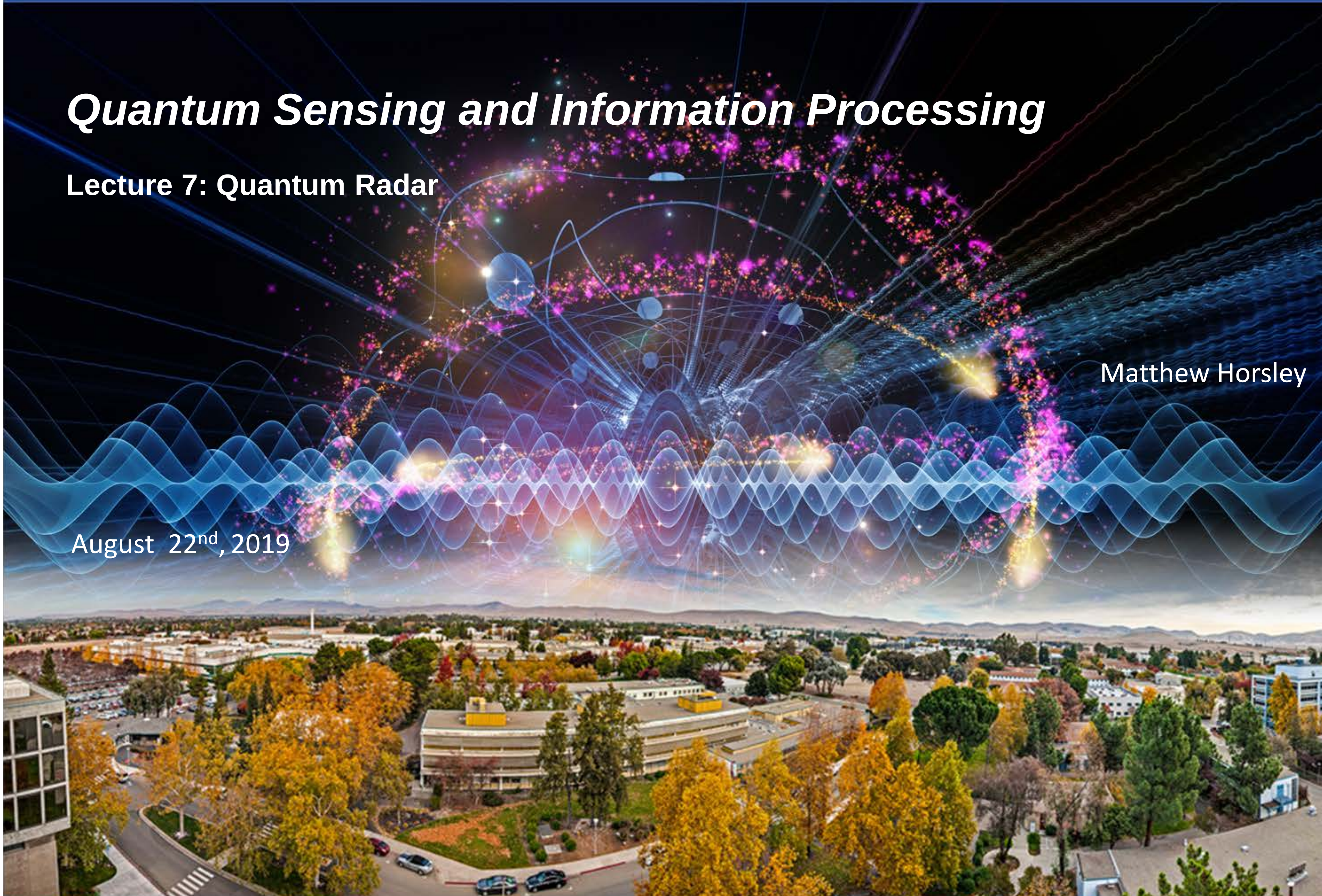
Quantum Sensing and Information Processing

Lecture 7: Quantum Radar

Matthew Horsley

August 22nd, 2019



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Schedules for remaining lectures

- **Error Modelling**

  Thursday, September 26th at 2:00 in the B543 Auditorium

- **Control of Quantum Devices**

  TBD

Schedule posted to Lab calendar – subscribe to receive updates

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- ENG S&T: Rob Sharpe

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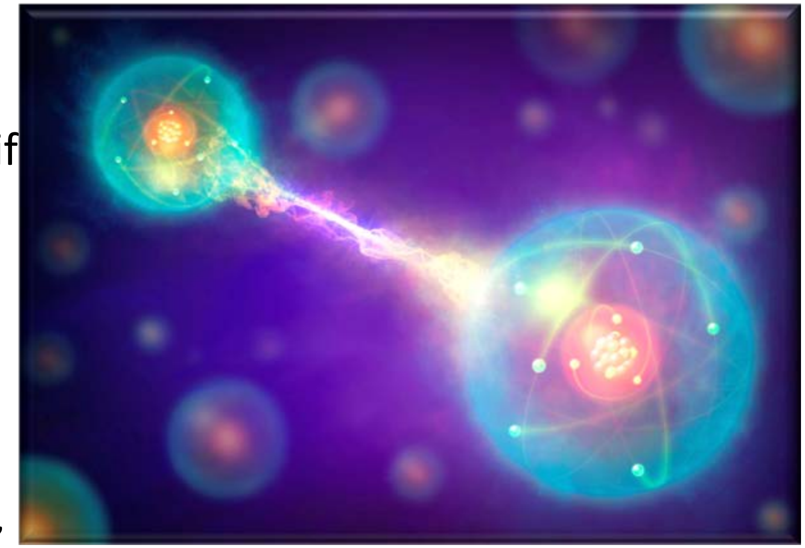
Early History of Quantum Radar

Date	Title	Author/
1991	Impulse transmitter and quantum detection system	US Navy
2002	Positioning and clock synchronization through entanglement	Giovannetti et al
2005	Entangled photon range finding system and method	General dynamic advanced information systems
2005	Radar systems and methods using entangled quantum particles	Lockheed Martin Corporation
2007	DARPA quantum sensors program	US
2008	Imaging with non-degenerate frequency entangled photons	Boeing Patent
2008	Sensor systems and methods using entangled quantum particles	Lockheed Martin Corporation Patent
2008	Enhanced sensitivity of photodetection with Quantum Illumination	Seth Lloyd

Quantum Illumination Publication Described First Viable Approach to a Quantum Radar

Entanglement

- A working definition of entanglement:
  - 2 separate systems are considered entangled if one or more of their properties can not be defined independent of each other
    - Entanglement gives rise to measurements of particle properties that are strongly correlated, independent of their separation
    - quantum state has to be described using a single, non-separable wavefunction



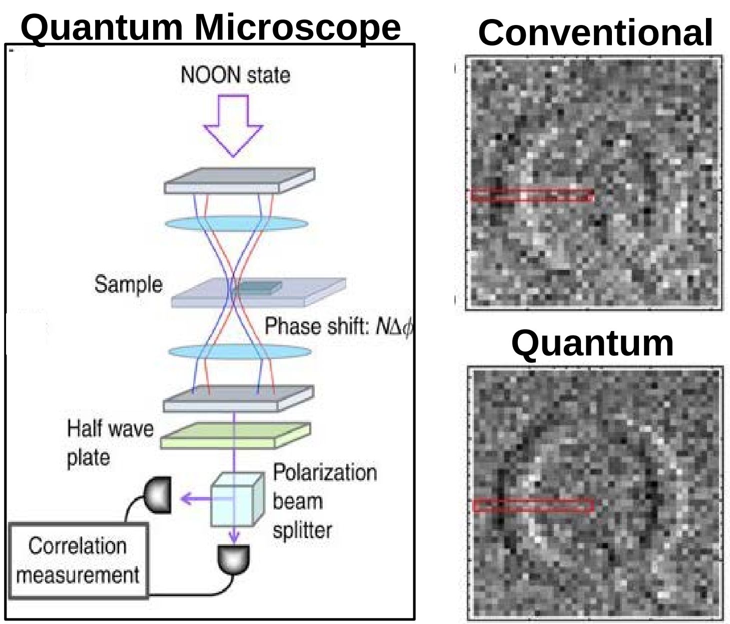
- Involves concepts which are truly difficult to fully accept
  - Entangled particles travel in a kind of superposition of all their possible states
    - Orthodox viewpoint*: entangled property doesn't exist until a measurement is made!
  - Once measured, the two entangled particles somehow instantly communicate to ensure their states have the proper values

* **Wheeler's delayed-choice gedanken experiment with a single atom**, *Nature Physics* **volume 11**, pages 539–542 (2015)

Why Entangle at All? What Can it Do For You?

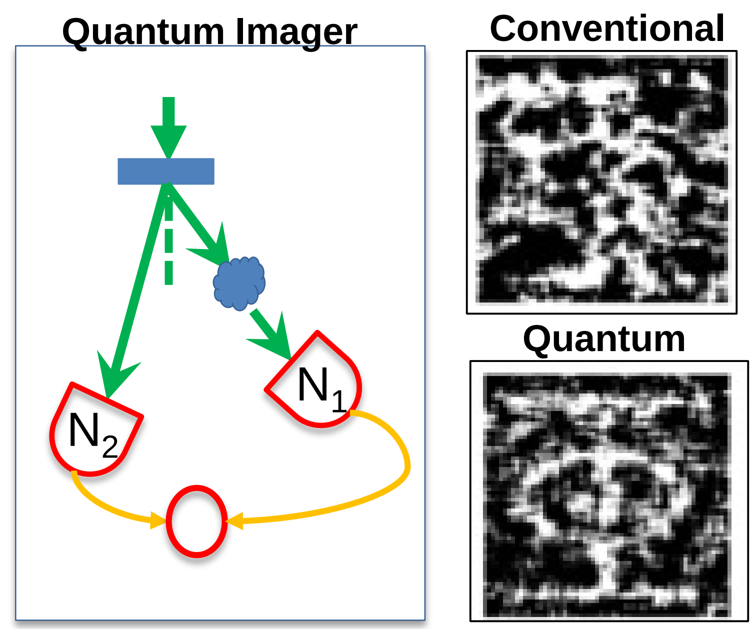
- Entanglement-based sensing can beat classical limits!

