Towards Cosmic Neutrino Background detection

Symposium on the PTOLEMY project

23 Ottobre 2019 ore 14:00 - Dipartimento di Fisica - Aula Caianiello

Superconducting Nanowire Single Photon Detectors

SNSPDs

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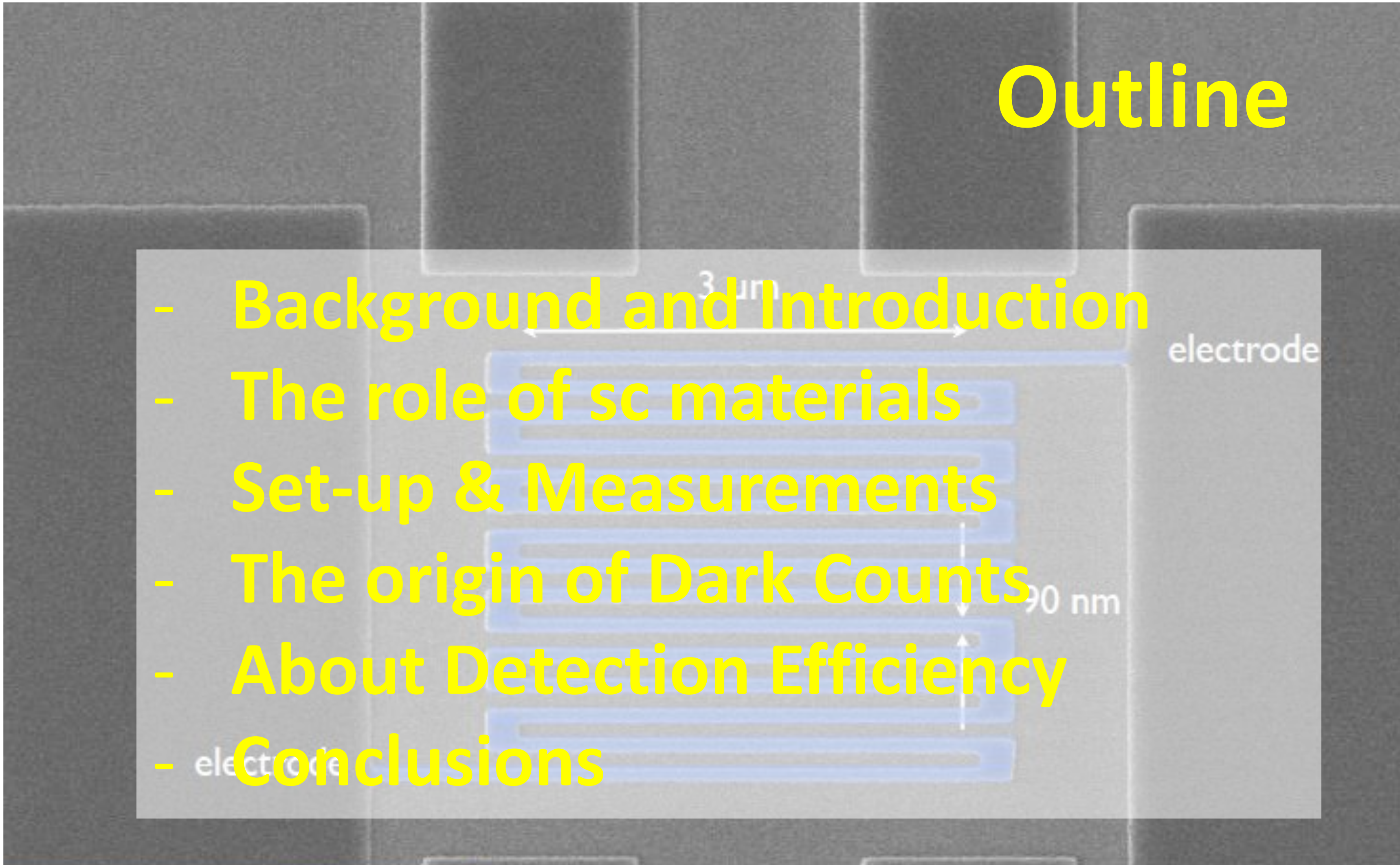
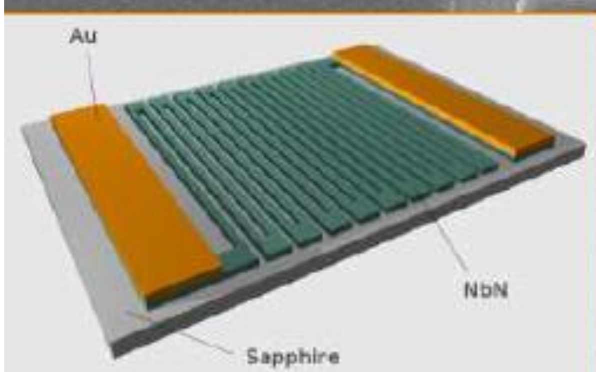
Outline

- Background and Introduction
- The role of sc materials
- Set-up & Measurements
- The origin of Dark Counts
- About Detection Efficiency
- Conclusions





Yang et al., IEEE TAS (2005)

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

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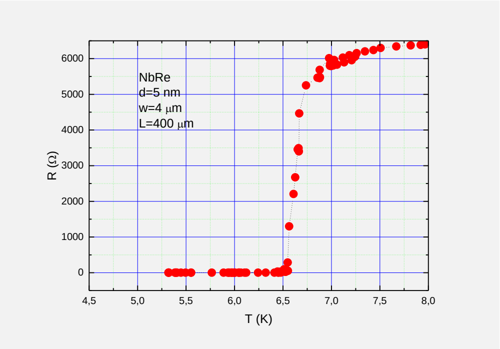
PTOLEMY Meeting
Napoli 2019

Advantages of superconductive detectors

large number of quasiparticle creation by Cooper-pair breaking



- sharp normal - superconductor transition
- low heat capacitance
- kinetic inductance change
- wide choice of materials (A,Z,…..)

- Superheated Superconducting Granules: **SSG**
- Transition Edge Sensors: **TES**
- Hot Electron Superconducting Photodetectors: **HESP**
- Superconducting Tunnel Junctions: **STJ**
- Josephson Junctions: **JJ**

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Photon Detectors

Semiconductors

a) One optical photon creates only one electron-hole pair (typical bandgap 1-2 eV)

b) At low temperatures, relaxation and response times are long.

Superconductors

a) One optical photon creates ~100–1000 excited electrons (superconducting gap ~ 2 meV for NbN)

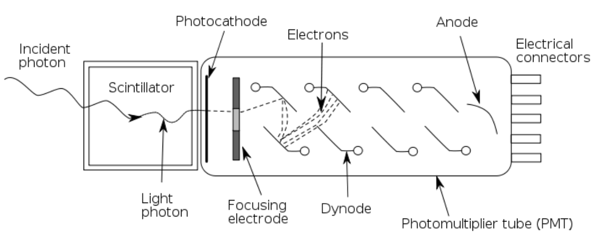
b) Relaxation is ultrafast even at low temperatures

Superconductivity is a macroscopic quantum phenomenon.

Low temperature environment reduces background noise and thermal fluctuations responsible for dark counts.

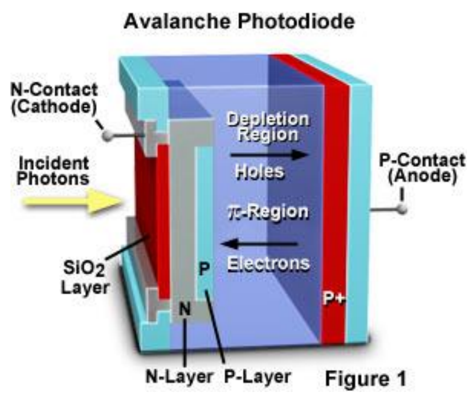
Single Photon Detectors (SPDs)

PMT



High Bias Voltage ~ KV

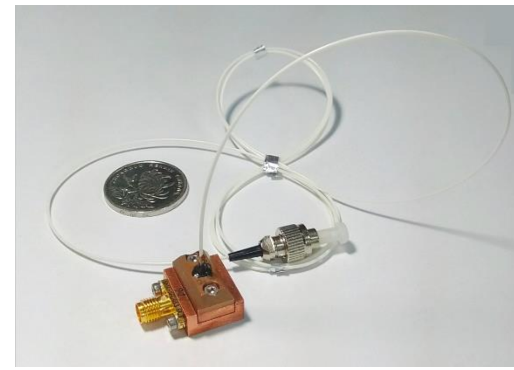
APD

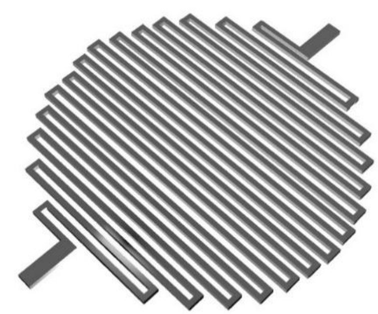


Voltage Bias : ~10V

SNSPD

Since 2001





Current Bias : ~ 10μA

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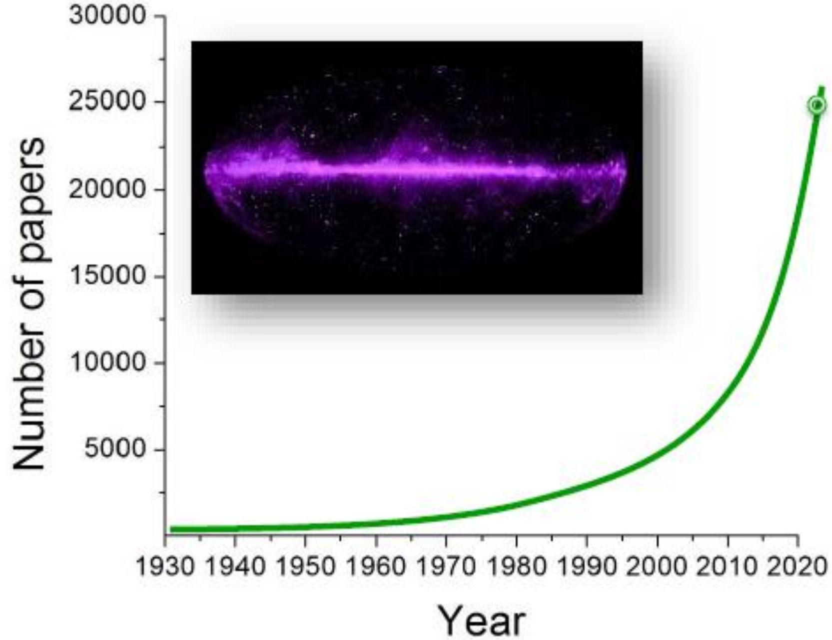
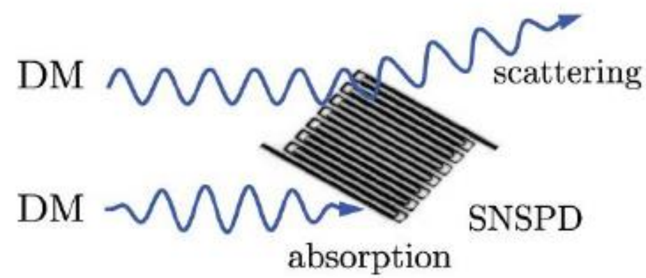
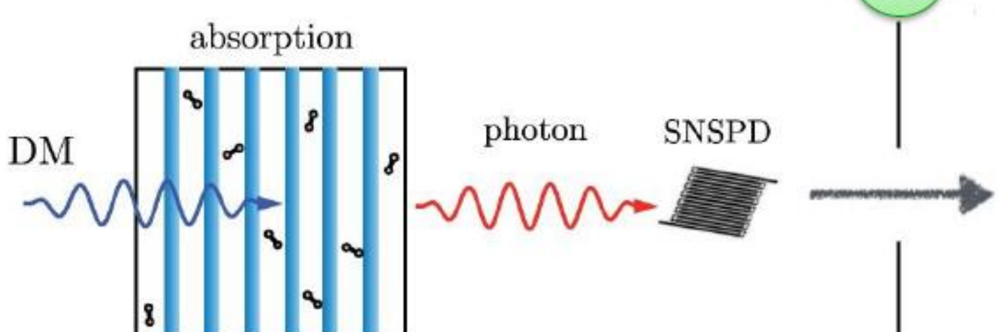
SNSPDs toward DM

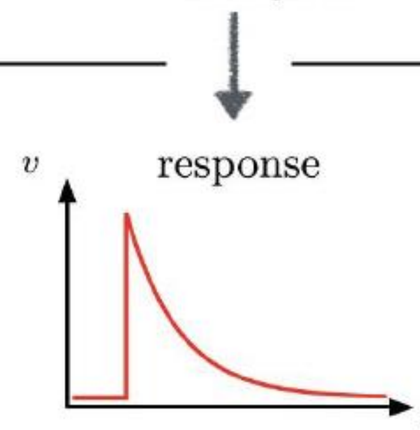
Mass ranging 10 meV – 10 eV



Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo and K. K. Berggren, "Detecting Dark Matter with Superconducting Nanowires," arXiv:1903.05101 [hep-ph], submitted to PRL







Masha Baryakhtar, Junwu Huang, Robert Lasenby, Phys.Rev. D98 (2018) no.3, 035006 (arXiv:1803.11455)

Courtesy of I Charaev, LTD20

Dark-Matter Searching using superconducting nanowire

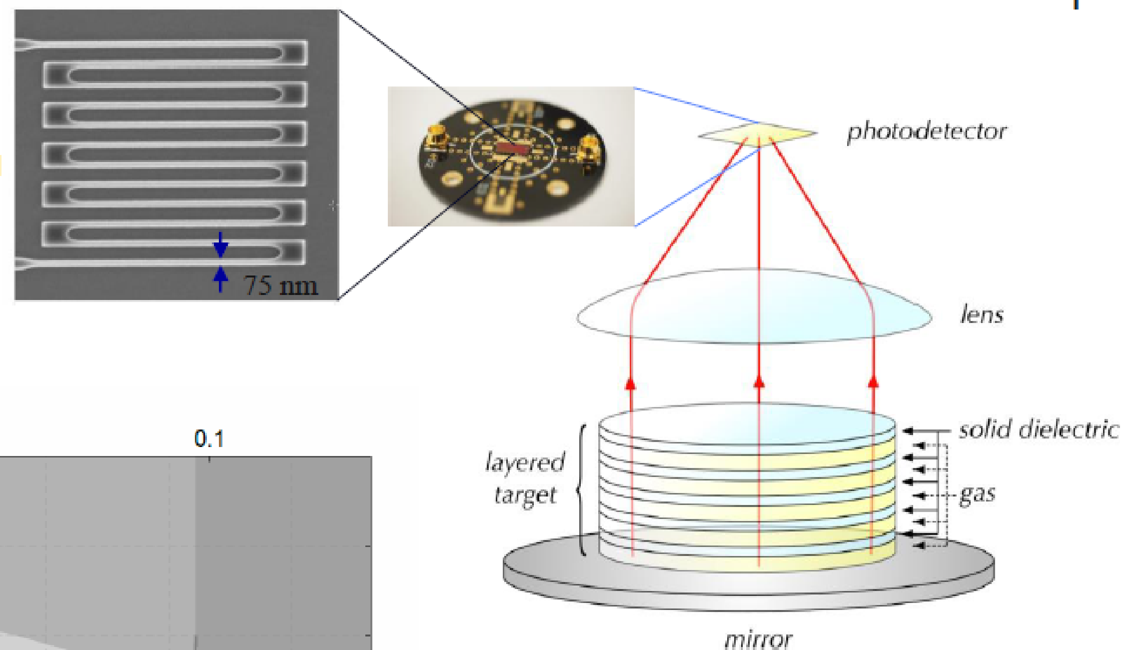
Collaboration of fundamental physics theorists, device designers, and system integrators and engineers:

