IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) October 2014
Invited Presentation 4EOr2C-02 given at ASC 2014, Charlotte, August 10 – 15, 2014.

The temperature dependence of superconducting single photon detectors is a vortex effect

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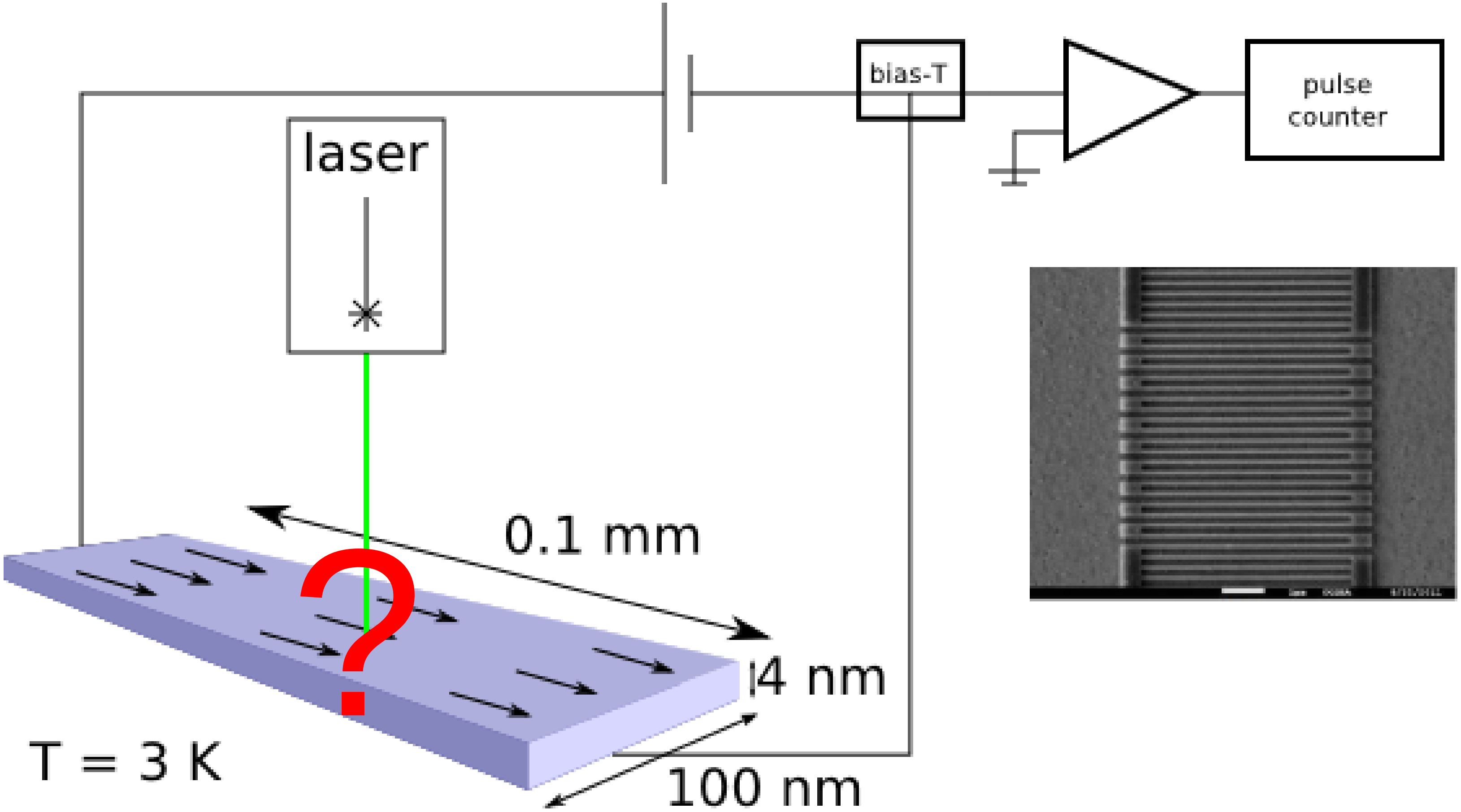
[3)] IFN, Rome, Italy

Goal: investigate SSPD fundamentals



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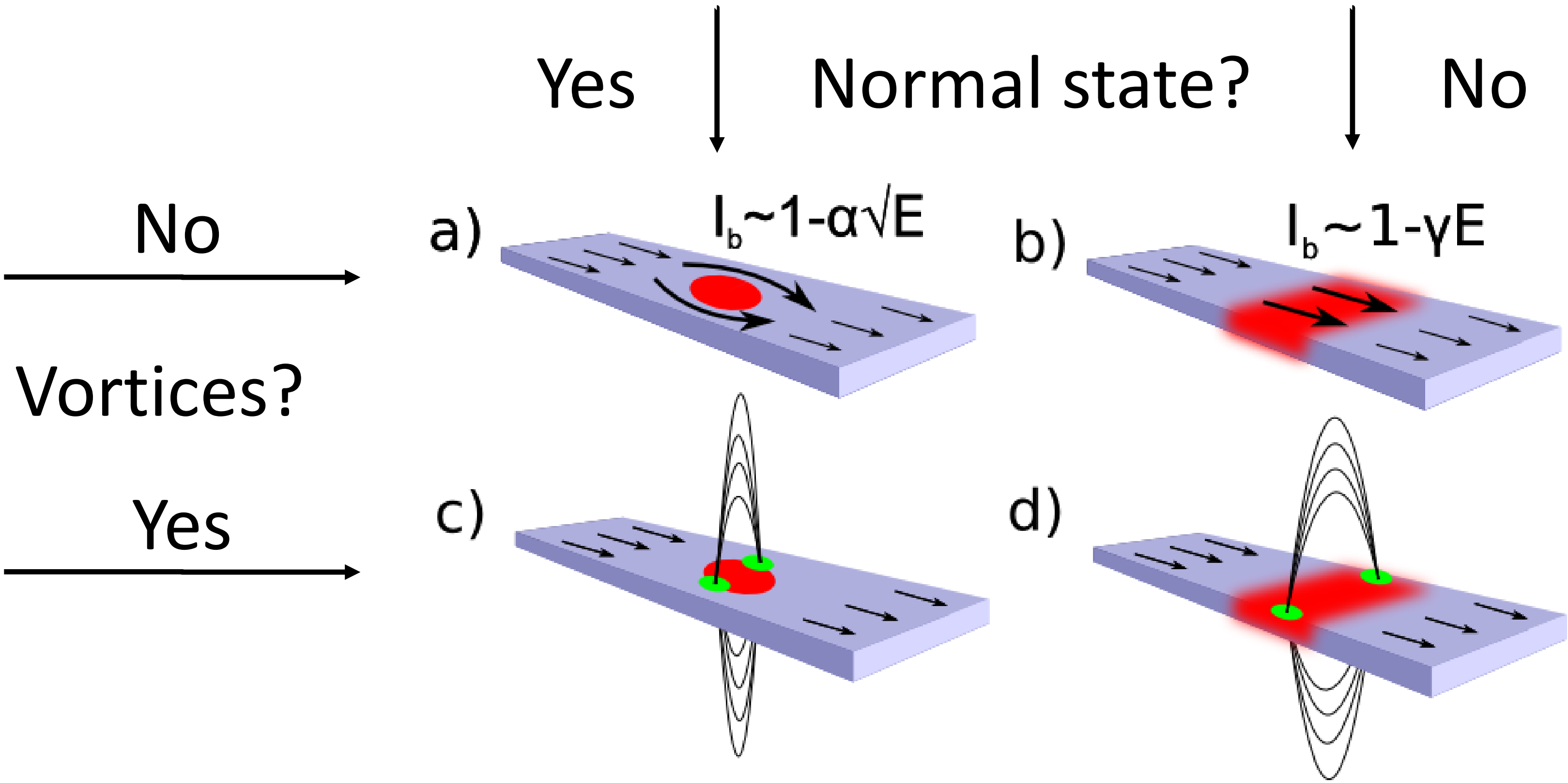
Four models



Four models

Yes | Normal state? | No

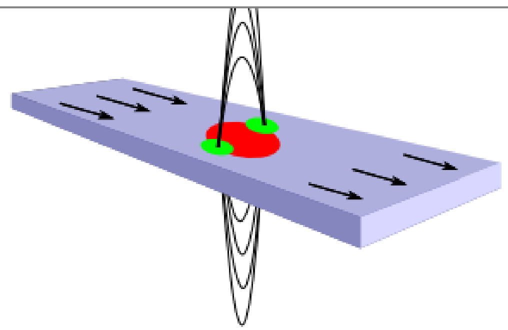
No →

Vortices?

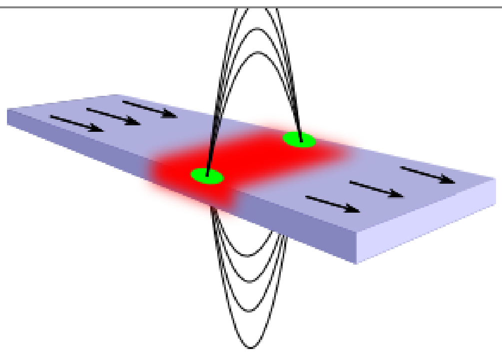
Yes →

Energy-current relationship is key!

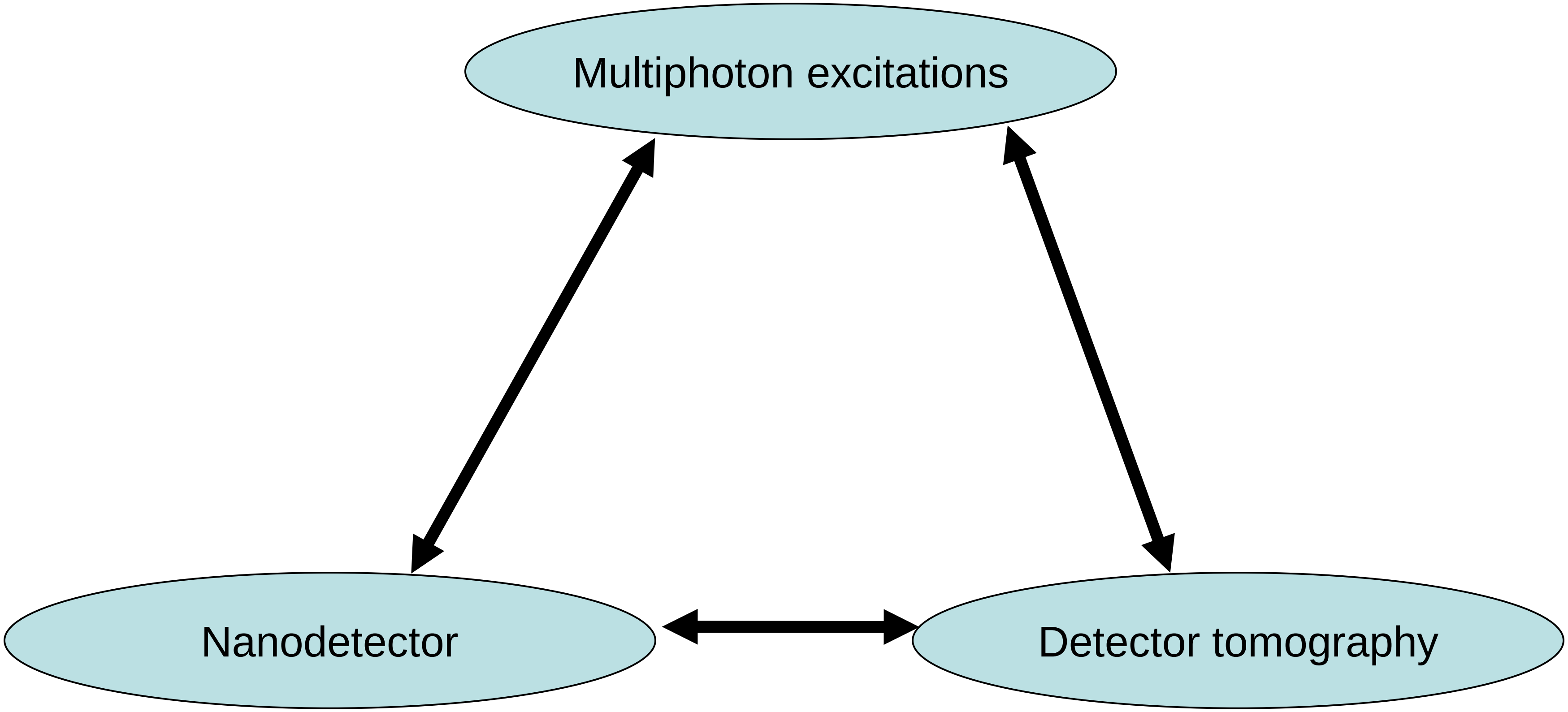
c)



d)



