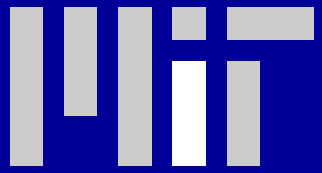
Superconducting Nanowire Single-Photon Detectors

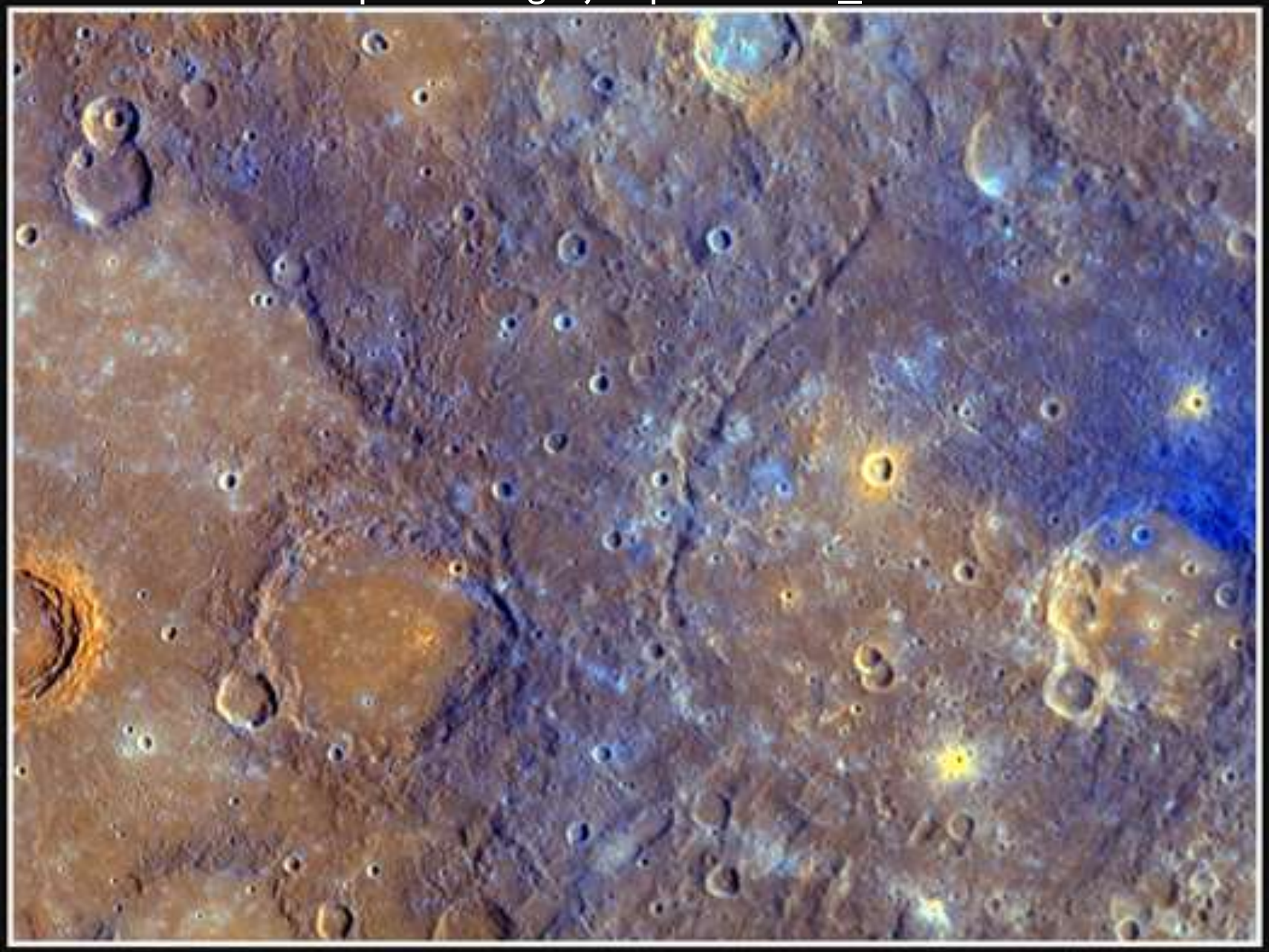


K. K. Berggren

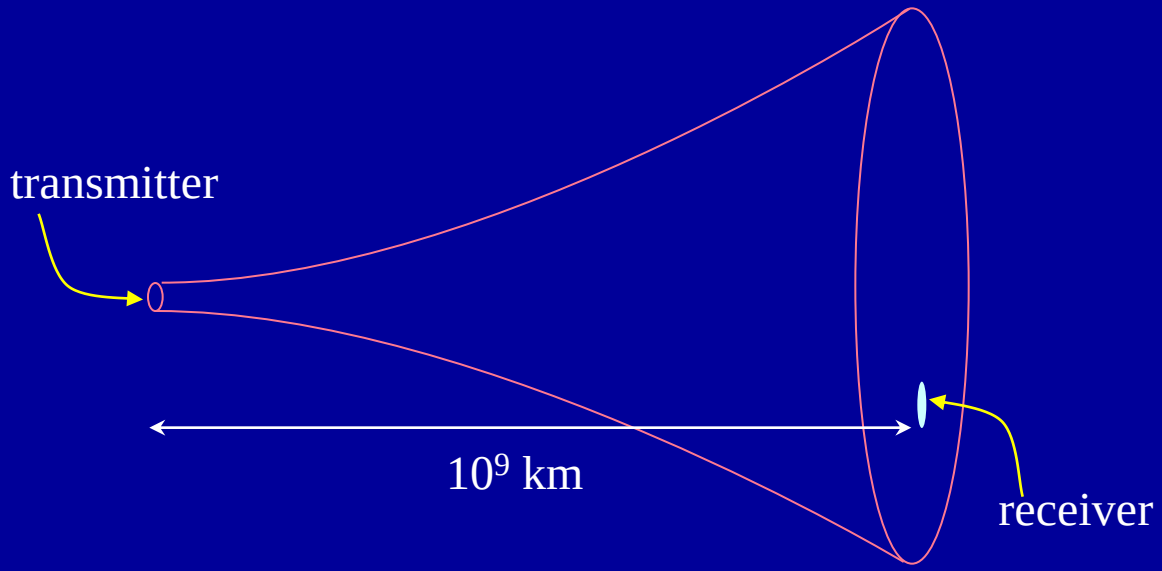
Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

berggren@mit.edu

http://messenger.jhuapl.edu/news_room



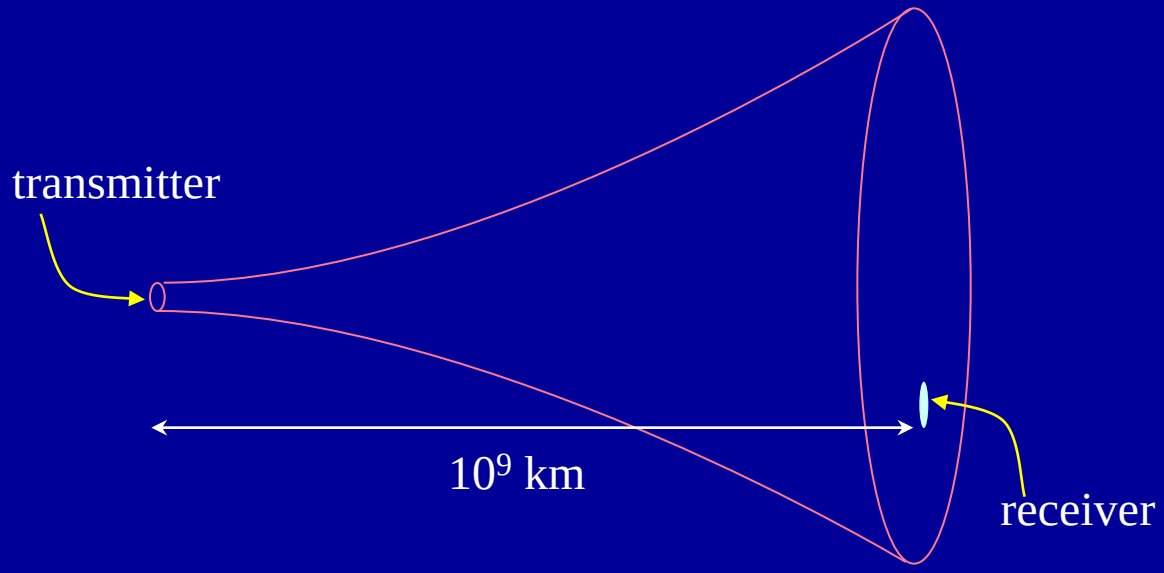
Free-Space Optical Communications



*Boroson, Biswas, Edwards, "Overview of NASA's mars laser communications demonstration system," FREE-SPACE LASER COMM. TECH. XVI **5338**: 16-28, 2004*

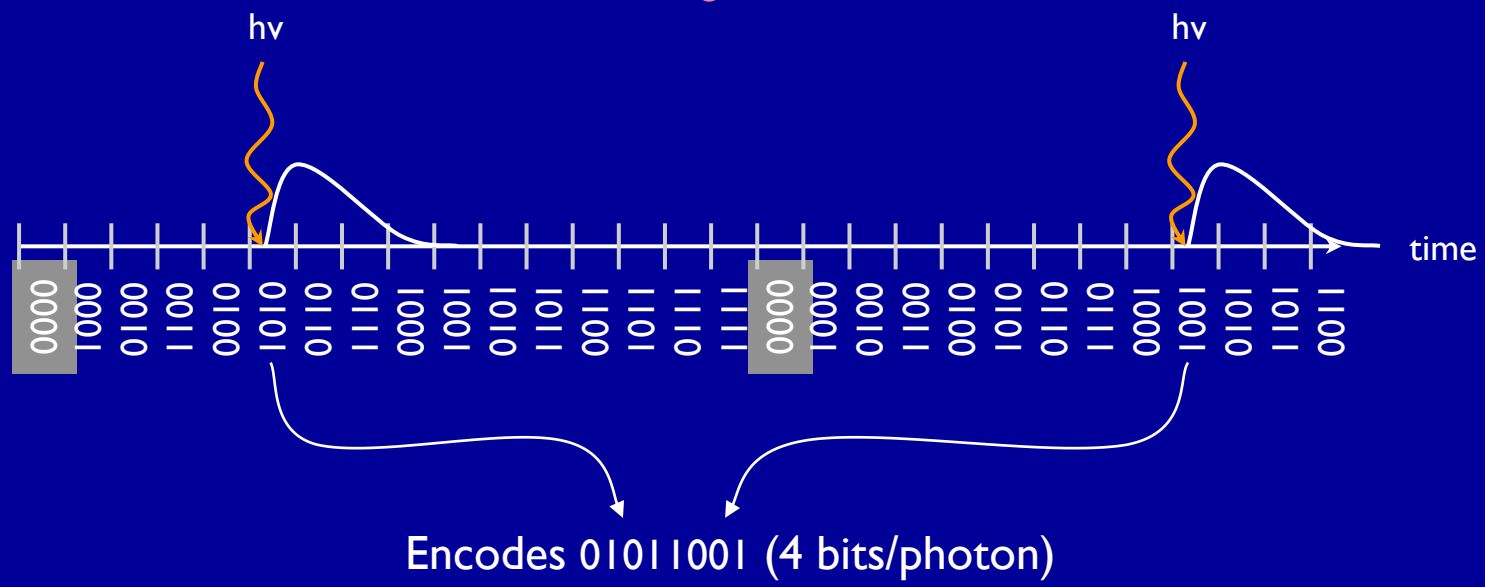
*Toyoshima, et. al., "Comparison of microwave and light wave communication systems in space applications," Opt. Eng. **46** 015003 (2007)*

Free-Space Optical Communications



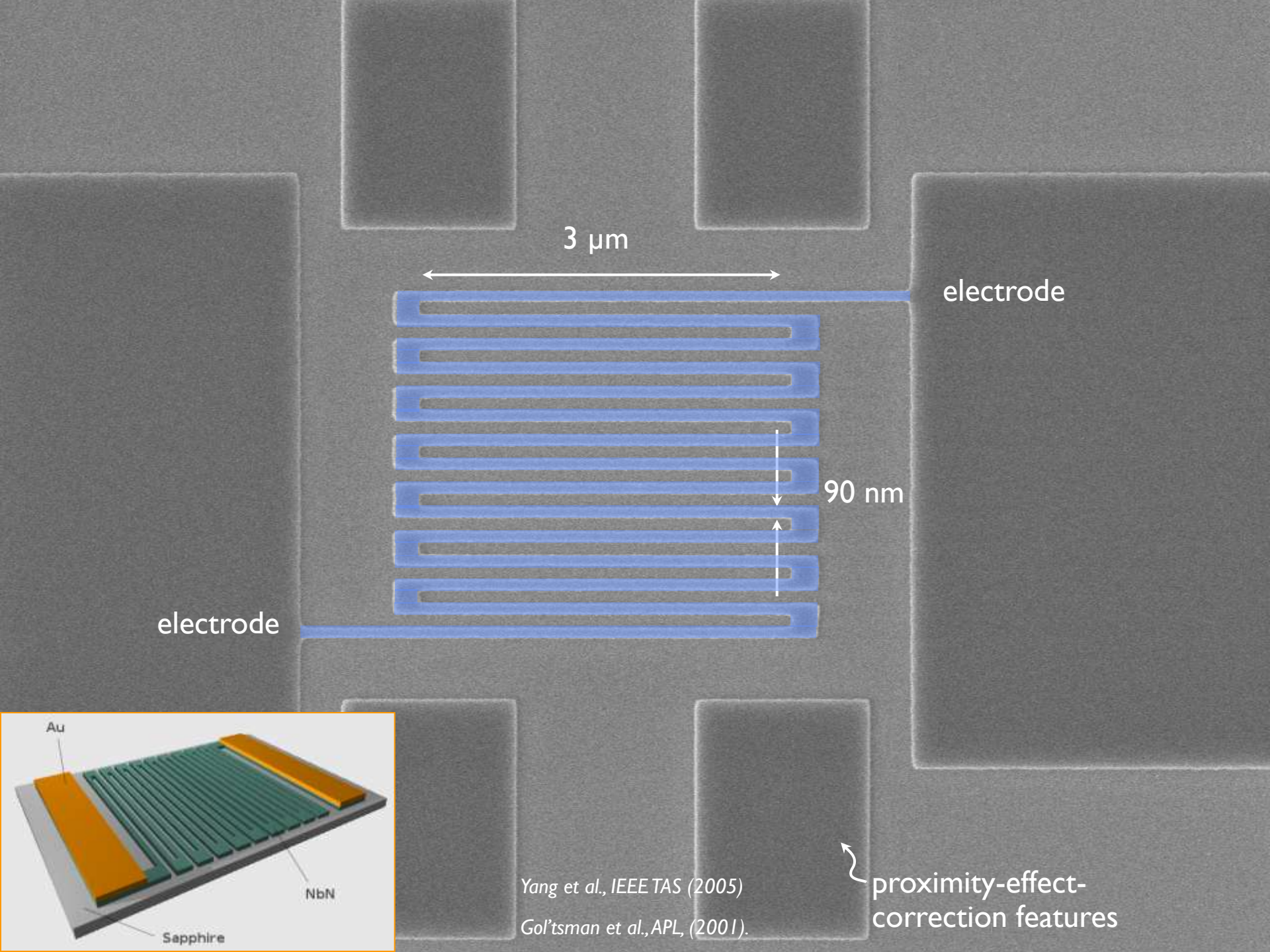
*Boroson, Biswas, Edwards, "Overview of NASA's mars laser communications demonstration system," FREE-SPACE LASER COMM. TECH. XVI **5338**: 16-28, 2004*

*Toyoshima, et. al., "Comparison of microwave and light wave communication systems in space applications," Opt. Eng. **46** 015003 (2007)*



Photons

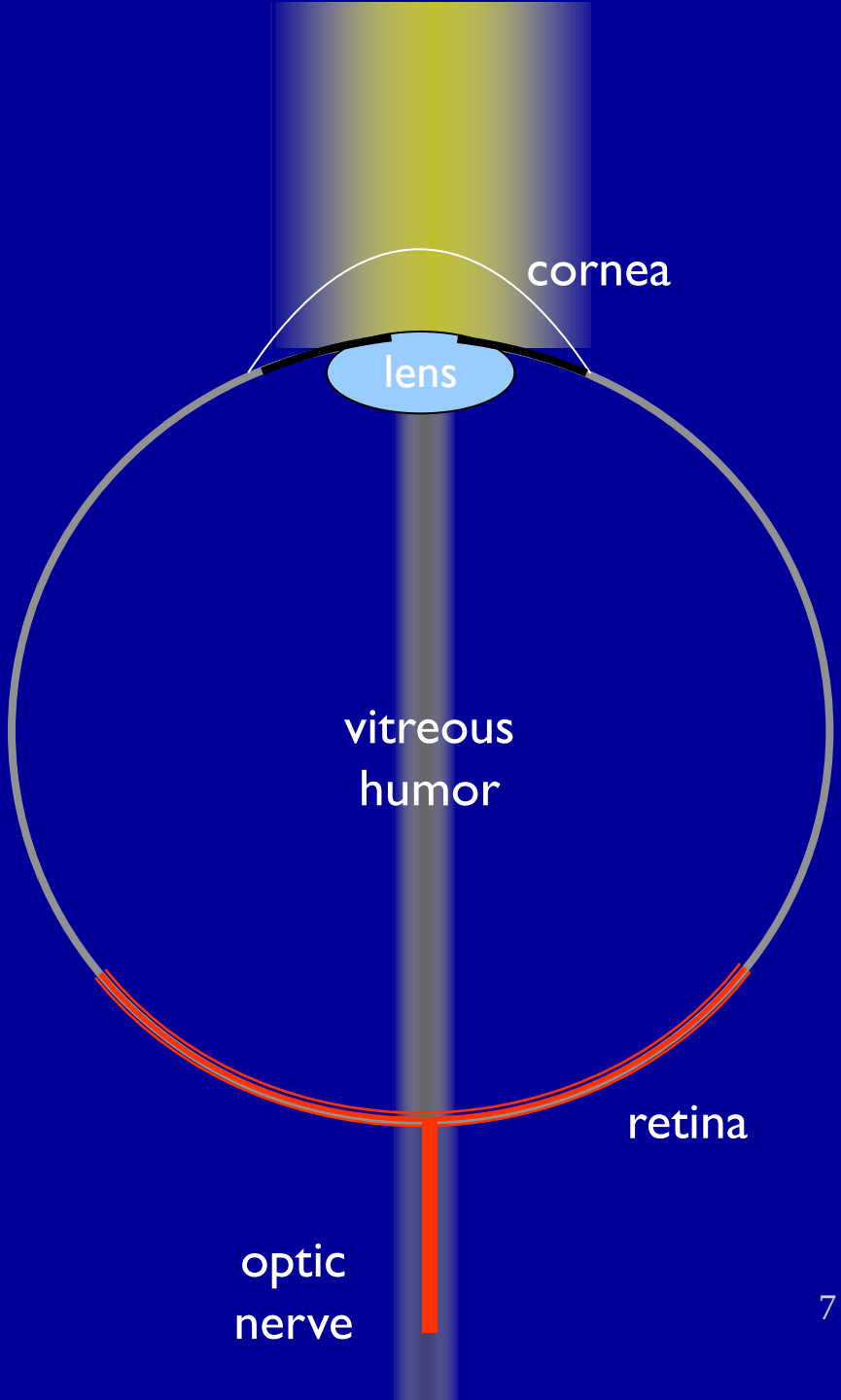
- Illumination in eye from 1 pixel of laptop at 100 km in 1 sec
- Energy inversely proportional to wavelength
  - Longer wavelength => harder to detect



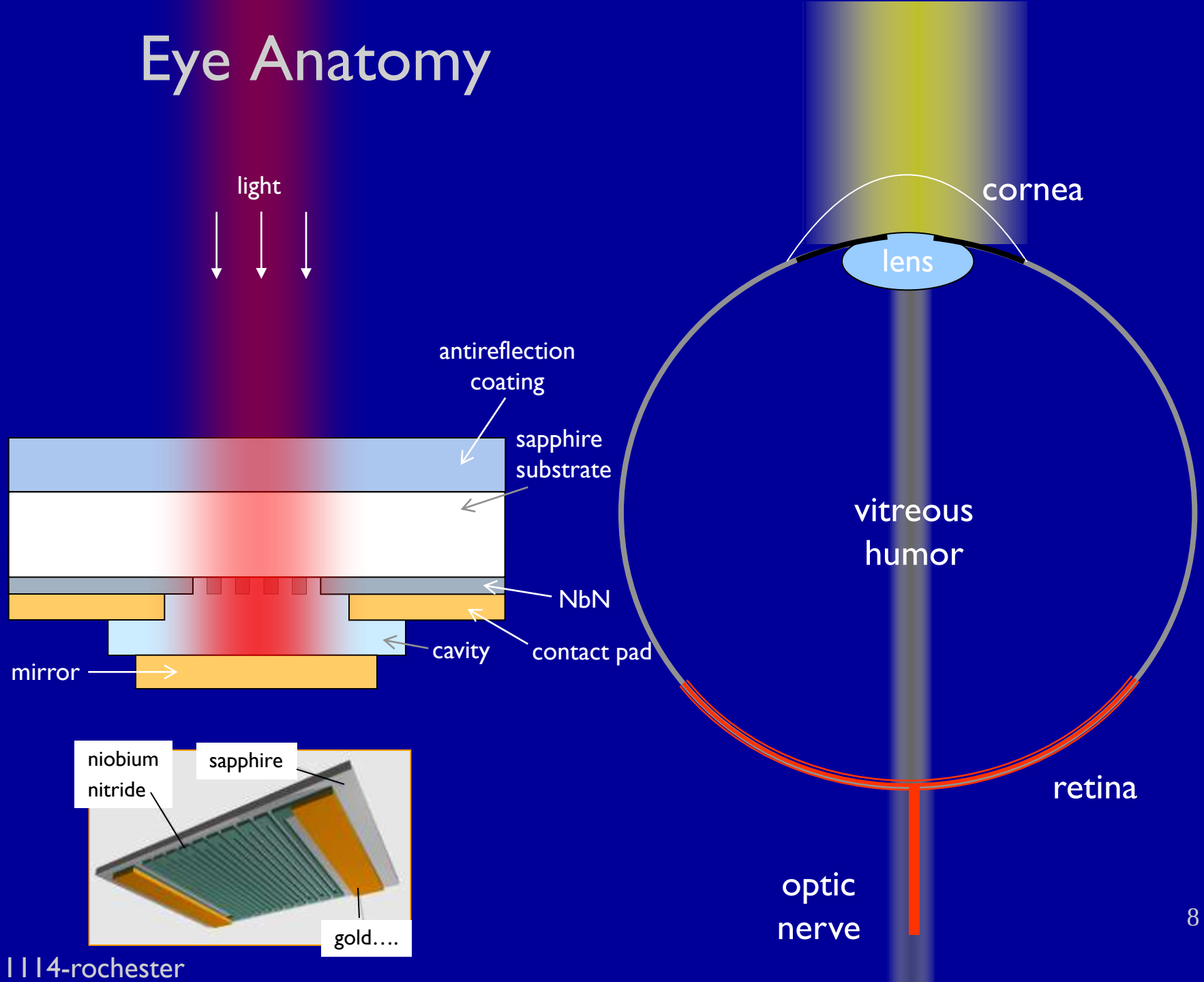
Yang et al., IEEE TAS (2005)

Gol'tsman et al., APL, (2001).

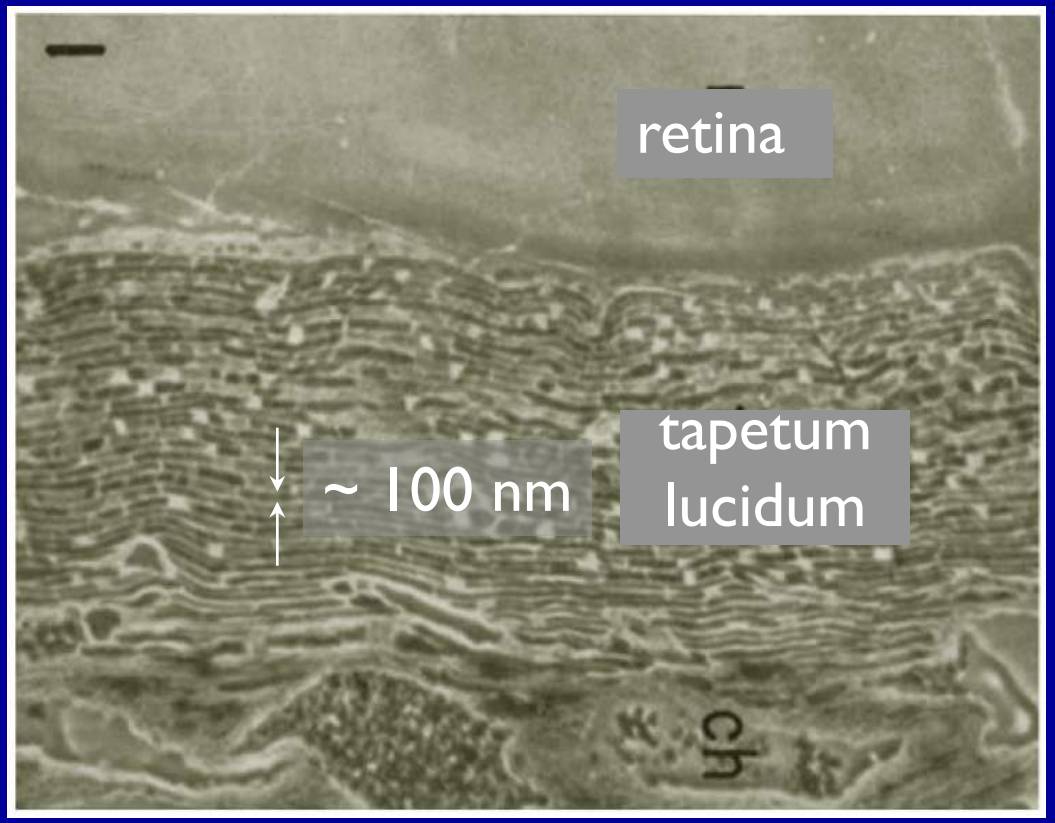
Eye Anatomy



Eye Anatomy

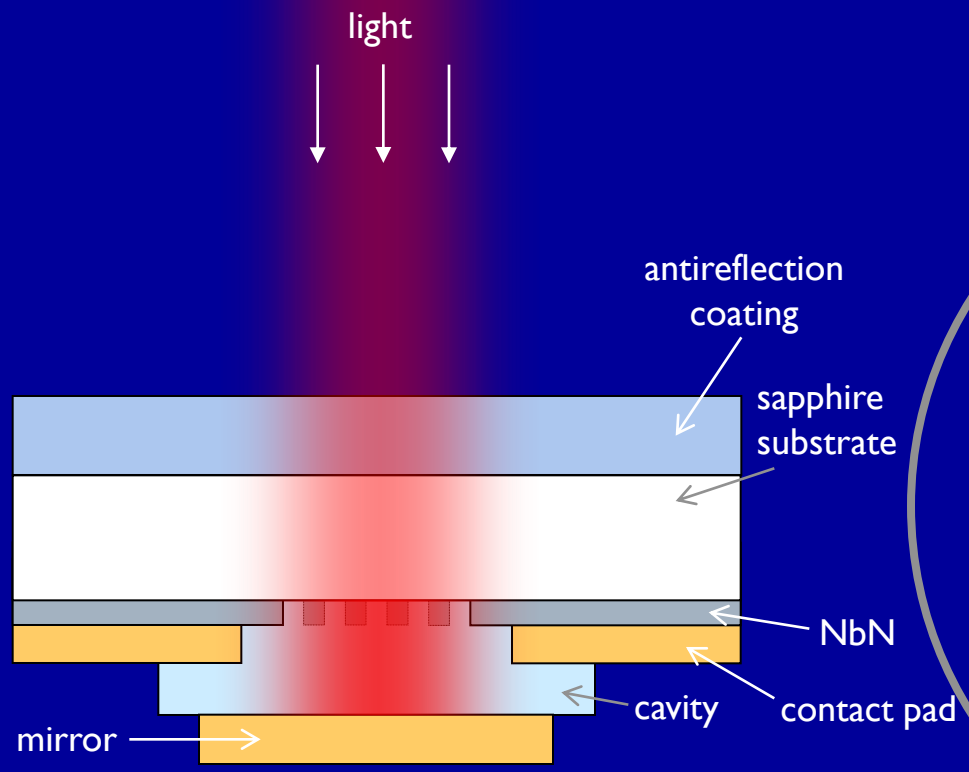

light
antireflection coating
sapphire substrate
NbN
cavity
contact pad
mirror
niobium nitride
sapphire
gold….
cornea
lens
vitreous humor
retina
optic nerve

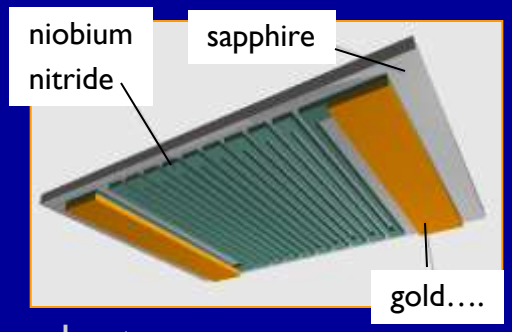
Tapetum Lucidum of a Cat

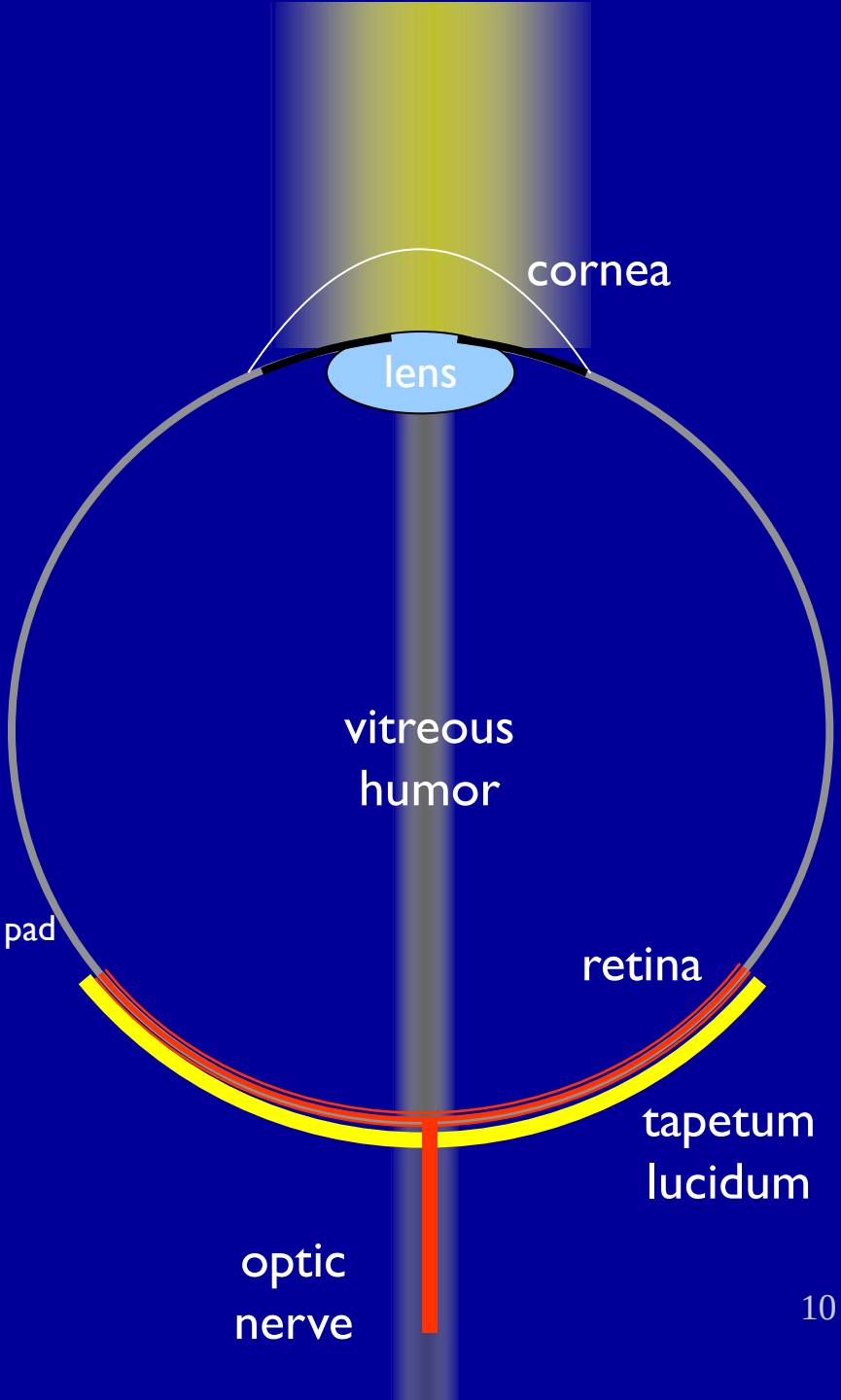


Bernstein and Pease, "Electron Microscopy of the Tapetum Lucidum of the Cat" Journal of Cell Biology, Vol. 5, 35-39, (1959)

Eye Anatomy

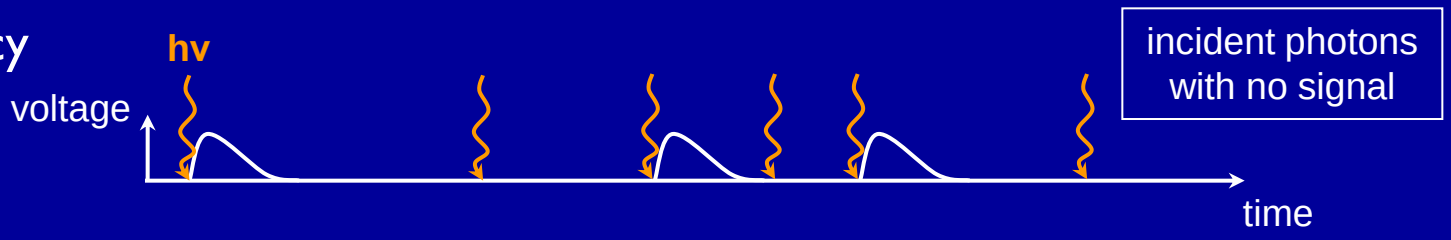

light
antireflection coating
sapphire substrate
NbN
cavity
contact pad
mirror


niobium nitride
sapphire
gold….

