QUANTUM SENSORS of the DARK UNIVERSE:

Exploiting Quantum Entanglement in the Laboratory for Detection of Exotic Particles and Fields

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Track 13: Detectors for Future Facilities: R&D, Novel Techniques

OUTLINE

1.   *Role of Sensors: Classical and Quantum*

2.   *Entangled Universe: challenges remaining "in and beyond" the "Standard Model" of Particle Physics: Cosmic Archaeology of "small signals" from early universe*

3.   *Exploiting Quantum Entanglement :*
   → *Cavity-Qubit Detection of "Dark" sector*
   → *Atomic Interferometric Probe of the "Early Universe" and the "Dark" sector*
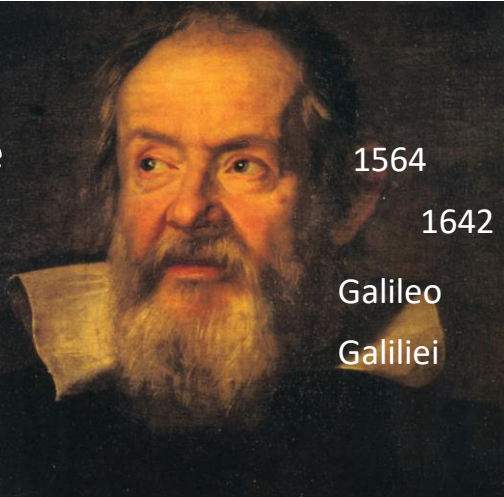   → *Designer materials: "Dirac" and Weyl"*

4. Outlook

HISTORICAL ROLE of PRECISION MEASUREMENTS :
Instrumentation as the great enabler of measurement

"Measure what is measureable and make measureable what is not so."

1564

1642

Galileo Galiliei

5

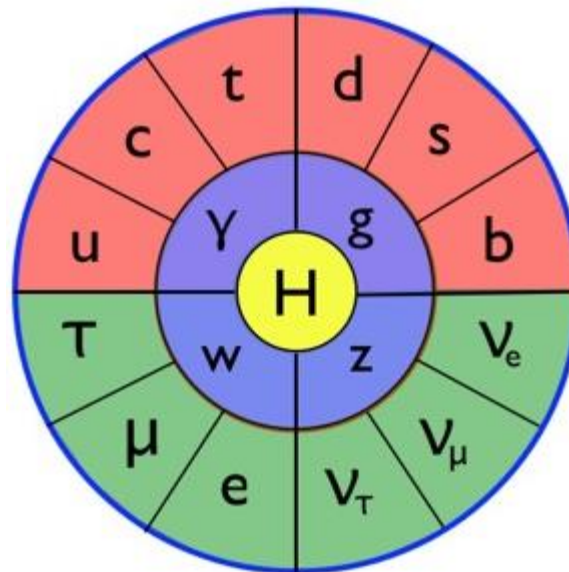*"Nothing tends so much to the advancement of knowledge as the application of a new instrument"*

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

Galileo's telescope, Newton's microscope, ...

A large number of dedicated particle physics experimentalists, theorists and accelerator scientists, have now developed what I will call

The Standard Model Mandala

Latest Discovery: Higgs particle!!
But understanding Higgs, Neutrinos etc. require higher energy accelerators with demanding global resources

Telescopes to the early universe

Reaching the energy scale in the laboratory to create the "dark" matter regime in Universe's evolution is daunting! But, the "relics" and "fossils" are all there, albeit as very weak "tremors" from the Big-Bang early universe! Need "Cosmic Archaeology"!
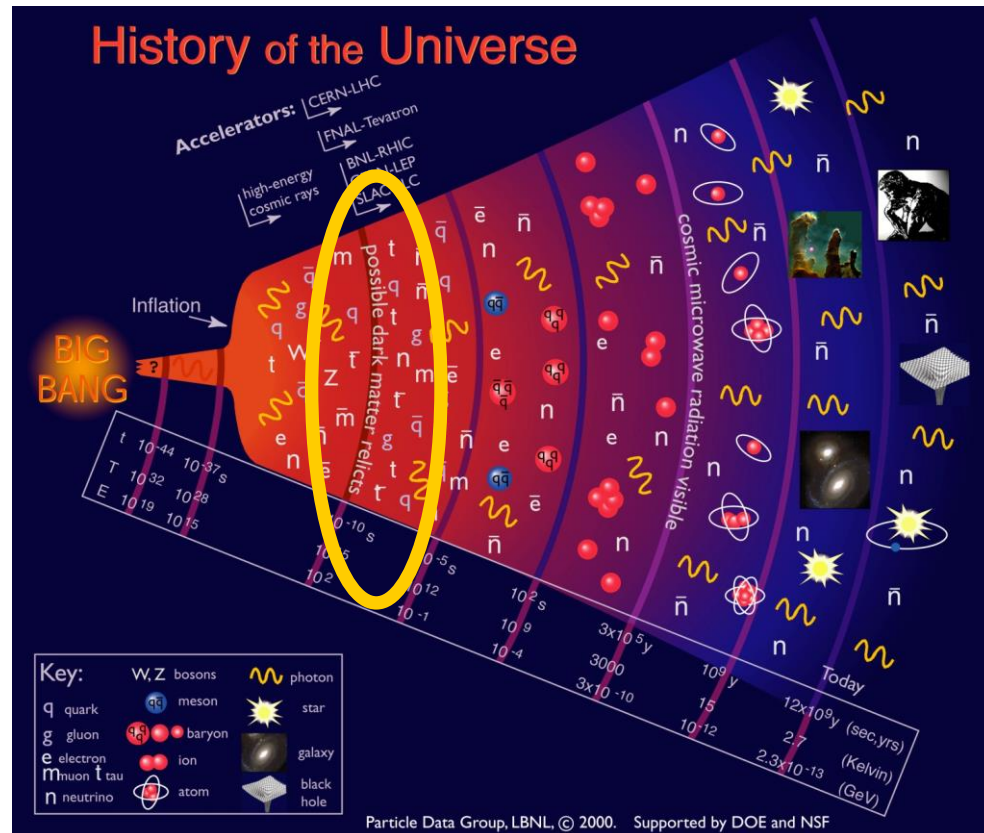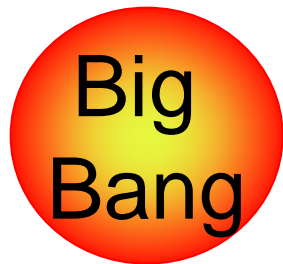
Universe was already "entangled" at the Planck-scale. There was a single wavefunction of the universe at the Planck –scale: Ψ_{Planck}

