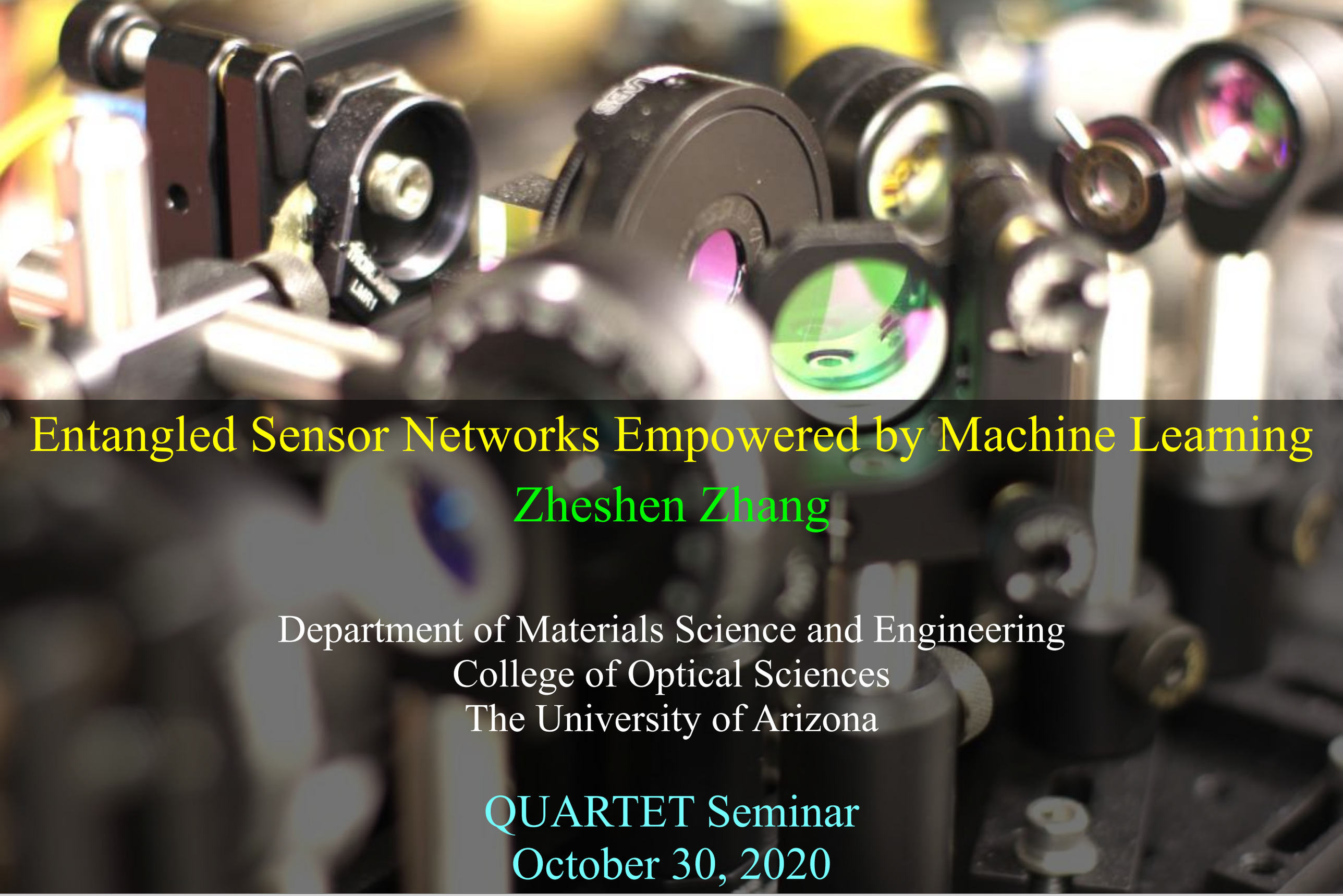


Entangled Sensor Networks Empowered by Machine Learning

Zheshen Zhang

Department of Materials Science and Engineering
College of Optical Sciences
The University of Arizona

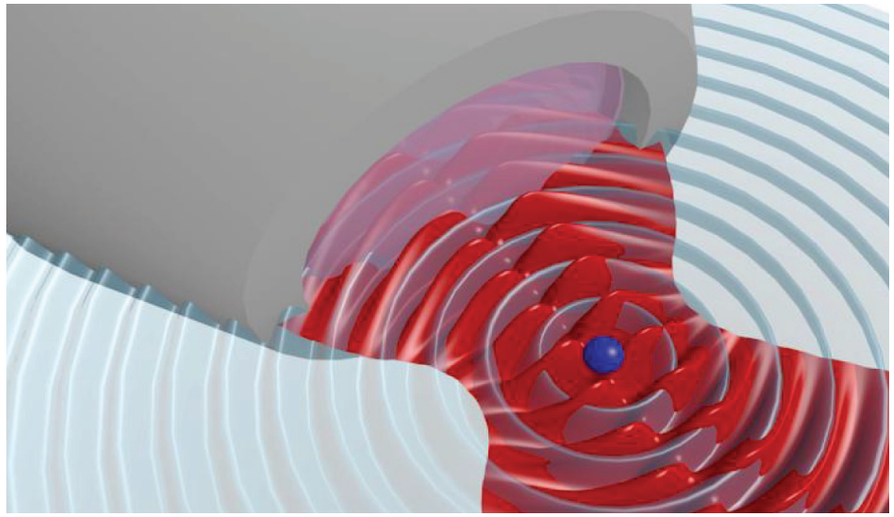
QUARTET Seminar
October 30, 2020

Quantum Sensing Applications

Gravitation-wave detection

Nature Photon. **7,** 613–619 (2013)

Biological imaging

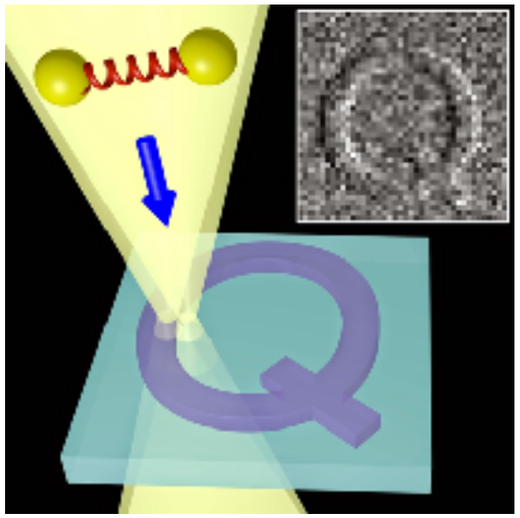


Nature Photon. **7,** 229–233 (2013)

Time-keeping

Nature Phys. **10,** 582 (2014)

Microscopy



Nature Comm. **4,** 2426 (2013)

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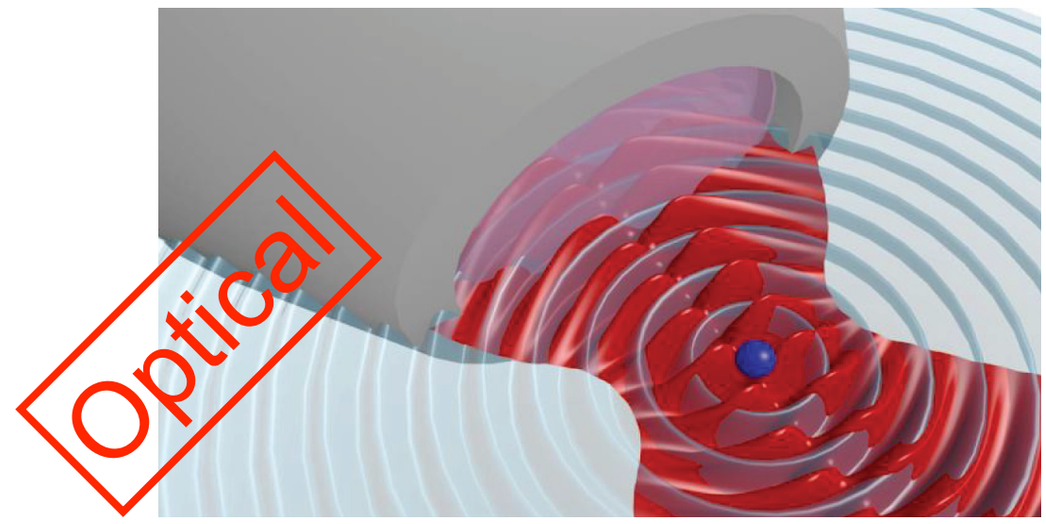
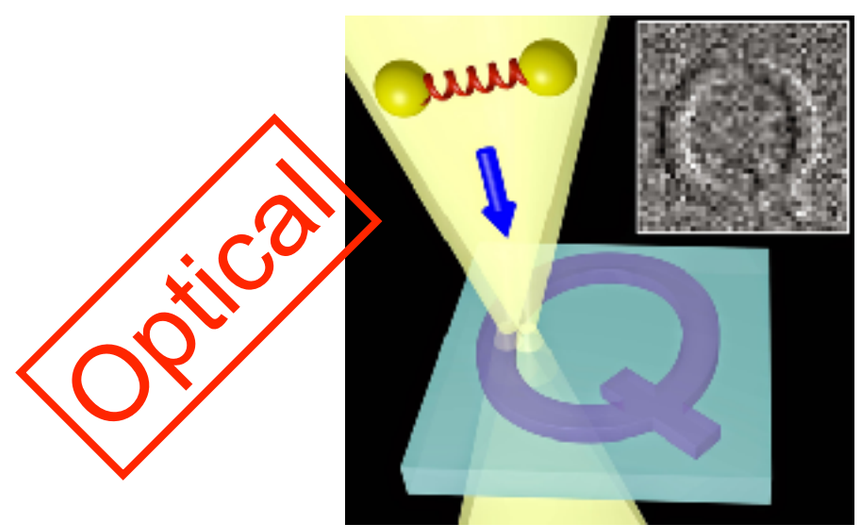


Nature Photon. **7,** 229–233 (2013)

Time-keeping

Nature Phys. **10,** 582 (2014)

Microscopy



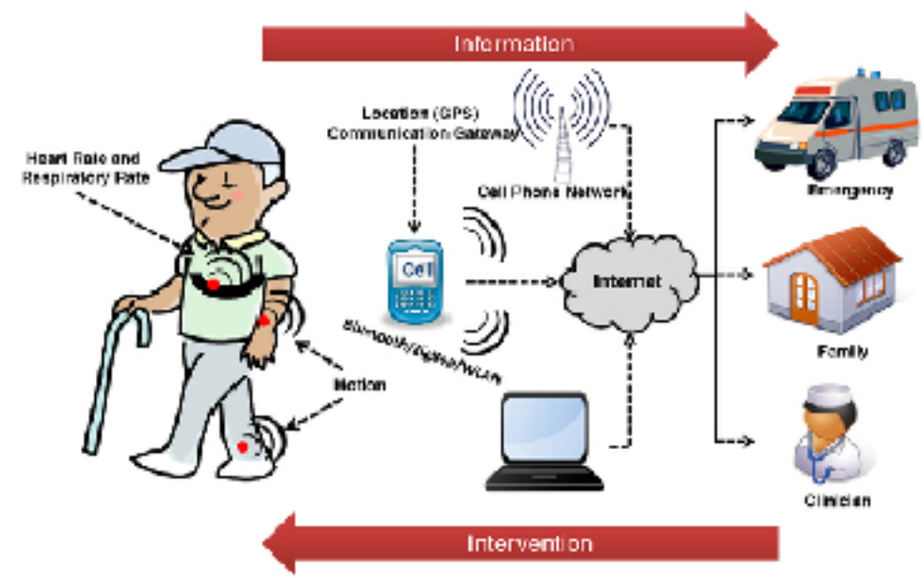
Nature Comm. **4,** 2426 (2013)

Radio-frequency (RF) Sensing

But many sensing tasks are not in the optical domain!

Global Position System

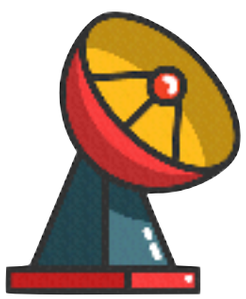
Health Monitoring



Radar & Target Detection

Object Tracking

Quantum Illumination Target Detection



Entanglement transmitter

target present

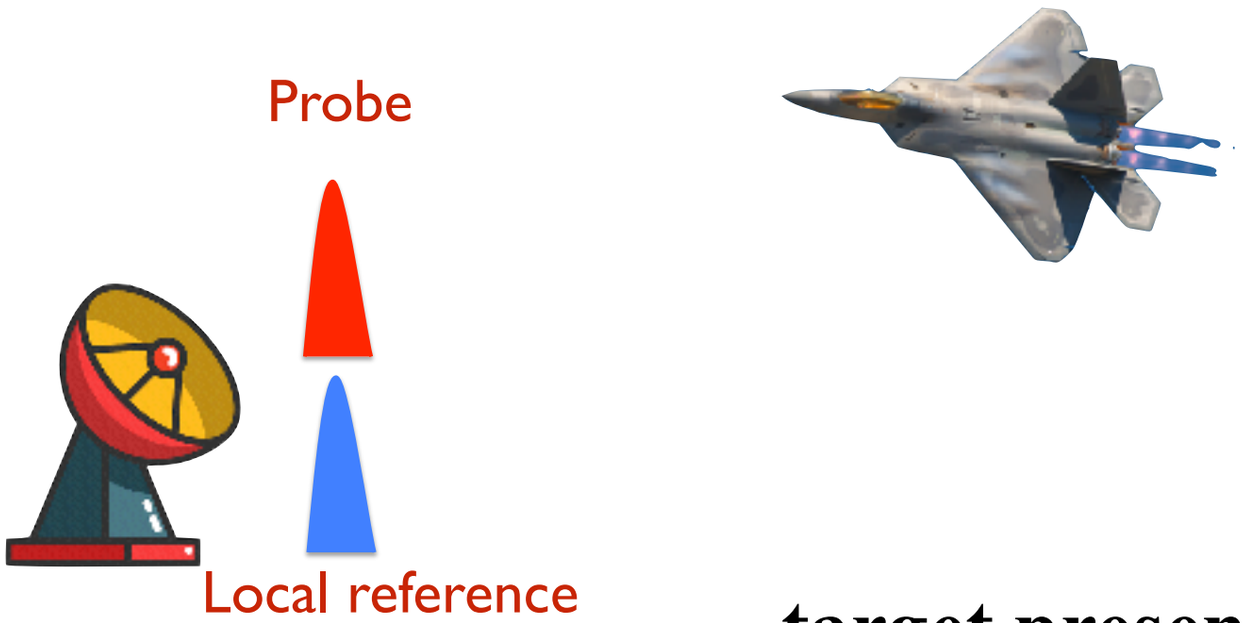
Quantum receiver

Entanglement transmitter

target absent

Quantum receiver

Quantum Illumination Target Detection



Quantum Illumination Target Detection

Radar return

Retained reference

Entanglement transmitter

target present

Quantum receiver

Entanglement transmitter

target absent

Quantum receiver

Quantum Illumination Target Detection

Radar return

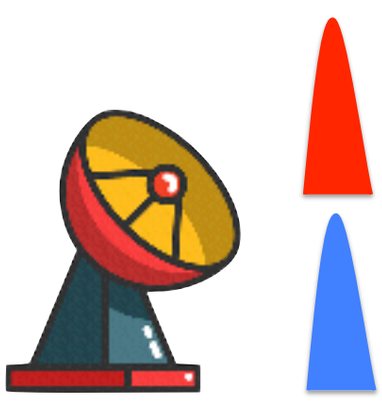
Retained reference

Entanglement transmitter

target present

Quantum receiver

Probe



Local reference

Entanglement transmitter

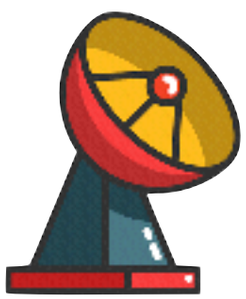
target absent

Quantum receiver

Quantum Illumination Target Detection

Radar return

Retained reference

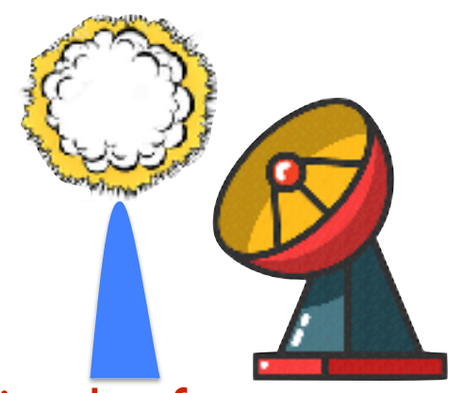


Entanglement transmitter

target present

Quantum receiver

Radar return



Retained reference

Entanglement transmitter

target absent

Quantum receiver

Signal-to-Noise Ratios (SNRs)

