Detection of quantum state of photons

Mirko Lobino

INFN Workshop on Future Detectors

Bari 17/10/2022

UNIVERSITÀ DI TRENTO

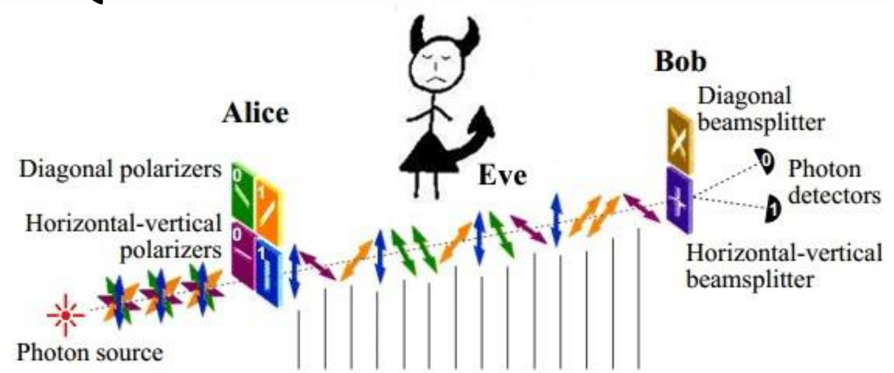
TIFPA Trento Institute for Fundamental Physics and Applications

Overview

- Detection of photons for quantum applications
- Semiconductor based photons
- Superconducting single photon detectors
- Homodyne detection
- Improving resolution with quantum state of light

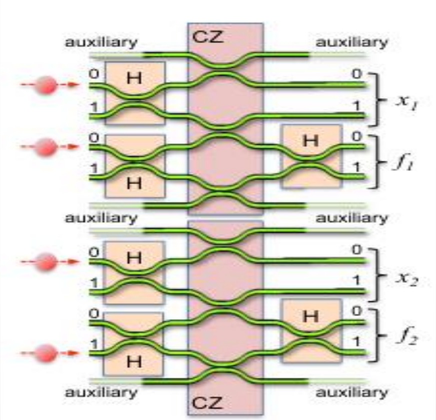
What do we use photons for?

Quantum communication



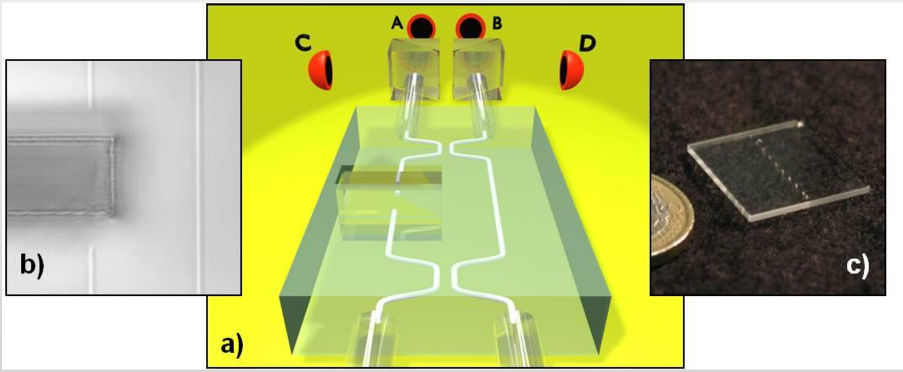
https://www.researchgate.net/figure/The-Principle-of-QC-According-to-the-BB84-Protocol_fig6_305768369

Quantum computation



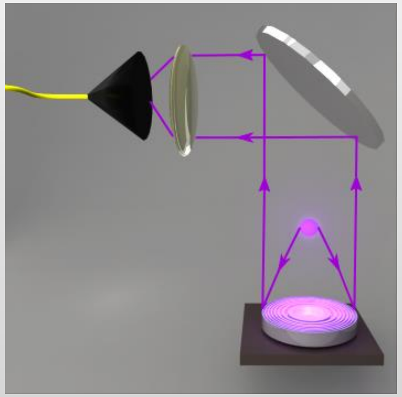
A. Politi, et al, *Science* **325**, 1221, (2009).

Quantum metrology



Crespi et al, Applied Physics Letters 100, 233704 (2012)

Atomic read-out

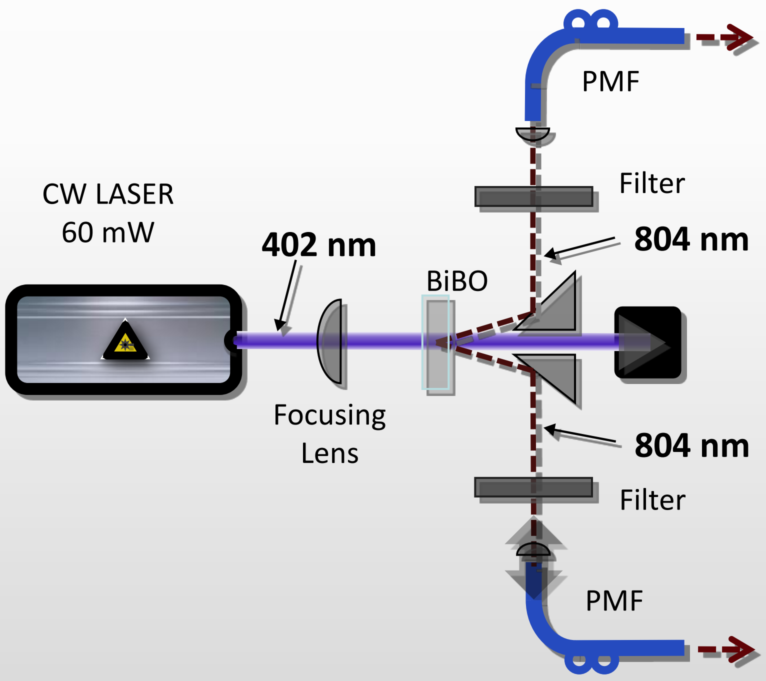


Ghadimi et al, npj Quantum Information 3, 4 (2017)