$$H_A \otimes H_B. \ \rightarrow \ |\psi\rangle_A \otimes |\phi\rangle_B.$$

$$\Psi_{\text{Planck}} \rightarrow \Psi_A \otimes \Psi_B$$

$$|\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A \otimes |j\rangle_B$$

Emerging Quantum Initiatives:
Quantum Sensors invoking 'Quantum Entanglement'

QUANTUM SENSORS - *Mais, qu'est-ce que c'est?*

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

WHY Invoke Quantum Entanglement?

Quantum Entanglement allows for "Squeezed" states and approach the quantum limit of a single photon

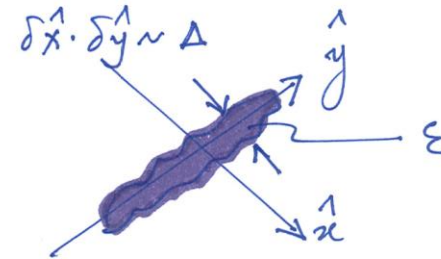Why so? QUANTUM ENTANGLEMENT ALLOWS for "SQUEEZED" STATES

"ENTANGLED"

$(x \wedge y)$
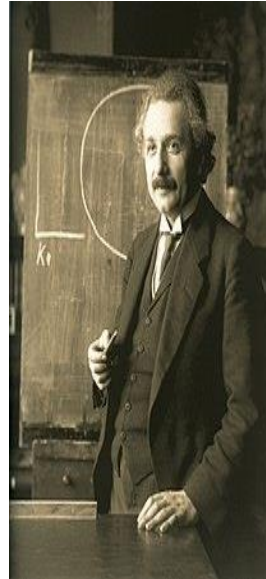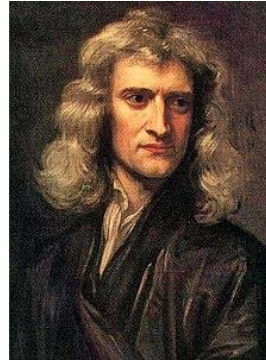
"INDEPENDENT"

(x, y)

Allows for "squeezing" information content in 'x' to narrowly constrained values at the cost of "scattering" back and depositing non-essential information into "y"

$|x, y$

$\delta \hat{x} \cdot \delta \hat{y} \sim \Delta$
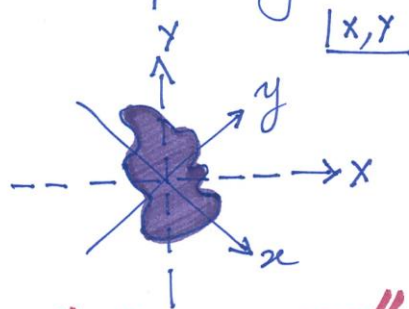
Quantum "state-space" allows for "SQUEEZED" STATES.

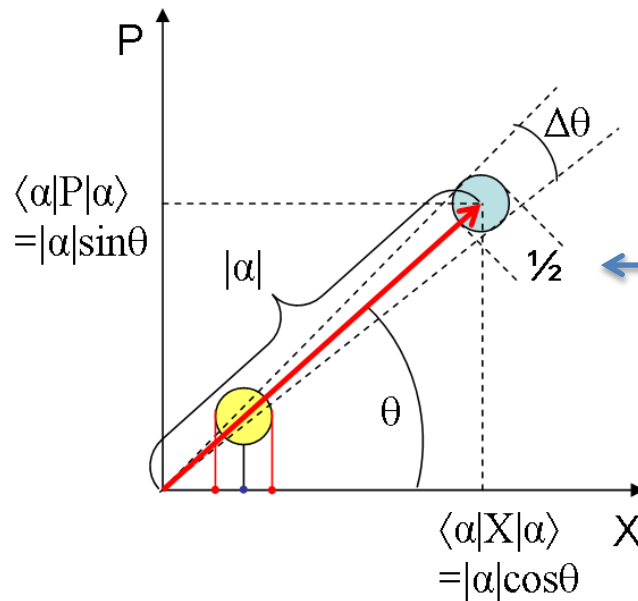$\delta \hat{x} < \varepsilon$, non-essential information in $\delta \hat{y} > \Delta / \varepsilon$

EXAMPLE: Low Level Detection of Radio-Frequency Waves: 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 many high frequency high precision signal detection schemes for exotic searches of very "weak" processes..
Need new sensor technology….

