Quantum sensors

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Outline

- ➢ What is a quantum sensor?
- ➢ Quantum sensors in the two infinities field
- ❖ Superconducting sensors for Dark Matter
- ❖ Squeezed states for gravitational waves
- ❖ Low-dimensional materials, quantum dots for calorimetry
- ➢ Conclusion

References:

S. Haroche
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Quantum sensors

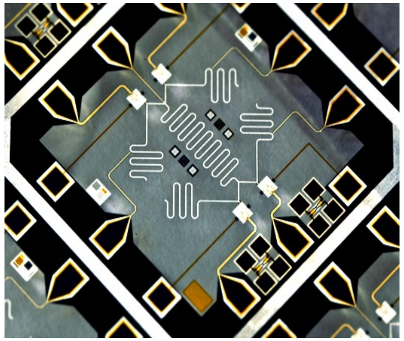
Almost one century after the birth of Quantum Mechanics, a second revolution (the second one) has started with the the so-called Quantum Technology.
Quantum Technology is a technology that uses the principles of superposition, entanglement and oscillation in quantum mechanics as well as other quantum phenomena such Bose-Einstein condensation and superconductivity in the field of computing (qubits), cryptography (Bell states) and detection (quantum sensors)

- **Quantum cryptography**
  - This is a well advanced field. It is used in secure communication (QKD) and data protection (defence, finances, health…)
  - Production and using 2-photon EPRs travelling tens of Km (cables) and hundreds of Km (satellite) is in place since a few years.

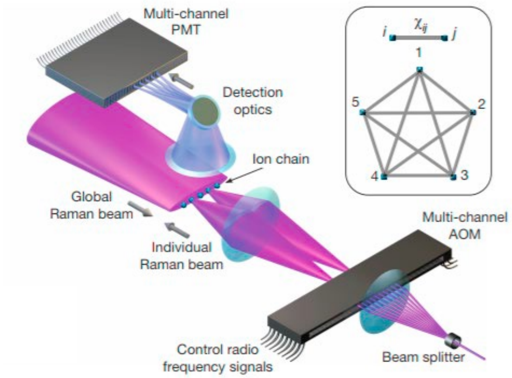
- **Quantum computing**
  - Very challenging fields. It deals with producing qubits (superposition of two quantum states), intricating and manipulating them through logic gates with quantum-based codes (shor, Steane, Gross,…)
  - Decoherence and errors are the main challenges.
  - Big companies like IBM, Google, Intel, Microsoft, D-Wave and Rigetti are dedicating huge budgets for
  - As an example IBM: 127-qubit Eagle, 433-qubit Osprey and 1121-qubit Condor

Qubits

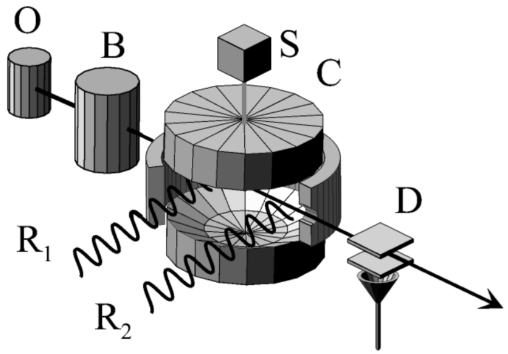
The most developed:



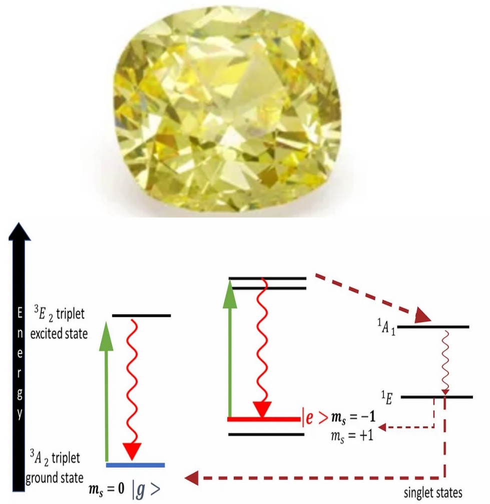
Superconducting circuit



Trapped ions



cQED



N.V.

Each of them has its own advantages and drawbacks

-Decoherence time (tens of μs to a few seconds)

-Operation conditions like temperature : few mK° to room temperature

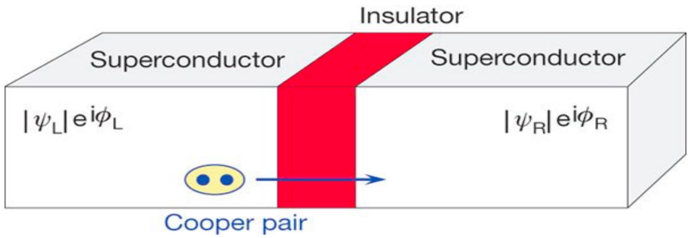
-Sensitivity to the environment and radiation

Quantum Sensors

- Most of the quantum sensors are benefiting from the development conducted on qubits, namely the superconducting circuits
- They are commonly used to detect tiny EM fields (SQUID can detect down to $2\ 10^{-11}$ Tesla (Earth magnetic field is 10^{-5} Tesla)→
  - Medical application (brain imaging-magnetoencephalography)
  - Geological survey (oil, gas, ..)
  - Military (submarine detection…)
- They are so sensitive that stringent noise reduction and calibration are unavoidable in many cases
- In particular and astroparticle physics two kinds of sensors/ quantum techniques are used

  - Superconducting circuits: KIDS, TES, SQUIDS are devices that are operated at very low temperature and using superconducting materials. They are essentially used to detect Electromagnetic Radiation (Microwave waves and X rays) and Dark Matter (DM)
  - Squeezed states: optical tools exploiting the possibility of preparing photons in a quantum states for which the quantum uncertainty of one of the measured variables (one quadrature) can be lower the so-called Standard Quantum Noise Limit leading to a significant S/N improvement
  - Low-dimensional materials: 0,1 and 2 D nanostructured materials. For instance 0D (quantum dots) have quantized energy spectrum like atoms. Their energy levels can be tailored allowing their use in many detection application like calorimetry for energy and PID measurement

Superconducting sensors



Josephson junction is the basic element of these sensors

At $T<T_C$ electrons (of opposite spin orientations) form pairs whose potential energy is in the range 10^{-4} -10^{-5} eV

These electrons can be described by a coherent wave function $\psi = |\psi| \exp(i\,\delta)$

The Cooper pairs represent about 10^{-4} of the electrons population.

