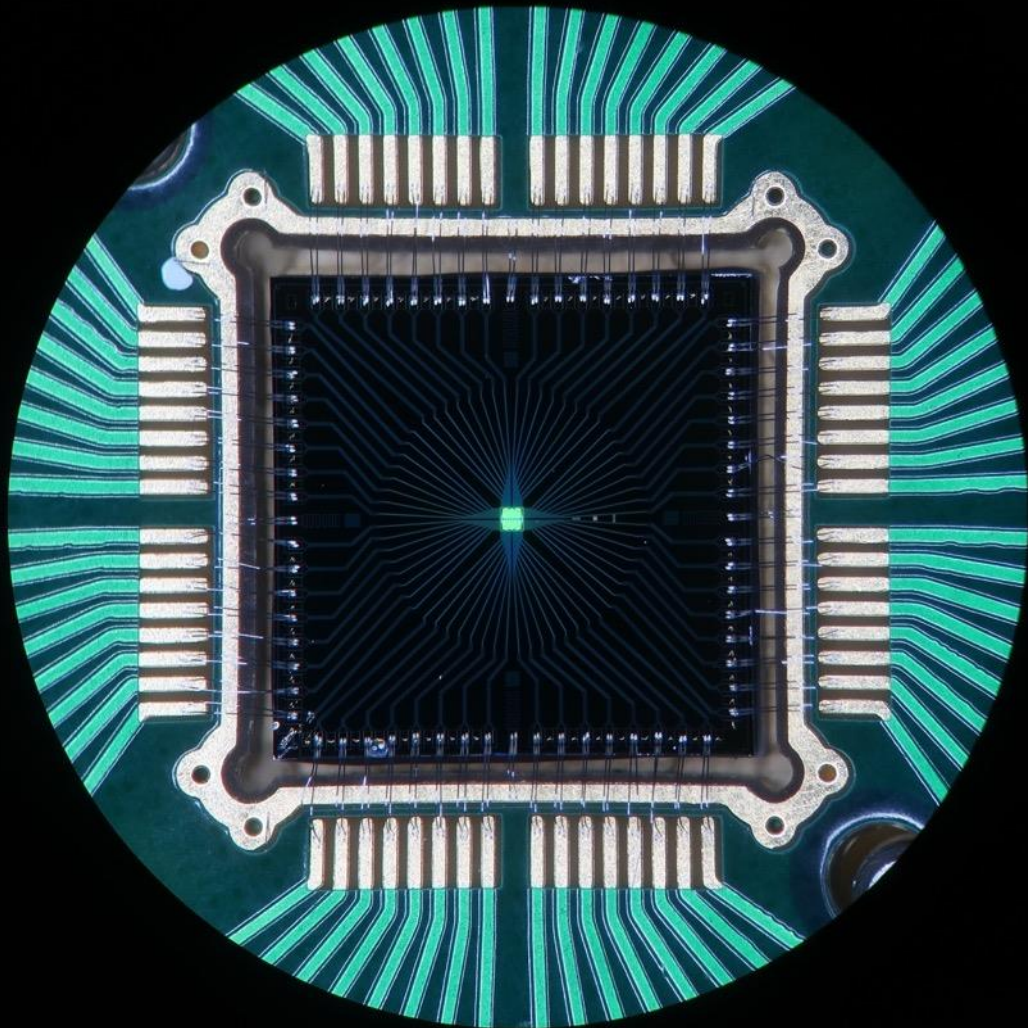




Quantum Sensing for Astronomy: Technologies and Techniques

Matt Shaw

Jet Propulsion Laboratory

2 September 2026

Ad Astra Workshop, Caltech
Pasadena, CA

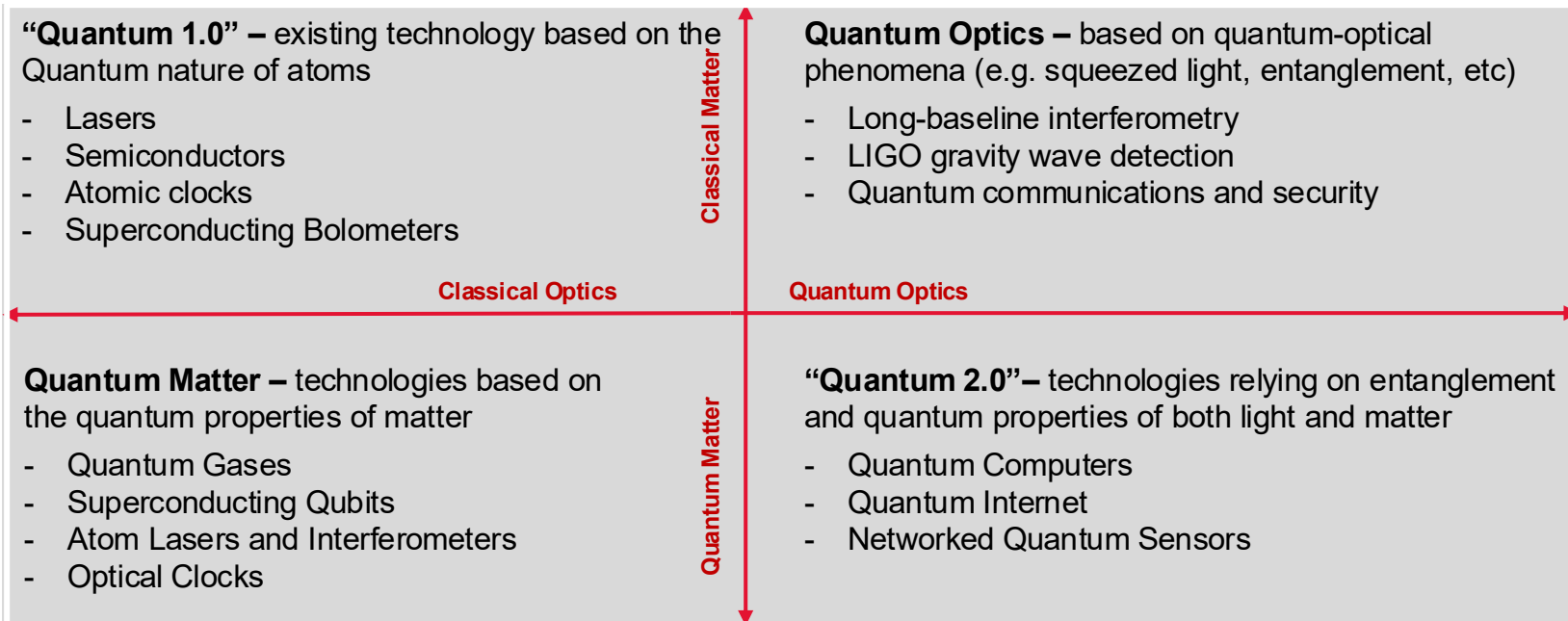


Jet Propulsion Laboratory
California Institute of Technology

What is Quantum Sensing?

The use of quantum mechanical effects to enhance physical measurements or evade classical limits

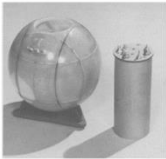
0 result for "quantum sensing"



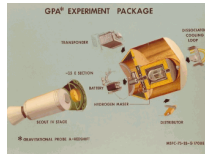
Examples of Quantum Sensing Technologies

- Superconducting Detectors, Amplifiers, SQUIDs
- Atom interferometers, Bose-Einstein Condensates
- Quantum Magnetometers
- Rydberg RF Sensors
- Atomic Clocks, Optical Lattice Clocks, Networked Sensors