Quantum Non-Demolition (QND) single photon counting technique can do much better : Probing cavity photon number exactly without absorbing/destroying any photon

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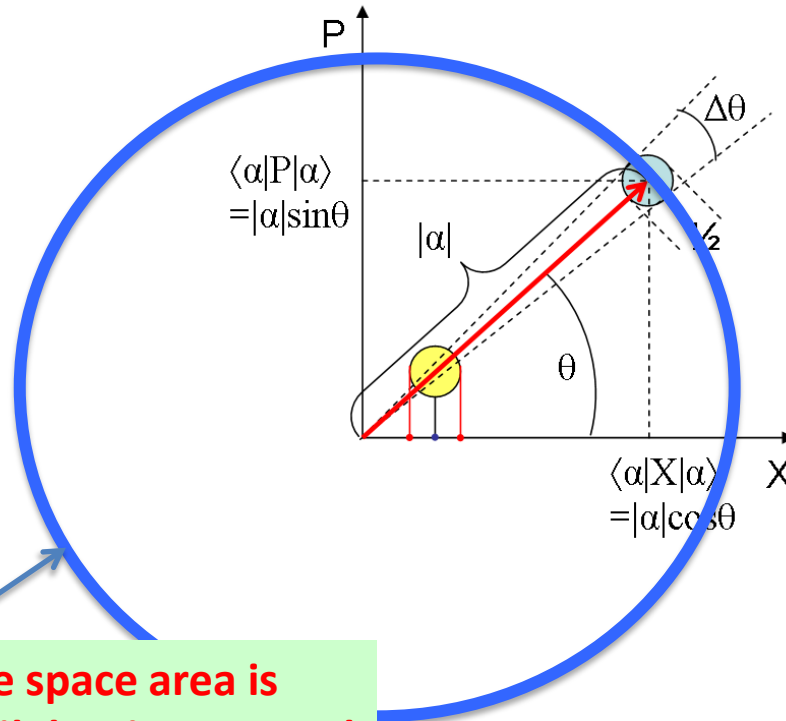

Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

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.

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

4 orders of magnitude improvement in sensitivity for probing "ultra-weak" processes!

Noise rates, qubits vs quantum-limited amplifiers
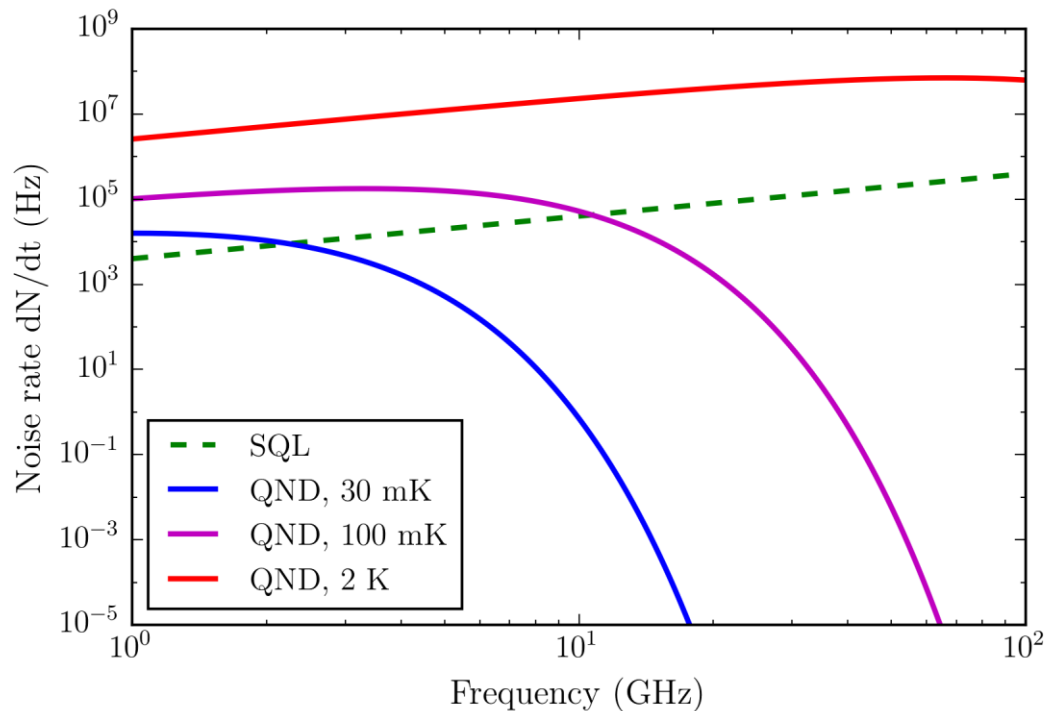
Linear amplifiers suffer from the "standard quantum limit" (SQL, Caves, 1980): 1 photon's worth of noise per frequency-resolved mode. Quantum Non-Demolition (QND) measurements' noise is blackbody-dominant. Cooling to O(10) mK gives clear benefits.