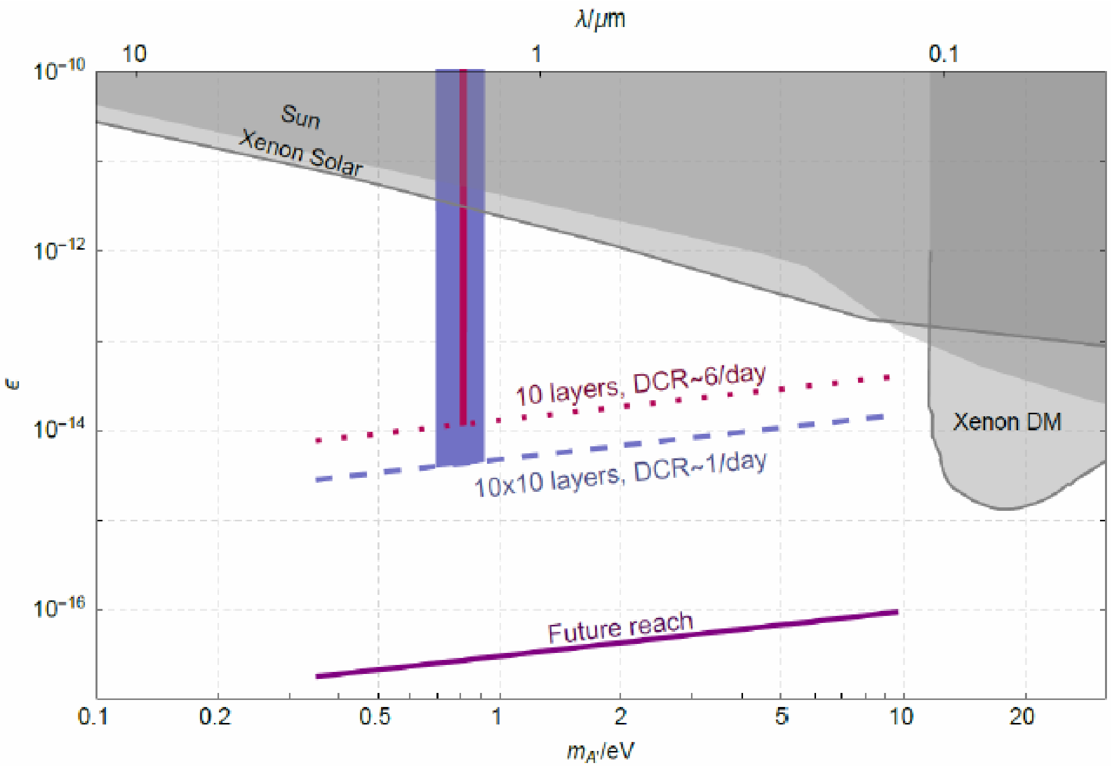
(1) Use quantum interference of dark matte to build up population in a single-photon state;

(2) Use detector technology perfected for quantum-optics to sense photon.

superconducting detector

Dark-Matter Detector Concept

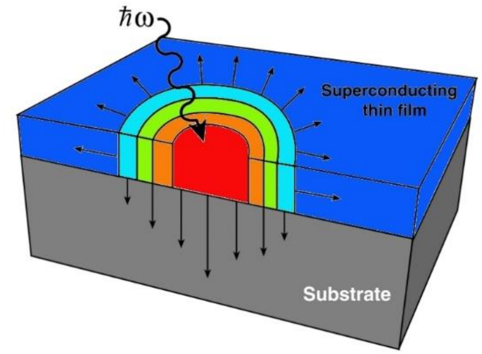


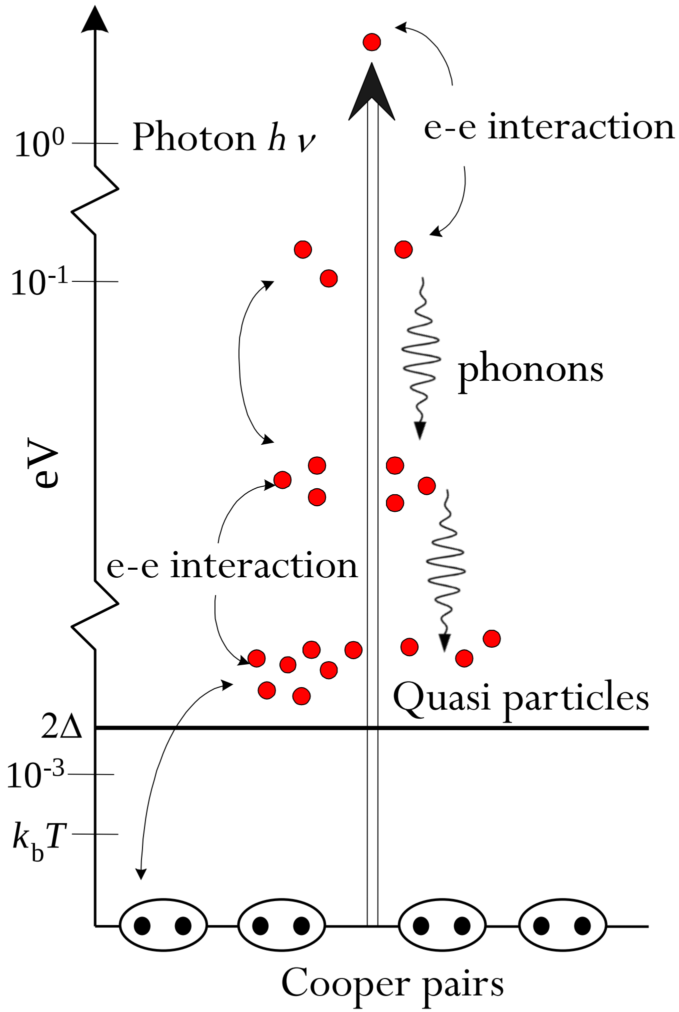


Key advantage of these detectors is low Dark Count Rate (DCR). Depending on number of layers in target, and achievable DCR, reach of experiment could extend well beyond what is possible today

Courtesy of I Charaev, LTD20

Cascade of broken Cooper pairs





- Photon breaks a cooper pair
- Thermalizes making $h\nu/\Delta$ qp's
- # gain but no E gain yet
- E resolution / photon # counting determined by shot noise
- Gain comes from change R or L

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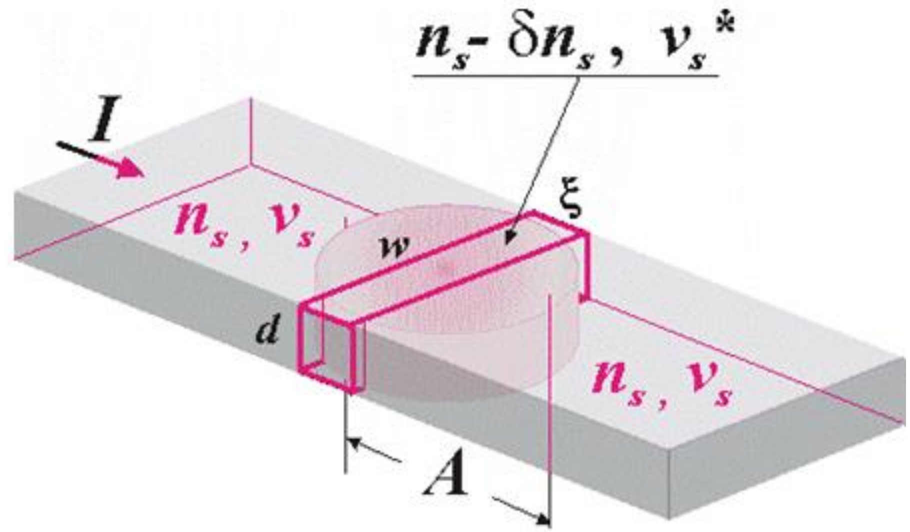
Refined Hot-Spot Model

Super-current density: $j_S = 2en_S v_S$

Critical-current density: $j_C = 2en_S v_C$



Charge flow conservation

$$(n_S - \delta n_S)v_S' = n_S v_S$$

$$v_S' = \frac{n_S}{n_S - \delta n_S} v_S$$

Switching criteria

$$e(n_S - \delta n_S)v_S^* \geq e\,n_S v_C = j_C$$

See: Semenov et al., Europ. Phys. J., 2005

Courtesy of M Siegel

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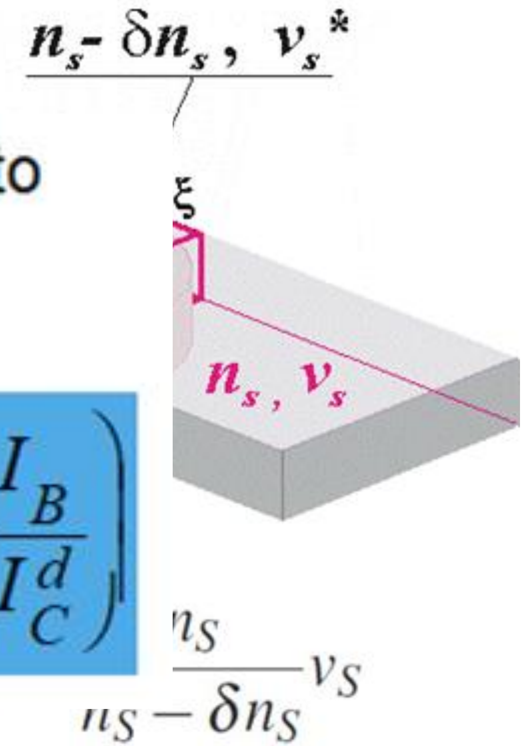
Refined Hot-Spot Model

Super-(

Critical-

Minimum photon energy necessary to create a count event:

$$\varepsilon = \frac{hc}{\lambda_0} = \frac{3\sqrt{\pi}}{4\varsigma}\Delta^2 W d N_0 \sqrt{D\tau}\left(1 - \frac{I_B}{I_C^d}\right)$$



Switching criteria

$$e(n_S - \delta n_S)v_S^* \geq e\, n_S v_C = j_C$$

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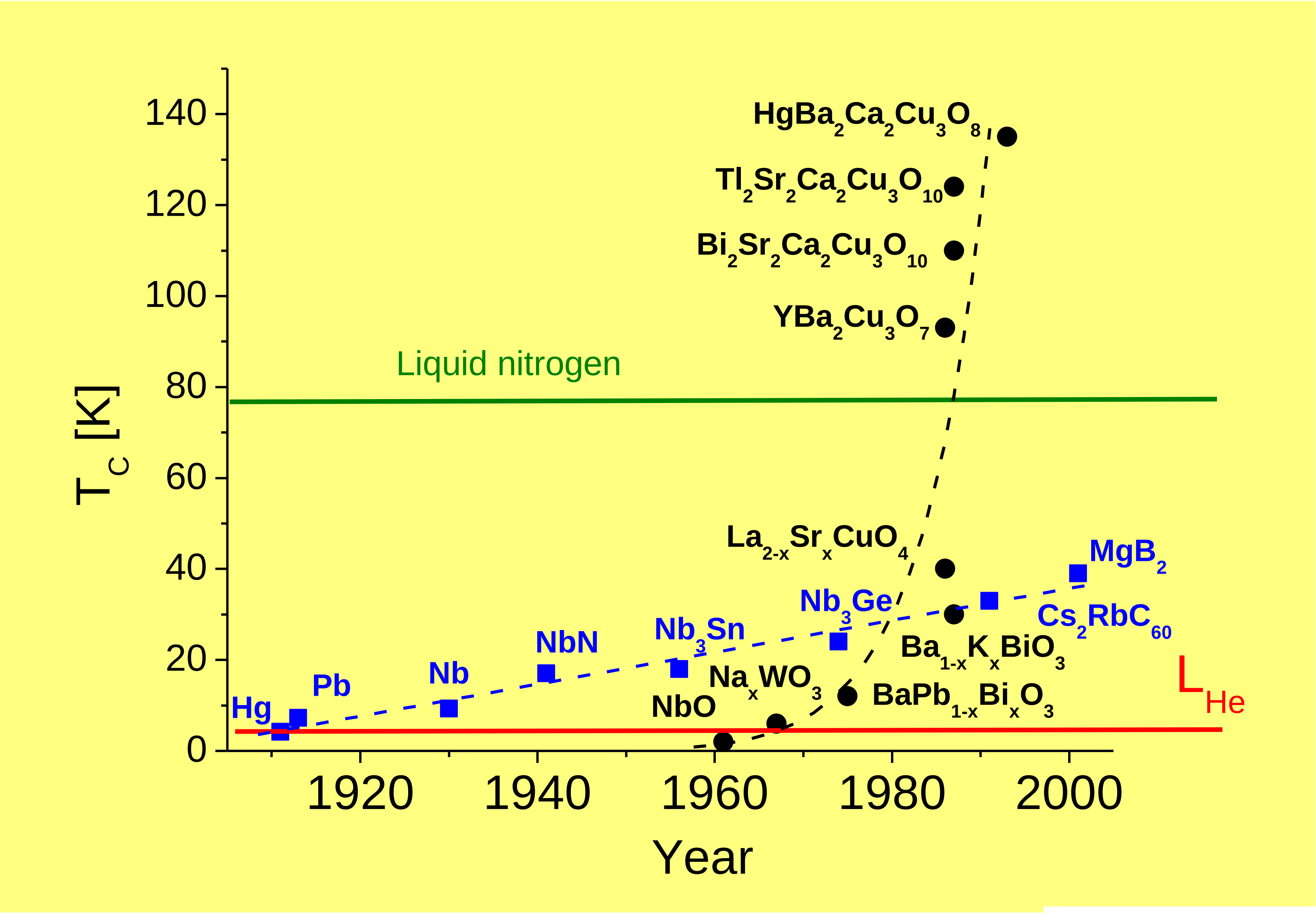
Courtesy of M Siegel

Superconducting Materials



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SNSPD : Materials

The Silicides family

SSPD performance in the **mid- and far-IR ranges** can be improved further by using **narrow-gap superconductors** with **a low quasi-particle diffusivity**.

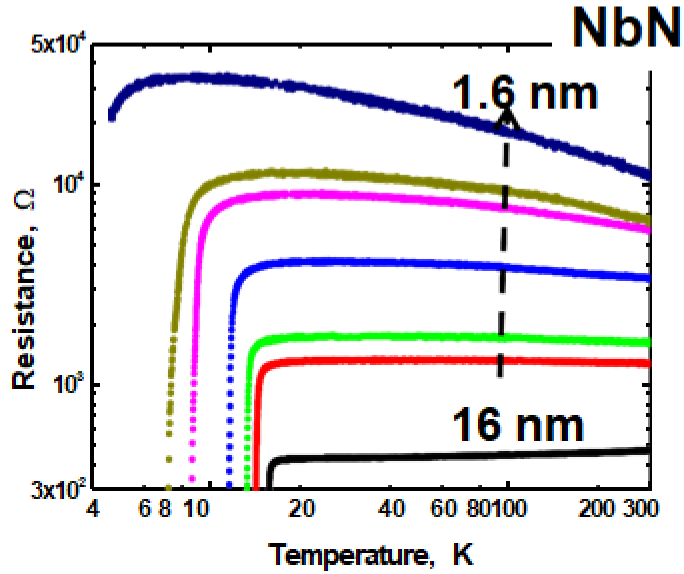
Materials	T_c K	T_c (4nm) K	ξ nm	λ nm	ρ μΩ cm	N_o 10^{21}states eV^{-1} cm^{-3}	D cm^2/s	J_c MA/cm^2	τ_0 ps
NbN	**16**	**9-11**	**5**	**380** **900-1300**	**100-240**	**56**	**0.5**	**6-7**	**60**
$W_{0.75}Si_{0.25}$	**5**	**3.7**	**7,3**	**768**		**26**	**0,70**	**0.8**	
$Mo_{0.8}Si_{0.2}$	**7.5**	**4.3**		**734**	**198**			**1.3**	

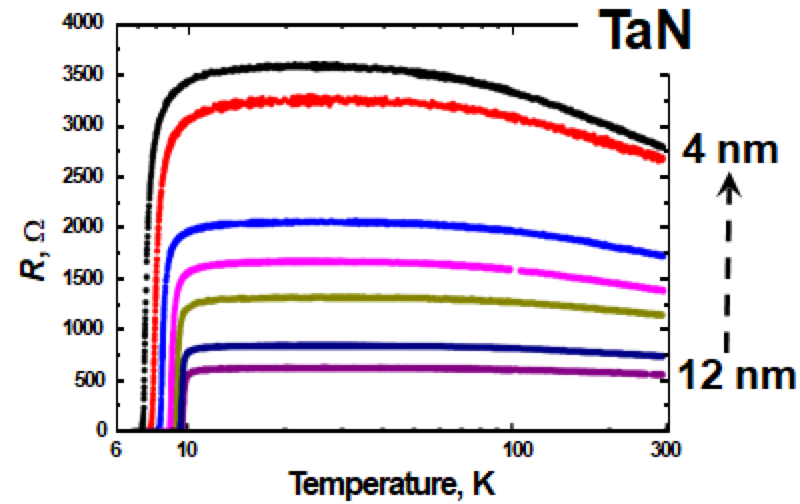
- amorphous → better integration with integrated optical cavity
- larger hot-spot and energy sensitivity
- better quantum efficiency

