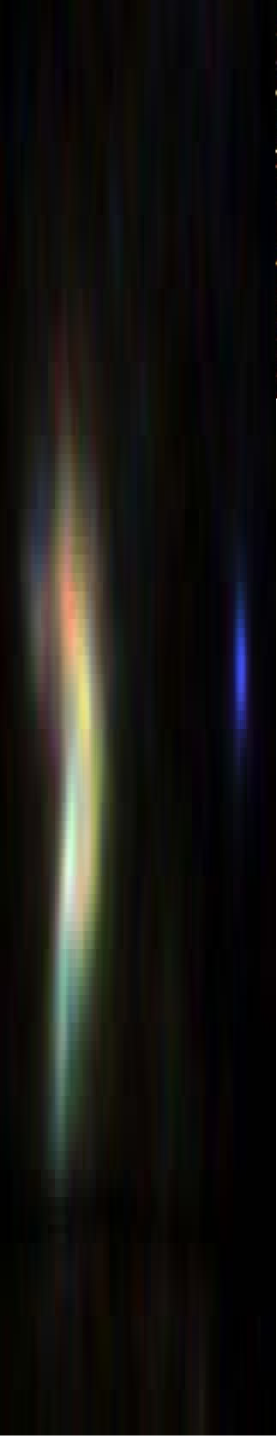


# *Discovery-class Research via*

# *Quantum Sensors Sans Frontier!!*

*Swapan Chattopadhyay (Fermilab/NIU)*

*February 25, 2016*
*Hilton Washington DC North/Gaithersburg*

*Presentation to the Doe Round Table* **:**

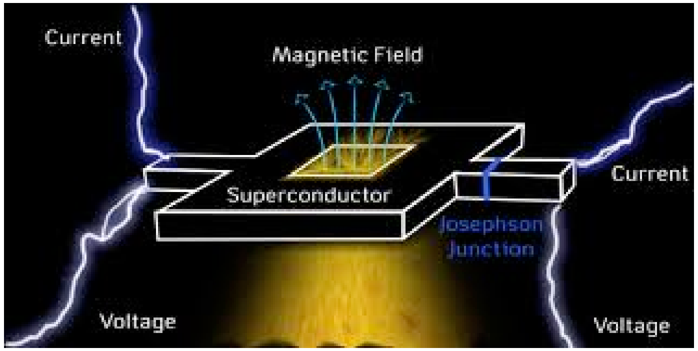
**QUANTUM SENSORS at the INTERSECTION of FUNDAMENTAL SCIENCE, QIS and COMPUTING**

*"Nothing tends so much to the advancement of knowledge as the application of a new instrument"*

**-- Sir Humphrey Davy in "Elements of Chemical Philosophy" (1812)**

**Quantum Sensors – *i.e. instruments that exploit quantum physics in general and the fundamental phenomenon of quantum entanglement in natural systems* -- have the potential of enabling "precision-" and "discovery-class" research in fundamental science, QIS and computing.**

**State-of-the-art precision instruments can detect weak effects with high precision:**
**Fundamental Science and QIS → Quantum-limited macroscopic sensors**
**Advanced Computing → Quantum-limited macroscopic computers**

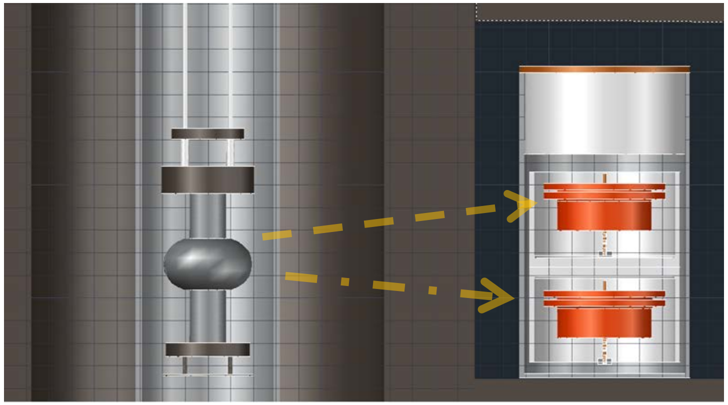



$$\text{Magnetic Field} \lesssim 10^{-16} \frac{\text{T}}{\sqrt{\text{Hz}}}$$

(SQUIDs, atomic magnetometers)

$$\text{Accelerometers} \lesssim 10^{-13} \frac{\text{g}}{\sqrt{\text{Hz}}}$$

(Atom and optical interferometers)



