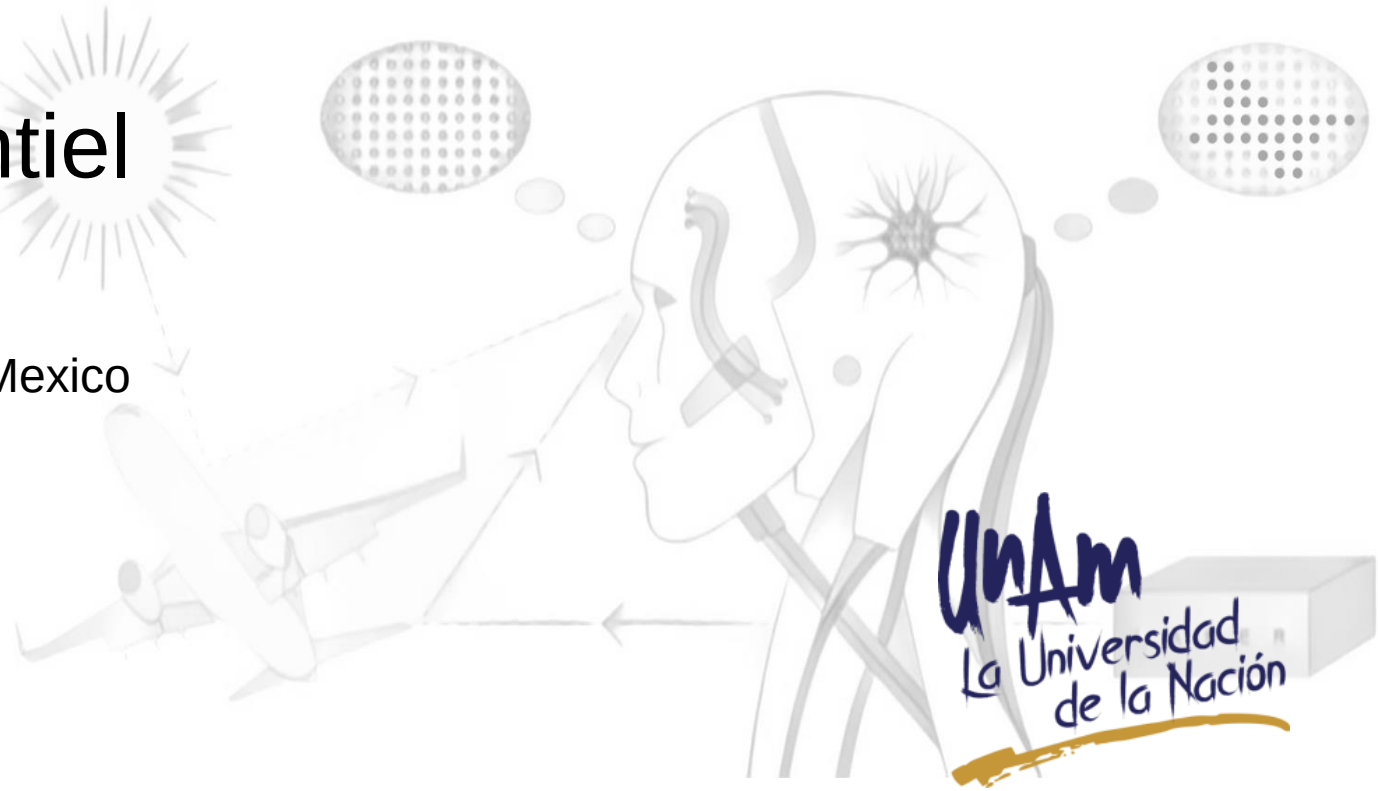
Smart Quantum Statistical Imaging beyond the Abbe-Rayleigh Criterion

Roberto de J. León-Montiel

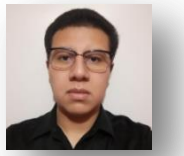
ICN – The Institute of Nuclear Sciences

UNAM – National Autonomous University of Mexico



Micro and Nanophotonics Lab @ UNAM

Undergraduate



Tomas Arvizu

Master's student

Arturo Pedroza

Ph.D. Students

Áulide Martínez

Samuel Corona

Postdocs

José D. Huerta

Jorge A. Peralta

CONACYT
Consejo Nacional de Ciencia y Tecnología

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SECRETARÍA DE EDUCACIÓN PÚBLICA

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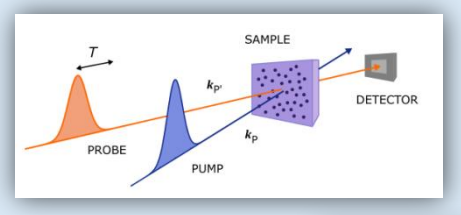
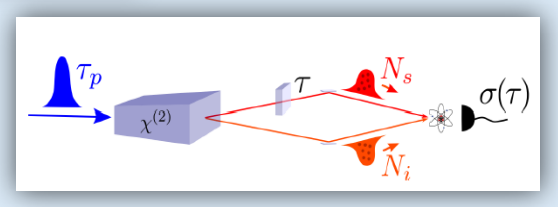
Instituto de Ciencias Nucleares UNAM

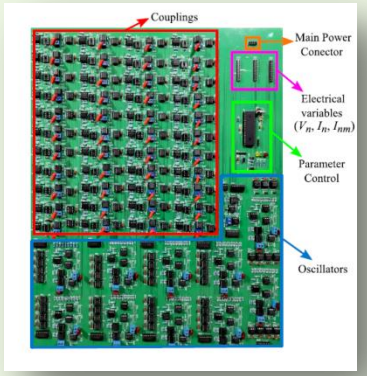
Spectroscopy with non-classical light

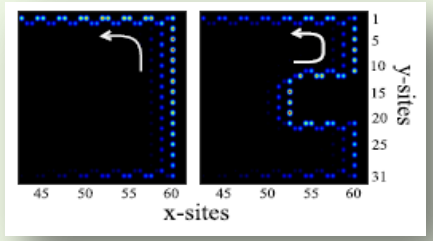




A. Martínez-Tapia, RJLM *et al.,* APL Photonics **8**, 036104 (2023)
S. Corona-Aquino, RJLM *et al.,* J. Phys. Chem. A **126**, 2185 (2022)
L. Mertenskötter, K. Busch, and RJLM, JOSA B **38**, C63 (2021)
RJLM, J. Phys. **1540**, 012015 (2020)

Quantum transport in complex systems





M. A. Quiroz-Juárez, RJLM, *et al.*, EPJ Plus **138**, 775 (2023)
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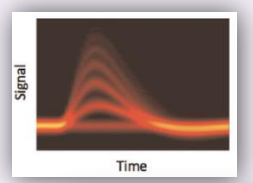
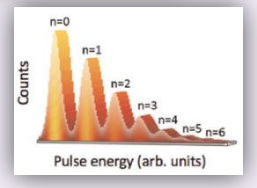
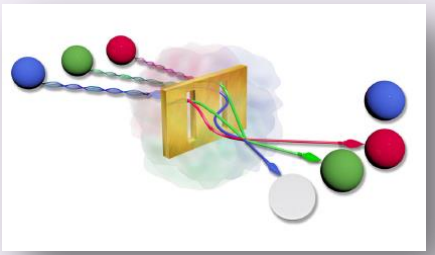
Multiphoton quantum-state engineering and quantum simulation







M. Hong, RJLM *et al.,* Laser & Photonics Reviews 23001117 (2023)
C. You, RJLM *et al.,* npj Quantum Information **9**, 50 (2023)
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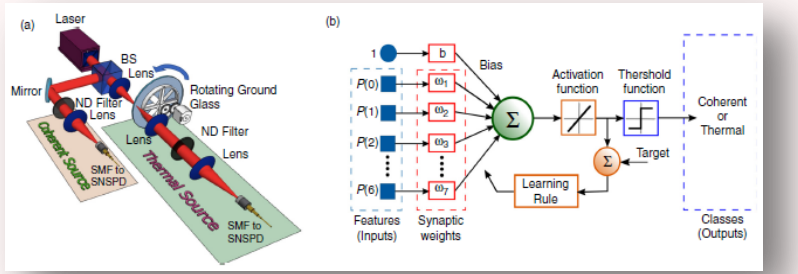
C. You, RJLM *et al.*, Nature Communications **12**, 5161 (2021)

Smart quantum (and classical) optics experiments



M. L. J. Lollie, RJLM, *et al.*, Mach. Learn.: Sci. Technol. **3**, 035006 (2022)
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A. Villegas, RJLM *et al.,* Photonics **9**, 74 (2022)
M. A. Quiroz-Juárez, RJLM *et al.,* Plos One **16**, e0257234 (2021)
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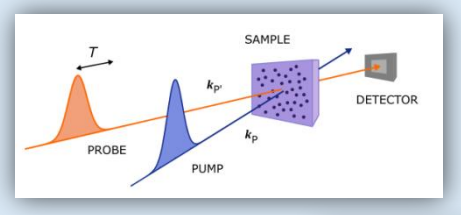

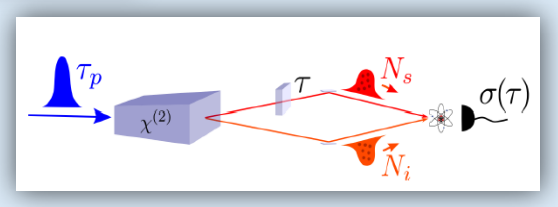

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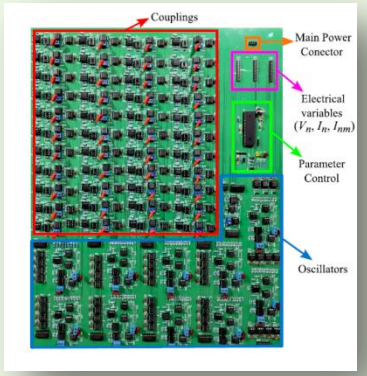

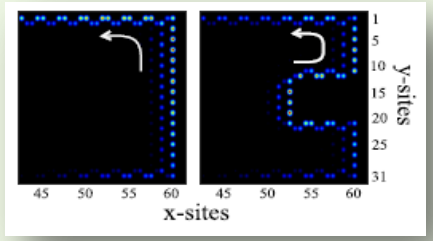

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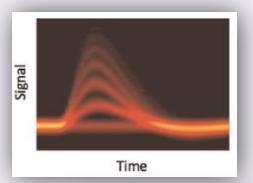

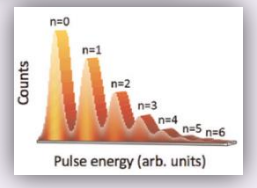

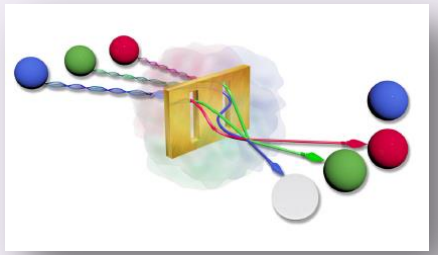

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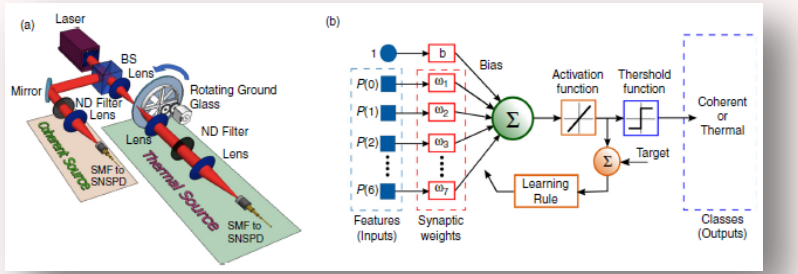