Generation of photons

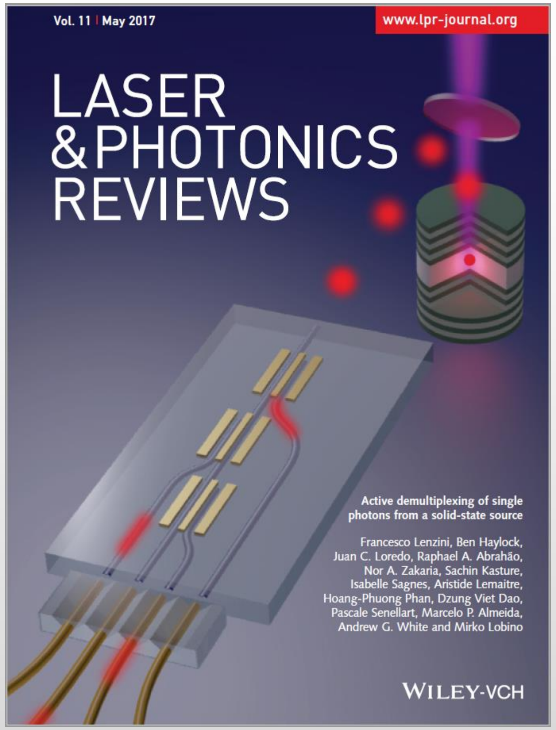
- Probabilistic sources

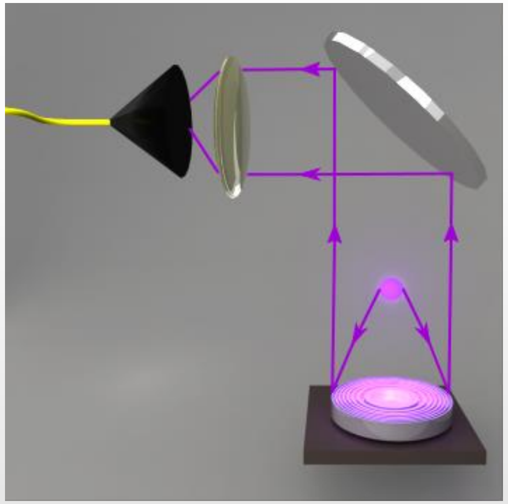
Parametric down conversion



- Deterministic sources

Quantum emitters





Ghadimi et al, npj Quantum Information 3, 4 (2017)

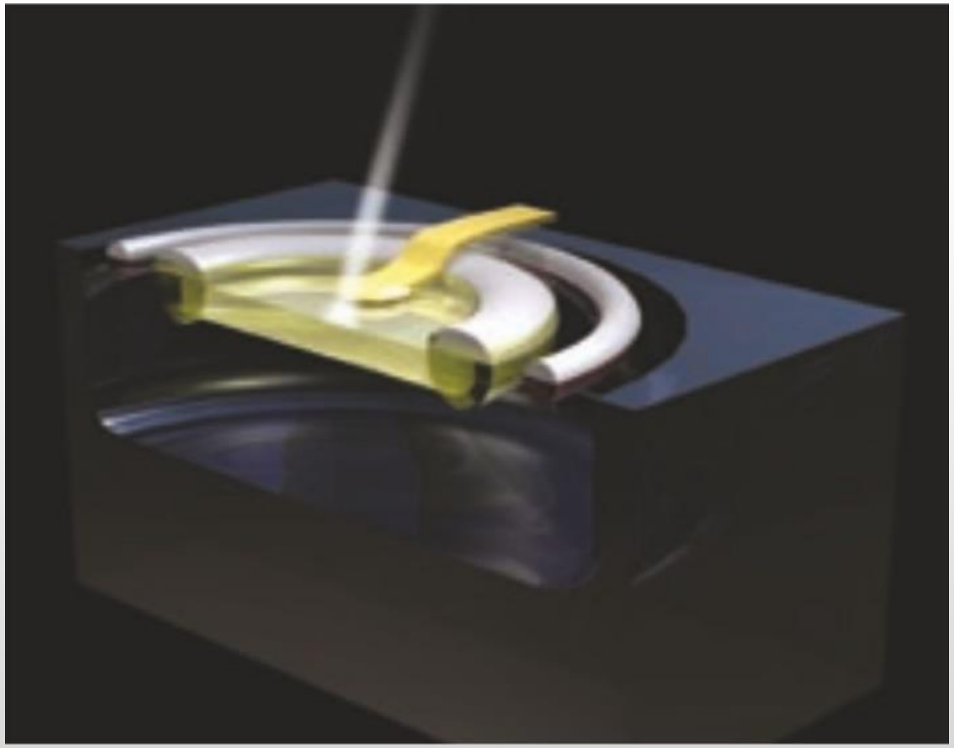
Silicon Single photon detectors (Si-SPD)

- A photodiode operating in the Geiger mode
- Not good for infrared (λ>1000 nm) because of the energy gap of Si (E_{gap}= 1.12 eV)
- Afterpulse (100 ns to 500 ns)
- Detection efficiency 65% (@600 nm)
- around 20 dark counts per second
- It does not resolve the number of photons

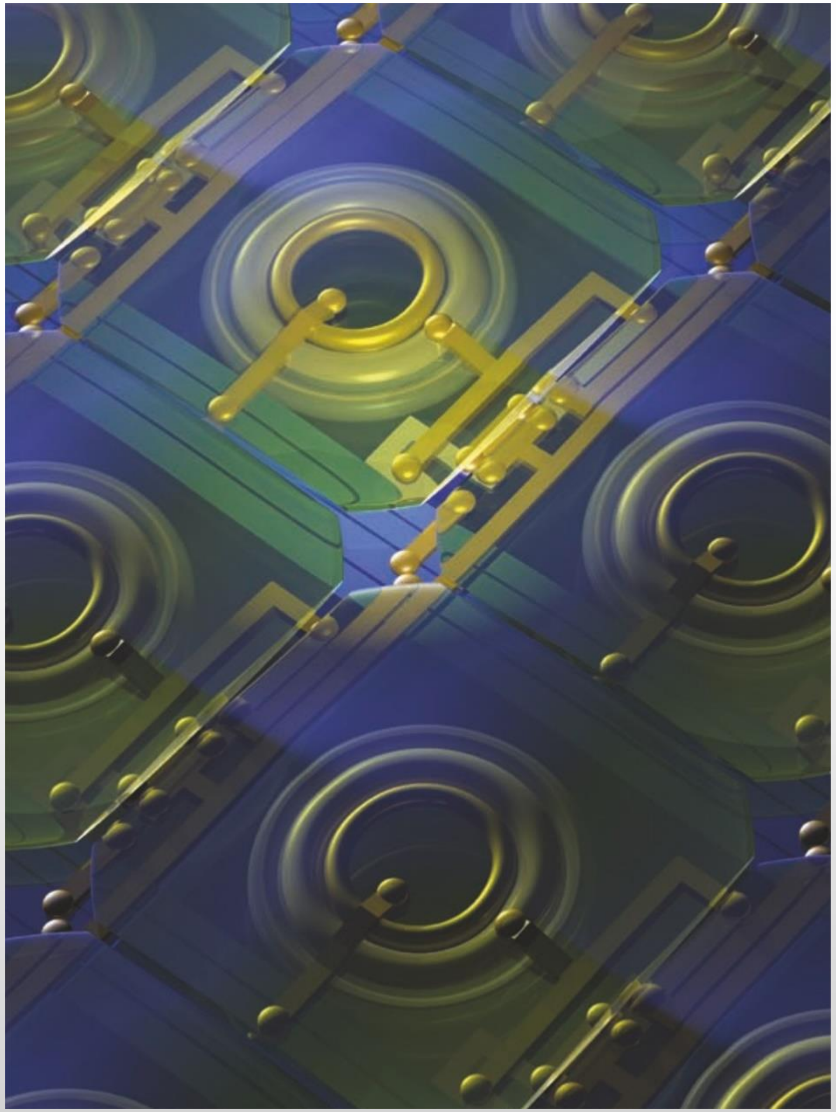
https://www.excelitas.com/product-category/single-photon-counting-modules