(Cavities with Q ~ 10 E10)

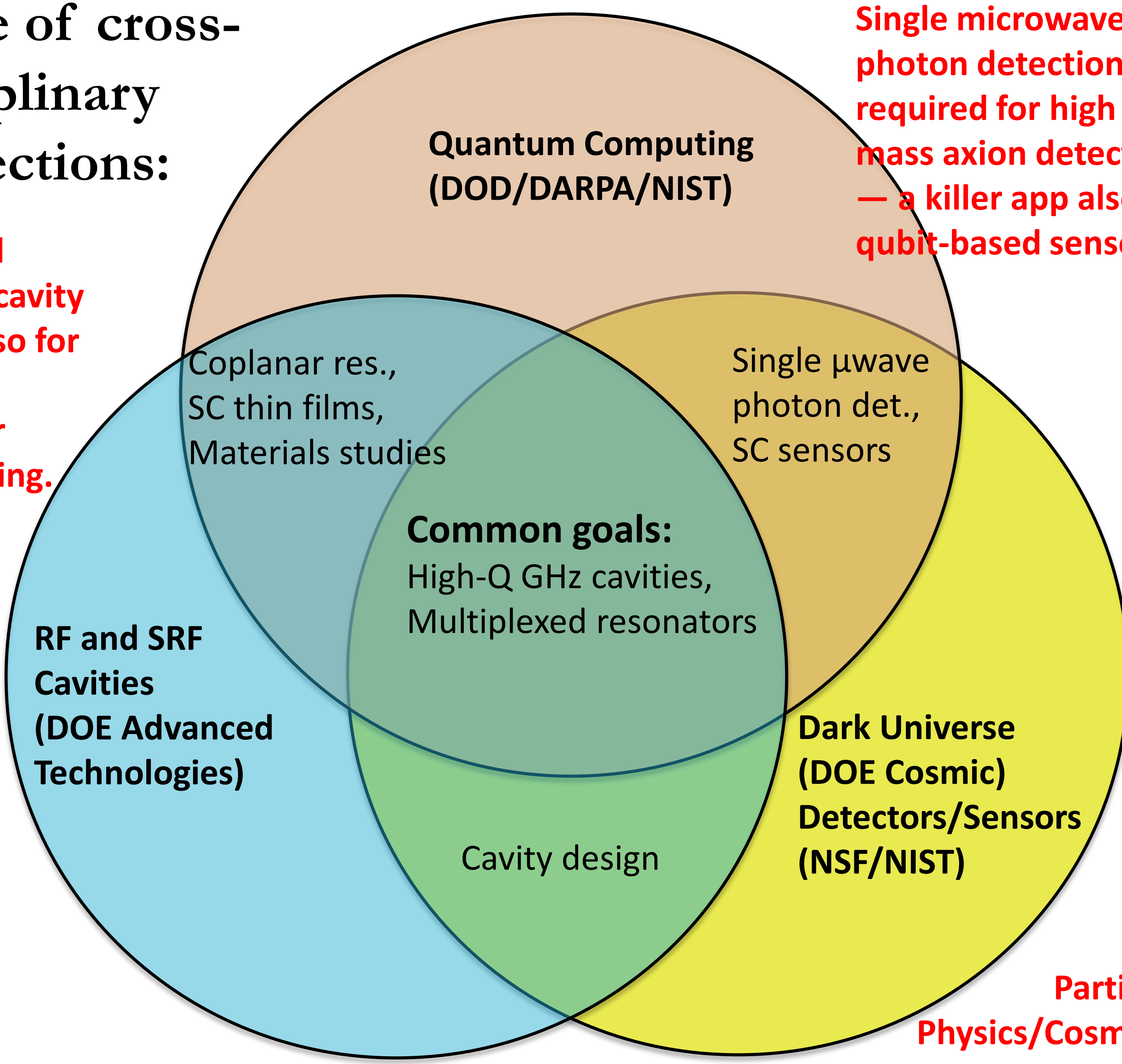
Figure 1: Prototype tuneable detector cavity (variable cell to cell Coupling), Bulk Niobium.

