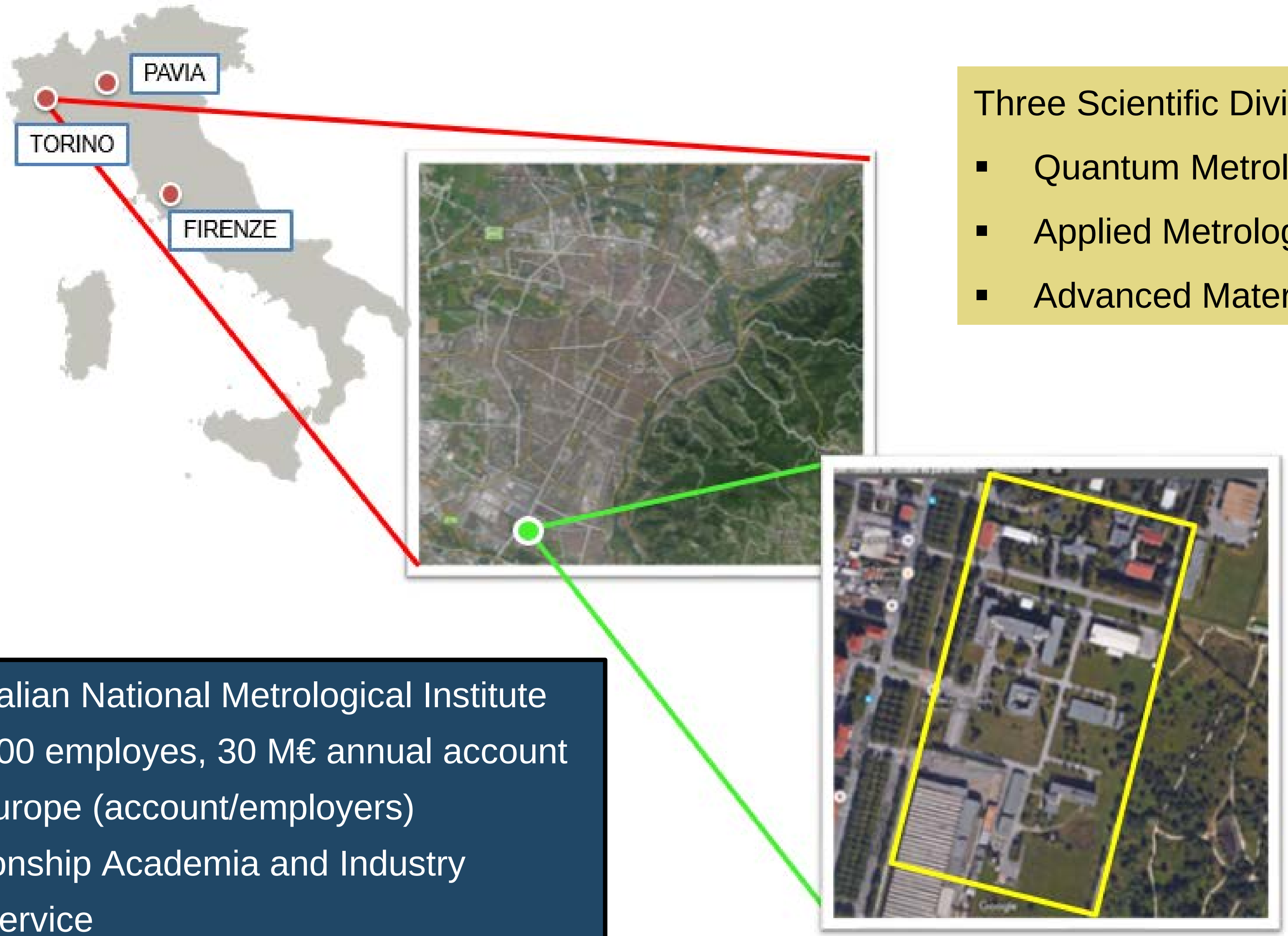
Quantum-enhanced measurements exploiting spatial-resolving-detectors

Ivo Pietro DEGIOVANNI
INRIM & EMN-Q Chair & INFN

INRIM IN A NUTSHELL



Three Scientific Divisions:

- Quantum Metrology and Nanotechnology
- Applied Metrology and Engineering
- Advanced Materials and Life Science

INRIM - the Italian National Metrological Institute

- More than 200 employes, 30 M€ annual account
- 4th NMI in Europe (account/employers)
- Strong relationship Academia and Industry
- Calibration Service
- Located in Turin, Pavia, and Florence

QUANTUM TECHNOLOGIES

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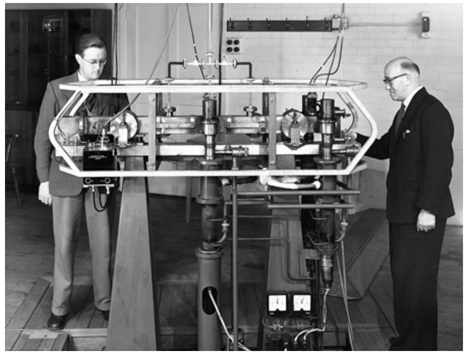
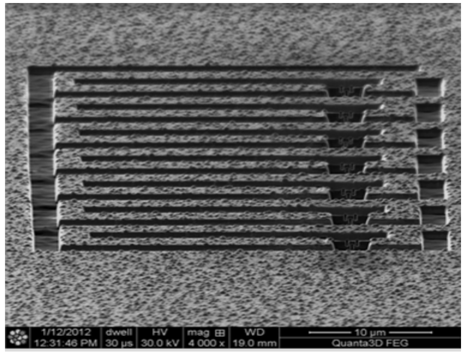
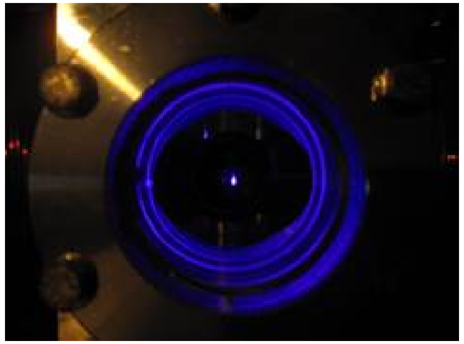
Quantum Metrology: shortest hystory



1967:
Time is the first SI unit **quantum**-based

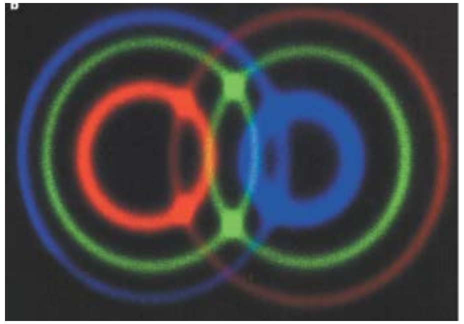


1975-1990:
Electrical units go **quantum**: Josephson effect, Hall effect, single-electron tunnelling



1990-2020:
Laser cooling and quantum optics: game changers for the measurements accuracy.

Nanostructured materials open new opportunities

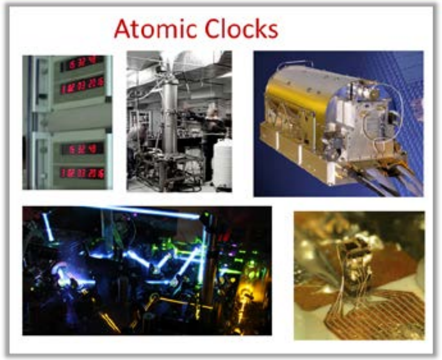


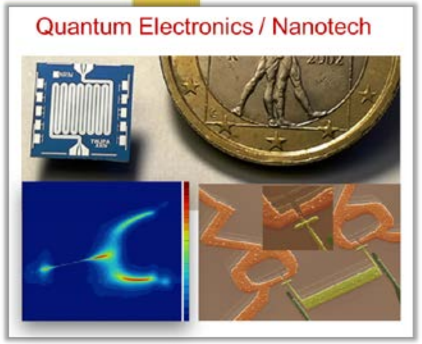
Today:
Nanophotonics, Entanglement, Atoms-on-a-chip
Metamaterials and nanostructures are the game changers in metrology and sensing

INRIM IN A NUTSHELL

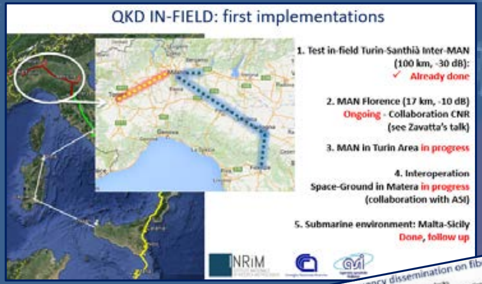
Quantum Metrology and Nanotechnology Division

Physics Chemistry and Nanotechnology
Quantum Electronics
Quantum Optics & Photometry
Time and Frequency





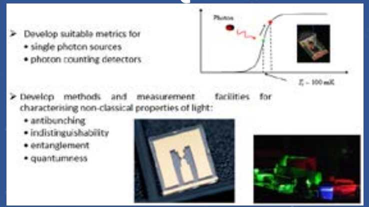
ITALIAN QUANTUM BACKBONE – 1850 Km



A complete platform for QKD

Components
Methods
Metrology and Standardisation
In-field Test
Implementation Security of QKD

Metrology for QKD and QT



Characterisation of optical components in QKD system

Single-Photon sources
Single Photon detectors
Quantum hacking coutermeasures,
Q-encoders and Q-RNG

Standardisation of QKD

ETSI World Class Standards
CEN CENELEC Focus Group on Quantum Technologies

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EURAMET EMN for Quantum Technologies: EMN-Q

EURAMET

EUROPEAN
METROLOGY
NETWORKS

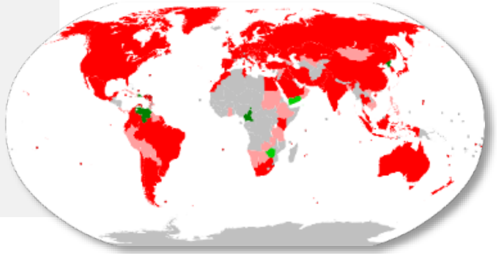
QUANTUM
TECHNOLOGIES

International Metrology and EURAMET

National Metrology Institutes (NMIs)

- **… develop and maintain metrology infrastructure worldwide** in response to the needs from science, industry and society. Their core mission includes
  - cutting-edge measurement research, and
  - sustainable capabilities for measurement, calibration, testing and conformity assessment.

- … harmonise and quality-assure their capabilities under the **Metre Convention:**
  International treaty, established in 1875 to ensure measurement conformity between countries
  (initially 17, now more than 60).



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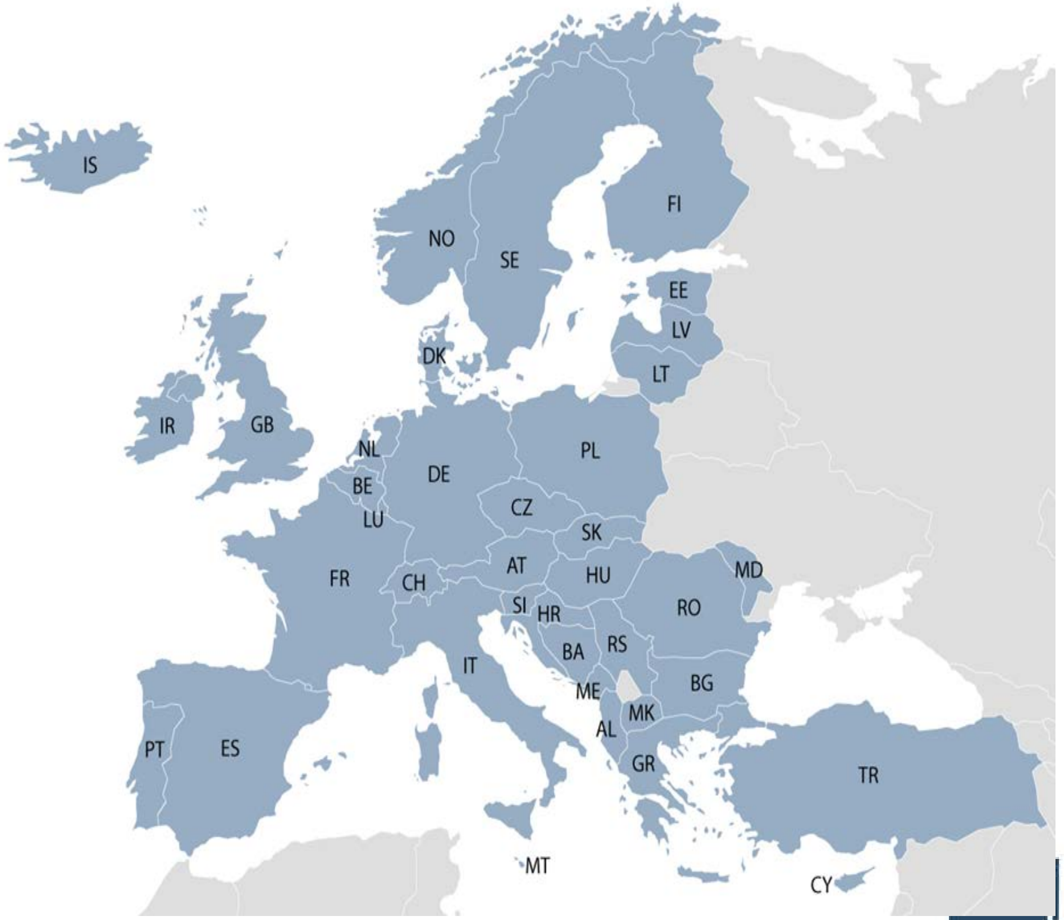
International Metrology and EURAMET

EURAMET, the Regional Metrology Organisation (RMO) of Europe

- **38 National Metrology Institutes** (Members)
- **77 Designated Institutes** (Associates)
- **16 international Liaison Organisations** (e.g. IAEA, BIPM, WMO, EA, Eurachem, Eurolab)
- Providing stakeholders with **world-leading measurement solutions and standards**
- Securing **world-wide trust** and **acceptance** of measurements, for all aspects of business and society
- Implementing **Metrology Research Programmes**



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EMN for Quantum Technologies: EMN-Q

EMN-Q Strategic Agenda (22 Oct. 2020)

Rationale

- **To align with industrial requirements, those of the EC Quantum Technologies Flagship,** national and inter-governmental quantum technology (QT) programmes, and of any **relevant stakeholders;**
- **to contribute to QT developments** through NMI's and DI's research and innovation activities;
- **to give input into the standardisation & certification** of QT;
- **to promote of the benefits of metrology** to the stakeholders.

Vision

EMN-Q aims at being the recognised European unique reference point representing European metrology for Quantum Technologies.

Today, EMN-Q has **18 EURAMET Members and Partners** from 15 countries.

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Outline

Quantum Optics with Spatial Resolving Detector @ INRIM

- … with CCD
- … with Single-photon confocal microscope
- … with SPAD arrays

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Quantum Optics Group @INRIM

Since 1998 …

https://quantum-optics.inrim.it/home-page

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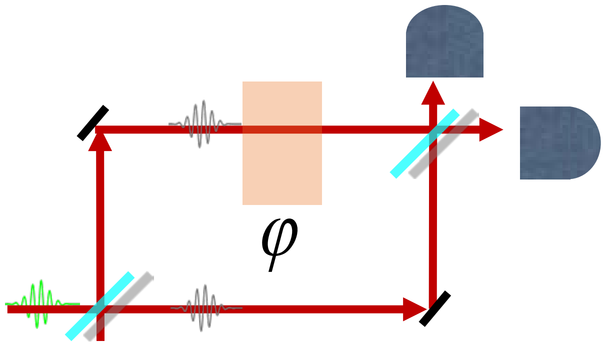
Quantum Enhanced Measurement

The Shot-Noise Limit

- **phase**

-Interferometry

-GW detectors

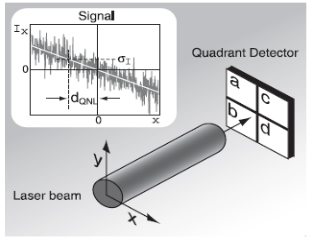


$$\Delta\varphi_{\min} \approx \frac{1}{\sqrt{N}}$$

- **Displacement:**

-lithography

-beams, particles tracking



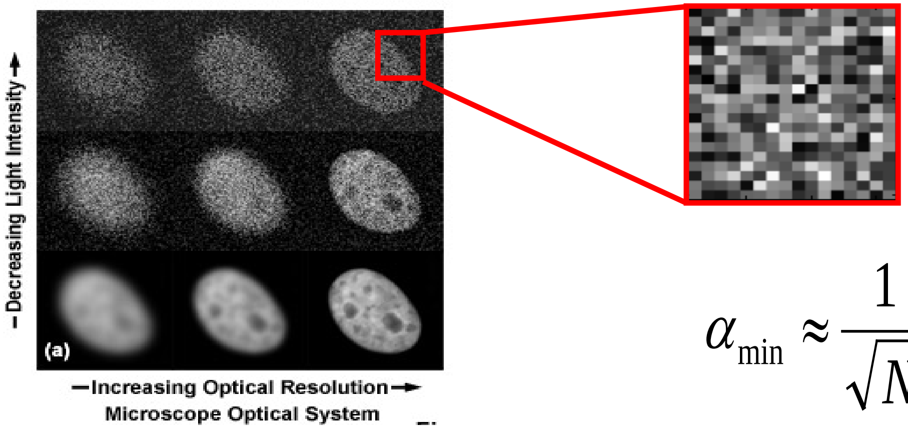
$$X_R \approx \lambda \frac{f}{D} \qquad \Delta x_{\min} \approx \frac{X_R}{\sqrt{N}}$$

- **Absorption/reflection:**

-Imaging

-microscopy

-Target recognition



$$\alpha_{\min} \approx \frac{1}{\sqrt{N}}$$

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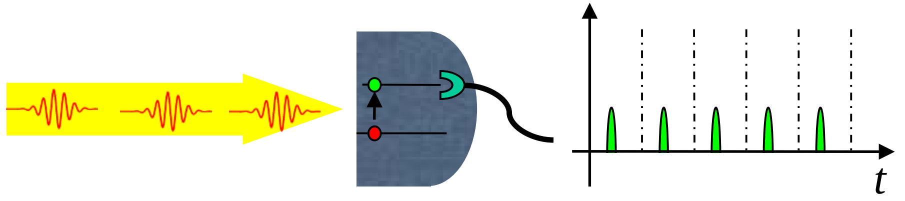
Quantum Enhanced Measurement

However quantum mechanics predicts existence of quantum states of light which allow to beat the shot-noise limit

Fock state $|N\rangle$

Single photon source : $|1\rangle$

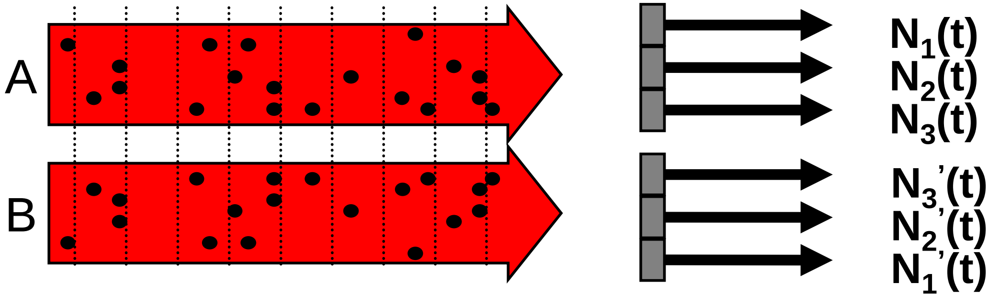


$\Delta N \approx 0$!!!

non-classical correlation and entanglement :

Twin beam:

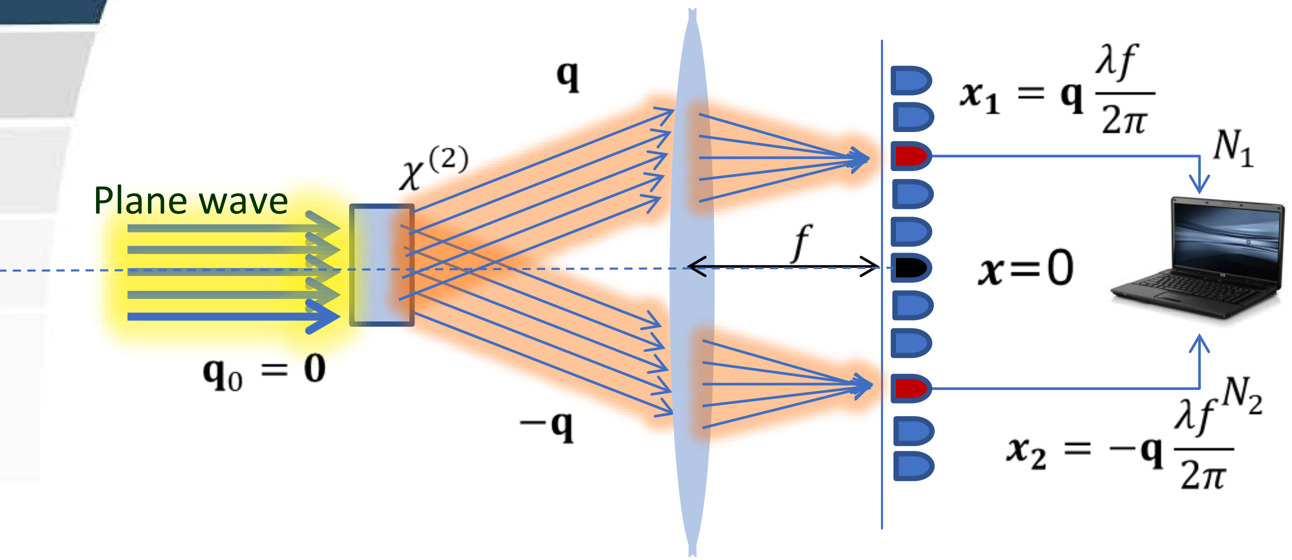
$$\left|\Psi_{AB}^{(TWB)}\right\rangle = \prod_{\mathbf{k}} \left[\sum_{n} C_{\mathbf{k}}(n)\, |n_{\mathbf{k}}\rangle_A |n_{-\mathbf{k}}\rangle_B \right]$$

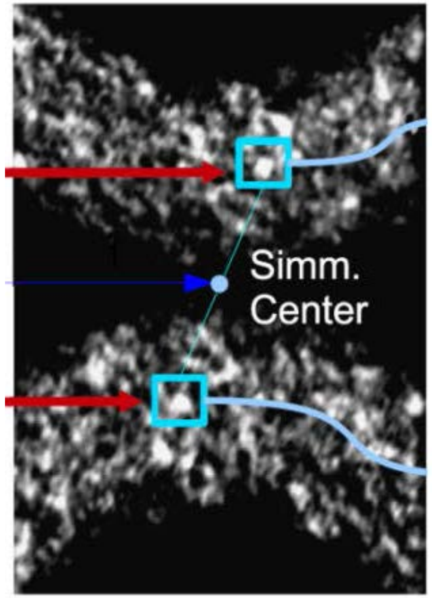


$$\sigma = \frac{Var(N_i - N'_i)}{\langle N_i + N'_i \rangle} < 1$$

QUANTUM

Quantum Enhanced Measurement





- Parametric Down Conversion: spontaneous decay of a pump photon in a photon pair (energy and momentum conservation).
- Transverse momentum conservation $\mathbf{q}_0 = \mathbf{q}_1 + \mathbf{q}_2$ implies photon pairs propagate along correlated directions.
- In the Far Field plane waves are focused in points → Two point-like detectors would detect perfect two-modes quantum correlation (both in low and high gain regime)

$$\sigma = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2 \rangle} = 1 - \eta < 1$$

NON-CLASSICAL

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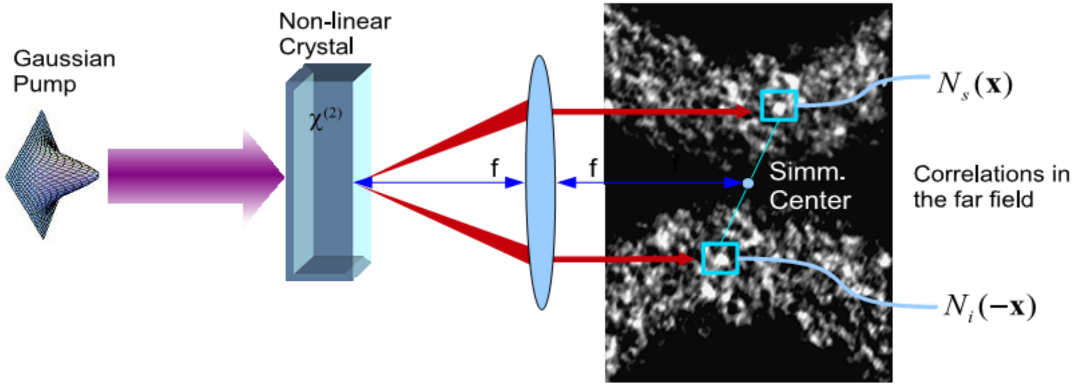
CCD camera calibration