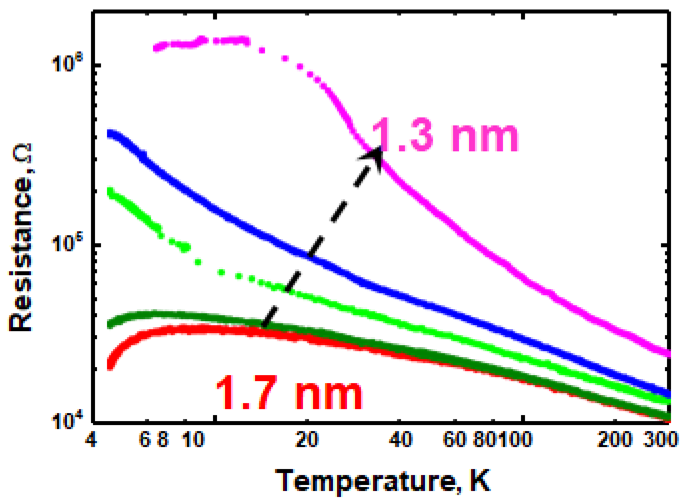
WSi - The new player: the highest system detection efficiency **(93%)**
Appl. Phys. Lett. 105, 122601 2014, *Phys. Rev B* 94, 174509 (2016) and *Nature Photonics* 7 211 (2013)

MoSi - higher temperatures for efficient SSPD operation, *Supercond. Sci. Technol*. 27 095012 (2014)

SNSPD : Materials







$$\varepsilon = \frac{hc}{\lambda_0} = \frac{3\sqrt{\pi}}{4\varsigma}\Delta^2 W d N_0 \sqrt{D\tau}\left(1 - \frac{I_B}{I_C^d}\right)$$

Courtesy of M Siegel

SNSPD : Materials

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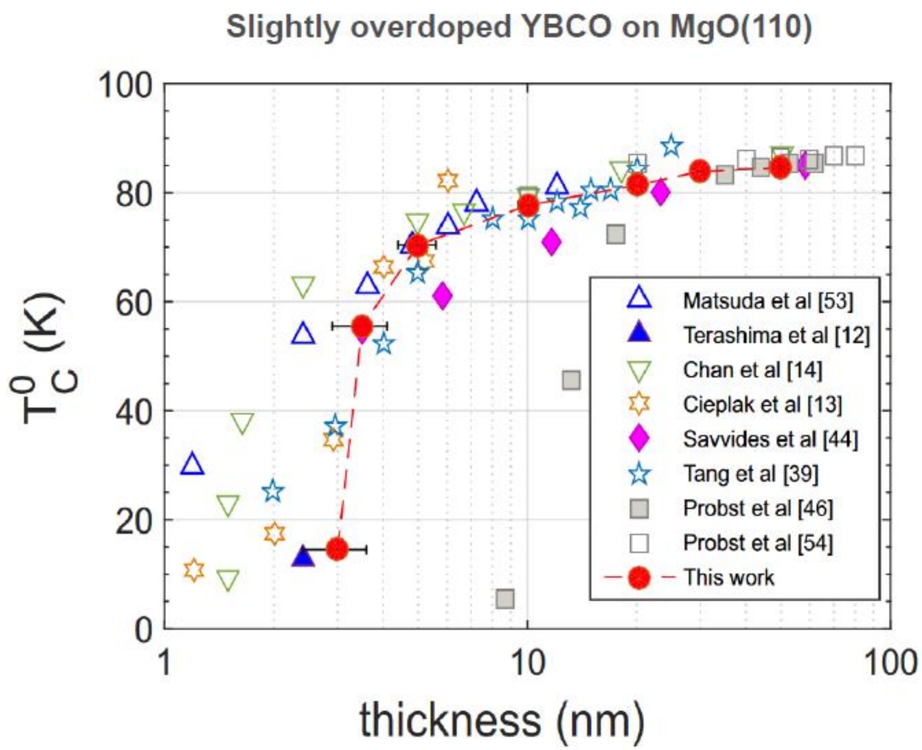
UNIVERSITY OF TECHNOLOGY

YBCO films down to few nm

- Our films show good quality down to t=5 nm
- We have shown that the same also holds for underdoped films



R. Arpaia, …, T. Bauch and FL *Phys. Rev. B* **96**, 064525 (2017)

Courtesy of F Lombardi

SNSPD : Materials

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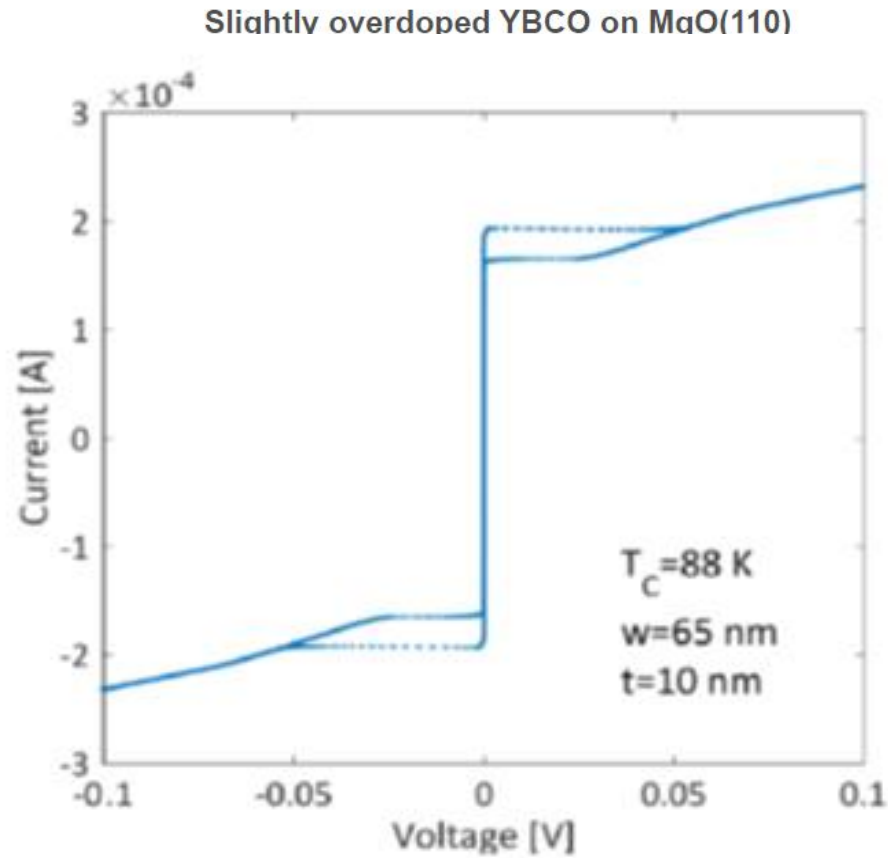

Courtesy of F Lombardi

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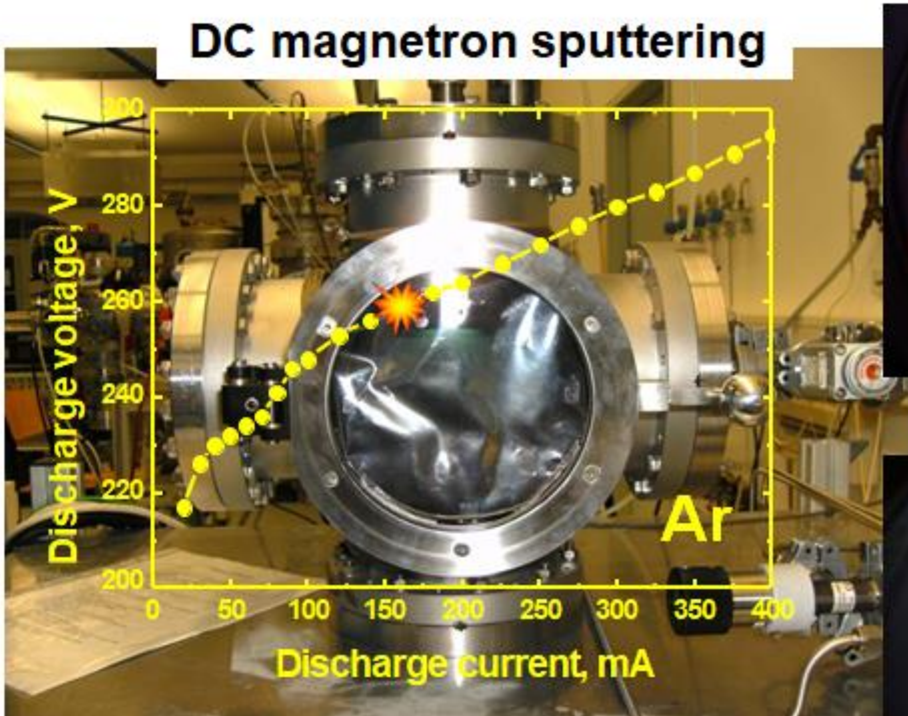
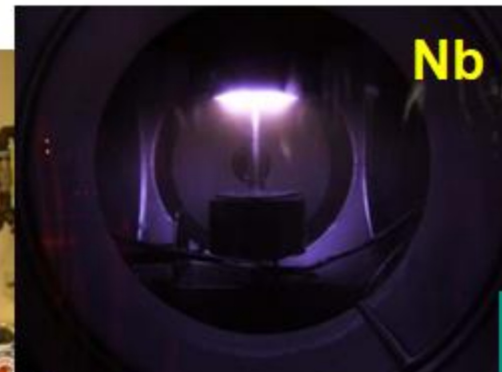
Material choice

Small energy gap superconductors:

	Al	Ti	Nb	Ta
T_C, K	2	0.4	9.3	4.5

$$\varepsilon = \frac{hc}{\lambda_0} = \frac{3\sqrt{\pi}}{4\varsigma}\Delta^2 W d N_0 \sqrt{D\tau}\left(1 - \frac{I_B}{I_C^d}\right)$$





- 2 inch Nb, Ta target
- t° = 750 C
- P_{Ar} = 3.5*10^{-3} mbar

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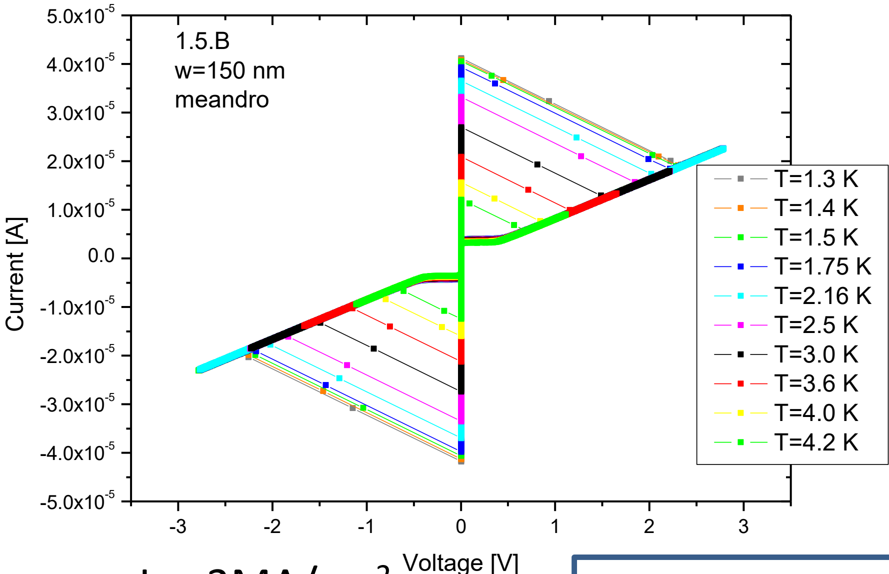
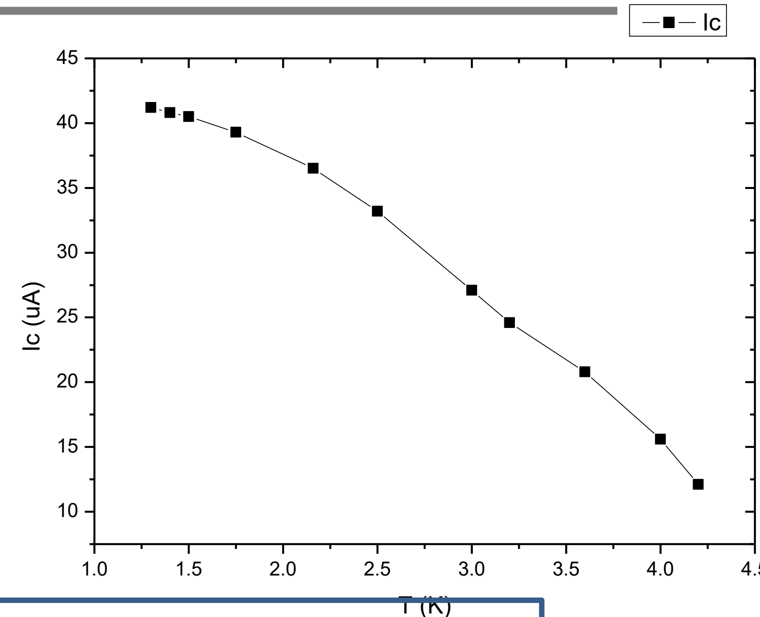
SNSPD : Materials



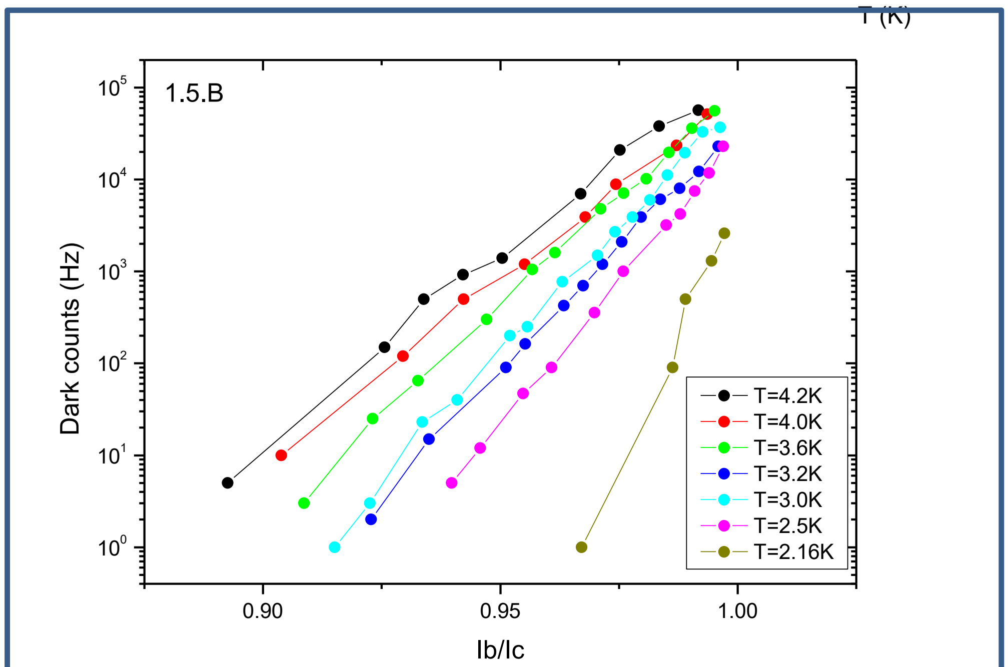


Jc= 3MA/cm^2

T=1.3 K

MoSi thin films (8nm)