Quantum Illumination

$$\mathrm{SNR}_Q \propto \frac{\kappa_S N_S}{N_B}$$

Classical Illumination

$$\mathrm{SNR}_C \propto \frac{\kappa_S N_S}{2N_B}$$

$$\frac{\mathrm{SNR}_Q}{\mathrm{SNR}_C} = 2$$

Quantum radar ideally outperforms the classical radar by 3 dB at the same signal power level

Quantum Illumination Works

Theory

S. Lloyd, Science **321**, 1463 (2008)

S.-H. Tan *et al.*, Phys. Rev. Lett. **101**, 253601 (2008)

S. Guha and B. I. Erkmen, Phys. Rev. A **80**, 052310 (2009)

S. Barzanjeh *et al.*, Phys. Rev. Lett. **114**, 080503 (2015)

Q. Zhuang *et al.*, Phys. Rev. Lett. **118**, 040801 (2017)

Q. Zhuang *et al.*, Phys. Rev. A **96**, 020302(R) (2017)

A. Karsa *et al.*, Phys. Rev. Research **2**, 023414 (2020)

Experiment

E. D. Lopaeva *et al.*, Phys. Rev. Lett. **110**, 153603 (2013)

Z. Zhang *et al.*, Phys. Rev. Lett. **114**, 110506 (2015)

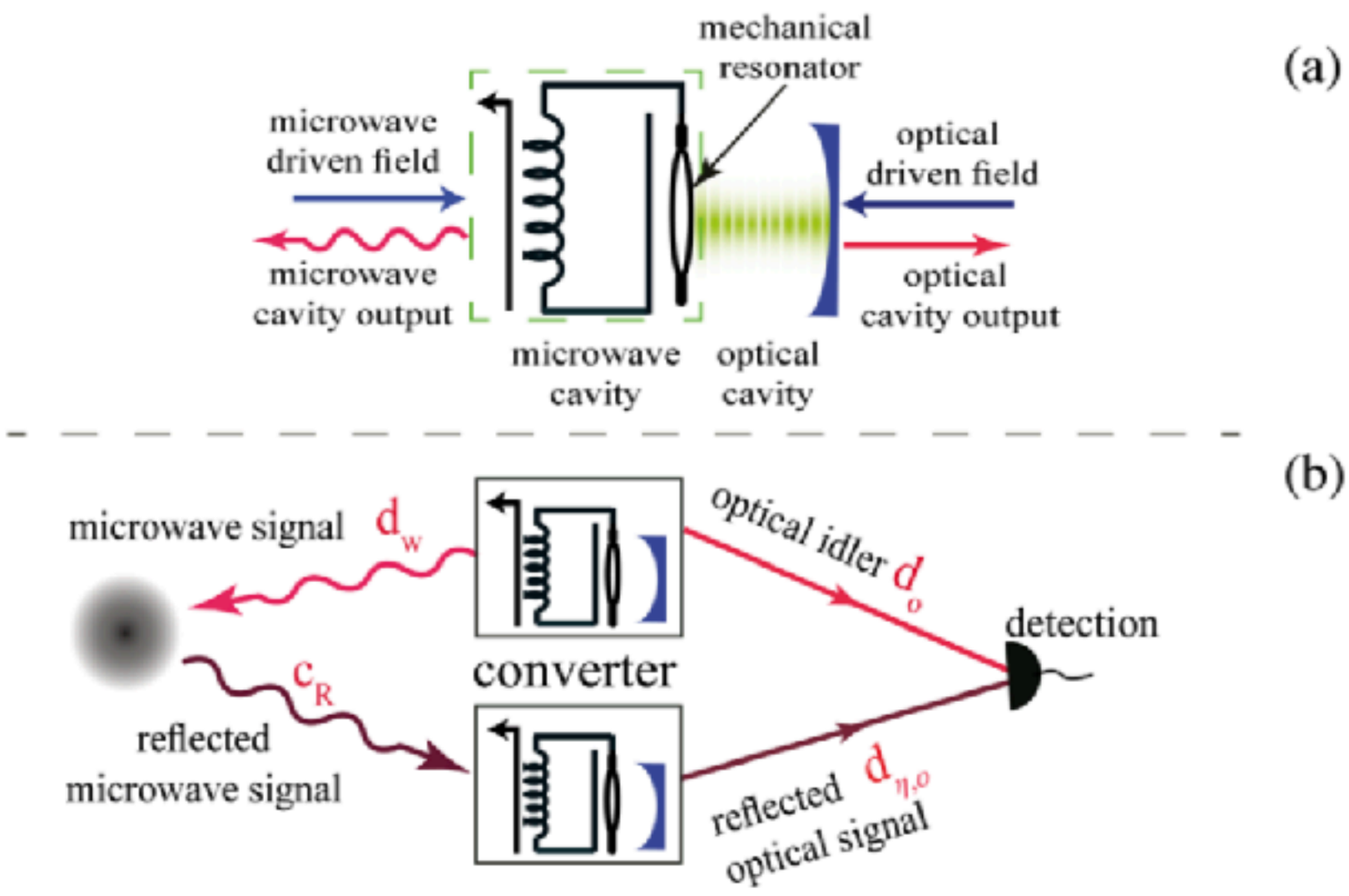
C. W. Sandbo Chang *et al.*, Appl. Phys. Lett. **114**, 112601 (2019)

Y. Zhang *et al.*, Phys. Rev. A **101**, 053808 (2020)

S. Barzanjeh *et al.*, Sci. Adv. **6**, eabb0451 (2020)

T. Gregory *et al.*, Sci. Adv. **6**, eaay2652 (2020)

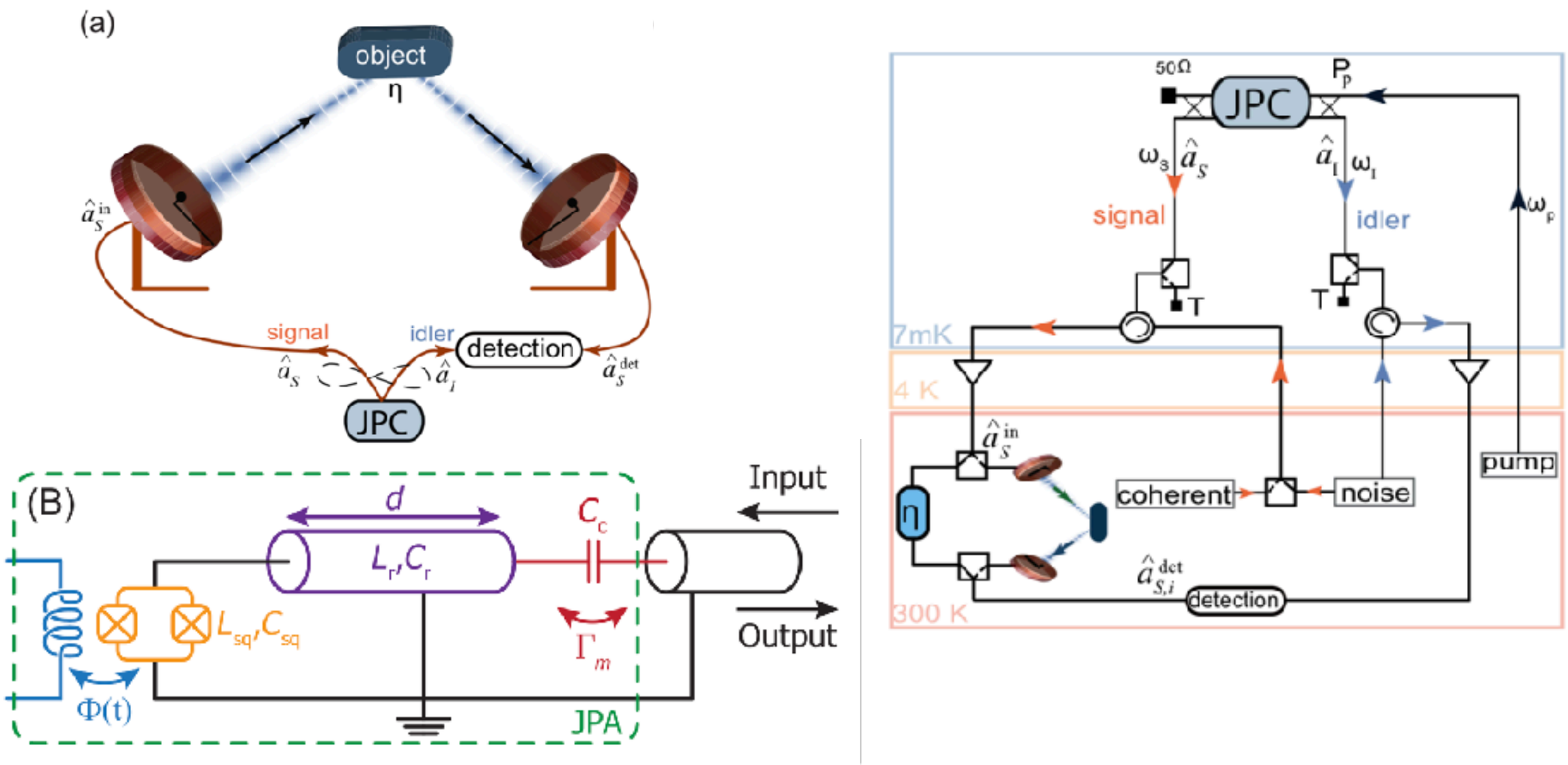
Microwave Quantum Illumination



- Opto-mechanics creates microwave/photonic entanglement
- Microwave signal as probe

S. Barzanjeh *et al.*, Phys. Rev. Lett. **114,** 080503 (2015)

Microwave QI Experiment



- Josephson parametric converter creates entanglement
- 3x improved SNR by QI over a classical regime

C. W. Sandbo Chang *et al.*, Appl. Phys. Lett. **114**, 112601 (2019)
S. Barzanjeh *et al.*, Sci. Adv. **6**, eabb0451 (2020)

Limitations of Quantum Illumination

- Quantum probe signal typically weak (nW power)
  ➡ Impact on range, SNR, etc.
- Difficult to outperform practical classical schemes with Watts of signal power
- Challenges in entanglement source/quantum receiver

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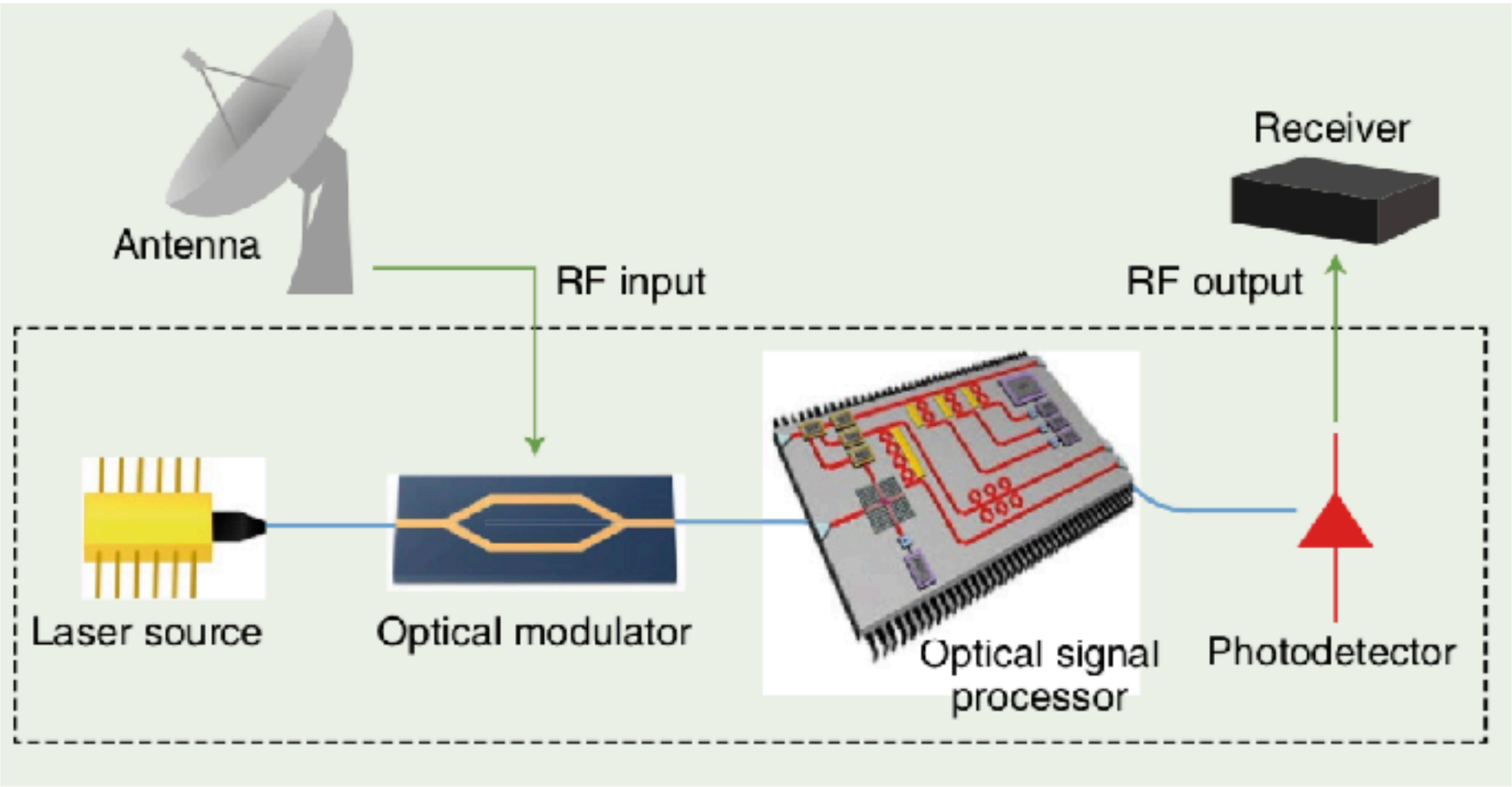
- Difficult to outperform practical classical schemes with Watts of signal power
- Challenges in entanglement source/quantum receiver

How can quantum resources benefit practical radar scenarios?

