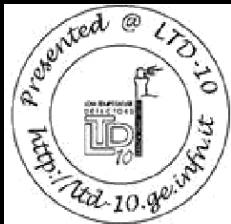




# Ultimate Performance of a Superconducting Quantum Detector



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Konstantin Il'in, Uni Karlsruhe, Germany

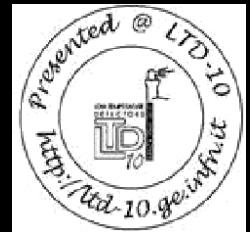
Heinz-Wilhelm Hübers, DLR

Michael Siegel, Uni Karlsruhe, Germany





# OUTLINE



## Idea – Mechanism

- HOT-SOPT Mechanism of Single photon Detection in a current carrying superconducting film

## Experiment - Verification

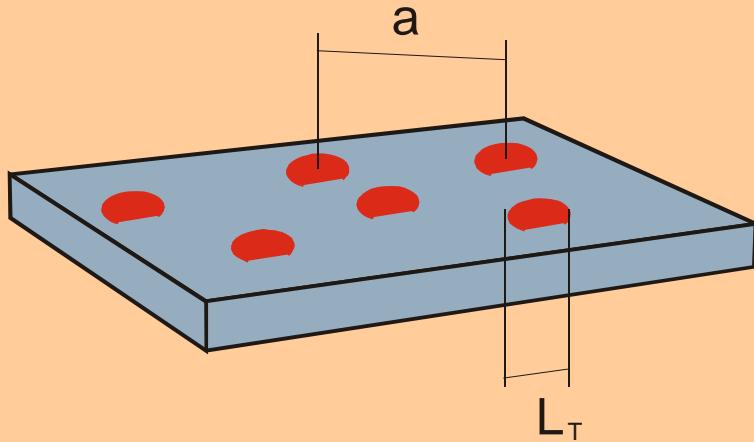
- NbN and Nb single-photon detectors. They work, but...
- Modified NbN – first confirmation of the mechanism

## Applications

- Background limited quantum detector for astronomy
- Quantum detector for X-ray spectroscopy and microanalysis



## Microscopically uniform and discrete detection regimes



$L_T = (D \tau_T)^{1/2}$ ,  $\tau_T$  is the cooling time of electrons

$a \ll L_T$

$a \gg L_T$

**Microscopically uniform regime      Discrete, quantum regime**

For 10- $\mu\text{m}$  wavelength the demarcating power flux

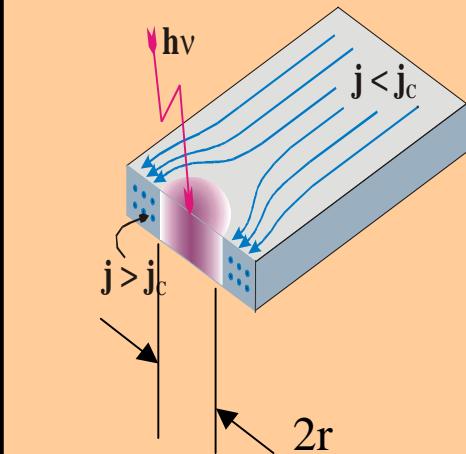
$$3 \cdot 10^{-19} \text{ W/cm}^2 (\tau_T \approx 10^{-11} \text{ s}, 4 \text{ K})$$

or

$$3 \cdot 10^{-24} \text{ W/cm}^2 (\tau_T \approx 10^{-6} \text{ s}, 0.1 \text{ K})$$



# Current Assisted Hot-Spot Detection Regime



**Detection criteria**

$$2 \frac{r_m}{w} \geq 1 - \frac{I}{I_C}$$

A.Semenov et. al,  
Physica C 351, 349 (2001),  
European J. Appl. Phys. (2003)

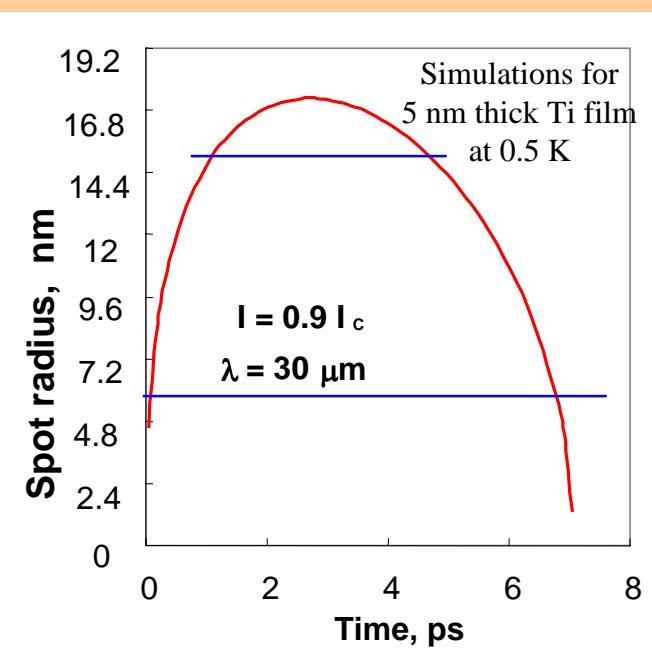


$$r_m = \sqrt{\zeta \frac{h\nu}{\Delta} \frac{1}{2D\tau_{th} d N_0 \Delta}} \left( \frac{1}{\pi^4 N_0 \Delta} \right)^{1/3} \ln \left( 1 + \pi^2 \frac{h\nu}{\Delta} \frac{1}{D\tau_{th} d N_0 \Delta} \right)$$