Naples



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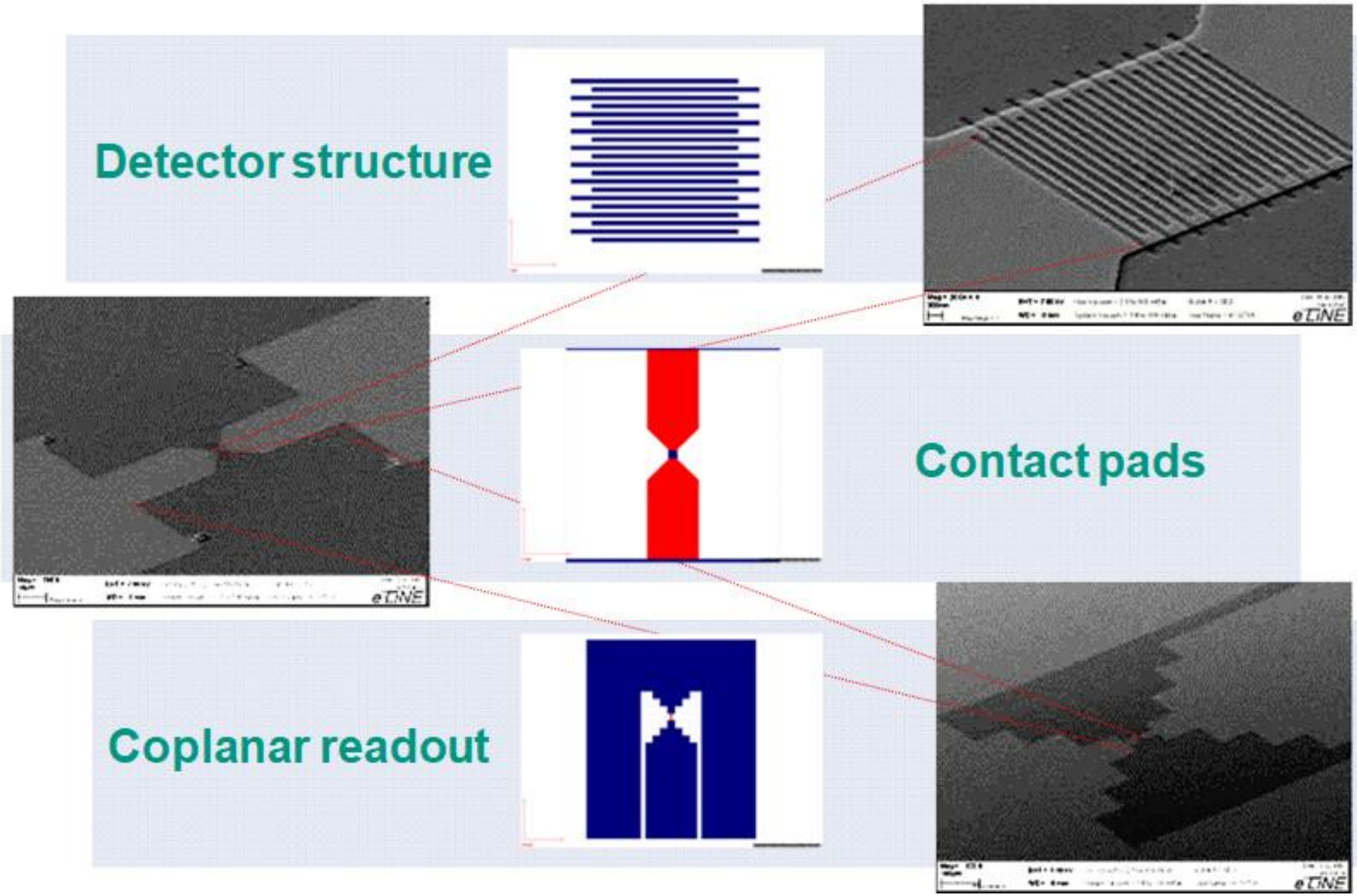
Fabrication

Patterning by electron beam lithographie and reactive ion milling



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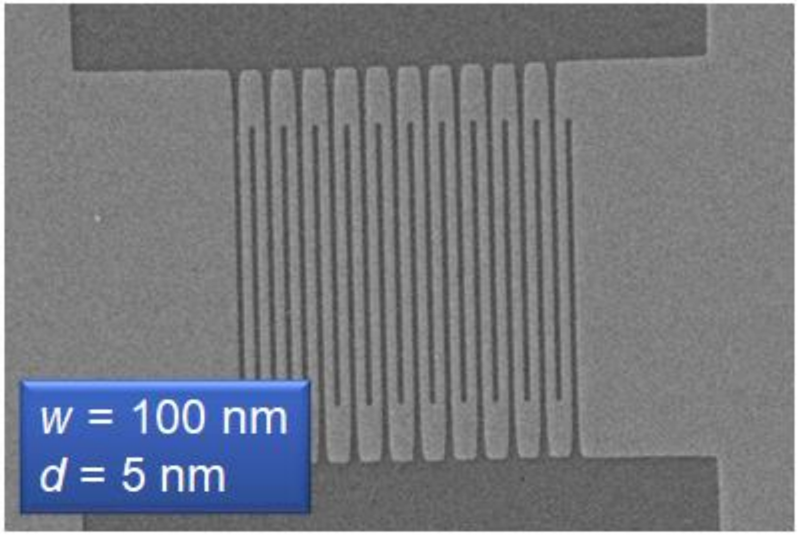
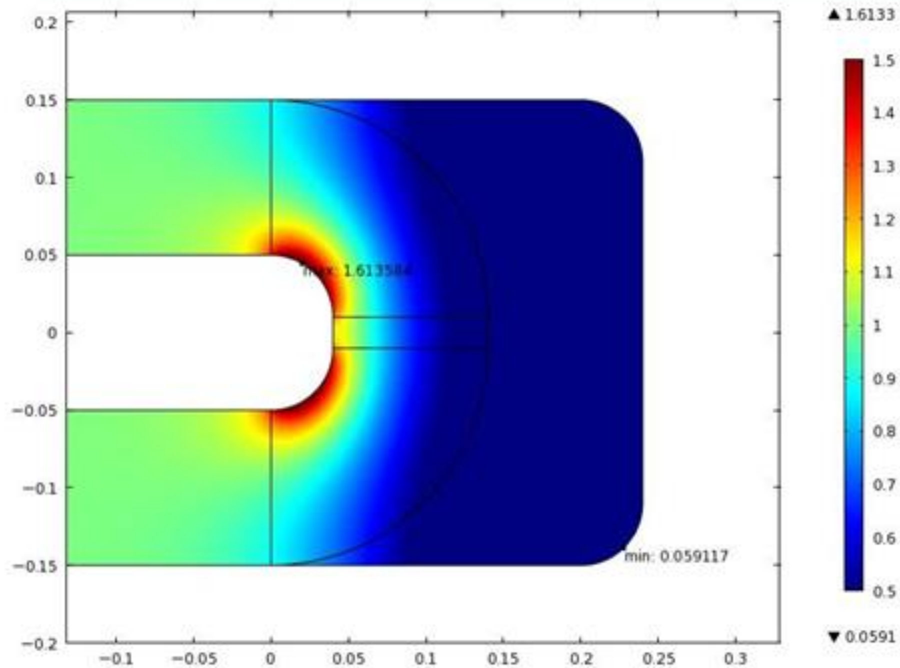
Current crowding effect



Spectral detection efficiency of SNSPD
- small cross section *wd*
- High I_{bias}/I_C ratio



Superconductor:
For *w,d* < l (London penetration depth)

- Uniform current distribution, only defined by geometry
- Local current desity at inner edge exceeds density on the straight lines by >50%!

Current crowding can be reduced if turns have low angle and large radius

Henrich et al., Phys. Rev. B 86, 144504 (2012)

Courtesy of M Siegel

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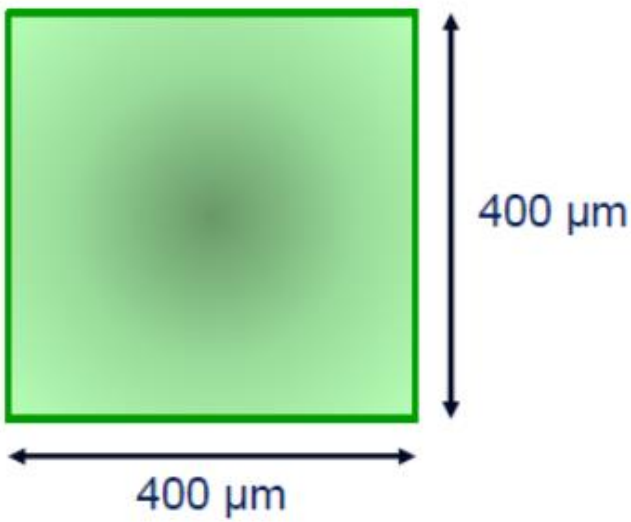
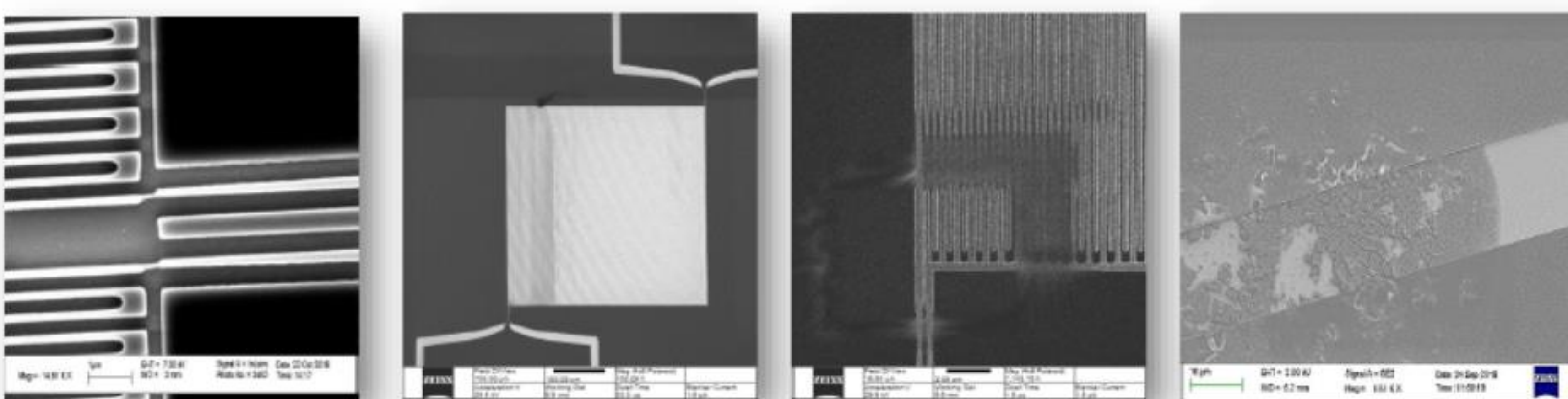


High probability of defects

- Cross-section variations: non-uniformity of the thickness or width of the film
- Nanowire edge defects or internal structural defects
- Current-crowding

Requirements

- Long-term stability of electron-beam parameters and long-term suppression of external acoustic, mechanic, and electro-magnetic interferences
- Uniformity of resist

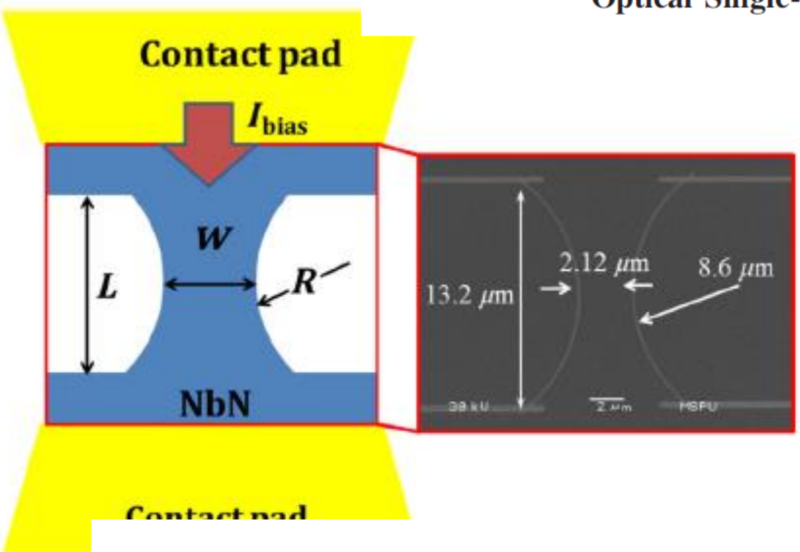


Courtesy of I Charaev, LTD20

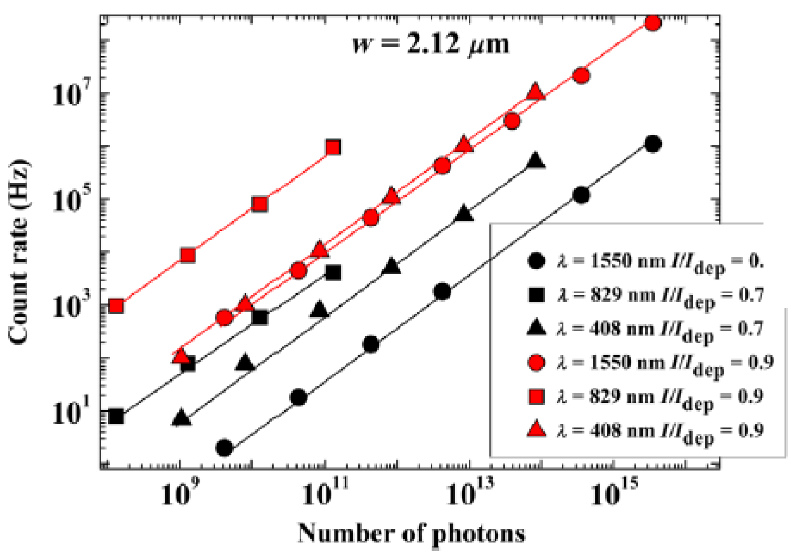
Good news?!

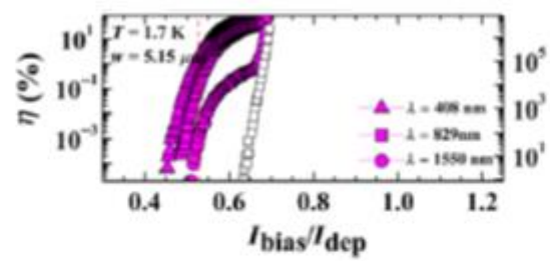
PHYSICAL REVIEW APPLIED **9**, 064037 (2018)

Optical Single-Photon Detection in Micrometer-Scale NbN Bridges



Width (μm)	T_c (K)	ρ (20 K) (μΩ cm)	j_c (4.2 K) (A/cm²)
0.53	8.25	386	3.16×10^6
1.61	8.35	396	2.74×10^6
2.12	8.5	393	3.75×10^6
3.07	8.35	398	3.06×10^6
4.04	8.35	402	2.52×10^6
5.15	8.35	427	2.28×10^6





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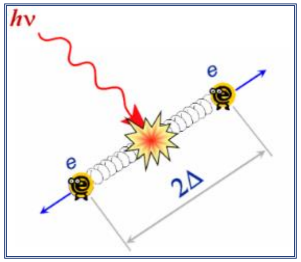
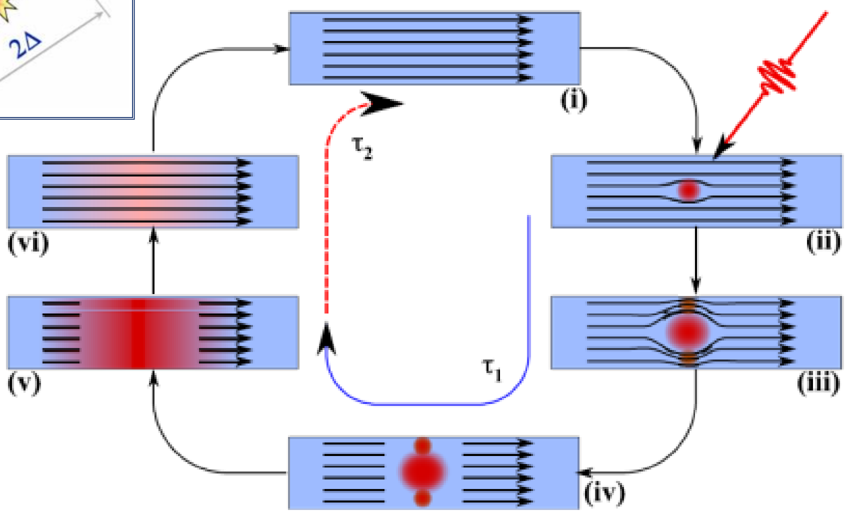
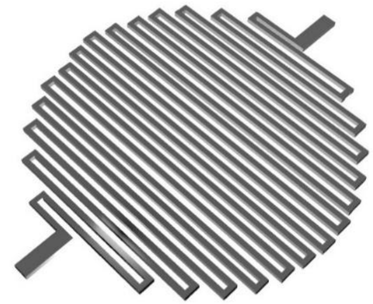
Detection Mechanism

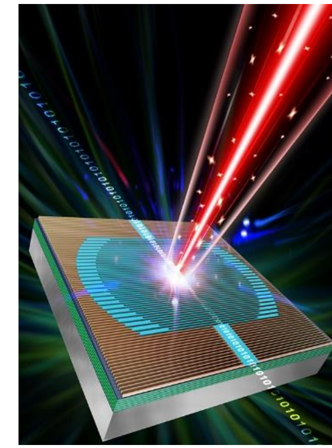
Cooper pair breaking by single photon

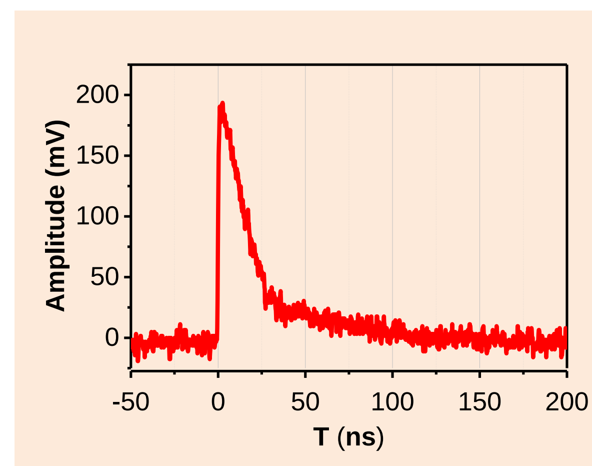
Goltsman et al, Appl Phys Lett, 2001, 79:705