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A. Villegas, RJLM *et al.,* Photonics **9**, 74 (2022)
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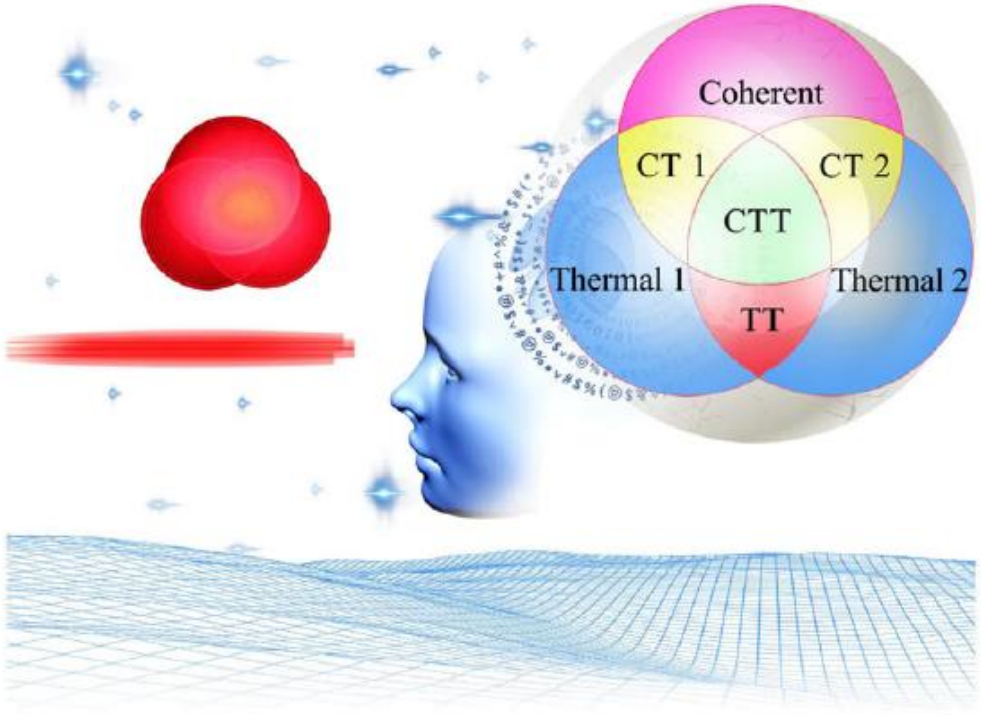
Smart Quantum Statistical Imaging (Quantum Smart Camera)



Omar Magaña-Loaiza

Chenglong You

Mario A. Quiroz-Juarez

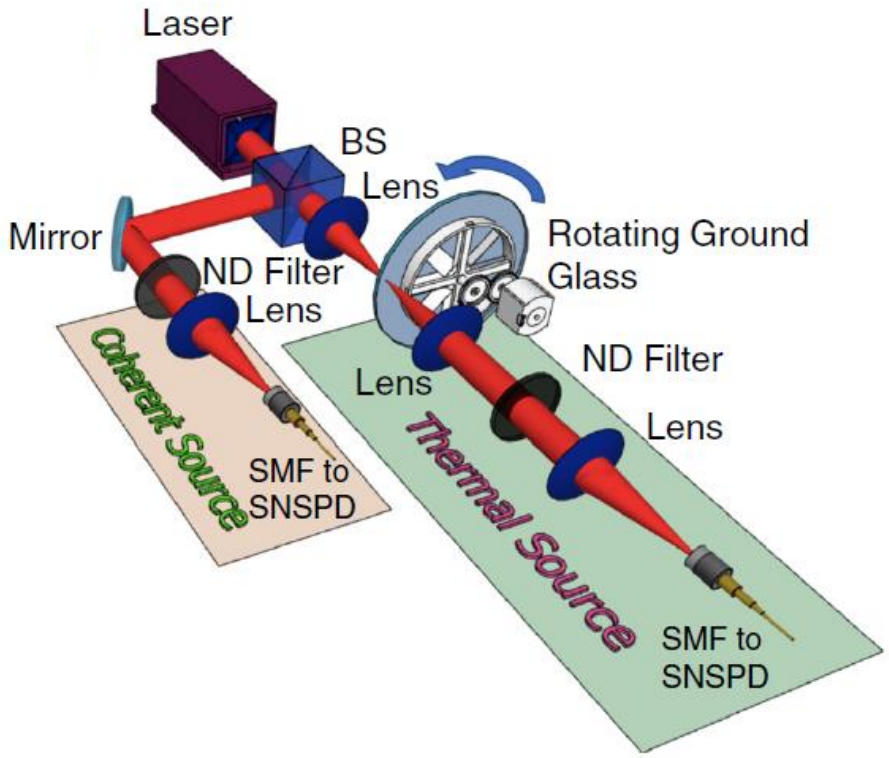
C F A T A

Smart Quantum Statistical Imaging (Quantum Smart Camera)

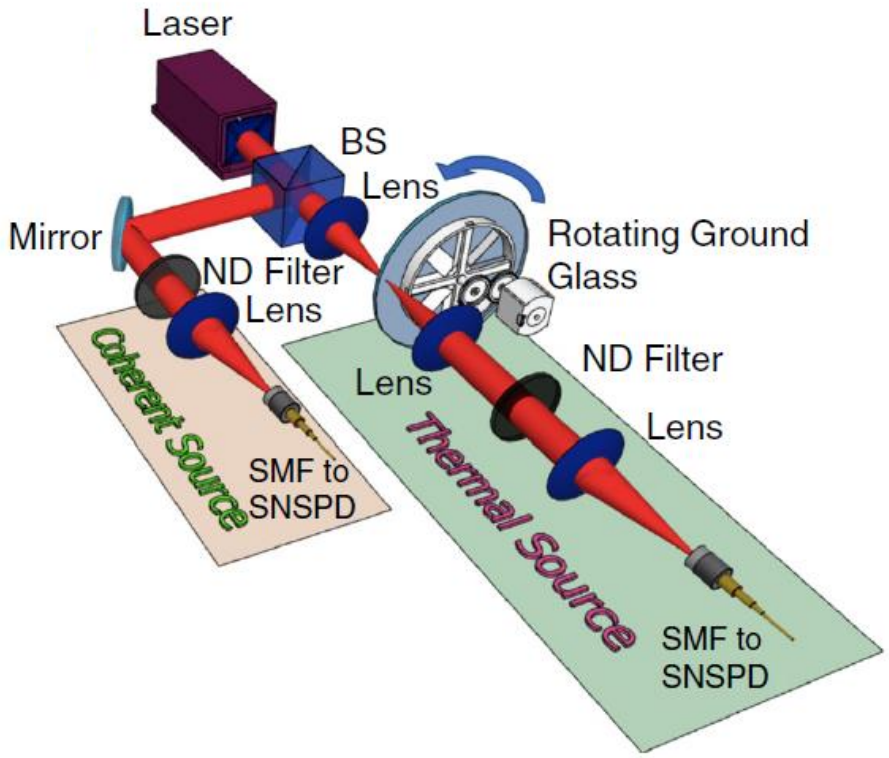
- **Identification of light sources using machine learning**
  Applied Physics Reviews **7**, 021404 (2020)

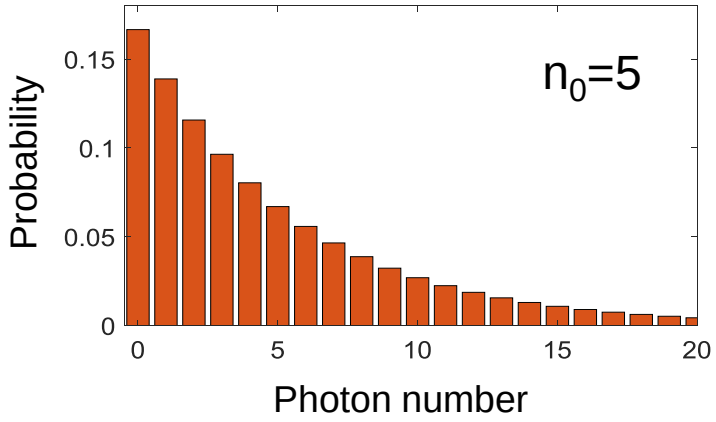
- **Observation of the modification of quantum statistics of plasmonic systems**
  Nature Communications **12**, 5161 (2021)

