Quantum information science and high energy physics at ORNL

How quantum information science and high energy physics meet

Raphael Pooser

Team Lead, Quantum Sensing Team,

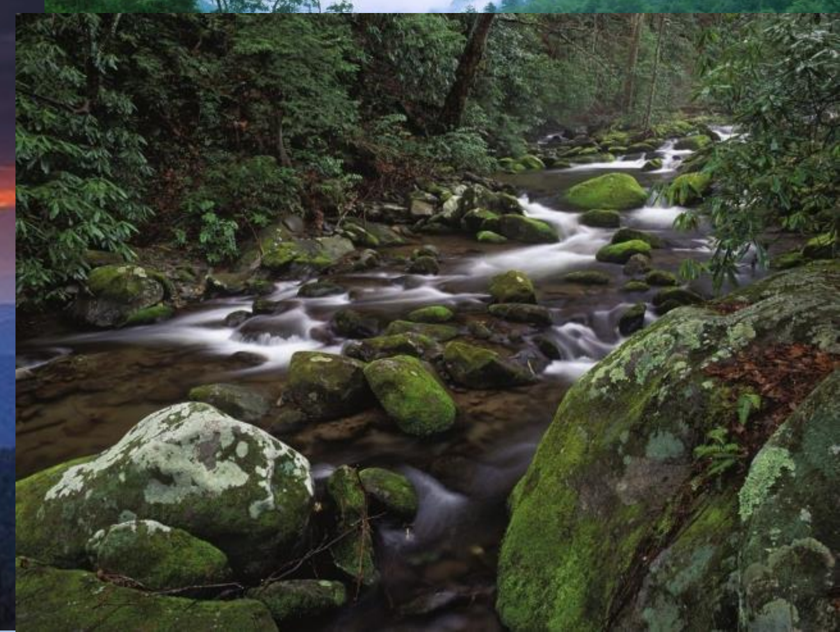
Ali Passian, Phil Evans, Ben Lawrie

Quantum information science group and Quantum Computing Institute, Oak Ridge National Laboratory

ORNL: DOE's largest science and energy laboratory

- $1.65B budget
- 4,400 employees
- 3,000 research guests annually
- $500M modernization investment
- Nation's largest materials research portfolio
- Most powerful open scientific computing facility
- World's most intense neutron source
- World-class research reactor
- Nation's most diverse energy portfolio
- Managing billion-dollar U.S. ITER project


GREAT SMOKY
MOUNTAINS
NATIONAL PARK
AN INTERNATIONAL BIOSPHERE RESERVE



Organization

Computing & Computational Sciences Directorate
J. Nichols

Computation Sciences & Engineering Division
S. Gleason

Quantum Information Science Group
W. Grice

Quantum Communication Team
N. Peters
- J. Lukens
- B. Qi
- B. Williams

Quantum Computing Team
T. Humble
- R. Bennink
- E. Dumitrescu
- K. Hamilton
- P. Lougovski
- F. Mohiyaddin

Quantum Sensing Team
R. Pooser
- P. Evans
- B. Lawrie
- A. Passian
- M. Salhi
- J. Schaake

Quantum Information Science

Information Processing

- Sensing
- Communication
- Computing

Quantum Physics

- Limited Readability
- Fragile Systems
- No-Cloning Theorem
- Inherent Randomness
- Nonlocal Correlations
- Inherent Parallelism
- Large State Space

Information is physical!

Quantum Information Science

Science at the quantum scale for transformative solutions in communication, computing, and sensing.

Research Thrusts

QIS

Quantum Communication

Privacy assurance for data storage & distribution

Quantum Computing

Scalable algorithms for science, industry, & security

Quantum-Enhanced Sensing

Better data with less time and energy

Quantum sensing team

Raphael

Phil Evans

Ben Lawrie

Ali Passian

Marouane Salhi

Jason Schaake

Matt Feldman

Quantum sensing team

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Phil Evans

Ben Lawrie

Ali Passian

Marouane Salhi

Jason Schaake

Matt Feldman

Nick Peters

Joe Lukens

OAK RIDGE National Laboratory

Quantum sensing team

Raphael

Phil Evans

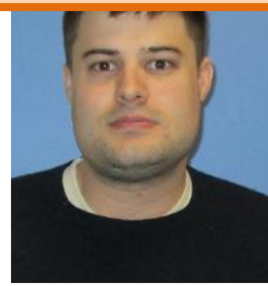
Ben Lawrie

Ali Passian

Marouane Salhi

We are interested in partnering to expand our quantum sensing expertise, application space, and broaden our horizons

Jason Schaake

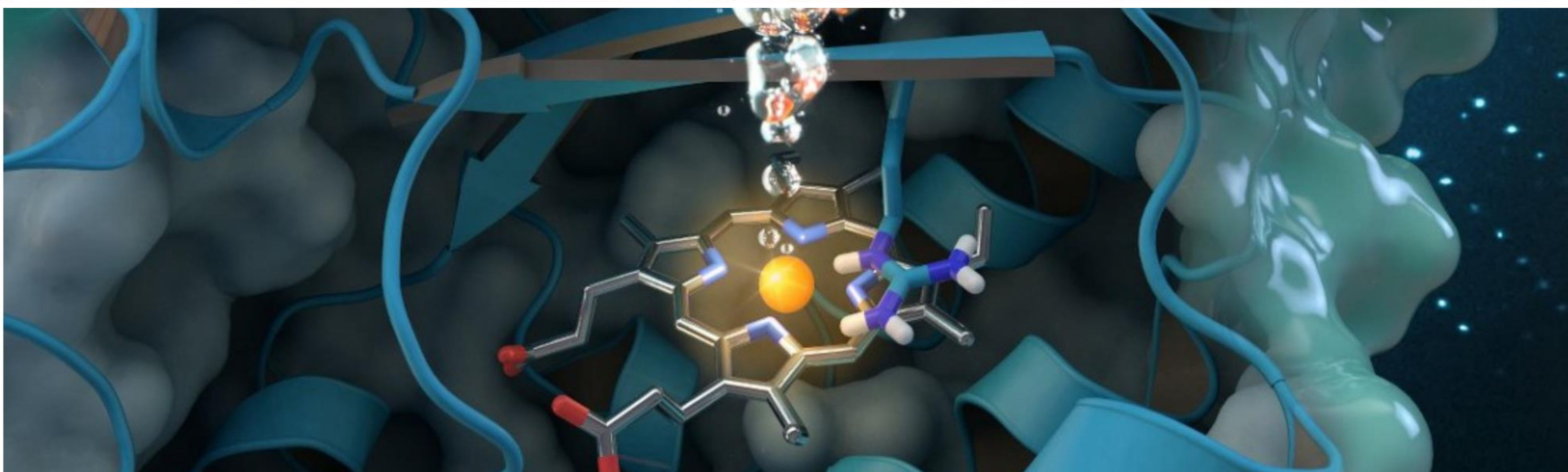


Matt Feldman

Nick Peters

Joe Lukens


Spallation Neutron Source



HFIR

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdynya[2], B. Cabrera-...

