From SPAD array technology to quantum spectroscopy and imaging

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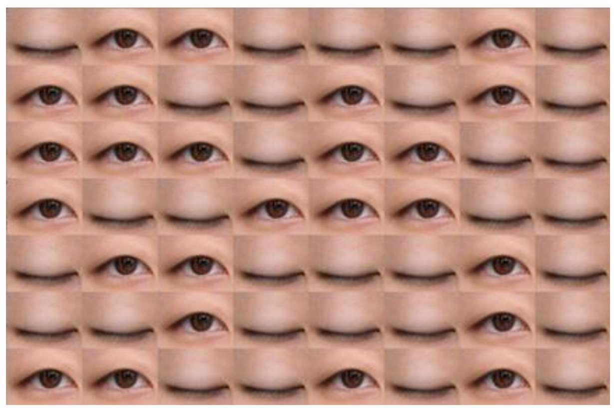


AMOS retreat, May 2022

Outline

- Reminder on photon correlations
- How we detect single photons?
- SPAD array properties
- Some applications of photon correlations in quantum dot spectroscopy

  - Multiexciton spectroscopy by photon statistics

  - Heralded spectroscopy of quantum sources

  - Heralded imaging

- Conclusion

The Hanbury Brown and Twiss stellar interferometer

HB&T proposed a new kind of telescope to measure the angle subtended by an object in the sky – which does not require a large mirror to resolve the size

1046 NATURE November 10, 1956 Vol. 178

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN
Jodrell Bank Experimental Station, University of Manchester
AND
Dr. R. Q. TWISS
Services Electronics Research Laboratory, Baldock

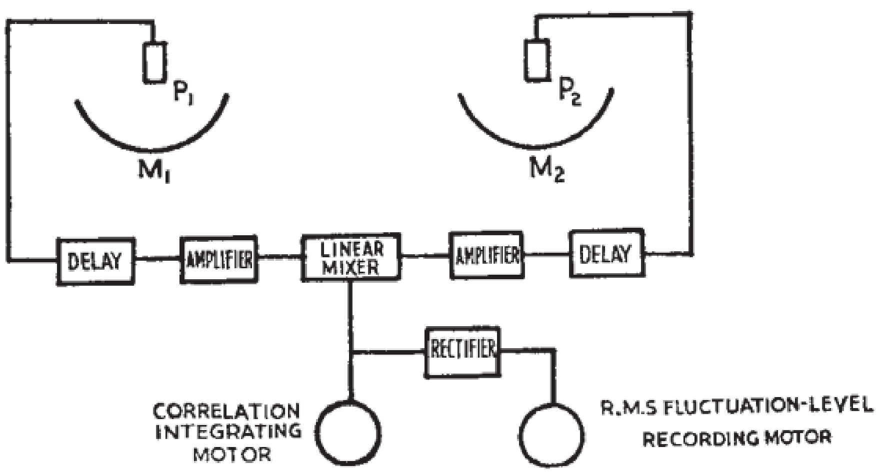


Fig. 1. Simplified diagram of the apparatus

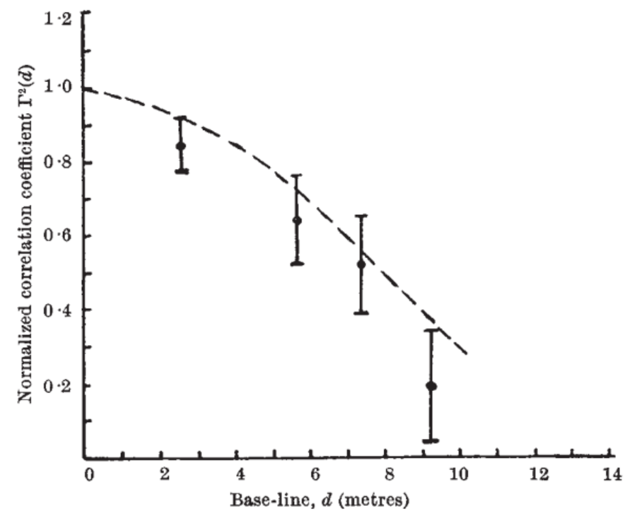
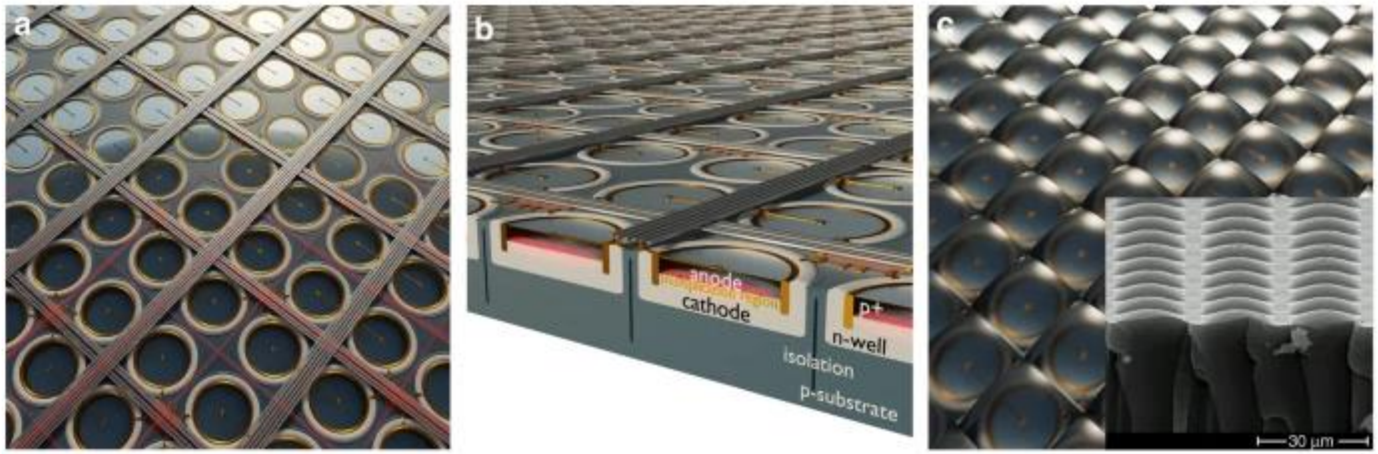