Identification of light sources using machine learning

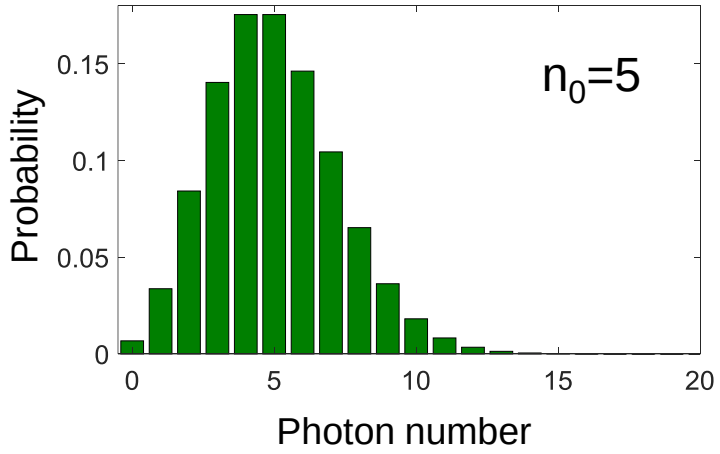


Identification of light sources using machine learning



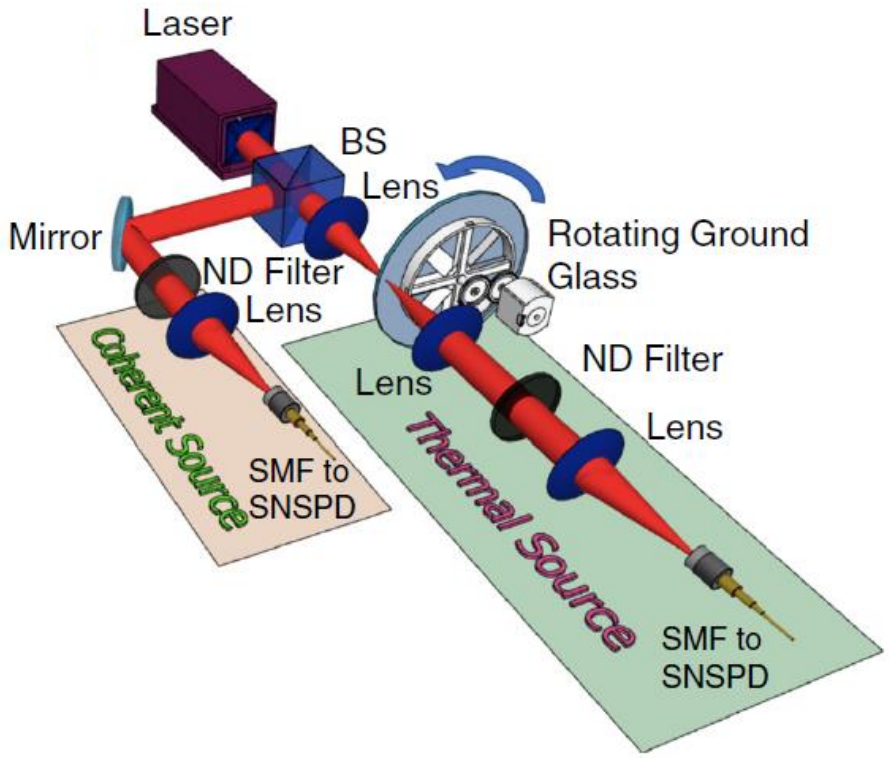


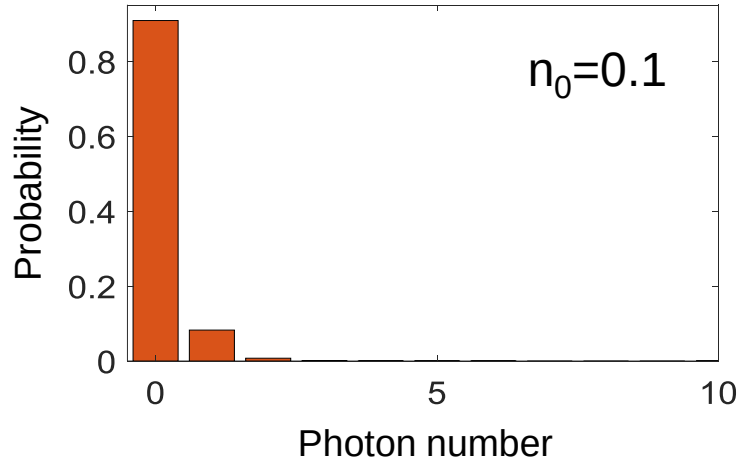
Thermal light



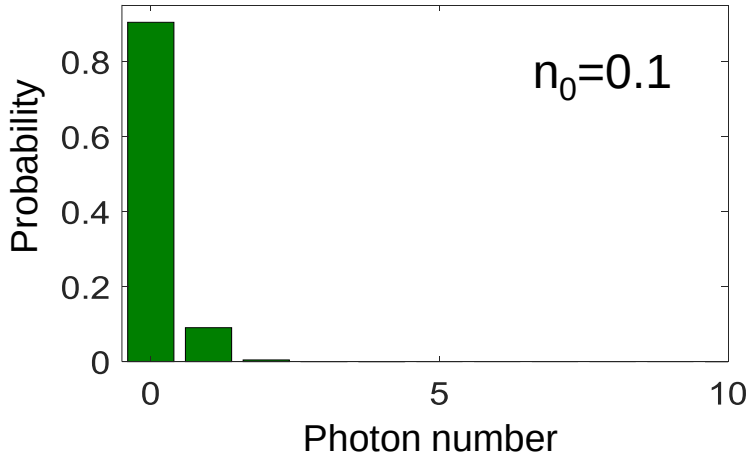
Coherent Light

Identification of light sources using machine learning





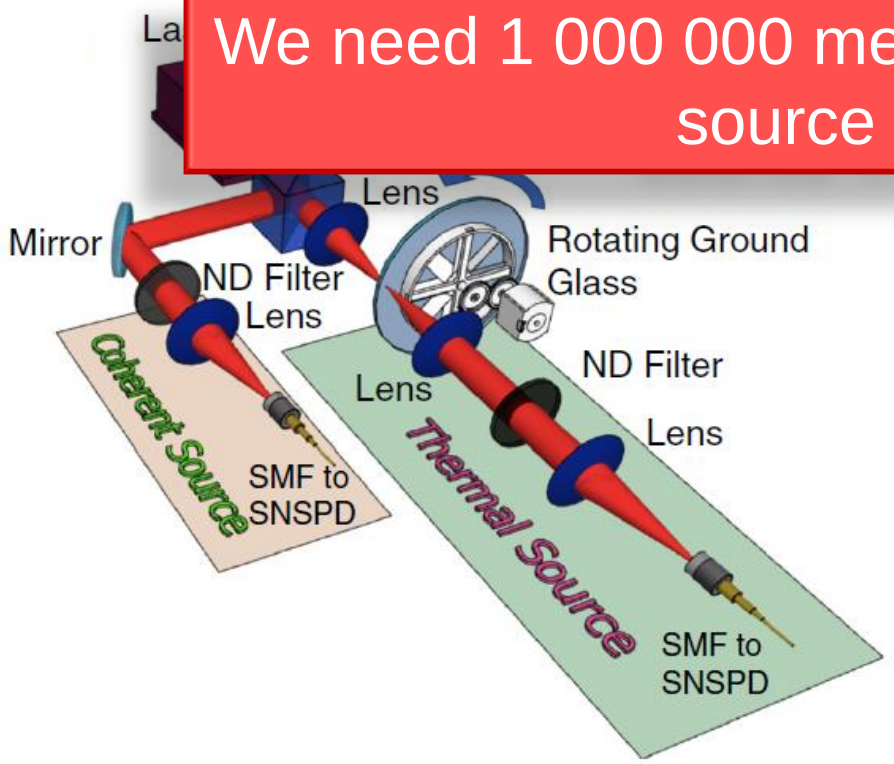
Thermal light

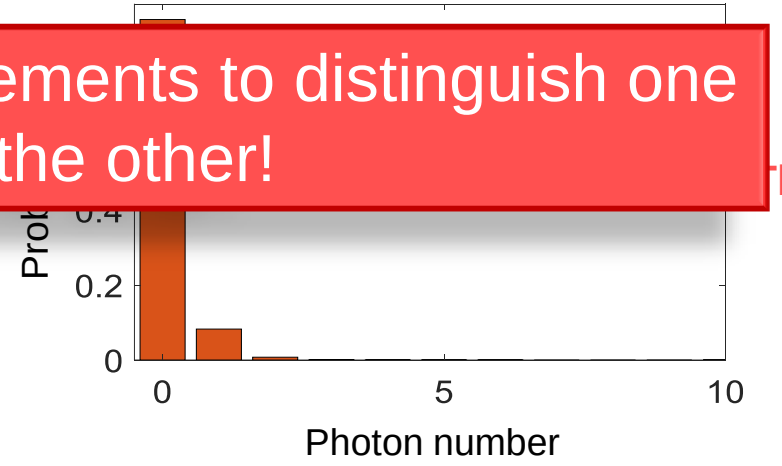


Coherent Light

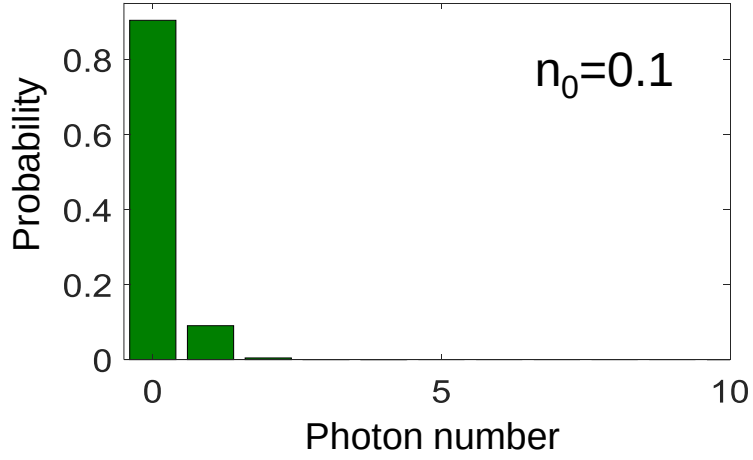
Identification of light sources using machine learning

We need 1 000 000 measurements to distinguish one source from the other!





Thermal light



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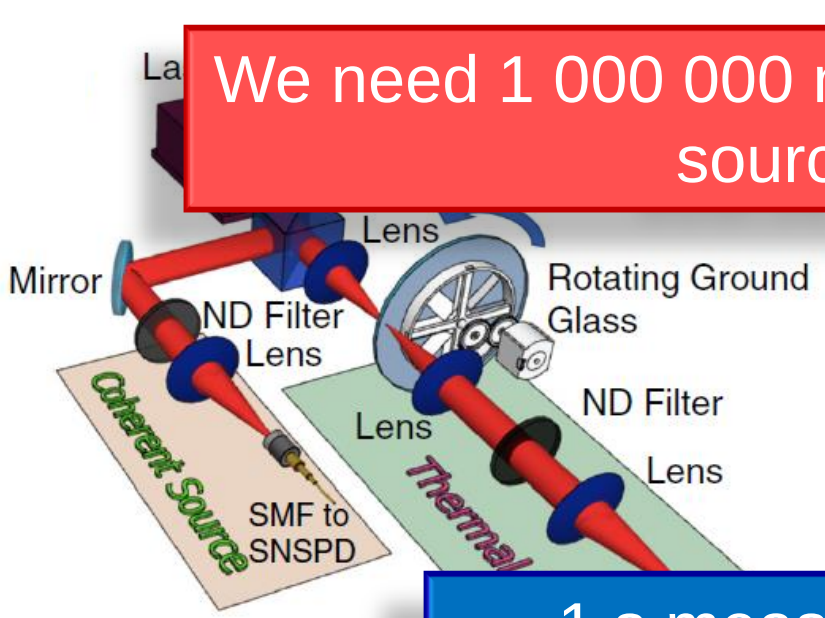
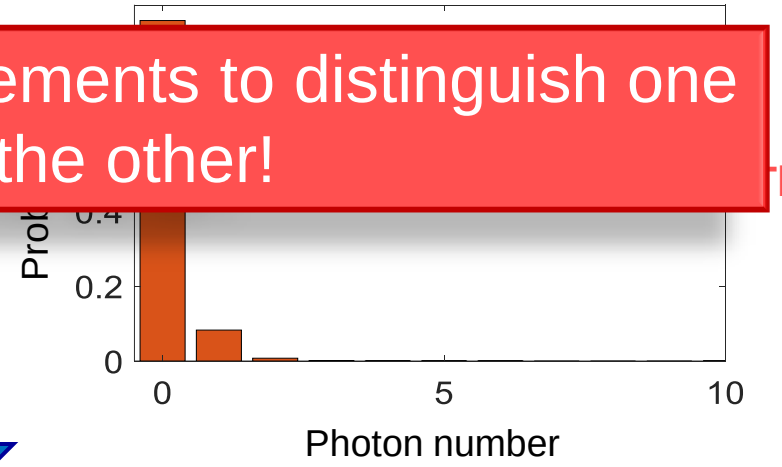
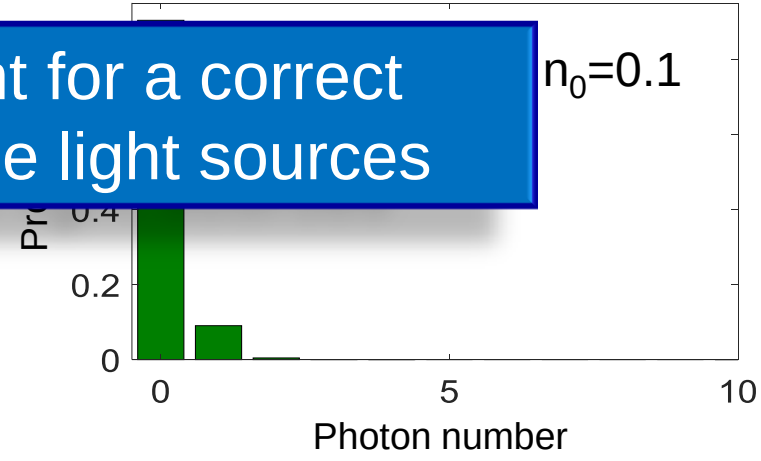