Their number (**n**i) and their phase (δ_i) In a superconductor metal are the most important parameters in addition to the $\mathbf{T_C}$

A current **I** flows between the two metals $\mathbf{I = I_0 \sin(\delta)}$ **(DC Josephson law)** with δ is the difference of the two phases

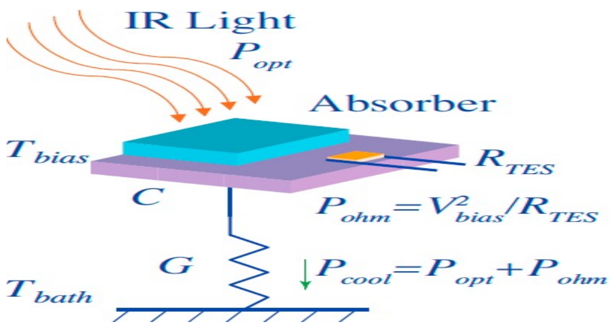
Josephson Junction in an open circuit could be assimilated to a LC circuit with a capacitor **C** and a no-linear inductance **L**

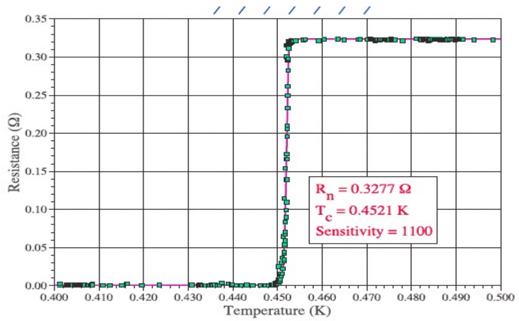
Superconducting sensors

Transition Edge Sensor (TES)

If the temperature of the JJ increases beyond T_C the Cooper pairs start to be broken and the transition from superconductor to normal states occurs leading to a sudden increase of the resistance of the Junction.

By circulating in a superconductor film a current I slightly smaller than the critical current into the junction, the Junction can detect very small increases of temperature due to the energy by photons or phonons.

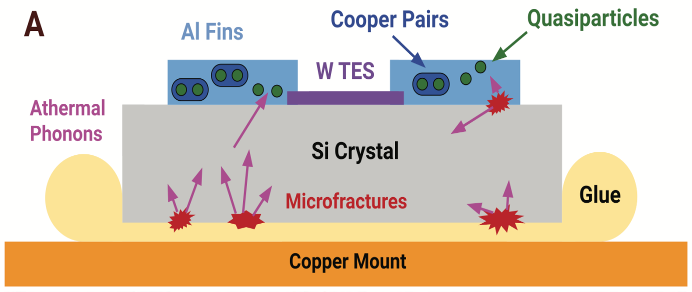


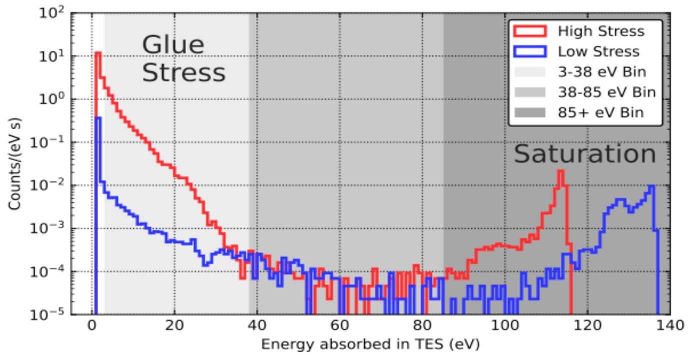


The increase of the resistance and thus the tension signal is proportional to the energy deposit.
Multiplexed readout is well adapted to read out a large number of TES
The sensitivity of a TES is improved by reducing its capacitance and T→ $\sigma^2 = C\, K_\beta T^2$ (calo)
→ Operating TES at tens of mK° is a target.

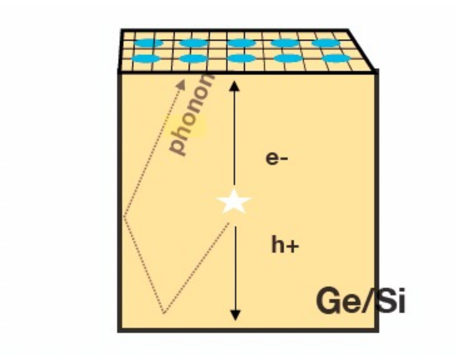
- An important aspect of the TES is the efficient recovery of all the phonons produced in the absorber. But phonons due to stress can be produced during a long period of time adding to uncontrolled noise

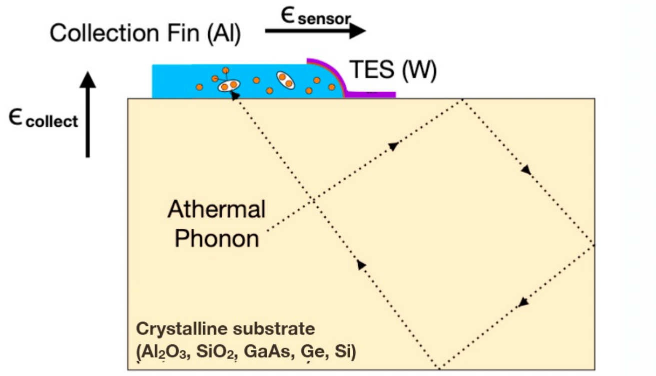
- TES should be protected against radiation and also cosmics that can break too many Cooper pairs

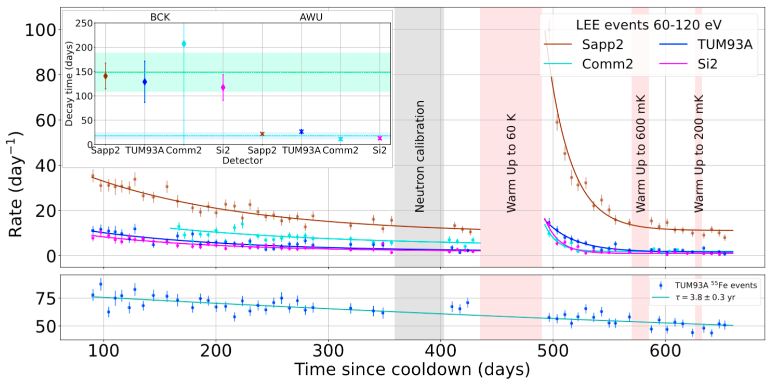




TESSERACT project @LSM will use the TES technology with Ge bolometer to extend the mass range of DM to meV to GeV facing the same challenges (LEE). TES is already used with success at **APC (QUBIC)**







AC Josephson law

If the circuit including a JJ is open the passage of Cooper pairs from one side to the other create a capacitive tension V that modifies the relative phase:

$d\delta/dt = (2e/\hbar)\ V$

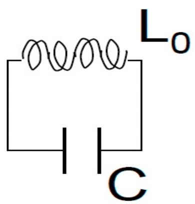
$V=2e(n-n_0)/C$ where $n-n_0=P$ is the number of excess of Cooper pairs on the two sides of the the insulator.