Photon energy vs Superconducting gap/Cooper Pair energy

hν (1eV) vs 2Δ (6.4 meV)

*** Ultrathin nanowire (~5 nm thick and ~100 nm wide)**

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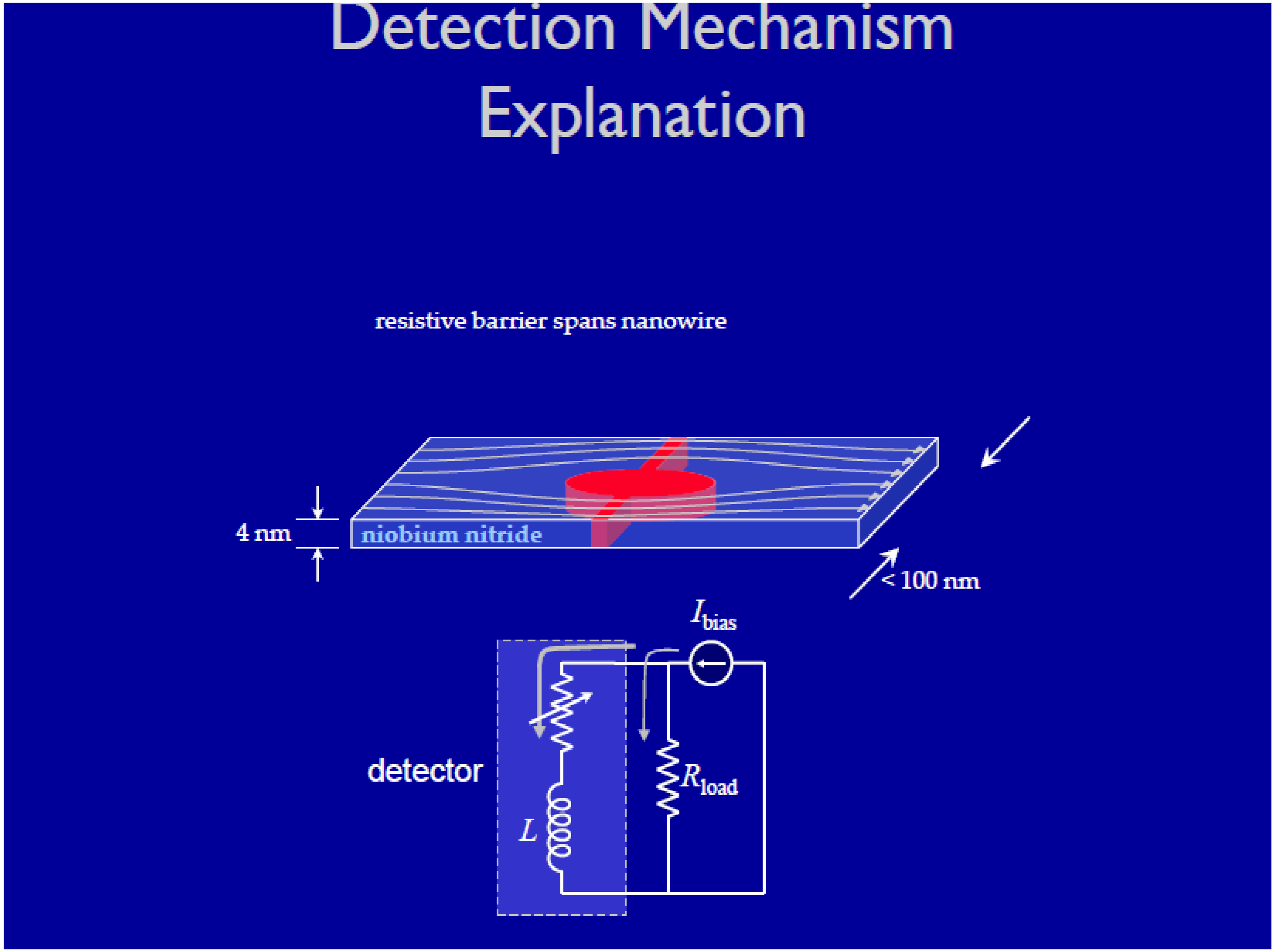
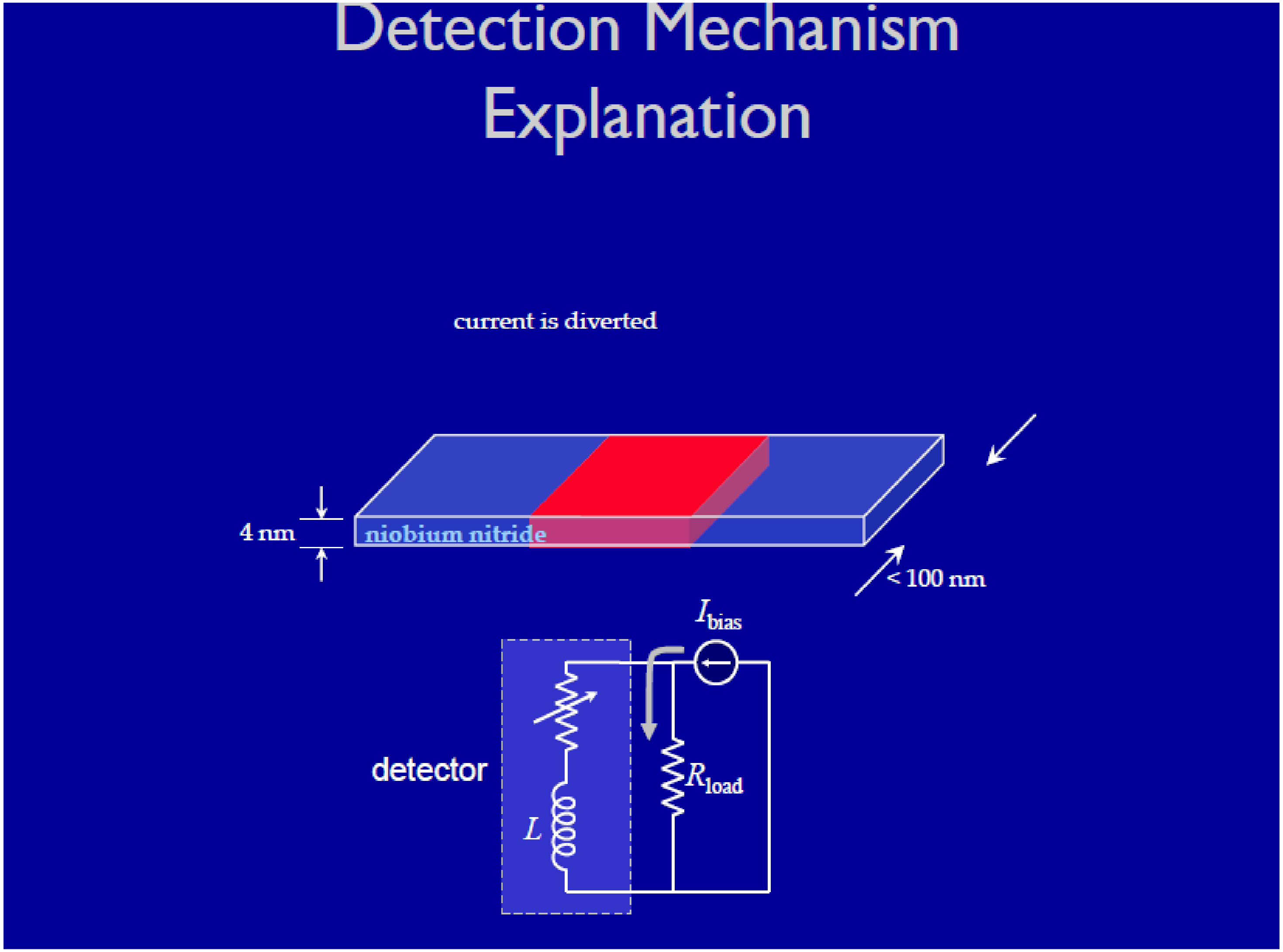
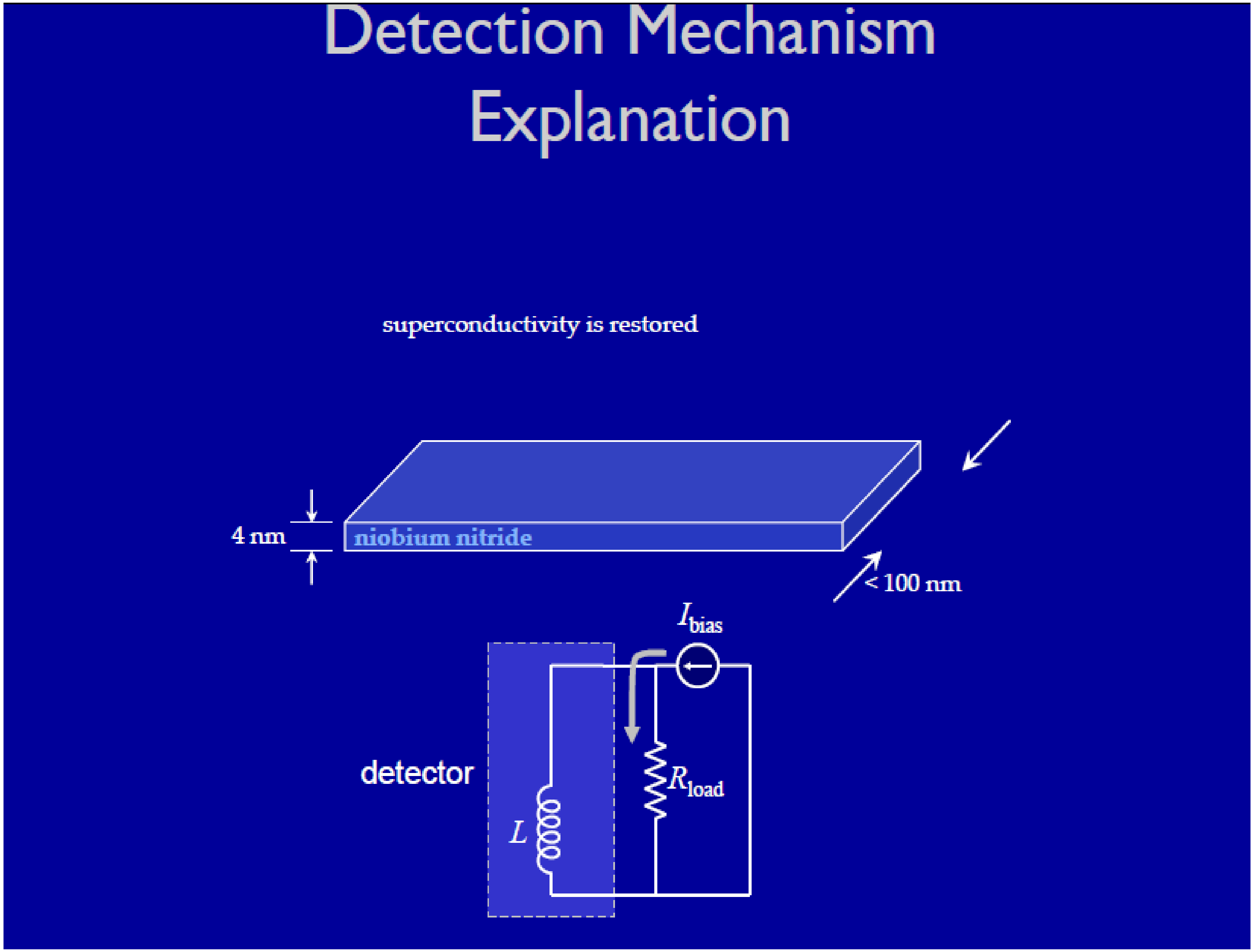
Detection Mechanism



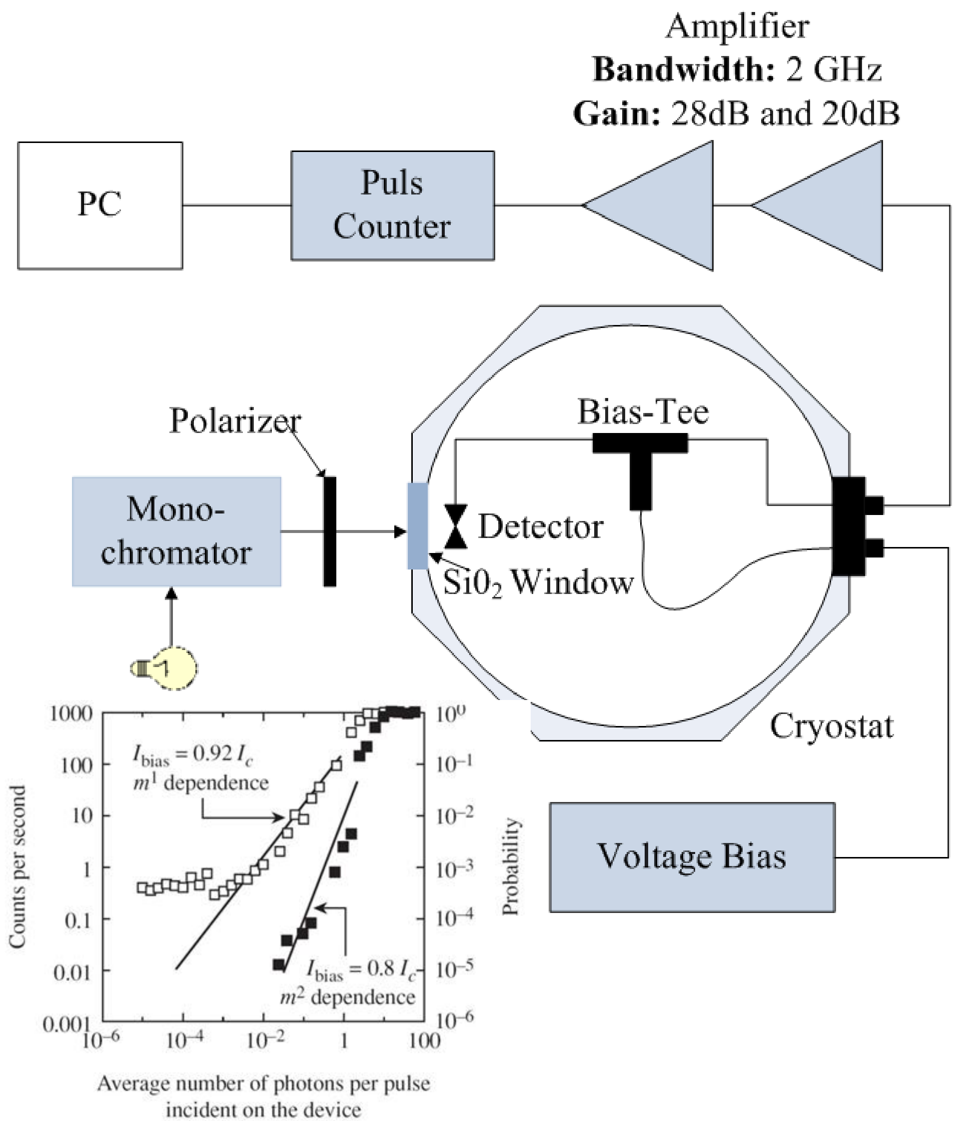
Detection Mechanism



Detection Mechanism



SNSPD - Experimental Setup



^{4}He Bath Cryostat

- Vacuum chamber
- Liquid helium cooled
- Feed troughs for electrical contacts
- SiO_2 window for radiation input

Electrical Part

- RF-micro strip line, Coaxial line
- Bias-Tee for DC/AC coupling
- Low noise voltage source
- RF-amplifier

  48 dB, 2 GHz bandwidth
- Pulse Counter

(SR400, BW: 250 MHz)