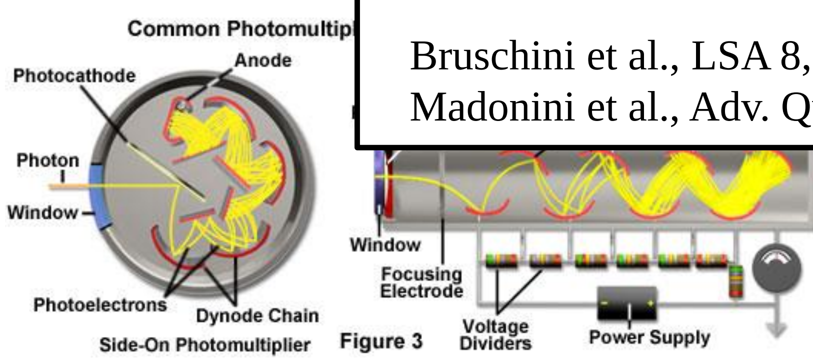
Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

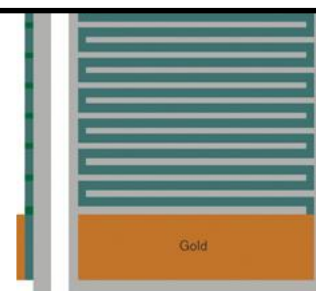
How do we detect single photons?

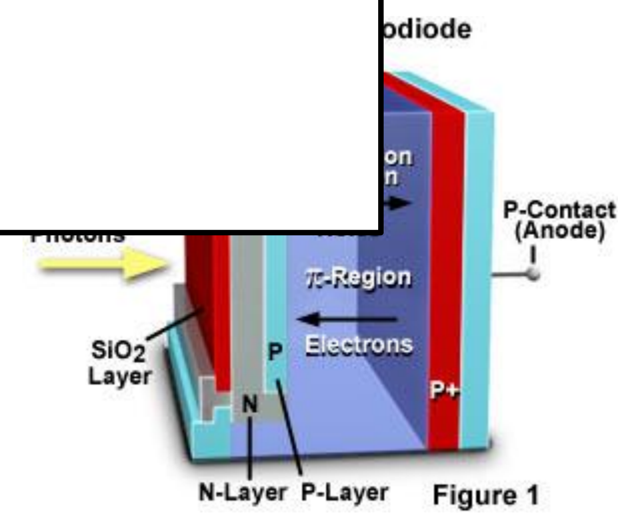


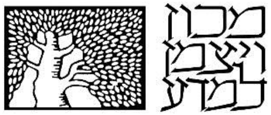
There’s a new kid on the block – monolithic SPAD array imaging sensors

Bruschini et al., LSA 8, 87 (2019)
Madonini et al., Adv. Quantum Tech. 4, 2100005 (2021)