Array of single photon detectors (Si)

- They can be fabricate in arrays
- Integrated with fast time stamping electronics



Images are a courtesy of Prof. Charbon, EPFL

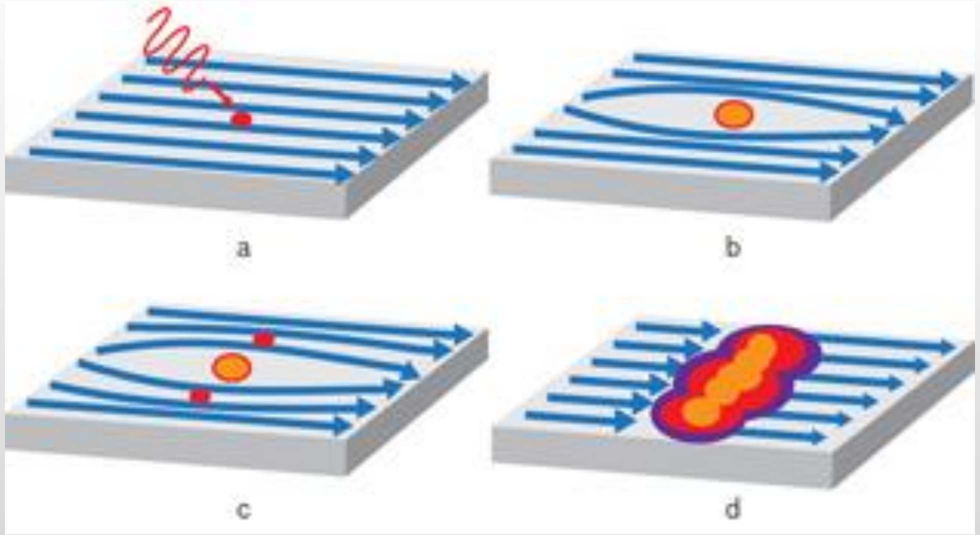


InGaAs Single photon detectors (InGaAs-SPD)

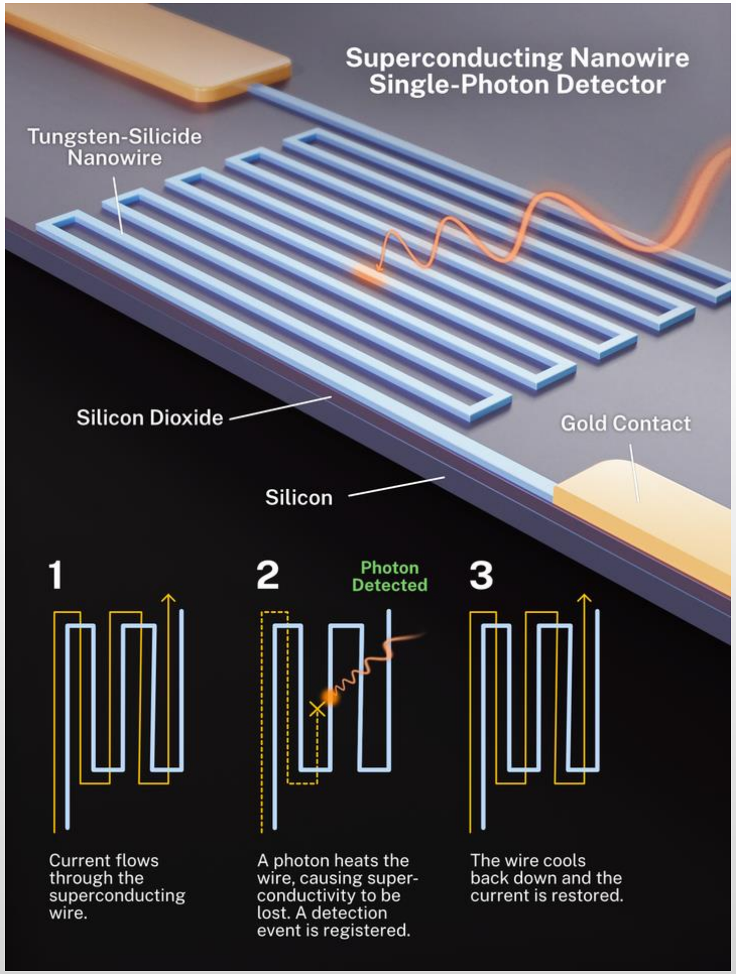
- Similar to Si-SPD but with general worst specs
- Good for infrared (λ>1000 nm)
- Higher afterpulse probability (1μs deadtime)
- Detection efficiency 25% (@1550 nm)
- around 800 dark counts per second at 10% efficiency
- It does not resolve the number of photons

Superconducting single photon detectors

- They represent the state of the art in single photon detection
- A superconducting nanowire is driven close to its critical current