Microwave/RF Photonic Sensing

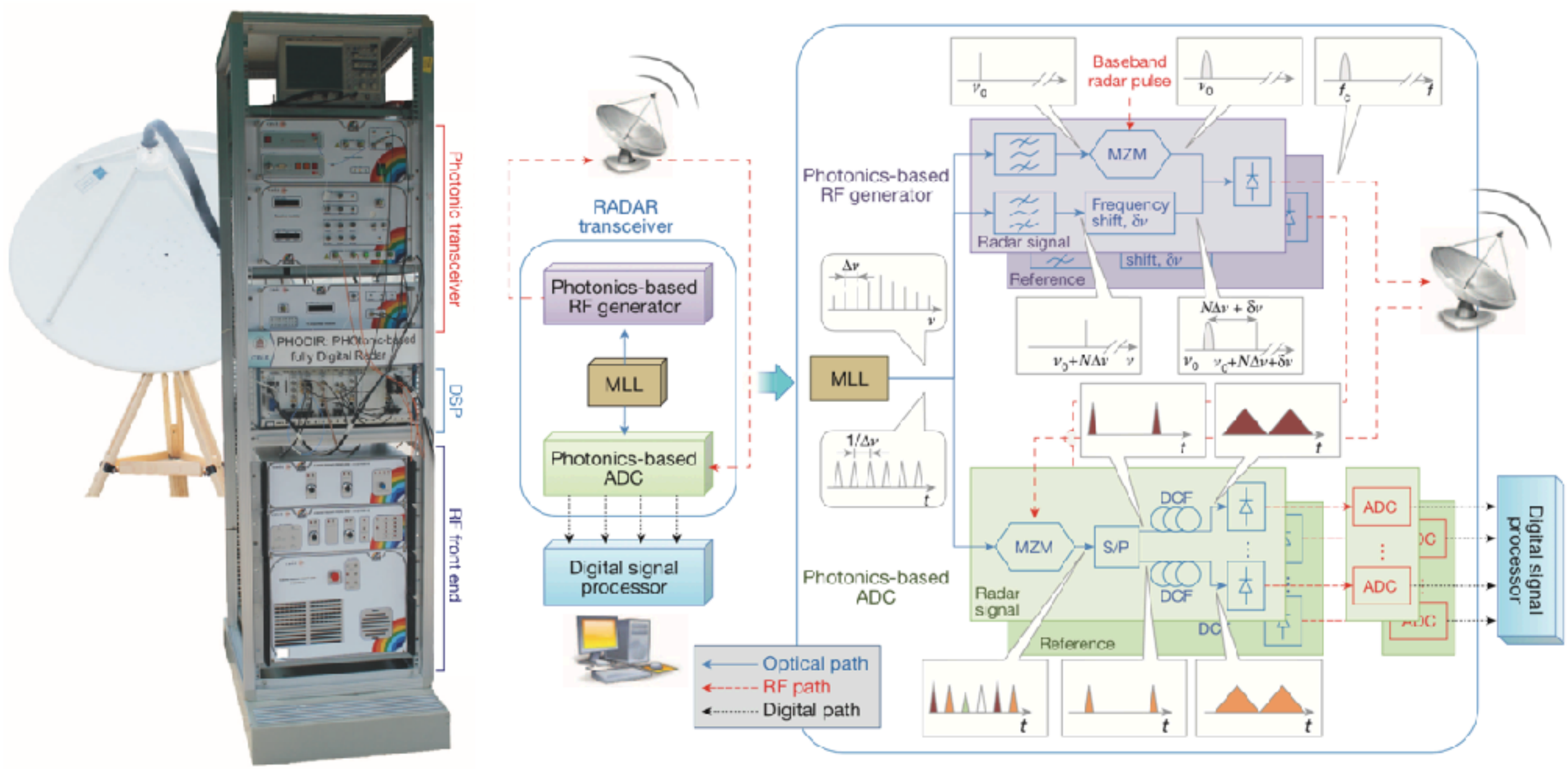


Advantages

- Large optical bandwidth for signal processing
- Long transmission distance in optical fiber
- Flexibility in tailoring RF frequency response

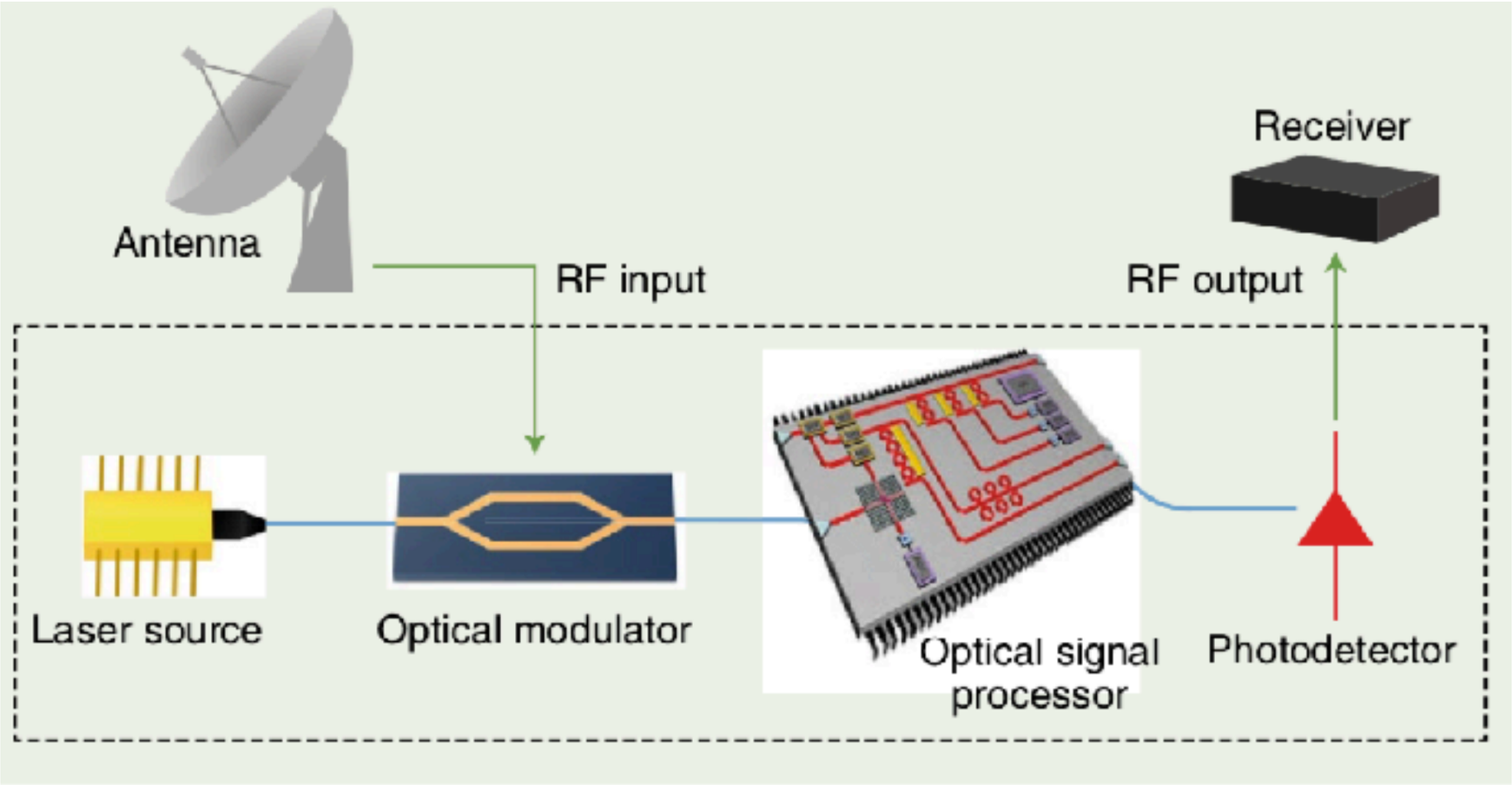
D. Marpaung, J. Yao, and J. Capmany, Nature Photon. **13**, 80–90 (2019)

RF-Photonic Radar

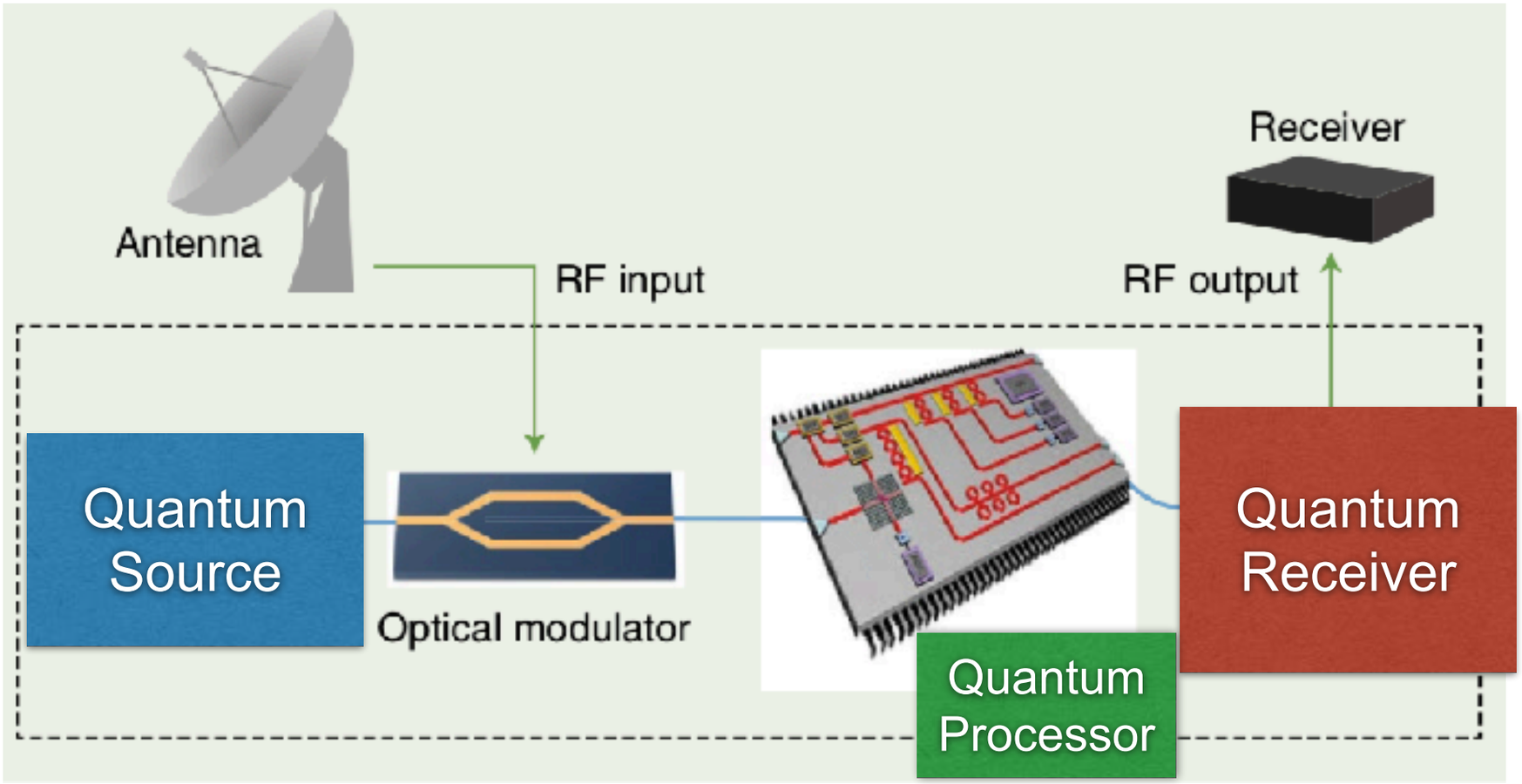


P. Ghelfi *et al.*, Nature **507**, 341 (2014)

Quantum-Enhanced RF-Photonic Sensing



Quantum-Enhanced RF-Photonic Sensing



Advantages

- Quantum resources are locally well preserved
- Can accommodate strong classical probe signals
- Can serve as passive receivers for, e.g., navigation
- Compatible with current infrastructure

Sensor Networks/Arrays

Also, a network of sensors are needed in certain tasks!

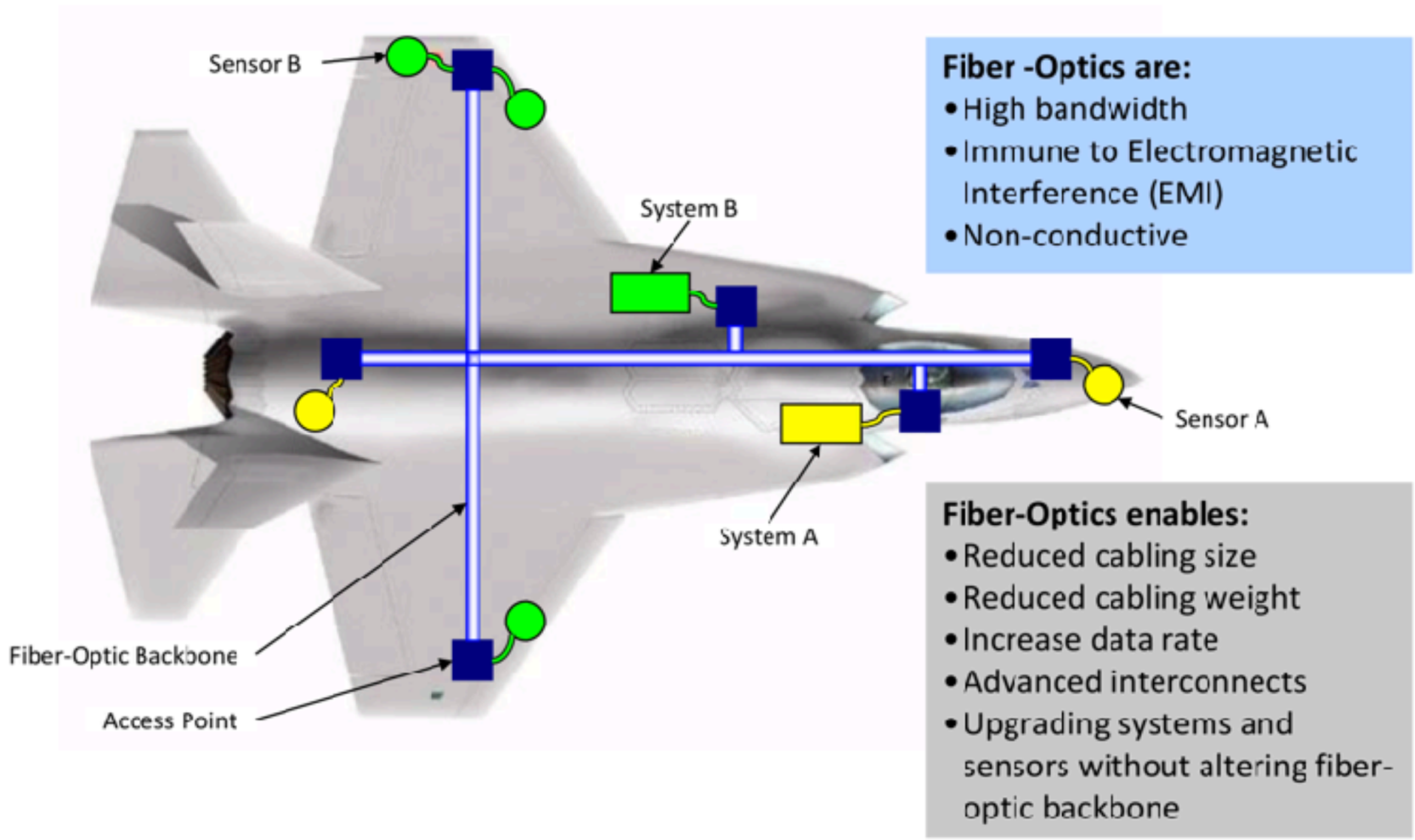
Caremas (CCD Array)

