Photon-number-resolving detector free of systematic errors & nonclassical light characterization towards counting single emitters

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QOLO

GAČR
CZECH SCIENCE FOUNDATION
Project 17-26143S

By measuring the statistics of light, we can see deeper and identify more complex structures

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

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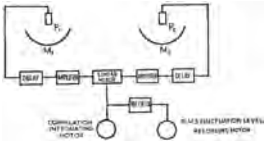

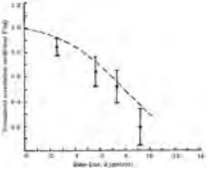

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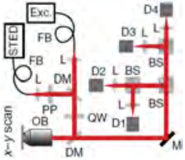
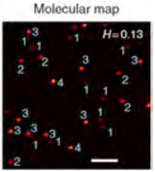
Mapping molecules in scanning far-field fluorescence nanoscopy

Haisen Ta[1], Jan Keller[1], Markus Haltmeier[2,3], Sinem K. Saka[4], Jürgen Schmied[5], Felipe Opazo[4], Philip Tinnefeld[5], Axel Munk[2,6] & Stefan W. Hell[1]

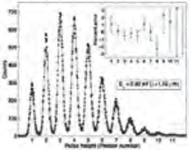


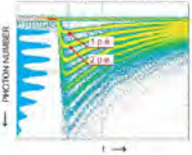


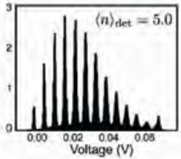
The key requirement for exploring statistical properties of light is the ability to distinguish individual photons

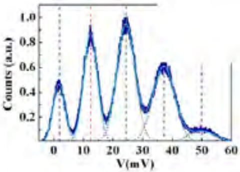
Photon-number-resolving detectors (PNRD)

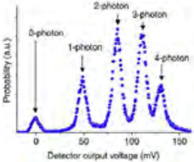
- inherent energy/quanta resolution (VLPC, TES)
- multi-pixel (SPAD matrix, SNSPD matrix)

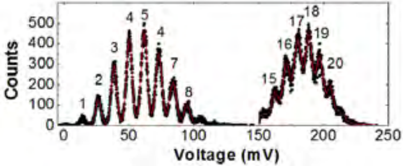


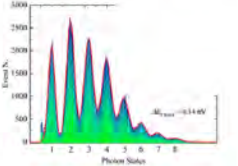












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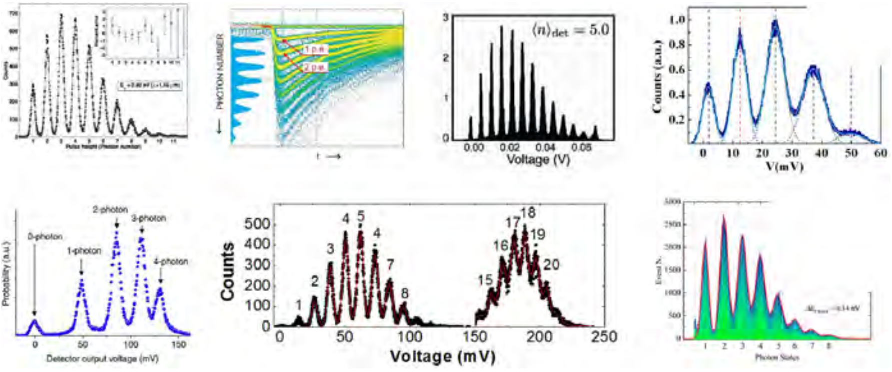
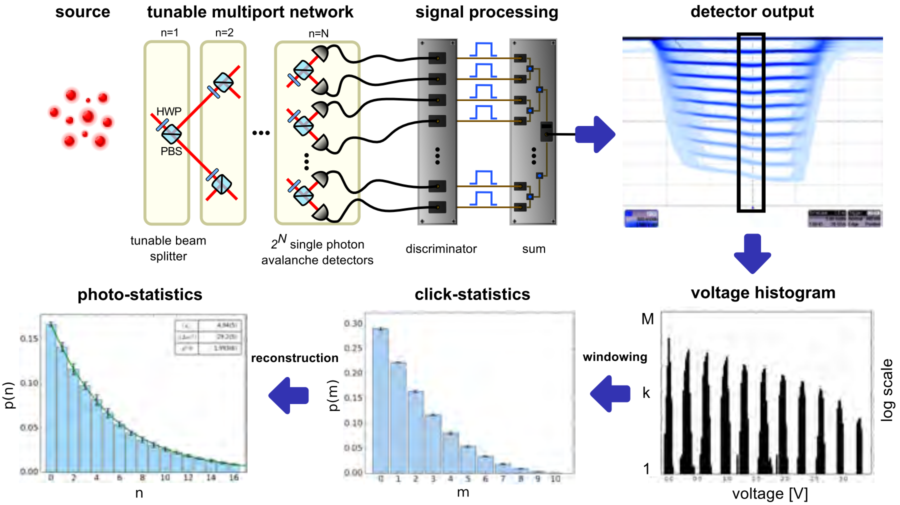