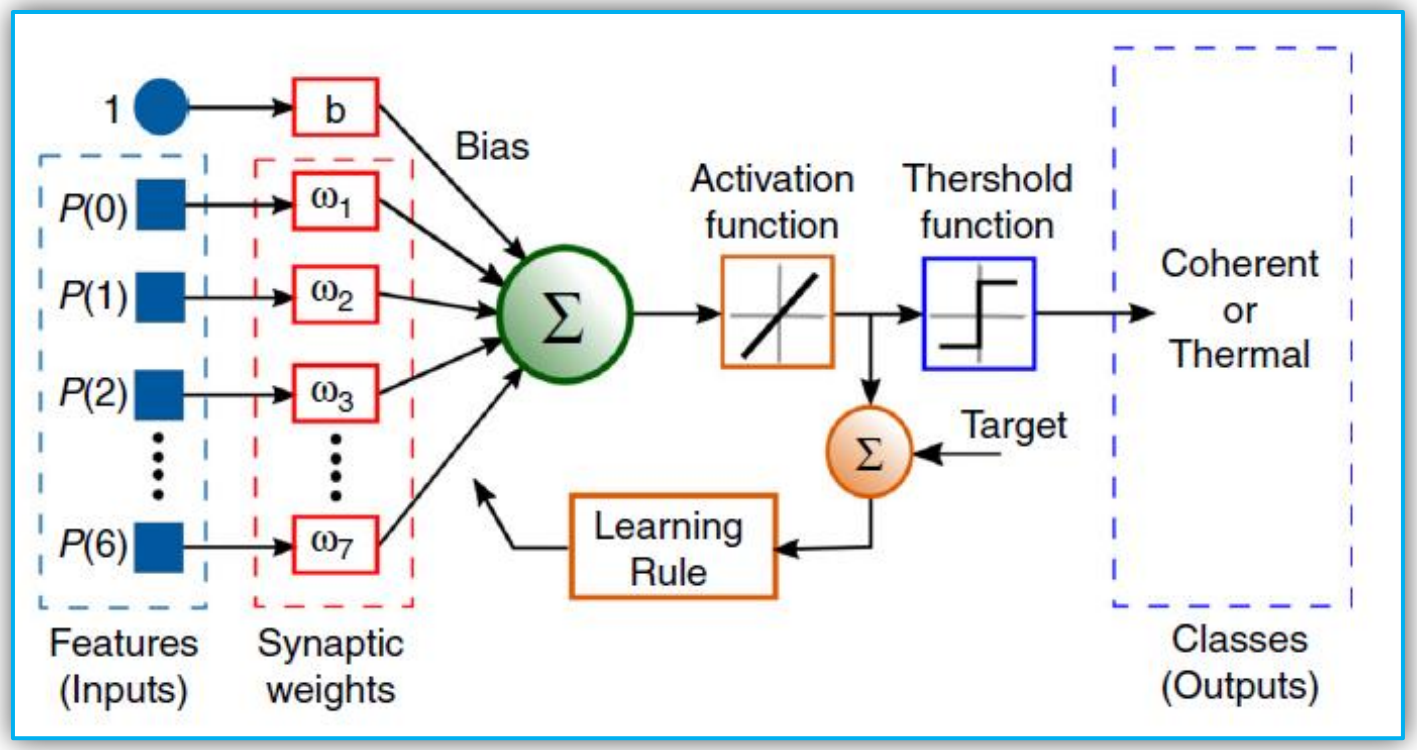
Thermal light

1 s measurement for a correct identification of the light sources



Coherent Light

ADALINE = ADAptive LINear Element



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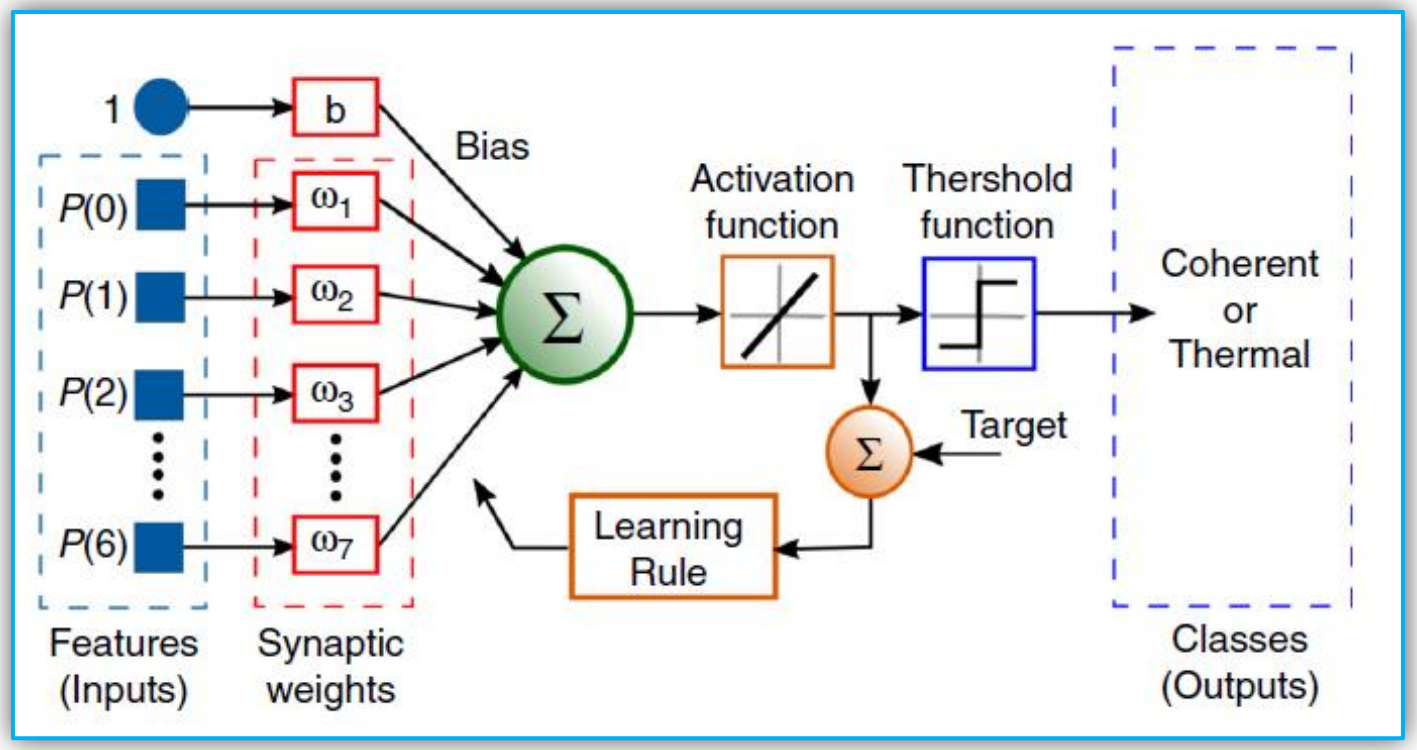
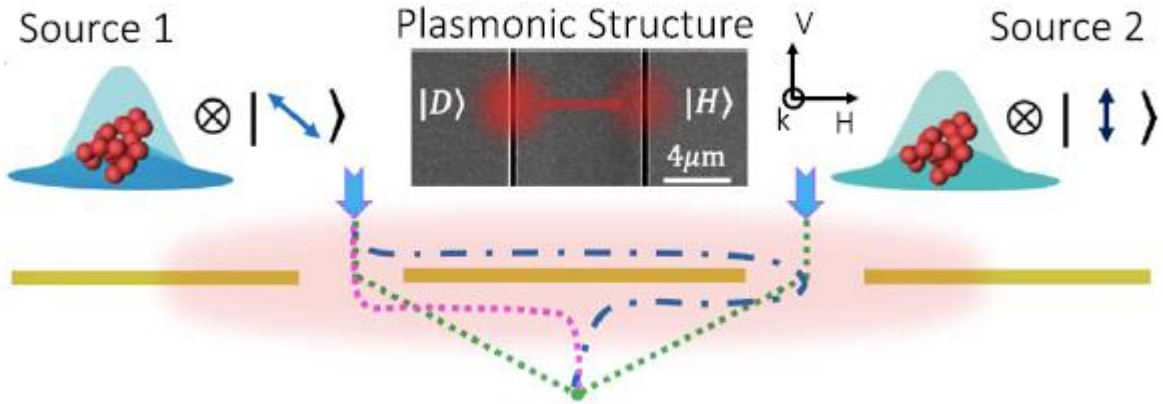


~20 microseconds

50 000 times faster!!

Applied Physics Reviews **7**, 021404 (2020)

Modification of photon statistics of plasmonic systems

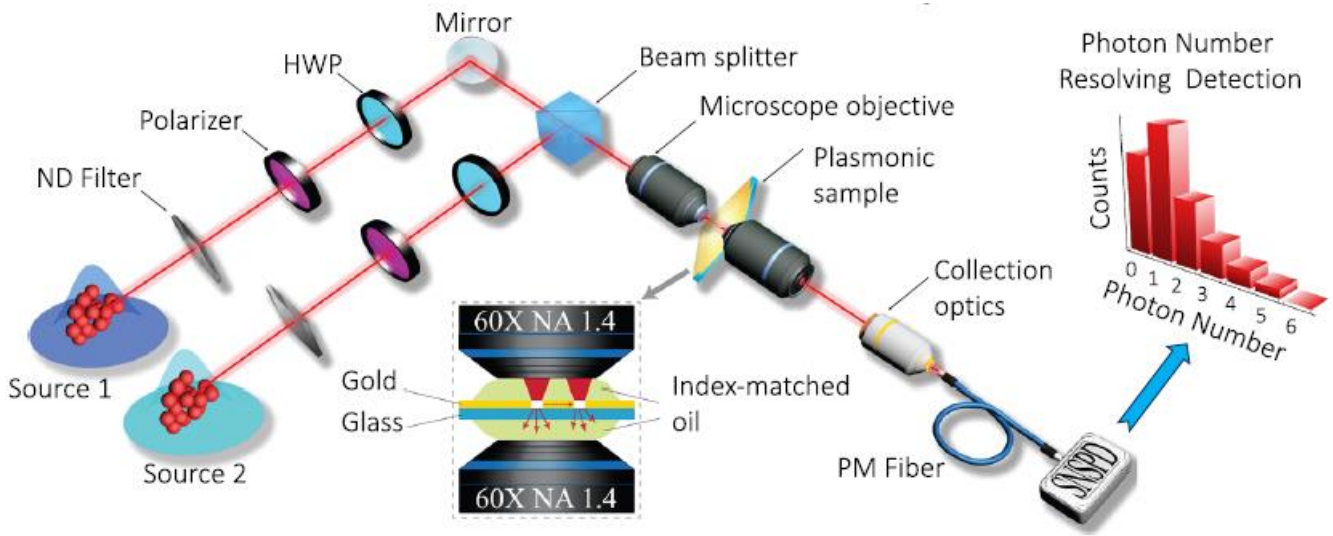


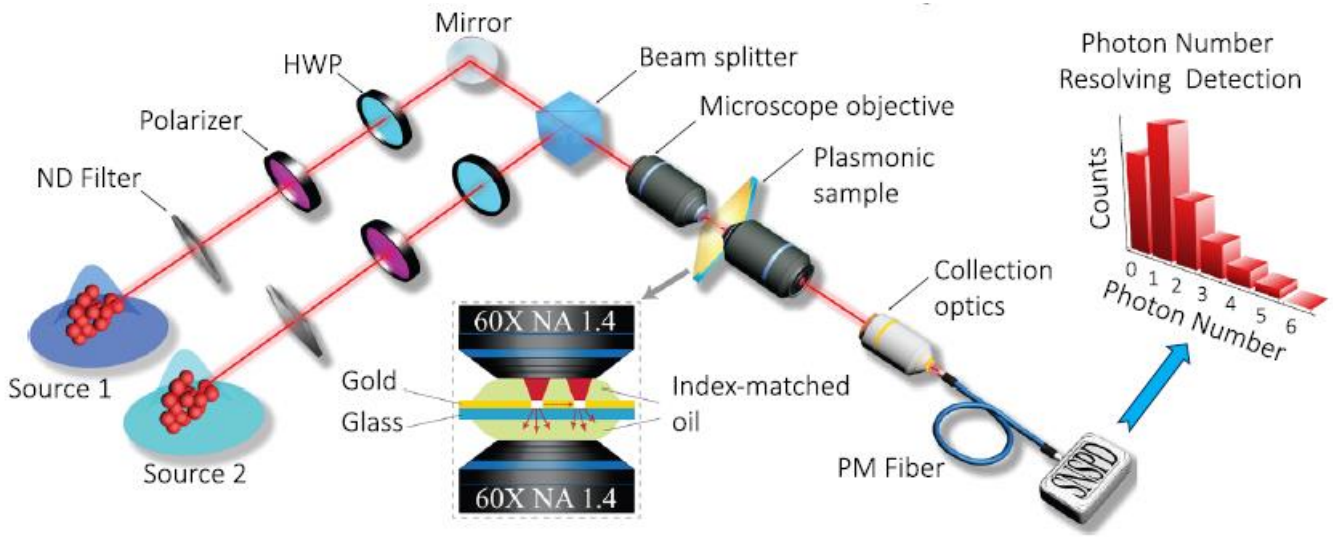
Indistinguishable sources: $P_{det}(\alpha) = \int P_1(\alpha - \alpha')P_2(\alpha')d^2\alpha' \implies p_{det}(n) = \langle n|\rho_{det}|n\rangle, \ with \ \rho_{det} = \int P_{det}(\alpha)|\alpha\rangle\langle\alpha|d^2\alpha$