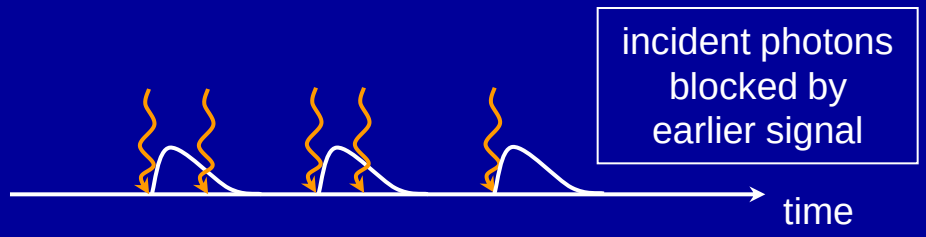

cornea
lens
vitreous humor
retina
tapetum lucidum
optic nerve

Characteristics of Photon Detectors

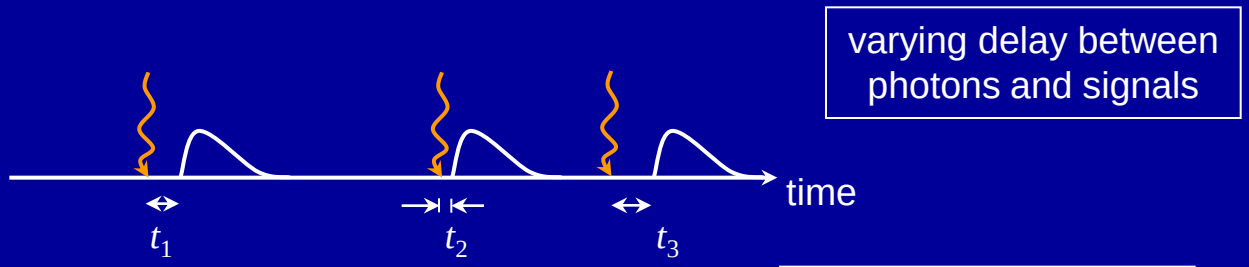
- Efficiency



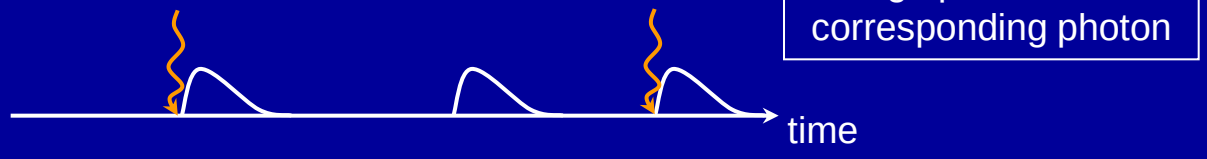
- Reset time



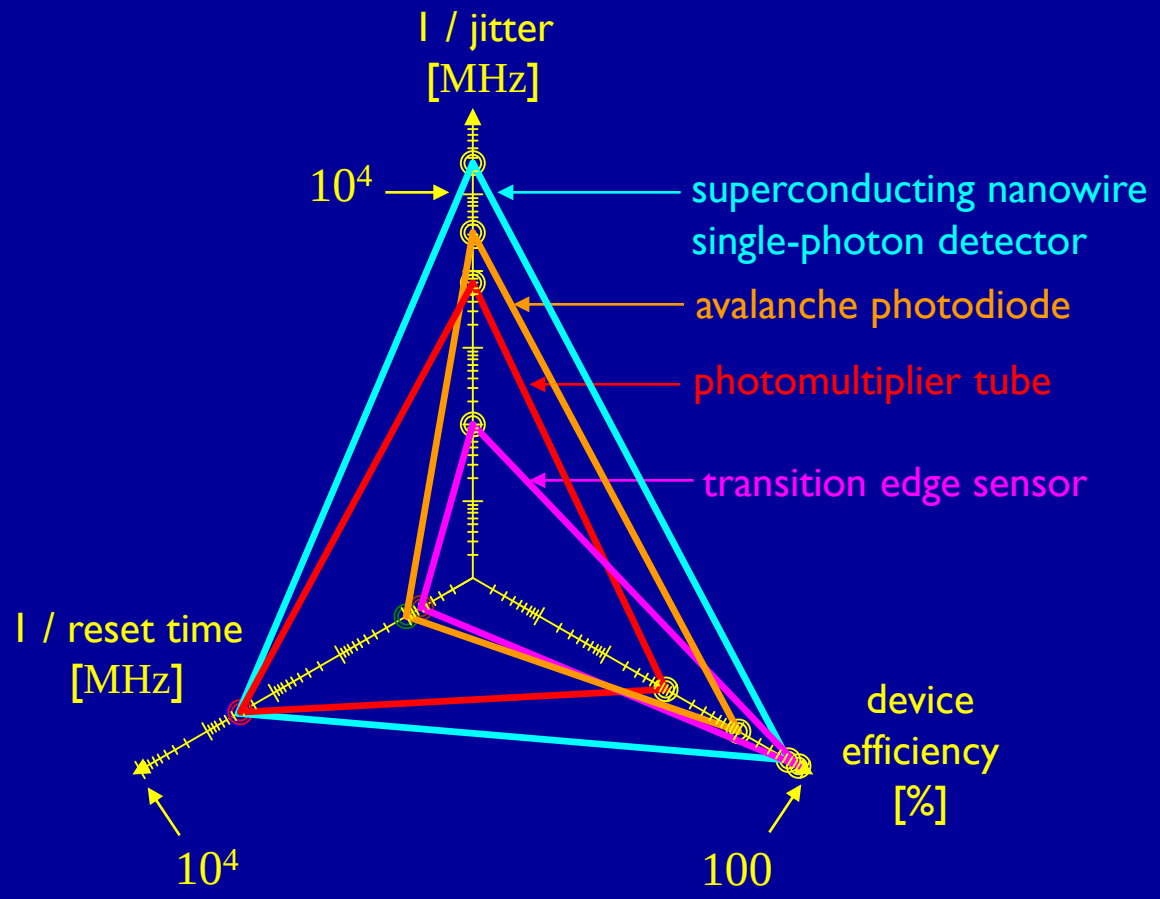
- Jitter



- Dark count rate



Nanowire Single-Photon Detector



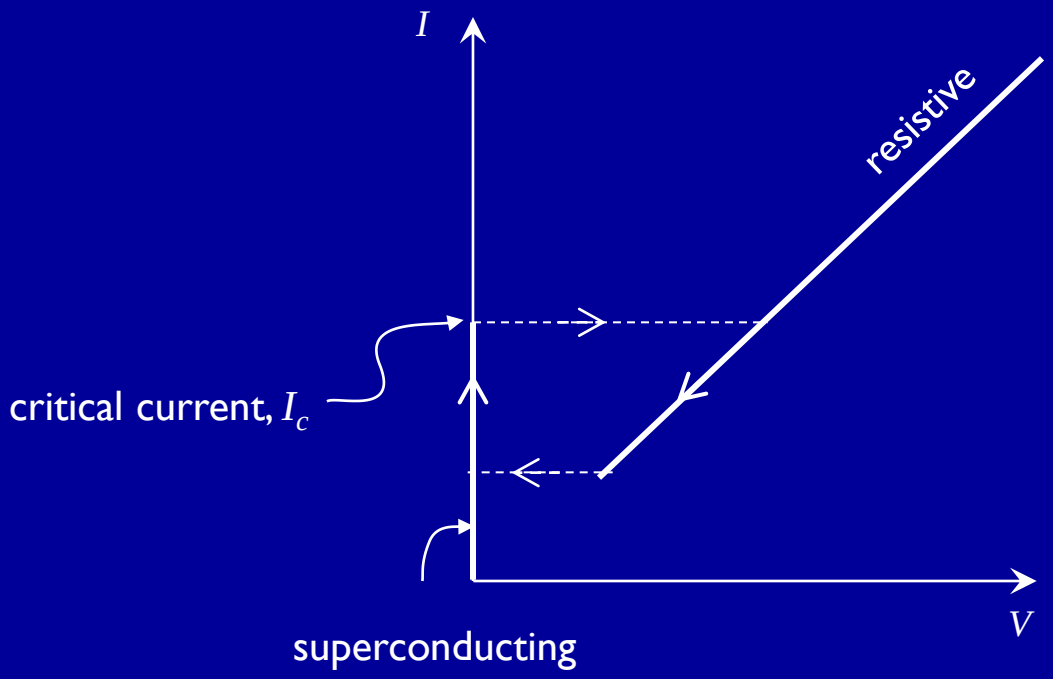
Comparison at 1.55 μm

APPLICATIONS

- VLSI device evaluation
- LIDAR
- Communication
  - quantum
  - interplanetary

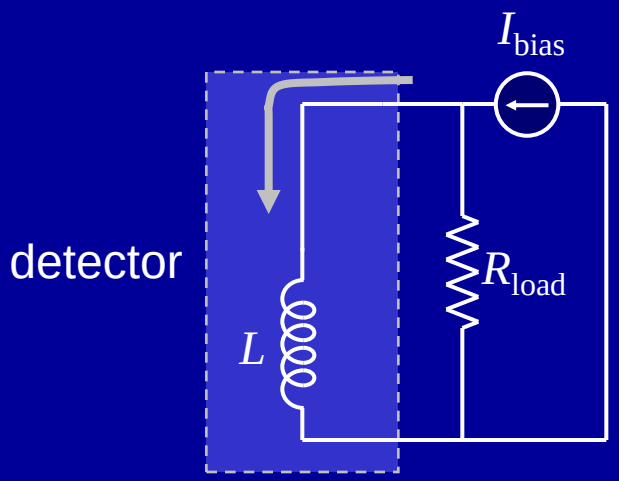
DEVICE OPERATION

Superconductive Nanowire Behavior

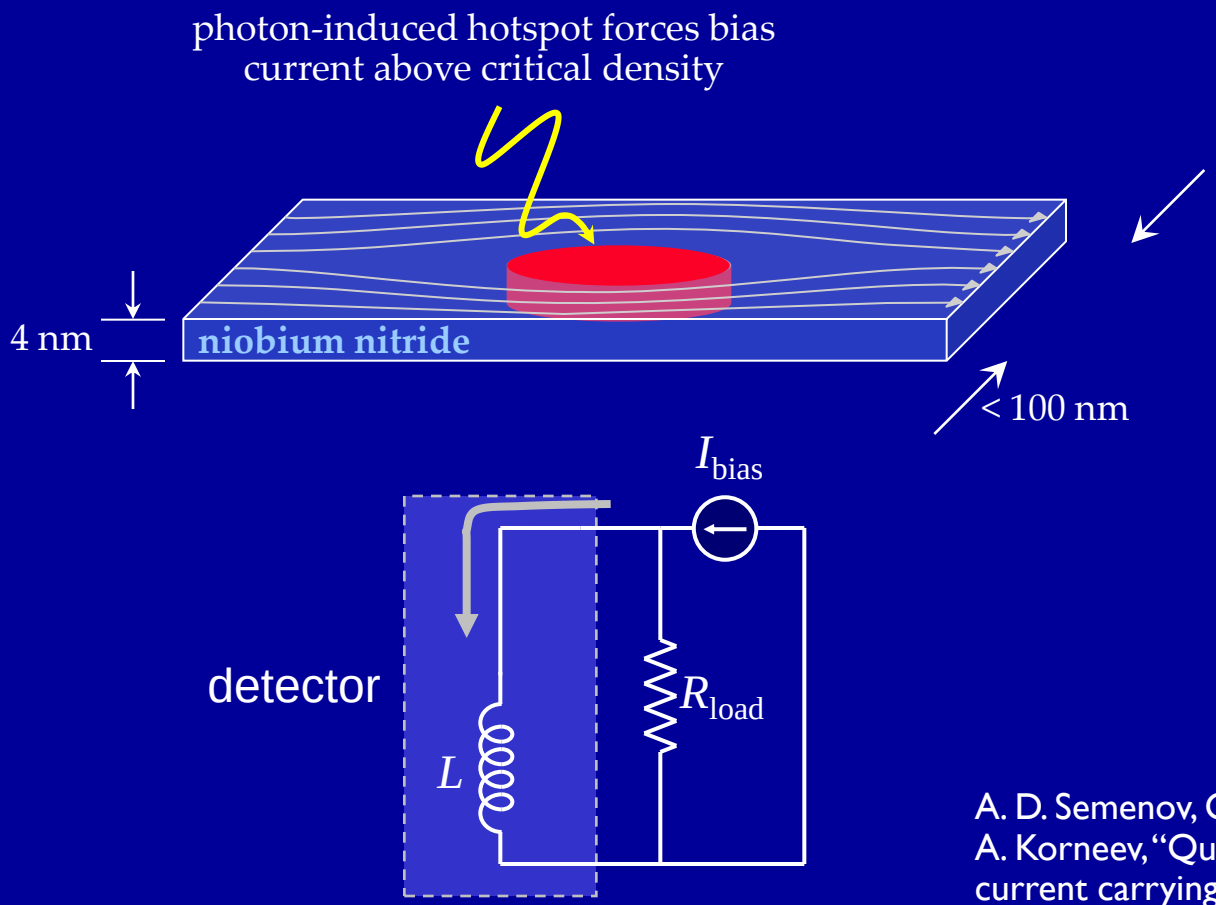


Detection Mechanism Explanation

superconductor is biased near its transition

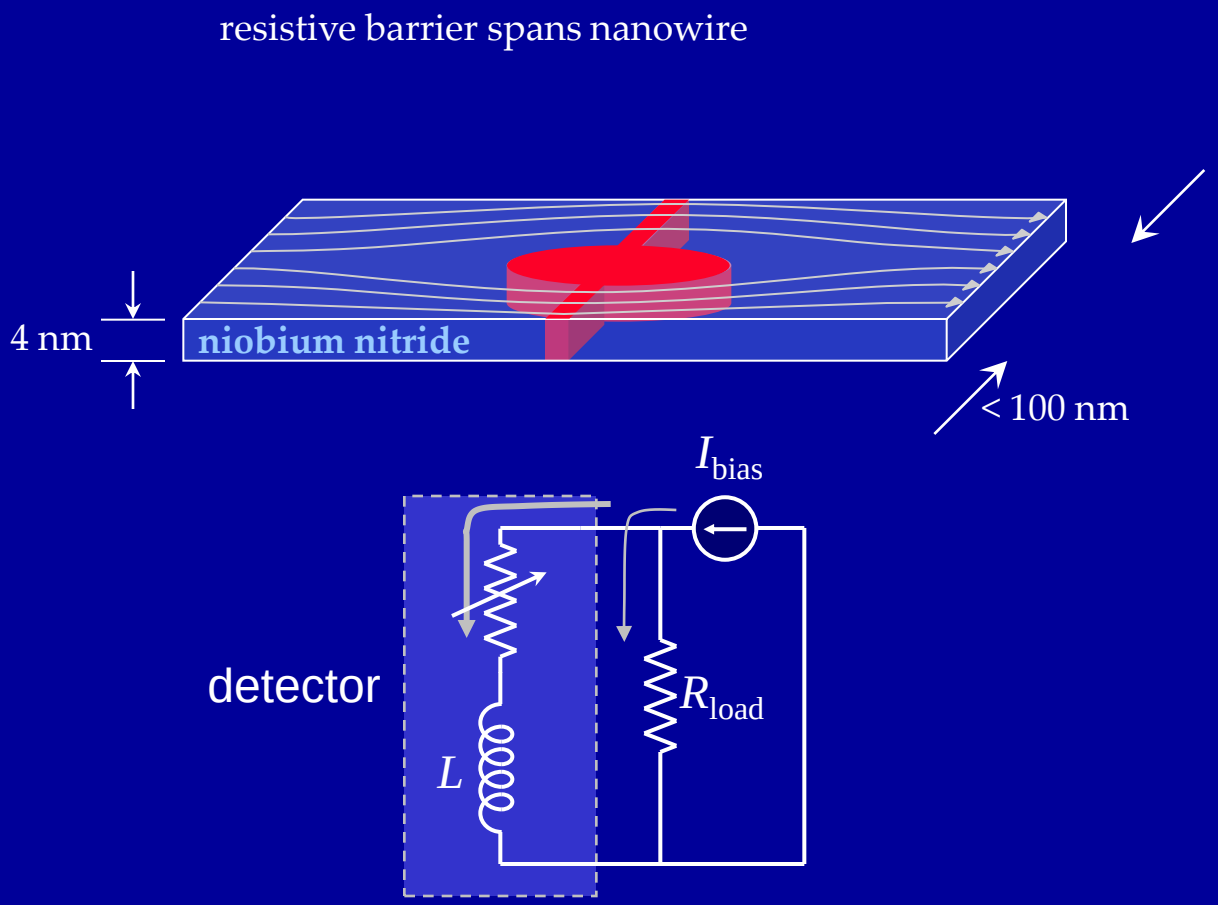


Detection Mechanism Explanation



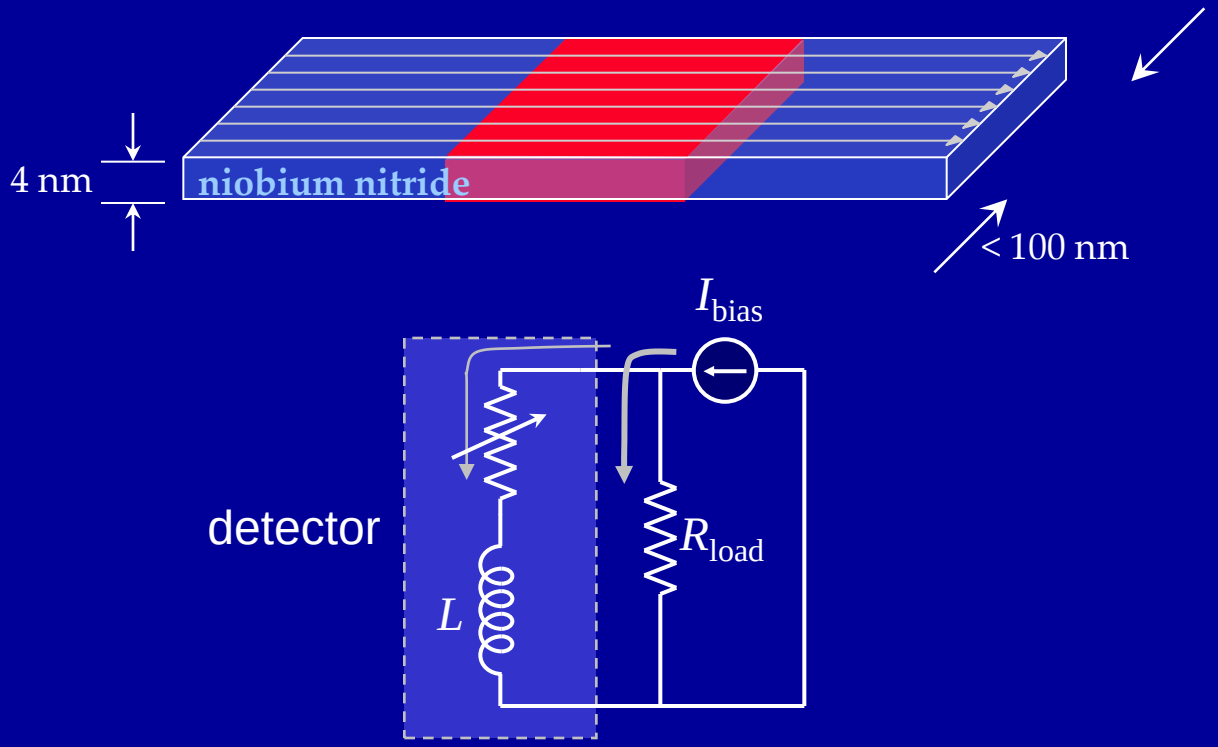
A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C, vol. 351*, pp. 349–356, 2001.

Detection Mechanism Explanation

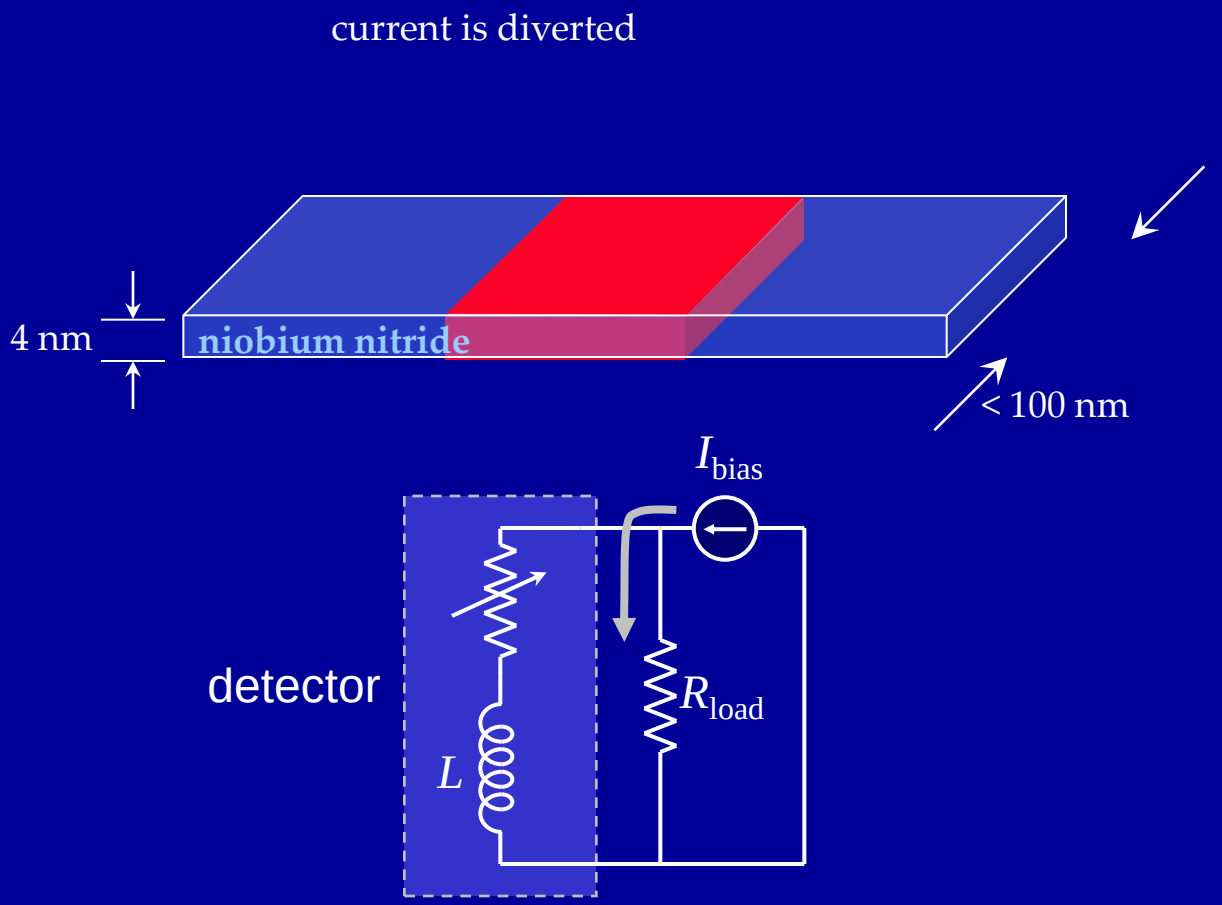


Detection Mechanism Explanation

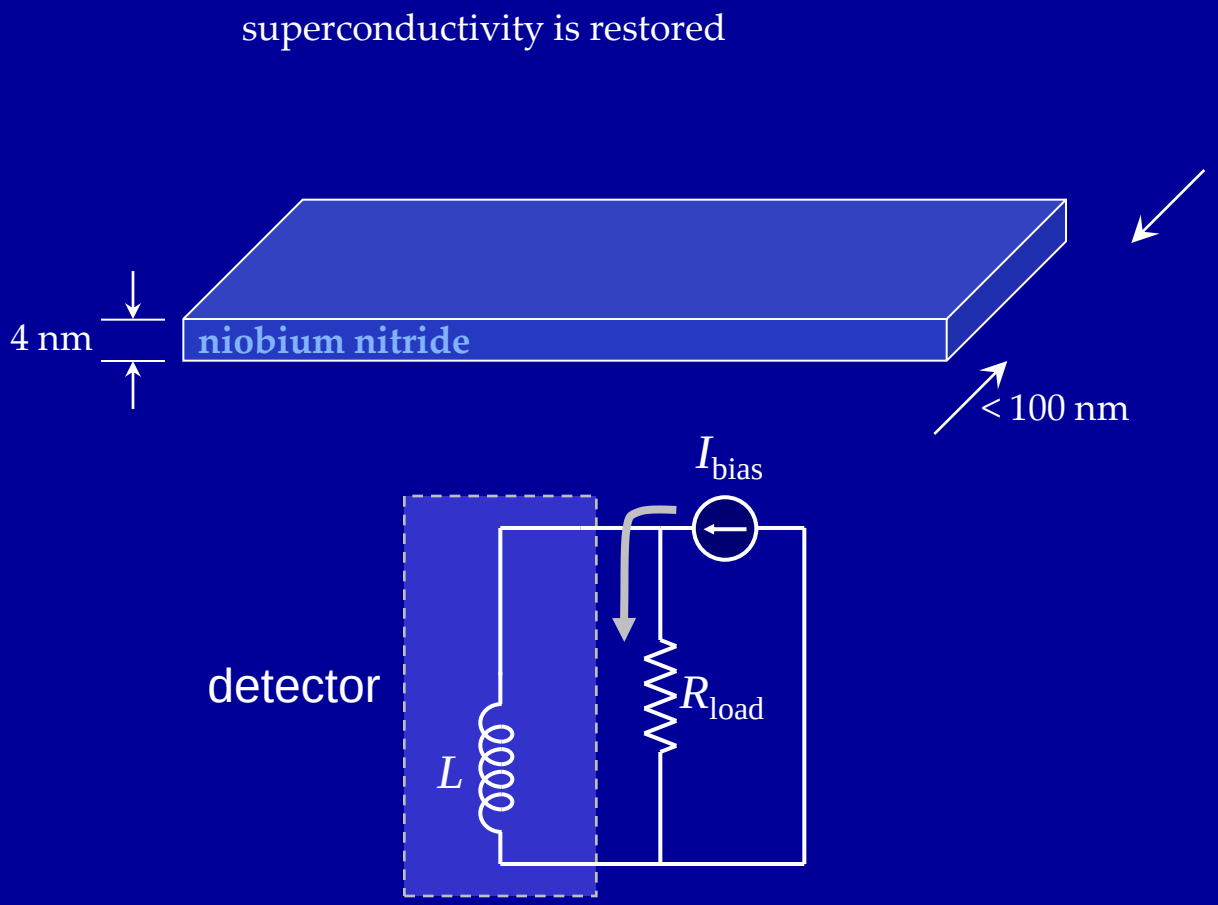
resistance grows from heating



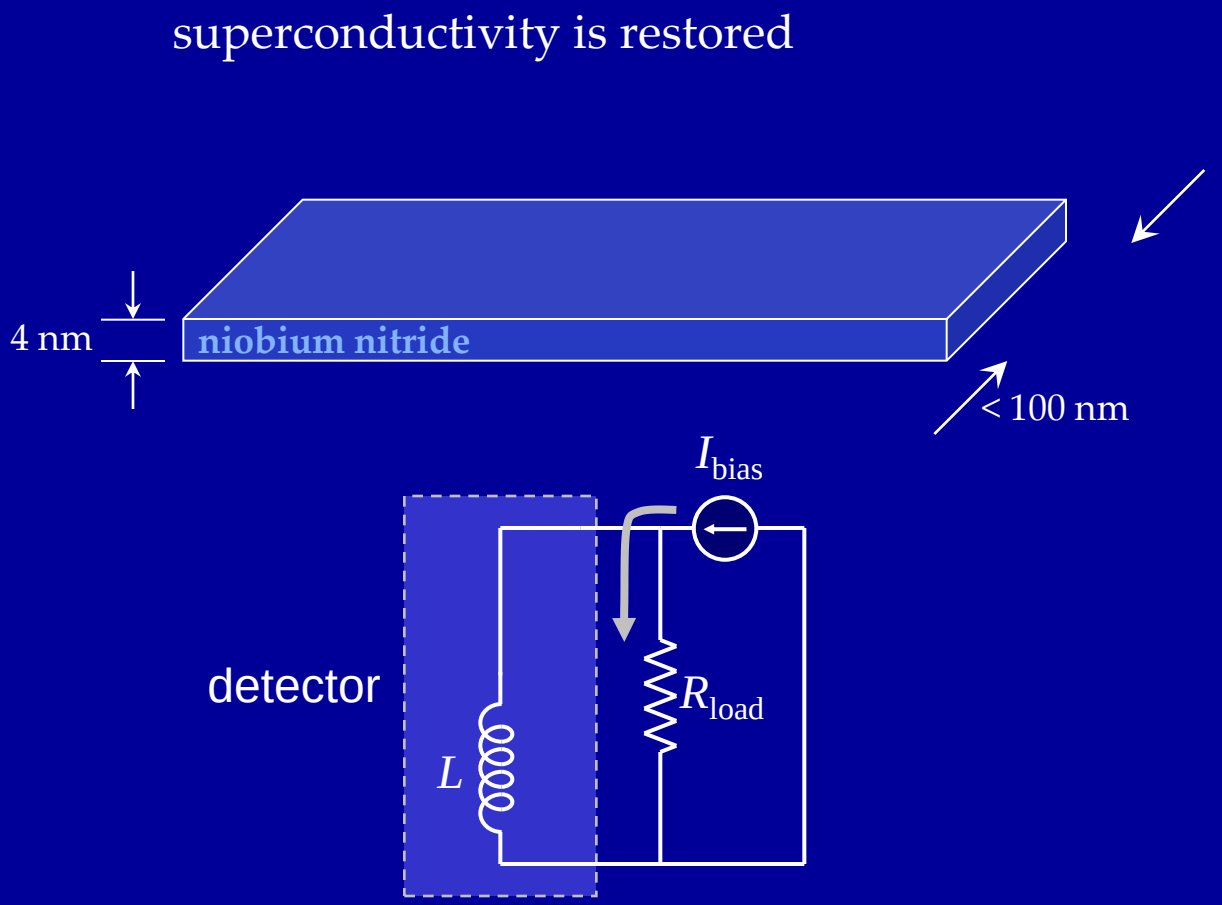
Detection Mechanism Explanation



Detection Mechanism Explanation



Detection Mechanism Explanation



Karl Berggren (karlberggr... | YouTube - kinetic induct...

www.youtube.com/watch?v=MAHkYROmriY

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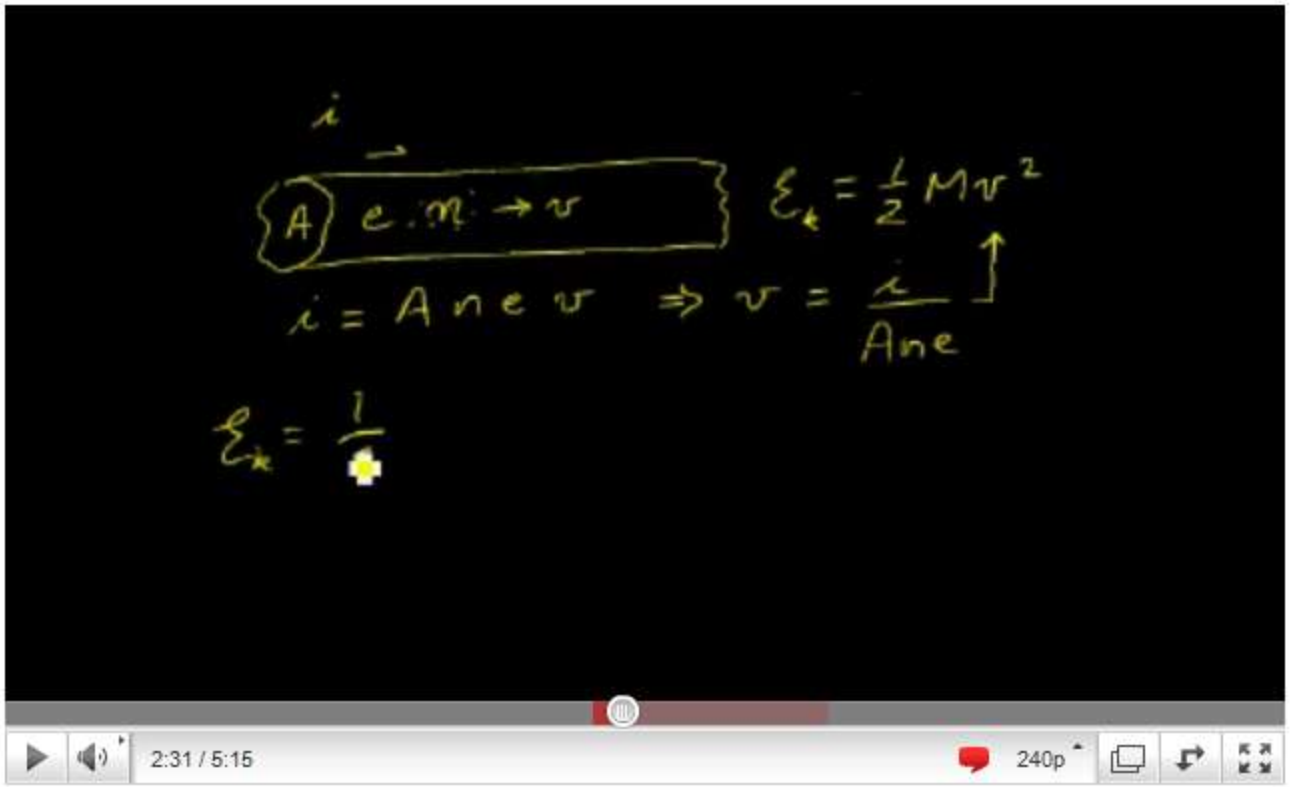
kinetic inductance explained

karlberggren | 1 videos | Subscribe



This video is public.

Suggestions

For Mat
by tothe
100,784

Full Live
Trailer
by coder
16,161 v

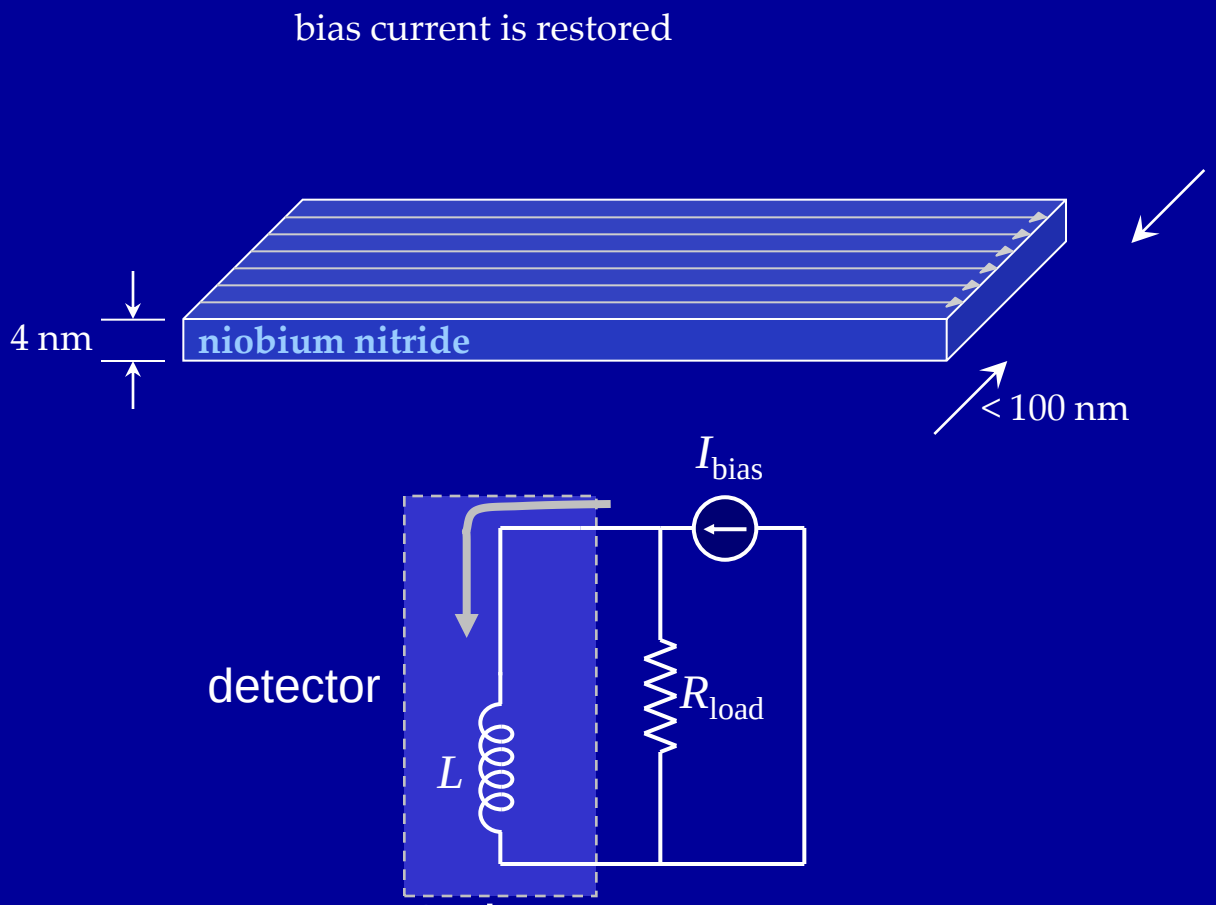
Observi
off-shell
by camer
370 view

Lec 23
and Ma
by MIT
29,603 v

MIT Phy
Resona
by mittec
119,443

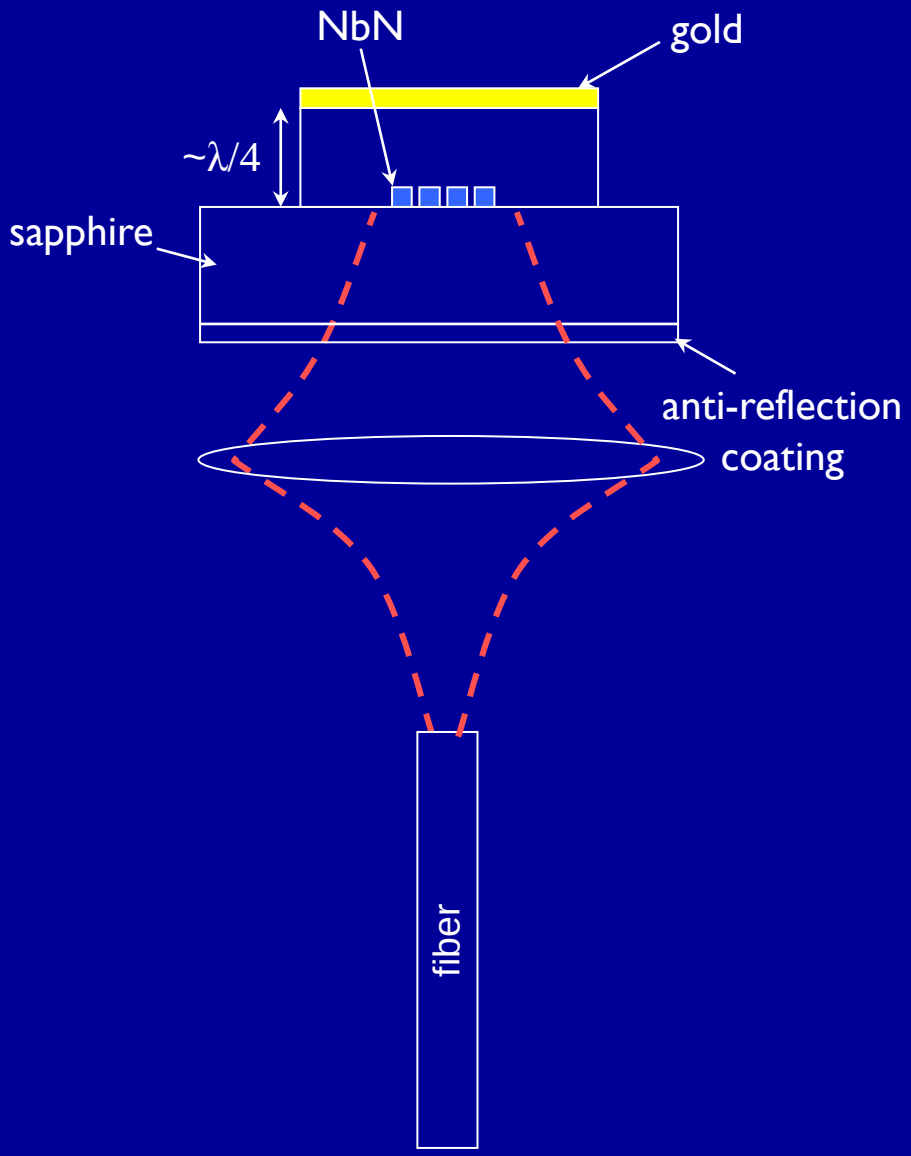
Lec 20

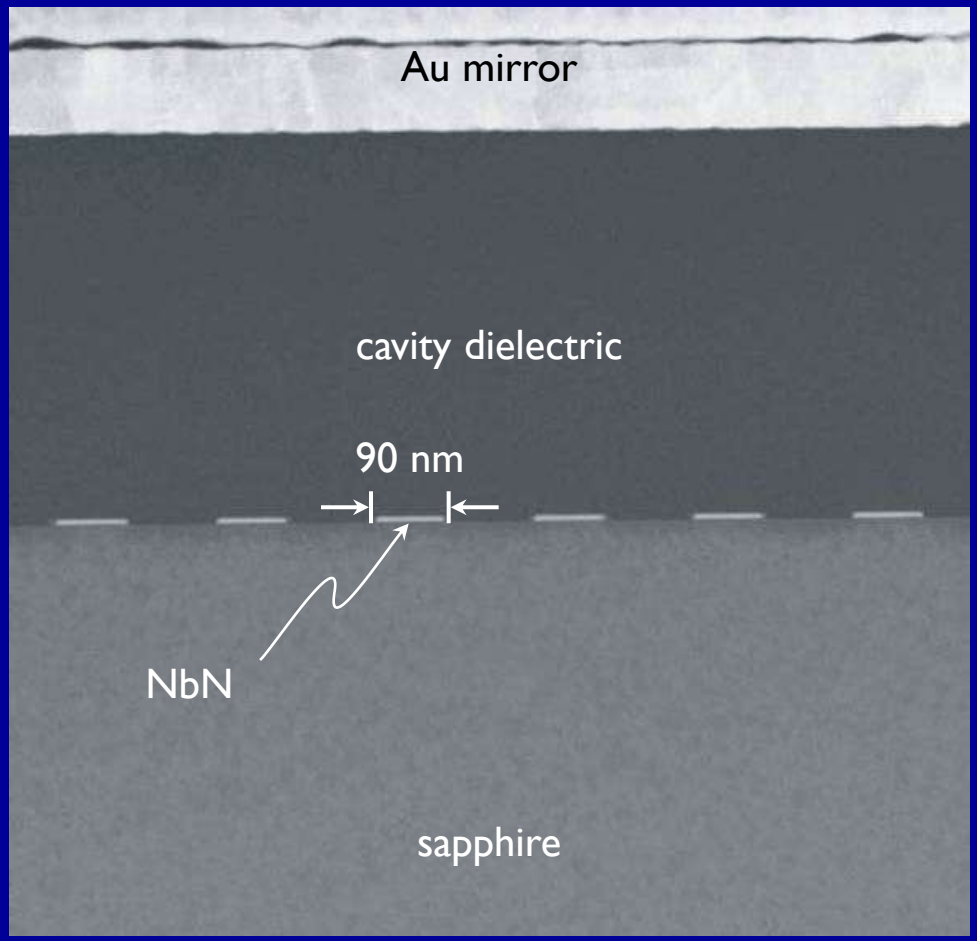
Detection Mechanism Explanation



Kerman, Dauler, Keicher, Yang, KB, Gol'tsman, Voronov, *Applied Physics Letters*, **(2006)**

