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Covert optical detection under adverse weather conditions (2022-2023)

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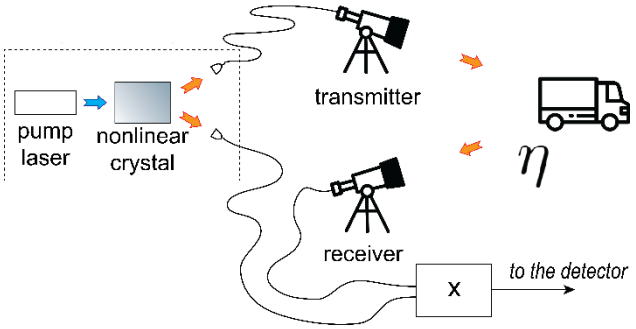
Outline:

- Introduction and project description
- Target detection with correlated photons
- Light source optimization
- System performance
- Potential applications
- Summary and Outlook

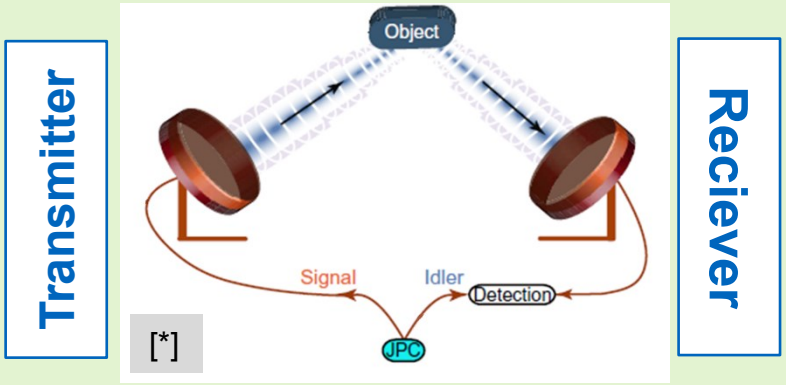
Introduction: correlation-enhanced target detection

An entanglement-based approach to improving an optical radar's capability to detect a weakly-reflecting target embedded in background noise that can be much stronger than the target return.

[J.H. Shapiro // *IEEE A&E Systems Magazine* **35**, 8-20 (2020).]



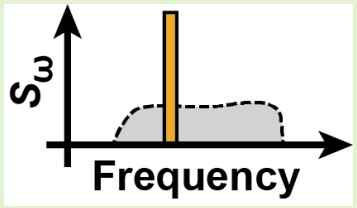
Boosting the performance of a radar



- Initial suggestion: Signal-to-noise improvement of 2^*d* times (*d* – number of modes)
- Signal-to-noise improvement of +6 dB over any conceivable classical radar
- Noise rejection, large number of modes needed.

Can the entanglement* survive an entanglement-breaking lossy channel?

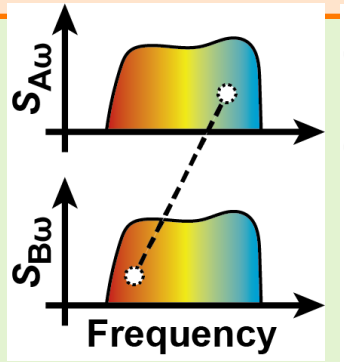
$$^{*}\,|\Psi_{AB}\rangle \neq |\Psi_{A}\rangle\,|\Psi_{B}\rangle$$

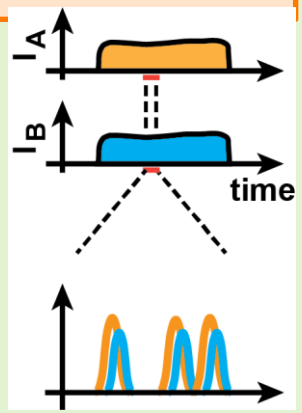


classical

vs

quantum





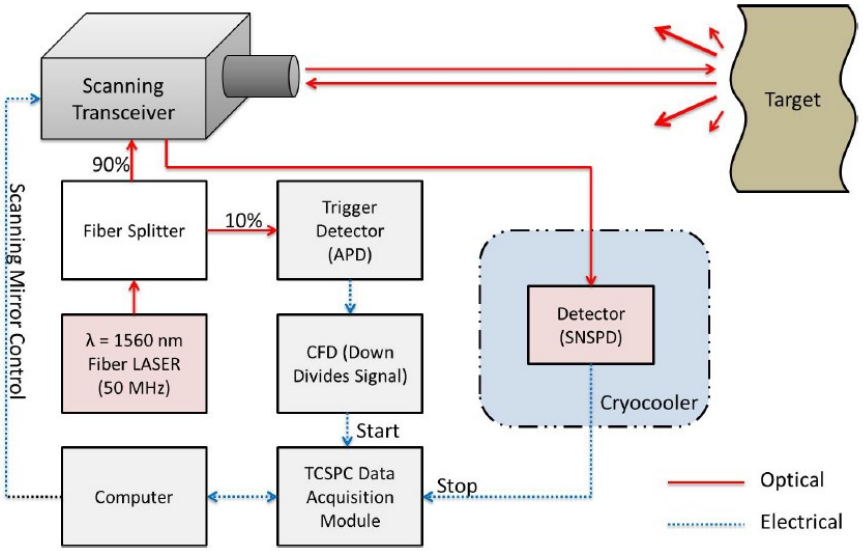
Broad spectrum, large time interval, random values for each realization => makes hard to observe externally

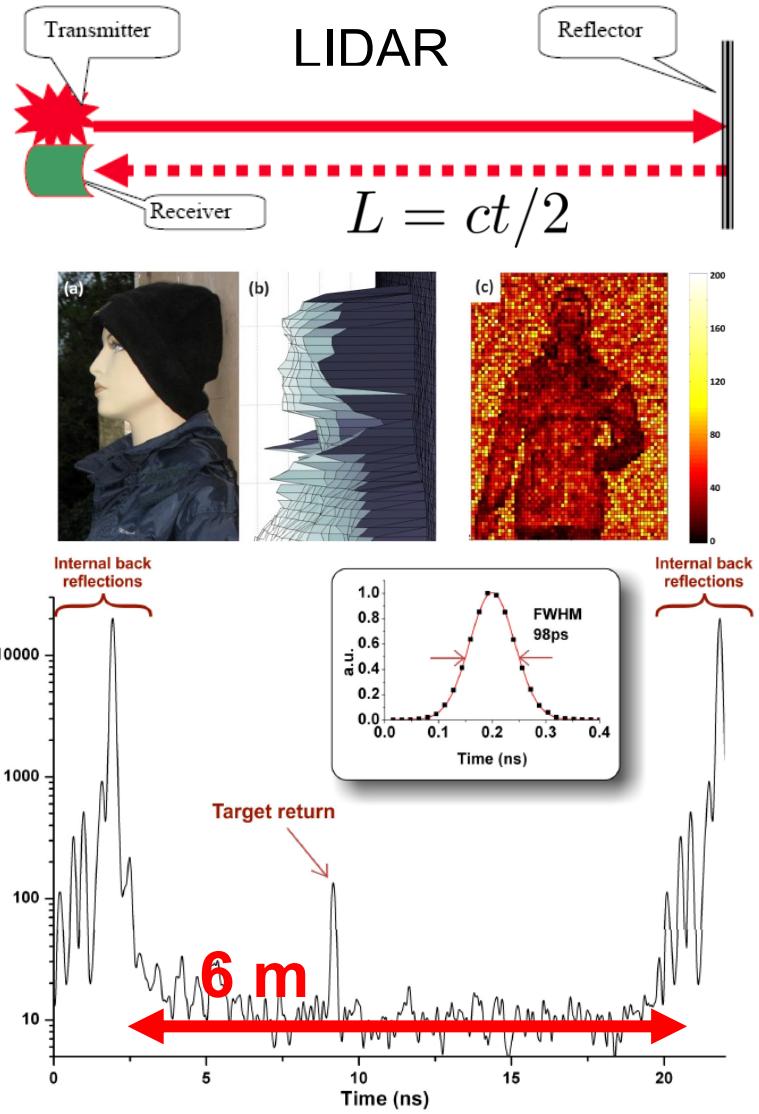
[* S. Barzanjeh *et al.* // *Sci. Adv.* **6** (19), eabb0451 (2020).]

Optics: Existing methods for target detection

Lidar (**Li**ght **D**etection **a**nd **R**anging) approach:

- send a pulse;
- detect reflection;
- measure the elapsed time.