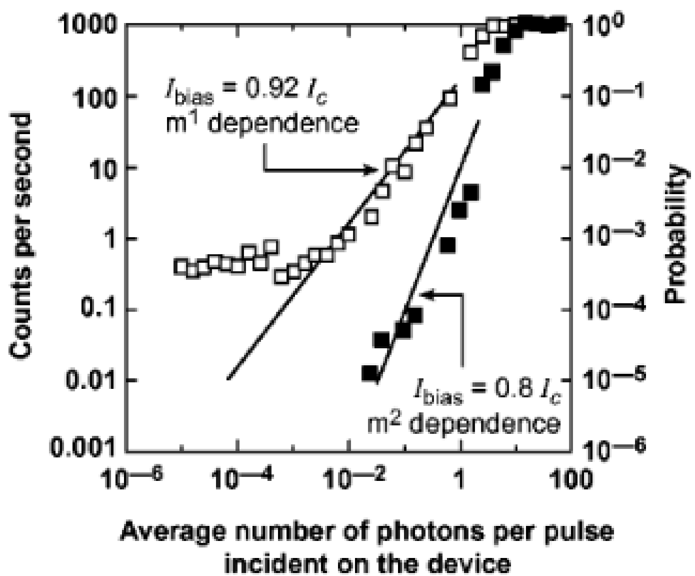
Three inter-related techniques:



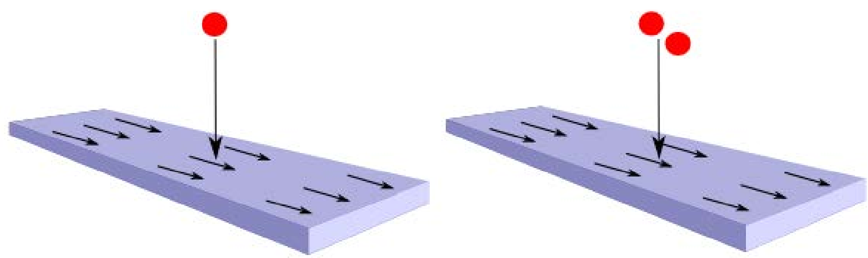
Multiphoton excitations

- Observed in 2001 [1], but considered a curiosity
- Important experimental tool:
  - Enhanced dynamic range
  - Probe with multiple energies in a single experiment

Appl. Phys. Lett., Vol. 79, No. 6, 6 August 2001

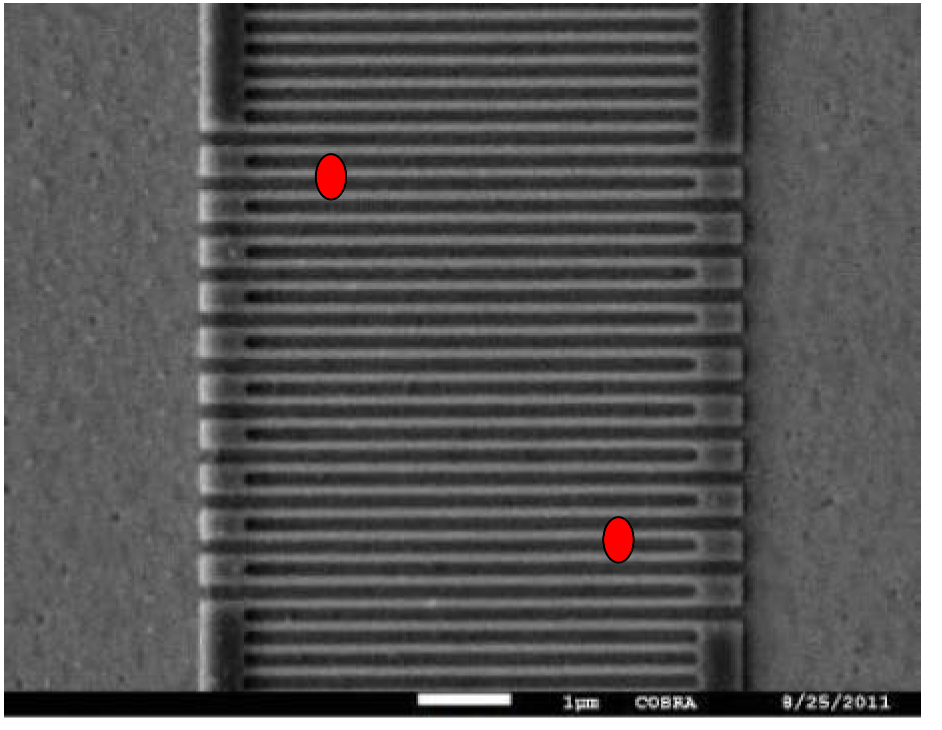


[1] Goltsman APL **79** (2001)



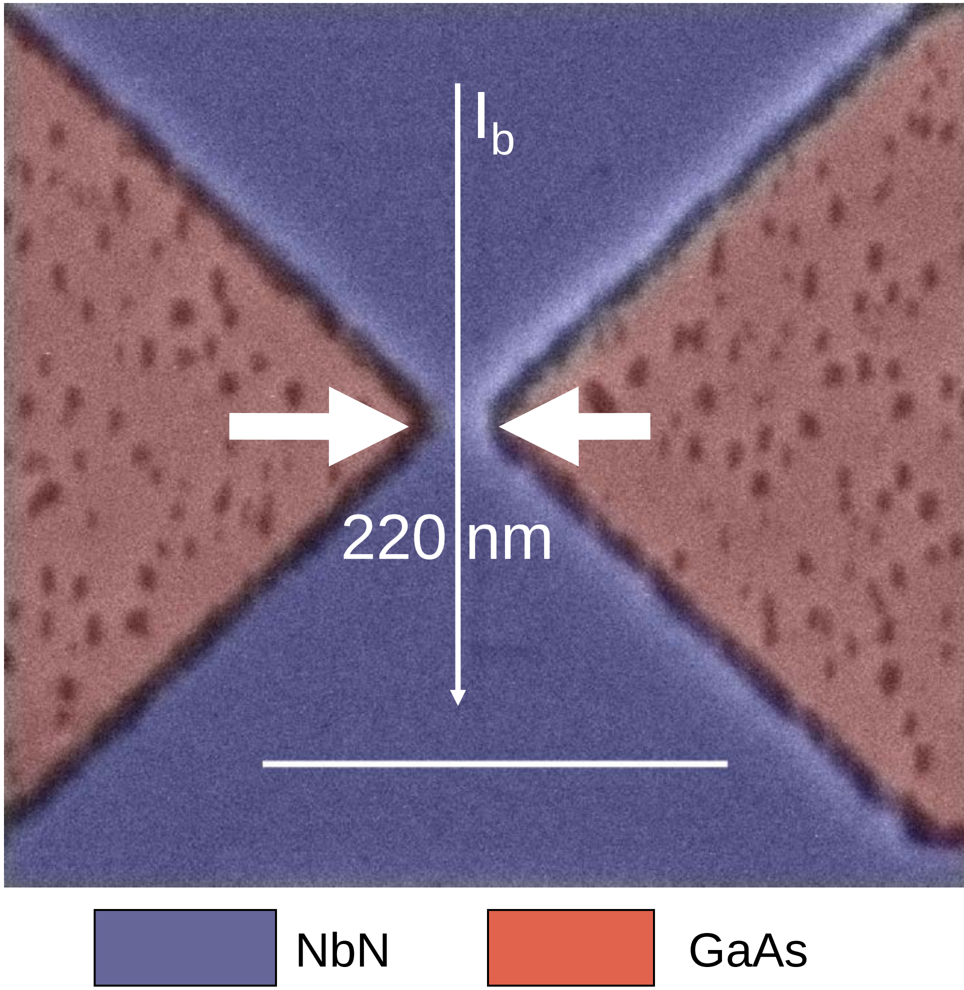
How to study multiphoton excitations?

- Exist in meander, but surpressed due to geometry
- Furthermore: meander has:
  - Bends
  - ‘Constrictions’
- Fundamental study, so efficiency not an issue

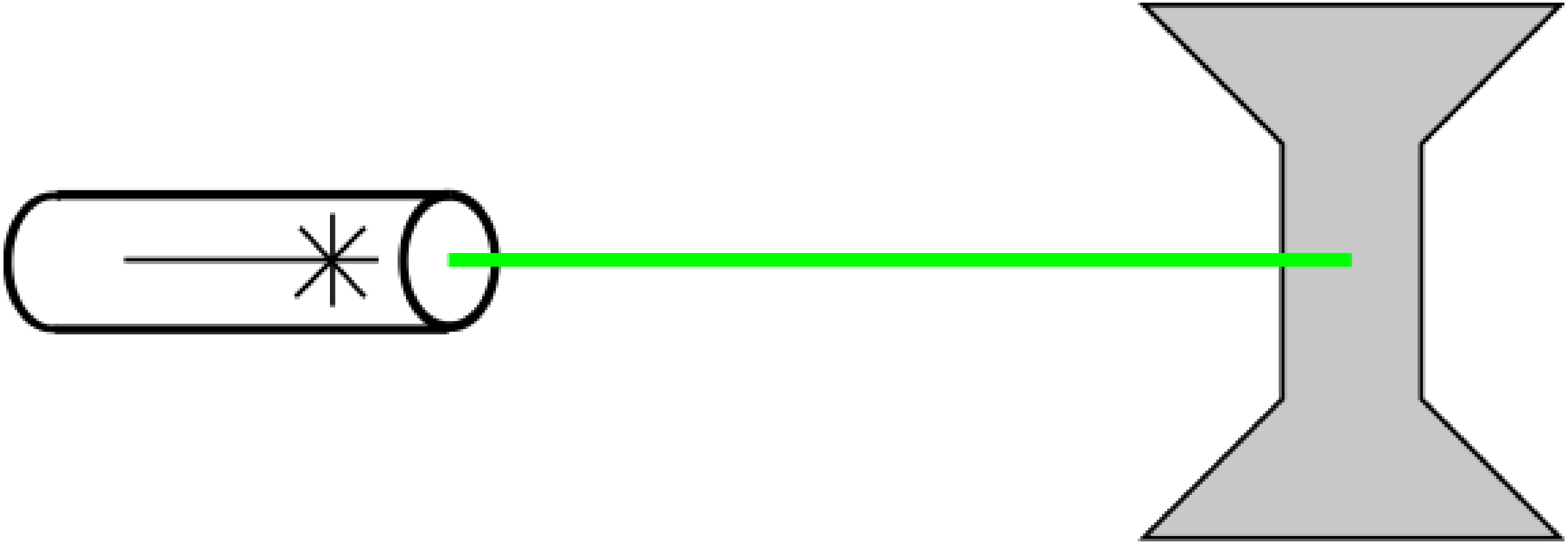


Our sample: nanodetector

- One active point, 150, 220 nm wide NbN on GaAs (5 nm)
- Simple geometry
- Few fabrication errors
- Several multiphoton processes at once

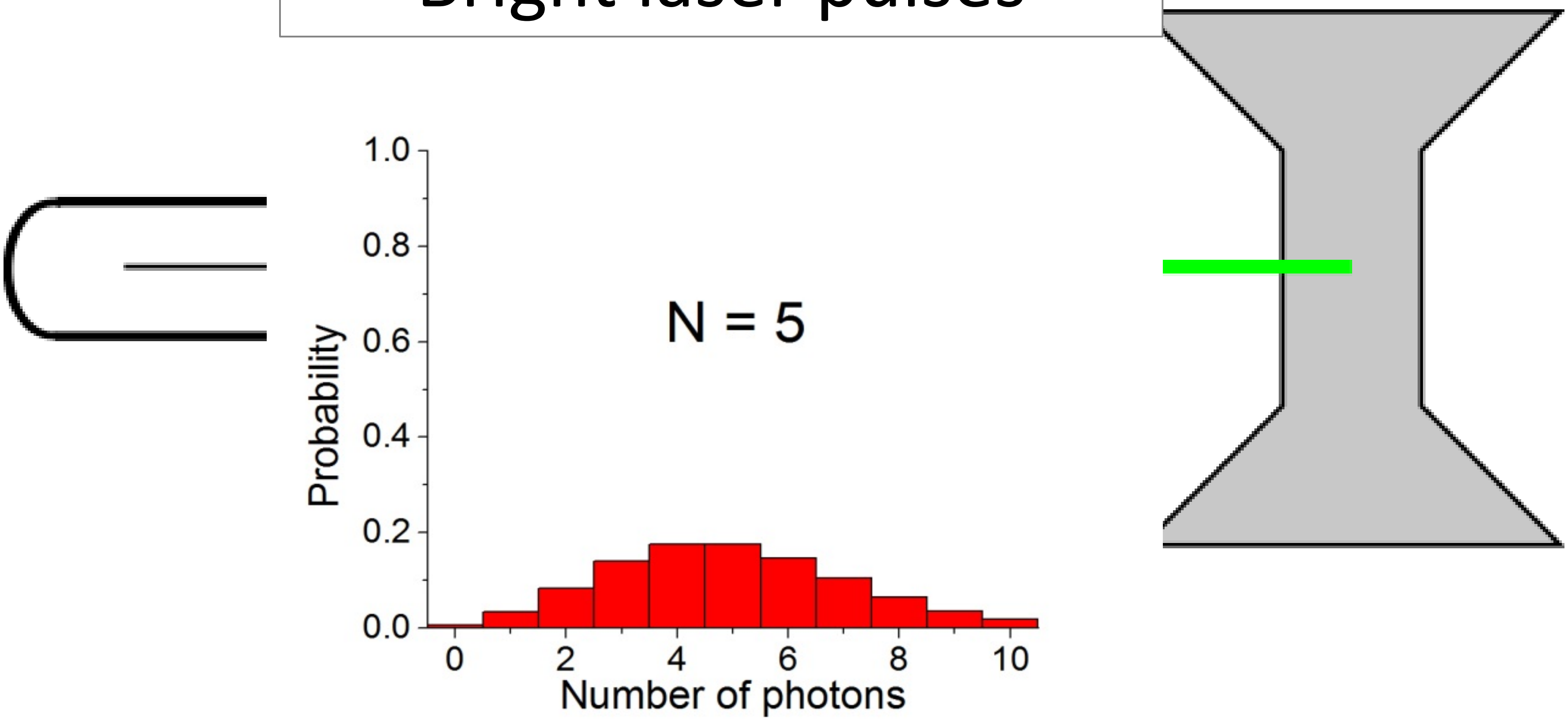


How do you make multiphoton excitations?



