QUANTUM SENSORS of the DARK and EARLY UNIVERSE:

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

Swapan Chattopadhyay

CERN Colloquium, September 3, 2020

OUTLINE

1. *Role of Precision Sensors → Classical and Quantum*

2. *"Higgs" and the "Neutrino" → frontier of accelerator-based research to complete the "Standard Model"*

3. *Challenges "Beyond the Standard Model" of Particle Physics:*

   Cosmic Archaeology of "small signals" from "early"/ "dark" universe

4. *Exploiting Quantum Entanglement:*

   → *Cavity-Qubit Detection of "Dark" sector*

   → *Atomic Interferometric Probe of the "Early Universe" /"Dark Sector"*

   → *Other Quantum Sensors: NMR, NV Centers, "Dirac" and Weyl" materials*

5. *Neuroscience, Life Science*

6. *Outlook*

ACKNOWLEDGEMENTS

1. Gian Francesco Giudice and Wolfgang Lerche for inviting me to present this colloquium

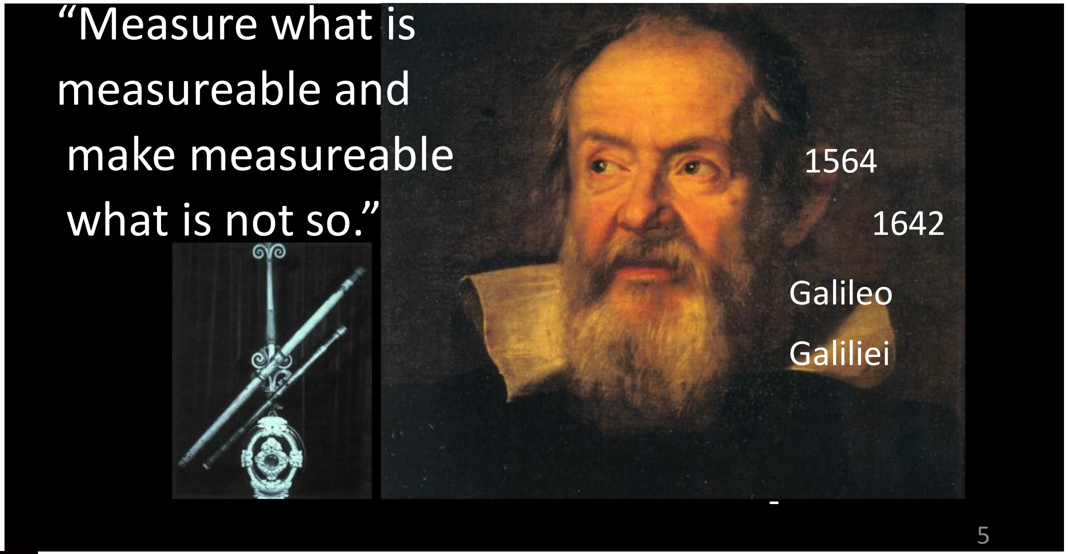
2. US DOE and NSF Quantum Initiatives/Programs

3. US Snowmass 2021 Study Groups: HEP, Energy, Cosmic, Accelerators, Detector and Instrumentation Frontiers & European Particle Physics Strategy 2020

4. Aaron Chou (Fermilab)
   Jason Hogan (Stanford)

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

"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

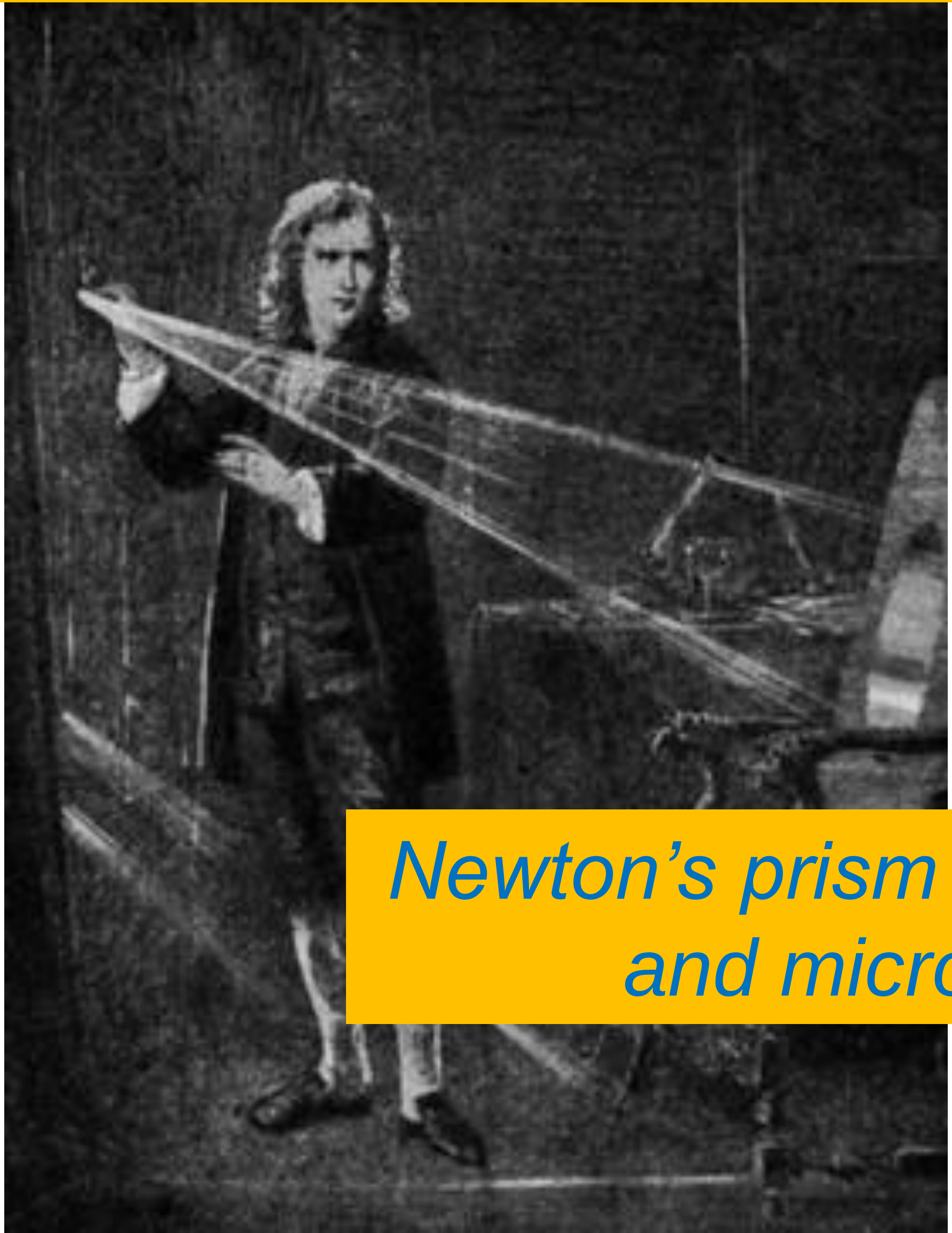
From looking into the “outer” space

Galileo’s telescope

H. J. Detouche, Parigi, XIX secolo

GALILEO PRESENTA IL CANNOCCHIALE AL DOGE LEONARDO DONA’

…To looking into the "inner" space



Newton's prism spectrometer and microscope

TODAY’s and Tomorrow's INSTRUMENTS

GRAND INSTRUMENTS

Particle Accelerators, Synchrotron Radiation Sources, Free Electron lasers, Large-scale Intense Atomic Lasers

Telescopes, Satellites, Large-scale Laser Interferometers

Multi-ton Deep Underground Experiments

MEZZO-SCALE and TABLE-TOP

Quantum Sensors as Complementary Instruments of Choice

Innovative Particle Accelerators of Ever-Increasing Energy and Size in 20th Century → 21st dawn

1m **Cyclotron**

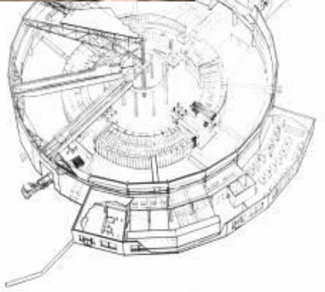
Nobel Trio: Walton, Rutherford, Cockcroft

10m **Cockcroft-Walton**

100m **Wideröe Linac**

~400m **Bevatron**

3km **SLAC**

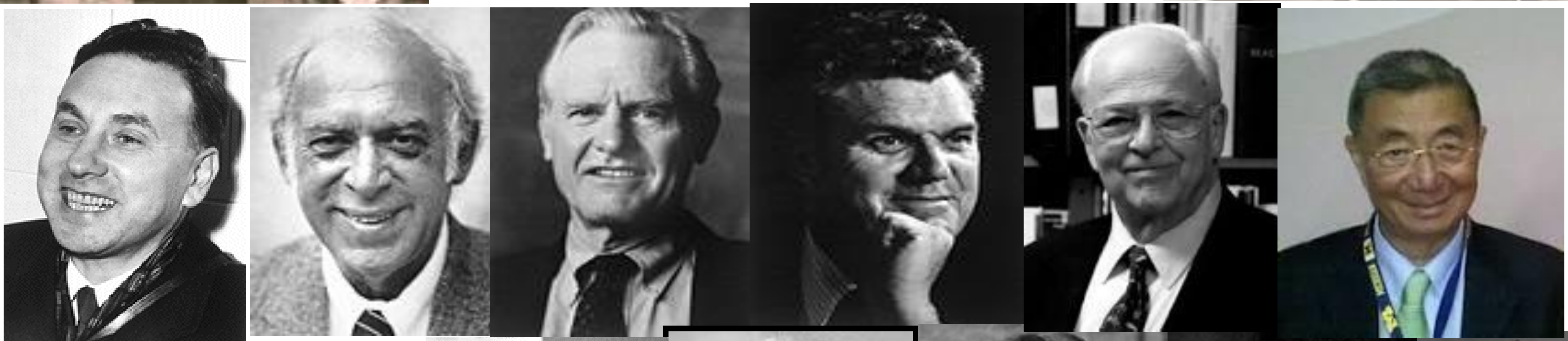


10km **Tevatron**

27km **LEP/LHC**

100km **FCC/ILC/CepC/CLIC**

Rutherford, Cockcroft, Walton, Wideroe, Sloan, Hofstadter, Friedman, Kendall, Taylor, Richter, Ting, ……..

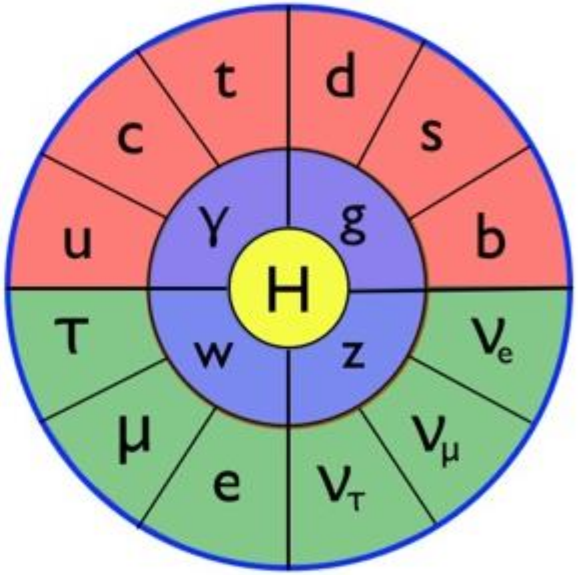


Lederman,
Rubbia,
van der Meer,
Roentgen,…….

Thomson and Thomson Jr., Davisson, Bragg and Bragg Jr.

Many dedicated particle physics experimentalists, theorists and accelerator scientists, have now developed what I will call

The Standard Model Mandala



Latest Discovery: Higgs particle!!

Latest in the series: HIGGS observed, but we barely understand it! - Higgs physics can be explored in possible future colliders: HL-LHC, HE-LHC, FCC, ILC, CLIC, CepC

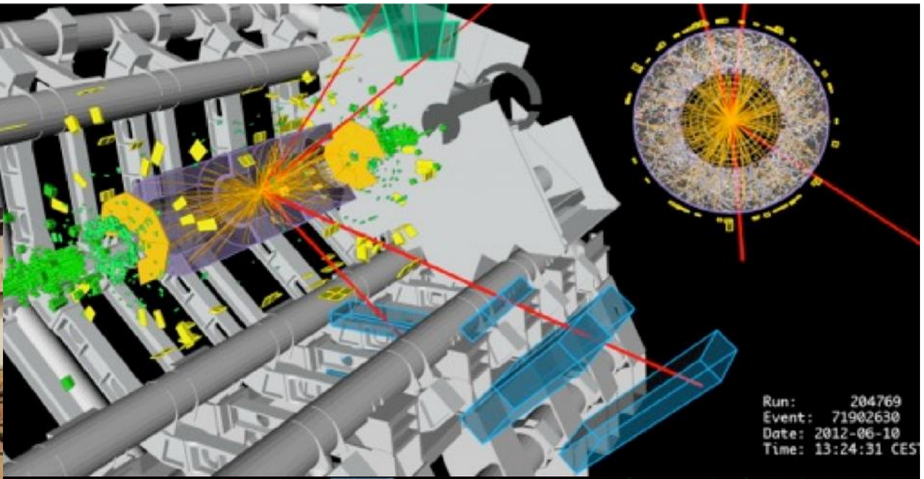
2012.7.4

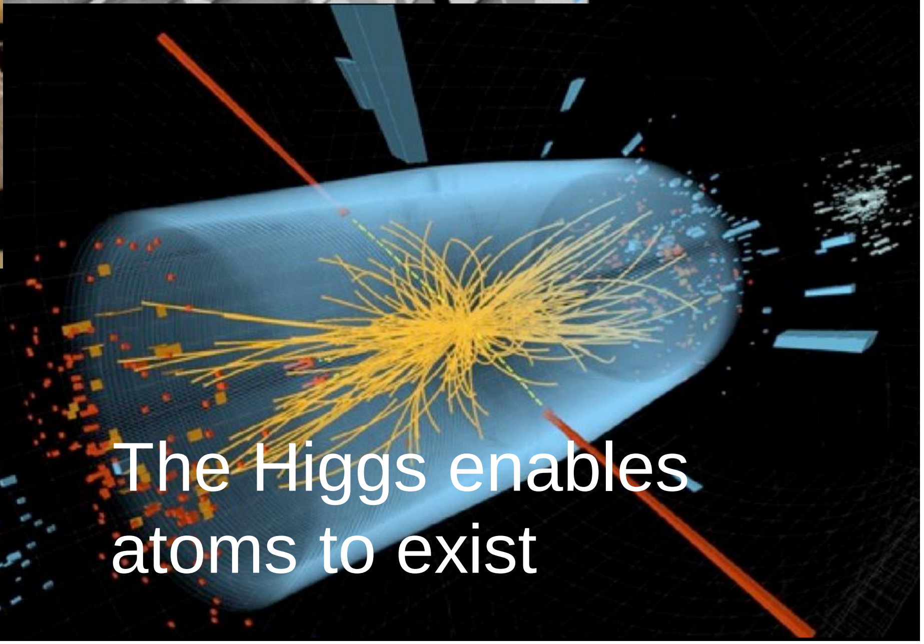
discovery of Higgs boson

theory : 1964

design : 1984

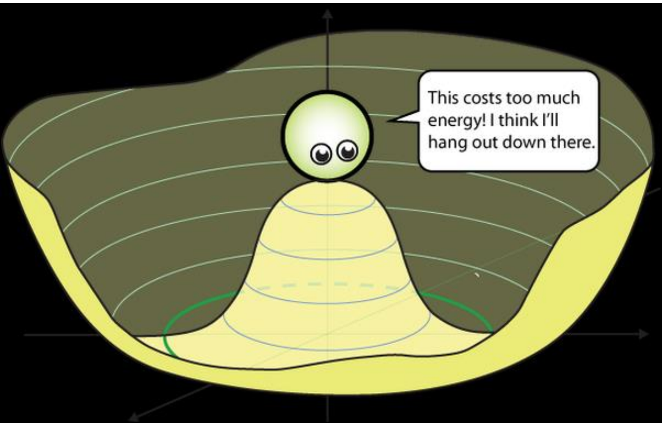
construction : 1998

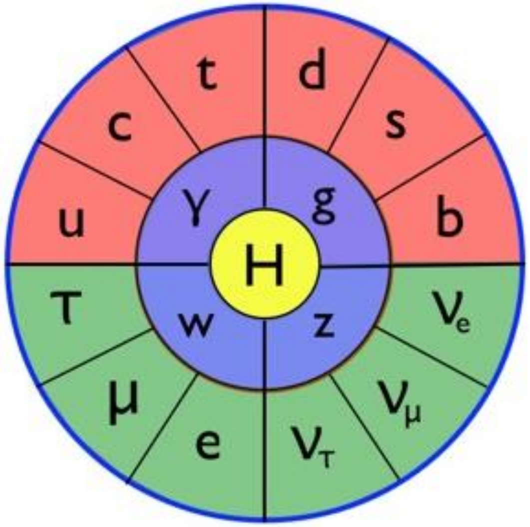


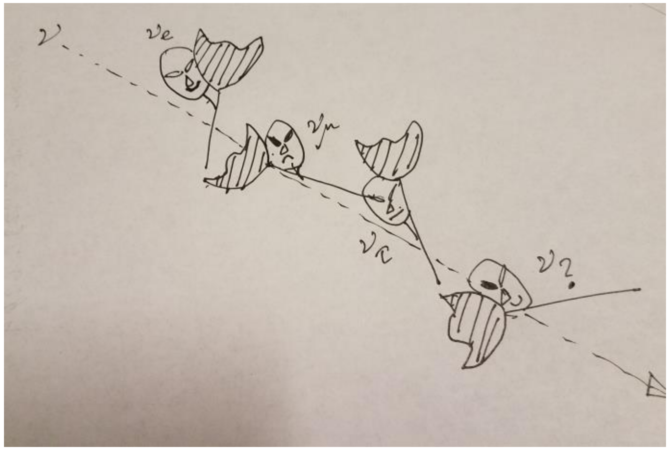


The Higgs enables atoms to exist

The Standard Model Mandala: Least understood: "mysterious" Higgs and "elusive" Neutrinos







To advance understanding of Higgs, need even higher energy colliders than available today:

→ **FCC (CERN plan or elsewhere), ILC/CLIC,..**

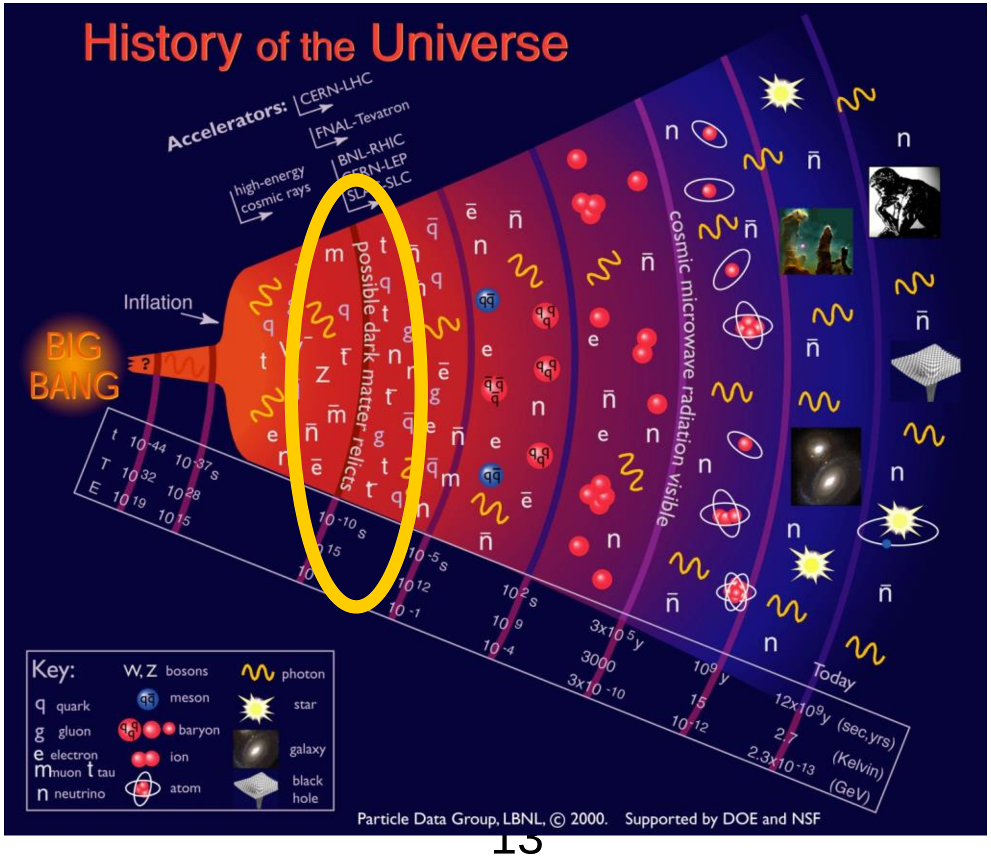
To advance understanding of Neutrinos, need higher power proton accelerators for long-baseline Neutrino experiments:

→ **Y2K (Japan) and DUNE/PIP-II (US)**

Telescopes to the early universe

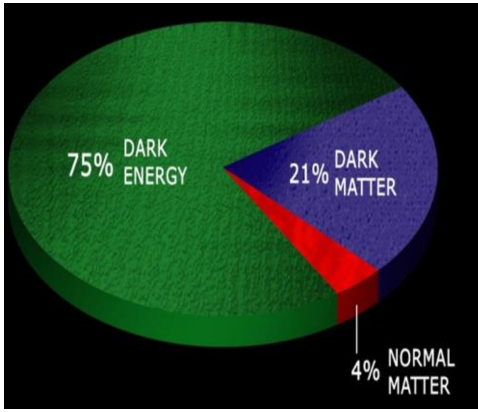
Reaching the energy scale in the laboratory to simulate the earlier times and higher energies in the Universe's evolution is daunting! But, the "signals" are all there in the space-time of our laboratories, albeit as very weak "tremors" and "fossils" from the Big-Bang early universe! Need "Cosmic Archaeology"!