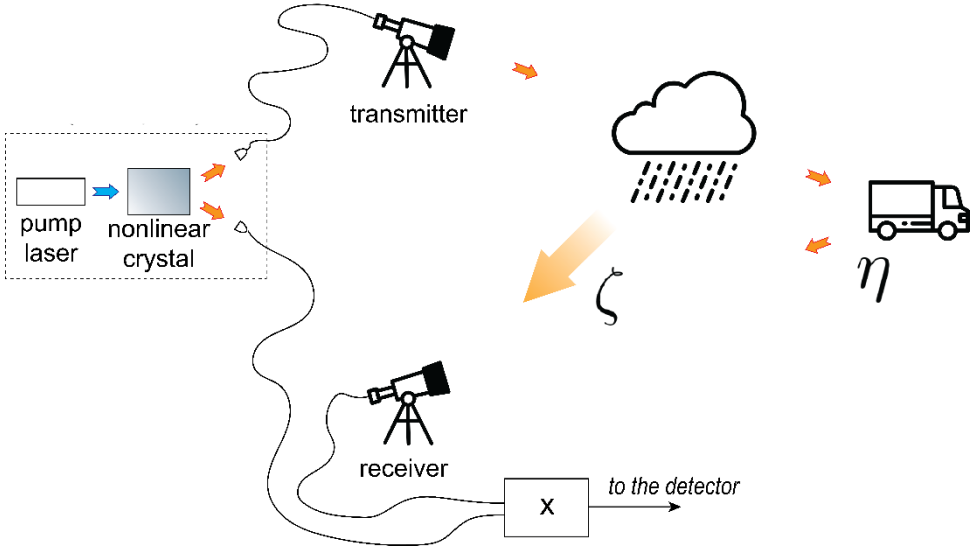




- Operating distance: ~ 1 km (*)
- Depth imaging: ~ 1 mm resolution (*)
  - Optical output: 1.5 μm, 50 MHz, < 1 ps, 250 μW mean = 5 W peak
  - Detection: cryogenically cooled (3 K) superconducting nanowire

[A.McCarthy et al. // *Optics Express* **21**, 8904 (2013)]

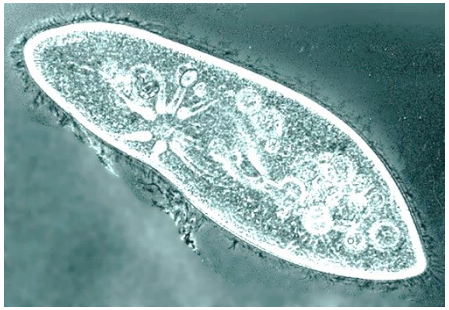
Drawbacks of conventional detection under adverse weather conditions



Rain, fog, and snow introduce additional scattering.
More losses to the signal, greater visibility of the source to external observers.

Radiofrequency range: strong background from the atmosphere.

Covert surveillance:
scattering of the transmitted radiation makes the illumination source visible to an external observer.

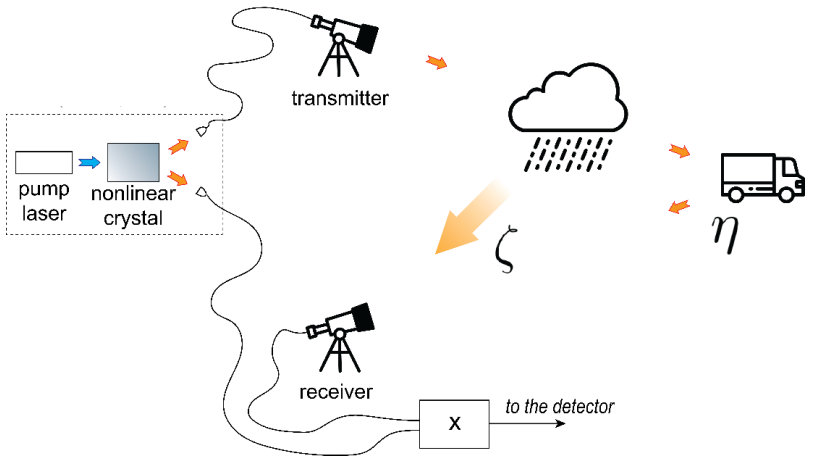


Microscopy applications: reflection from the cover glass; scattering from the tissues.

Covert optical detection under adverse weather conditions

Project goal:

to study the impact of heterogeneous dynamically changing environment on the performance of a correlation-based target detection system.



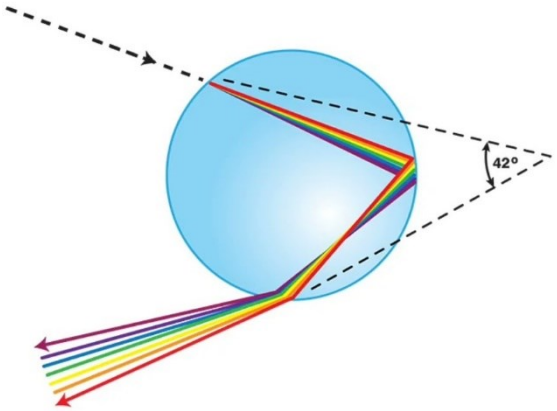
Proposed methods:

- correlated beams for increasing the signal-to-noise ratio and keeping the values of instantaneous and mean power at low level;
- change the type of the optical source;
- novel data processing techniques.

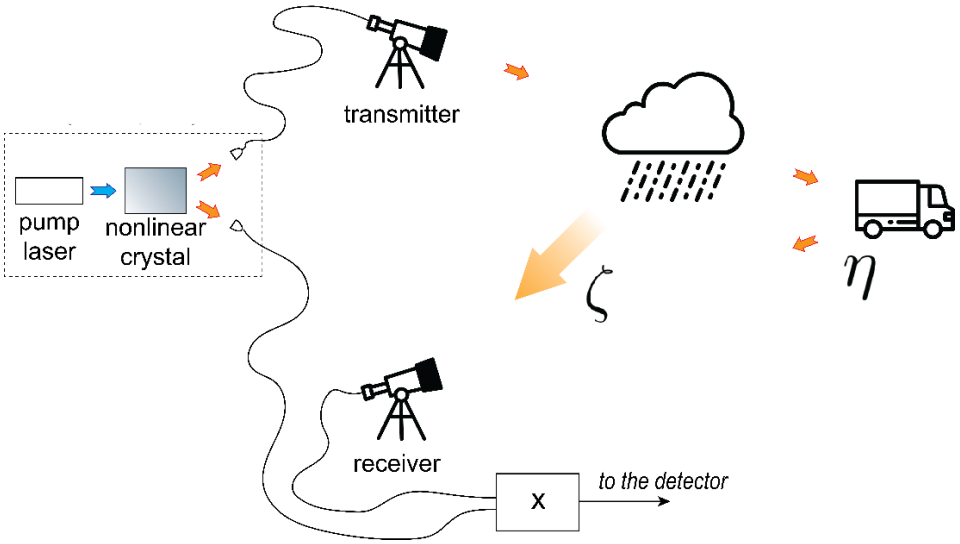
Research objectives:

1. to design a broadband source of correlated beams based on a nonlinear-optical crystal;
2. to elaborate data processing techniques to maximize the detection efficiency;
3. to estimate the achievable properties of the system in terms of operating distance, speed, and the detection efficiency as a function of the emitted optical power.

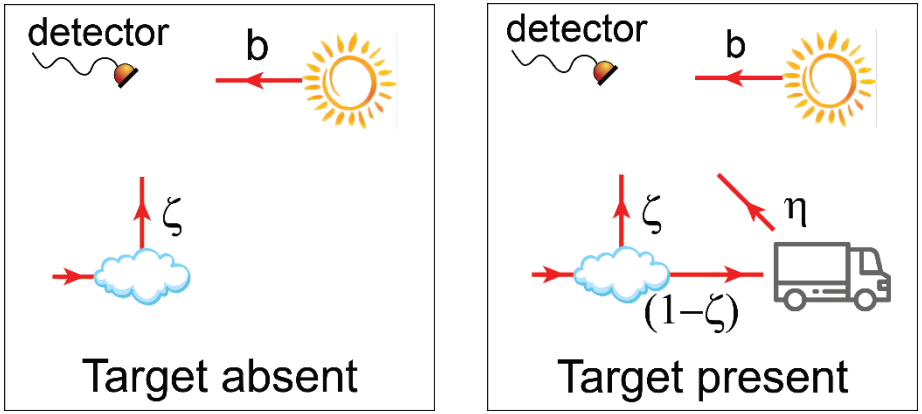
How to model rain droplets / fog?



- Main effect: additional reflectance (ζ)
- Losses are taken into account by reducing the target effective reflectance (η)



How to model rain droplets / fog?