SNSPD integrated in an optical cavity

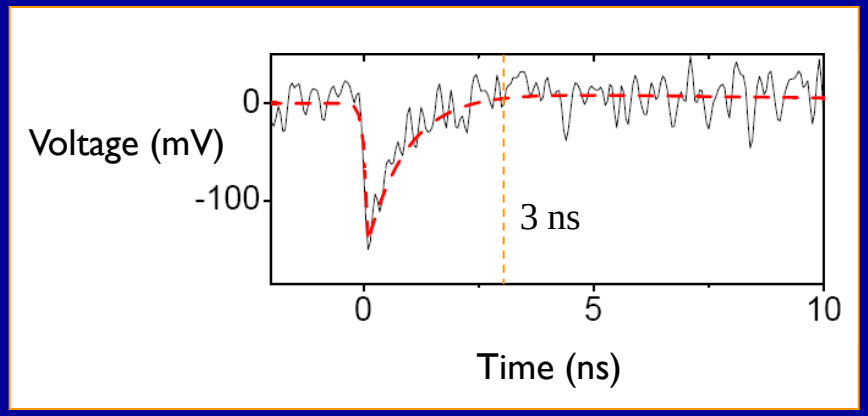




Cross-section transmission-electron micrograph

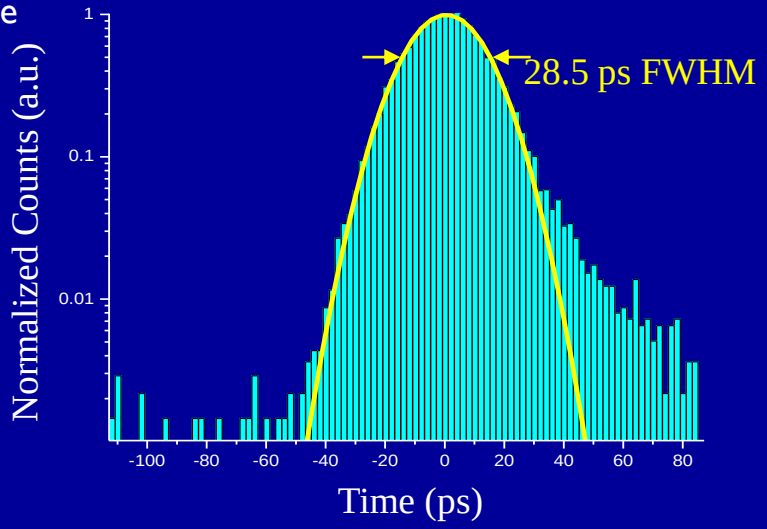
Rosfjord et al., *Opt. Express* (2006)

Summary of Device Performance

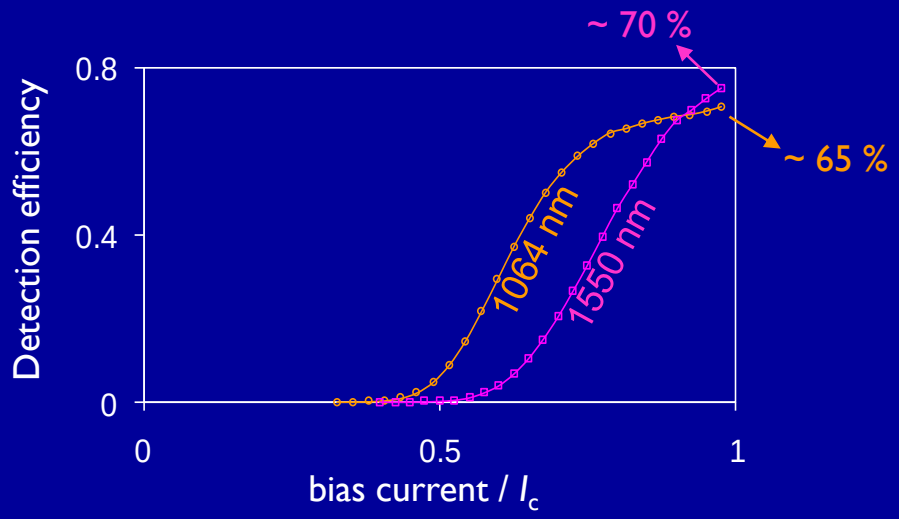


Kerman et al. in APL (2006)

1 ps, 1550 nm optical pulse



Background Counts
~100 s^{-1}
(97.5% bias, 2.7K)

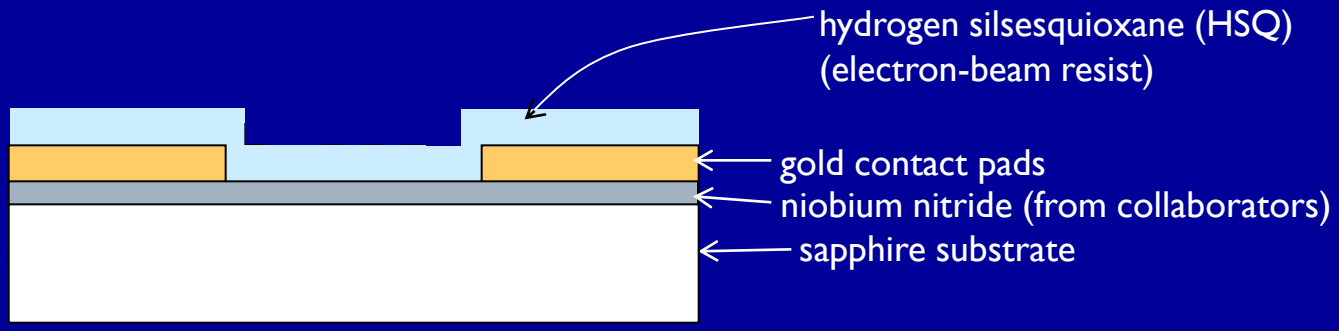


70-nm-wide detector, 140-nm pitch
210-nm-thick cavity

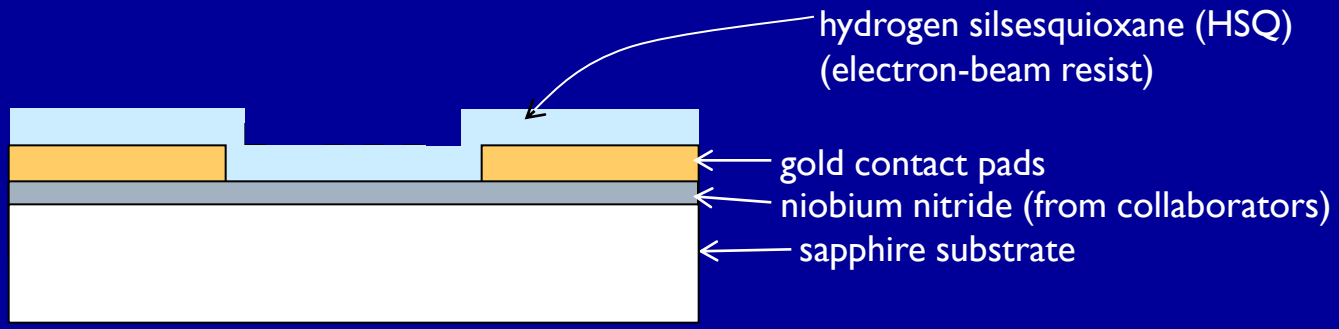
Collaboration with Lincoln Laboratory

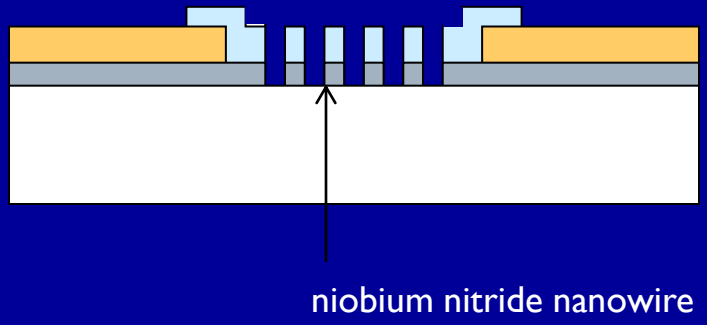
FABRICATION

Basic Fabrication Flow

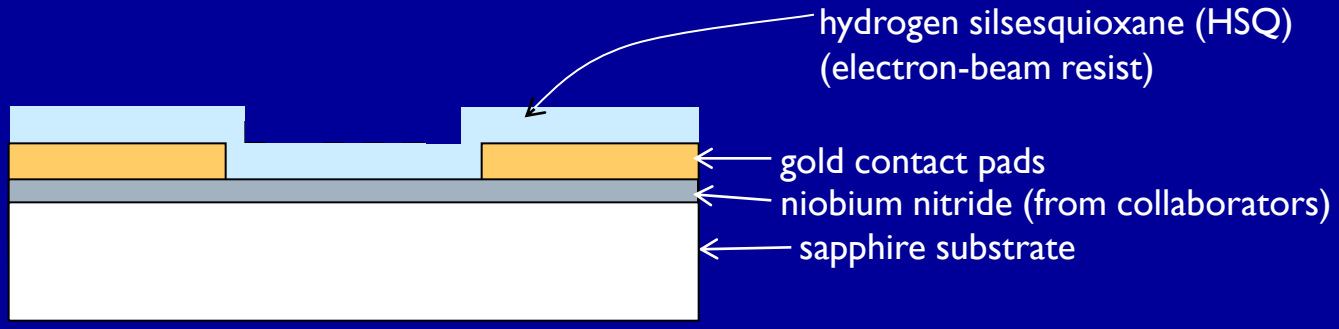


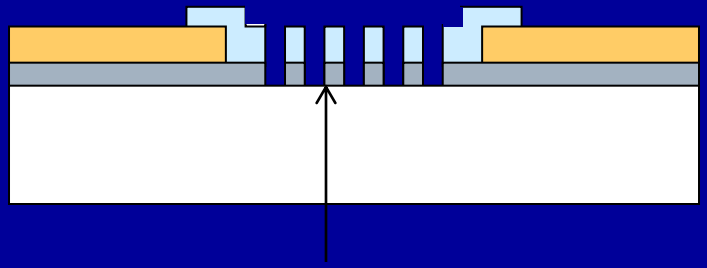
Basic Fabrication Flow

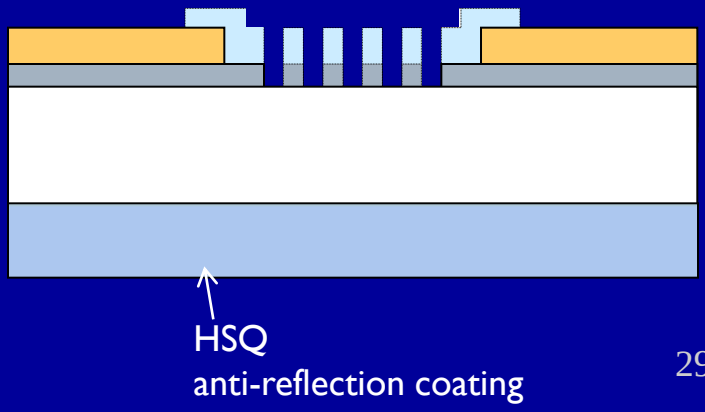




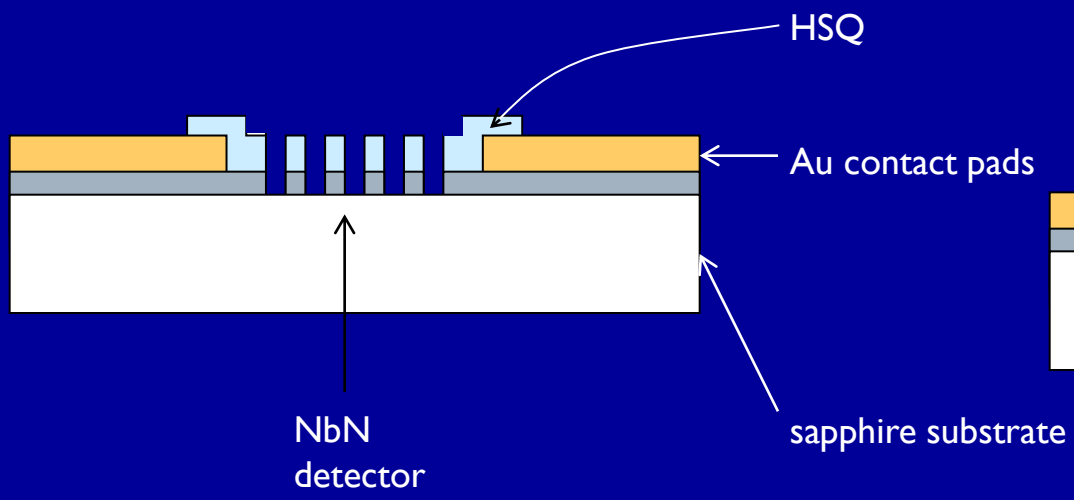
Basic Fabrication Flow

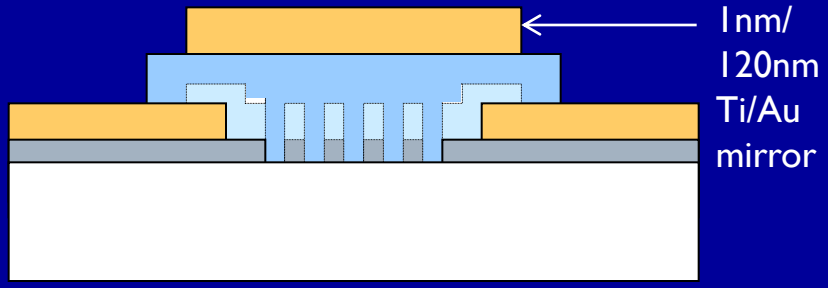


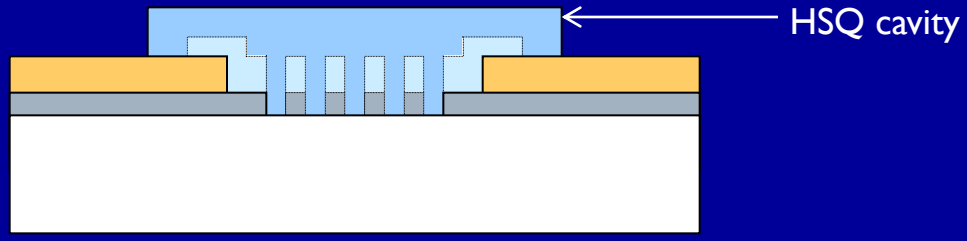


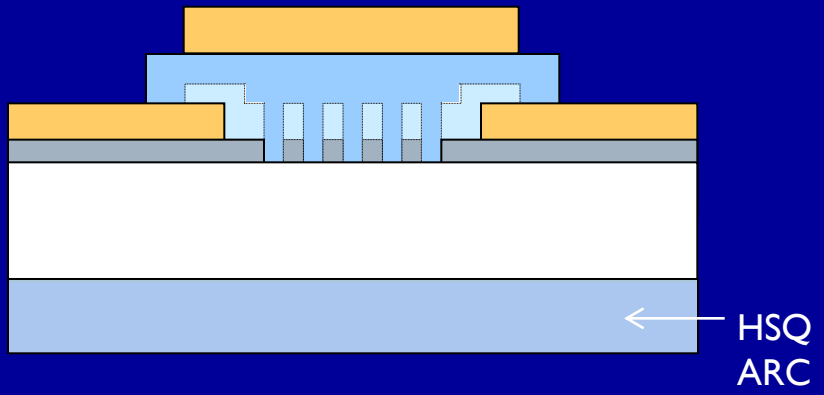


Cavity Fabrication Flow

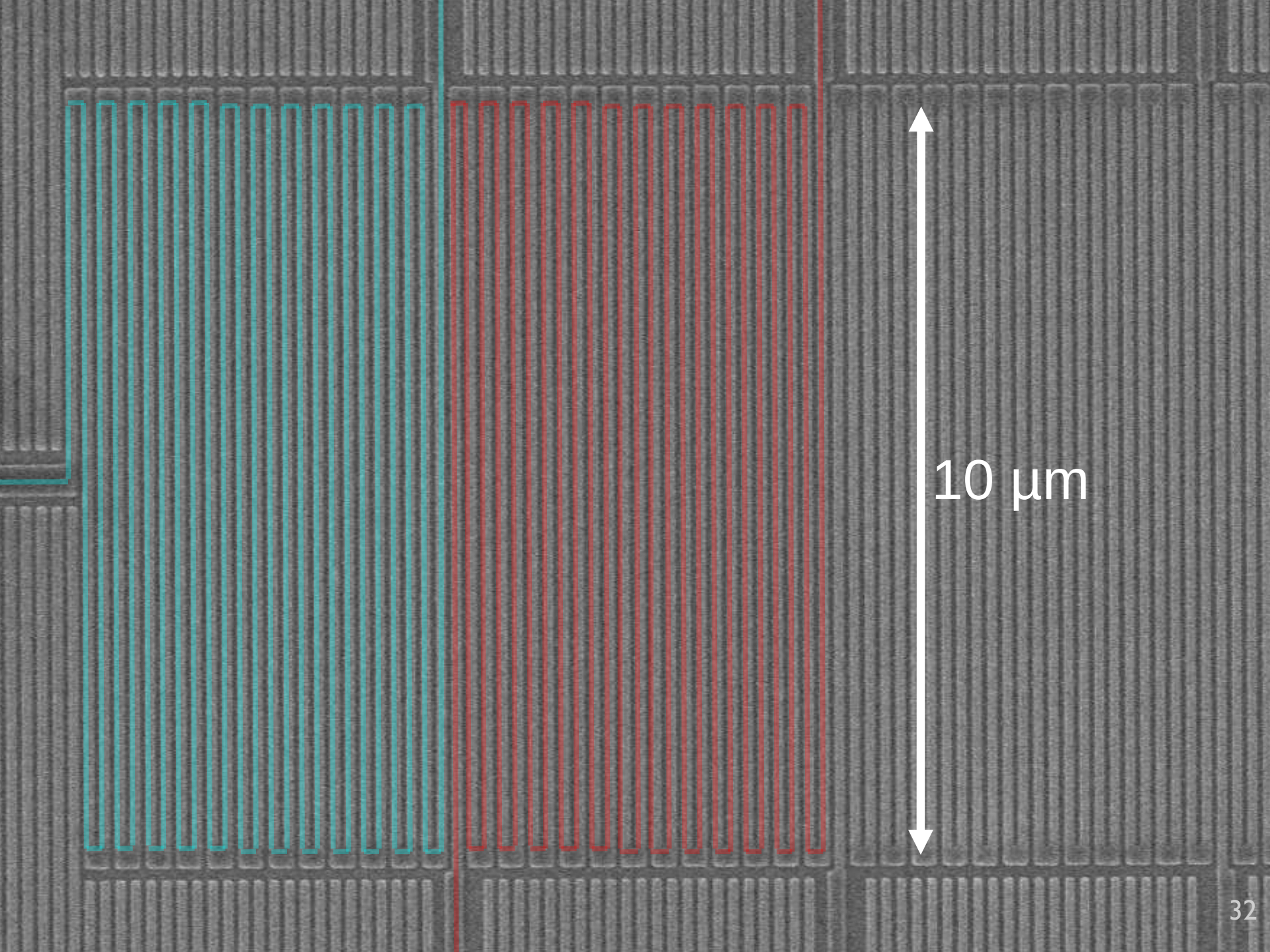




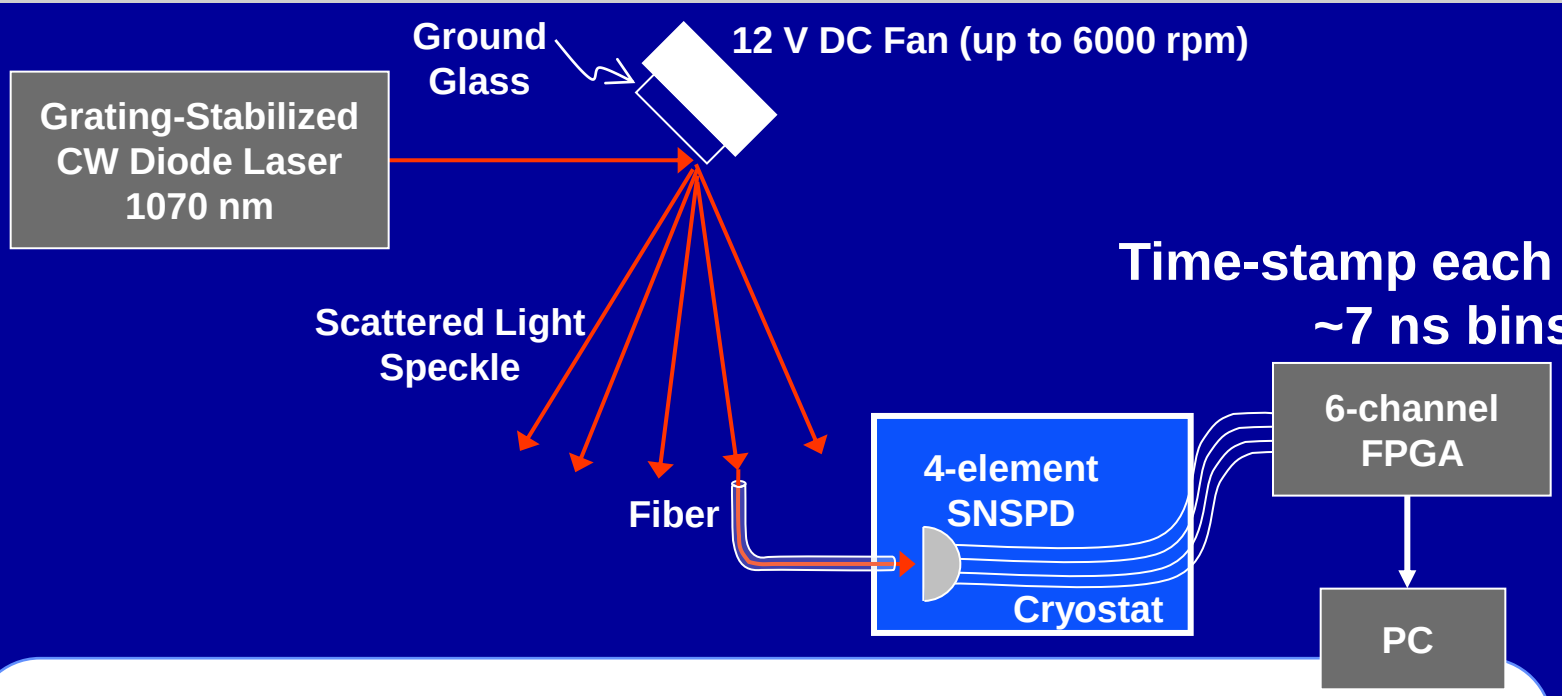


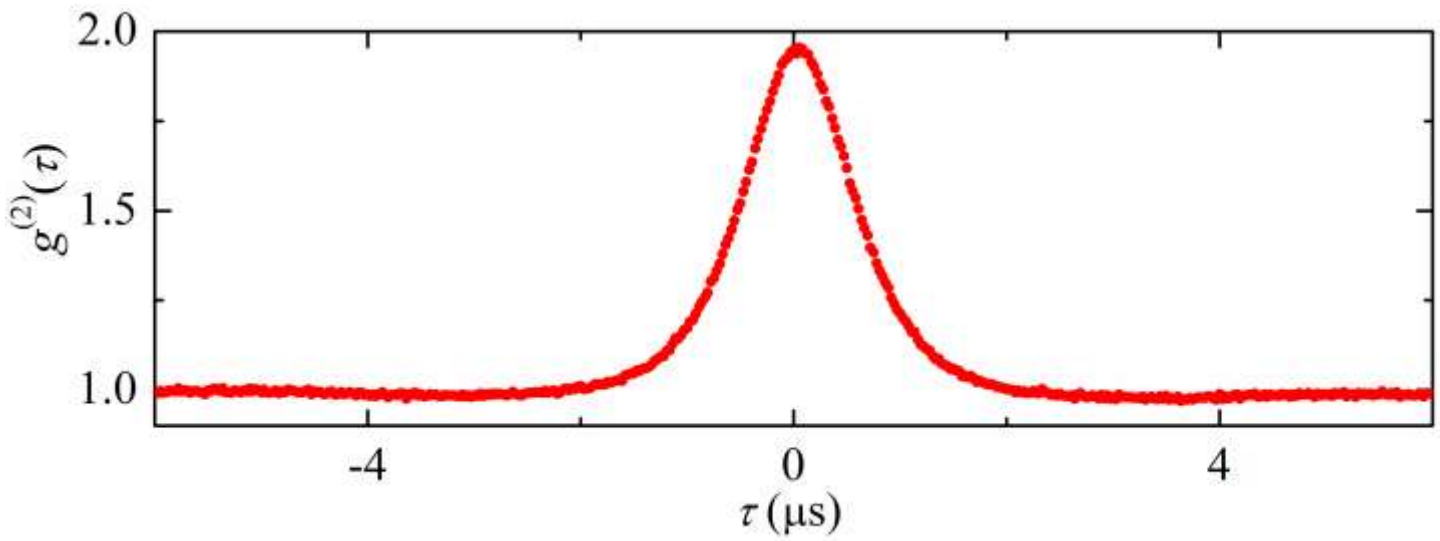


APPLICATION

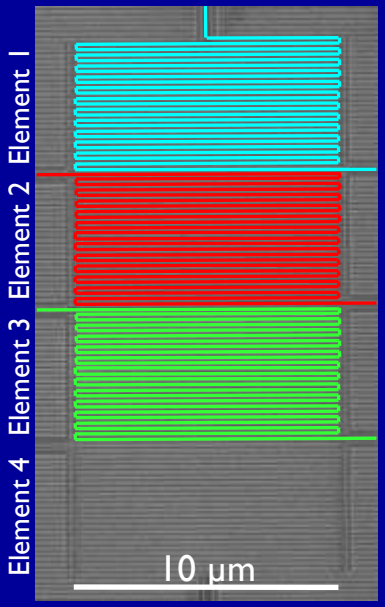

10 µm

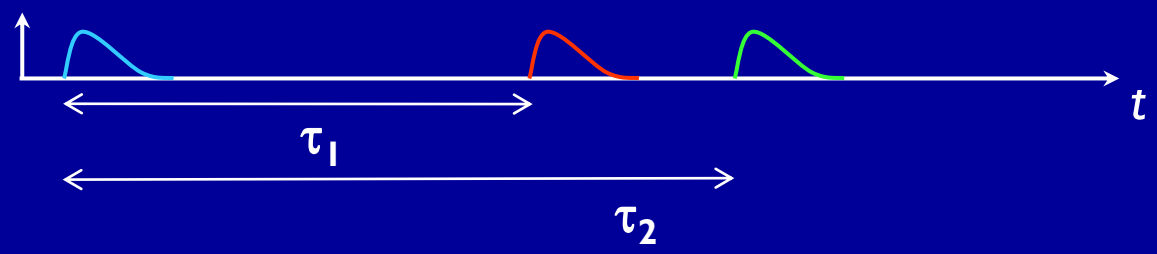
Pseudo-Thermal Source Setup





3-photon coincidences





2-photon coincidence conditions:

$\tau_1 = 0$

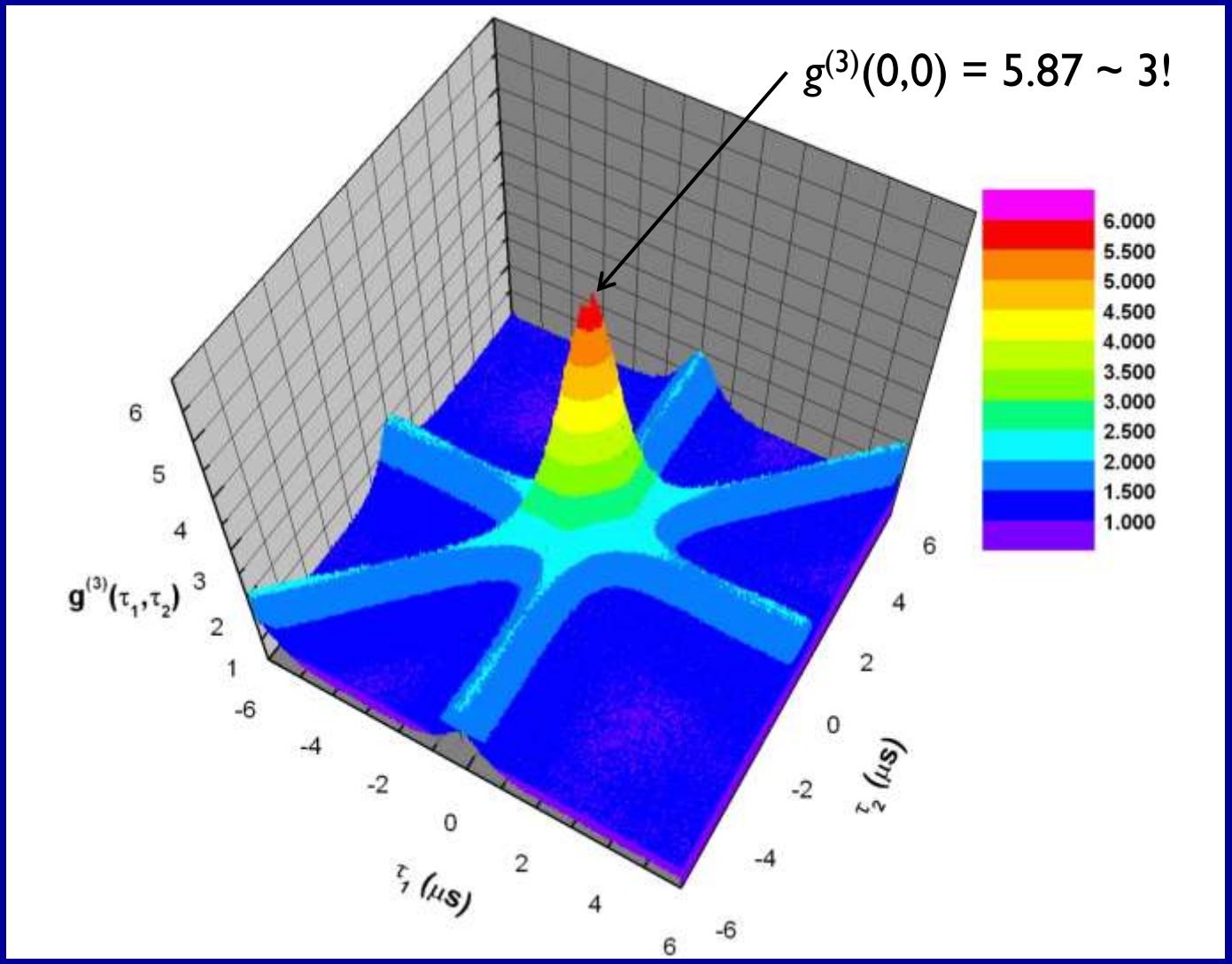
$\tau_2 = 0$

$\tau_1 = \tau_2$

3-photon coincidence :

$\tau_1 = \tau_2 = 0$

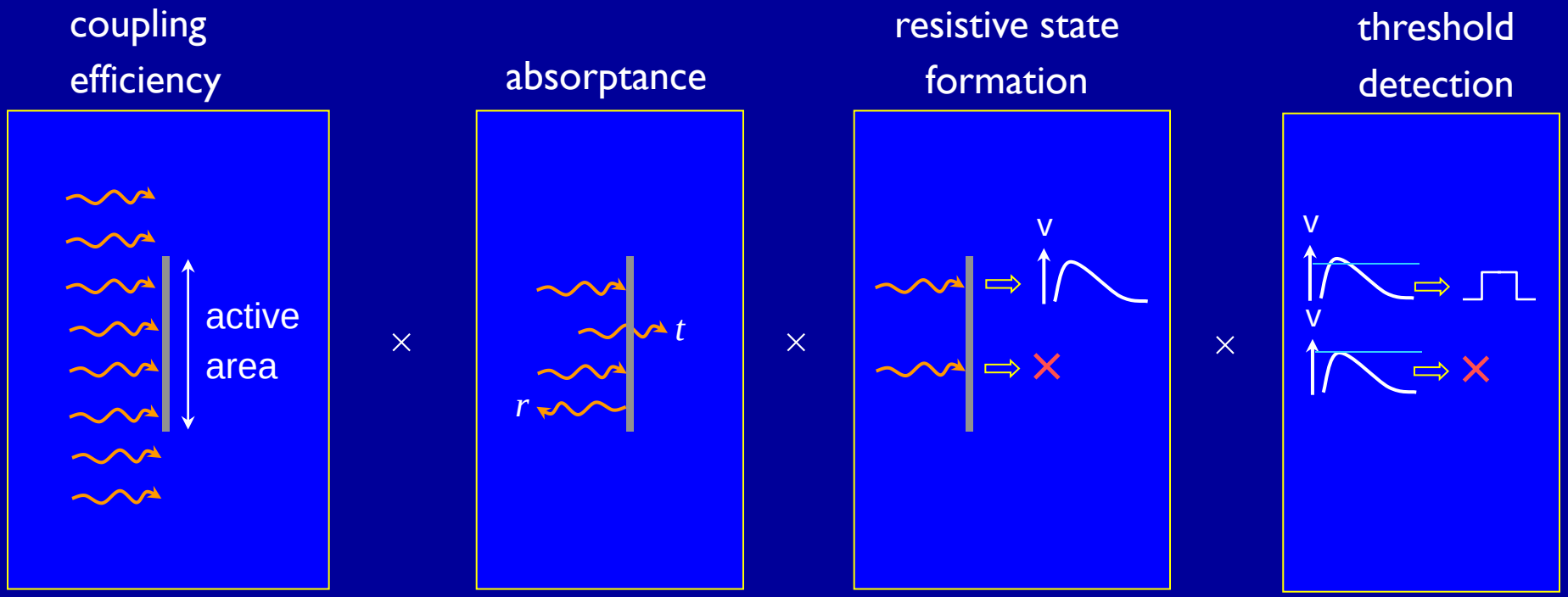
3rd-order Intensity Correlations



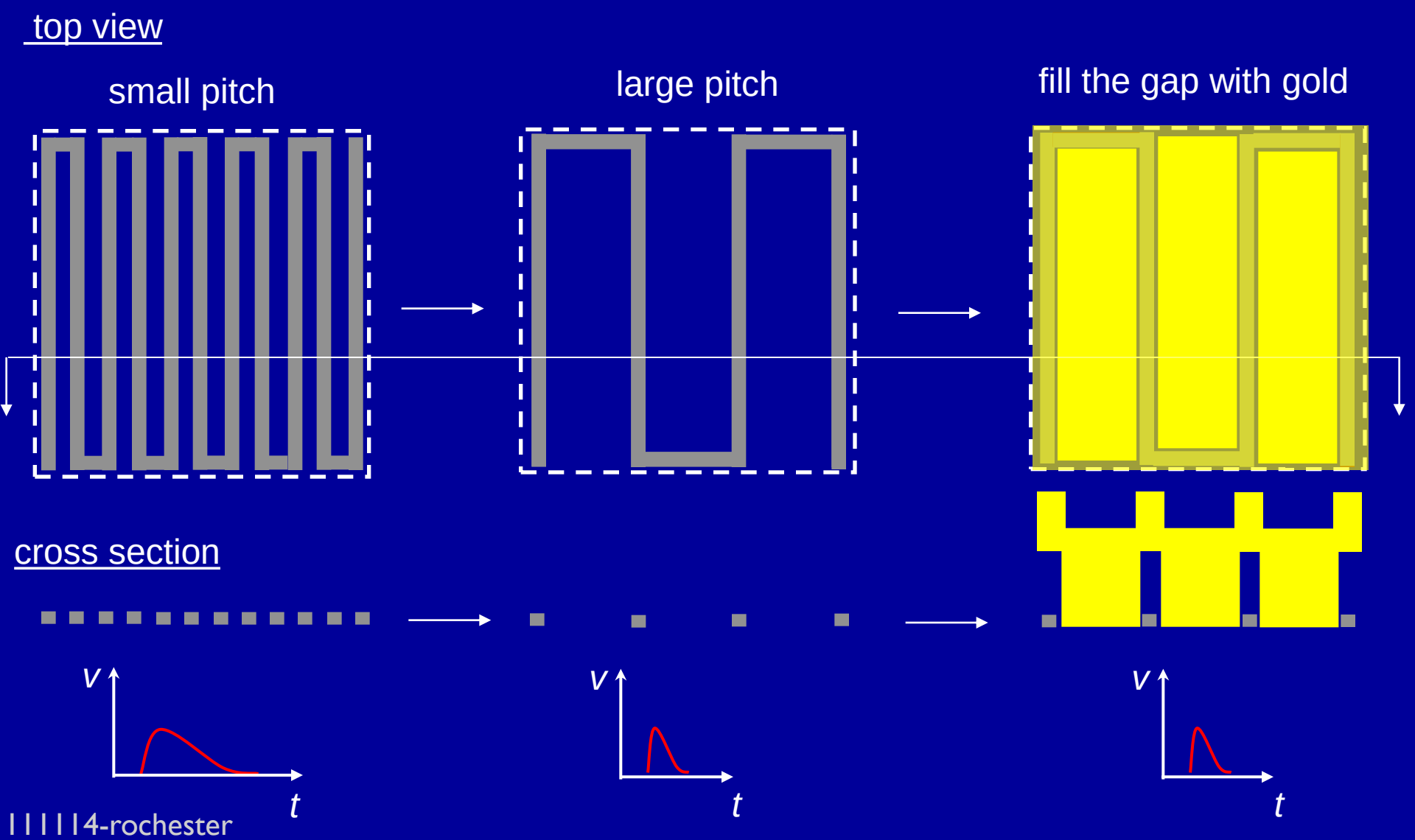
"High-order temporal coherences of chaotic and laser light", Stevens, Baek, Dauler, Kerman, Molnar, Hamilton, Berggren, Mirin, and Nam, *Optics Express, 18, 1430 (2010)*