Mariner 4 (1964)
Optically Pumped Vector
Magnetometer



Gravity Probe A (1976)
Hydrogen Maser



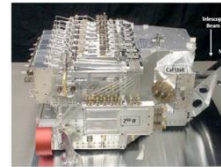
Superfluid Helium
in Microgravity



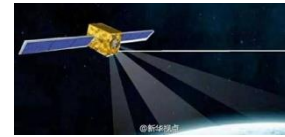
Gravity Probe B (2004)
London Moment
Gyroscopes, SQUIDs



Herschel (2009)
SIS, HEB Mixers



Micius (2016)
Quantum Key Distribution
Quantum Teleportation



DSAC (2019)
Hg Ion Clock



CAL (2018)
BEC, Atom
Interferometer



Quantum Inertial
Sensor (2025)



1960

1970

1980

1990

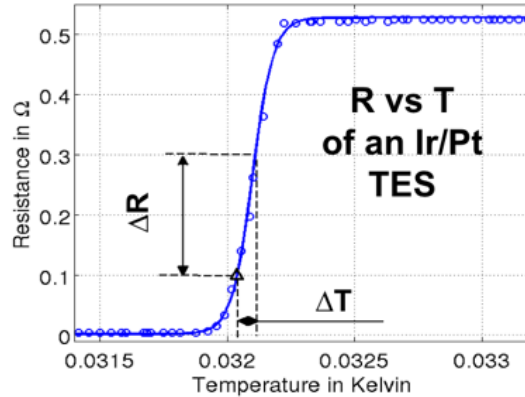
2000

2010

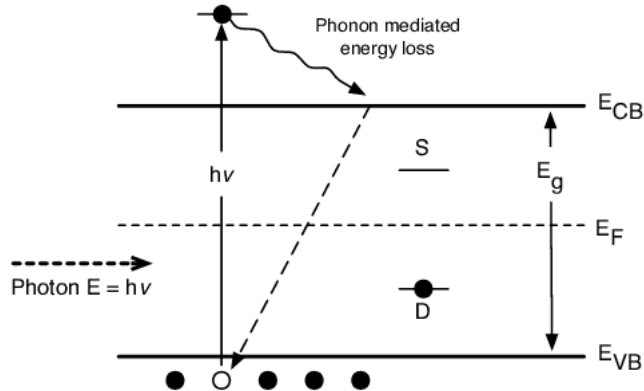
2020

Why Superconducting Detectors?

Superconducting detectors are the lowest noise, highest sensitivity detectors available – but they require cryogenic operation (0.05 – 4K).

