QUARTET Kickoff meeting
INRIM knowhow related to the objectives of QUARTET

INRIM
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Outline

• The Quantum Optics Group in INRIM/Main Research Lines

• Description of some experiments/technologies

• INRIM role in the project
8+2 Permanent Staff:
- Marco Genovese (Leader)
- Alessio Avella
- Ivo P. Degiovanni
- Marco Gramegna
- Fabrizio Piacentini
- Ivano Ruo-Berchera
- Paolo Traina
- Ekaterina Moreva
- + G. Brida and A. Meda

2 Post Doc:
- Ettore Bernardi
- Elena Losero

4 PhD students:
- Giulia Petrini
- Giuseppe Ortolano
- Enrico Rebufello
- Salvatore Virzi

Several undergraduate students

Recent sponsors:
- EU Projects
- Italian Minister of Research
- Bank Foundation: Compagnia di San Paolo.
- John Templeton Foundation
- NATO

http://quantumoptics.inrim.it/
QUANTUM OPTICS GROUP at INRIM

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QUARTET
Quantum Pattern Recognition

36 months Postdoc open position in TORINO

http://quantumoptics.inrim.it/
Quantum Imaging and sensing
- Sub shot noise imaging/target detection
- Superresolution
- Ghost Imaging
- Interferometry

NV centers in diamond
- Optically detected magnetic resonance (ODMR)
- Magnetic/electric/temp/ Bio sensing

Quantum measurements
- Weak value
- Protective/genetic measurements

Metrology for quantum technology
- Single photon sources: telecom (heralded) and visible
- Traceable characterization component for QKD (and QKD standardization)
## Experimental Loss Estimation towards the UQL

### Ultimate quantum limit (UQL):

\[
\Delta \alpha_{\text{UQL}} = \sqrt{\frac{\alpha (1 - \alpha)}{\langle n \rangle}}
\]


### For coherent state:

\[
\Delta \alpha_{\text{Coh}} = \sqrt{\frac{1 - \alpha}{\langle n \rangle}}
\]

### Fock and Twin Beam states reach the UQL

\[
\Delta \alpha_{\text{TWB}} = \Delta \alpha_{\text{UQL}}
\]

\[
\Delta \alpha_{\text{Fock}} = \Delta \alpha_{\text{UQL}}
\]

for \( \langle n \rangle \geq 1 \)


[Monras, A. & Illuminati, PRA83(1), 012315 (2011)]

Quantum advantage, in particular for small absorption\ high transmission \( (\alpha \ll 1) \)!
Experimental Loss Estimation towards the UQL

Twin-beam from SPDC and lossless detection ($\gamma = 1, \sigma = 0$):

$$|TWB\rangle_{PR} = \langle n \rangle + 1 \left[ \left( \sum_{n=0}^{\infty} \left( \frac{\langle n \rangle}{\langle n \rangle + 1} \right)^{n/2} \langle n \rangle \right) \langle n \rangle \right]$$

Noise Reduction Factor

$$\sigma_\gamma = \frac{\Delta^2 (N_R - \gamma N_P)}{\langle N_R + \gamma N_P \rangle}$$

$\sigma_\gamma = 1 < 1$ \nonclassical correlation

Estimation strategy:

$$S_\alpha = 1 - \gamma \frac{N_P}{N_R}$$

$$\gamma = \frac{\langle N_R \rangle}{\langle N_P \rangle}$$

Uncertainty:

$$\Delta^2 S_\alpha \approx \frac{U_{uql}^2}{\langle N_P \rangle} + \frac{(1 - \alpha)^2 2\sigma_\gamma}{\gamma}$$

Twin beam (two mode squeezing) reaches the UQL with a simple estimation strategy based on intensity measurement.
Twin-beam with losses ($\gamma = 1, \sigma = 1 - \eta$):

$$\Delta^2 S_{\alpha} \simeq U_{wq1}^2 + \frac{(1 - \alpha)^2}{\langle N_P \rangle} 2\sigma \gamma$$

Estimation strategy:

$$S_\alpha = 1 - \gamma \frac{N'_P}{N_R}$$

$$\gamma = \frac{\langle N_R \rangle}{\langle N_P \rangle}$$

Uncertainty:

$$\Delta^2 S_{\alpha,\eta} \simeq U_{wq1}^2 + 2\frac{(1 - \alpha)^2}{\langle N_P \rangle} (1 - \eta)$$

E. Losero et al. Scientific Reports, 8, 7431 (2018)

Optimized Estimation strategy:

$$S'_\alpha = 1 - \frac{N'_P - k\Delta N_R + \delta E}{\langle N_P \rangle}$$

$$k_{opt} = f_1(\eta_P, \eta_R, F_P, F_R)$$

$$\delta E = f_2(\eta_P, \eta_R, F_P, F_R)$$

It requires detector and source characterization:

$$\Delta^2 S_{\alpha,\eta}^{(TWB)} \simeq U_{wq1}^2 + \frac{(1 - \alpha)^2}{\langle N_P \rangle} (1 - \eta^2)$$