Wireless Sensor Networks

Phased-Array Radars

Sonar Arrays

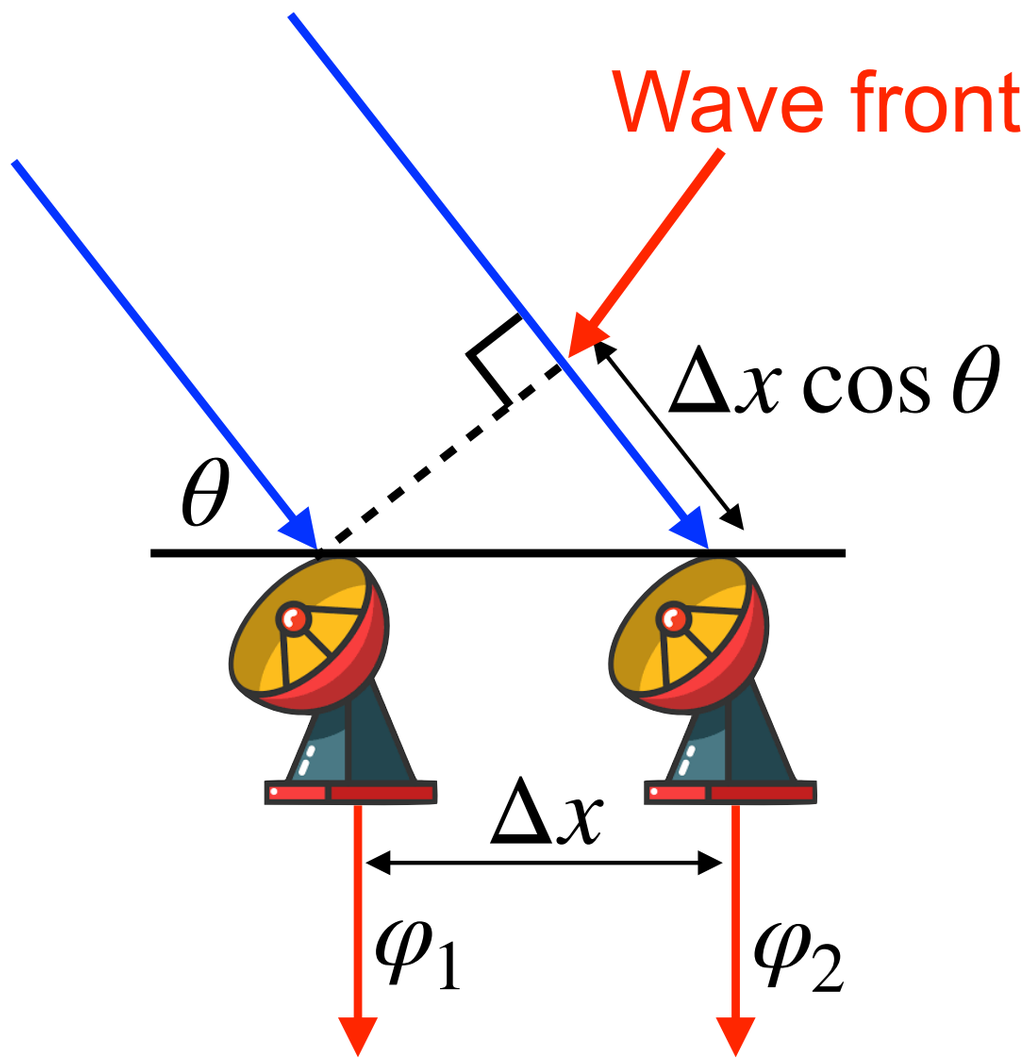
RF-Photonic Sensor Array



Advanced Technology Laboratories, Lockheed Martin Corporation (2018)

Global Parameter Estimation in RF Sensing

Two RF sensors work collectively to estimate angle of arrival (AoA)



Phase-difference measurement, $\varphi_1 - \varphi_2 \propto \Delta x \cos\theta$, derives AoA.

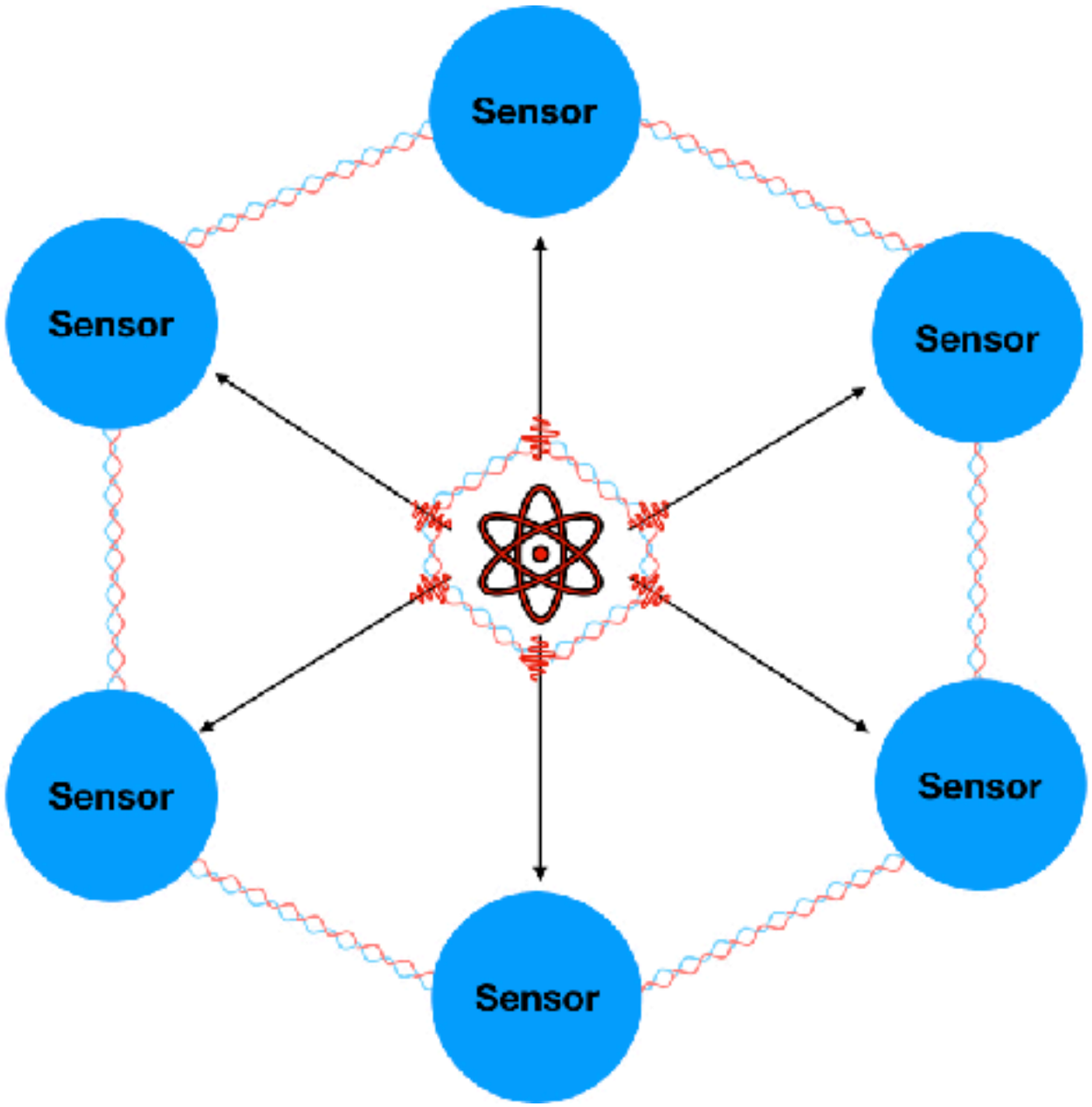
Distributed Quantum Sensing

Quantum advantage when estimating global parameters using entanglement.

Root mean square error (rms) scale as: $1/M$

M: number of entangled sensors

For separable sensors,
rms error scales as $1/\sqrt{M}$



Q. Zhuang *et al.* Phys. Rev. A **97**, 032329 (2018)

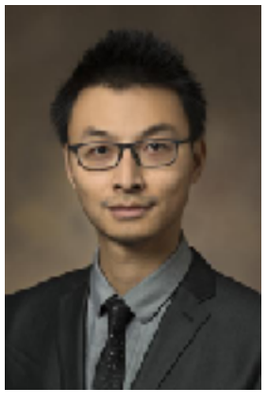
W. Ge *et al.* Phys. Rev. Lett. **121**, 043604 (2018)

T. Proctor *et al.* Phys. Rev. Lett. **120**, 080501 (2018)

Quantum Sensor Networks

Use entangled sensors based on continuous variables (CVs)

Q. Zhuang, Z. Zhang, and J. H. Shapiro, Phys. Rev. A **97**, 032329 (2018)



Quntao Zhuang

Jeff Shapiro

See also Theory: P. C. Humphreys *et al.*, Phys. Rev. Lett. **111**, 070403(2013)
W. Ge et al., Phys. Rev. Lett. **121**, 043604 (2018)
T. Proctor, P. Knott, and J. Dunningham, Phys. Rev. Lett. **120**, 080501 (2018)
Experiment: X. Guo *et al.*, Nat. Phys. **16**, 281 (2020).

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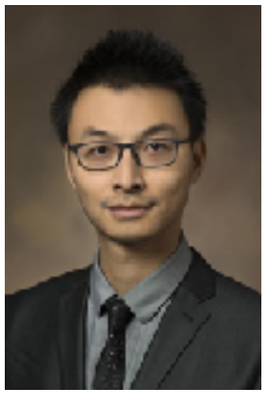

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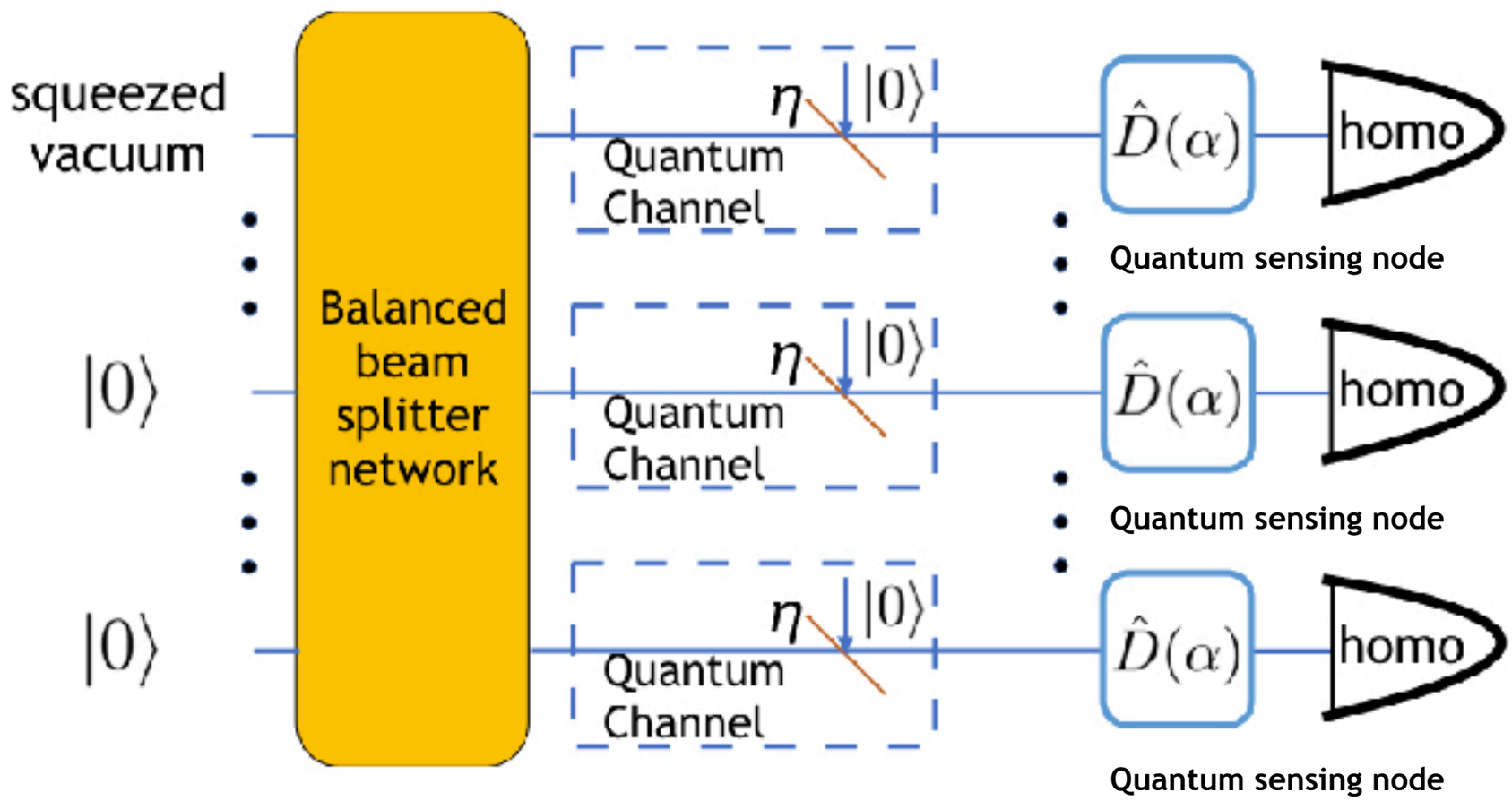
Jeff Shapiro



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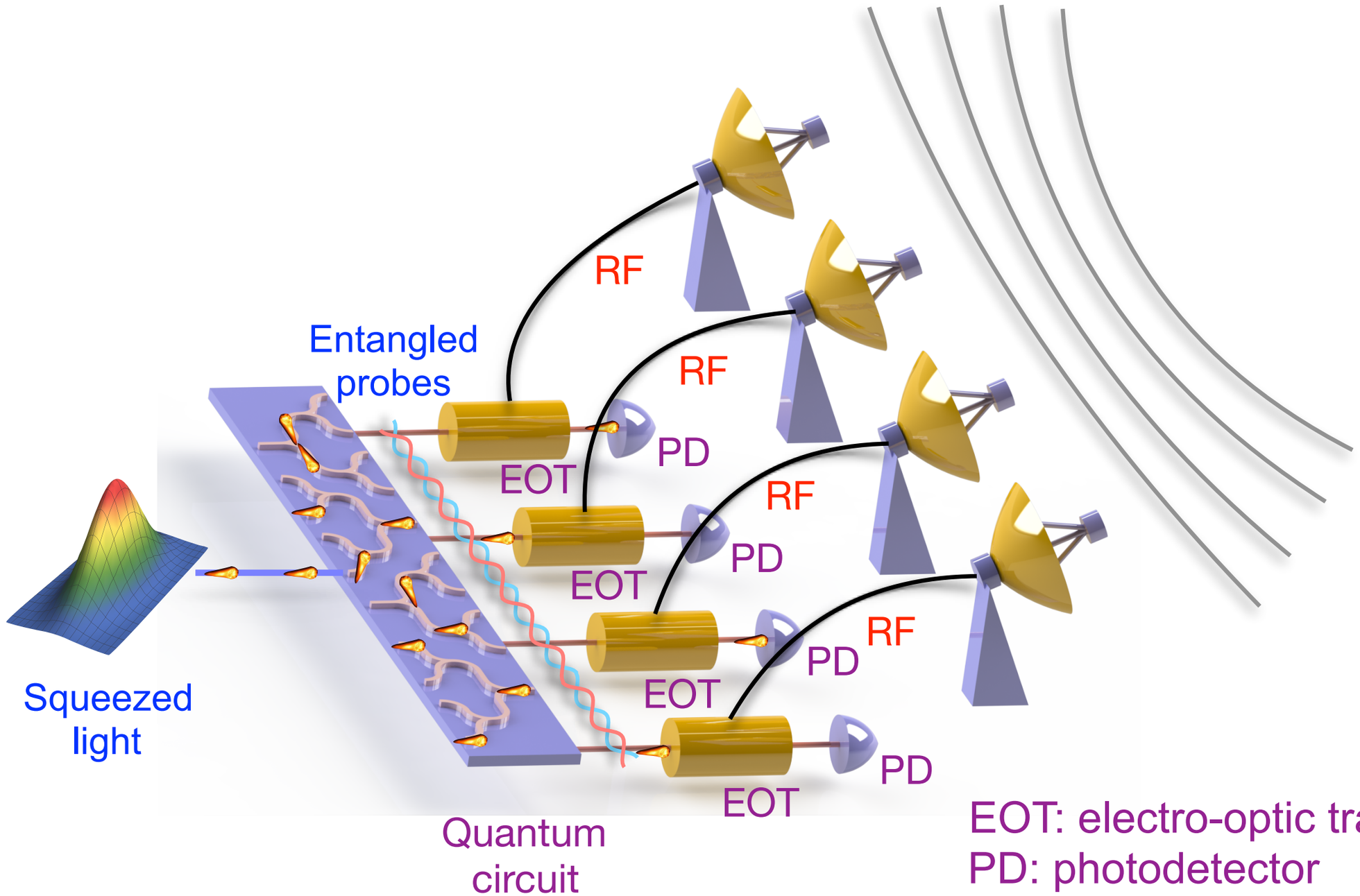
Experiment: X. Guo *et al.*, Nat. Phys. **16**, 281 (2020).