Quantum Sensors: APPLICATIONS

→ *Searches for New particles/Interactions:* *"Dark" Matter/Energy* ***

→ *Probes of the very early universe:* *Inflationary Cosmology* ***

→ *Quantum Computers:* *Quantum Information Science*
    CRYPTOGRAPHY, MARKET OPTIMIZATION, ARTIFICIAL INTELLIGENCE

→ *Bio-Signals (magneto-encephalography):* *Neuro-science*

→ *New "strongly correlated" Materials:* *Material Science of*
    DESIGNER MATERIALS: "Dirac" and "Weyl" materials for
    particle and field detection ***

→ *Detection of "Weak" Environmental Signals:* *Geo-science*
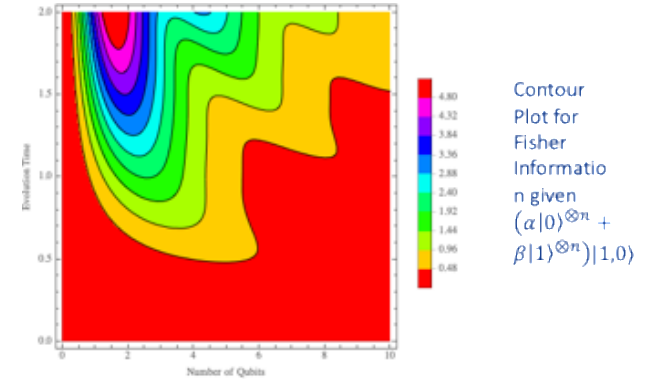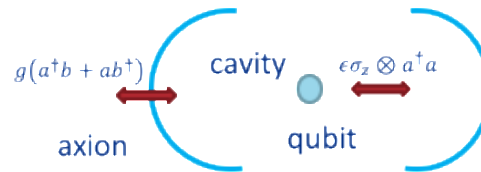   *CLIMATE CHANGE SCIENCE*
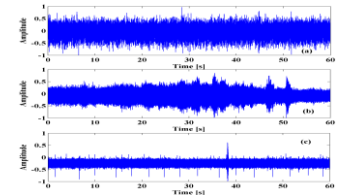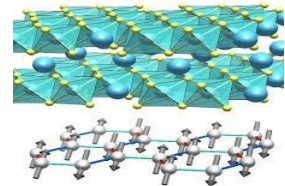
*** *I will briefly address these topics*

# Qubit-based single microwave photon sensors for Dark Matter "Axion" detection   [+   DOE QI]
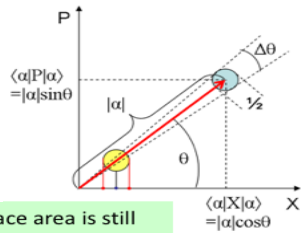
HEISING-SIMONS FOUNDATION

$\langle\alpha|P|\alpha\rangle$
$=|\alpha|\sin\theta$

$\langle\alpha|X|\alpha\rangle$
$=|\alpha|\cos\theta$

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

$g(a^\dagger b + ab^\dagger)$ cavity $\epsilon\sigma_z \otimes a^\dagger a$

axion   qubit

Contour Plot for Fisher Information given $(\alpha|0\rangle^{\otimes n} + \beta|1\rangle^{\otimes n})|1,0\rangle$

- **Increase the signal photon rate by using superconducting qubits as QND detectors and an high-Q cavity in a non-classical state**
  - **sensitive to incoming axion waves with any arbitrary phase**

- **Reduce impact of read errors by incorporating multi-qubit readout**
  - **Possibly further improving by preparing them in an entangled state and even utilizing quantum ML**

Qubit Spectroscopy

$|n = 0\rangle$

$|n = 1\rangle$

$|n = 2\rangle$
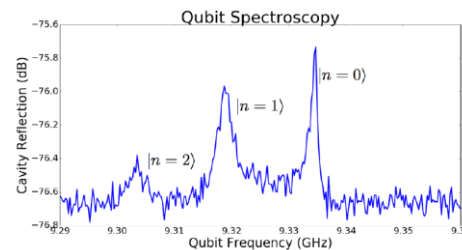
Qubit-based detectors enable coverage of remaining dark matter Axion parameter space – basis of Gen-3 ADMX experiment
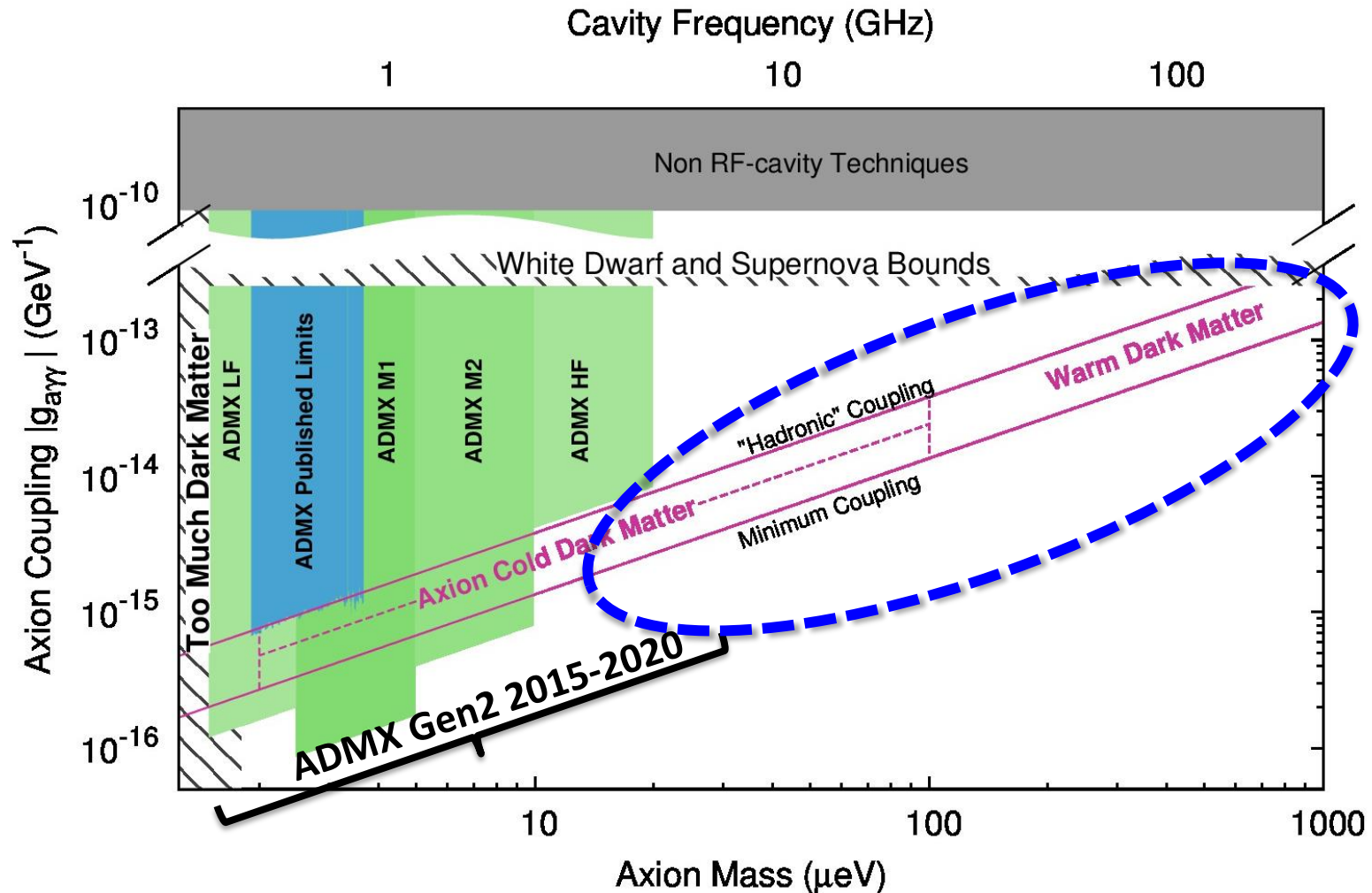

