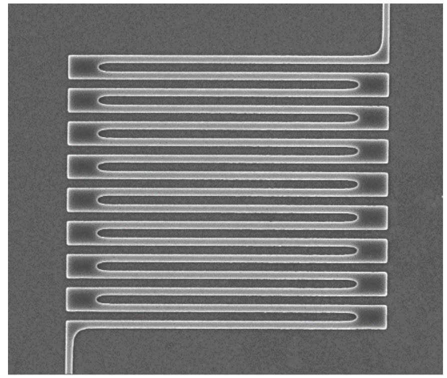
single photon (1), two photon (6), three photon (4), four count (1)

Photon number resolving!



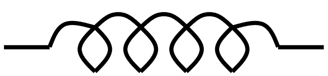


Q: what is the equivalent circuit model of an SNSPD?



Inductor

L_K

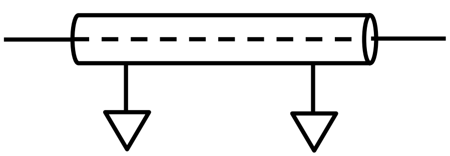


Lumped device

- Nanowire's kinetic *L*
- Microwave design
- Impedance match
- Differential readout
- …

Transmission line

L, Z_n, V_n



Distributed device

SNSPImager

Thank you!