[Optics Expr. **18**, 20572 (2010); APL **105**, 10113 (2014); Opt. Lett. **41**, 1841 (2016)]

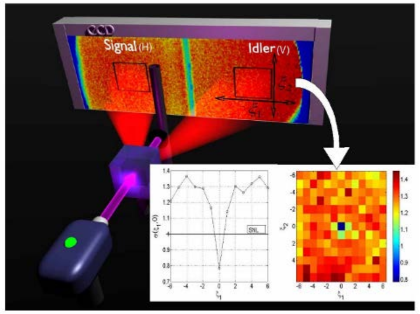
Bright Multimode Twin-Beams used to calibrate scientific CCD camera



$$|\psi(\mathbf{q})\rangle = \sum_n C_{\mathbf{q}}(n)|n\rangle_{i,\mathbf{q}}|n\rangle_{s,-\mathbf{q}}$$

NRF: $$\sigma \equiv \frac{\langle \delta^2 N_- \rangle}{\langle N_i + N_s \rangle}$$

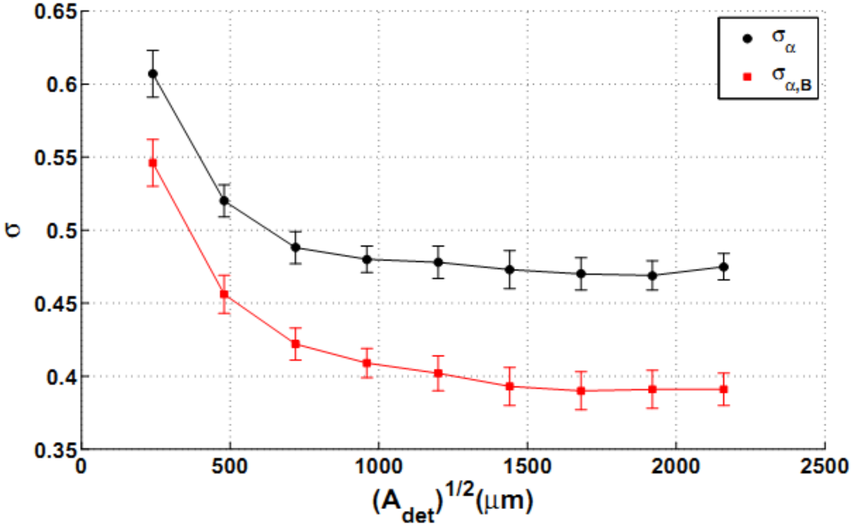
$$\langle \delta^2 N_- \rangle \equiv \langle \delta^2 N_s \rangle + \langle \delta^2 N_i \rangle - 2\langle \delta N_i \delta N_s \rangle$$



Corrected NRF

$$\sigma_\alpha \equiv \frac{\langle \delta^2 (N_s - \alpha N_i) \rangle}{2\langle N_s \rangle} = \frac{1}{2}(1+\alpha) - \eta_s$$

$$\alpha = \langle N_s \rangle / \langle N_i \rangle$$



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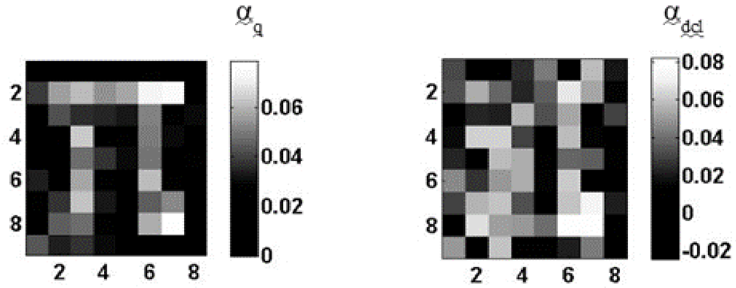
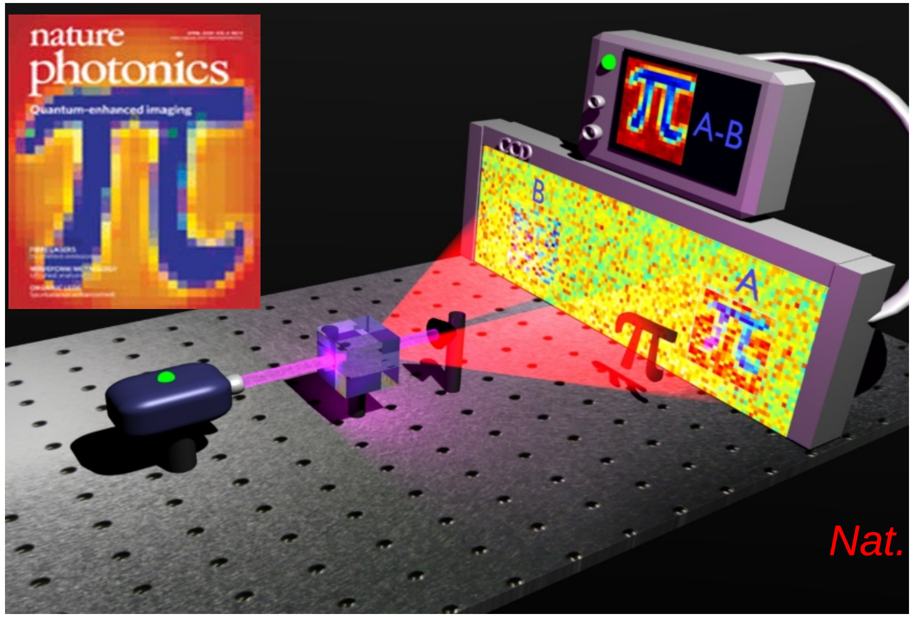
Sub-Shot-Noise Imaging

Sub-Shot Noise Imaging

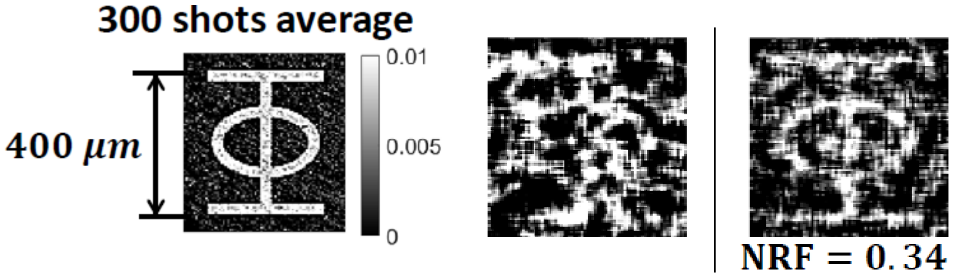
Beating the shot-noise with quantum light





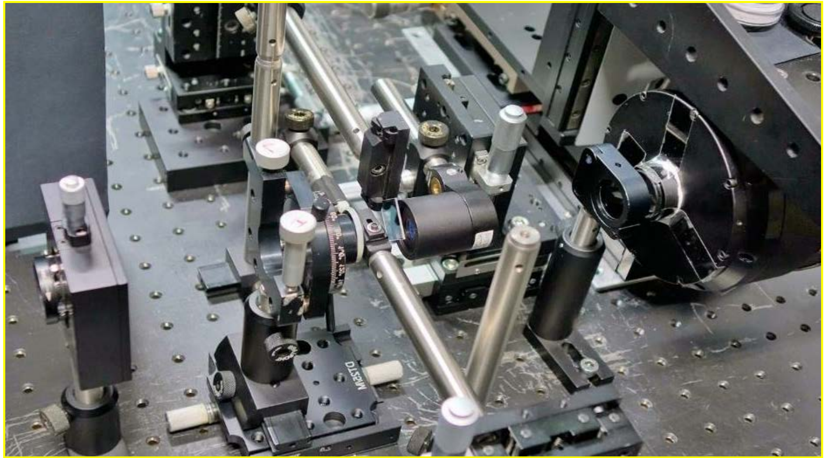
Nat. Photonics **4**, 227 (2010)

Wide-Field Sub-Shot Noise Microscope



5 μm resolution

Light S&A **6**, e17005 (2017)



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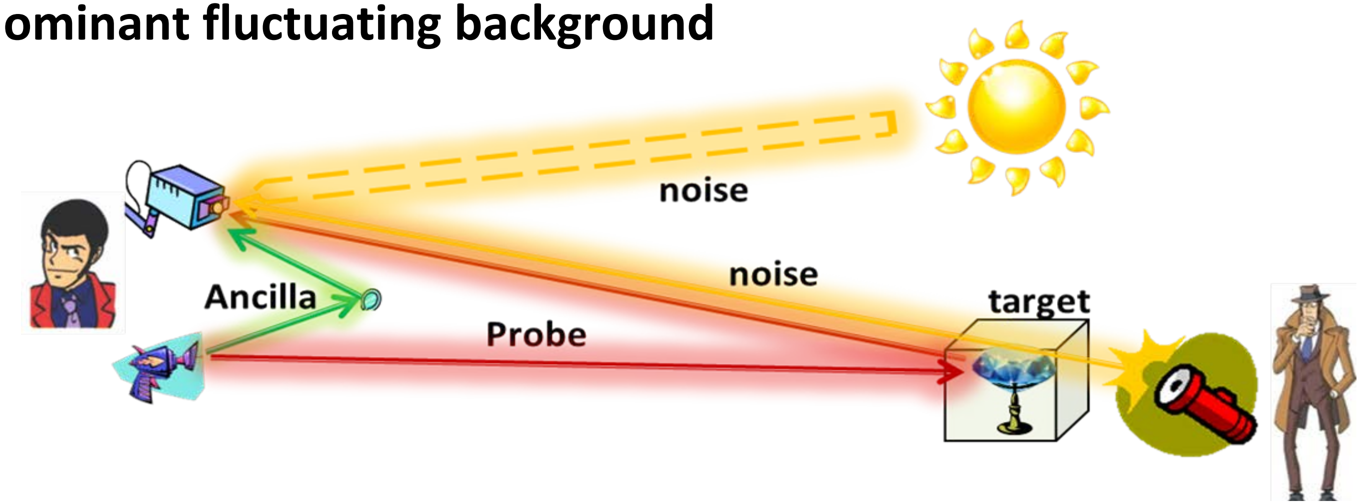
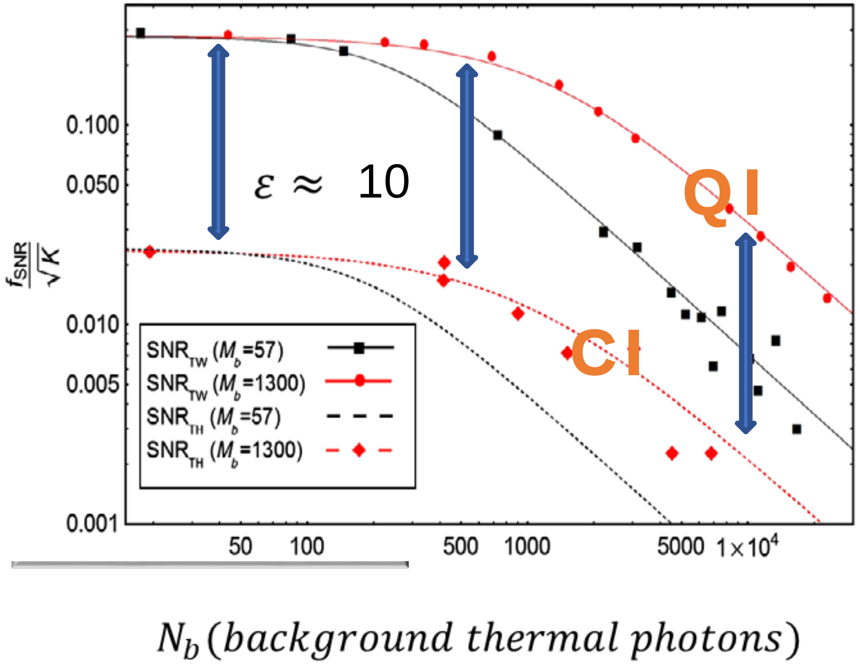
Quantum Illumination

Problem: detection of a partially reflecting target which is immersed in a dominant fluctuating background



Quantum illumination takes advantage of an ancillary beam, quantum correlated /entangled with the probe, by a joint measurement of the two.

- ✓ **Large quantum enhancement!**
- ✓ **Independent of noise and losses!**
- ✓ **Non-classical signature does not survive the noise**



Lopaeva *et al*, PRL **110**, 153603 (2013)

QUANTUM TECHNOLOGIES

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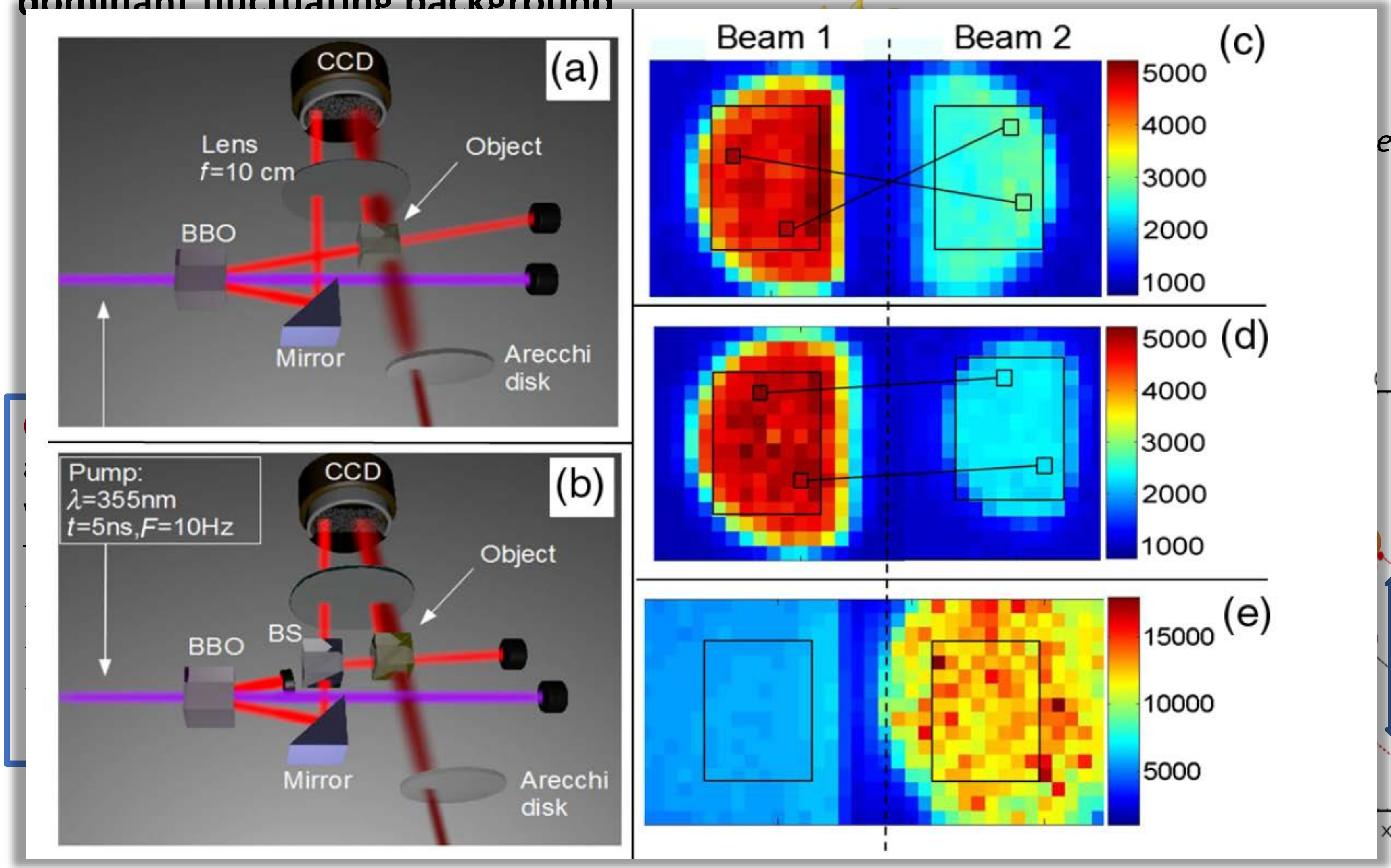
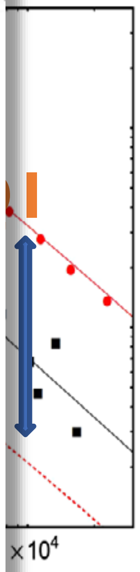


et al, PRL 110, 153603 (2013)



Lopaeva *et al*, PRL 110, 153603 (2013)

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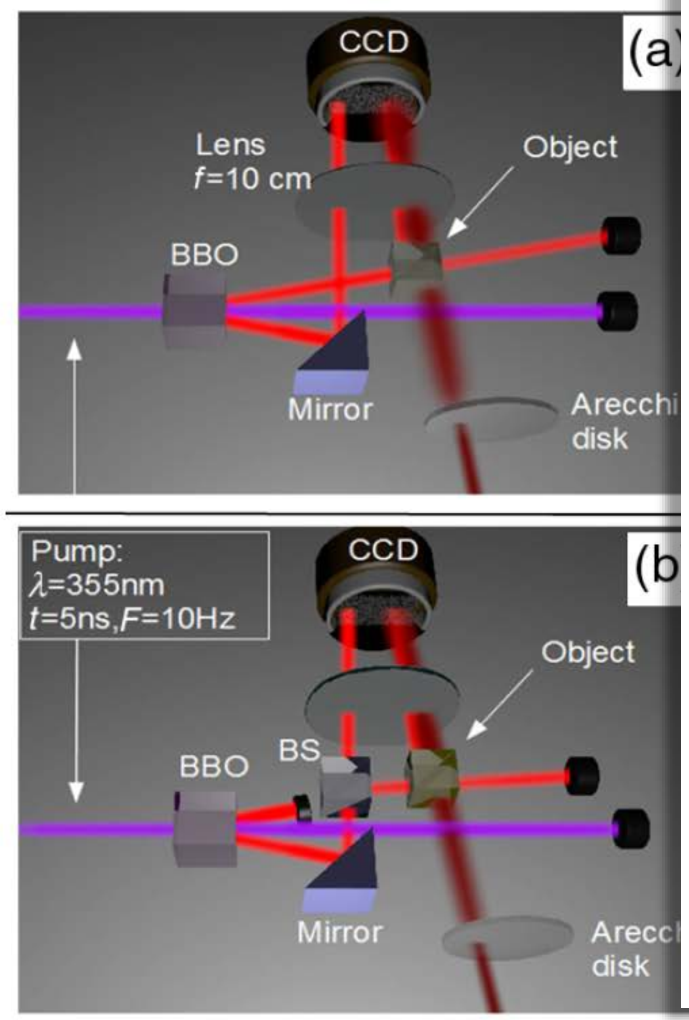

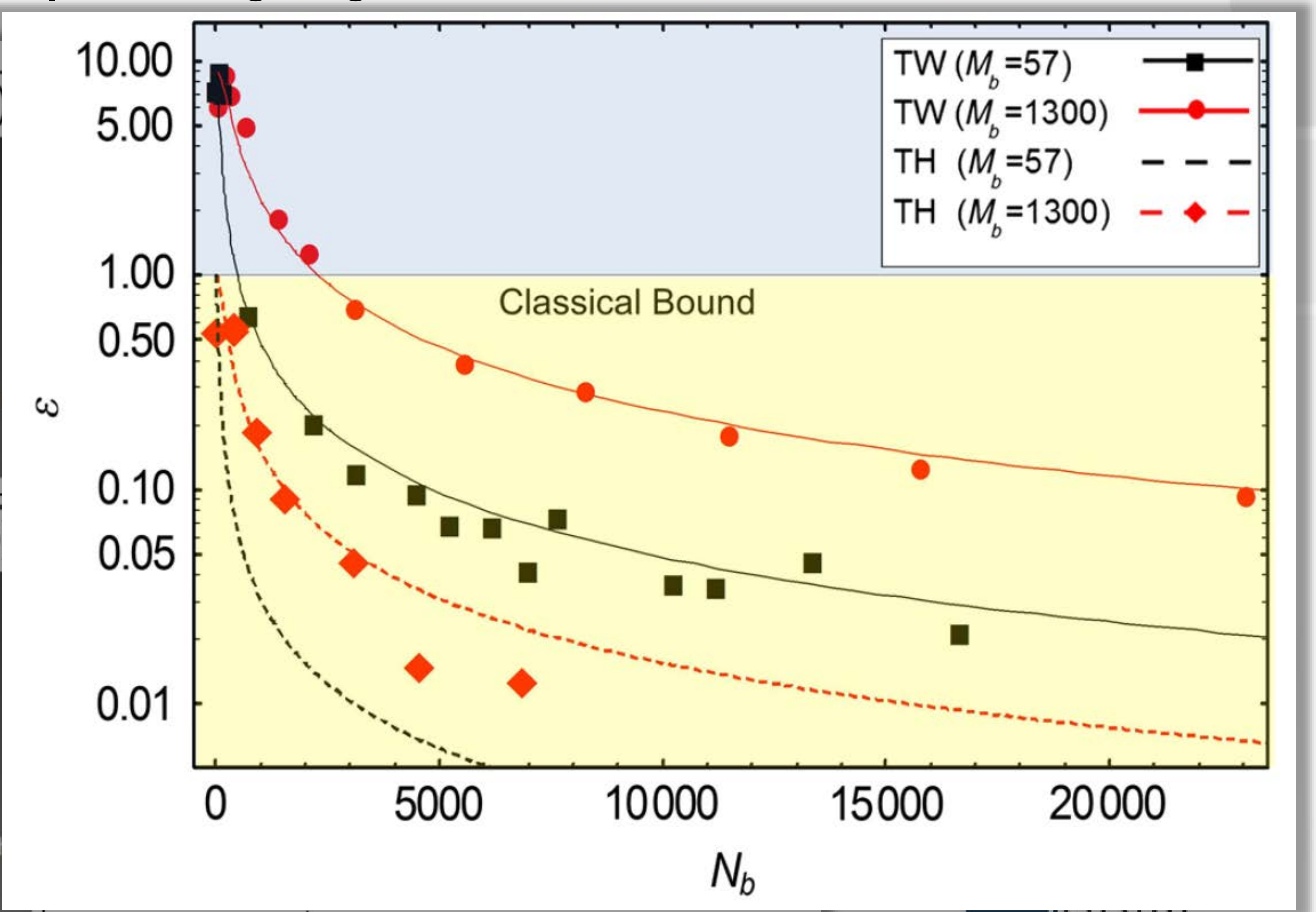

Lopaeva *et al*, PRL 110, 153603 (2013)

N_b (background thermal photons)

Quantum Conformance Test (Reading)

Quantum Hypothesis Testing

Physical process $\mathcal{P}_x$ *producing a quantum object (the SUT* $\mathcal{E}_{\mathcal{T}}$ *)*

The process $\mathcal{P}_x$ *described by the ensemble* $\{g_x(\tau), \varepsilon_\tau\}$

$g_x(\tau)$ *probability distribution defines the SUT* $\mathcal{E}_{\mathcal{T}}$

*The **conformance test** consists in ruling whether an unknown process should be labeled*
- "reference" process $\mathcal{P}_0$
- "defective" process $\mathcal{P}_1$

● ***False negative*** p_{10} ***:*** a SUT produced by a conform process (*x* = 0) is labeled as defective (*y* = 1);
An economic loss for a manufacturer when a conform process is considered defective. We will

● ***False positive*** p_{01} ***:*** a SUT produced by a defective process (x = 1) is labeled as conform (y = 0).
This outcome represents a risk since possibly unsafe products are released.

$$p_{err} = (p_{01} + p_{10})/2$$

Ortolano et al., Sci. Adv.**7**, eabm3093 (2021)
Ortolano et al., Sci. Adv.**7**, eabc7796 (2021)