E. Losero et al. Scientific Reports, 8, 7431 (2018)

The optimized estimator performs better, especially for inefficient detection.
For high efficiency \( S_\alpha \) and \( S'_\alpha \) perform very similarly.

\[ \eta_R = \eta_P = 0.77 \]

TWB advantage over Coh/Poissonian > 1.5

TWB advantage over Class. Corr. > 2

\[ \eta_R = 0.77 \]

\[ \eta_R = 0.43 \]

\( UQL \)

\( \alpha \)

\( \Delta_\alpha \)

\( \Delta S^{(\text{unc})} \)

\( \Delta S'_\alpha \)

\( \Delta S_\alpha \)

\( U_{\text{coh}} \)

\( \Delta S^{(\text{bBBB})} \)

\( U_{\text{uql}} \)
For high efficiency $S_\alpha$ and $S'_\alpha$ perform very similarly

\[ \eta_P = 0.76, \eta_R = 0.43 \]

For low efficiency the optimized $S'_\alpha$ is definitely better

Sub-Shot Noise Wide Field Imaging (SSNWFI)

Spatially distributed sample $\alpha(\vec{x})$ is detected by large number of pixels (thousands or more) collecting light in parallel.

Thousands of spatial modes with non-classical features must be generated and detected efficiently by the “pixels” (Detection modes should fit the spatial mode structure of the source).

The optimized estimator gives significant advantage for low $\eta_{coll}$, at the end improving the resolution at the same SNR.

Noise Reduction vs Resolution

Uncertainty in the propagation direction of correlated photons ($A_{coh}$) determines a lower bound to the spatial resolution or better the spatial scale at which the noise reduction can be done efficiently

$$\sigma = \frac{Var(N_i - N_s)}{\langle N_i + N_s \rangle} = 1 - \eta \cdot \eta_{coll}(L/2r)$$

$L = \text{size of the pixel}$

$2r = \text{coherence length}$

$$\sigma = \begin{cases} 
1 & \text{if } L/2r > \eta_{coll} \\
\eta_{coll} & \text{otherwise}
\end{cases}$$
300 shots average

- 8000 pixels wide field
- 5 \( \mu \text{m} \) resolution

[Samantaray N, Ruo-Berchera I, Meda A, Genovese M, Light: Science and Appl. 6 e17005(2017)]

In practice, 3 times better resolution with the optimized estimator (paper in preparation)
COH (Poiss)  Class. Corr.  TWB  TWB (opt)

300 shots average

• 8000 pixels wide field
• 5 μm resolution

[Samantaray N, Ruo-Berchera I, Meda A, Genovese M, Light: Science and Appl. 6 e17005(2017)]
Detection of a partially reflecting target which is immersed in a dominant 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

Further Assumptions in Lopaeva et al, PRL 110, 153603 (2013):
- only photon number/intensity detection is allowed
- no a priori information on the noise background → the first order momenta of the distribution (mean values $\langle N_1 \rangle$, $\langle N_2 \rangle$) are not informative
**Setup:** spatially multimode Twin Beams, measured by means of a CCD camera in a linear regime

$N \sim 10^4$ photons per pixel per shot

$M >> 1$ temporal modes per pixel per shot

**Strategy:** measuring the covariance

$$\langle \delta N_1 \delta N_2 \rangle$$

between the joint photon numbers distribution

**Classical strategy:** exploiting Classical correlated beams.
**Setup:** spatially multimode Twin Beams, measured by means of a CCD camera in a linear regime

\[ N \sim 10^4 \text{ photons per pixel per shot} \]

\( M \gg 1 \) temporal modes per pixel per shot

**Strategy:** measuring the covariance

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between the joint photon numbers distribution

**Classical strategy:** exploiting Classical correlated beams.
**Signal-to-noise ratio vs thermal background**

\[
\frac{SNR_{Qi}}{SNR_{Cl}} = \varepsilon_{TWB} \approx \frac{(1 + \mu)}{\mu}
\]

\[
\mu = \frac{N}{M} \quad \text{number of photon/mode}
\]

- **Non-Classicality is lost**

\[
\varepsilon = \frac{\langle \delta N_1 \delta N_2 \rangle}{\sqrt{\langle \delta^2 N_1 \rangle \langle \delta^2 N_2 \rangle}}
\]

- Large quantum enhancement!
- Independent of noise and losses!
- Non-classical signature does not survive the noise
Photon counting capabilities by EMCCD

- Each pixel operated as single photon detector (click /no-click)
- Possibility of spatially multiplexed PNRD
- SPDC non-classical correlation in counting regime demonstrated
- Efficiency determined by relation

\[ \sigma = 1 - \eta \]
Determining the Quantum Expectation Value by Measuring a Single Photon/Protective measurement

Photon counting by SPAD Array

**SPAD+TDC camera**

- **Features**
  - Multi-modality: photon-counting, 2D imaging, 3D time-of-flight ranging, TDC (time-correlated single-photon counting)
  - 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

**Weak int. + Protection**

**Projective measurement**
• The planar fluorescence map from $n$ NV centers defects in diamond. Each of them is a single photon source.

$$S(x) \propto \sum_{\alpha=1}^{n} P_\alpha(x)$$
Intensity map gives no information on the number and position of centers if they are closer than DIFFRACTION LIMIT.
• **Intensity map** gives no information on the number and position of centers if they are closer than **DIFFRACTION LIMIT**

\[ n = 2 \]

\[ P(x) \]

• **Antibunching** of single photon emitters gives more information by measuring photon coincidences

[Schwartz & Oron, PRA 85, 033812 (2012)]
[Schwartz et al., Nano Lett. 13, 5832 (2013)]
Intensity map gives no information on the number and position of centers if they are closer than DIFFRACTION LIMIT.