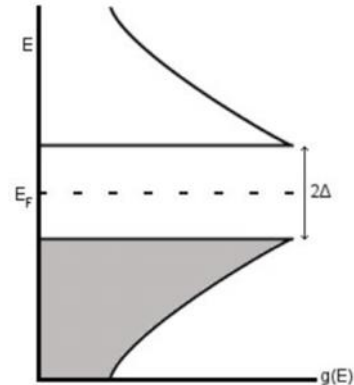


C. Chang (ANL)



Semiconductor Bandgap

- Si 1.12 eV
- InGaAs 0.75 eV



Superconducting Gap Energy

- Nb 2.32 meV
- Al 0.34 meV

Astronomy

Metrology

Dark Matter

Remote Sensing

Biomedical Imaging

Laser Communication

Quantum

Landscape of Superconducting Detectors

Coherent Receivers

Direct Detection

Photon Counting

SIS Mixers

HEB

TKID

MKID

Qubits

TES

Parametric Amplifiers

QCDs

SNSPDs

wavelength
frequency
photon energy

10 cm
3 GHz
12 μeV

1 cm
30 GHz
120 μeV

1 mm
300 GHz
1.2 meV

100 μm
3 THz
12 meV

10 μm
30 THz
120 meV

1 μm
300 THz
1.2 eV

100 nm
3000 THz
12 eV

RF

microwave

mm-wave

submillimeter
terahertz
far-infrared

mid-infrared
near
infrared

visible
UV

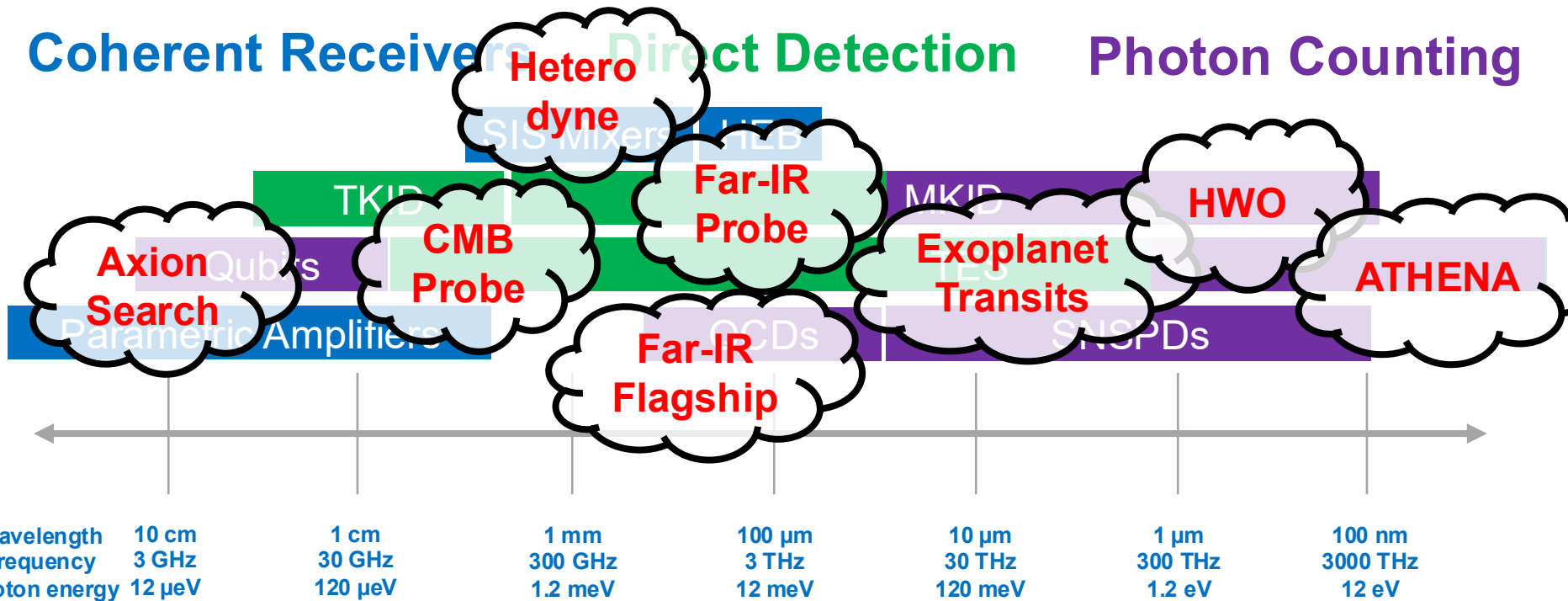
x-ray

Landscape of Superconducting Detectors

Coherent Receivers

Direct Detection

Photon Counting



RF

microwave

mm-wave

submillimeter
terahertz
far-infrared

mid-infrared

near
infrared

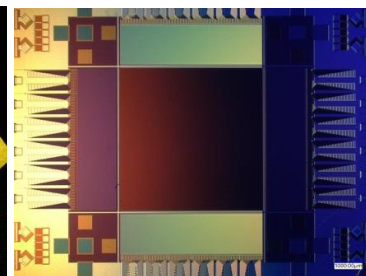
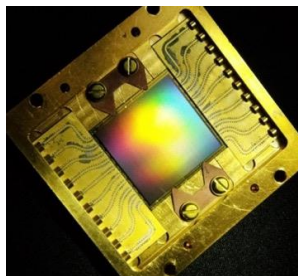
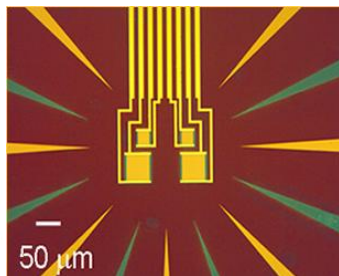
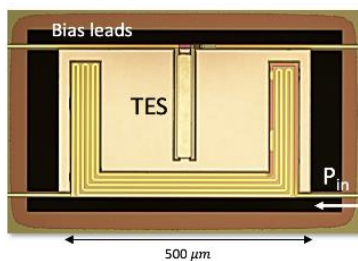
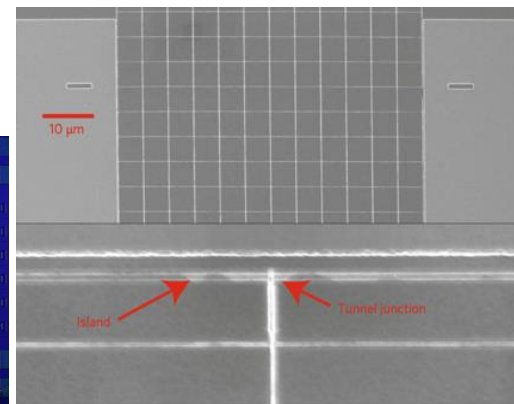
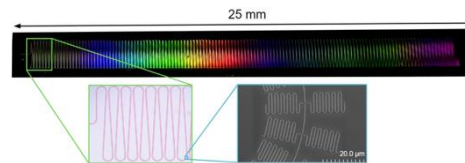
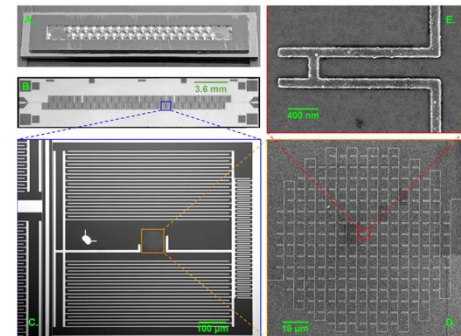
visible