How do you make multiphoton excitations?

Bright laser pulses



Quantum detector tomography

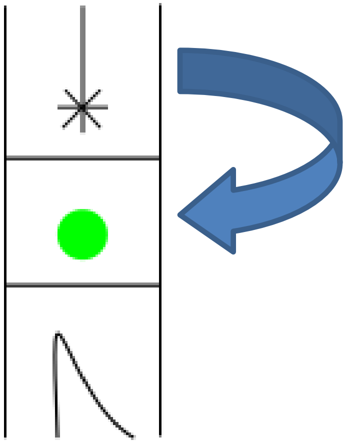
QDT is the bookkeeping of photon number probabilities, click probabilities and detection probabilities

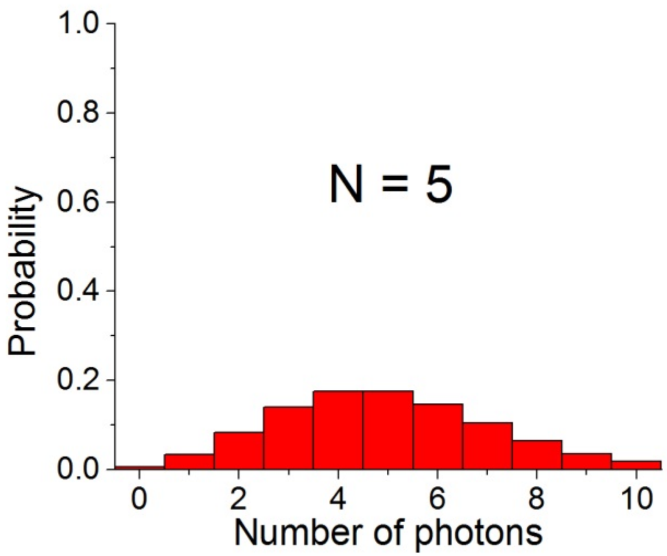
Known from theory

Intensity

# of photons

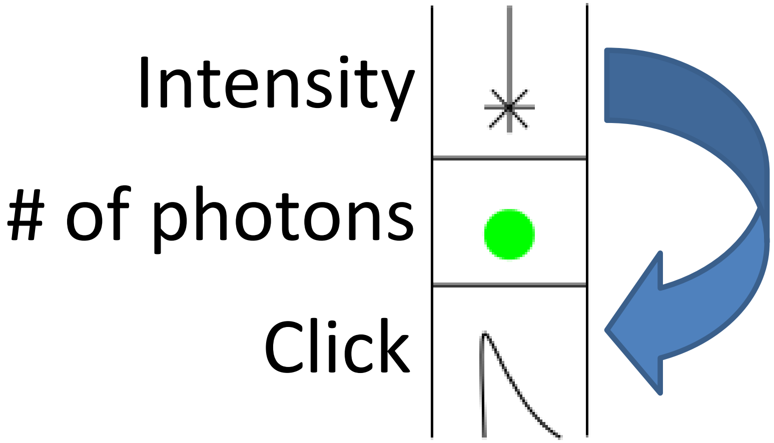
Click

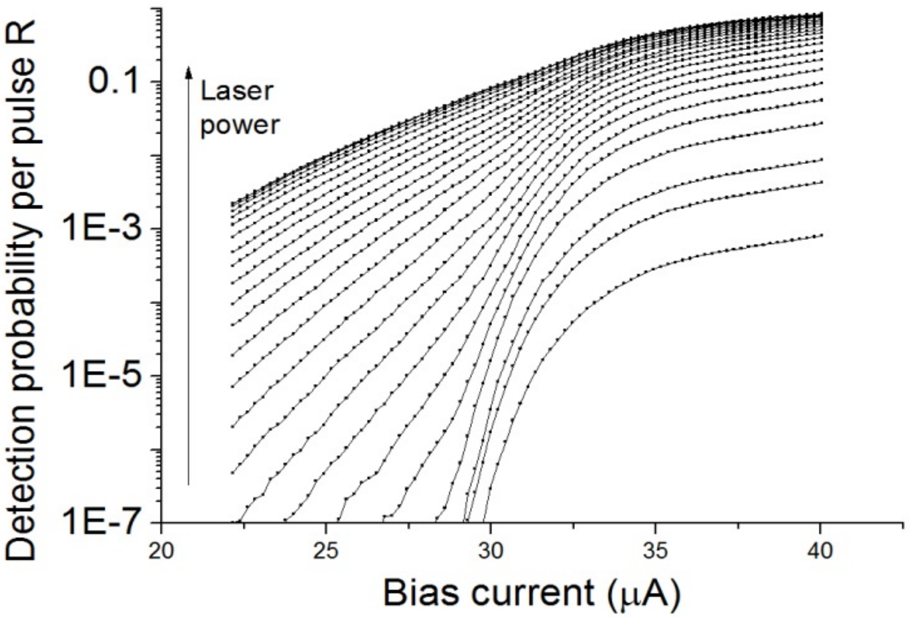




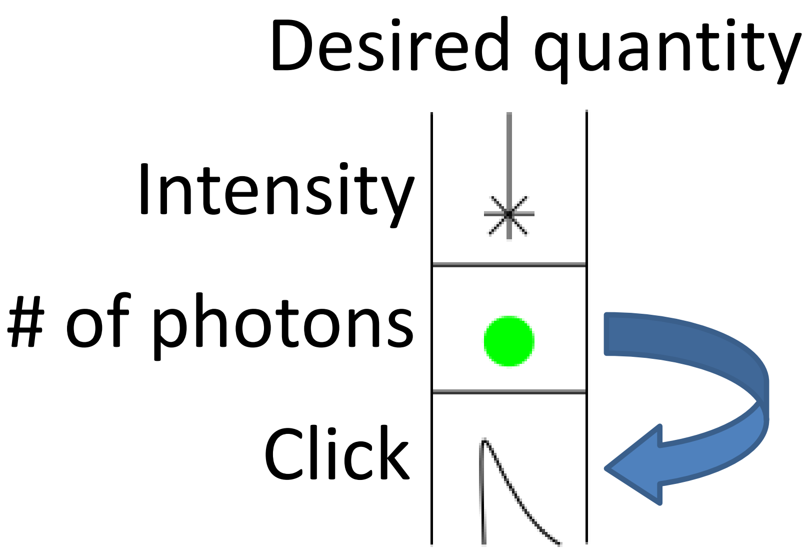
Quantum detector tomography

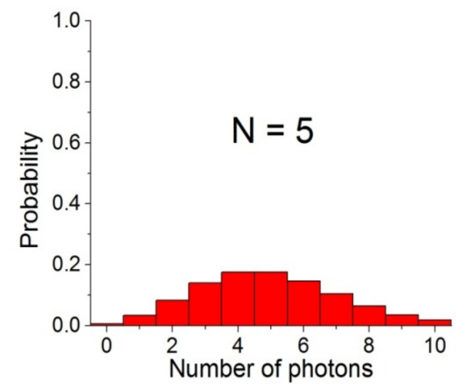
Measured experimentally

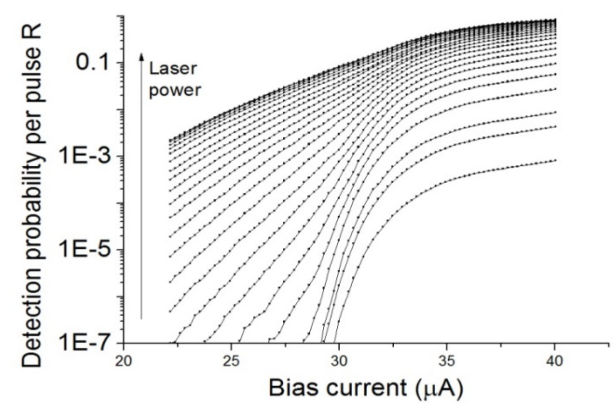




Quantum detector tomography

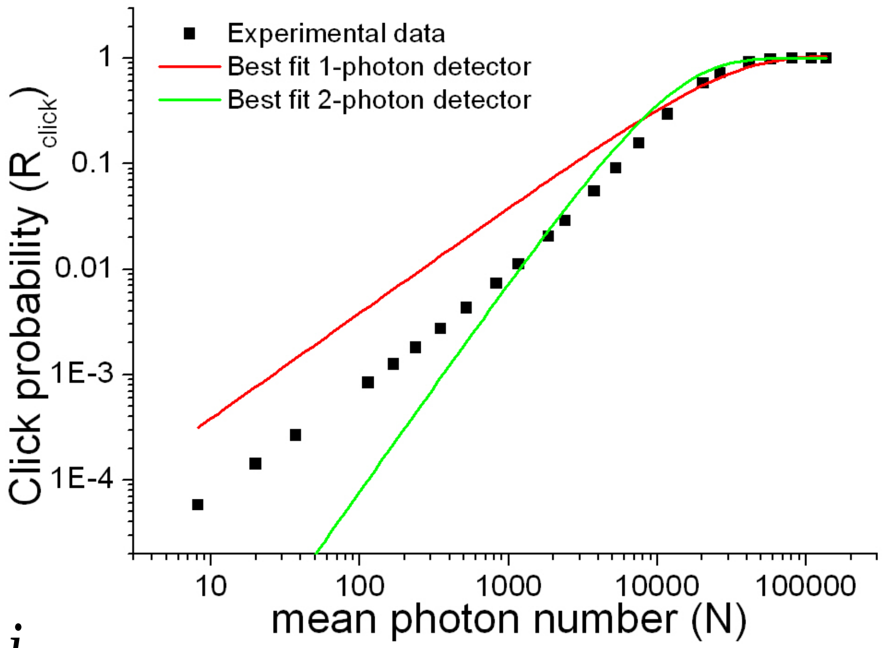






Detector Tomography

- Measure counts vs input intensity
- Response to i photons given by p_i
- Treat linear efficiency seperately, but as free parameter



$$R(N) = e^{-\eta N} \sum_i p_i \frac{(\eta N)^i}{i!}$$

Renema et al, Optics Express 2012

Detector Tomography

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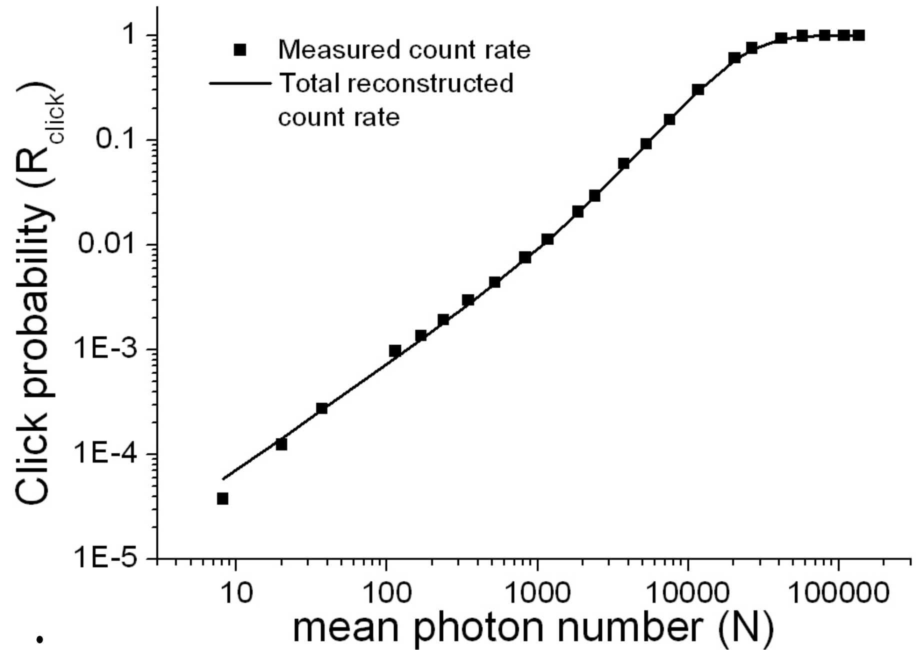