(Coupled SC cavities: GW transfers energy between modes)

# Example of cross-disciplinary connections:

**The materials and superconducting cavity studies crucial also for research in long lifetime qubits for quantum computing.**

**Single microwave photon detection is required for high mass axion detection — a killer app also for qubit-based sensors.**




**Particle Physics/Cosmology**

# EXAMPLES

***Quantum sensors exploit Quantum effects (including the Science of Quantum Entanglement) in Atomic Systems, Solids (Superconductors, topological materials, etc.), Cavity Electrodynamics, etc. and are critical to advancing Information Science and Computing and answering fundamental science questions: A New Particle? Non-gravitational Interaction? Gravitational Waves and Inflationary Cosmology? Dark Matter? Dark Energy? Effects are very weak, need unprecedented precision for detection.***

→ **Cavity Electrodynamics with Quantum Non-Demolition Single Photon Counting: Dark Matter Detection;**

→ **Atom Interferometer/Accelerometer: Dark Matter, Dark Energy and Low Frequency Gravitational Waves Detection;**

→ **Nuclear Magnetic Resonance: designer "quantum-entangled" materials for axion-dark matter detection.**

## EXAMPLE: DARK MATTER and FORCE ESTIMATES

$$\Omega_{DE} = 6.3\times10^{-10}\ Jm^{-3}$$

The average observed Dark Energy density, assuming uniform density, is the same energy density possessed by a static electric field of:

$$E = 12\ V/m$$

Dark Energy is even higher implying:

$\Omega_{DM}$ $E \sim 10\ kV/m$ !! Dark Matter

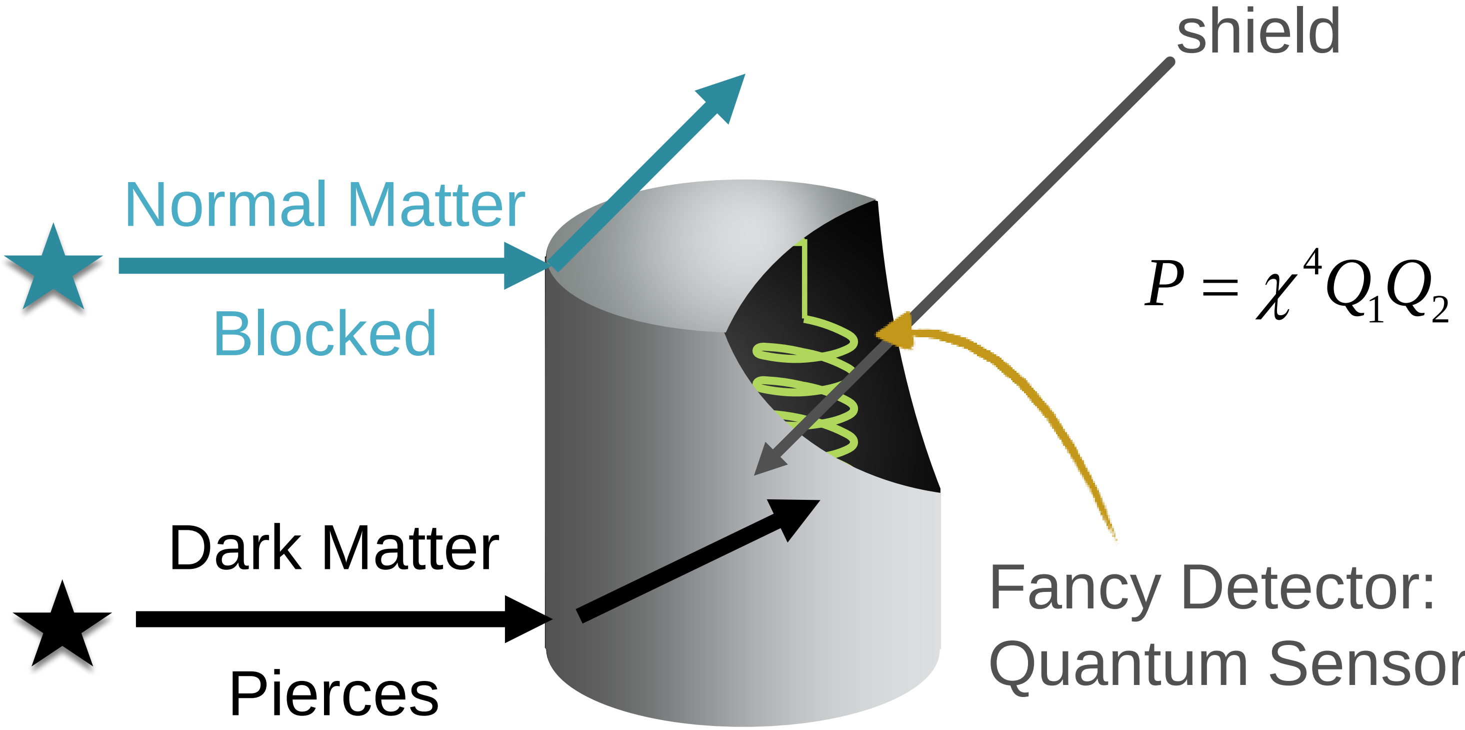
$\sim 4\times10^{-10}\ Nm^{-2}$

→ Measurement of Casimir effect (1996)

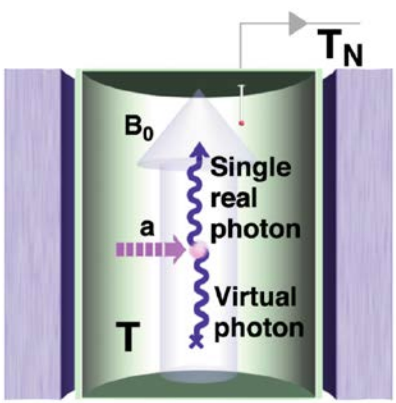
$\sim 1.3\times10^{-10}\ Nm^{-2}$

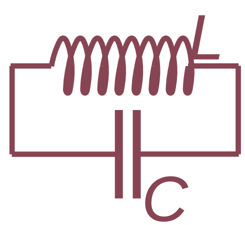
→ Cold cathode ionization gauge

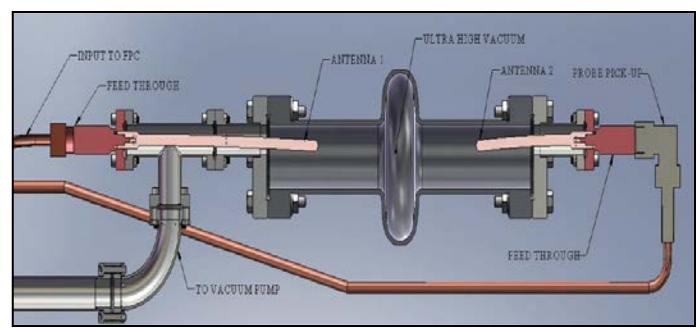
# Dark Matter Detection: What kind of Effects are we looking for?
# 1 in 10,000,000,000,000,000,000,000,000