- (time or) spatial multiplexing

Reconfigurable PNRD free of systematic errors*

*) For reasonably low photon numbers. Or when click statistics is enough.



Photon statistics can be estimated from raw clicks

- Direct (pseudo)inverse
- Maximum likelihood (expectation-maximization)
  [Řeháček et al. PRA 67, 061801R (2003); Marsili et al. NJP 11, 045022 (2009)]
- EME algorithm – hi-fi, no oscillation, faster convergence
  [Hloušek *et al.*, in preparation]

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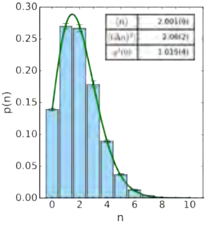
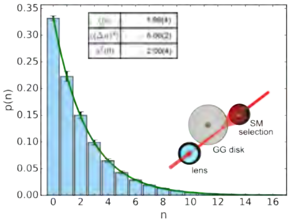
Classical states in/out of thermal equilibrium

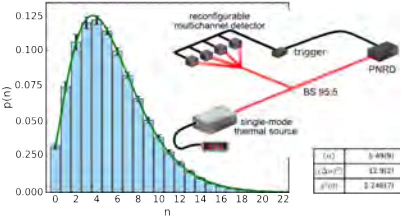
coherent Poissonian



thermal Bose-Einstein



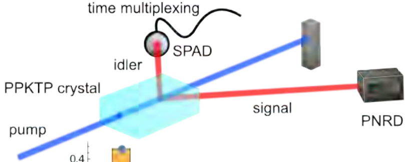
three-photon subtracted thermal

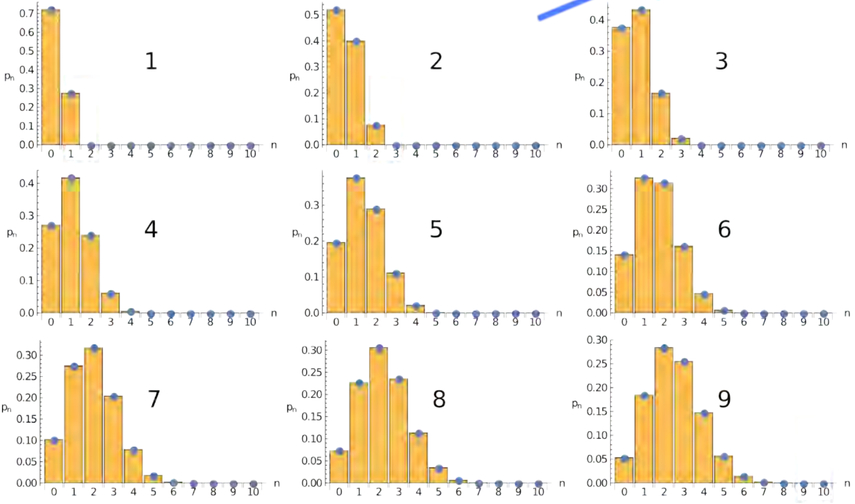


[Hloušek *et al.*, Sci. Rep. (2017)]