Distinguishable sources: $p_{det}(n) = \sum_{m=0}^{n} p_1(n-m)p_2(m)$

R. J. Glauber, Phys. Rev. **131**, 2766 (1963)

E. C. G. Sudarshan, Phys. Rev. Lett. **10**, 277 (1963)


Mirror
HWP
Beam splitter
Polarizer
Microscope objective
ND Filter
Plasmonic sample
Collection optics
Source 1
Source 2
60X NA 1.4
Gold
Glass
Index-matched oil
60X NA 1.4
PM Fiber
SNSPD
Photon Number Resolving Detection
Counts
0 1 2 3 4 5 6
Photon Number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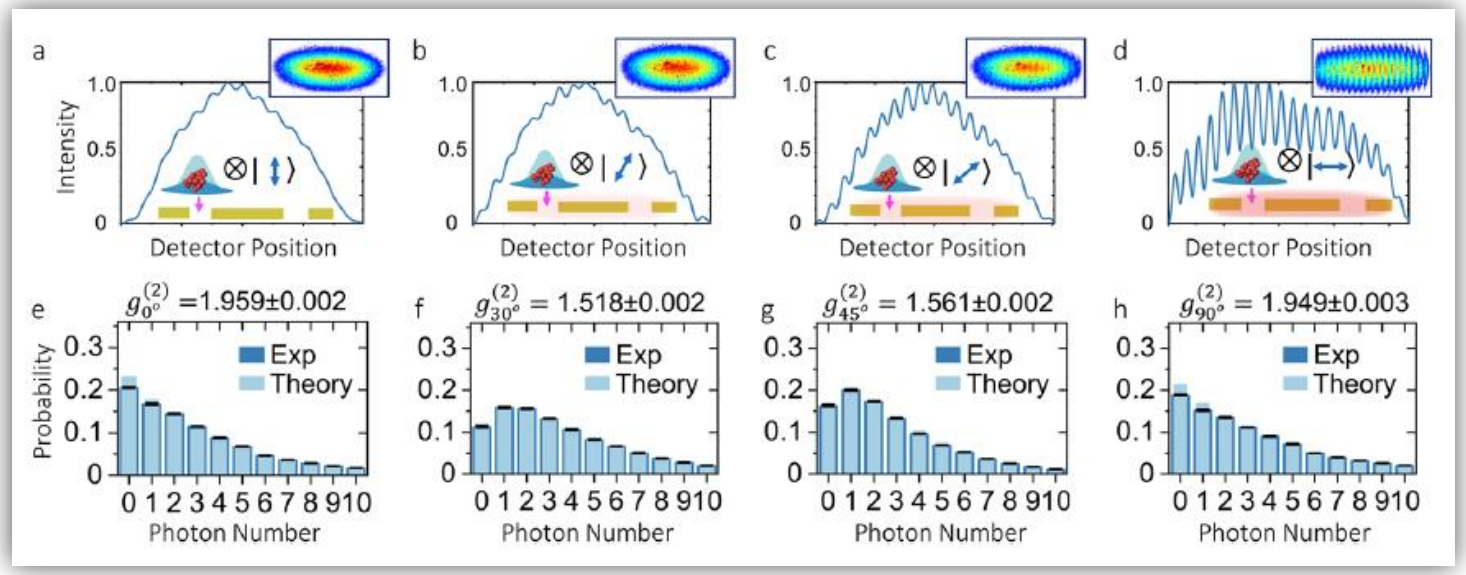
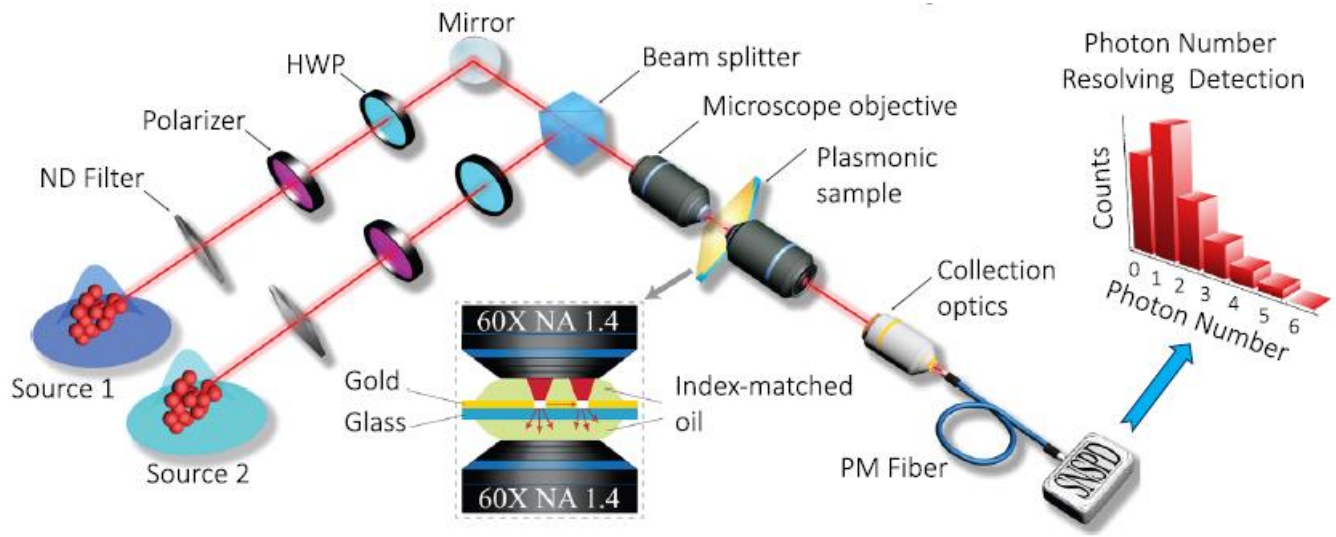

a
b
c
d
Intensity
Detector Position
e
f
g
h
$g^{(2)}_{0°}$ =1.959±0.002
$g^{(2)}_{30°}$ = 1.518±0.002
$g^{(2)}_{45°}$ = 1.561±0.002
$g^{(2)}_{90°}$ = 1.949±0.003
Exp
Theory
Probability
Photon Number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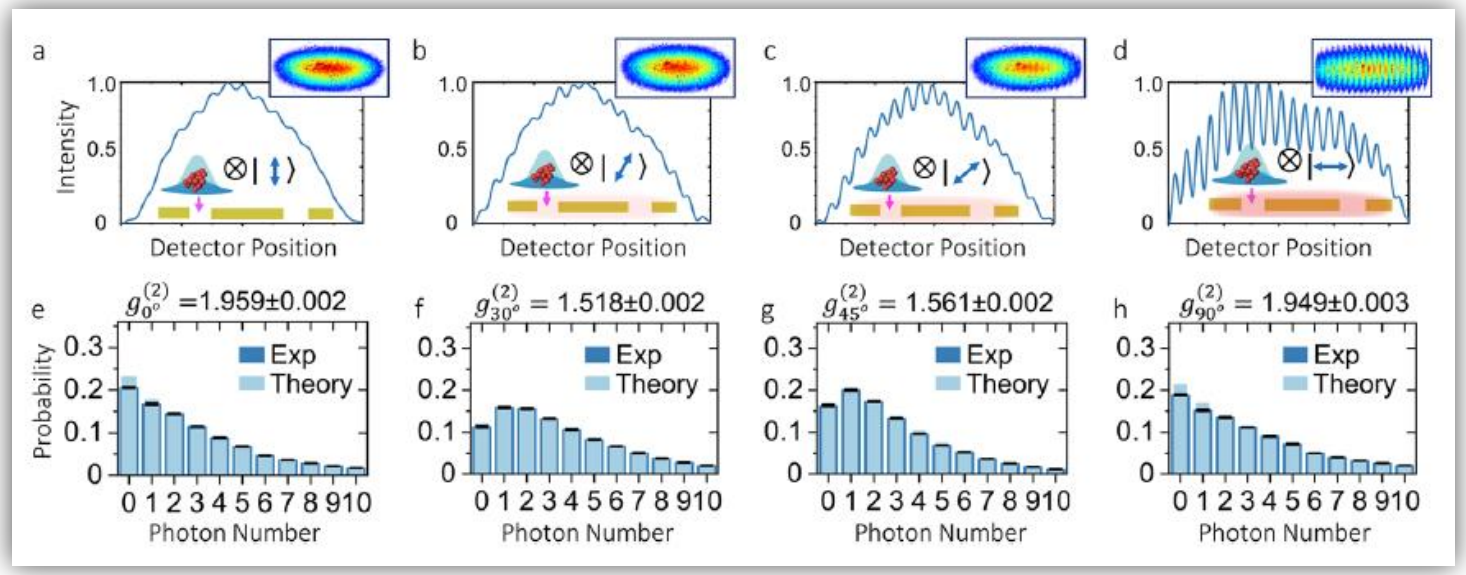
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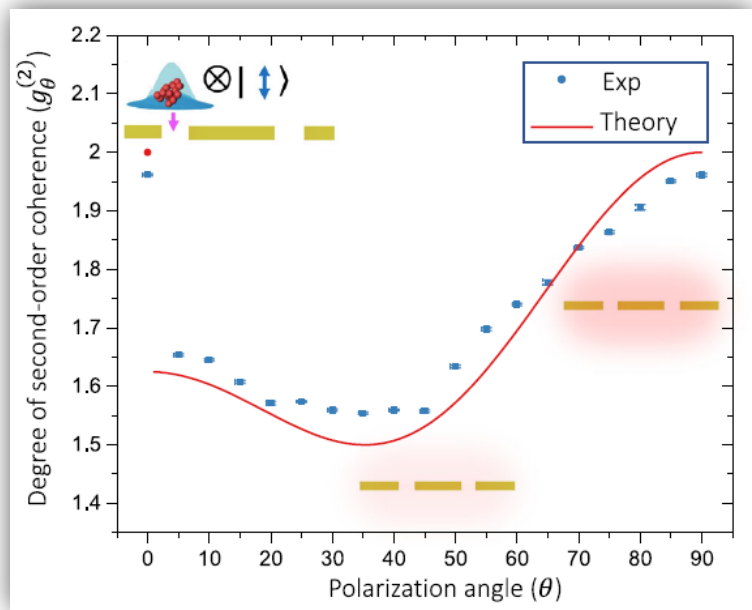
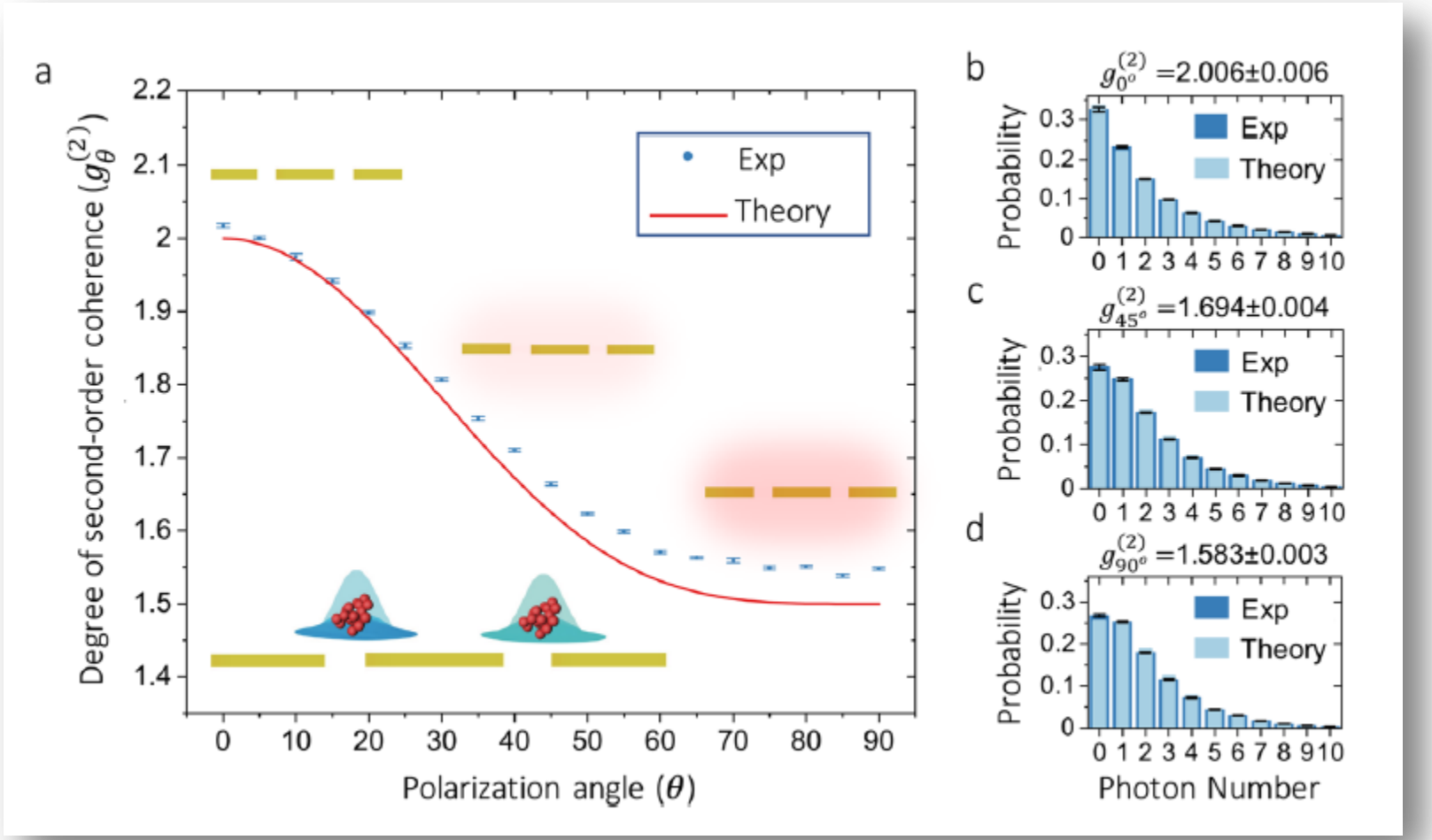
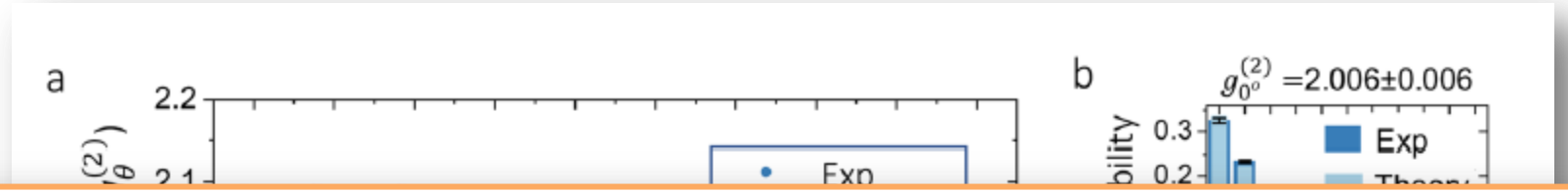
Probability
Exp
Theory
Photon Number