**The detection mechanism features:**

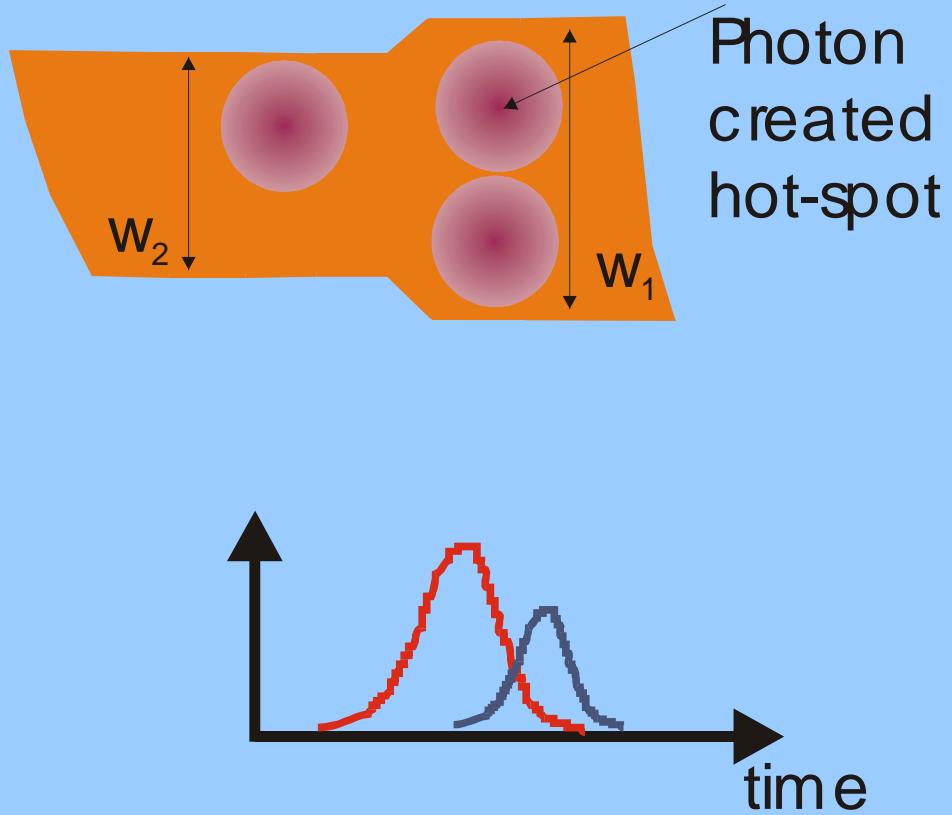
- tunable spectral cutoff
$$r_m \propto \sqrt{h\nu/T_C}$$

- energy resolution



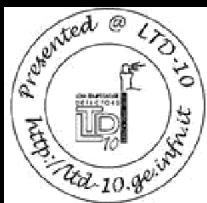


## Multiphonon process



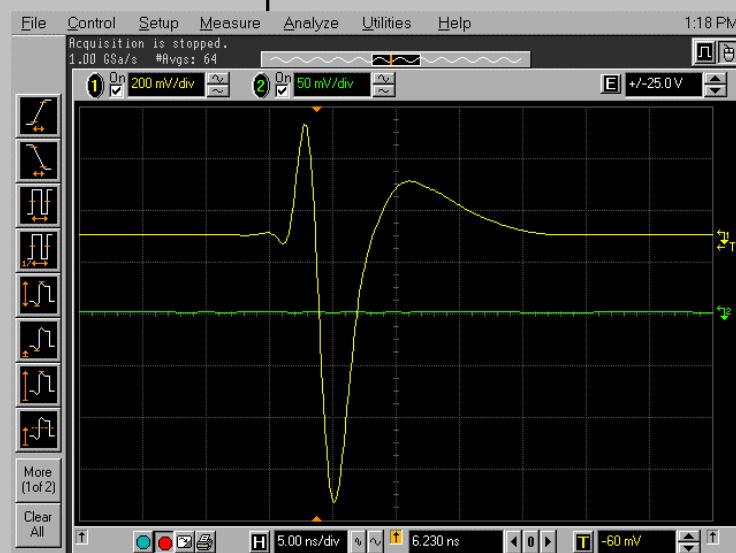
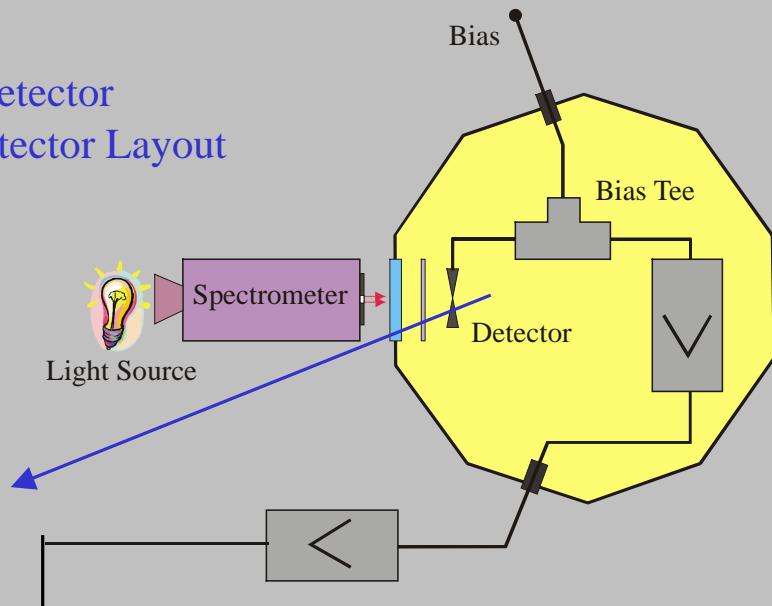
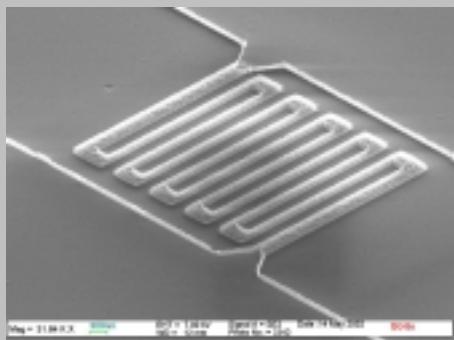
**Probability of absorbing  $m$  photons from the pulse containing  $N$  photons**