Exploit non-separable nature of entangled state to beat classical resolution limit



"An entanglement-enhanced microscope", Takafumi et al, 2013

Exploit correlations between entangled state observables to beat classical noise limit



"Photon-number correlation for quantum enhanced imaging and sensing", Meda et al 2017

Classes of Quantum Radar

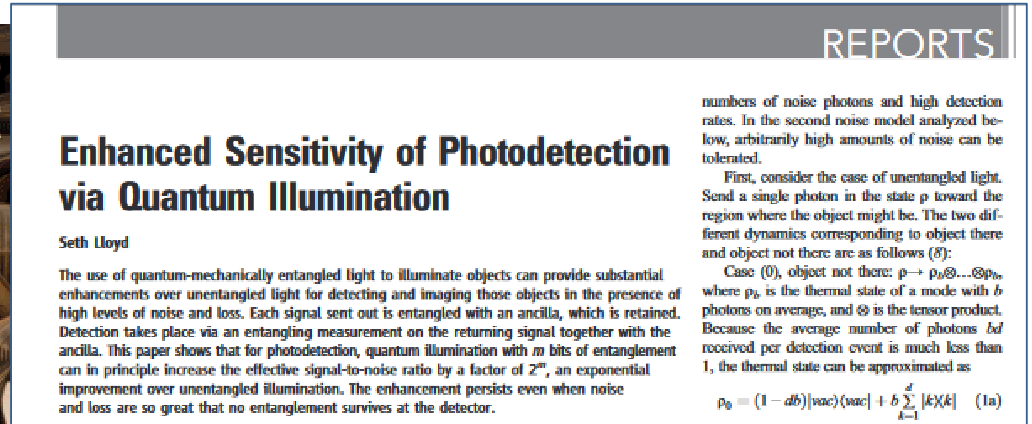
Class / Property	Interferometric	Single Photon	Enhanced Receiver	Quantum Illumination
Type	Active	Active	Passive	Active
Entanglement?	Yes	No	Yes	Yes
Operational Concept	Interferometer using entangled states of light	Radar using single photon at a time offers superior range resolution	Return signal is used to modulate a squeezed light signal generated inside receiver	Use entangled states of light to perform a quantum hypothesis test
Advantages	Superior phase resolution	Superior range resolution, no entanglement required	Enhanced SNR, classical source	Superior sensitivity, anti-spoof, Does not require entanglement to survive noisy environments
Challenges	Requires entanglement to survive propagation	Slow, short range	Complicated design, modest improvements in SNR	Requires significant advancements in numerous (& challenging!) quantum technologies

Currently, Quantum Illumination is Best Bet Going Forward

Outline

- Introduction
- Quantum Illumination
- Physics Challenges to Quantum Radar
- Outlook

Quantum Illumination



REPORTS

Enhanced Sensitivity of Photodetection via Quantum Illumination

Seth Lloyd

The use of quantum-mechanically entangled light to illuminate objects can provide substantial enhancements over unentangled light for detecting and imaging those objects in the presence of high levels of noise and loss. Each signal sent out is entangled with an ancilla, which is retained. Detection takes place via an entangling measurement on the returning signal together with the ancilla. This paper shows that for photodetection, quantum illumination with m bits of entanglement can in principle increase the effective signal-to-noise ratio by a factor of 2^m, an exponential improvement over unentangled illumination. The enhancement persists even when noise and loss are so great that no entanglement survives at the detector.

numbers of noise photons and high detection rates. In the second noise model analyzed below, arbitrarily high amounts of noise can be tolerated.

First, consider the case of unentangled light. Send a single photon in the state ρ toward the region where the object might be. The two different dynamics corresponding to object there and object not there are as follows (8):

Case (0), object not there: $\rho \rightarrow \rho_b \otimes \ldots \otimes \rho_b$, where ρ_b is the thermal state of a mode with b photons on average, and $\otimes$ is the tensor product. Because the average number of photons bd received per detection event is much less than 1, the thermal state can be approximated as

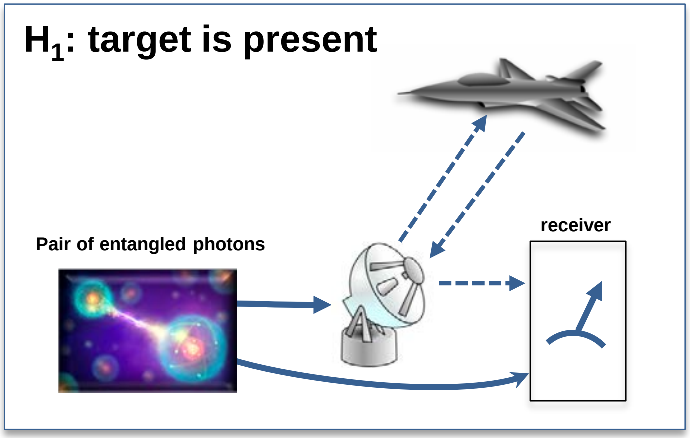
$$\rho_0 = (1 - db)|vac\rangle\langle vac| + b\sum_{k=1}^{d}|k\rangle\langle k| \quad (1a)$$

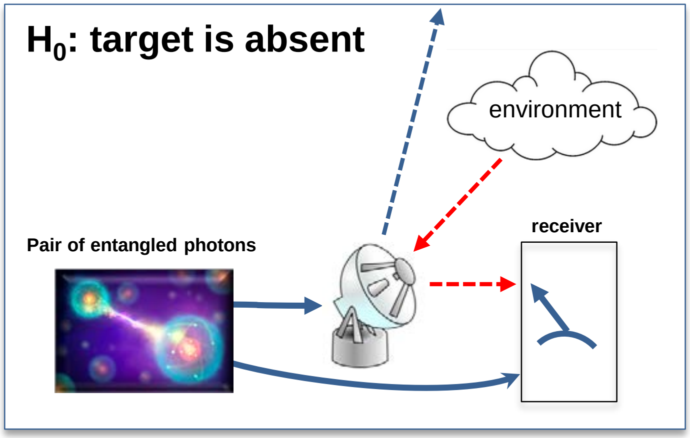
- Conventional radars shine light in direction of a suspected object, look for the reflection
  - Typically, only a very small fraction of the light makes its way back to radar
  - In noisy environments, detecting a weak signal in a strong background is hard
- Intuition: if you entangle the signal with an ancilla, then it will be harder for the noise to masquerade as the returning signal
  - Holds even in cases where noise and loss completely destroy the initial entanglement!

First feasible approach to a truly quantum radar

Quantum Hypothesis Test

- A Radar (quantum or conventional) is a device that lets us perform a hypothesis test

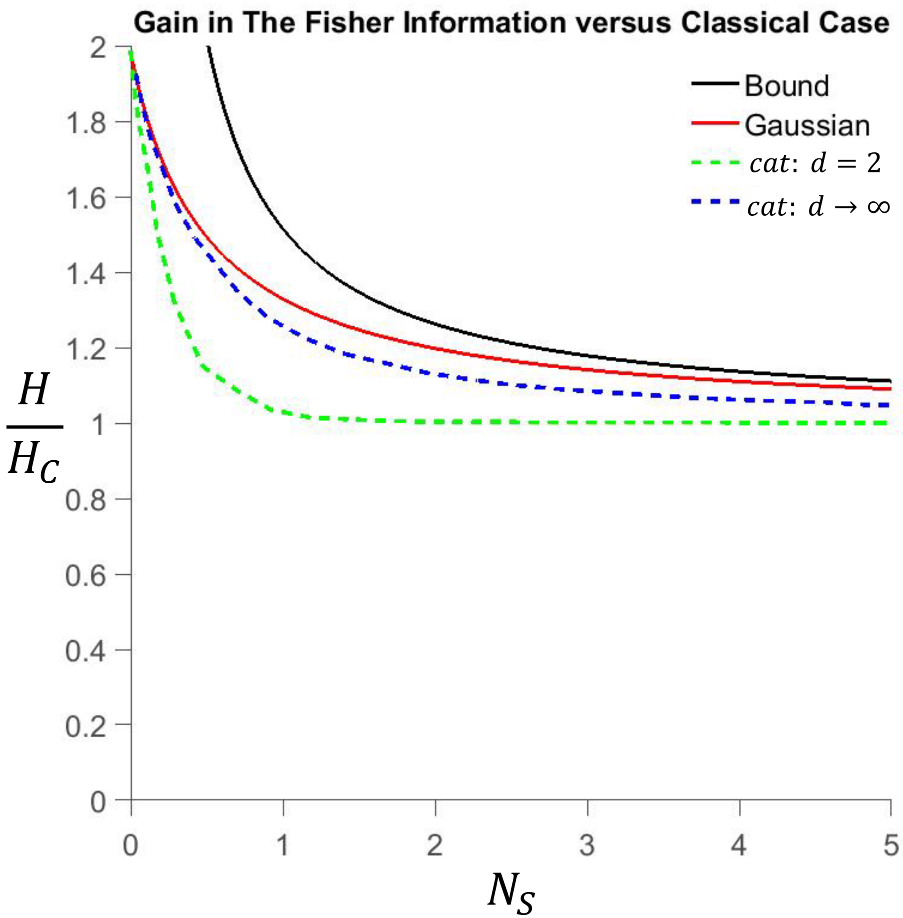




- In order to test our hypothesis, we need to collect evidence
  - Both kinds of radar use photons to collect information
  - Conventional radar uses coherent states, quantum radar uses entangled states

- For a confident decision, we will have to use many photons
  - In a low-loss, low-noise scenario, a single photon would suffice
  - Information capacity of entangled states > coherent states
  - Quantum radars can collect more information using less photons → very sensitive!