Antibunching of single photon emitters gives more information by measuring photon coincidences.

Standard fluorescence map (single counts) + $g^{(2)}$ map

- [Schwartz & Oron, PRA 85, 033812 (2012)]
- [Schwartz et al., Nano Lett. 13, 5832 (2013)]
- [Gatto Monticone et al. PRL. 113, 143602 (2014)]
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Antibunching of single photon emitters gives more information by measuring photon coincidences

\[ n = 2 \]

\[ \mathcal{P}(x) \]

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[Schwartz & Oron, PRA 85, 033812 (2012)]
[Schwartz et al., Nano Lett. 13, 5832 (2013)]

[Gatto Monticone et al. PRL. 113, 143602 (2014)]
\[ \sum_{\alpha=1}^{n} [p_\alpha(x)]^k = \langle \hat{N} \rangle^k \left[ 1 - \frac{k-1}{k} g^{(2)} \right] \]

- \(k = 2\)
- \(k = 3\)
- \(k = 4\)

Intensity maps

\[ \sum_{\alpha=1}^{n} [p_\alpha(x)]^4 = \langle \hat{N} \rangle^4 \left\{ 1 - 2g^{(2)} + \frac{1}{2} g^{(2)}^2 + \frac{2}{3} g^{(3)} - \frac{1}{6} g^{(4)} \right\} \]

Abbe diffraction limit:

\[ 1/\sqrt{k} \]

Gatto Monticone et al. PRL. 113, 143602 (2014)
T2.3 (M12-24) Experiment(s) on quantum reading (DTU, NKT, INRIM)
Lab setup for basic experiments on binary quantum reading. Experiment based on homodyne receivers and Bell-type detections (DTU, NKT). Experiment based on photon-counting receivers (INRIM).
**T2.3 (M12-24) Experiment(s) on quantum reading (DTU, NKT, INRIM)**

Lab setup for basic experiments on *binary quantum reading*. Experiment based on homodyne receivers and Bell-type detections (DTU, NKT). *Experiment based on photon-counting receivers (INRIM).*

Some sub-optimal measurement scheme has been mentioned and proposed for CV receiver (Bell state measurement)

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**What about photo-counting receivers?**
**T2.3** (M12-24) Experiment(s) on quantum reading (DTU, NKT, INRIM)
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Some sub-optimal measurement scheme has been mentioned and proposed for CV receiver (Bell state measurement)

**What about photo-counting receivers?**

**The only experiment in quantum reading?**

Experimental implementation of unambiguous quantum reading
**T2.5 (M24-36)** Experiments on quantum pattern recognition (INRIM, DTU)
Lab setup and basic experiment on (un)supervised recognition (data clustering). Experiment(s) based on spatial multimode parallel probing and reading and/or quantum correlations across the cells (INRIM). Experiment(s) based on single-cell addressing and entangled ancillas (DTU). Experiment(s) for real-time measuring of absorption in a Petri dish (DTU).

**D2.4 M36** Experimental quantum pattern recognition (article) – INRIM

**T3.5 (M24-36)** Experiment(s) on microwave quantum illumination (IST, Aalto, INRIM)
Proof-of-principle implementation of the protocol in a dilution fridge with thermal noise artificially added to the signal modes. Microwave entanglement is generated by a superconducting Josephson parametric amplifier and output detection is realized by using two different approaches: post-processed heterodyne measurement (IST) and single photo-detection via transmon qubits (Aalto). The experiment will also benefit from all the previous know-how in the optical setting (INRIM).
Thank You!

😊

Recall….

QUARTET
Quantum Pattern Recognition

36 months Postdoc open position in TORINO
Advanced sensing protocols

- **Sensor:** Nitrogen-Vacancy center in diamond

  **Electronic spin structure**

  \[ \Delta \nu = \frac{2 g_e \mu_B B_z}{h} \]

  - Process: Optically detected magnetic resonance (ODMR)

  - Techniques:
    - Lock-in Techniques
    - Temperature sensing (sensitivity=5 mK/Hz^{1/2})
    - Magnetic Field sensing (sensitivity=40 nT/Hz^{1/2})

- **Goal:** Electric/Magnetic field sensing in integrated electronic devices or bio systems

- **Techniques:**
  - Lock-in Techniques
  - Temperature sensing (sensitivity=5 mK/Hz^{1/2})
  - Magnetic Field sensing (sensitivity=40 nT/Hz^{1/2})