https://archive.ll.mit.edu/publications/labnotes/nanowirephotondetector.html



https://www.nist.gov/image/superconducting-nanowire-single-photon-detector

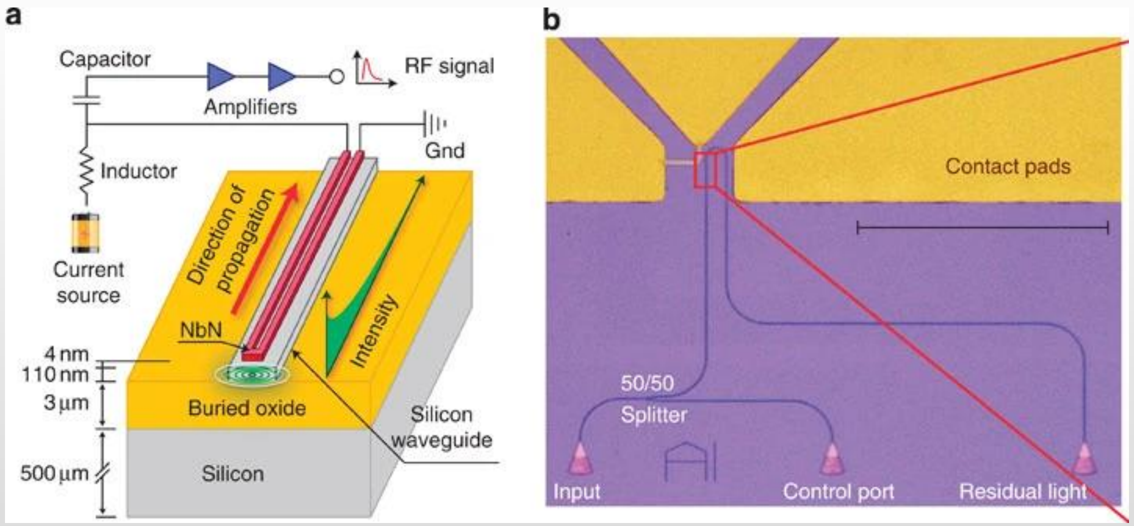
Superconducting single photon detectors

- Made of a superconducting nanowire (4-6 nm thickness and 500 nm width)
- Material: NbN, NbTiN and Wsi
- Efficiency >85% @1550nm, Low timing jitter: <15 ps, High count rate: >80 MHz, Low dark count rate: <10 Hz
- Detect photons up to 10 μm wavelength (APL Photonics 6, 056101, 2021)

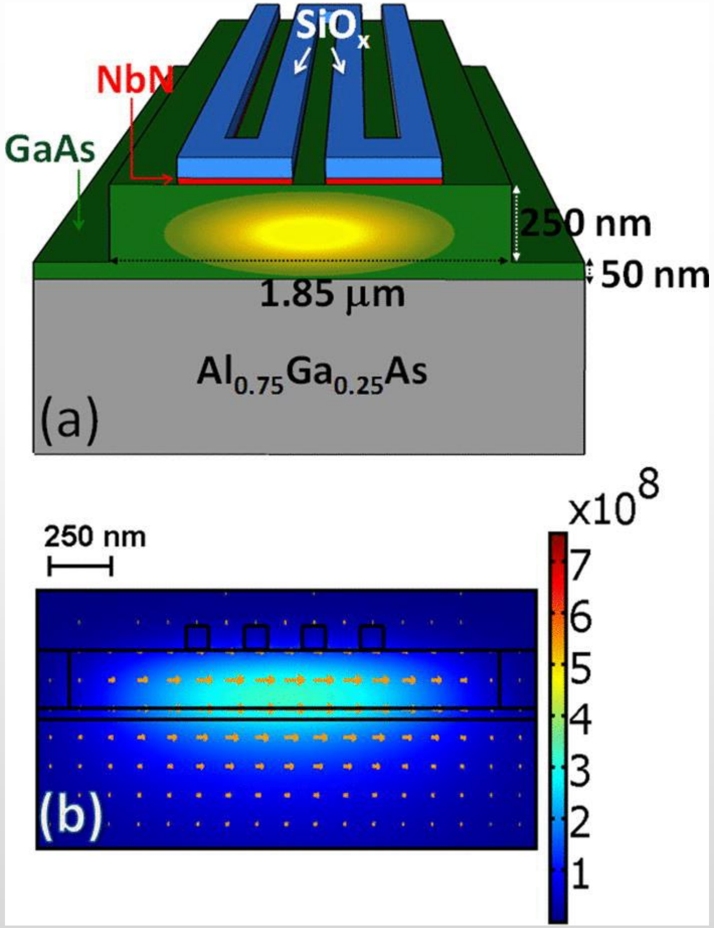
https://www.idquantique.com/quantum-sensing/products/id281-snspd-series/

Integrating the SNSPD with optical waveguides

- Best way to bring the efficiency close to 100%
- Photons are absorbed by evanescent coupling
- Longer interaction length



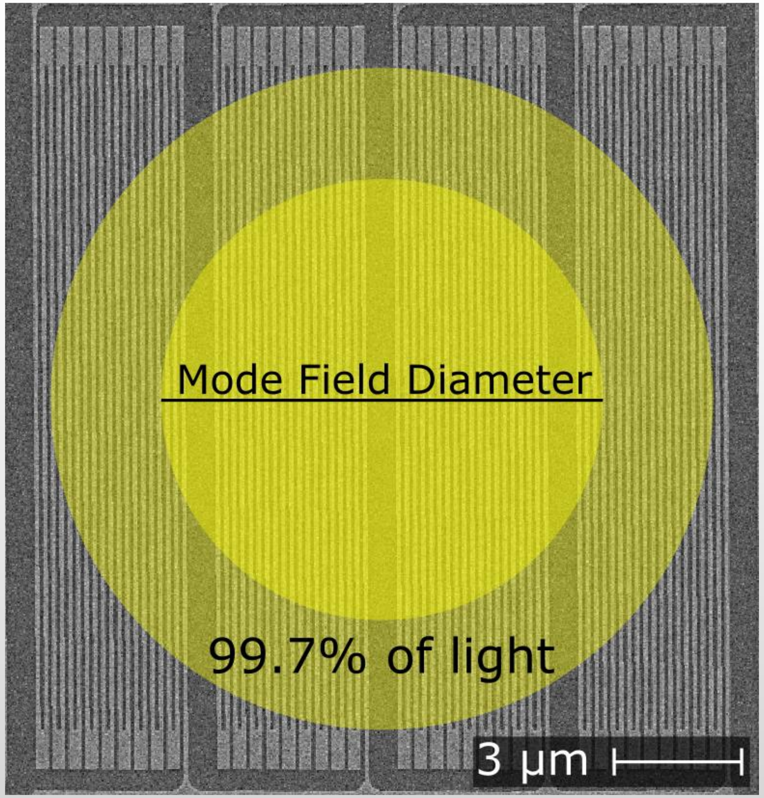
Pernice et al, Nature Comm. 3, 1325 (2012)