Information Capacity of Entangled States

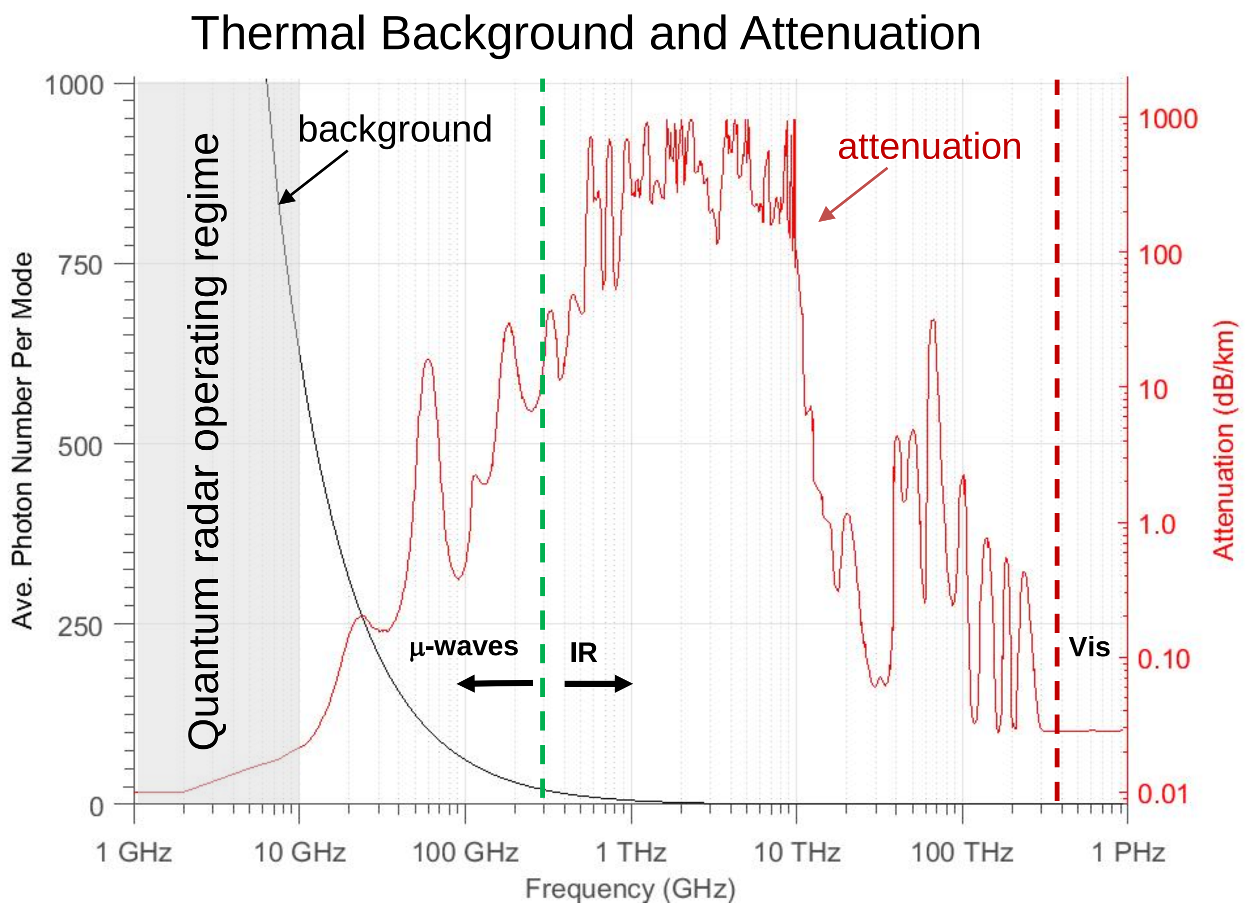


- Quantum Estimation Methods for Quantum Illumination
  - PRL 118, 070803 2017
  - Considered problem of estimating reflectivity parameter for Quantum Illumination
  - Treated near-term, sub-optimal receiver performance based on local measurements
  - Provides analytical bounds on Quantum Fisher Information (H) for various quantum states (Coherent, Gaussian & Schrödinger Cat)
  - Shows that probability of error, $P_{I,II}$, in performing binary hypothesis scales exponentially with number of trials, M (i.e. the number of photons) and the information capacity of the state, H :

$$P_{I,II} \propto e^{-HM}$$

Quantum States with High Information Content Provide Better Performance

Quantum Illumination Works Best Using Microwaves

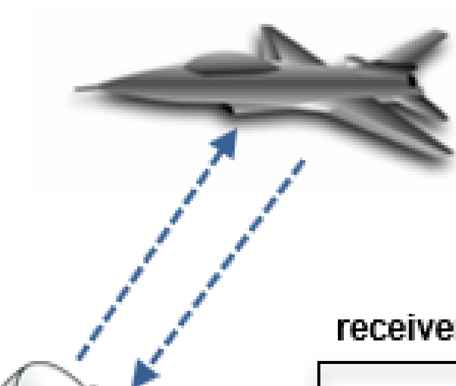


- Quantum illumination provides benefits over conventional radar in cases where **background is high** and **target is small**
  - Low attenuation, high background levels favor operation at microwave frequencies

Considerations For Modeling Performance

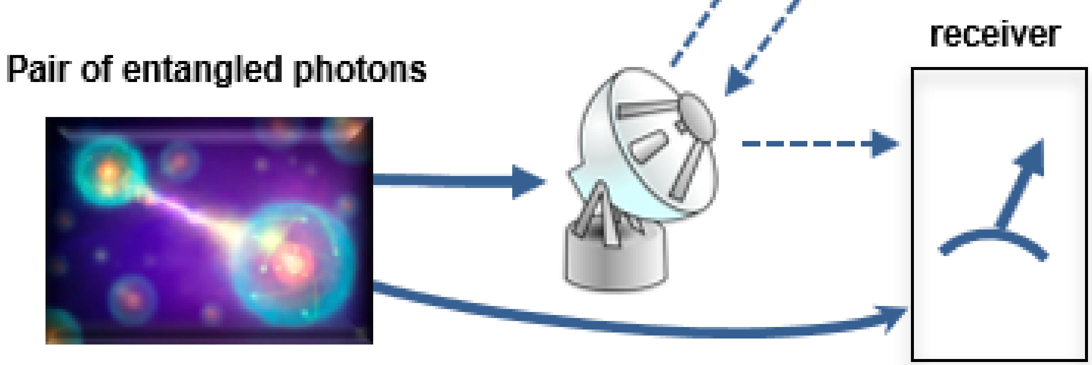
Entangled photon states diffract and propagate just like coherent states

→ treat propagation losses in same manner as conventional radar



Model target response as simple beam splitter

- known amplitude, constant phase
- unknown amplitude, variable phase



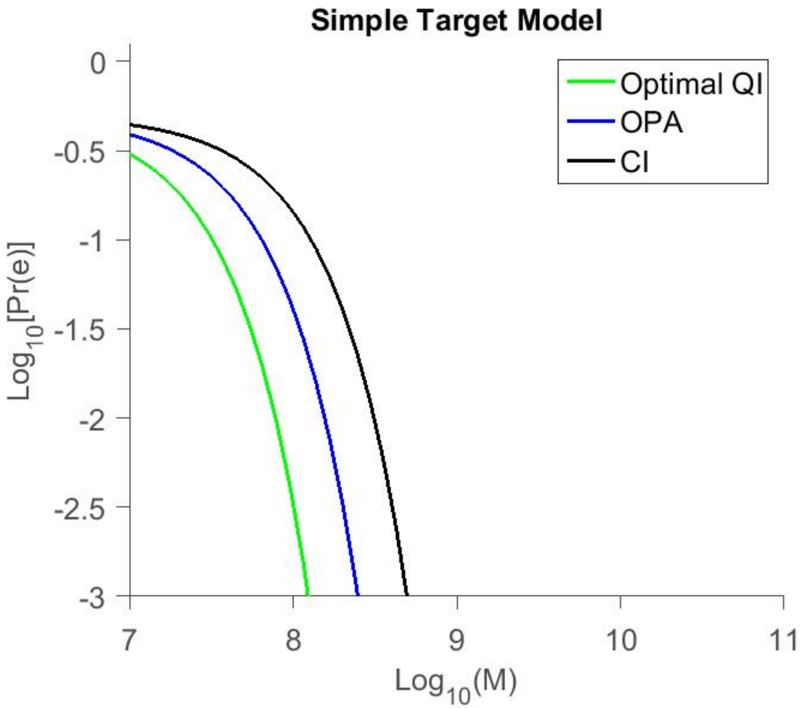
Receiver performance can be estimated in simple way using Bernoulli statistics