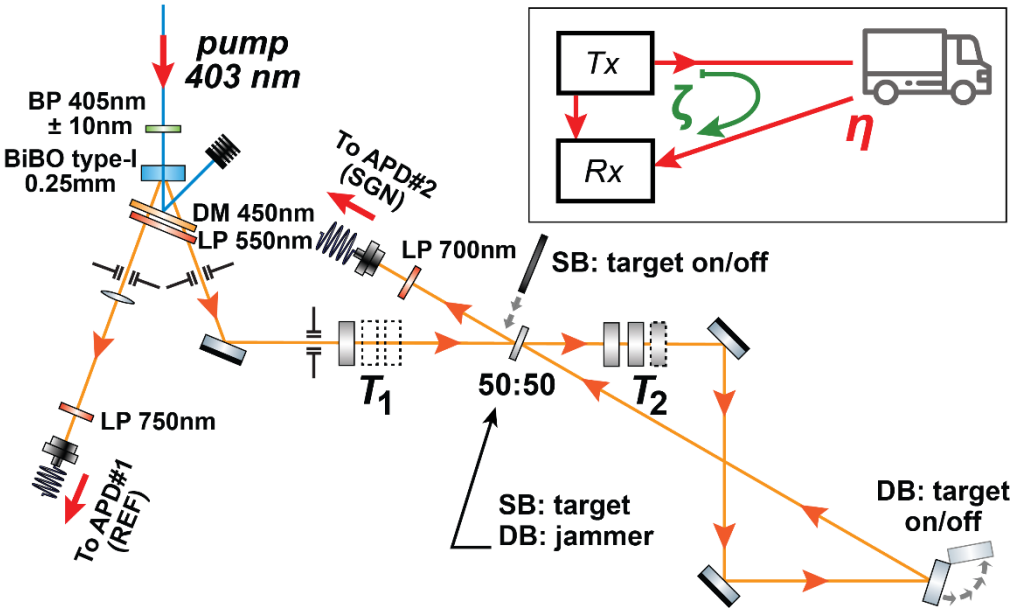
(idler beam not shown)

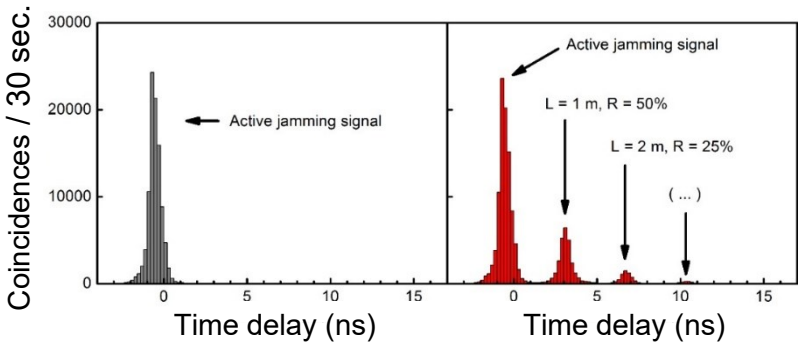
- Background noise is not correlated with the stored idler beam.
- A jamming object ("jammer") passively reflects part of the radiation sent to the target. Perfect correlations!
- The more one sends, the greater the noise.

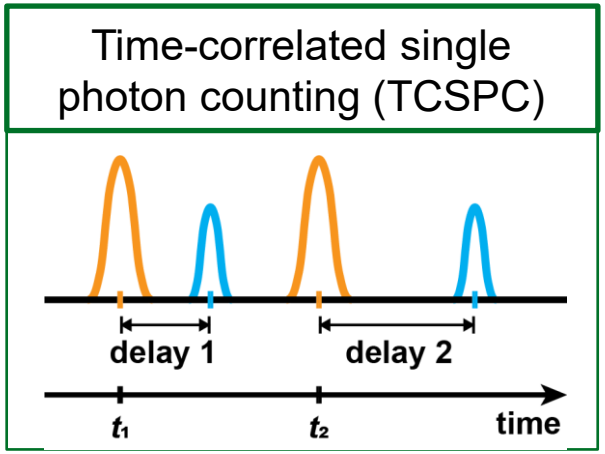
- Main effect: additional reflectance (ζ) ***"jamming object"***
- Losses are taken into account by reducing the target effective reflectance (η)

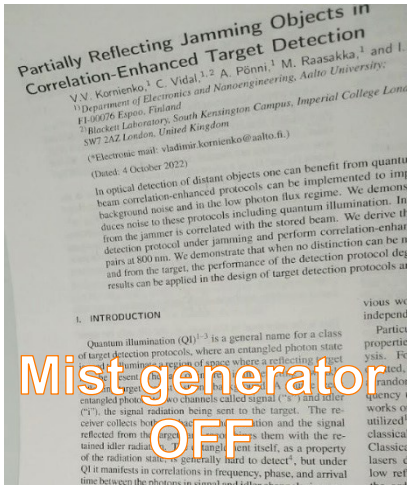
Research question: how to minimize the impact of the jamming object on the correlation-enhanced target detection with entangled photons.

Target detection with correlated photons









- Single-beam interrogation (SB): only APD#2 is used; APD#1 (REF) is ignored.
- Double-beam interrogation (DB): both APD#1 and APD#2 are used; coincidence detection.

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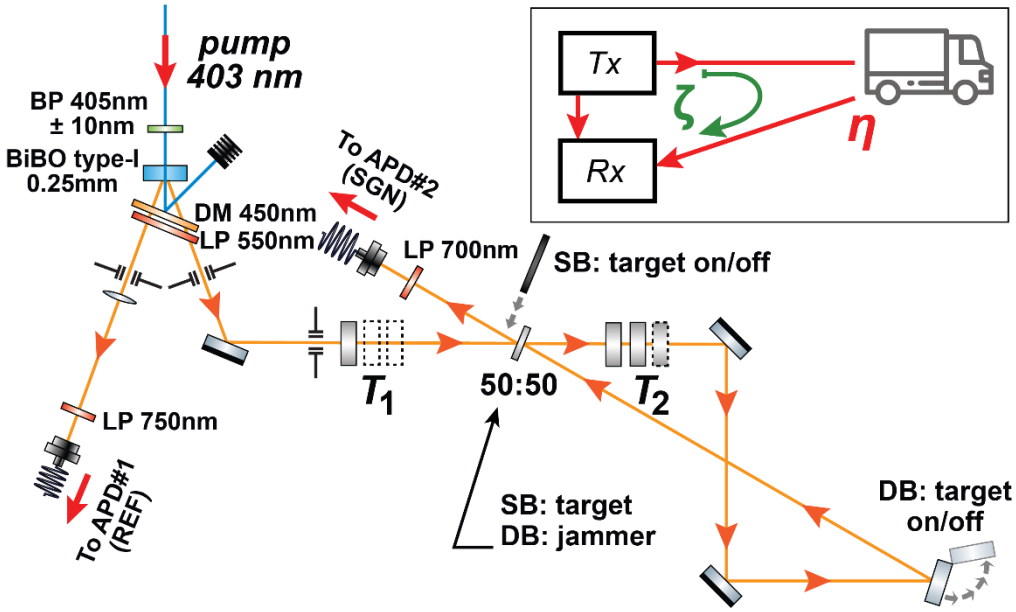
[V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, “Partially Reflecting Jamming Objects in Correlation-Enhanced Target Detection” // (submitted to *APL Quantum*, 2023)]

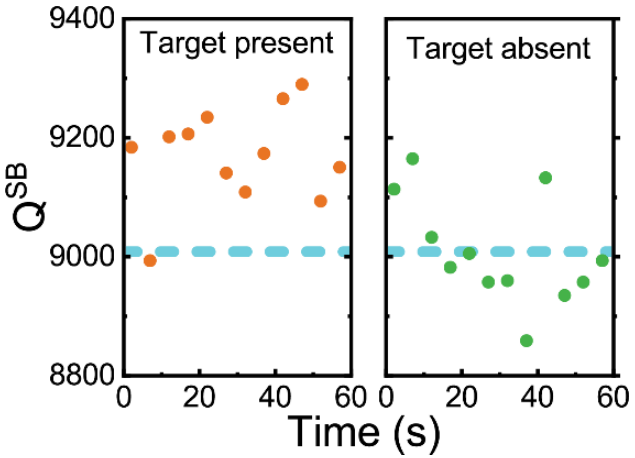
Target detection with correlated photons

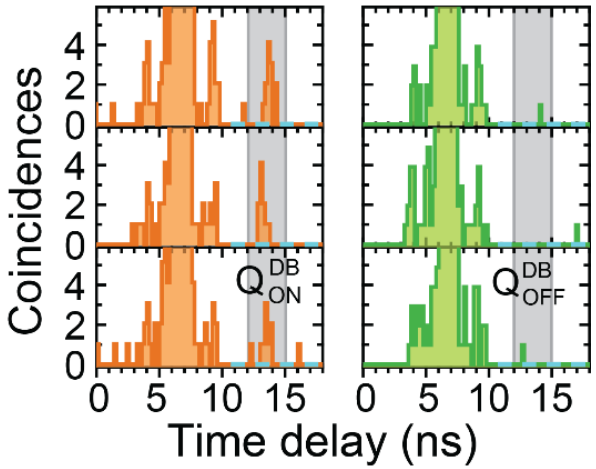


- Single-beam interrogation (SB): only APD#2 is used; APD#1 (REF) is ignored.
- Double-beam interrogation (DB): both APD#1 and APD#2 are used; coincidence detection.