Entangled RF-Photonic Sensor Network

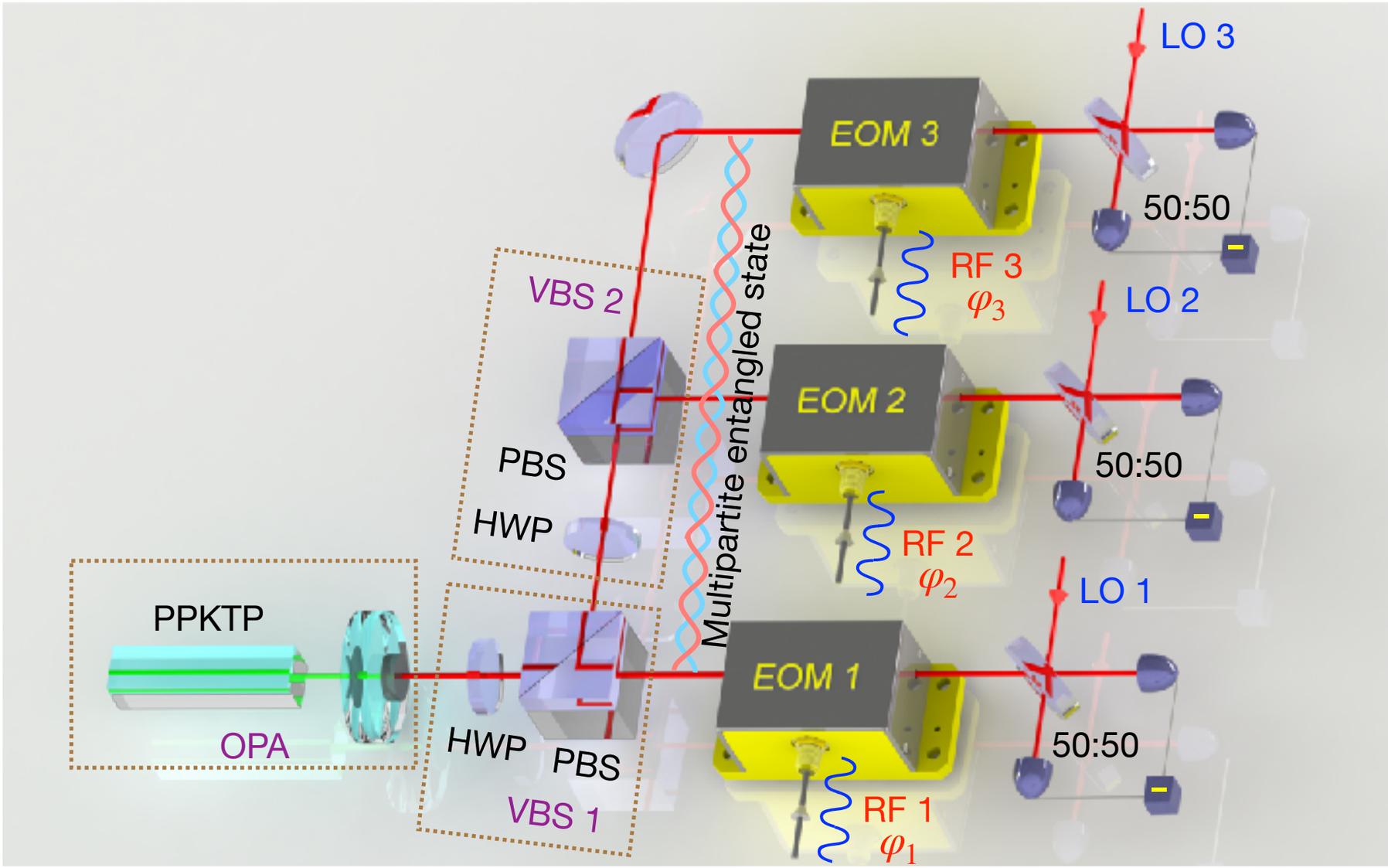
Y. Xia *et al.*, Phys. Rev. Lett. **124**, 150502 (2020)

Entangled RF-photonic sensors estimate global property of the RF field



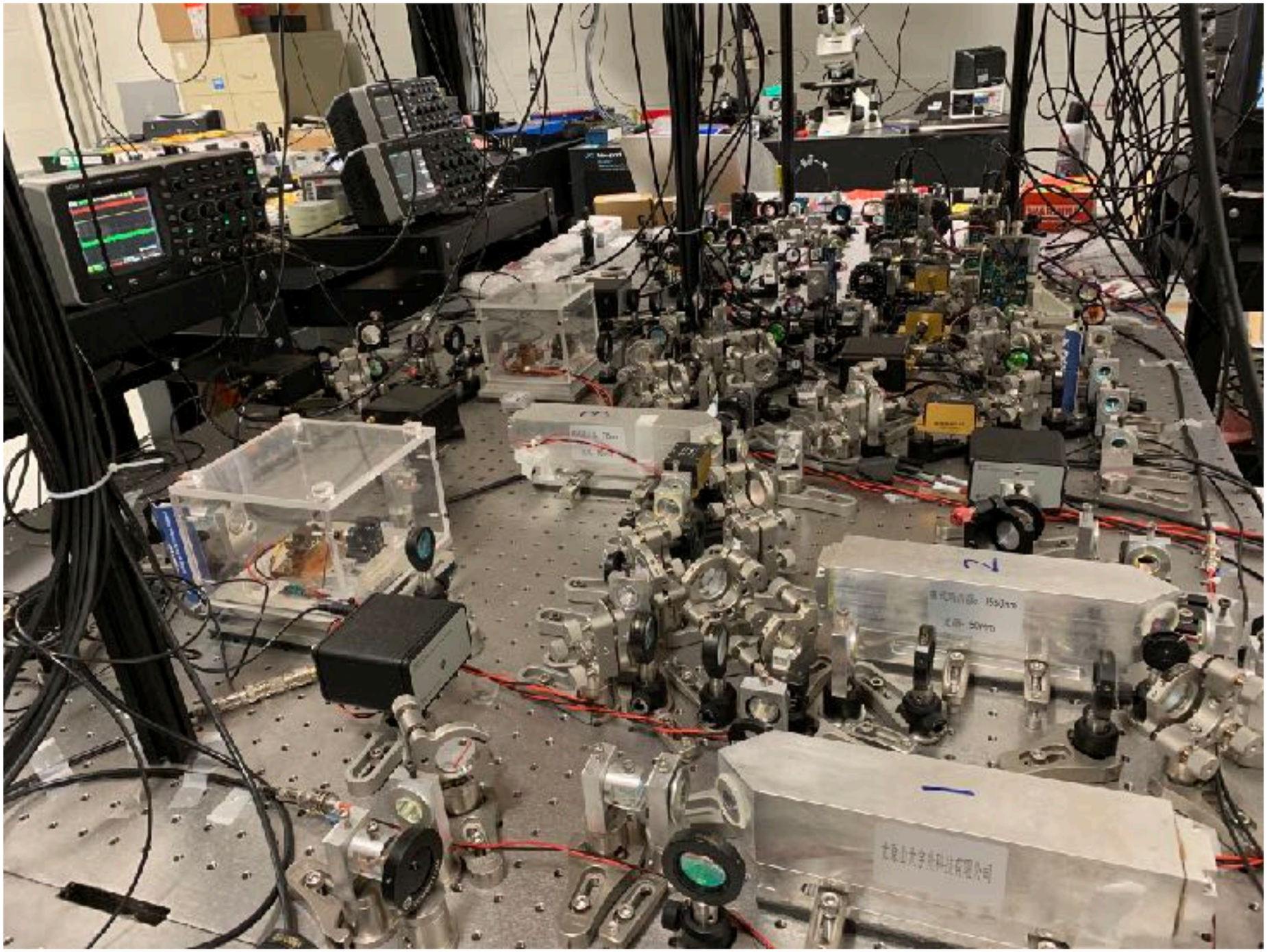
Experimental Demonstration

Y. Xia *et al.*, Phys. Rev. Lett. **124**, 150502 (2020)



OPO: optical parametric oscillator; VBS: variable beam splitter
EOM: electro-optic modulator; LO: local oscillator

Experimental Setup



http://quantum.lab.arizona.edu

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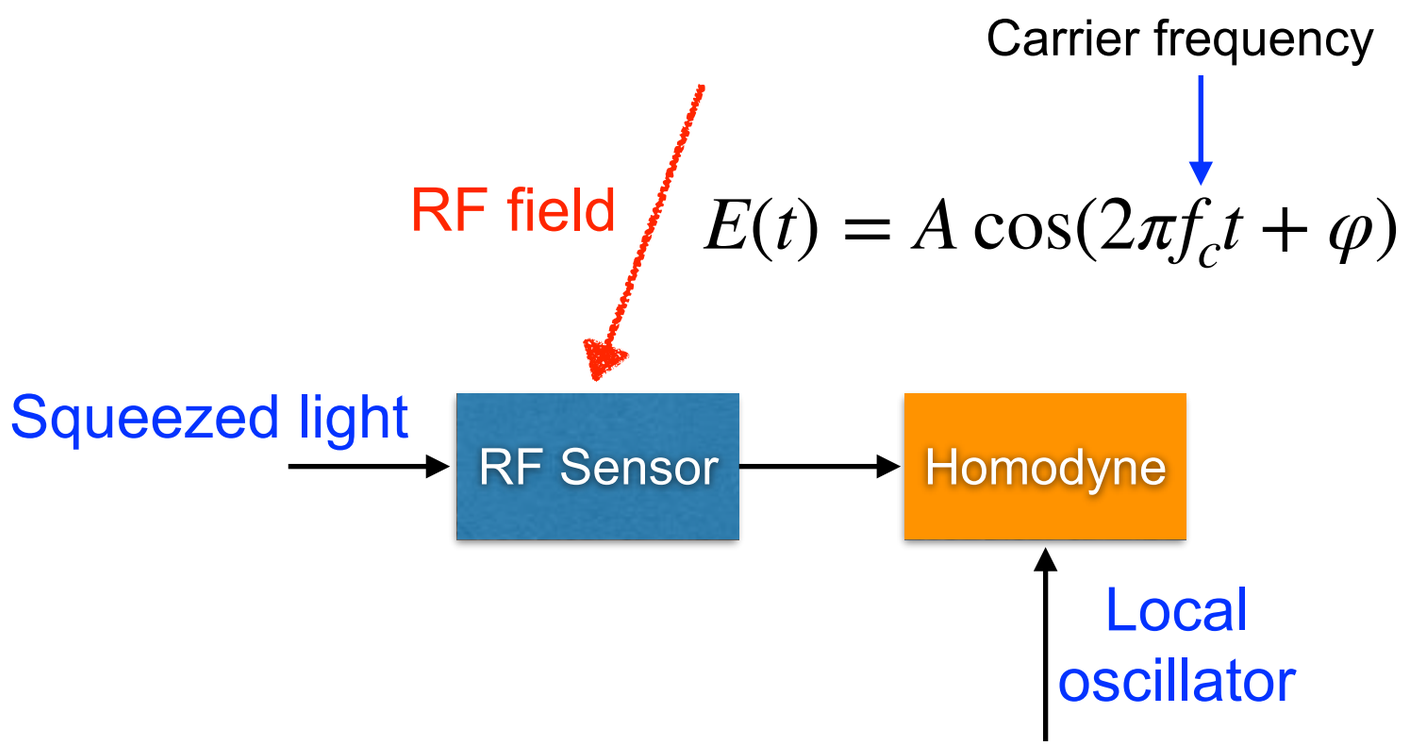
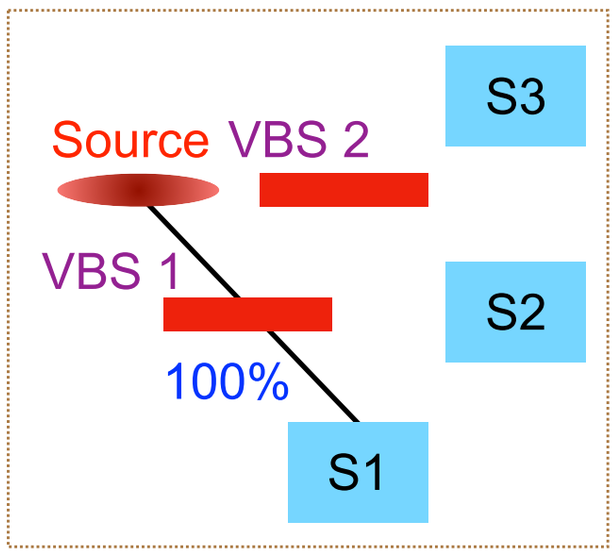
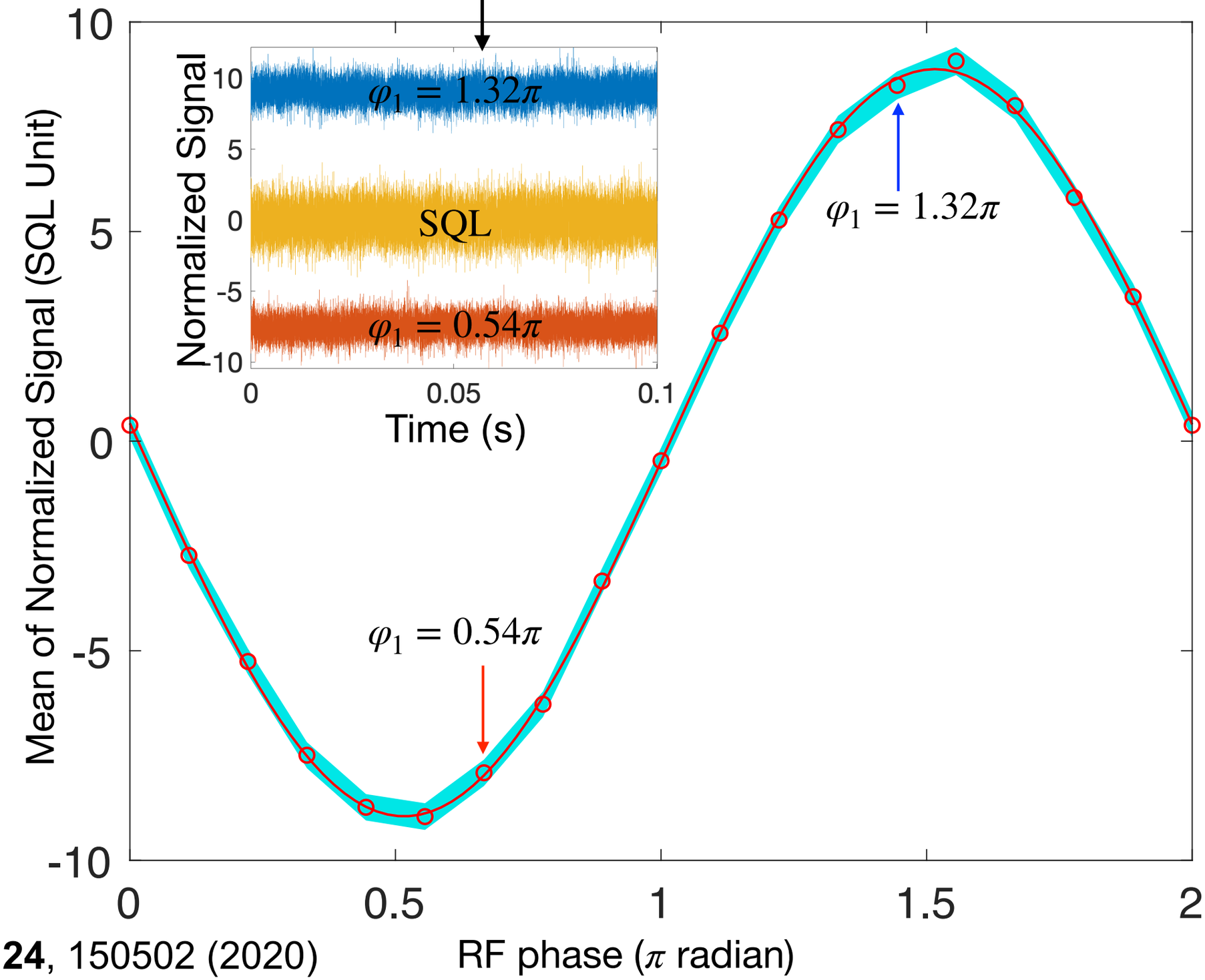
Single-Node Quantum-Enhanced RF Sensing