Big Bang



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

now



Universe was already "entangled" at the Planck-scale. There was a single wavefunction of the universe at the Planck –scale: Ψ_{Planck}

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

$$\Psi_{\text{Planck}} \rightarrow \Psi_{\text{A}} \otimes \Psi_{\text{B}}$$

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

PHYSICAL MEASURE of the DARK SECTOR:

DARK MATTER/ENERGY and FORCE ESTIMATES

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

Corresponds to energy density of a static electric field:

E = 12 V/m (Dark Energy)

"Dark Matter" density is even higher implying:

Ω_{DM} E ~ 10 kV/m !! (Dark Matter)

Must look for "AC"-effects (fluctuations) on a fixed background!

~ $4\times10^{-10}\ \mathrm{Nm}^{-2}$ → Measurement of Casimir effect (1996)

~ $1.3\times10^{-10}\ \mathrm{Nm}^{-2}$ → Cold cathode ionization gauge

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.**

Ordinary Quantum Limits in Impulse Sensing

Standard quantum limit for momentum transfer:

$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

1.5 MeV (m = 1 ng, ω = 1 kHz)

1.5 μeV (m = 1 m_e, ω = 1 kHz)

Again this is just a benchmark. “Simple” and natural ways to go below this level:

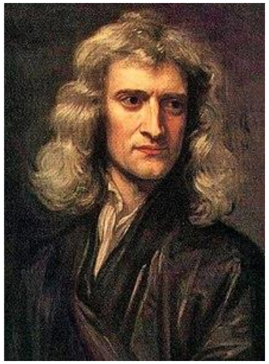
- **Beat the Zero-point noise**
- **Squeezing, Non-demolition/back-action evasion**
- **State transport and transduction**
- **Single photon detectors**
- **Measuring arbitrarily small forces**
- **Cooper pair-breaking detectors**

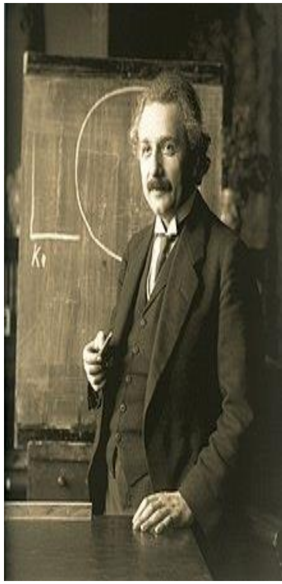
Quantum Sensing Enables:

- Ultralight Wavelike Dark Matter (Generalized Axions, Hidden Sector Photons, Scalars) detection
- Scattering/Absorption of Dark Matter Particles
- Electric Dipole Moment measurements (e, p, n)
- Gravitational Waves detection
- Dark Energy detection
- Detection of Variations of Fundamental Symmetries
- Detection of New Forces and Particles

WHY Invoke Quantum Entanglement?

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





Why so? QUANTUM ENTANGLEMENT ALLOWS for "SQUEEZED" STATES

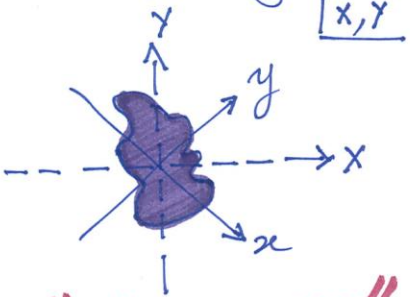
"ENTANGLED"

$(x \wedge y)$

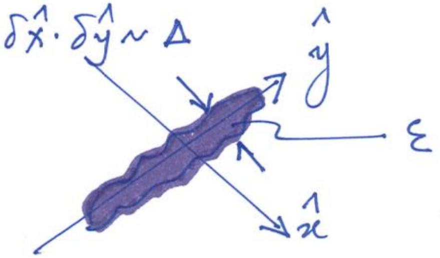
"INDEPENDENT"

(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"



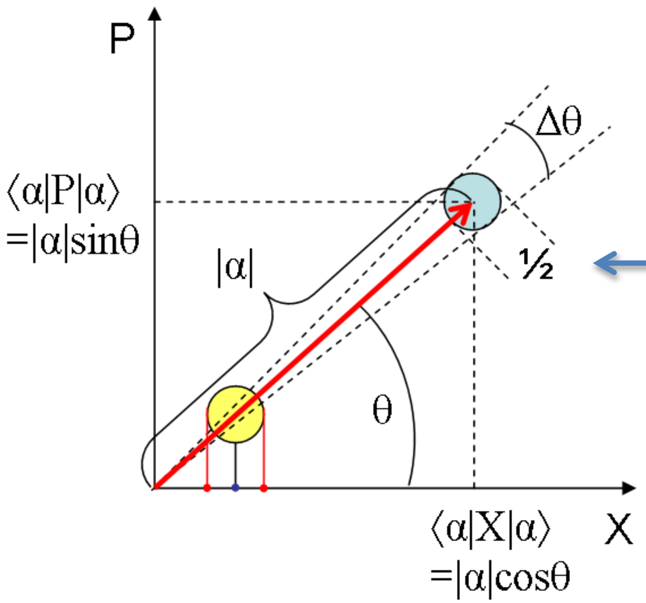
$\delta\hat{x}\cdot\delta\hat{y} \sim \Delta$



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)

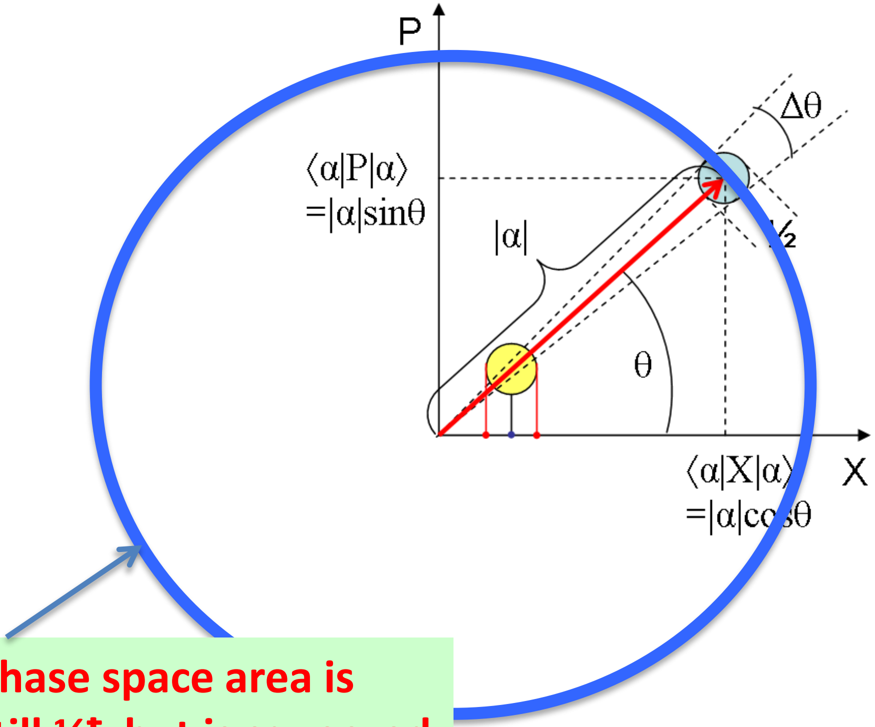
Thermal noise = ½ kT per resolved mode
→ Quantum noise = 1 photon per resolved mode in the T=0 limit.

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.



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

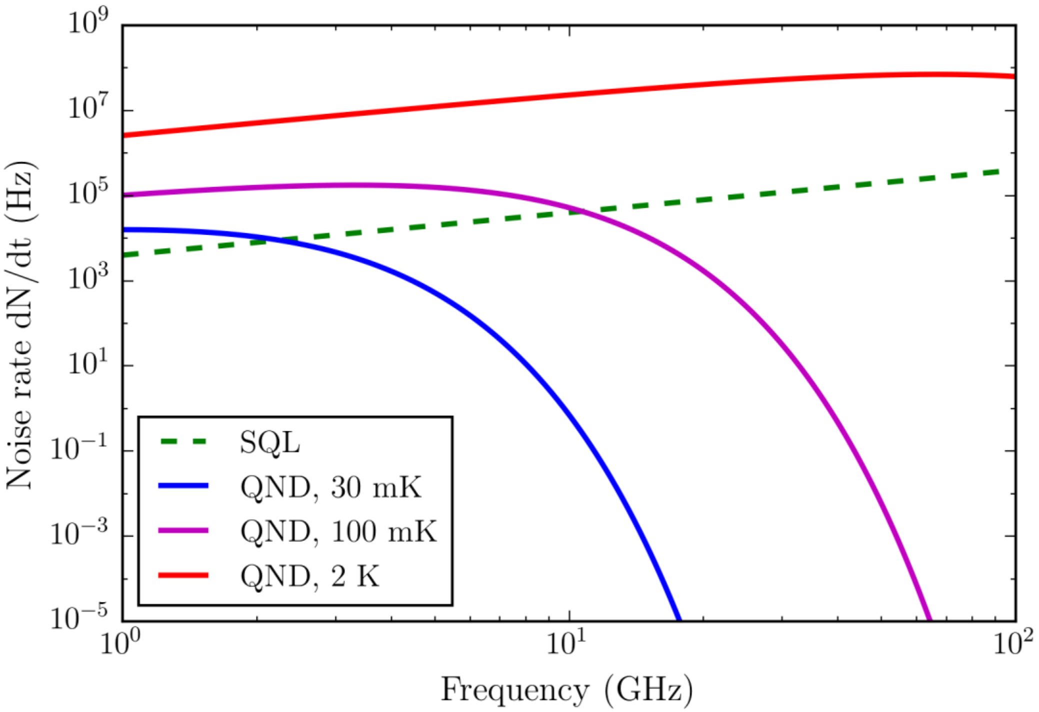
Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

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 probing “ultra-weak” processes!

Noise rates, qubits vs quantum-limited amplifiers

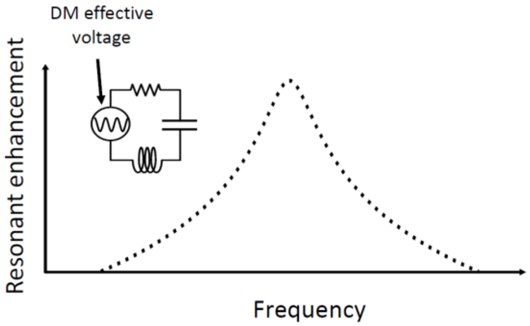


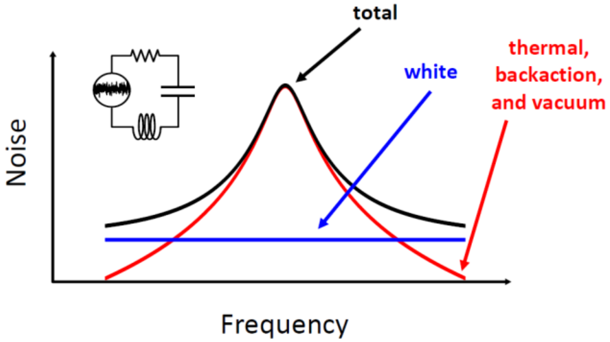
Linear amplifiers suffer from the "standard quantum limit" (SQL, Caves, 1980): 1 photon's worth of noise per frequency-resolved mode. Quantum Non-Demolition (QND) measurements' noise is blackbody-dominant. Cooling to O(10) mK gives clear benefits.

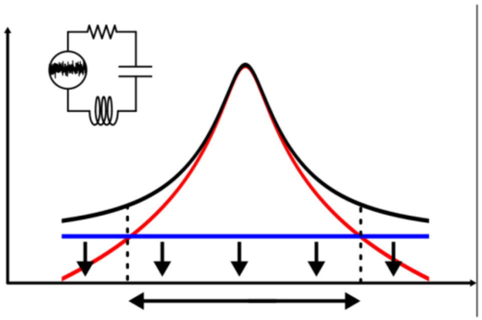
RF QUANTUM CONVERETERS

“Coherent Wave-like Oscillations”

Total Noise = White Noise (amplifier imprecision) + Other Noise (thermal, vacuum and quantum back-action Fluctuations). Thermal noise is an important noise source for f<300 MHz (2 micro eV)



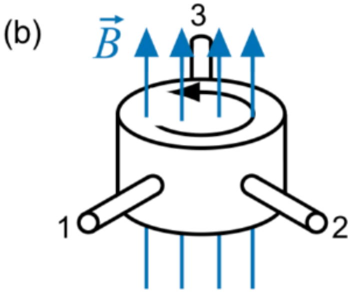




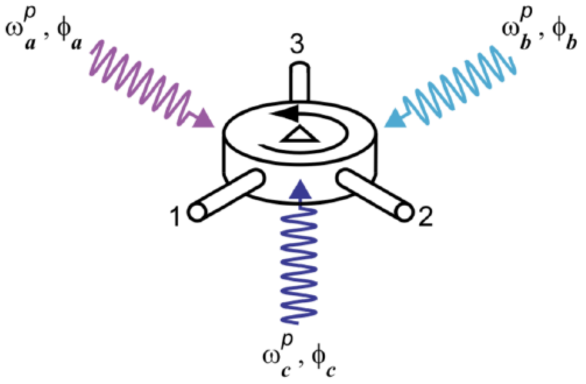
Photon Counting not effective. Invent method of Quantum Non-demolition to evade quantum back-action, thus reducing white noise without adding to back-action, for a single quadrature (amplitude or phase), leading to constant SNR maintained over a broader bandwidth, thus enhancing search rate.

MICROWAVE QUANTUM ELECTRONICS:
UNITARY QUANTUM UP-DOWN CONVERTERS

Measurement of subtle signals requires ultralow loss non-reciprocal devices to transport quantum states

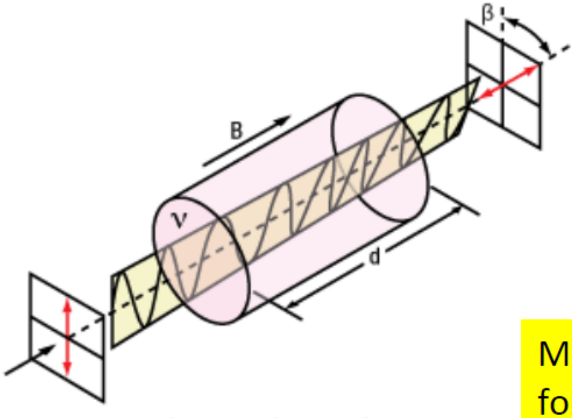


Conventional ferrite-based circulator
using **magnetic flux** for T-violation



$$\phi_{tot} = \sum_{i=a,b,c} s_i(\omega_i^p t + \phi_i) = \pi/2$$

Upconverting Josephson circulator
using **Berry flux** for T-violation
(K. Sliwa et.al, 2015)

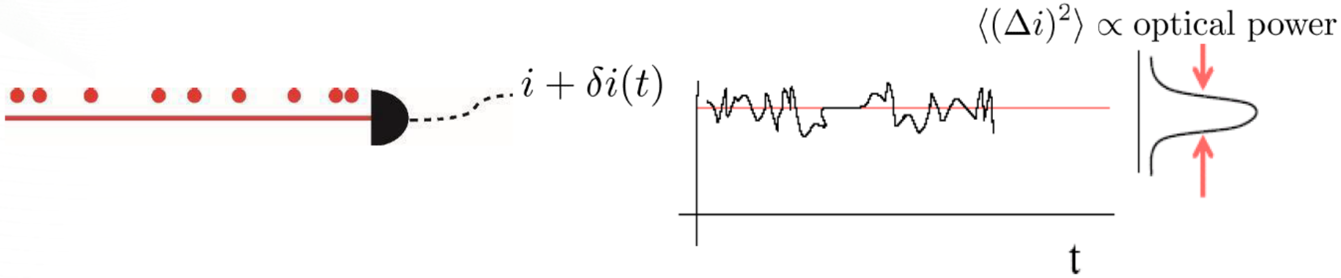


Faraday isolator for
optical interferometers

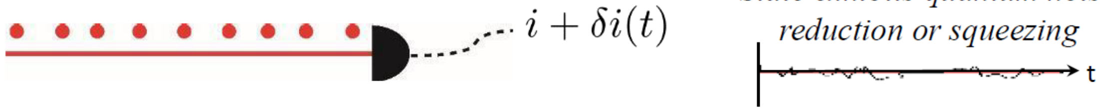
More generally, **unitary up/down-converters** are useful for transducing signals to different frequencies where there exists convenient sensor/amplifier technology.

Quantum Noise Reduction

- Quantum noise can be viewed as a result of light being composed of discrete photons with a random temporal distribution.



- This noise represents the shot noise limit (SNL) and is the minimum noise level for a classical state of light.
- Can generate states of light with less noise in amplitude through the use of a nonlinear process that can emit pairs of photons.



State exhibits quantum noise reduction or squeezing

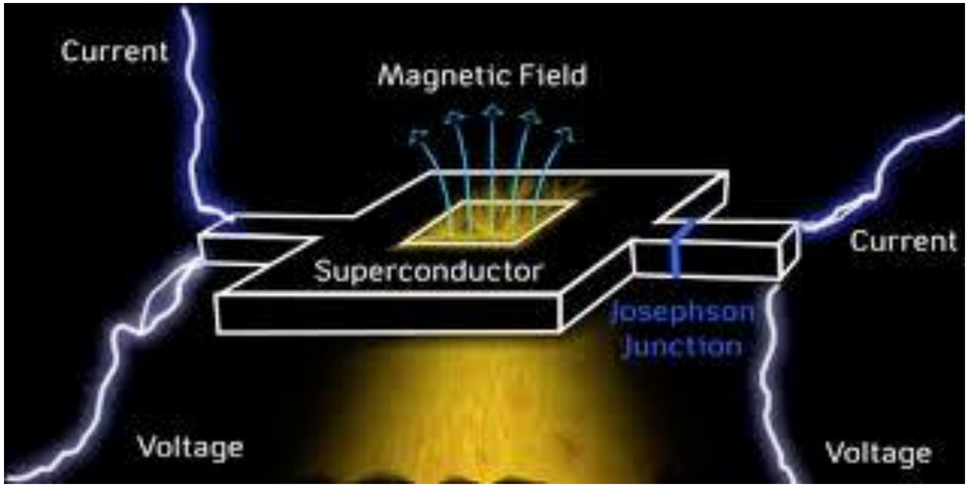
- Amount of quantum noise reduction increases with strength of nonlinearity.