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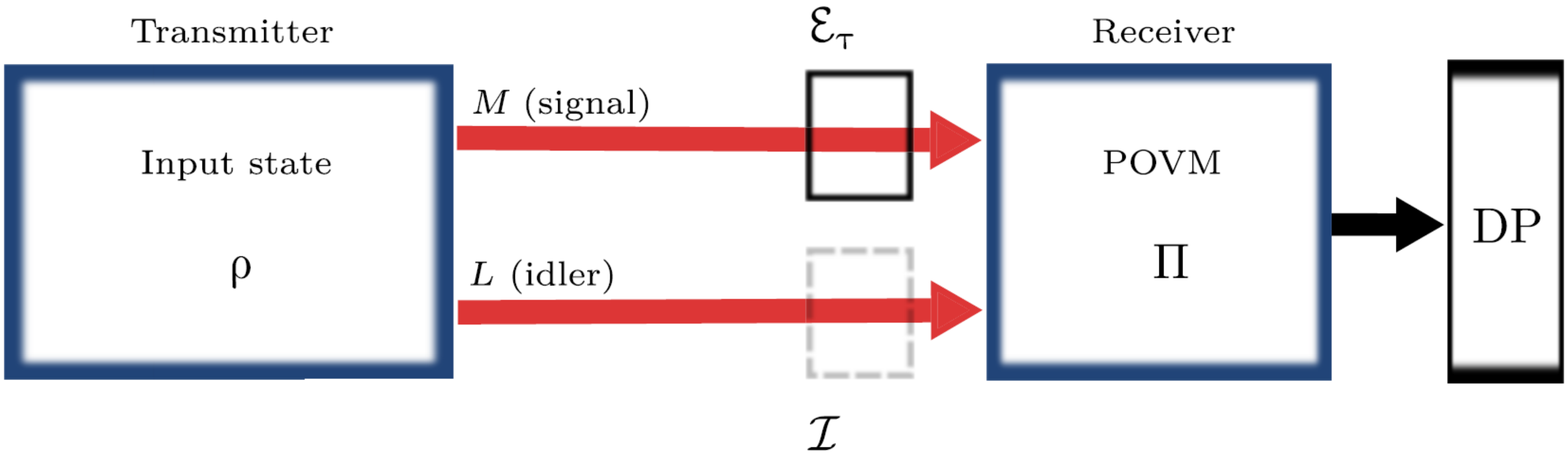
Quantum Conformance Test (Reading)



$D(\rho_0, \rho_1) = \|\rho_0 - \rho_1\|/2$ is the trace distance

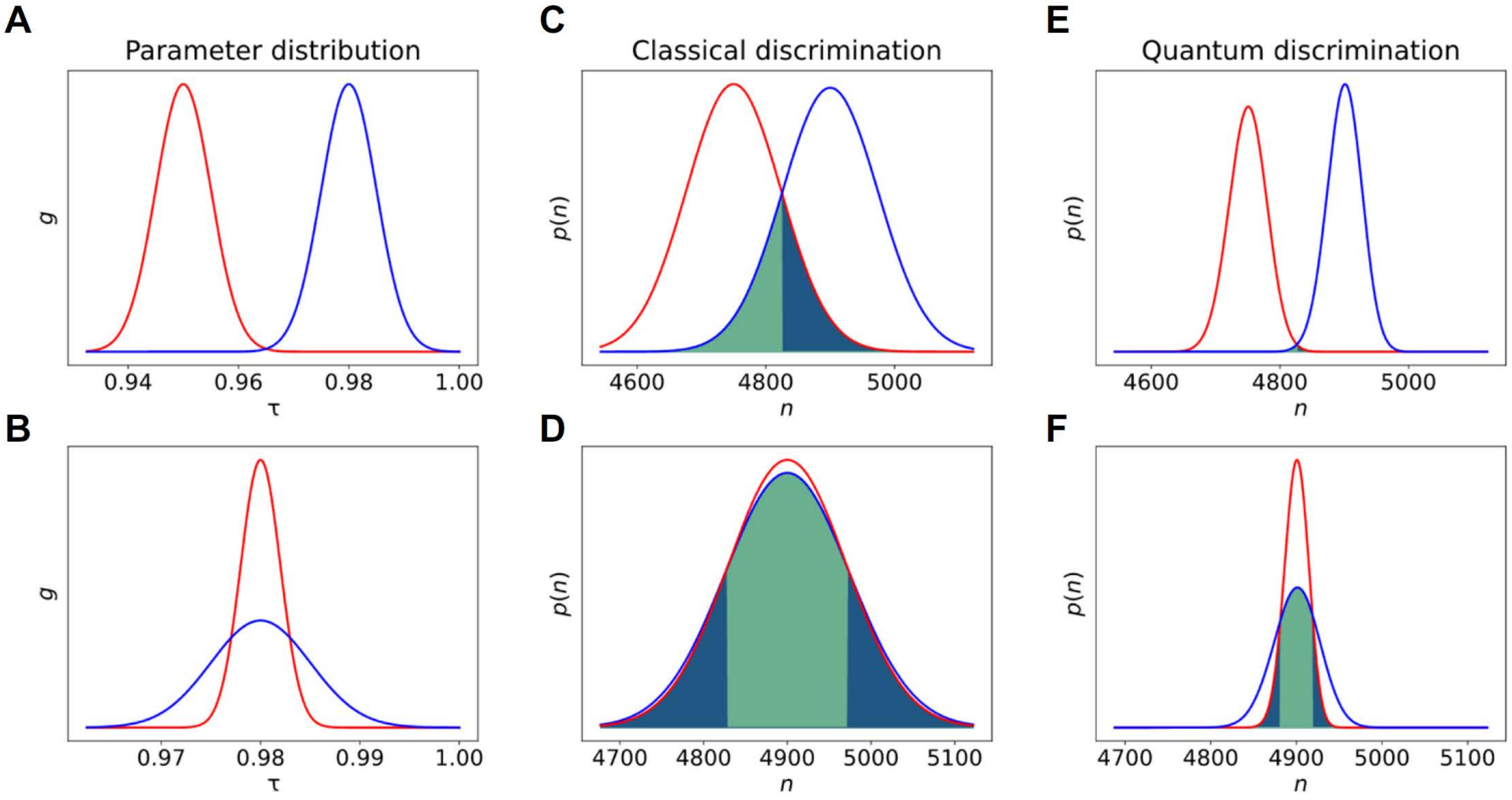
$$\rho_0 = \mathbb{E}_{\mathcal{P}_0}[(\mathcal{E}_\tau \otimes \mathcal{I})\rho] \rightarrow \text{reference process}$$

$$\rho_1 = \mathbb{E}_{\mathcal{P}_1}[(\mathcal{E}_\tau \otimes \mathcal{I})\rho] \rightarrow \text{defective process}$$

$$p_{\mathrm{err}} = \frac{1}{2}(1 - D(\rho_0, \rho_1))$$

Ortolano et al., Sci. Adv.**7**, eabm3093 (2021)
Ortolano et al., Sci. Adv.**7**, eabc7796 (2021)

Quantum Conformance Test (Reading)



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Ortolano et al., Sci. Adv.**7**, eabm3093 (2021)
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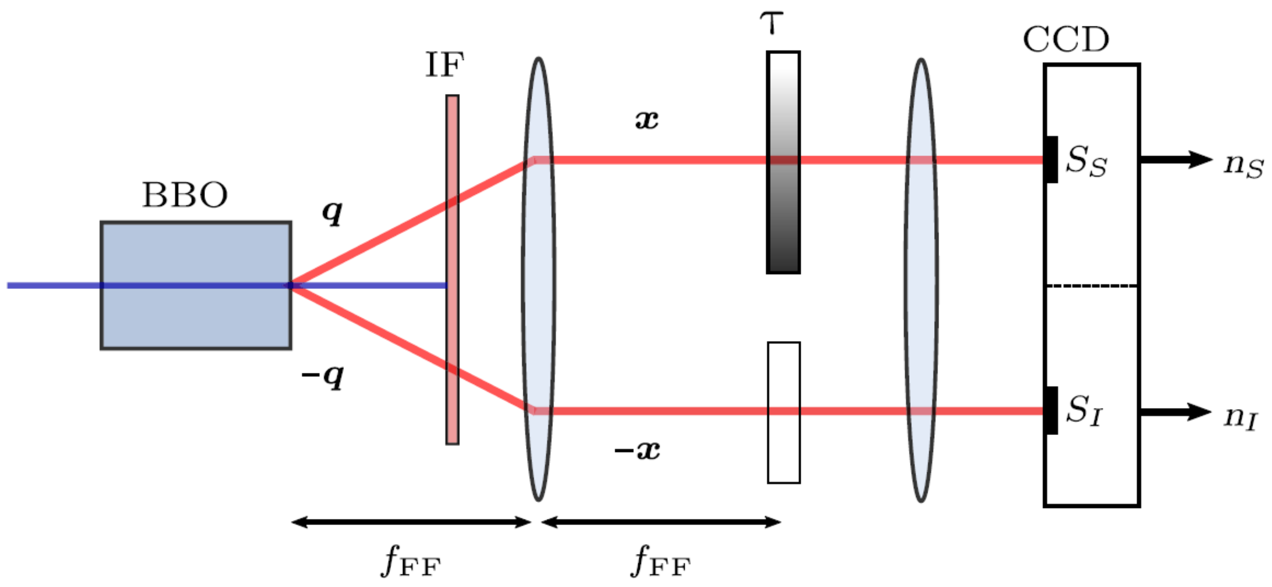

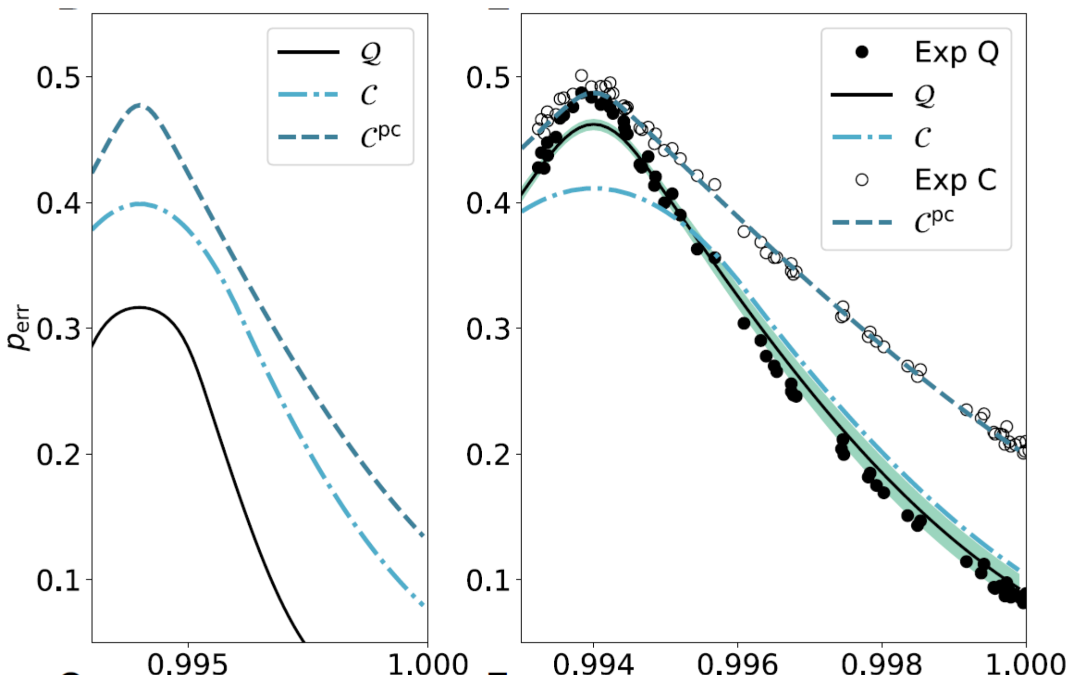

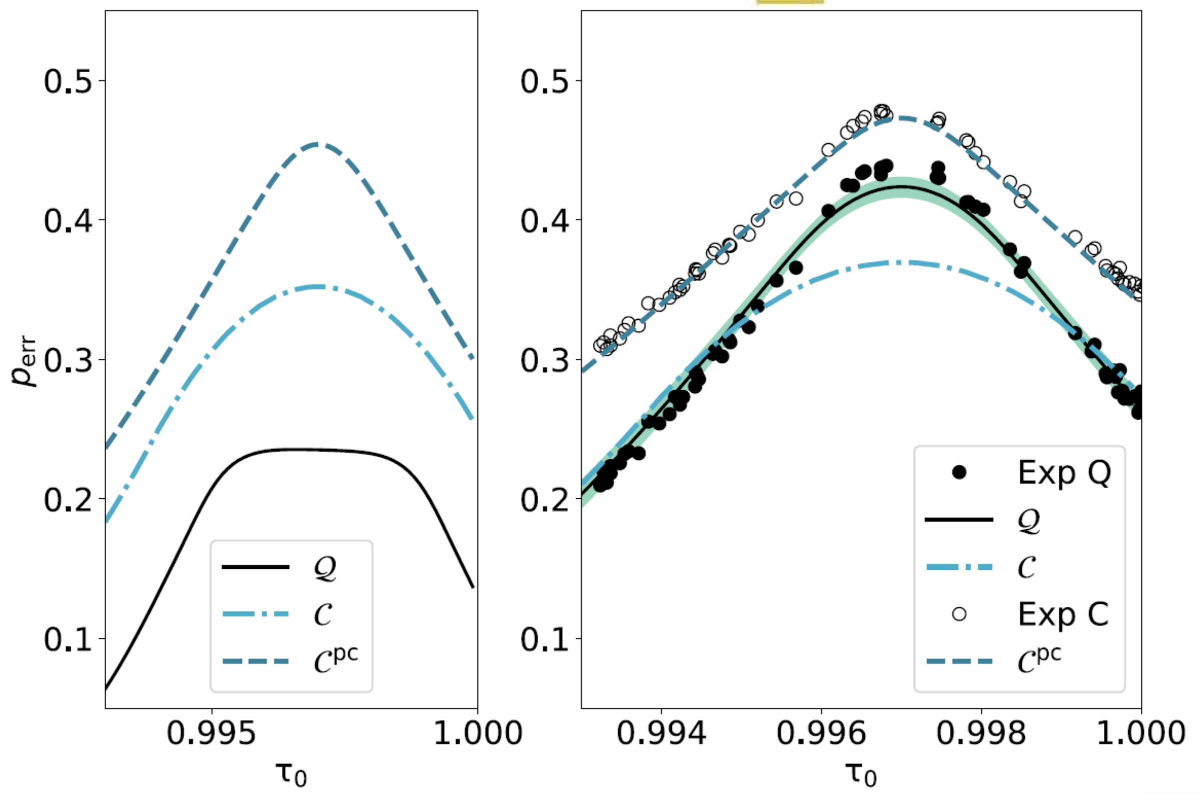

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Ortolano et al., Sci. Adv.**7**, eabm3093 (2021)
Ortolano et al., Sci. Adv.**7**, eabc7796 (2021)

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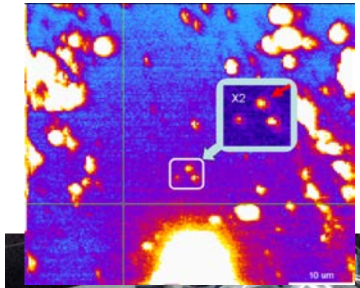
Color centers in diamond

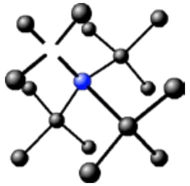
5.5 eV energy gap can host several defects with optical transitions

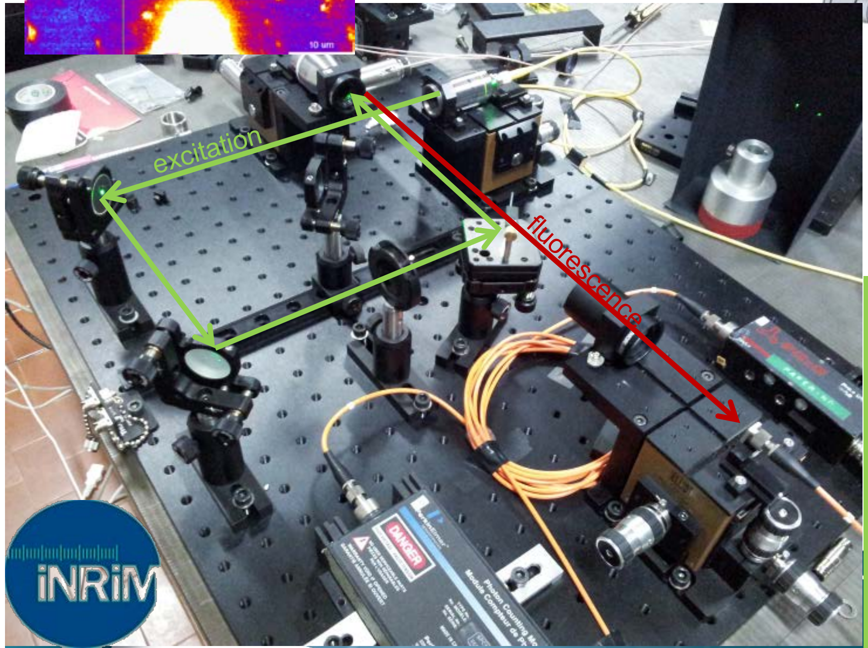
Defects emitting in the visible spectrum: **color centers**

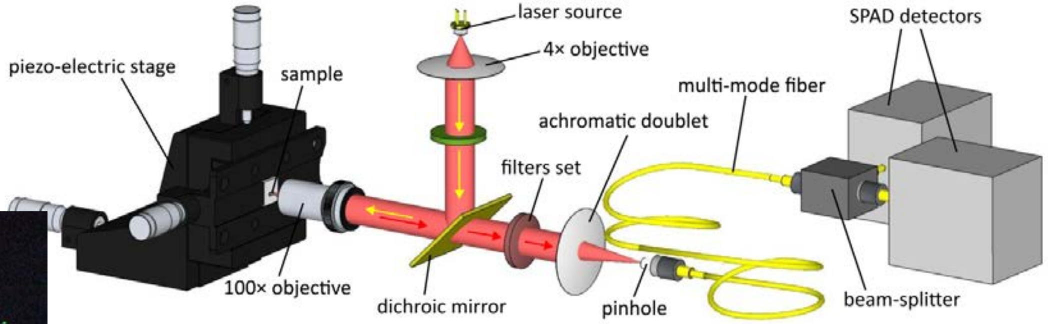
Point defects: individual optical transitions → single-photon emission

Operation at **room temperature; stable** (no photobleaching) **fluorescence**









SP-sensitive Confocal-Microsc.

- Off-resonant excitation: (Solid state diode lasers)
- Fibre Detection: coupled APD Perkin Elmer SPCM-AQR
- Air and oil objectives (NA = 0.9 and 1.3 resp.)

UNIVERSITÀ DI TORINO

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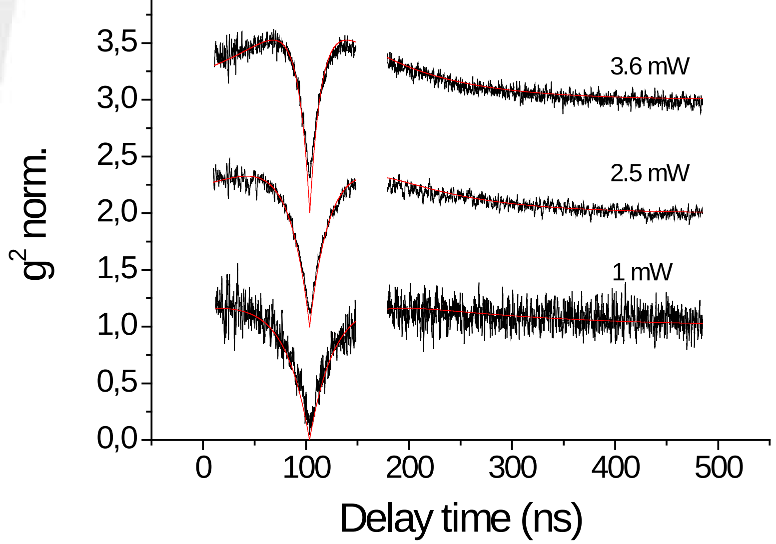
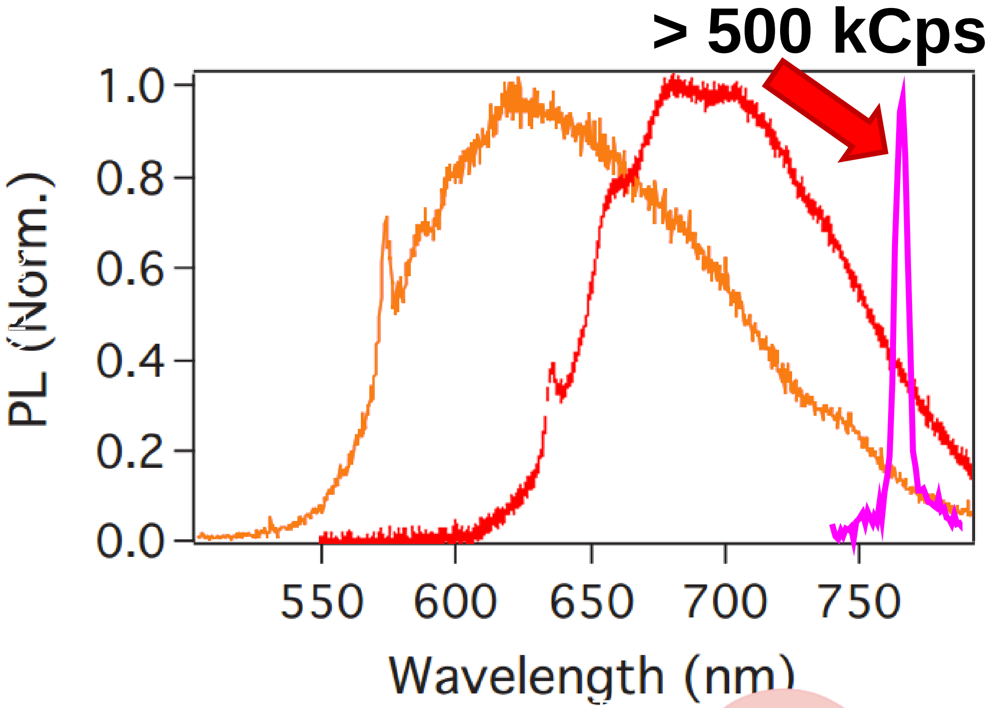
Color-centers as SPSs

Non-NV colour centres *vs* NV centers

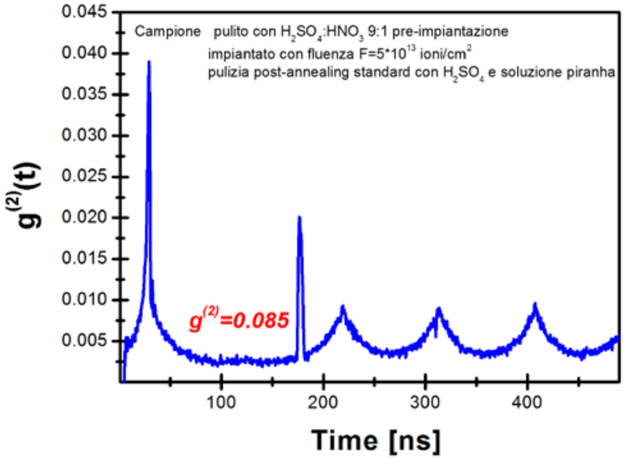
✓ Narrow emission (<u>< 5 nm, upper limit</u>)

✓ Shorter lifetime (0.7 – 3 ns)

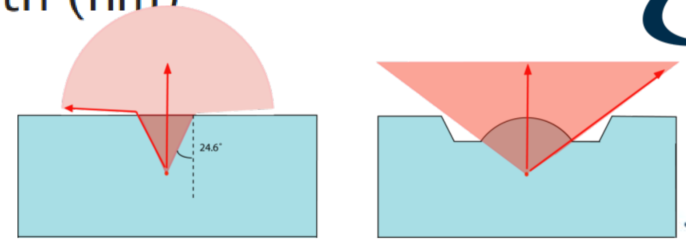


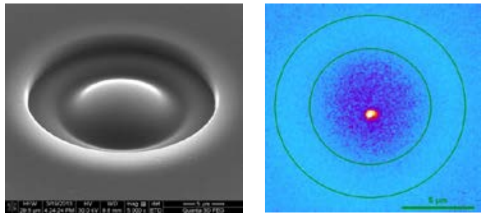


N-V: Metrologia **49**, S156 (2012)
Native NIR: NJP **16**, 053005 (2014)
Sn: ACS photonics **4**, 2580 (2017)
He: App.Phys.Lett. **111**, 111105 (2017)
Pb: ACS Photonics **5**, 4864 (2018)
N-V: P.R.App. **10**, 014024 (2018)
F: Sci.Rep. **10**, 1 (2020)
Pb: NJP **23**, 063032 (2021)
Mg: arxiv.org/abs/2206.08670 (2022)



High diamond refractive index implies small limit angle for total internal reflection -> small amount of light collected





Solid immersion lens FIB (30 keV Ga^+ FIB)
5x collection increase

IJQI **12**, 1560011 (2014)

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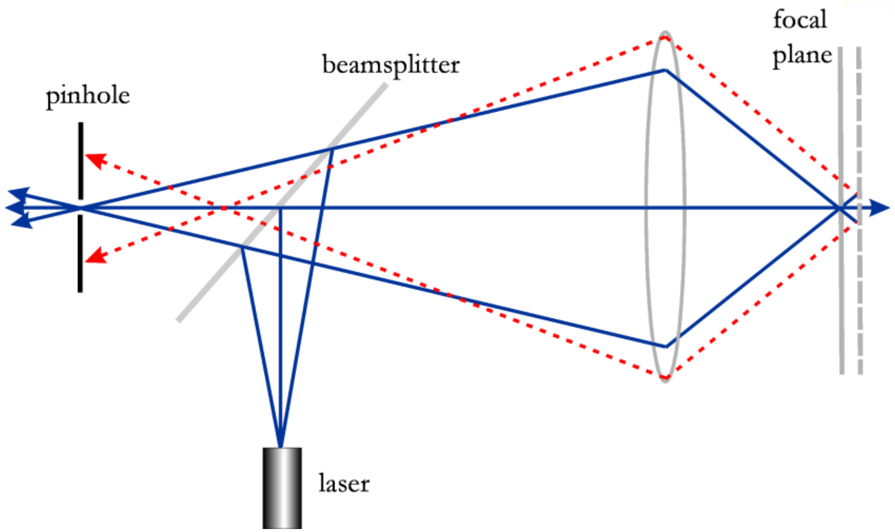
Confocal microscope

Confocal microscopy: imaging technique able to increase optical resolution and contrast of a micrograph by using point illumination and a spatial pinhole to eliminate out-of-focus light in specimens that are thicker than the focal plane. It enables the reconstruction of 3D structures from the obtained images.