Radiation coming from the jammer (ρ'_J) and from the target (ρ'_T) can be described by an indistinguishability parameter μ:

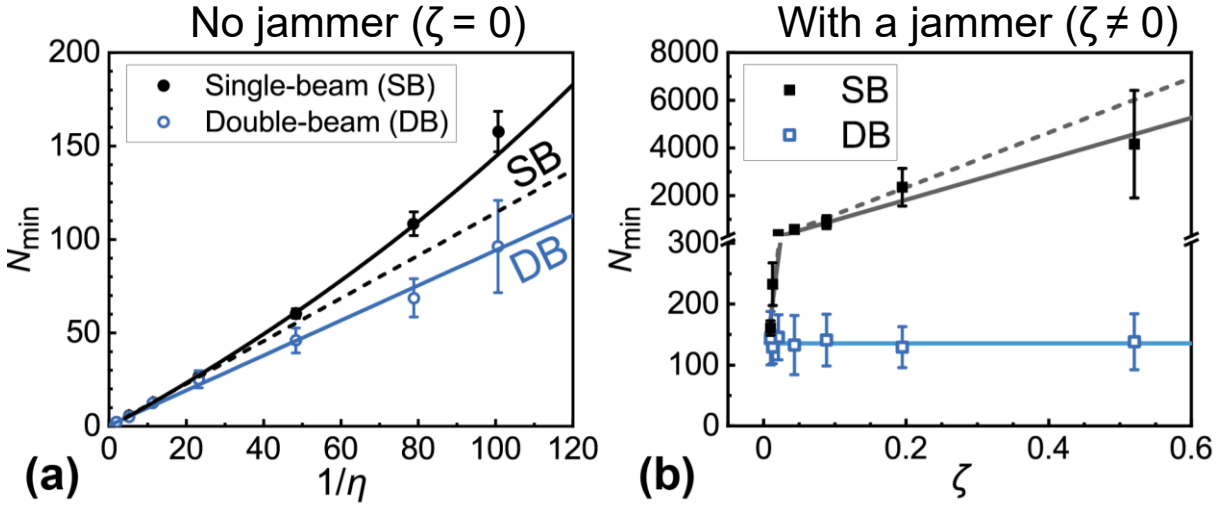
$$\mu \equiv \frac{\mathrm{Tr}\,\rho'_J\rho'_T}{\mathrm{Tr}\,\rho'^2_T}\ ,\ \mu \in [0;1]$$





[V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, "Partially Reflecting Jamming Objects in Correlation-Enhanced Target Detection" // (submitted to *APL Quantum*, 2023)]

Target detection with correlated photons



$$N_{min}^{\mathrm{SB}} \propto \frac{\eta + \mu^{\mathrm{SB}}\zeta + b}{\eta^2}$$

($\mu^{\mathrm{SB}} = 1$: fully indistinguishable)

$$N_{min}^{\mathrm{DB}} \propto \frac{\eta + \mu^{\mathrm{DB}}\zeta + b/d}{\eta^2}$$

($\mu^{\mathrm{DB}} = 0$: fully distinguishable)

b – number of background photons per mode; *d* – number of modes.

- We derived the equations governing the performance of the target detection protocol under jamming.
- The impact of the jammer can be described with a parameter μ.
- A jamming object with the reflectance ζ deteriorates the performance of the target detection protocol by a factor of $\zeta / b\,d$.
- We performed correlation-enhanced target detection with optical entangled photon pairs at 800 nm.
- The results can be applied to the design of target detection protocols and in developing advanced imaging techniques.

[V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, "Partially Reflecting Jamming Objects in Correlation-Enhanced Target Detection" // (submitted to *APL Quantum*, 2023)]

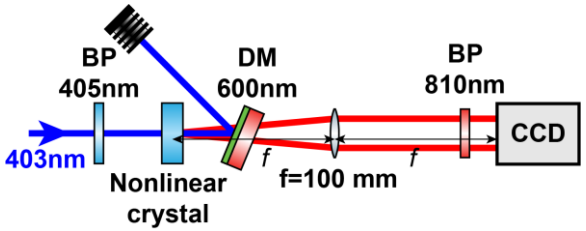
Source optimization

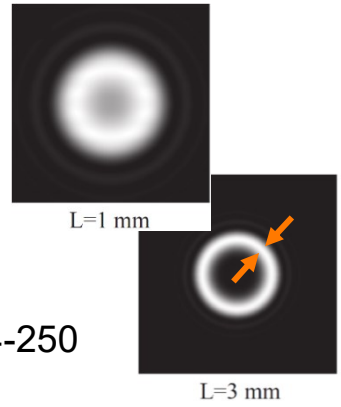
Unconditional photon detection probability (single counts):

$$\frac{dw^{uncond}}{dk_{1\perp x}} = \int dk_{2\perp x} \left|\Psi(k_{1\perp x}, k_{2\perp x})\right|^2$$

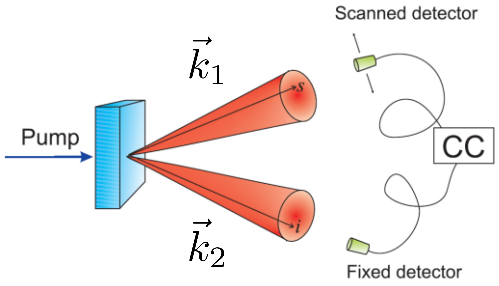
Conditional photon detection probability (coincidences):

$$\frac{dw^{cond}}{dx_1} = \frac{\left|\Psi(k_{1\perp x}, k_{2\perp})\right|^2}{\int dk_{1\perp x} \left|\Psi(k_{1\perp x}, k_{2\perp x})\right|^2}\Bigg|_{k_{2\perp x}}$$

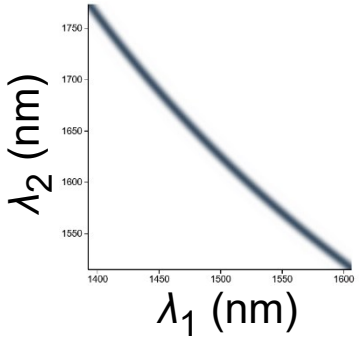




optical pump:10 mW @403 nm
EM-CCD: 1s, 300 frames, gain: 4-250



CC – coincidence counting circuit



$\Psi(\mathbf{k}_1,\mathbf{k}_2)$ is a biphoton field amplitude.
It can be computed using the formalism of macroscopic nonlinear optics.

- Optimization goal: maximize w^{cond} in the region of interest.
- Photon source already saturates the detection system => keep the value of w^{cond} constant while making the source more broadband.

Source optimization

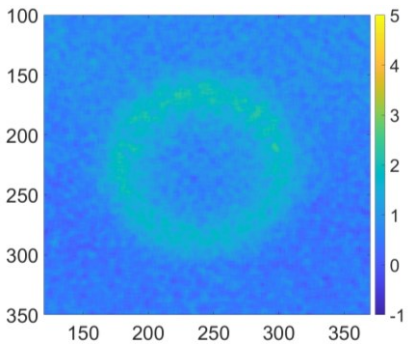
Unconditional probability (w^{uncond}):

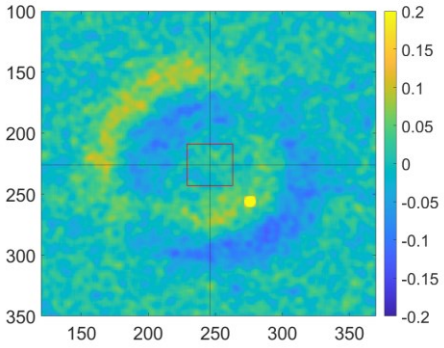
Correlation coefficient:

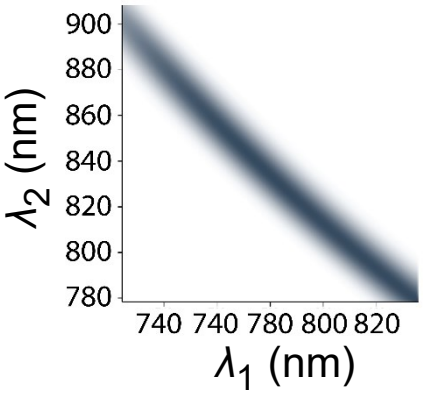
Conditional probability (w^{cond}):

Broadband source:
time per frame: 2 sec.