NANO-ANTENNAE

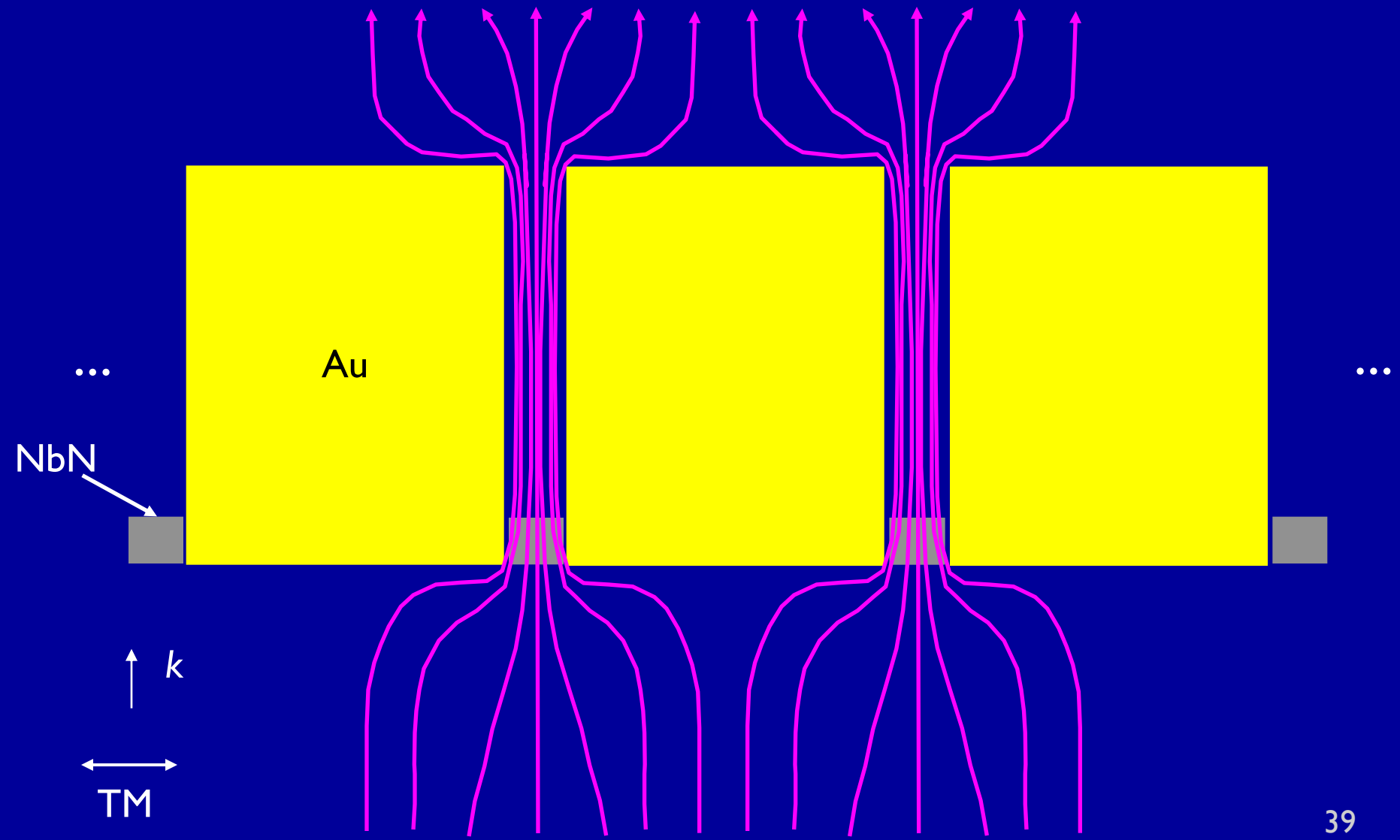
The Three Keys to Efficiency



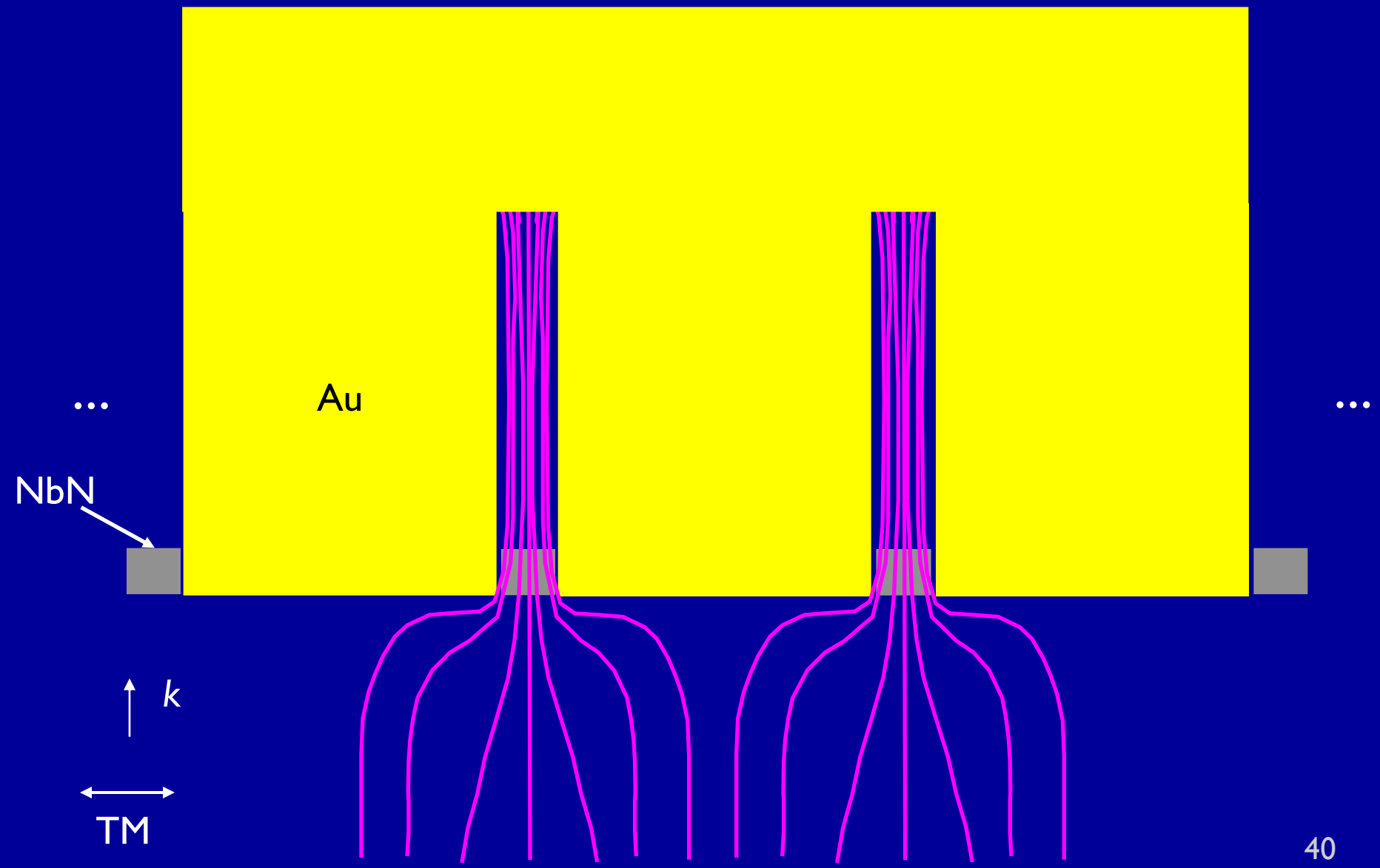
Antenna – Integrated Detector



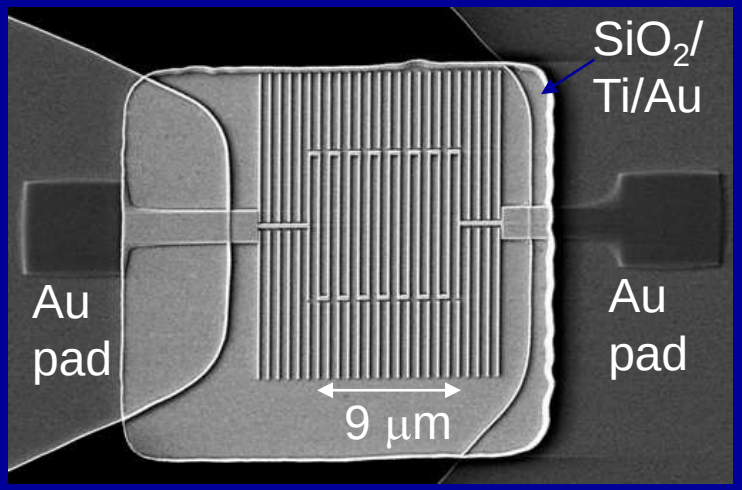
Optical Nano-Antenna



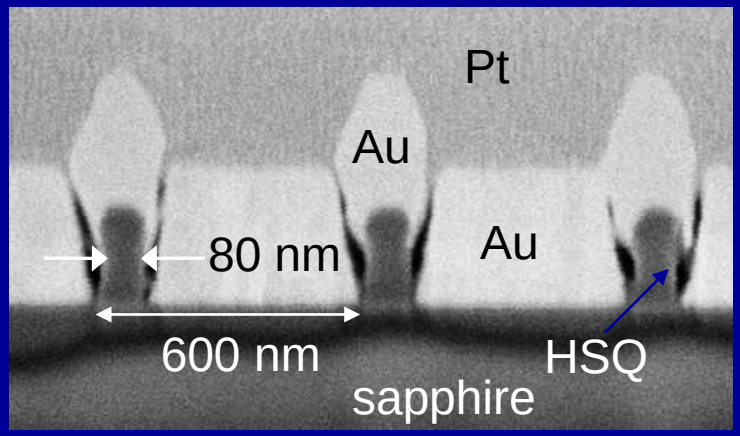
Optical Nano-Antenna



Fabrication



ion-beam cross-section

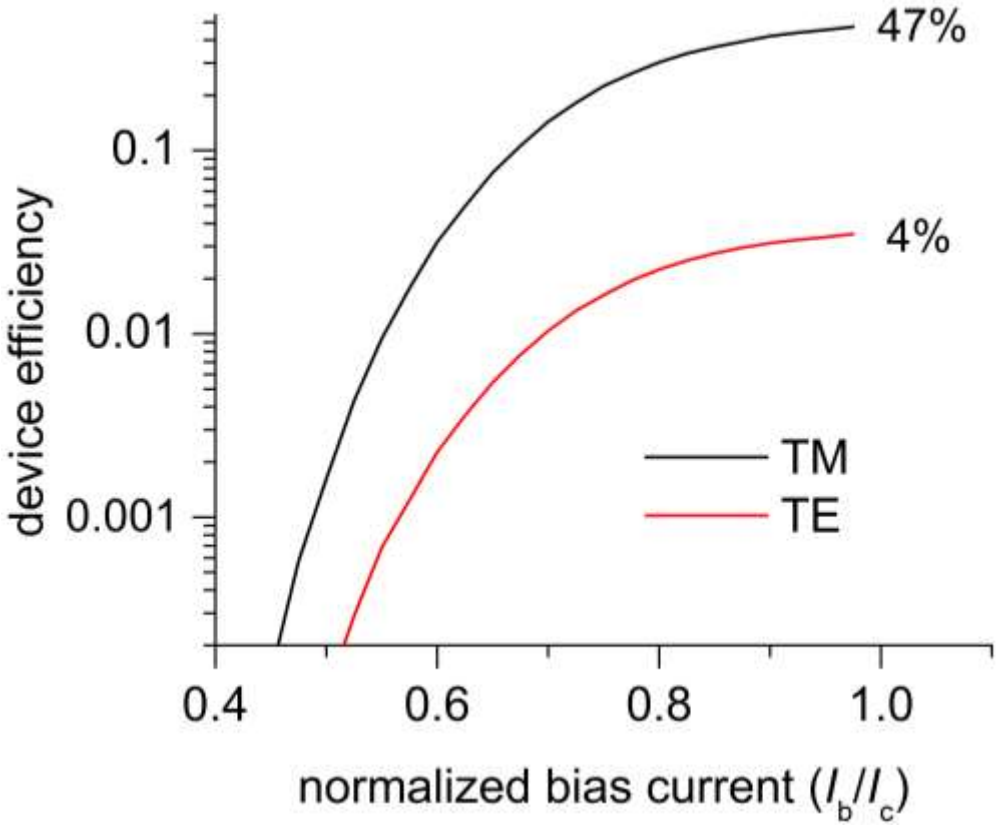


fabrication challenges

- e-beam writing on thick HSQ
- gold migration in evaporation

Nano-Optical Antenna for Nanowire Detectors

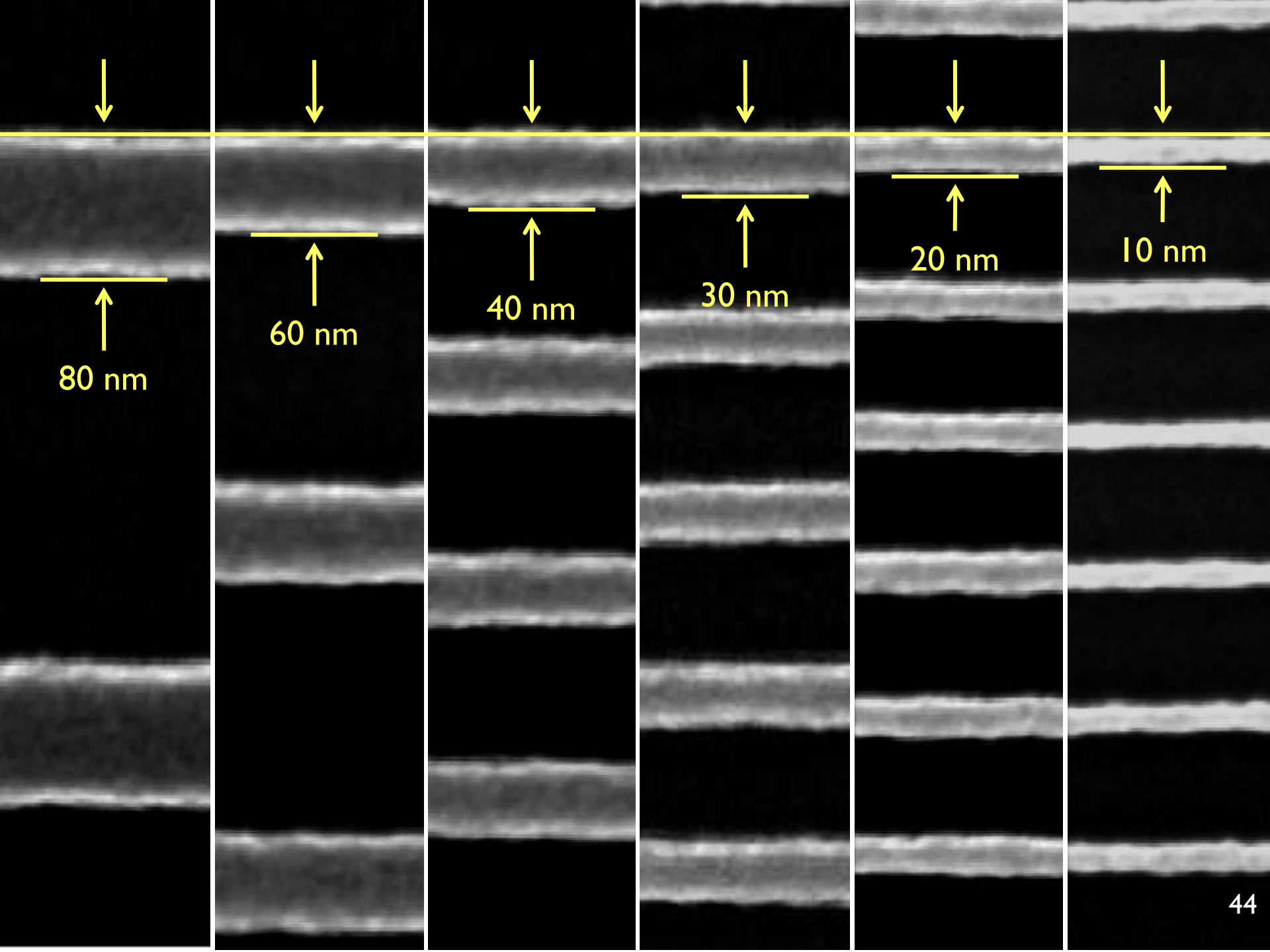
- Nano-antennae improve collection, permitting 3 x area, with same reset time

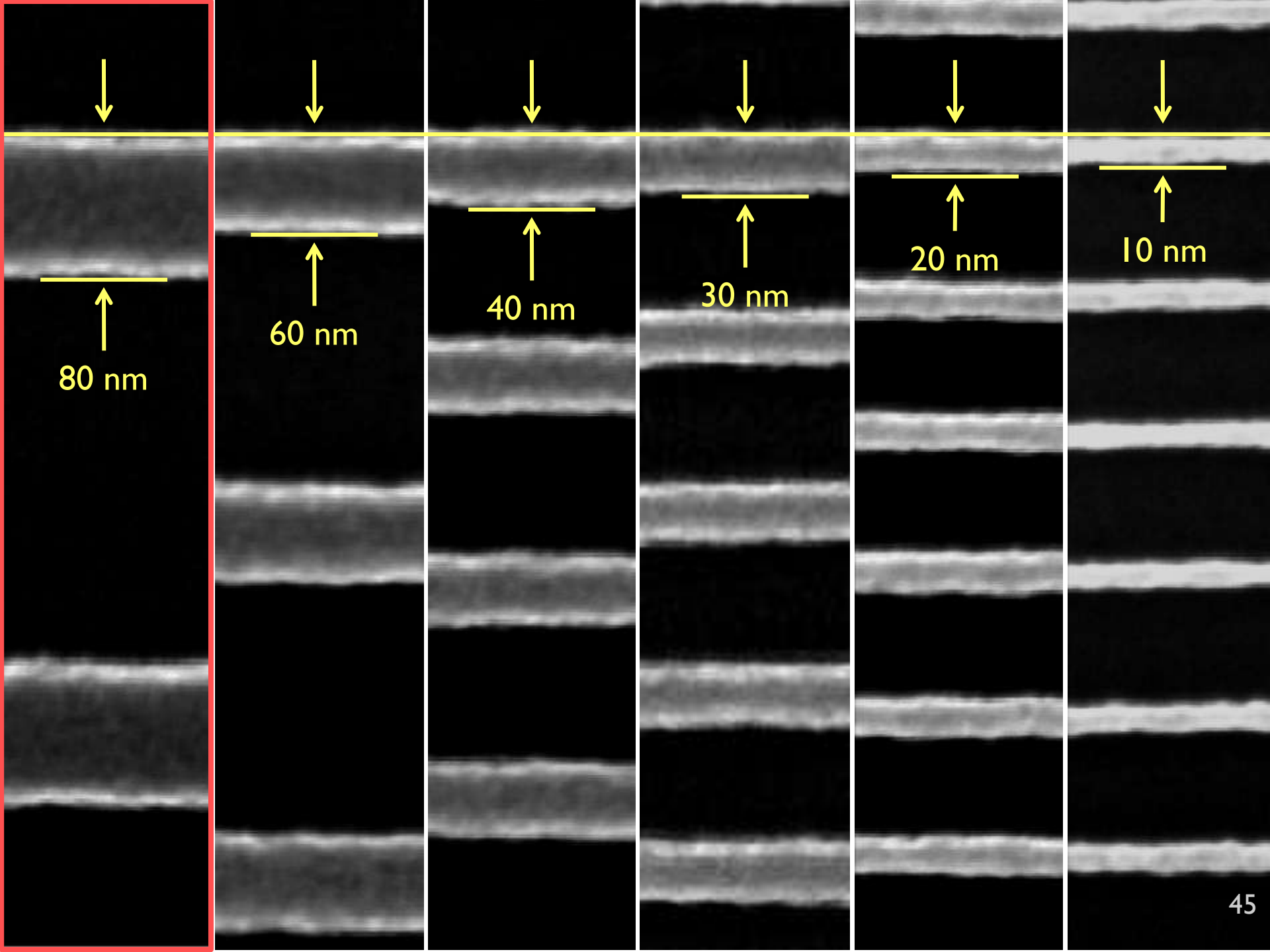


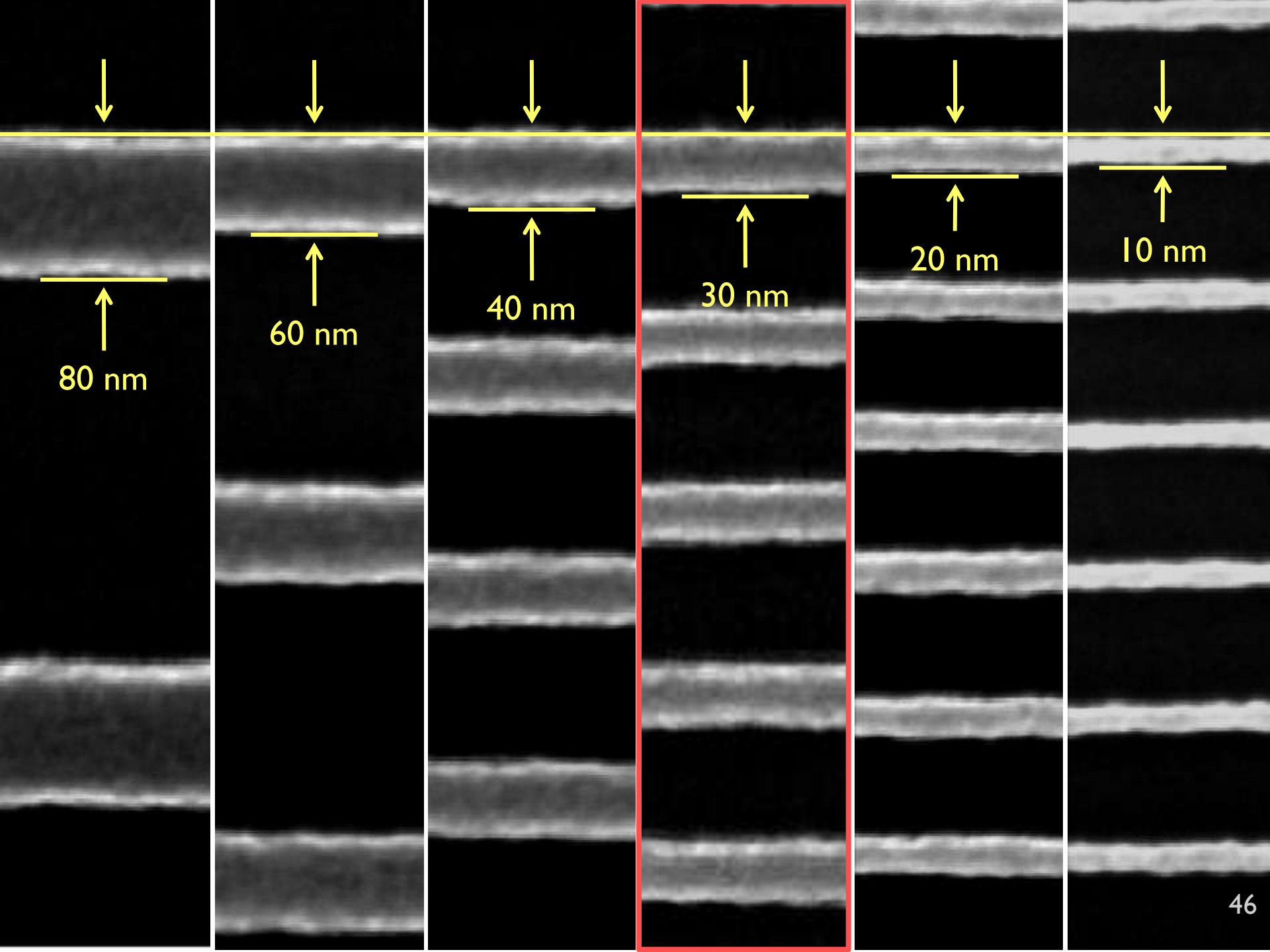
- 600-nm pitch, 9-μm-by-9-μm area
- 47% device efficiency
- 5 ns reset time