Lots of low hanging fruit for fundamental science applications in time frame of a decade as knowledge transfer before a practical quantum computer becomes practical in many decades!

Probing the Very Early Universe and the "Dark" Universe:
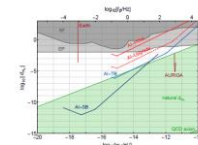## via Atomic Beam Interferometry

Detection of Stochastic Low Frequency Gravitational Wave Background from the "Inflationary" Era + Perturbed Atomic Transitions via Coupling of the Electromagnetic Sector (i.e. fine structure constant) with the "Dark" sector
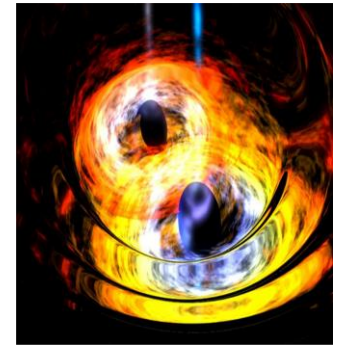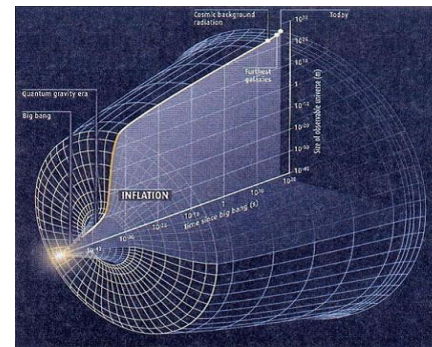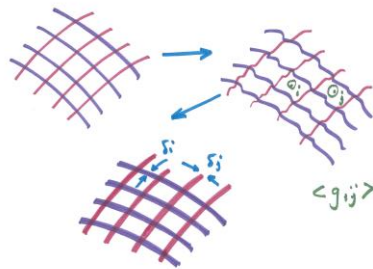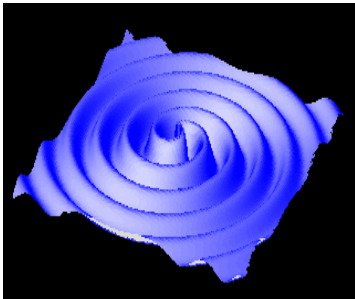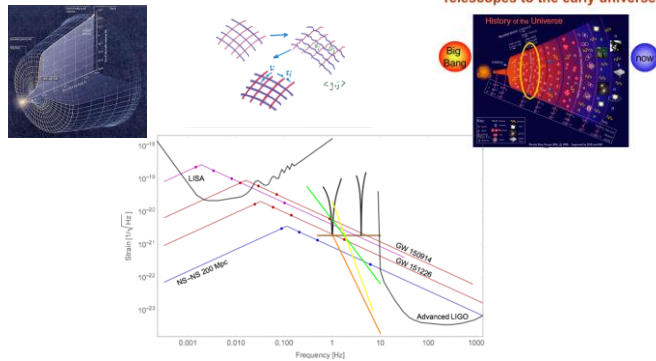
Strain: (dl/l) ~10E-25 @ 1 Hz??