BiBO (bismuth borate)
length 0.25 mm
pump beam waist 0.1 mm
pump bandwidth 5 nm

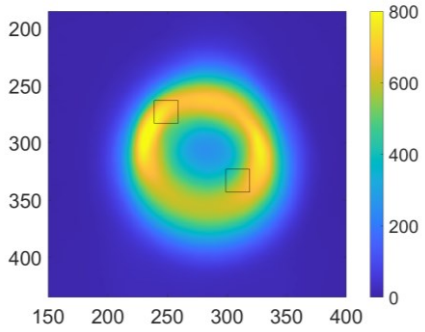


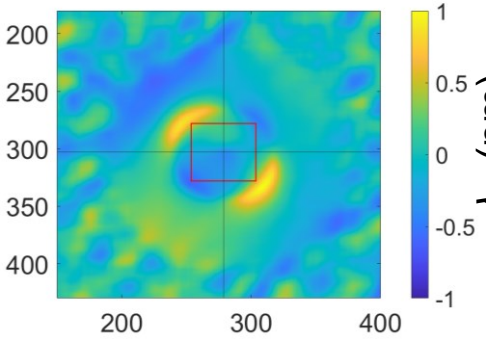


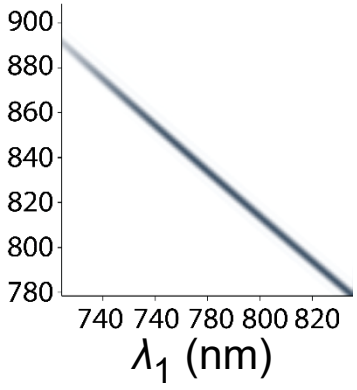


High-flux source:
time per frame: 15 ms

BBO (beta-barium borate)
length 10 mm
pump beam waist 1.0 mm
pump bandwidth 5 nm



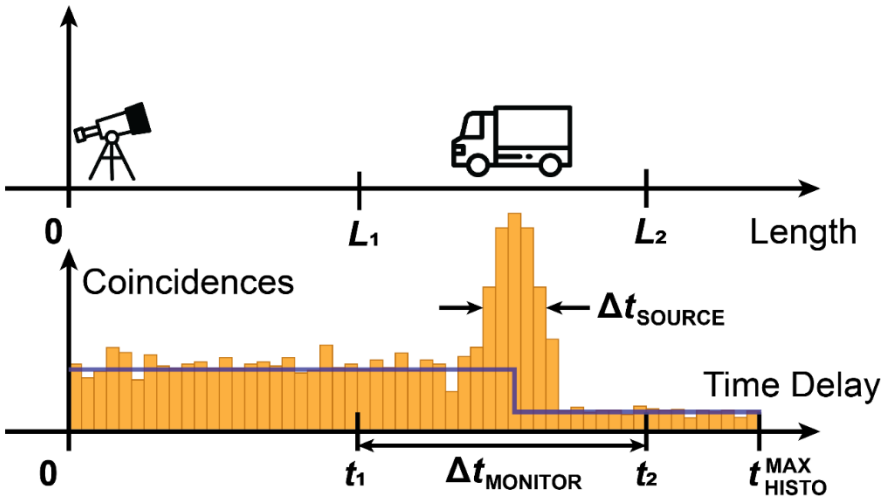




- Two different-purpose sources have been proposed:

1) broadband source for filling the maximum amount of frequency modes (short crystal);
2) high-flux source based on a long crystal.

Limitations on the ultimate system performance



Range of the monitored distances:

$$\Delta t_{\mathrm{MONITORED}} \equiv \frac{2\,L}{c} < t^{\mathrm{MAX}}_{\mathrm{HISTO}}$$

Maximal brightness of the source:

$$I_{\mathrm{MAX}} \propto \frac{1}{t^{\mathrm{MAX}}_{\mathrm{HISTO}}}$$

Background suppression coefficient:

$$\propto b\,d\,\frac{t^{\mathrm{MAX}}_{\mathrm{HISTO}}}{\Delta t_{\mathrm{SOURCE}}}$$

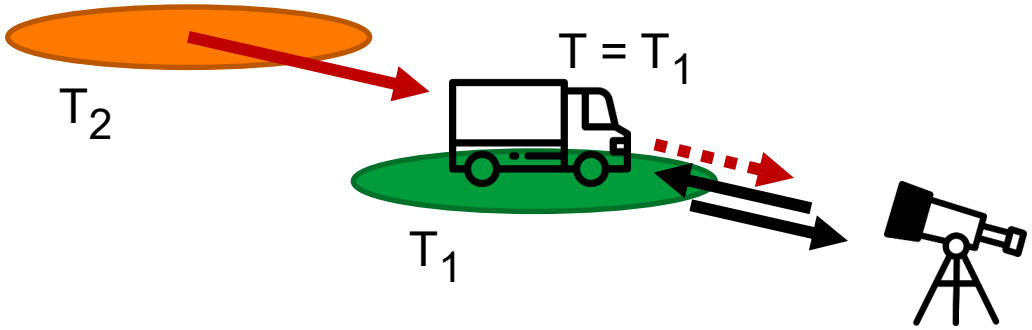
- Photon-counting detection limits the max. value of the optical power: time between the adjacent pulses (photons) should be less than $\Delta L/(2c)$ (similar to a lidar).
- Our results demonstrate the detection of targets with reflectance values down to 4% at 6 m distance with 1 s integration time.
- With an optimized source and improved filtering, we expect increase of the ranging distance (up to 100 m), but not the integration time (limitation of the detection method).
- Current sources easily reach the max. available biphoton rate of ~10^6 Hz.

$$t^{\mathrm{MAX}}_{\mathrm{HISTO}}(L_1 - L_2 = 100\ \mathrm{m}) > 600\ \mathrm{ns}$$

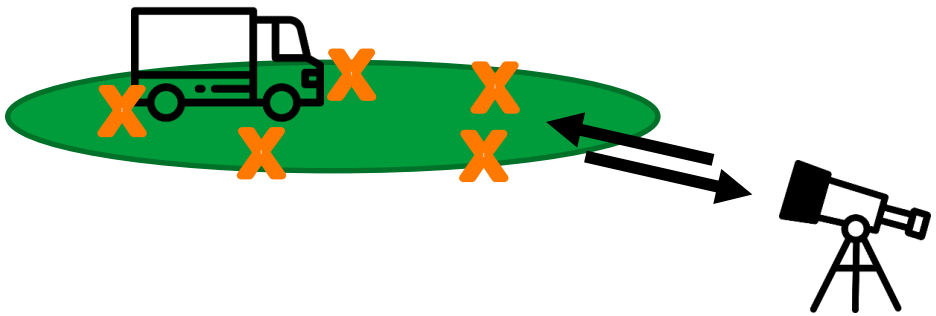
$$I_{\mathrm{MAX}} = \frac{1}{t^{\mathrm{MAX}}_{\mathrm{HISTO}}} < 1\ \mathrm{MHz}$$

Potential applications

In addition to a conventional radar application (send light – detect the reflected light), the following methods can also be used:



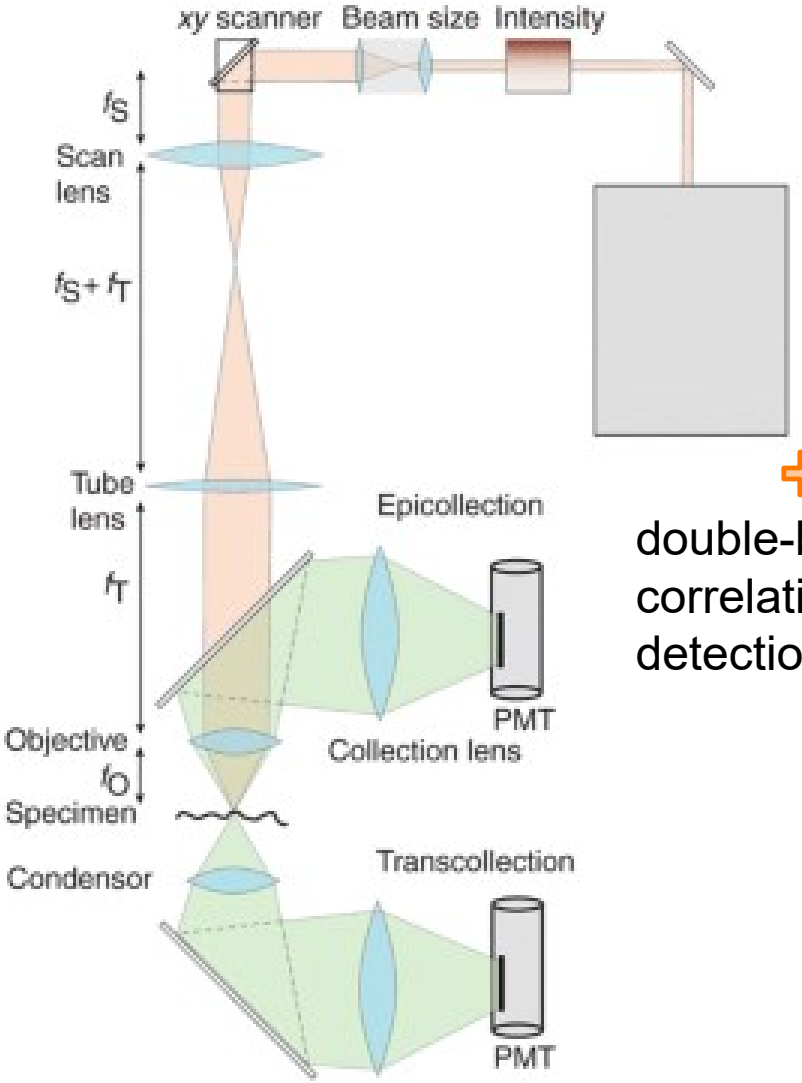
- Change can be detected in the background radiation (dark red lines, solid and dashed), even when the target has low reflectance thus making the reflectance measurement (black lines) hard.