Hu et. al. Optics Express, 2010

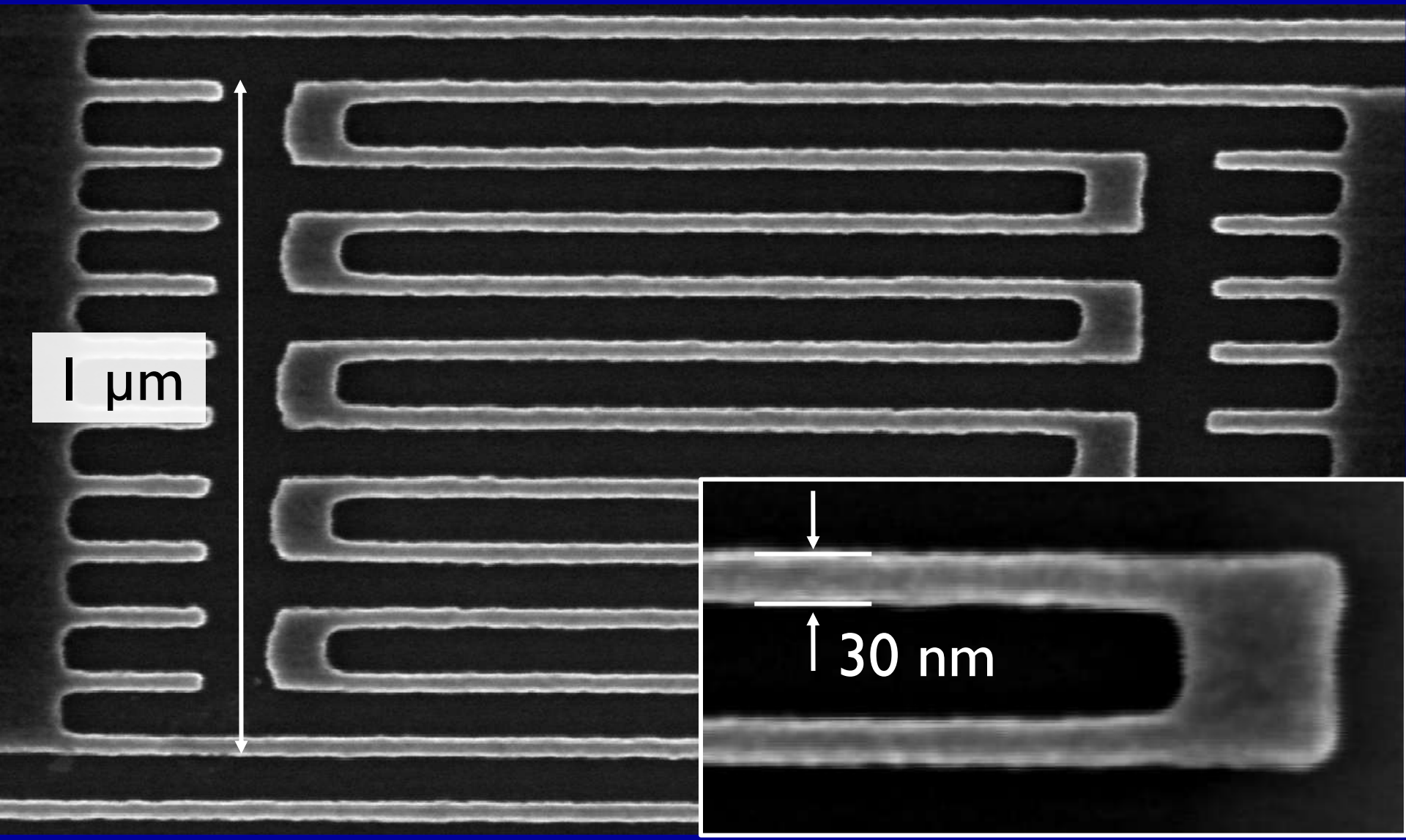
SUB-30-NM DEVICES


80 nm
60 nm
40 nm
30 nm
20 nm
10 nm


80 nm
60 nm
40 nm
30 nm
20 nm
10 nm

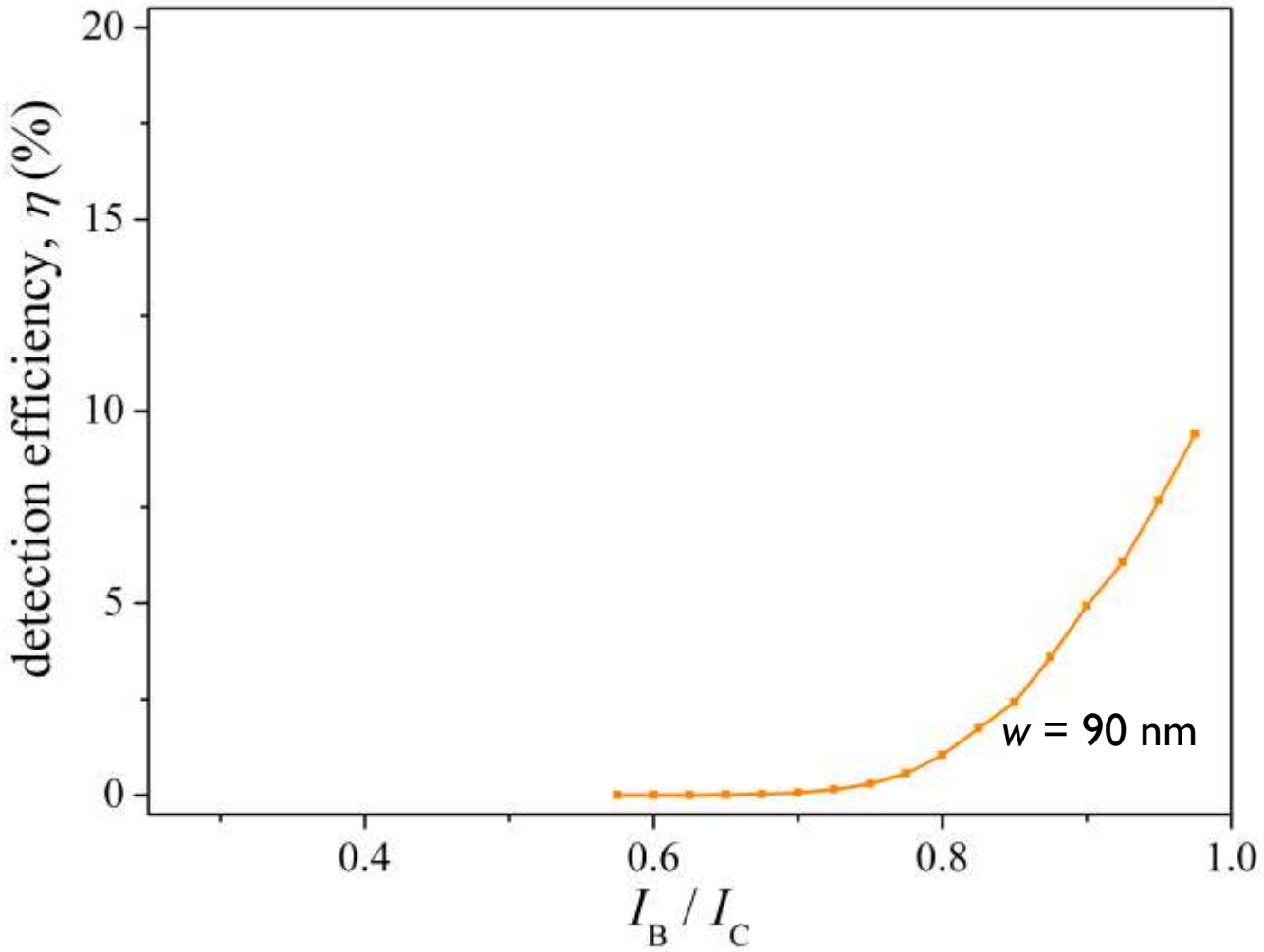

80 nm
60 nm
40 nm
30 nm
20 nm
10 nm

30-nm-wide-nanowire SNSPD



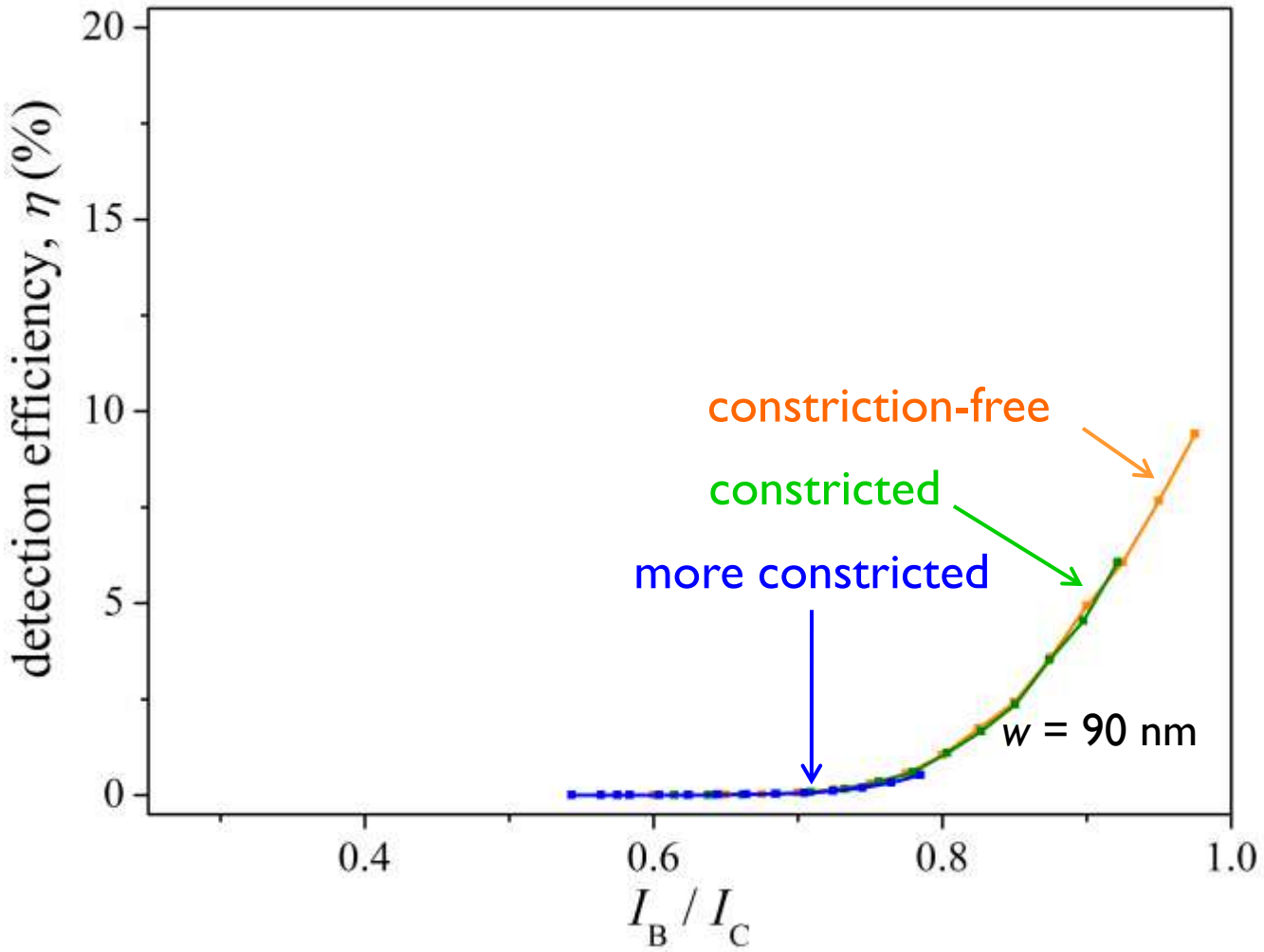
Standard vs Ultranarrow-Nanowire SNSPDs

Constrictions



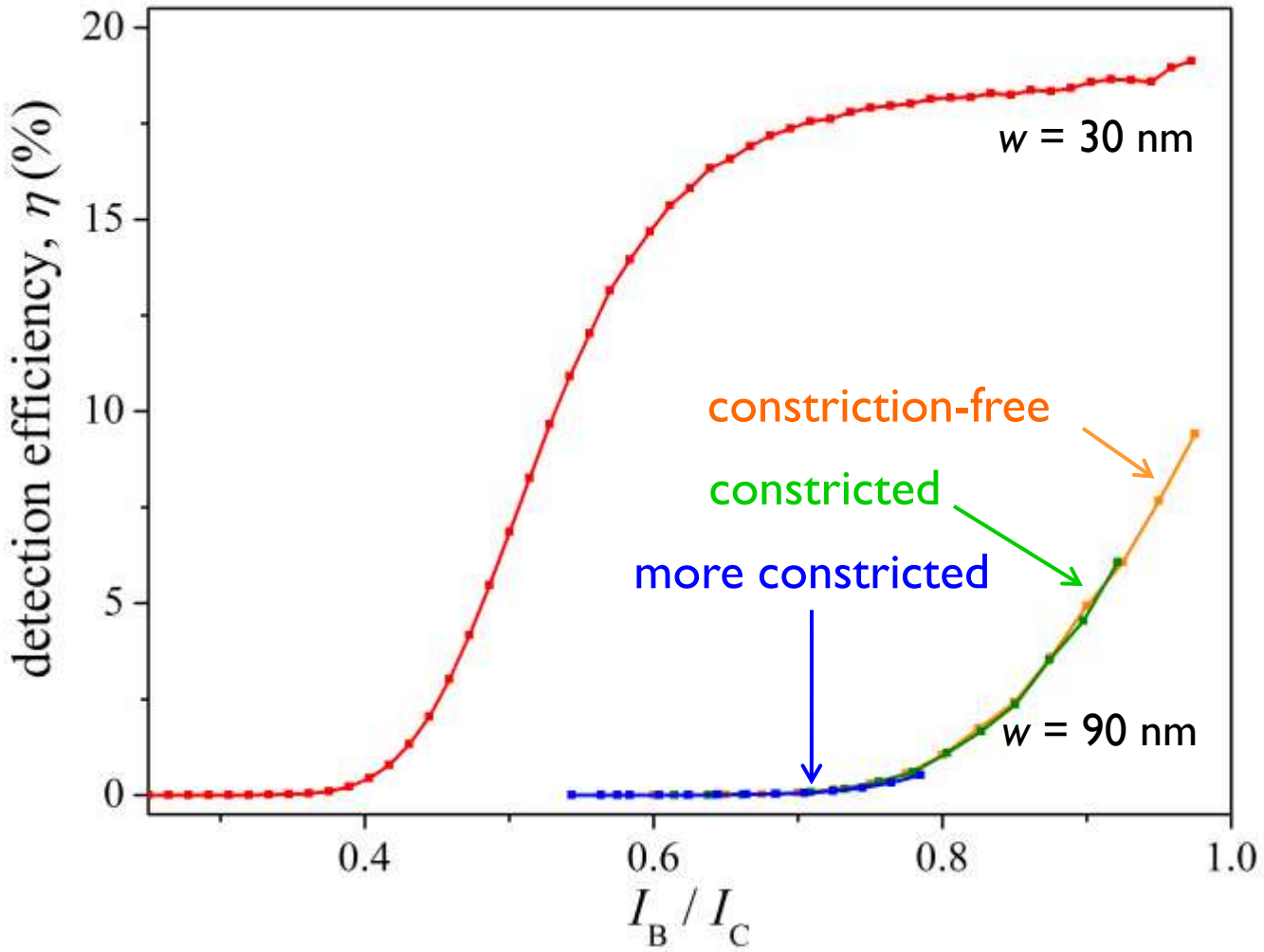
Standard vs Ultranarrow-Nanowire SNSPDs

Constrictions



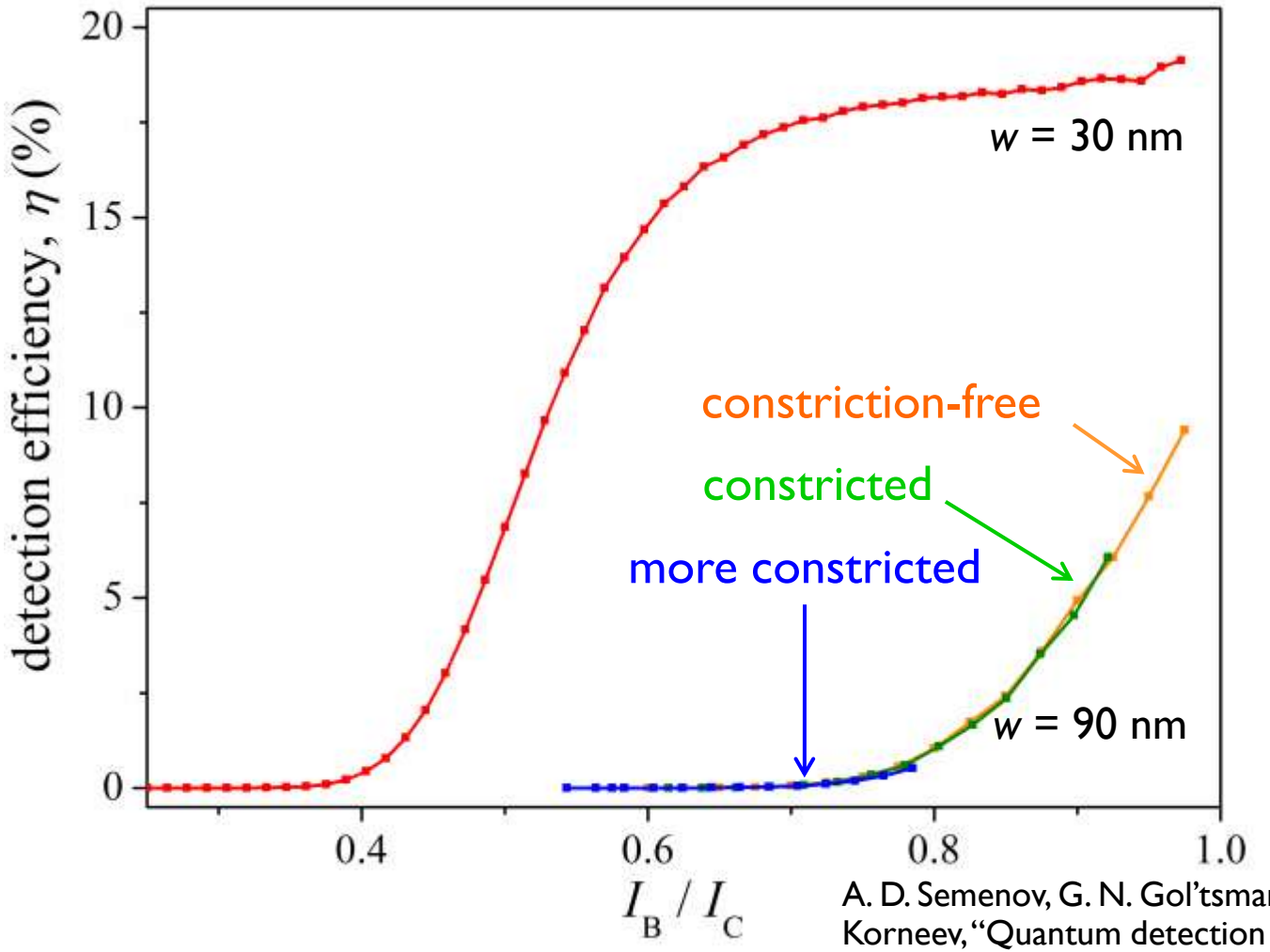
Standard vs Ultranarrow-Nanowire SNSPDs

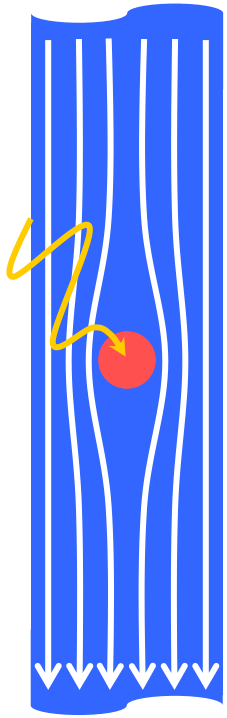
Constrictions



Standard vs Ultranarrow-Nanowire SNSPDs

Constrictions

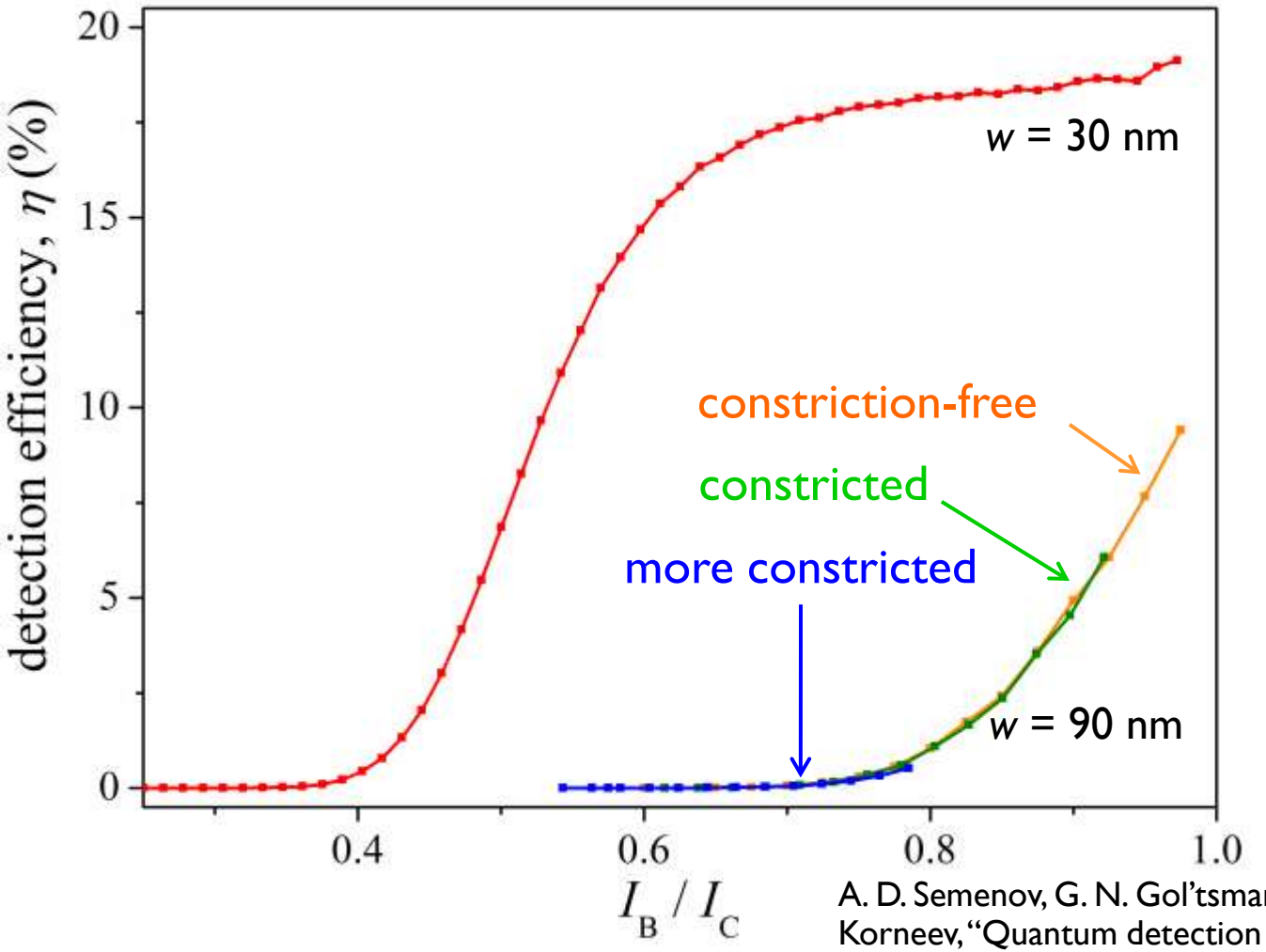


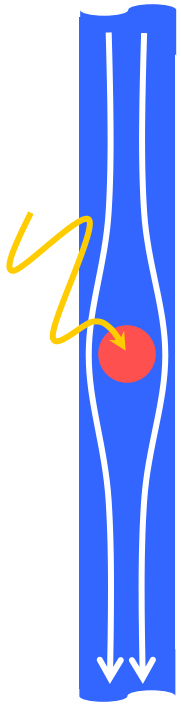


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C, vol. 351*, pp. 349–356, 2001.

Standard vs Ultranarrow-Nanowire SNSPDs

Constrictions

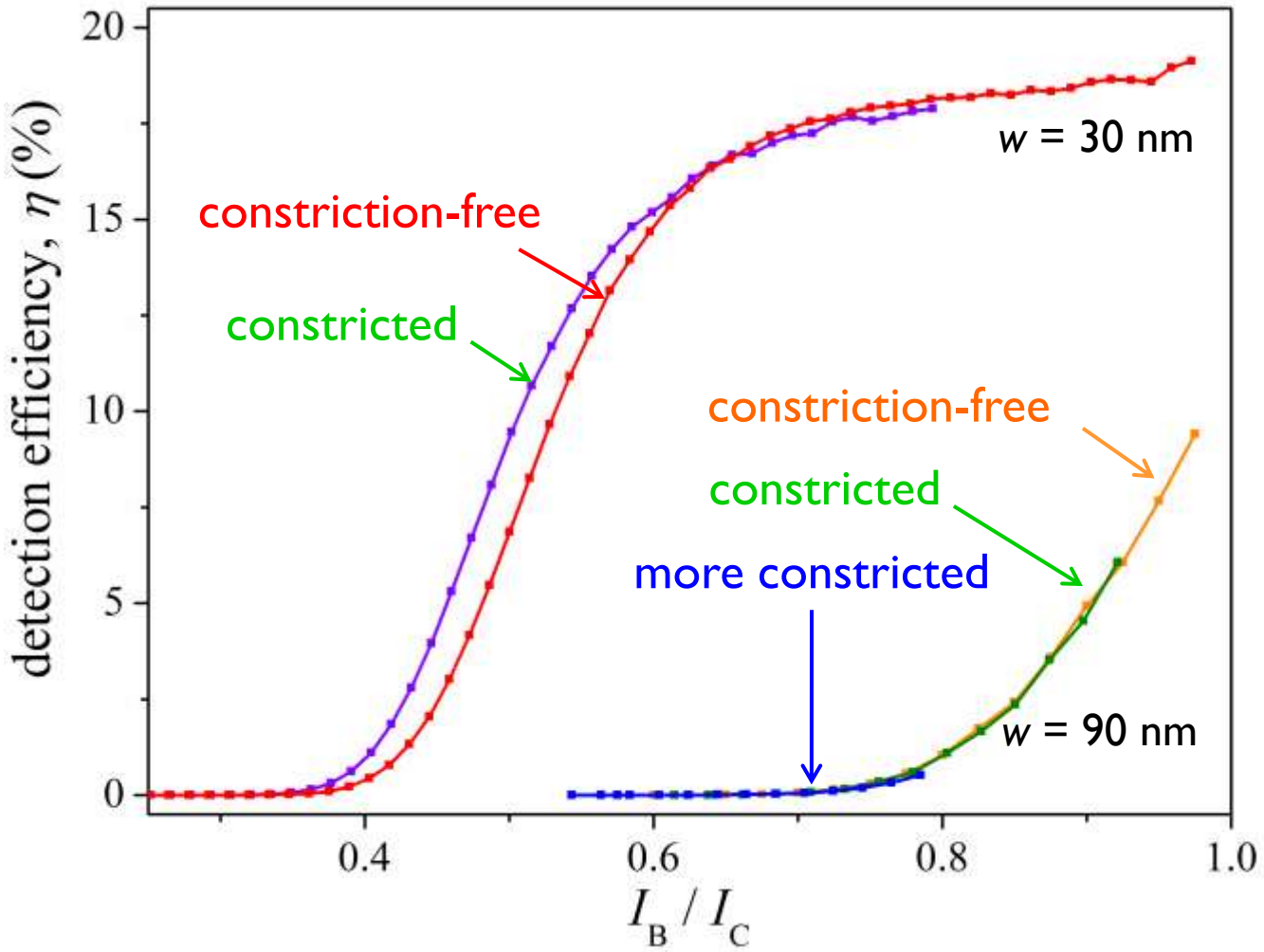




A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C, vol. 351*, pp. 349–356, 2001.

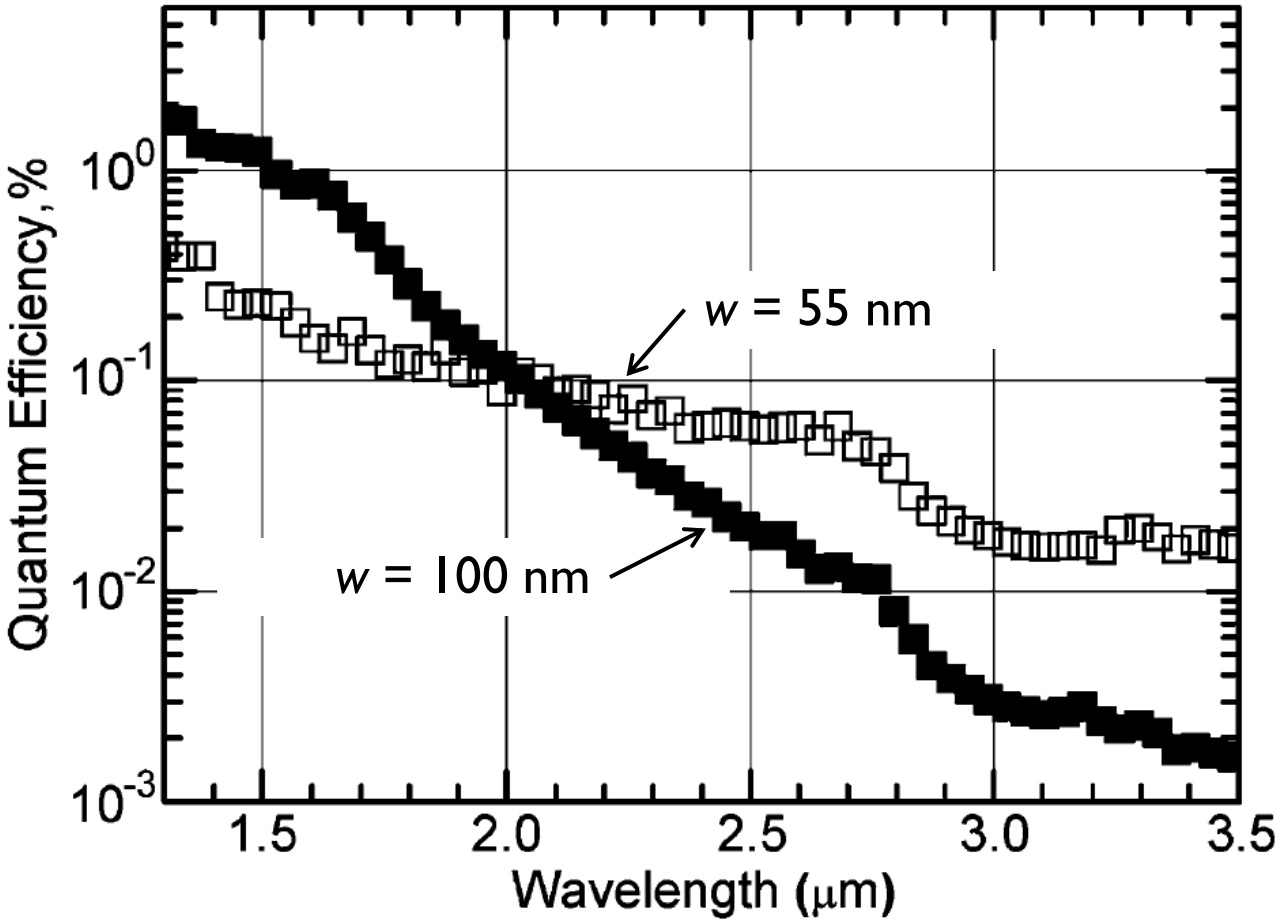
Standard vs Ultranarrow-Nanowire SNSPDs

Constrictions



Standard vs Ultranarrow-Nanowire SNSPDs

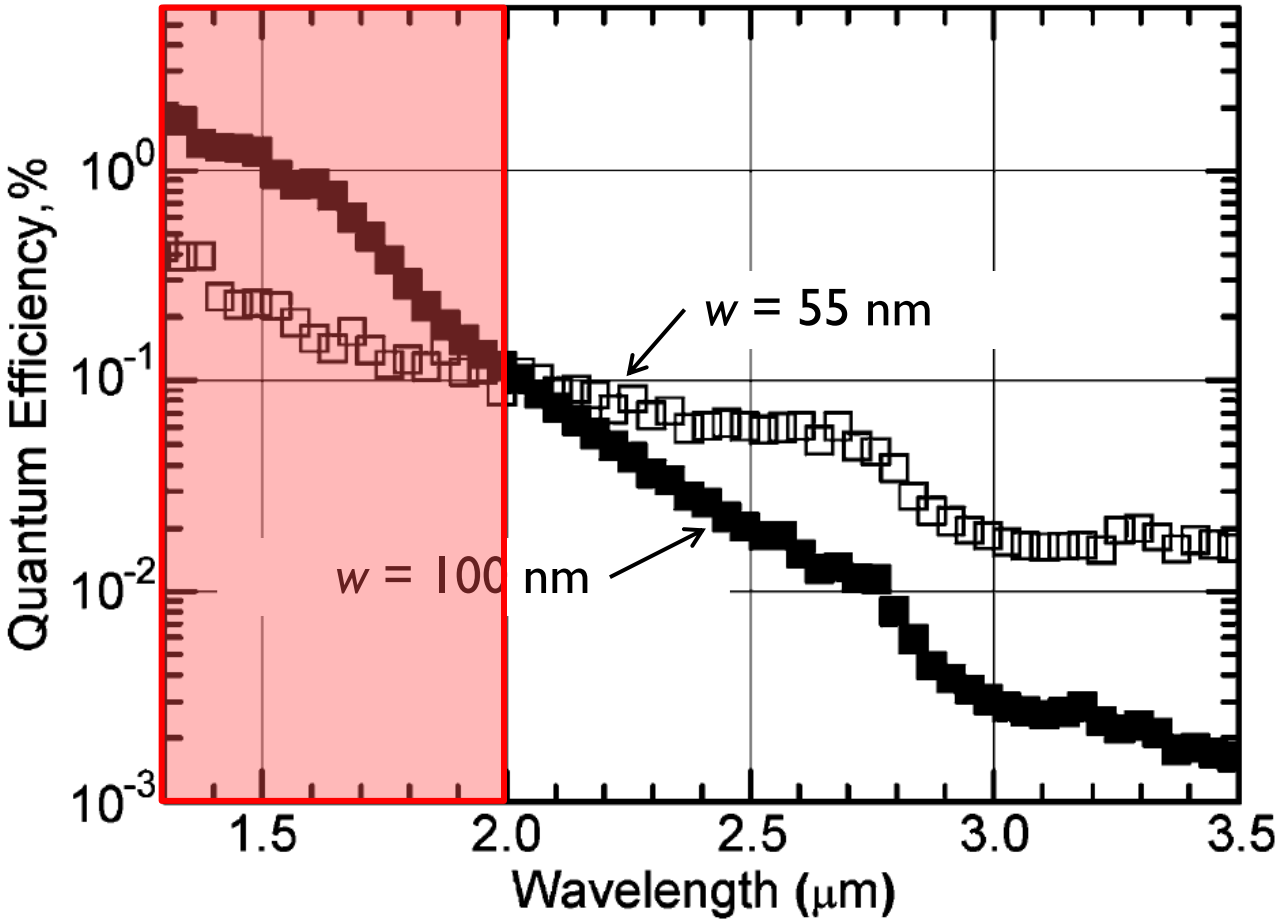
Negligible responsivity above 2 μm



Gol'tsman et al., *IEEE Trans. Appl. Supercond* (2011)

Standard vs Ultranarrow-Nanowire SNSPDs

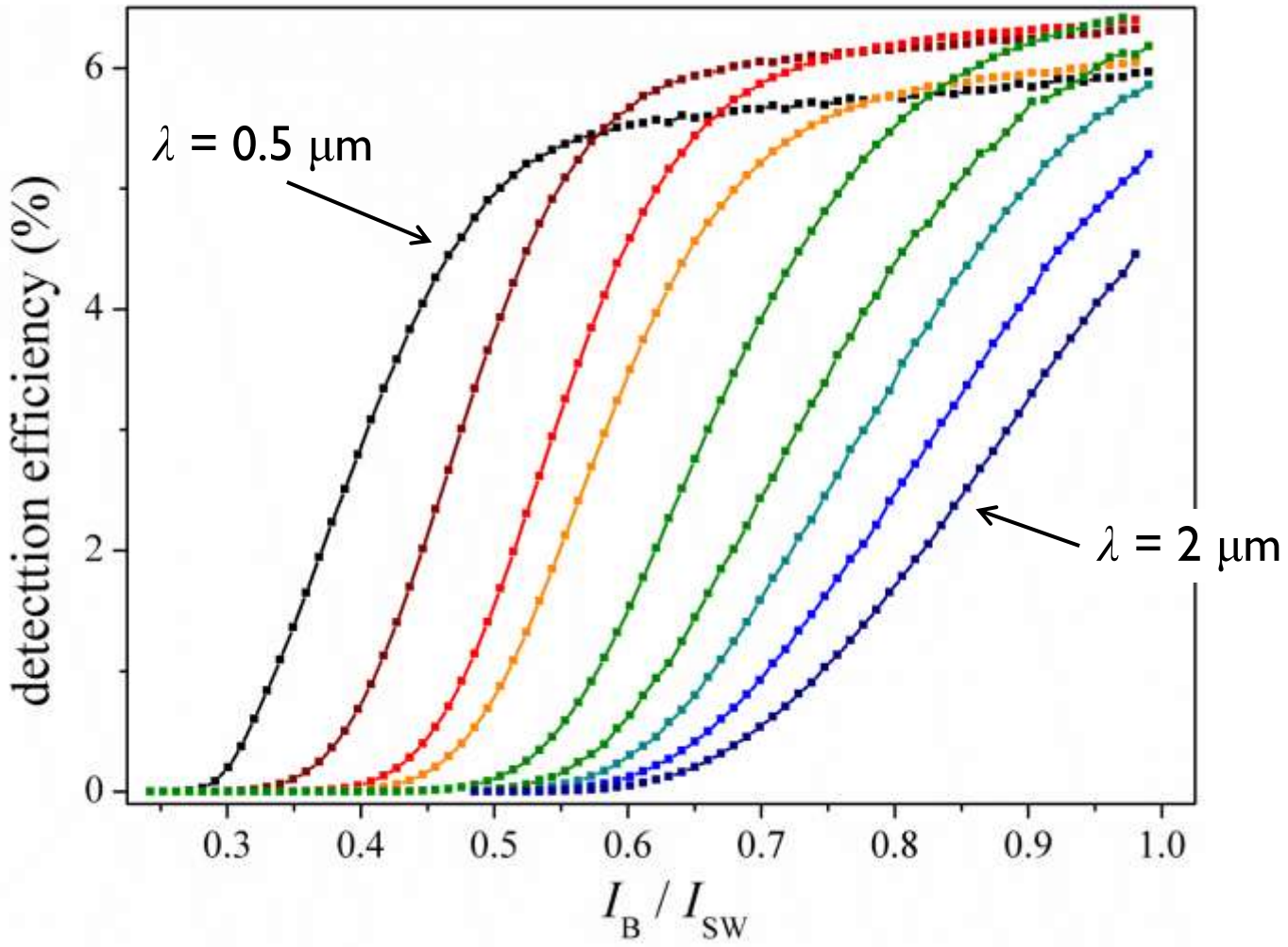
Negligible responsivity above 2 μm



Gol'tsman et al., *IEEE Trans. Appl. Supercond* (2011)

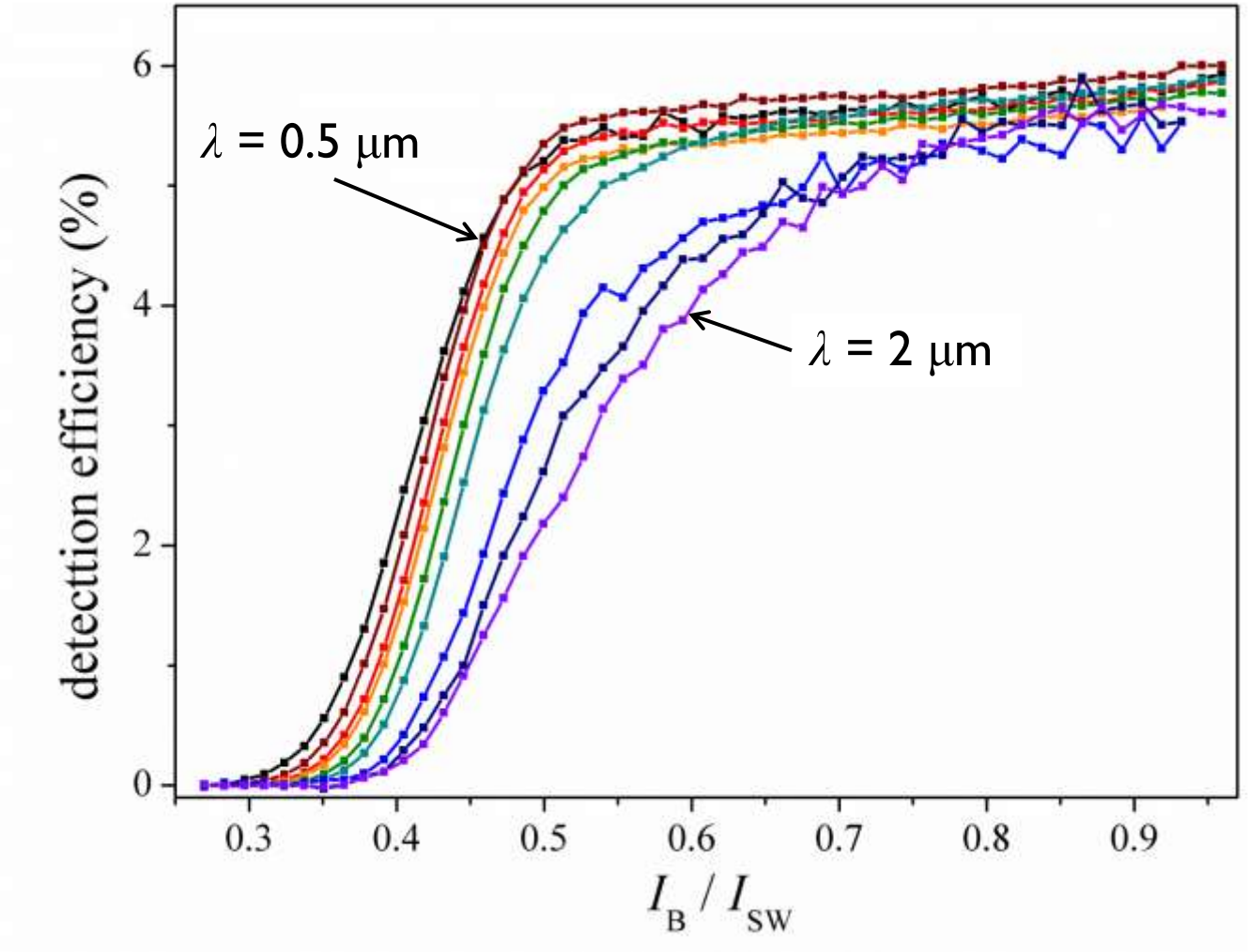
Detection efficiency vs I_B and wavelength

w = 85 nm

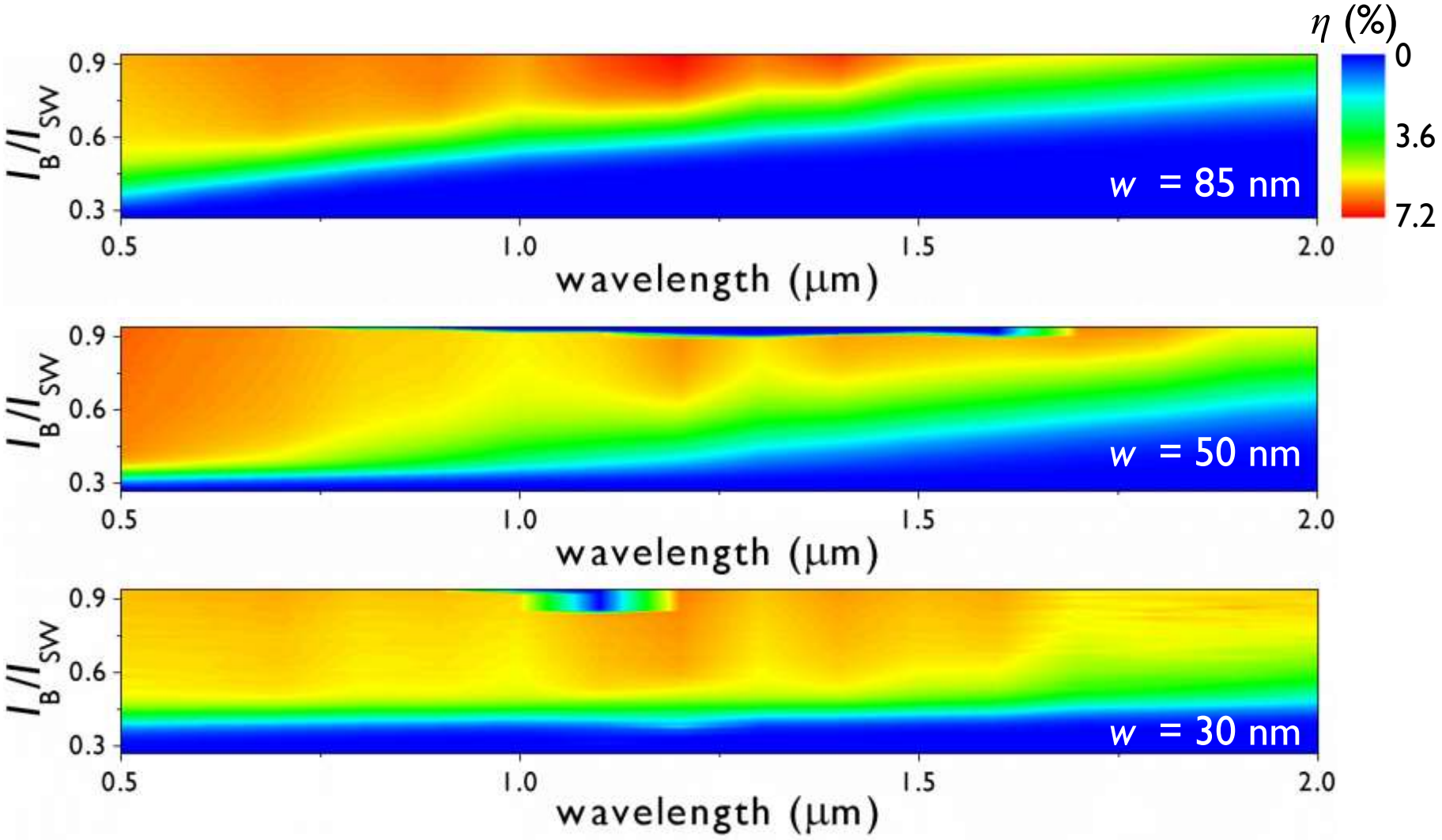


Detection efficiency vs I_B and wavelength

w = 30 nm

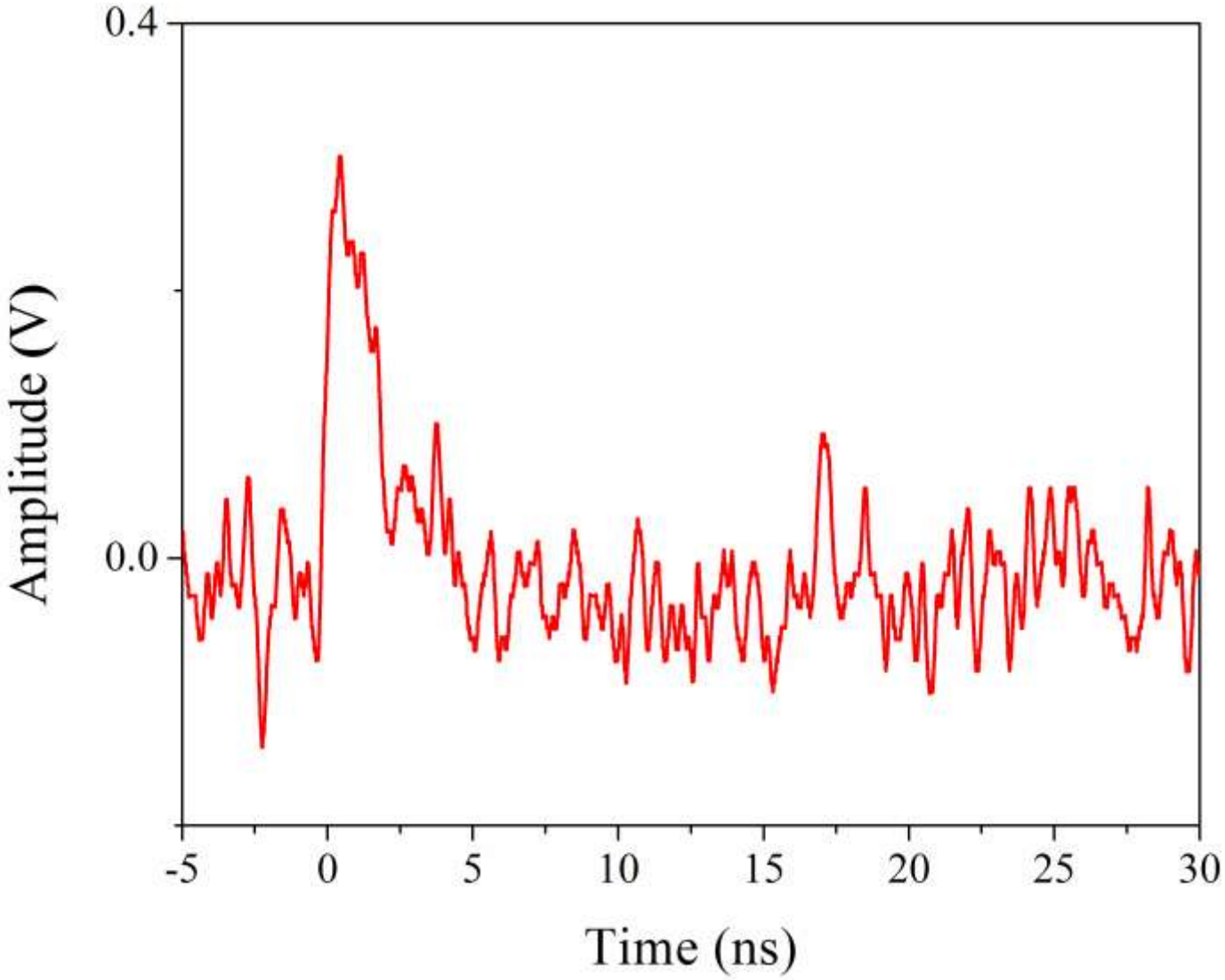


Detection efficiency vs I_B, wavelength and width

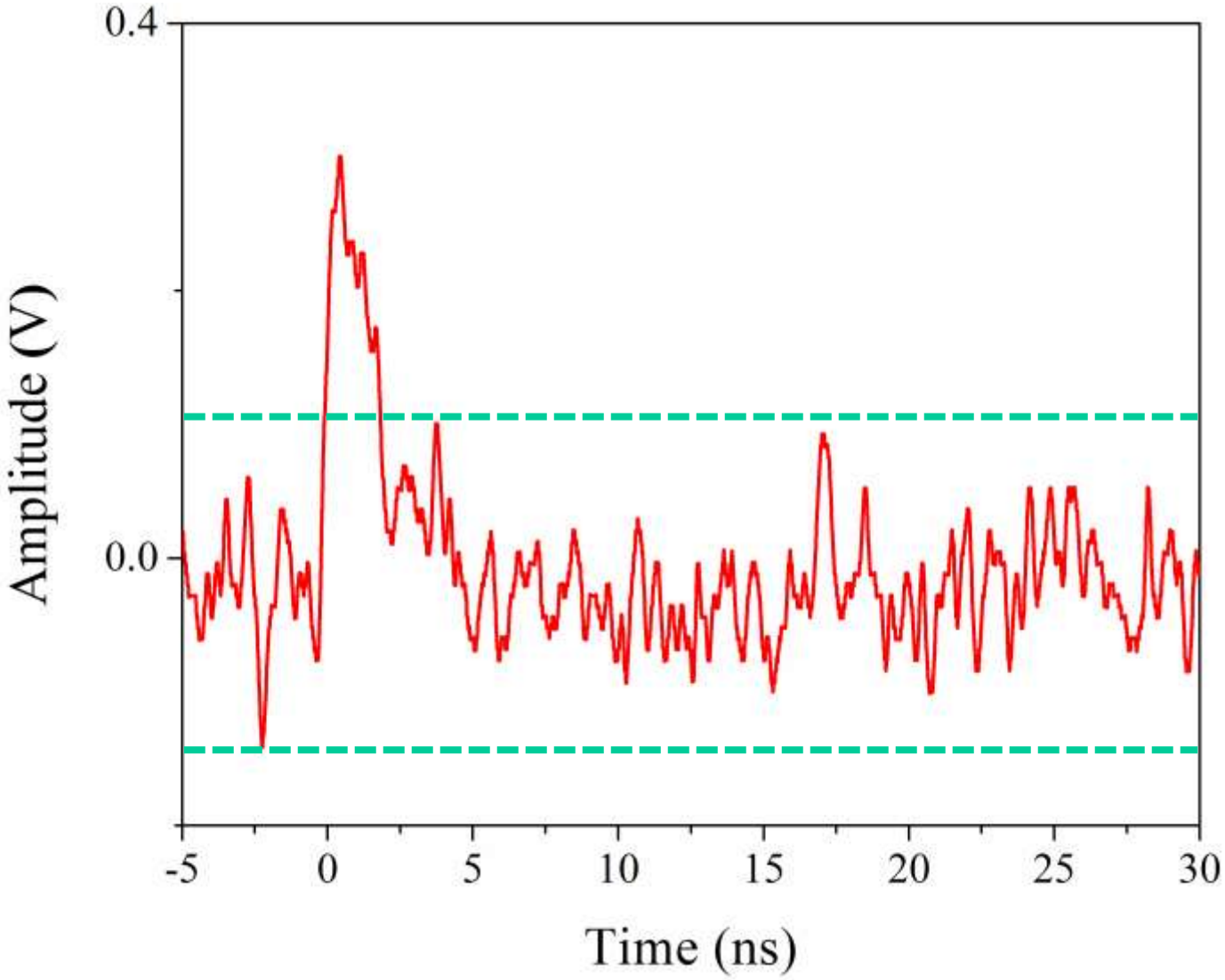


SIGNAL TO NOISE RATIO

Low signal to noise ratio



Low signal to noise ratio

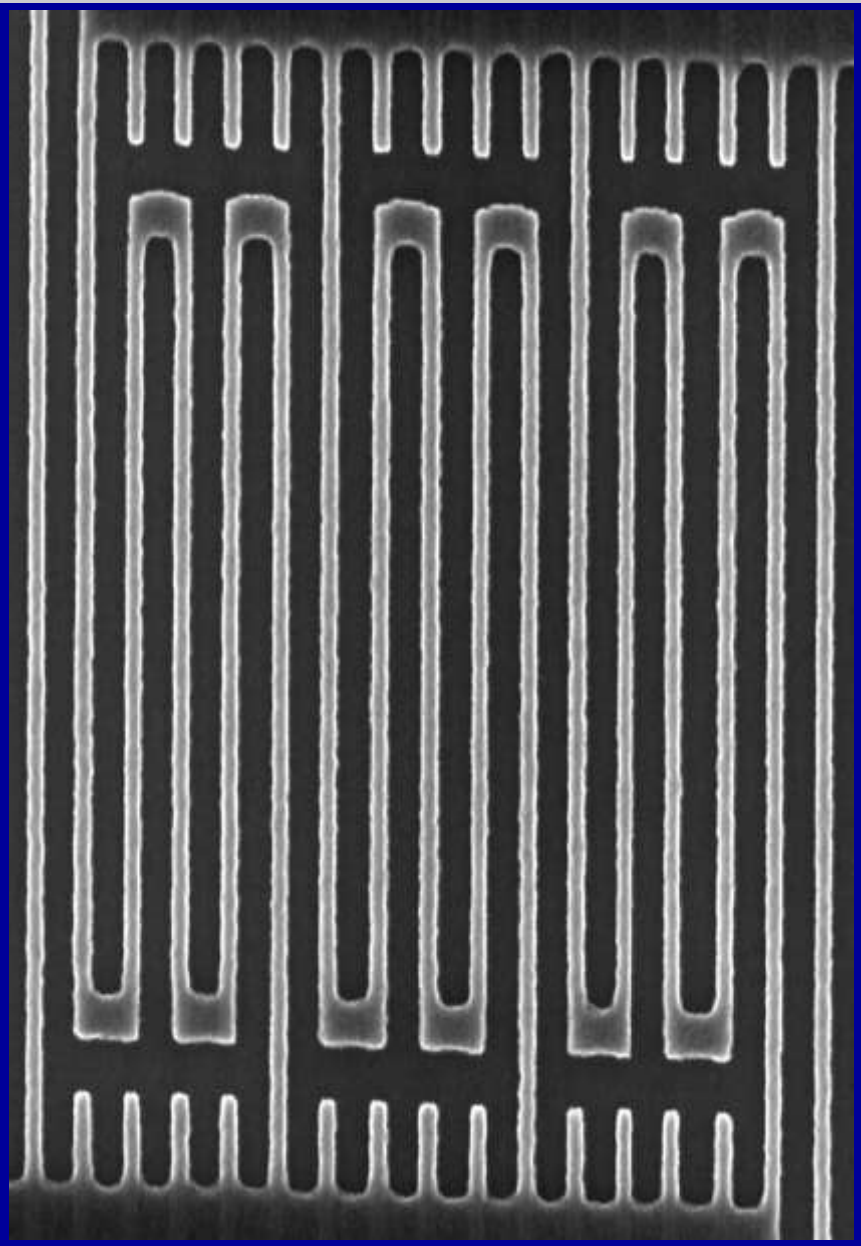


“A Cascade Switching Superconducting Single Photon Detector,”