Emission from several single emitters

agrees with attenuated Fock states
within the precision of $\Delta p_n \lesssim 5 \times 10^{-4}$





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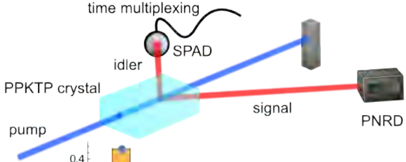
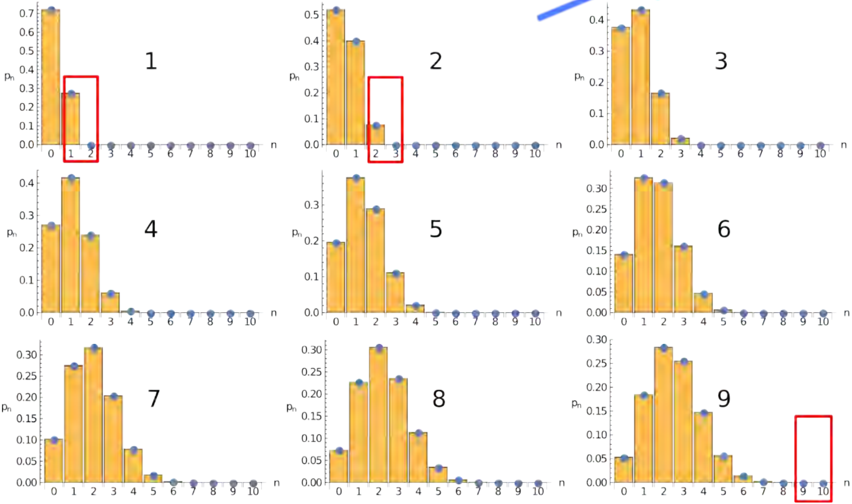
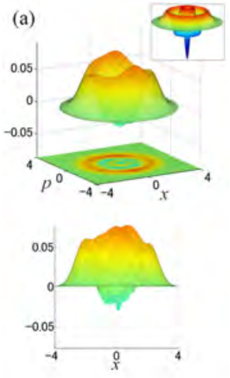




Higher Fock states are hard to detect

Negative Wigner function

Up to $|3\rangle$: Yukawa *et al.*, Opt. Express 21, 5529 (2013).



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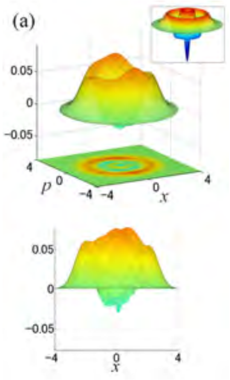

Nonclassical light

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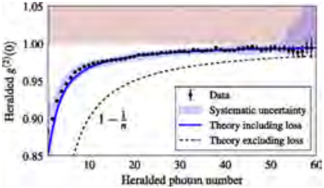
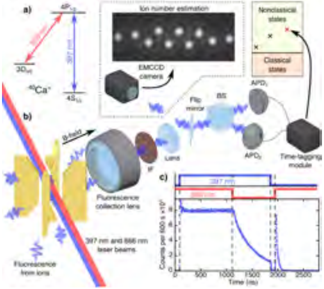


Up to 1500: Obšil *et al.*, arXiv:1705.04472 (2017).