$$P = \chi^4 Q_1 Q_2 \frac{m_{\gamma'}^8}{\omega_0^8} |G|^2$$

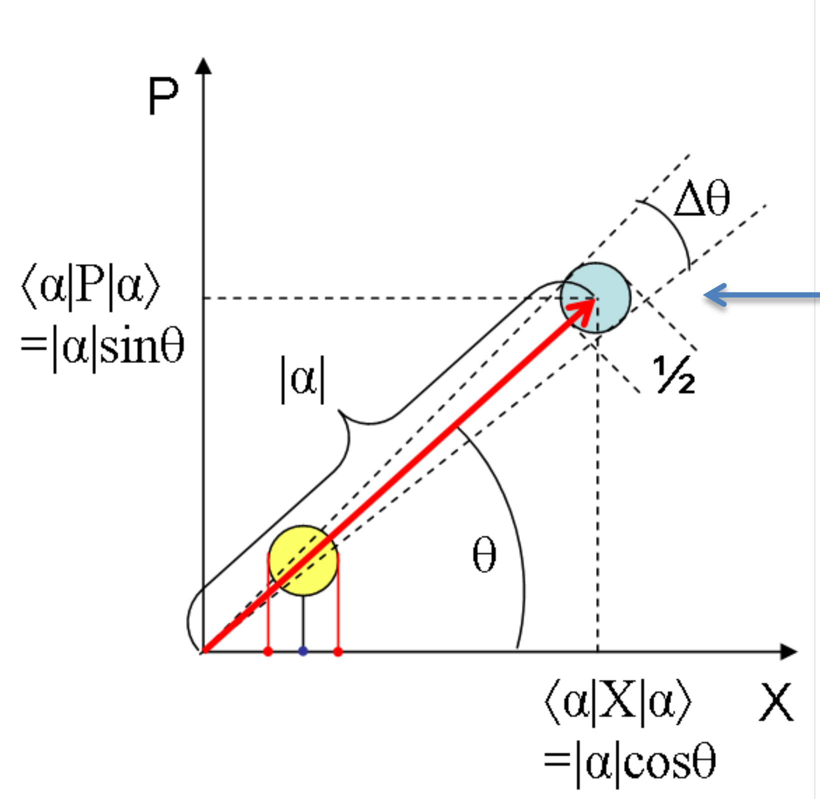



Tunable superconducting resonant LC circuit (a radio)