+ See all authors and affiliations

Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126
DOI: 10.1126/science.aao0990

OAK RIDGE, Tenn., Aug. 3, 2017--After more than a year of operation at the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL), the COHERENT experiment, using the world's smallest neutrino detector, has found a big fingerprint of the elusive, electrically neutral particles that interact only weakly with matter.

The research, performed at ORNL's Spallation Neutron Source (SNS) and published in the journal *Science*, provides

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdynya[2], B. Cabrera-...
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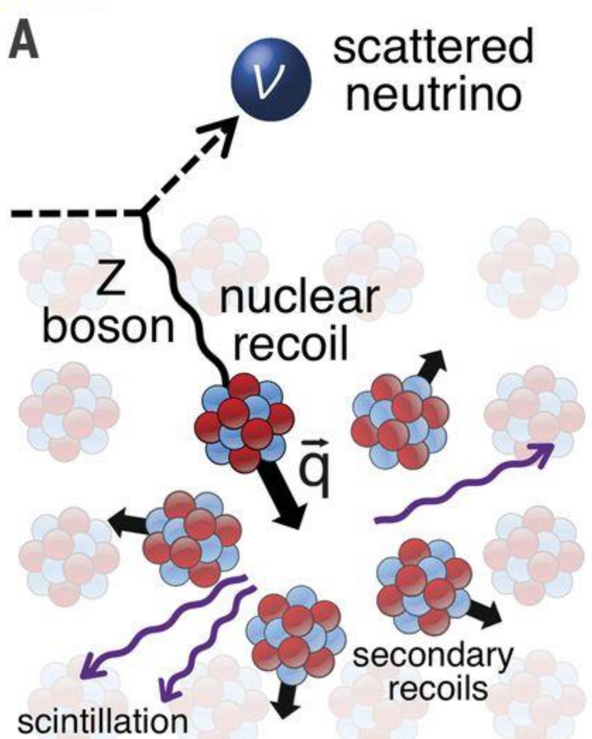

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NL's
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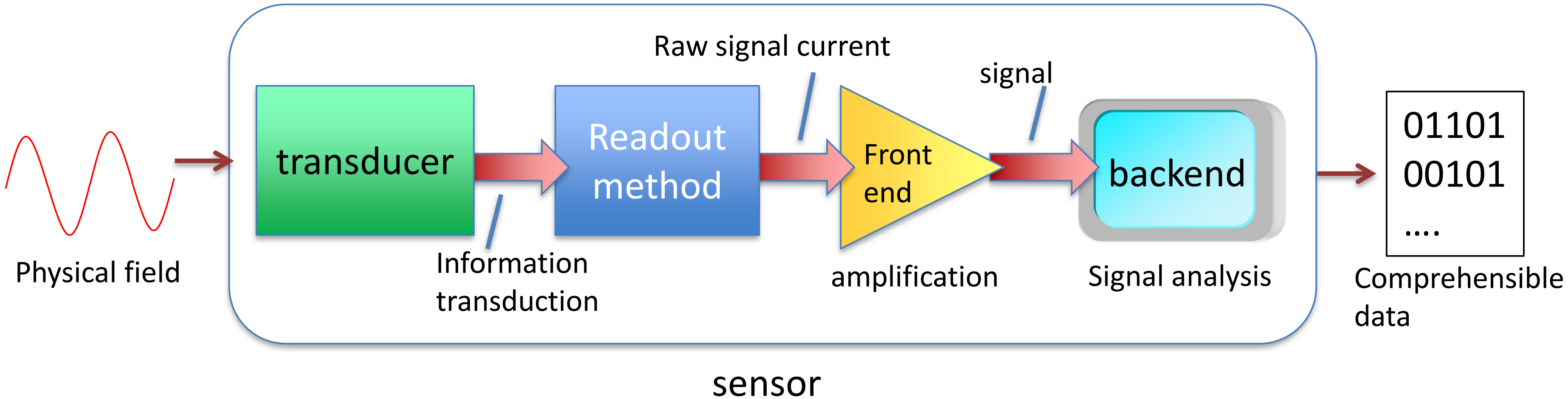
published in the journal *Science*, provides

Sensors in General

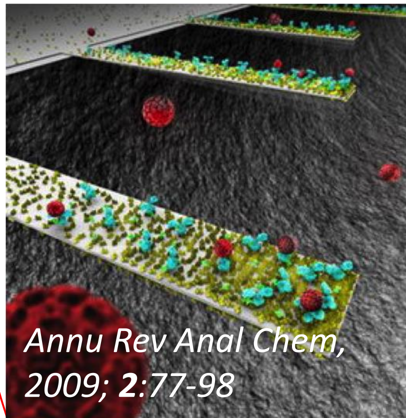
- Sensors can be defined as devices that detect physical quantities by transducing them to (potentially macroscopic) understandable signals
- One way to construct a sensor:

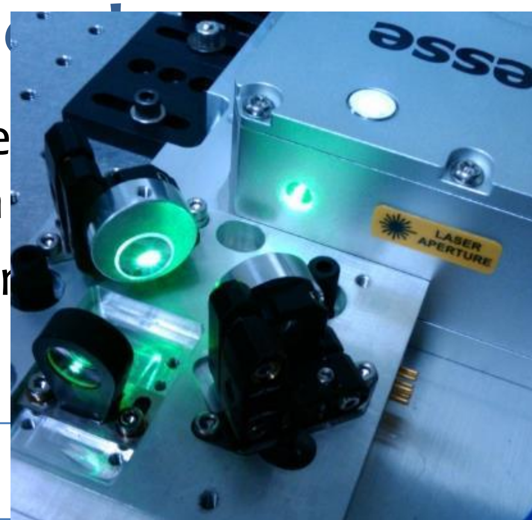


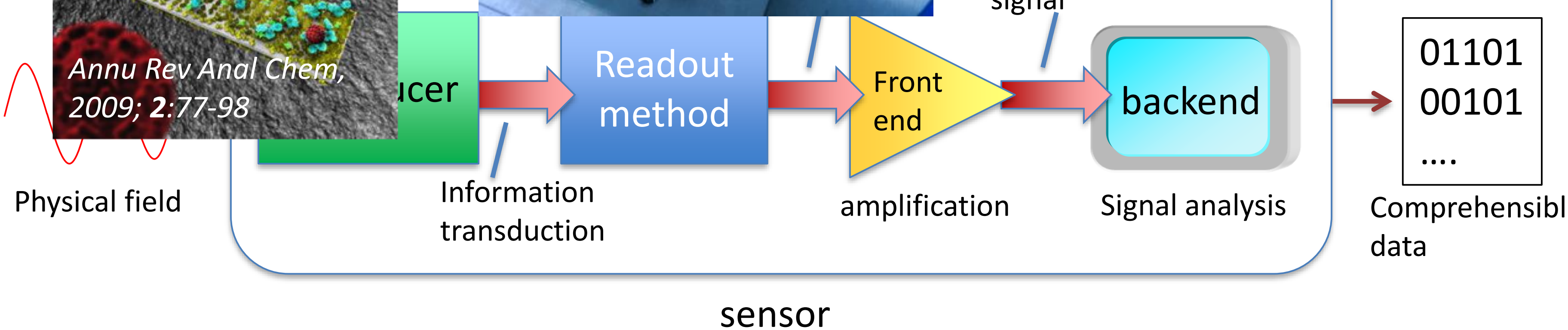
- In some sensors readout methods can be included in transducer or front end
- Noise occurs in each component

Sensors in Gen…

- Sensors can be de… tect physical quantities by transducing them … opic) understandable signals
  …onstr…







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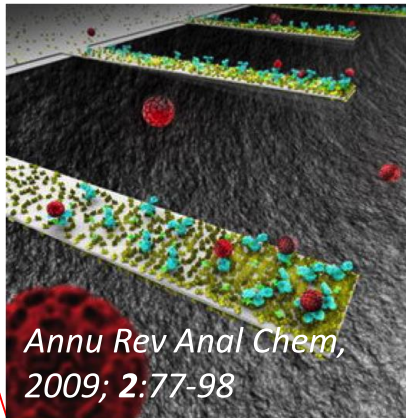
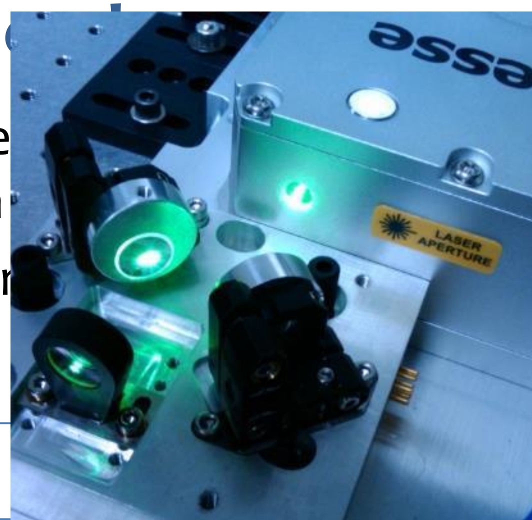


Annu Rev Anal Chem, 2009; ***2****:77-98*



ucer

Readout method

Front end

backend

01101
00101
....