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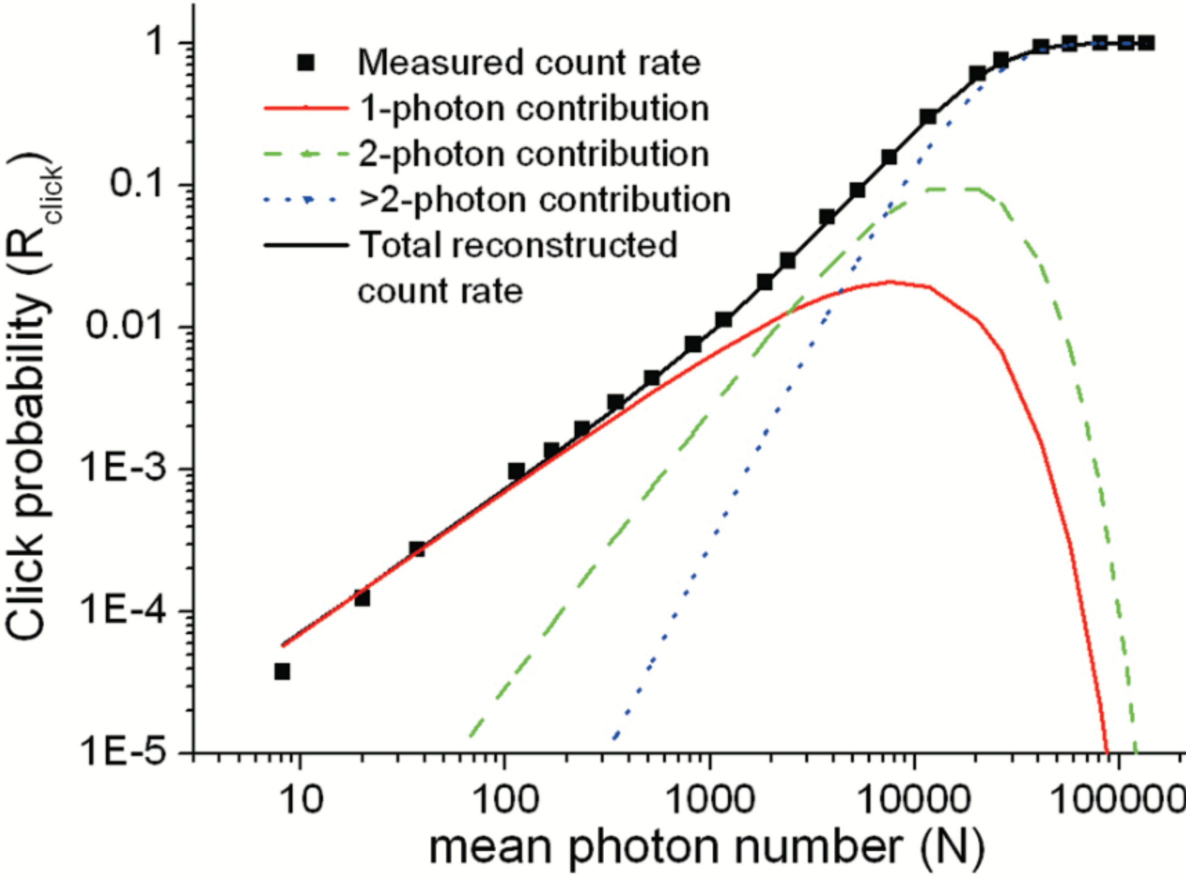
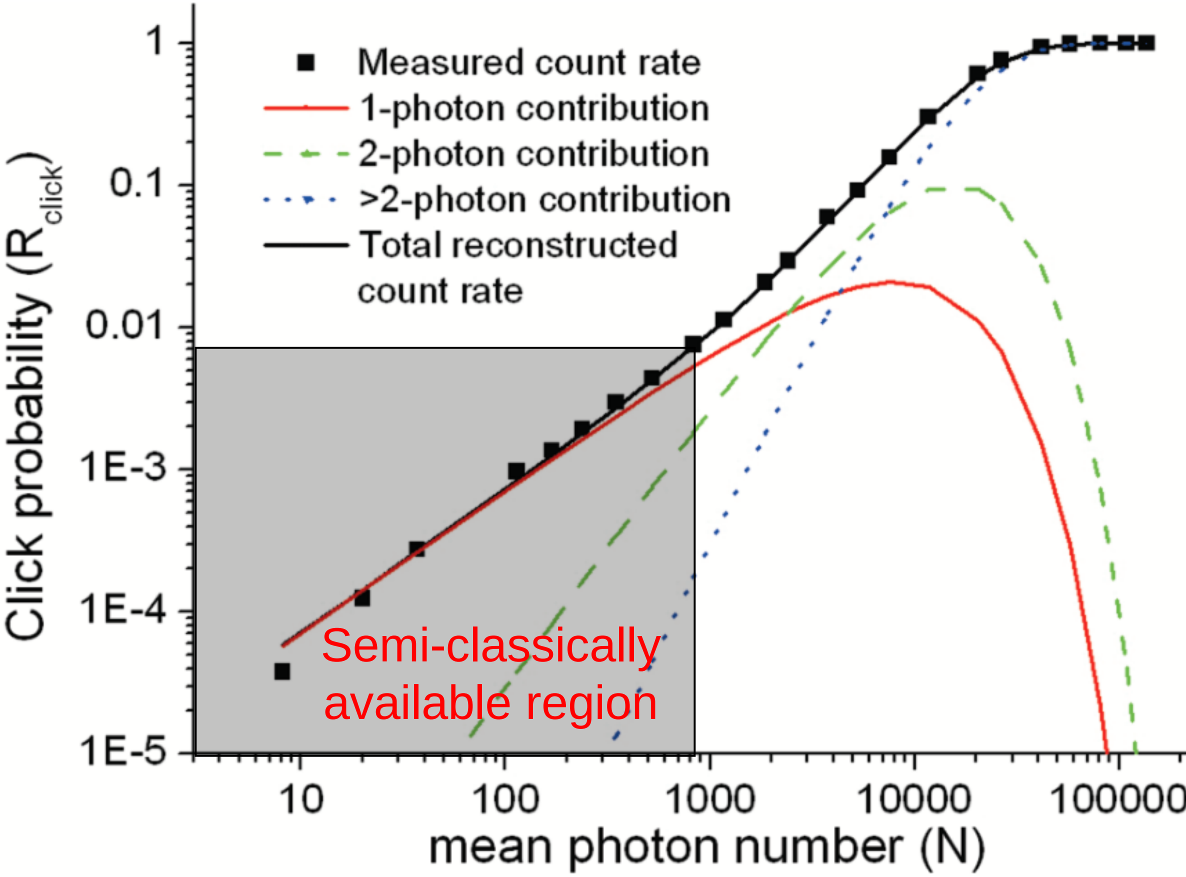
Complete tomography

- 1, 2 photon processes present



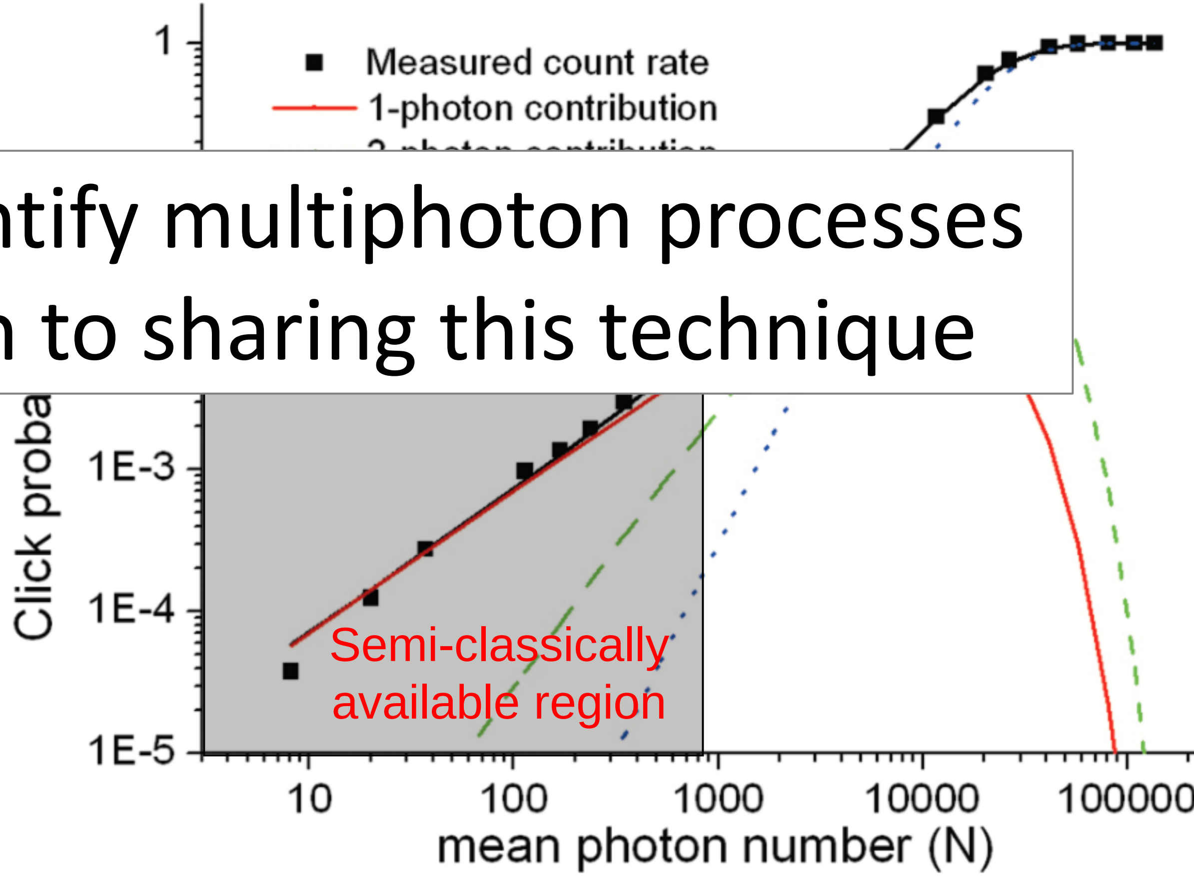
Complete tomography

- 1, 2 photon processes present
- Usual method $R = (\eta N)^i$ restricted to $\eta N \ll 1$, lowest i