UV

x-ray

New Observables Enabled by Superconducting Detectors

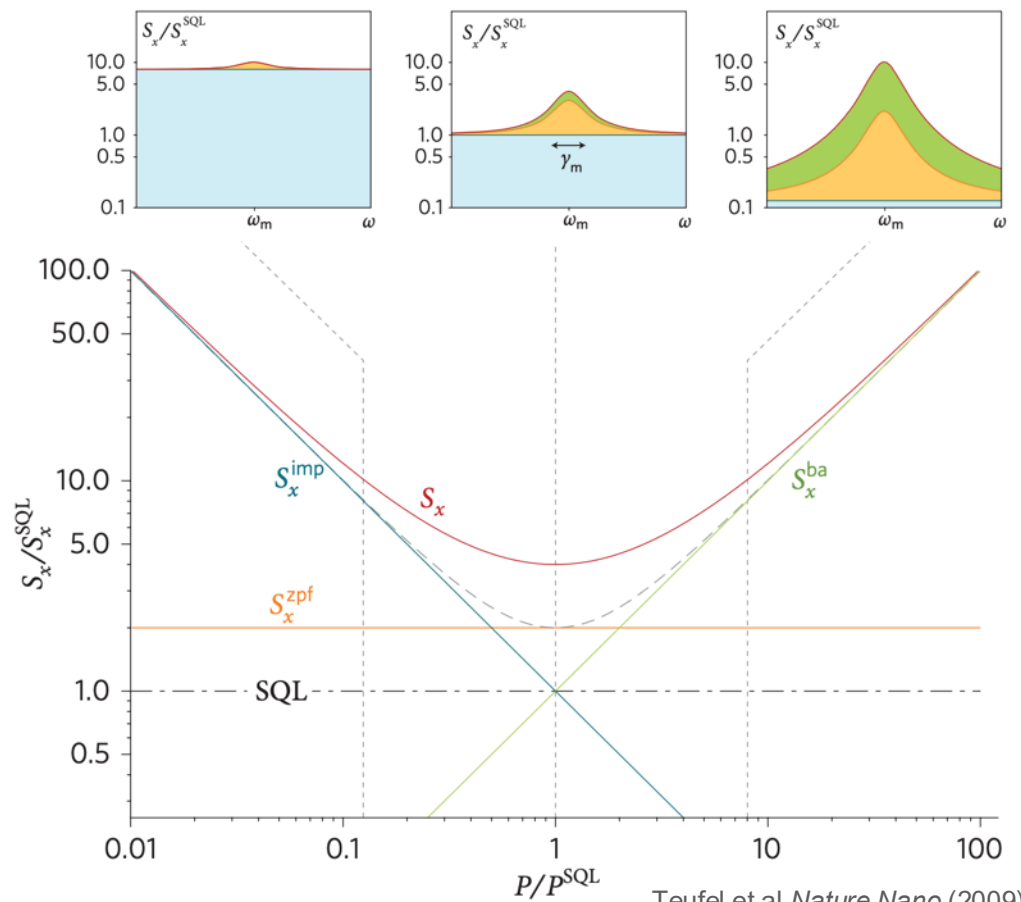
- Ultra-sensitive detectors for CMB observatories (TES, TKID, paramp)
- Ultra-sensitive arrays for submillimeter spectroscopy (MKID)
- Energy-resolved optical photon counting (TES, MKID)
- Mid- and far-infrared time-resolved single photon counting (SNSPD)
- Megapixel-scale cameras for time-resolved imaging (SNSPD)
- Submillimeter single photon counting (QCD)
- Low-energy neutrino detection (QCD)
- Quantum-limited microwave and millimeter-wave measurements (paramp)
- High-resolution terahertz spectroscopy (SIS and HEB mixers)



Amplifiers at the Standard Quantum Limit

- The SQL is the minimum amount of noise allowed by quantum mechanics for a phase-insensitive amplifier
- SQL is the noise which is present when photon shot noise equals backaction
- In a microwave amplifier, SQL is due to zero-point fluctuations in idler mode
- A parametric amplifier is phase-sensitive, enabling a quantum nondemolition measurement which “beats” the SQL in one quadrature
- This produces a quantum “squeezed state” at the output

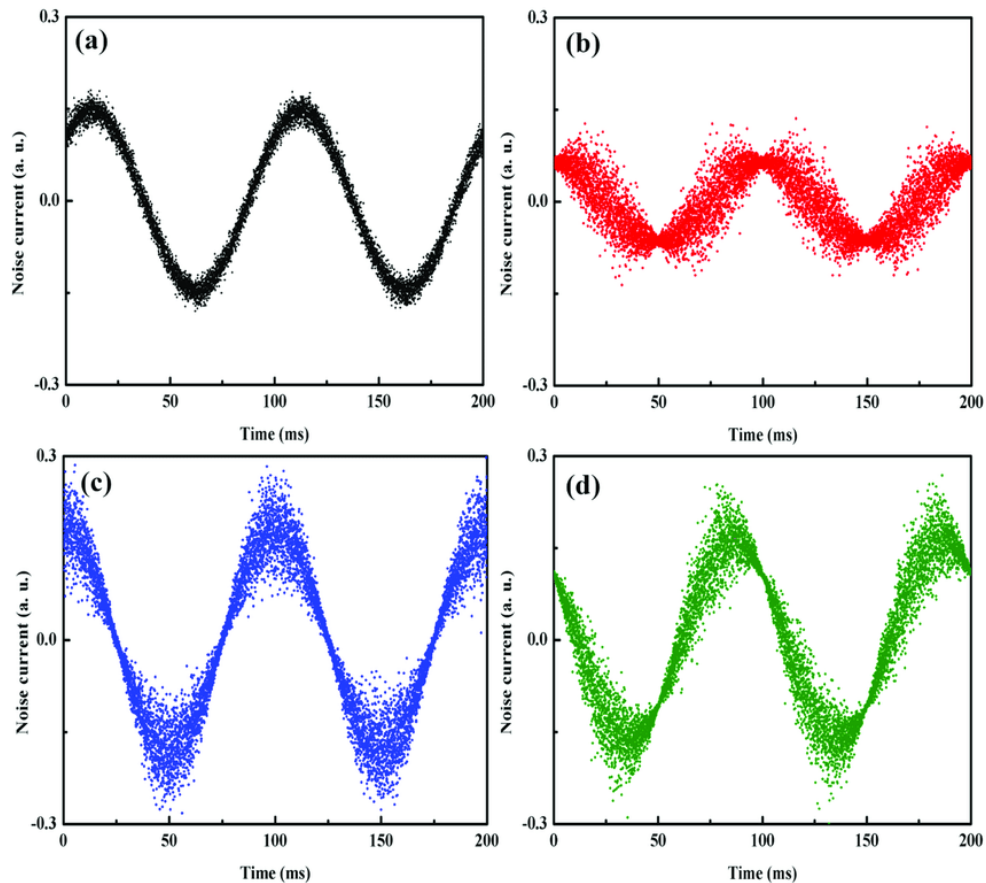
$$k_B T_N[\omega] \geq \hbar \omega / 2$$