Physical field

Information transduction

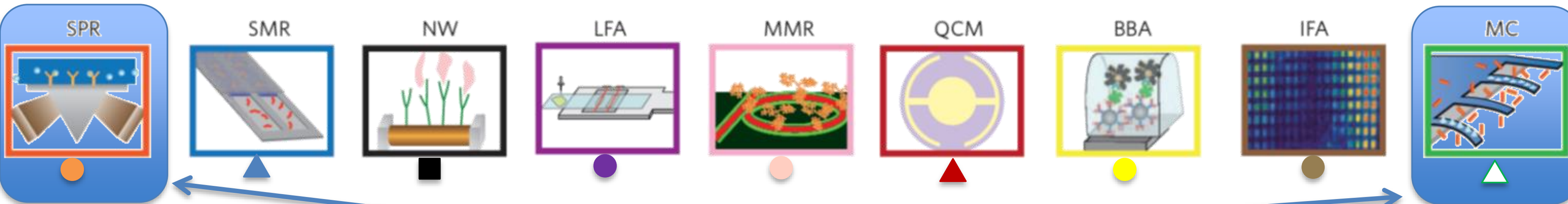
Signal analysis

Comprehensible data

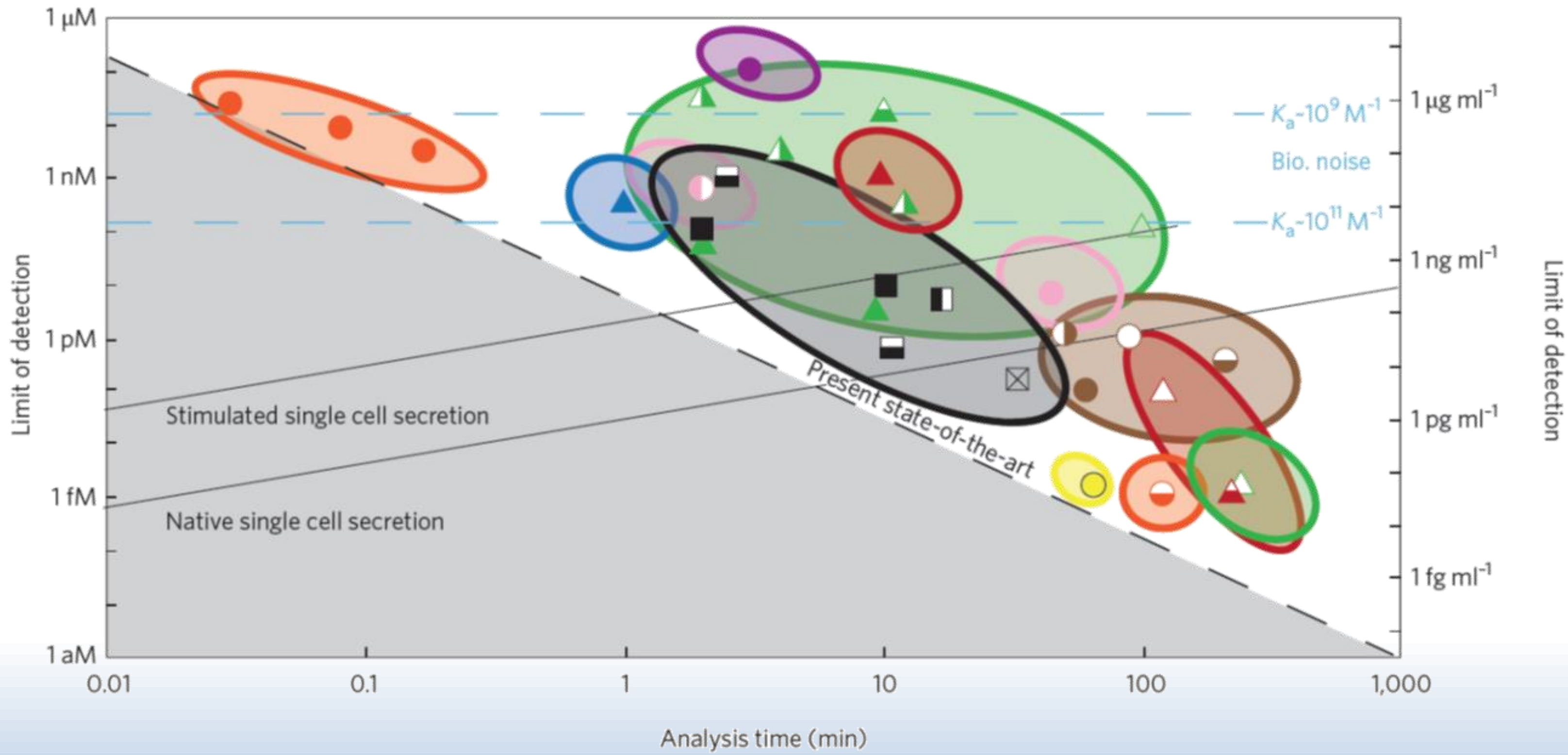
senso

- In some sensors readout methods can be included in transducer or front end
- Noise occurs in each component

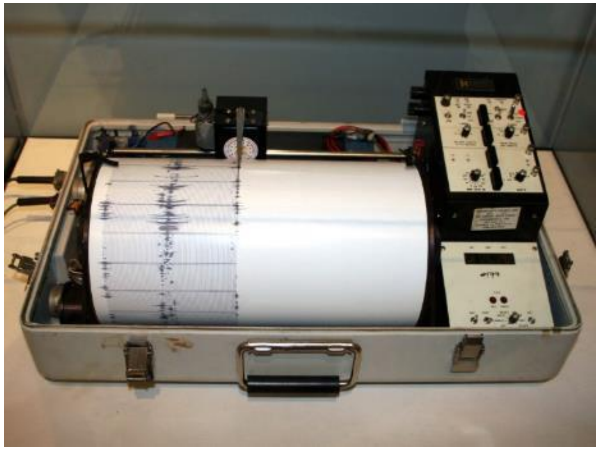
Sensitivity Depends on Integration Time



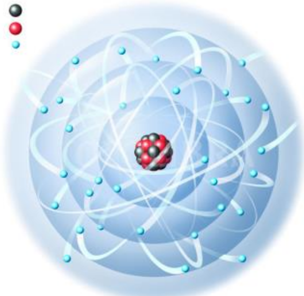
Included in this talk



Sensor size matters



macro



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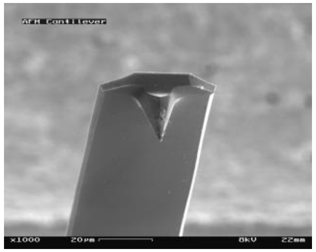


Micro, nano

nanoscale processes require tiny sensors, often limited by **quantum** processes

The fundamental detection limit in many systems is determined by quantum mechanics (e.g., Heisenberg uncertainty principle) **because a full description of the sensor requires quantum theory**

We are done

President Obama
@POTUS

Follow

Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.

6:43 PM - 11 Feb 2016

9,433 21,272

Why use squeezed light?

President Obama @POTUS

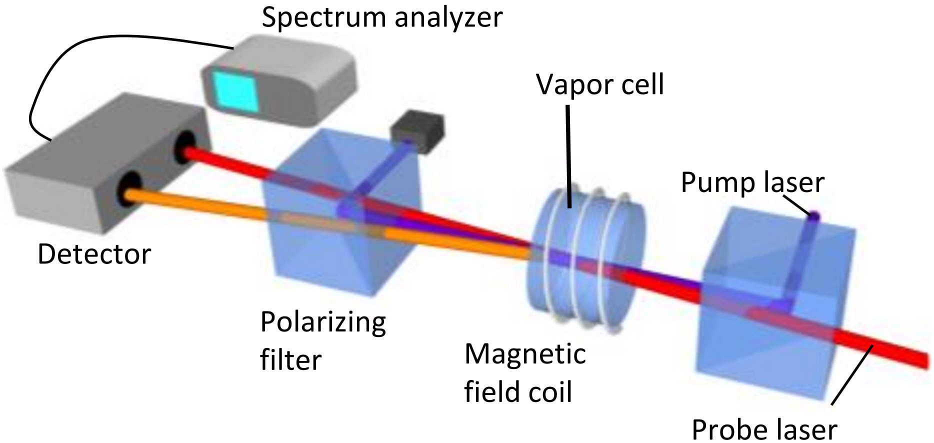
Follow

You guys better use #squeezed_light if you want to see further out into the universe, or smaller GW signals, though.