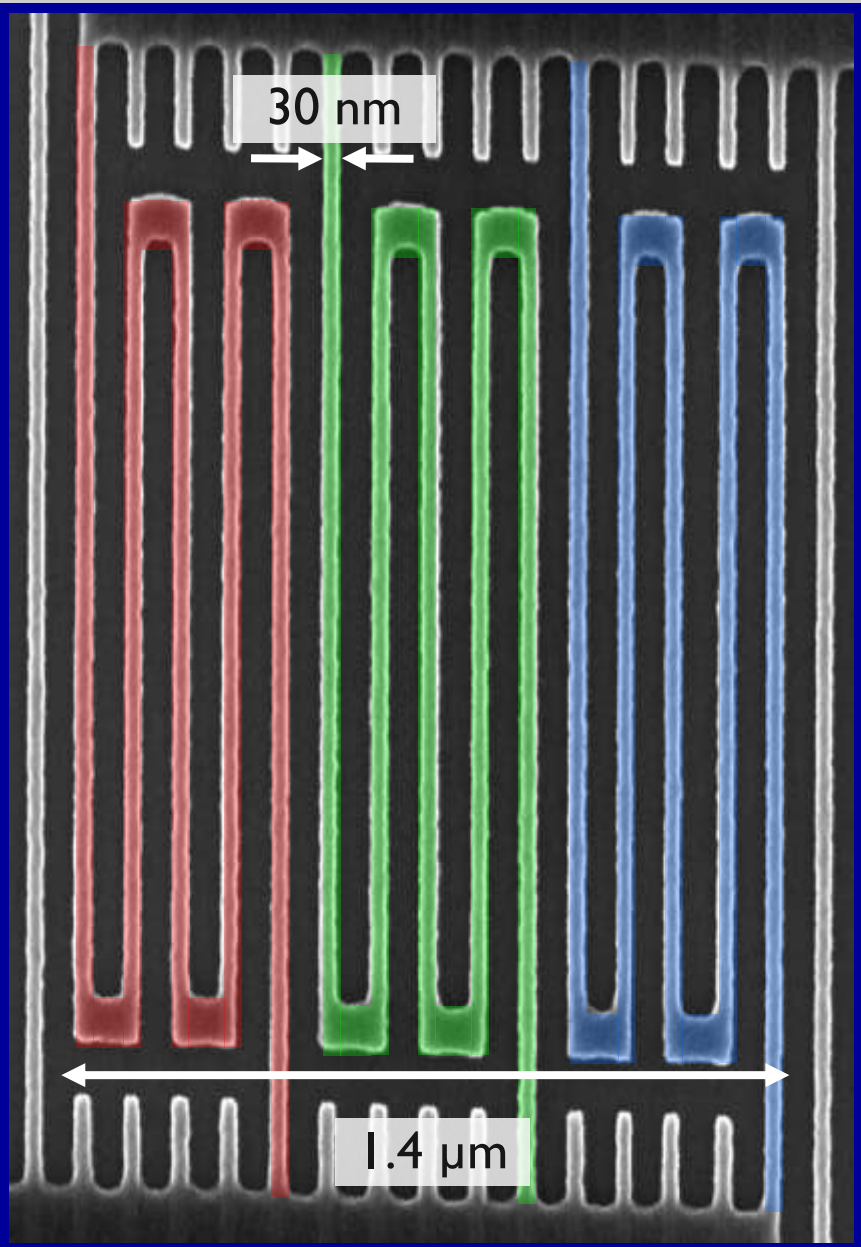
M. Ejrnaes, R. Cristiano, O. Quaranta, S. Pagano, A. Gaggero, F. Mattioli, R. Leoni, B. Voronov, and G. Gol'tsman,

Appl. Phys. Lett. 91, 262509 (2007)

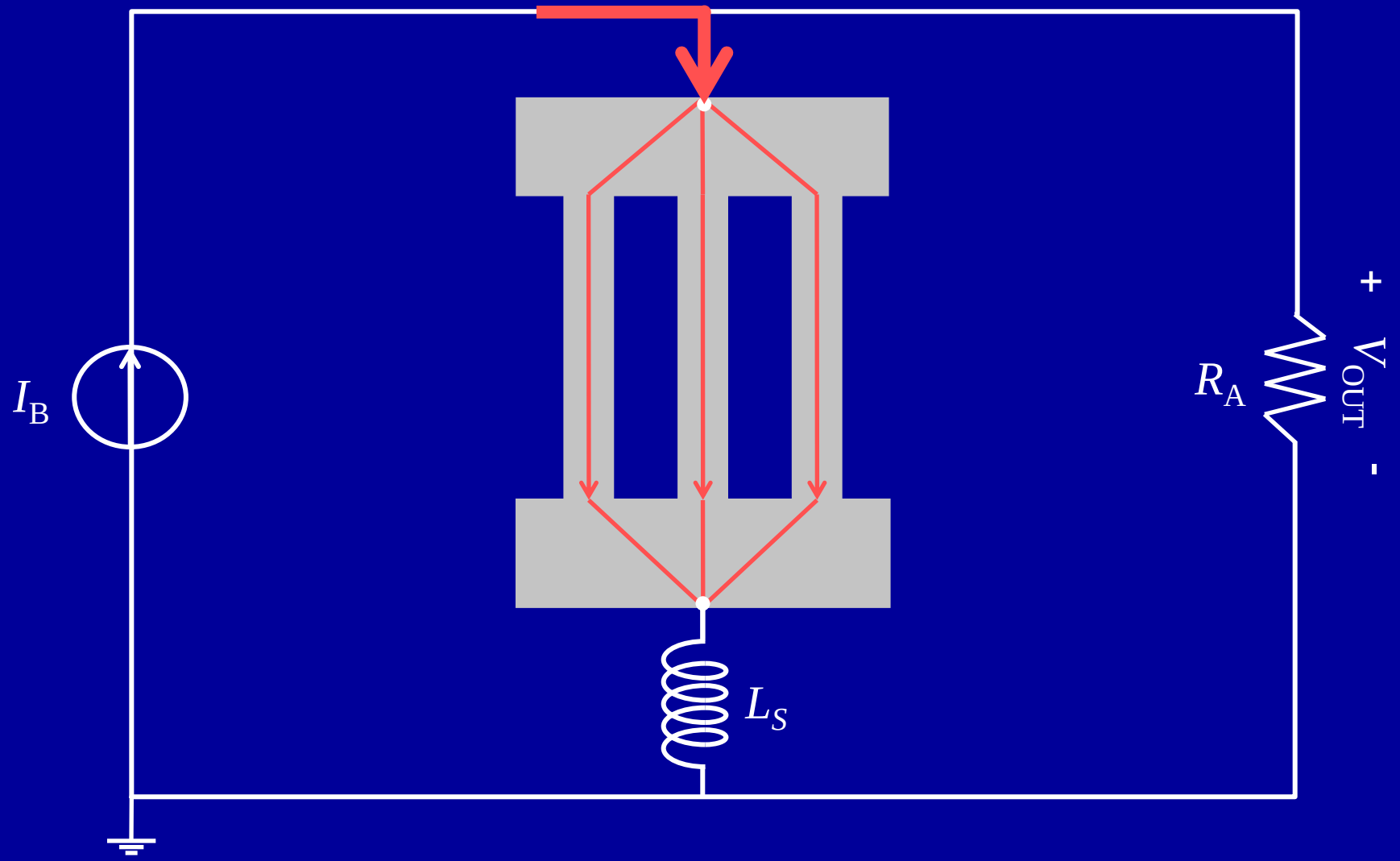
Superconducting Nanowire Avalanche Photodetectors (SNAPs)



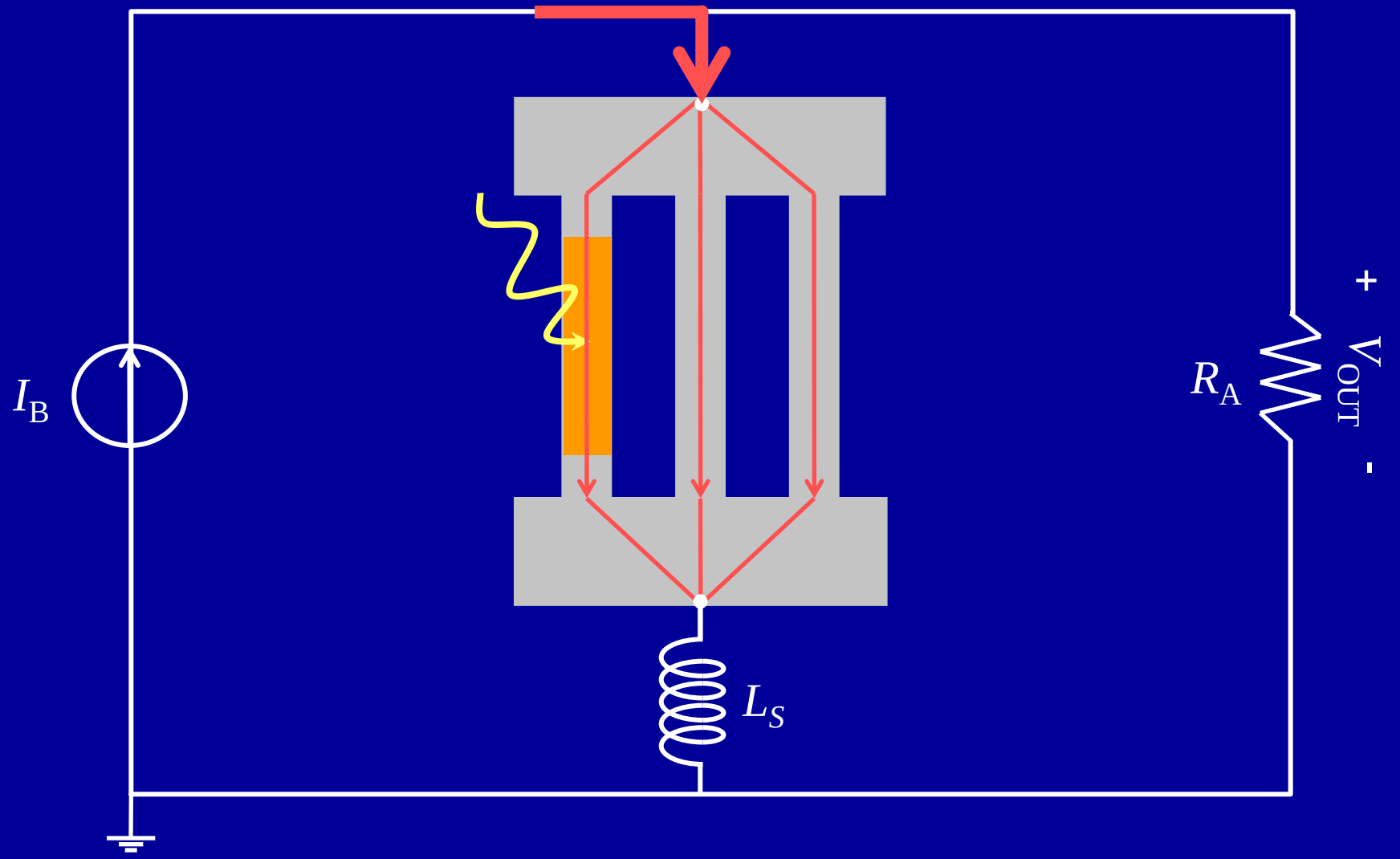
Superconducting Nanowire Avalanche Photodetectors (SNAPs)