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Ultracold Gases in Space

Quantum Matter – studies of the quantum properties of matter

- Bose-Einstein condensates and Fermi gases
- Wave-like nature of matter
- Heisenberg uncertainty principle
- Quantum collisions

Studies of complex systems

- Superfluids & superconductors
- Nuclear matter
- Cosmological phenomena

Atom interferometers

- Utilizes interference of atomic matter waves.
- High-precision measurements of inertial forces, rotations, and gravitational physics

Fundamental Physics / Astronomy

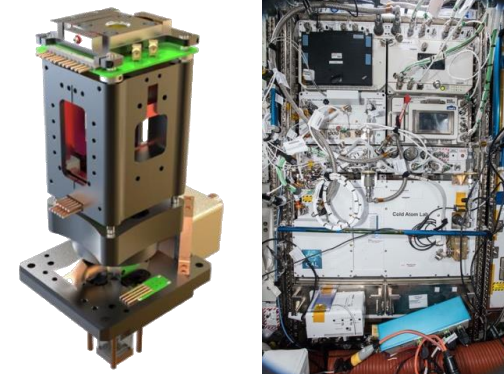
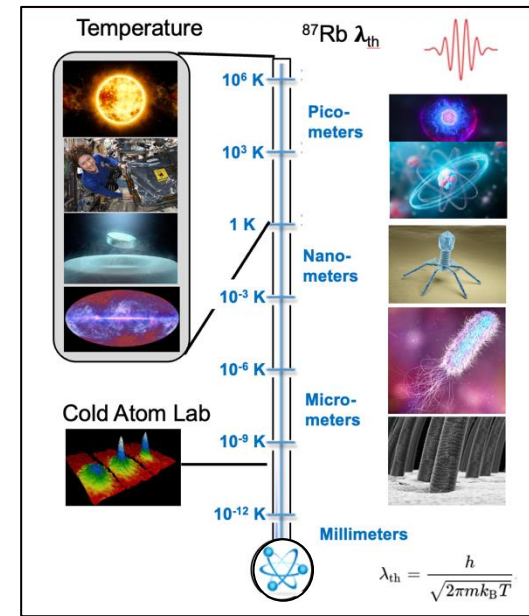
- Weak Equivalence Principle
- Frame-dragging
- Spin-gravity coupling
- Inverse square law
- Dark particle detection
- Gravity wave detection

Optical Clocks

- Frequency reference based on metastable optical transitions.
- Stability exceeding 10^{-16} at 1 second and 10^{-19} total accuracy

Planetary Science & Spacecraft PNT

- Drag-free referencing
- One-way navigation
- Gravity sensing for geodesy, subsurface measurement, etc.

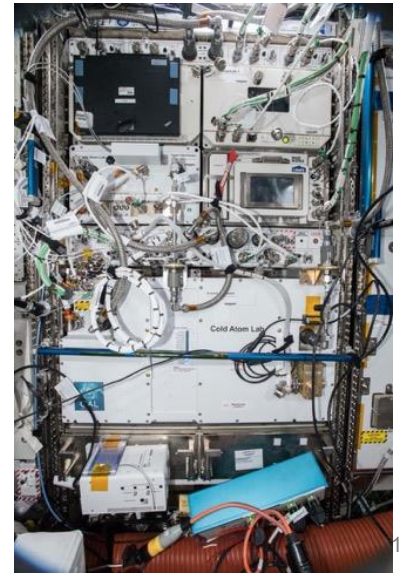
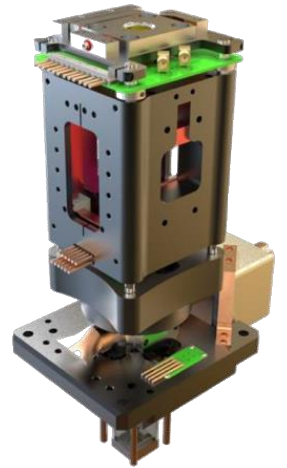


Cold Atom Lab

The Coolest Experiment in the Universe

Utilizes the microgravity environment of the ISS to perform measurements that can't be achieved on Earth.

- Multiple atomic species: (^{87}Rb , ^{39}K , and ^{41}K)
- Bose-Einstein condensates.
- Two-axis imaging detection.
- Ability to prepare a variety of quantum states and tune their interactions.
- Dual-species atom interferometry.