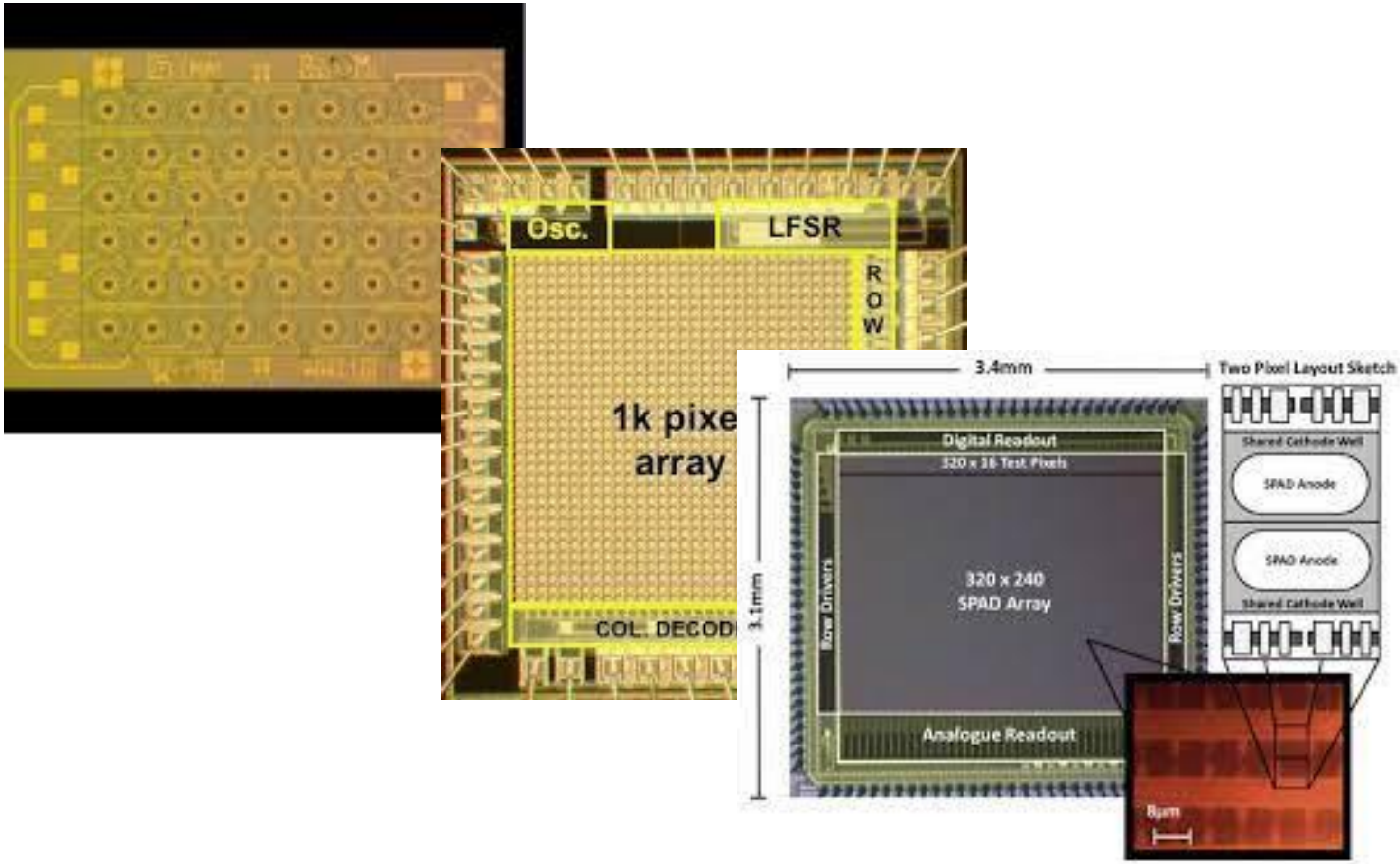








Evolution



Now at 1Mpixels …
and counting

Detector parameters

- Quantum efficiency – typically up to 50% (max in green-yellow)
- Fill factor – up to ~70% (with microlenses)
- Timing accuracy – typically 100ps, but <10ps already demonstrated
- Dead time – typical 50ns
- Dark counts – typical 100 cts/s
- Pixel numbers – up to ~1000 with TDCs, ~1Mpixel gated
- Saturation – typically 2-3Mcts/s
- Frame rates – up to 100,000 (for gated imagers)

- Cost – will be in the $10K-$100K range (depending on parameters)

Open issues

- NIR response
  - first InGaAs SPAD arrays are coming out. Need to be cooled to circa -70°C but will enable operation
  - Thicker Si SPAD arrays could provide solution up to ~800nm
- Crosstalk
  - SPADs emit light when they detect light. Crosstalk probabilities are in the range of 0.1%. Presents compromise with fill factor.
- Uniformity
  - Detectors contain still too many ‘hot’ pixels. Uniformity is not amazing
- Data rates
  - For large detectors data rates are prohibitively large. On-chip processing becomes a must.

So what are SPAD arrays good for?

- LIDARs

- Fast lifetime imaging
- Enhanced saturation properties in low-light level scenarios
- Ultrafast metrology
- Quantum imaging and spectroscopy!

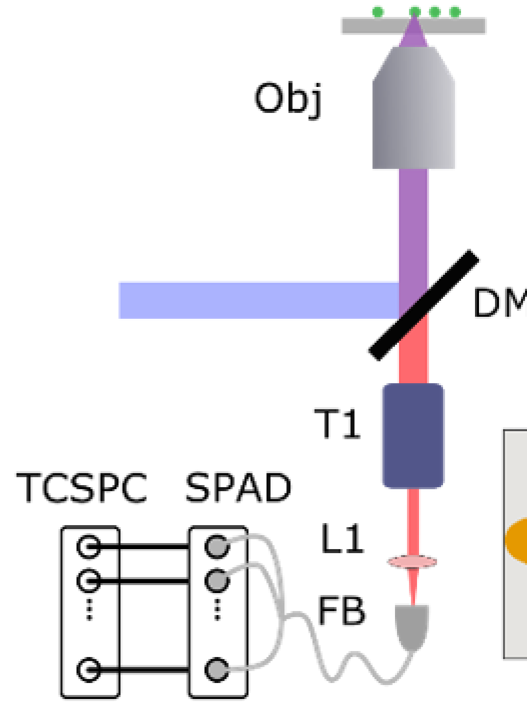
Imaging with quantum light

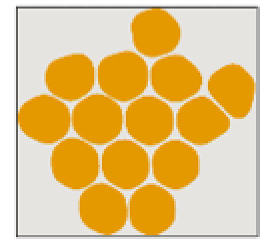
Until not too long ago, we used a "fiber bundle camera" for quantum imaging.

It was:
1. (very) Expensive
2. Not scalable

But even with that we got

- STORM at higher emitter density (demo)
- Confocal superresolution imaging based on photon statistics

