EEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2014.
Presentation given at the KRYO 2013 Workshop, Oct. 7th, 2013.

Detector Tomography of Superconducting Single Photon Detectors

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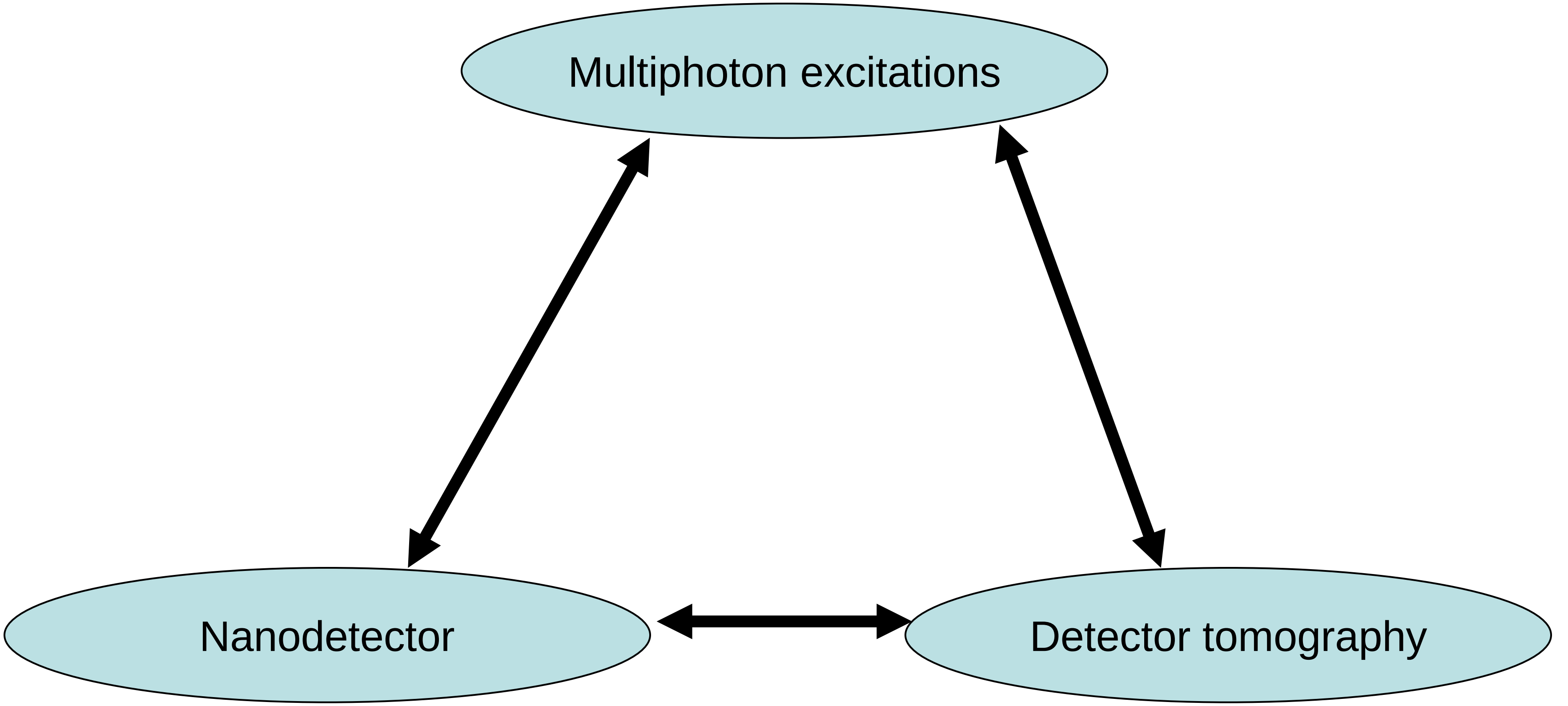
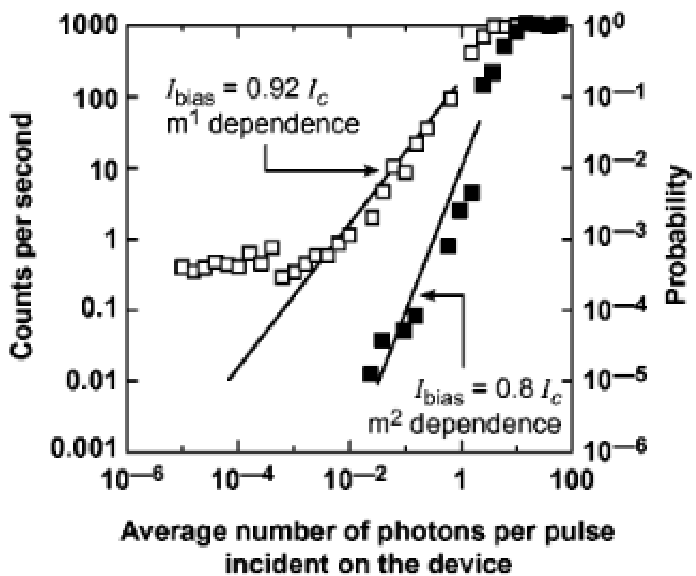
Goal: investigate SSPD fundamentals



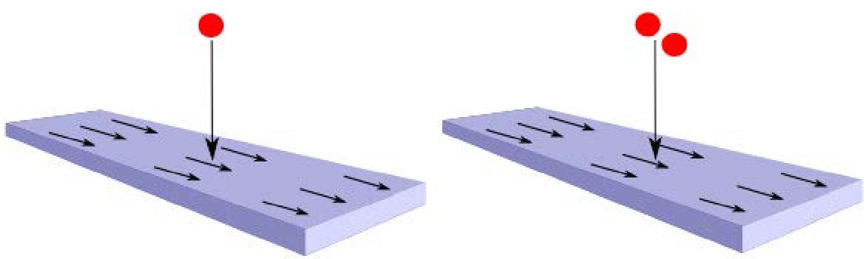
Multiphoton excitations

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

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

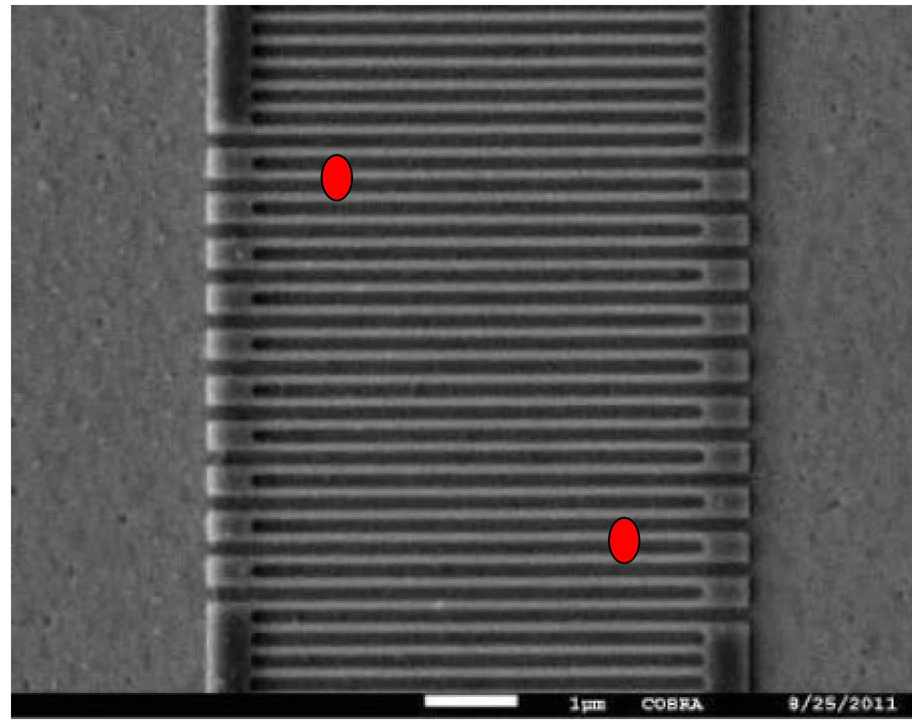


[1] Goltsman APL **79** (2001)