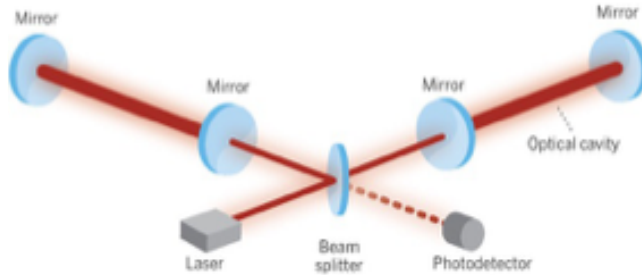
The world's first multi-user facility for the study of quantum gases in space

Atom Interferometry

Optical Interferometers

The ultimate motion sensor

In a LIGO interferometer, light waves leaking out of the two storage arms ordinarily interfere to send light back to the laser. By stretching the two arms by different amounts, a gravitational wave would alter the interference and send light toward a photodetector.



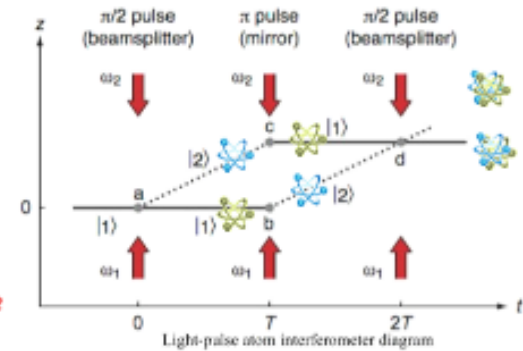
G. GRULLÓN/SCIENCE

- Constructive or destructive interference of **optical waves** traveling two paths gives sensitive information about path-length and environmental perturbations on each branch.
- LIGO is a quintessential example of application of Laser Interferometers for Fundamental Physics, but extensive practical applications have realized.
- Sensitivity grows with the length of each path, the signal strength on the photodetector and quantum-enhanced detection.

Light-Pulse Atom Interferometers



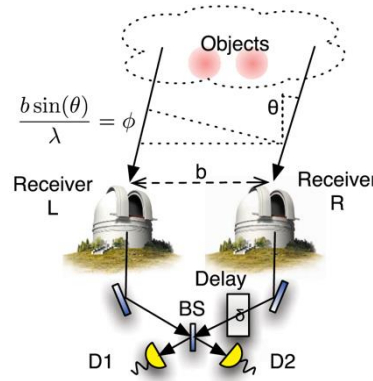
$$\Delta\Phi = 2k a T^2$$



- Constructive or destructive interference of **matter waves**, in which each atom simultaneously travels two paths gives sensitive information about forces and environmental perturbations on the atoms.
- Benefits from recent developments with quantum matter and optical clocks to provide state of the art sensitivity to gravity and inertial forces
- Sensitivity grows **quadratically** with the AI interrogation time and with the number of atoms.

Intensity Interferometry

- The original quantum optics experiment
- The original application of quantum sensing in astronomy
- Photon arrival times from two telescopes are correlated to extract mutual coherence of an astronomical source
- Multiple baselines can be combined to achieve synthetic aperture images
- Fundamental SNR disadvantage compared to amplitude interferometry
- Insensitive to atmosphere, telescope quality, baseline length

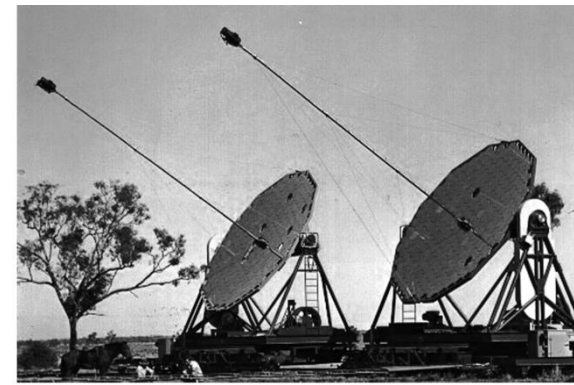
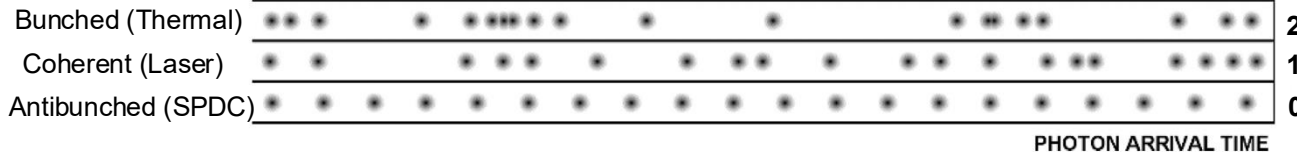


Amplitude Interferometer

$$|\gamma_{12}| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$\langle I_1(t) I_2(t) \rangle = \langle E_1(t) E_1^*(t) \cdot E_2(t) E_2^*(t) \rangle = \langle I_1 \rangle \langle I_2 \rangle (1 + |\gamma_{12}|^2)$$

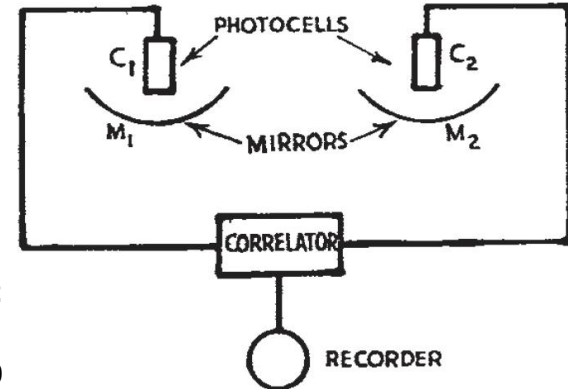
$$1 + |\gamma_{12}|^2 = \langle E_1(t + \tau) E_2^*(t) \rangle$$



Narrabri Intensity Interferometer (1974)