Complete tomography

- 1, 2 photon processes
- R = (ηN)ⁱ restricted to ηN << 1, lowest i



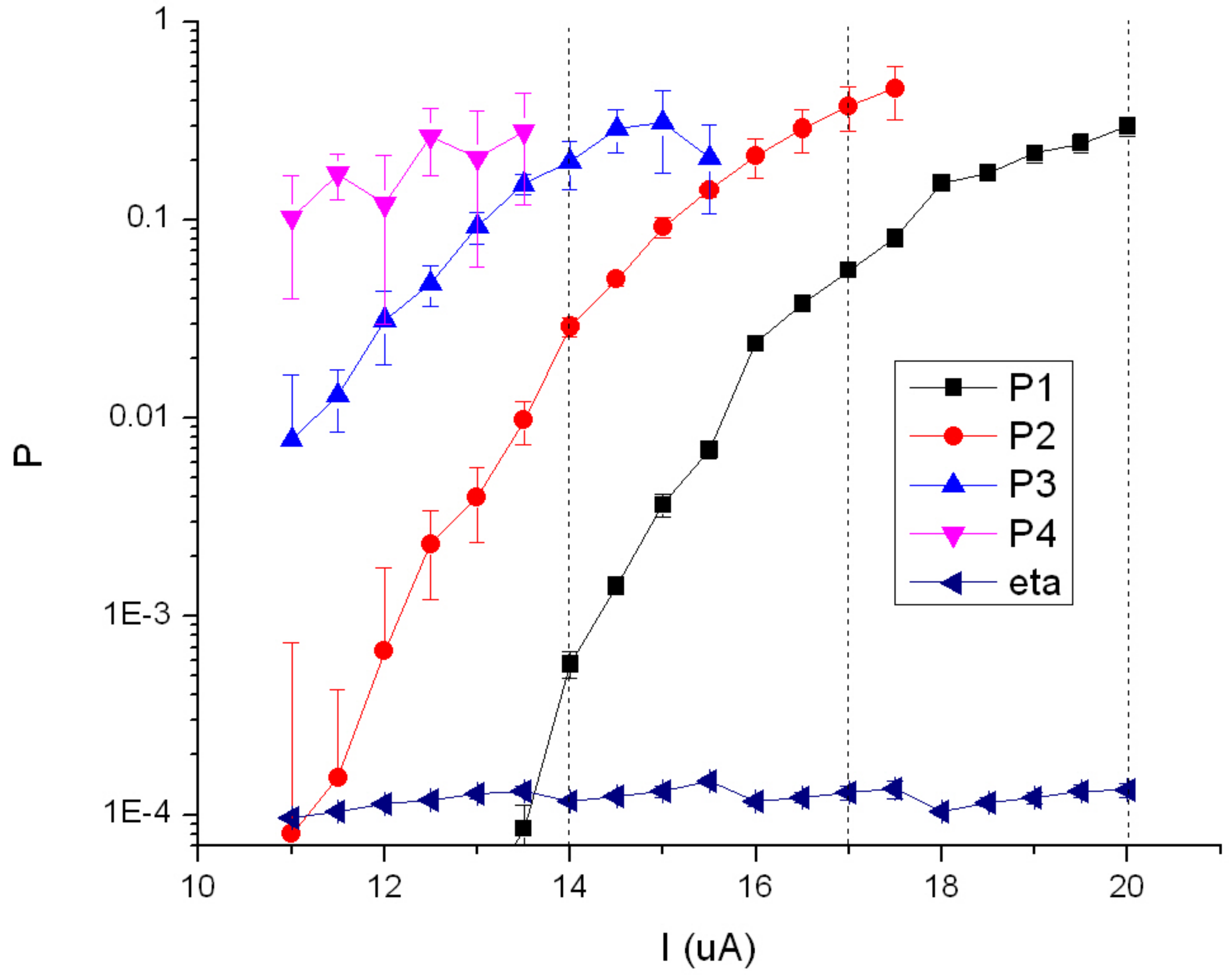
QDT can quantify multiphoton processes

We are open to sharing this technique

Now repeat this many times

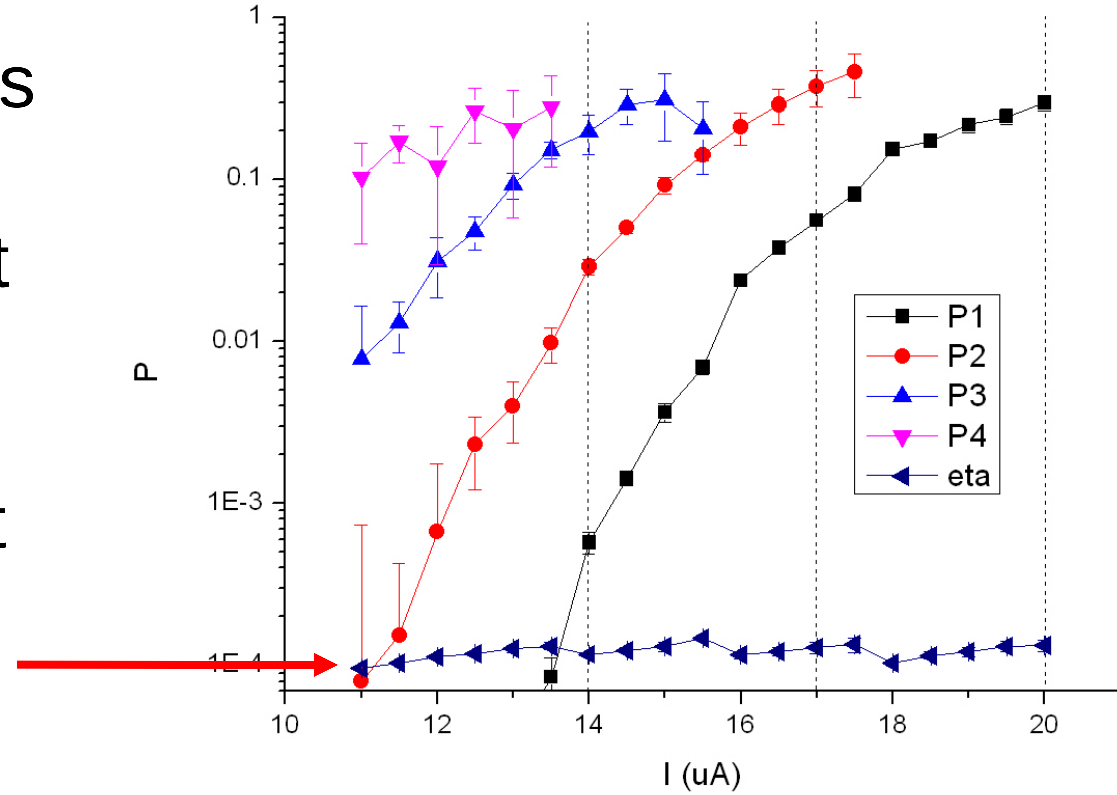
- For each current, vary the input power
- From the power dependence, reconstruct which photon processes are present

Result from tomography



Result from tomography

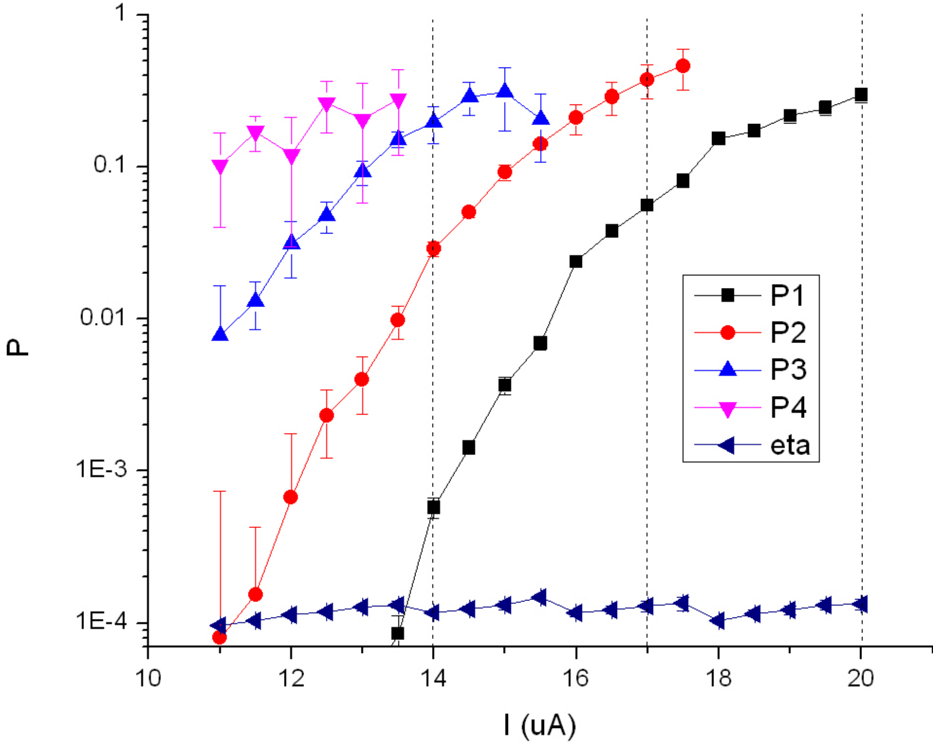
- We find: linear efficiency is independent of bias current
- This is a result, not an assumption (agnostic)
- Number consistent with overlap x absorption



Renema *et al*, Optics Express **20**, 2806-2813 (2012)

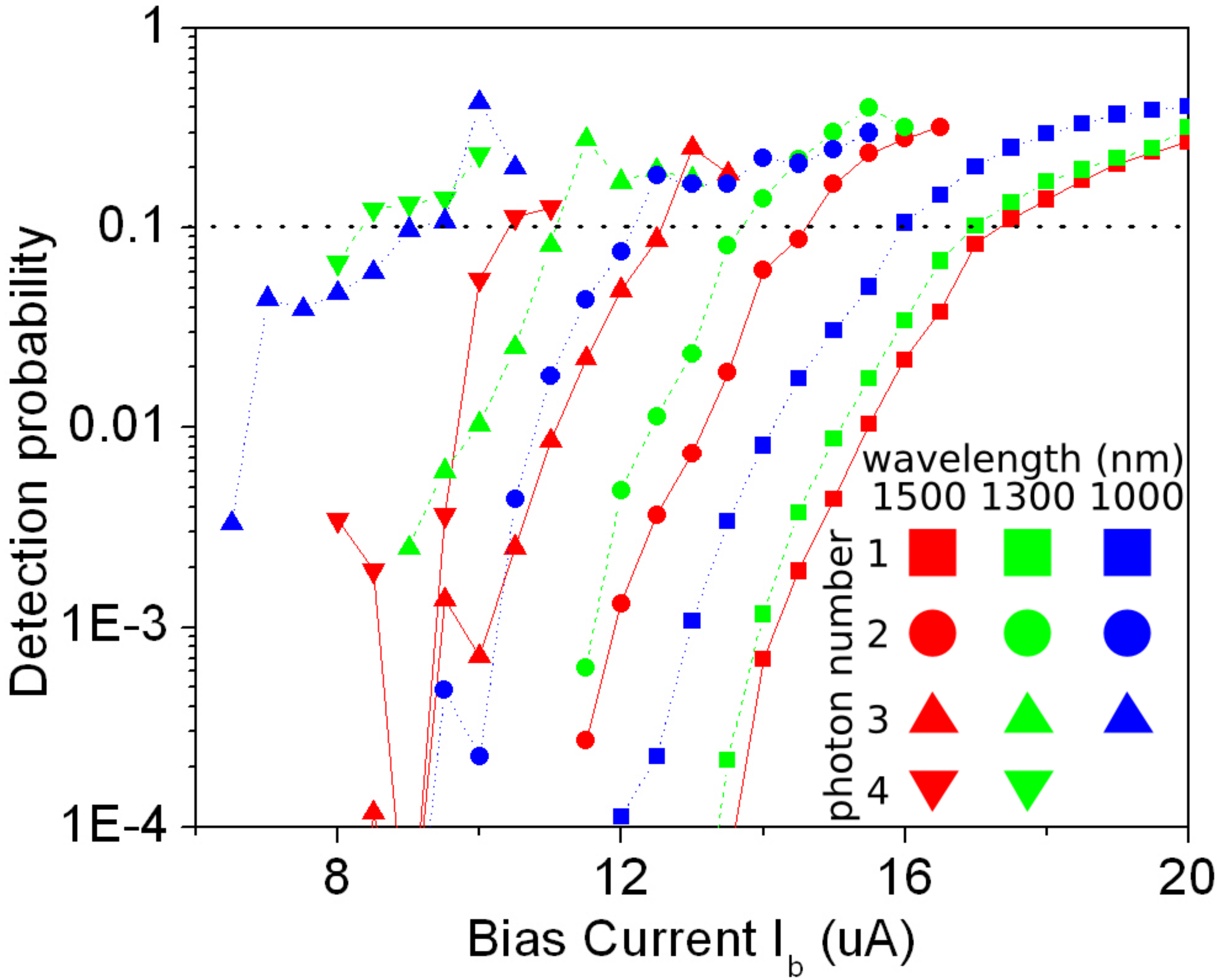
Result from tomography

- P_i internal response of the detector
- Independent of absorption, independent of incoupling
- There is more than linear efficiency

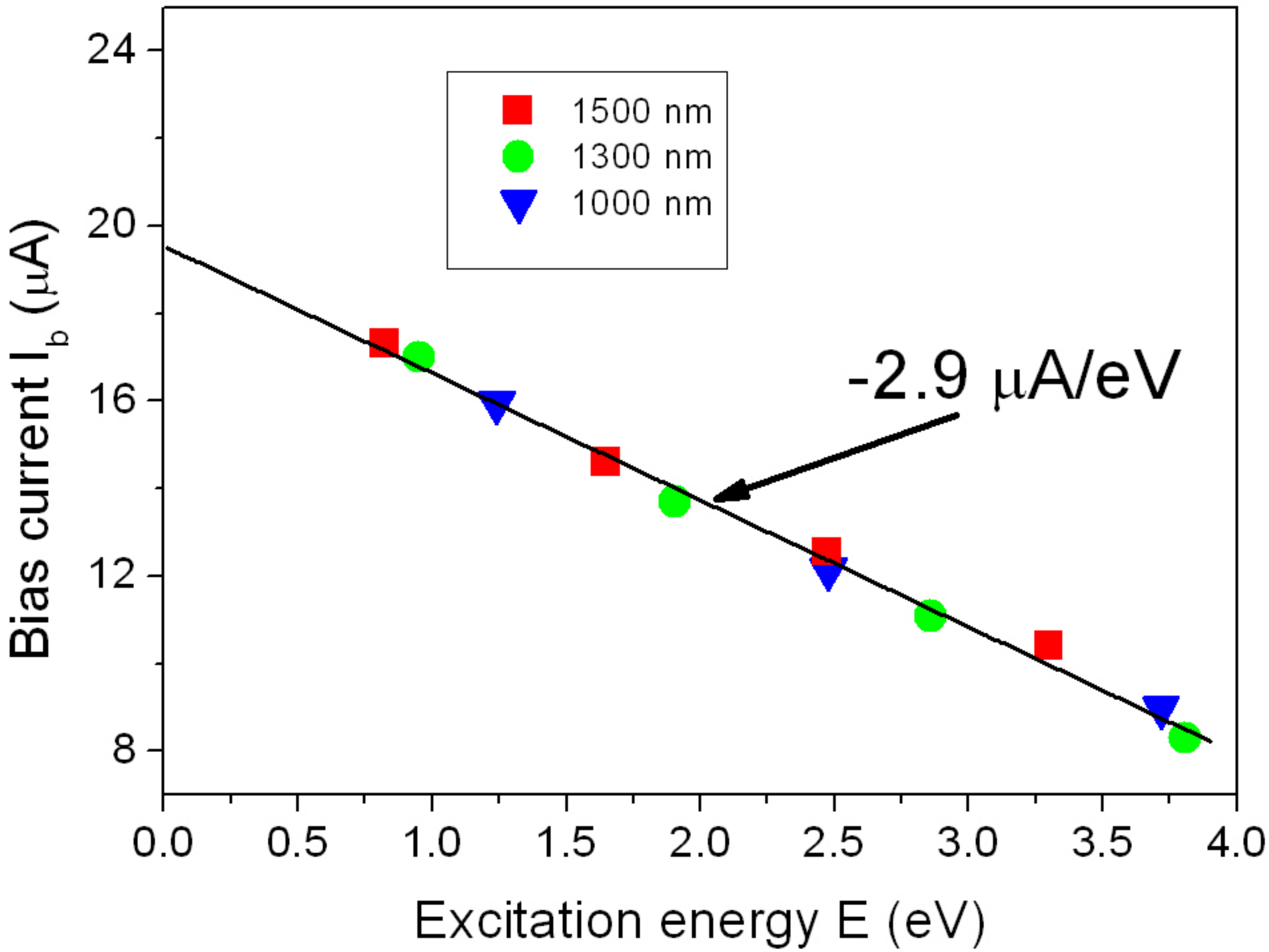


Renema *et al*, Optics Express **20**, 2806-2813 (2012)