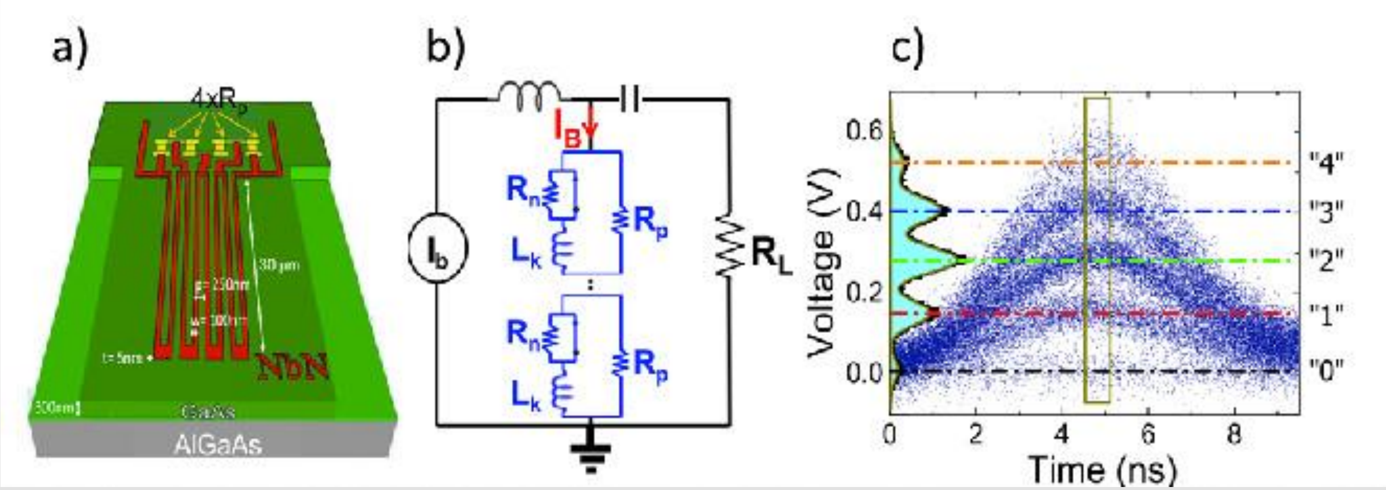
Sprengers et al, Appl. Phys. Lett. **99**, 181110 (2011)

Multiplexing of SNSPDs

- Multiple detectors can be integrated on a waveguide
- Probabilistic photon number resolving capability



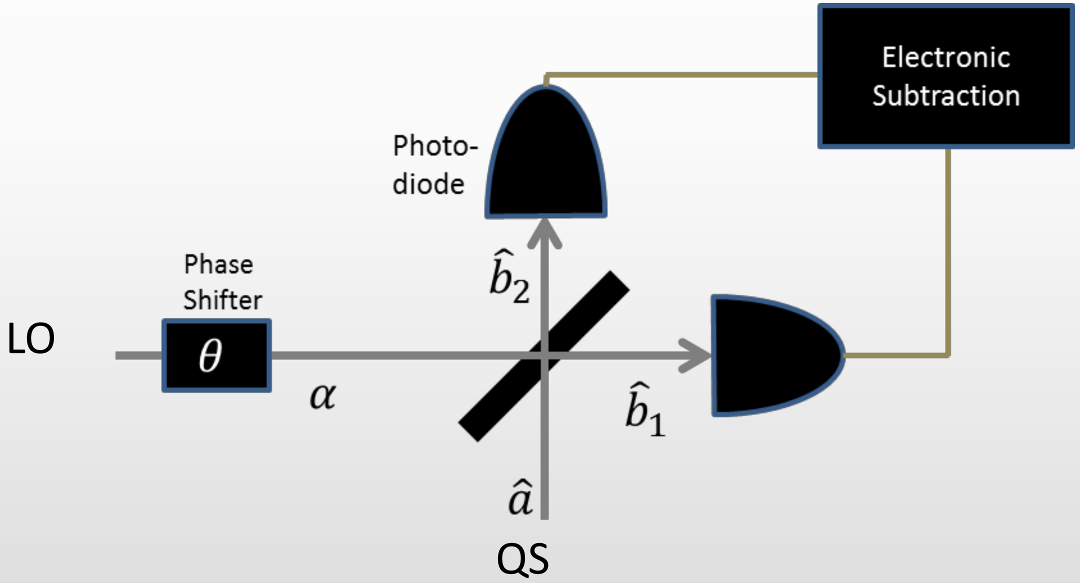
Stasi et al, Arxiv2207.14538



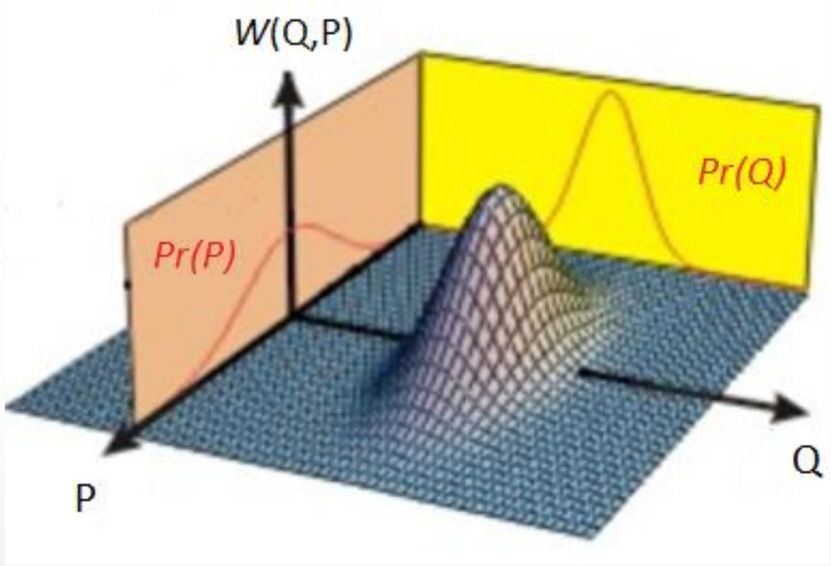
Sahin et al, Appl. Phys. Lett. **103**, 111116 (2013)

Homodyne detection

- Quantum Signal (QS) is mixed with a local oscillator (LO) on a balanced beam splitter
- Measures the difference in current produced by the two photodiodes.