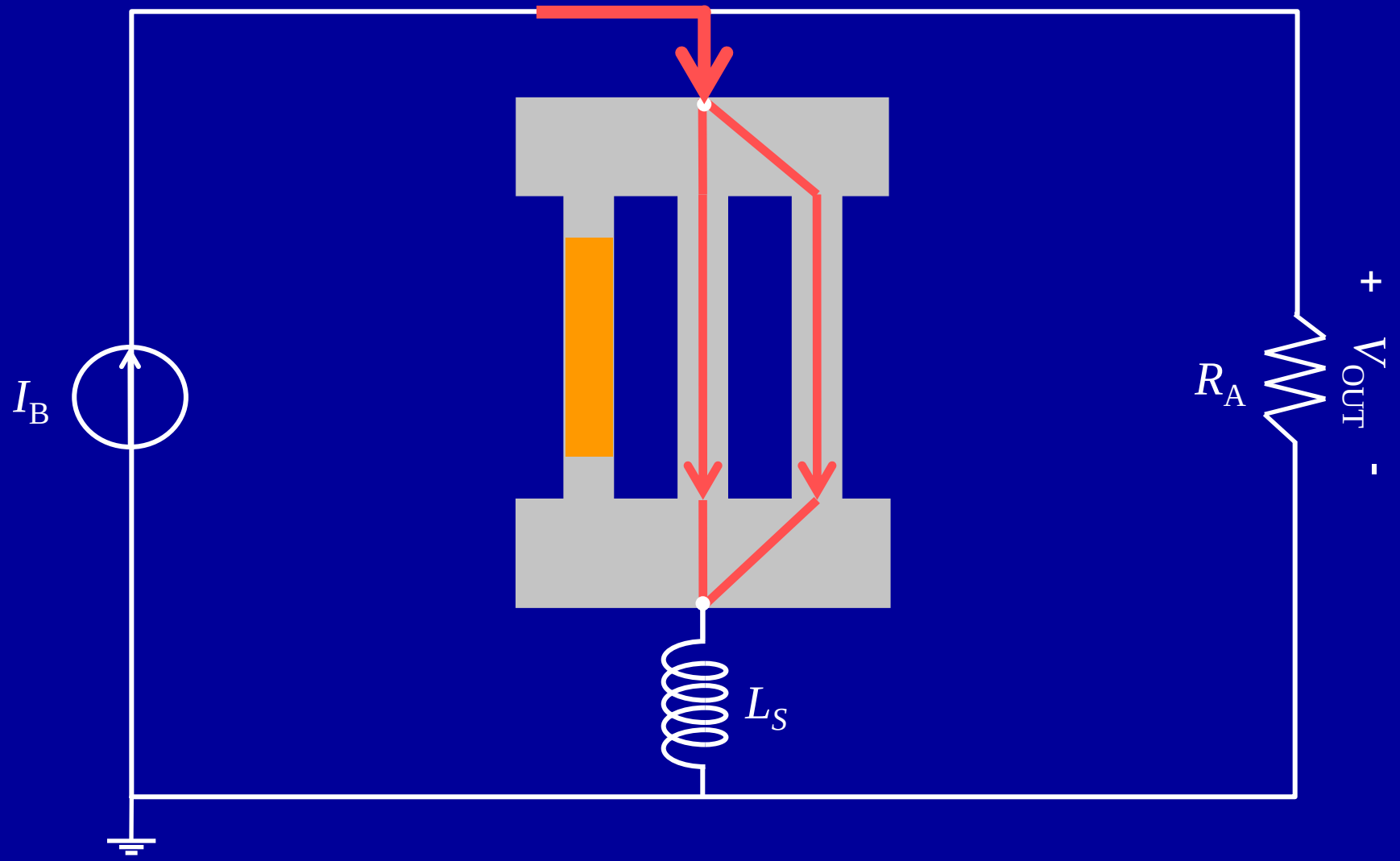
Basic model of SNAP operation



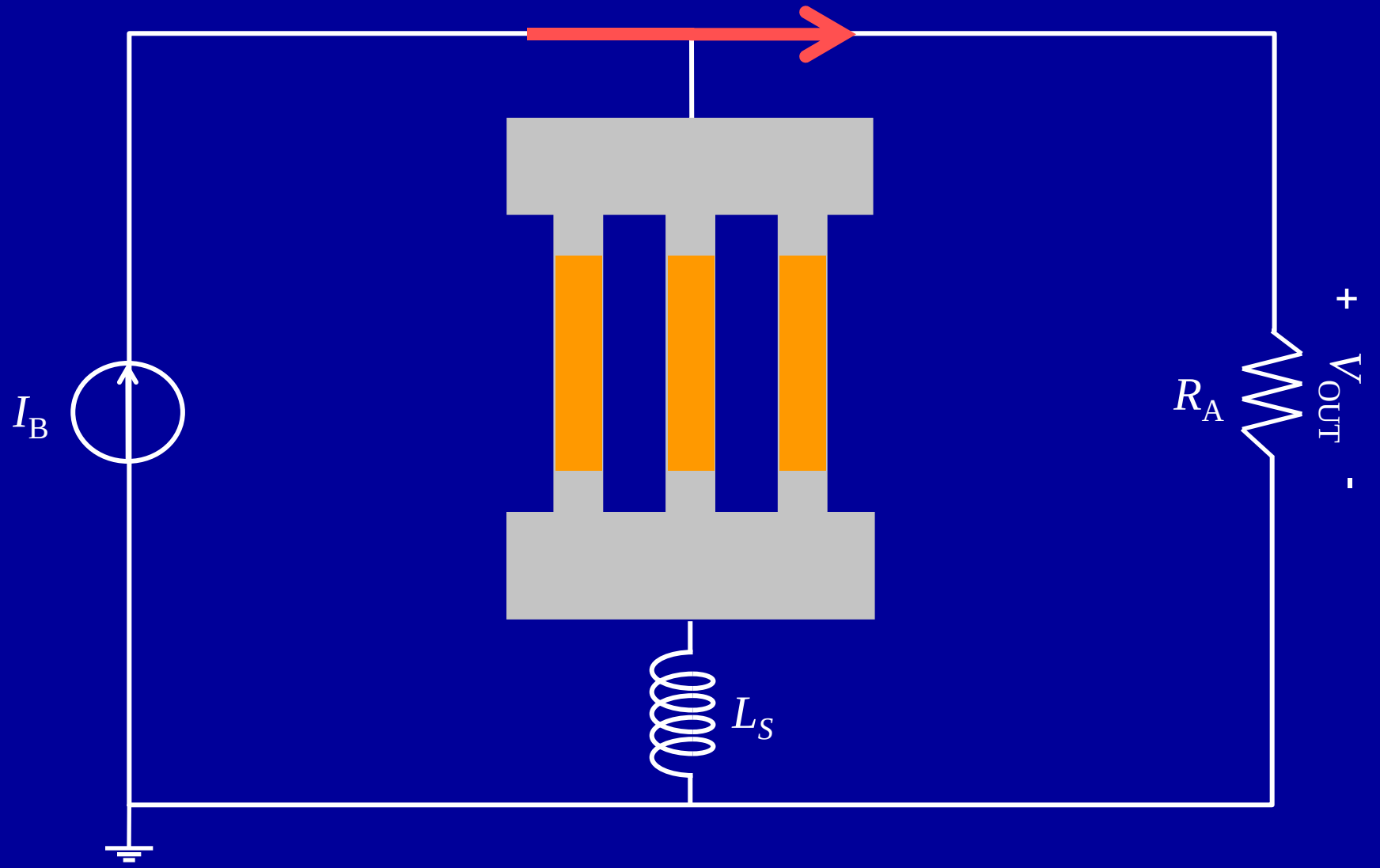
Basic model of SNAP operation



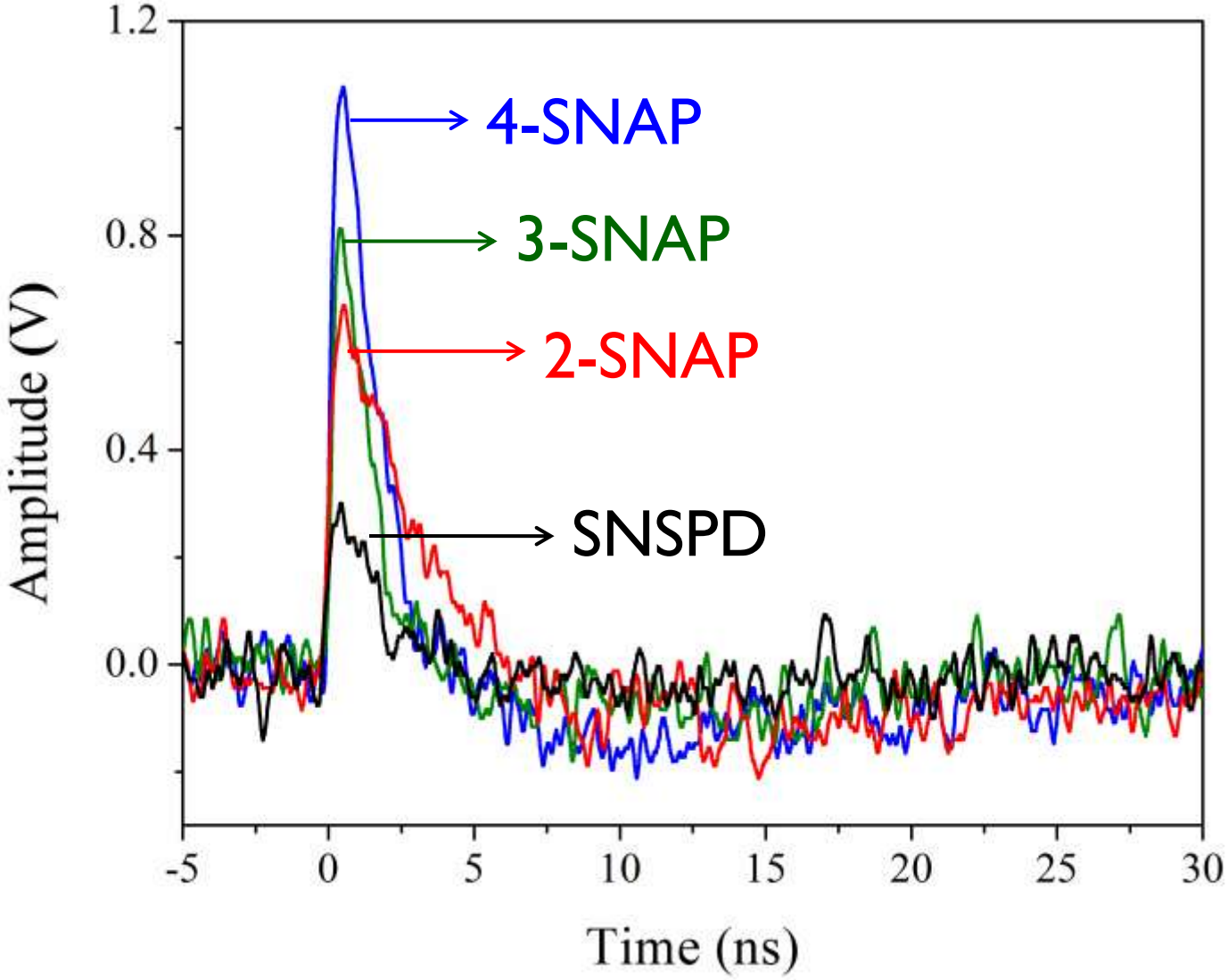
Basic model of SNAP operation



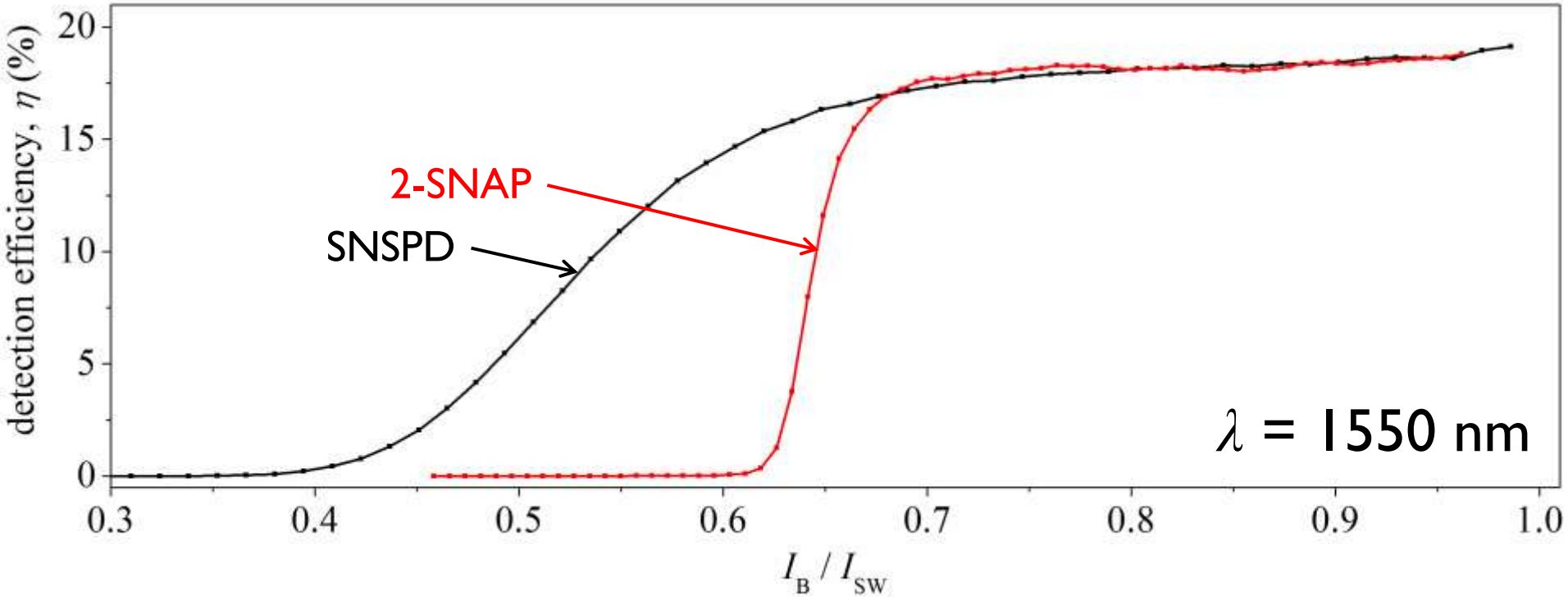
Basic model of SNAP operation



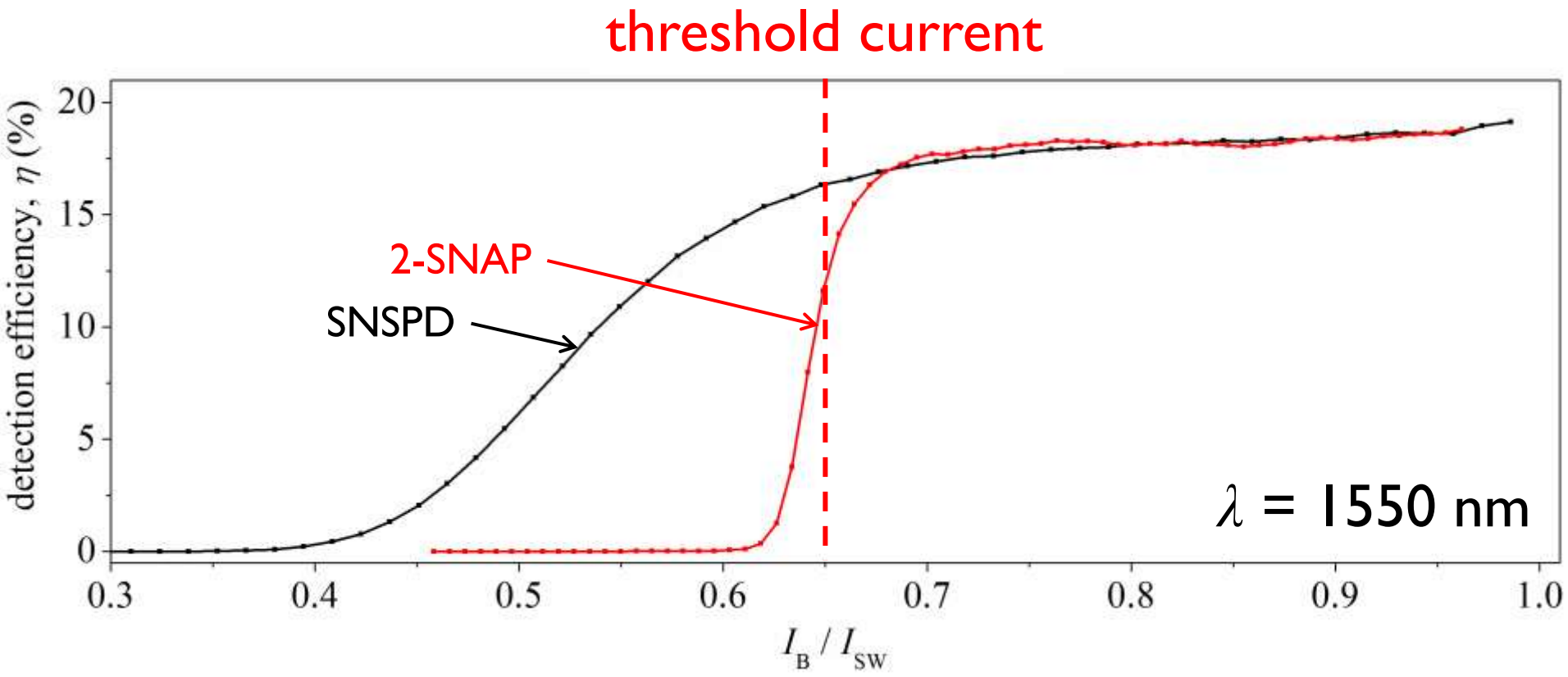
SNAPs improve the SNR



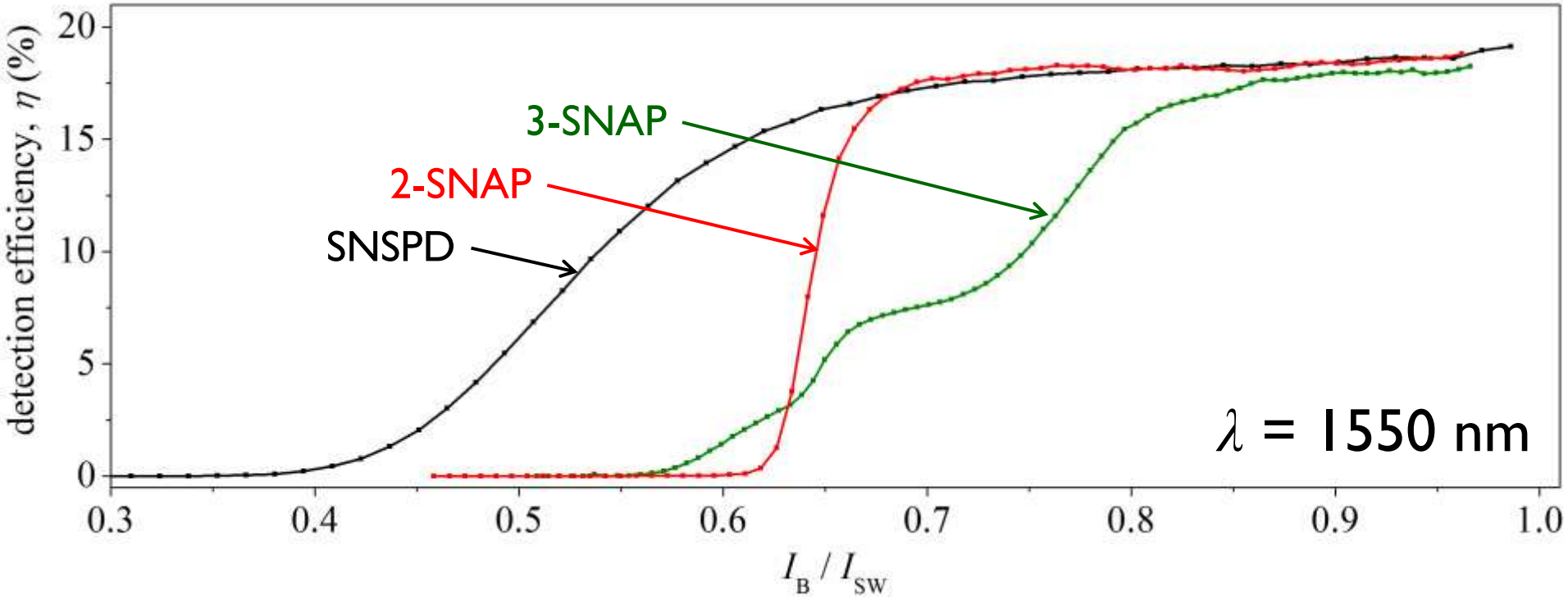
Experimental results



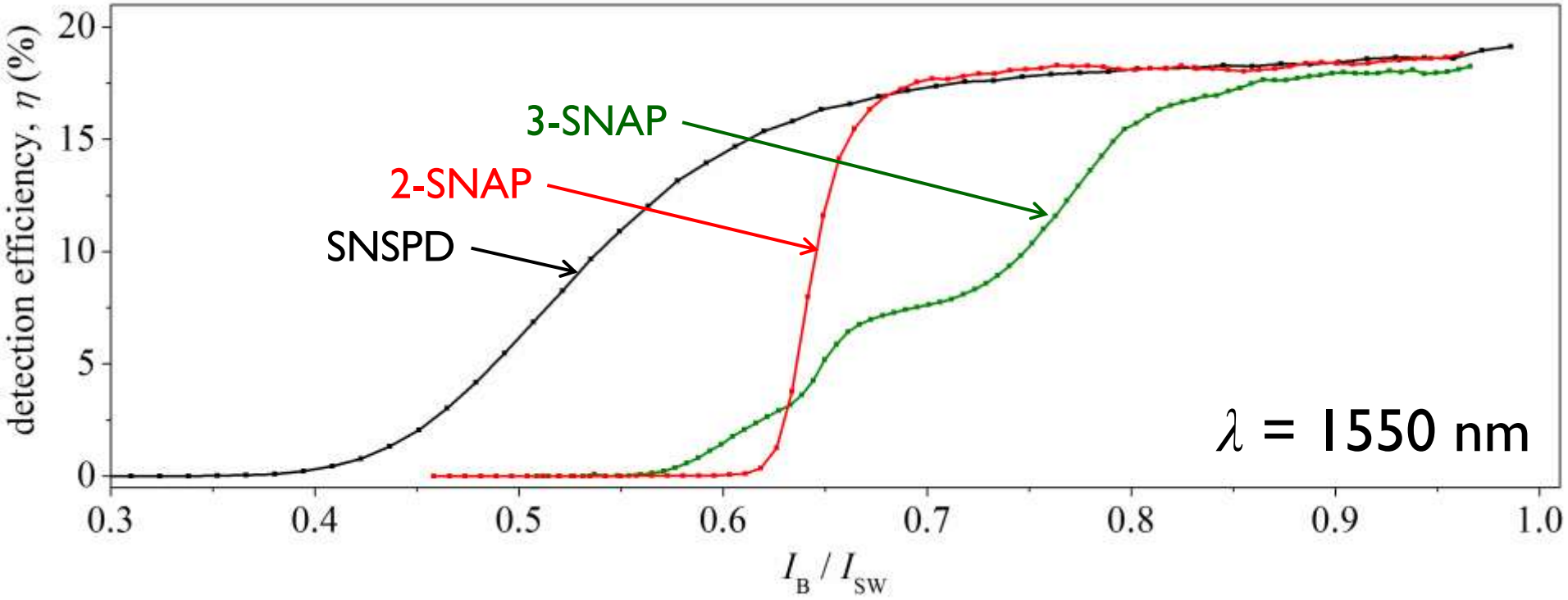
Experimental results



Experimental results

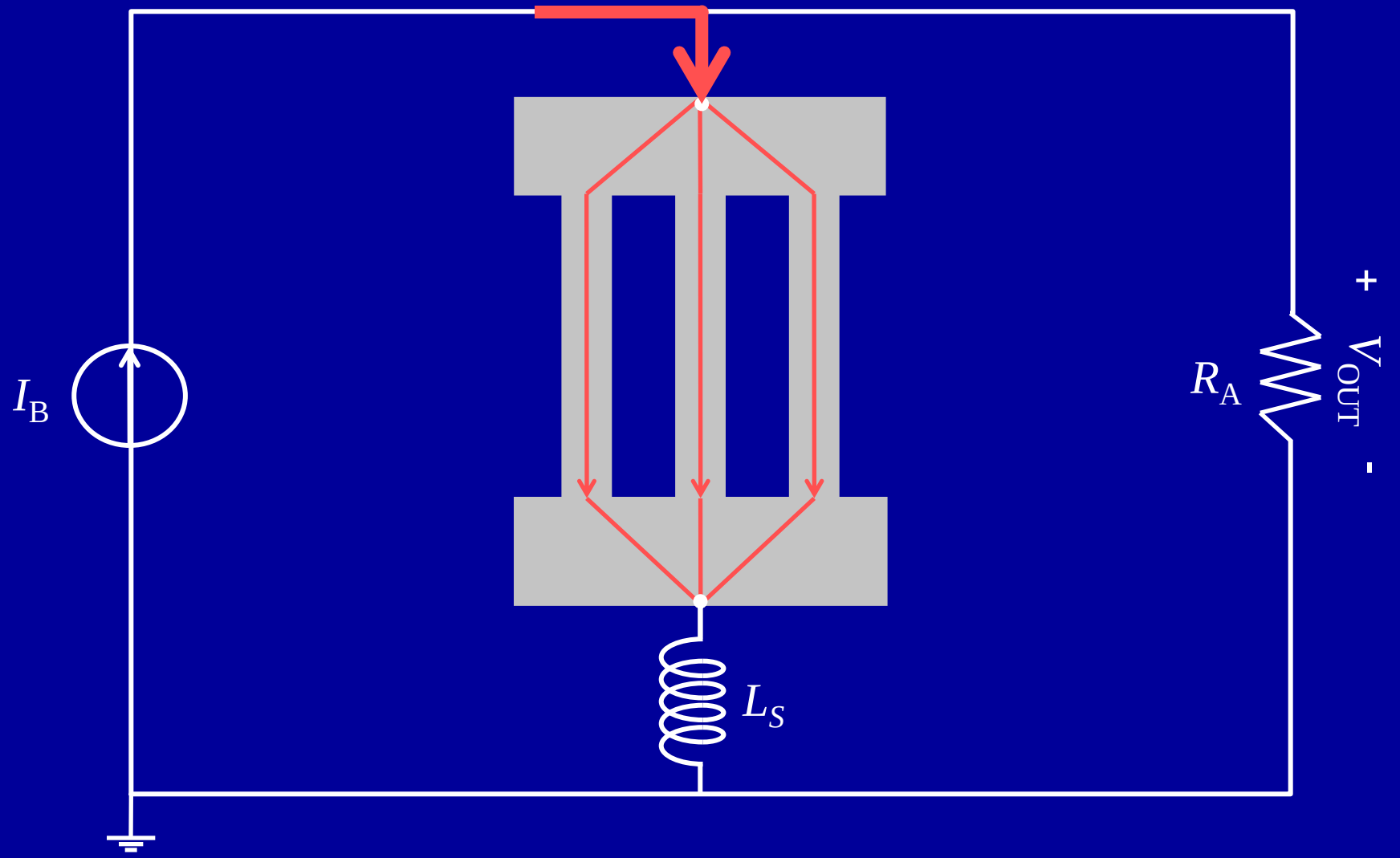


Experimental results

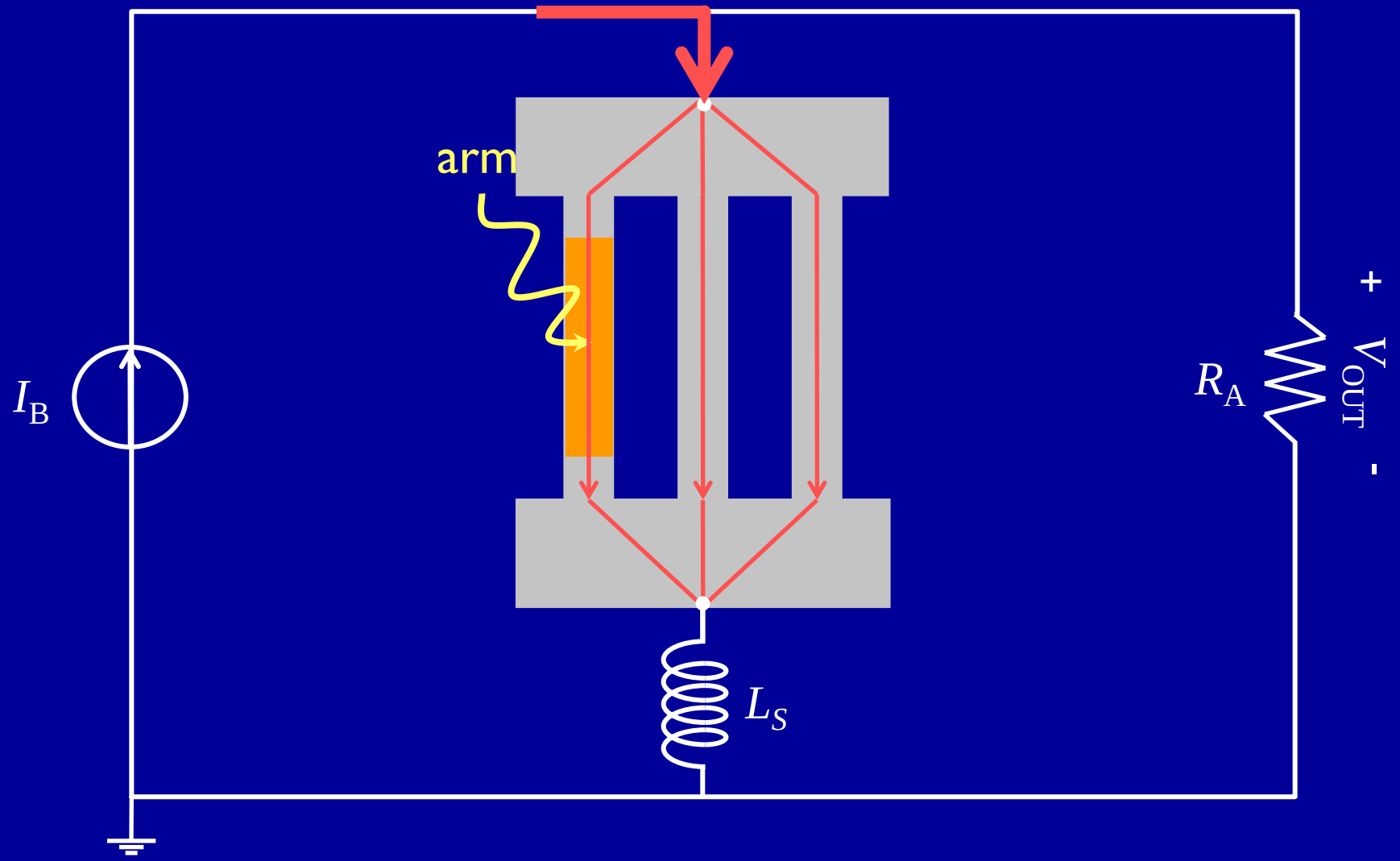


In which bias range are 3-SNAPs working as single-photon detectors?

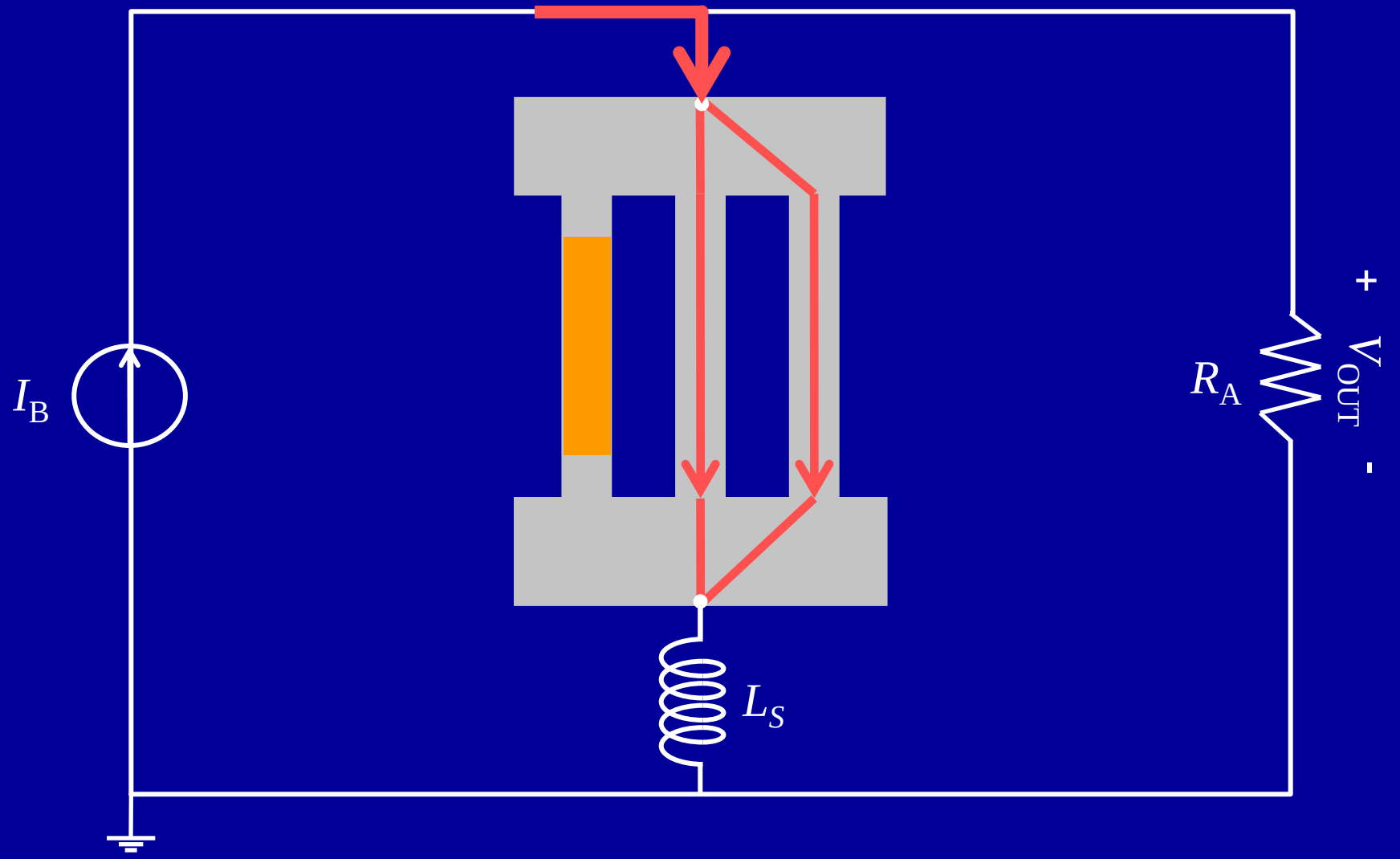
SNAP operation below the avalanche current



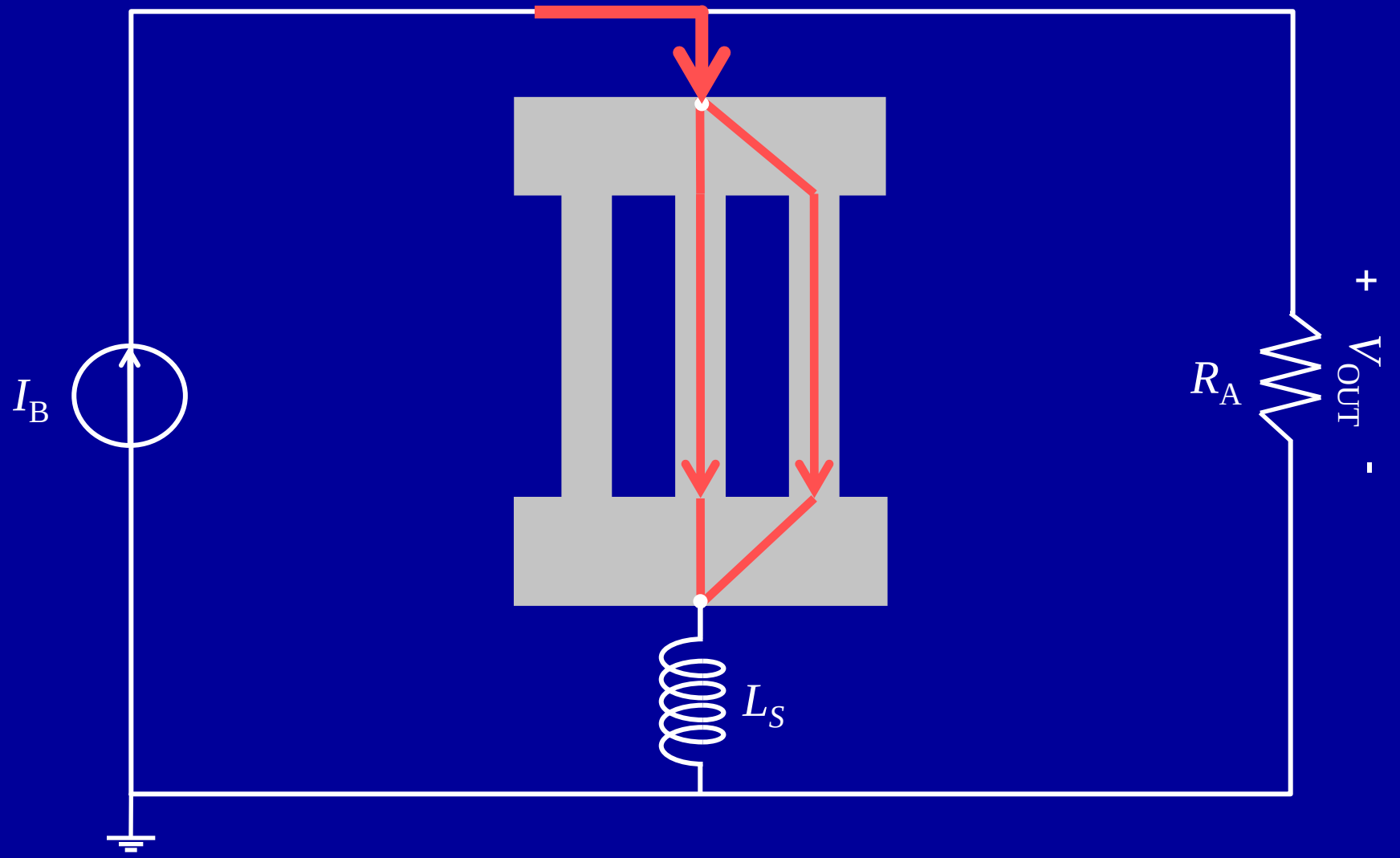
SNAP operation below the avalanche current



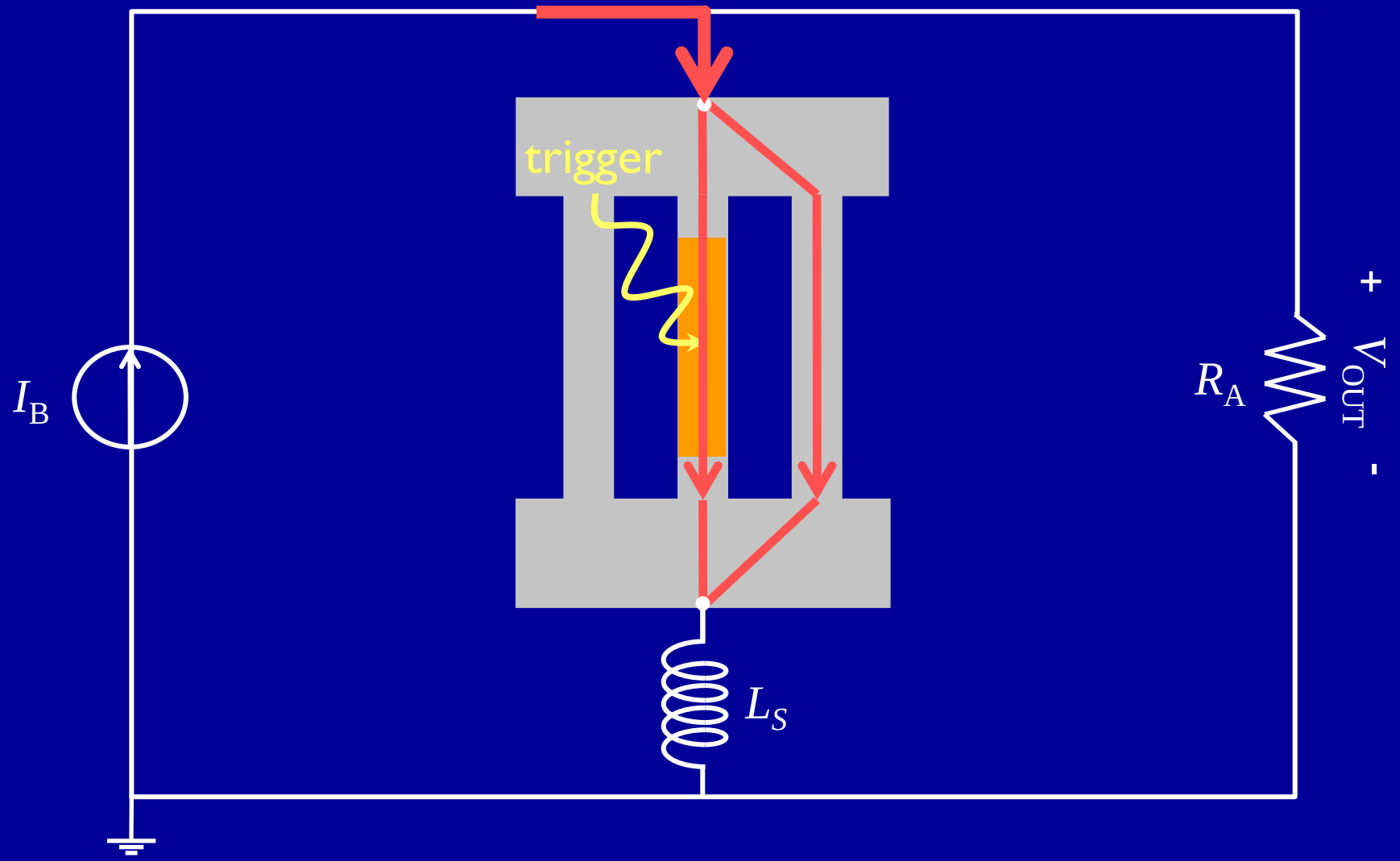
SNAP operation below the avalanche current



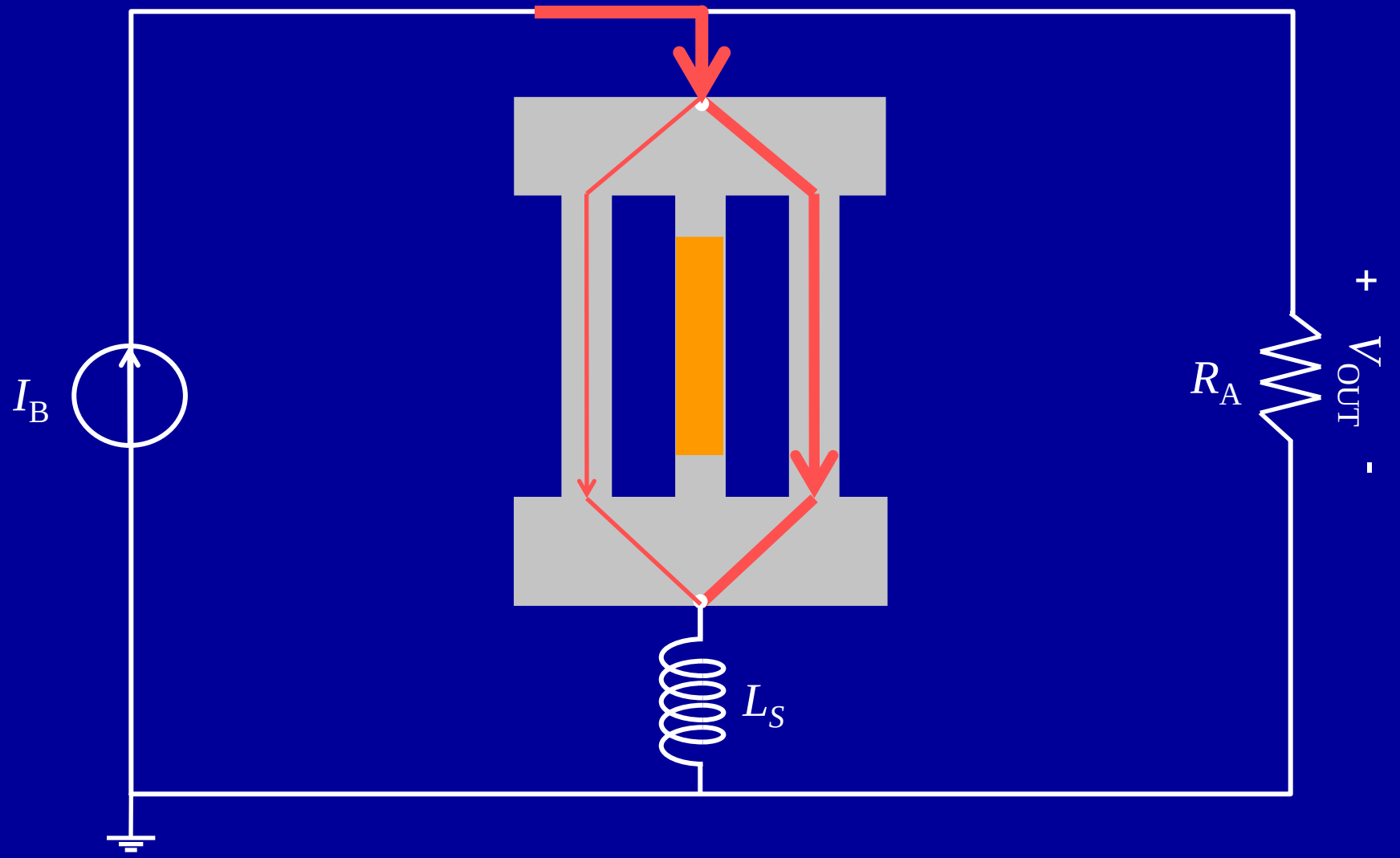
SNAP operation below the avalanche current



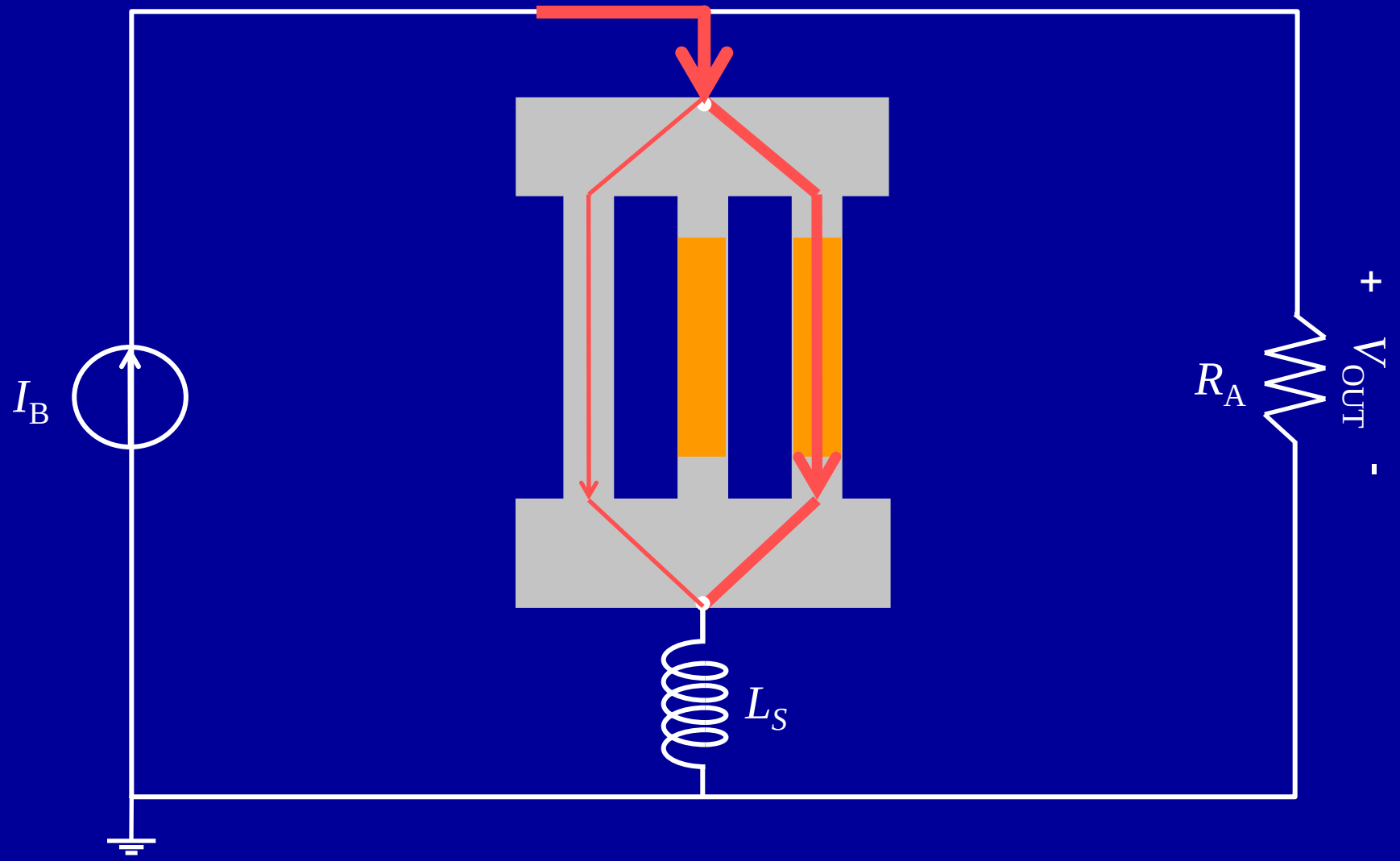
SNAP operation below the avalanche current



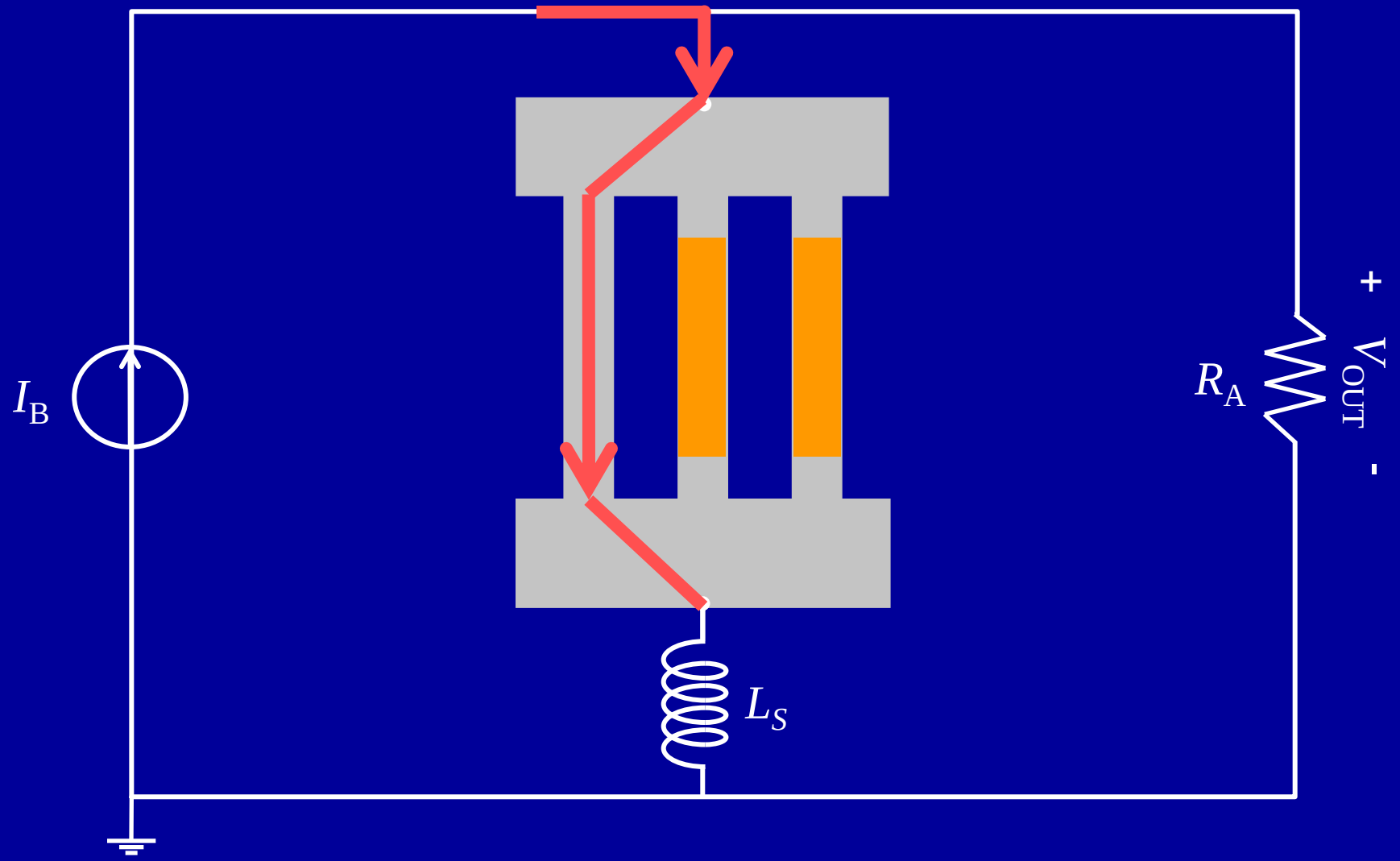
SNAP operation below the avalanche current



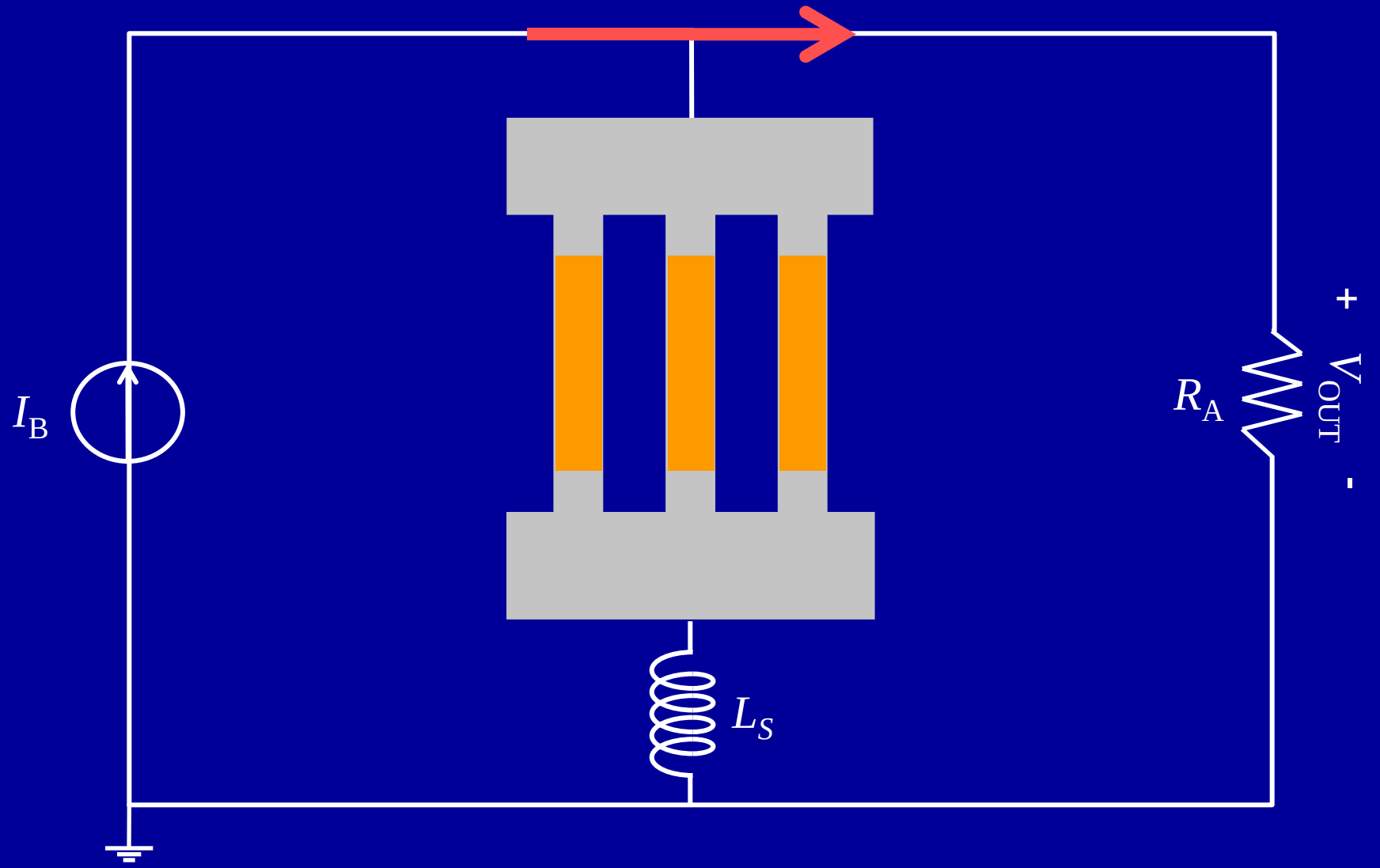
SNAP operation below the avalanche current



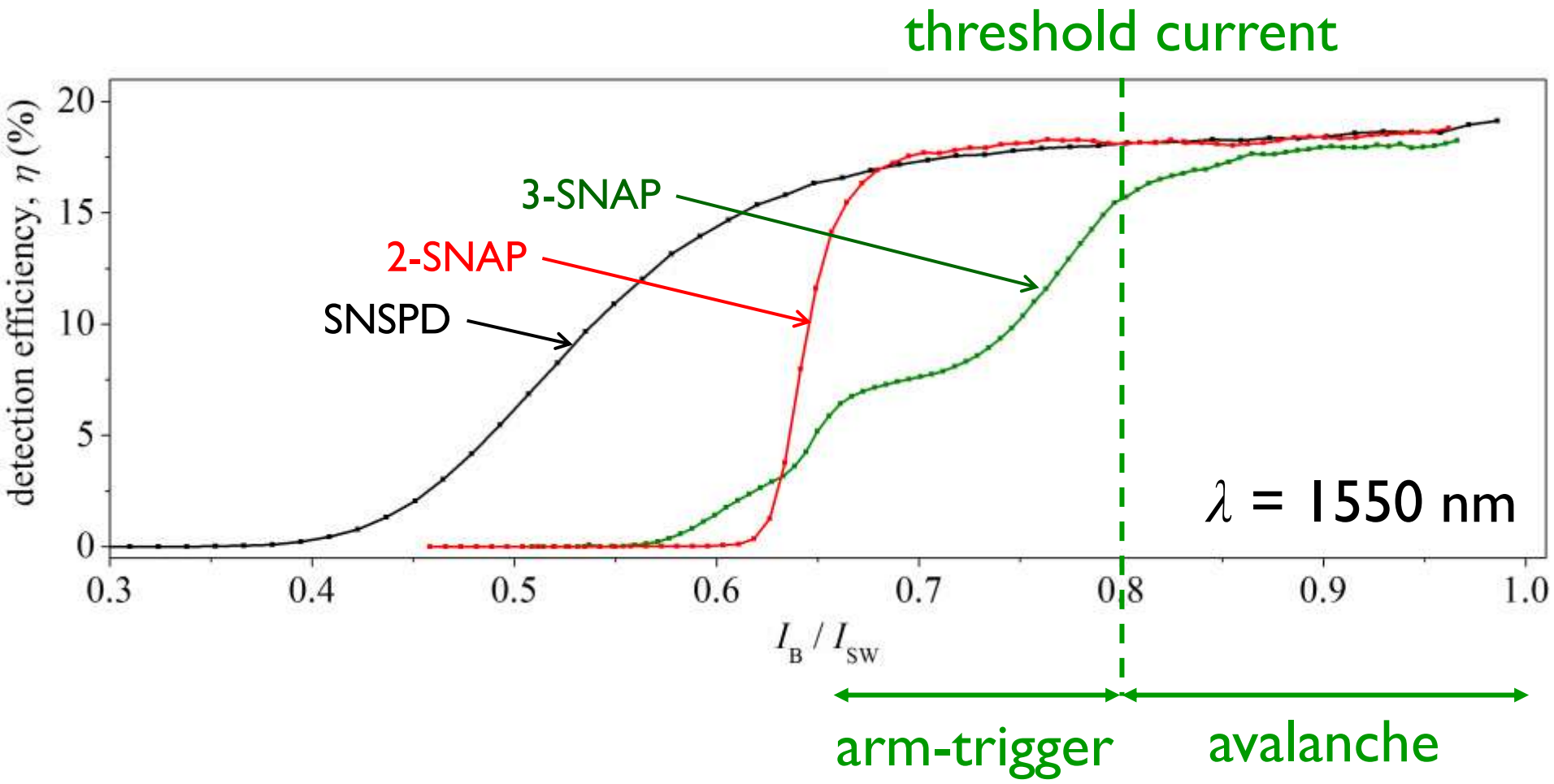
SNAP operation below the avalanche current