- If the background has features providing high reflectance in certain areas (90° retro-reflectors), the change in the reflected signal can be measured.

Working principle: the object (target) changes both how the radar radiation is reflected, and how background radiation is the transmitted.

Potential applications



Correlated photons can be used in microscopy applications with light-sensitive specimen: ultraviolet light in biomedical imaging, with the need to reduce the light level.

+

double-beam correlation-enhanced detection

Our analytic results help engineering the source of quantum light that would provide the system with the ultimate performance.

[F. Helmchen *et al*. // *Nature Methods* **2**, 932 (2005)]

Summary

- We performed correlation-enhanced target detection with entangled optical photon pairs at 800 nm.
- Analytical description is developed for the impact of a partially reflecting object on the optical target detection protocol. An undistinguishable (μ=1) jamming object with the reflectance ζ deteriorates the performance of the target detection protocol by a factor of ζ/bd (b – thermal photons per mode, d – number of modes). A quantitative metrics μ of indistinguishability is introduced.
- We performed the optimization of the photon source for target detection:

– broadband source (0.25 mm BiBO with 0.1 mm pump beam diameter);
– high-flux source (10 mm BBO with 1.0 mm pump beam diameter).

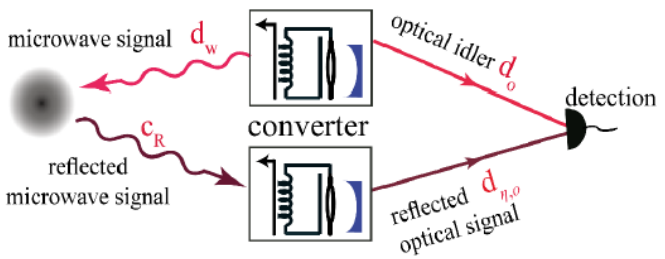
- System performance: detection of targets with reflectance values down to 4% at 6 m distance with 1 s integration time. With an optimized source and improved filtering, expected ranging distance is up to 100 m; integration time – still in the range of a few seconds due to the limitations of the detection method. Maximal available biphoton rate for photon counting is ~10^6 Hz.
- Result dissemination in 2023:

1. Article manuscript submitted to *APL Quantum*.
2. Conference presentations: CLEO Europe (Munich, Germany); Quantum 2023 (Turin, Italy).

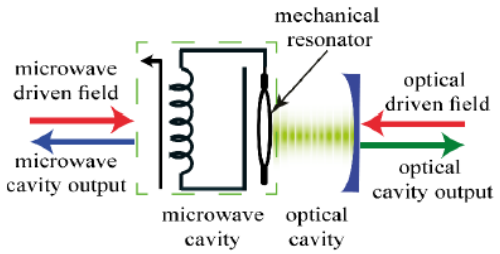
- The results can be applied to the design of target detection protocols and in developing advanced imaging techniques.

Thank you for your attention!

Correlation-enhanced target detection in the microwave frequency range



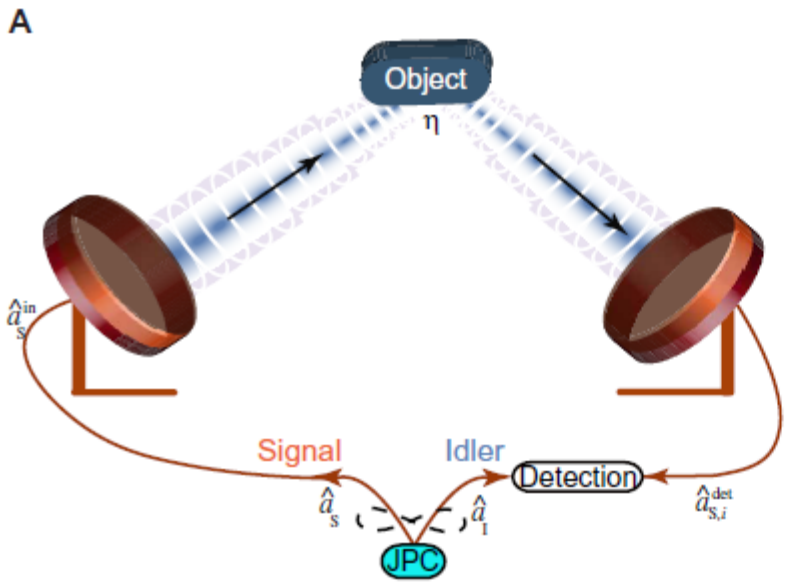
(a) QI radar configuration

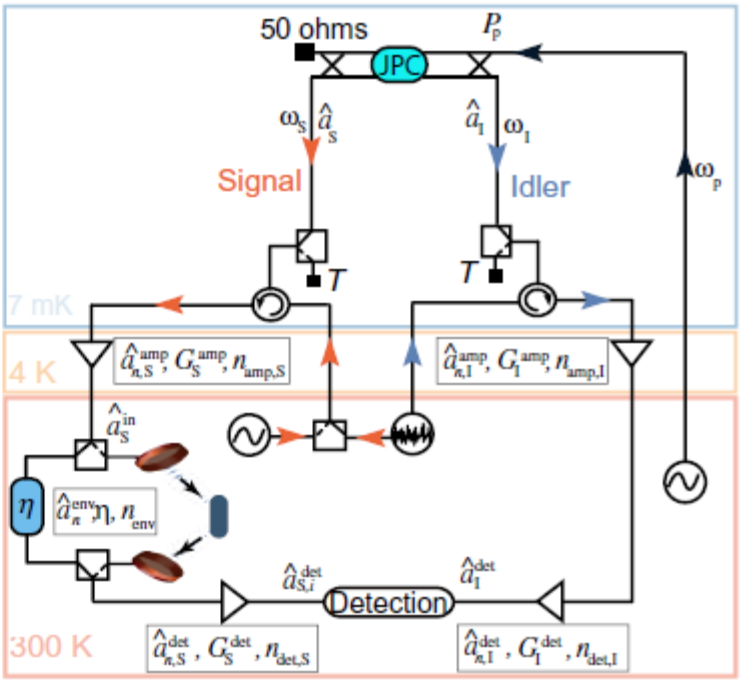


(b) EOM converter

[S. Barzanjeh, S. Guha, C. Weedbrook. D. Vitali, J. H. Shapiro, and S. Pirandola, "Microwave quantum illumination" // *Phys. Rev. Lett.* **114**, 080503 (2015).]

FIG. 4. Schematic for Barzanjeh *et al.*'s microwave quantum illumination [41]. (a) QI radar configuration. (b) Electro-optomechanical (EOM) converter configuration.

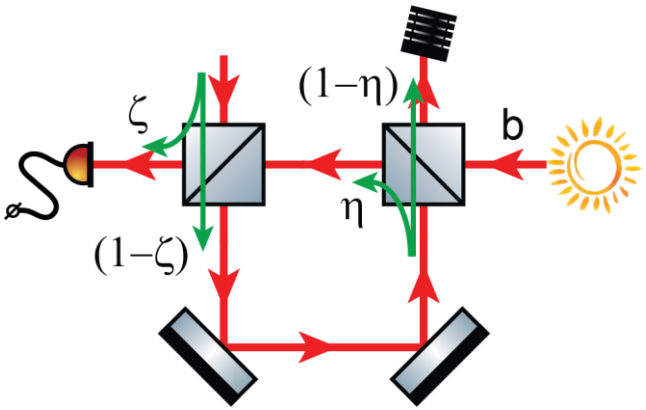




[S. Barzanjeh *et al.* // *Sci. Adv.* **6** (19), eabb0451 (2020)]

Protocol details

Double beam interrogation (**DB**) protocol: coincidence counting between the two channels.
Single beam interrogation (**SB**) protocol: only the photons in the signal channel are used.
Large number *d* of radiation modes is assumed. The probabilities ζ and η to detect a photon reflected from the jammer and from the target, correspondingly.
A weakly reflective jammer ($\zeta << 1$) and an even fainter target ($\eta < \zeta$).