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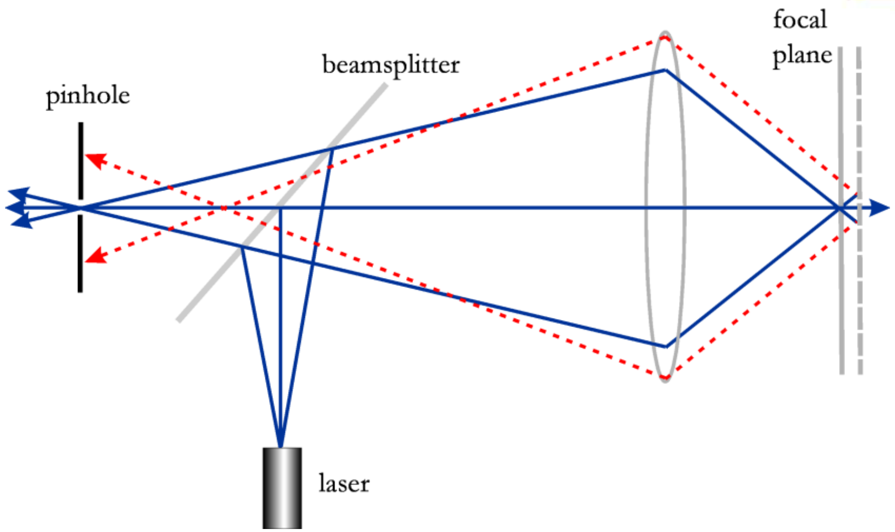
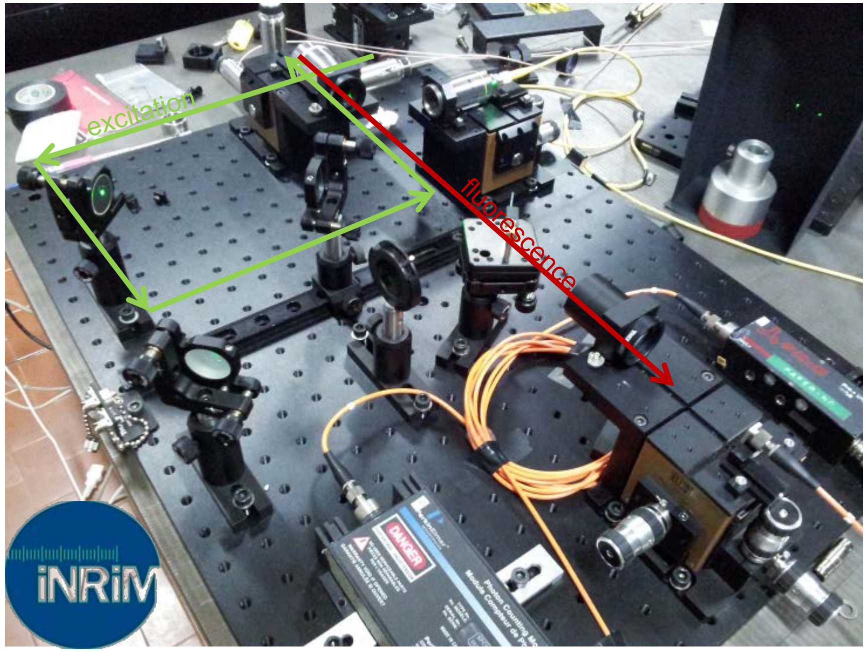


Single-photon confocal microscope



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Abbe diffraction limit

The observation of sub-wavelength structures with microscopes is difficult because of the **Abbe diffraction limit**.
The maximum obtainable imaging resolution in classical far-field microscopy is

$$d = \frac{0.61\,\lambda}{NA}$$

Beating the Abbe diffraction limit

- Near-field microscopy: plasmonic nanoantennas, nanosized tip …
- Far-field microscopy:
    - Optical patterning + Nonlinear response (e.g. STED, SIM, …)
    - Single molecule imaging by photoactivation or photoswitching (e.g. GSD, STORM, PALM, …)

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Abbe diffraction limit

The o… s with microscopes is difficult
becau…
The m… in classical far-field microscopy is

λ

Beati… :

- Near… nas, nanosized tip …
- Far-fi…
  - C… (e.g. STED, SIM, …)
  - S… ion or photoswitching (e.g.
    G…

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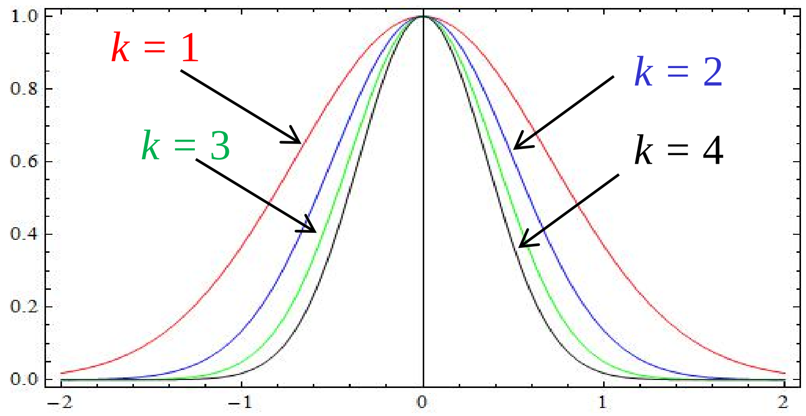
Beating the Abbe diffraction limit with SPSs

$\mathcal{P}(x)$ is essentially the PSF generated by the point-size SPS

(Probability of detecting a photon at the image position *x* from a single-photon source)

Reducing the size of PSF: $[\mathcal{P}(x)]^k$

$$\mathrm{FWHM}^{(k)} \sim \frac{\mathrm{FWHM}^{(1)}}{\sqrt{k}}$$



PRL 113, 143602 (2014)

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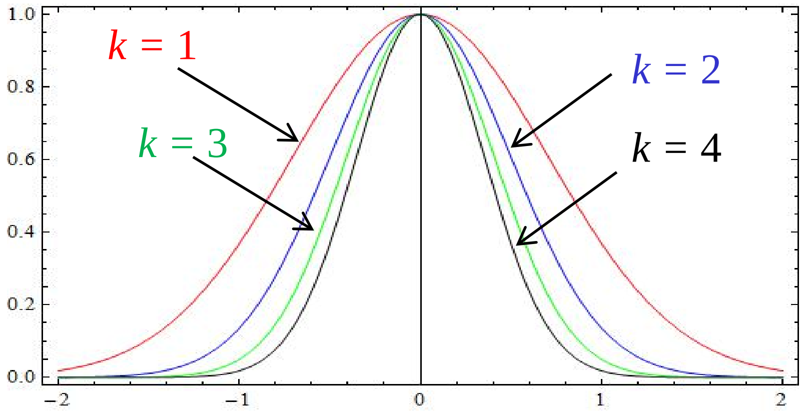
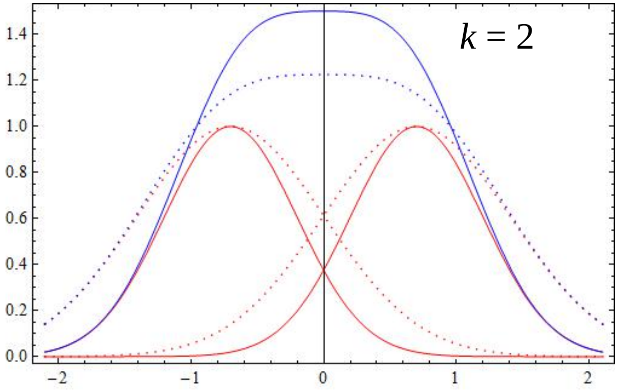
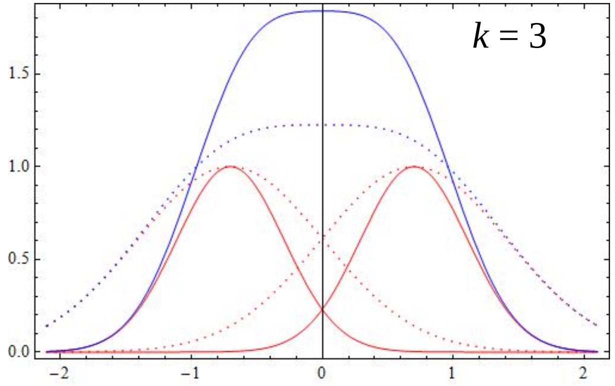
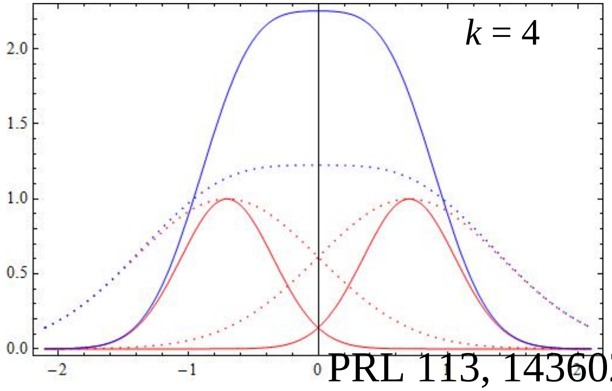


The fluorescence signal from n SPS at the position x: $S(x) \propto \sum_{\alpha=1}^{n} \mathcal{P}_\alpha(x)$

$S^k(x)$







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Beating the Abbe diffraction limit with SPSs

To improve the resolution: $S^k(x)$

$$S(x) \propto \sum_{\alpha=1}^{n} \mathcal{P}_\alpha(x)$$

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Beating the Abbe diffraction limit with SPSs

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PRL 113, 143602 (2014)

Beating the Abbe diffraction limit with SPSs

To improve the resolution: ~~$S^k(x)$~~

$$S(x) \propto \sum_{\alpha=1}^{n} \mathcal{P}_\alpha(x)$$

$$S^k(x) \propto \sum_{\alpha=1}^{n} [\mathcal{P}_\alpha(x)]^k + c.p. \quad \longrightarrow \quad \sum_{\alpha=1}^{n} [\mathcal{P}_\alpha(x)]^k$$

PRL 113, 143602 (2014)

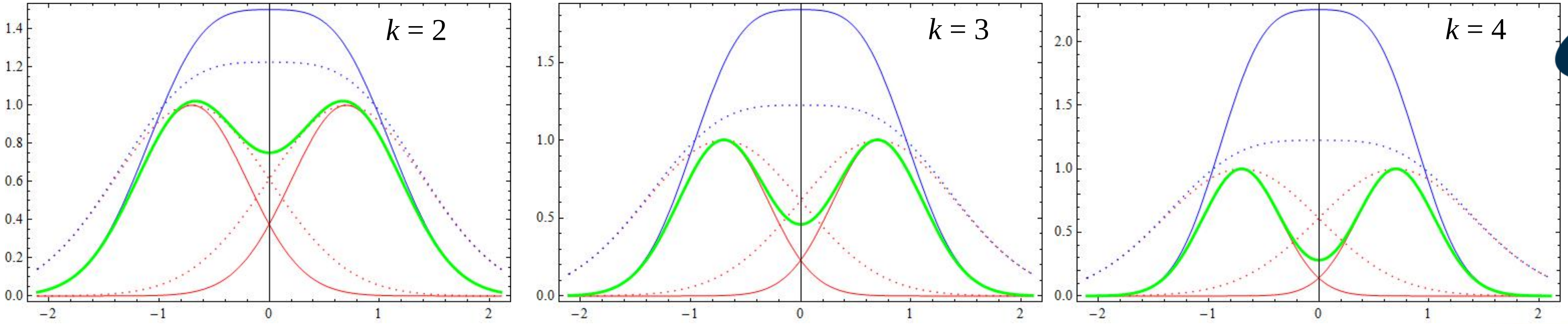
Beating the Abbe diffraction limit with SPSs

To improve the resolution: ~~$S^k(x)$~~

$$S(x) \propto \sum_{\alpha=1}^{n} \mathcal{P}_\alpha(x)$$

$$S^k(x) \propto \sum_{\alpha=1}^{n} [\mathcal{P}_\alpha(x)]^k + ~~c.p.~~$$

$$\rightarrow \quad \sum_{\alpha=1}^{n} [\mathcal{P}_\alpha(x)]^k$$



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Beating the Abbe diffraction limit with SPSs

MODEL

To obtain the resolution enhancement: $$\sum_{\alpha=1}^{n}[\mathcal{P}_\alpha(x)]^k$$

We exploit the Glauber's autocorrelation functions, e.g.

$k = 2$ $$\sum_{\alpha=1}^{n}[\mathcal{P}_\alpha(x))]^2 = \langle\hat{N}\rangle^2[1-g^{(2)})]$$

$k = 3$ $$\sum_{\alpha=1}^{n}[\mathcal{P}_\alpha(x)]^3 = \langle\hat{N}\rangle^3[1-\frac{3}{2}g^{(2)}+\frac{1}{2}g^{(3)})]$$

$k = 4$ $$\sum_{\alpha=1}^{n}[\mathcal{P}_\alpha(x)]^4 = \langle\hat{N}\rangle^4\{1-2g^{(2)}+\frac{1}{2}[g^{(2)}]^2+\frac{2}{3}g^{(3)}-\frac{1}{6}g^{(4)}\}$$

$k = 5$ $$\sum_{\alpha=1}^{n}[\mathcal{P}_\alpha(x))]^5 = \langle\hat{N}\rangle^5\{1-\frac{5}{2}g^{(2)}+\frac{5}{4}[g^{(2)}]^2+\frac{5}{6}g^{(3)}-\frac{5}{12}g^{(2)}g^{(3)}-\frac{5}{24}g^{(4)}+\frac{1}{24}g^{(5)}\}$$

… …

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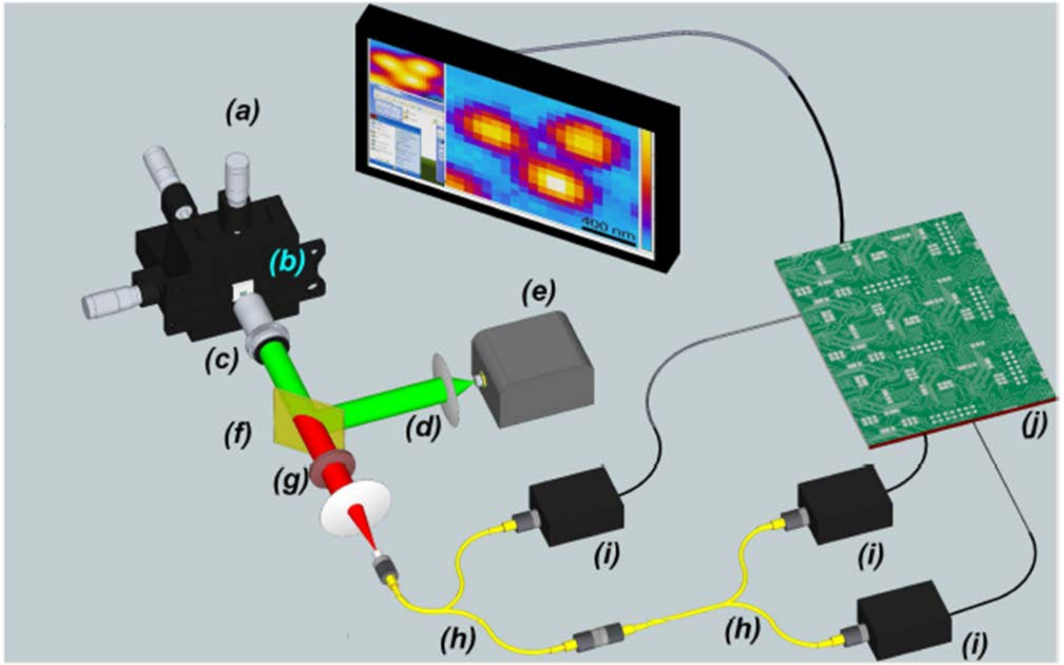
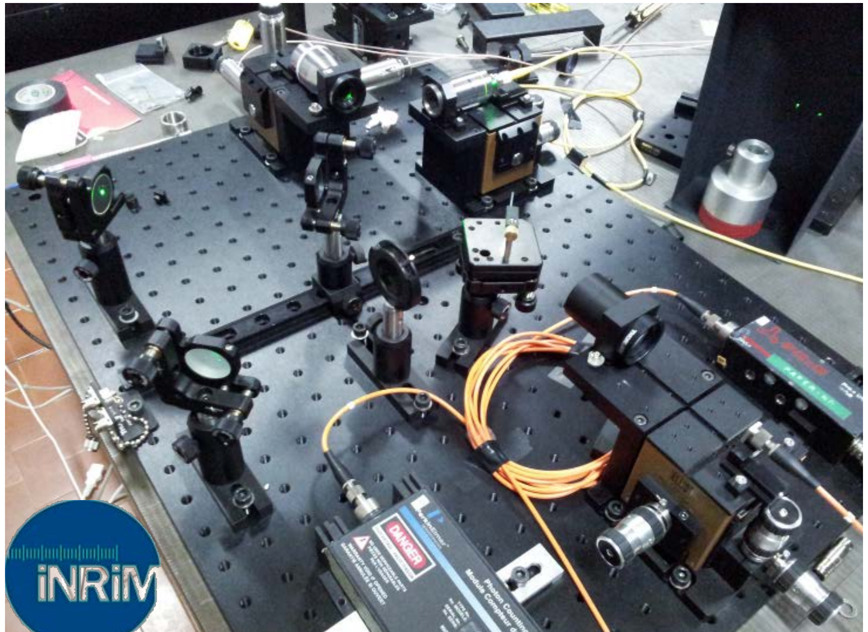
Beating the Abbe diffraction limit with SPSs

EXPERIMENTAL SETUP & RESULTS



- Excitation: @ 532 nm
  (Solid state diode laser)
- XYZ closed-loop piezo stage
- Detection λ> 570 nm
- Fibre coupled SPCMs in a **Detector Tree** configuration.
- 100X oil objective (NA = 1.3)



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EXPERIMENTAL SETUP & RESULTS

elementsix

electronic-grade Polycristallyne diamond

(a)&(b) typical photoluminescence maps of NV centers

(c) $g^{(2)}$ map

(d) $g^{(3)}$ map

(e) Super-resolved map ($k = 2$)

(f) Super-resolved map ($k = 3$)

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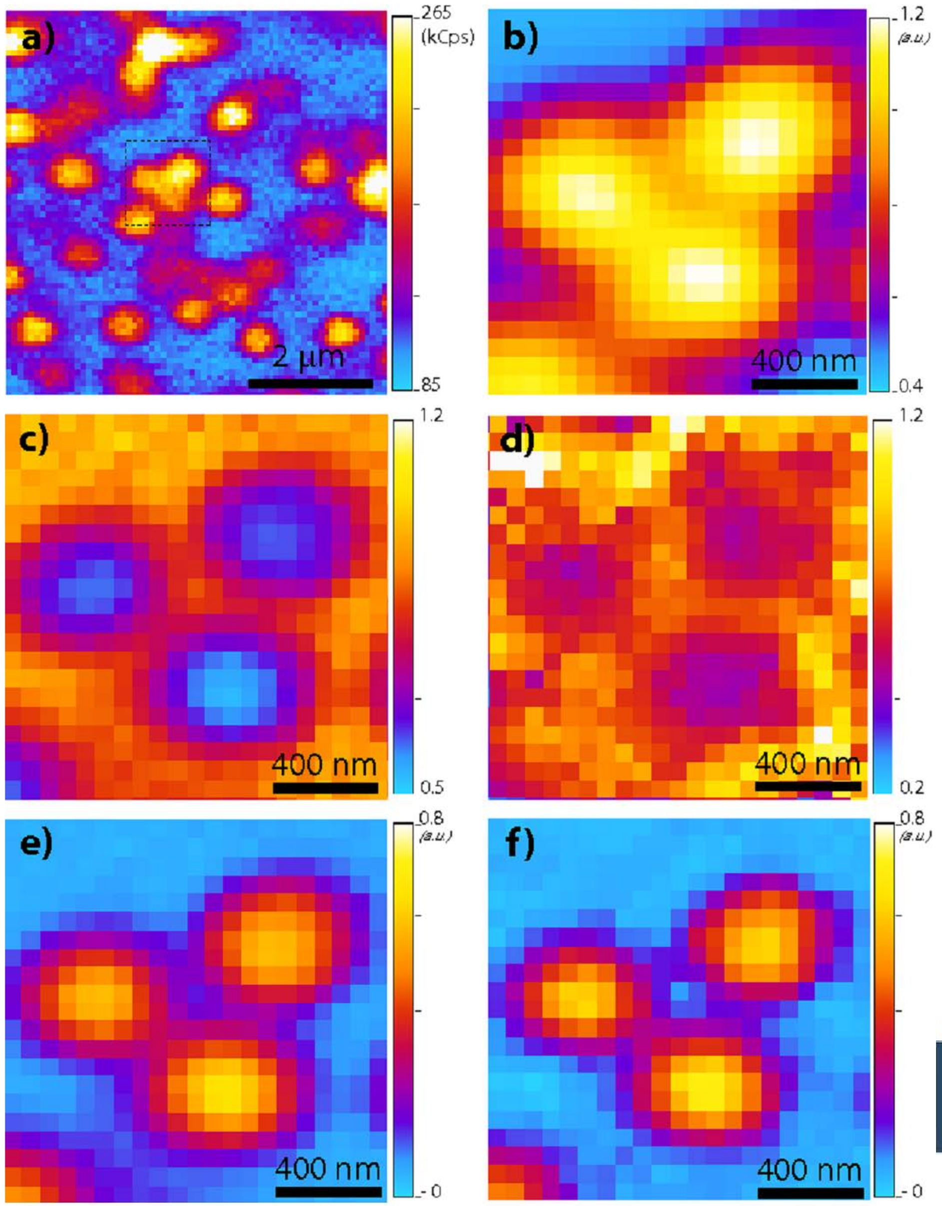