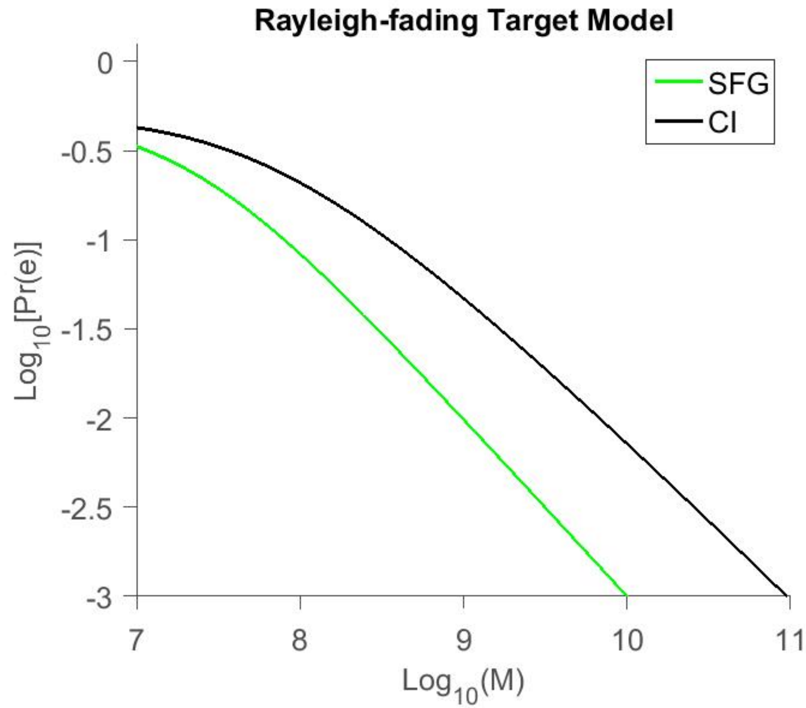
→ how many photons do we have to count in order to confidently distinguish signal from thermal background

Higher levels of entanglement result in significant increases in the Signal-to-Noise ratio (m = bits of entanglement)

→ $SNR \propto 2^m$

Expected Performance



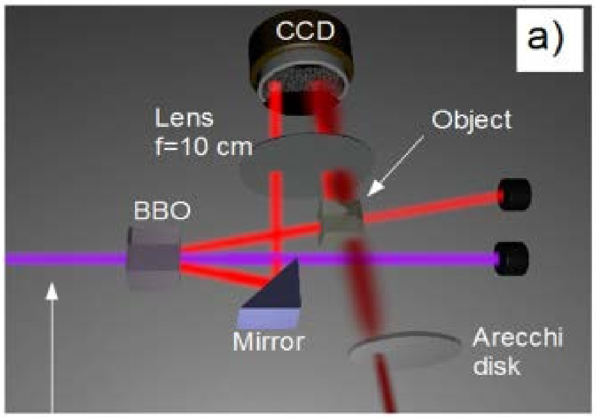


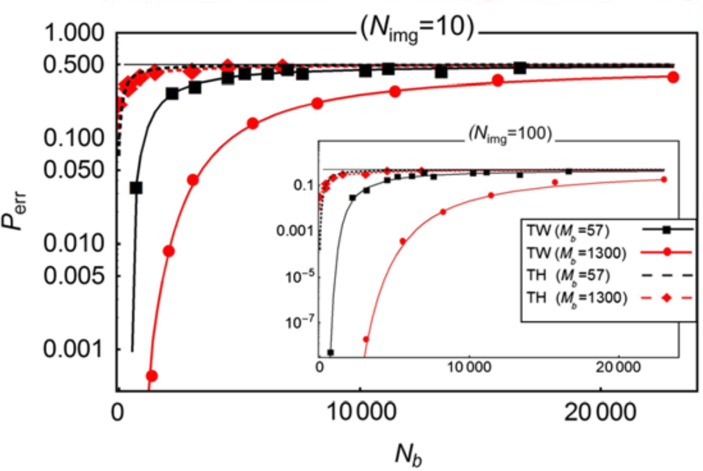
Results obtained from equations derived in: **Quantum illumination for enhanced detection of Rayleigh-fading targets,** Phys. Rev. A 96, 020302 (2017)

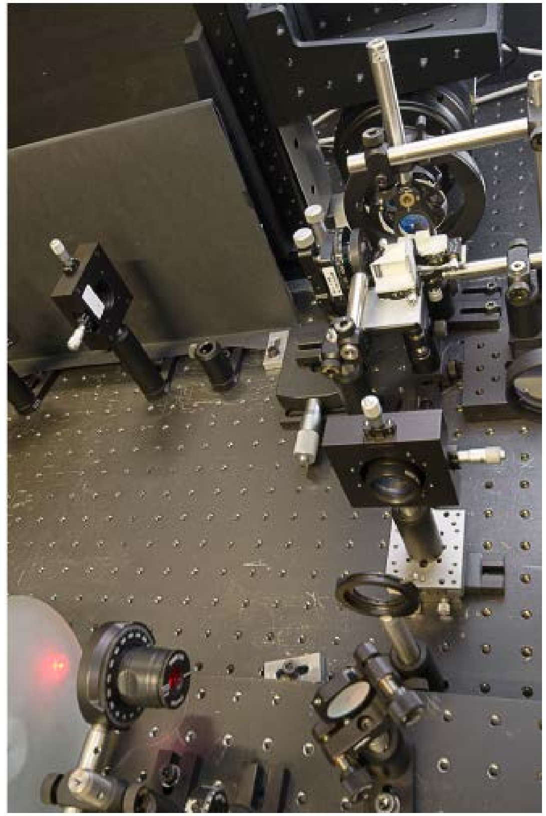
Realistic target models significantly impair optimum quantum reception
- Few target model classes exhibit constant phase for the return signal
- Many targets will scintillate, return phase well represented as uniform random
- Rayleigh-fading QI target detection has an error probability that decreases sub-exponentially with increasing photon number