Single-Node Quantum-Enhanced RF Sensing



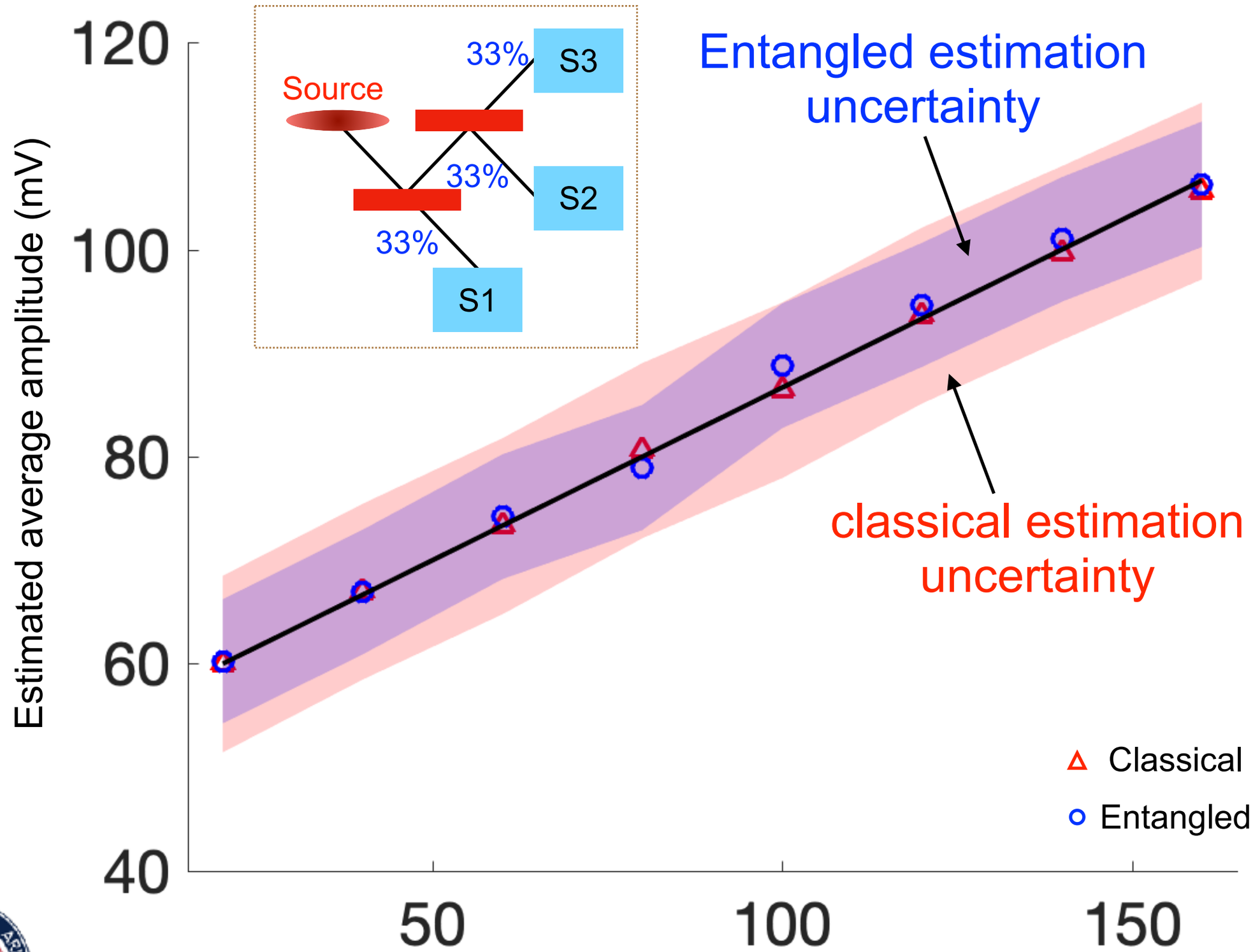
Time-domain measurement



Sensitivity below the standard quantum limit (SQL) in estimating the RF phase!

Phys. Rev. Lett. **124**, 150502 (2020)

Entangled Sensor Average Amplitude Estimation



http://quantum.lab.arizona.edu

PRL **124**, 150502 (2020)

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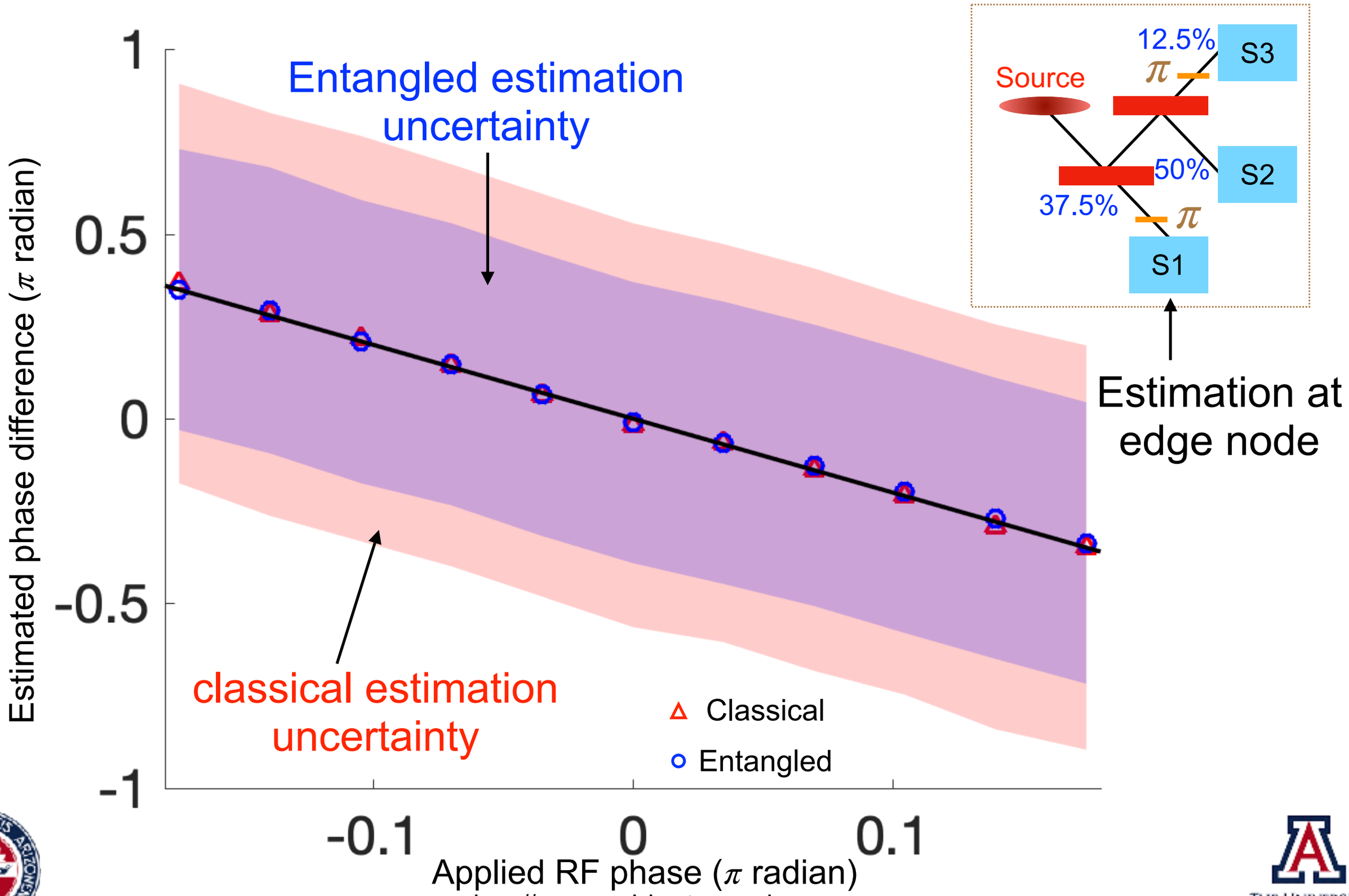
Entangled Sensor Phase Difference Estimation



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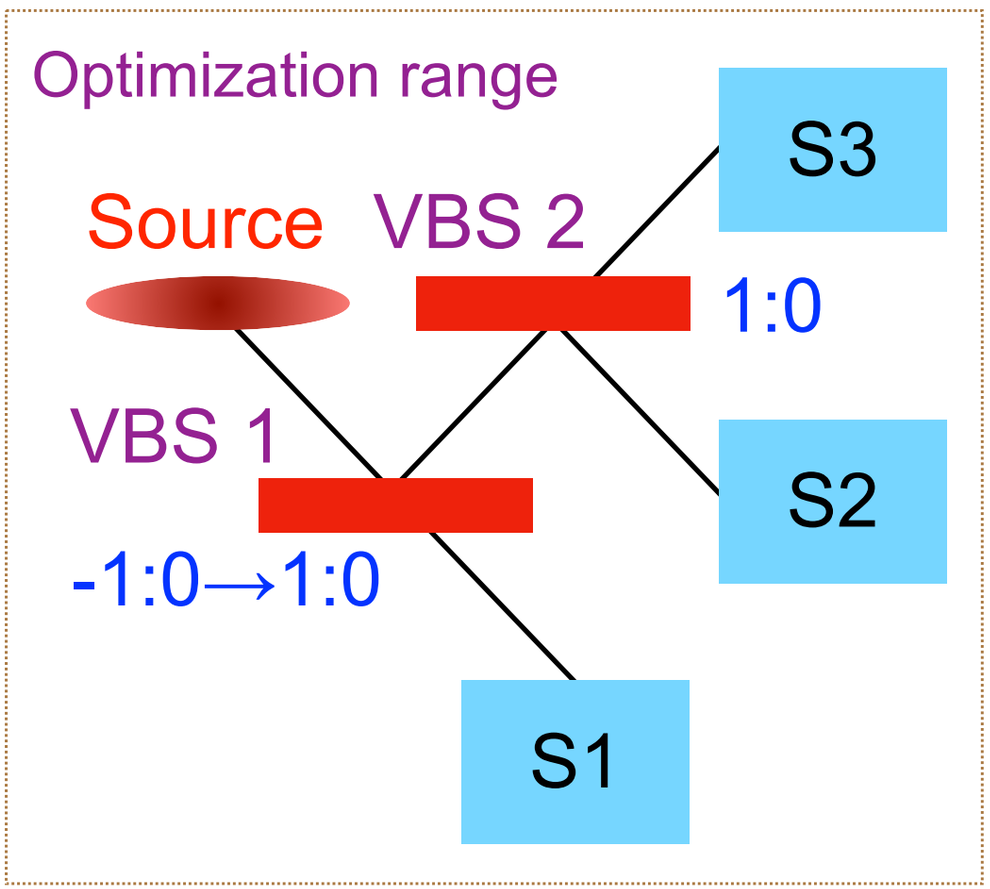
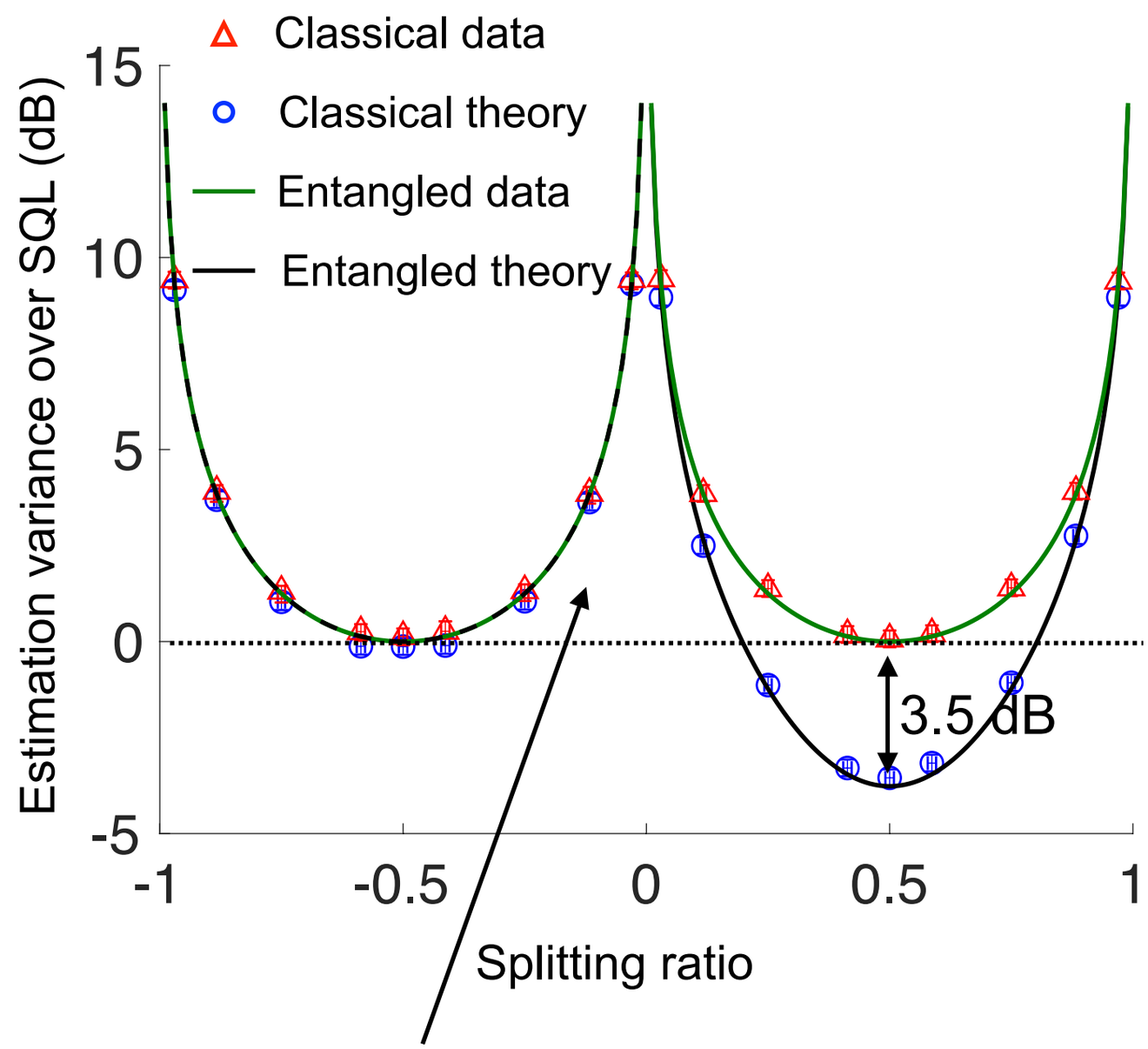
Entanglement Optimization