$$P(m) = \frac{e^N N^m}{m!} \propto \frac{N^m}{m!} \quad \text{for small } N$$



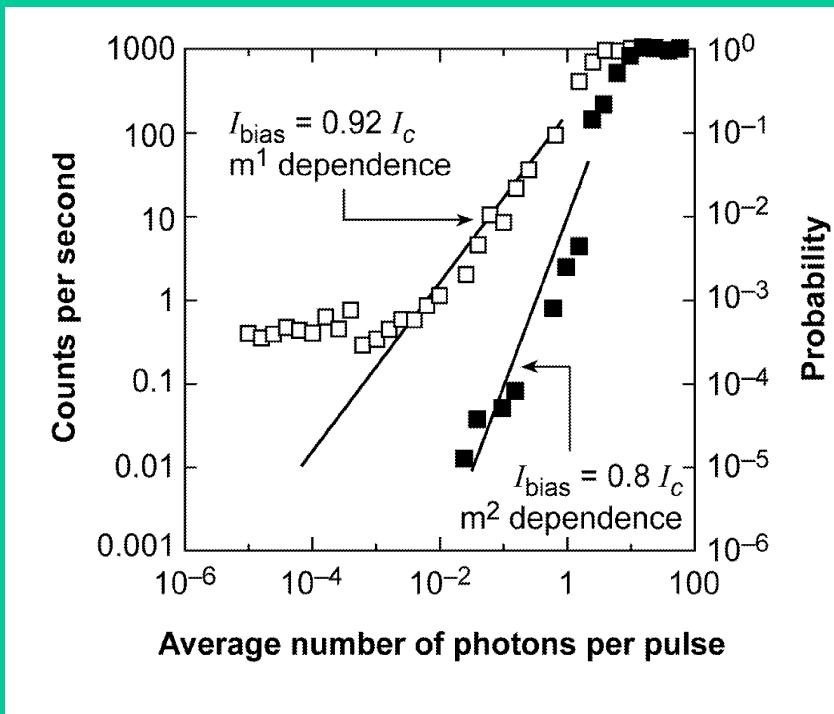
## Experiment - CW regime

Nb single-photon detector  
Experimental Setup & Detector Layout



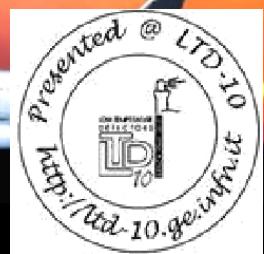


## Experimental data single & multiphoton regime



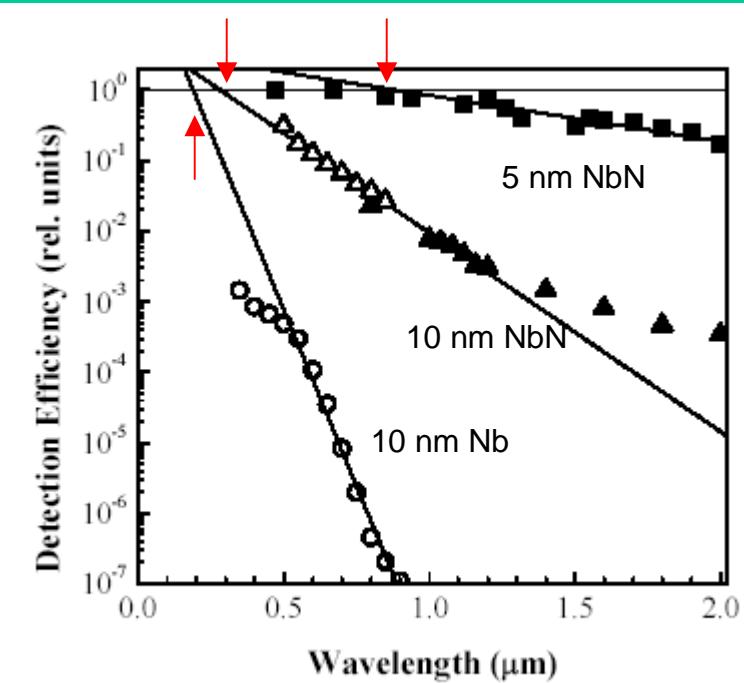
Göl'tsman et all, APL 2001, MSPU in co-operation with the University of Rochester, USA

Time delay of the resistive state formation has been recently demonstrated that confirms the current assisted nature of the detection mechanism.  
Uni. Rochester & MSPU, PRB 2003