Multiple wavelengths



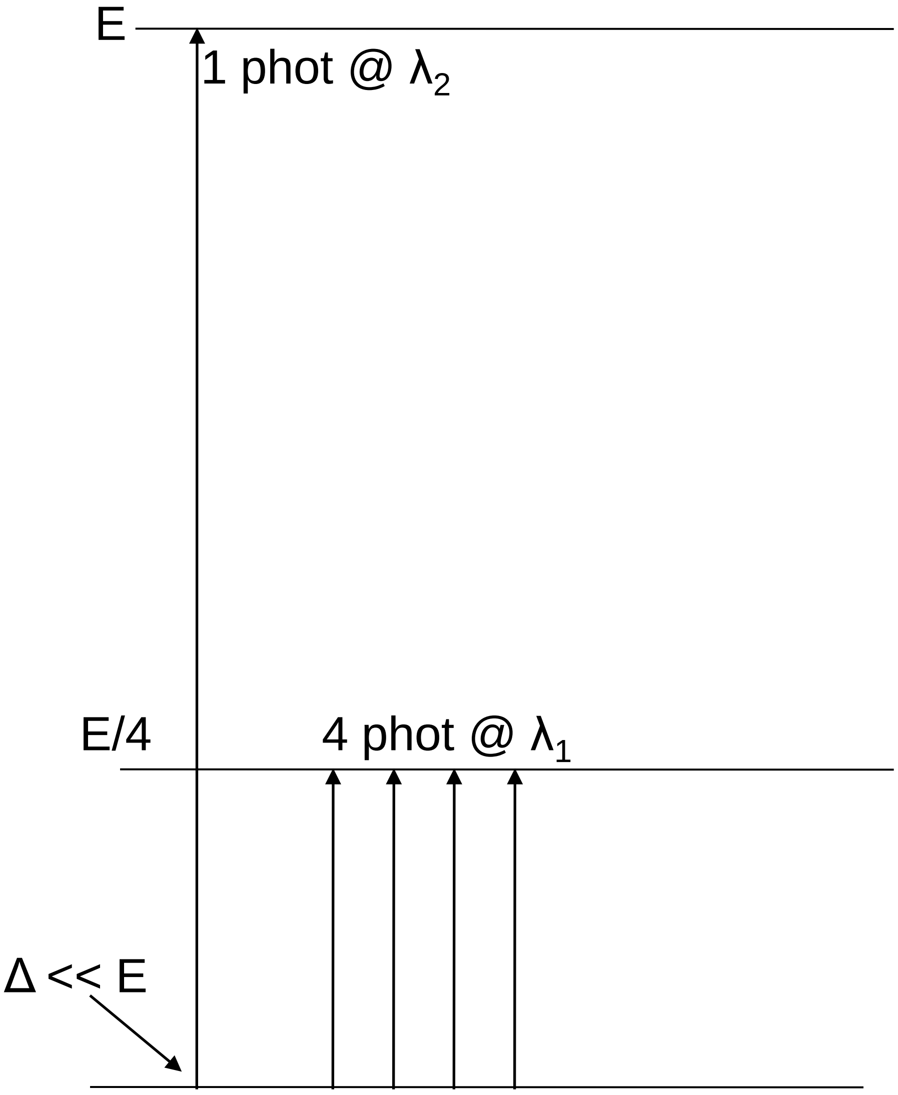
Interchange energy/current



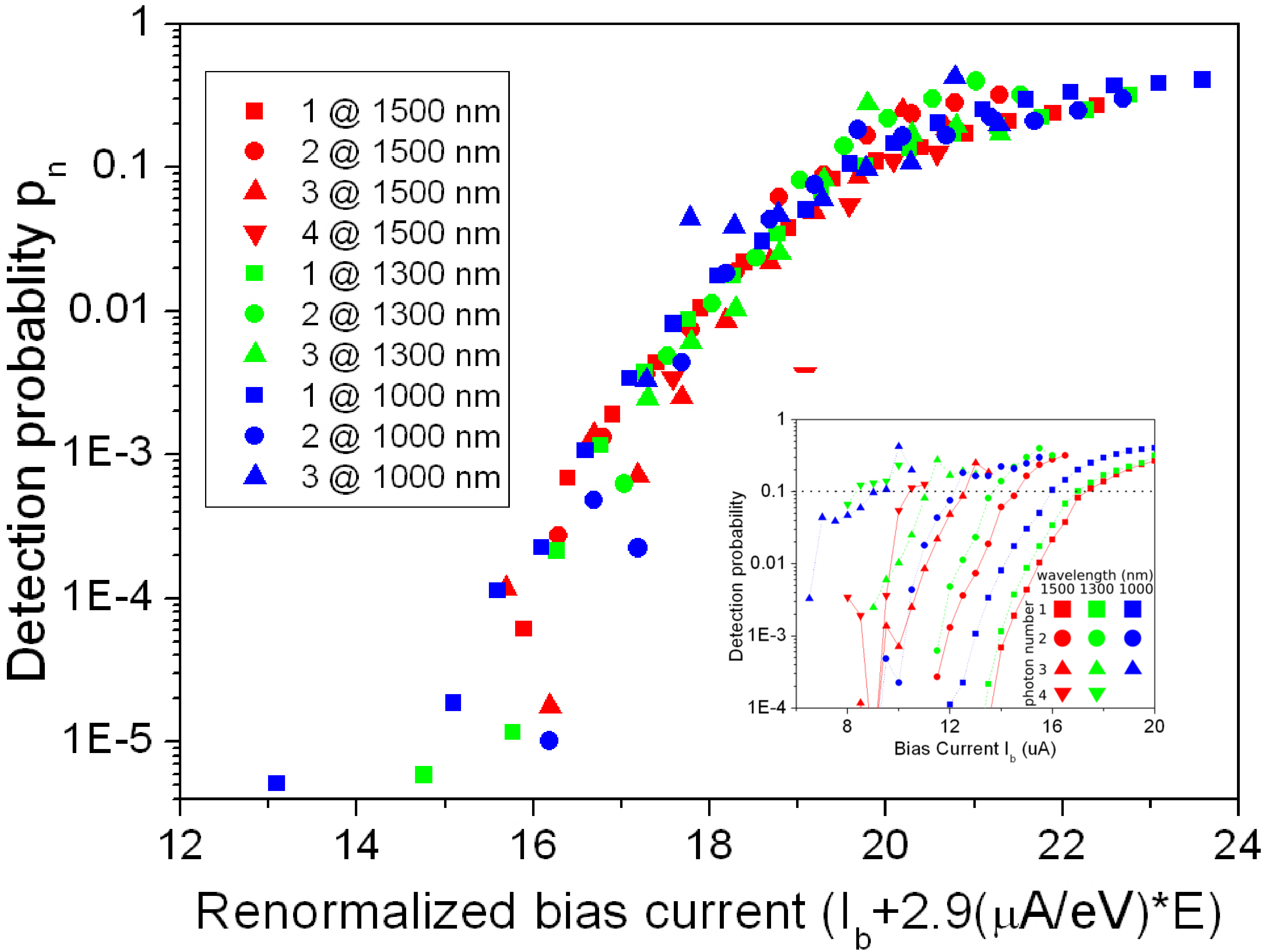
QP conversion is linear

- No dependence on initial number of photons, only energy
- Detector is an energy detector

Renema *et al*, Phys Rev B **87**, 174526 (2013)

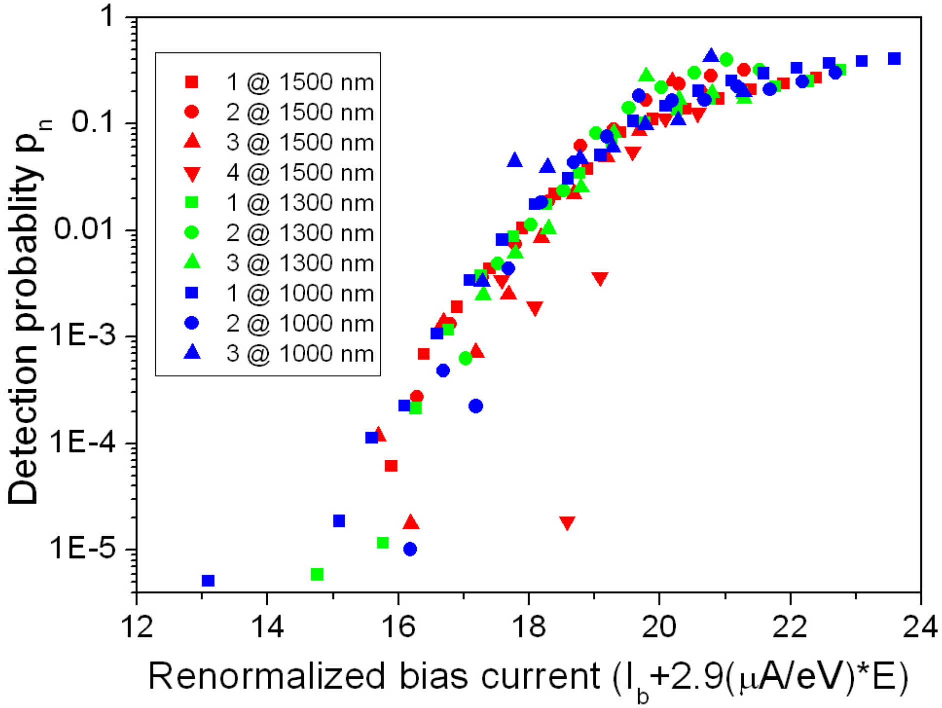


Universal curve



Universal curve

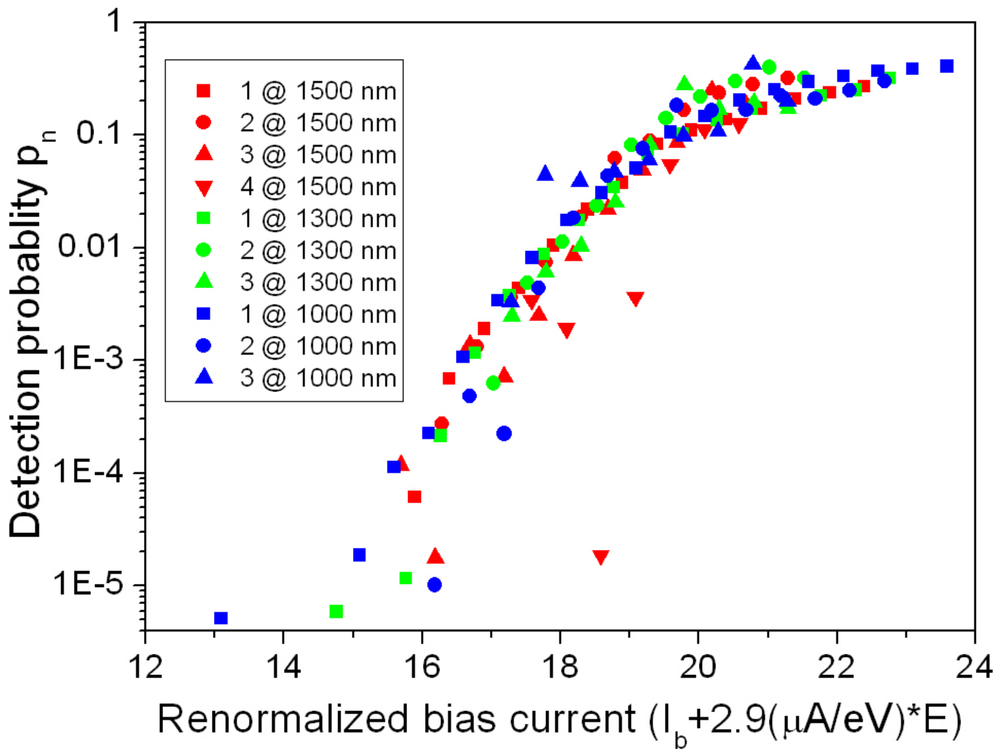
- $R(I,\lambda,N) = R(I+\gamma E)$ with $E = N*hc/\lambda$
- Goes beyond measuring edge of the plateau region



Renema *et al*, Phys Rev B **87**, 174526 (2013)

Universal curve

- Fluctuation-assisted scales in the same way as plateau response
- Results compatible with theory (both Engel & Vodolazov)