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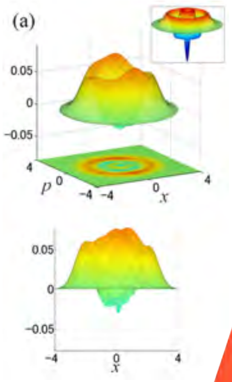

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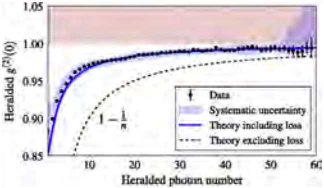

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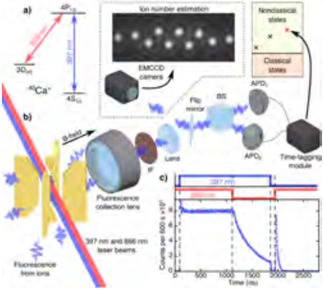

Quantum non-Gaussian states (QNG)
cannot be expressed as a mixture of Gaussian states

$\rho \neq \int P(\lambda) \, |\lambda\rangle\langle\lambda| \, \mathrm{d}\lambda$

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Criteria for single-photon state:

- p_0–p_1 [Filip & Mišta, PRL 106, 200401 (2011)]
  loss vs. noise (multiphoton contribution) test
- P_0–P_{00} [Lachman & Filip, PRA 88, 063841 (2013)]
- Wigner function criterion [Genoni *et al.*, PRA 87, 062104 (2013)]

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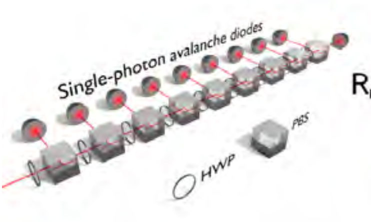
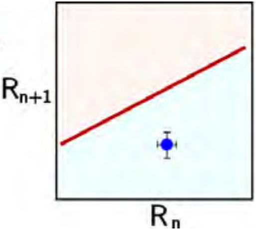
Apart from being fundamental quantum property...
are there any applications of QNG?

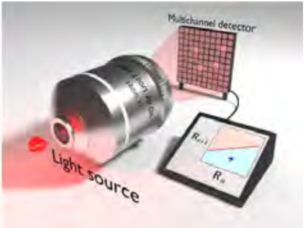
- Metrology of single photon sources [Straka *et al.* PRL 113, 223603 (2014); Predojević *et al.* Opt. Express 22, 4789, (2014)]
- Sufficiency for discrete-variable QKD security [Lasota *et al.* PRA 96, 012301 (2017)]

Quantum non-Gaussianity for multiphoton states

Criteria hierarchy based on particle indivisibility
[Straka *et al.* arXiv:1611.02504 (2016)]
Quantum features can be assessed directly from the click statistics







Theory: maximizing linear functional $F(a) = R_n + aR_{n+1}$
[Lachman & Filip, Opt. Express 24, 27352 (2016)]

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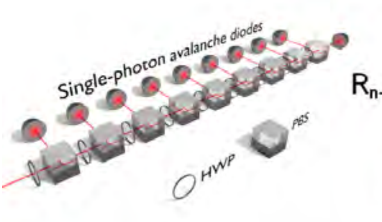