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



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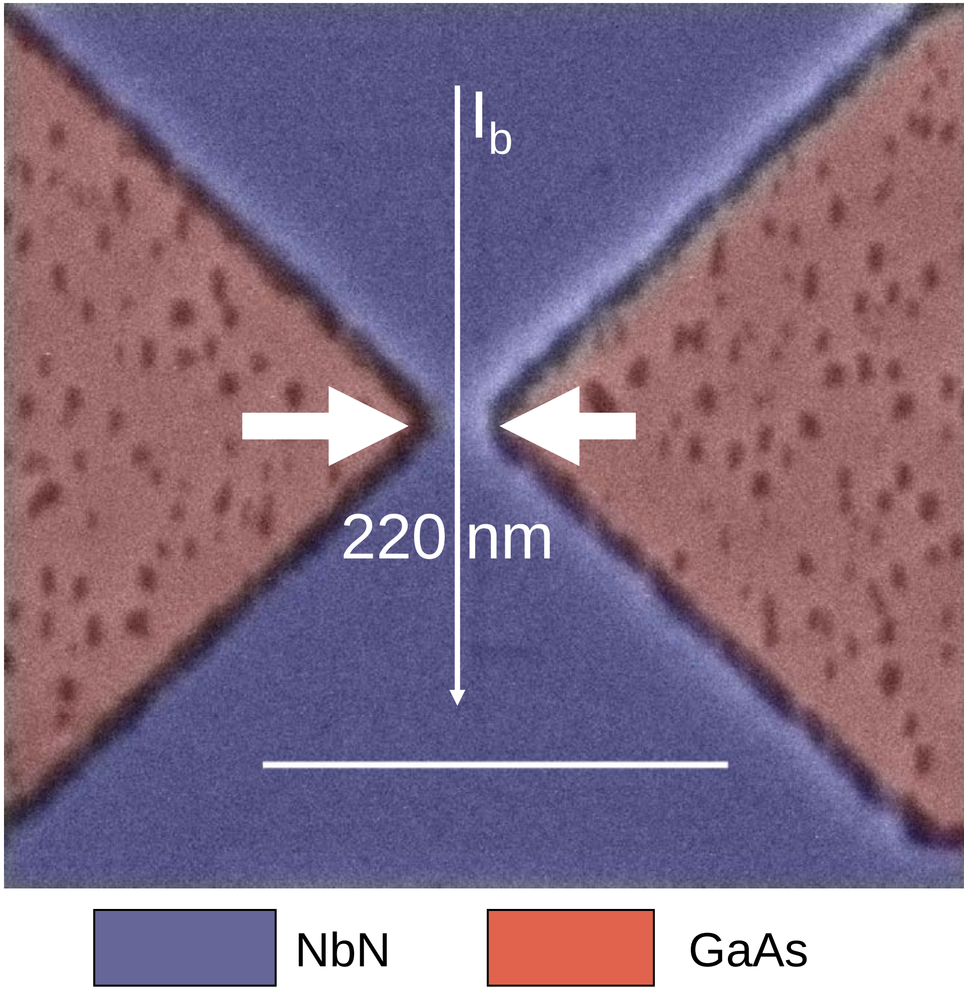
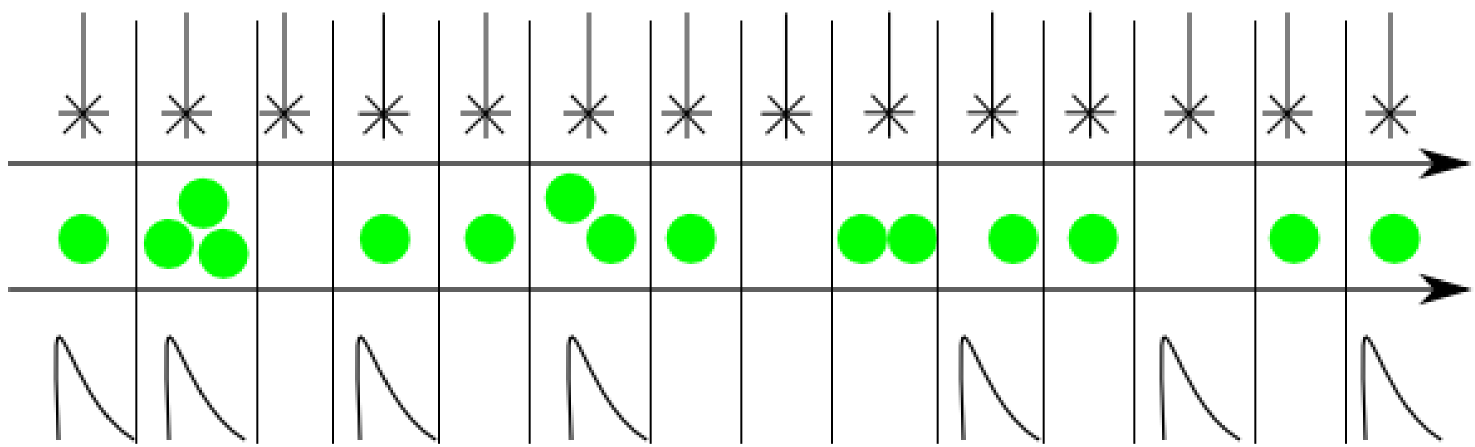
Our sample: nanodetector

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



Detector tomography

- Method to measure strength of multiphoton processes
- Gives probability that detector responds to N photons



$$\left.\begin{array}{r}P(\text{detection}|\text{Intensity})\\ P(\#\text{ photons}|\text{Intensity})\end{array}\right\} P(\text{detection}|\#\text{ photons}$$

Why detector tomography?

- Fundamentals: Agnostic description
- Applications: Complete description

SSPD modeling:
1) Efficiency
2) Dark counts
3) Constrictions
4) Varying efficiency over active area
5) Effects of cavity
6) ???

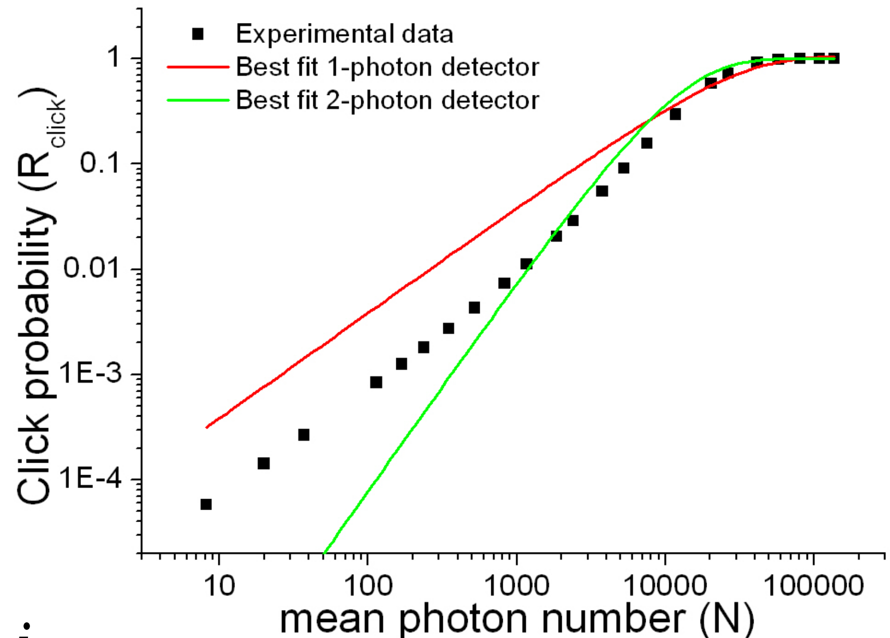
Why detector tomography?

- Fundamentals: Agnostic description
- Applications: Complete description

Detector tomography:
p_i : probability of click given i photons

How to do 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

- Measure counts vs input intensity
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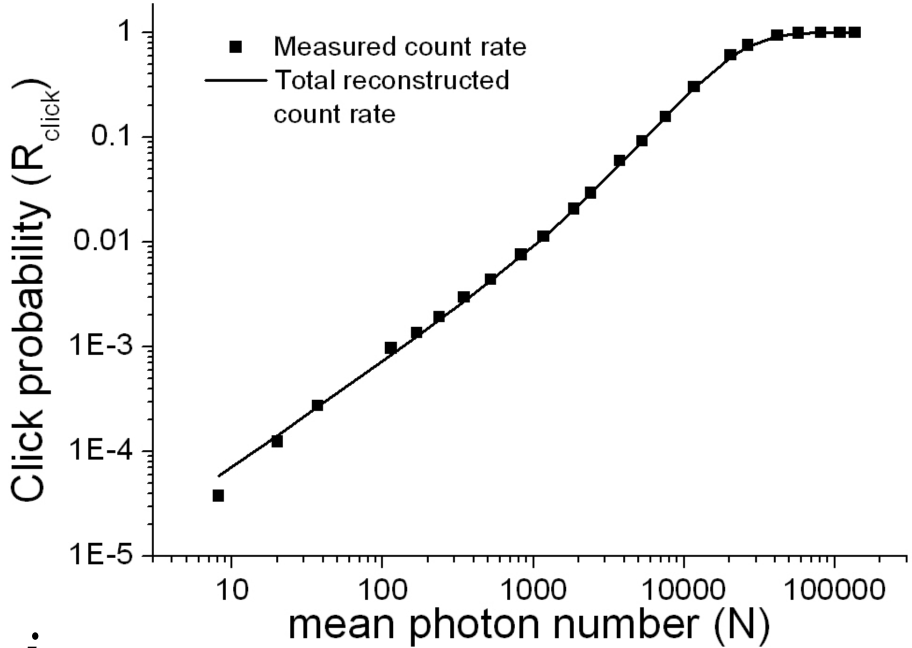

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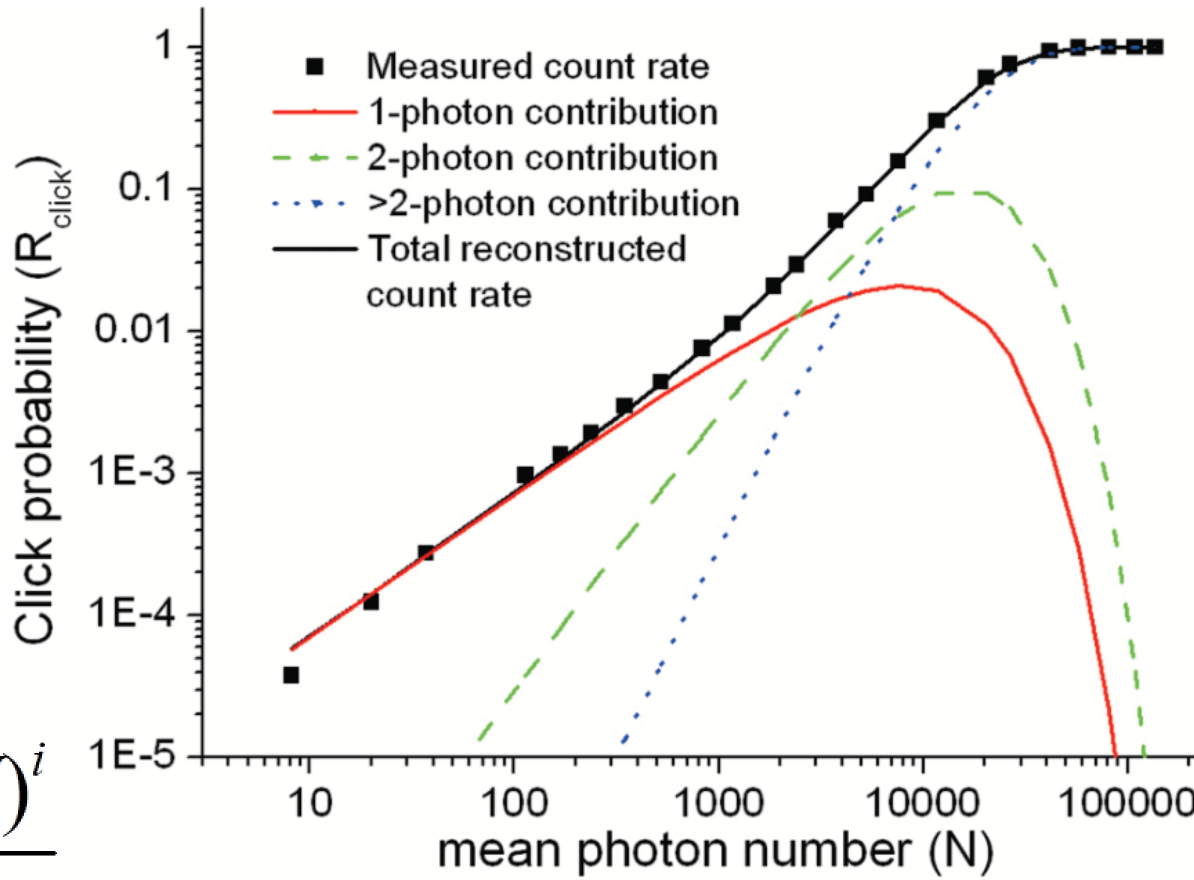
Renema et al, Optics Express 2012