The two Josephson laws provide the dynamics of Cooper movement in the Junction. This could be represented by a Hamiltonian

$$H_J = \frac{2e^2p^2}{C} - \frac{\hbar I_0}{2e}\cos\delta = E_C p^2 - E_J \cos\delta$$

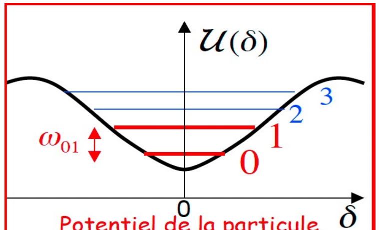
The first term is the contribution of the capacitive energy and the second one could be assimilated to an inductance one (anharmonic) leading to well defined eigen states with different ω_{ij} for different (I,j)

At first approximation the JJ is assimilated to a resonator LC.



$$\omega = \frac{1}{\sqrt{L_0 C}}$$

The frequency of JJ is of the order of few GHz

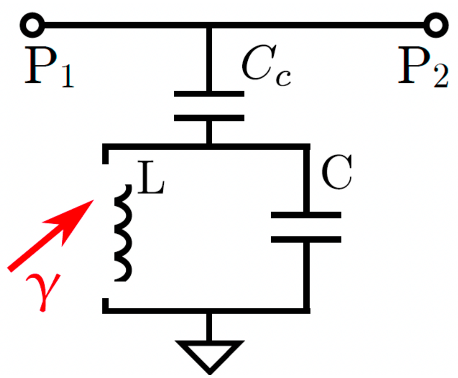


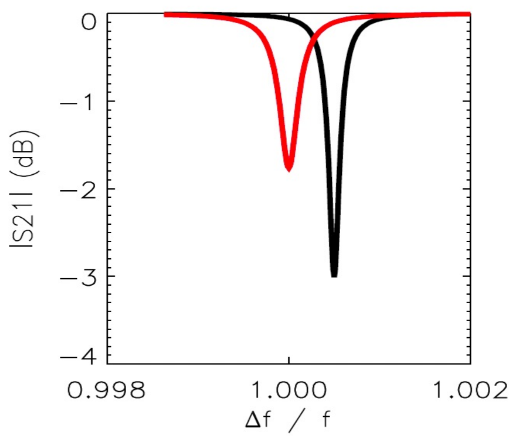
Potentiel de la particule effective représentant la JJ en circuit ouvert avec ses niveaux d'énergie. Les deux plus bas définissent un qubit

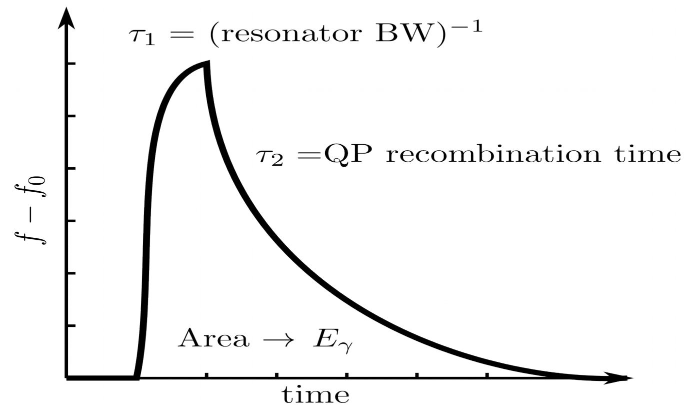
Superconducting sensors

Kinematic Inductance Detector (KID)

The inductance of the JJ inversely depends on the number of Copper pairs.
When the JJ absorbs a photon, some Cooper pairs are broken increasing the inductance of the junction and therefore reducing the frequency f of the LC circuit
This reduction of frequency can be detected by coupling the JJ with a resonator usually made of 1/2 or 1/4 wavelength antenna coupled line.







- KID are not fast as TES
- It is hard to achieve resonator frequency lower than 1 GHz
- To obtain good resolution the resonator quality (Q) should be very high. However,2-D resonator could not exceed 10^5 with the available technologies. **This technology was successfully used by LSPC and IP2I and APC**

Superconducting sensors

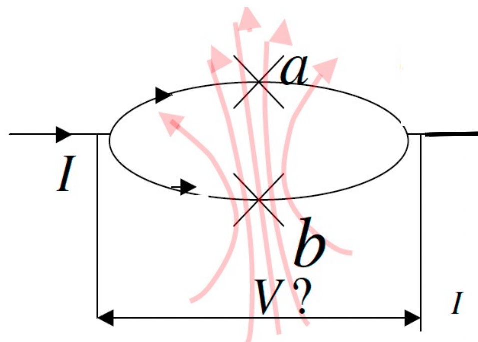
SQUID

When a magnetic field is applied to a Josephson Junction the Aharonov-Bohm effect is respected leading to the fact that the flux is quantified $\frac{2e}{\hbar}\oint \vec{A}.d\vec{l} = 2\pi\frac{\Phi}{\Phi_0} = \delta$ Φ_0 = h/(2e) is the quantum flux.

As a consequence when a magnetic field is applied on a JJ an additional current is produced so the total flux crossing the junction respects the previous equation. The appearance of such a current allows to detect tiny magnetic field since Φ_0 is very small.

To better exploit this propriety Superconductor QUantum Interference Device (SQUID) was proposed.

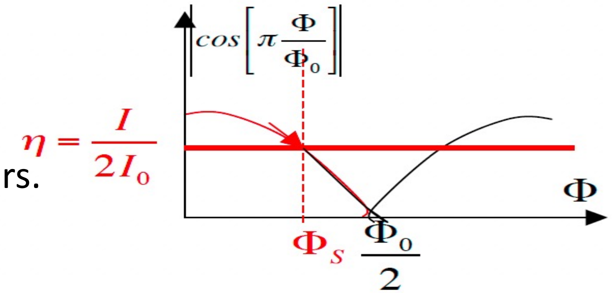
SQUID is a loop made of 2 superconductors



$$\delta_a - \delta_b + 2\pi\frac{\Phi}{\Phi_0} = 0 \qquad \delta_a + \delta_b = \delta_0$$

$$I = I_a + I_b = I_0 \sin\left(\delta_0 + \pi\frac{\Phi}{\Phi_0}\right) + I_0 \sin\left(\delta_0 - \pi\frac{\Phi}{\Phi_0}\right) = 2I_0 \sin\delta_0 \cos\pi\frac{\Phi}{\Phi_0}$$