Radiation Source

- Optical range 400nm to 2000nm

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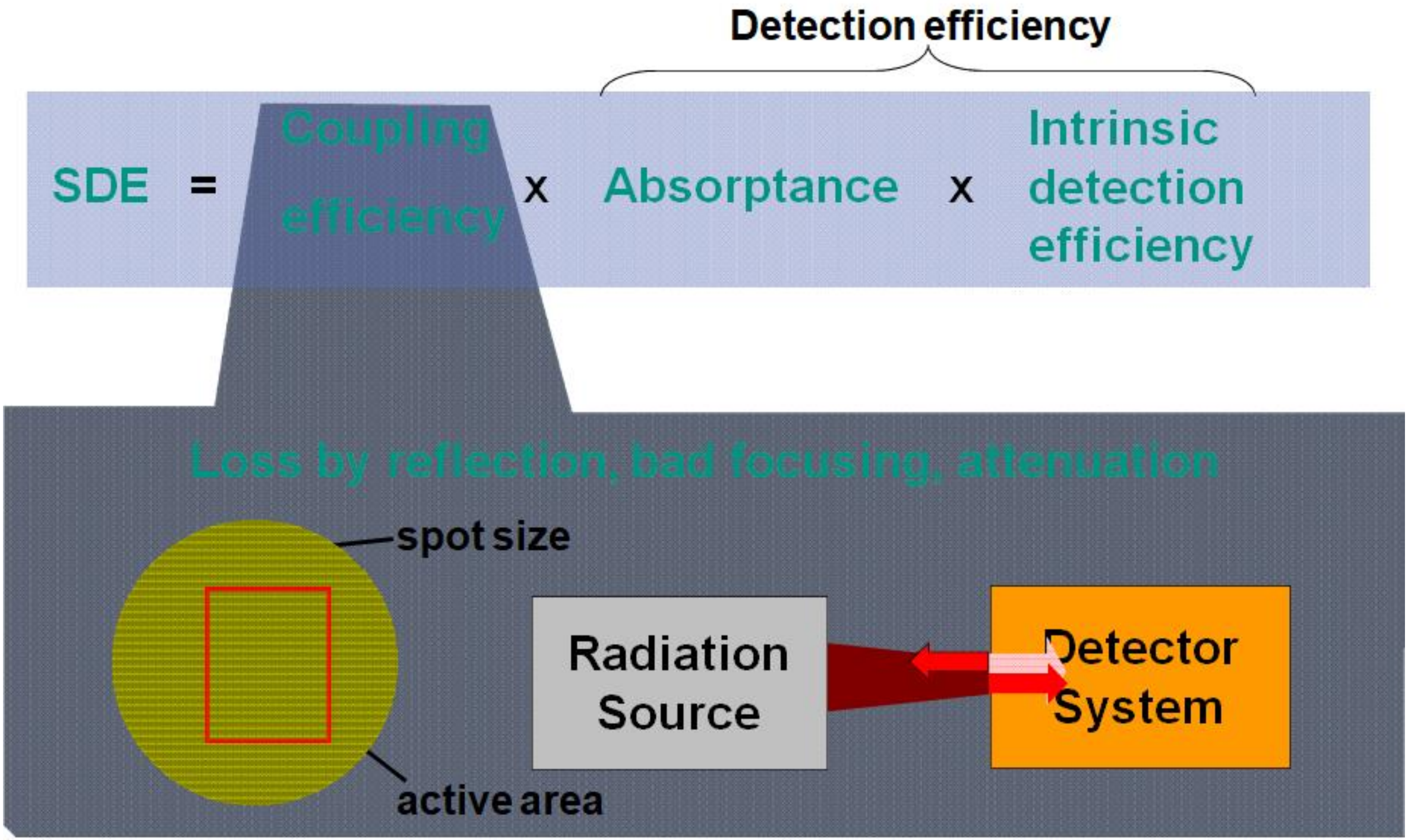
System Detection Efficiency



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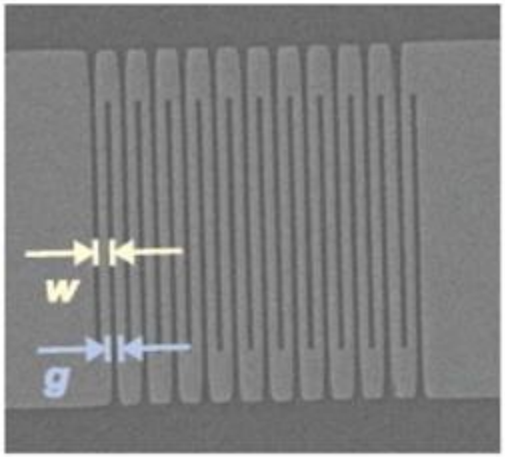
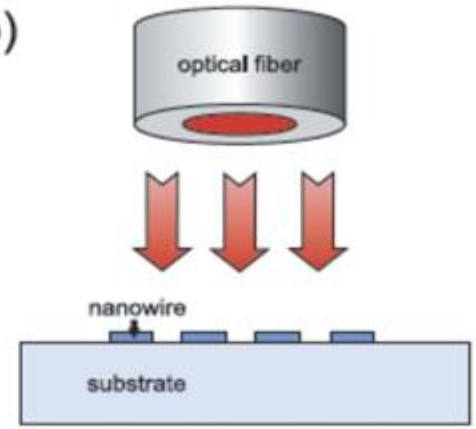
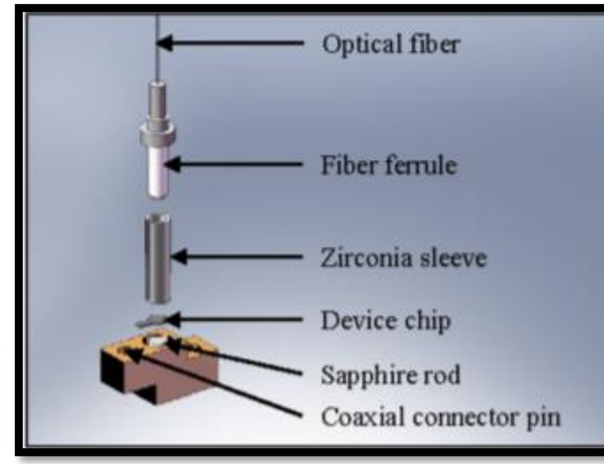
Improved optical coupling

a)

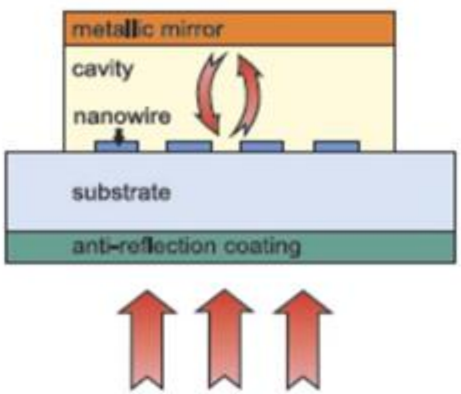


b)

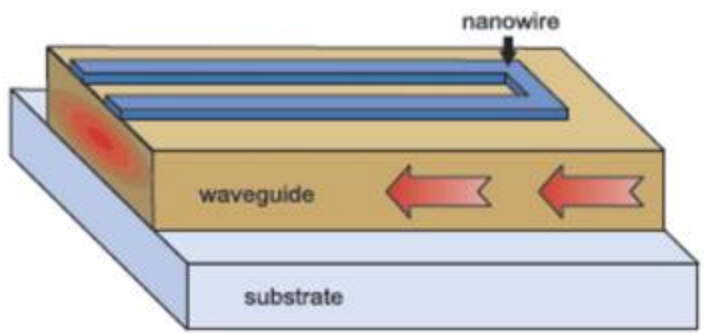




c)

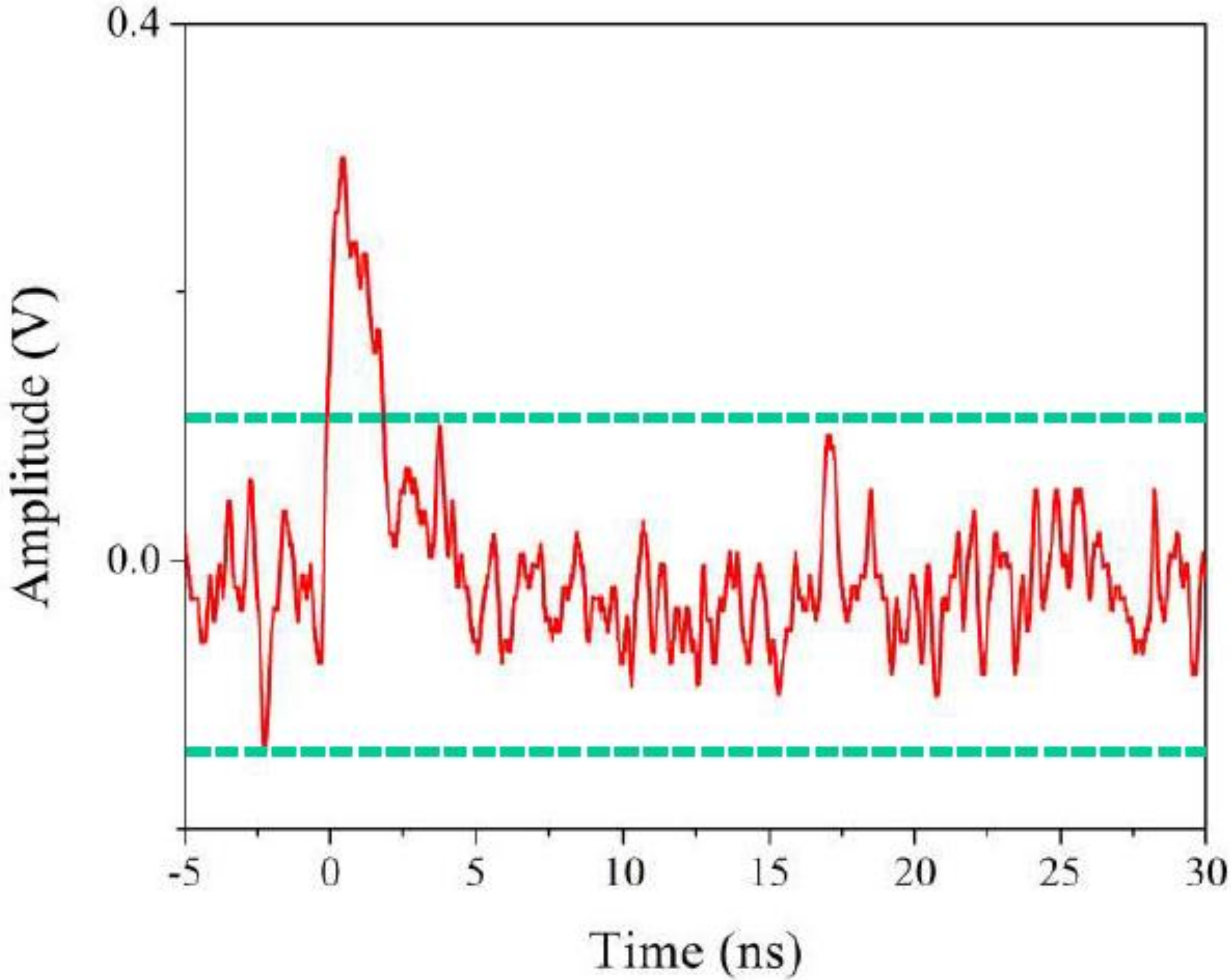


d)



Ref.: C. M. Natarajan et al., Superconductor Science and Technology, 25, 063001, 2012.

Low signal to noise ratio



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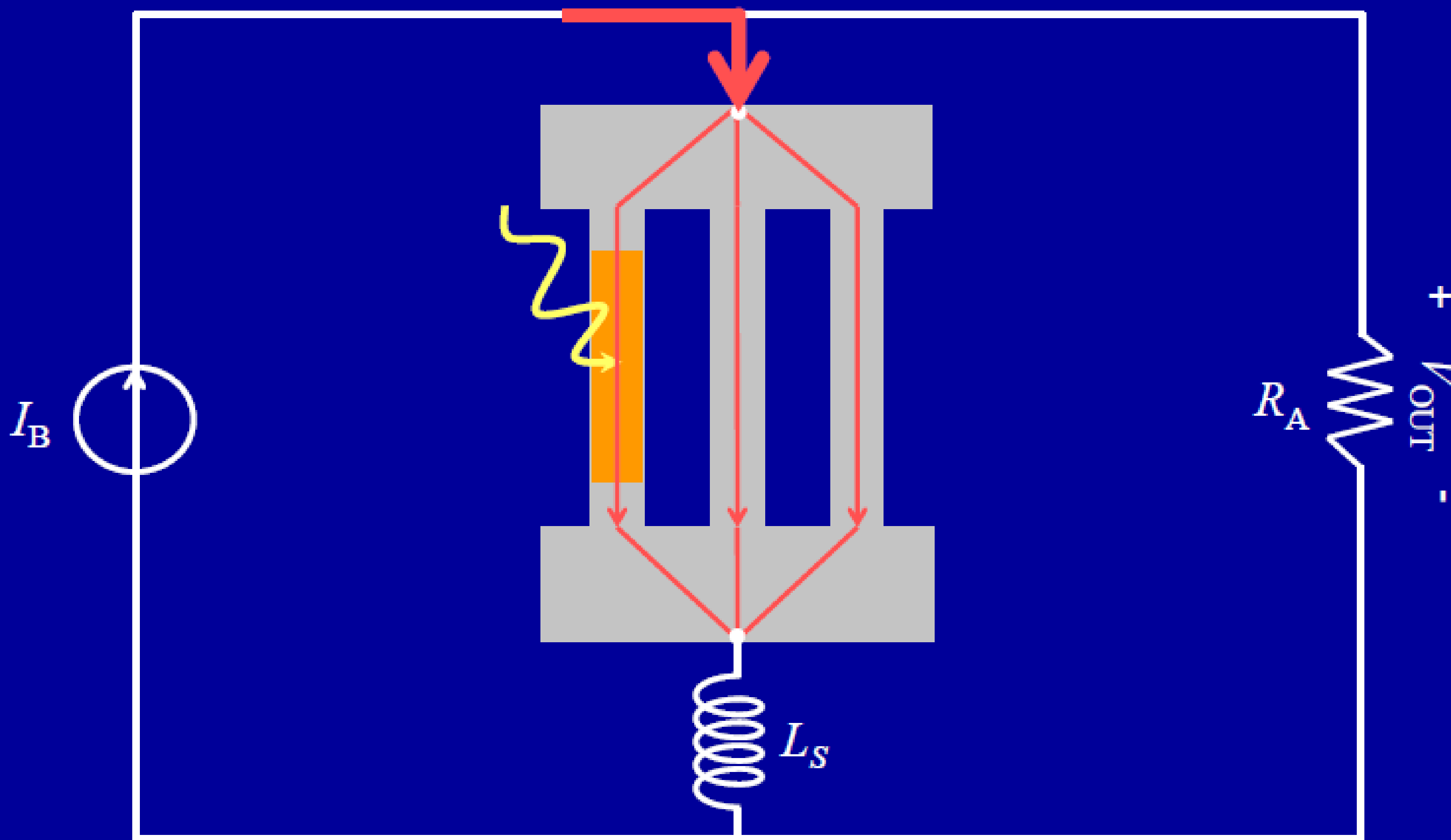
Basic model of SNAP operation



Ejrnaes, *et al. APL* 91 262509 (2007)
Ejrnaes *et al. SUST* 22 055006 (2009)

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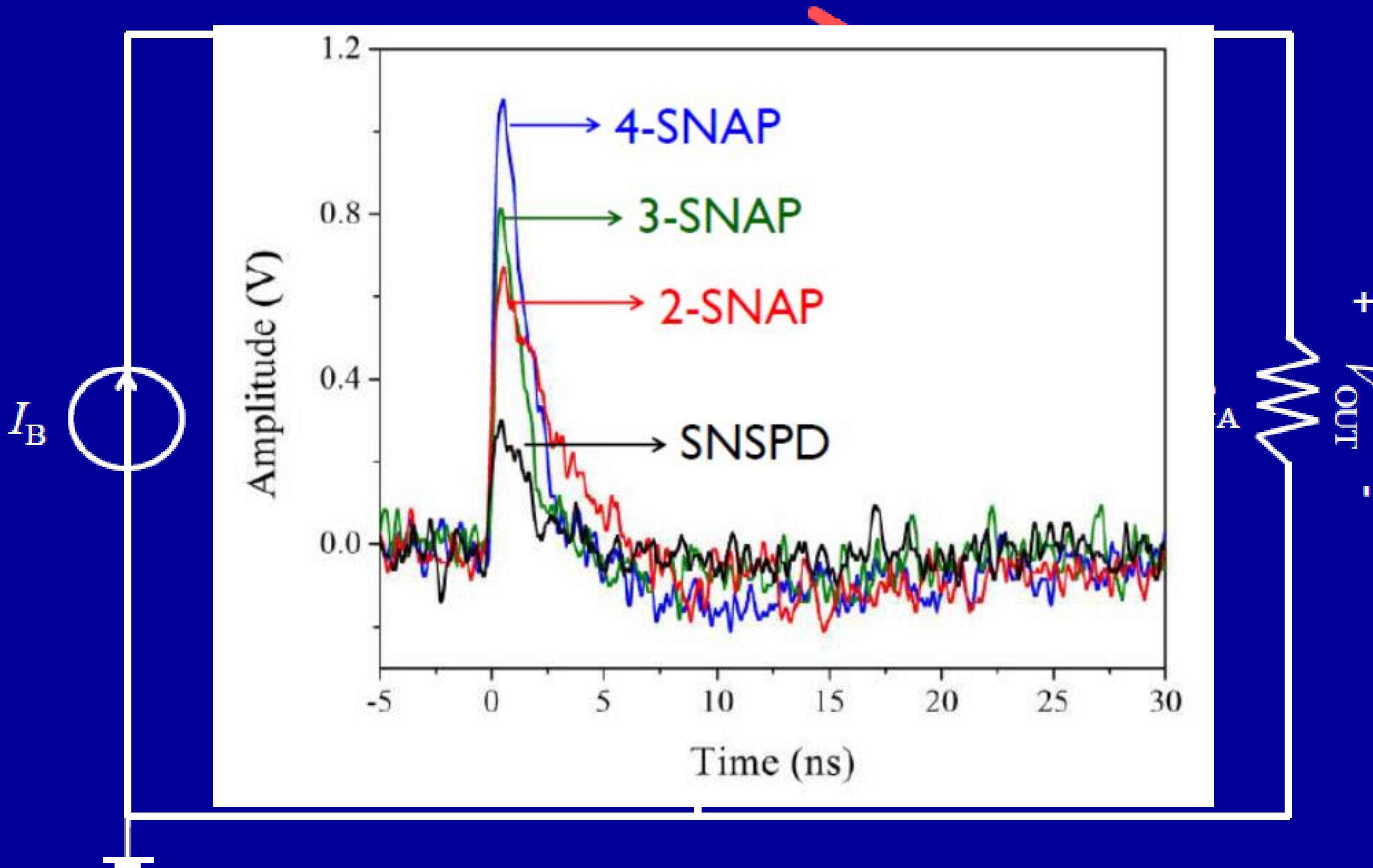
Basic model of SNAP operation