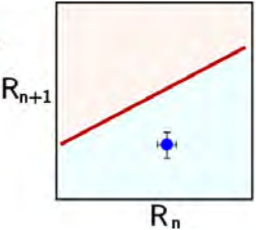

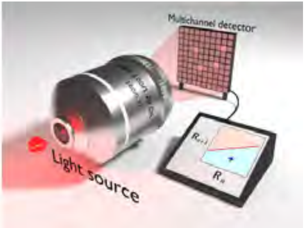

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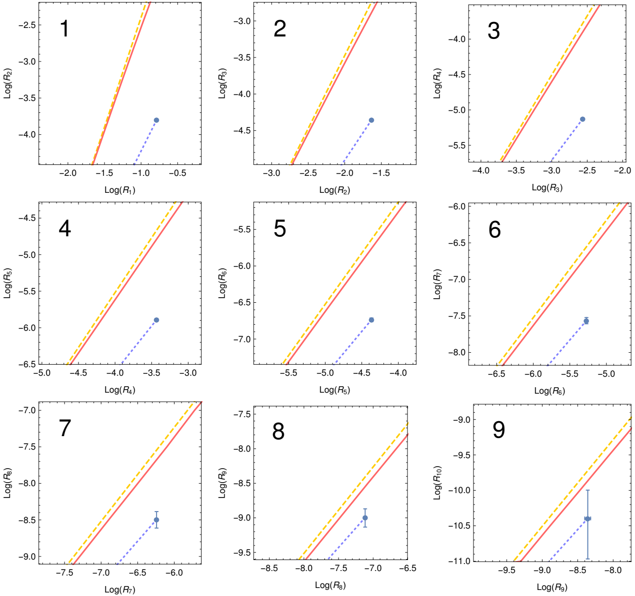
[Lachman & Filip, Opt. Express 24, 27352 (2016)]

Also for nonclassicality
[Sperling *et al.* PRL 118, 163602 (2017); PRA 96, 013804 (2017)]

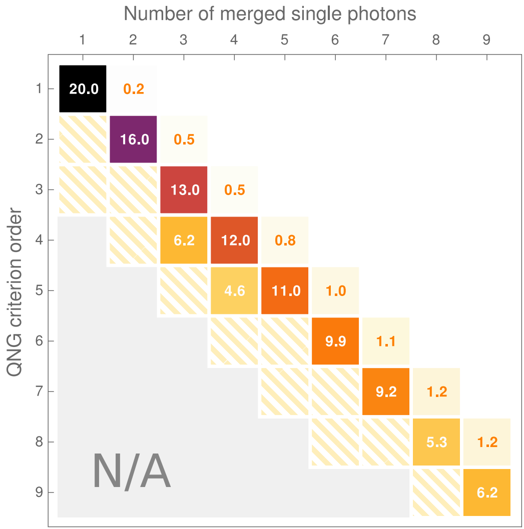
QNG demonstrated up to 9 single emitters



[Straka *et al.*, arXiv:1611.02504 (2016)]

QNG is loss-tolerant but more challenging than NCL

QNG depth = the loss which the state can withstand and still be QND



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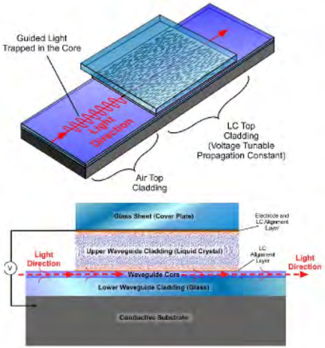
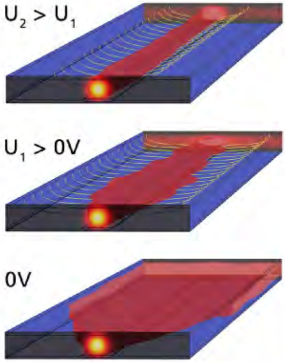
Towards integrated tunable reconfigurable PNRD

Waveguides with tunable couplers/switches and well isolated detectors



Vescent Photonics
(Analog Devices)



Fraunhofer IPMS

F. Costache et al., Variable optical power splitter with field-induced waveguides in liquid crystals, OFC.2014.Th1A.7 (2014)

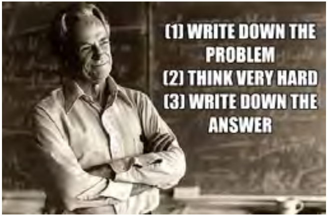
Our team – Quantum Optics Lab Olomouc

Experiment

Josef Hloušek
Robert Stárek
Petr Obšil
Ivo Straka
Martina Miková
Lukáš Slodička
Michal Mičuda (poster P2_02)
Miroslav Ježek

Theory

Lukáš Lachman (poster P1_11)
Ladislav Mišta
Radim Filip
Jaromír Fiurášek



Join our experimental group!

PhD students and
junior postdocs wanted