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electronic

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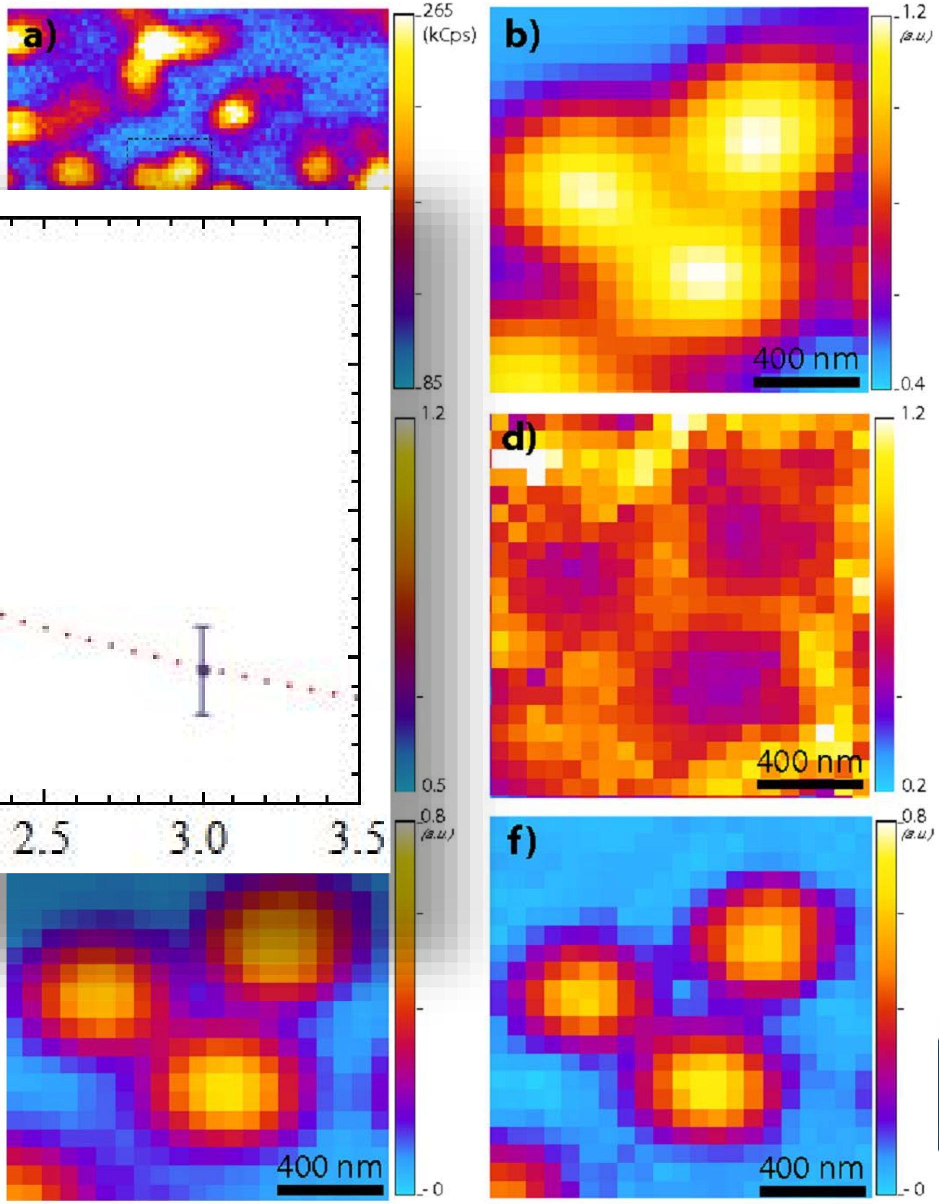
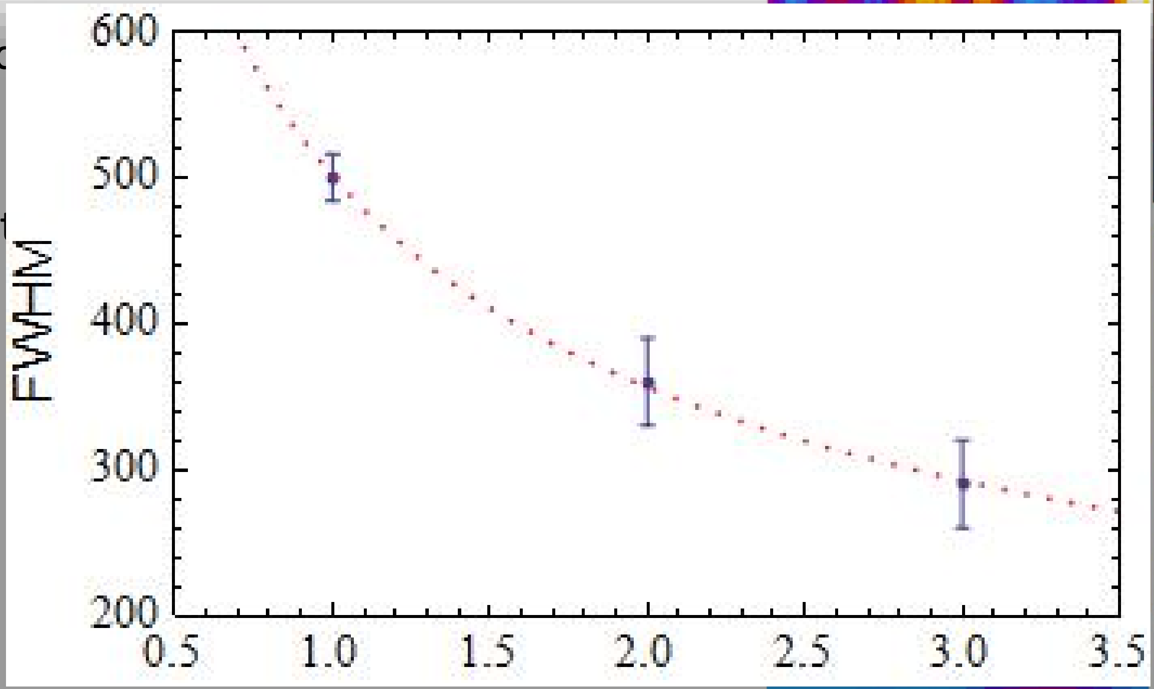
(f) Super-resolved map (k = 3)





PRL 113, 143602 (2014)

Beating the Abbe diffraction limit with SPSs

EXPERIMENTAL SETUP & RESULTS

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$$\langle \hat{N} \rangle^2 [1 - g^{(2)})]$$

$g^{(3)} = 0$

(d) Super-resolved map (k = 3)

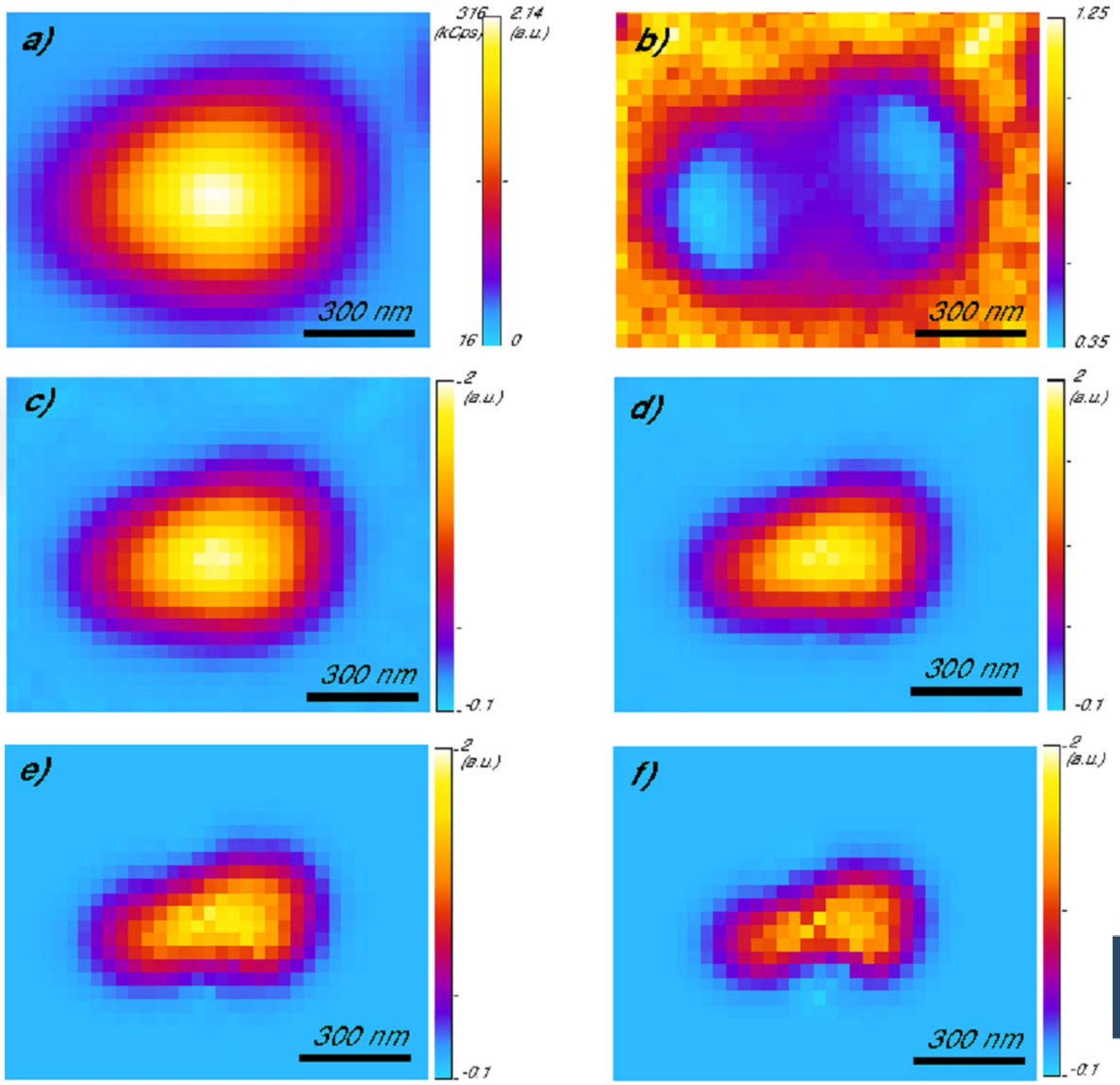
$$\langle \hat{N} \rangle^3 [1 - \frac{3}{2} g^{(2)} + \frac{1}{2} g^{(3)})]$$

(e) Super-resolved map (k = 4)

$$\langle \hat{N} \rangle^4 \{1 - 2g^{(2)} + \frac{1}{2}[g^{(2)}]^2 + \frac{2}{3} g^{(3)} - \frac{1}{6} g^{(4)}\}$$

(f) Super-resolved map (k = 5)

$$\langle \hat{N} \rangle^5 \{1 - \frac{5}{2} g^{(2)} + \frac{5}{4}[g^{(2)}]^2 + \frac{5}{6} g^{(3)} + - \frac{5}{12} g^{(2)} g^{(3)} - \frac{5}{24} g^{(4)} + \frac{1}{24} g^{(5)}\}$$



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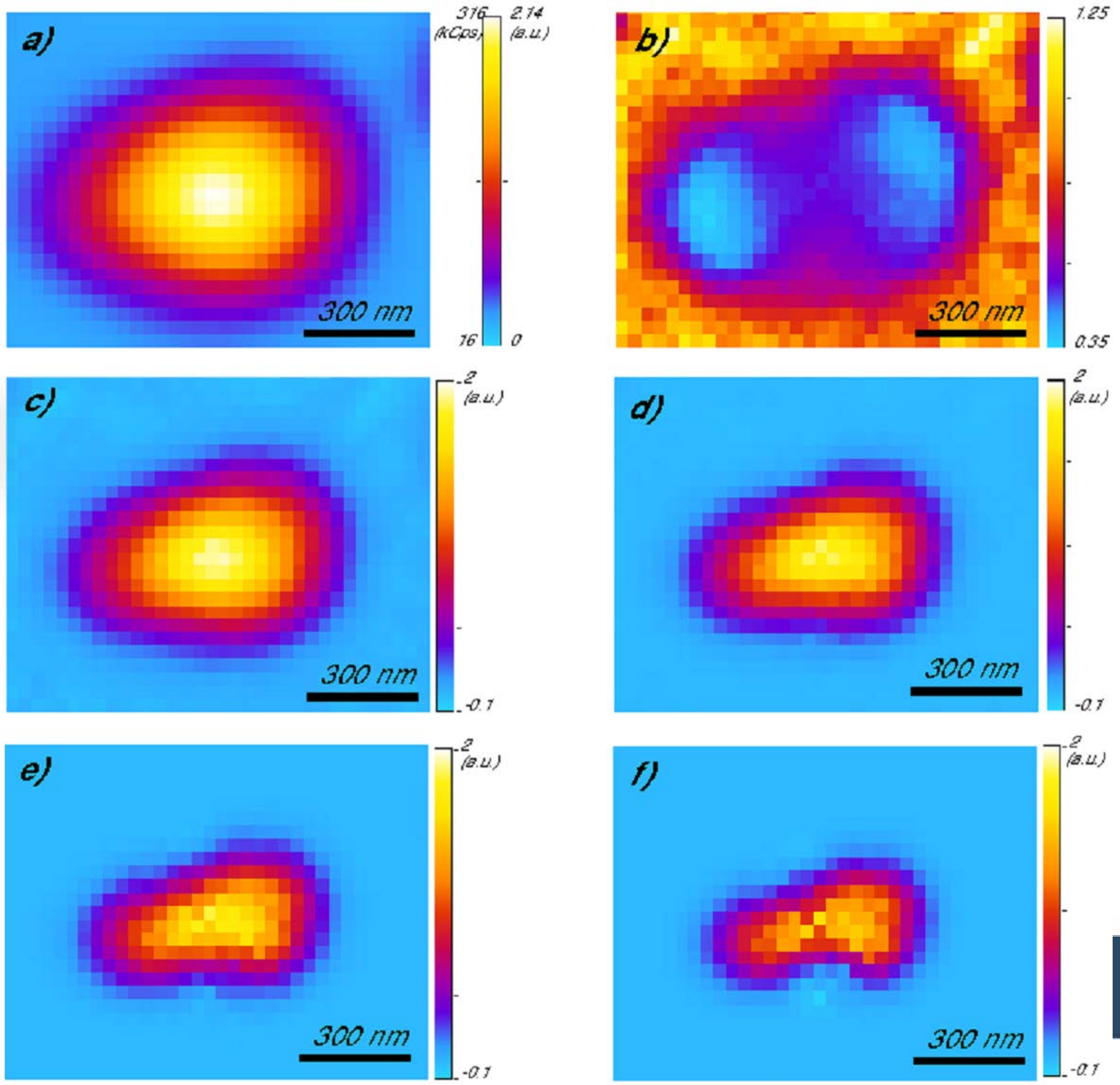

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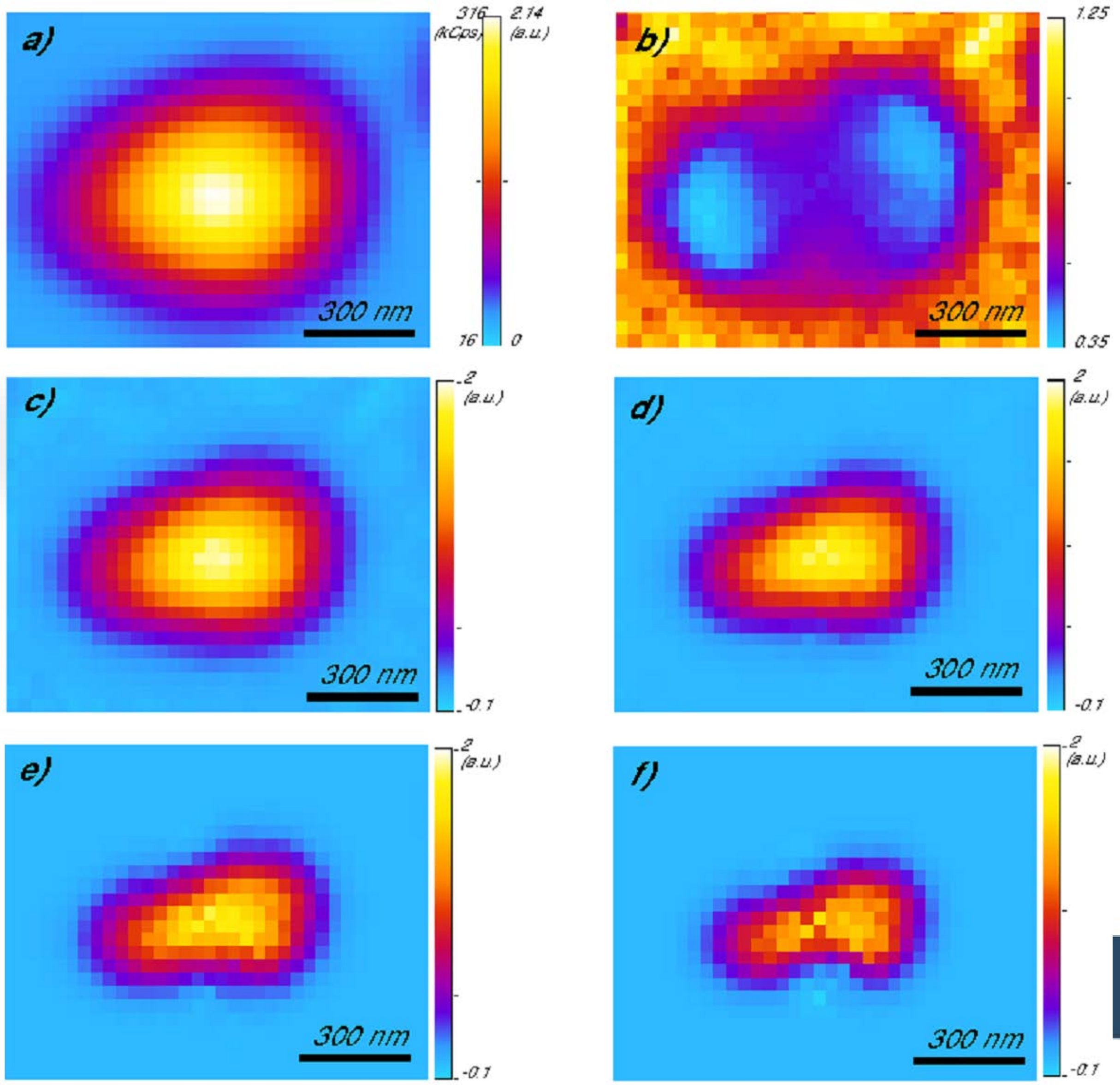

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Traditional "sharp" measurement in QM

Standard "sharp" measurement:

$$\widehat{A} = \sum_n \lambda_n \widehat{\Pi}_n \qquad \widehat{\Pi}_n = |\psi_n\rangle\langle\psi_n| \qquad \mathrm{Tr}[\widehat{A}\widehat{\rho}] = \sum_n \lambda_n \mathrm{Tr}[\widehat{\Pi}_n \widehat{\rho}]$$

Single projective measurement:

$$\widehat{\rho} \overset{\widehat{\Pi}_k}{\Longrightarrow} |\psi_k\rangle \qquad \mathrm{Prob}(\psi_k|\rho) = \mathrm{Tr}[\widehat{\Pi}_k \widehat{\rho}]$$

Wave function collapse

↕

Non-commuting observables can't be simultaneously measured!

Joint/sequential projective measurements:

$$\widehat{\rho} \overset{\widehat{\Pi}_k}{\Longrightarrow} |\psi_k\rangle \overset{\widehat{\Pi}_n}{\Longrightarrow} |\psi_n\rangle \qquad \mathrm{Tr}[\widehat{\Pi}_n \widehat{\Pi}_k \widehat{\rho}] \ldots ?$$

$$\mathrm{Tr}\left[\widehat{\Pi}_n \left(\widehat{\Pi}_k \widehat{\rho} \widehat{\Pi}_k\right)\right] = \mathrm{Prob}(\psi_n|\psi_k)\mathrm{Prob}(\psi_k|\rho)$$

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Weak measurements

Weak measurements [Aharonov et al., PRL 60 (1988)]: little information is extracted from a single measurement event, but the state does NOT collapse.

Weak value: $\langle \widehat{A} \rangle_w = \frac{\langle \psi_f | \widehat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$

Pre-selected state: $|\psi_i\rangle$

Post-selected state: $|\psi_f\rangle$

Von Neumann coupling between an observable $\widehat{A}$ and a pointer observable $\widehat{P}$: $\widehat{U} = \exp(-ig\widehat{A} \otimes \widehat{P})$

Projective measurement (post-selection on $|\psi_f\rangle$): $\widehat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$

$$|\Psi_{out}\rangle = \widehat{\Pi}_f \widehat{U} |\Psi_{in}\rangle = \widehat{\Pi}_f \widehat{U} |\psi_i\rangle \otimes |\phi_p\rangle$$

$\widehat{X}$ and $\widehat{P}$ canonically conjugated

Weak interaction approximation: $\langle \widehat{X} \rangle = \frac{\langle \Psi_{out} | \widehat{X} | \Psi_{out} \rangle}{\langle \psi_i | \widehat{\Pi}_f | \psi_i \rangle} = g \, \mathrm{Re}[\langle \widehat{A} \rangle_w]$

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Weak measurements

Some interesting properties:

- $\langle \hat{A} \rangle_w$ is a complex number
- $\mathrm{Re}[\langle \hat{A} \rangle_w]$ is unbounded!

$$\langle \hat{A} \rangle_w = \frac{\langle \psi_f | \hat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$$

$$\hat{U} = \exp(-ig\hat{A} \otimes \hat{P})$$

$$\hat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$$

Interpretation of weak values:

- $\mathrm{Re}[\langle \hat{A} \rangle_w]$ conditioned average in the limit of 0 disturbance [Dressel et al., PRL 104 (2010)]
- $\mathrm{Im}[\langle \hat{A} \rangle_w]$ arising from disturbance related to the von Neumann coupling [Dressel and Jordan, PRA 85 (2012)]
- Expectation values as averages of weak values [Aharonov and Botero, PRA 72 (2005)] $\langle A \rangle_i = \sum_f |\langle \psi_i | \psi_f \rangle|^2 \, \langle \hat{A} \rangle_w$
- POVMs can be realized as a sequence of weak values [Oreshkov and Brun, PRL 95 (2005)]

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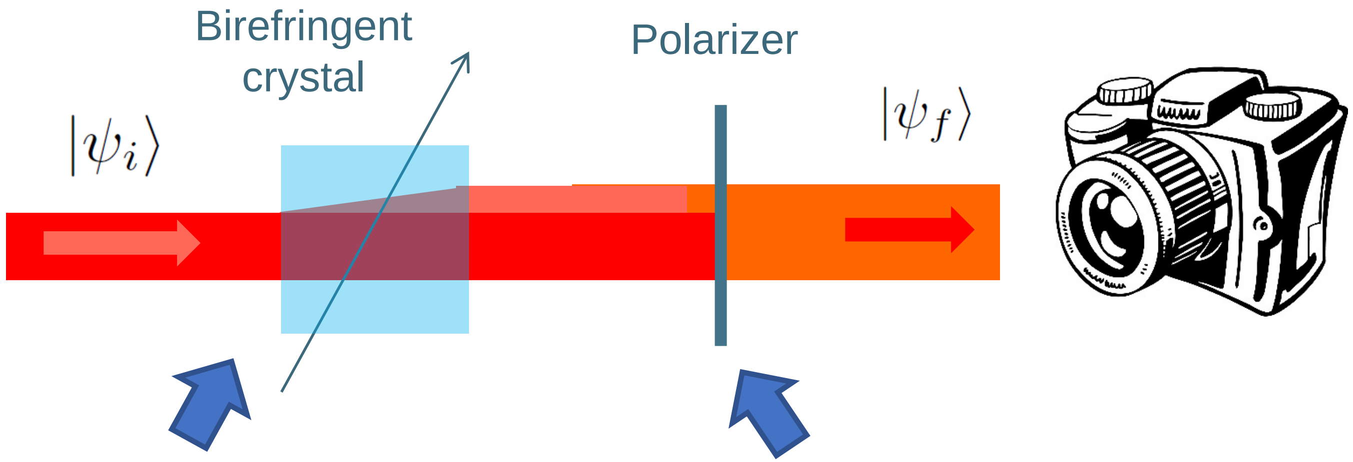
Weak measurements with photons