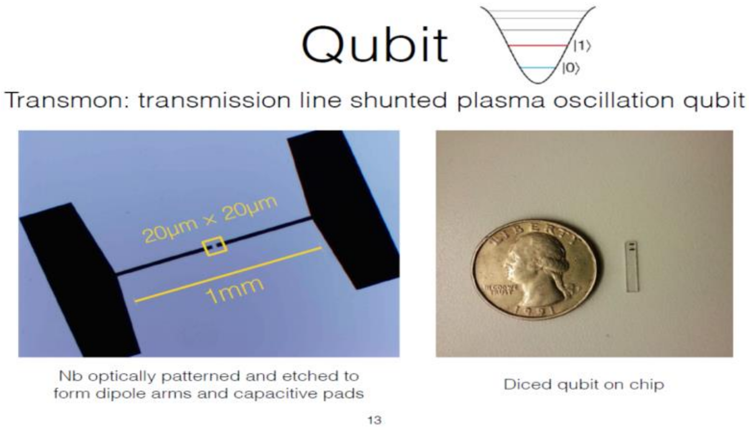
Creating macroscopic quantum systems and yet preserving long-lived quantum coherence is the key phrase in the future potential of Quantum Sensors….

EXAMPLES:

State-of-the-art Performance Reach of Quantum Sensors

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





Transmon: transmission line shunted plasma oscillation qubit

Nb optically patterned and etched to form dipole arms and capacitive pads

Diced qubit on chip

13

SQUIDs: Superconducting Quantum Interference Devices as precision 'Magnetometers'

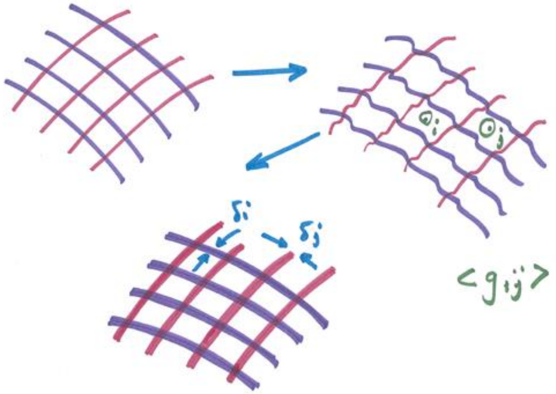
Can mimic a 'two-level atomic system' artificially and act as a quantum bit: '0' or '1'

OR '-1' or '+1'

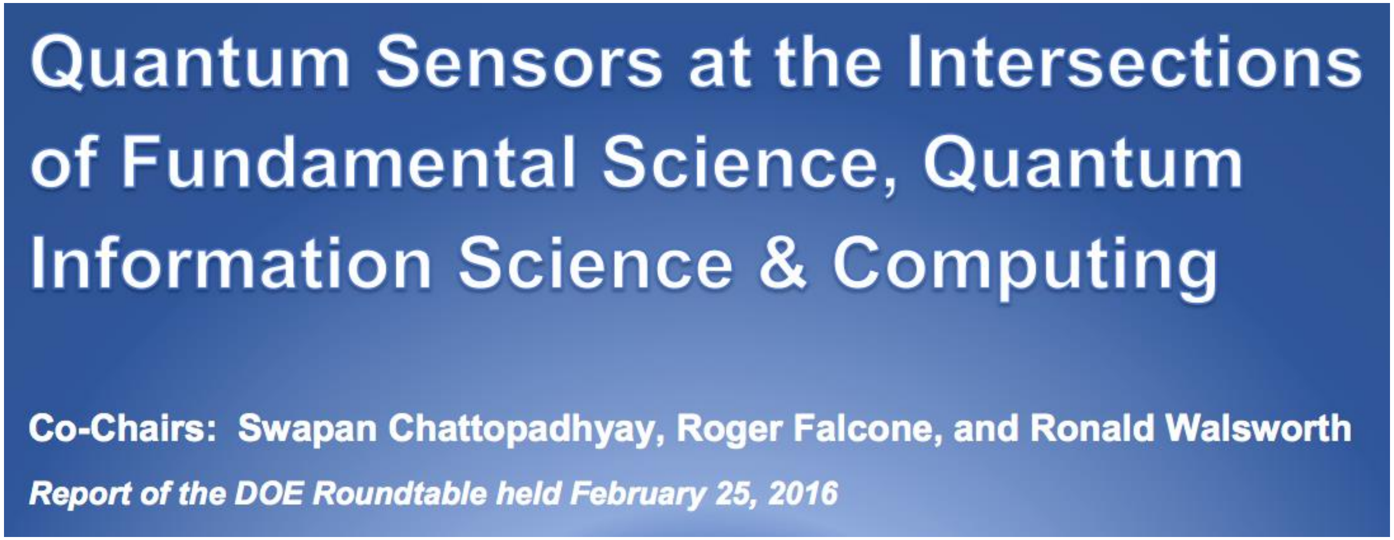
OR 'up' or 'down'

EXAMPLES:
State-of-the-art Performance Reach of Quantum Sensors

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



Atomic Beam Interferometers as ‘Gravity Gradiometers’
Can detect tiniest fluctuations of gravity or associated fluctuations of “space-time”-metric



Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science & Computing

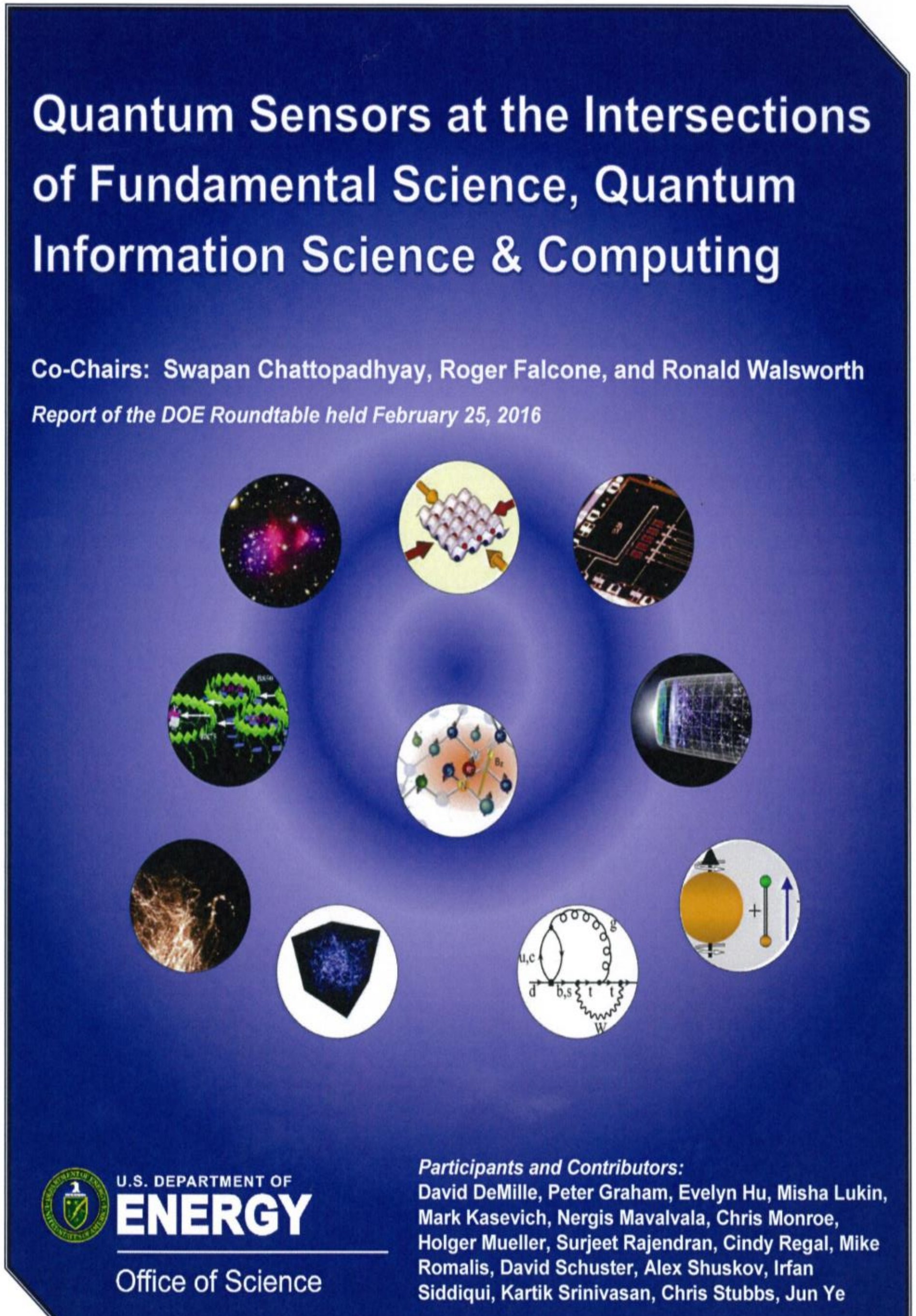
Co-Chairs: Swapan Chattopadhyay, Roger Falcone, and Ronald Walsworth

Report of the DOE Roundtable held February 25, 2016

DOE
ROUND TABLE

Feb. 25, 2016
Gaithersburg, Maryland
(OHEP, ASCR, BES)
including NSF, NIST
and OSTP

Cross-cutting Opportunities and challenges at the quantum frontier that includes quantum sensors for HEP, material science and quantum computing



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U.S. DEPARTMENT OF
ENERGY
Office of Science

Participants and Contributors:
David DeMille, Peter Graham, Evelyn Hu, Misha Lukin, Mark Kasevich, Nergis Mavalvala, Chris Monroe, Holger Mueller, Surjeet Rajendran, Cindy Regal, Mike Romalis, David Schuster, Alex Shuskov, Irfan Siddiqui, Kartik Srinivasan, Chris Stubbs, Jun Ye

Google, Microsoft, IBM, Harvard, Yale, Stanford, U. Chicago, FNAL, ANL, LBNL, ORNL…all gather on October 18, 2016 at…

Quantum information at OSTP

Identifying Strategic Options for Advancing Quantum Information

OCTOBER 18, 2016 AT 4:23 PM ET BY ALTAF H. (TOF) CARIM AND WILLIAM T. (TIM) POLK

- October White House meeting of leaders of this community, broadly defined
- Included David Awschalom of U. Chicago, me, big honchos from Google, Microsoft, IBM, Harvard, Yale, Stanford, etc.
- Recognition that a revolution is coming in this area, but requires pulling together an interdisciplinary community, including HEP

National Quantum Program Model

- → **Quantum Initiatives program started in 2018 by US DOE Office of Science and NSF**

- → **Distributed across US west coast, east coast and central states**

- → **Quantum Program expected to grow to $600 M/year in a few years' time, pending success of the pilot programs**

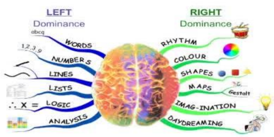
- → **Mezzo-scale model of 6 to 12 prime research groups across the country including universities and laboratories receiving $ 10 M - $25 M per year for 5 years is already funded in the US starting this year, 2020.**

Quantum Sensors: APPLICATIONS

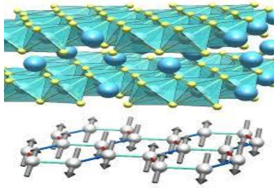
→ *Searches for New particles/Interactions: "Dark" Matter/Energy ****

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

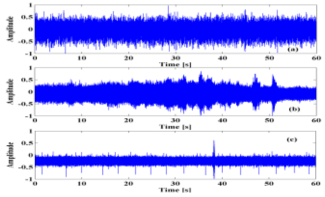
→ *Quantum Computers: Quantum Information Science*
CRYPTOGRAPHY, MARKET OPTIMIZATION, ARTIFICIAL INTELLIGE



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



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

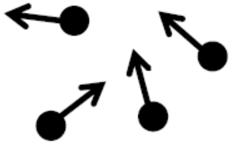


→ *Detection of "Weak" Environmental Signals: Geo-science*
CLIMATE CHANGE SCIENCE

**** I will briefly address these topics*

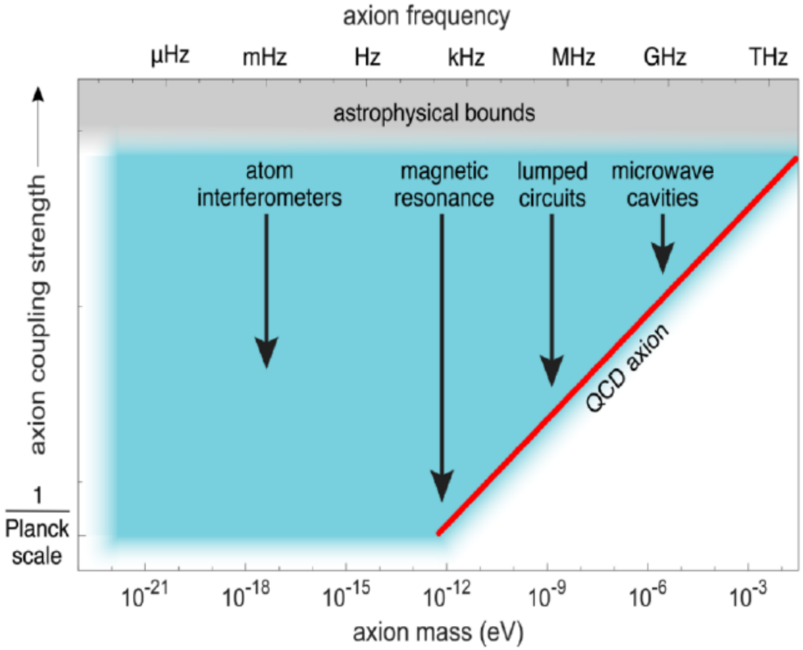
Ultralight dark matter

WIMPS
- Mass ~10 GeV (10x proton)
- Particle-like (deposit energy in detector)



"Ultralight" dark matter (e.g., axions, dilatons, etc.)
- Low mass, high number density
- Would act like a **classical field**

One example is the axion, and axion-like particles:

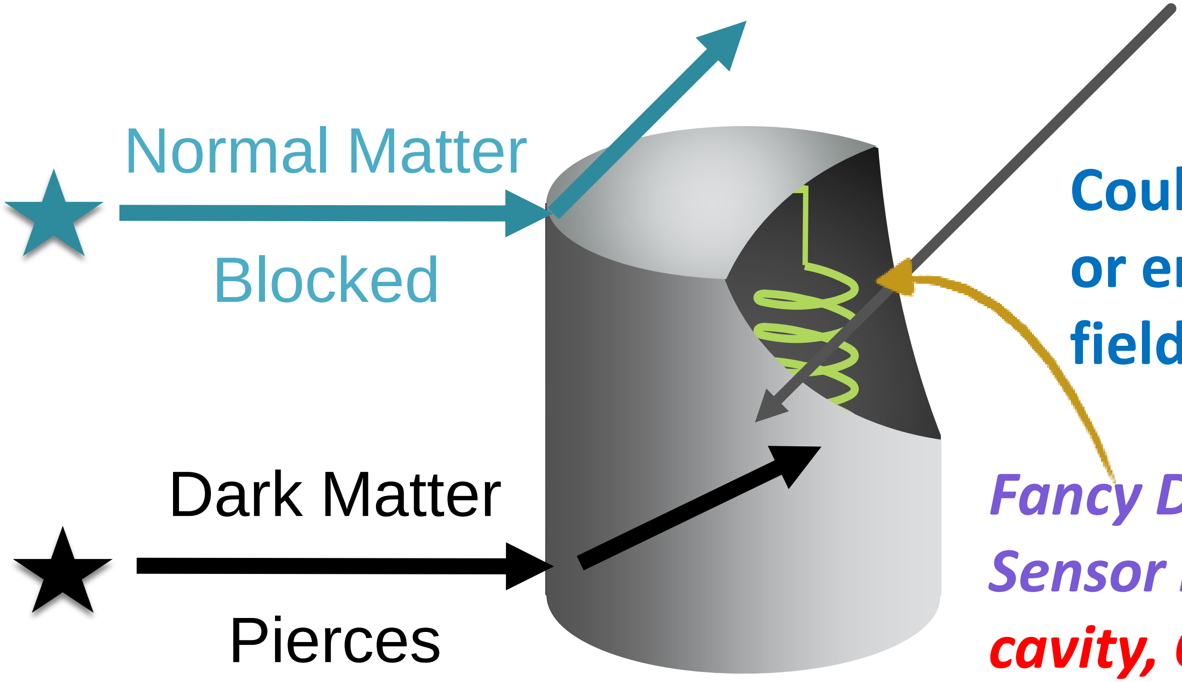


Dark matter BRN report

Cavity-Qubit Electrodynamics to probe for “dark” sector particles:

Axions, Hidden Sector Photons,…

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



shield

Normal Matter

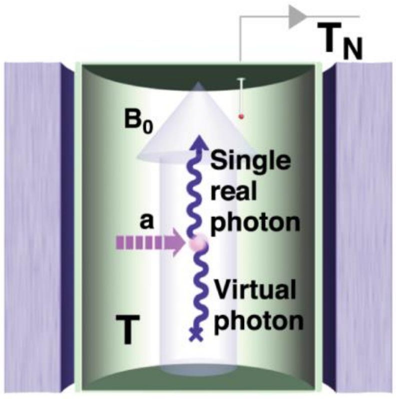
Blocked

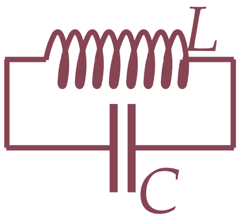
Dark Matter

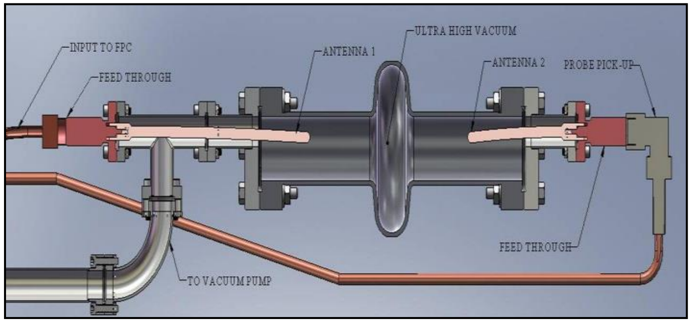
Pierces

Could detect “Dark photons” or embedded in a magnetic field, could detect “Axions”.

Fancy Detector: Quantum Sensor inside a superconducting cavity, Q ~ 10E11

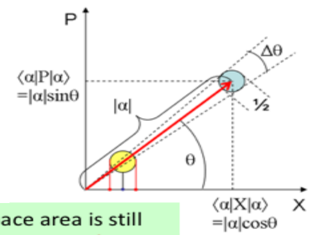




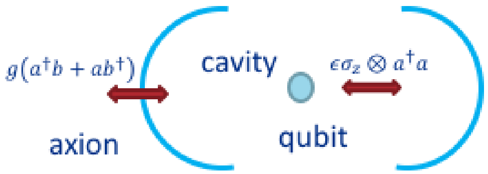


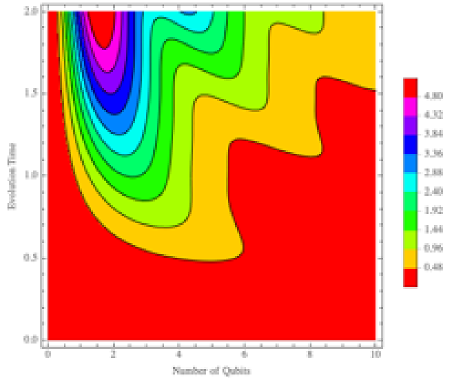
Tunable superconducting resonant LC circuit (a radio)

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



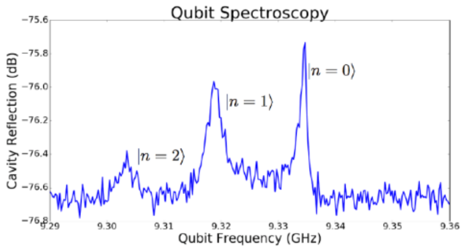
Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.