# Low Level RF Detection:
# Quantum-limited amplifiers suffer from zero-point noise



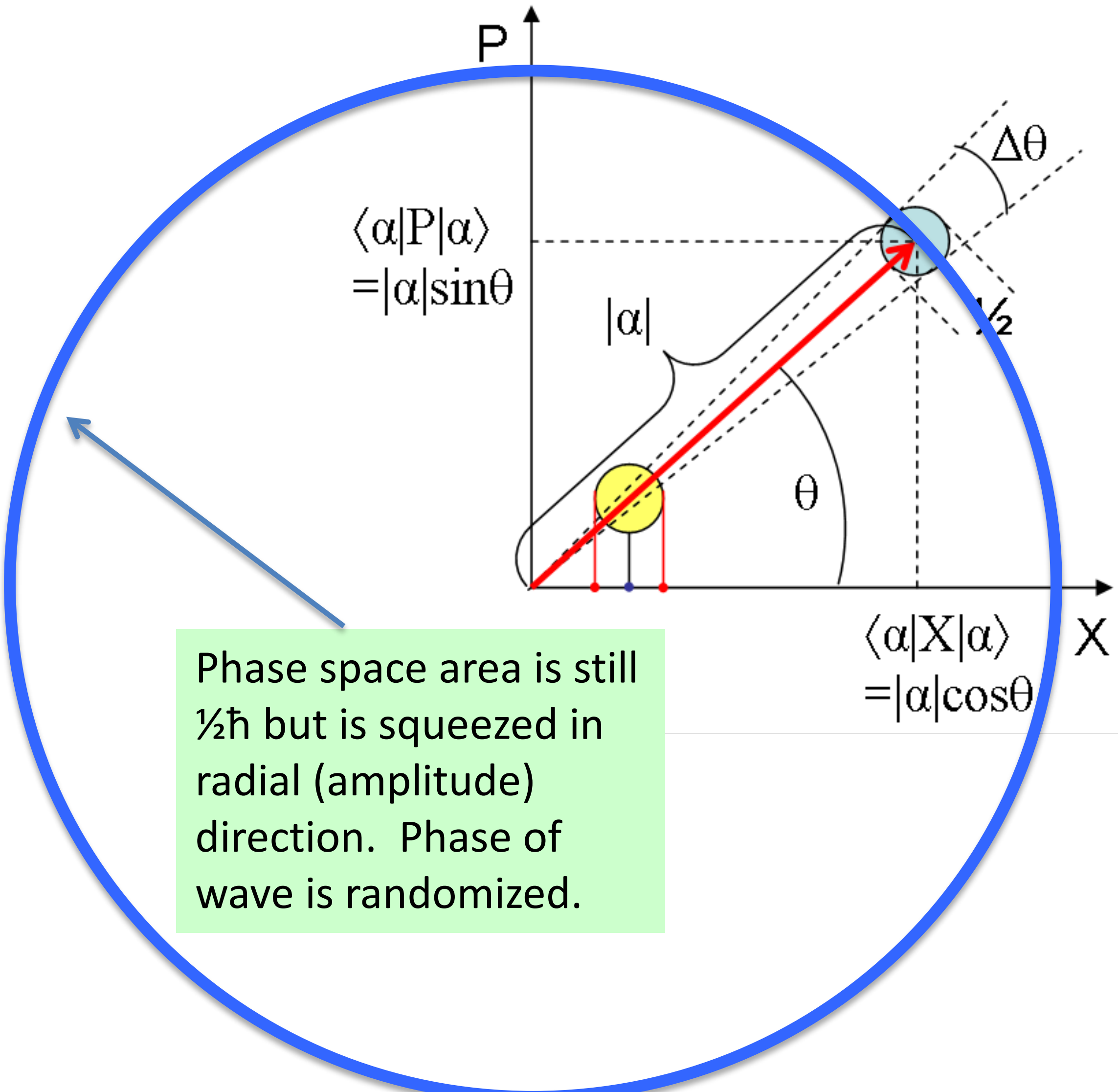

½ ħ= quantum of phase space area.
**Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.**
(Caves, 1982)

Thermal noise = ½ kT per resolved mode
→ Quantum noise = 1 photon per resolved mode in the T=0 limit.

**Noise photon rate exceeds signal rate in high frequency dark matter axion searches.**
Need new sensor technology….

# Quantum non-demolition (QND) single photon counting can do much better

*Number operator* commutes with the Hamiltonian→ all back reaction is put into the phase. Measure exact photon number. Noise = shot noise, thermal backgrounds.




Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

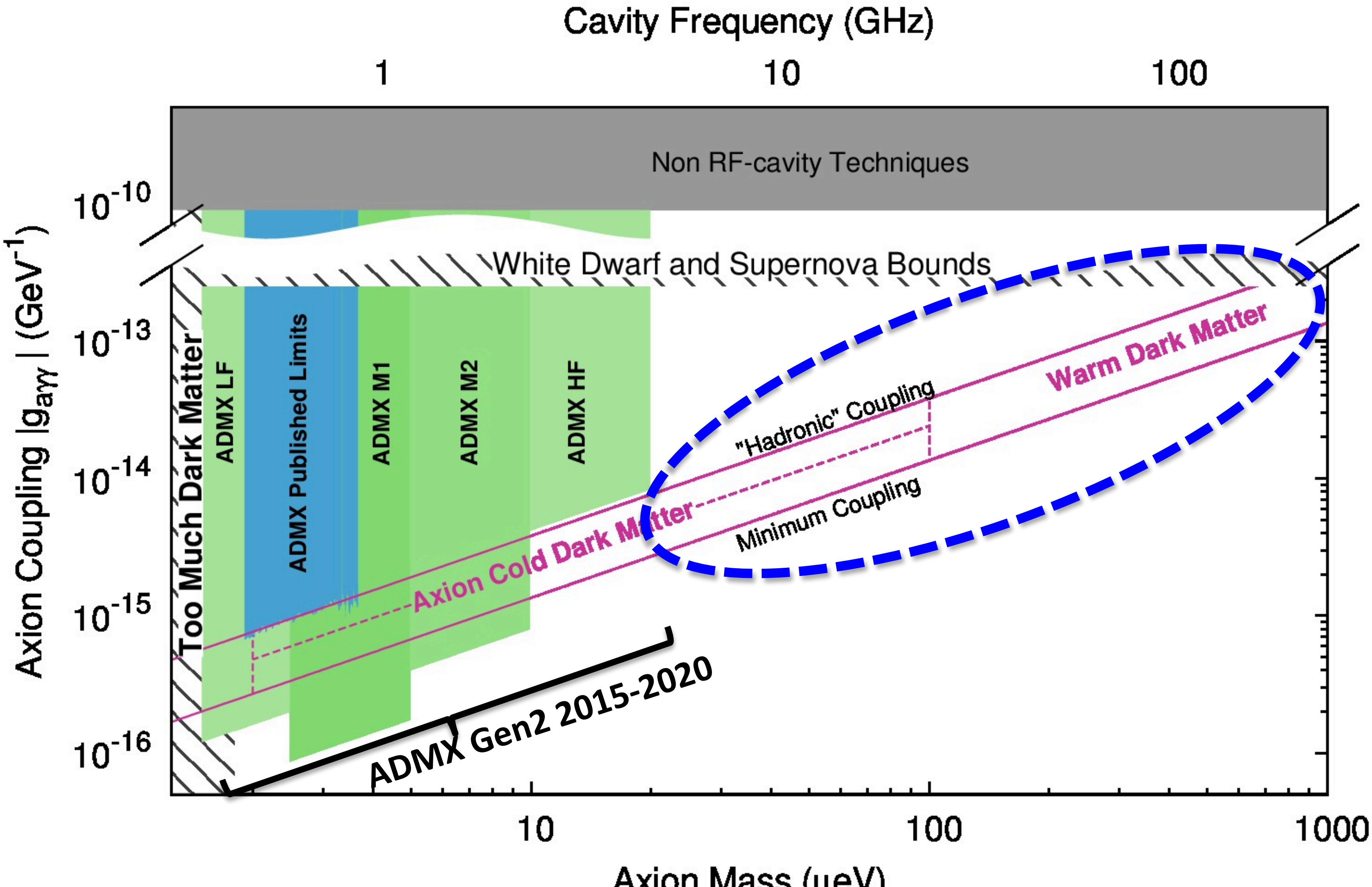
Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