Initial state:

$$|\Psi_{in}\rangle = |\psi_i\rangle \otimes |\phi_x\rangle$$

$$|\psi_i\rangle = \cos\theta_i |H\rangle + \sin\theta_i |V\rangle$$ polarization component

$$|\phi_x\rangle = \frac{1}{\sqrt{\sigma\sqrt{2\pi}}} \int dx\, e^{-\frac{x^2}{4\sigma^2}} |x\rangle$$ spatial (Gaussian) component



$$\widehat{U} = e^{-ig\widehat{A}\otimes\widehat{\mathbf{P}}}$$

$$\widehat{A} \longrightarrow \widehat{\Pi}_V = |V\rangle\langle V|$$

$$\widehat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$$

We measure the position observable $\widehat{X}$, canonically coniugated to the transverse momentum $\widehat{\mathbf{P}}$

$$\langle\widehat{X}\rangle = g\mathrm{Re}[\langle\widehat{\Pi}_V\rangle_w]$$

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Joint and sequential weak measurements

Weak values *«challenge one of the canonical dicta of QM: that non commuting observables cannot be simultaneously measured»*

«the fact that one hardly disturbs the systems in making WM means that one can in principle measure different variables in succession» [Mitchison, Jozsa and Popescu, PRA 76 (2007)]

Joint weak measurement

Resch et al., PRL 92, 130402 (2004)

$$\widehat{U} = \exp[-i(g_x\widehat{A}\otimes\widehat{P}_x + g_y\widehat{B}\otimes\widehat{P}_y)]$$

$$\langle\widehat{X}\widehat{Y}\rangle = \frac{1}{4}g_x g_y \mathrm{Re}\left[\langle\widehat{A}\widehat{B}+\widehat{B}\widehat{A}\rangle_w + +2\langle\widehat{A}\rangle_w^*\langle\widehat{B}\rangle_w\right]$$

Sequential weak measurement

Mitchinson et al., PRA 76, 062105 (2007)

$$\widehat{U}_y = \exp(-ig_y\widehat{B}\otimes\widehat{P}_y)$$

$$\widehat{U}_x = \exp(-ig_x\widehat{A}\otimes\widehat{P}_x)$$

$$\langle\widehat{X}\widehat{Y}\rangle = \frac{1}{2}g_x g_y \mathrm{Re}\left[\langle\widehat{A}\widehat{B}\rangle_w + \langle\widehat{A}\rangle_w^*\langle\widehat{B}\rangle_w\right]$$

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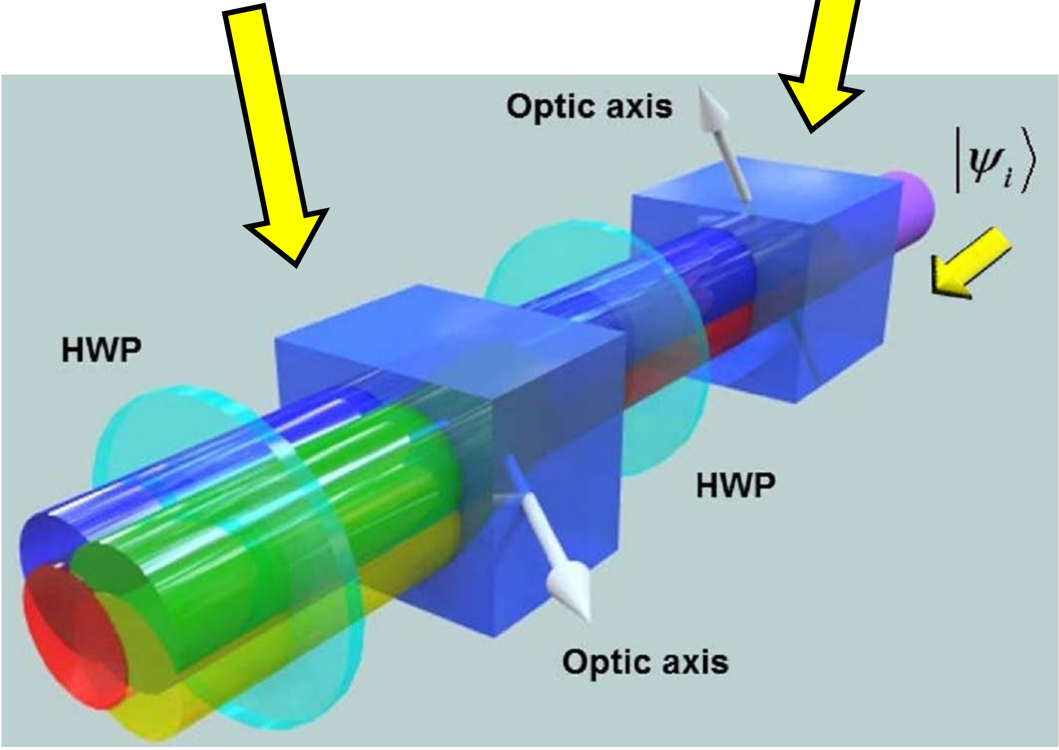
Sequential weak measurements

$$\widehat{A} \longrightarrow \widehat{\Pi}_V = |V\rangle\langle V|$$

$$\widehat{B} \longrightarrow \widehat{\Pi}_\psi = |\psi\rangle\langle\psi|$$

$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

$$\widehat{U}_x = e^{-ig_x\widehat{\Pi}_\psi\otimes\widehat{P}_x} \qquad \widehat{U}_y = e^{-ig_y\widehat{\Pi}_V\otimes\widehat{P}_y}$$



Linearly polarized pre- and post-selection states $|\psi_i\rangle, \ |\psi_f\rangle$

$$\begin{cases} \langle\widehat{X}\rangle = g_x\langle\widehat{\Pi}_\psi\rangle_w \\ \langle\widehat{Y}\rangle = g_y\langle\widehat{\Pi}_V\rangle_w \\ \langle\widehat{X}\widehat{Y}\rangle = \frac{1}{2}g_x g_y\left(\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w + \langle\widehat{\Pi}_\psi\rangle_w\langle\widehat{\Pi}_V\rangle_w\right) \end{cases}$$

Piacentini et al., PRL **117**, 170402 (2016)

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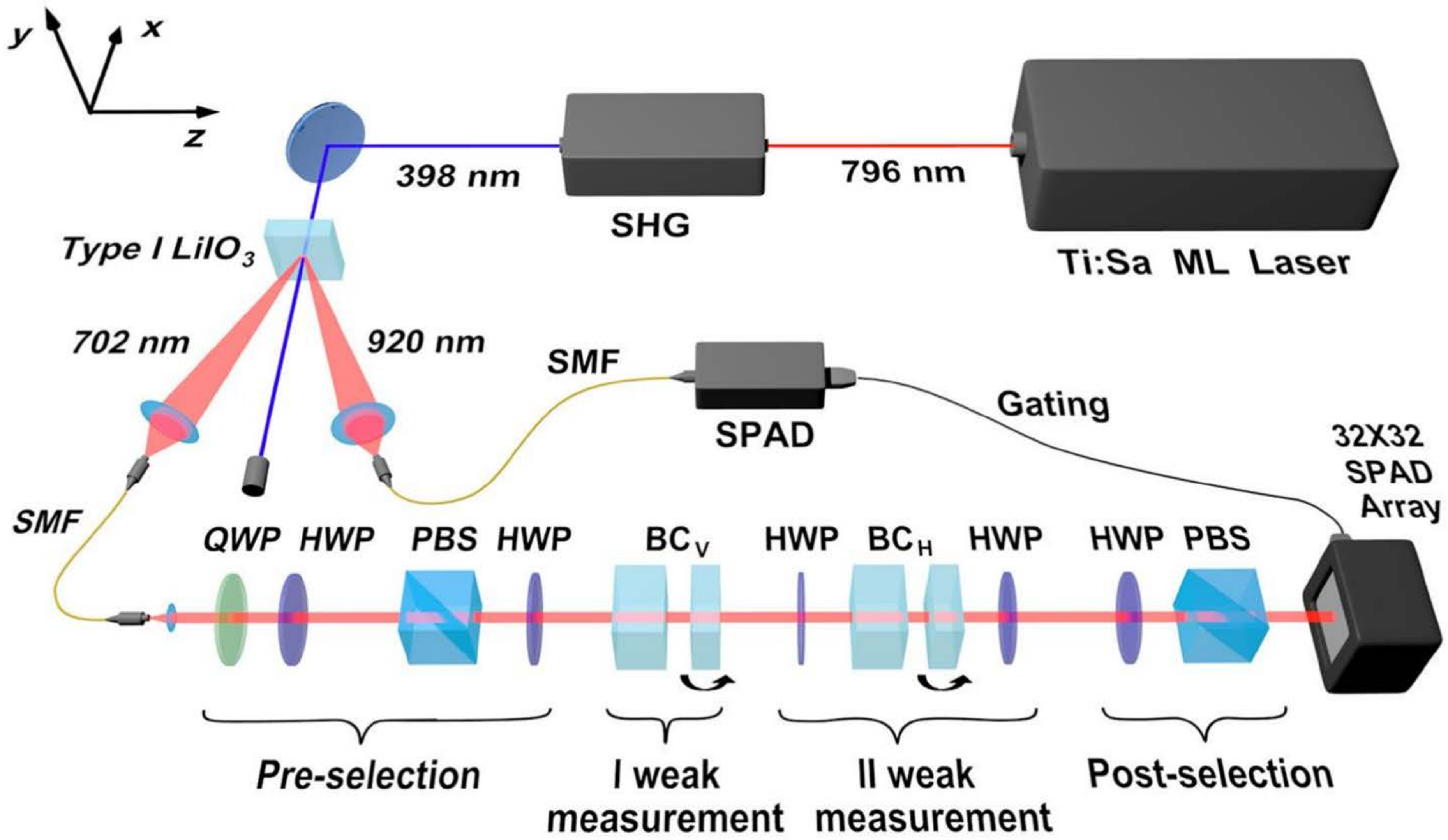
Sequential weak measurements



Piacentini et al., PRL **117**, 170402 (2016)

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Sequential weak measurements

32x32
SPAD+TDC camera

SPADlab

Features

- Multi-modality: photon-counting, 2D imaging, 3D time-of-flight ranging, TCSPC (time-correlated single-photon counting)
- Image dimension: 32x32 (1024) pixels
- In-pixel counter: 6 bit (photon-counting)
- In-pixel TDC: 10 bit (photon-timing)
- Max frame rate: 100,000 fps (burst) and 10,000 fps (continuous)
- Timing resolution: 312 ps – 0.9 ns
- Full scale range: 320 ns – 0.92 μs
- Hardware interface: USB 2.0
- Software interface: Matlab

Fig. 1: SPAD camera for 2D imaging, 3D ranging and TCSPC photon-counting.

POLITECNICO MILANO 1863

F. Villa *et al.*, CMOS imager with 1024 SPADs and TDCs 474 for single-photon timing and 3-D time-of-flight,
IEEE J. Sel. 475 Top. Quantum Electron. 20, 364 (2014).

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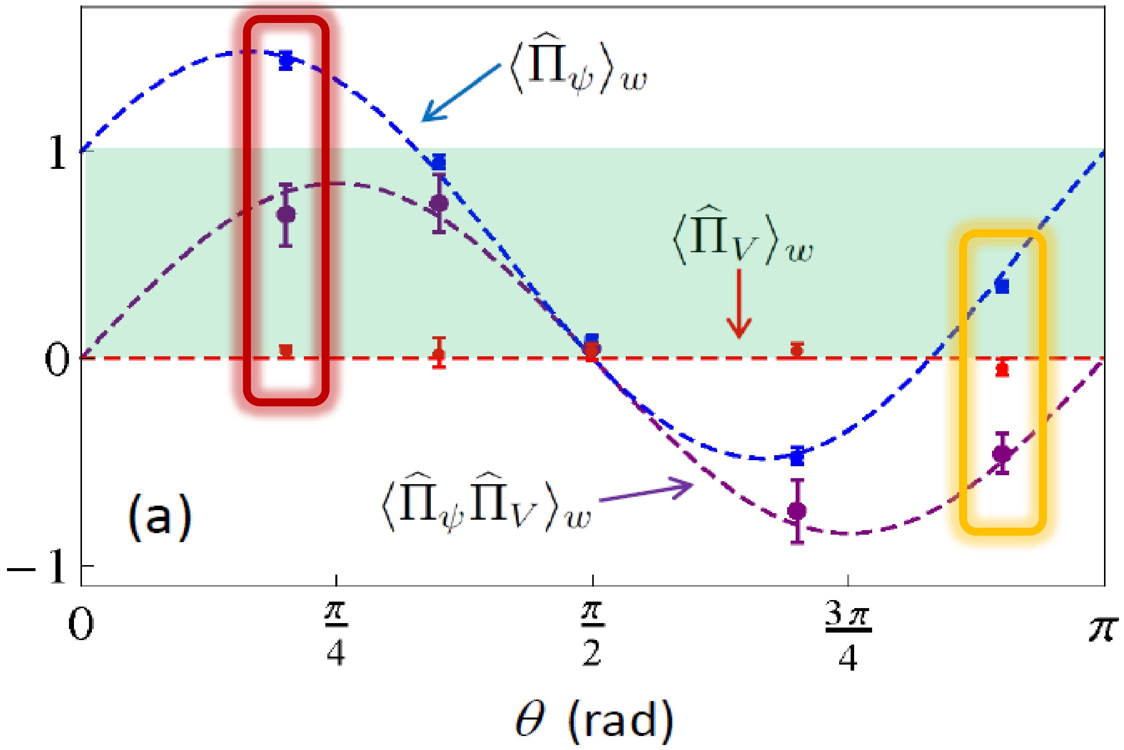
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Sequential weak measurements

Measured weak values (data points) compared with the theoretical predictions (curves)

$$\widehat{\Pi}_V = |V\rangle\langle V| \qquad \widehat{\Pi}_\psi = |\psi\rangle\langle\psi| \qquad (|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle)$$

$$|\psi_i\rangle = 0.588|H\rangle + 0.809|V\rangle \qquad |\psi_f\rangle = |H\rangle$$



$$\langle\widehat{\Pi}_V\rangle_w = 0.03(3)$$
$$\langle\widehat{\Pi}_\psi\rangle_w = 1.44(4)$$
$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = 0.69(15)$$

$$\langle\widehat{\Pi}_V\rangle_w = -0.04(3)$$
$$\langle\widehat{\Pi}_\psi\rangle_w = 0.35(4)$$
$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = -0.46(10)$$

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Piacentini et al., PRL **117**, 170402 (2016)

Sequential weak measurements

Measured weak values (data points) compared with the theoretical predictions (curves)

$$\widehat{\Pi}_V = |V\rangle\langle V| \qquad \widehat{\Pi}_\psi = |\psi\rangle\langle\psi| \qquad (|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle)$$

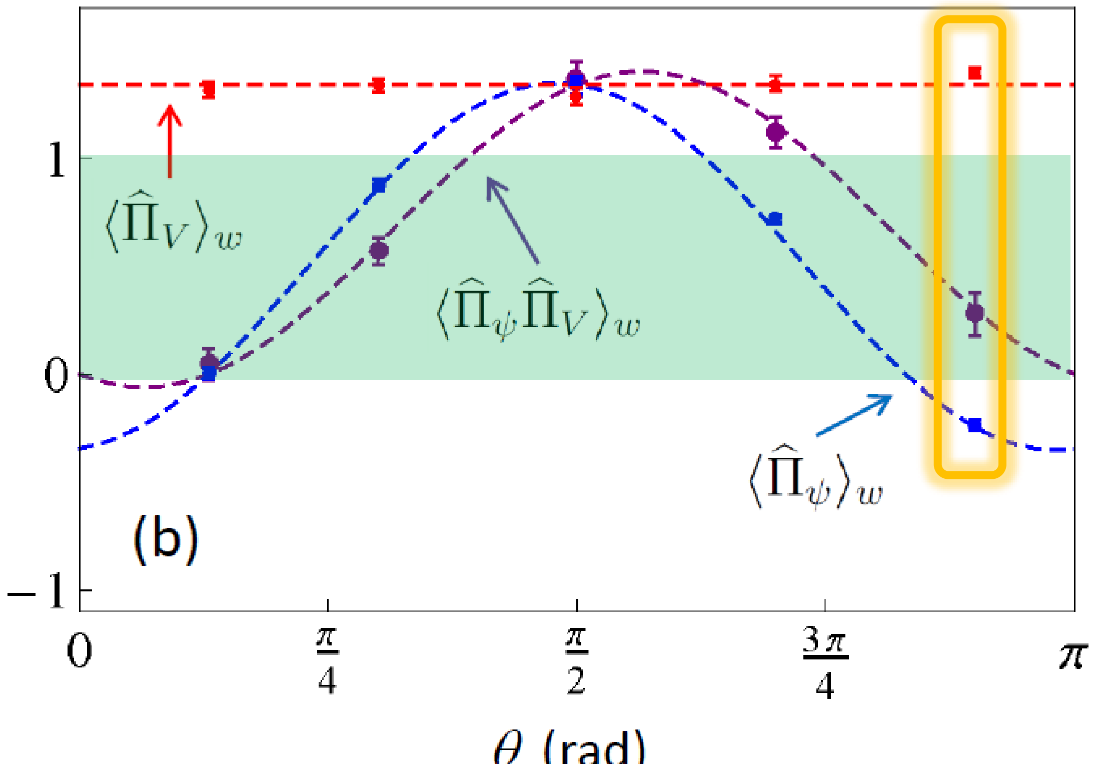
$$|\psi_i\rangle = 0.509|H\rangle + 0.861|V\rangle$$

$$|\psi_f\rangle = -0.397|H\rangle + 0.918|V\rangle$$

$$\langle\widehat{\Pi}_V\rangle_w = 1.40(4)$$

$$\langle\widehat{\Pi}_\psi\rangle_w = -0.24(3)$$

$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = 0.28(10)$$



Piacentini et al., PRL **117**, 170402 (2016)

QUANTUM TECHNOLOGIES

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Genetic Quantum Measurement

Estimating an expectation value by measuring a single photon

«Classical»-Coin-Tossing

Task: Investigation on the coins «fairness» produced by a mint (all coins are identical)

Probability of «head» in a single toss: β

In N trails the probability of having n «head» is: $B(n \mid N)$

The "fairness" of the mint production

Estimation of $\beta = \frac{\langle n \rangle}{N}$

Uncertainty in the Estimation: $u_\beta = \sqrt{\frac{\beta(1-\beta)}{N}}$

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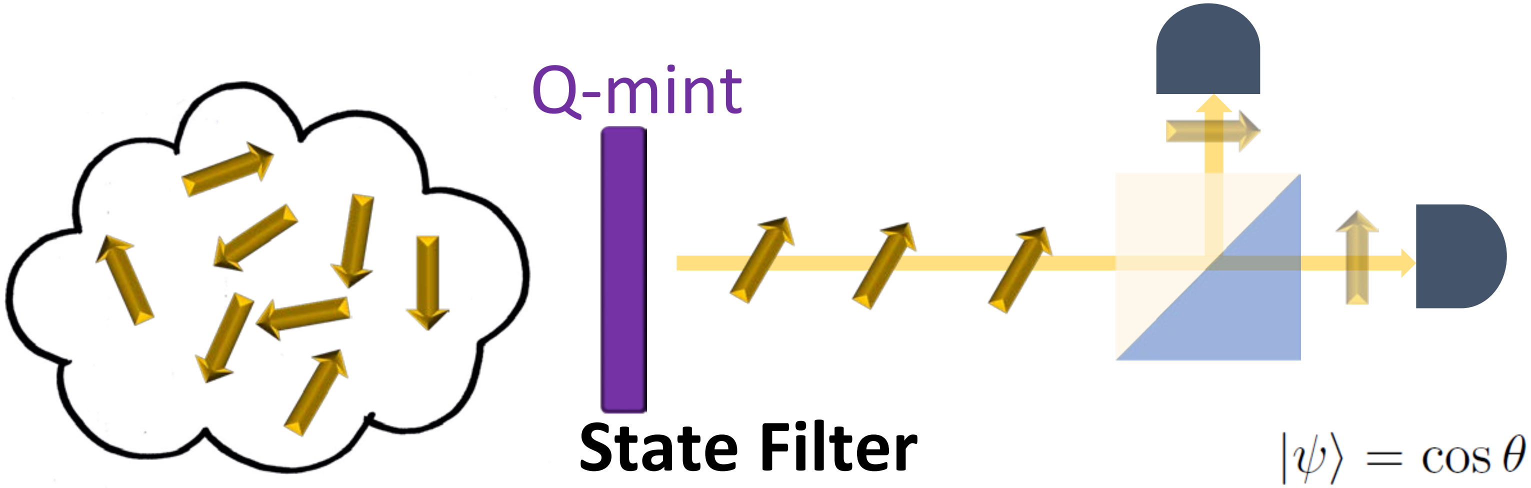
Quantum-Coin-Tossing

Task: Investigation on the Q-coins «fairness» produced by a Q-mint



$\Pi_\psi = |\psi\rangle\langle\psi|$

$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$

The "fairness" of the Q-mint production: $P = |H\rangle\langle H| - |V\rangle\langle V|$

$$u_{\mathrm{PBS}}(P) = \sqrt{\langle P^2\rangle - \langle P\rangle^2} = \frac{|\sin(2\theta)|}{\sqrt{M}}$$

Equivalent to "classical" coin tossing

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Nature Phys. **13**, 1191 (2017)

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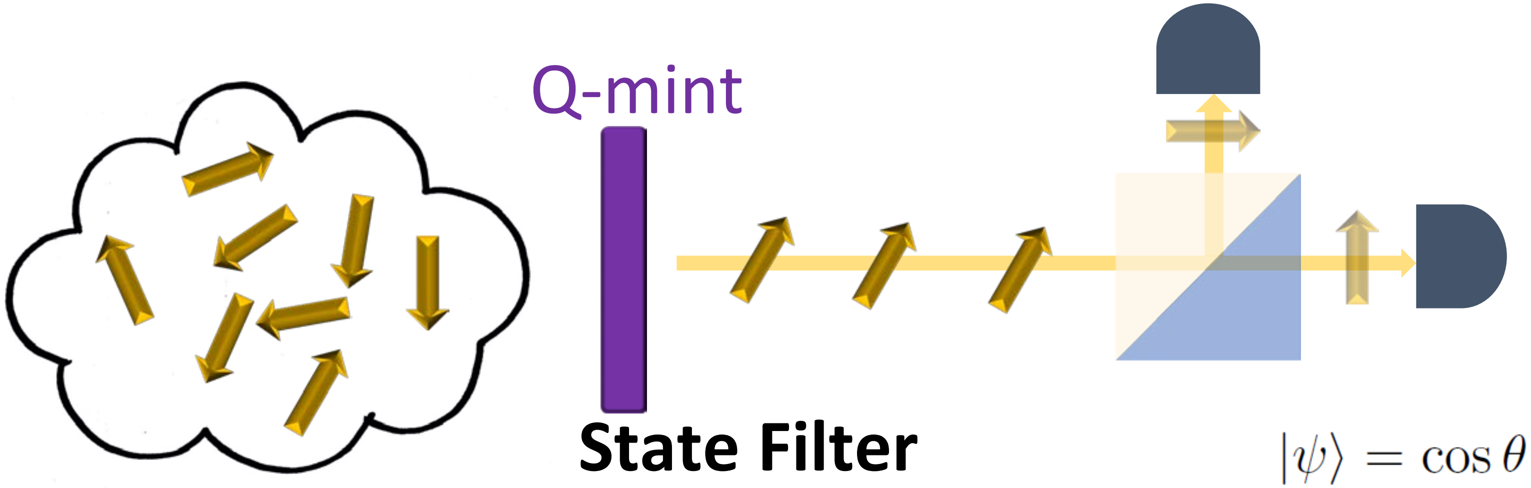
Quantum-Coin-Tossing

Task: Investigation on the Q-coins «fairness» produced by a Q-mint



$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

Quantum "weirdness" may help?