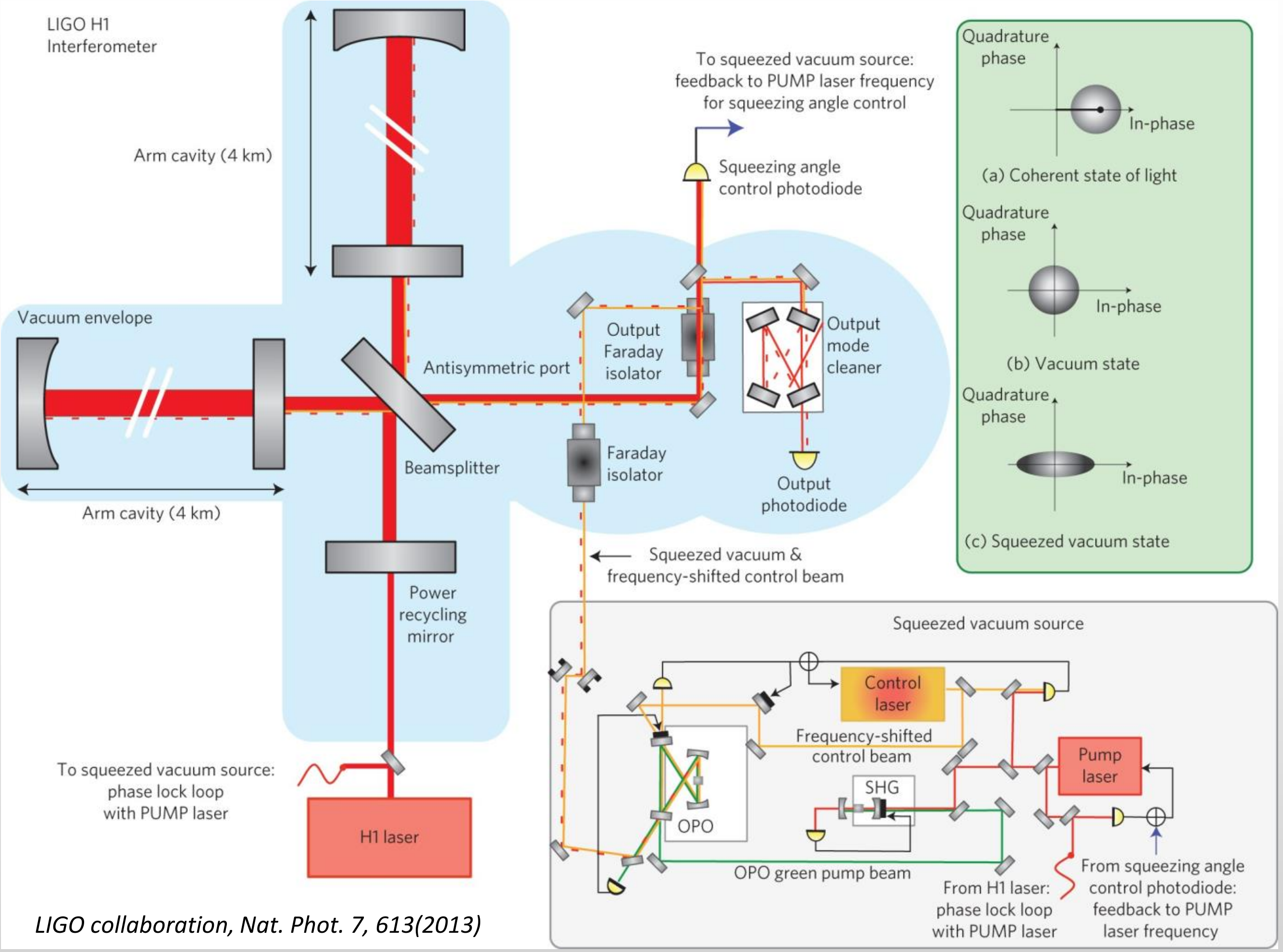
$$\hat{E} = \hat{Q}\cos(\omega t) + \hat{P}\sin(\omega t)$$



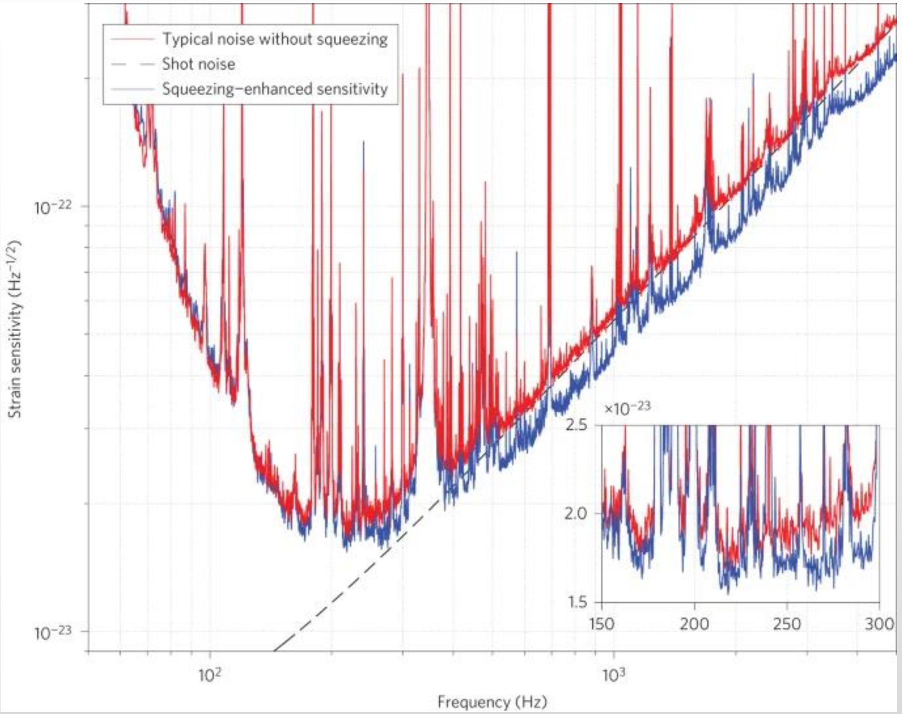
Image(altered) from: http://www.iqst.ca/quantech/wigner.php

Quantum enhanced measurement

- Squeezed light used for enhancing the sensitivity of LIGO (up to 2.15 dB)



LIGO collaboration, Nat. Phot. 7, 613(2013)