Complete tomography

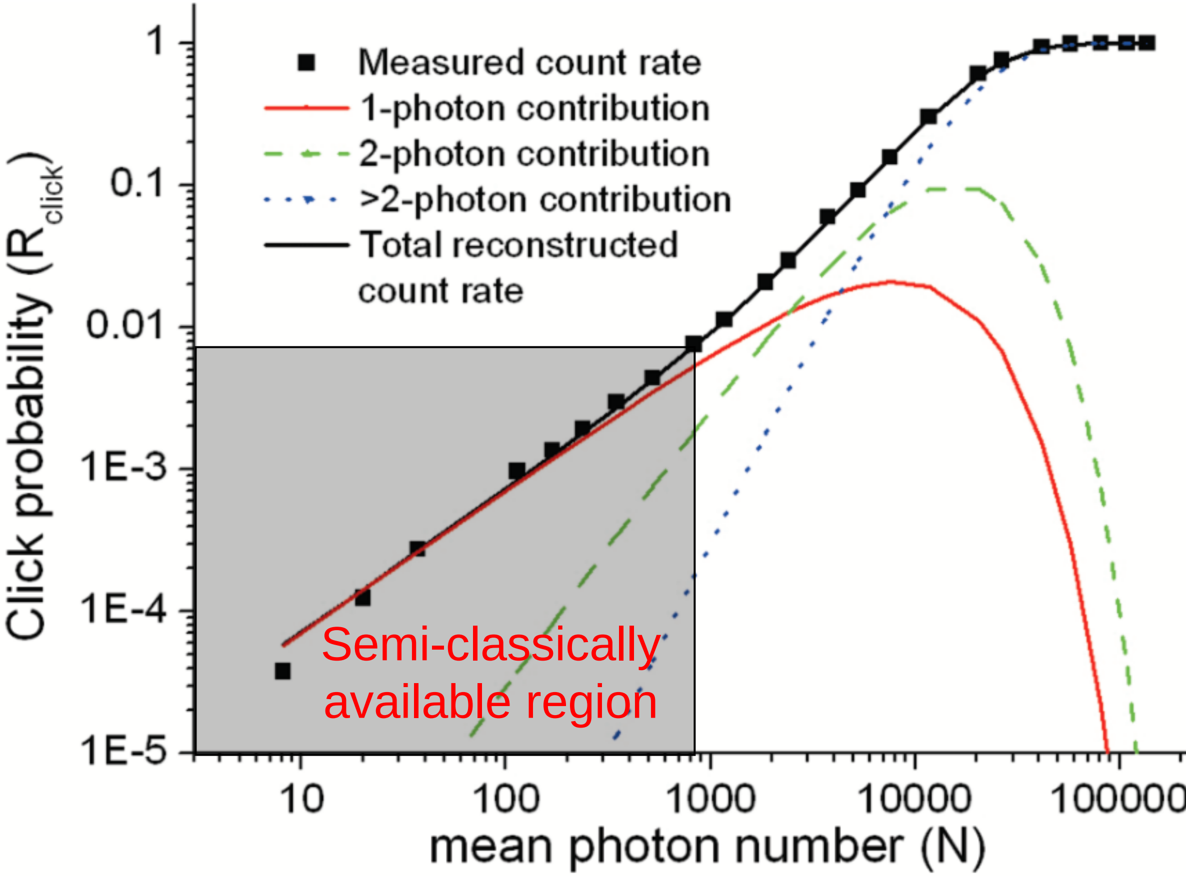
- 1, 2 photon processes present



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

Complete tomography

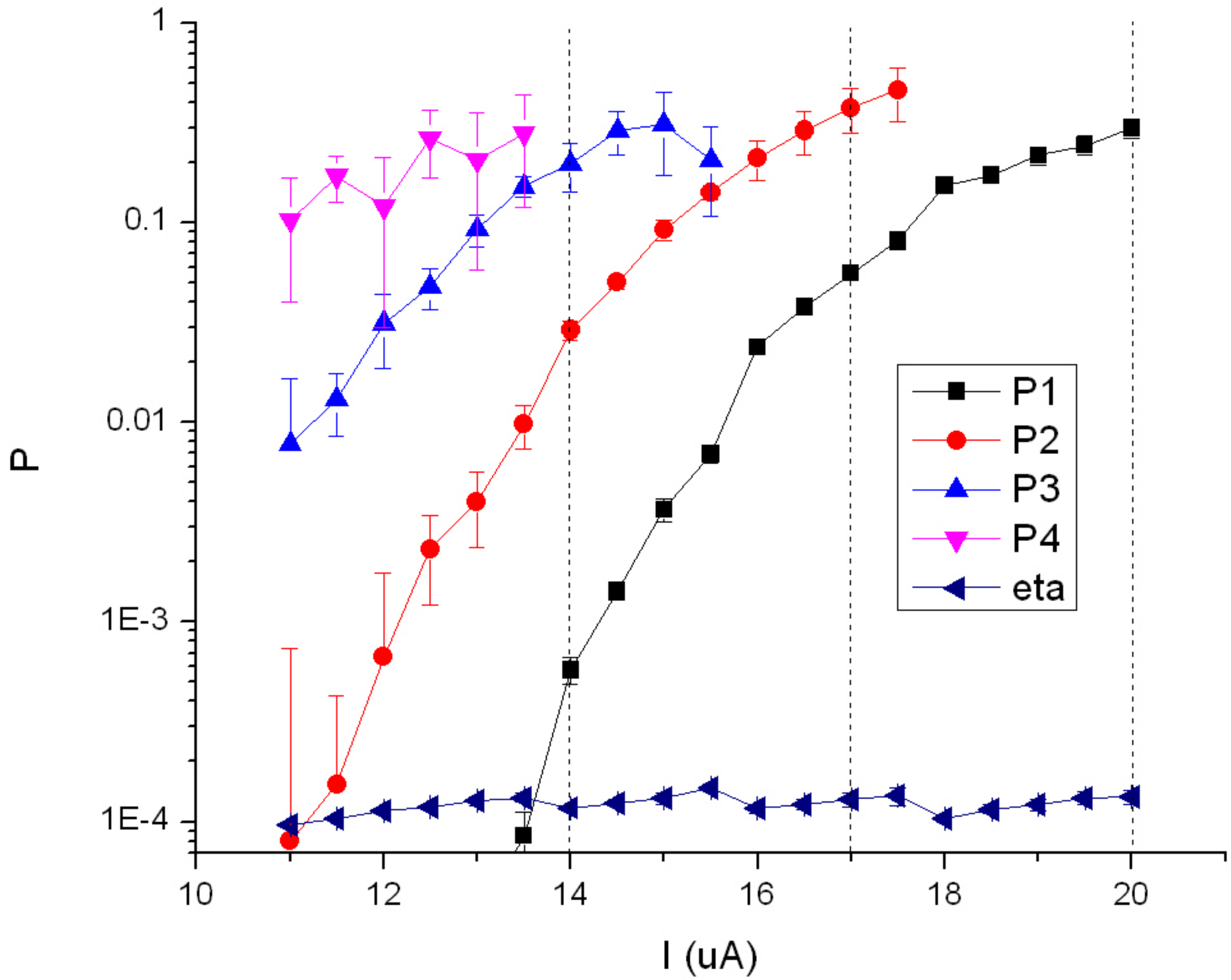
- 1, 2 photon processes present
- Usual method $R = (\eta N)^i$ restricted to $\eta N << 1$, lowest *i*



Now repeat this many times

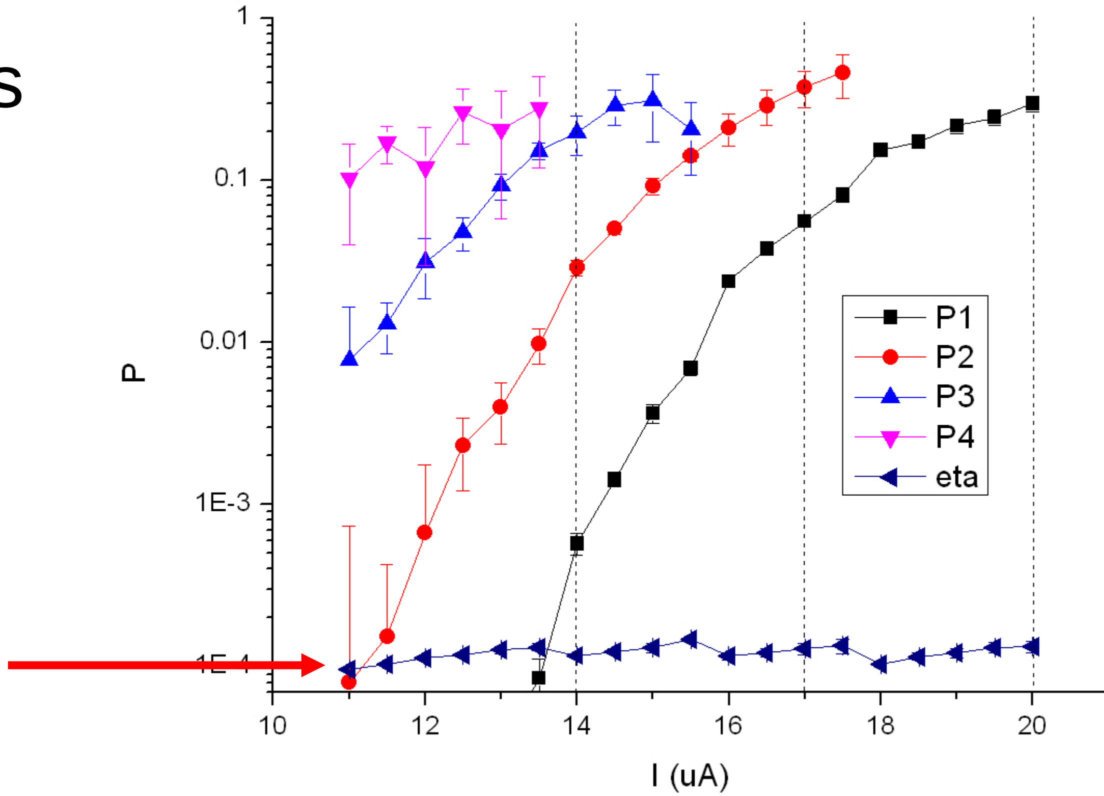
- For each current, vary the input power
- From the power dependence, reconstruct which photon processes are present