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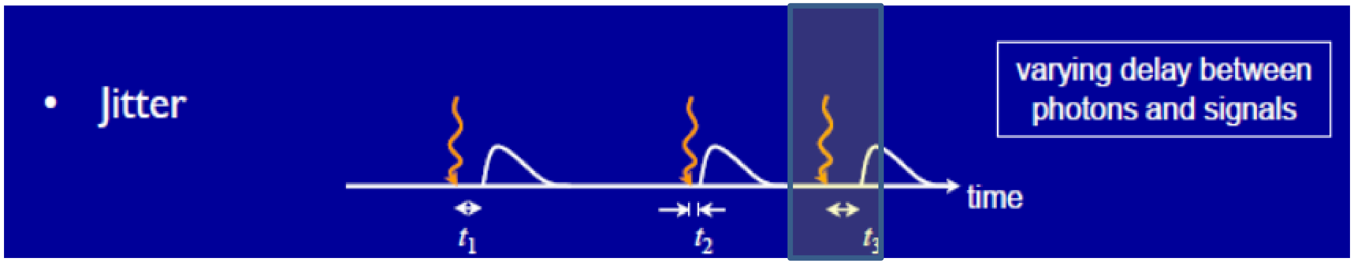
The timing Jitter



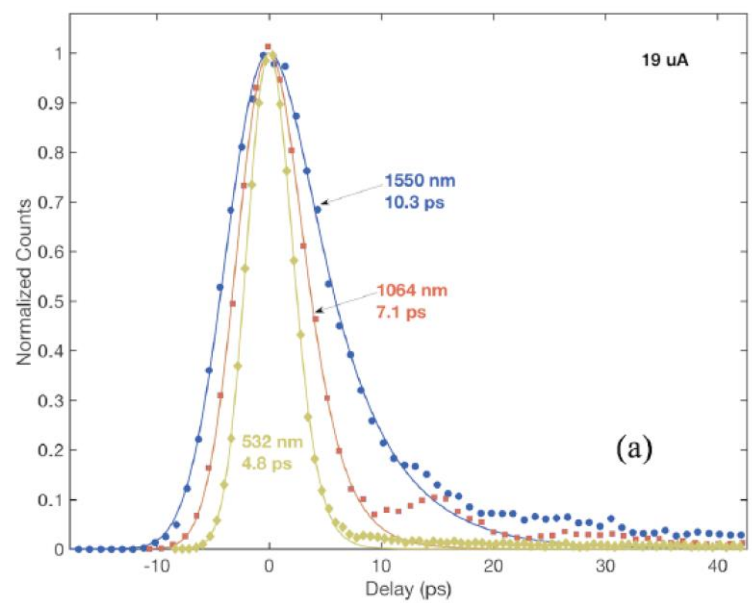
The timing jitter TJ is the variation in the time span between the photon absorption and the appearance of an output voltage pulse

The TJ of a SNSPD depends on
(a) the equilibrium between electrons and phonons in the energy cascade;
(b) the order parameter time $\tau\Delta$ in S -> N: instability generates phase-slip lines or vortices (dissipative);
(c) the nucleation and expansion of the N domain (dissipative);

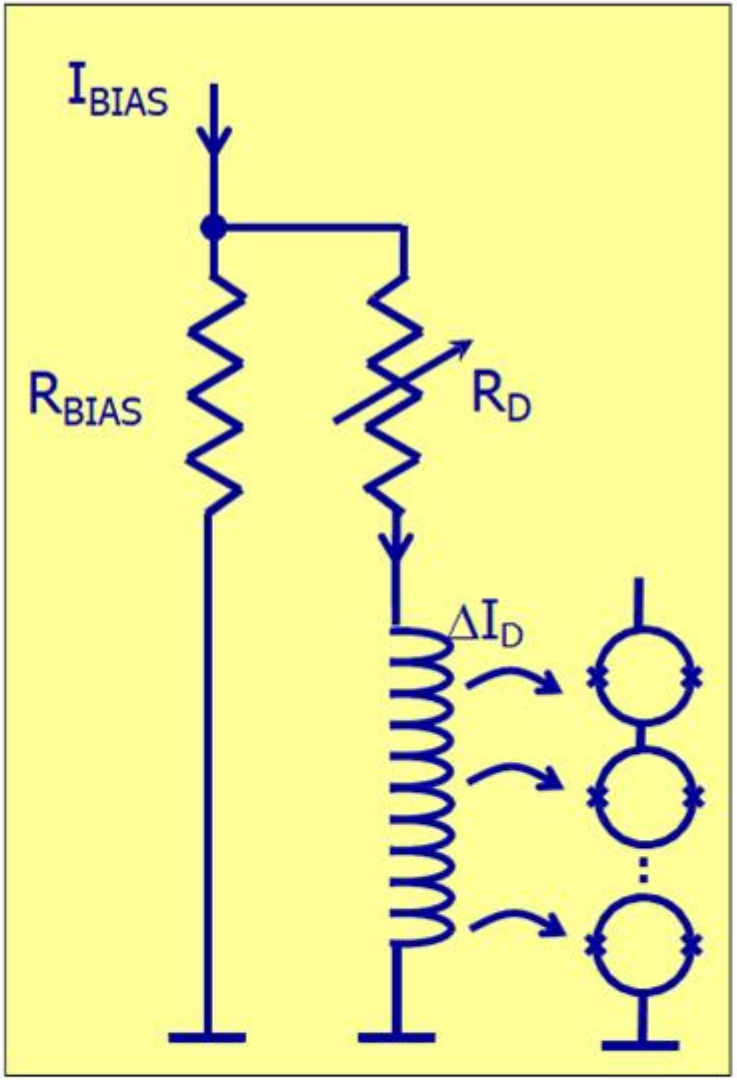
The rate of N growth influences electrical noise, and hence TJ through the signal rising edge.

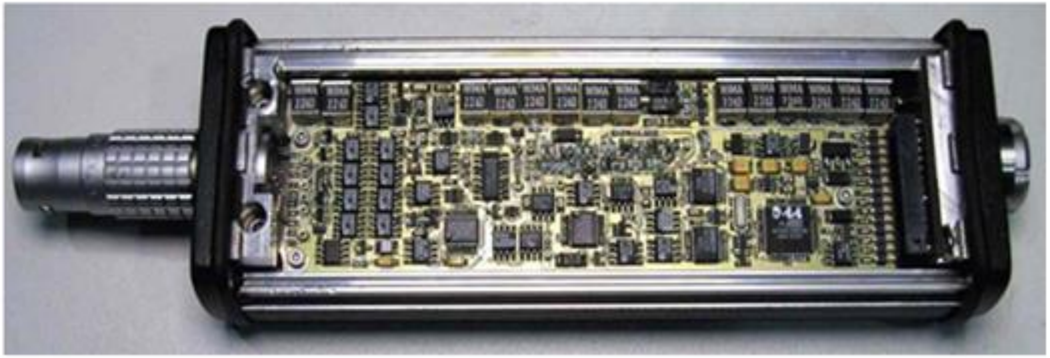
Intrinsic TJ < 5 ps

JPL FW3F.3, CLEO 2018



SSPD - SQUID Readout Scheme





SQUID-Amplifier from PTB Berlin

Now in Naples, @Dept Physics…https://seeqc.eu/

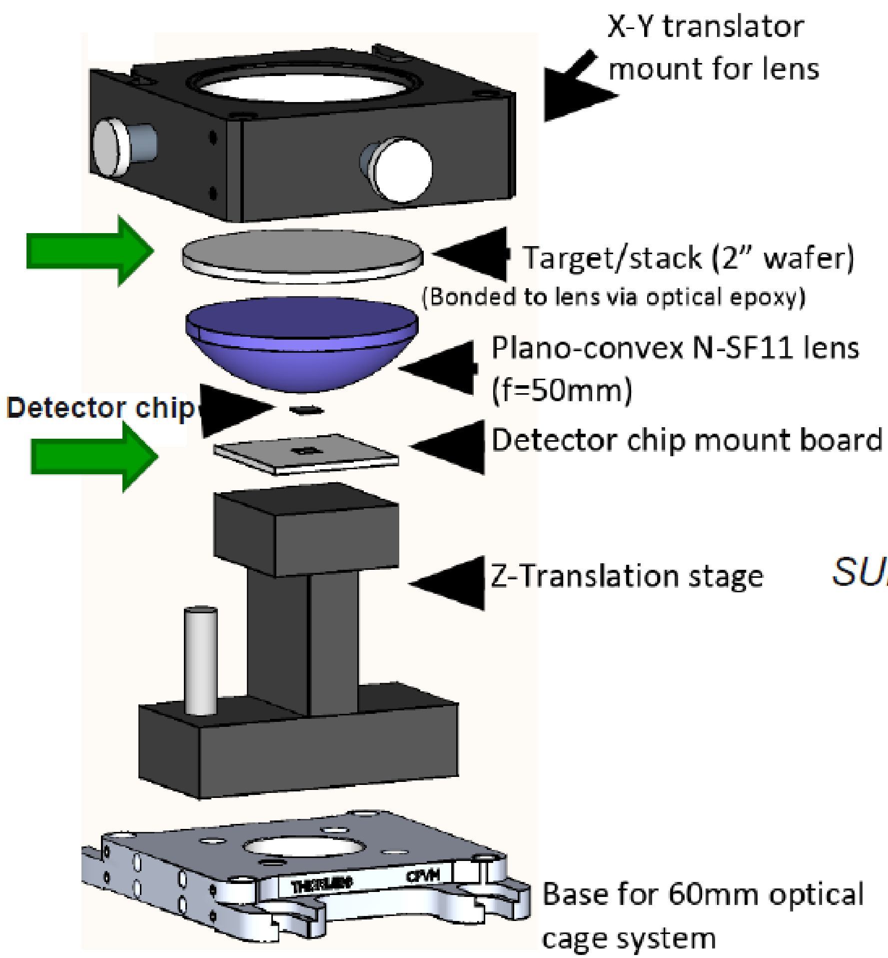
SeeQC.EU

SeeQC.EU Superconducting Quantum Technologies

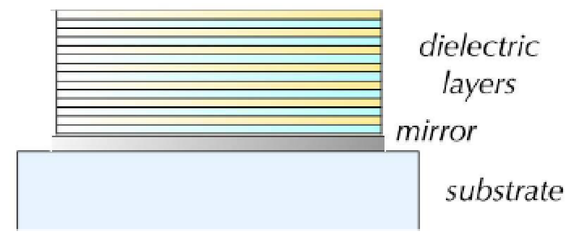
SNSPD - Experimental Setup

Multilayer optical haloscope

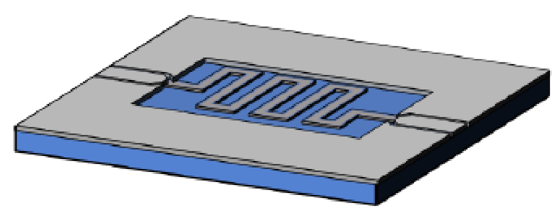
@MIT



MULTILAYER OPTICAL TARGET



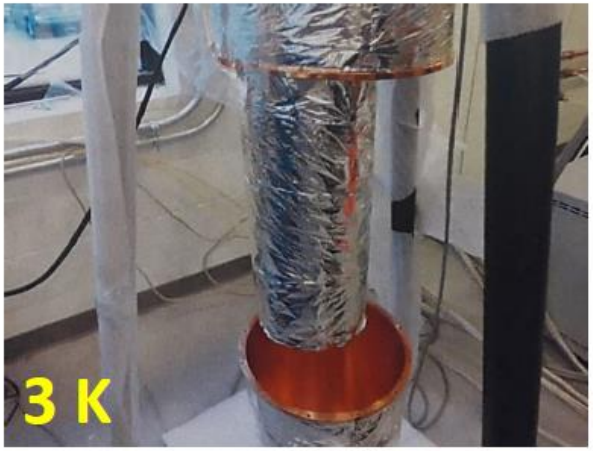
SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTOR (SNSPD)



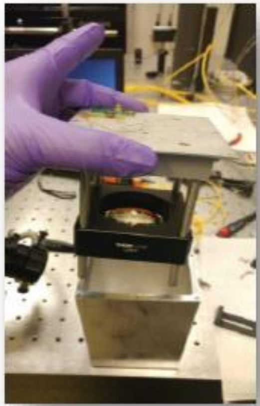
Courtesy of I Charaev, LTD20

SNSPD - Experimental Setup

@MIT



Assembled haloscope with device prototype



Optical fiber connection removed

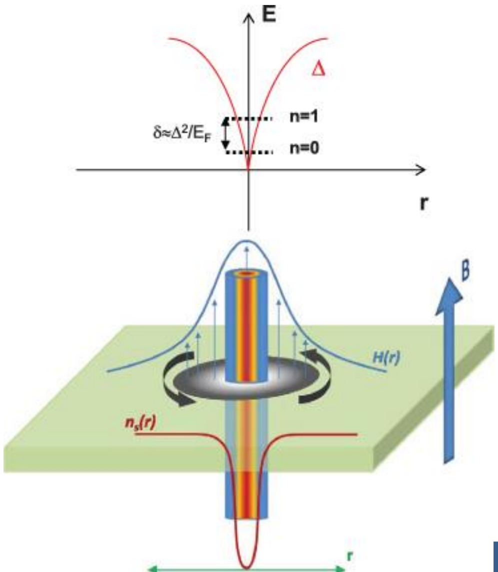
Multi-layer superinsulation (apr. 100 layers in total) on 3 K and 40 K radiation shields

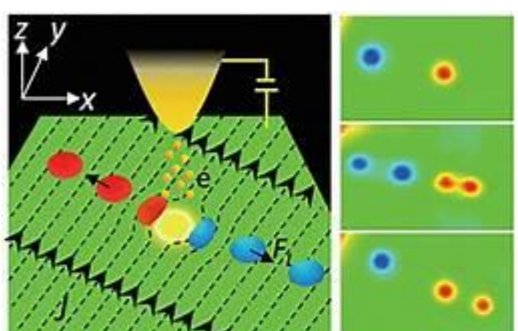
Courtesy of I Charaev, LTD20

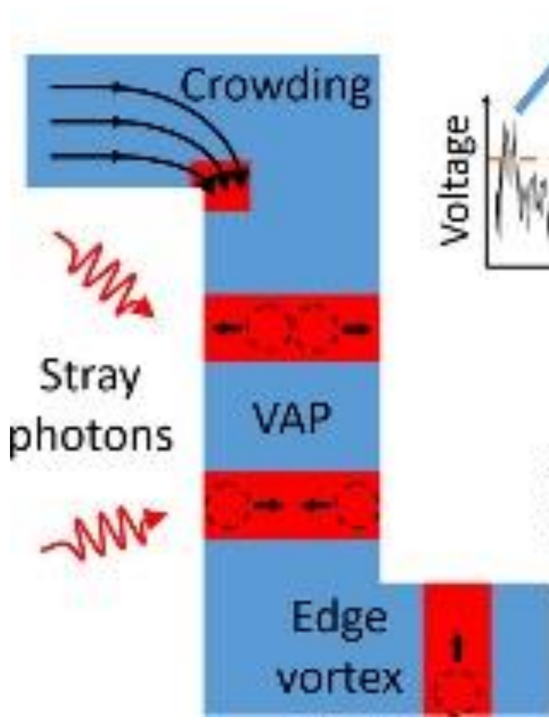
Origin of Dark count rate

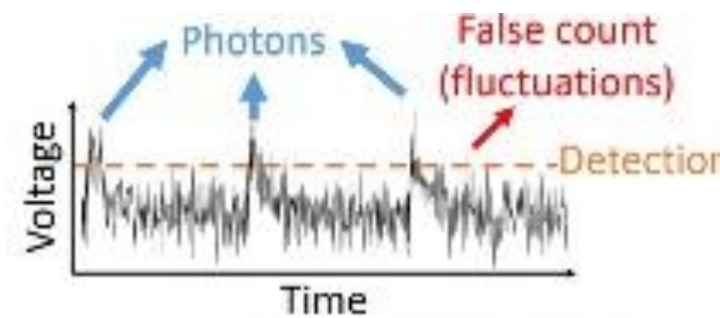
- Dark count rate

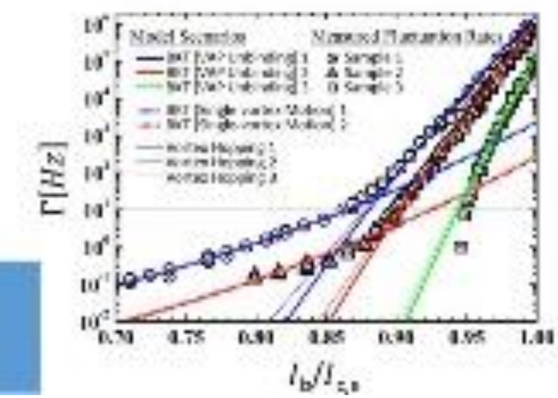
voltage pulses with no corresponding photon