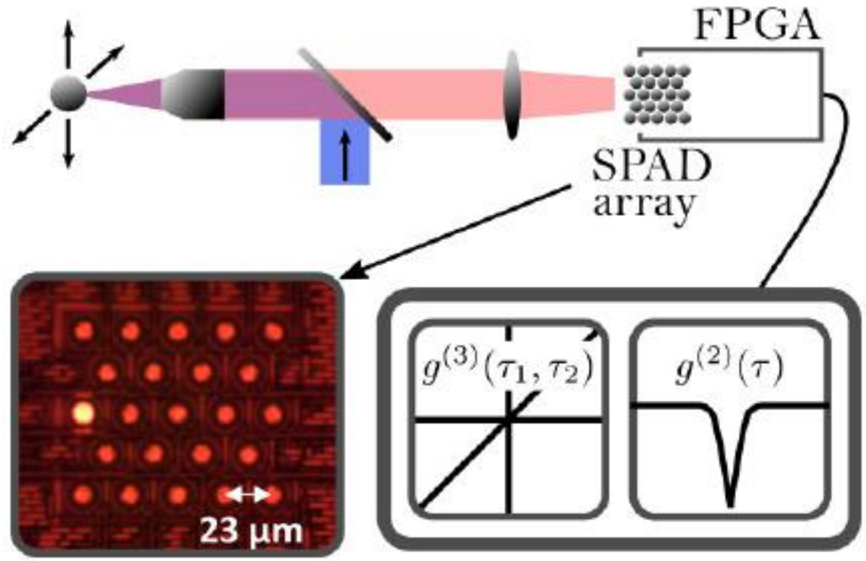


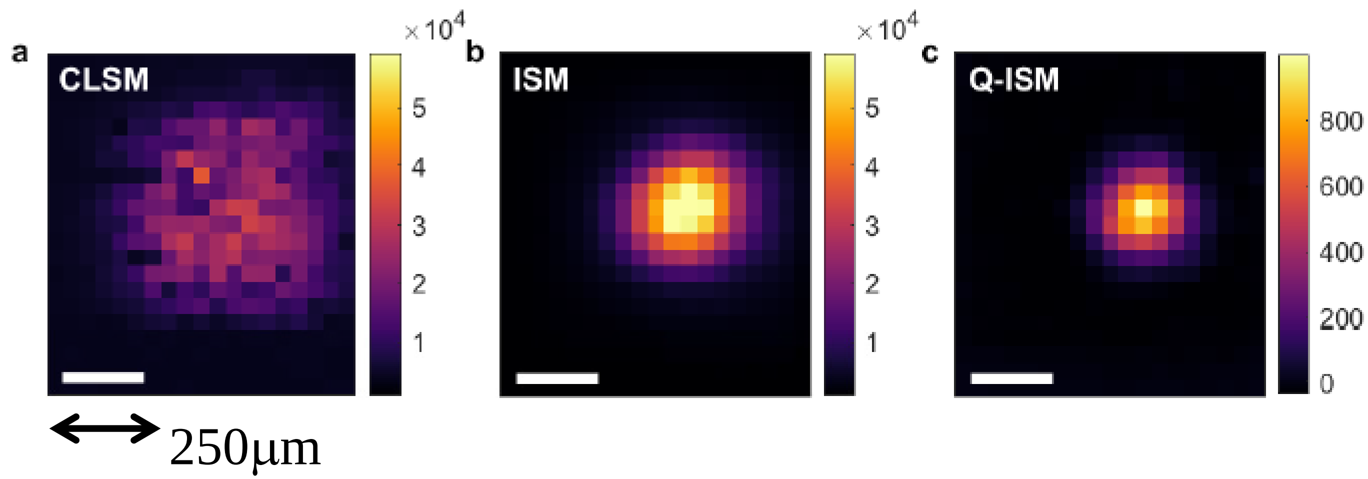


Photon statistics with SPAD arrays

Replace the fiber bundle + 15 detectors (~100k$) with a CMOS SPAD array (<10k$)

Crosstalk is an issue but can be overcome since it is time-independent (if done carefully)