Result from tomography



Result from tomography

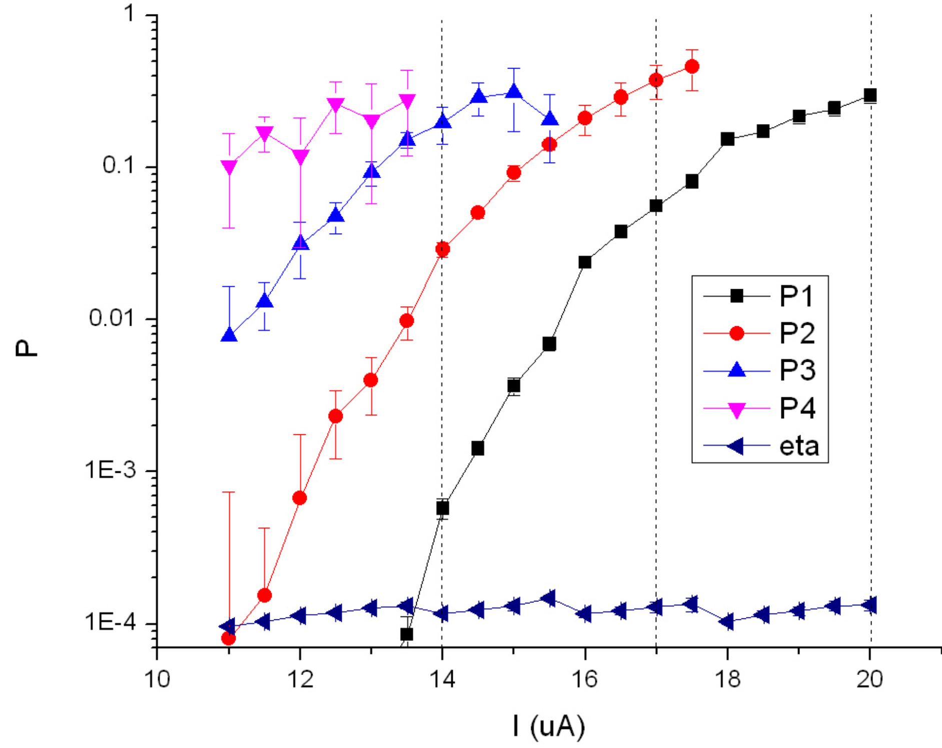
- We find: linear efficiency is independent of bias current
- This is a result, not an assumption (agnostic)
- Number consistent with overlap x absorption



Tomography code available, see also Renema et al, Optics Express 2012

Result from tomography

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



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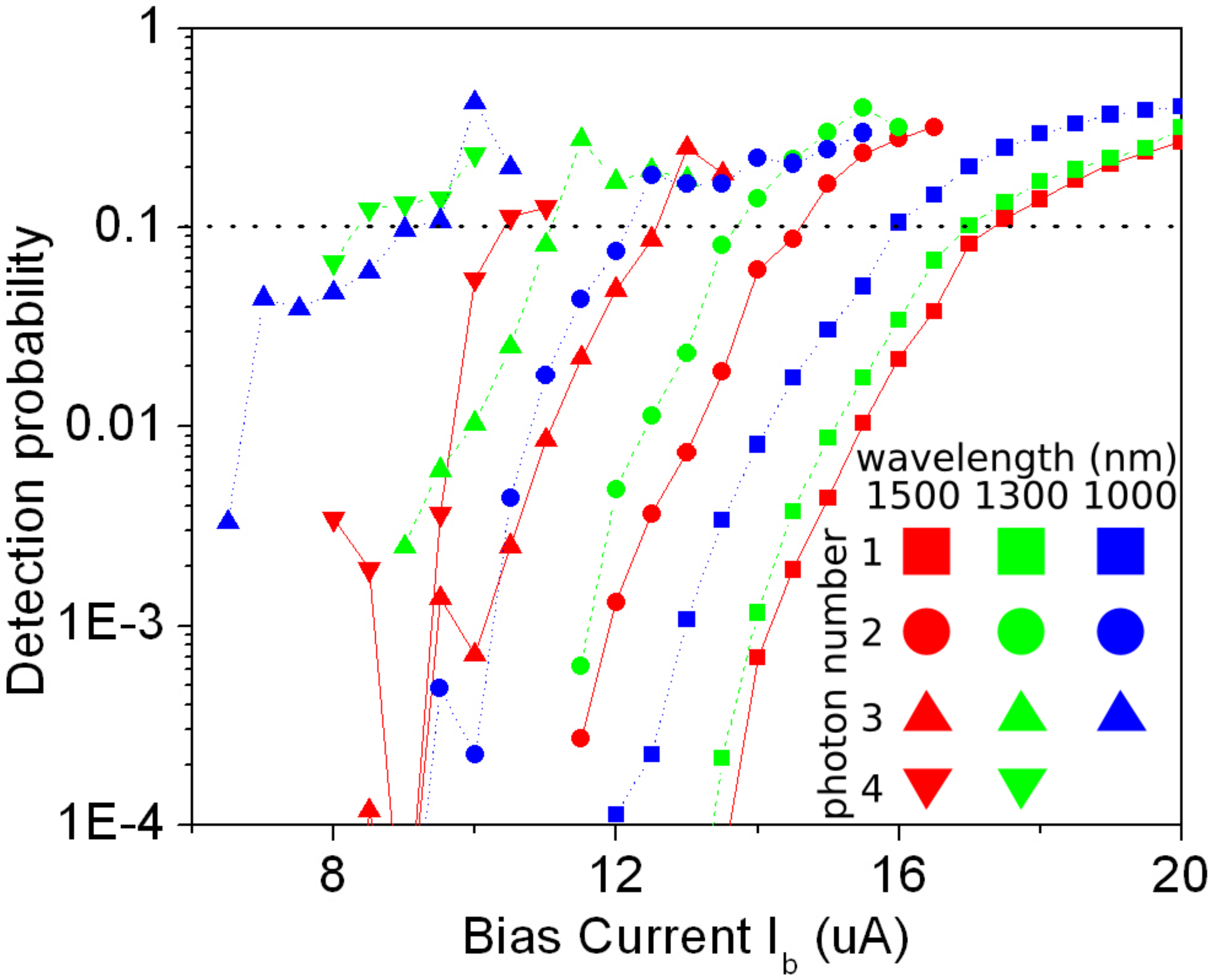
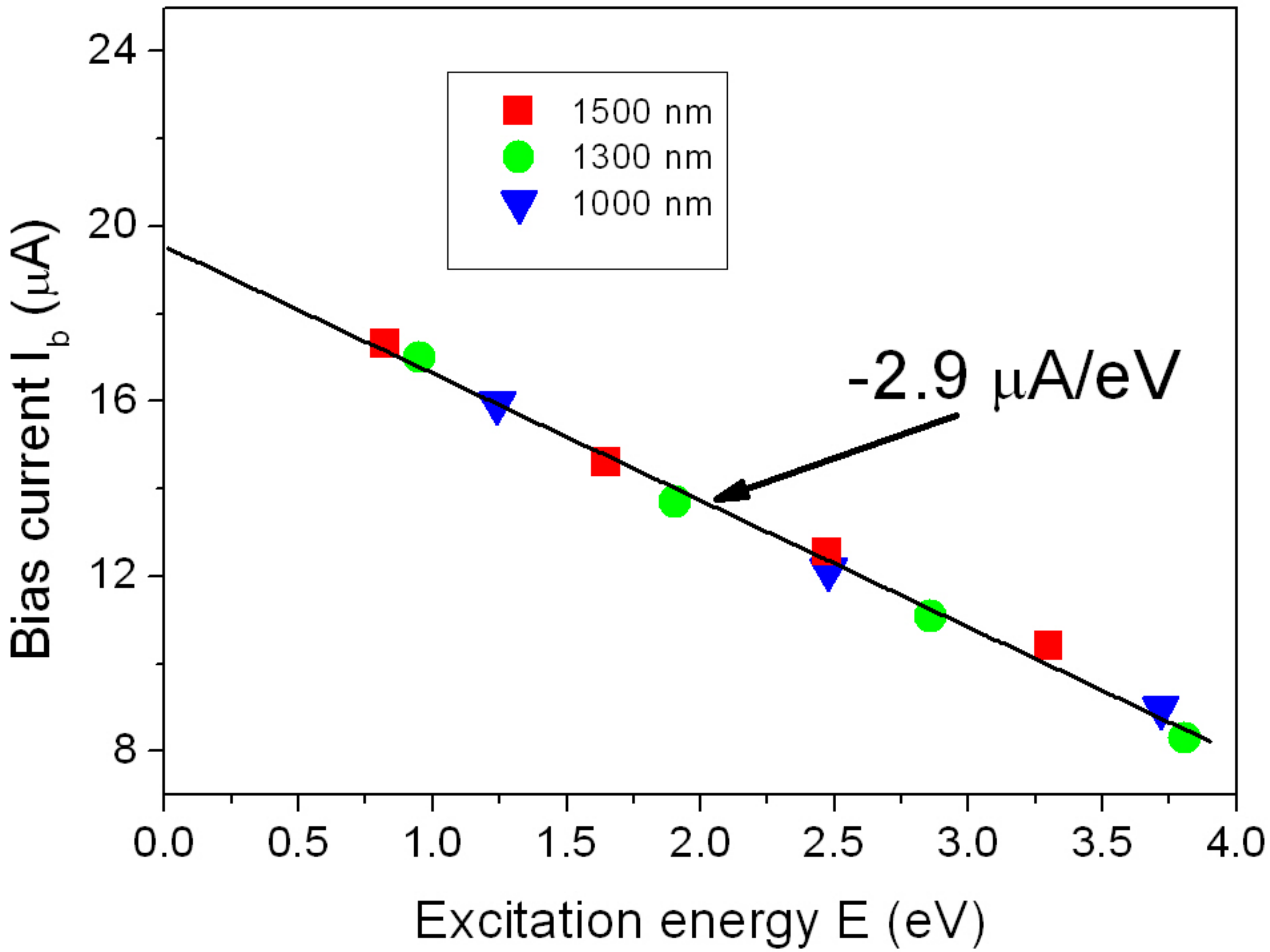
Multiple wavelengths