A new INFN experiment: UNIDET

Trento Institute for Fundamental Physics and Applications

FONDAZIONE BRUNO KESSLER

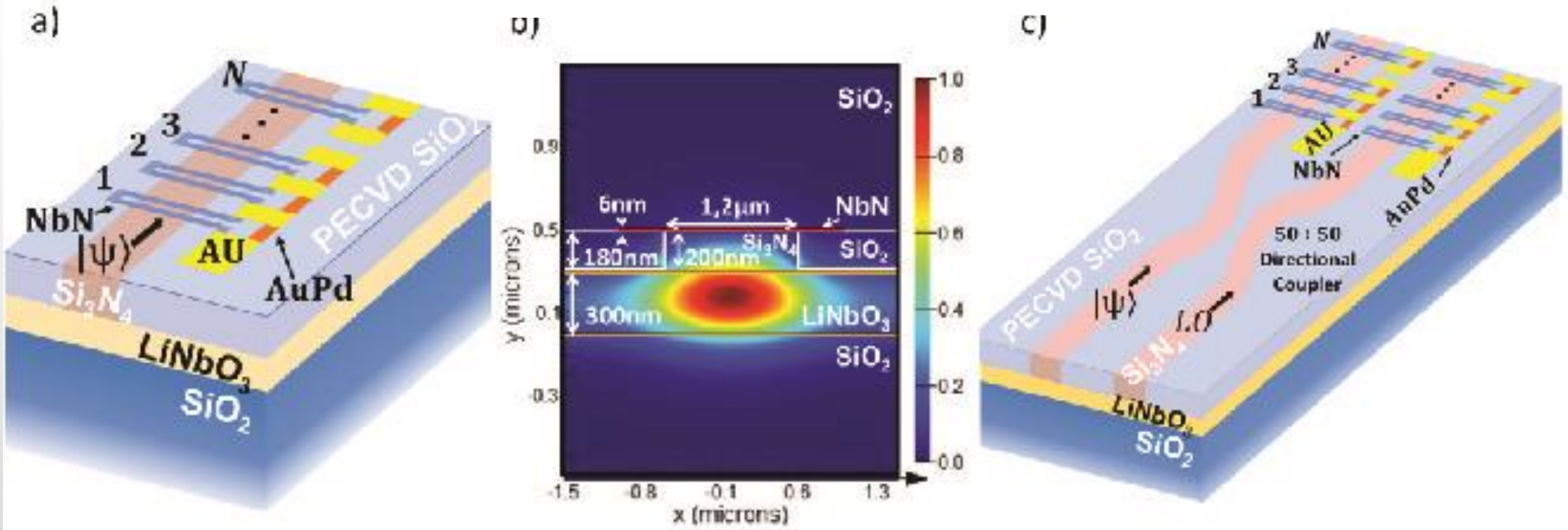
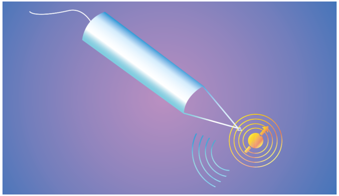
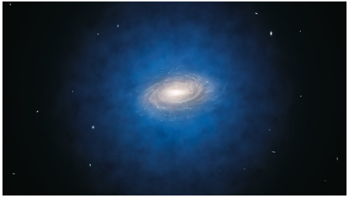


Figure 2 a) Schematic of the integrated PNR to develop in this project showing a series of N pixels composed by a NbN nanowire (80 nm width) and an AuPd on-chip parallel resistance (Rp=20 Ω value). b) Field intensity for the first TE mode propagating in the waveguide where the light absorption in each NbN nanowire element is at 3.4%. c) Schematic of the hybrid detector.

Conclusion

- Overview of the main detection strategies for quantum technology with photons
- Avalanche photodiodes
- Superconducting single photon detectors and photon number resolving detectors
- Homodyne detection and quantum enhanced measurement





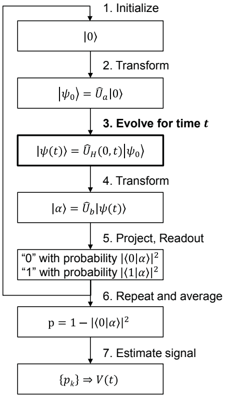
Quantum sensing in wave-like dark matter search

Caterina Braggio
INFN Workshop for future detectors
17-19 October 2022, Bari

QUANTUM SENSING: a definition

"Quantum sensing" describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity
Rev. Mod. Phys. 89, 035002 (2017)

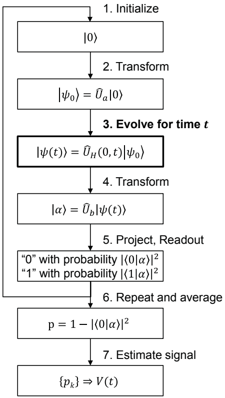
1. Use of a **quantum object** to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels, i.e. electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.
2. Use of **quantum coherence** (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity
3. Use of **quantum entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically.



Basic protocol

quantum sensing experiments typically follow a generic sequence of processes known as:

1. sensor initialization into a known basis state
2. interaction with the signal
3. sensor readout
4. signal estimation



quantum sensors are **extremely sensitive** to disturbances

$\Longrightarrow$ they have the potential to become extraordinary **measuring instruments** in specific application areas quantum sensors are **extremely sensitive** to disturbances

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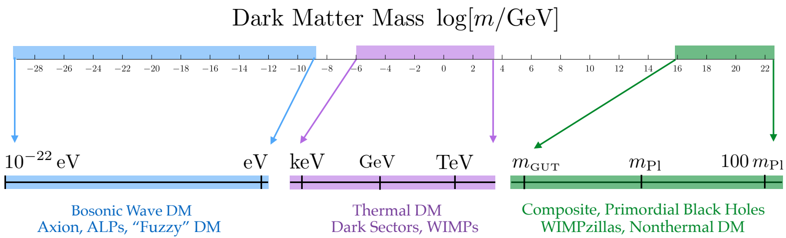
what about particle physics?



– $\simeq$ 10 eV is considered a fundamental watershed
– **quantum sensing** $\rightarrow$ significant opportunities for **wave-like DM** and in the 10 keV-1MeV range

Experimental methods

– axion/dark photon **haloscopes** $\rightarrow$ *well established field*
– **collective excitations** in solid state materials (magnons, phonons) $\rightarrow$ *only recently proposed, very promising*

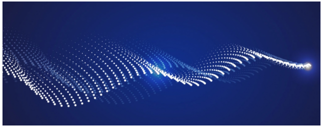
Dark Matter waves

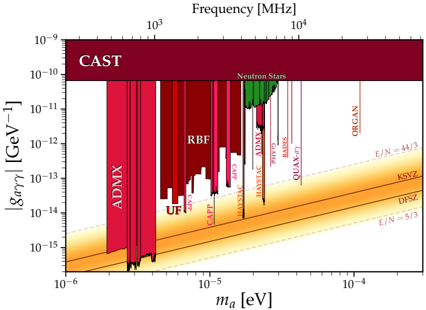
$$m_a \simeq h\nu_a \qquad 1\,\mu\text{eV} \leftrightarrow 0.25\,\text{GHz}$$

particle $\Leftrightarrow$ wave

$$\lambda = \frac{h}{mv}, \qquad h\nu = E = mc^2 + \frac{1}{2}mv^2$$

For **light** and **massless** particles the wavelength can be large.