Degree of second-order coherence ($g^{(2)}_{\theta}$)
Exp
Theory
Polarization angle (θ)


a
Degree of second-order coherence ($g_\theta^{(2)}$)
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
Exp
Theory
0 10 20 30 40 50 60 70 80 90
Polarization angle (θ)
b
$g_{0^o}^{(2)}$ =2.006±0.006
c
$g_{45^o}^{(2)}$ =1.694±0.004
d
$g_{90^o}^{(2)}$ =1.583±0.003
Probability
0.3
0.2
0.1
0
Exp
Theory
0 1 2 3 4 5 6 7 8 9 10
Photon Number



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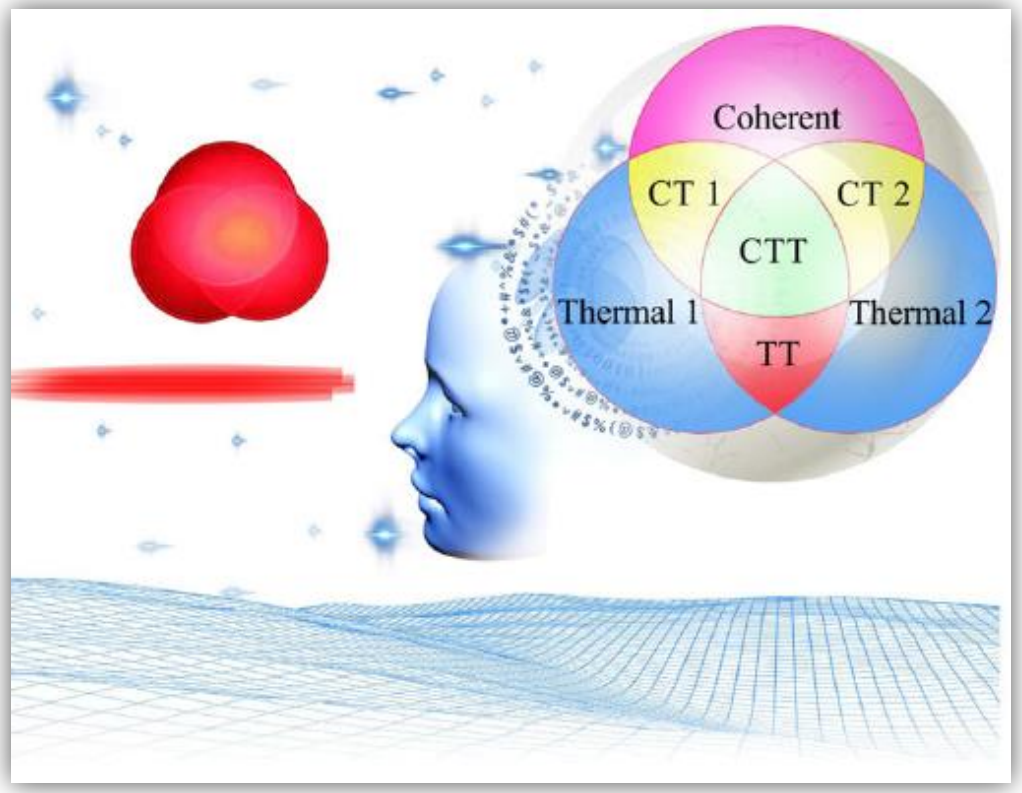
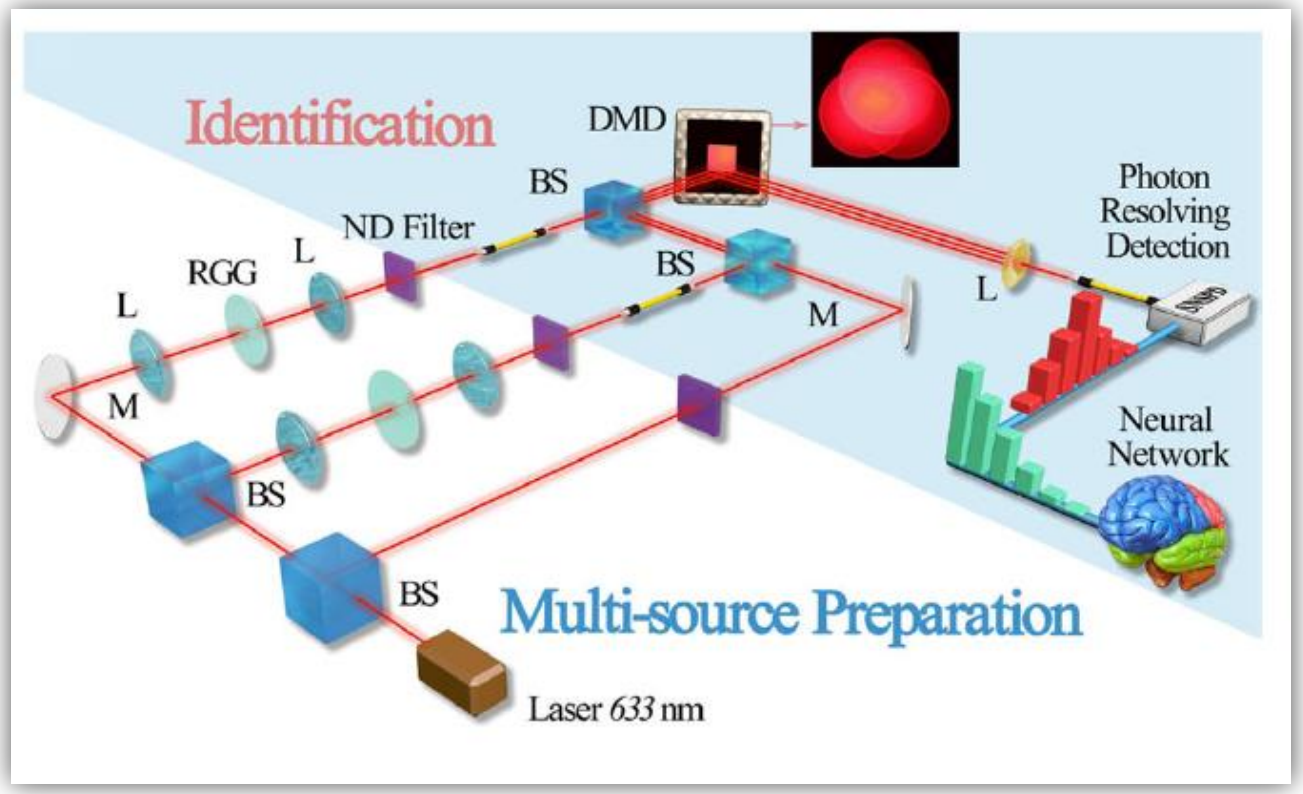
Observation of the modification of quantum statistics of plasmonic systems

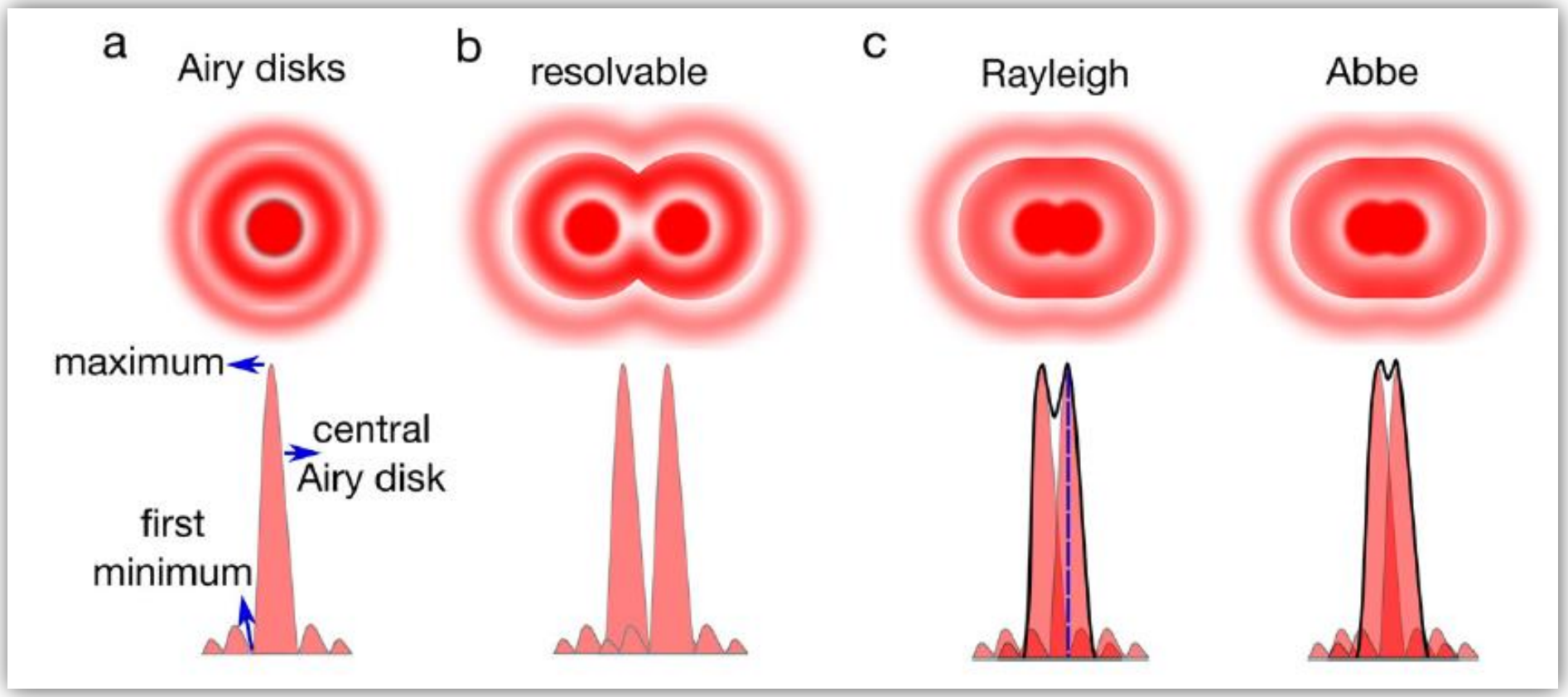
Chenglong You[1,6], Mingyuan Hong[1,6], Narayan Bhusal[1], Jinnan Chen[2], Mario A. Quiroz-Juárez[3], Joshua Fabre[1], Fatemeh Mostafavi[1], Junpeng Guo[2], Israel De Leon[4], Roberto de J. León-Montiel[5] & Omar S. Magaña-Loaiza[1✉]

Nature Communications **12**, 5161 (2021)

Smart Quantum Statistical Imaging beyond the Abbe-Rayleigh Criterion







E. Sezgin, J. Phys.: Condens. Matter **29**, 273001 (2017)

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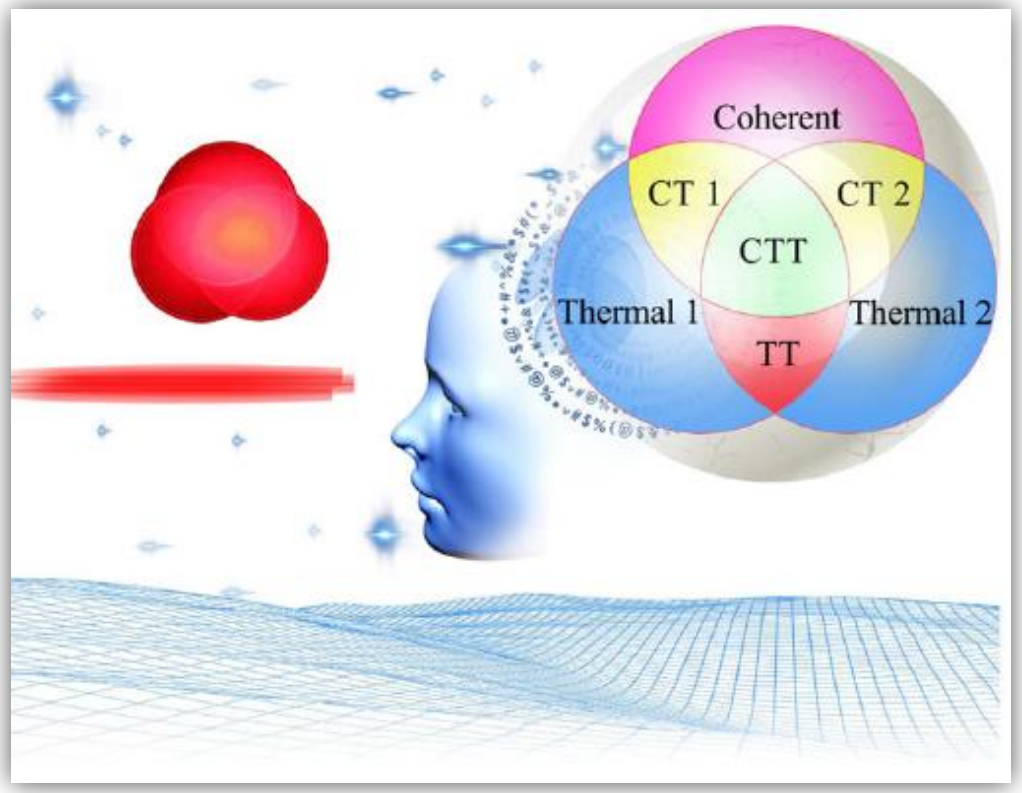