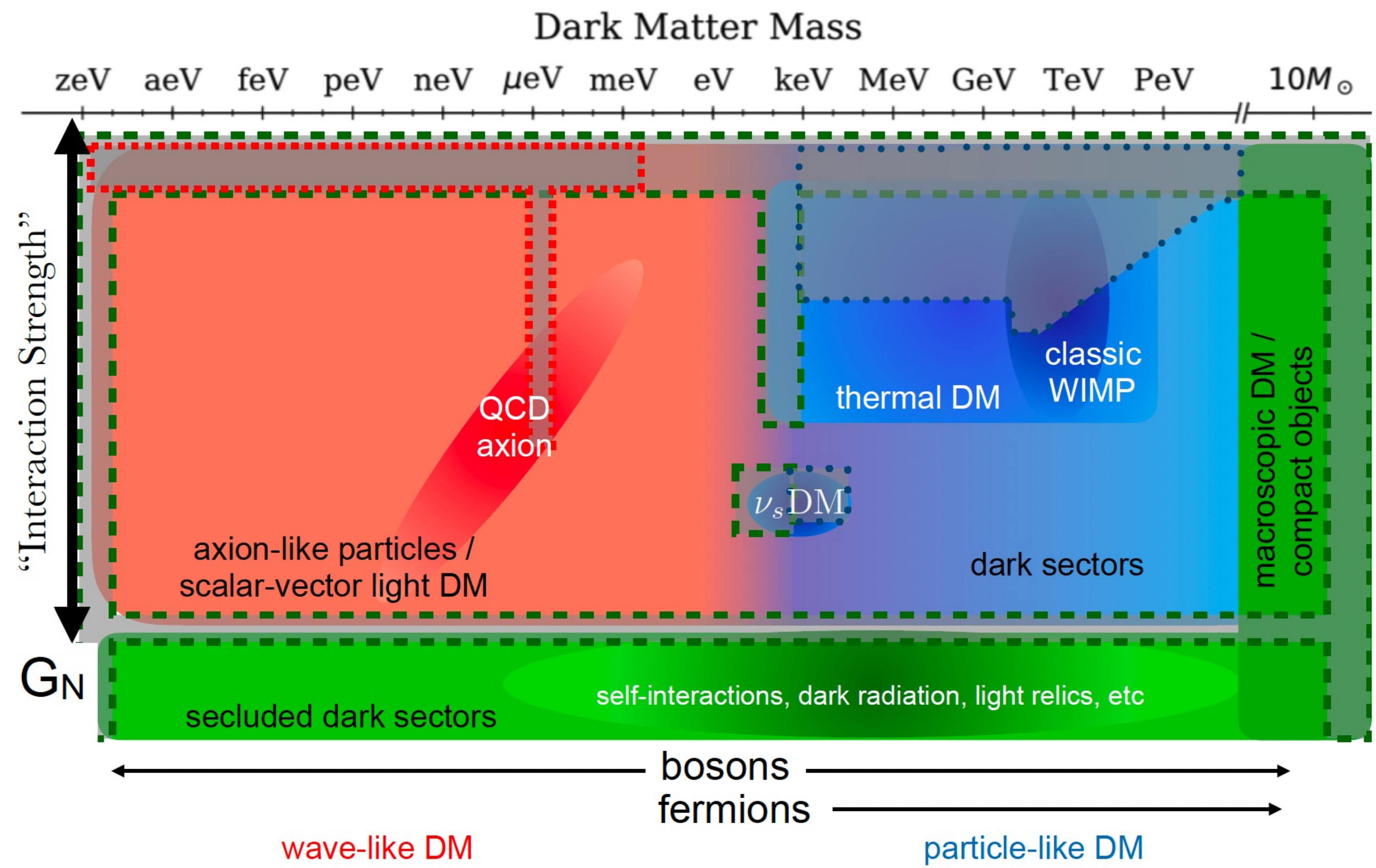
By fixing I =2η I_0 with η<1, we define $\Phi_S = \frac{\Phi_0}{\pi} Arc\cos\eta$



we can see that when the flux exceeds a certain value Φ_s

The SQUID transits from the superconducting to the normal state and a tension appears.

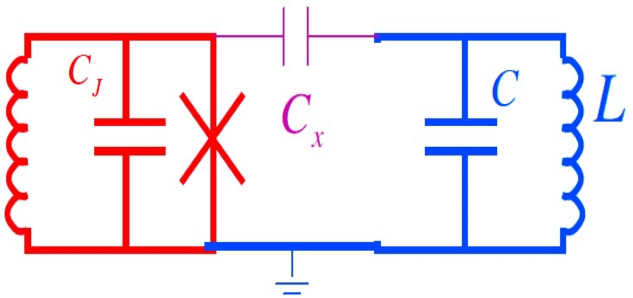
SQUIDs are often use with TES and KID as an amplifier of signals

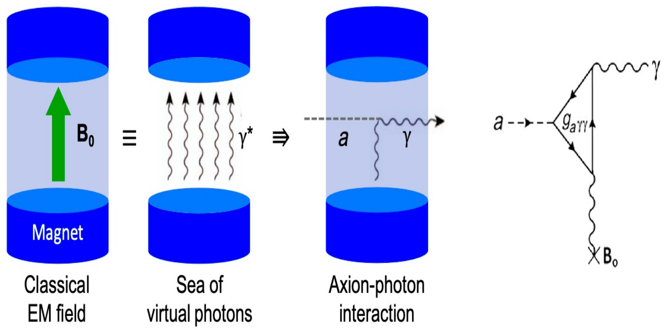


Dark Matter Mass
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 10M⊙
"Interaction Strength"
QCD axion
axion-like particles / scalar-vector light DM
νsDM
thermal DM
classic WIMP
dark sectors
macroscopic DM / compact objects
GN
secluded dark sectors
self-interactions, dark radiation, light relics, etc
bosons
fermions
wave-like DM
particle-like DM

cQED&Superconducting sensors

APL are hard to detect using superconducting sensors directly due to their very small mass
They can however be revealed by their interaction with a magnetic field resulting in the production of photons in a well tuned cavity. The production of a photon



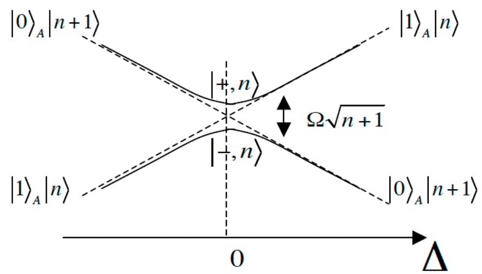


The interaction between the quantum sensor and the cQED is well known and is similar to the interaction of Rydberg atoms in the EM cavity developed by S. Haroche. This interaction is well approximated by the interaction part of the Hamiltonian of Jaynes-Cummings used in QED

$$H'_{\text{int}} \approx -\frac{C_X\,\hbar\omega_{LC}}{2\sqrt{CC_J}}\left(\sigma_+ a + \sigma_- a^\dagger\right) = -\frac{\hbar\Omega}{2}\left(\sigma_+ a + \sigma_- a^\dagger\right)$$

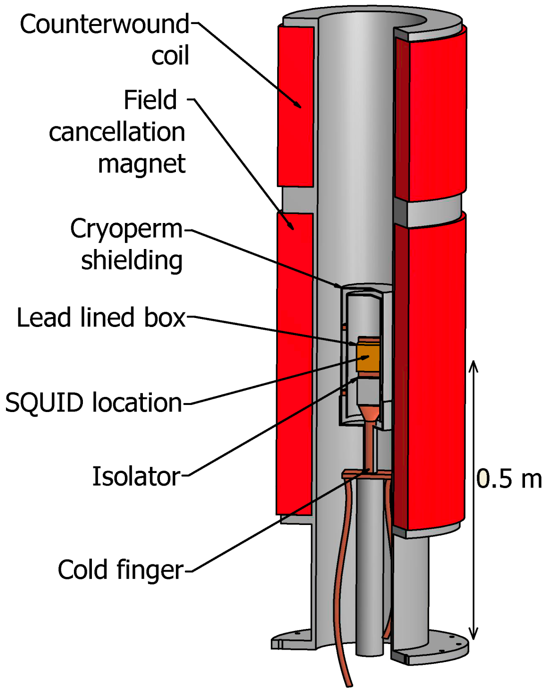
With the solutions at resonance :

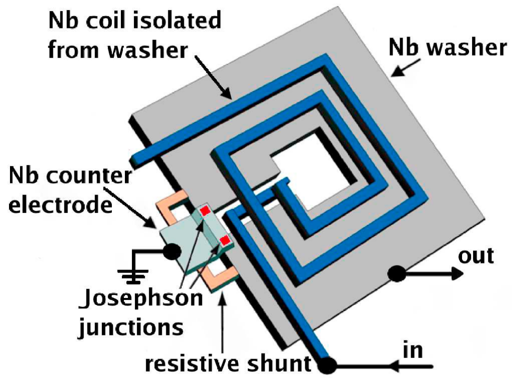
$$|\pm,n\rangle = \frac{1}{\sqrt{2}}\left[|1\rangle_A |n\rangle \pm |0\rangle_A |n+1\rangle\right] \qquad E_{\pm,n} = \left(n+\frac{1}{2}\right)\hbar\omega \pm \frac{\hbar\Omega\sqrt{n+1}}{2}$$



Changing C_X allows scan frequency

When a photon is produced in the cavity, the state of the superconductor circuit is impacted and the change is detected . Squids are used here as an amplifiers.