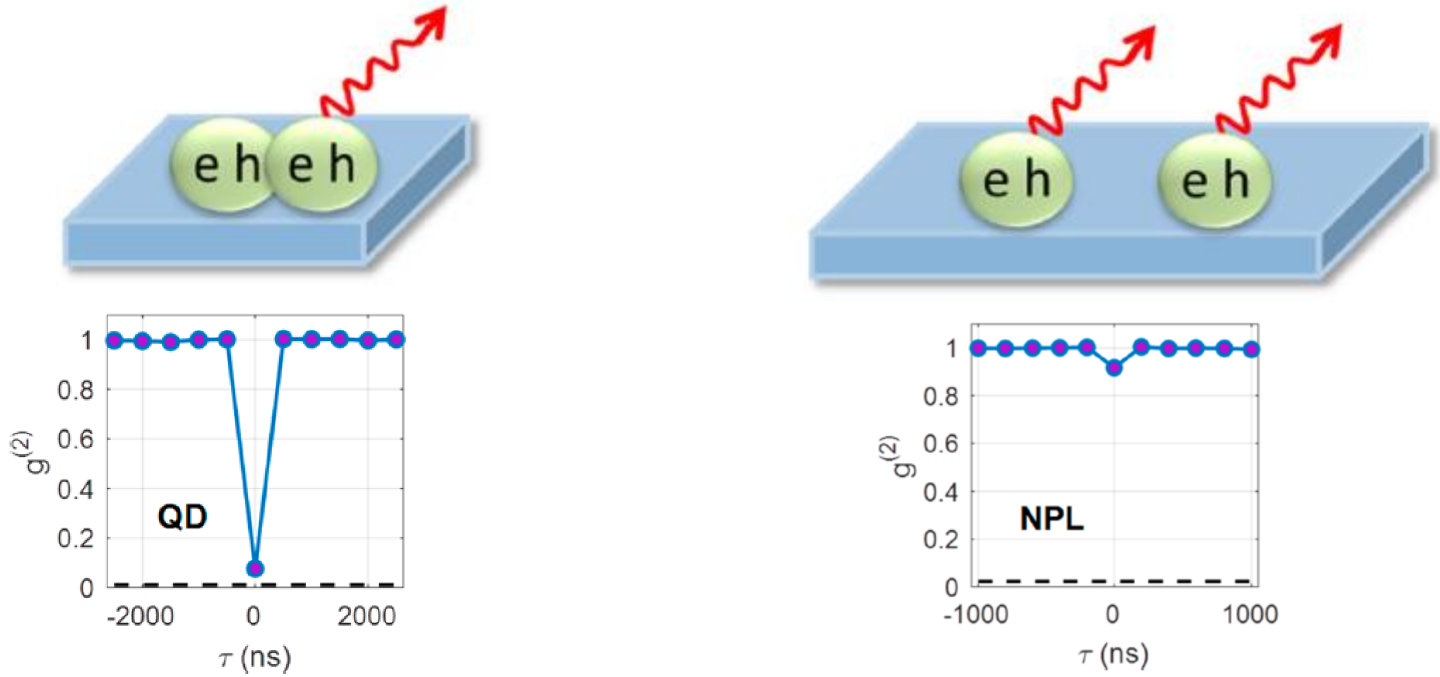




G. Lubin, DO et al., Optics Express 27, 32863 (2019)

Quantum spectroscopy

Can we replace 'traditional' spectroscopy with photon statistics?

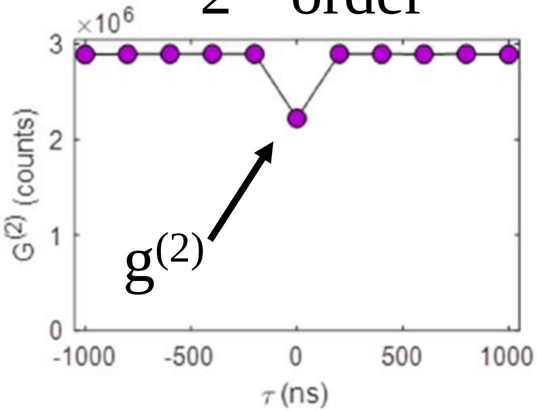


In larger nanocrystals (e.g. nanoplatelets) antibunching is not complete.
Is there information in the higher order photon correlations?