## Experimental data

### Beyond the spectral cut-off ?



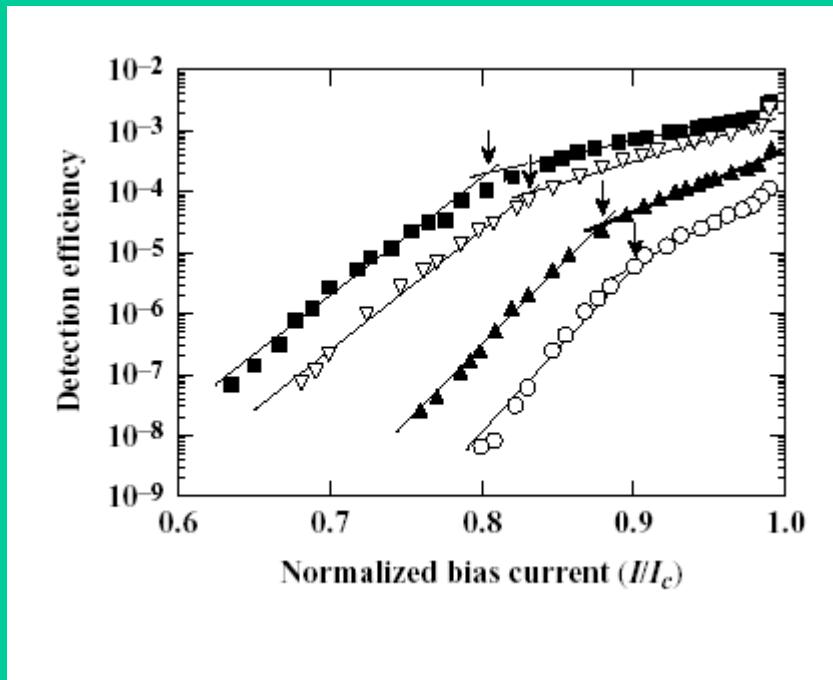
Thicker films or those with better diffusivity shows no plateau - detection efficiency decreases with the wavelength

**NbN - Verevkin et al, APL 2002**



# Experimental data

## Beyond the spectral cut-off ?



There is no plateau in the current dependences of the detection efficiency, instead it continuously drops when current decreases. The slope depends on the photon energy

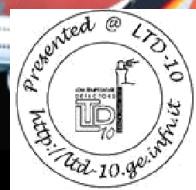
Verevkin et all, APL 2002



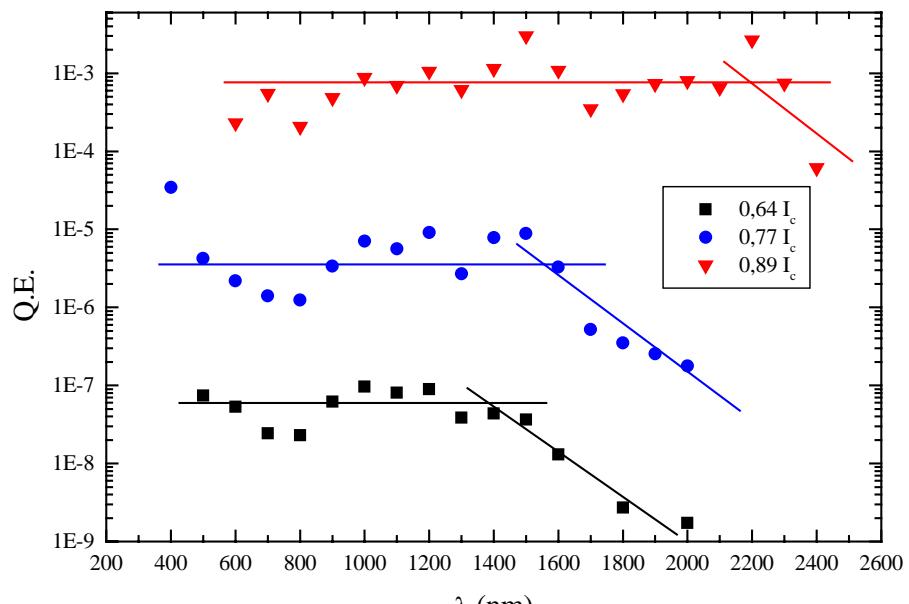
## What about another material?

We used NbN films deposited at low N<sub>2</sub> pressure and at a high deposition rate. Nitrogen deficiency resulted in lower transition temperature, smaller critical current and reduced density of electronic states.





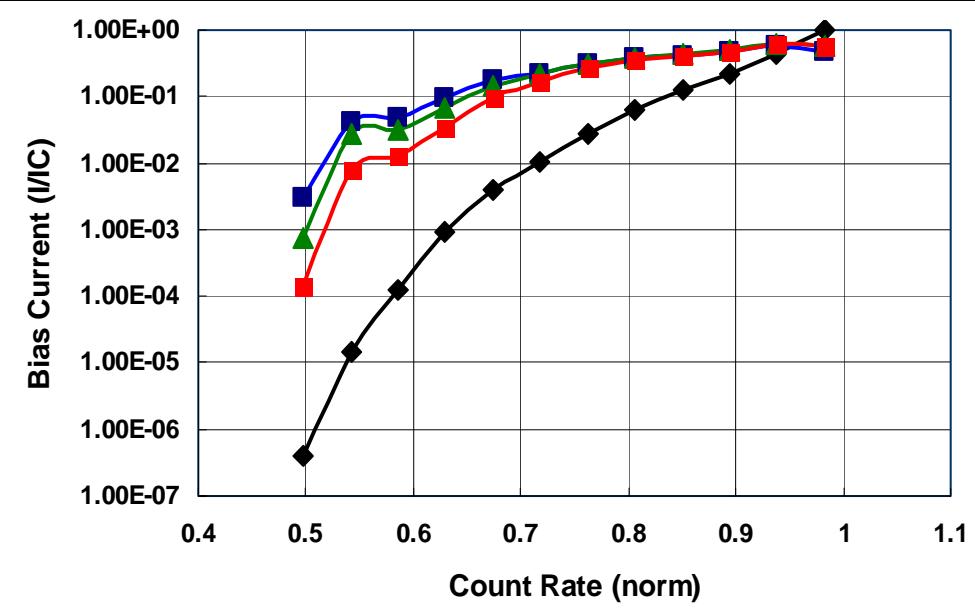
## Spectral cut-off



The hot-spot model predicts constant efficiency before the cut-off and vanishing efficiency at larger wavelengths. Indeed, there appears the plateau and the clearly seen roll-off wavelength that depends on the bias current