Interchange energy/current



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

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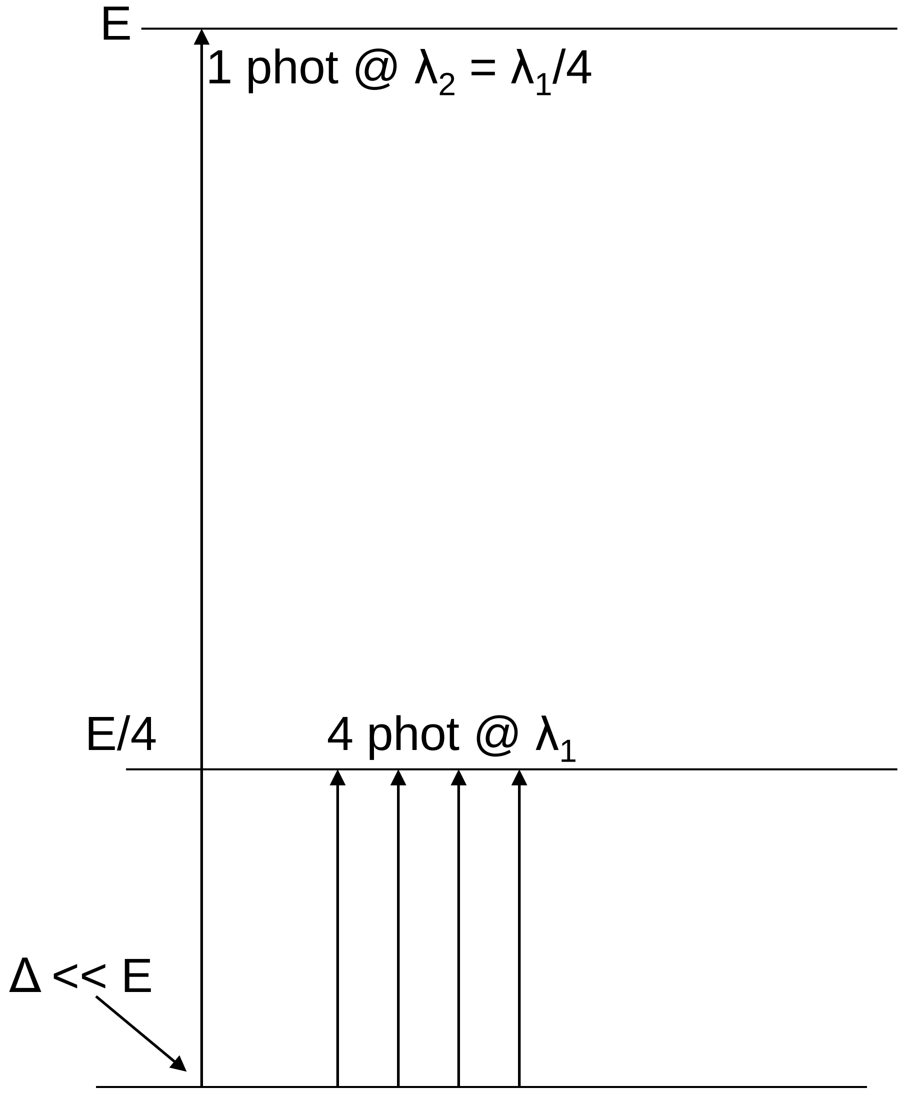
QP conversion is linear

- No dependence on initial number of photons, only energy
- Excitation insensitive to details of how you made it
- Detector is an <u>energy detector</u>



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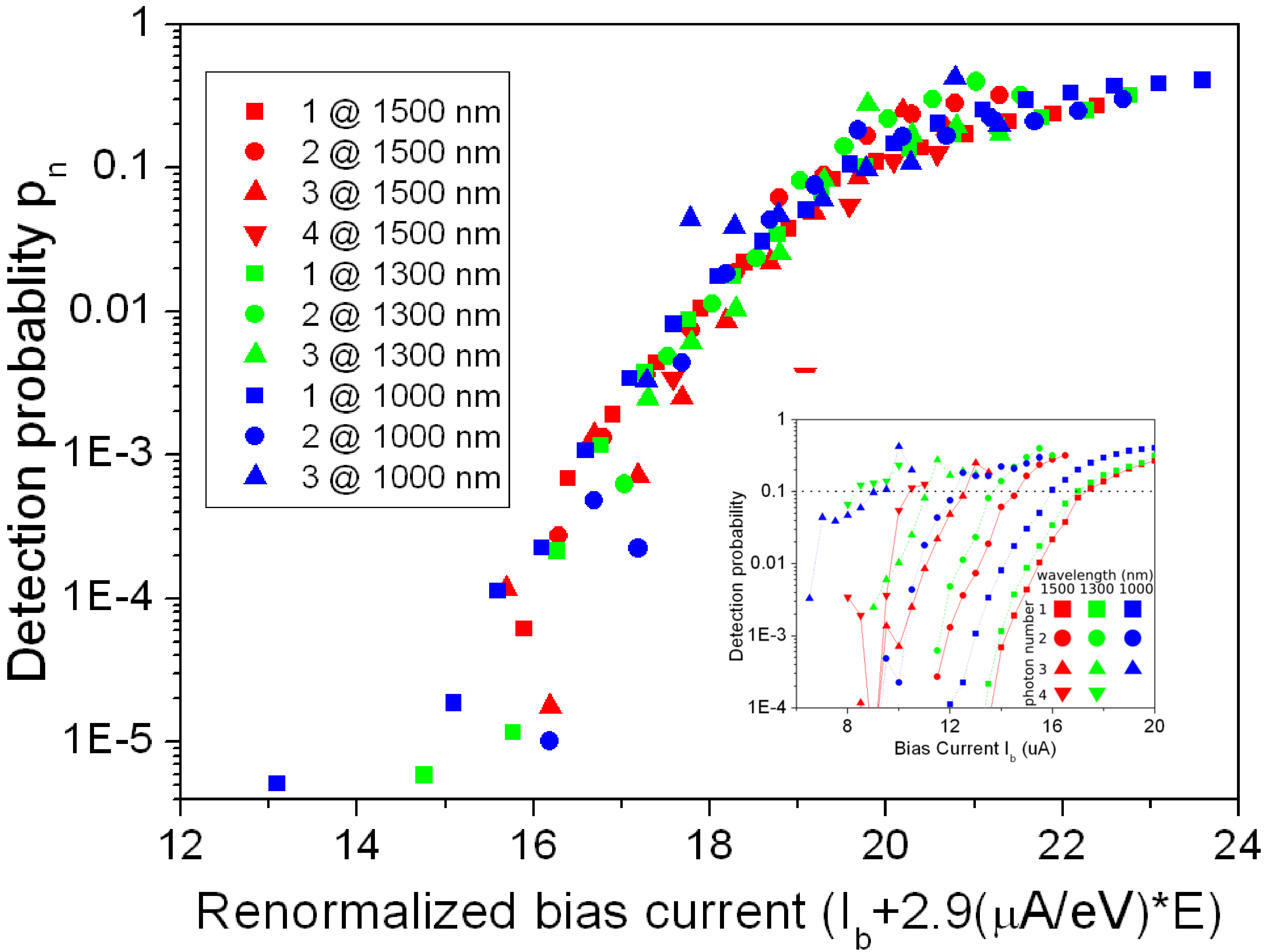
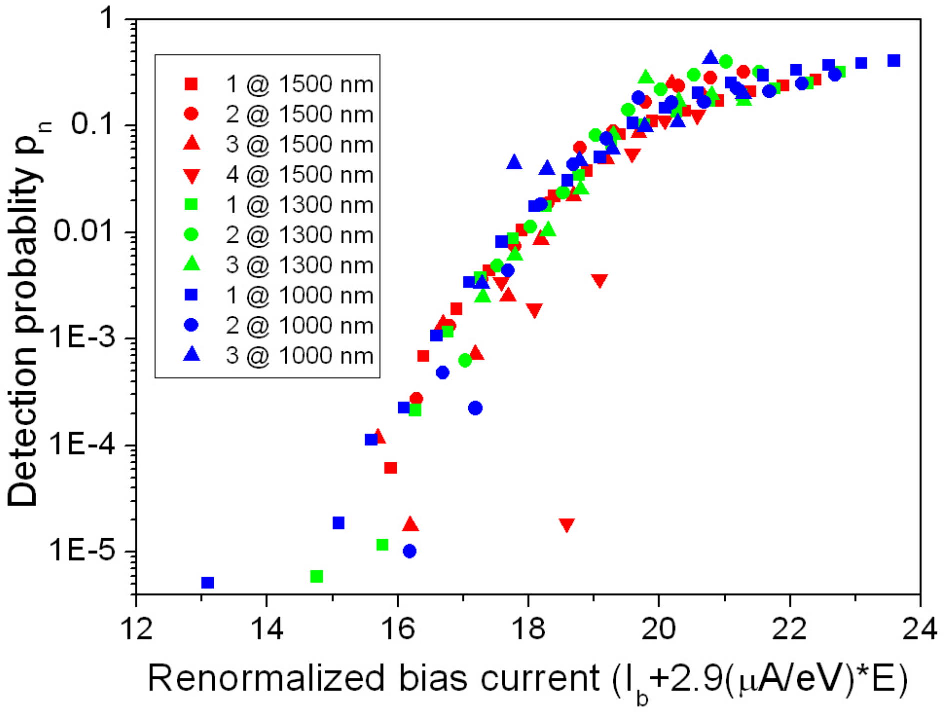
Universal curve