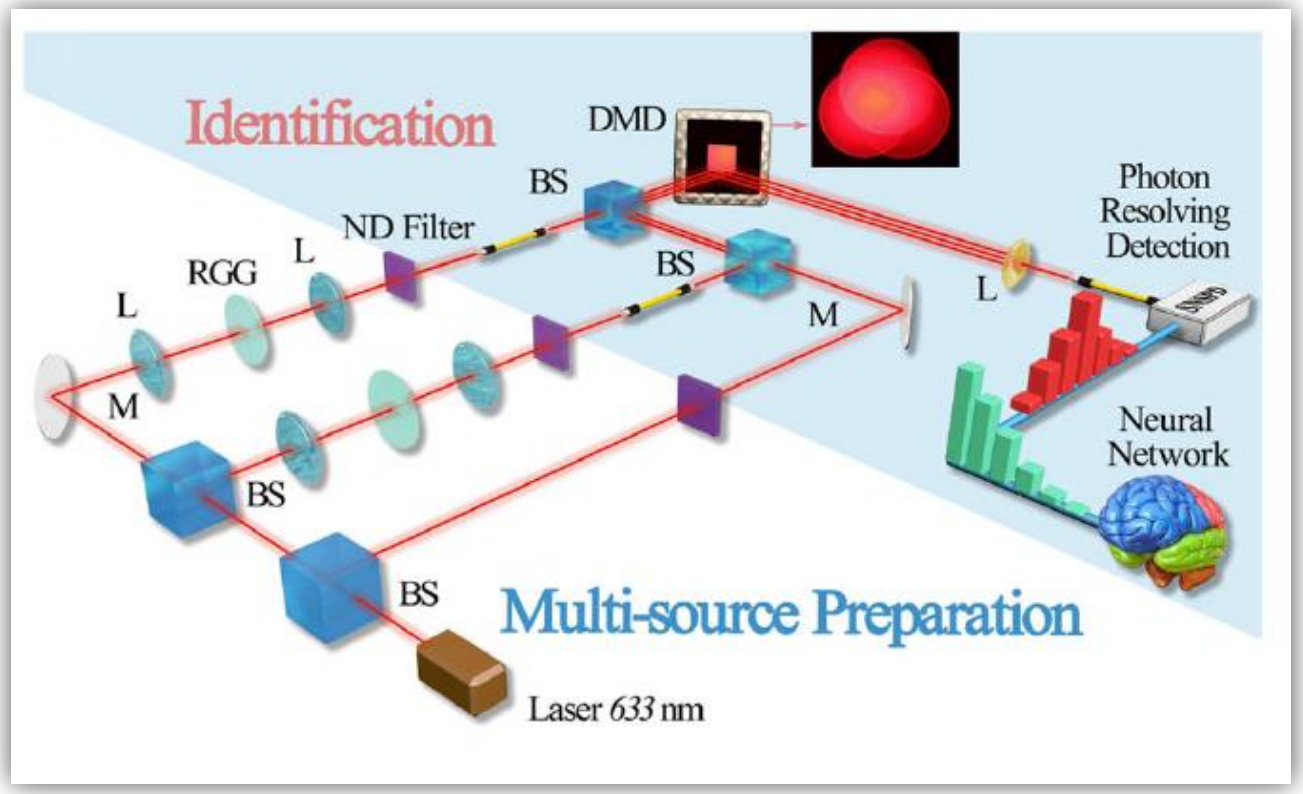

Photon-number distribution of N coherent and M thermal indistinguishable, independent sources:

$$p_{\text{th-coh}}(n) = \frac{(m_{\text{tot}})^n \exp\left(-|\alpha_{\text{tot}}|^2/m_{\text{tot}}\right)}{\pi\,(m_{\text{tot}}+1)^{n+1}} \sum_{k=0}^{n} \frac{1}{k!(n-k)!} \Gamma\left(\frac{1}{2}+n-k\right)\Gamma\left(\frac{1}{2}+k\right)$$
$$\times\, {}_1F_1\left(\frac{1}{2}+n-k;\frac{1}{2};\frac{(\text{Re}[\alpha_{\text{tot}}])^2}{m_{\text{tot}}\,(m_{\text{tot}}+1)}\right) {}_1F_1\left(\frac{1}{2}+k;\frac{1}{2};\frac{(\text{Im}[\alpha_{\text{tot}}])^2}{m_{\text{tot}}\,(m_{\text{tot}}+1)}\right),$$

npj Quantum Inf. **8**, 83 (2022)

with $m_{\text{tot}} = \sum_{l=1}^{M} \bar{m}_l$ and $\alpha_{\text{tot}} = \sum_{k=1}^{N} \alpha_k$. $\Gamma(z)$ and ${}_1F_1(a;b;z)$ are the Euler gamma and the Kummer confluent hypergeometric functions, respectively.

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npj Quantum Inf. **8**, 83 (2022)

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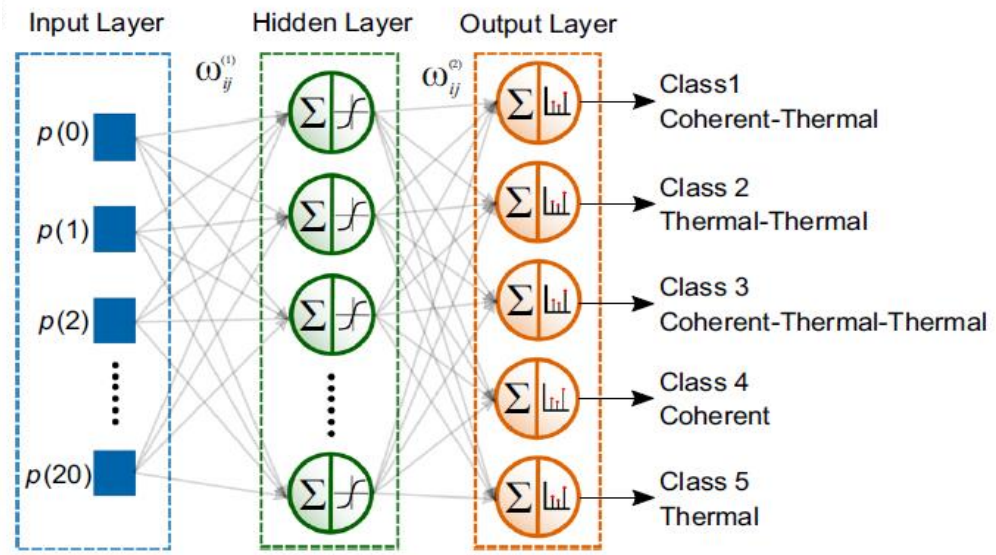
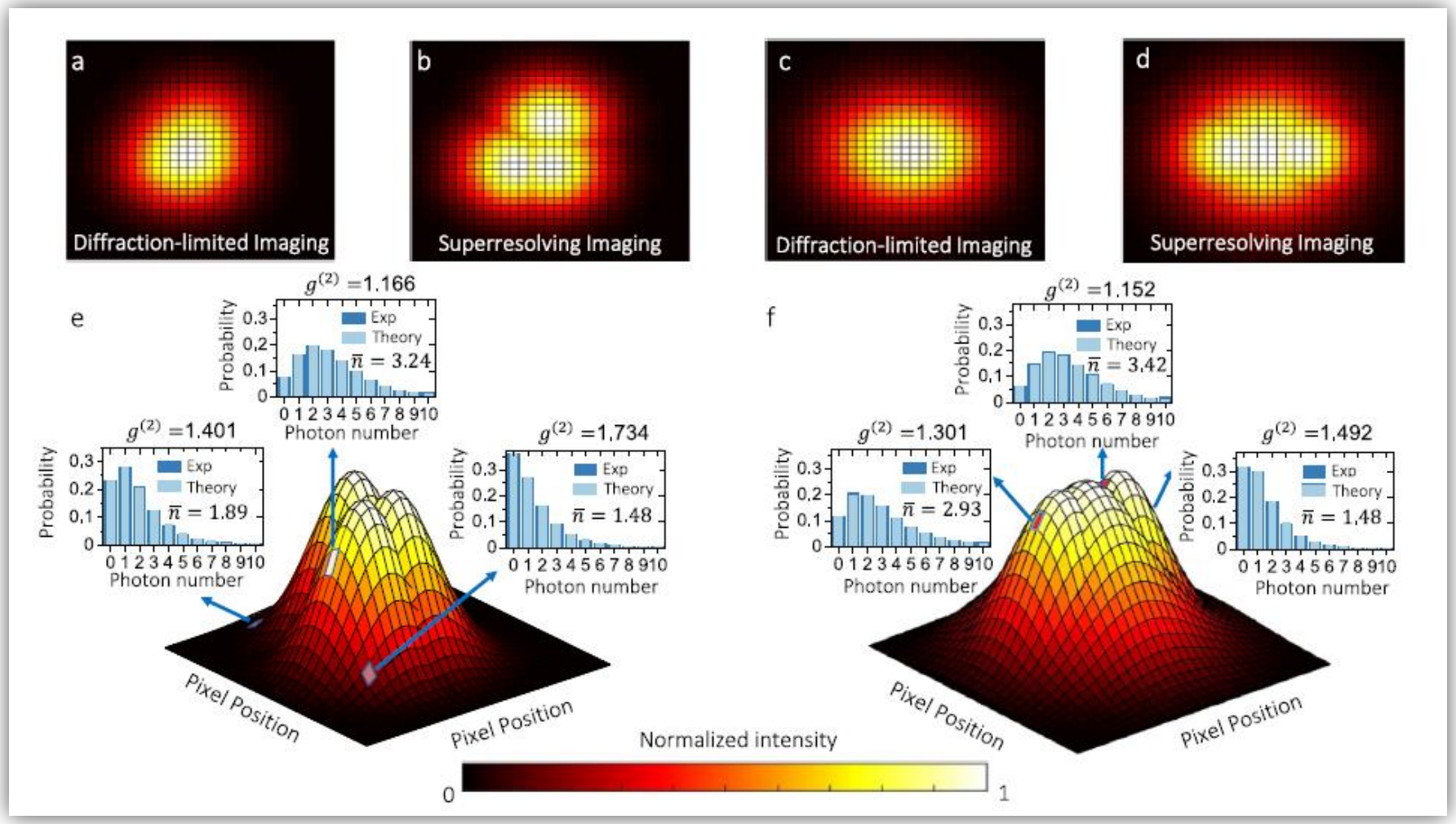
$p(n), \bar{n}, g^{(2)}$