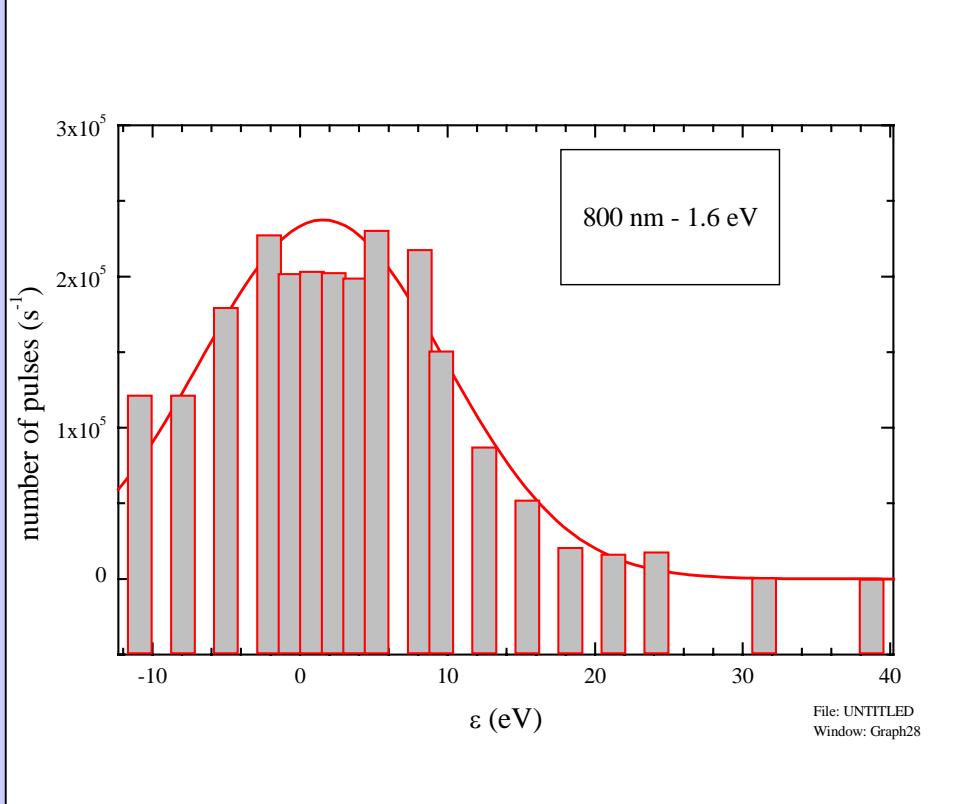
## Signal counts vs Bias Current



Current dependences of signal counts show almost “ideal” behaviour. However, the model predicts abrupt drop of the efficiency beyond the roll-off



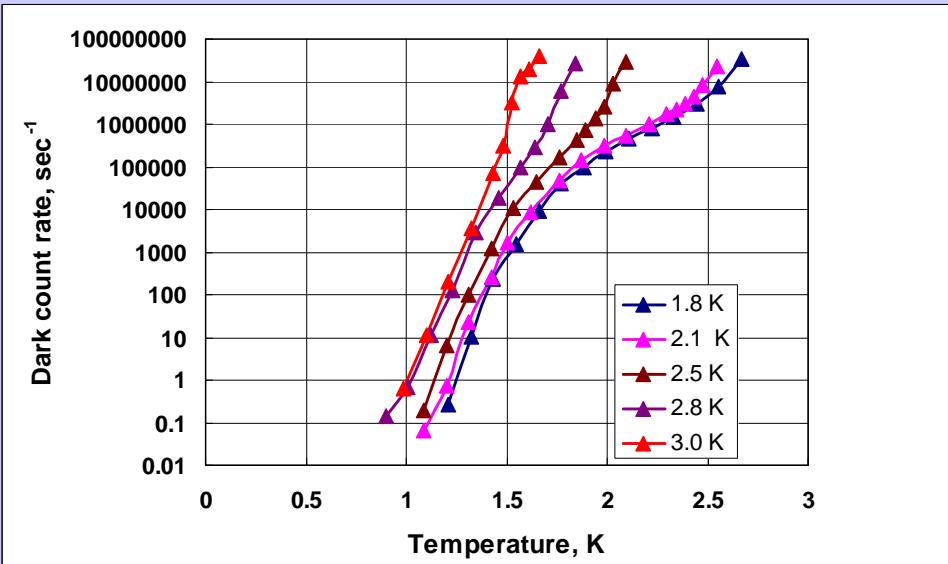
## Energy resolution



The HWFM resolution of 12 eV was found for unoptimized readout.