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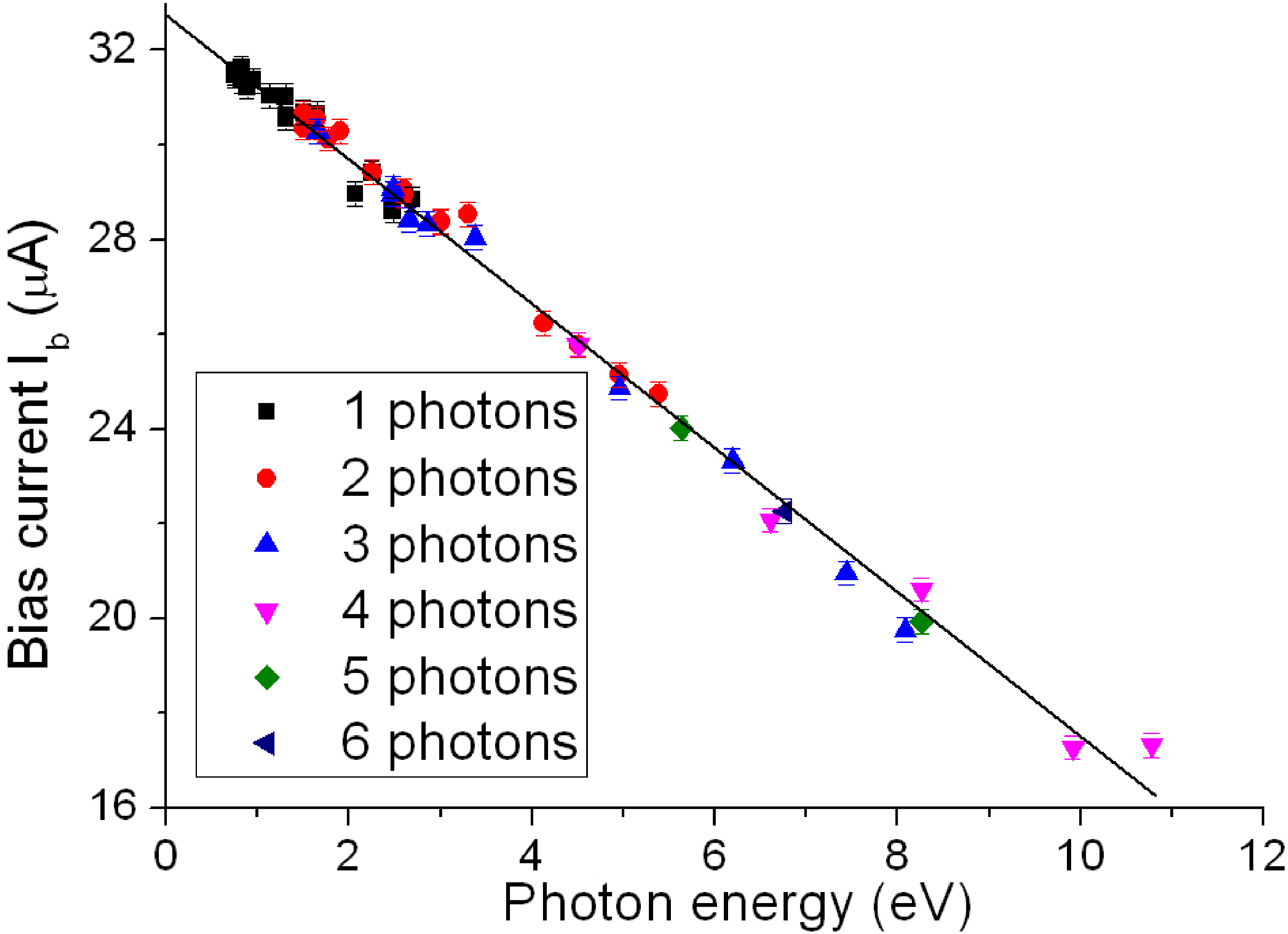
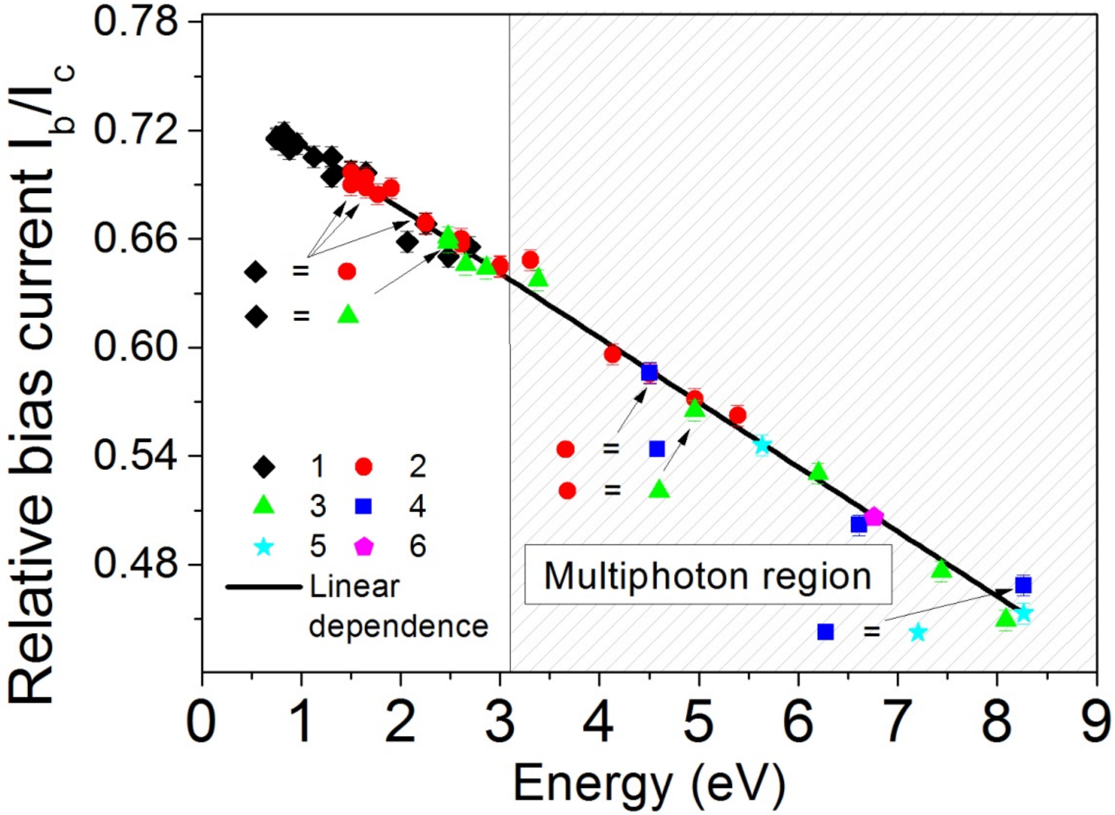
Result on 220 nm detector

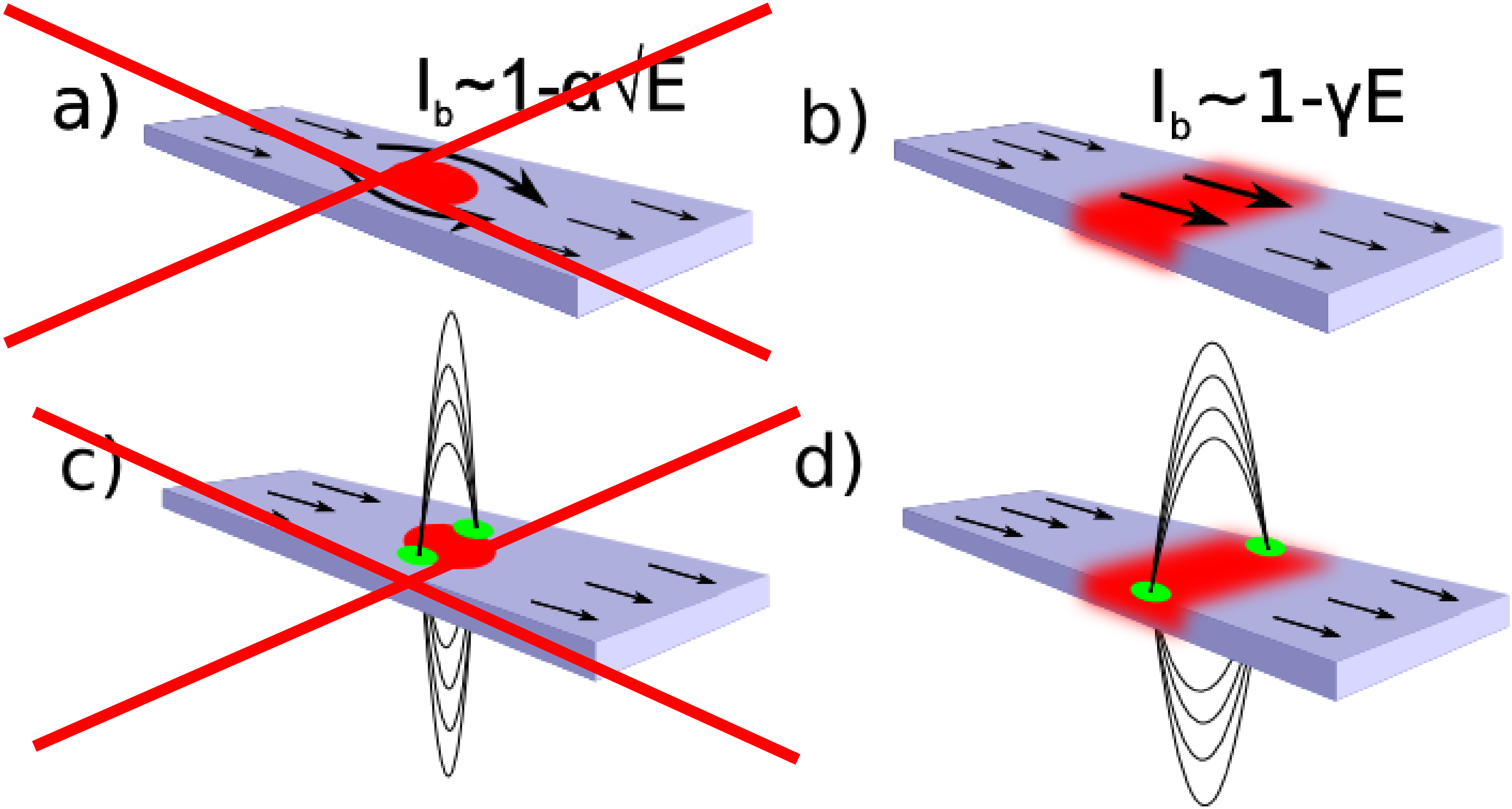


Extreme dynamic range

- Find $I_b = I_0 - \gamma E$
- 10.8 eV (X-UV): λ_{eff} = 115 nm
- Photon regimes overlap -> no stitching errors