6:43 PM - 11 Feb 2016

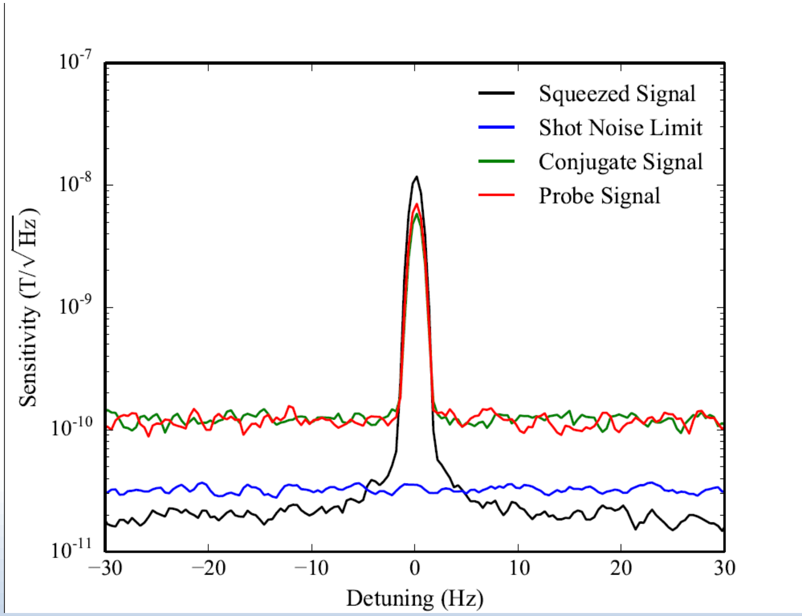
9,433 21,272

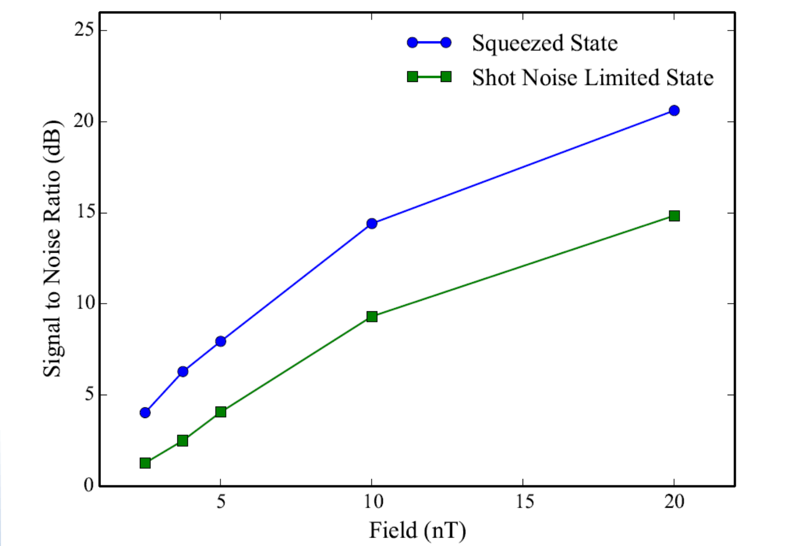
Quantum Magnetometry



4.5dB QNR below the shot noise limit

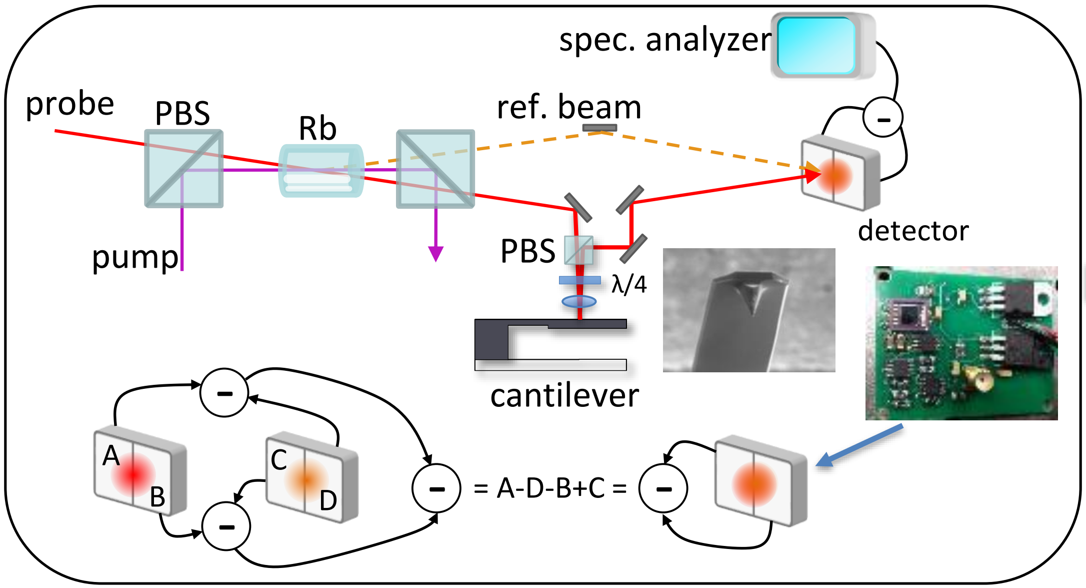
Otterstrom, Lawrie, Pooser, Optics Letters, 39, 6533 (2014)