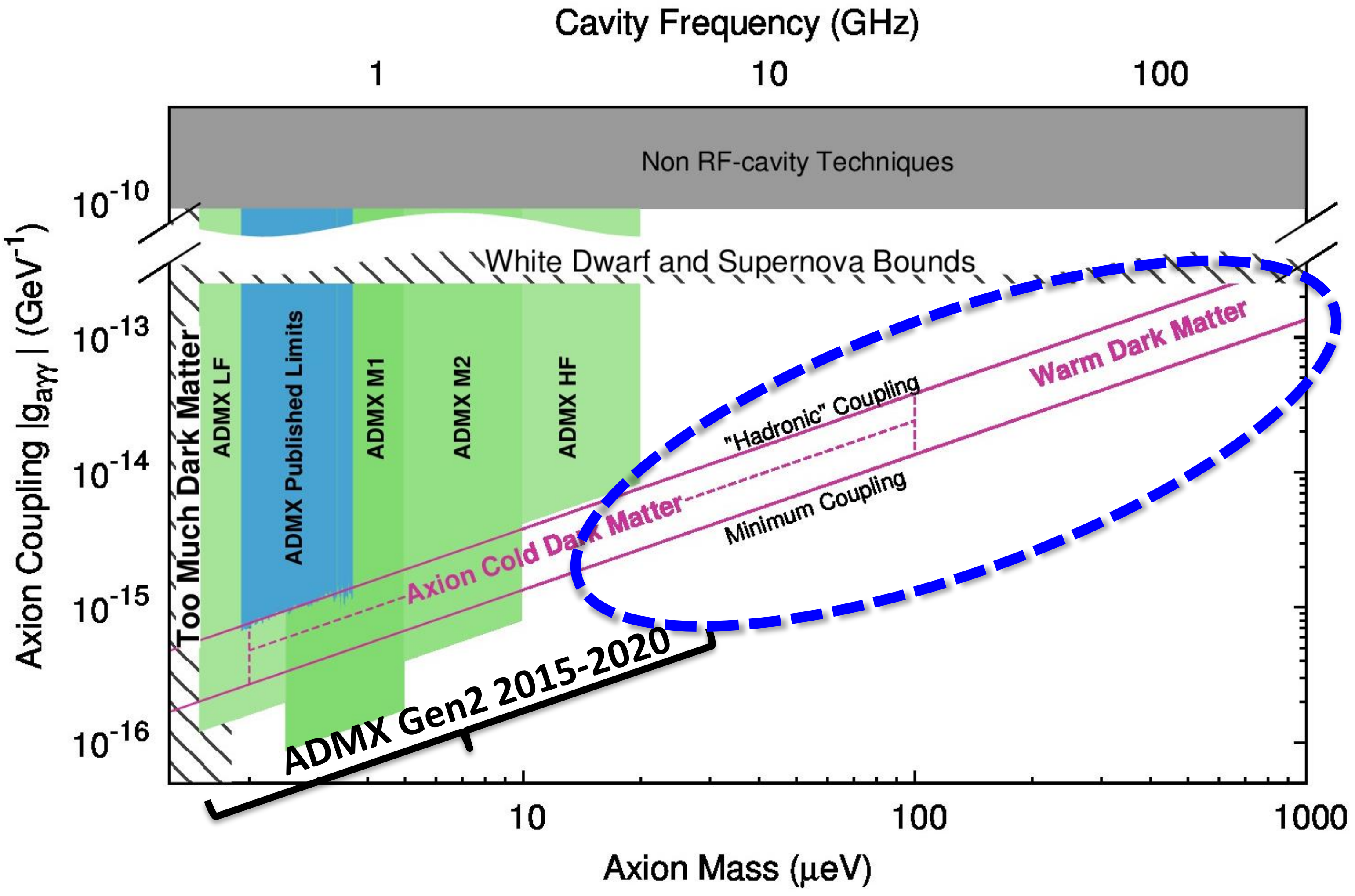


Contour Plot for Fisher Information given $(\alpha|0\rangle^{\otimes n} + \beta|1\rangle^{\otimes n})|1,0\rangle$

- Increase the signal photon rate by using superconducting qubits as QND detectors and a high-Q Superconducting 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-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

Probing the Very Early Universe and the "Dark" Universe:
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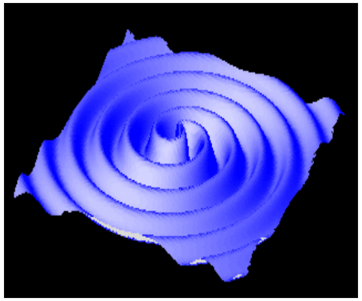
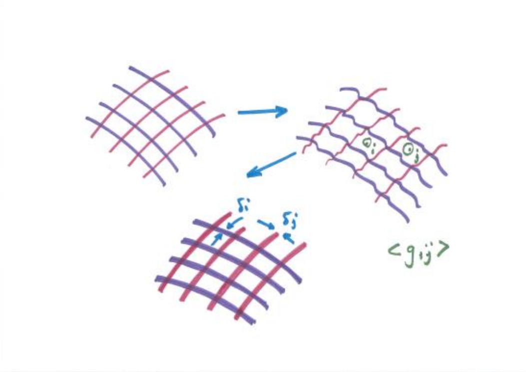
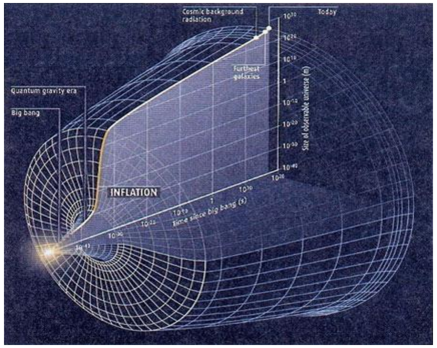
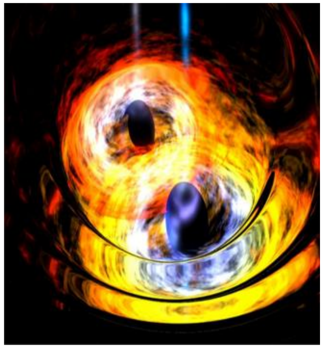
Detection of Stochastic Low Frequency Gravitational Wave Background from the "Inflationary" Era + Perturbed Atomic Transitions via Coupling of the Electromagnetic Sector (i.e. fine structure constant) with the "Dark" sector









Strain: (dl/l) ~10E-25 @ 1 Hz??

Ultralight scalar dark matter

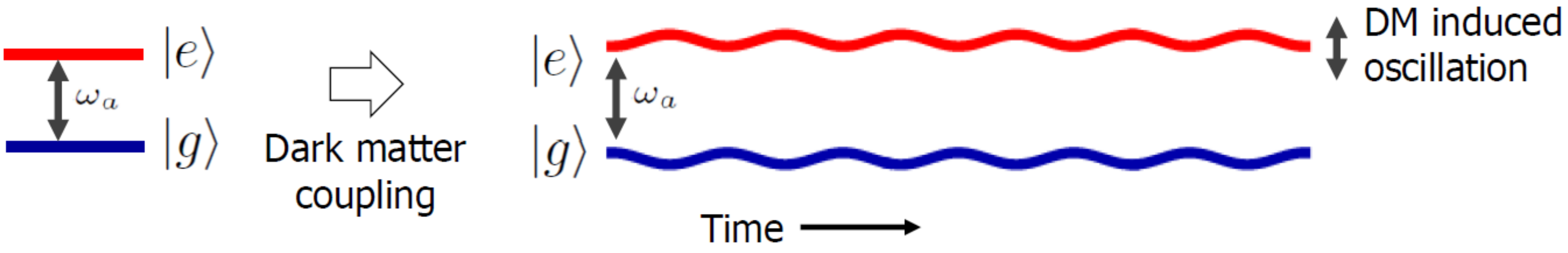
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\,\phi\left[\underbrace{d_{m_e} m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

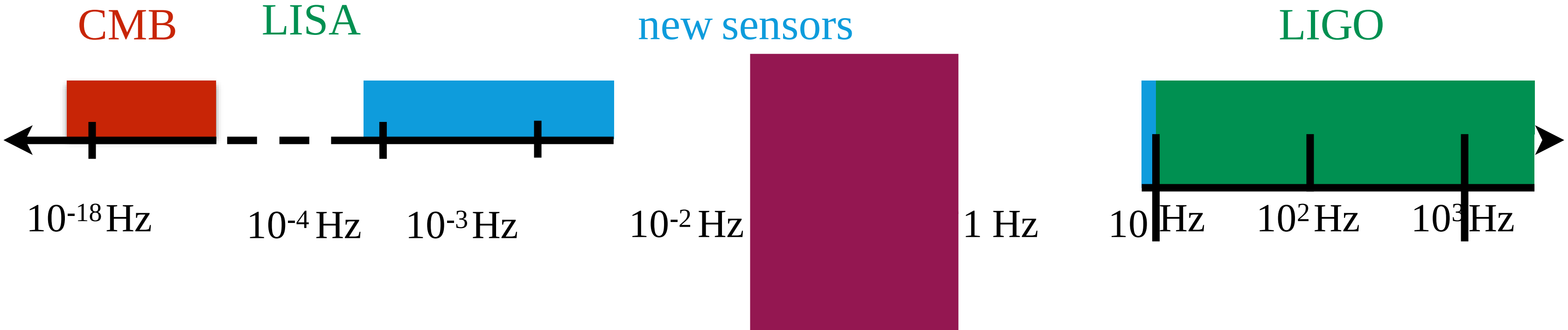
$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:



Gravitational Wave Spectrum



CMB

LISA

new sensors

LIGO

10^{-18} Hz

10^{-4} Hz

10^{-3} Hz

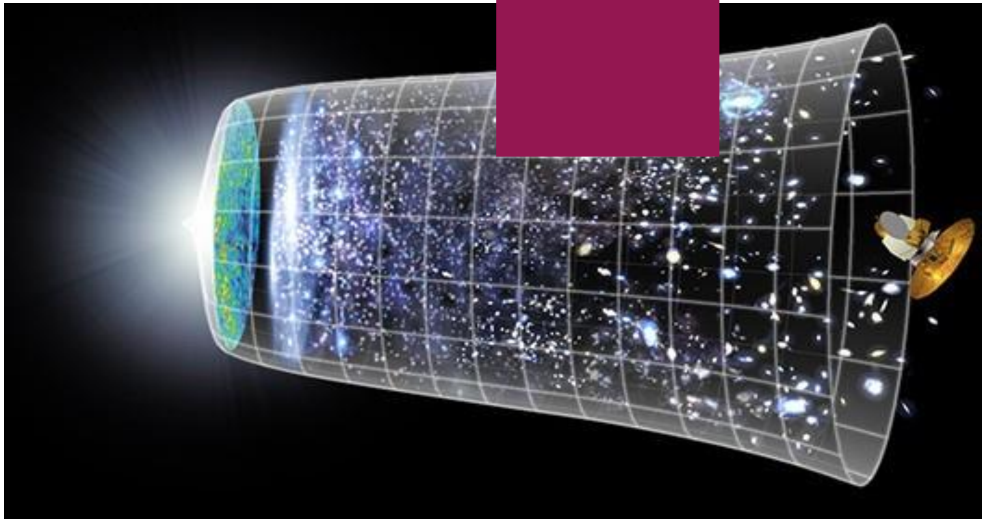
10^{-2} Hz

1 Hz

10 Hz

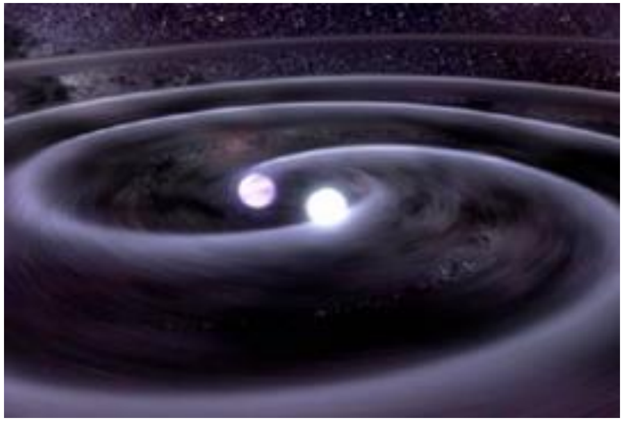
10^{2} Hz

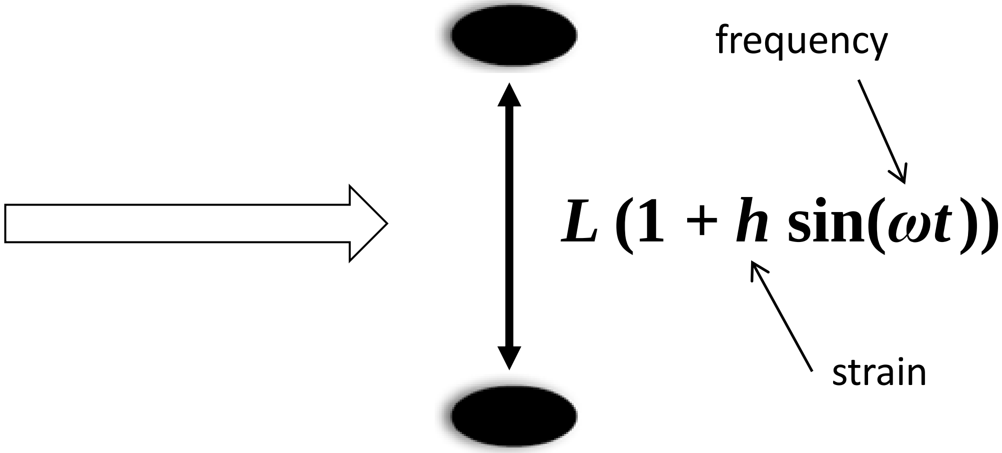
10^{3} Hz



Gravitational radiation in the mid-band falls in a gap between the lower and uppoer reaches of earth-based LIGO and space-based LISA

GW detection with atoms playing both roles: clock and inertial reference





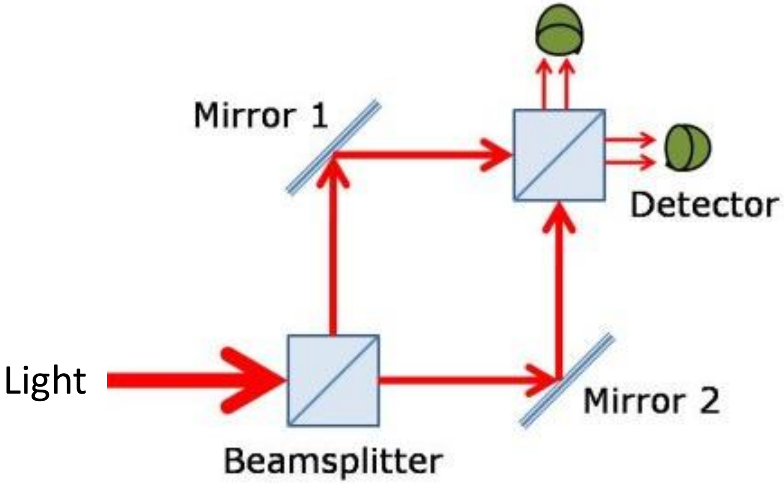
$$L\,(1 + h\sin(\omega t))$$

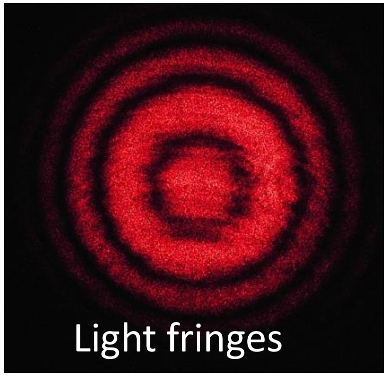
Measure differential acceleration between two inertial masses

	LIGO	Atom Interferometry
Proof mass	Suspended end mirrors	Freely falling atoms
Proof mass separation	Laser interferometry	Light flight time
Reference	2nd interferometer arm	Atomic phase (clock)

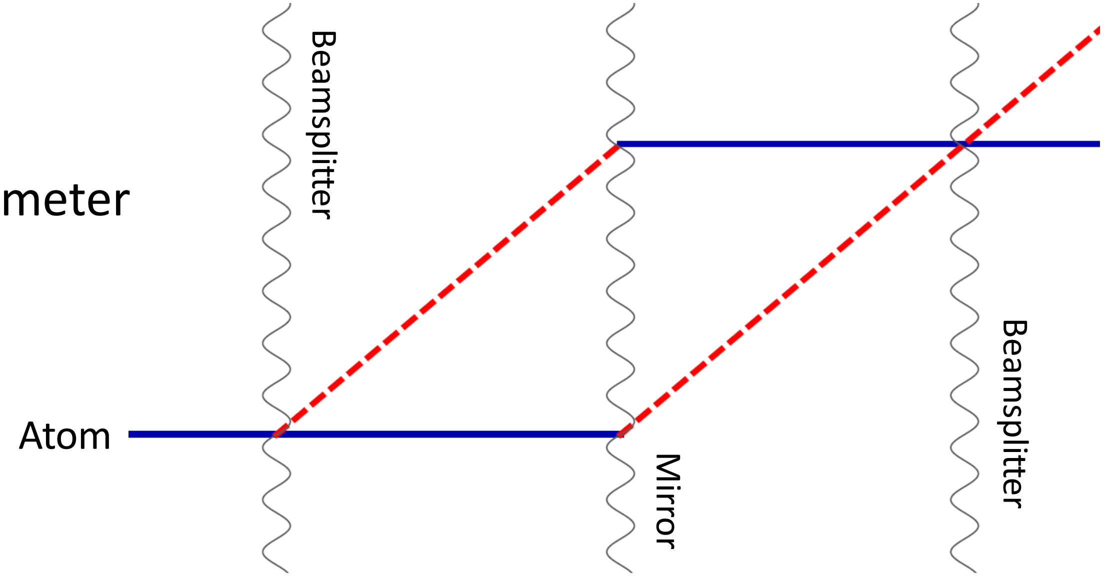
Atom interference

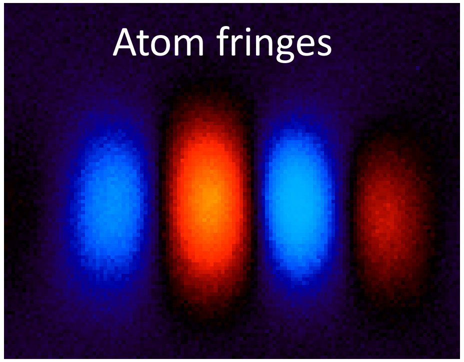
Light interferometer





Atom interferometer





http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Light Pulse Atom Interferometry

$$|\text{atom}\rangle = |p\rangle$$

π/2 pulse

"beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p+k\rangle)$$

π pulse

"mirror"

$$\frac{1}{\sqrt{2}}(|p+k\rangle + e^{i\Delta\phi}|p\rangle)$$

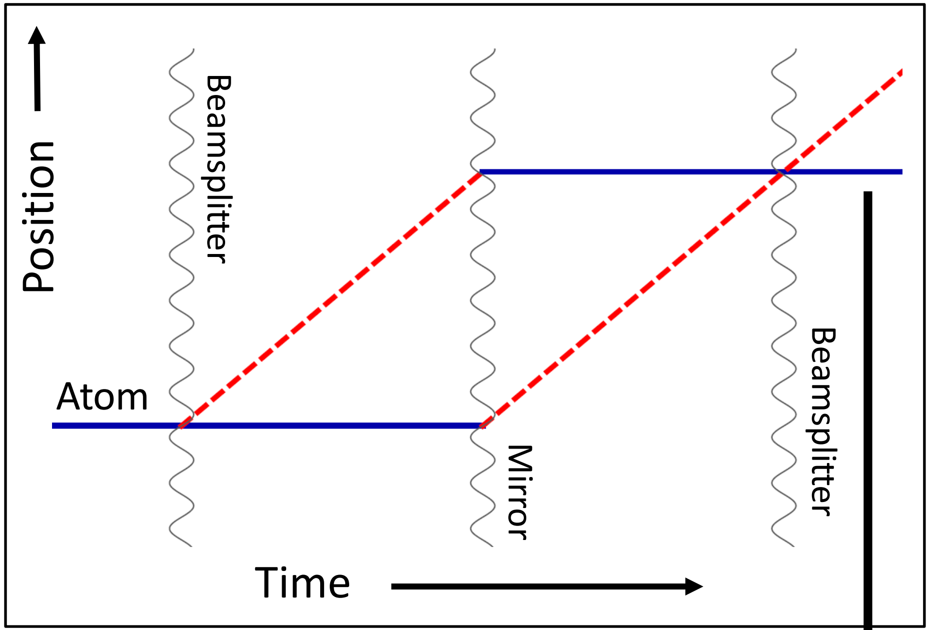
π/2 pulse

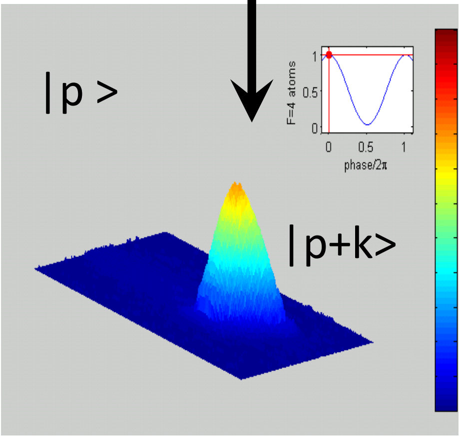
"beamsplitter"

$$\frac{1}{2}((1+e^{i\Delta\phi})|p\rangle + ((1-e^{i\Delta\phi}))|p+k\rangle)$$

$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |p+k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$





Wave function of atom has phase factor exp(iϕ)

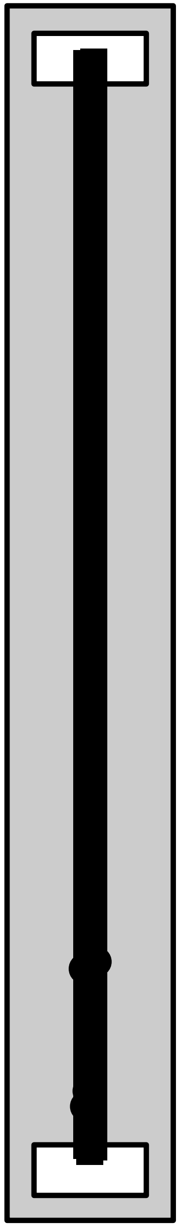
- The phase ϕ changes as atom falls through changing gravitational potential.
- Probability *P* of detecting the atom at one output of the interferometer is

  $$\Delta\phi = \Delta\phi_1 - \Delta\phi_2$$

  $\Delta\phi_1, \Delta\phi_2$ are phases accumulated by matter waves on the two paths
- The probability

  $$P = (1 + \cos\Delta\phi) / 2$$

  is measured by laser-driven fluorescence at the detector.