Implemented as solid state qubits for quantum computing, (Schoelkopf/ Schuster, 2007)

At T<30 mK, 10 GHz, Boltzmann-suppressed thermal blackbody photon background rate is $10^{-4}$ of zero-point noise.

**4 orders of magnitude improvement in sensitivity for axion, neutrino spectroscopy!**

# Qubit-based detectors would enable coverage of remaining dark matter axion parameter space (courtesy: A. Chou)



# Dark Matter/Energy/Low-frequency Gravitational Wave Detection with Atomic Interferometers

$$\text{Acceleration Per Baryon: } \frac{gE'}{m_n} \sim 10^{-10}\,\frac{\mathrm{m}}{\mathrm{s}^2}\left(\frac{g}{10^{-21}}\right)$$

$$\text{Atomic Accelerometers } \gtrapprox 10^{-12}\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}\ (@\ 1\ \mathrm{Hz})$$

Improvements seem possible with resonant schemes and longer arm accelerometers and atomic interferometers overs 100’s of meter

(Courtesy: Surjeet Rajendran and colleagues at Stanford, SLAC, Harvard)

# Dark Energy and Gravitational Wave Detection with Accelerometers

**Gravitational waves @ 1 Hz could open the window for direct tests of cosmic inflation, frequency range inaccessible to LIGO/LISA. Atomic interferometers can also be sensitive detectors of "dark" energy.**