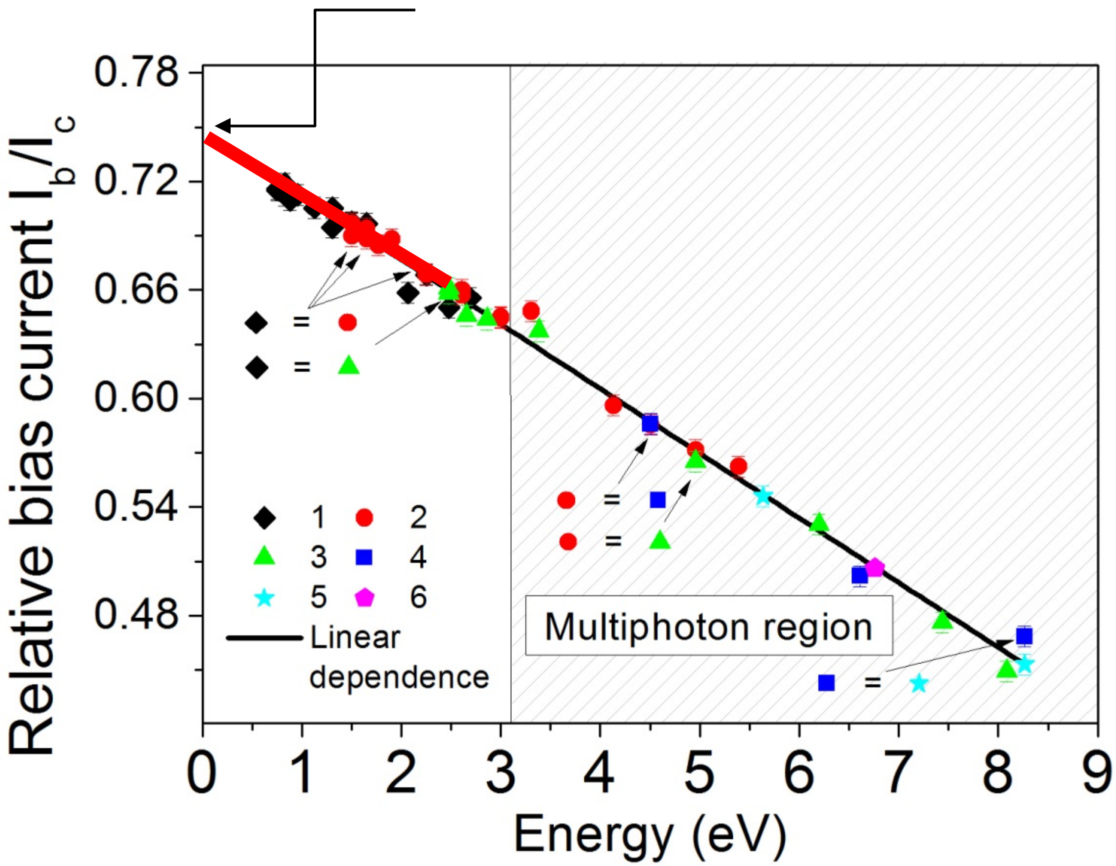


First conclusion

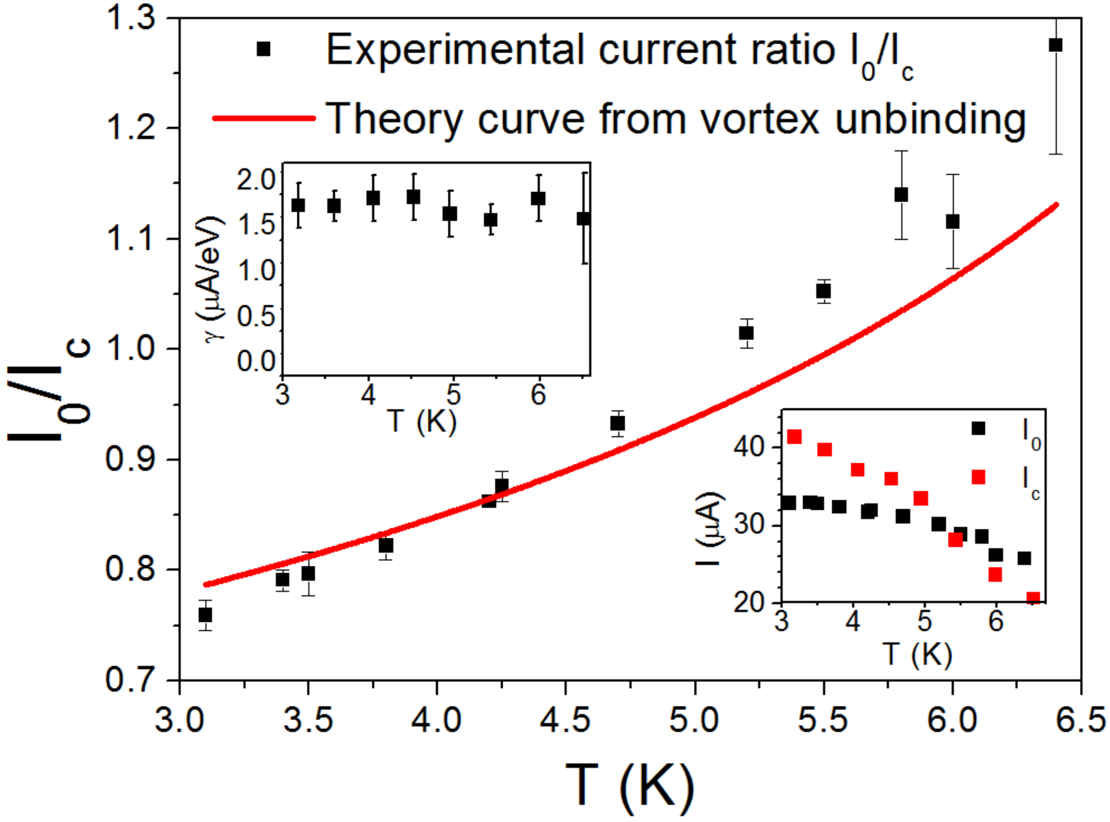


Moreover

$I_0 \neq I_c$!!!

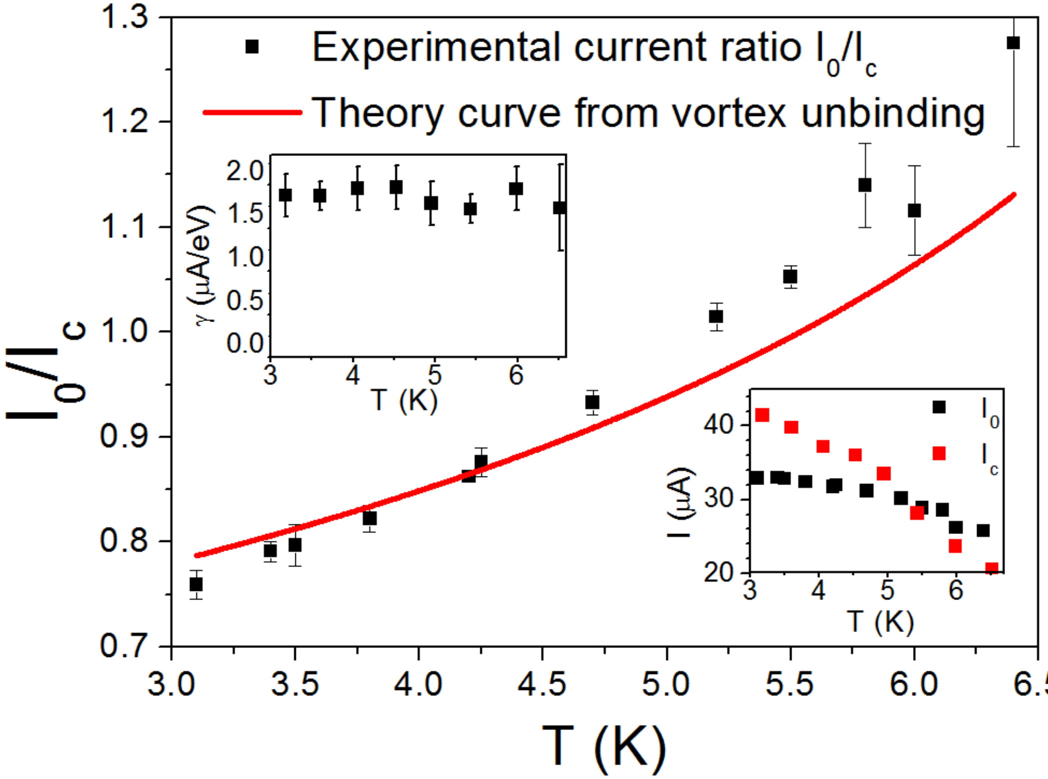


Temperature dependence of I_0



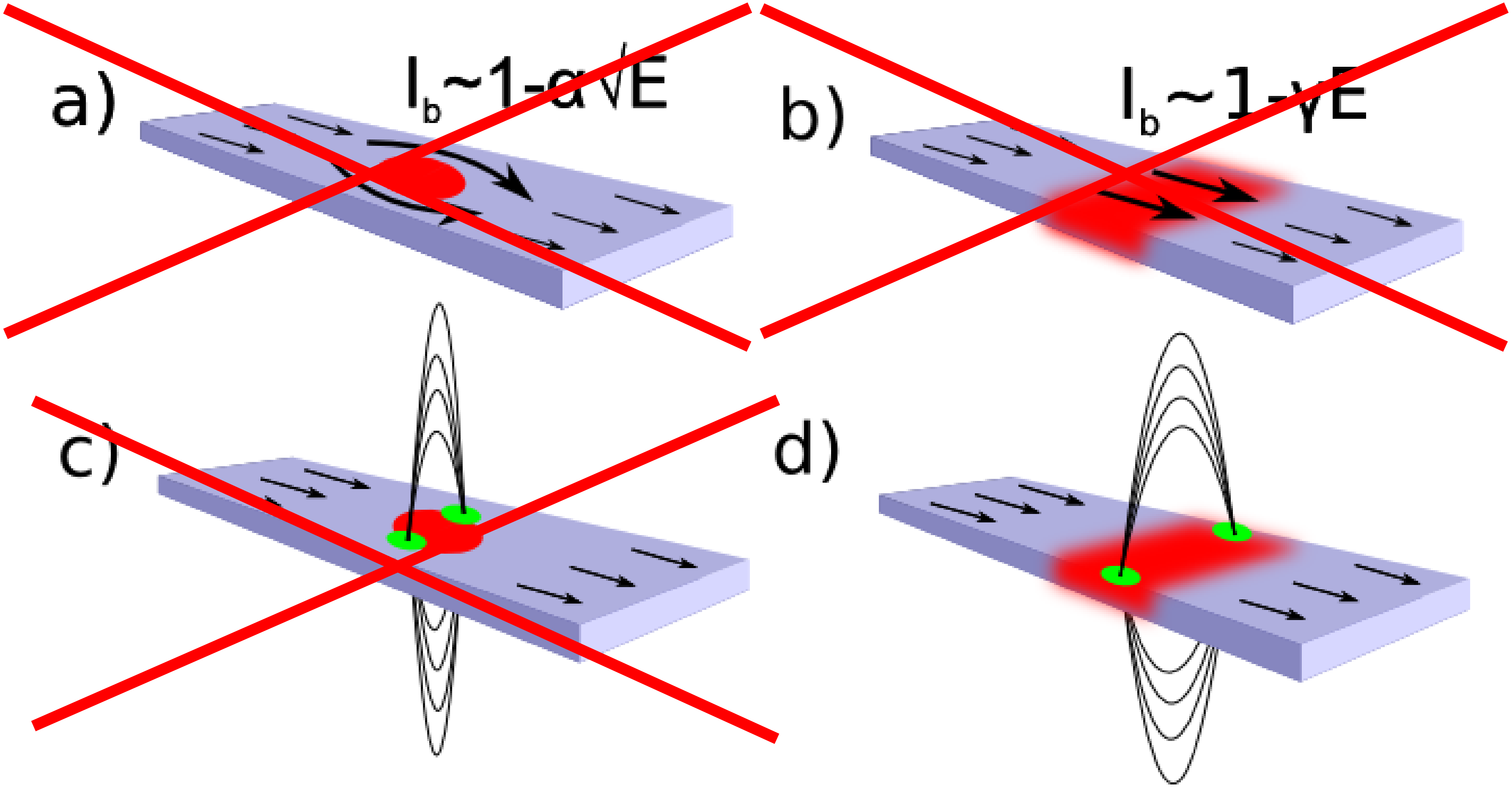
Temperature dependence of I_0

- $I_b = I_0 - \gamma E$
- Only I_0 temperature dependent
- Find cases $I_0 > I_c$ and $I_0 < I_c$
- Ratio I_0 / I_c follows vortex entry energy prediction



Renema *et al*, Phys Rev Letters **112**, 117604 (2014)

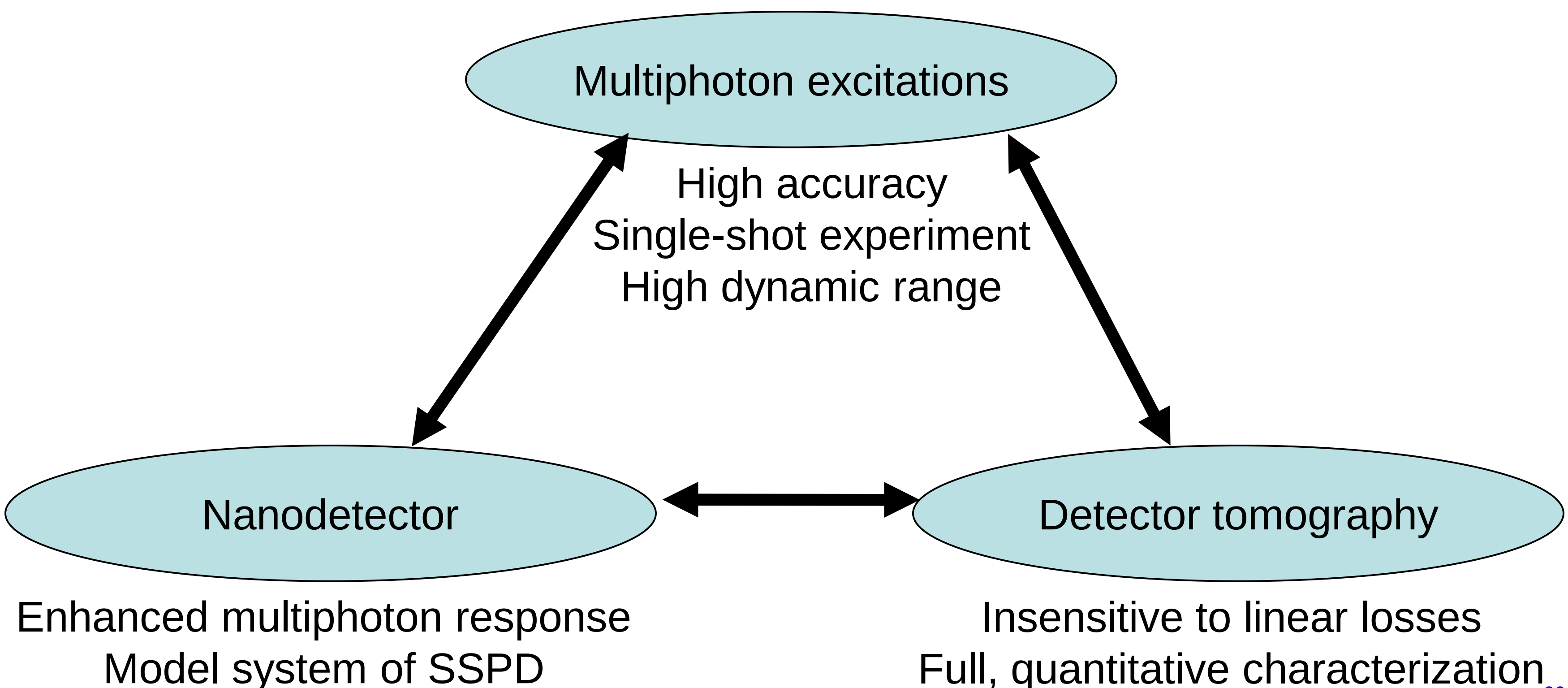
Second conclusion



Renema *et al*, Phys Rev Letters **112**, 117604 (2014)

Conclusions

- There is more in the detector than linear effiency
- Quantum tomography useful for inner workings of detector
- Linear energy-current relation up to X-UV
- Temperature dependence fixed by vortex behaviour



Acknowledgements



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Mathematics: R. Gill

Numerical simulations: A. Engel

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Renema *et al*, Optics Express **20**, 2806-2813 (2012)
JJ Renema et al, Phys Rev A **86,** 062113 (2012)
Renema *et al*, Phys Rev B **87**, 174526 (2013)
Renema *et al*, Phys Rev Letters **112**, 117604 (2014)