CORRELATION BETWEEN PHOTONS IN TWO COHERENT BEAMS OF LIGHT

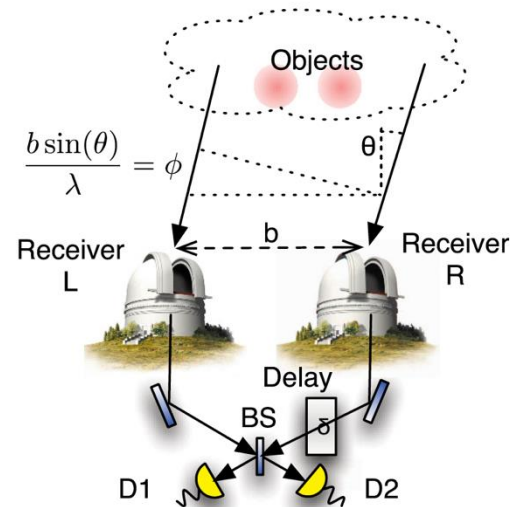
By R. HANBURY BROWN
University of Manchester, Jodrell Bank Experimental Station
AND
R. Q. TWISS
Services Electronics Research Laboratory, Baldock



HBT, *Nature* (1956)

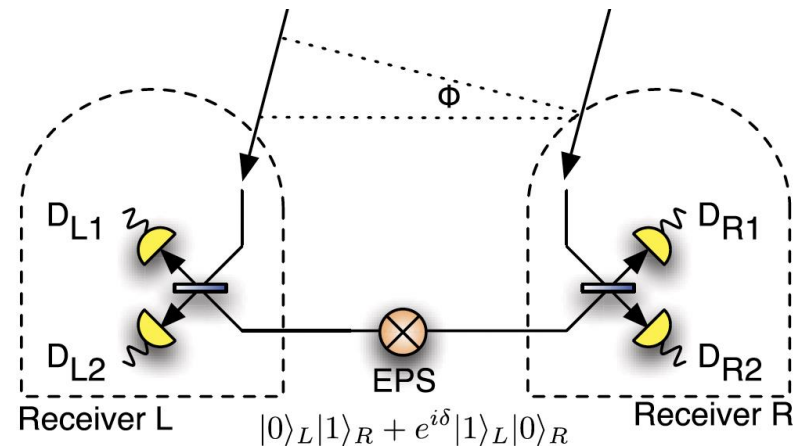
Quantum Optical VLBI

- An alternative approach to amplitude interferometry which does not require physically interfering light from two telescopes on a beamsplitter
- A pair of entangled photons is distributed between two telescopes
- Independent Bell state measurements are jointly performed between the astronomical photon and the entangled photon, at each telescope, measurements compared to reconstruct phase (similar to quantum teleportation)
- This allows for arbitrarily long baselines without propagation loss



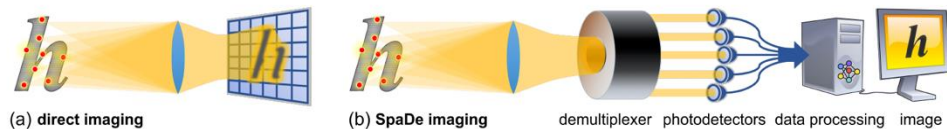
Open Questions

- Entangled photon pairs are required for every astronomical photon in every temporal and spatial mode
- Some papers have suggested storing entangled photons in quantum memories, and performing post-processing on quantum computers
- Are there astronomical use cases for ultra-long baselines, where sources are not over-resolved?
- Are there simpler alternatives to realize ultra-long baseline interferometers?

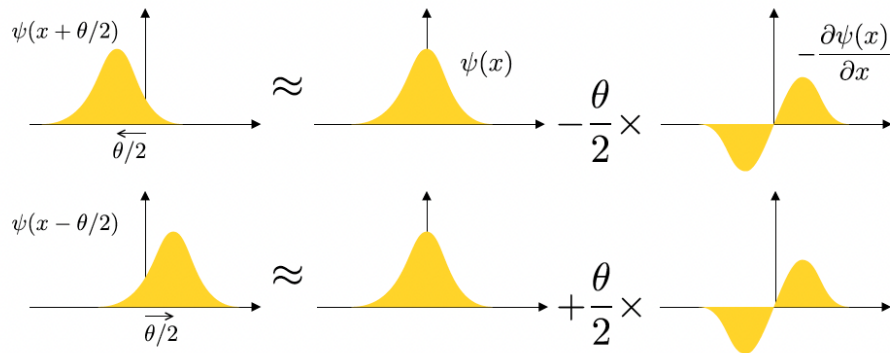


Superresolution: Spatial Mode Demultiplexing

- Are there clever approaches to beat the Rayleigh criterion?

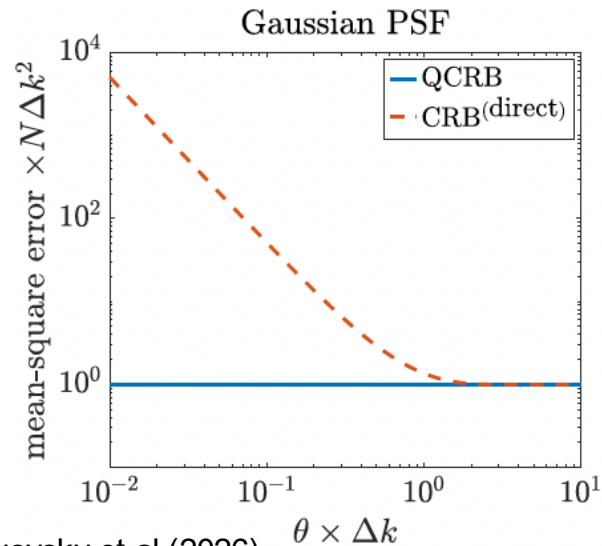
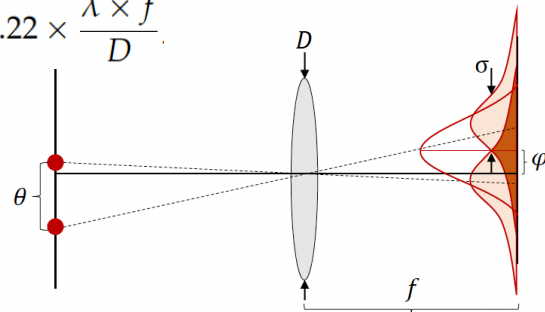