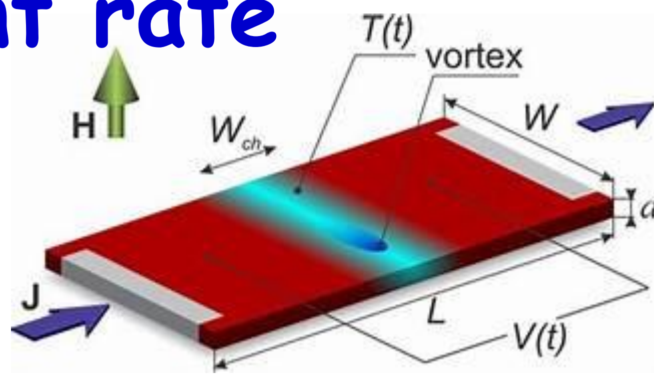






G Pepe, Napoli 2019

Origin of Dark count rate

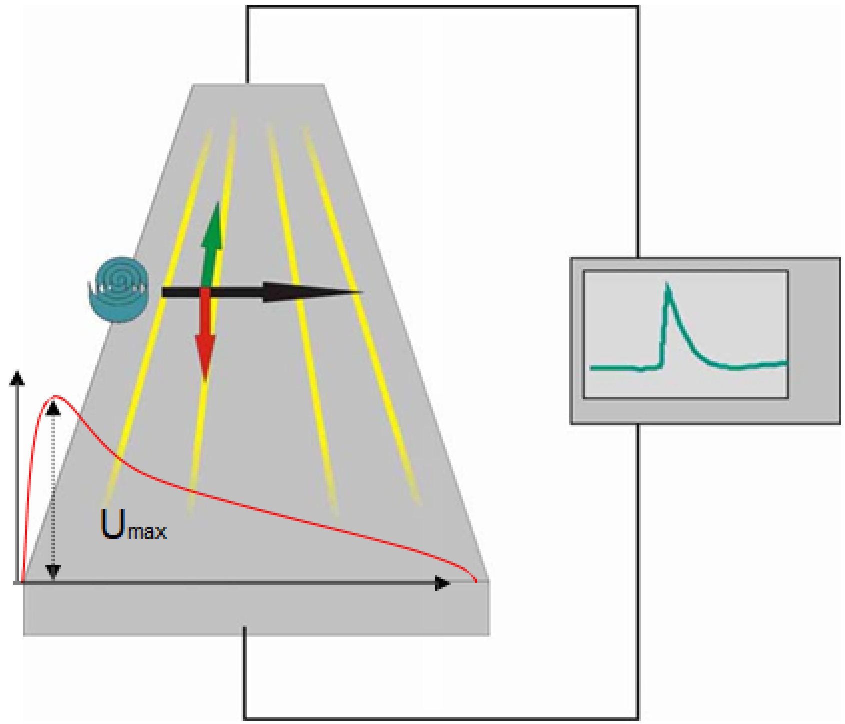


Vortex Mechanism

- Potential barrier avoids nucleation and crossing of vortices.
- Certain probability exists that vortex nevertheless nucleates due to thermal activation.
- Absorbed photon delivers photon energy and reduces linearly potential barrier.

→ Probability increases

$$P \propto I_B \exp\left|\left(\frac{U_{pot,\max}}{k_B T}\right)\right|$$



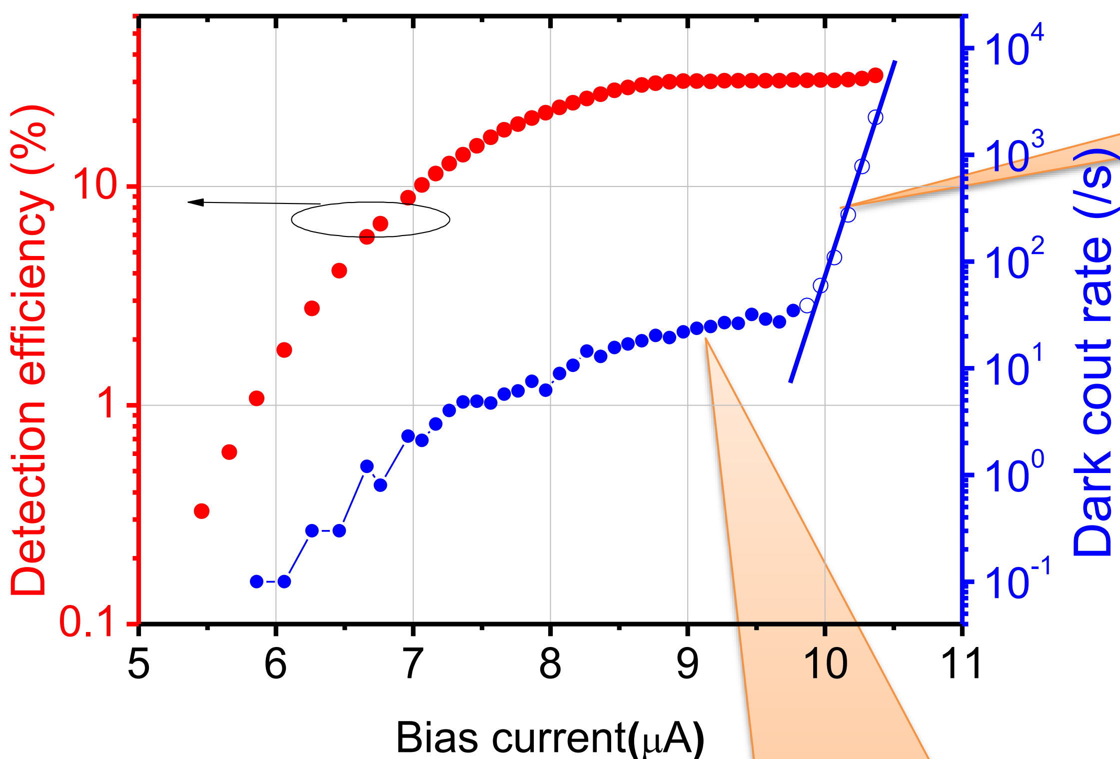
After nucleation, vortex is swept by Lorentz force and causes a pulse.

$k_B T << U_{pot,\max}$ $\quad$ $U_{pot,\max} = f(\Phi_0, \lambda, d, w, \Delta)$

Hofherr et al., Phys. Rev. B 80, 054510 (2009)

Origin of Dark count rate

DE & DCR vs Bias Current



✓ Vortex-related

✓ Blackbody Radiation of fiber

G Pepe, Napoli 2019

Where we are…where w’re going

Fabrication of high quality superconducting ultrathin films for SNSPDs: NbN, MoSi, MoRe

Nanopatterning of <20x20 um2 area SNSPDs also in collaboration with CNR IFN Rome, Chalmers University -> nanofabrication upgrade *in progress*

Measurement set-up for DE nd DCR without shielding and direct fibre coupling at 4K->

- **closed-cycle 2K cryogenic system quipped with two SNSPDs lines optimized at different wavelenghts, i.e. <1550nm and up to 2300nm;**
- **fibre optic line within a TRITON cryo system for measurements down to 20mK;**
- **possibility of developing superconducting read-out electronics within the SeeQC_EU collaboration.**

Possibility to cover within scientific collaborations with quantum optics groups

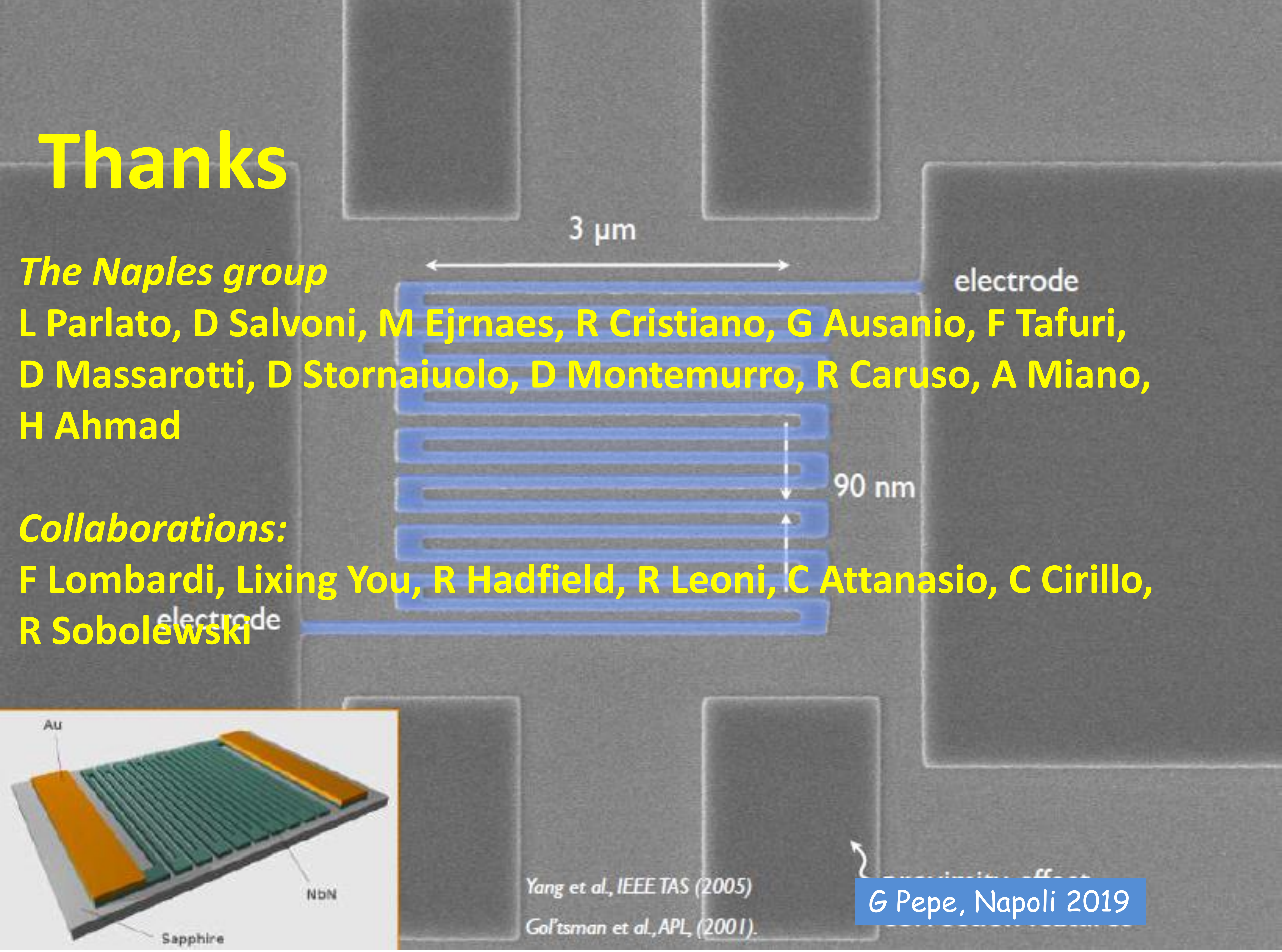
Thanks

The Naples group

L Parlato, D Salvoni, M Ejrnaes, R Cristiano, G Ausanio, F Tafuri, D Massarotti, D Stornaiuolo, D Montemurro, R Caruso, A Miano, H Ahmad

Collaborations:

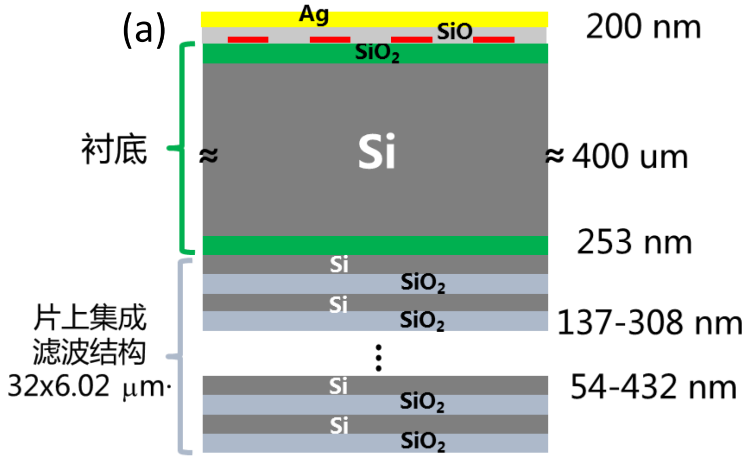
F Lombardi, Lixing You, R Hadfield, R Leoni, C Attanasio, C Cirillo, R Sobolewski



Yang et al., IEEE TAS (2005)

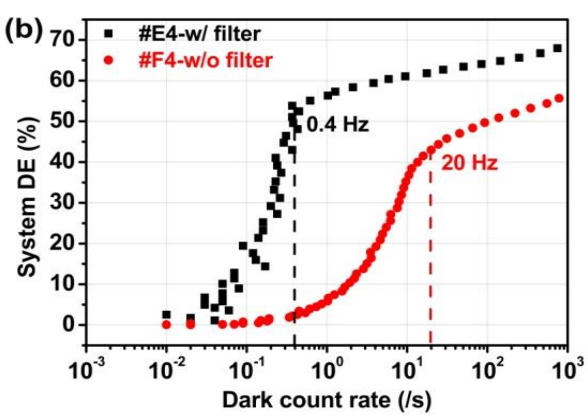
Gol'tsman et al., APL (2001).

How to suppress thermal DCR

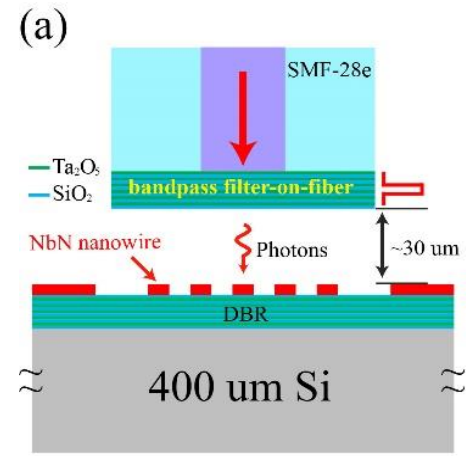


Onchip filter on backside

OE 22, 16267 (2014) Patents in CN, USA, JP

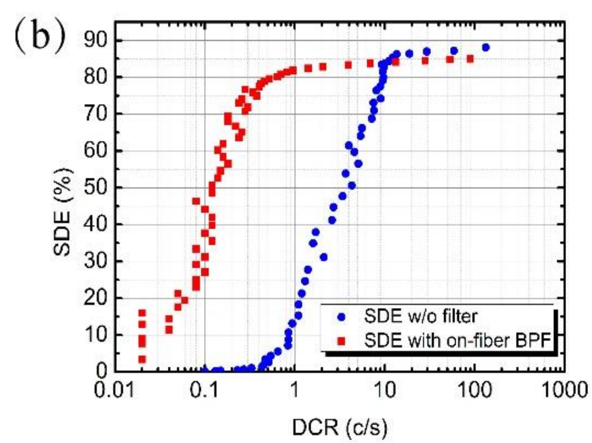


DE56%@DCR0.4Hz @ Y2014



Filter on fiber tip

SUST 2018



DE80%@DCR1Hz @ Y2017

G Pepe, Napoli 2019