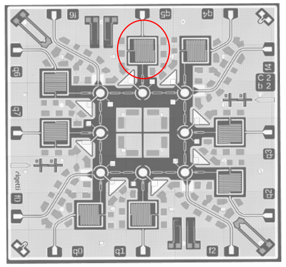
ADMX

cQED&Superconducting sensors

- The lower the temperature of the superconducting circuit the lower the noise
- The higher the Q value the longer one maintain the cavity in the desired conditions

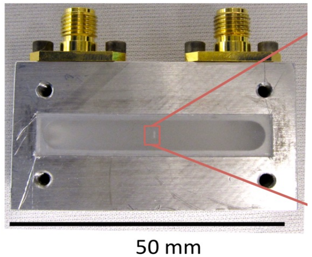
2D

3D



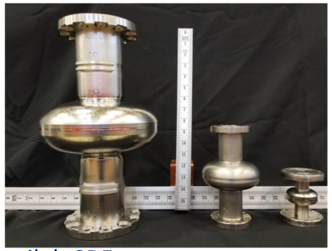
Rigetti 8-qubit processor

$Q \sim 10^5$
$T_{coherence} \sim 1$ us



3D transmon

$Q \sim 10^8$
$T_{coherence} \sim 1$ ms



Fermilab SRF resonators

$Q > 10^{10}$
$T_{coherence} > 1$ s

SRF cavities developed for high energy could play a important role.
Minimized 3D RF cavities are being developed. **The excellent expertise in IN2P3 (IJCLAB)** could be a big asset for our future experiments

Squeezed states

Vacuum, coherent and squeezed states

The electric field in a cavity of volume V can be expressed in second quantification as

$$\hat{E}(t) = \frac{E_0}{2}\left(\hat{a}e^{-i\omega t} + \hat{a}^{\dagger}e^{i\omega t}\right) \qquad E_0 = \sqrt{\hbar\omega/V}.$$

â, $â^{\dagger}$ are the annihilation and creation operators of a photon and satisfy the boson commutation relation $[â,â^{\dagger}]=1$. They can be replaced by two other operators X, Y tells que:

$$\hat{E}(t) = E_0\left(\hat{X}\cos\omega t + \hat{Y}\sin\omega t\right)$$

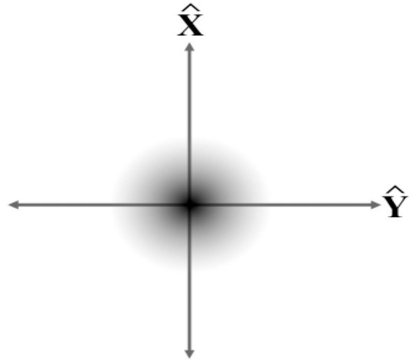
$$\hat{X} = (\hat{a}^{\dagger} + \hat{a}) \qquad \hat{Y} = (\hat{a} - \hat{a}^{\dagger})/i \qquad [\hat{X},\hat{Y}] = 2i. \qquad \langle(\Delta\hat{X})^2\rangle\langle(\Delta\hat{Y})^2\rangle \geq 1.$$ Heisenberg inequality

The Hamiltonian describing the electromagnetic energy in the cavity

$H = \hbar\omega\,(\hat{a}\hat{a}^{\dagger} + ½)$ This is the Hamiltonian of a Harmonic Oscillator and $\hat{a}\hat{a}^{\dagger}=N$ is the photon number operator

Vacuum, coherent and squeezed states

In the fundamental state $|0\rangle$ of an H.O corresponding to 0 quantum (zero photon here), the Heisenberg equality is obtained and one can represent the average value of the two variables and their uncertainties in the Phase space of the two conjugates variables as a circle (same uncertainty for the two variables)

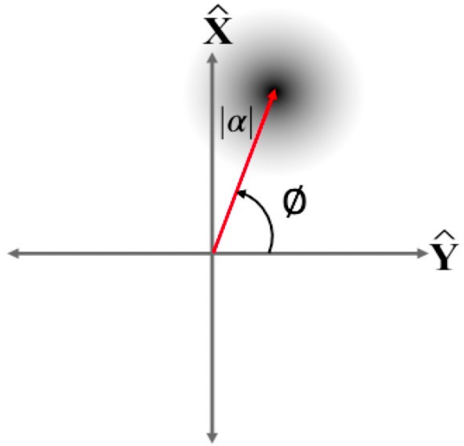


The laser beam used in cavities like Fabry-Perot interferometer is a coherent state which is an eigen state of the operator â.

$$|\alpha\rangle = \exp(-\frac{|\alpha|^2}{2}) \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle . \qquad P(n) = |\langle n|\alpha\rangle|^2 = \exp(-|\alpha|^2)\frac{|\alpha|^{2n}}{n!}$$

We know however that the coherent state is obtained by a displacement of the vacuum state in the phase space

$$|\alpha\rangle = \hat{D}(\alpha)\,|0\rangle = \exp(\alpha\hat{a}^\dagger + \alpha^*\hat{a})\,|0\rangle$$

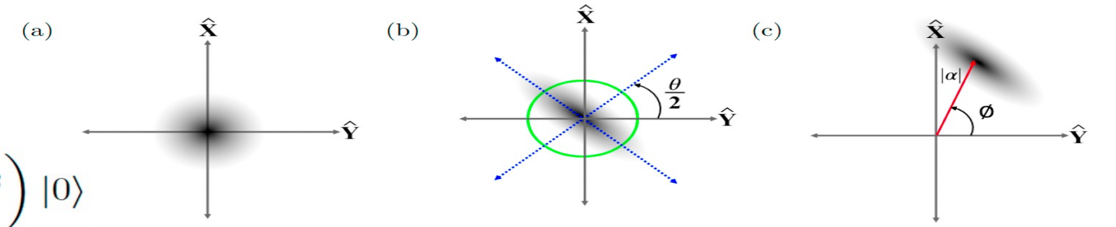


This state keeps the same relation of uncertainty for the two conjugate variables. The uncertainty of X and Y are called in this case the Standard Quantum Noise Limit

One-mode squeezed states

Imagine however that we are interested to measure with a great precision one of the two variables and want that our experimental measurement not to suffer from the SQNL Is there any possibility?
The answer is YES.