The Quantum-Cramer-Rao Bound: $u_{\text{QCR}}(P) \geq \frac{1}{\sqrt{M\mathcal{J}}}$

Q-Fisher Information: $\mathcal{J} = \frac{1}{|\sin(2\theta)|}$

Equivalent to "classical" coin tossing

Nature Phys. **13**, 1191 (2017)

Genetic Quantum Measurement

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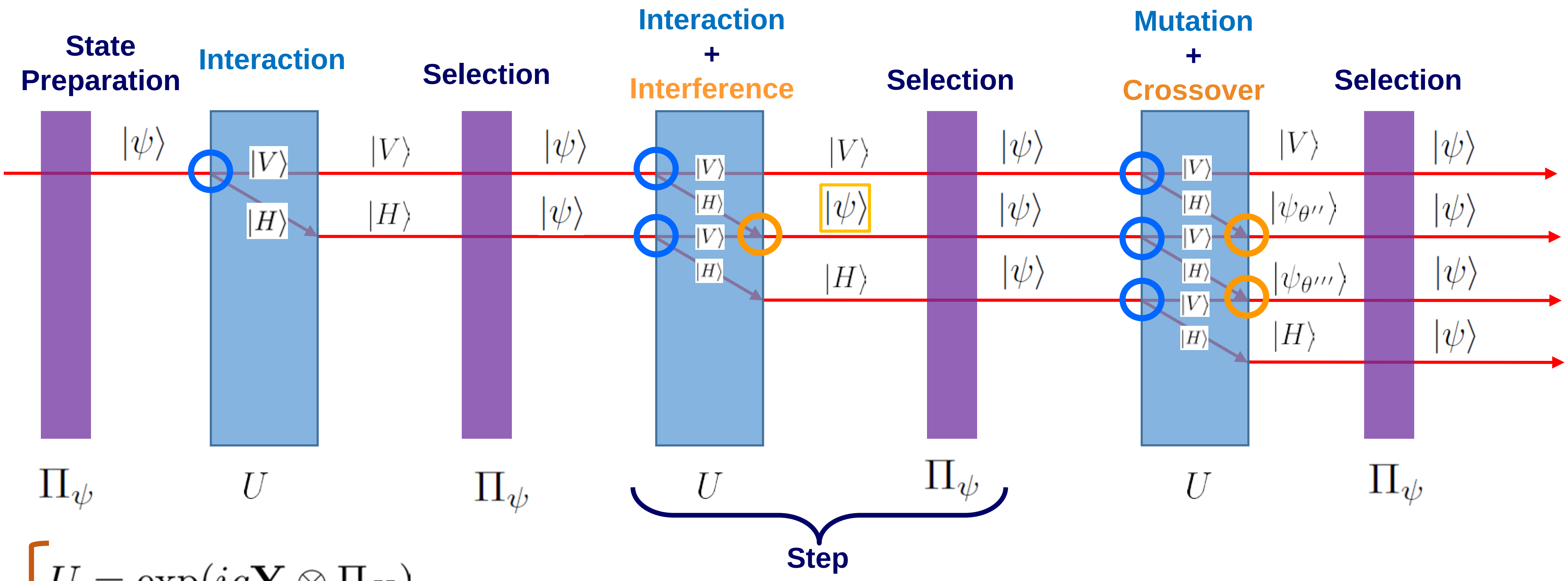
***GQM**: a sequence of **identical steps** consisting of a **interaction-interference** stage and a **selection** measurement (equiv. state preparation)*



$$\begin{cases} U = \exp(ig\mathbf{Y} \otimes \Pi_H) \\ \Pi_\psi = |\psi\rangle\langle\psi| \end{cases}$$

-) Group of **Selective** components (Q-mints) **assumed** identical

-) **Storage cavity** with a single Q-mint (e.g. PRL 103,163602)

-) …

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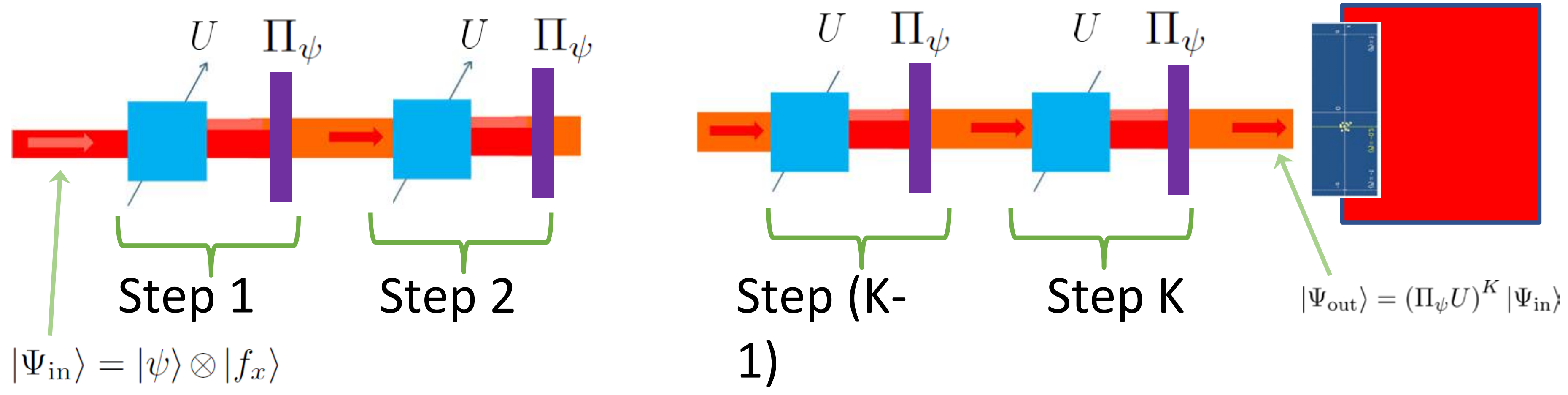
Nature Phys. **13**, 1191 (2017)

Genetic Quantum Measurement

Estimating an expectation value by measuring a single photon



The "fairness" of the Q-mint(s) production can be estimated by measuring the ***expected value*** *of the* ***position*** *of the detected photons:*

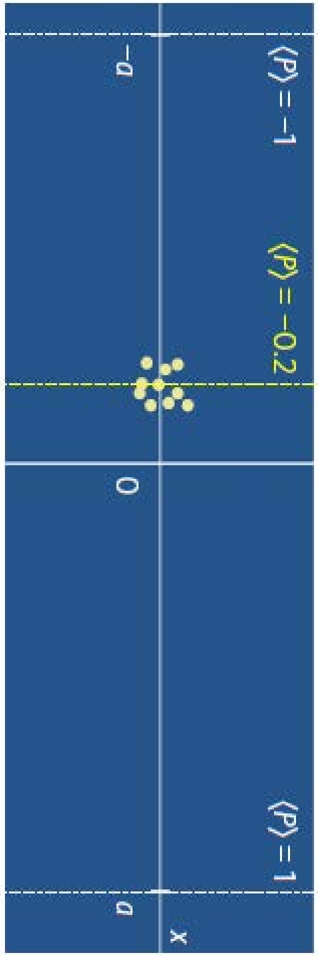
$$\epsilon(x) = \frac{Kg}{2} \langle P \rangle$$

$$P = |H\rangle\langle H| - |V\rangle\langle V|$$

with uncertainty $u(P) = u(x)\,\frac{2}{Kg}$

scaling with the number M of detected photons as: M $^{-1/2}$

$$u(x) = \sqrt{\epsilon(x^2) - \epsilon(x)^2} \qquad \epsilon(x^n) = \int \mathrm{d}x\; x^n F_K(x)$$



Nature Phys. **13**, 1191 (2017)

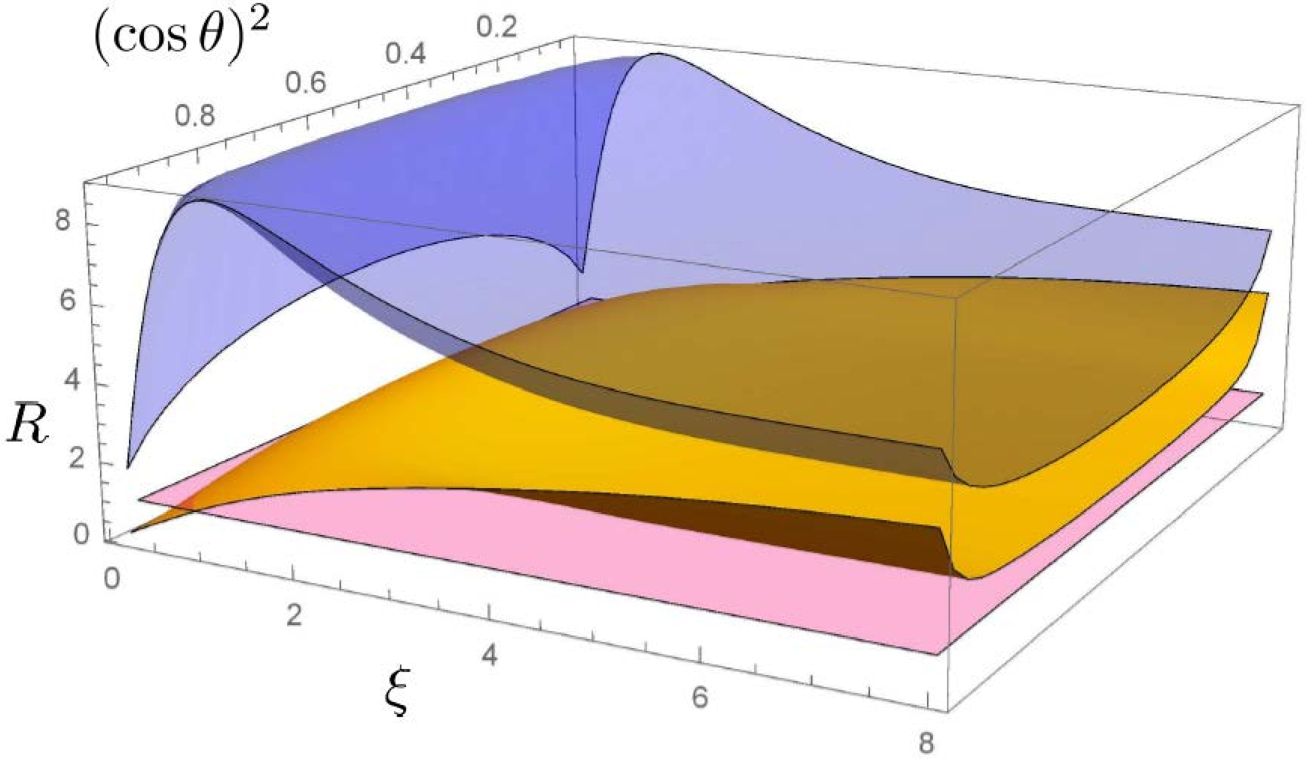
Genetic Quantum Measurement

Estimating an expectation value by measuring a single photon

Comparison between the uncertainty on P with the GQM approach ($u(P)$) and the one given by projective measurement ($u_{\text{PBS}}(P)$) with the **same number of initial photons,** i.e. M detected photons for the GQM; corresponding to $M p_{\text{sur}}(K)^{-1}$

initial photons both in t

$$R = \frac{u_{\text{PBS}}(P)}{u(P)}$$



Yellow K=7

Blue K=100

Pink R=1

$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

$$\xi = g/\sigma$$

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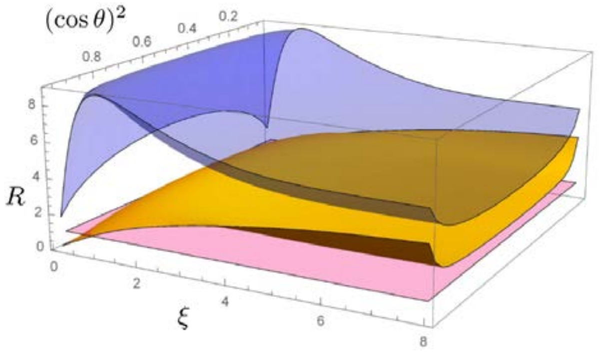
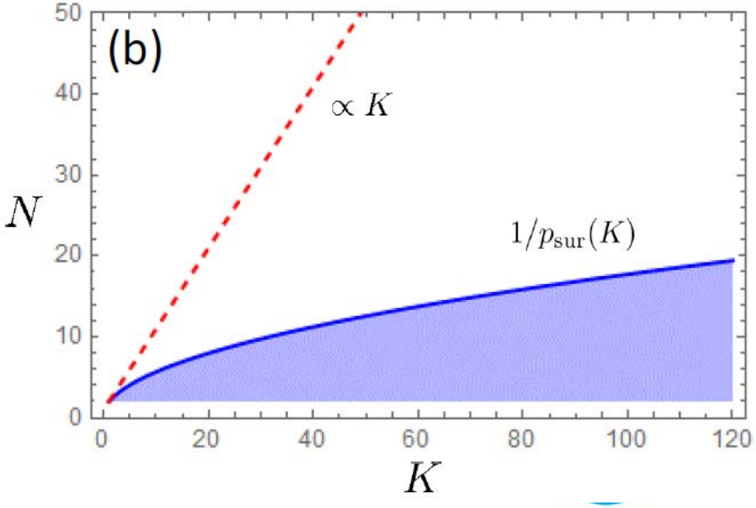
Genetic Quantum Measurement

Estimating an expectation value by measuring a single photon

*Where this **extraordinary** superiority of **GQM** vs projective measurement **saturating QCR** bound comes from?*



1) The uncertainty in GQM scales as $(N\,K)^{-1/2}$, while the number of initial photon used are $N/p_{sur}(K)$



2) Q-CR Bound. Fisher information associated to the POVM associated to the estimation of λ

$$F_X(\lambda) = \int d\nu \frac{[\partial_\lambda \operatorname{tr}(\Pi(x)\rho_\lambda)]^2}{\operatorname{tr}(\Pi(x)\rho_\lambda)}$$

The **optimal estimation** saturates $J(\lambda)$ (QFI) $F_X(\lambda) \leqslant J(\lambda)$

We are **outside** this framework since our POVM depends on the parameter to be estimate Π_λ ; because of the **selection:** Π_ψ

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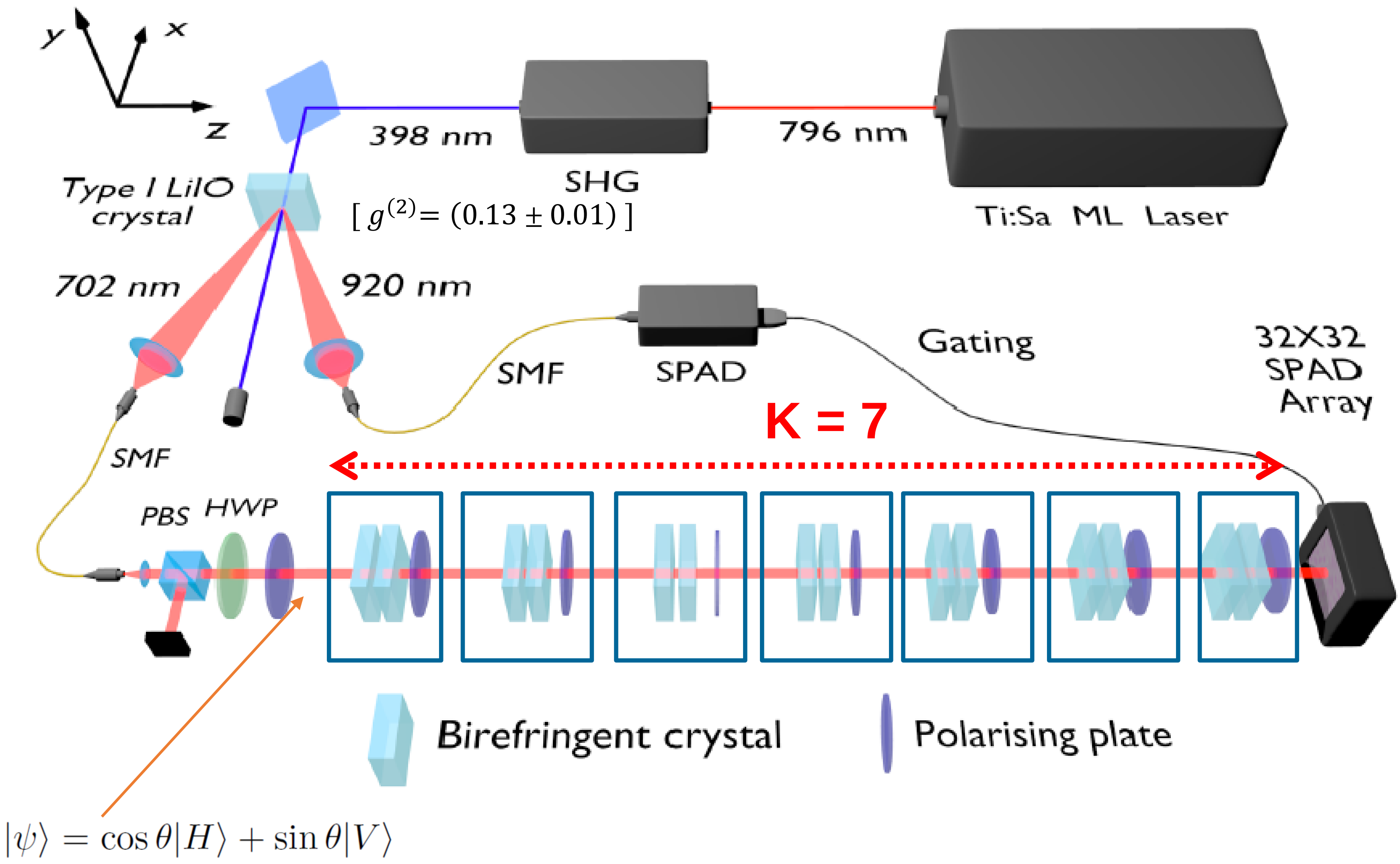

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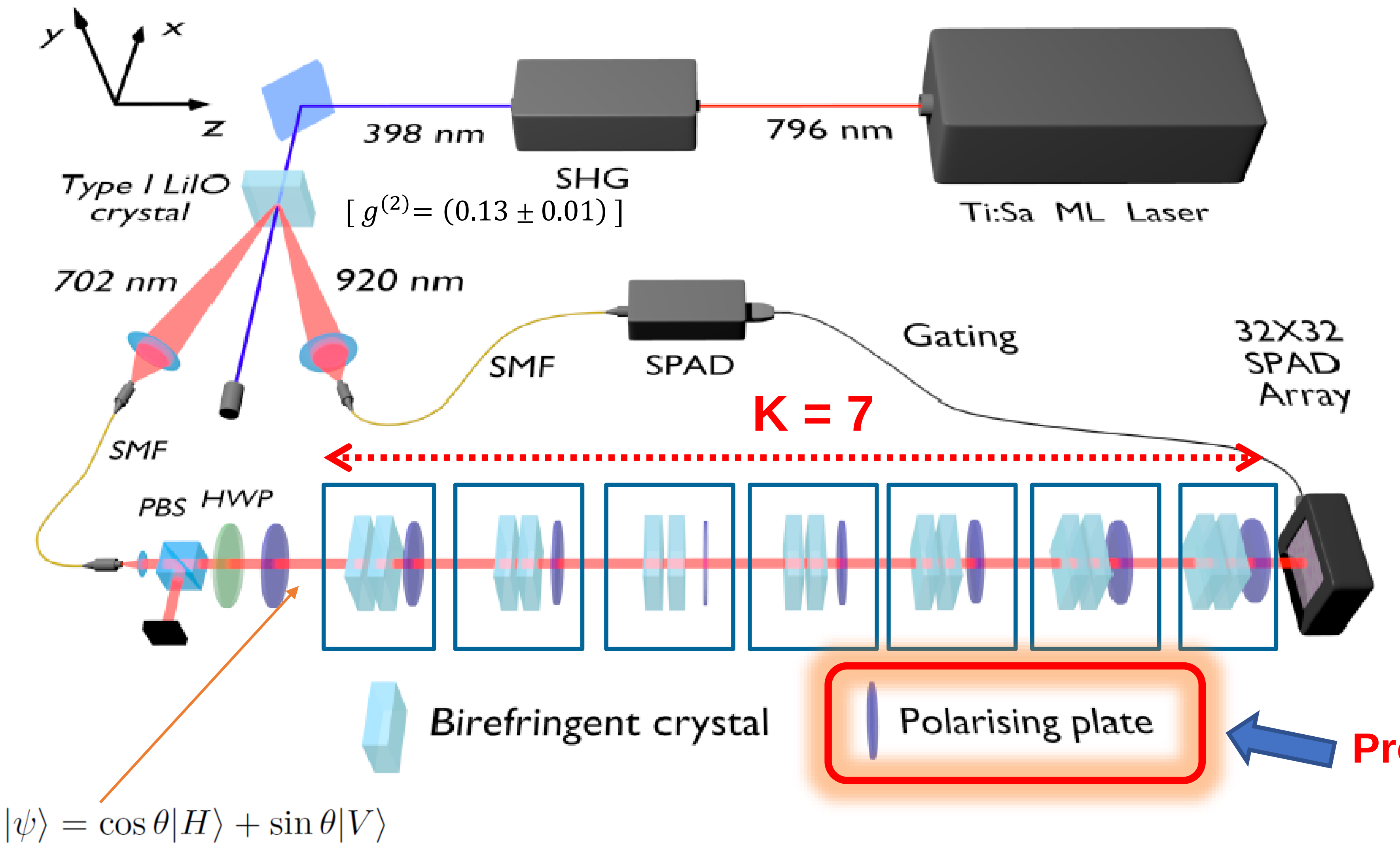

Protection!!!