# Overall Scheme of Midband Atomic Gravitational Interferometric Sensor (MAGIS-100) [Moore Foundation +DOE QI]
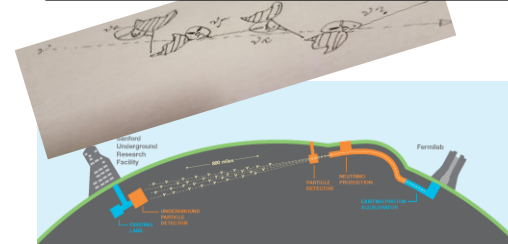
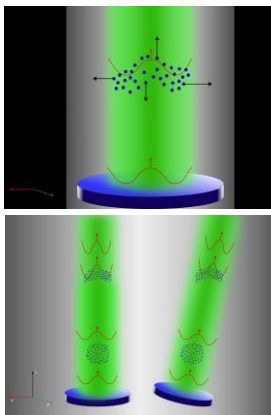**DARK and EARLY UNIVERSE (Light Dark Matter Particles or Waves, meV to eV)**

Implementation of MAGIS-100 in Fermilab 100 meter NuMI shaft and eventually to DUNE 4000 km mine shaft in South Dakota

STOCHASTIC GRAVITATIONAL BACKGROUND RADIATION from EARLY UNIVESE (100 mHz – 10 Hz) Projected Sweet Spot in mid-band
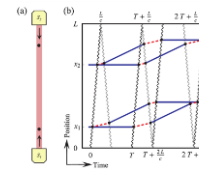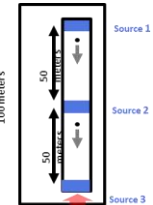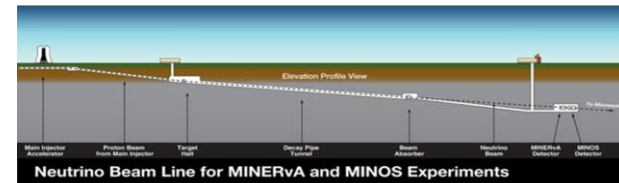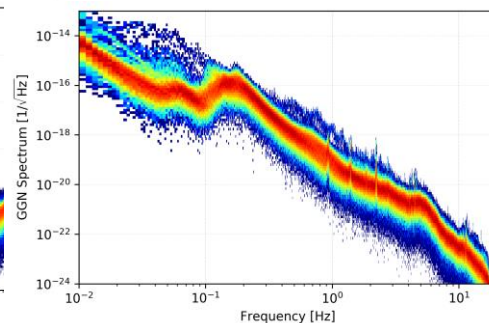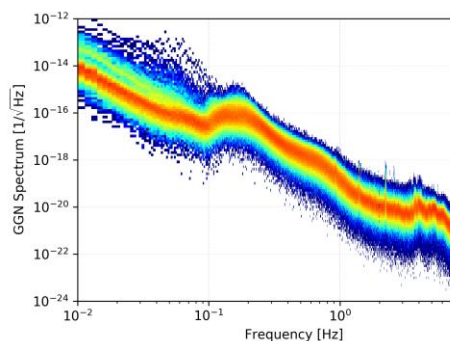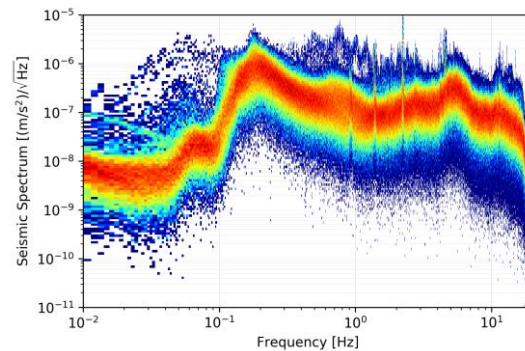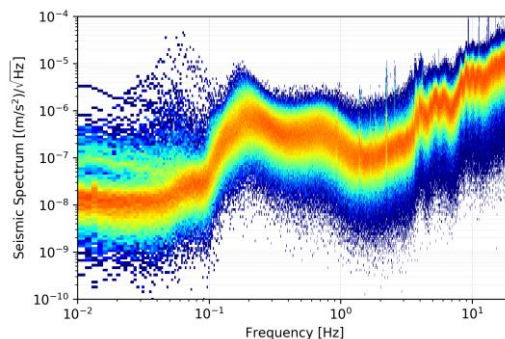
Laser Wavefront Aberrations

Acceleration (top) and Gravity Gradient Noise (below) at the surface (left) and at the bottom (right) of the MAGIS-100 shaft at Fermilab

	Phase shift	Notes
1	$n\delta \cos(k_t x_i) \sin\left(\frac{k_t^2}{2k}H\right)$	First Order in δ
1	$(0.325\,\text{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\sin\left(k_t^2 H/2k\right)}{0.65}\right)$	
2	$-\dfrac{k_t^4 n^2 \delta^2 T\hbar \cos(k_t x_i)\cos\left(\frac{k_t^2}{2k}H\right)\cos(k_t T v_t + k_t x_i)\cos\left(\frac{gk_t^2 T^2}{4k}-\frac{k_t^2 T v_z}{2k}-\frac{k_t^2}{2k}H\right)}{8k^2 m}$	Longitudinal Kicks
2	$(-1.25\times 10^{-11}\,\text{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\cos\left(k_t^2 H/2k\right)}{0.7}\right)$	
3	$\dfrac{k_t^2 n^2 \delta^2 T\hbar \sin(k_t x_i)\sin\left(\frac{k_t^2}{2k}H\right)\sin(k_t T v_t + k_t x_i)\sin\left(\frac{gk_t^2 T^2}{4k}-\frac{k_t^2 T v_z}{2k}-\frac{k_t^2}{2k}H\right)}{2m}$	Transverse Kicks
3	$(-4.33\times 10^{-9}\,\text{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\sin\left(k_t^2 H/2k\right)}{-0.2}\right)$	