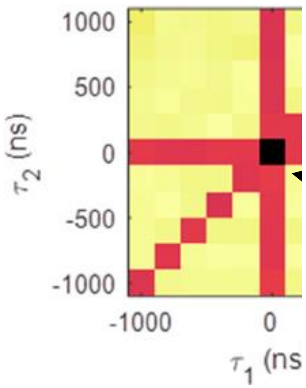
The short answer is "Yes" …

Higher order antibunching spectroscopy

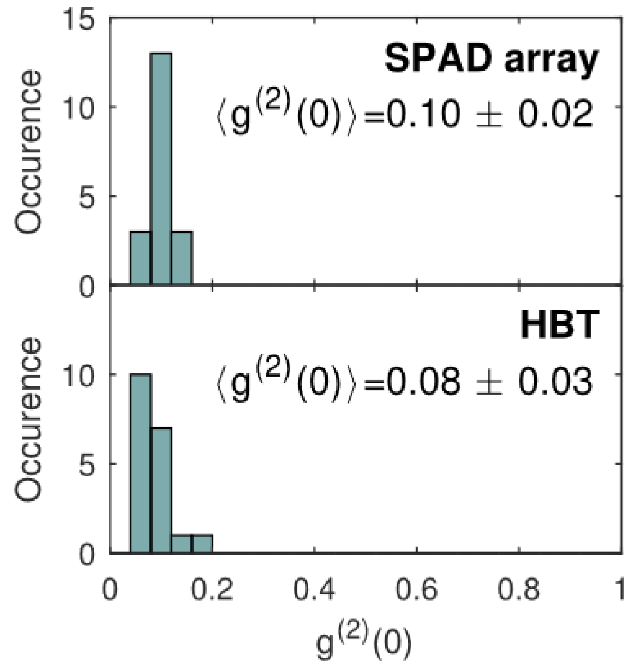
2^{nd} order

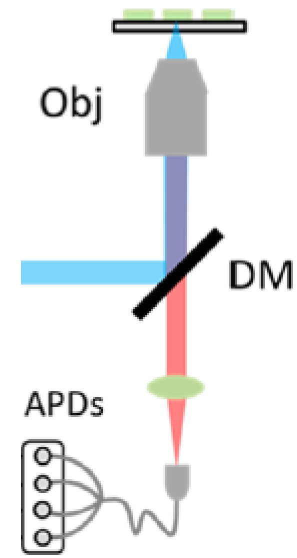


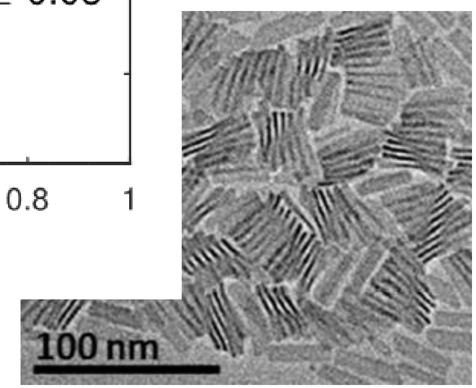
3^{rd} or



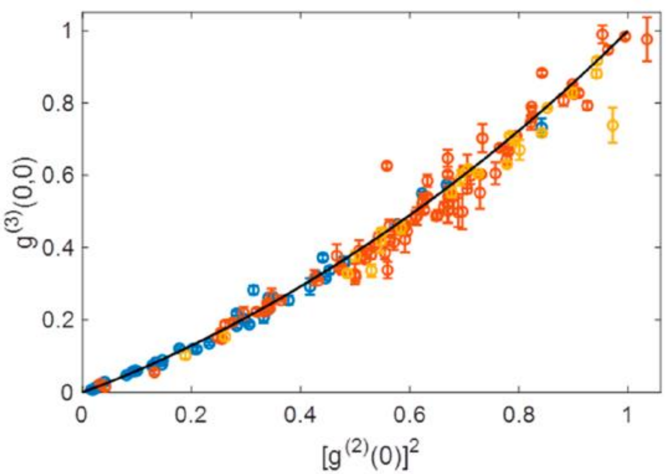
Can also be done with SPAD arrays

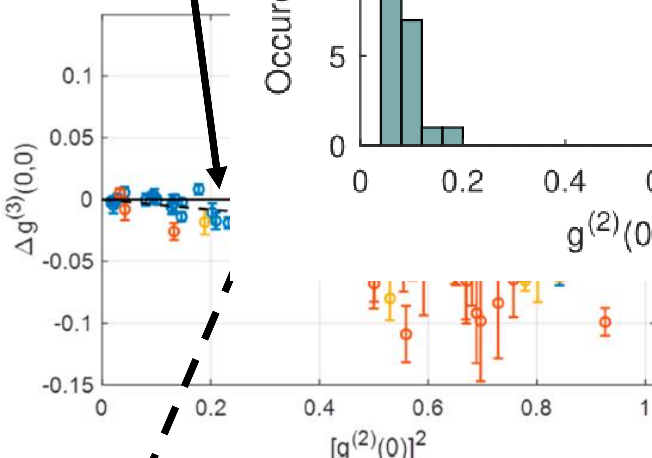






Two body inte



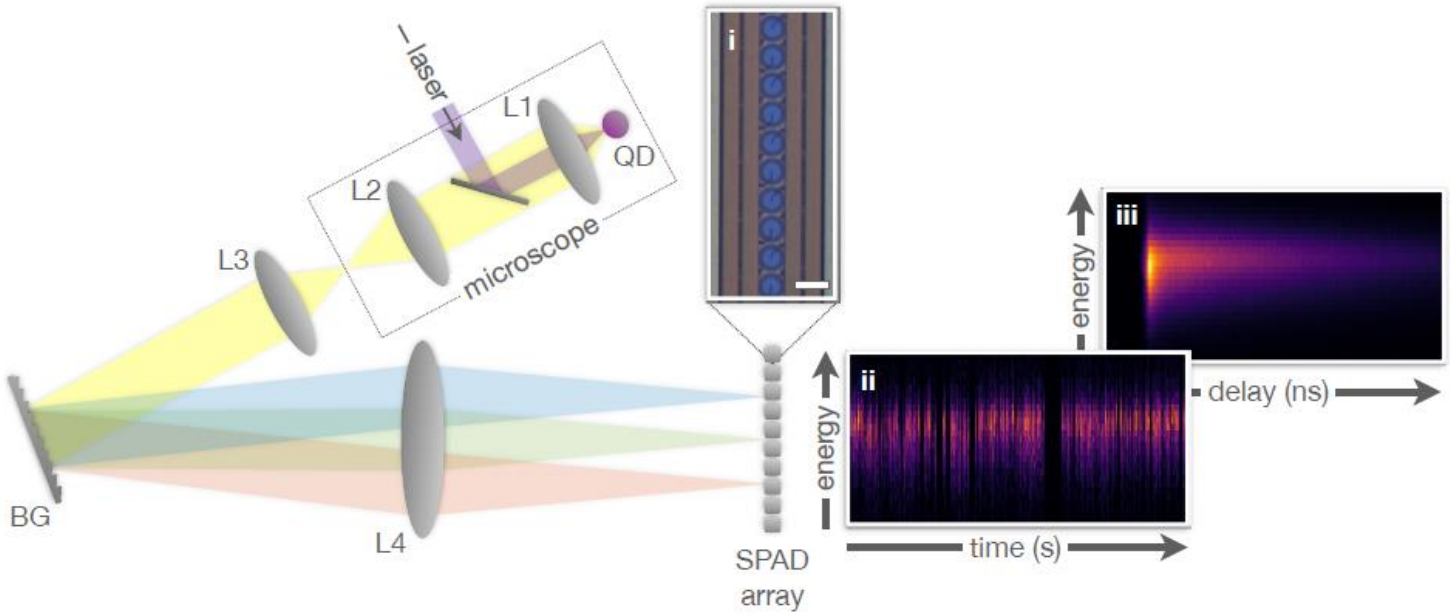


With three body correction

D. Amgar, DO, et al., Nano Lett. 19, 8741 (2019) ; G. Lubin, DO et al., Optics Express 27, 32863 (2019)

Heralded spectroscopy

Monolithic arrays of single photon spectrometers can provide access to previously unexplored properties at the single particle level, multiplexing photon correlations along another dimension



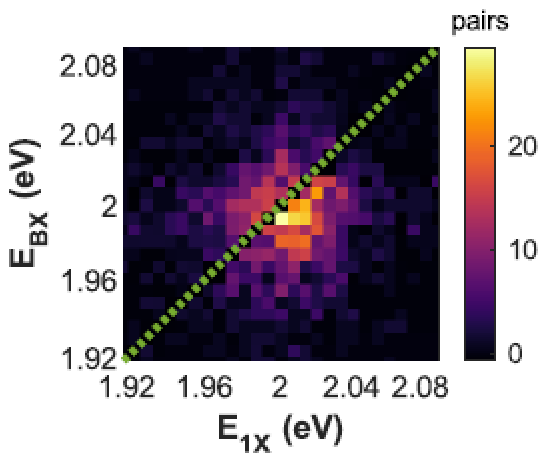
Single-photon time resolved spectrometer based on a 1D SPAD array:
~1ns time resolution, 2nm spectral resolution - simultenaously