Universal curve

- R(I,λ,N) = R(I+γE) with E = N*hc/λ
- Goes beyond measuring edge of the plateau region



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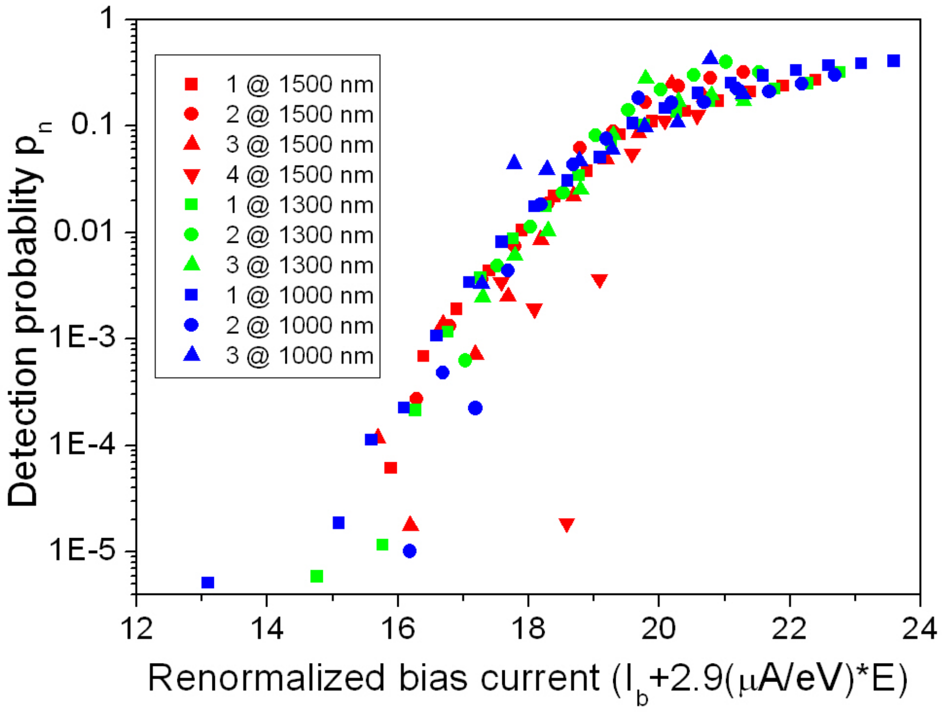
Universal curve

- Fluctuation-assisted scales in the same way as plateau response
- Challenge for theorists: explain this curve



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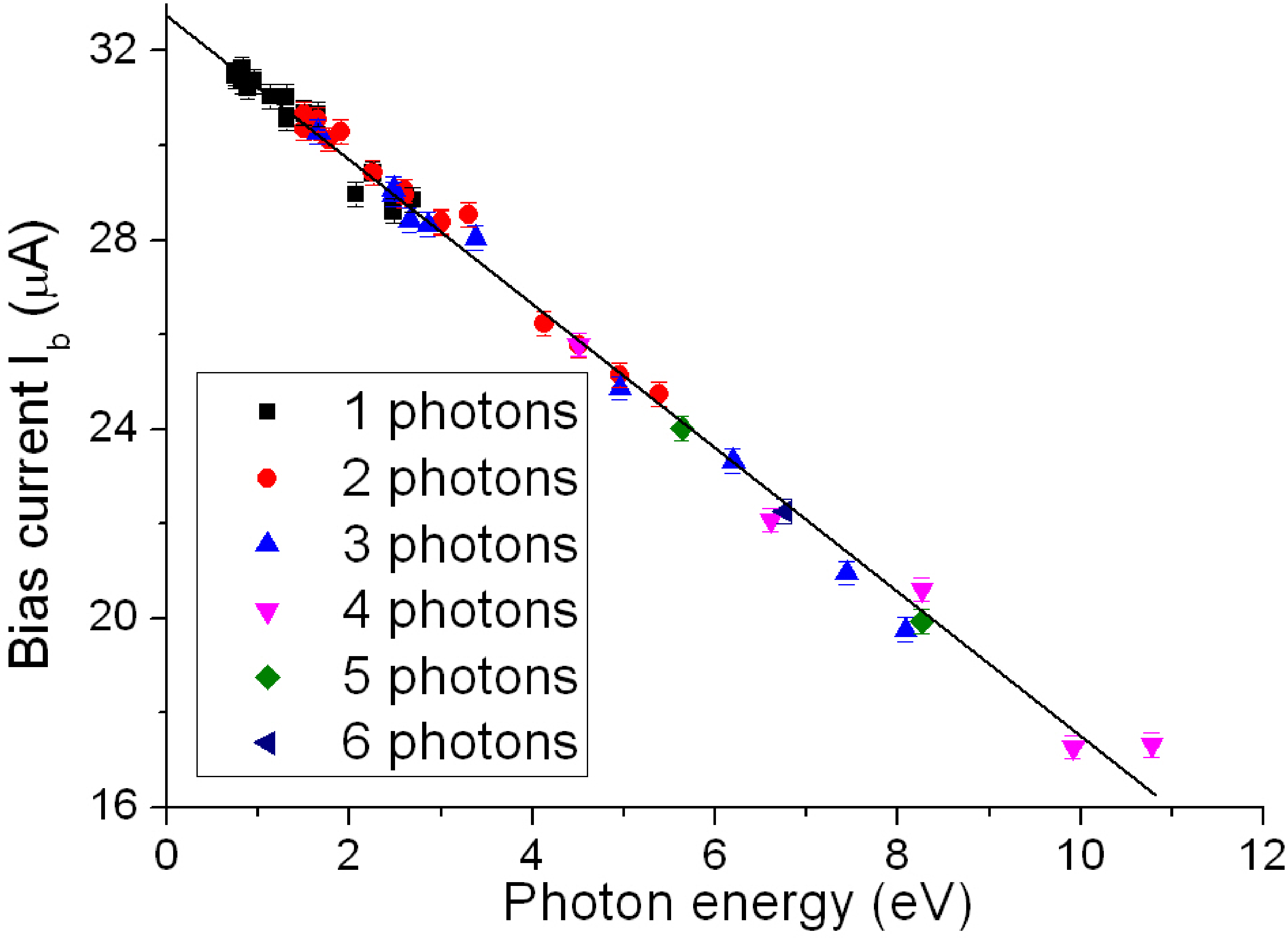
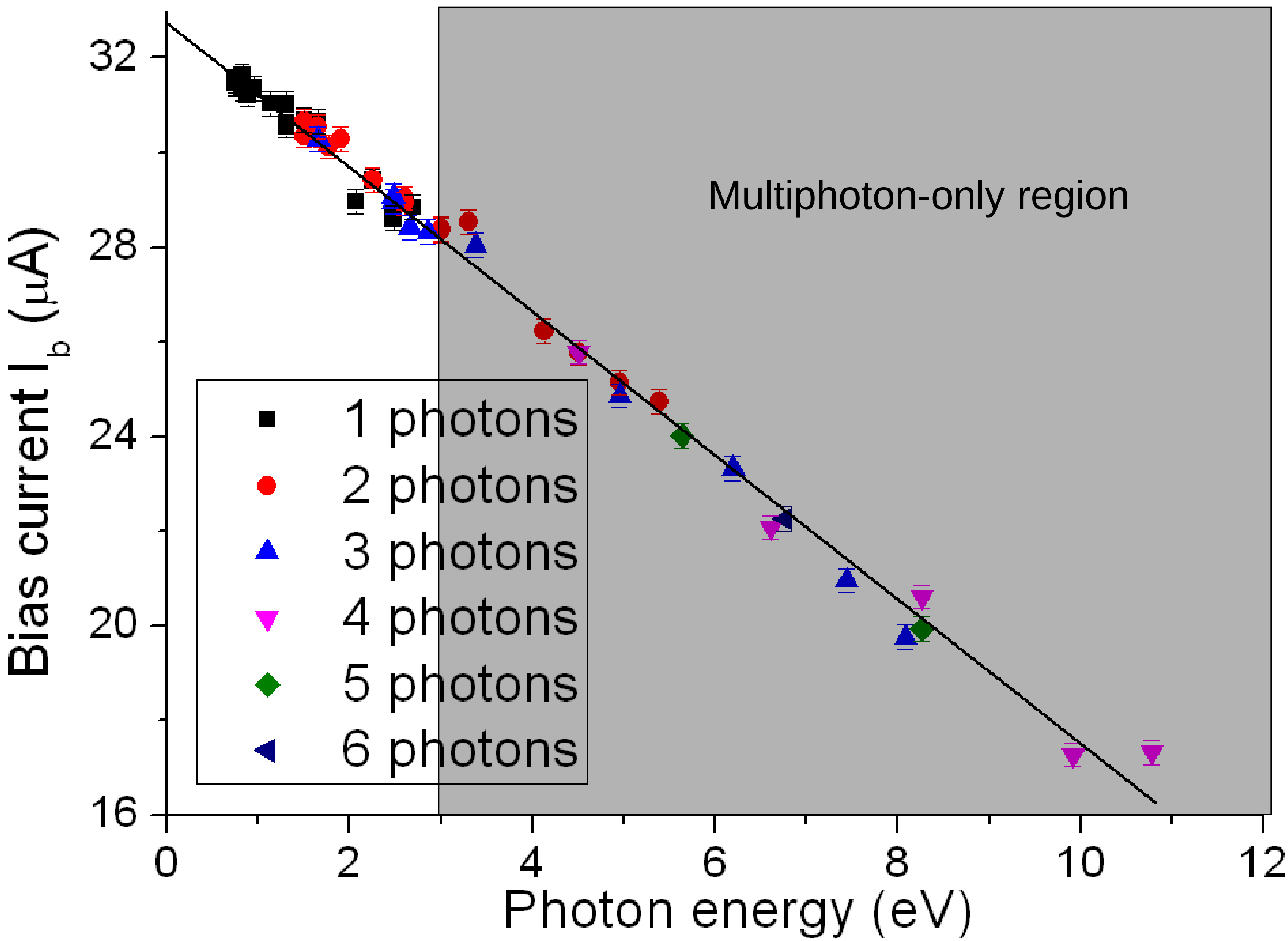
Result on 220 nm detector