Experimental Realization of Quantum Illumination

Lopaeva et al 2013 PRL 110, 153603



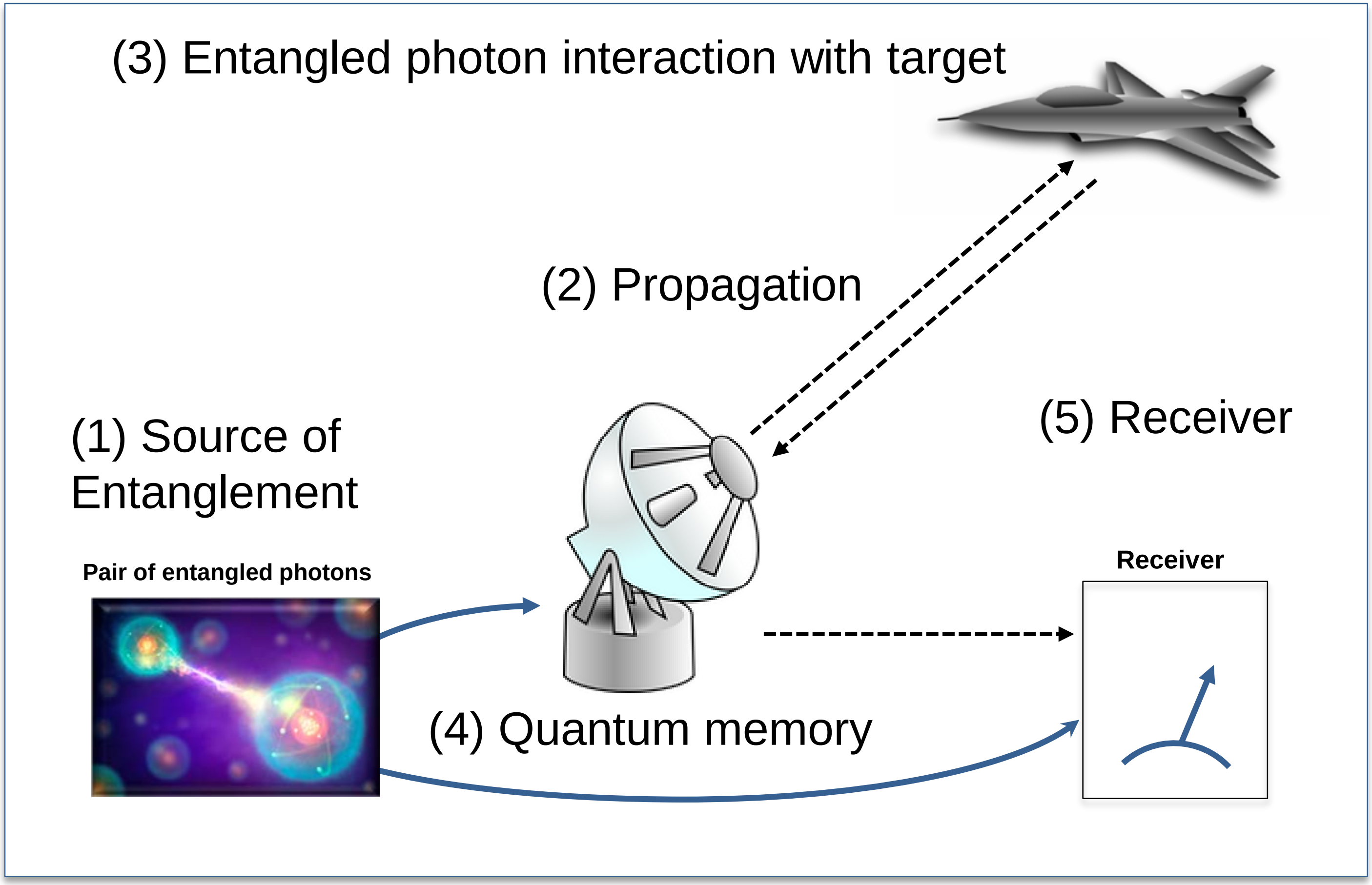




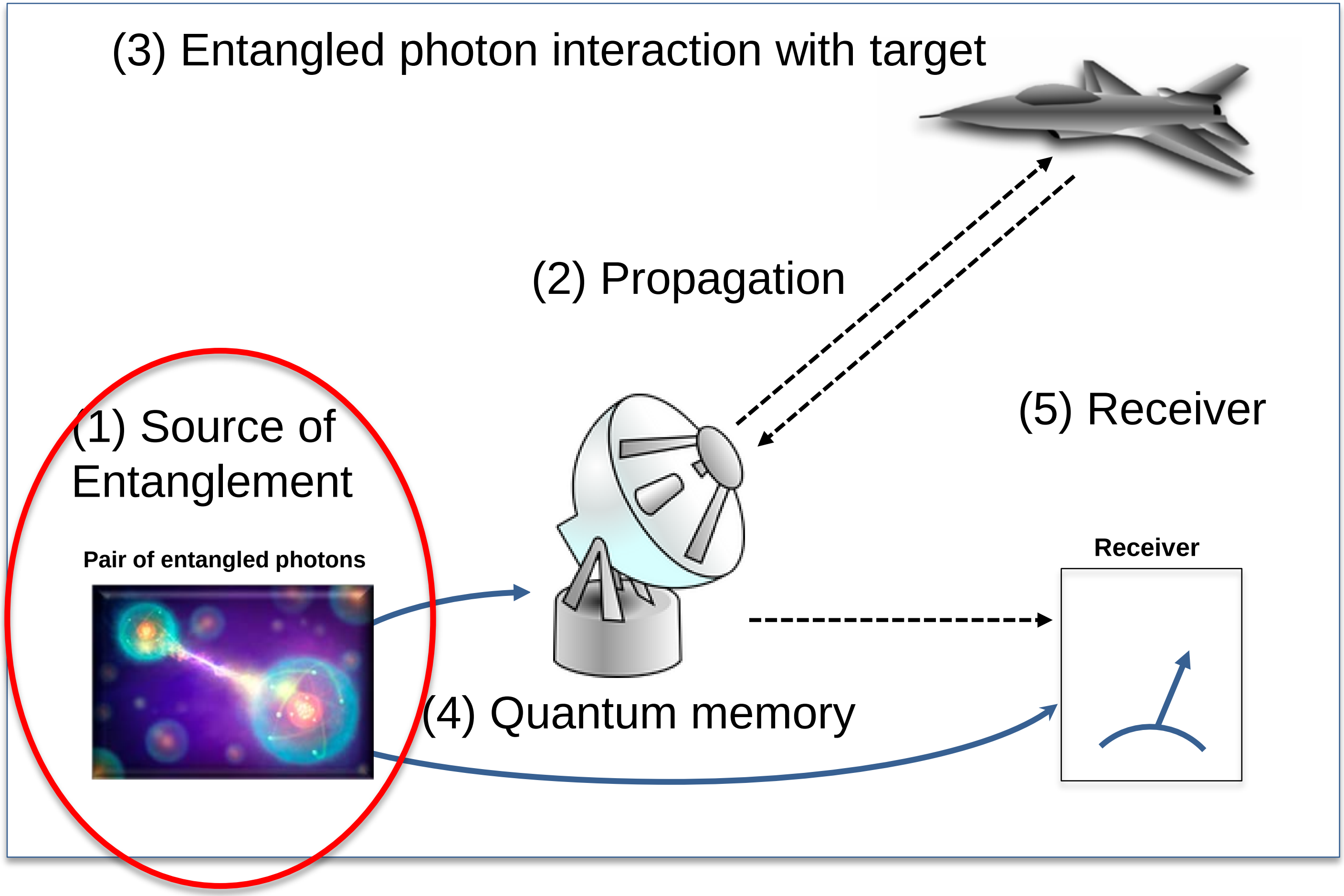
- SPDC source using a BBO crystal to generate two intensity-correlated light beams in orthogonal polarizations.
- Detection was performed using coincidence counter
- The target object was a beam splitter, placed in one of the two entangled beams before detection.
  - The beam splitter object was also illuminated by photons scattered on an Arecchi's rotating ground glass to simulate a thermal environment.

First experimental implementation showed robustness against noise and losses, demonstrated a quantum enhancement in entanglement-breaking environments

Key Physics Challenges Facing Quantum Radar

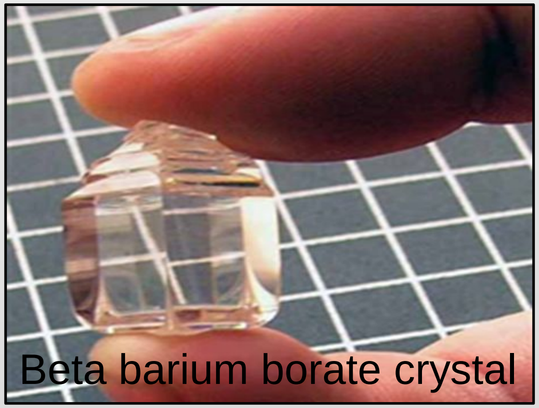


Key Physics Challenges Facing Quantum Radar



Sources of Entanglement

Spontaneous Parametric Down Conversion

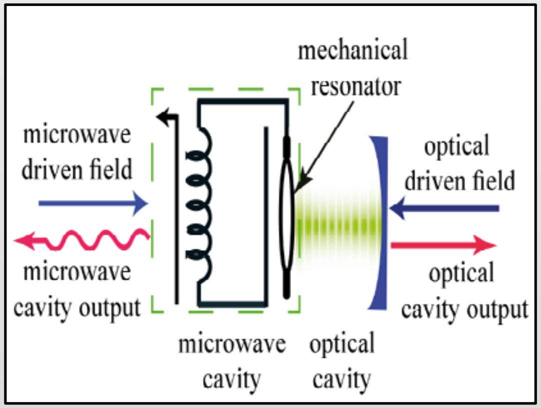


A nonlinear optical process where a photon spontaneously splits into 2 lower energy photons (which are entangled)

Requires nonlinear optical properties (e.g. found in BBO crystals)

Only works at low powers

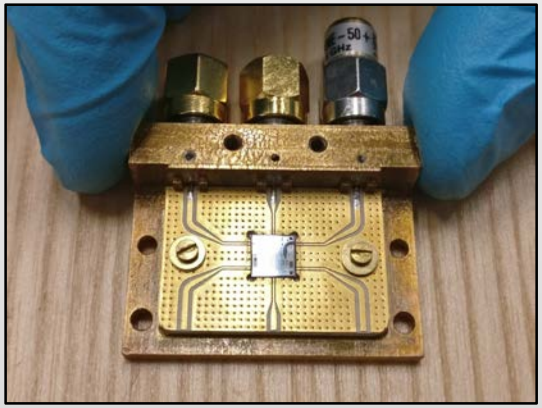
Optical-Microwave Hybrid



Generate entangled photons in visible spectrum, convert them to microwaves for propagation to/from target, see "Microwave Quantum Illumination", Barzanjeh et al

Difficult to fabricate, limited to low powers

Direct Generation at Microwave Frequencies



Generate entangled photons in microwave spectrum using a superconducting Josephson parametric amplifier, see "Microwave Quantum Radar: An Experimental Validation", Luong et al

Has long term potential as bright source of entanglement

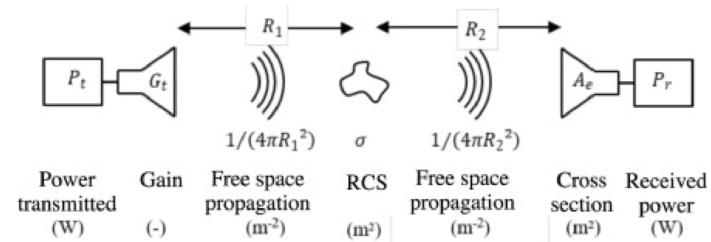
How Many Entangled Photons Can We Create?

How many do we need to create?

Conventional Radar Type	Freq.	Pulse width	Peak Power	# of Photons Transmitted	# of Photons Received (assume 1 m^2 antenna, 1 m^2 RCS)			
					1 km	10 km	100 km	1000 km
AN/SPS-40 	400-450 MHz	60 us	250 kW	5.3×10^{25}	8.5×10^{12}	8.5×10^{8}	85069	8.5
PAVE PAWS 	420-450 MHz	0.25-16 ms	600 kW	3.3×10^{28}	5.5×10^{15}	5.5×10^{11}	5.5×10^{7}	5,572