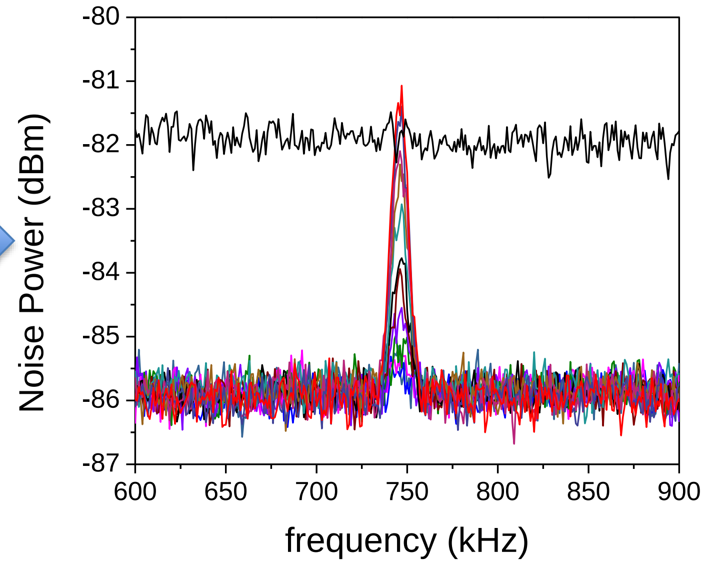




Ultra Sensitive Microcantilever Displacement Measurement

Noise floor reduced to less than 40% of the shot noise limit

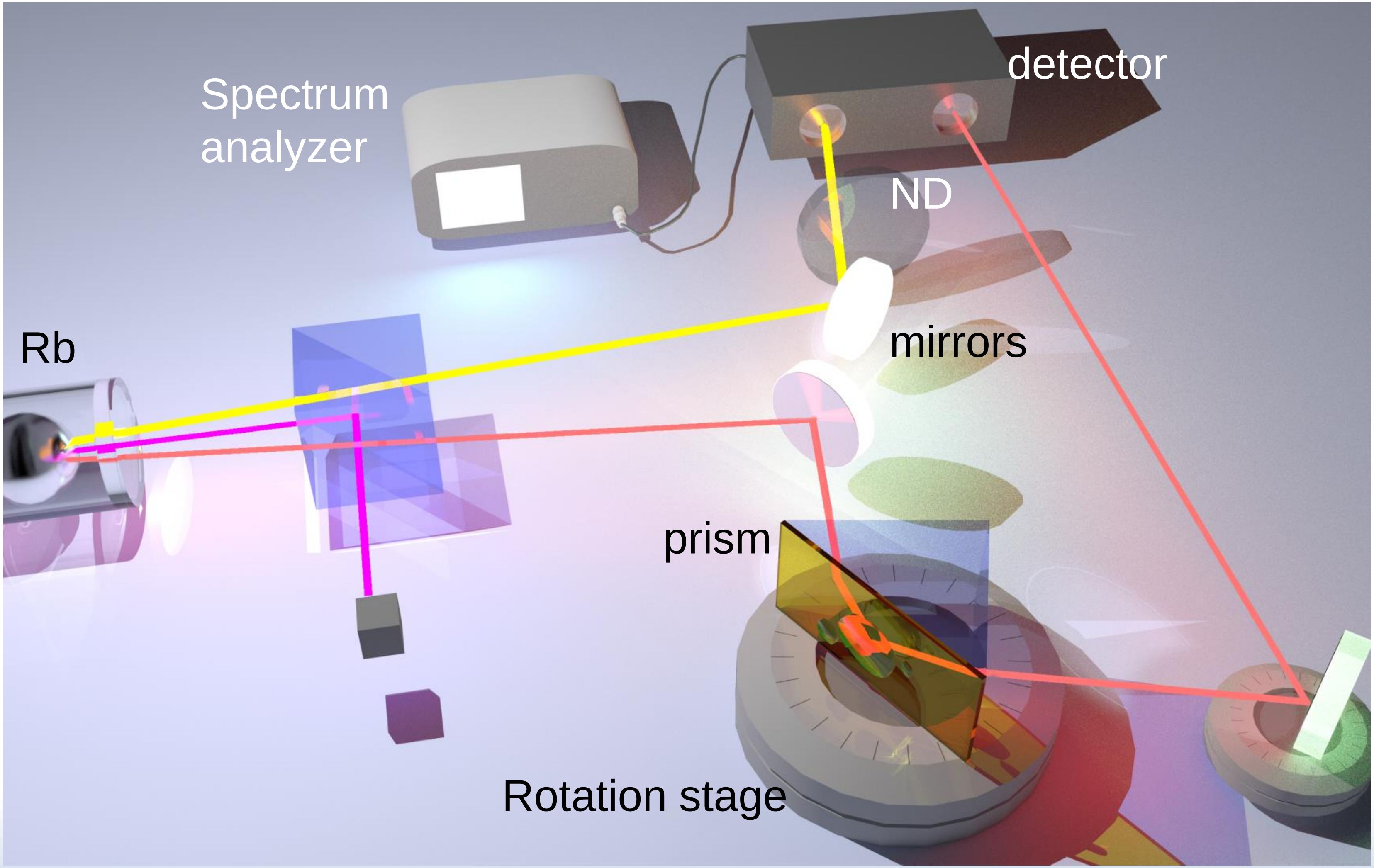




135 fm amplitude displacement modulation measured for 4dB squeezing in 10 kHz acquisition window; 1.35 fm possible in 1 Hz acquisition window. Record for AFM sensitivity

R. C. Pooser, B. Lawrie, Optica 2(5) 393-399 (2015)

Plasmonic trace sensing with squeezed light



nature physics

LETTERS

PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Hunting for topological dark matter with atomic clocks

A. Derevianko[1]* and M. Pospelov[2,3]

"networks or correlated atomic clocks can be used as a powerful tool to search for topological dark matter"

ASTROPHYSICS

Atom-interferometry constraints on dark energy

P. Hamilton,[1]* M. Jaffe,[1] P. Haslinger,[1] Q. Simmons,[1] H. Müller,[1,2]† J. Khoury[3]

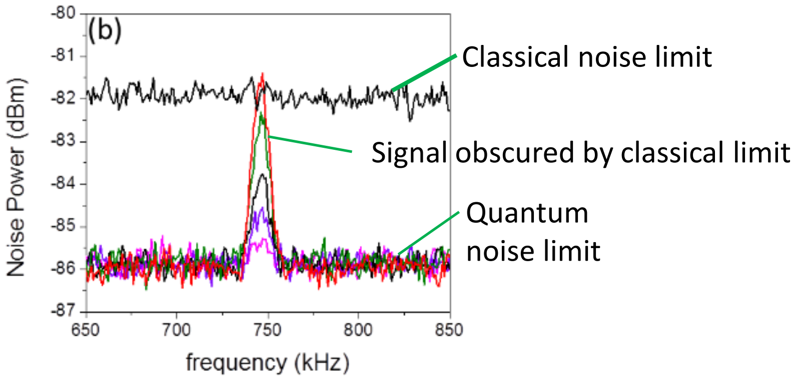
SCIENCE 21 AUGUST 2015 • VOL 349 ISSUE 6250 849

Also see: proposals to squeeze microwave background field;
e.g. arXiv:1607.02529v2 [hep-ph]