## Experimental data Dark counts

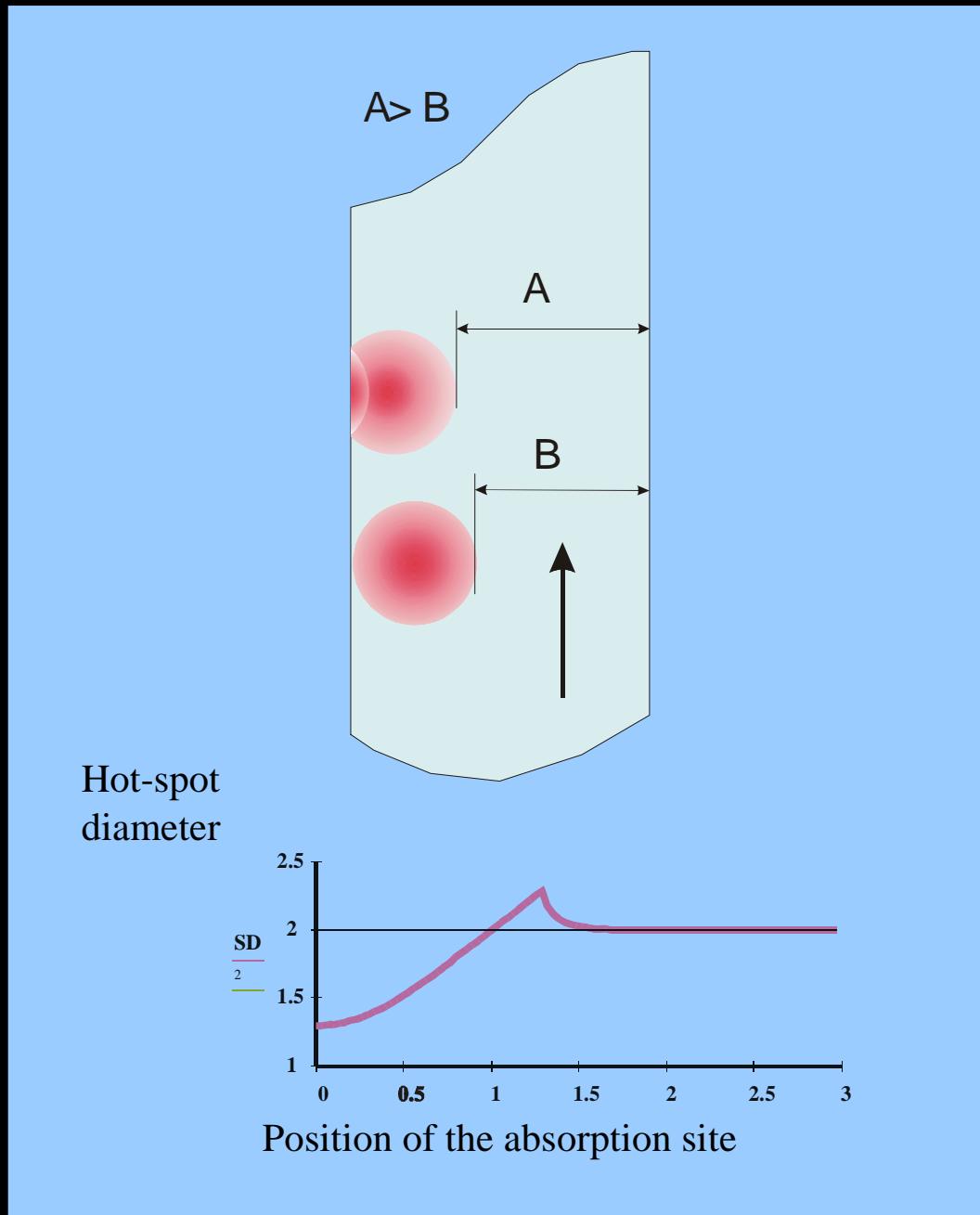


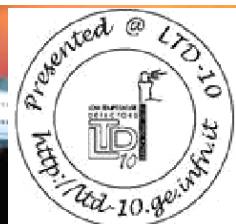
$$n = A_R \exp\left[-\frac{\Delta F \xi^2 d}{k_B T} \left(1 - \left(\frac{I}{I_C}\right)^2\right)\right]$$

Dark counts appear due to order-parameter fluctuations. Relevant volume has the size comparable to the coherence length.