G. Lubin, DO, et al., Nano Lett. 21, 6756 (2021)

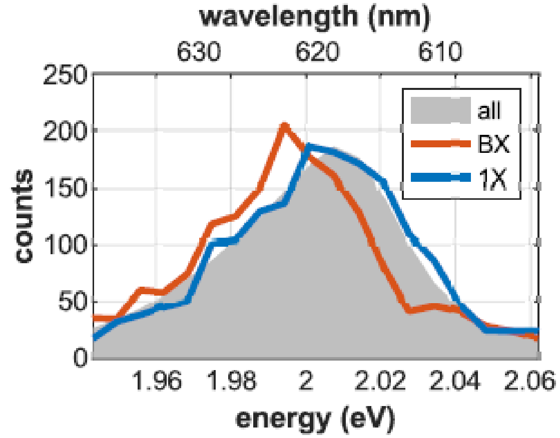
Heralded multiexciton spectroscopy

This enables to identify photon pairs emitted following a single excitation cycle and post-select only events involving a pair of photons (BX-X cascaded emission)

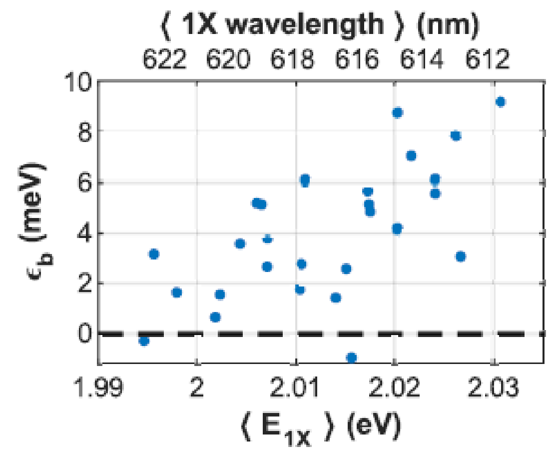
First photon



Second photon



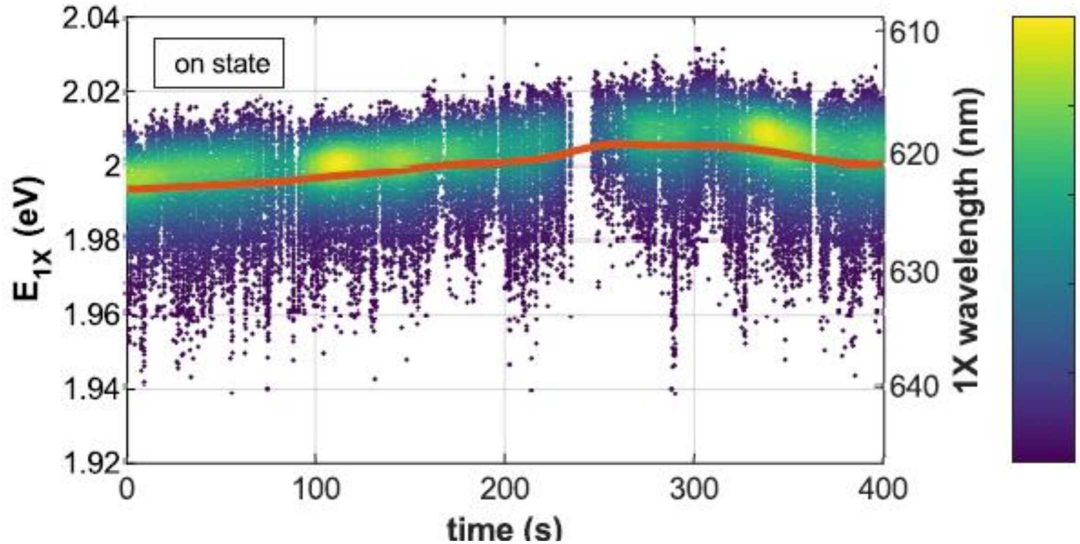
This reveals “hidden” inhomogeneous broadening



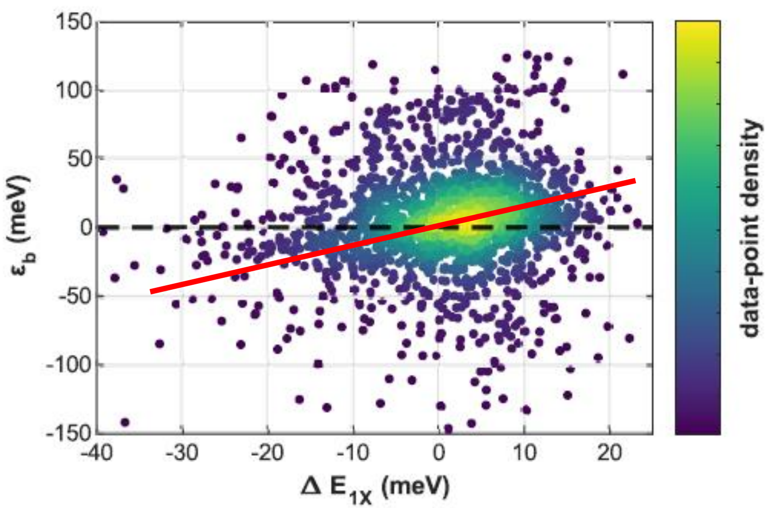
G. Lubin, DO, et al., Nano Lett. 21, 6756 (2021)