The wavefunction

Phase

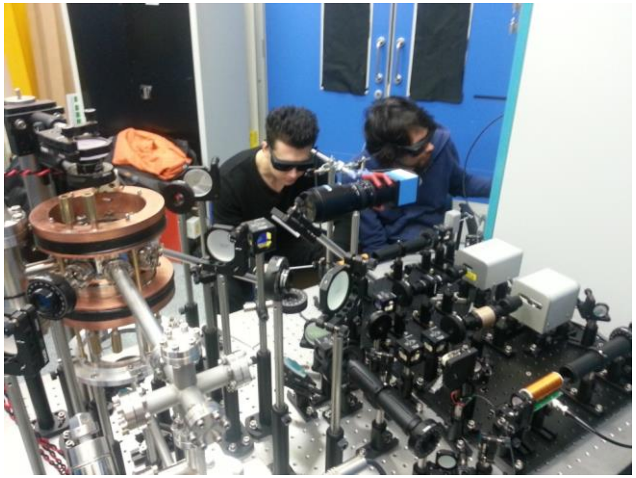
$\Phi \sim k.z \sim k.g.T^2$

10 m fall ~1 sec

100 m fall ~ 3.2 secs

1000 m fall ~ 10 secs

Typical Atom Trap as Source

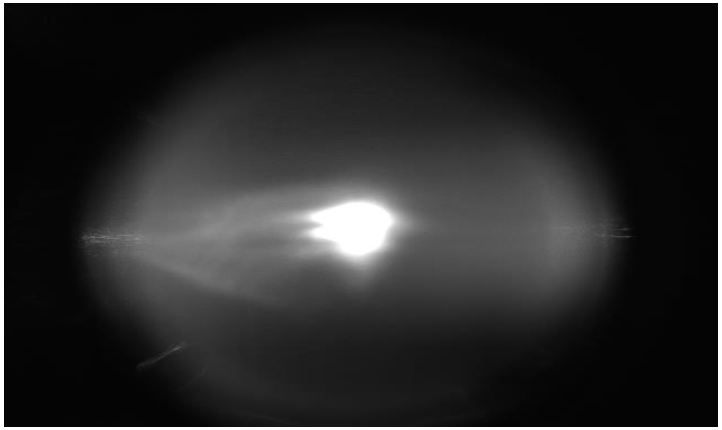


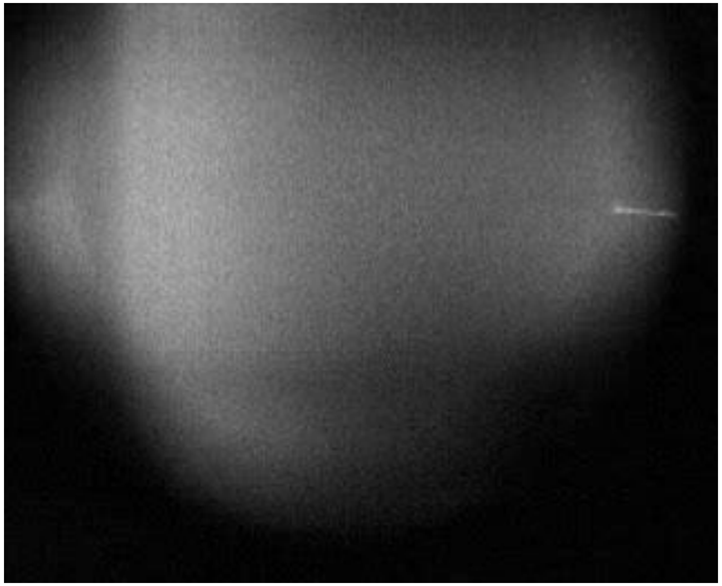
A cloud of ultra-cold atoms

- Temp ~ 5μk
- 17 x 10^6 Atoms

- A Portable Atom Trap built at a university lab → Today's record 50 pico-Kelvin with number of trapped atoms ~ 10^8

- Still needs improvement in stability, lifetime and repetition rate for being useful in interferometric detection of gravitational background or "dark" energy





Dark Energy and Gravitational Wave Detection with Accelerometers

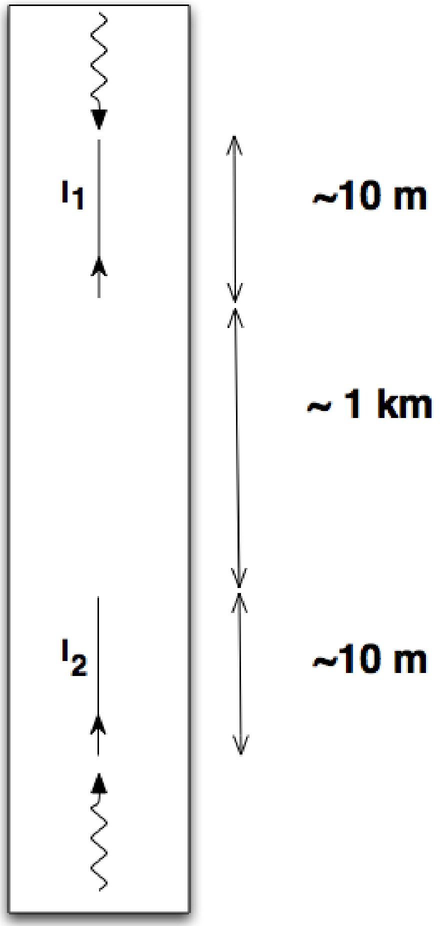
Gravitational waves @ 1 Hz could open the window for direct tests of cosmic inflation, frequency range inaccessible to LIGO/LISA. Atomic interferometers can also be sensitive detectors of "dark" energy.

EXAMPLE:

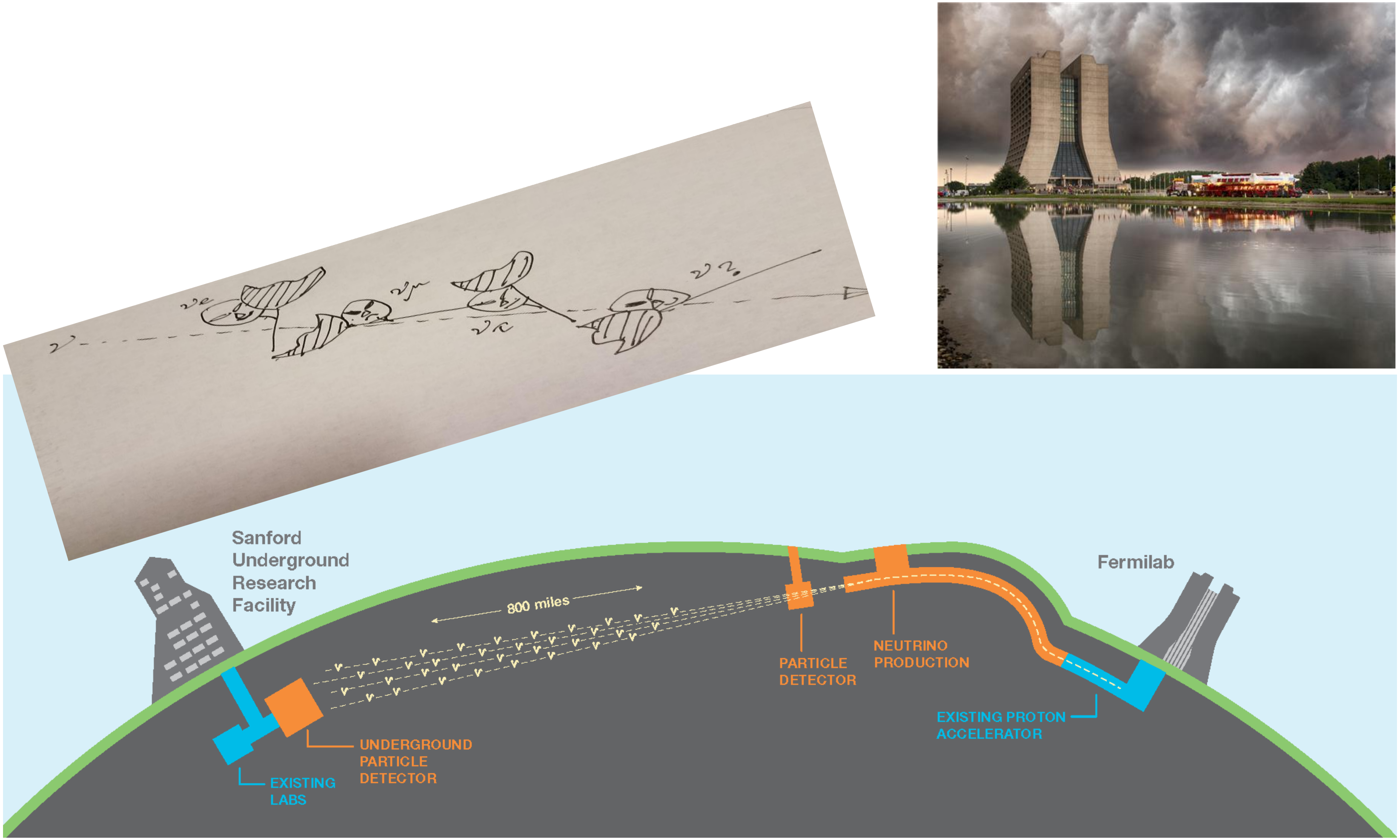
Two 10 m atom interferometers at either ends of a mine shaft. Both interferometers will be operated by common lasers. Signal scales with length ~ 1 km between interferometers.

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

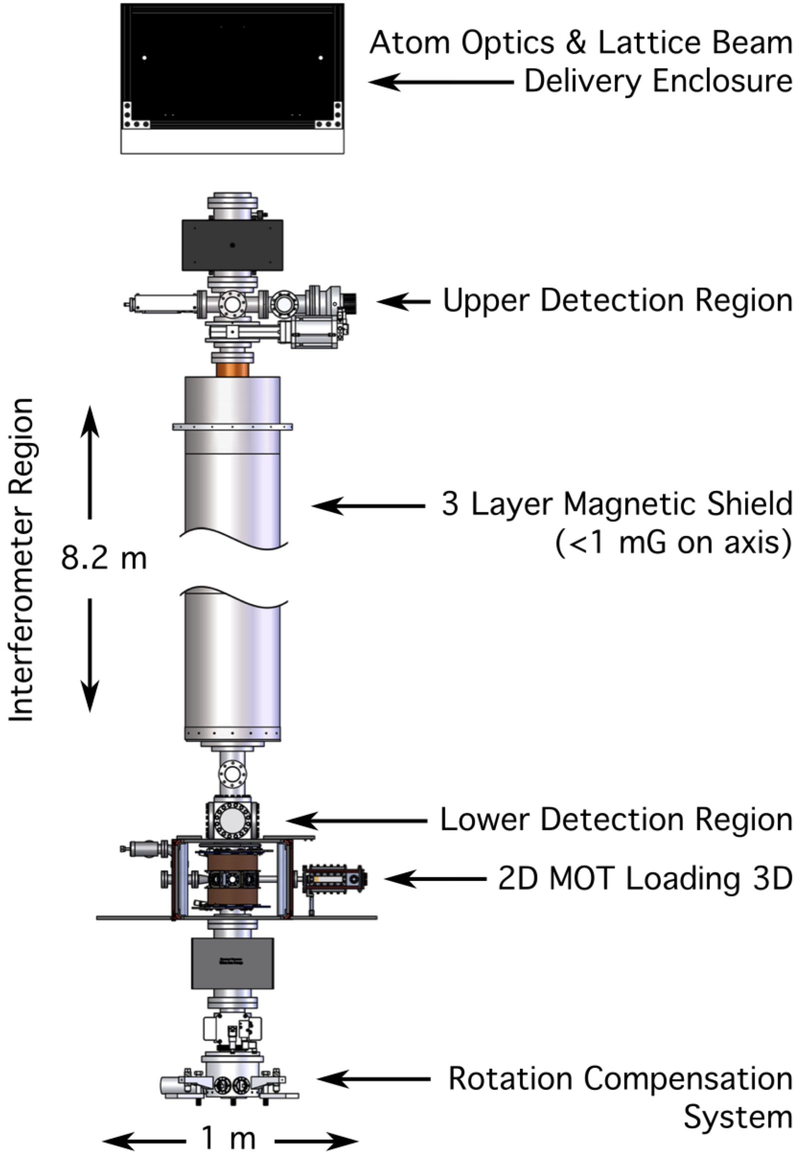
→ **POSSIBILITIES in the Sanford Lab where DUNE long-baseline neutrino experiment will be carried out by a global team using high powered beams from Fermilab sent to underground detectors with a vertical shaft of a few kilometers.**



LBNF-DUNE @ Fermilab
houses 4 km vertical shaft



10 meter scale atomic fountain at Stanford



Atom Optics & Lattice Beam Delivery Enclosure

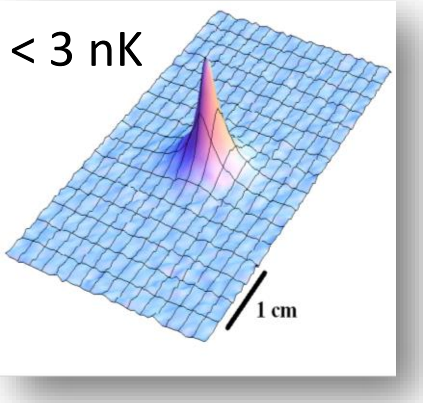
Upper Detection Region

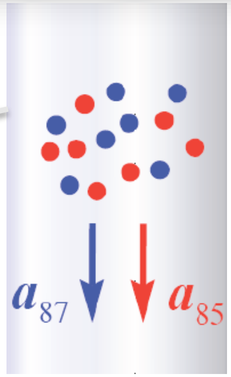
3 Layer Magnetic Shield (<1 mG on axis)

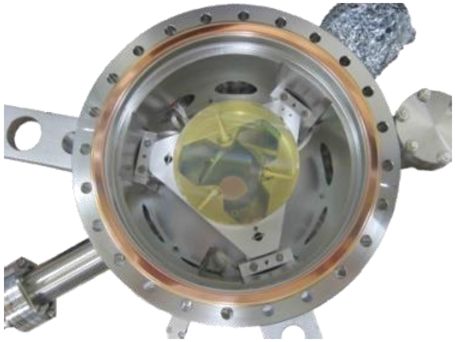
Lower Detection Region

2D MOT Loading 3D

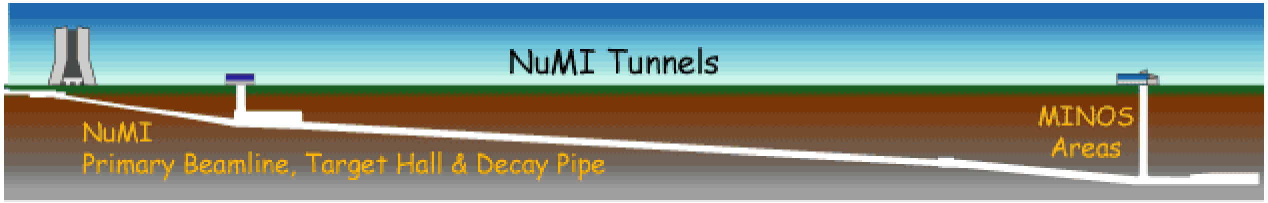
Rotation Compensation System

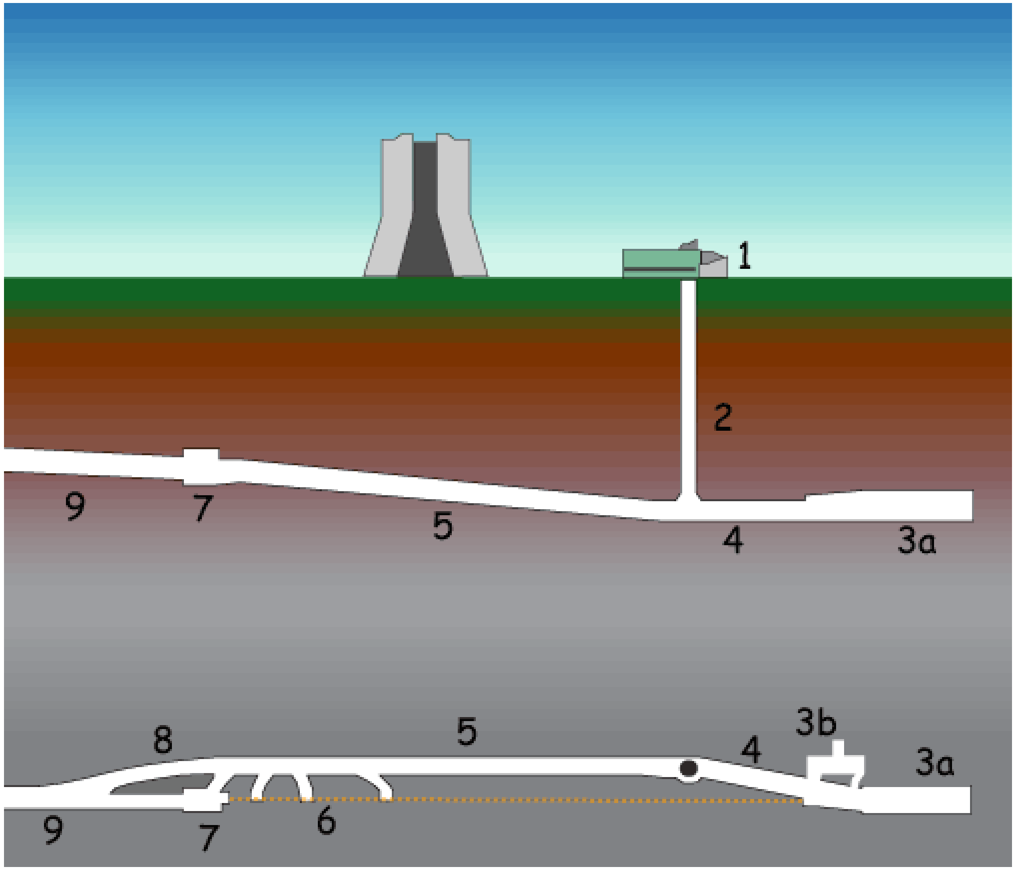






105 meter tall NuMI shaft in the MINOS





Early Explorations at Fermilab

Precision Neutrino science in deep underground facilities a Core Competency of Fermilab.