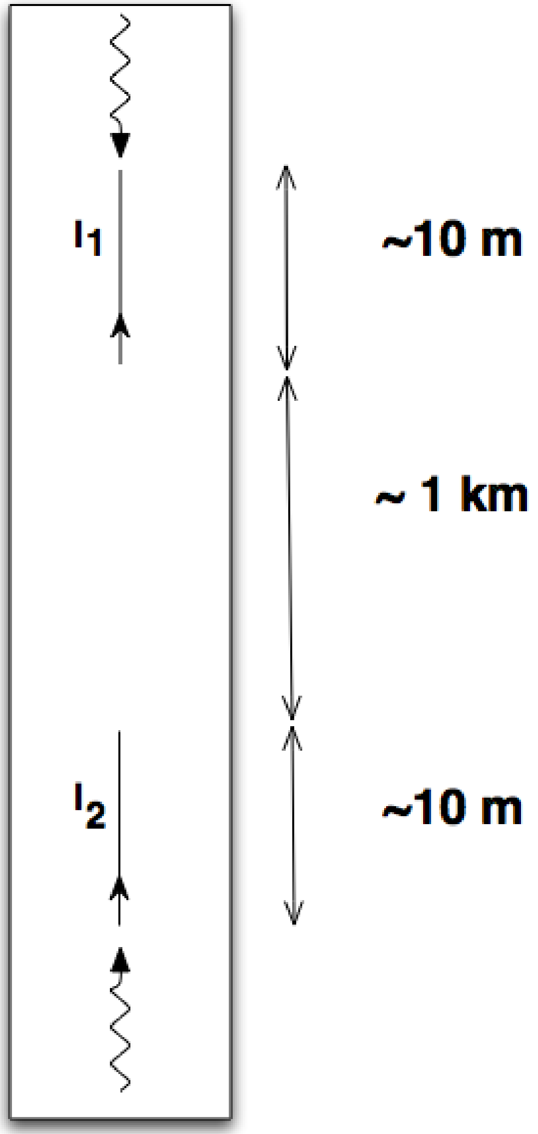
**EXAMPLE:**

**Two 10 m atom interferometers at either ends of a mine shaft.**

**Both interferometers are operated by common lasers.**

**Signal scales with the length ~ 1 km between interferometers.**

**Allows free fall time ~ 1s. Maximally sensitive in the 1 Hz band.**

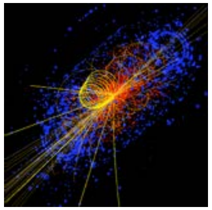



**→ POSSIBILITIES in the Sanford Lab?**

## PREVIOUS DOE MEETINGS ORGANIZED BY ITS "CONNECTIONS" PROGRAM IDENTIFYING CONNECTIONS between PARTICLE PHYSICS, QIS and OTHER DISCIPLINES

- **"Sensors for novel HEP experiments and detectors that intersect QIS"**
  **"Tools, Techniques, and Technology Connections of Particle Physics"**
  **"Grand Challenges at the Interface of QIS, Particle Physics and Computing"**
  **"Common Problems in Condensed Matter and High Energy Physics"**

  [Available @: http://science.energy.gov/hep/community-resources/reports/ ]



- **"Connections of Particle Physics with Other Disciplines"** and others presented at HEPAP 2014
  Edited: Curtis Callan (Princeton) and Shamit Kachru (Stanford/SLAC)

[Available @: http://science.energy.gov/hep/hepap/meetings/previous-meetings/]

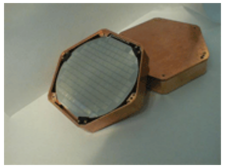
# RESULTING OUTLOOK

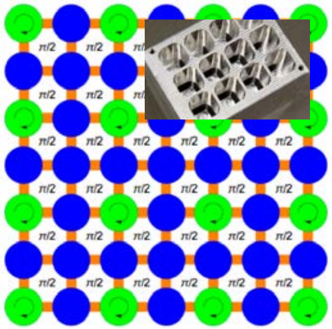
- Quantum information science has many overlapping technical challenges with fundamental sciences:

  → Technologies developed for quantum information science may be ideal for fundamental sciences (via enabling high precision instruments e.g. parametric amplifiers, QND single microwave cavity-photon detectors, atomic interferometers, accelerometers, novel materials etc.)

  → Conversely, the scientific demands on precision pushes the quantum information technology further

- Shared fundamental mysteries of quantum entangled systems with complementary approaches to advance both science and quantum information frontiers (high coherence strongly correlated complex and exotic materials, topological materials, high-Tc superconductors, atomic physics, bio-, neuro- and geo-sciences, science of cryptography, etc.).





# HOW to EXPLOIT THE PROMISE of “QUANTUM SENSORS Sans FRONTIER”!!

- **Today’s precision quantum technologies span across multiple disciplines: Electromagnetic Cavities, Accelerometers, SQUIDS, Atomic Beams, NMR, Designer Materials, Quantum Optics/Photonics, Single –qubit-noise-limited Amplifiers, etc.;**

- **Tremendous technological advancements in the last two decades promising great potential to address very “weak effects” in nature on a laboratory scale;**

- **Weak effects that demand to be explored with unprecedented precision are everywhere – from laboratory to outer space (particle physics, cosmology, astrophysics, atomic physics, material science, biology, geology, information science, ….);**

# HOW to EXPLOIT THE PROMISE of QUANTUM SENSORS Sans FRONTIER" ! (cont'd)

- **Potential "mezzo-scale" experiments/projects, involving cooperative and collaborative multi-investigator teams, in a synergistic program by diverse national agencies at diverse institutions and national facilities can be envisaged to advance the field to frontiers unexplored to date;**

- **This Round table is an attempt to find a way to benefit from better organic engagement with these fields and bring them into our fold. This will require us to go beyond "compartmentalization" of skills and programs and create a minimally feasible interdisciplinary collaboration -- technically, fiscally and administratively.**

- **Can this Round Table help start a dialogue to develop such a synergy and associated program? Both SCIENCE and TECHNOLOGY connections are inherent → Critical for the education, training and engagement of the next generation of scientists/engineers!**