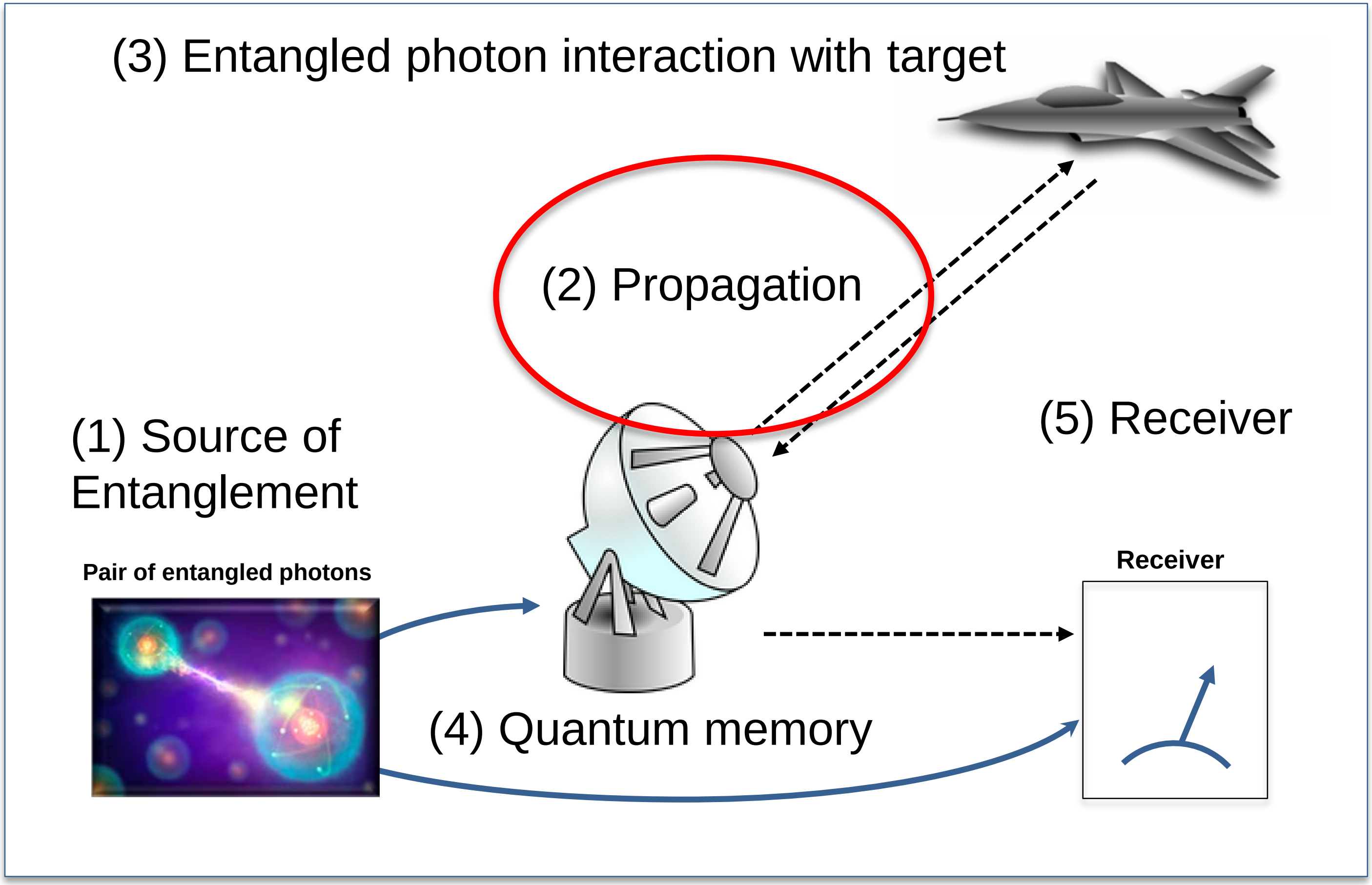
Source: Radar Handbook, 2nd Ed., 1990, Skolnik

Example quantum source:
"High fidelity field stop collection for polarization-entangled photon pair sources", 2018, Lohrmann et al.
A very bright source of entangled pairs: 100,000 pairs/s/mW
1 μs pulse at 1 mW: 0.1 pairs per pulse
1 W: 100
1 kW: 100,000

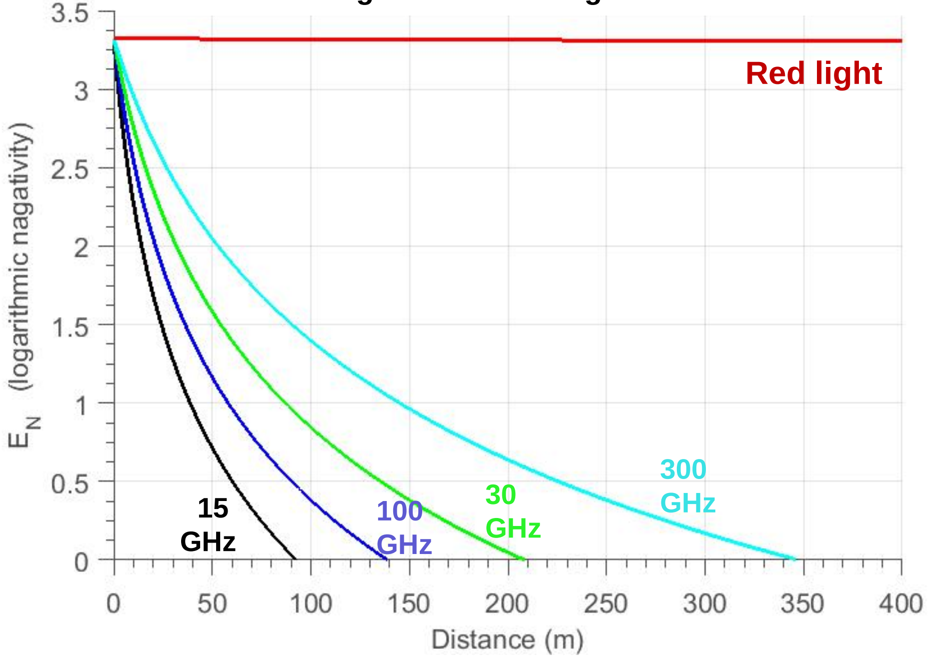


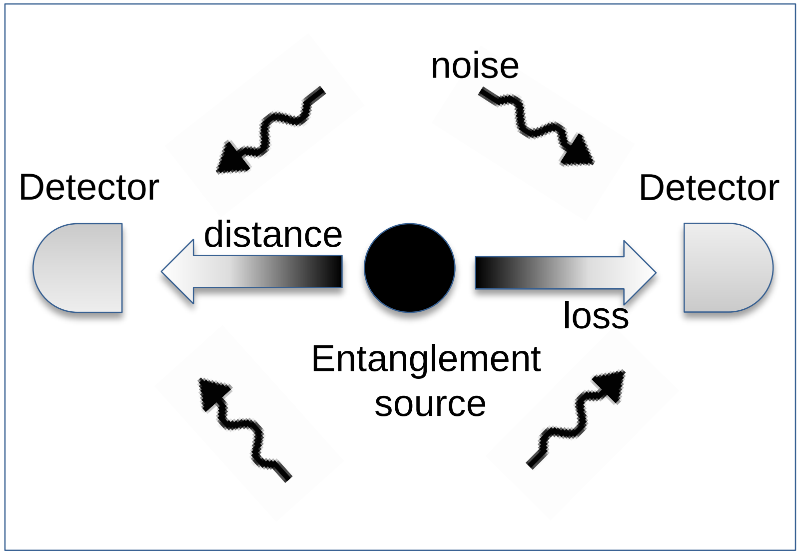
High Levels of Brightness Required to Achieve Long Range

Key Physics Challenges Facing Quantum Radar



Exploiting Entanglement in Noisy, Lossy Environments is Hard



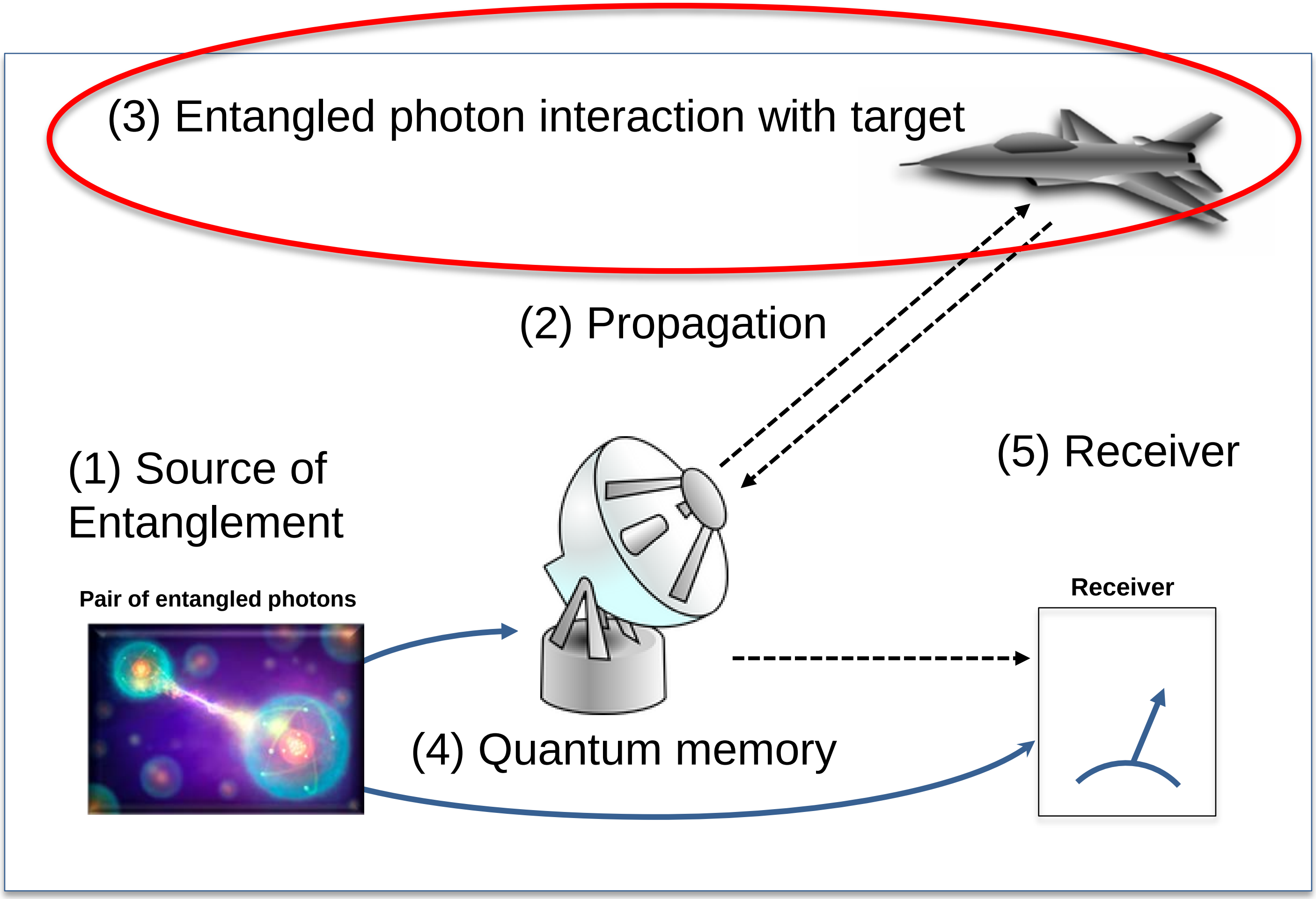


see "Quantum entanglement distribution in next-generation wireless communications systems" for details