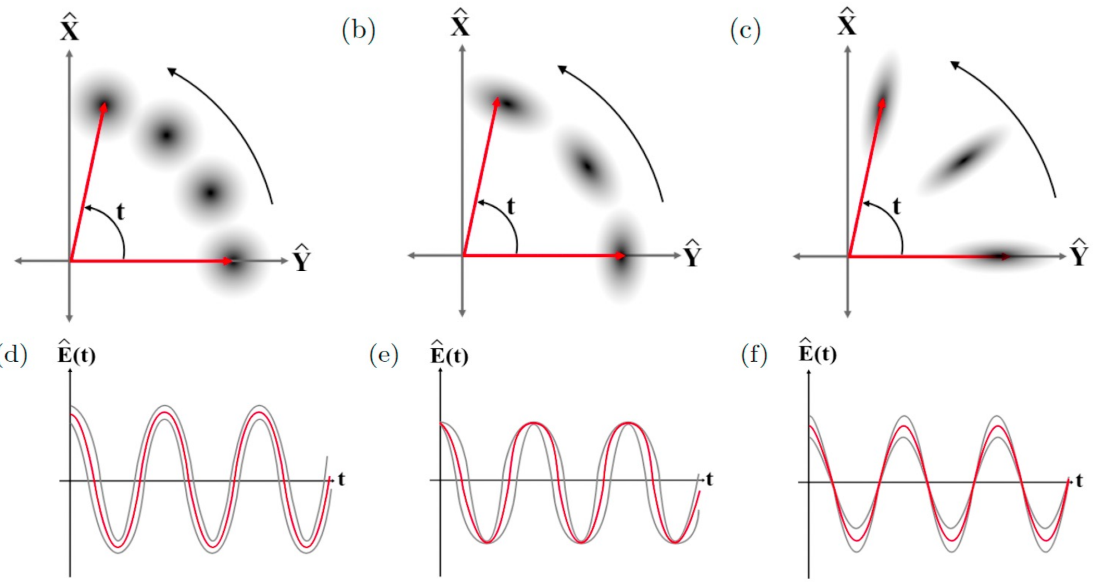
We transform the vacuum state into another one (squeezed vacuum) before to displace it using D(α)



$$|\alpha,\xi\rangle = \hat{D}(\alpha)\hat{S}(\xi)\,|0\rangle = \hat{D}(\alpha)\,\exp\left(\frac{1}{2}\xi^*\hat{a}^2 - \frac{1}{2}\xi\hat{a}^{\dagger 2}\right)|0\rangle$$

$$\xi = s\,\exp(i\theta)$$

$$\langle(\Delta\hat{X})^2\rangle = \exp(-2s) \quad \text{and} \quad \langle(\Delta\hat{Y})^2\rangle = \exp(2s).$$



The squeezing and its orientation could be determined by s and θ

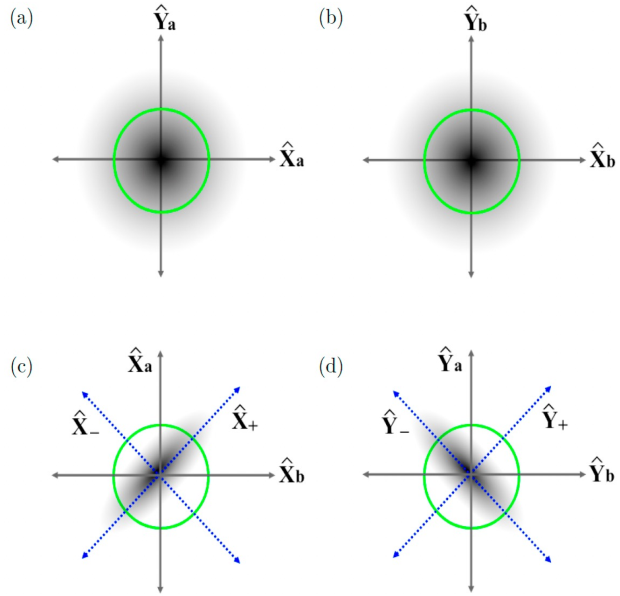
Two-mode squeezed states

$$|\alpha, \beta, \xi\rangle = \hat{D}(\alpha)_a \hat{D}(\beta)_b \hat{S}_{ab}(\xi)\,|0,0\rangle = \hat{D}(\alpha)_a \hat{D}(\beta)_b \exp\left(\xi^* \hat{a}\hat{b} - \xi \hat{a}^\dagger \hat{b}^\dagger\right) |($$

$$\hat{S}_{ab}(\xi) = \exp\left(\xi^* \hat{a}\hat{b} - \xi \hat{a}^\dagger \hat{b}^\dagger\right) \qquad \alpha = |\alpha| e^{i\phi_a} \qquad \beta = |\beta| e^{i\phi_b}$$

$$\hat{X}_\pm = (\hat{X}_a \pm \hat{X}_b)/\sqrt{2} \quad \text{and} \quad \hat{Y}_\pm = (\hat{Y}_a \pm \hat{Y}_b)/\sqrt{2}.$$

$$\langle(\Delta \hat{X}_\pm)^2\rangle = \exp(\pm 2s) \qquad \langle(\Delta \hat{Y}_\pm)^2\rangle = \exp(\mp 2s).$$



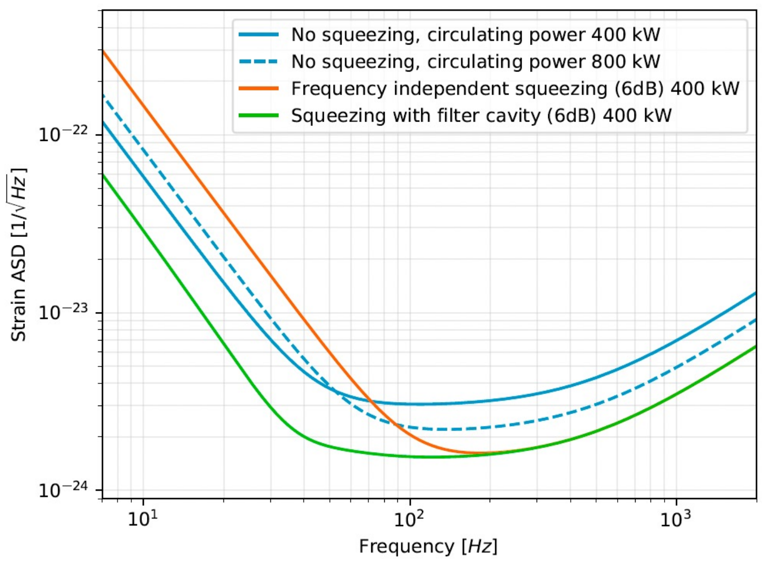
In the new state the uncertainty of one of the variable associate to the first mode is reduced and increased for that of the other and vice versa.