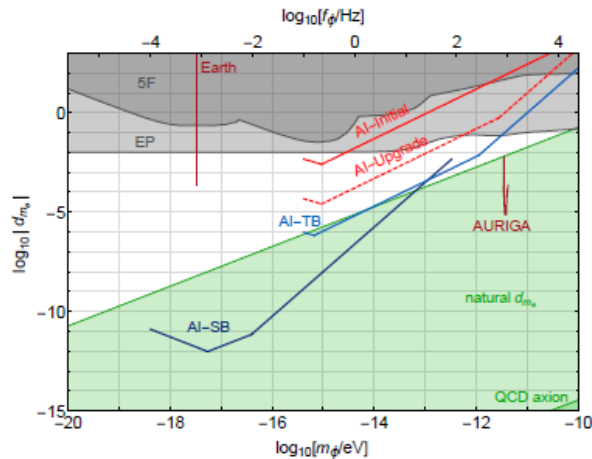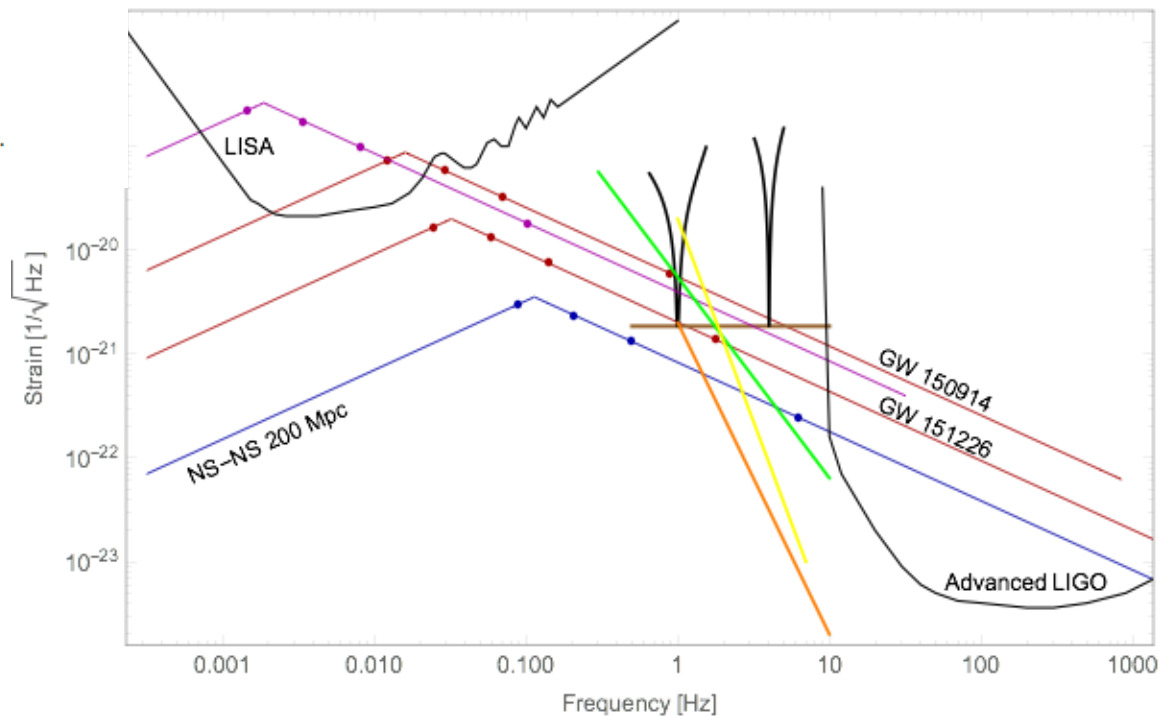# Sensitivity to Dark matter and Projected Terrestrial GW Sensitivity: MAGIS-100 "sweet spot" 0.1 Hz – 10 Hz


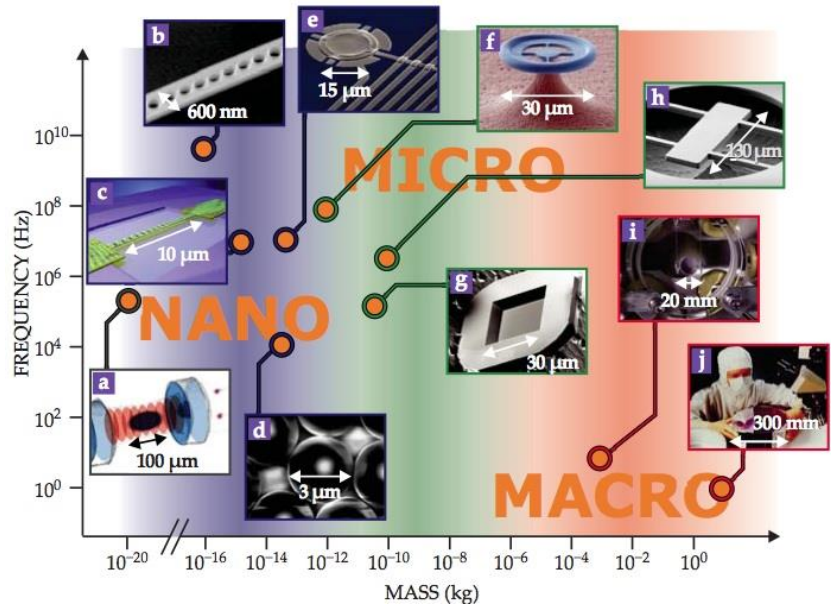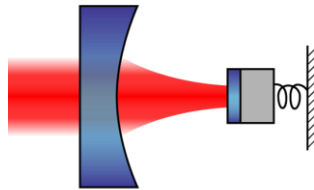Figure 1: MAGIS-100 sensitivity to ultralight dark matter.