Phase difference estimation at central node



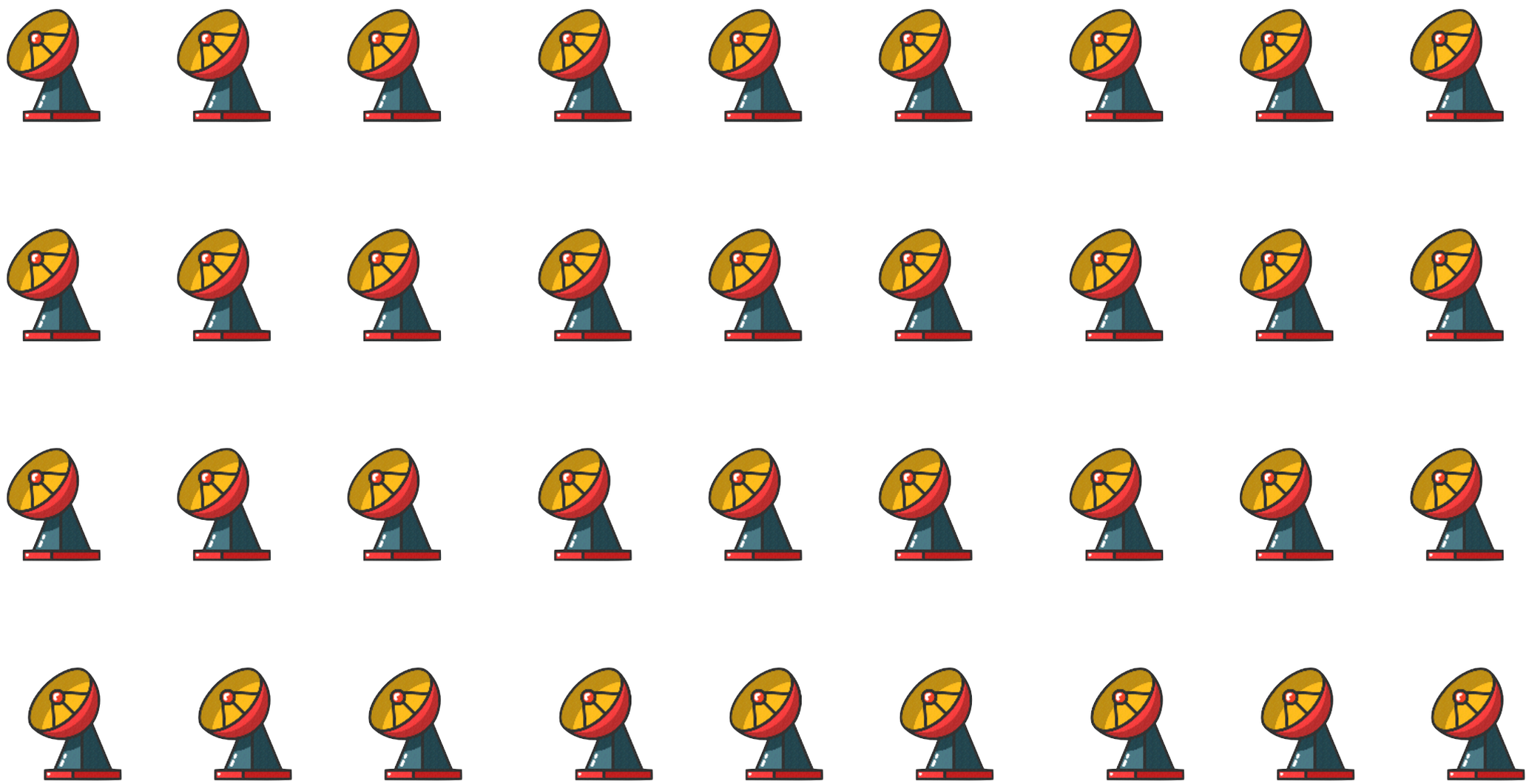


PRL **124**, 150502 (2020)

Symmetric classical vs. asymmetric entangled behaviors manifest quantum correlations!

Growing the Entangled Sensor Network

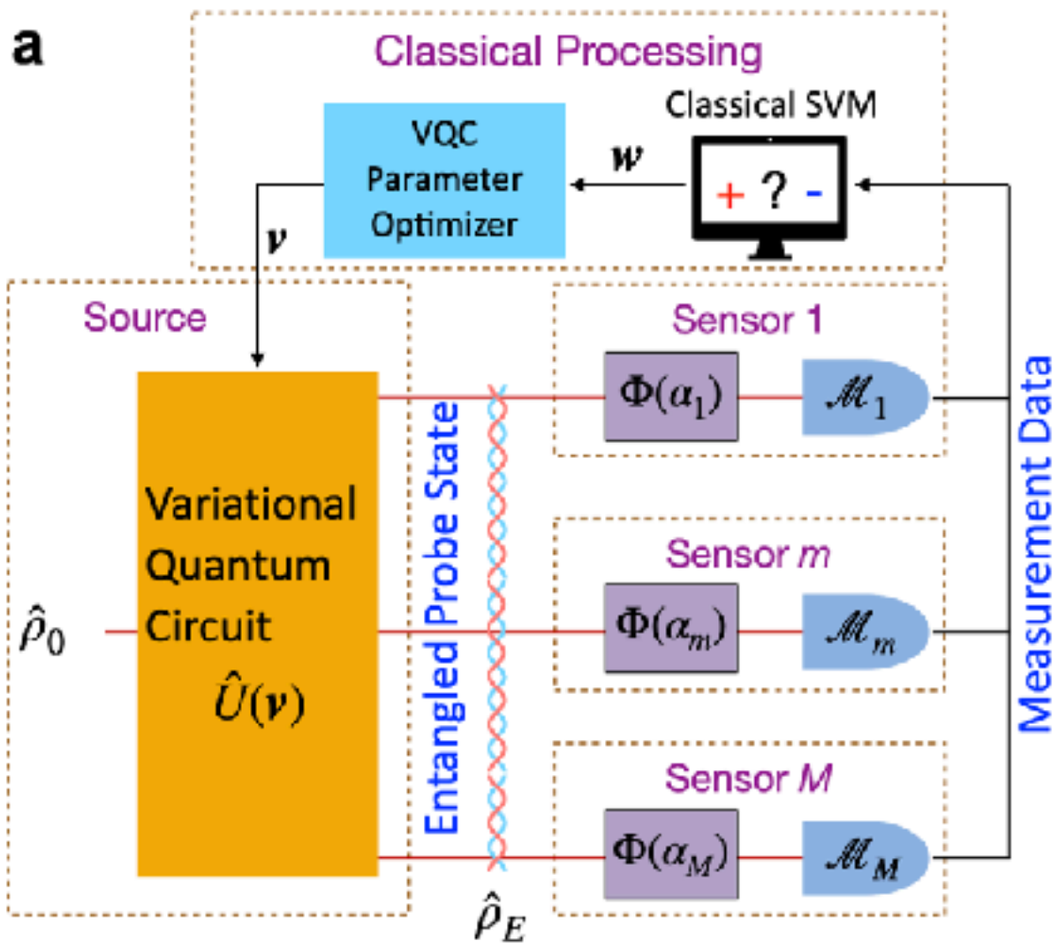
Growing the Entangled Sensor Network



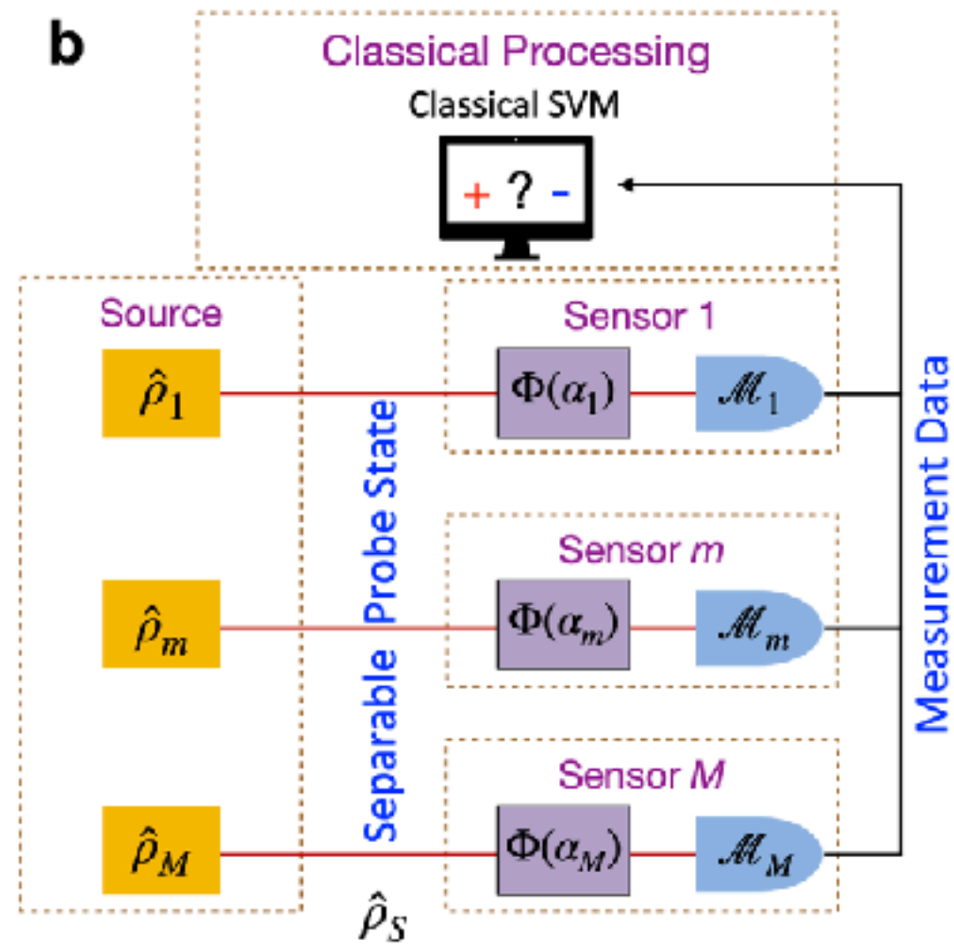
Larger entangled sensor network to solve more complex sensing problems, but what is the optimum multipartite entangled state for a particular problem?

Quantum vs. Classical Data Classification Using Machine Learning

Quantum



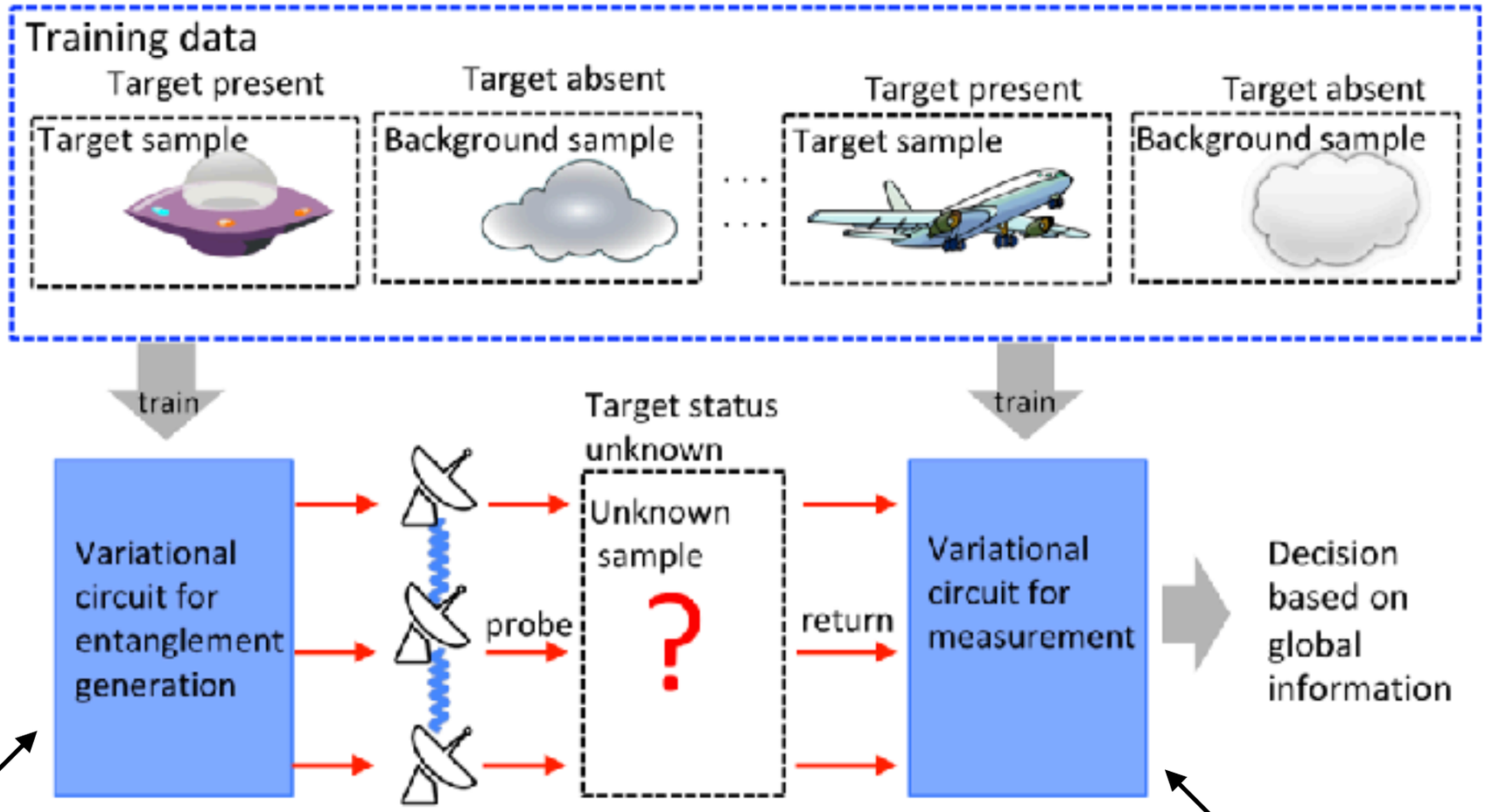
Classical



Supervised Learning Assisted by an Entangled Sensor Network (SLAEN)