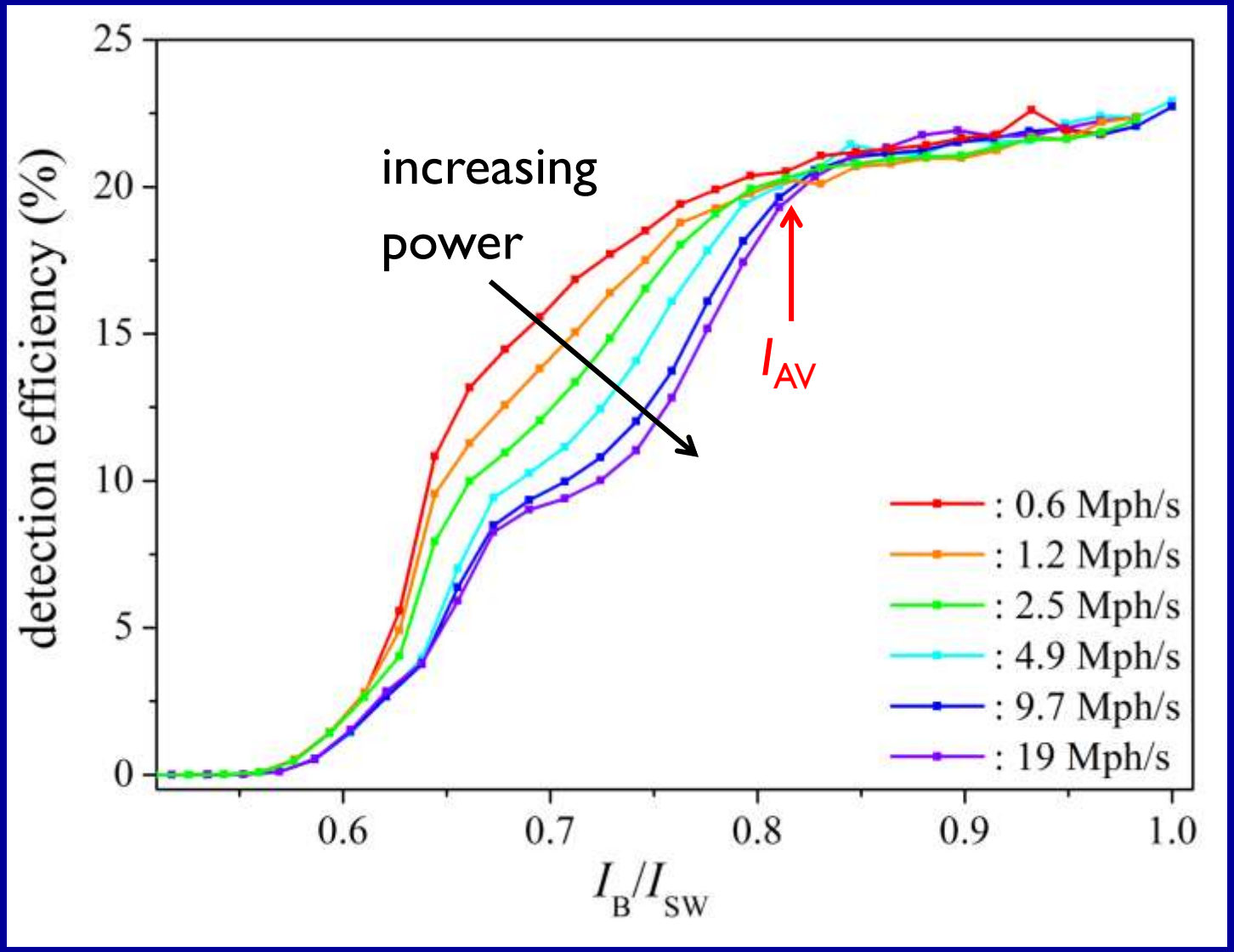
SNAP operation below the avalanche current



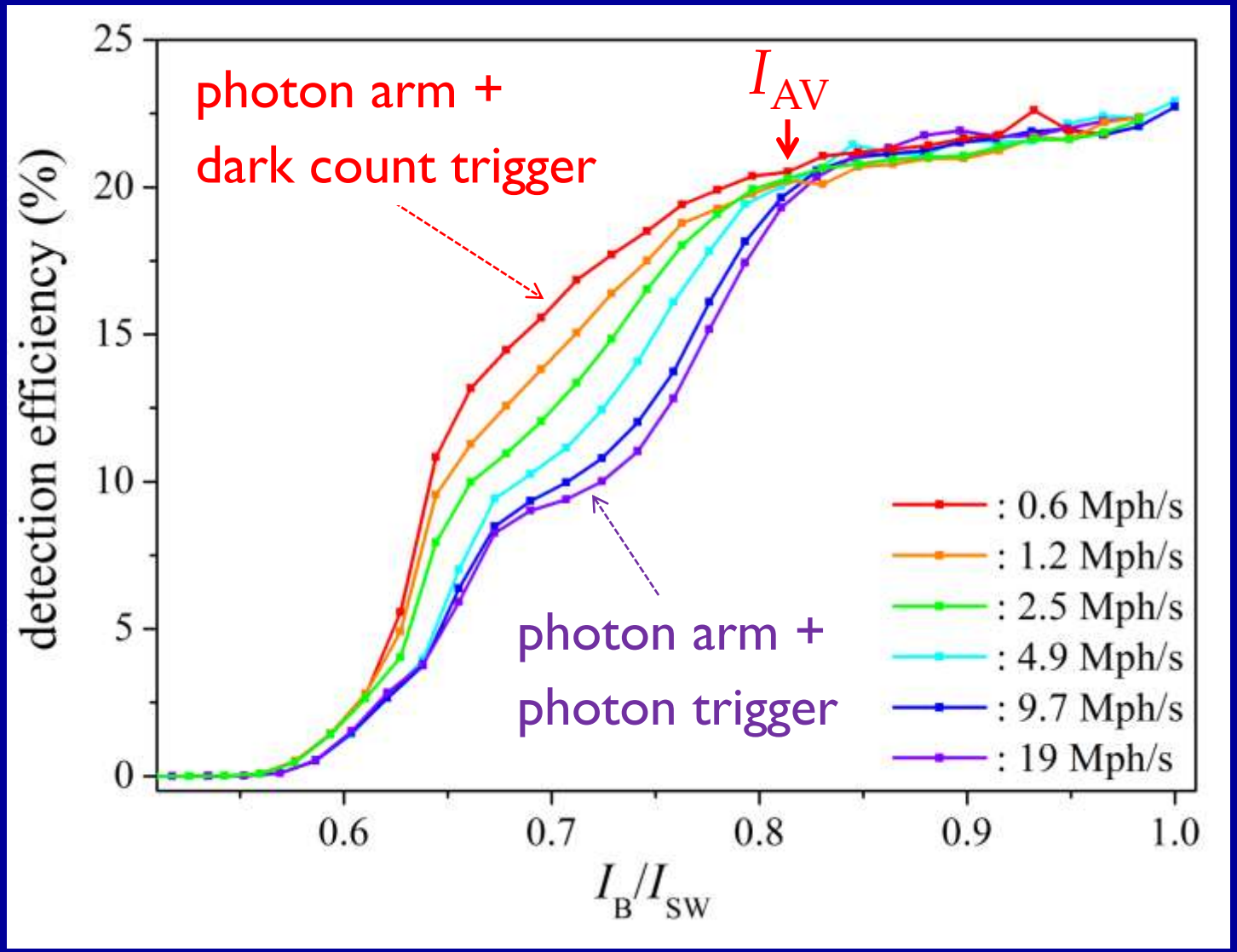
Experimental results



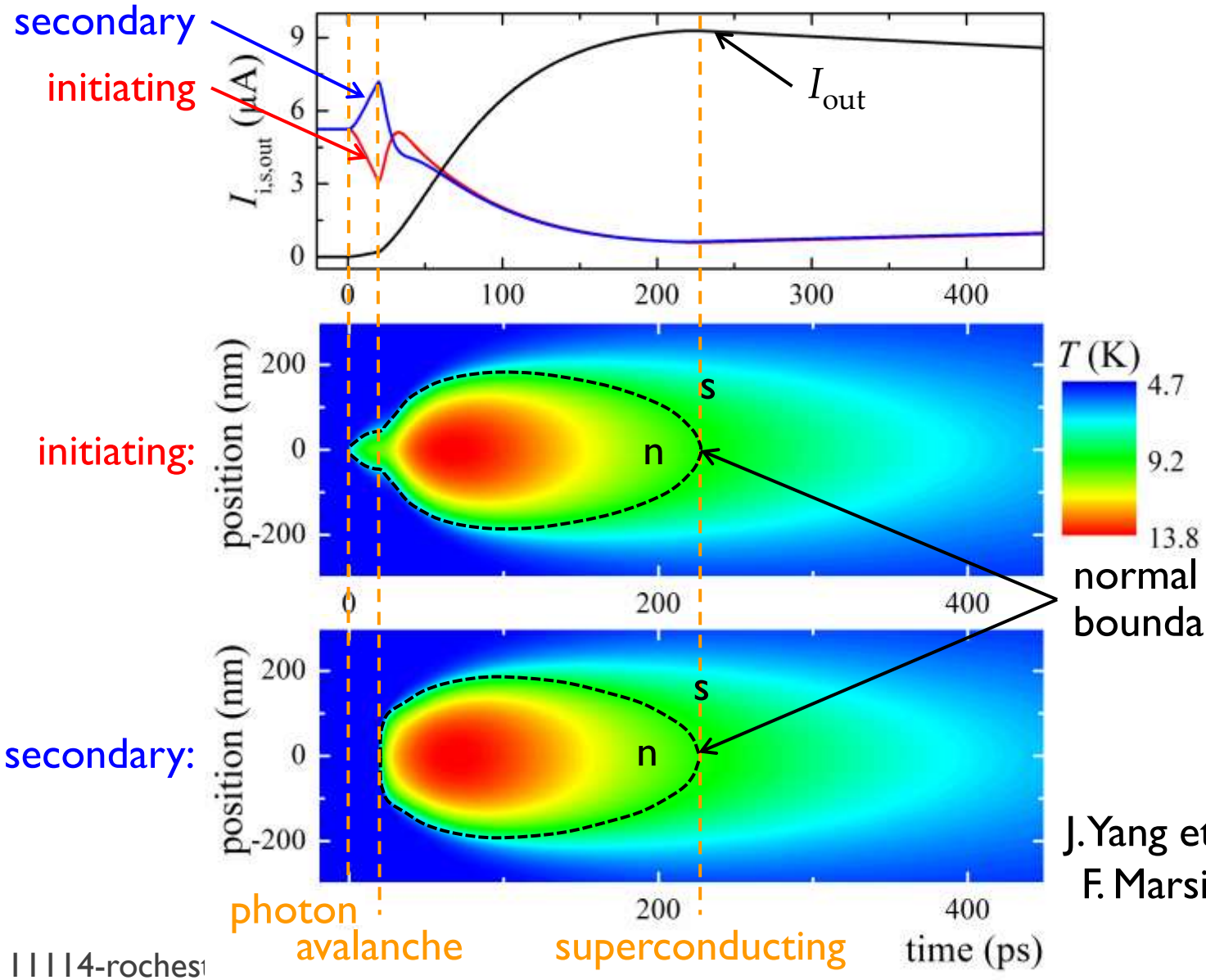
η Power Dependence Explained



η Power Dependence Explained

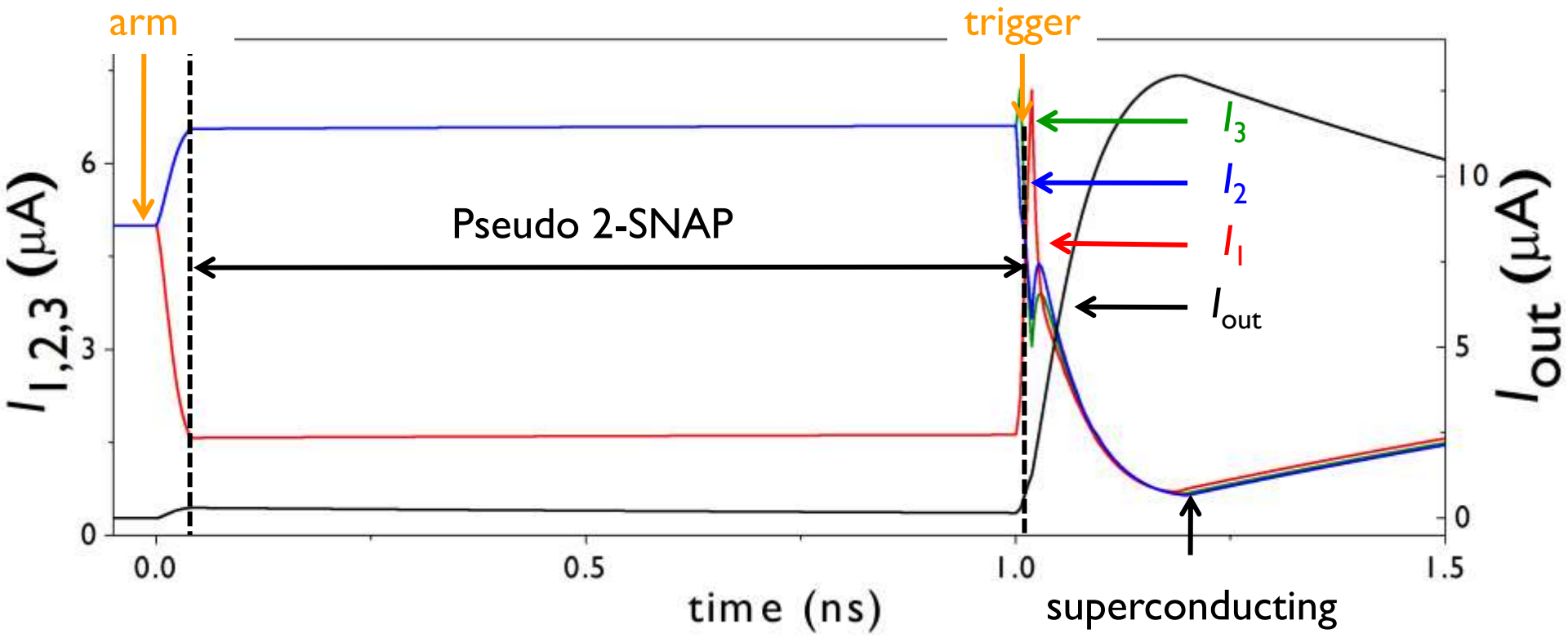


Electro-thermal simulation of SNAPs



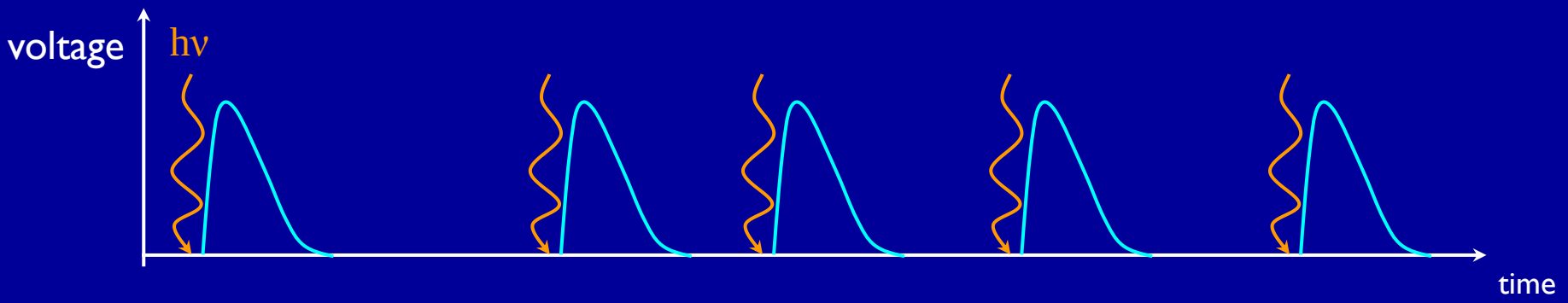
J. Yang et al. IEEE TAS (2007)
F. Marsili *et al.*, APL (2011)

3-SNAP in "arm-trigger" regime



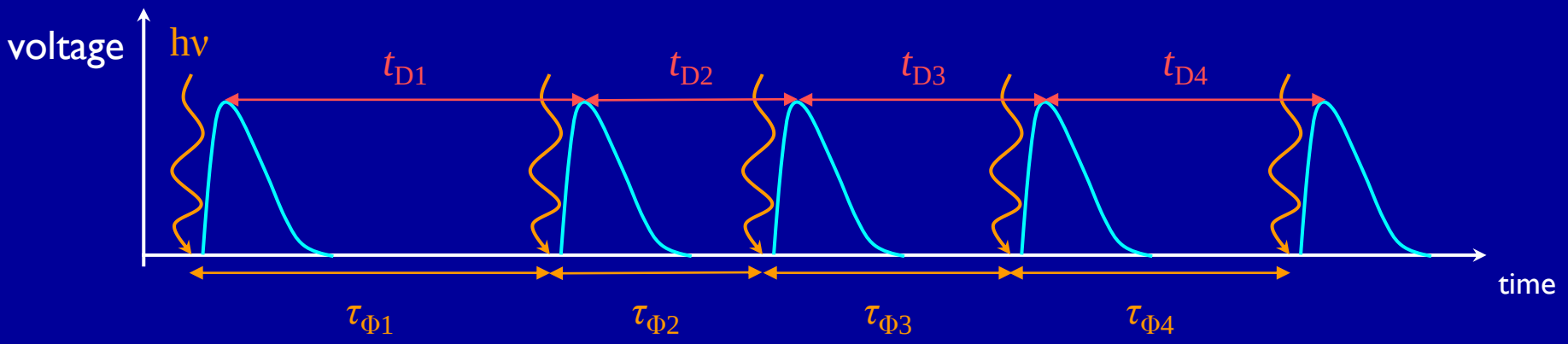
Inter-arrival time measurements

Avalanche mode:



Inter-arrival time measurements

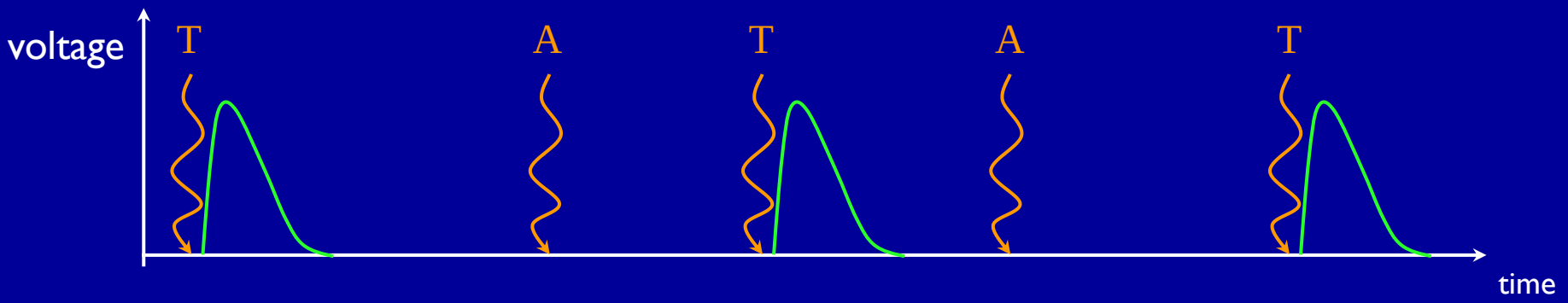
Avalanche mode:



$$f_{t_D}(t) = f_{\tau_\Phi}(t)$$

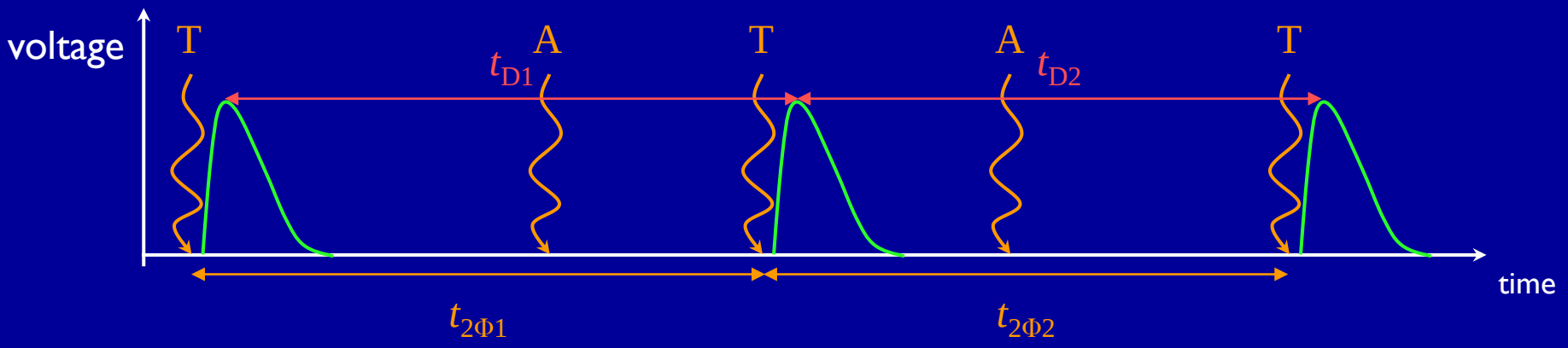
Inter-arrival time measurements

Arm-trigger mode:



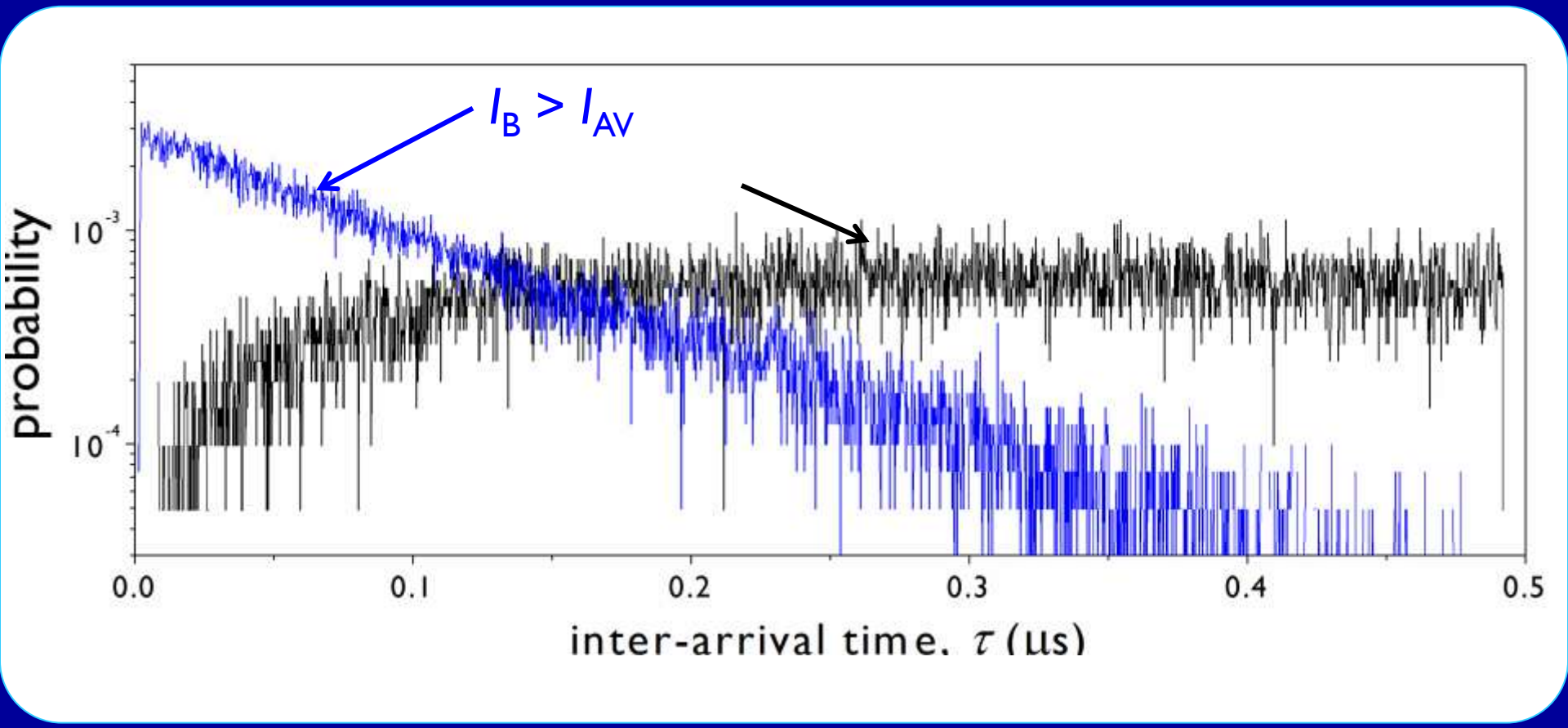
Inter-arrival time measurements

Arm-trigger mode:



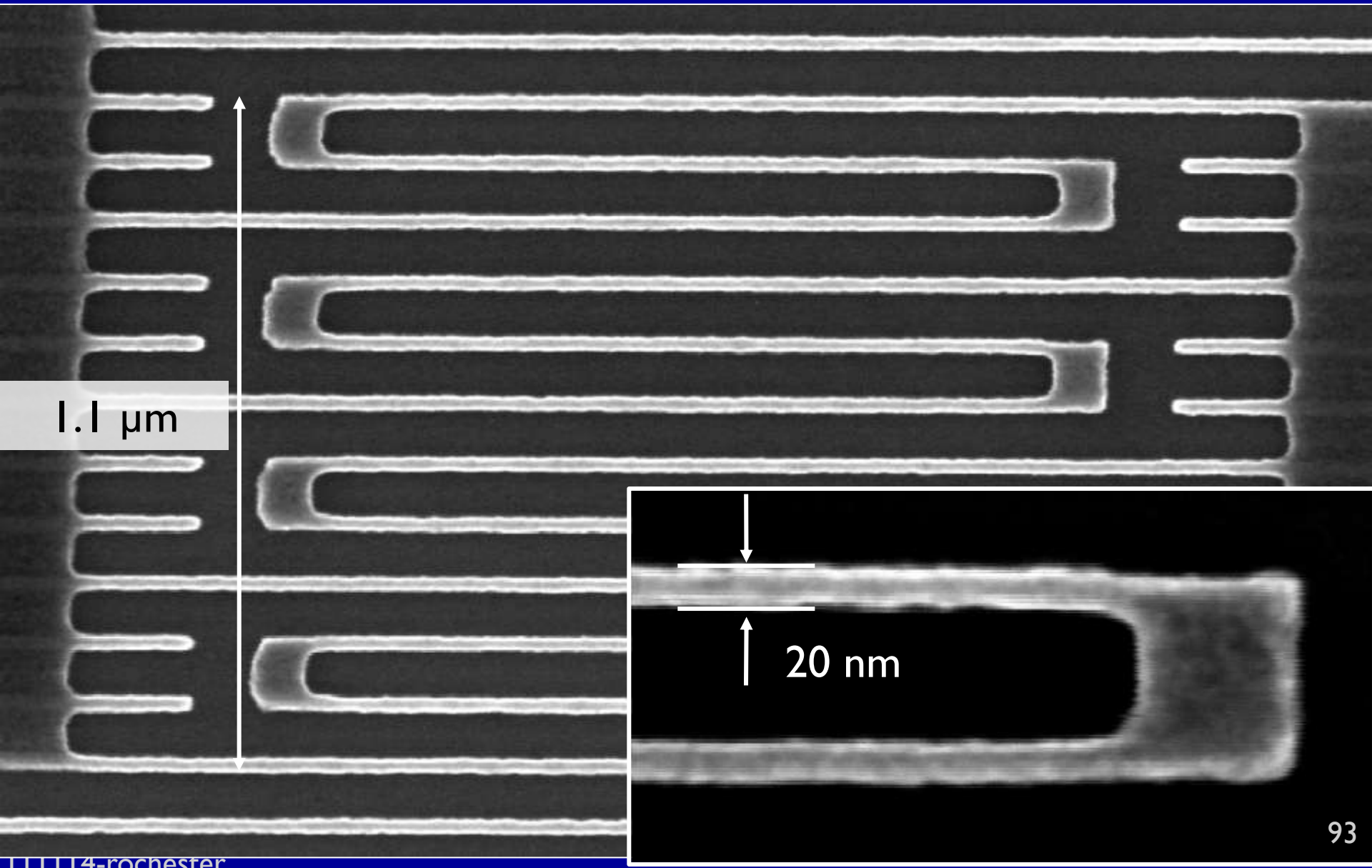
$$f_{t_D}(t) = f_{\tau_{2\Phi}}(t)$$

Inter-arrival time histograms

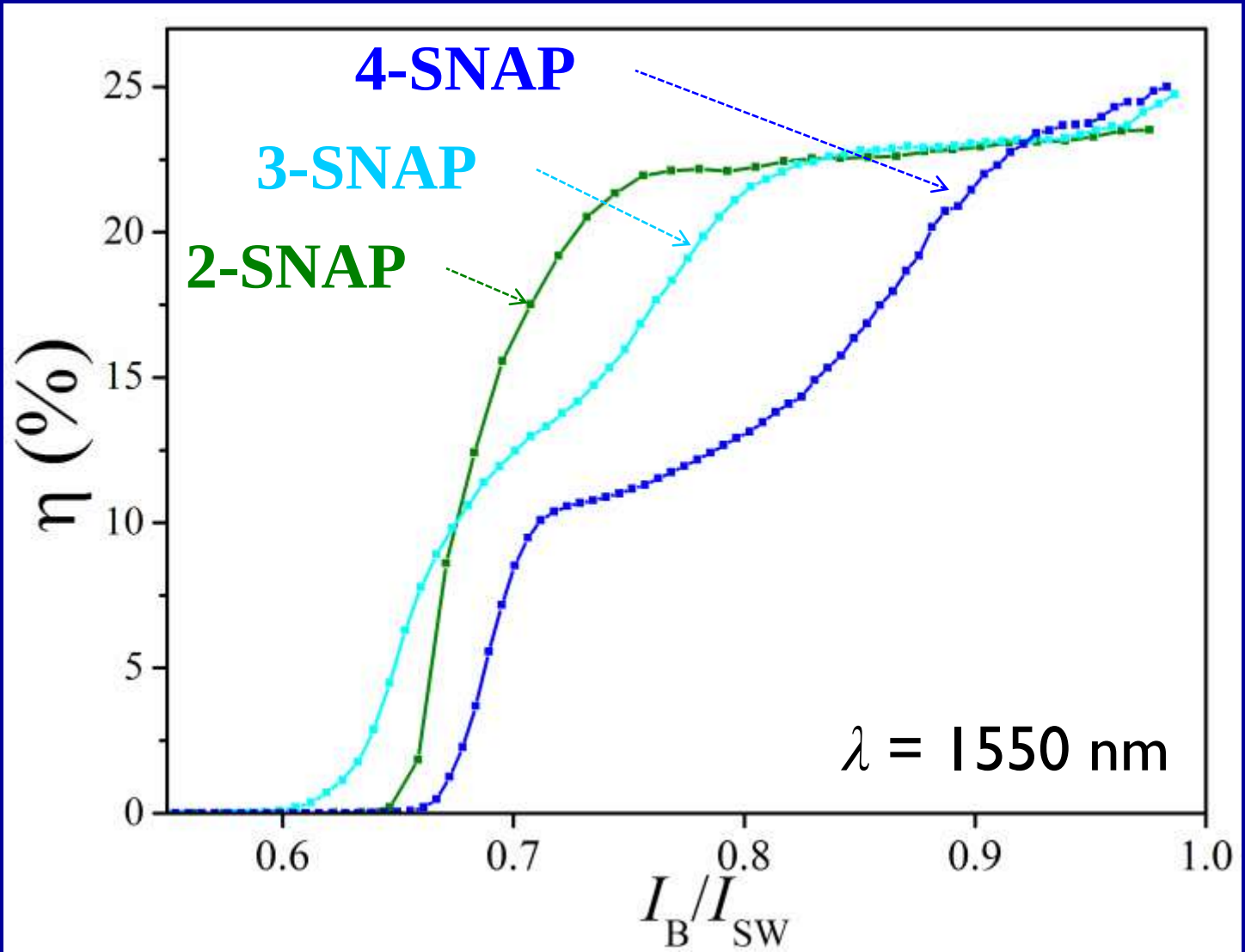


F. Marsili *et al.*, Nanolett. (2011)

20-nm-wide-nanowire SNAPs

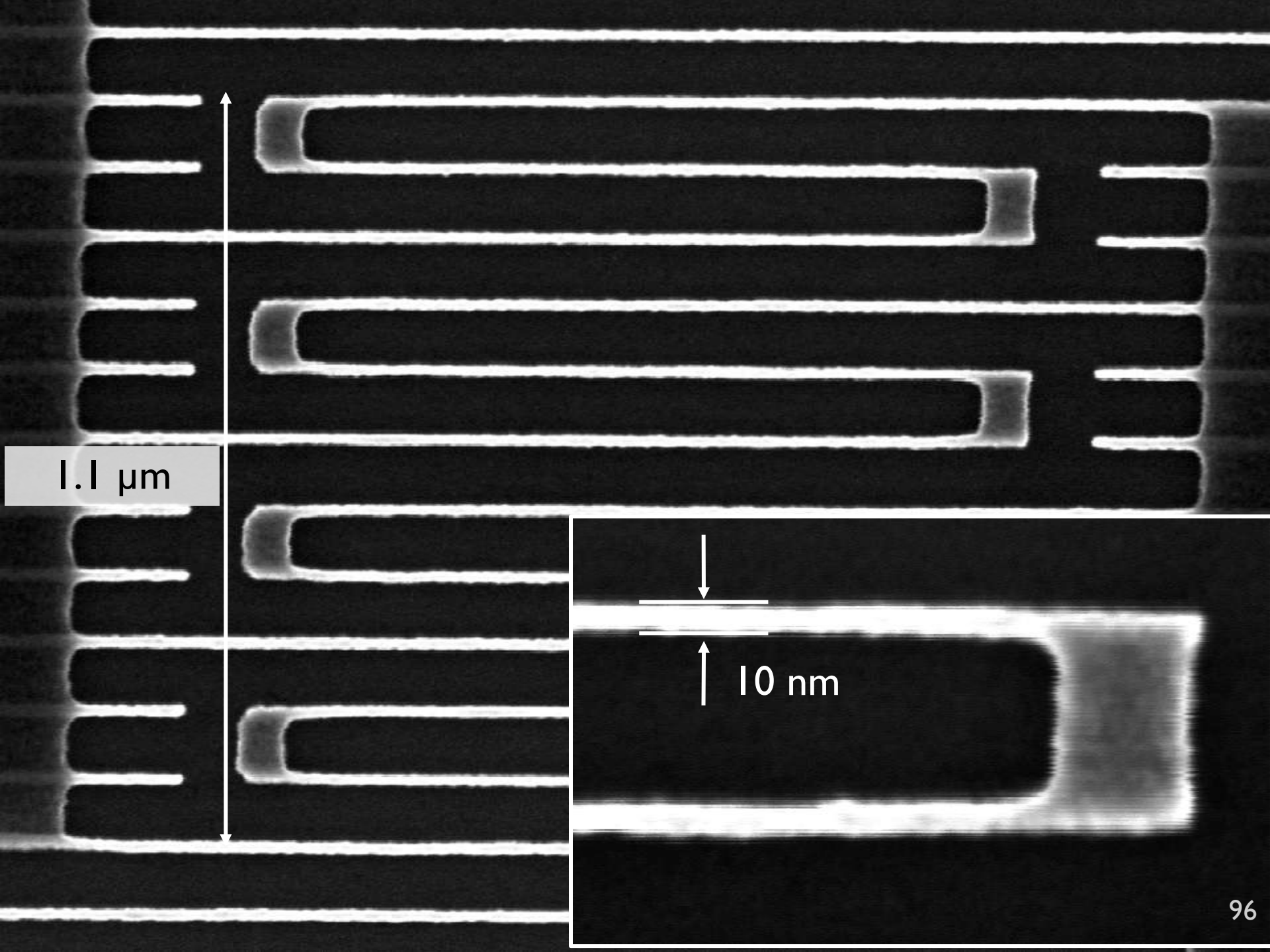


20-nm-nanowire-width SNAPs



The Future

- Scaling sensitivity out to longer wavelengths
  - (is high-efficiency single-photon detection possible at 10 um?)
- Understanding the source of jitter
  - Intrinsic to material? Electronic? Thermal? Electro-thermal?
  - Dependent on design/architecture? Engineerable?
- Can we break the 1 ns speed limit?
  - Need to investigate new materials
  - Need to investigate new device designs
- Is near-100% efficiency possible?


1.1 µm
10 nm

Acknowledgements

MIT Quantum Nanostructures and Nanofabrication Group
Vikas Anant (now at PhotonSpot)
Francesco Bellei
Andrew Dane
Eric Dauler (Lincoln Lab Fellow, now at Lincoln Laboratory)
Charles Herder (undergraduate)
Xiaolong Hu (now at U. of Michigan)
Hasan Korre
Francesco Marsilli (post-doc, now at NIST)
Faraz Najafi
Kristen Sunter
Joel Yang (ASTAR Fellowship, now at A*STAR)

MIT Lincoln Laboratory
Eric Dauler
Andrew J. Kerman
Richard Molnar
Bryan Robinson
Scott Hamilton

NIST
Martin J. Stevens
Burm Baek
Sae Woo Nam
Richard P. Mirin

Other Collaborators
M. Csete (U. of Szeged)
Boris Voronov (MSPU)
Gregory Gol'tsman (MSPU)

Sponsors
AFOSR, IARPA, DARPA, NASA, NSF

END OF PRESENTATION