- Instead of imaging light onto a focal plane, decompose the light into an orthonormal basis of Hermite-Gaussian modes, and perform independent photon counting and filtering on each mode



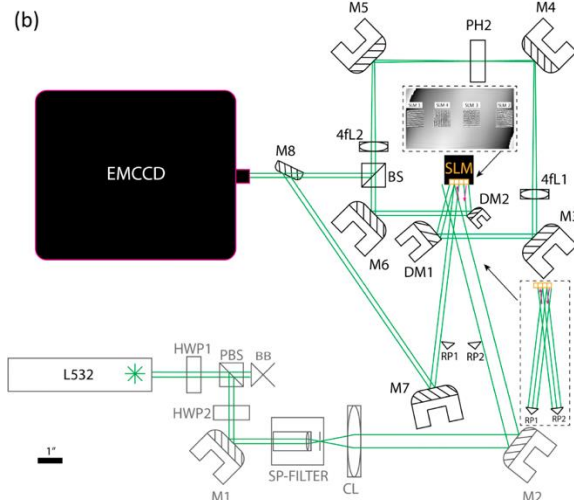
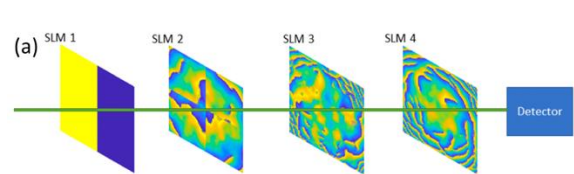
- It is theoretically possible to achieve the quantum Cramér-Rao Bound, which is independent of the separation between sources (Tsang 2017)

$$\theta_{\text{res}} = 1.22 \times \frac{\lambda \times f}{D}$$



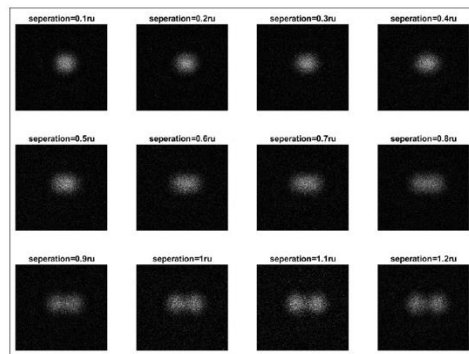
Lvovsky et al (2026)

Superresolution: Spatial Mode Demultiplexing

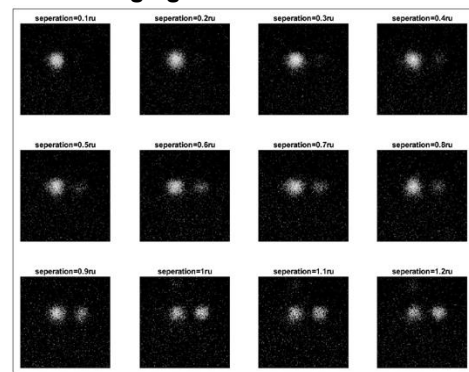


Ozer et al (2024)

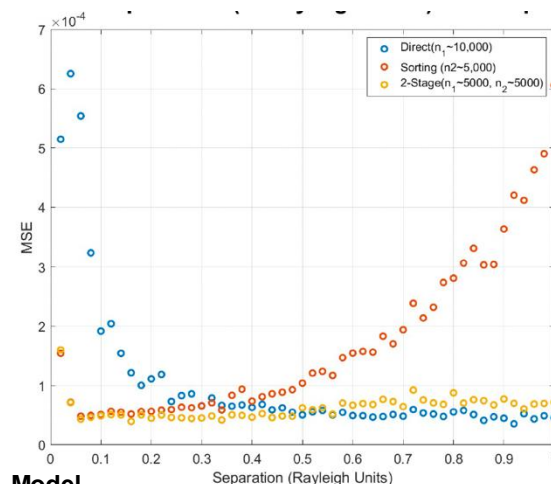
- Spatial mode demultiplexing can be achieved using Multiplane Light Conversion (MPLC) – passing light through a series of successive phase masks to break down light into its constituent LG modes



Direct Imaging

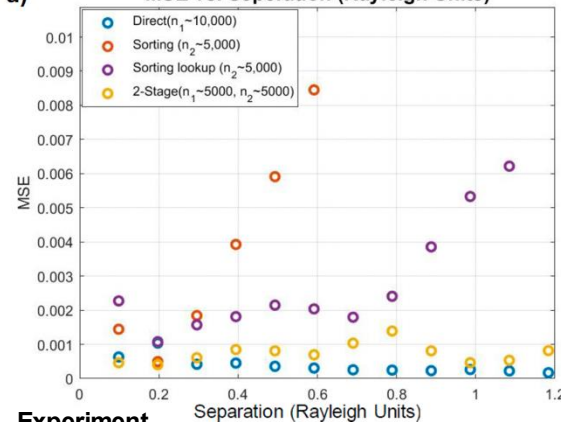


Mode Sorting



Model

a) MSE vs. Separation (Rayleigh Units)



Experiment

Summary

- There exist a wide range of quantum sensing technologies and techniques at varying levels of maturity
- There is a lively field of research exploring new methodologies and sensors, with rapid progress being made in the laboratory
- The astrophysics community should be on the lookout for opportunities to take advantage of new technologies and techniques as they arise

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