Q. Zhuang and Z. Zhang, Phys. Rev. X **9**, 041023 (2019)

Quntao Zhuang

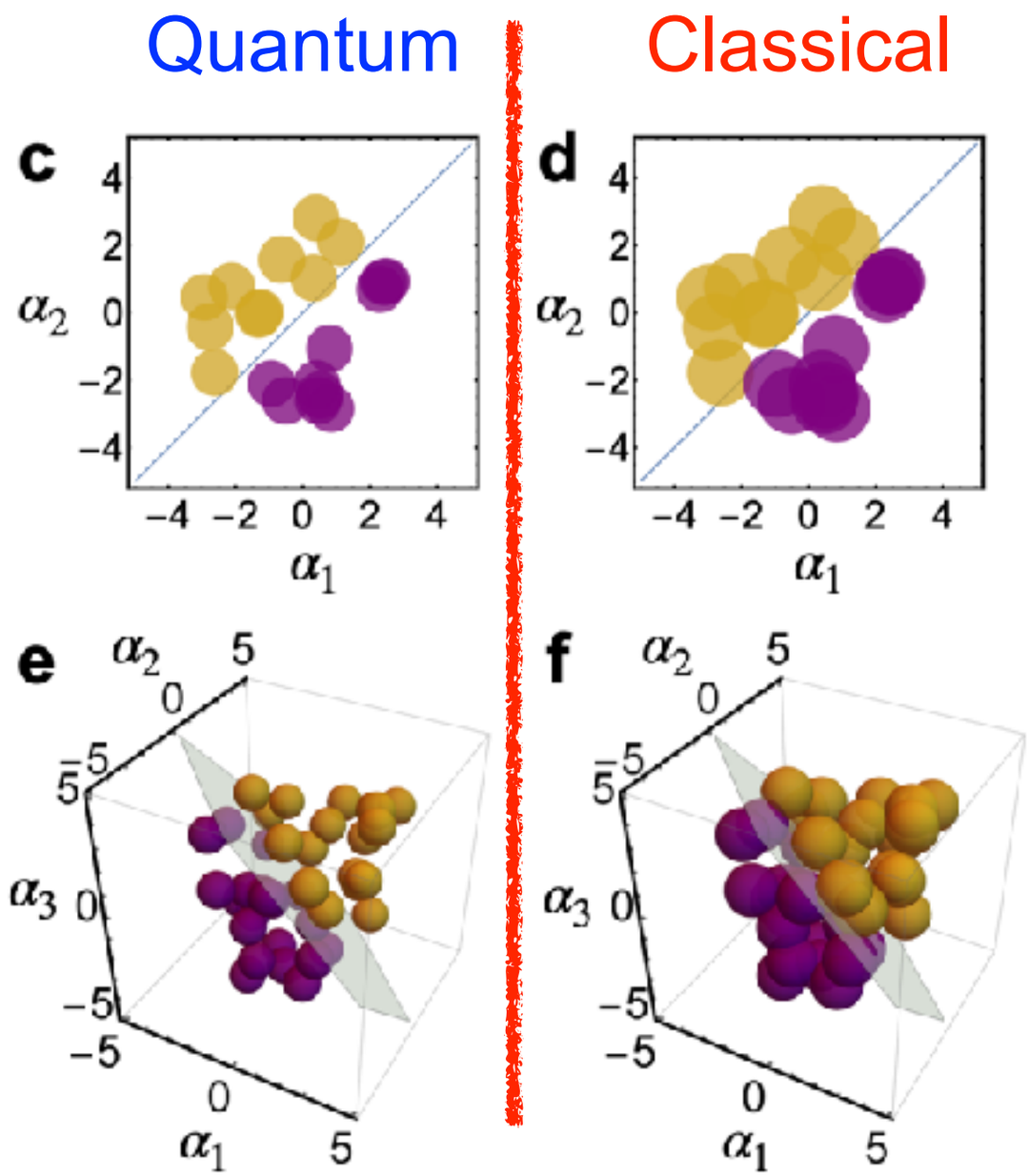


Probe state preparation

Measurement

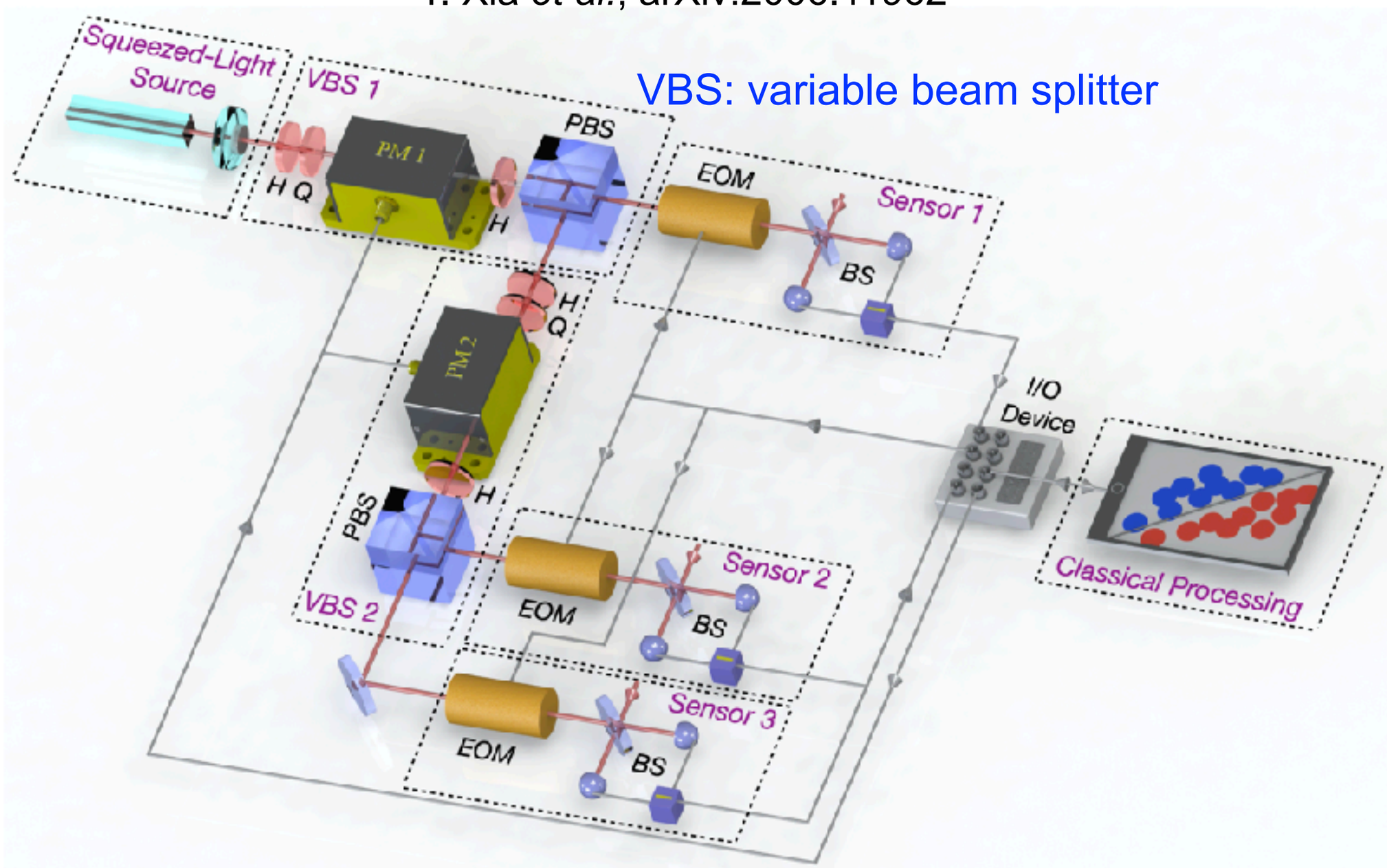
- Quantifiable quantum enhancement at the physical layer
- No need for quantum random-access memories
- Capable of data classification and compression

Quantum vs. Classical Data Classification



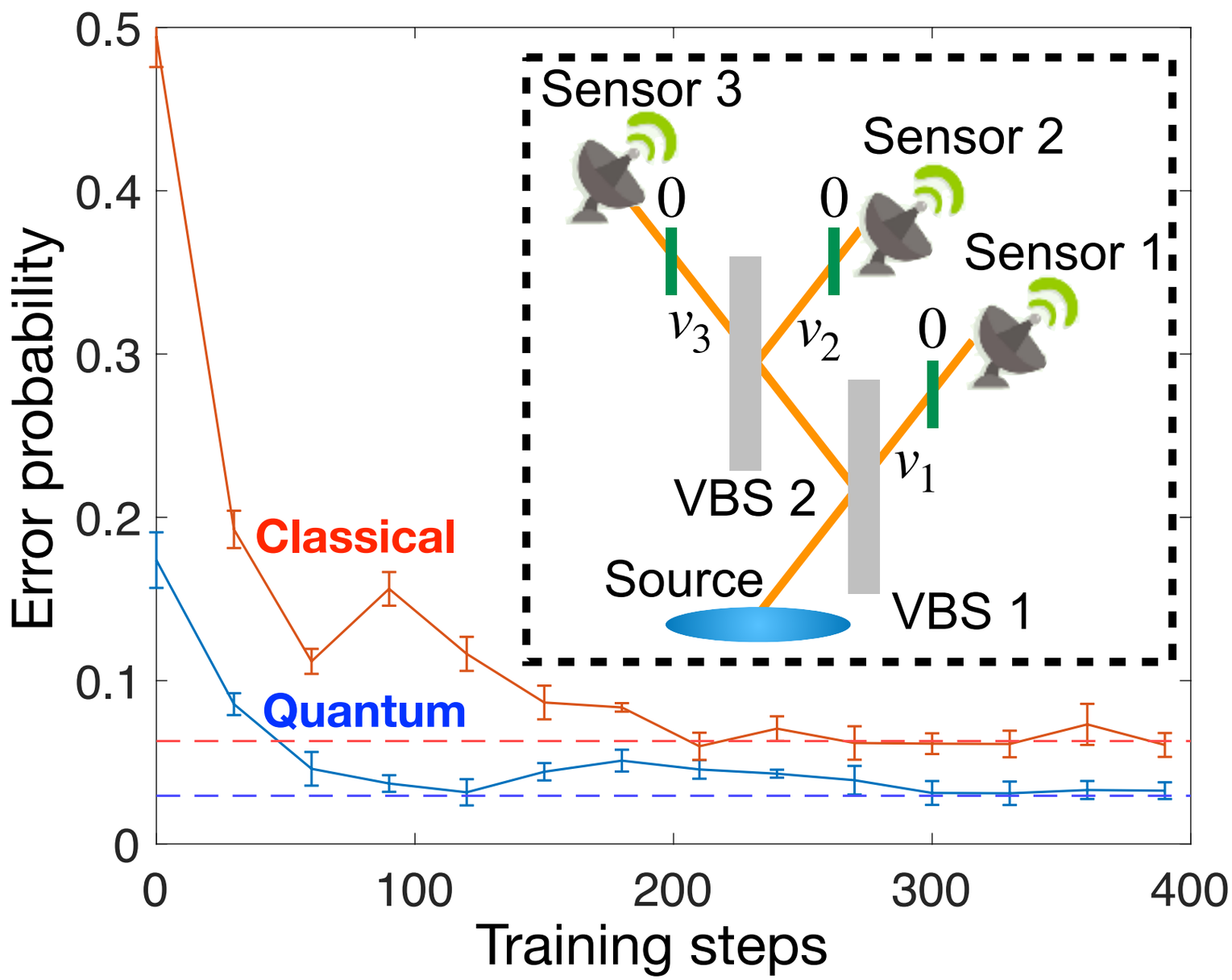
Quantum-Enhanced Data Classification Experiment

Y. Xia *et al.*, arXiv:2006.11962



Training Three Entangled Sensors

Error probability evolution during training



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arXiv:2006.11962

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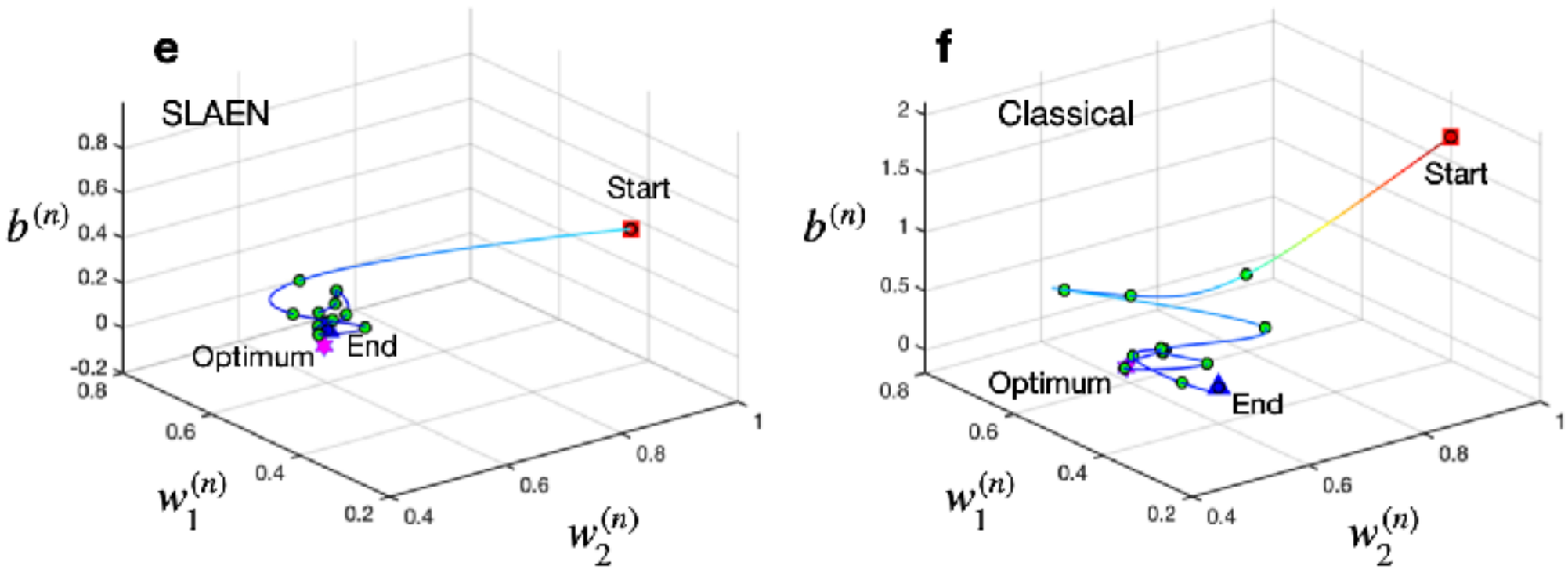
Training Three Entangled Sensors

Hyperplane parameters evolution during training



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arXiv:2006.11962

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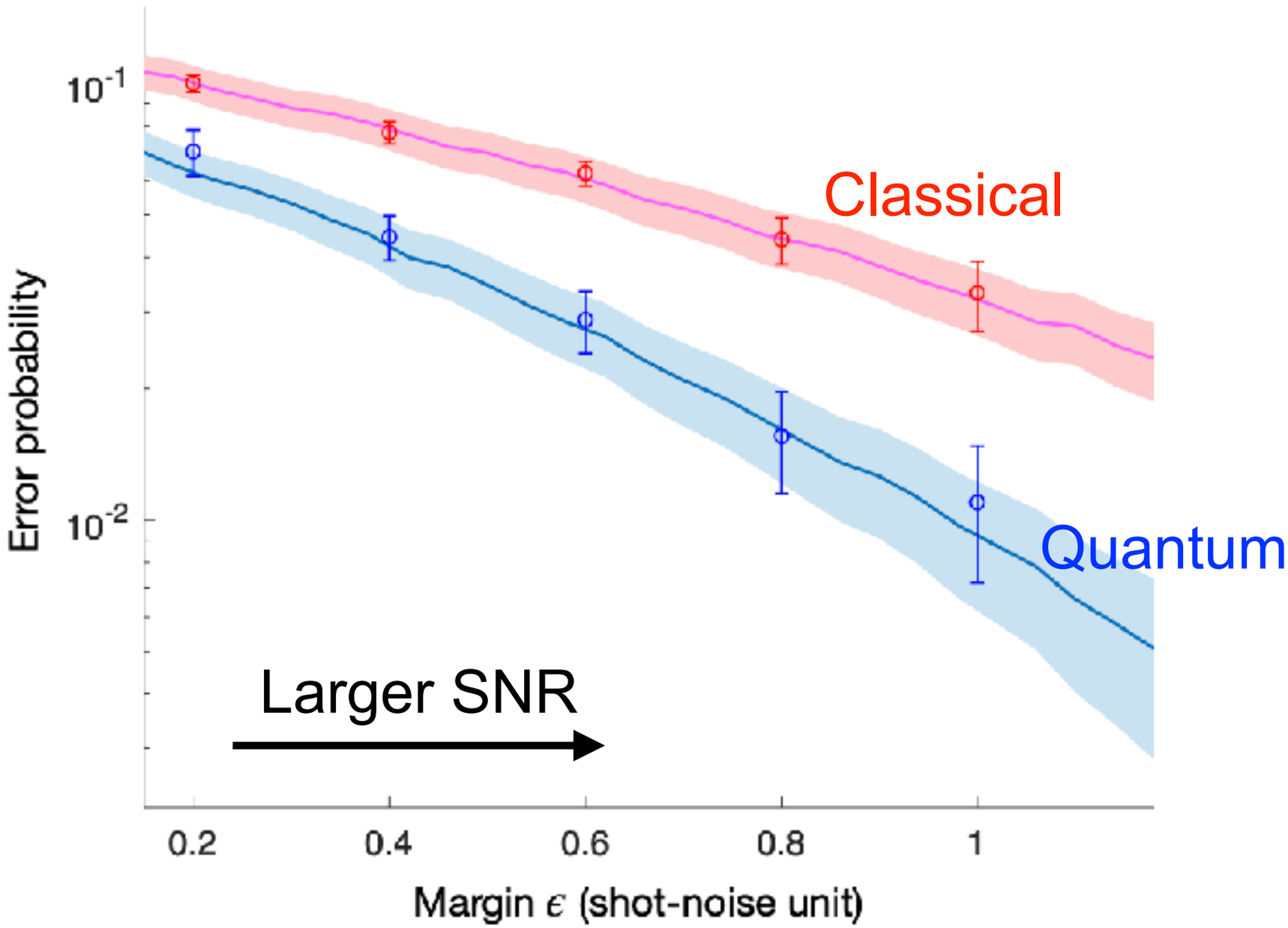
Scaling of Error Probability



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arXiv:2006.11962

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Summary

- Demonstrated entangled RF-photonic sensor network
- Verified advantage over classical separable sensor network in
  - Average field-amplitude estimation
  - Angle of arrival (AoA) estimation
- Supervised-learning assisted by an entangled sensor network (SLAEN)
  - Quantum-enhanced data classification
  - Experimental demonstration
- INQUIRE infrastructure & Engineering Research Center for Quantum Networks

Acknowledgments

University of Arizona

Quntao Zhuang

Yi Xia

Wei Li

General Dynamics

William Clark

Darlene Hart

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Office of Naval Research
Science & Technology

GENERAL DYNAMICS
Mission Systems

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