Target absent – **SB**:

$$\rho_0 = \zeta\,\rho_{\mathrm{J}} + (1-\zeta)\left(\rho_{\mathrm{TH}}\right) \ .$$

Target present – **SB** :

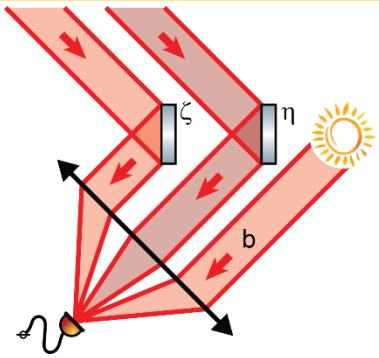
$$\rho_1 = \zeta\rho_{\mathrm{J}} + (1-\zeta)\left(\eta\,\rho_{\mathrm{T}} + (1-\eta)\rho_{TH}\right) \ .$$

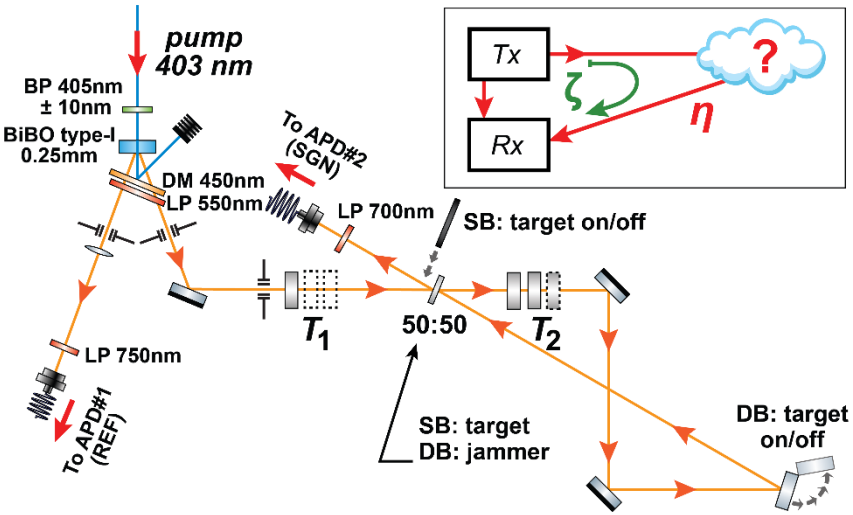
Thermal background:

$$\rho_{\mathrm{TH}} \approx (1-bd)\,|0\rangle_s\,\langle 0|_s + b\,\hat{\mathbf{I}}_s \qquad \hat{\mathbf{I}}_s \equiv \sum_{k_s=1}^{d} |1\rangle_{k_s}\,\langle 1|_{k_s}$$

Alternative multi-mode picture:

$$\rho_1 = \rho_{TH} \otimes \\ \otimes \left(|0\rangle\langle 0| + \zeta\rho_{\mathrm{J}}\right) \otimes \\ \otimes \left(|0\rangle\langle 0| + \eta\rho_{\mathrm{T}}\right) \ .$$





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Protocol details

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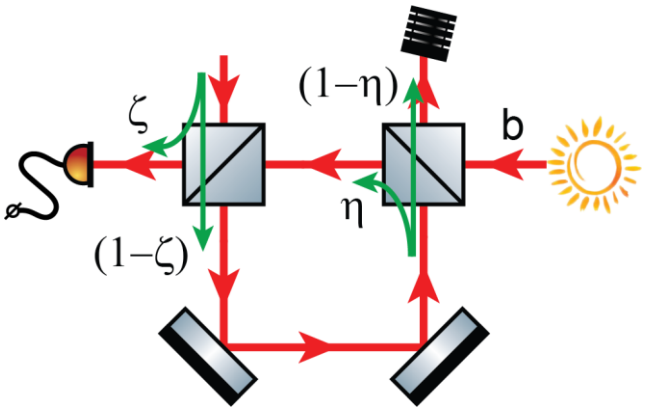


Target absent – **DB**:

$$\rho_0 = \zeta\,\rho_{\mathrm{J}} + (1-\zeta)\left(\rho_{\mathrm{TH}} \otimes \hat{\mathbf{I}}_i\right) .$$

Target present – **DB** :

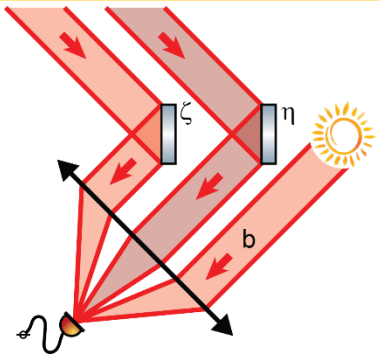
$$\rho_1 = \zeta\rho_{\mathrm{J}} + (1-\zeta)\left(\eta\,\rho_{\mathrm{T}} + (1-\eta)\rho_{TH} \otimes \hat{\mathbf{I}}_i\right) .$$

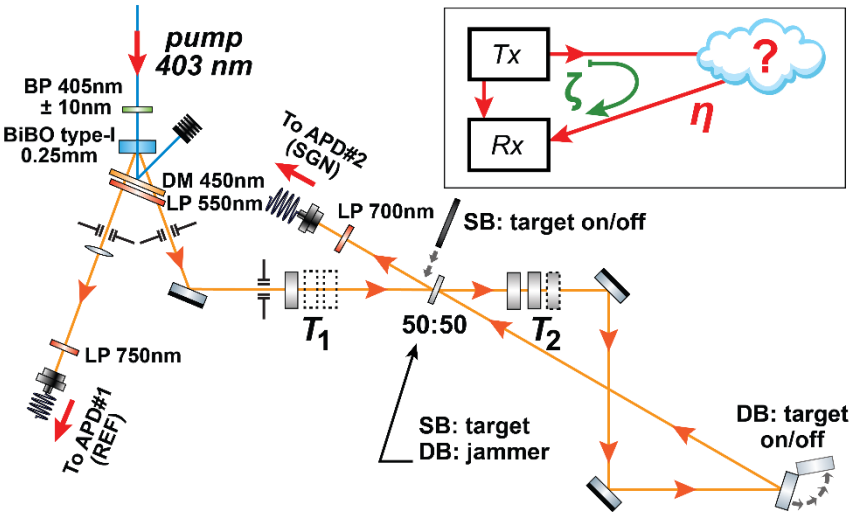
Thermal background:

$$\rho_{\mathrm{TH}} \approx (1-bd)\,|0\rangle_s\,\langle 0|_s + b\,\hat{\mathbf{I}}_s \qquad \hat{\mathbf{I}}_s \equiv \sum_{k_s=1}^{d} |1\rangle_{k_s}\,\langle 1|_{k_s}$$

Alternative multi-mode picture:

$$\rho_1 = \rho_{TH} \otimes$$
$$\otimes \left(|0\rangle\langle 0| + \zeta\rho_{\mathrm{J}}\right) \otimes$$
$$\otimes \left(|0\rangle\langle 0| + \eta\rho_{\mathrm{T}}\right) .$$





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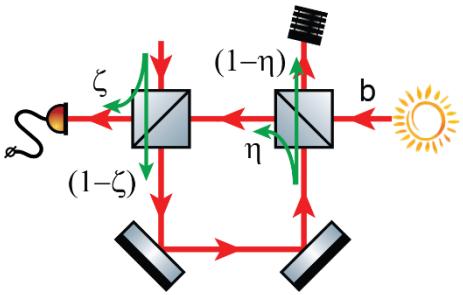
Protocol details



Target absent – **SB**:

$$\rho_0 = \zeta\,\rho_{\mathrm{J}} + (1-\zeta)\left(\rho_{\mathrm{TH}}\right) .$$

Target present:

$$\rho_1 = \zeta\rho_{\mathrm{J}} + (1-\zeta)\left(\eta\,\rho_{\mathrm{T}} + (1-\eta)\rho_{TH}\right) .$$

Thermal background:

$$\rho_{\mathrm{TH}} \approx (1-bd)\,|0\rangle_s\,\langle 0|_s + b\,\hat{\mathbf{I}}_s$$

Generated state:

DB: $$|\Psi\rangle_{s,i} \approx |0\rangle_s + \frac{A}{\sqrt{d}}\sum_{k=1}^{d} |1\rangle_{s_k}\,|1\rangle_{i_k}$$

SB: $$\rho_{\mathrm{IN}}^{\mathrm{SB}} = \mathrm{Tr_i}\,\rho_{\mathrm{IN}}^{\mathrm{DB}}$$

Chernoff bound (*N* – number of trials):

$$\mathrm{p}_{err}^{\mathrm{QCB}}(N) = \frac{1}{2}\left(\min_{\alpha\in[0;1]} \mathrm{Tr}\,\rho_0^{1-\alpha}\rho_1^{\alpha}\right)^N \equiv \frac{1}{2}\mathcal{F}^N$$

$$N_{min} = \frac{\ln\left(2p_{\mathrm{err}}^{\mathrm{LEV}}\right)}{\ln\mathcal{F}} .$$

Protocol details

$$\mathrm{p}_{err}^{\mathrm{QCB}}(N) = \frac{1}{2}\left(\min_{\alpha\in[0;1]} \operatorname{Tr}\rho_0^{1-\alpha}\rho_1^{\alpha}\right)^N \equiv \frac{1}{2}\mathcal{F}^N \qquad \begin{aligned}\rho_0 &= \zeta\,\rho_{\mathrm{J}} + (1-\zeta)\left(\rho_{\mathrm{TH}}\right) .\\ \rho_1 &= \zeta\rho_{\mathrm{J}} + (1-\zeta)\left(\eta\,\rho_{\mathrm{T}} + (1-\eta)\rho_{TH}\right) .\end{aligned}$$