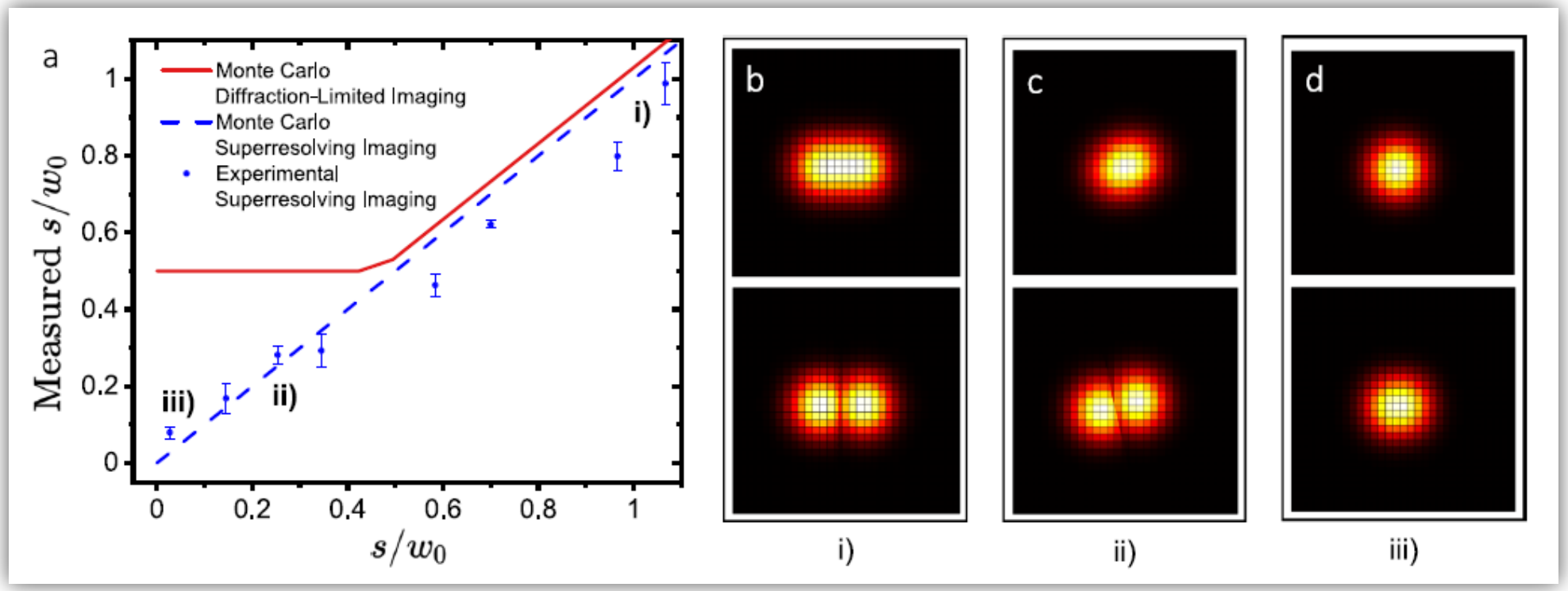


$\bar{n}_c$
$\bar{n}_{Th1}$
$\bar{n}_{Th2}$

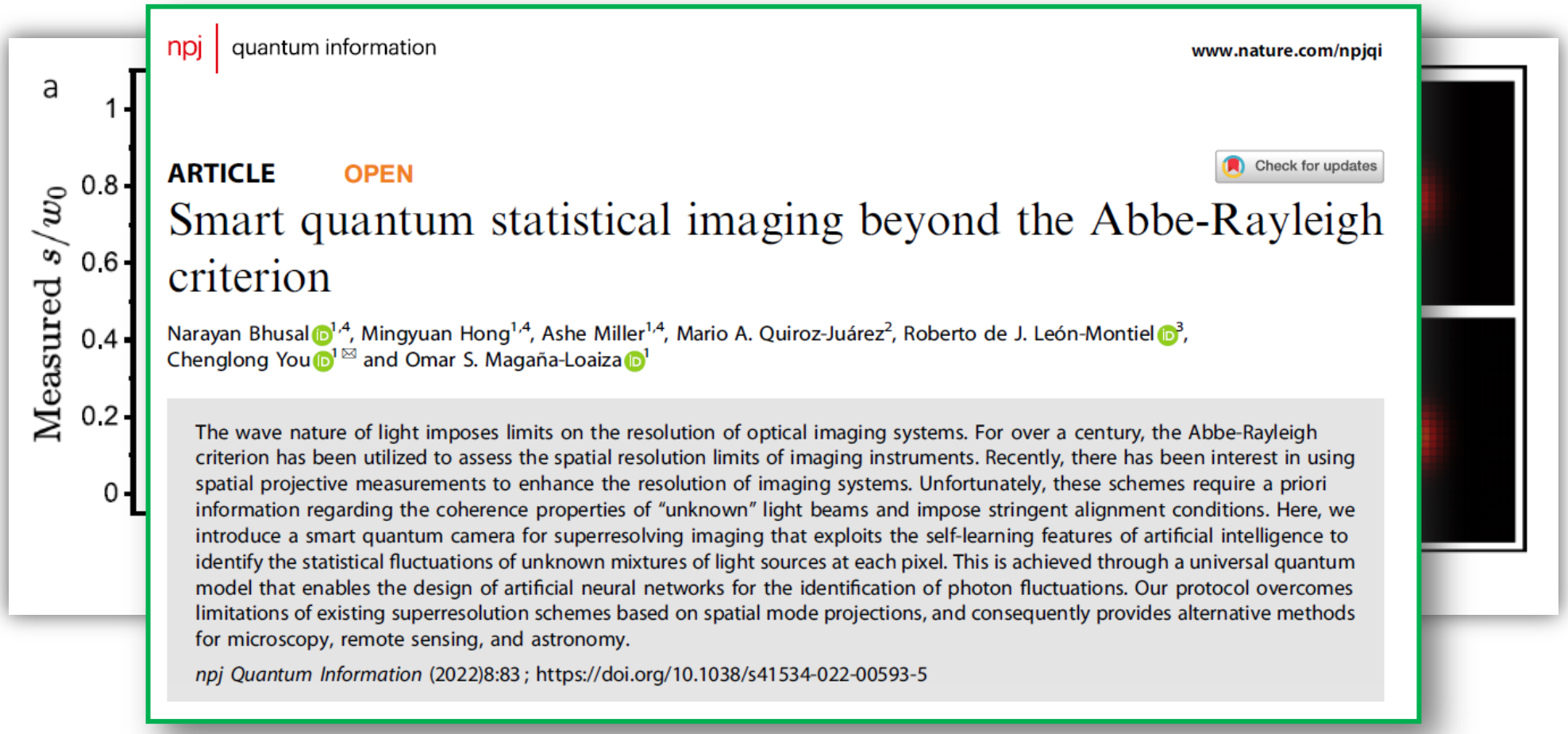
Experimental super-resolving imaging



Direct Imaging vs Smart Statistical Imaging



Direct Imaging vs Smart Statistical Imaging



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Smart quantum statistical imaging beyond the Abbe-Rayleigh criterion

Narayan Bhusal[1,4], Mingyuan Hong[1,4], Ashe Miller[1,4], Mario A. Quiroz-Juárez[2], Roberto de J. León-Montiel[3], Chenglong You[1] ✉ and Omar S. Magaña-Loaiza[1]

The wave nature of light imposes limits on the resolution of optical imaging systems. For over a century, the Abbe-Rayleigh criterion has been utilized to assess the spatial resolution limits of imaging instruments. Recently, there has been interest in using spatial projective measurements to enhance the resolution of imaging systems. Unfortunately, these schemes require a priori information regarding the coherence properties of "unknown" light beams and impose stringent alignment conditions. Here, we introduce a smart quantum camera for superresolving imaging that exploits the self-learning features of artificial intelligence to identify the statistical fluctuations of unknown mixtures of light sources at each pixel. This is achieved through a universal quantum model that enables the design of artificial neural networks for the identification of photon fluctuations. Our protocol overcomes limitations of existing superresolution schemes based on spatial mode projections, and consequently provides alternative methods for microscopy, remote sensing, and astronomy.

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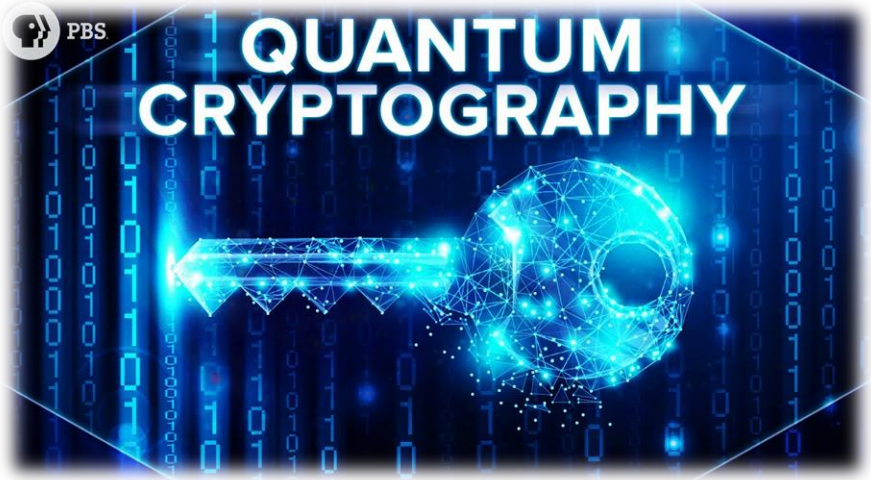
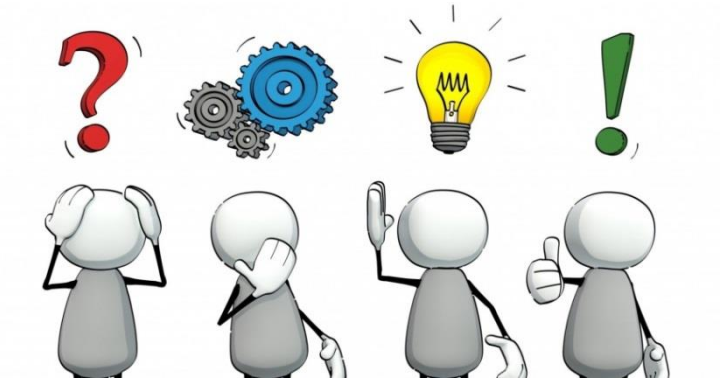
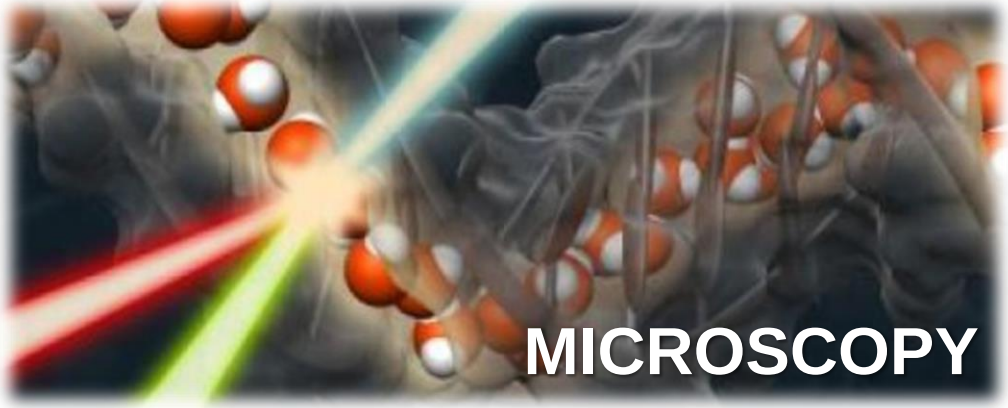
Our goal: To design and implement novel machine-learning-enabled photonic technologies!







hv photonics

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Article

Identification of Model Particle Mixtures Using Machine-Learning-Assisted Laser Diffraction

Arturo Villegas [1,*], Mario A. Quiroz-Juárez [2,3], Alfred B. U'Ren [2], Juan P. Torres [1,4] and Roberto de J. León-Montiel [2]

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High-dimensional encryption in optical fibers using spatial modes of light and machine learning

Michelle L J Lollie[1,4], Fatemeh Mostafavi[1,4], Narayan Bhusal[1], Mingyuan Hong[1], Chenglong You[1], Roberto de J León-Montiel[2], Omar S Magaña-Loaiza[1,*] and Mario A Quiroz-Juárez[3]

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Smart Machine Vision for Universal Spatial Mode Reconstruction

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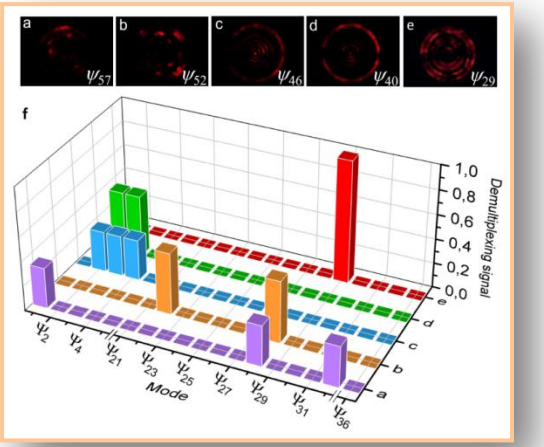
ArXiv: 2307.11841 (2023)



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