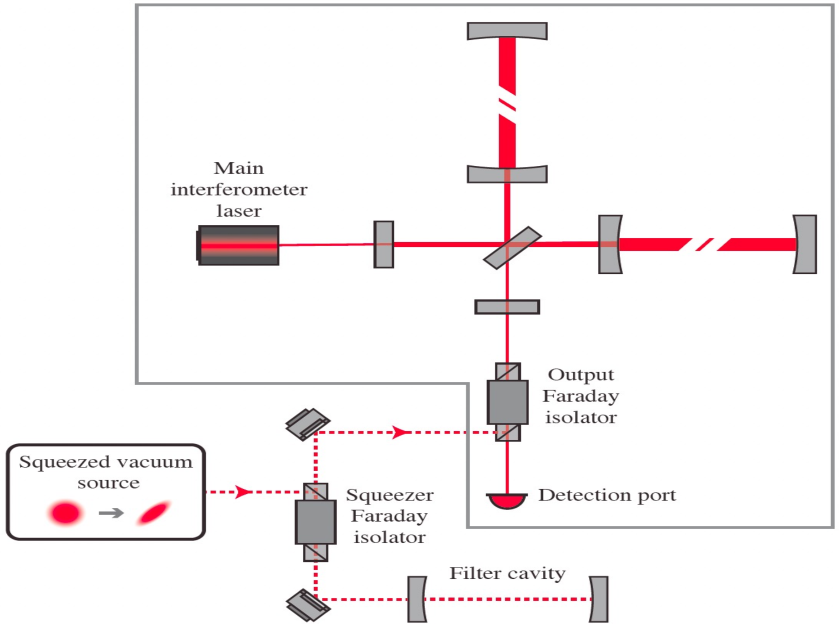
Not only we can reduce the noise of the variable we want to measure but we can control it by the one of the other mode

In practice one of the possibility to produce squeezed state we start with a photon of wavelength L and we use a special crystal (SPDC) that transform the photon into two photons with a wavelength 2L. The two photons are then fully correlated and a squeezed state is obtained in this

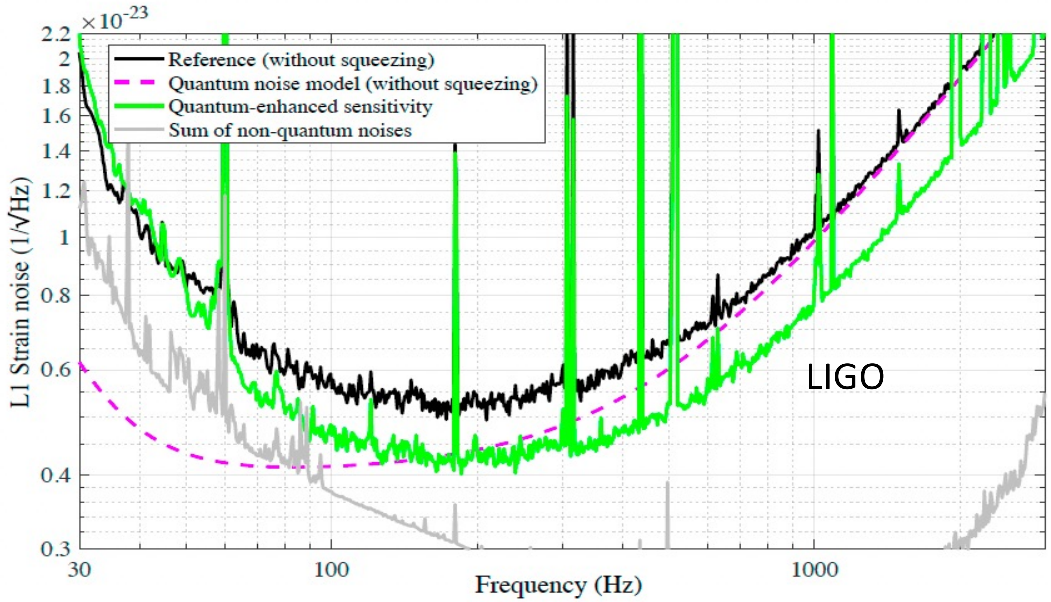
$$\mathbf{P}(\mathbf{r}, t) = \epsilon_0 \left[\chi^{(1)} \mathbf{E}(\mathbf{r}, t) + \chi^{(2)} \mathbf{E}^2(\mathbf{r}, t) + \chi^{(3)} \mathbf{E}^3(\mathbf{r}, t) + \chi^{(4)} \mathbf{E}^4(\mathbf{r}, t) + ...\right]$$

Impact of squeezed states on gravitational waves search

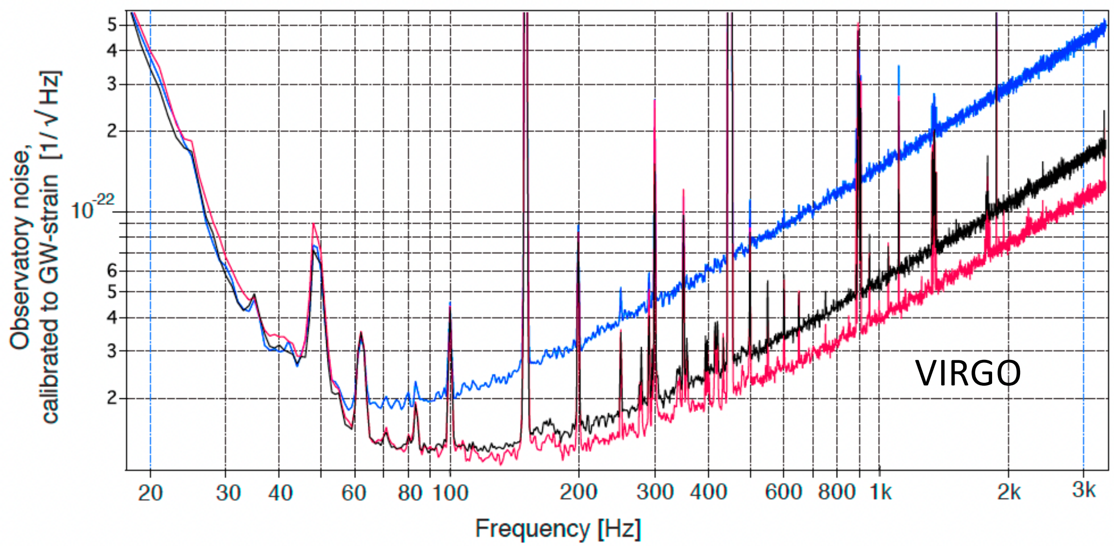




IJCLB in collaboration with LKB has developed such a technique. More efforts are still needed to reduce the noise and increase the S/N



×10^-23
Reference (without squeezing)
Quantum noise model (without squeezing)
Quantum-enhanced sensitivity
Sum of non-quantum noises
L1 Strain noise (1/√Hz)
Frequency (Hz)
LIGO

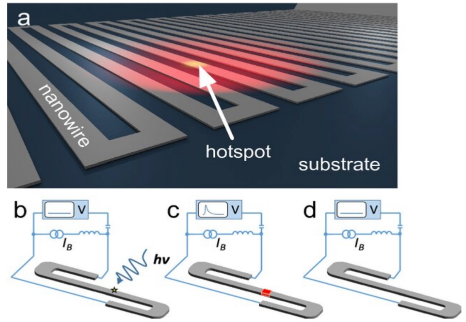


Observatory noise, calibrated to GW-strain [1/√Hz]
Frequency [Hz]
VIRGO

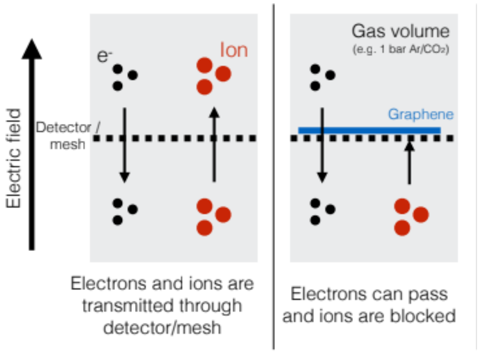
Low-dimensional materials

1D, 2D materials and nanodots (0D) provide a new opportunity to conceive new sensors with remarkable capabilities

- 1D materials made of superconducting metals are already used as an excellent photon detector with unprecedented spatial and time resolution (SNSPD)



- The 2D material like Graphene offer the possibility of a differential transmission between electrons and ions leading to a possible solution to the Back Ion Flow in gaseous TPC as well as other applications



Low-dimensional materials

Nanodots are found to behave in similar way to atoms (giant atoms). By varying their geometrical structure and their composition one can modify their photon emission and absorption spectra and also the decay time (nano or sub-nanosecond).