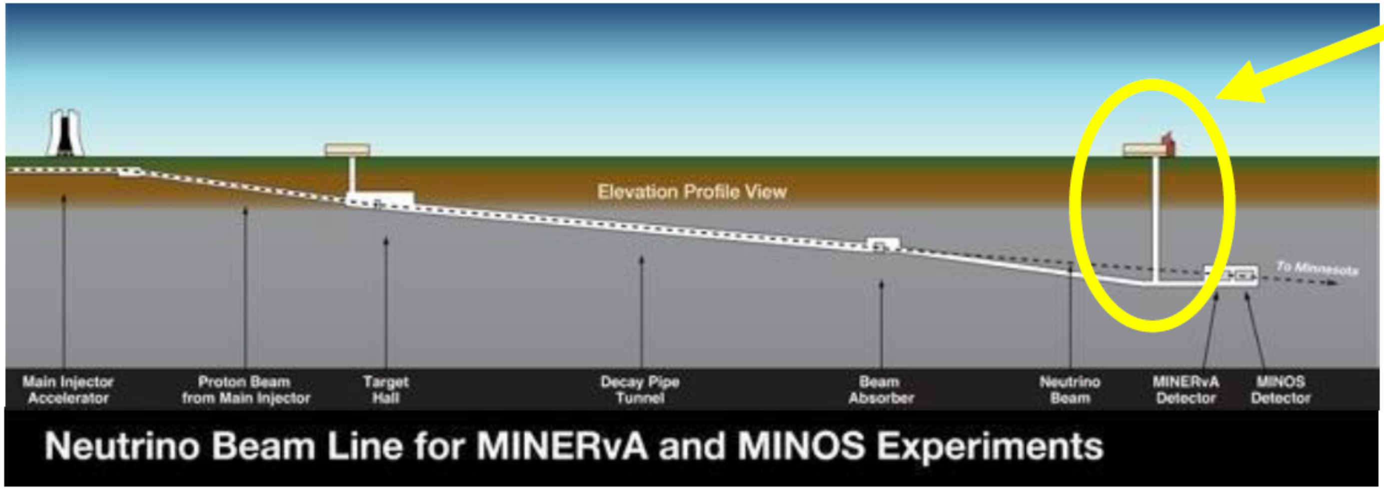
An vertical underground shaft a few kilometers long already exists at the Sanford Lab housing the DUNE experiment.

A 100 meter tall NuMI shaft already exists in the MINOS facility which can be carefully examined for an intermediate experiment.

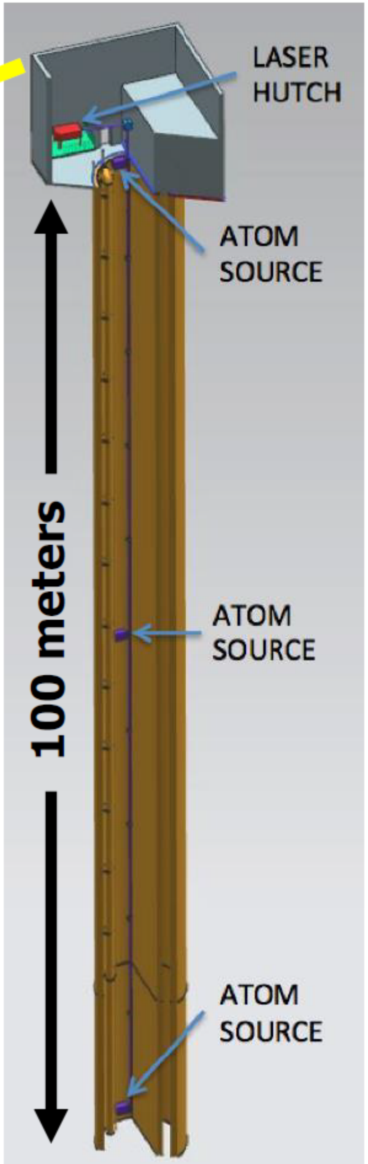
Hence “dark” sector and gravitational wave background search using Atomic Beam Interferometers at Fermilab.

MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



Neutrino Beam Line for MINERvA and MINOS Experiments



- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

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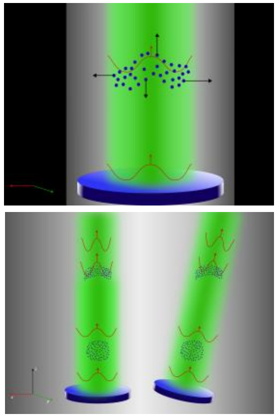
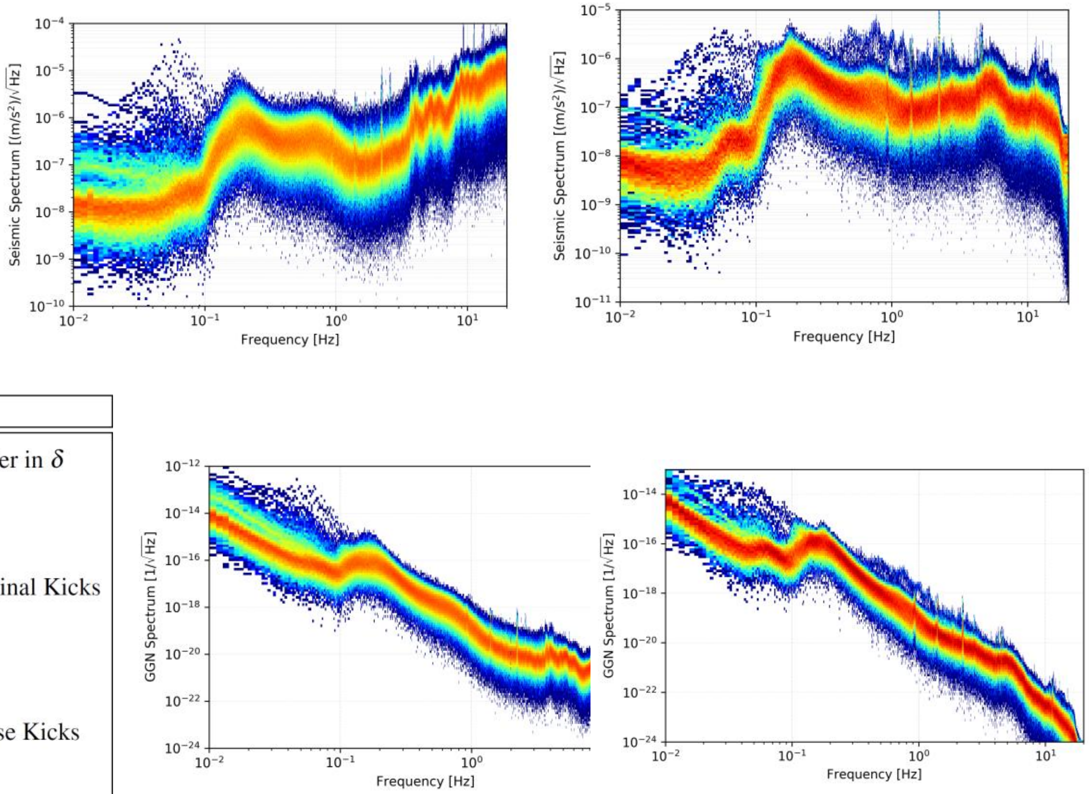
MAGIS-10 omic Gradiom or
and Primord

Laser Wavefront Aberrations



	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	$(0.325\,\mathrm{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\sin\left(k_t^2 H/2k\right)}{0.65}\right)$	
2	$-\frac{k_t^4 n^2\delta^2 T\hbar\cos(k_t x_i)\cos\left(\frac{k_t^2}{2k}H\right)\cos(k_t T v_t+k_t x_i)\cos\left(\frac{gk_t^2T^2}{4k}-\frac{k_t^2 T v_z}{2k}-\frac{k_t^2}{2k}H\right)}{8k^2 m}$	Longitudinal Kicks
2	$(-1.25\times10^{-11}\,\mathrm{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\cos\left(k_t^2 H/2k\right)}{0.7}\right)$	
3	$\frac{k_t^2 n^2\delta^2 T\hbar\sin(k_t x_i)\sin\left(\frac{k_t^2}{2k}H\right)\sin(k_t T v_t+k_t x_i)\sin\left(\frac{gk_t^2T^2}{4k}-\frac{k_t^2 T v_z}{2k}-\frac{k_t^2}{2k}H\right)}{2m}$	Transverse Kicks
3	$(-4.33\times10^{-9}\,\mathrm{rad})\left(\frac{n}{100}\right)\left(\frac{\delta}{0.005}\right)\left(\frac{\sin\left(k_t^2 H/2k\right)}{-0.2}\right)$	

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



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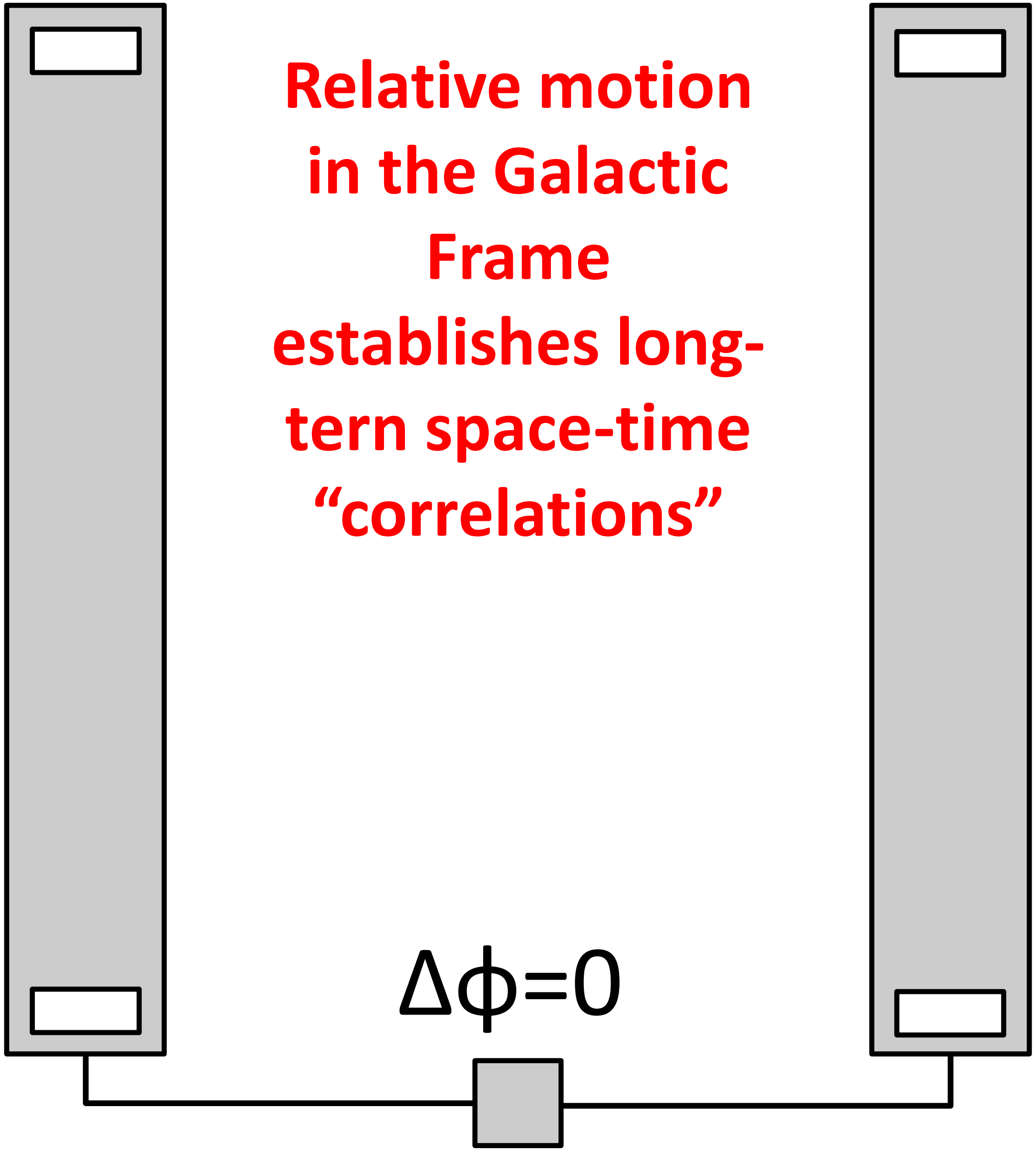
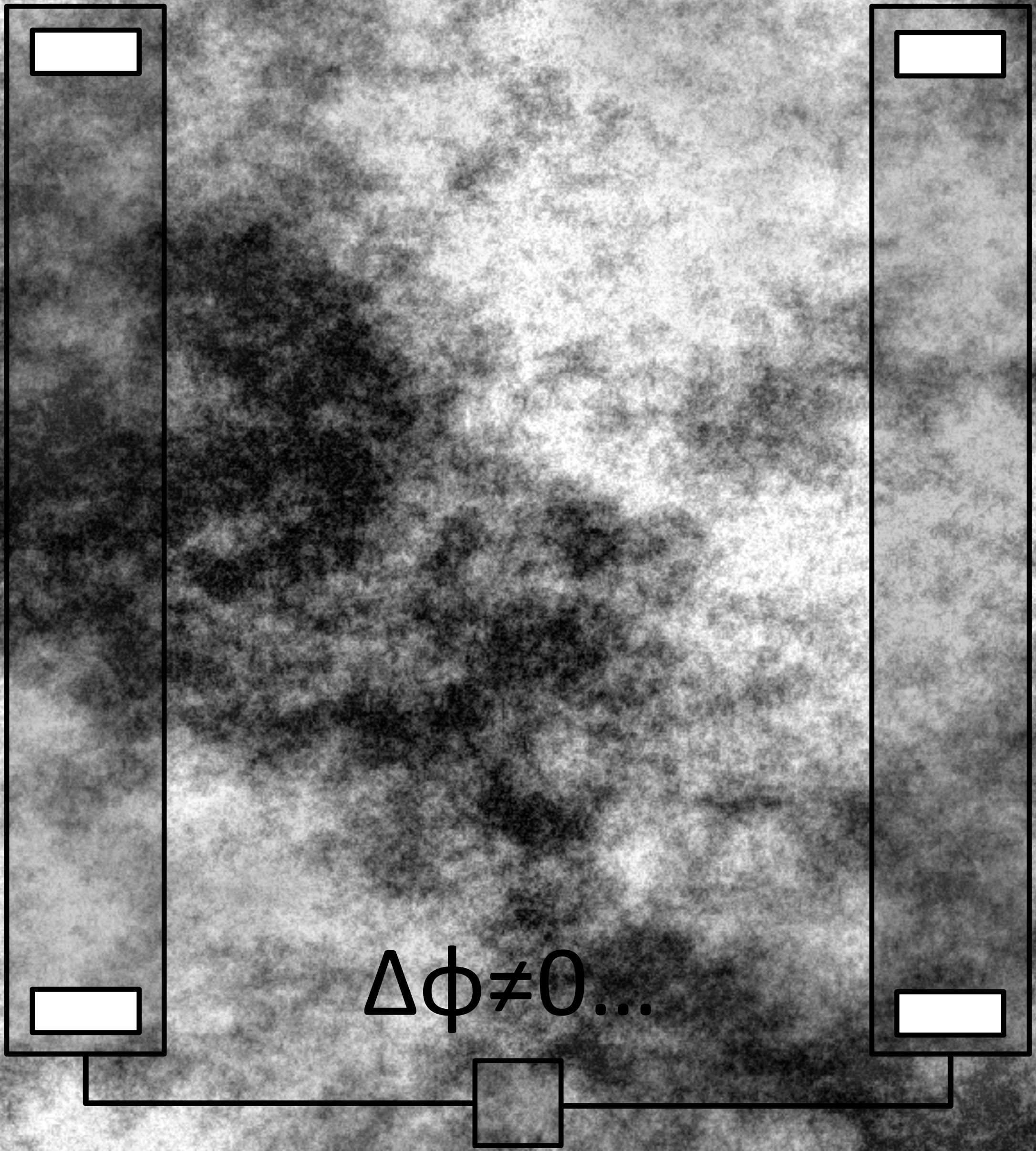
But useful to have two interferometric set-ups to establish correlations of the field



Relative motion in the Galactic Frame establishes long-tern space-time “correlations”

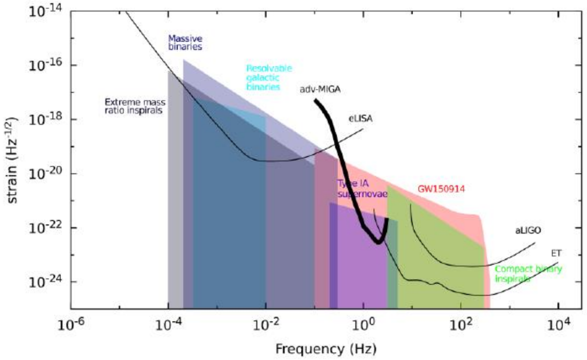
$\Delta\phi=0$



$\Delta\phi \neq 0$…

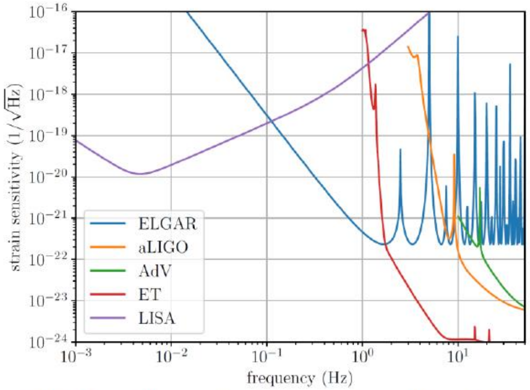
International efforts in atomic sensors for mid-band GW

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)

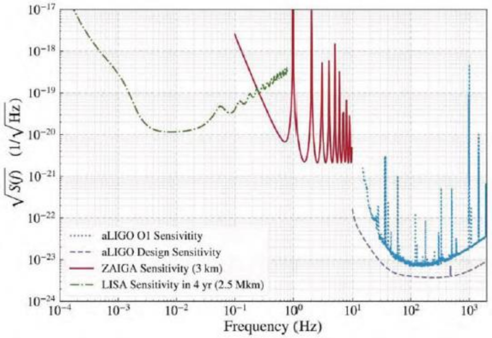


AION: Atom Interferometer Observatory and Network (UK)

ELGAR: European Laboratory for Gravitation and Atom-interferometric Research

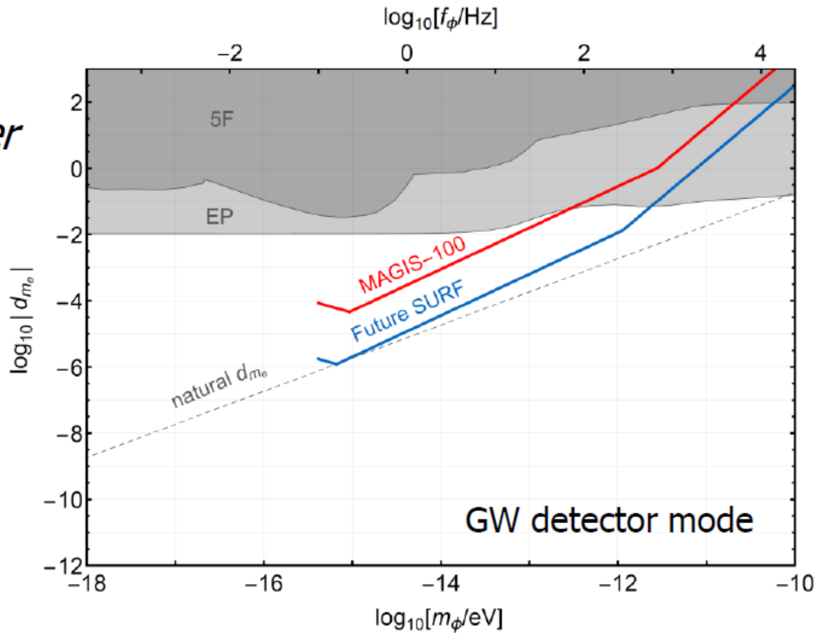


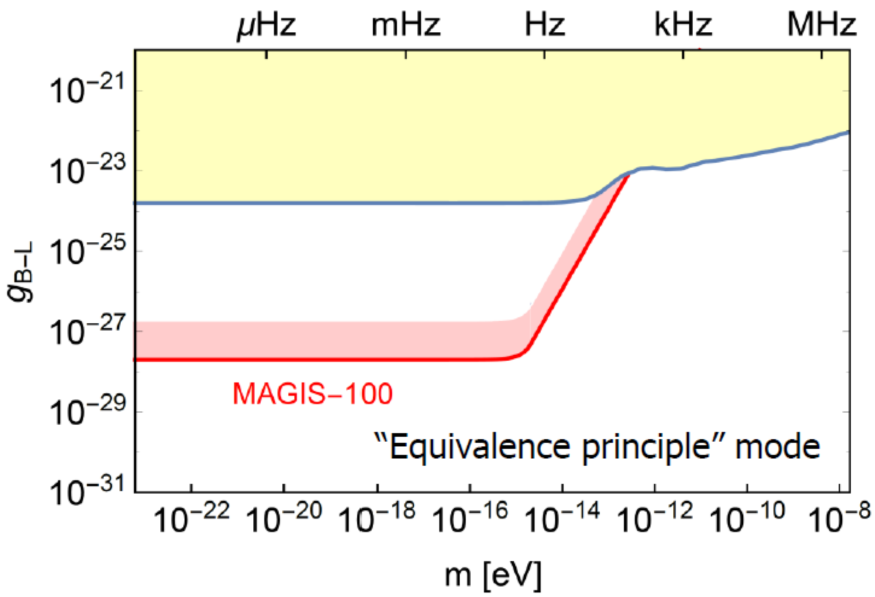
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)