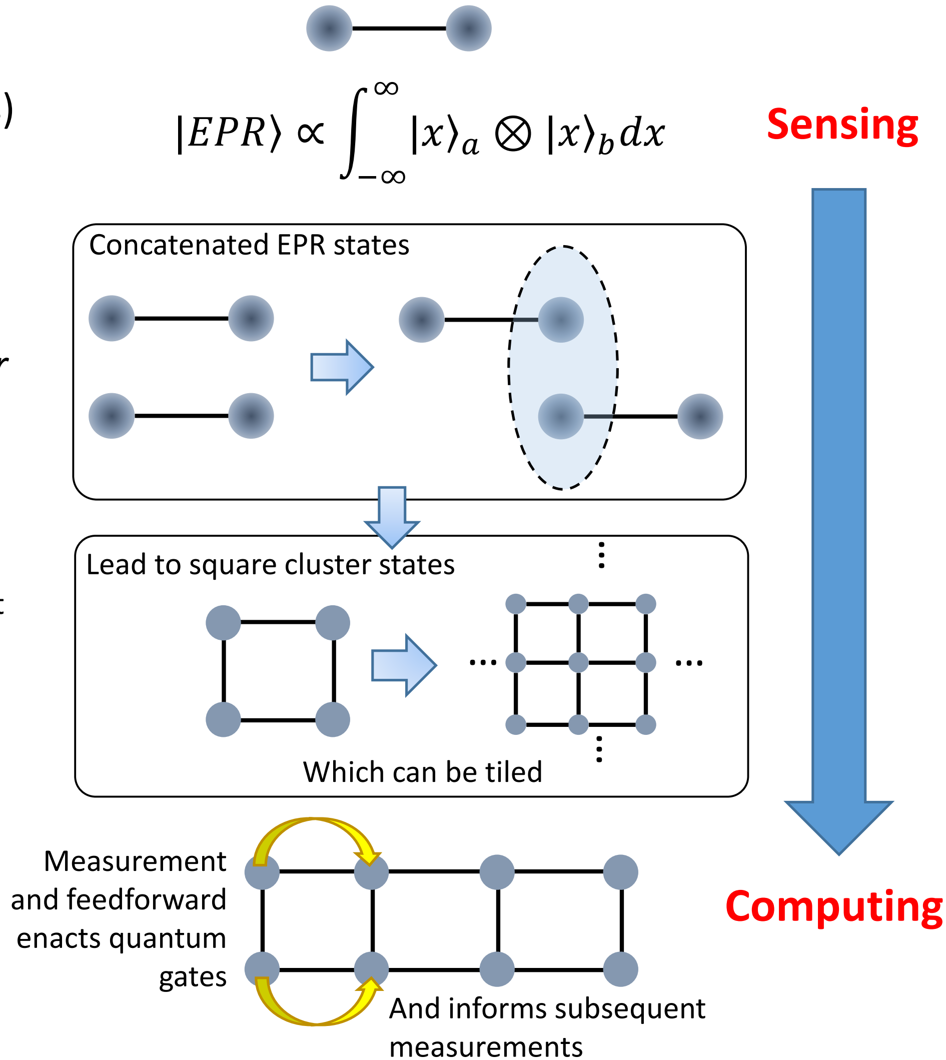
Oak Ridge National Laboratory

Quantum Sensing and Quantum Computing Across Quantum Networks

- Quantum networks are collections of qubits (nodes) connected by interactions, or quantum gates (edges)
- Simplest quantum network is the two qubit EPR state or Bell state, *which is a workhorse in quantum sensing*
  - The quantum correlations in EPR quantum networks can be used to *reduce the noise floor in measurements* – **quantum metrology**



- Indefinitely large quantum networks can be built by concatenating EPR states – *the same network is a resource for measurement-based quantum computing and distributed quantum sensors*

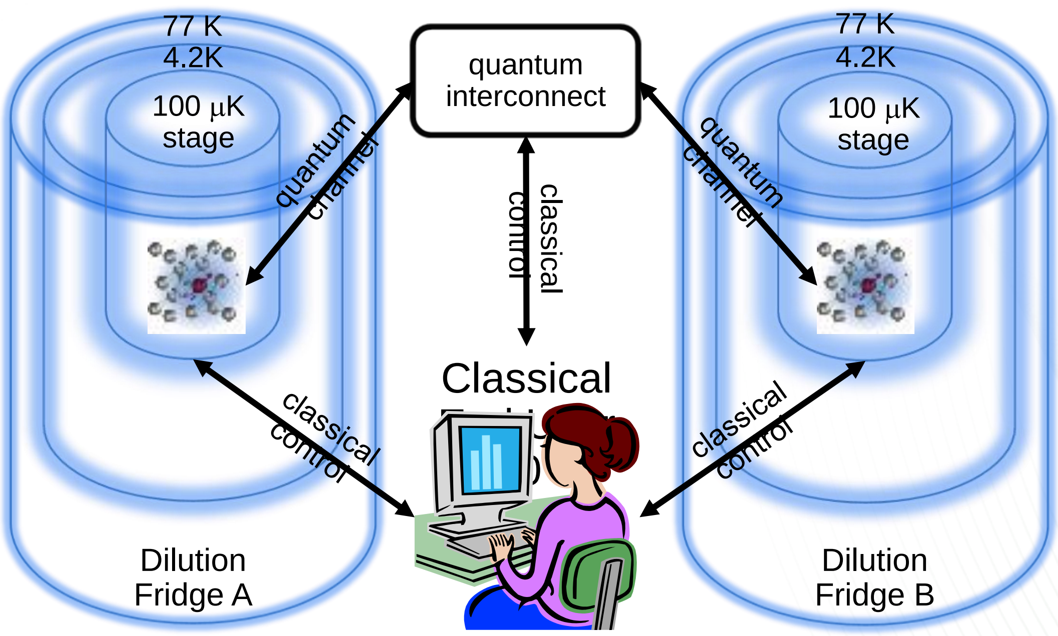


The know-how in generating long range entanglement for quantum sensing lends itself to building quantum computers. This is because in order to make these quantum sensors, one must build a *quantum network* with a *two qubit gate* interaction between the nodes.

Pavel Lougovski: *A Quantum Interconnect for Matter Qubits Based on Frequency-Encoded Photonic Qubits*

Develop a technology enabling exchange of quantum information between dissimilar matter qubits