Several materials have been studied in the last decade: CdSe, CdSe/CdZn/ZnS, ZnO , InGaN/GaN, $CsPbX_3$ (X = Cl, Br,I). Continuous efforts are maintained to find materials with high yield and increased Stokes shift

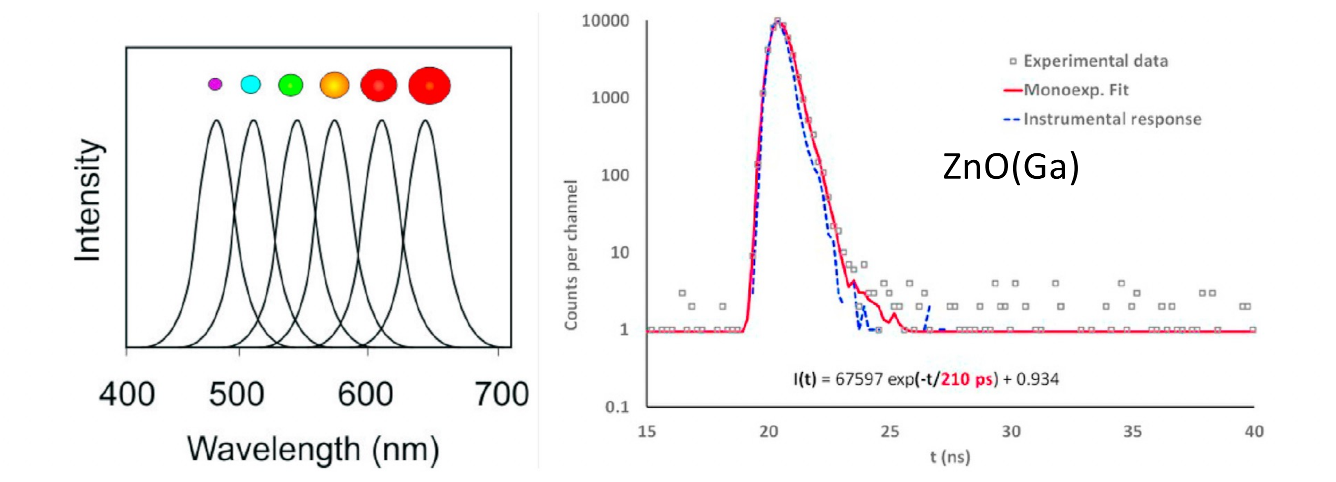
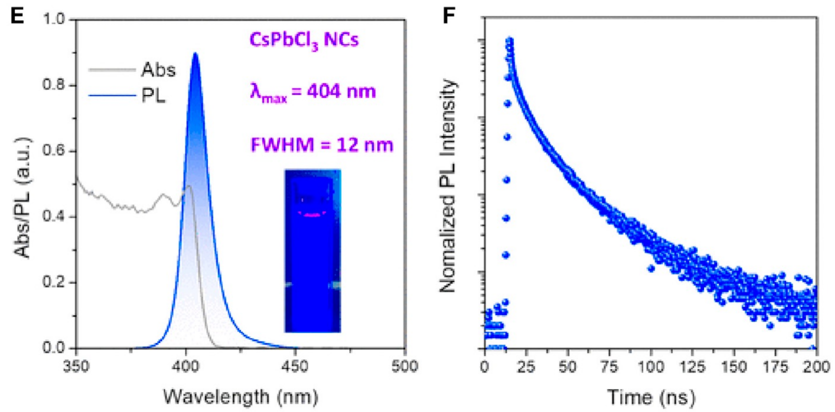


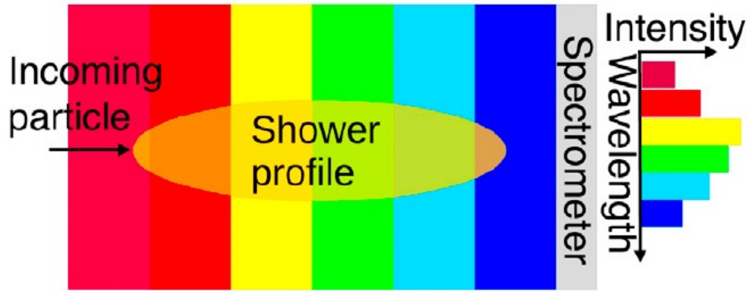
FIGURE 1 | Left: Emission spectrum as a function of nanocrystal size (from [22]). Right: decay time spectra of ZnO(Ga) under irradiation by X-rays (from [15]).

Low-dimensional materials



Some of these materials like the Perovskites can have very narrow bandwidth (tens of nm).

These materials can be a great asset in future EM calorimeters where they can be mixed with other scintillators in such a way that those with higher wavelength are placed in the first part of the calo and those with shorter wavelength are placed at the end in o produced photons by the material placed after.



The use of these materials can enhance the performances of the future calorimeters in terms of timing and also the localisation of the showers maximum leading to PID power in addition to the precise energy measurement

Several IN2P3 groups (IJCLAB, CPPM and IP2I) involved in developing scintillator-based ECAL could if not already use the new technologies for heir future calorimeters.

Other quantum sensors

- **Cold neutrons** : beam of very low energy neutrons are an excellent probe of new forces
  This exciting activity has been led by ILL and **LSCP**. New detector technology with excellent precision can enhance its power.

- **Positronium**: Positronium is a kind of special atom. (Hydrogen atom where proton is replaced by a positron). It can be in two spin states (s=1, ortho, S=0 para). The first decays into 3 photons (142 ns) while the second in two photons (125 ps). In both cases the photons are entangled and could be used as qubits or qudits. **IP2I** in collaboration with INL has initiated some R&D to produce positronium using nanohole structures

- **N.V. :** Could be used to study particle spins through the interaction with that of the N.V

Conclusion

- Quantum sensors are very exciting tools to measure faint phenomena

- They were developed outside our fields but we have some assets (cavities, electronics, expertise in cryogenics) that could be of big interest

- Also subatomic field is not a big contributor, it can be a big user

- We have limited knowledge in our community of Quantum Technology and this needs to be greatly enhanced. Probably dedicated summer schools like the one organised in U.S are the model to follow
- DRD5 is a new collaboration among the 8 proposed by ECFA. This may be a good place to be

- Quantum sensors are an excellent opportunity for our field but also for our physicists to very exciting activities