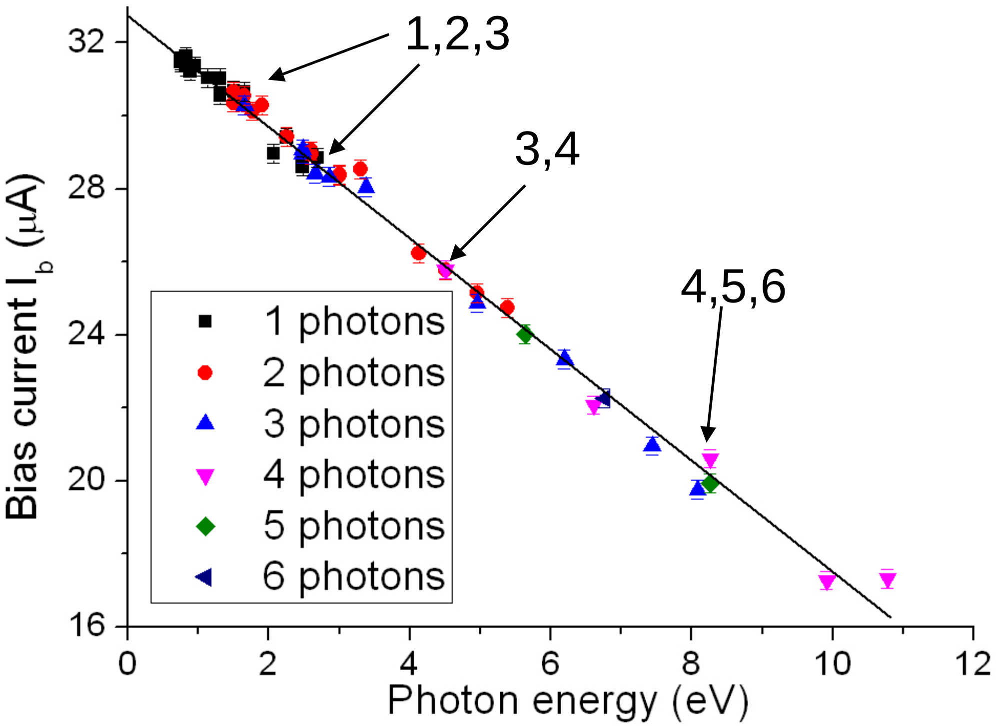


Result on 220 nm detector



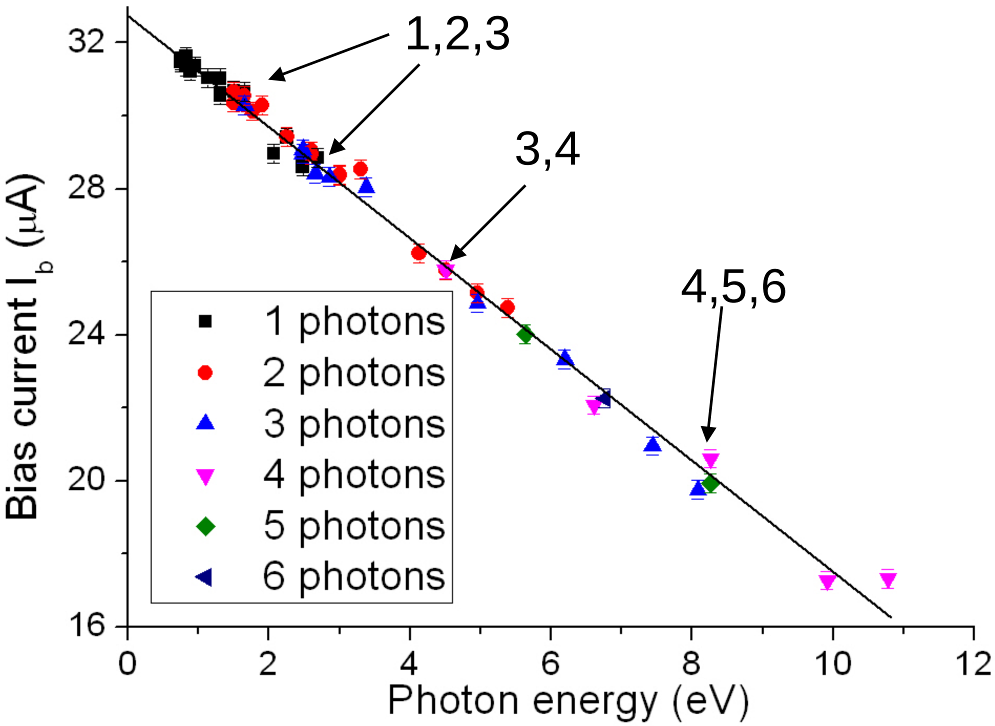
Extreme dynamic range

- 10.8 eV:
  λ_{eff} = 115 nm
- X-UV: not available with open-beam setup



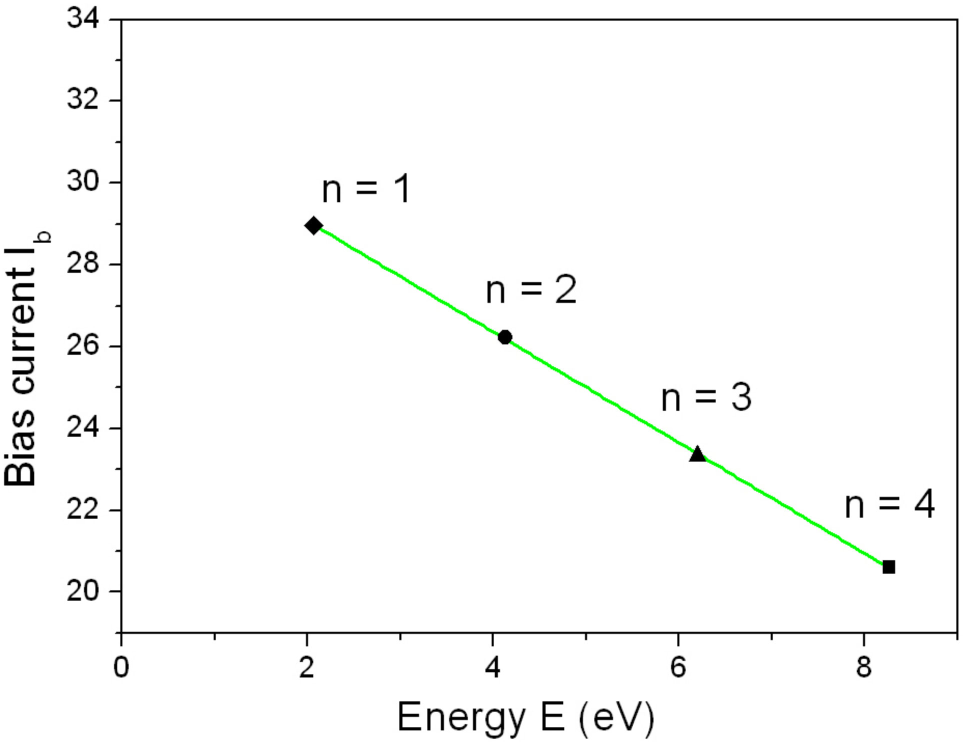
Extreme dynamic range

- Photon regimes overlap -> no stitching errors



Single experiment

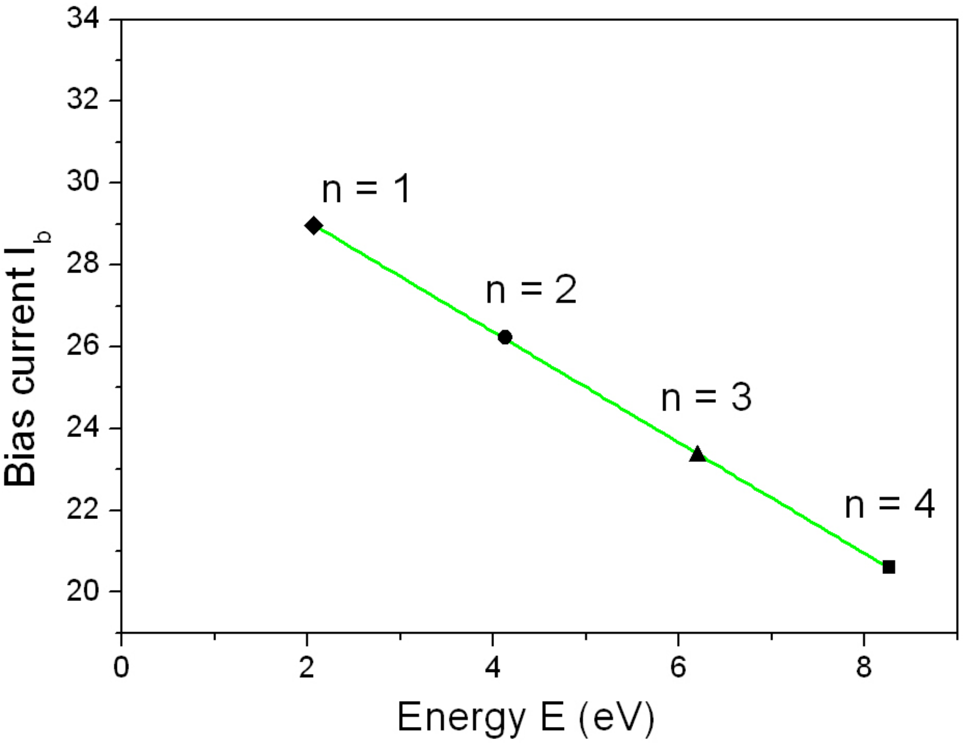
- Within single experiment 50 nA errors
- Allows for extremely accurate comparison with theory