Projected sensitivity to dark matter for MAGIS-100

Sensitivity to ultralight scalar dark matter





Sensitivity to B-L coupled new force (“fifth force” search)

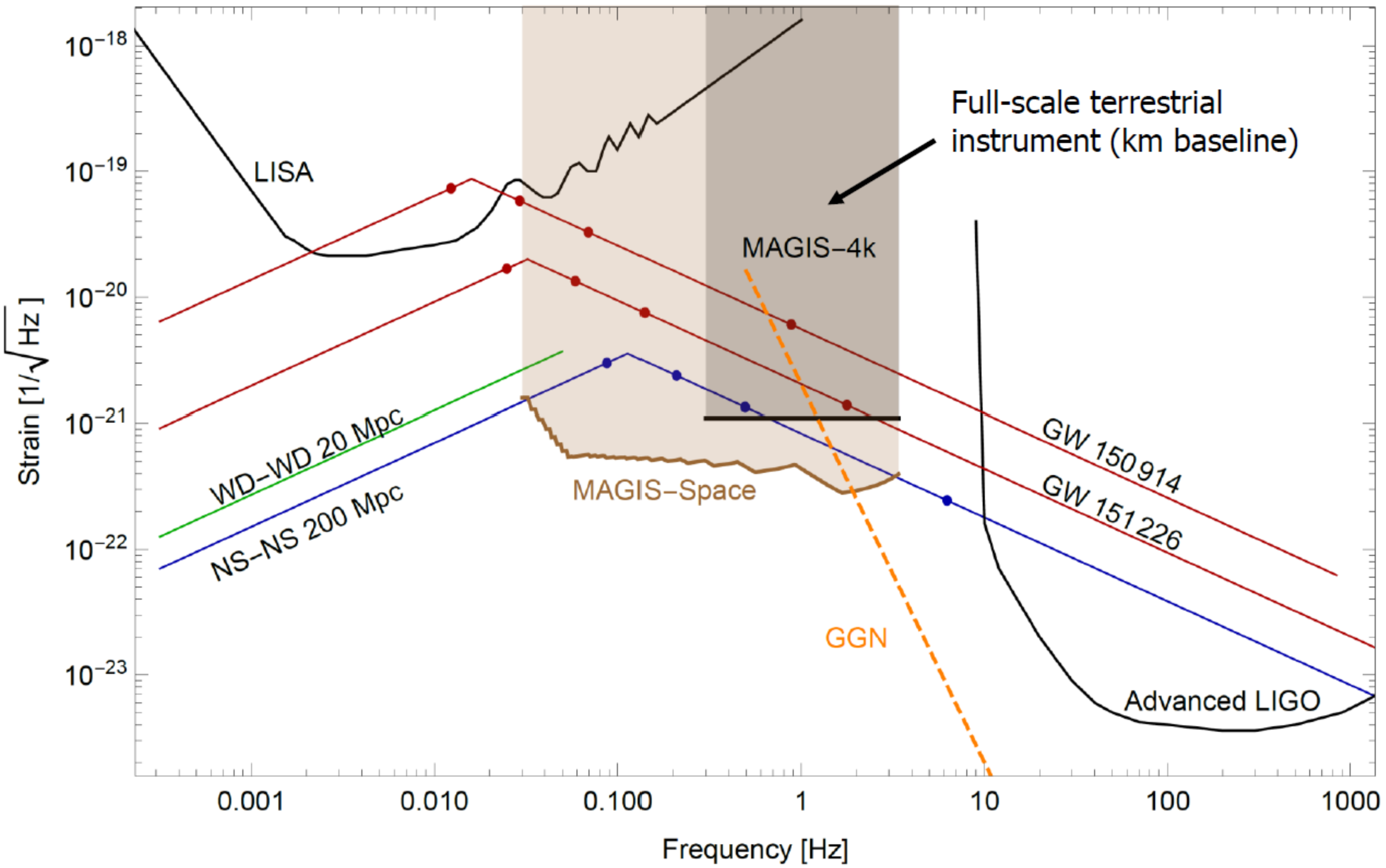
~ 1 year data taking

Assuming shot-noise limited phase resolution

Graham et al. PRD **93**, 075029 (2016).

Arvanitaki et al., PRD **97**, 075020 (2018).

Projected gravitational wave sensitivity



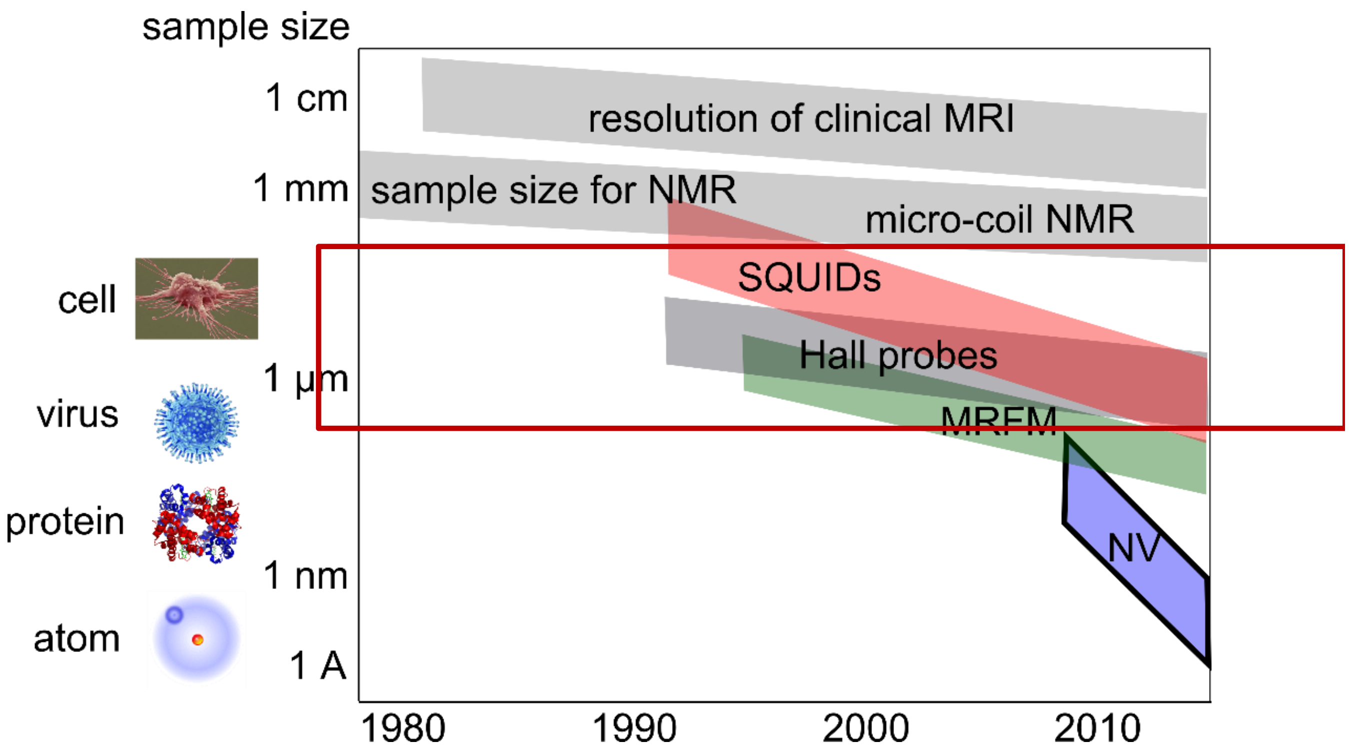
Dots indicate remaining lifetimes of 10 years, 1 year, 0.1 years, and 0.01 years

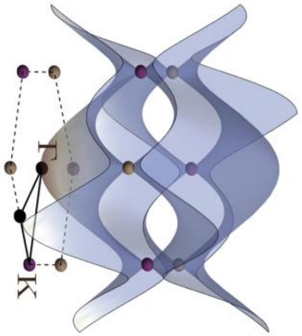
PROMISE of OTHER QUANTUM SENSORS:

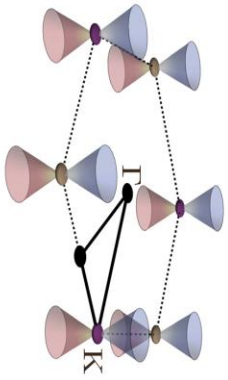
→ Today's state-of-the-art Quantum Cavity Opto-mechanics operate in any part of the EM Spectrum from kilogram to femtogram scale from DC to 10 GHz

→ 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







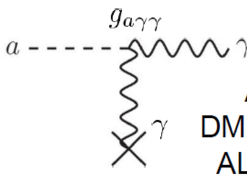
SPIN-BASED SEARCHES for ULTRALIGHT DARK MATTER and AXIONS

axion field amplitude

symmetry breaking scale

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

coupling to photons



ADMX, HAYSTAC, DM radio, ABRA, SHAFT, ALPS, CAST, IAXO, …

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

coupling to gluons

→ creates oscillating nucleon electric dipole moment (EDM)

→ spin to axion coupling:

$$H \propto \vec{d} \cdot \vec{E}_{eff}$$

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

coupling to fermions

→ creates axion "wind"

→ spin to axion "wind" coupling:

$$H \propto \vec{\mu} \cdot \vec{B}_{eff}$$

a figure of merit →

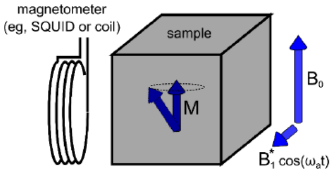
$$\xi = xp\sqrt{N\tau}$$

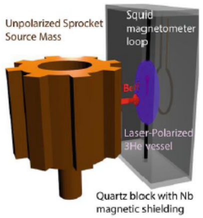
polarization

coherence time

number of spins

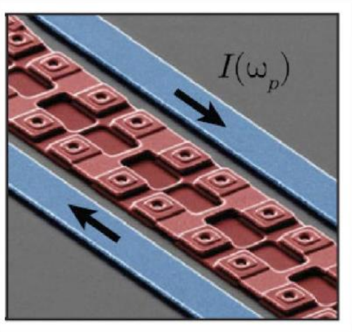
- CASPEr collaboration: g_d, g_{an} [D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)] [A. Garcon et al., *Science Adv.* **5**, eaax4539 (2019)]
- QUAX collaboration: g_{ae} [N. Crescini et al., *Phys. Rev. Lett.* **124**, 171801 (2020)]
- ARIADNE collaboration: g_{an} [A. Arvanitaki and A. Geraci, *Phys. Rev. Lett.* **113**, 161801 (2014)]

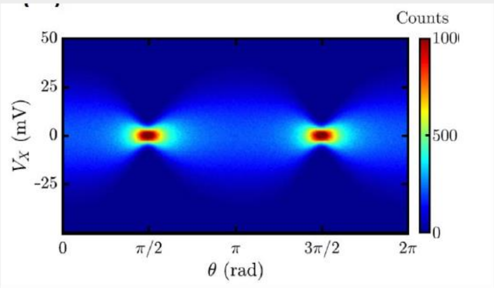


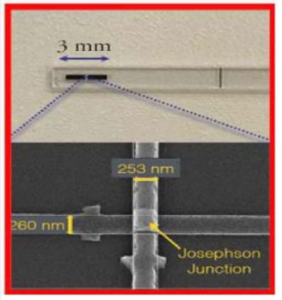


ENABLING TECHNOLOGIES → QUANTUM COMPUTERS and NETWORKS

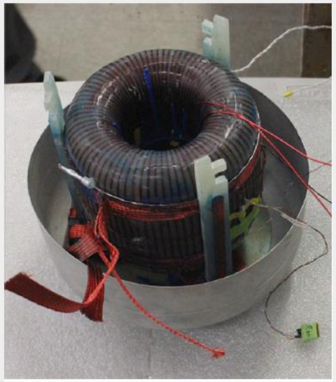
Superconducting sensors, quantum ensembles, low-threshold quantum calorimeters, high-Q cavities, magnets, cryogenics, electronics, computing,….



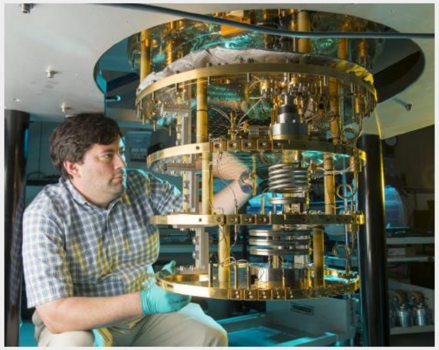




High-Q cavities



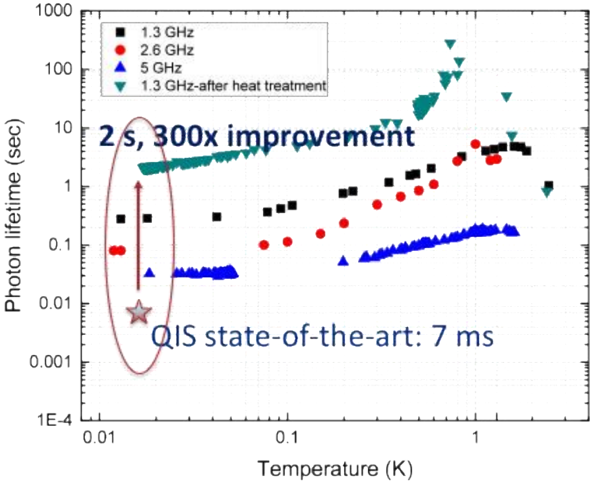
Magnets



Cryogenics

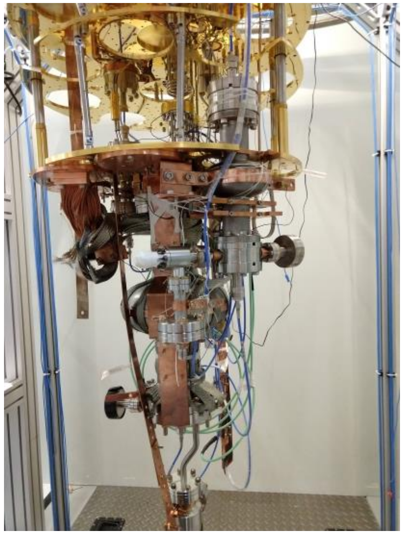
Superconducting cavity-Squid system as prototype 50 Qubit Quantum Computer [DOE/QI]

Accelerator cavities adapted for quantum regime



2 s, 300x improvement

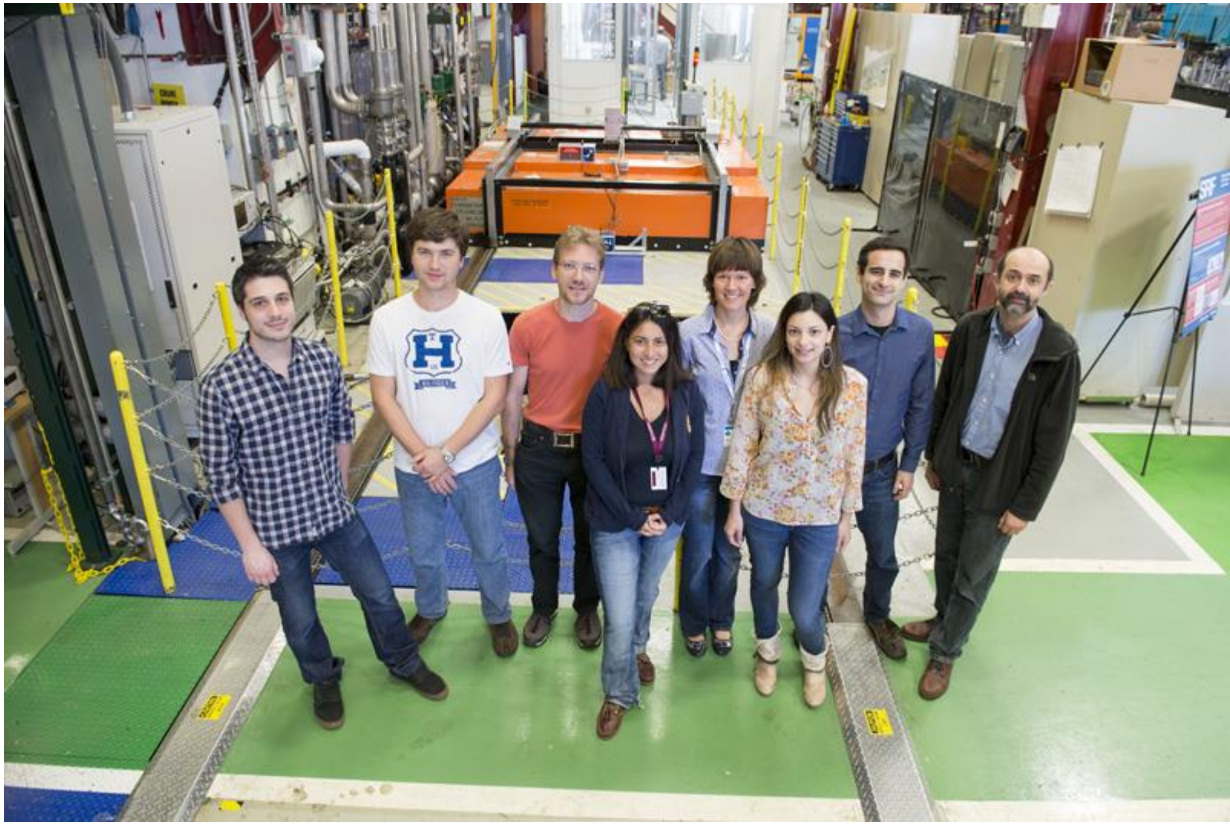
QIS state-of-the-art: 7 ms



WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

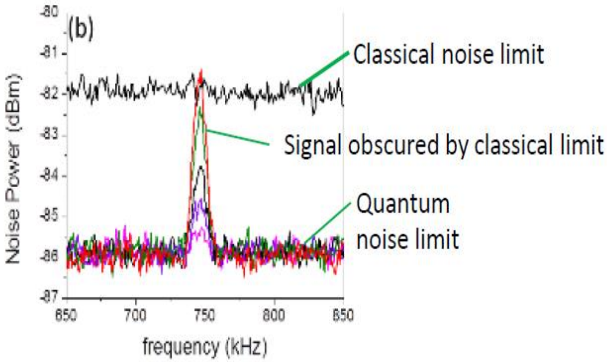
NIST

Existing collaboration with Northwestern in SRF science

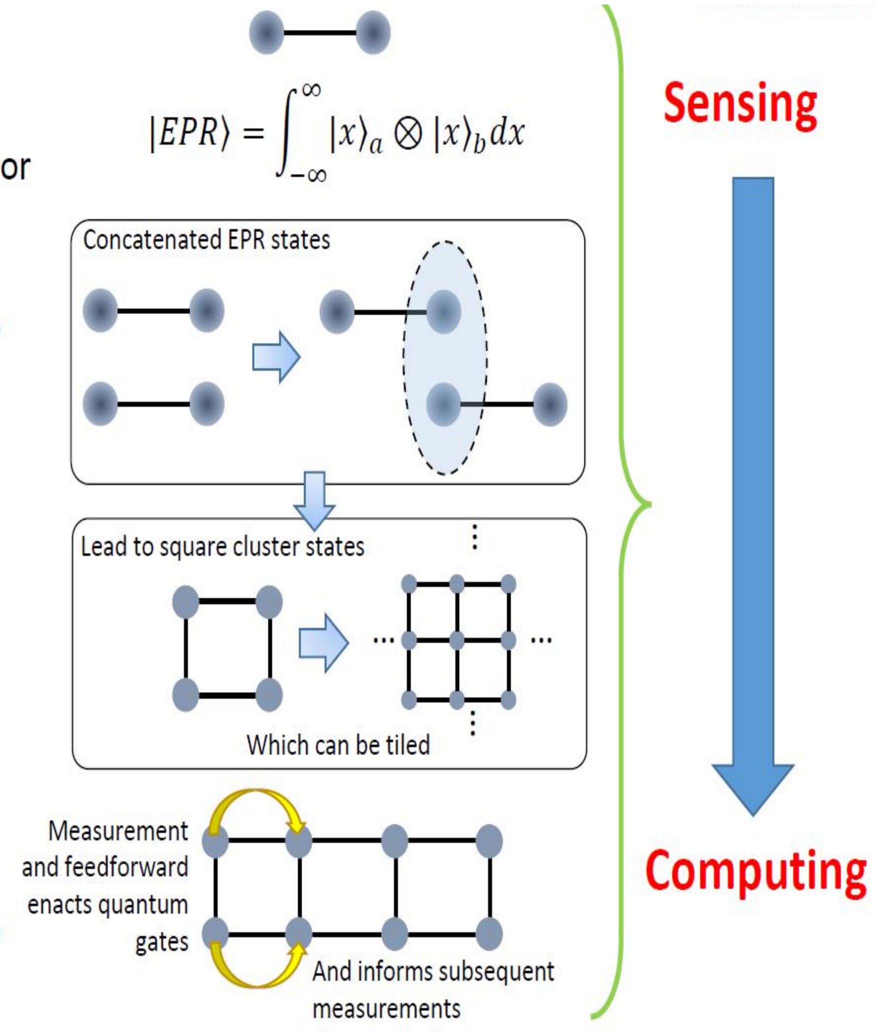


EXAMPLE: Quantum sensing → quantum teleportation → quantum computing across quantum networks