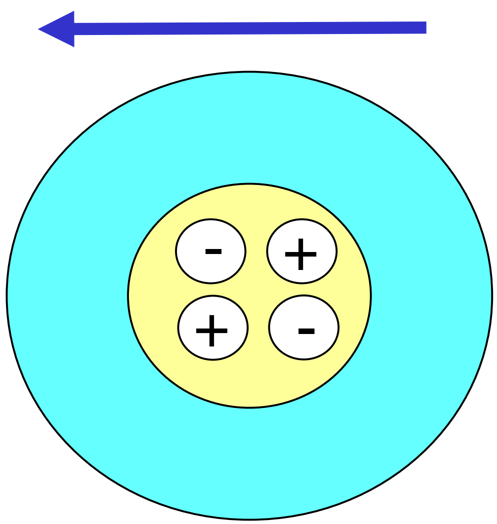
Heralded multiexciton spectroscopy

And study correlations at the single particle level, for example between spectral diffusion of BX and X transitions



BX less bound when X emission is redder (stronger stray field)

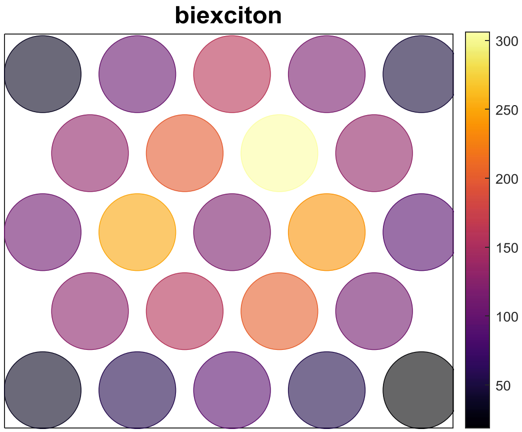




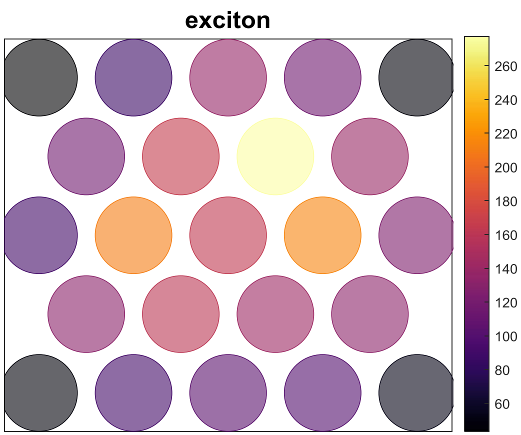
G. Lubin, DO, et al., Nano Lett. 21, 6756 (2021)

Heralded imaging

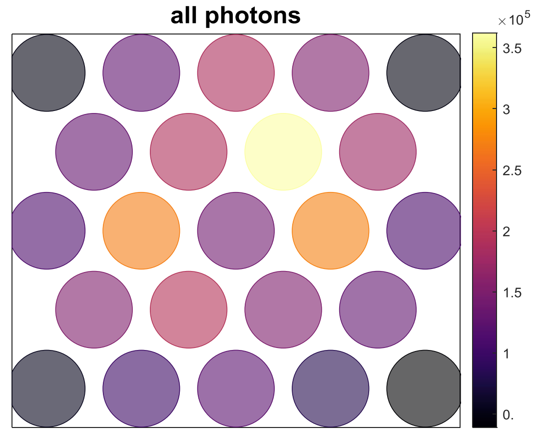
Similar logic, but now in real space … enabling us to study the transition dipole moment of transient states!

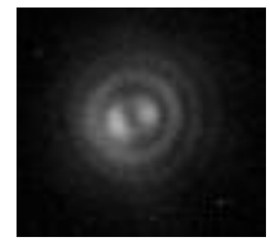


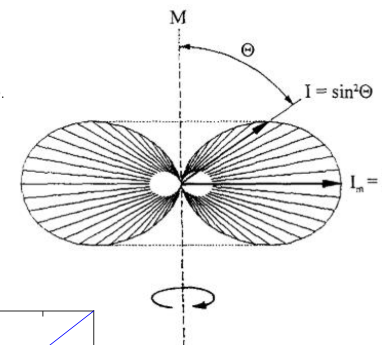
biexcitons –
detected **first**

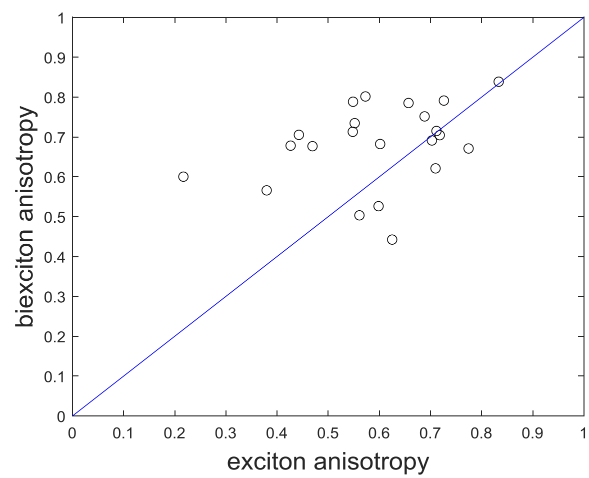


excitons –
detected **second**









Conclusions

Photon correlations are ubiquitous and are becoming not so hard to measure

They often contain information which is hard or impossible to obtain by other means

Advances in detector technology (especially CMOS-compatible SPAD arrays) will make this a simple and cheap tool to use, even in “standard” tools such as spectrometers (or cameras).

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