Comparison with theory

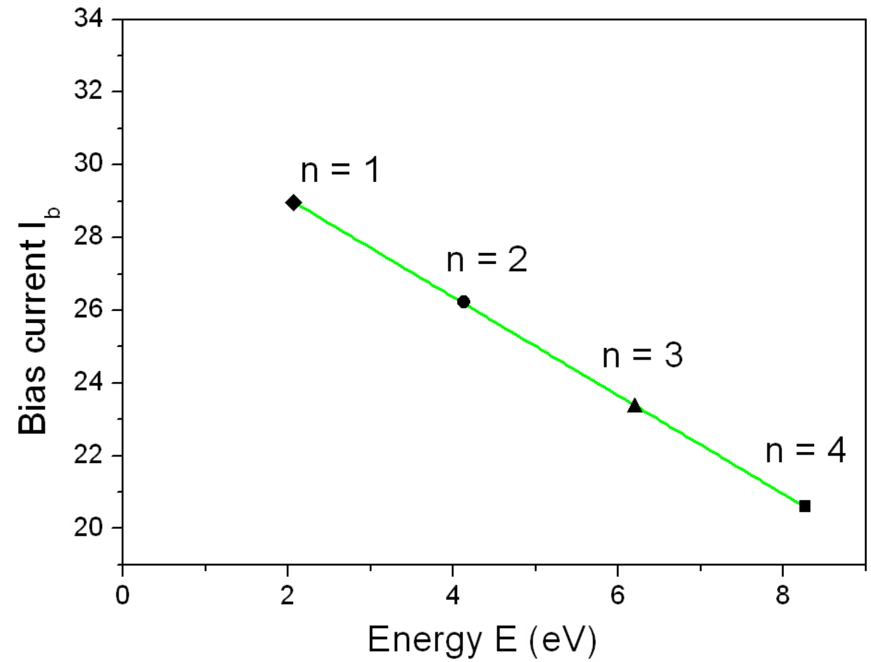
- We find: $I = I_0 + \gamma E$
- We find: $I_0 \neq I_c$
- $I_0 / I_c \sim 0.79 \pm 0.01$
- Very compatible with results of Engel *et al* arXiv: 1308:5781:

  $I_0 / I_c \sim 0.826$



Comparison with theory

- Accuracy sufficient to rule out alternatives to linear behaviour
  - Normal-code HS model
  - Time-dependent GL model (Zotova *et al*)
  - Bulaevskii model before Engel's corrections



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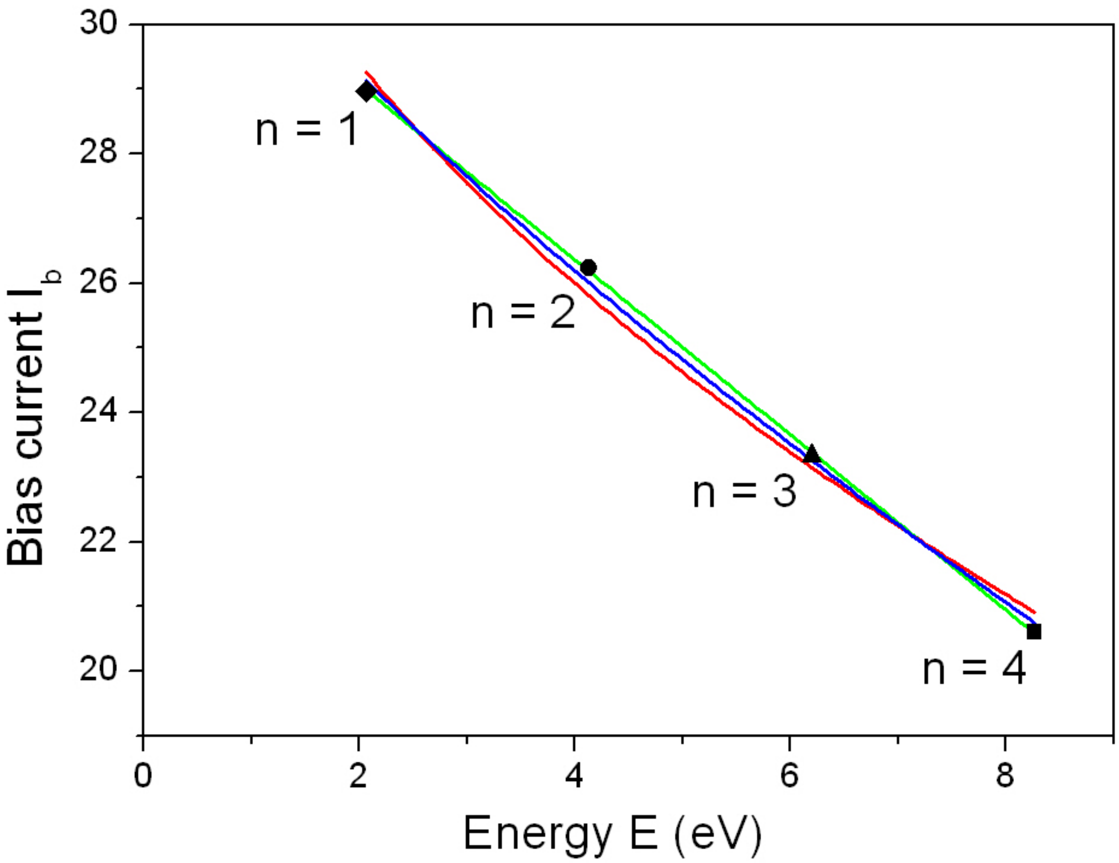
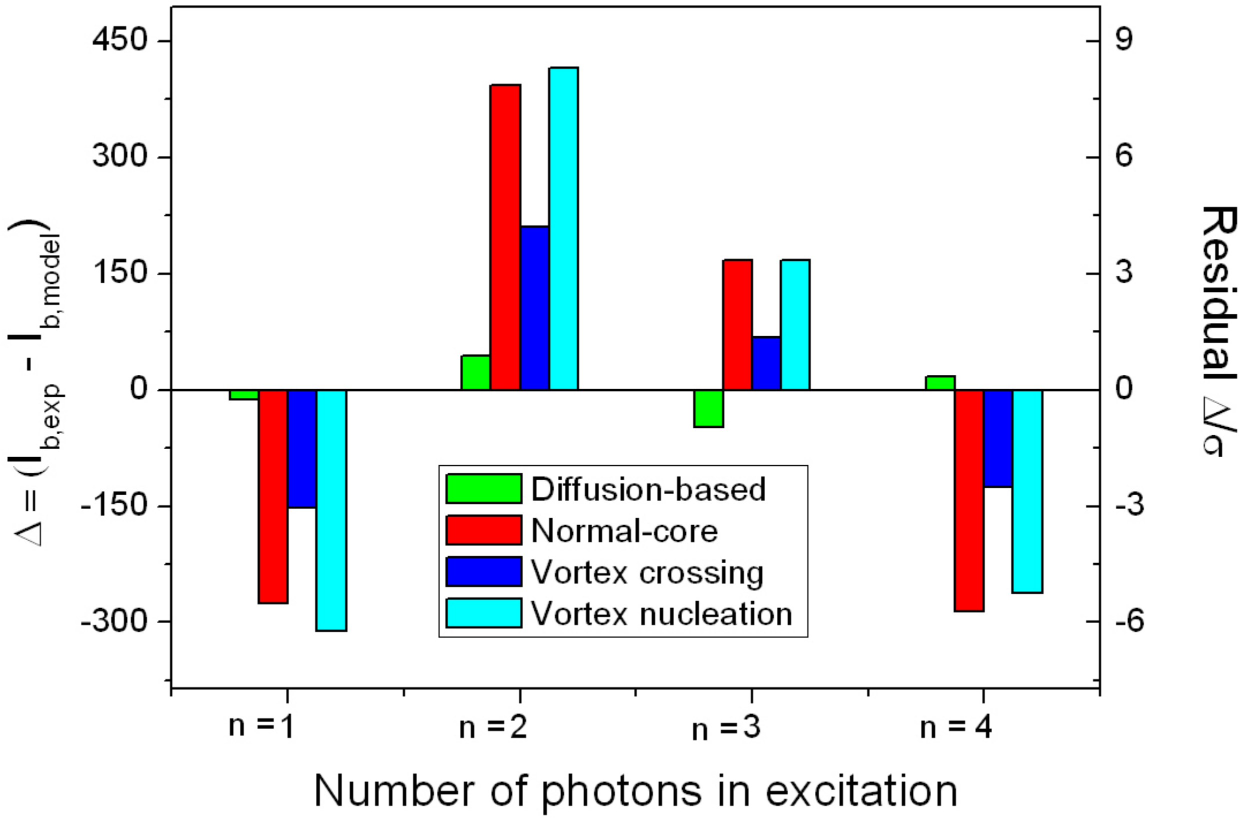
Comparison to theory



Comparison to theory



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Conclusions

- There is more in the detector than linear effiency
- Quantum tomography studies inner workings of detector
- Universal response curve
- Linear behavior up to X-UV

JR *et al*, OE **20**, (2012)
JR *et al*, PRA **79**, (2013)
JR *et al*, PRB **87**, (2013)

Multiphoton excitations

High accuracy
Single-shot experiment
High dynamic range

Nanodetector

Enhanced multiphoton response
Model system of SSPD

Detector tomography

Insensitive to linear losses
Full, quantitative characterization