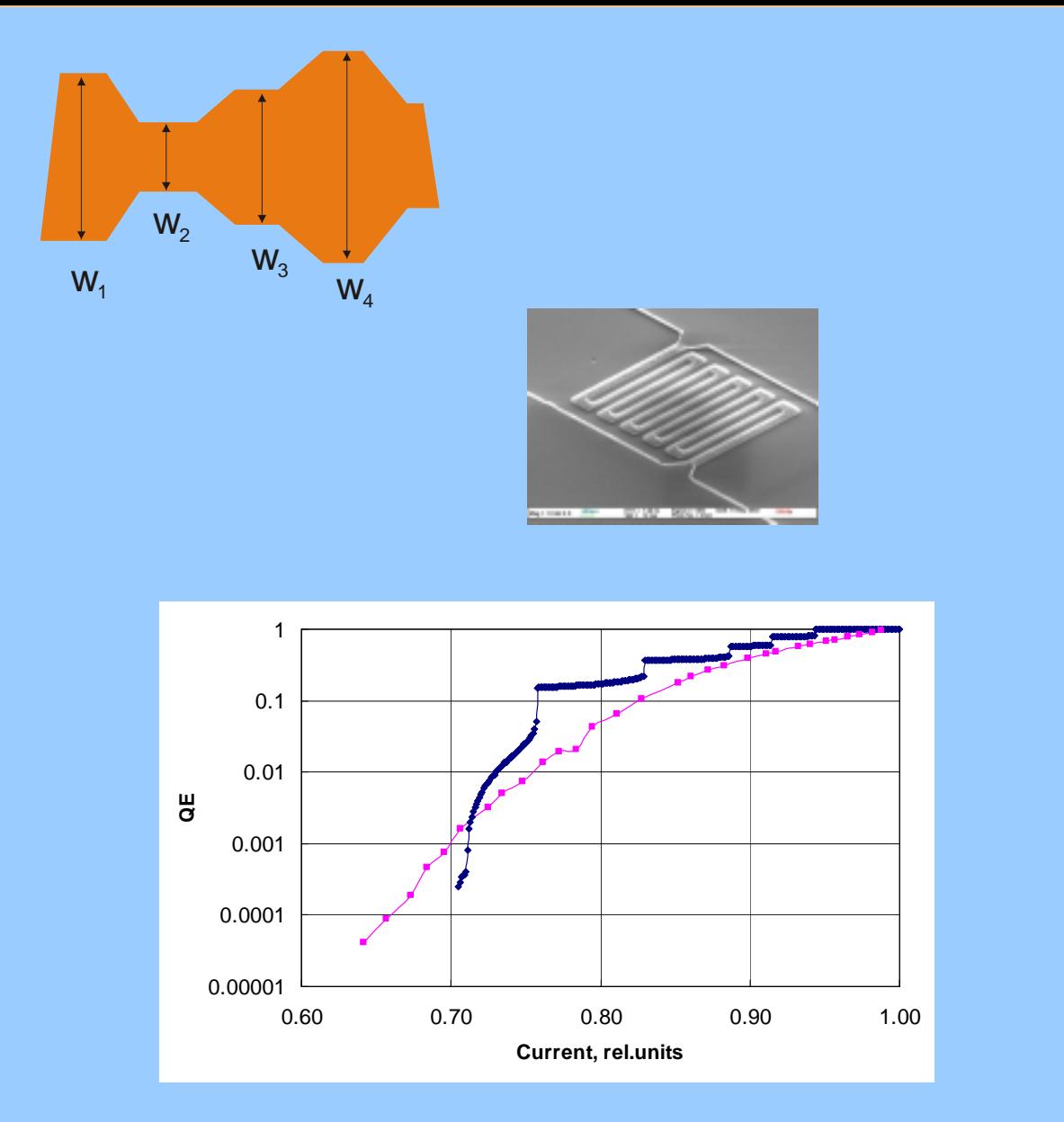


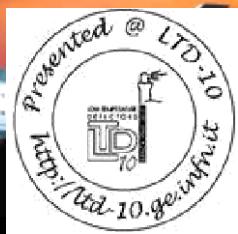
## Edge effect



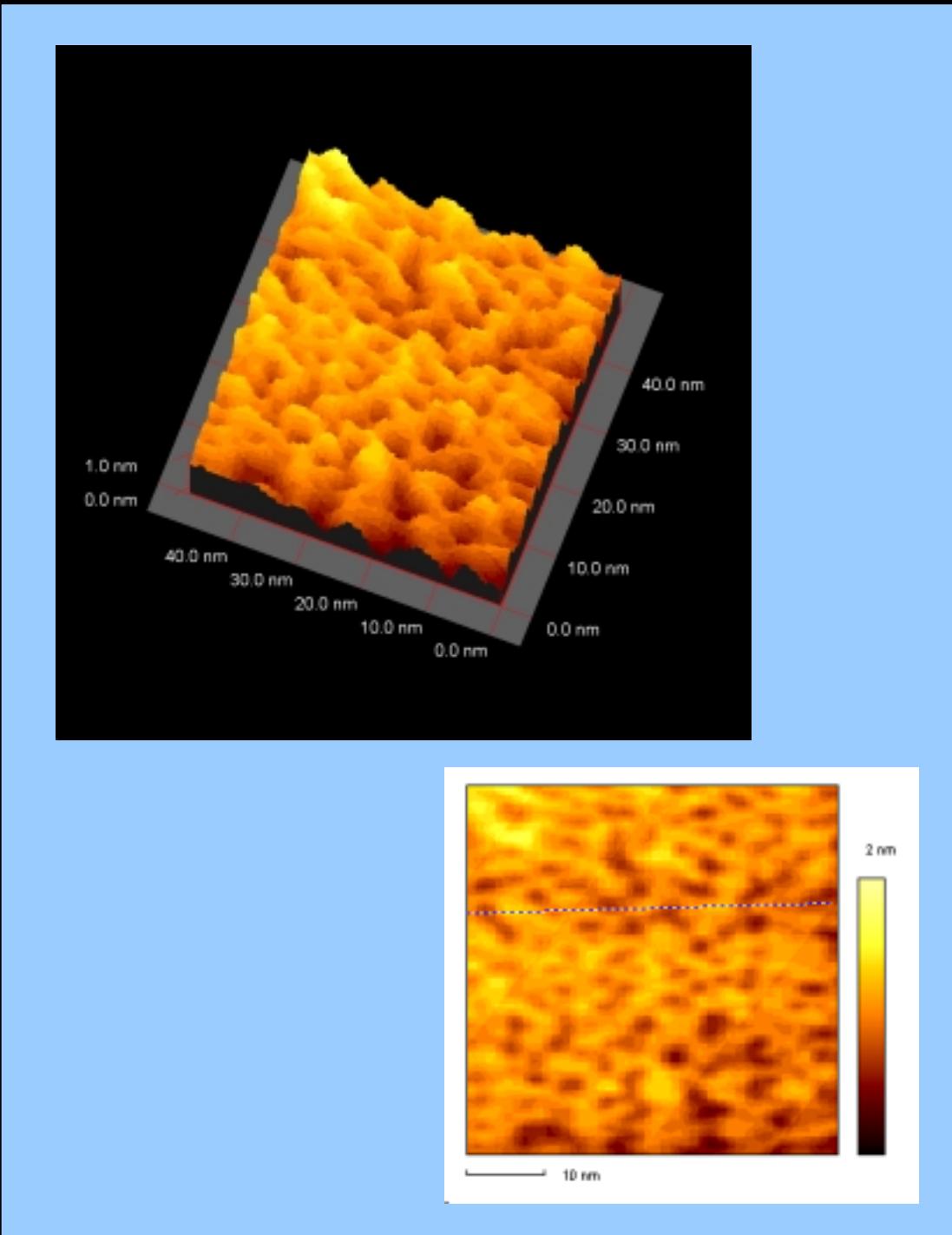


# Nonuniformities as possible reason for current dependence of QE



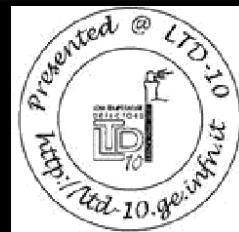


## Morphology of 3-nm thick NbN film





# Applications

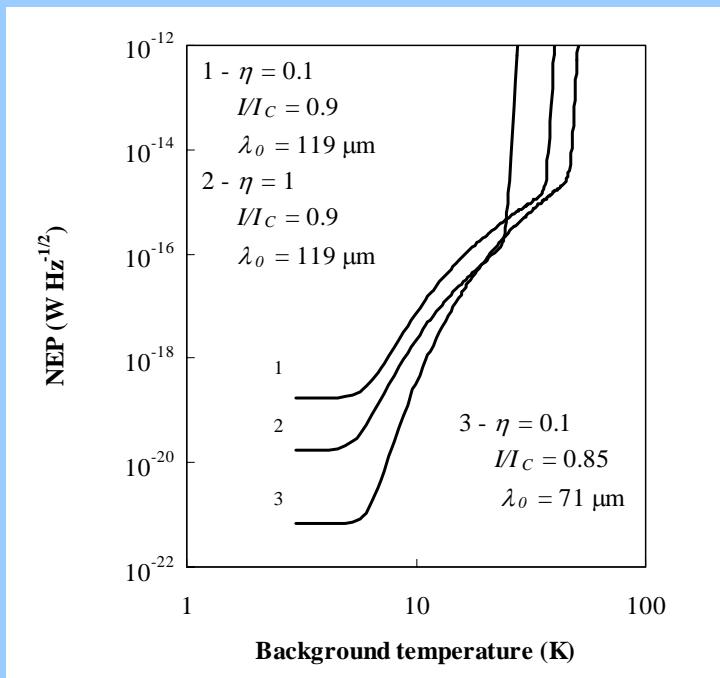


- **Debugging of transistors in the PC processors –**  
**University of Rochester & MSPU**
- **Spectroscopy of interstellar dust clouds at wavelengths around 70 mm.**  
**Background limited performance down to 4 K telescope temperature**
- **X-ray spectroscopy**  
**1 ppm energy resolution**
- **Solar blind applications where UV photons are detected in the presence of bright visible photon sources.**  
**Tune the cut-off wavelength to ultraviolet**
- **Another foreseen applications – tracing dynamics of single molecules, Quantum cryptography.**

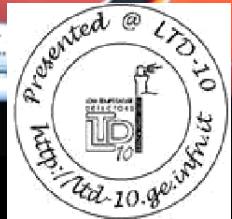


# Background limited quantum detector for astronomy

Computed Noise Equivalent Power for the Ti direct quantum detector