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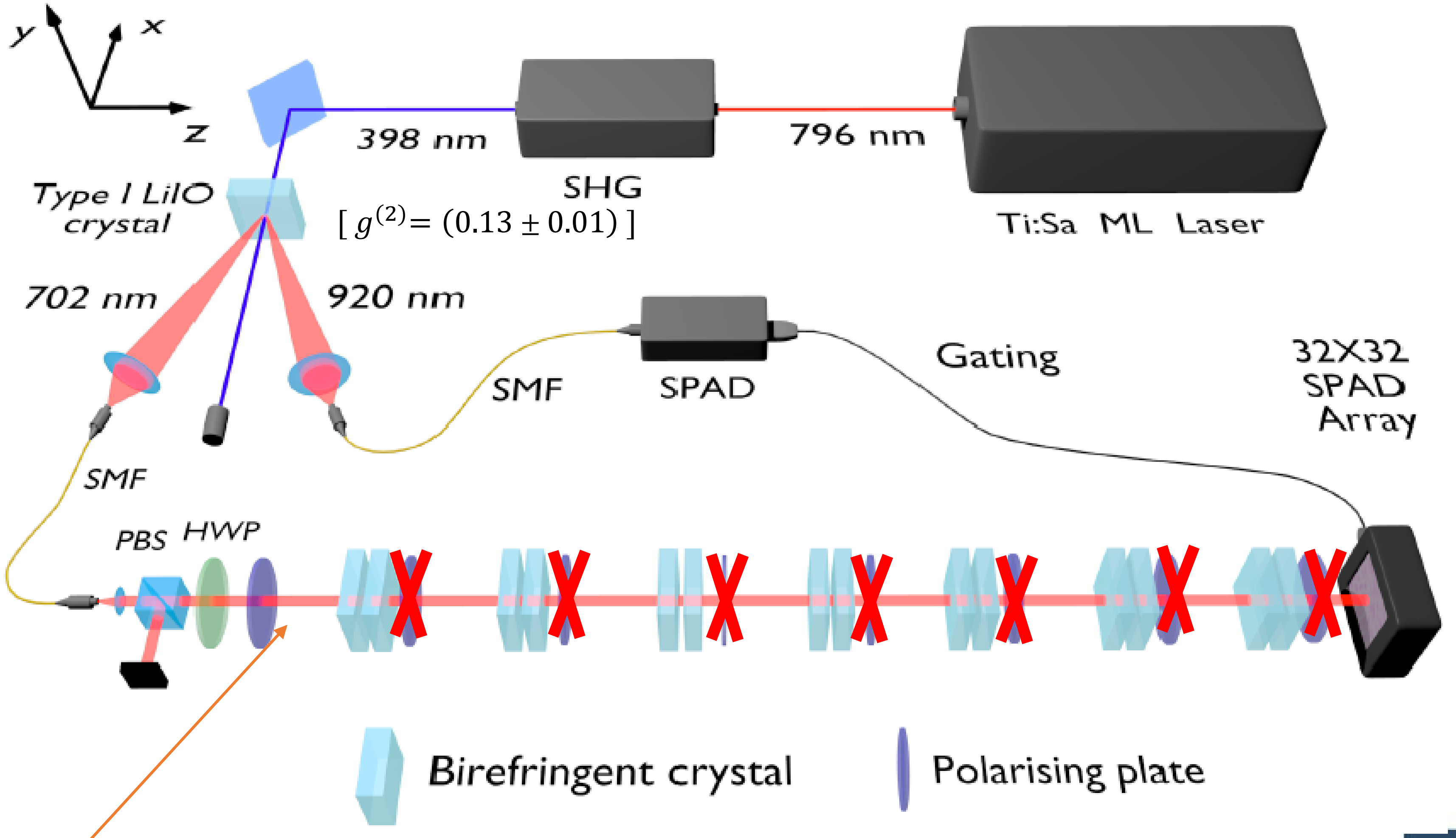

$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

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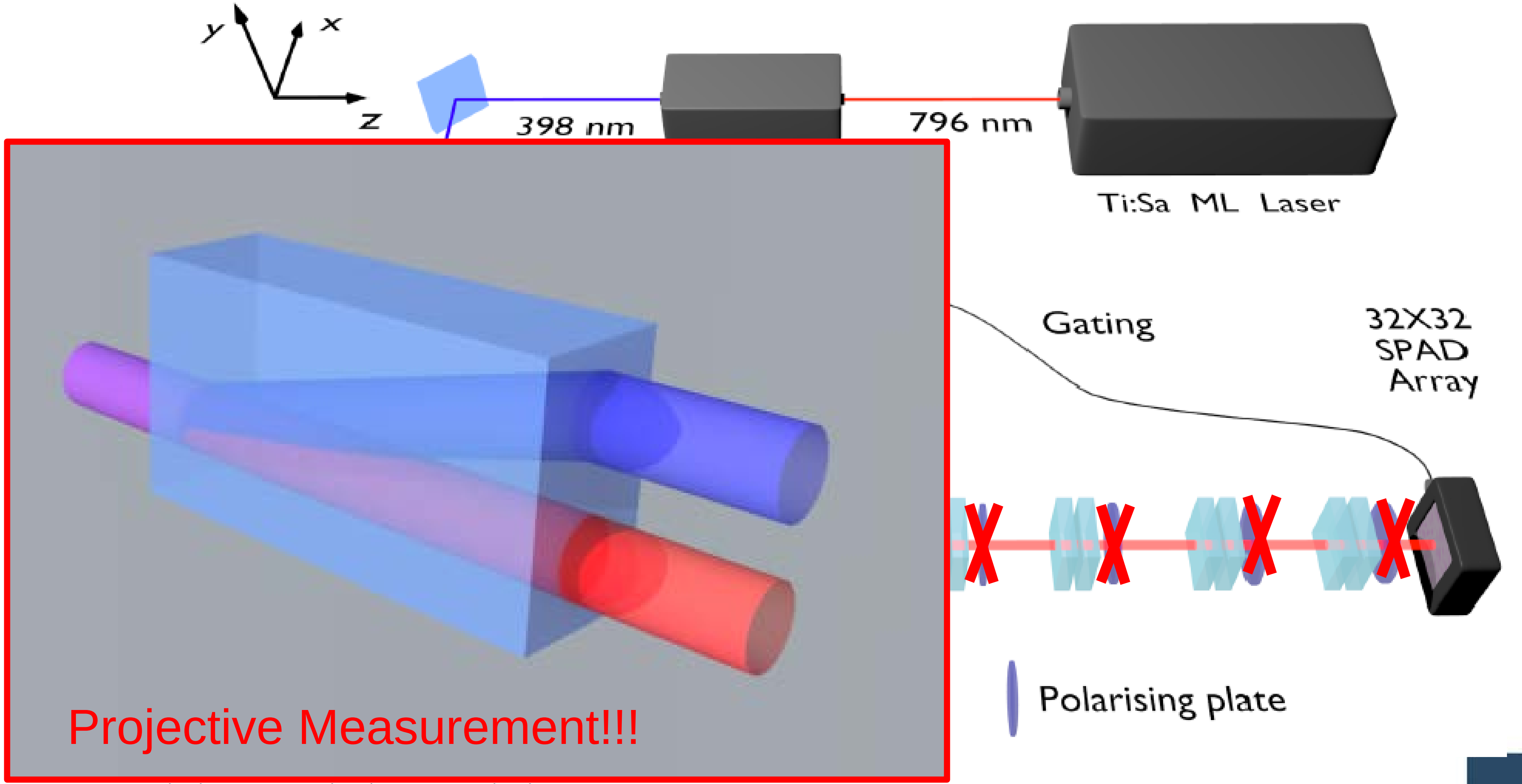

$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

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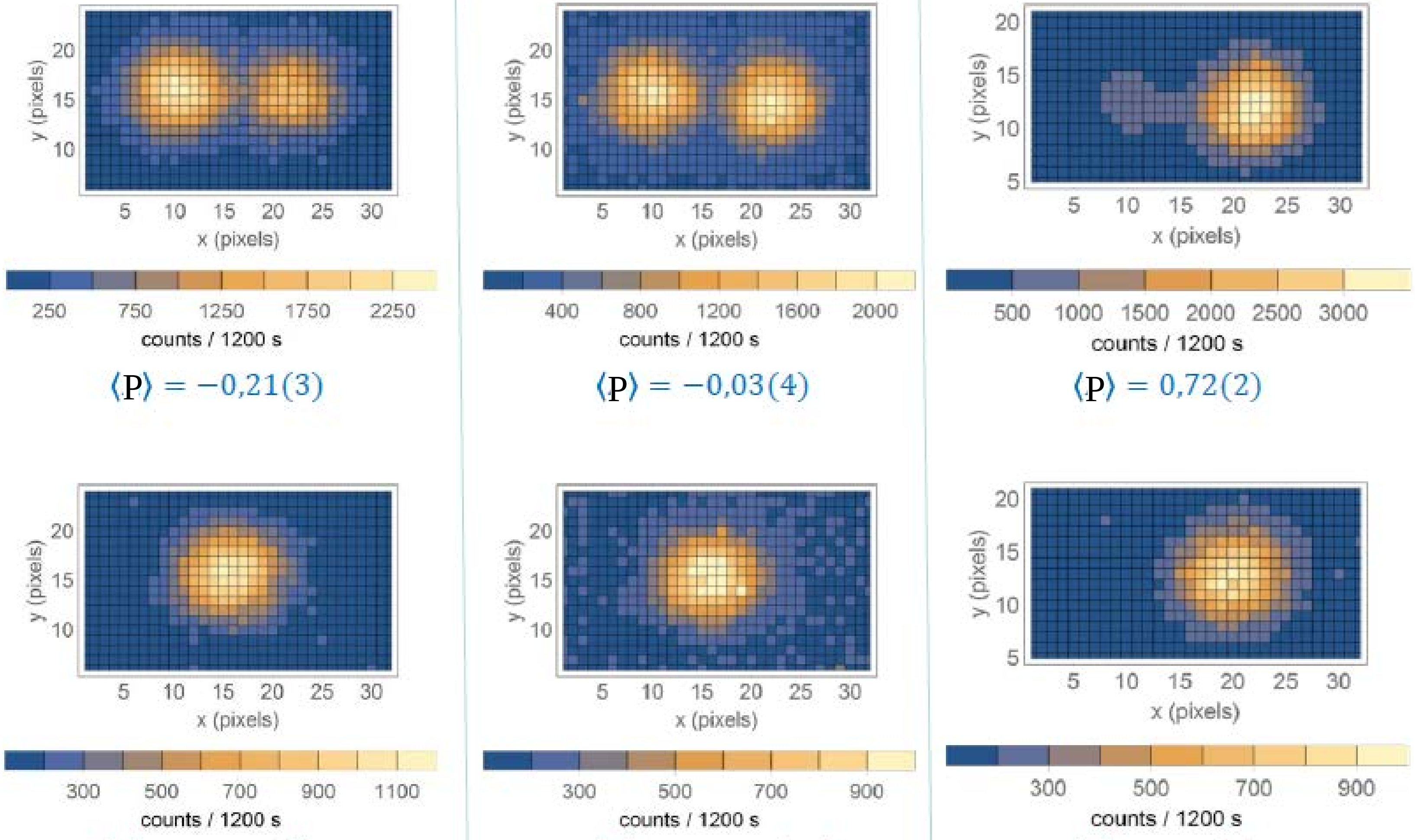
$\left\|\frac{17}{60}\pi\right\rangle = 0,629\,\|H\rangle + 0,777\,\|V\rangle$	$\|+\rangle = \frac{1}{\sqrt{2}}(\|H\rangle + \|V\rangle)$	$\left\|\frac{\pi}{8}\right\rangle = 0.924\,\|H\rangle + 0.383\,\|V\rangle$
$\langle P\rangle_{th} = -0{,}208$	$\langle P\rangle_{th} = 0$	$\langle P\rangle_{th} = 0{,}707$

Project. Meas.

GQM



Project. Meas.: $\langle P\rangle = -0{,}21(3)$ | $\langle P\rangle = -0{,}03(4)$ | $\langle P\rangle = 0{,}72(2)$

GQM: $\langle P\rangle = -0{,}19(2)$ | $\langle P\rangle = 0{,}0012(14)$ | $\langle P\rangle = 0{,}72(2)$

NATURE PHYSICS DOI: 10.1038/NPHYS4223

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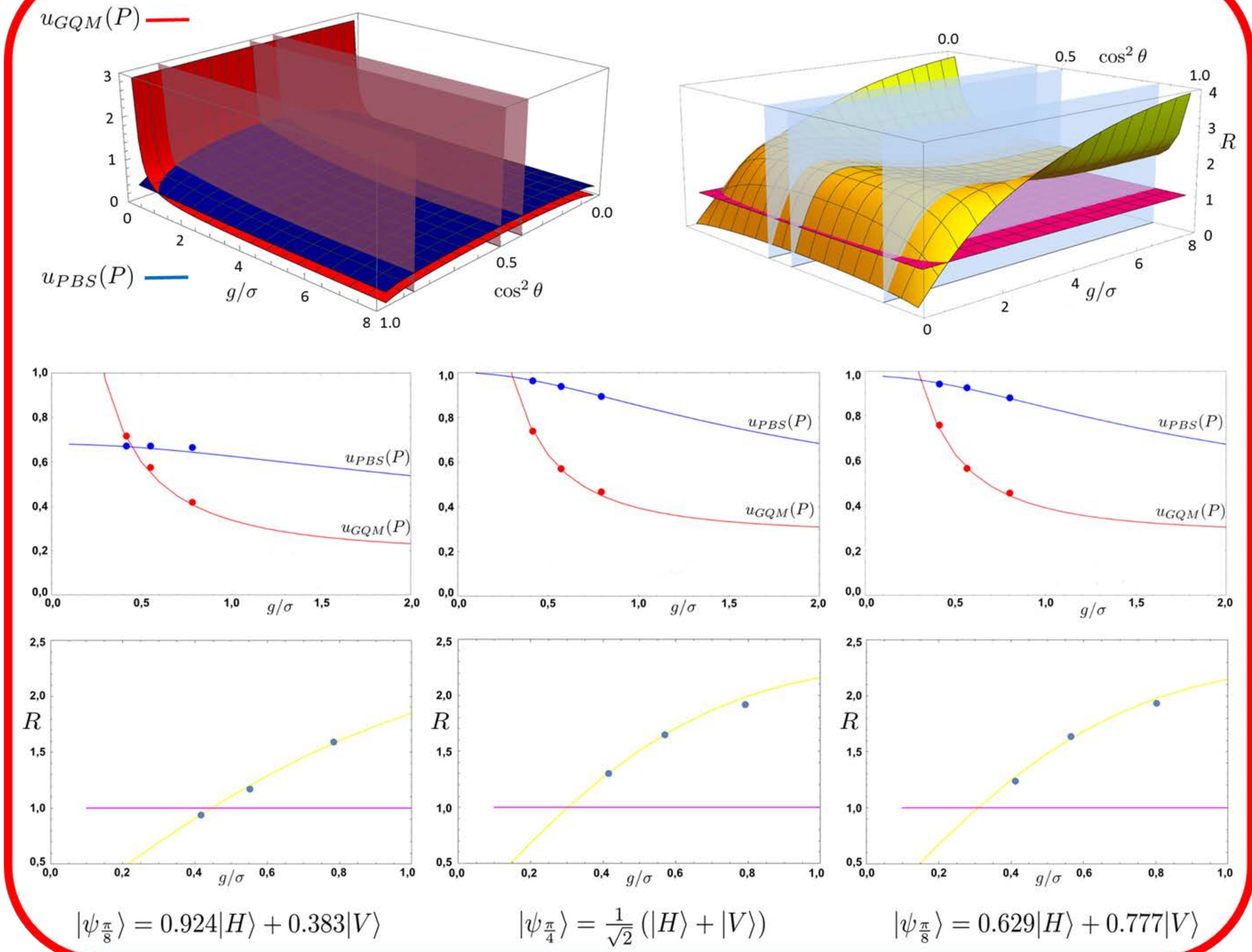

NATURE PHYSICS DOI: 10.1038/NPHYS4223

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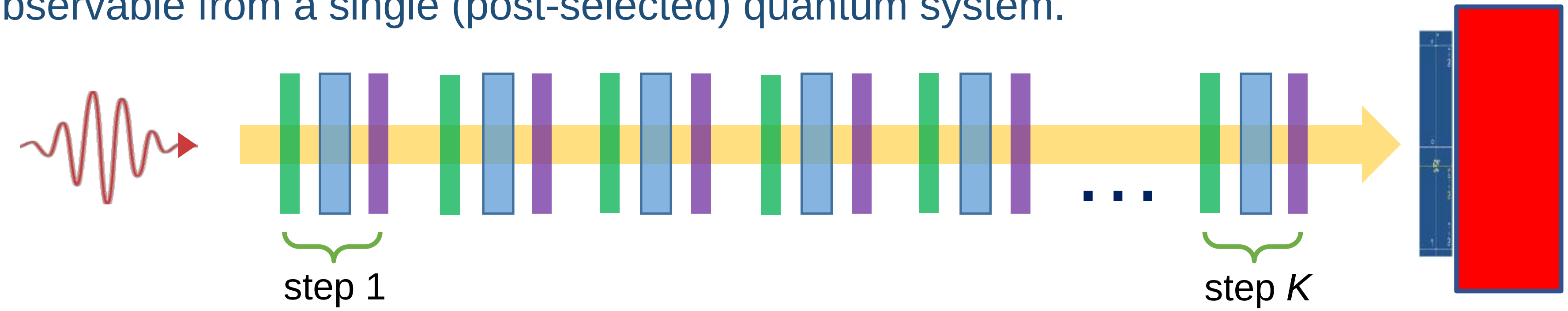
Nature Phys. **13**, 1191 (2017)

Robust Weak Measurement

Weak values with a single measurement event

Robust Weak Measurement: iterative measurement protocol able to extract the weak value of an observable from a single (post-selected) quantum system.



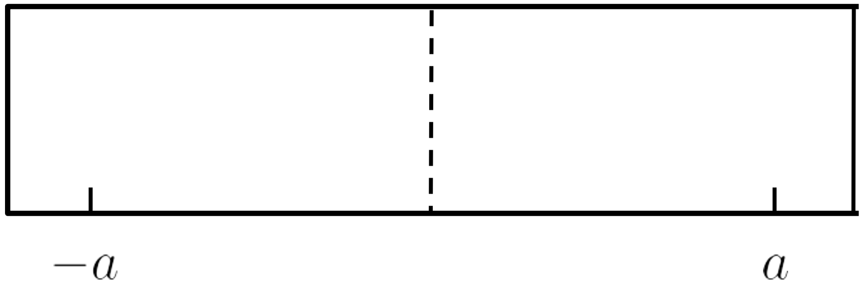
Pre-selection $|\psi_i\rangle$

Weak interaction

Post-selection $|\psi_f\rangle$

Light: Sci. & Appl. **10**, 106 (2021)

Anomalous weak value:



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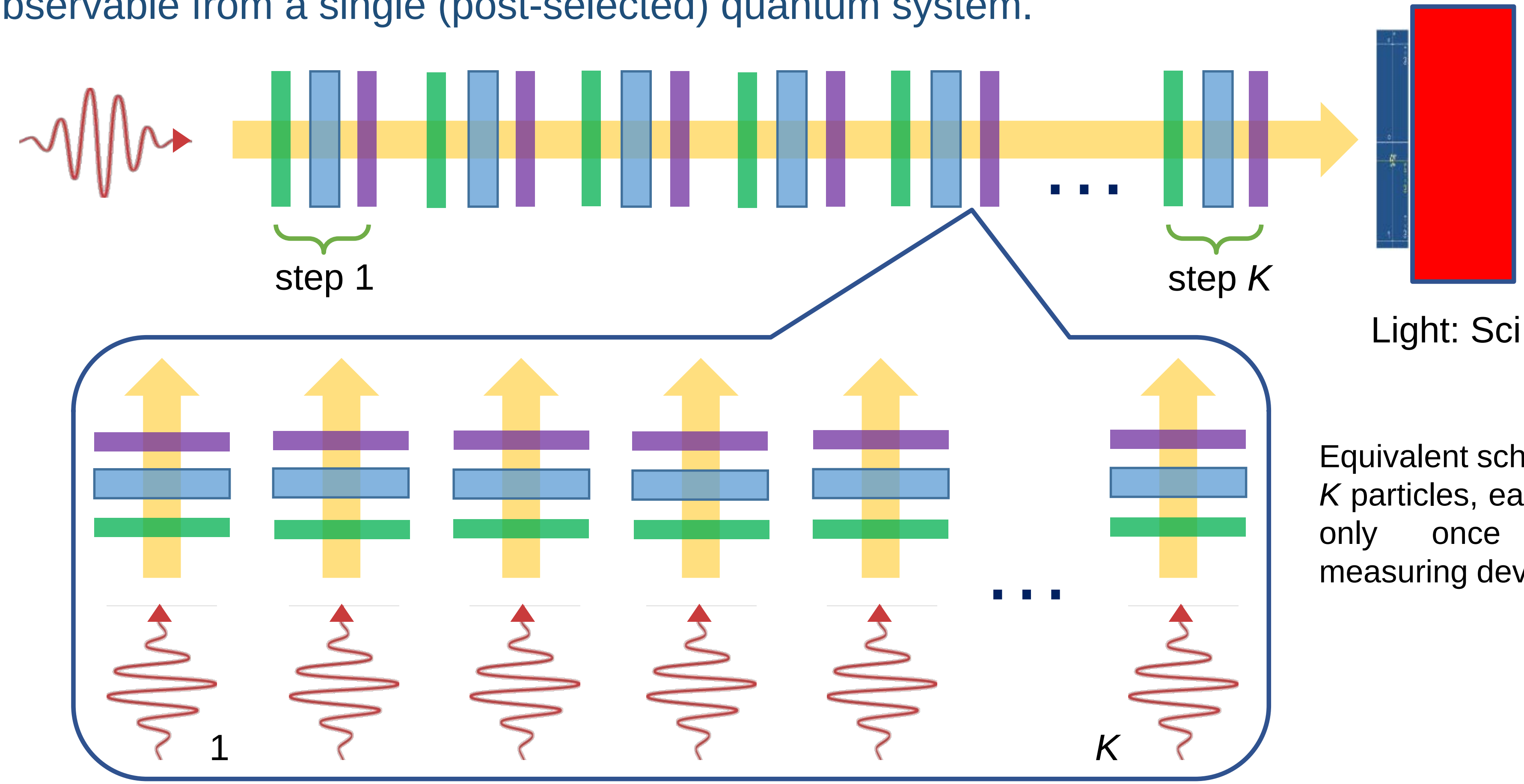
Light: S&A **10**, 106 (2021)

Robust Weak Measurement

Weak values with a single measurement event

Robust Weak Measurement: iterative measurement protocol able to extract the weak value of an observable from a single (post-selected) quantum system.



Light: Sci. & Appl. **10**, 106 (2021)

Equivalent scheme:
K particles, each coupled only once to the measuring device

Measured observable: $\sigma_3^{\Sigma} \equiv \sum_{k=1}^{K} \sigma_3^{(k)} \qquad \sigma_3^{(k)} = |H\rangle\langle H| - |V\rangle\langle V|$

Light: S&A **10**, 106 (2021)

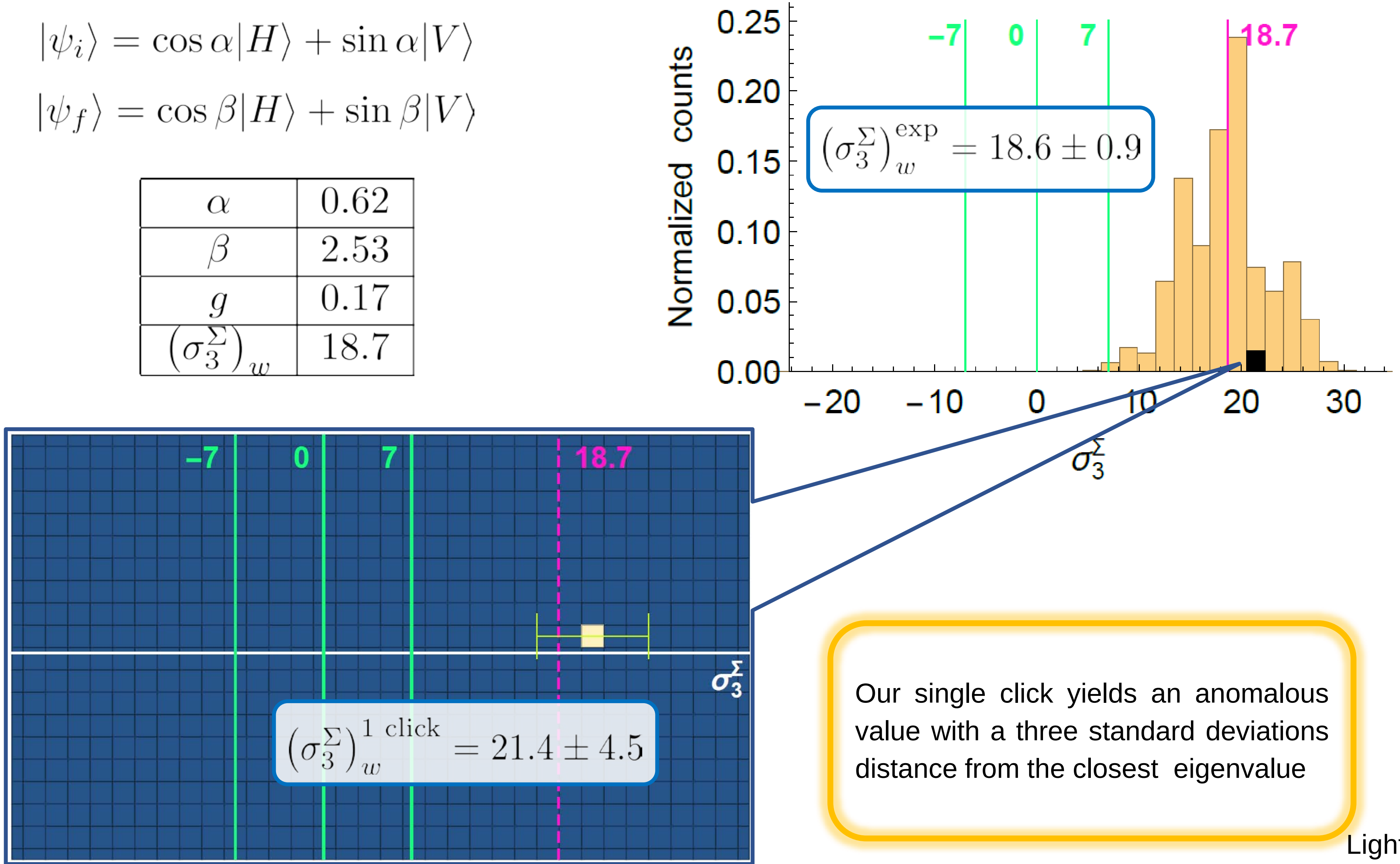
Robust Weak Measurement

Weak values with a single measurement event

$$|\psi_i\rangle = \cos\alpha|H\rangle + \sin\alpha|V\rangle$$

$$|\psi_f\rangle = \cos\beta|H\rangle + \sin\beta|V\rangle$$

α	0.62
β	2.53
g	0.17
$(\sigma_3^\Sigma)_w$	18.7



Our single click yields an anomalous value with a three standard deviations distance from the closest eigenvalue

… and this is not all …

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… but it is enough for today …

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Thanks for your attention!

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D Calonico	E Monticone	E Taralli
SA Castelletto	E Moreva	P Traina
A Cavanna	A Mura	S Virzì
L Ciavarella	C Novero	G Zanelli
C Clivati	G Petrini	M Zucco
Ivo Pietro Degiovanni	F Piacentini	
S Donadello	C Portesi	
M Genovese	ST Pradyumna	
M Gramegna	M Rajteri	
L Knoll	ML Rastello	
F Levi	E Rebufello	
MP Levi	I Ruo Berchera	
L Lolli	N Samantaray	

Thanks for your attention!

Collaborators

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