- 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*



$$|EPR\rangle = \int_{-\infty}^{\infty} |x\rangle_a \otimes |x\rangle_b dx$$

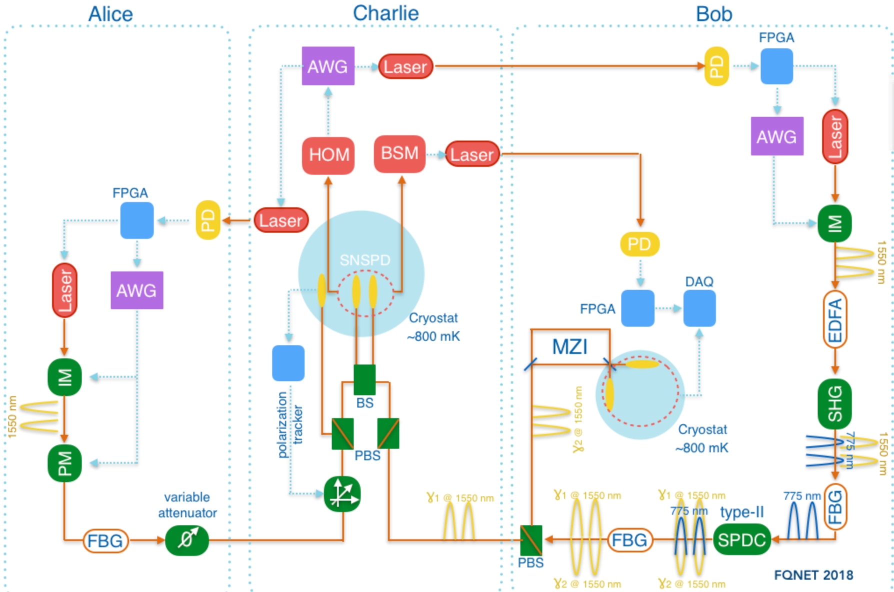
Fermilab quantum teleportation experiment (FQNET)

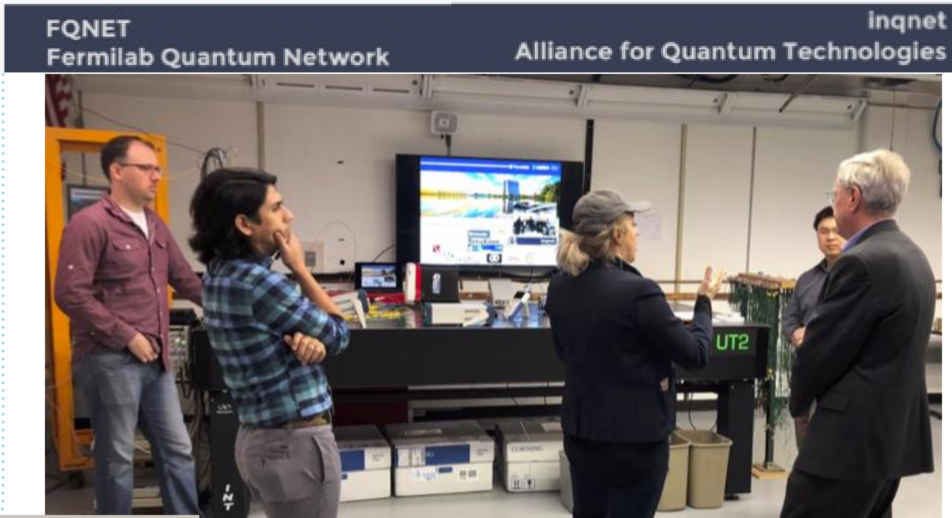
- *Time-binned optical photonic qubits over commercial telecom fiber*
- *Build and commissioned over the past 15 months and has achieved quantum teleportation*
- *Working on optimizing teleportation fidelity, stability & overall efficiency*
- *Next step to distribute quantum info between nodes across Fermilab*

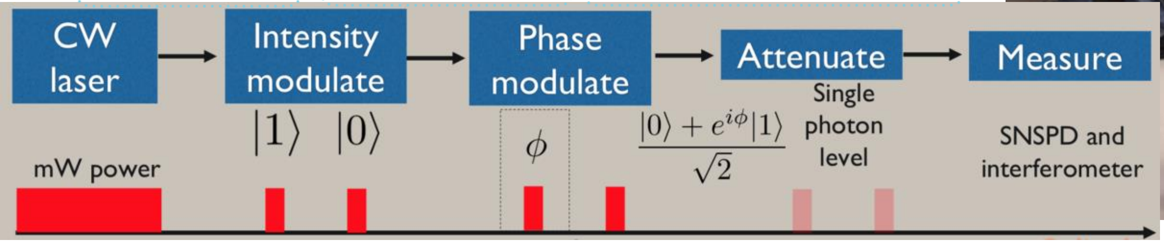
Caltech

JPL

AT&T







CW laser → Intensity modulate → Phase modulate → Attenuate → Measure

mW power

$|1\rangle \quad |0\rangle$

ϕ

$$\frac{|0\rangle + e^{i\phi}|1\rangle}{\sqrt{2}}$$

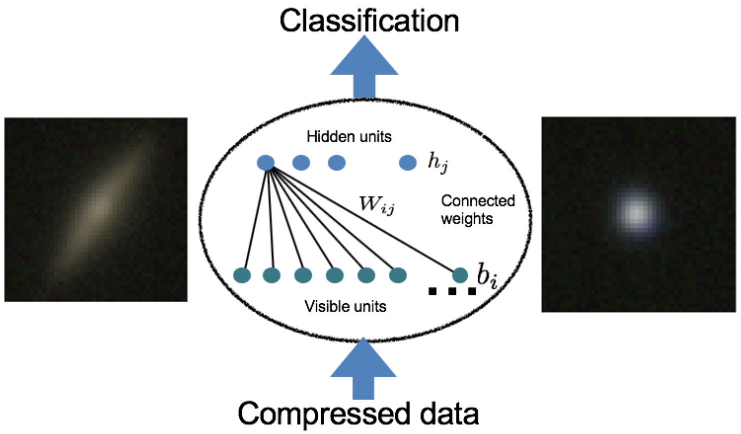
Single photon level

SNSPD and interferometer

Optimization and ML applications

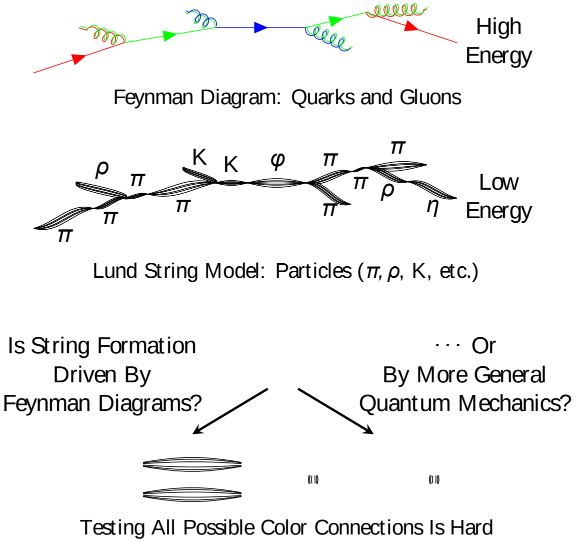
Partnering with Lockheed Martin and ORNL on Machine Learning problems in astrophysics:

- *Several projects targeting a D-Wave annealer: star/galaxy separation, anomaly detection, and autoencoders (for compression or simulation).*



Partnering with ORNL on optimization problems for LHC physics:

- *Employ a quantum annealer to estimate systematics due to Color Recombination models*
  - *Formulate as a binary constraint satisfaction problem*
- *Compare results with best-known classical solutions*
  - *Evaluate impact on current measurements*

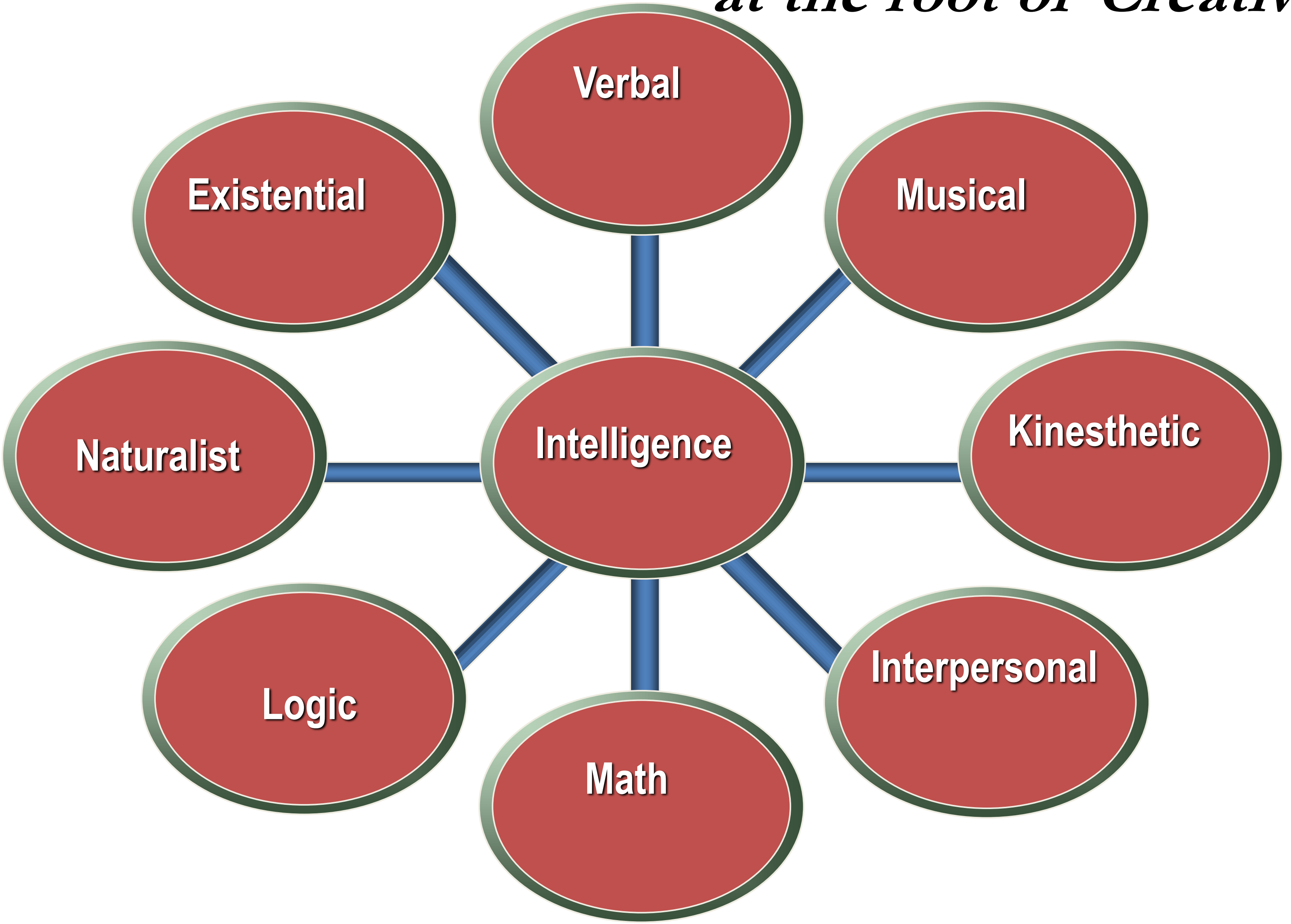


Neuroscience:

Functional Brain Mapping with Weak Magnetic Fields

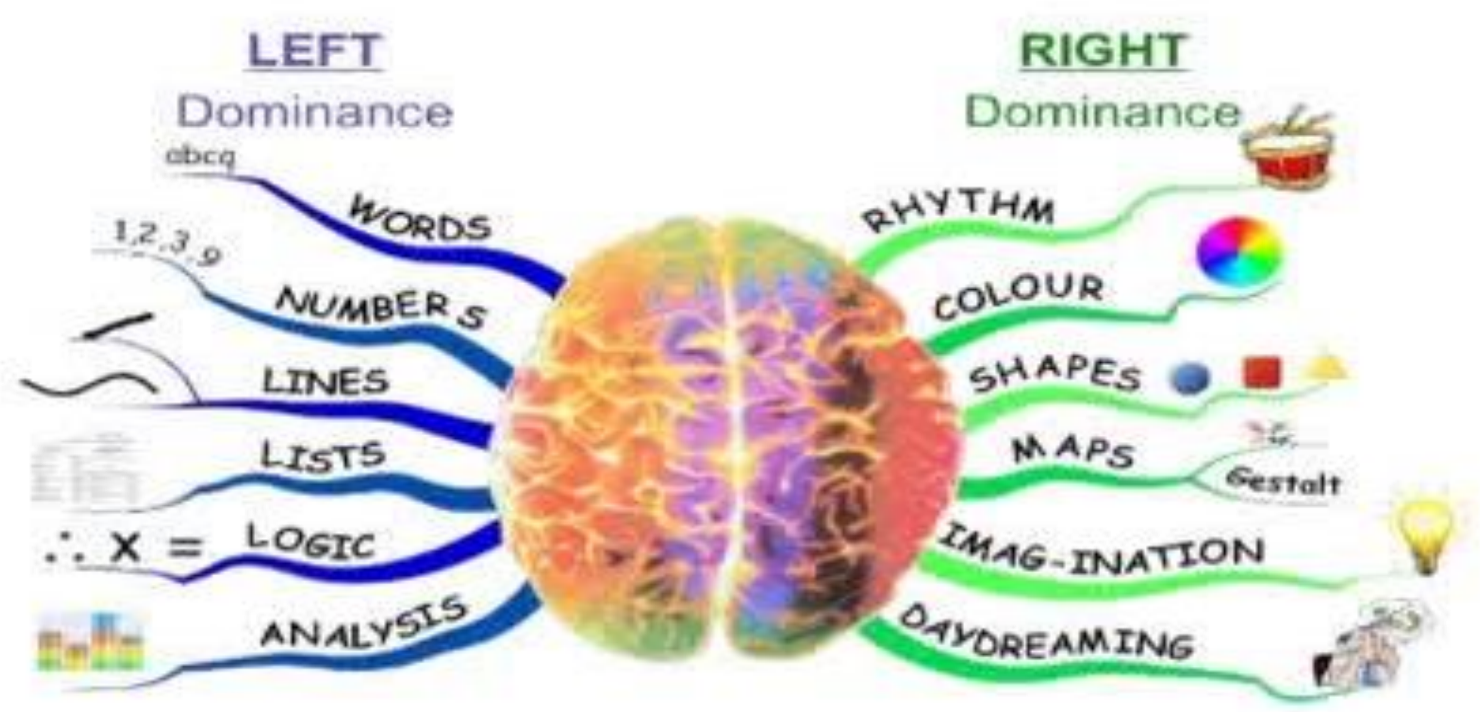
Magneto-Encephalography

Neuroscience: *Gardner's Multiple Intelligences at the root of Creativity*



Understanding Creativity requires
BRAIN MAPPING:
Creativity localization

T. Buzan "The Mind Map Book", 1995.



BRAIN MAPPING/BIOLOGICAL EXCITATIONS:

1. Physical mapping of the brain:

Physical Mapping the entire network of Neurons, Axons, and connections in the cerebral cortex is done through coherent x-ray imaging of brain slices via synchrotron radiation

2. Functional Mapping of the brain:

Mapping the extremely weak electromagnetic activity across the volume and cross-correlating is done via magneto encephalography requiring measuring extremely weak and fluctuating magnetic fields around the cortex

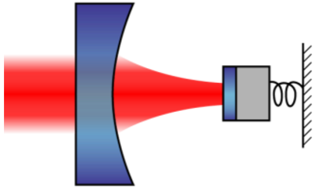
3. Low-energy Biological excitations

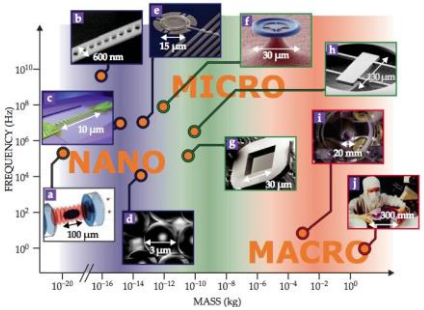
THz mm-wave yeast-cell excitations (Grundler and Keilmann et al at Max Planck Institute in Stuttgart, Germany → non-thermal biological effects PRL Voi. 51. No. 13, 26 September 1983, pp1214-1216 (pointed out by Fritz Caspers, CERN)

PROSPECTS:

TREMENDOUS POTENTIAL of QUANTUM SENSORS for COSMIC ARCHAEOLOGY

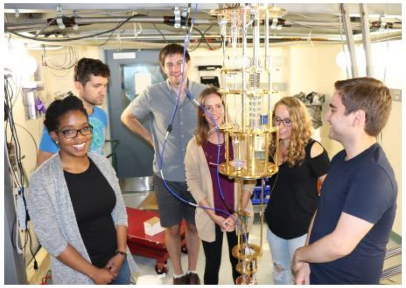
Detector development and particle physics community will benefit from further research investments into the areas of quantum-entangled materials, cavity-qubit entangled electronics, optically entangled atoms etc. to advance the precision detection of exotic particles and fields.

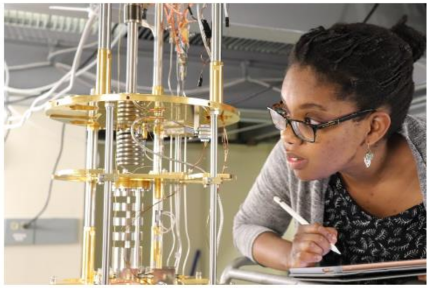


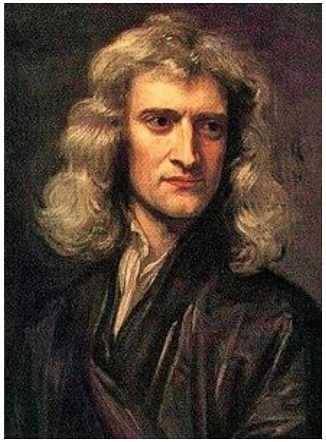


TRAINING THE QUANTUM WORKFORCE!!

Critical for the **EDUCATION, TRAINING, ENGAGEMENT** of the **NEXT GENERATION** in the **TWENTY-FIRST CENTURY ENLIGHTENMENT!**







Thank You!
For your
Attention!!!!!!!!