Frobenius inner product and Gram-Schmidt orthogonalization:

$$\langle \mathrm{A};\mathrm{B}\rangle_{\mathrm{F}} \equiv \operatorname{Tr}\mathrm{A}\mathrm{B}^{\dagger} \qquad \operatorname{proj}_{\mathrm{A}}\mathrm{B} = \frac{\langle \mathrm{B};\mathrm{A}\rangle_{\mathrm{F}}}{\langle \mathrm{A};\mathrm{A}\rangle_{\mathrm{F}}}\mathrm{A} = \frac{\operatorname{Tr}\mathrm{B}\mathrm{A}^{\dagger}}{\operatorname{Tr}\mathrm{A}\mathrm{A}^{\dagger}}\mathrm{A}$$

$$\operatorname{Tr}\left(e_1\mathrm{A}_1 + f_1\mathrm{A}_2 + g_1\mathrm{A}_3\right)\left(e_2\mathrm{A}_1^{\dagger} + f_2\mathrm{A}_2^{\dagger} + g_2\mathrm{A}_3^{\dagger}\right) = \\ = e_1e_2\operatorname{Tr}(\mathrm{A}_1\mathrm{A}_1^{\dagger}) + f_1f_2\operatorname{Tr}(\mathrm{A}_2\mathrm{A}_2^{\dagger}) + g_1g_2\operatorname{Tr}(\mathrm{A}_3\mathrm{A}_3^{\dagger})$$

$$\mathrm{A}_1 = |0\rangle\langle 0| \ ,$$

$$\mathrm{A}_2 = \rho_{\mathrm{T}} - \operatorname{proj}_{\mathrm{A}_0}\rho_{\mathrm{T}} = \rho_{\mathrm{T}} - \rho_{\mathrm{T}00}|0\rangle\langle 0| = \rho'_{\mathrm{T}} \ ,$$

$$\mathrm{A}_3 = \rho_{\mathrm{J}} - \operatorname{proj}_{\mathrm{A}_1}\rho_{\mathrm{J}} - \operatorname{proj}_{\mathrm{A}_2}\rho_{\mathrm{J}} = \rho'_{\mathrm{J}} - \mu\rho'_{\mathrm{T}} \ ,$$

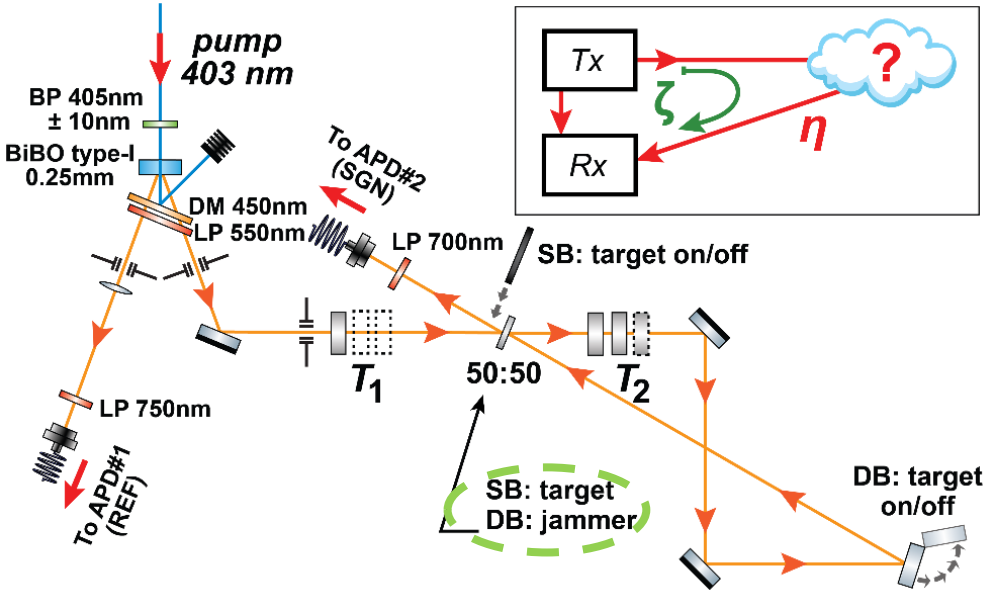
$$\mathrm{A}_4 = \hat{\mathbf{I}} - \rho'_{\mathrm{J}}\frac{\operatorname{Tr}\rho'_{\mathrm{J}} - \mu\operatorname{Tr}\rho'_{\mathrm{T}}}{\operatorname{Tr}\rho'^{2}_{\mathrm{J}} - \mu^2\operatorname{Tr}\rho'^{2}_{\mathrm{T}}} - \rho'_{\mathrm{T}}\frac{\frac{\operatorname{Tr}\rho'^{2}_{\mathrm{J}}}{\operatorname{Tr}\rho'^{2}_{\mathrm{T}}}\operatorname{Tr}\rho'_{\mathrm{T}} - \mu\operatorname{Tr}\rho'_{\mathrm{J}}}{\operatorname{Tr}\rho'^{2}_{\mathrm{J}} - \mu^2\operatorname{Tr}\rho'^{2}_{\mathrm{T}}} \approx \hat{\mathbf{I}} - \frac{\rho'_{\mathrm{J}}}{1+\mu} - \frac{\rho'_{\mathrm{T}}}{1+\mu} \ .$$

$$\mathrm{A}_5 = |0\rangle_{\mathrm{s}}\langle 0|_{\mathrm{s}} \otimes \hat{\mathbf{I}}_i \qquad \mathrm{A}_6 = \hat{\mathbf{I}}_{\mathrm{s}} \otimes |0\rangle_{\mathrm{i}}\langle 0|_{\mathrm{i}}$$

Indistinguishability parameter:

$$\mu \equiv \frac{\operatorname{Tr}\rho'_{\mathrm{J}}\rho'_{\mathrm{T}}}{\operatorname{Tr}\rho'^{2}_{\mathrm{T}}} \ , \quad \mu \in [0;1]$$

Target detection with correlated photons

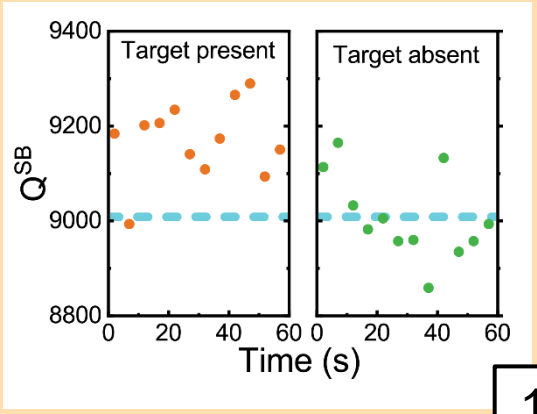


- Single-beam interrogation (SB): only APD#2 is used; APD#1 (REF) is ignored.
- Double-beam interrogation (DB): both APD#1 and APD#2 are used; coincidence detection.

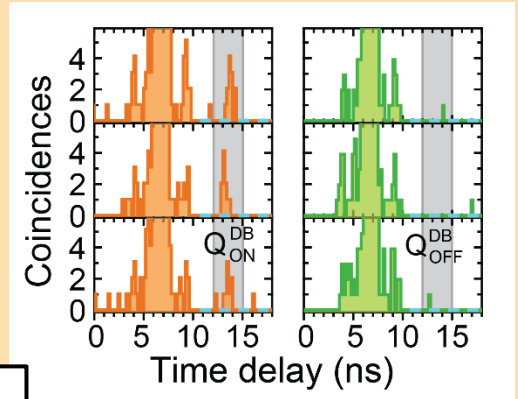
Radiation coming from the jammer (ρ'_J) and from the target (ρ'_T) can be described by an indistinguishability parameter μ:

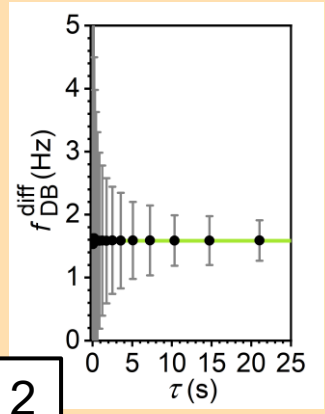
$$\mu \equiv \frac{\mathrm{Tr}\,\rho'_J\rho'_T}{\mathrm{Tr}\,\rho'^2_T}\ ,\ \mu \in [0;1]$$

Data processing steps:

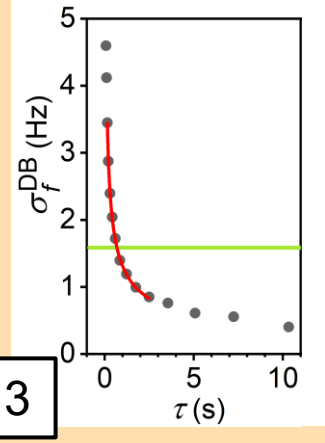


1





2



3

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[V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, "Partially Reflecting Jamming Objects in Correlation-Enhanced Target Detection" // (submitted to *APL Quantum*, 2023)]