OUTLOOK : Performance Reach of QUANTUM SENSORS:

→ **Today's state-of-the-art Quantum Cavity Opto-mechanics operate in any part of the EM Spectrum from kilogram to femtogram scale from DC to 10 GHz**

→ **Trapped Ions, Cold Molecules, Cold Atoms, NV (Nitrogen-Vacancy) centres**

→ **'Dirac' and 'Weyl' topological materials can couple ordinary matter to 'dark' matter by shrinking the 'band-gap' between valence and conduction bands**
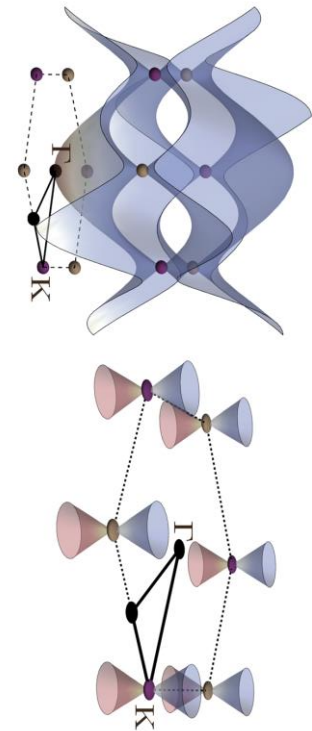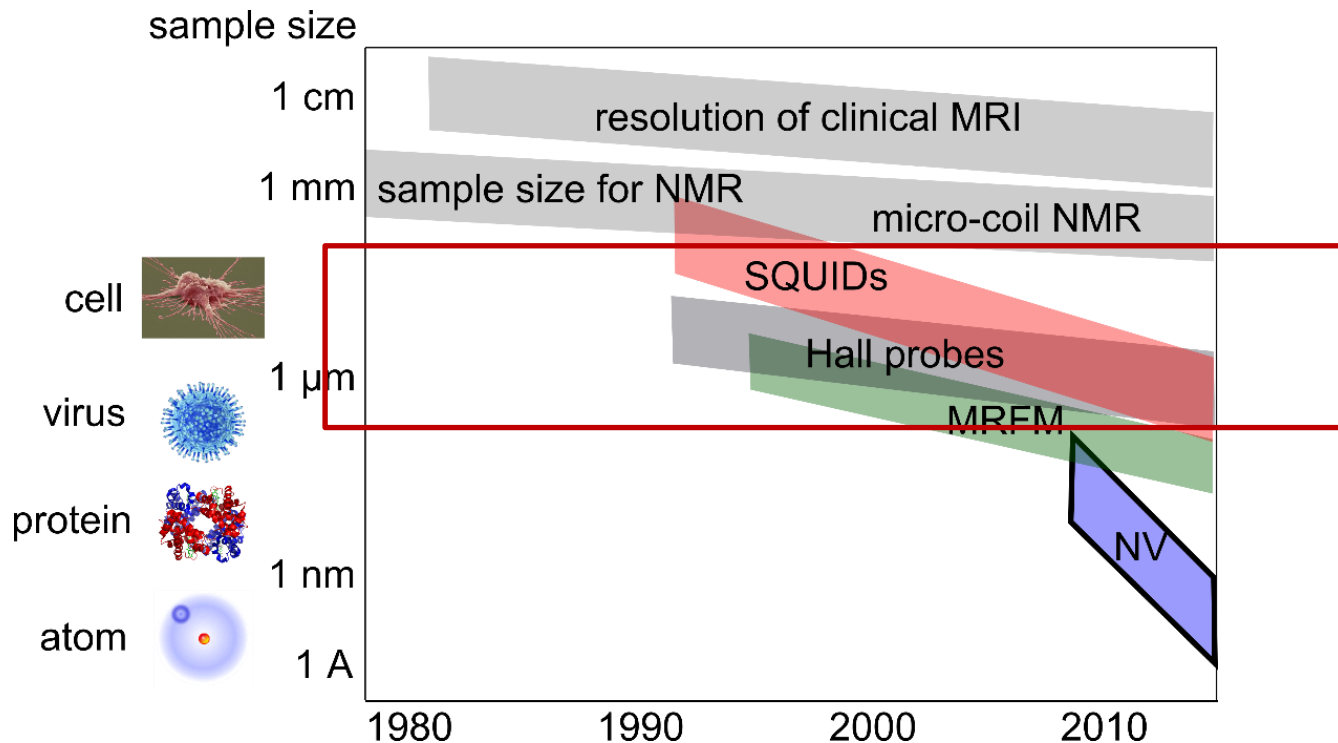
PROSPECTS

Detector development and community will benefit from further research investments into the areas of quantum-entangled materials, cavity-qubit entangled electronics, optically entangled atoms etc. to advance the precision detection of exotic particles and fields.

Thank You!!!