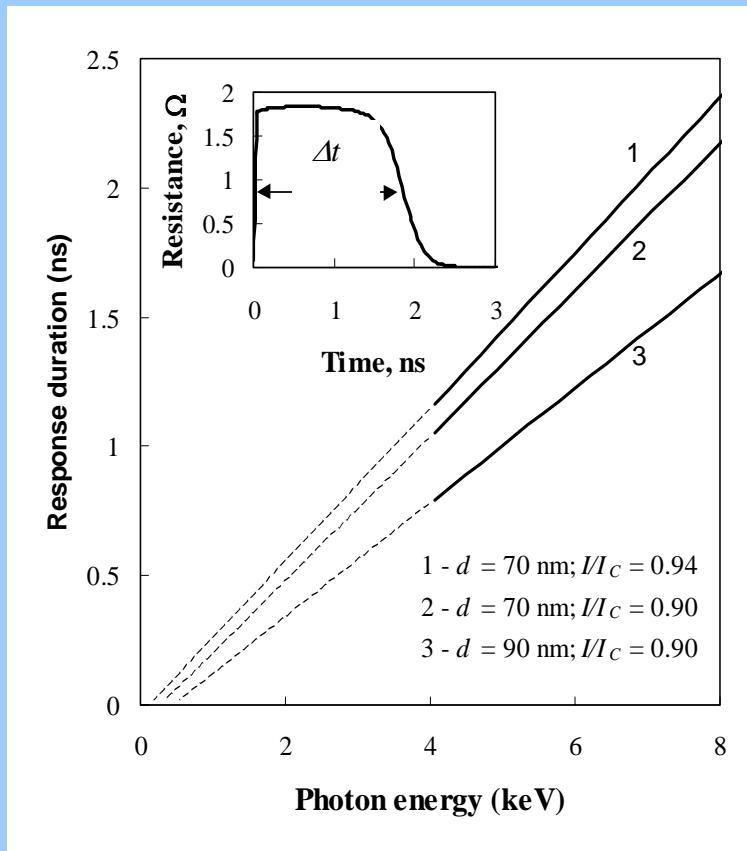


Expected energy resolution at 40 μm – 1/20  
that is sufficient for spectroscopy of interstellar  
dust clouds



## X-Ray Photon Counter

Response duration of the Ta X-ray photon counter as function of the photon energy



Pixel  $2.5 \times 2.5 \mu\text{m}^2$   
 Film thickness  $70 \text{ nm}$   
 Projected energy resolution -  $\approx 10^{-4}$  for 6 keV photons



## CONCLUSION

**The mechanism of current-assisted hot-spot single photon detection in a current biased superconducting film has been proposed**

**Practical NbN Superconducting Quantum Detectors have been demonstrated, although the mechanism is not yet fully proved.**

**Variation of the material parameters allowed us to observe key features of the envisioned detection mechanism.**

**The technology seems to be feasible for further applications. To prove that study of SQD based on another materials is necessary.**

**Special thanks to:**

**Gregory Gol'tsman**

**Alexander Korneev**

**Oleg Okunev**