- Entangled states are fragile
  - Whenever a system interacts with environment, information, energy & momentum are exchanged
  - This interaction with environment will typically single out a preferred set of states
    - see "Quantum Darwinism", *Nature Physics* volume 5, pages 181–188 (2009)

- Quantum Illumination benefits scale with Quantum Discord
  - Quantum discord quantifies the nonclassical correlations between two particles
    - See "How discord underlies the noise resilience of quantum illumination", N. J. of Physics, Vol 18 (2016)

Key Physics Challenges Facing Quantum Radar



Can entanglement survive interacting with target?

letters to nature

Plasmon-assisted transmission of entangled photons

E. Altewischer, M. P. van Exter & J. P. Woerdman

Leiden University, Huygens Laboratory, PO Box 9504, 2300 RA Leiden, The Netherlands

In order to confirm this f
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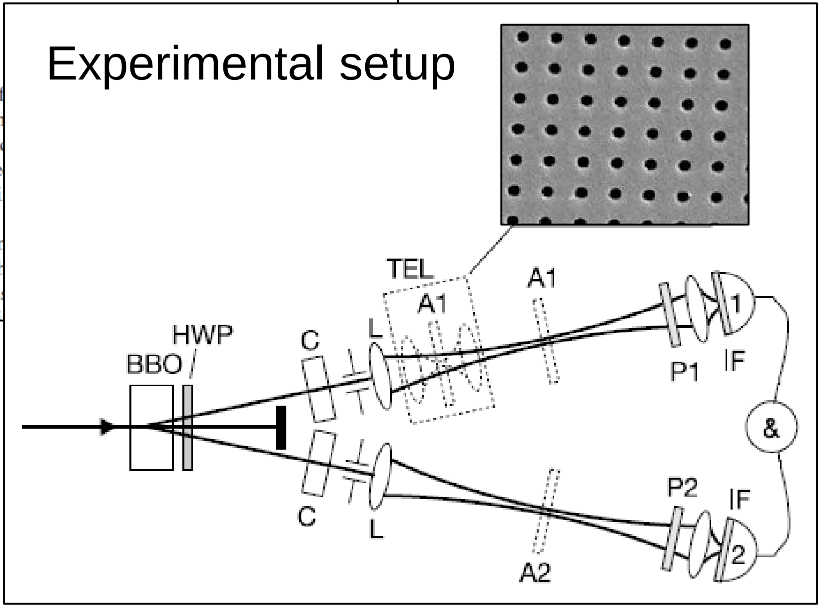
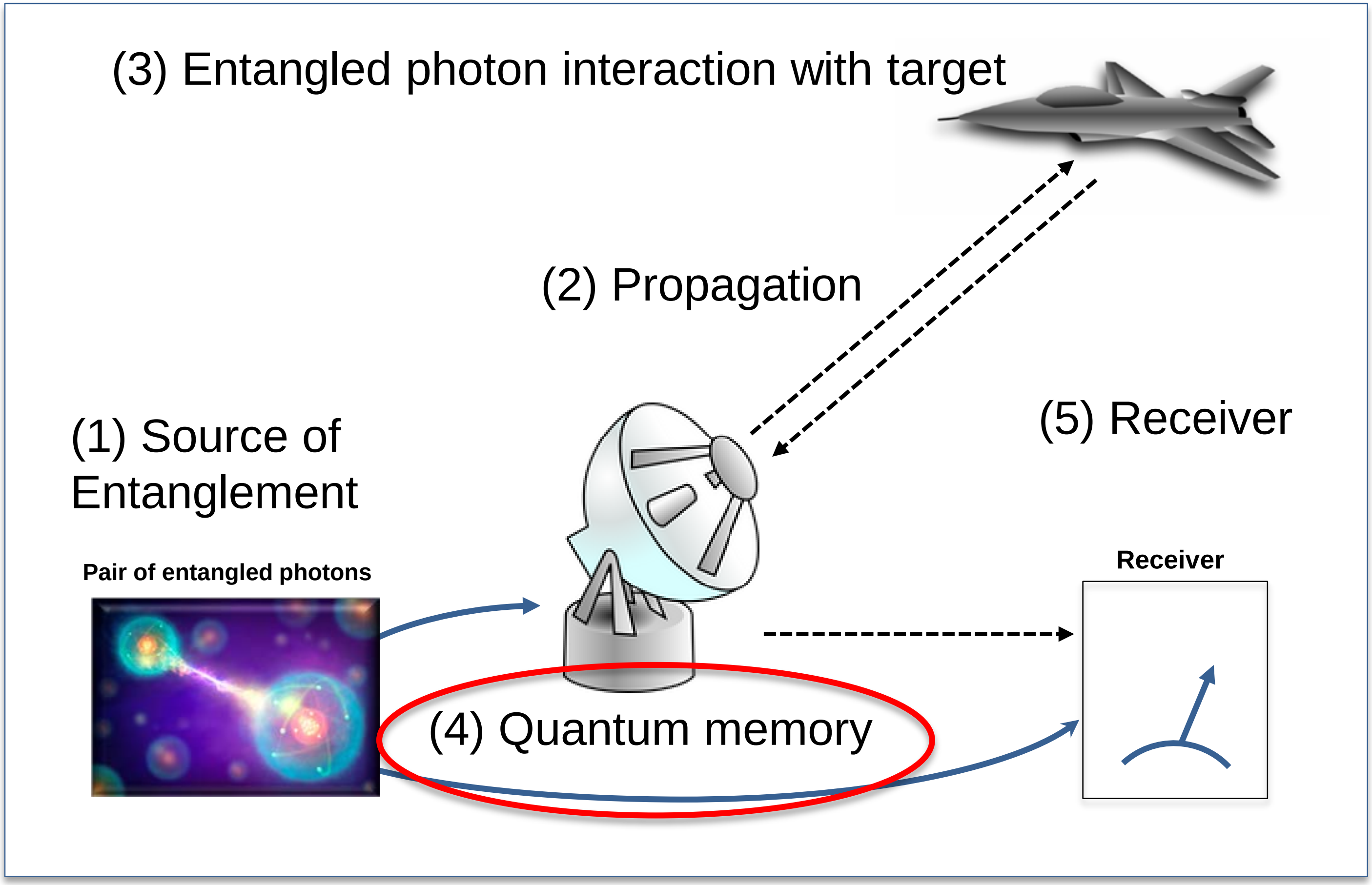


- What happens when entangled photons bounce off a mirror??
  - Experiment designed to study entanglement transfer between quantum systems
  - Experiment: Generate a pair of entangled photons, direct 1 photon onto gold foil with sub-wavelength holes, other photon travels unimpeded
  - Result: Coincidence measurements confirm photons still entangled despite the photon → plasmon → photon state transitions

Limited experimental experience shows photon-target interactions do not necessarily destroy entanglement-based correlations

Key Physics Challenges Facing Quantum Radar

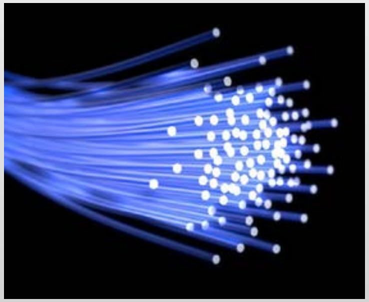


Quantum Memory

- Quantum Illumination protocol requires storage of idler signal
  - 3 dB of storage loss will negate any quantum benefit, requires low loss storage
  - In order to support radar search function, storage device will have to be engineered with a tunable coupler
    - Weak coupling to provide long storage times
    - Strong coupling to allow rapid extraction of photons for performing joint measurement at desired time

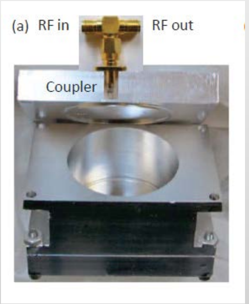
A few options:

Fiber Optic Loop



Best fiber attenuation limits maximum range to 11 km, fixed storage times

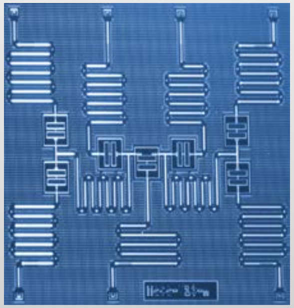
RF Cavity



"Reaching 10 ms single photon lifetimes for superconducting aluminum Cavities", Appl. Phys. Lett. 102, 192604 (2013)