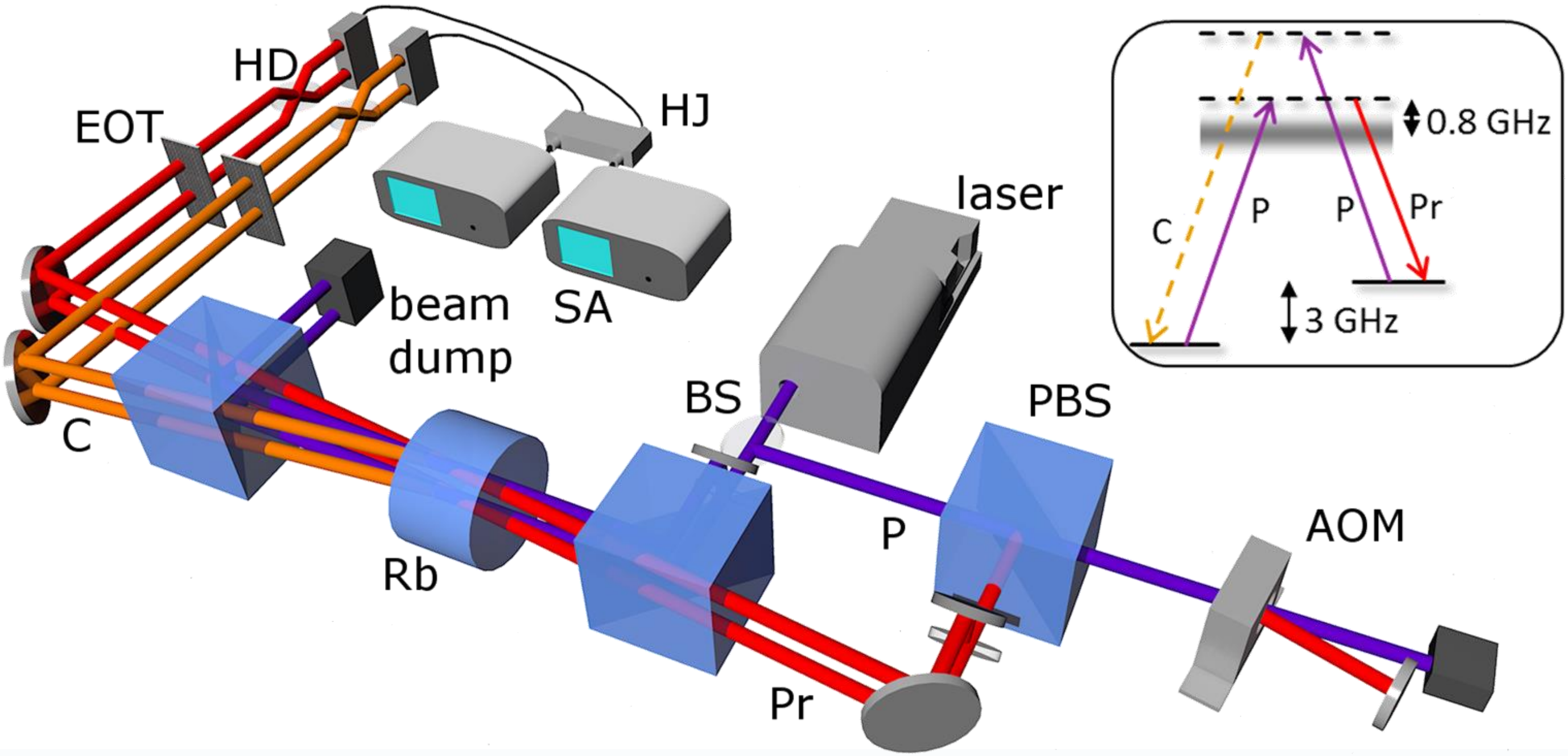
- Develop a protocol to mediate operations between remote qubits using single photons of different frequencies
- Experimentally demonstrate high-fidelity quantum operations on photons of dissimilar frequencies
- Utilize the technology as a part of the future material qubit testbed and quantum internet



OAK RIDGE National Laboratory

Long range continuous variable plasmonic networks

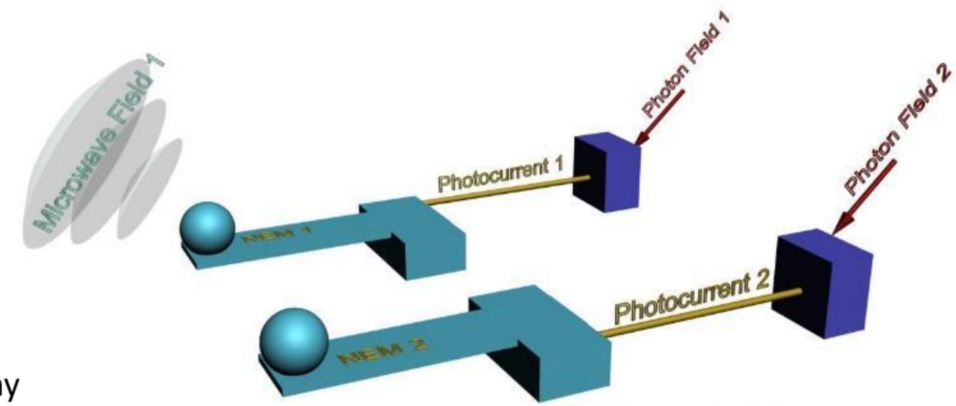
Long range entanglement among plasmons in separate substrates

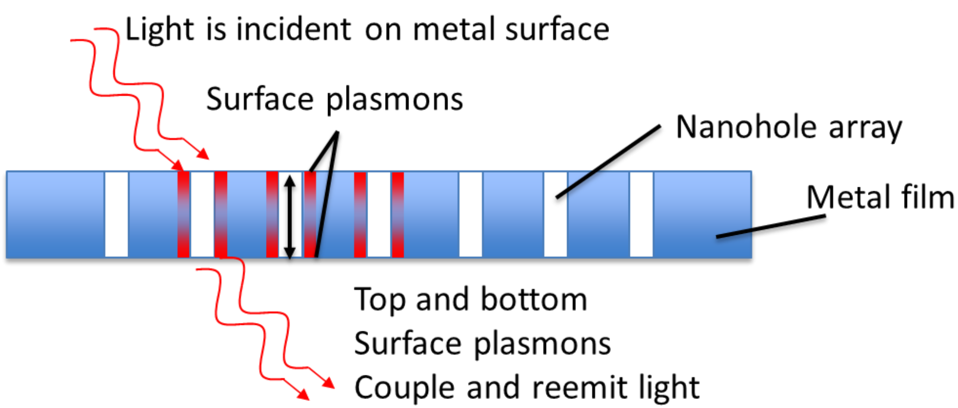


M. Holtfrerich, M. Dowran, R. Davidson, B. Lawrie, R. C. Pooser, A. Marino, Optica 3, 985-988 (2016).

Photonic to microwave transduction

- Complete coherent **electronic** transduction of quantum entanglement leads to coherent coupling to microwaves
  - In continuous variable quantum optics the quantum statistics are already encoded in the microwave sidebands of the optical field!
- Could lead to entangled networks of superconducting cavities





Quantum Sensing Networks

Integration of magneto optical traps (MOT) with a squeezed light source

- Current MOT optical readout limited by laser noise
  - Squeezed light source can enhance sensitivity of existing MOTs
- Entanglement exists between probe and conjugate beams
  - Quantum state transfer from probe beam → MOT
  - Teleport state from conjugate beam to a 2nd MOT
  - **MOTs are now entangled** - backbone of scalable quantum sensing network