Long life-times, potential for tunable coupler. Can handle high powers

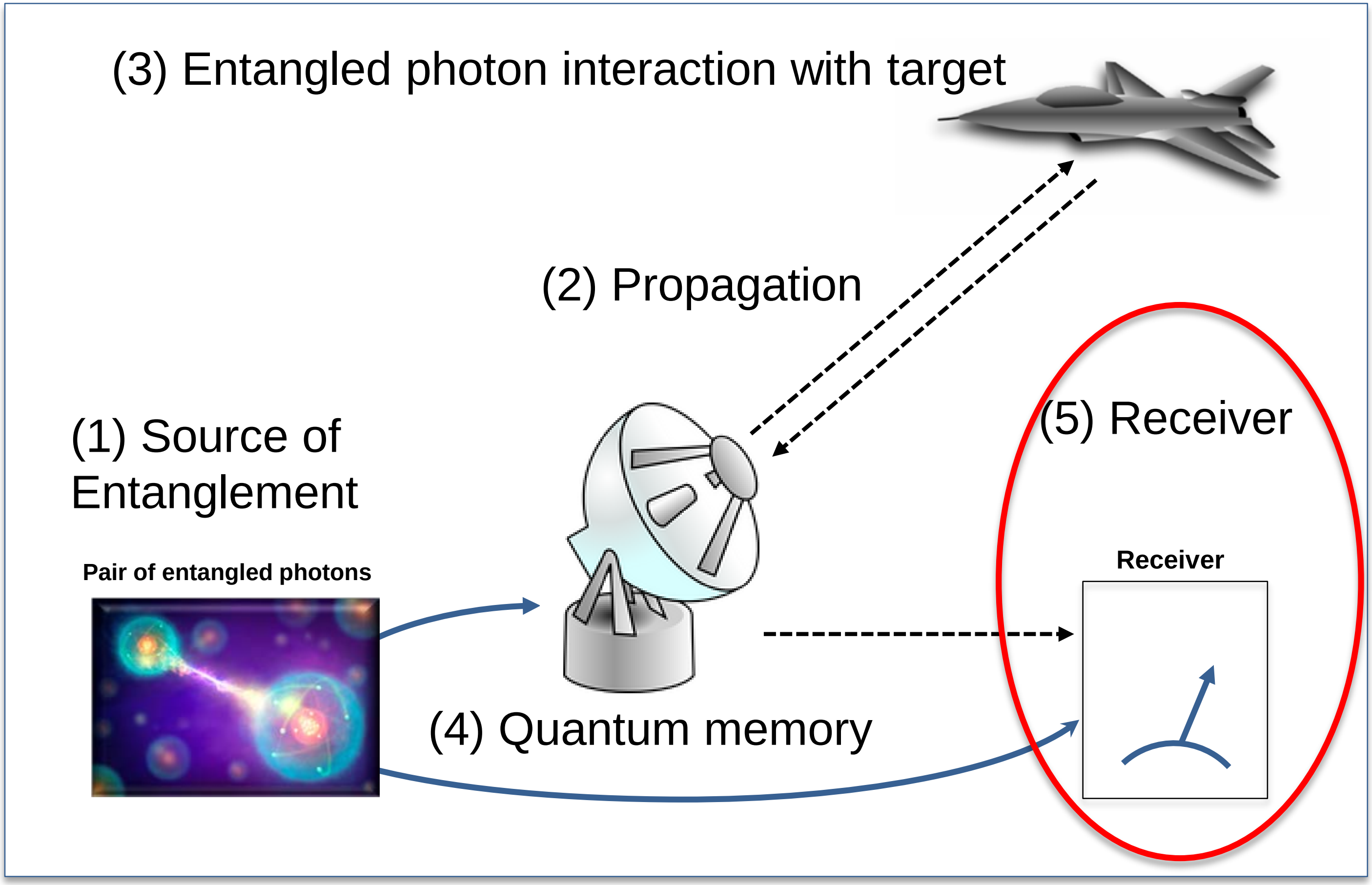
Qubit



IBM 7 Qubit Device

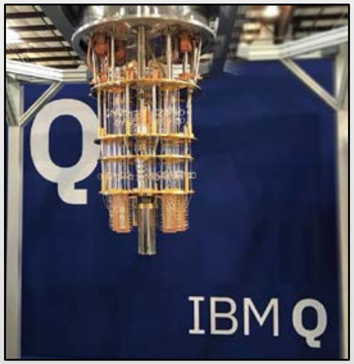
Potential to be integrated directly into receiver

Key Physics Challenges Facing Quantum Radar



Quantum Illumination Receivers

Helstrom Receiver

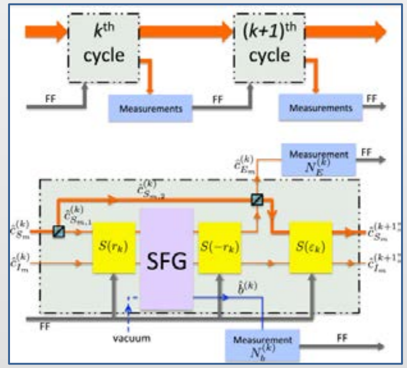


Helstrom studied how to optimally perform binary Quantum Hypothesis

Optimal performance requires performing a joint measurement of the photons used in the hypothesis test

Difficult to do for large numbers of photons. Optimal performance can be asymptotically achieved by using a quantum computer and performing a Quantum Schur Transform

Sum Frequency Generation

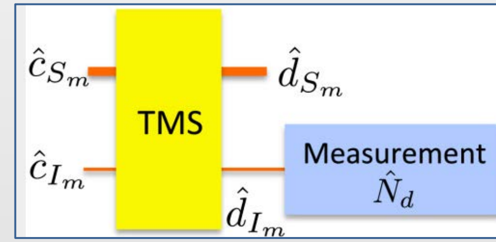


"Entanglement-enhanced Neyman–Pearson target detection using quantum illumination", J. of Opt. Soc B, vol. 34, 2017

Asymptotically optimal in constant amplitude case, difficult to implement

SFG is essentially the inverse of Spontaneous Parametric Down Conversion, M independent signal-idler mode pairs with the same phase-sensitive cross correlation can combine to produce a photon at the pump frequency

Optical Parametric Amplifier



"Gaussian-state quantum-illumination receivers for target detection" Phys. Rev. A 80, 052310 (2009).

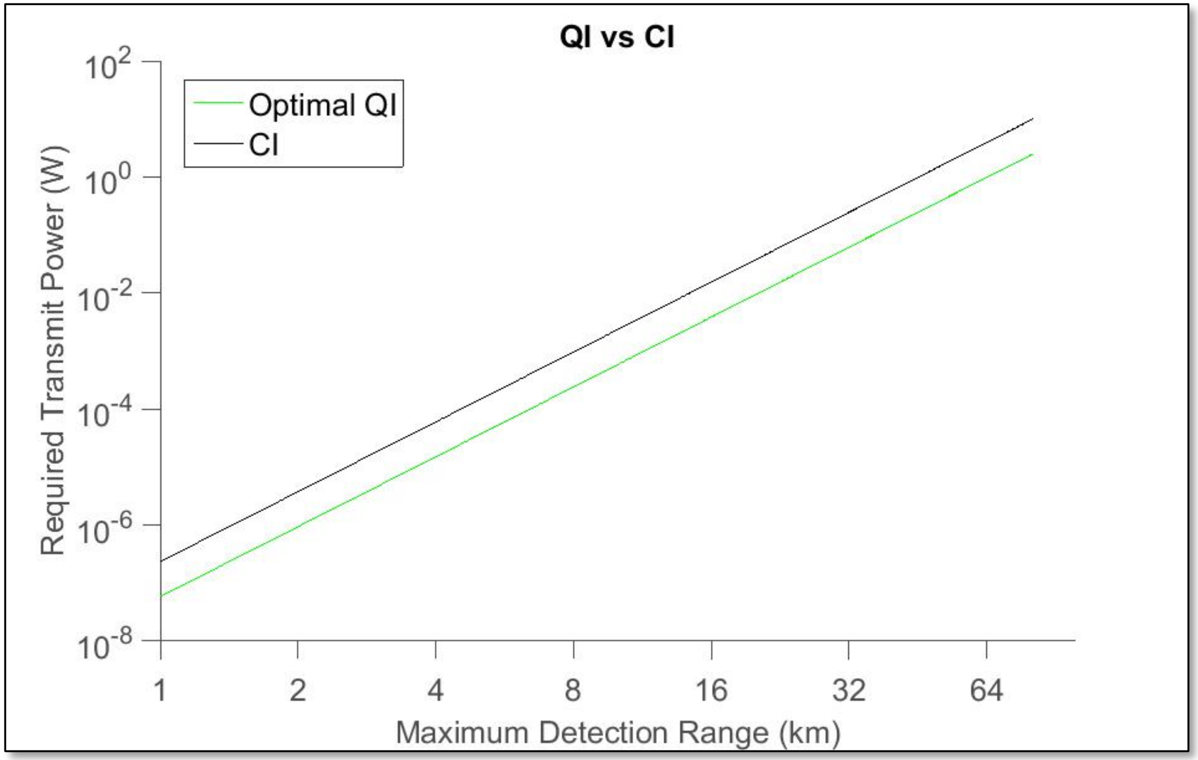
Sub-optimal, but can be implemented

Send photon pair, along with a pump beam, through an OPA. This essentially implements a number operator measurement (counting photons) on the photons emerging from the OPA crystal

For entangled states, the expected value of the number operator yields a slightly larger value than would be present if the photons were not entangled (i.e. background).

Expected Performance

- Example: Determine the power required to reliably detect a small object at a range R with a single pulse
  - Thermal background
  - 1 m^2 antenna
  - 1 m^2 object size
  - Pulse width of 1 msec
  - 4-8 GHz band (6 GHz)
  - Both radars (conventional, quantum) required to achieve SNR > 12 dB for detection
  - Assume Quantum radar performs optimally, uses SPDC entanglement source
  - Assume multi-pair production processes have been mitigated



For details, see: **Quantum illumination for enhanced detection of Rayleigh-fading targets,** Phys. Rev. A 96, 020302 (2017)

Quantum Radar Outperforms Conventional Radar, but Requires Extraordinary Bright Source of Entanglement

Summary

- Many physics-based challenges to implementing quantum illumination that have yet to be addressed
  - Classical radars can interrogate many potential target bins with a single pulse, yet current models of quantum radar may only query a single polarization, azimuth, elevation, range, Doppler bin at a time.
  - Creating sources with high brightness & entanglement
  - Better understanding of the photon → target → photon state transfer
  - Quantum memory with long lifetime and tunable coupling
  - Developing receivers that can achieve optimal performance for realistic target models
    - Random-amplitude targets and radar clutters seriously impair QI performance, issue should be addressed.

- The ultimate performance achievable by a quantum radar remains an open question
  - Addressing physics-based challenges will be key!

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