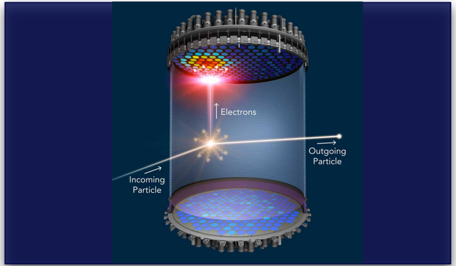


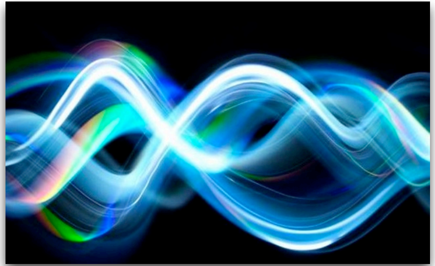
If these particles are also **bosons**, many particles **can occupy the same state**

$$\rho_{\text{DM}} = 0.3 - 0.4\,\text{GeV}\,\text{cm}^{-3} \qquad \Longrightarrow \qquad n_a \sim 3 \times 10^{12}(10^{-4}\text{eV}/m_a)\,\text{axions}/\text{cm}^3$$

it's a **macroscopic wave-like** behavior

AXION VS WIMP DETECTION





WIMP [1-100 GeV]
— number density is small
— tiny wavelength
— no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

AXION [$m_A \ll$ eV]
— number density is large (bosons)
— long wavelength
— coherence within detector

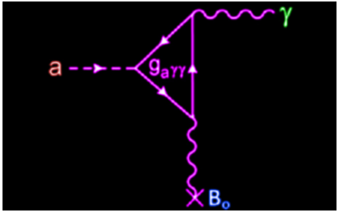
$\Longrightarrow$ observable: classical, oscillating, **background field**

HALOSCOPE - resonant search for axion DM in the Galactic halo

– original proposal by P. Sikivie (1983)

– search for axions as cold dark matter constituent: SHM from Λ_{CDM}, local DM density ρ
$\rightarrow$ signal is a **line** with 10^{-6} relative width in the energy($\rightarrow$ frequency) spectrum

– an **axion** may interact with a **strong** $\vec{B}$ **field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)



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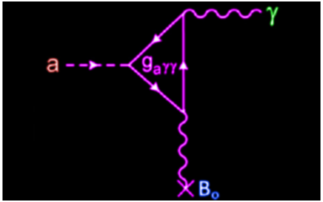


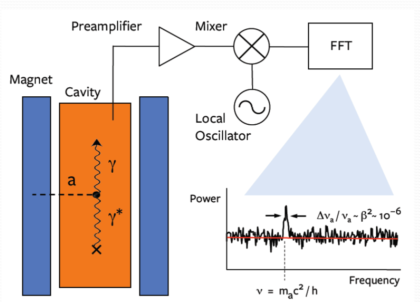
1. microwave cavity for resonant amplification
   -think of an HO driven by an external force-
2. with **tuneable frequency** to match the axion mass
3. the cavity is within the bore of a **SC magnet**
4. cavity signal is readout with a **low noise receiver**
5. cavity and receiver preamplifier are kept at base temperature of a **dilution refrigerator** $(10 - 50)$ mK

weak interactions with SM particles $\Longrightarrow 10^{-22}$ W signal power $\longleftrightarrow$ $\lesssim$Hz signal rate at 10 GHz

Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise, set by the laws of quantum mechanics (Standard Quantum Limit noise)

$T_{sys} = T_c + T_A$
T_c cavity physical temperature
T_A effective noise temperature of the amplifier

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right)$$



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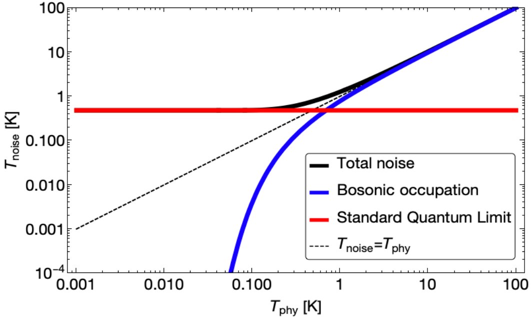


at 10 GHz frequency

STANDARD QUANTUM LIMIT IN LINEAR AMPLIFICATION

Any narrow bandwidth signal $\Delta\nu_c \ll \nu_c$ can be written as:

$$\begin{aligned} V(t) &= V_0[X_1\cos(2\pi\nu_c t) + X_2\sin(2\pi\nu_c t)] \\ &= V_0/2[a(t)\exp(-2\pi i\nu_c t) + a^*(t)\exp(+2\pi i\nu_c t)] \end{aligned}$$

X_1 and X_2 signal quadratures
$a, a^* \rightarrow$ to operators $a, a^\dagger$ with $[a, a^\dagger] = 1$ and $N = aa^\dagger$
Hamiltonian of the cavity mode is that of the HO:

$$\mathcal{H} = h\nu_c\left(N + \frac{1}{2}\right)$$

Alternatively, with $[X_1, X_2] = \frac{i}{2}$:

$$\mathcal{H} = \frac{h\nu_c}{2}(X_1^2 + X_2^2)$$

$$kT_{\text{sys}} = h\nu_c N_{sys} = \left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} + N_A\right)$$

Caves' Theorem: $N_A > 1/2$

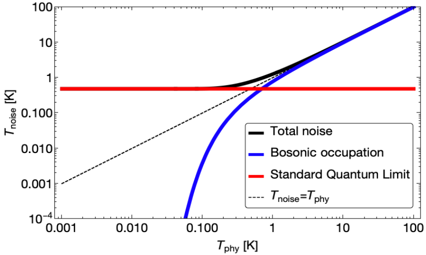
The quantum noise is a consequence of the base that we want to use to measure the content of the cavity.
A **linear amplifier** measures the amplitudes in phase and in quadrature, while a **photon counter** measures N.

BEYOND SQL: PHOTON COUNTING

- **Photon counting** is a game changer at high frequency and low temperatures: in the **energy eigenbasis** there is no intrinsic limit (SQL)

- unlimited (exponential) gain in the haloscope scan rate compared to linear amplification at SQL:

$$\frac{R_{\text{counter}}}{R_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$

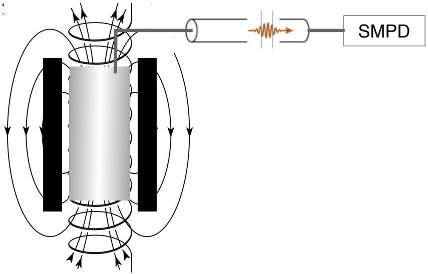


plot example at 10 GHz, where $T_{\text{SQL}} = h\nu/k_B \to 0.5\,\text{K}$

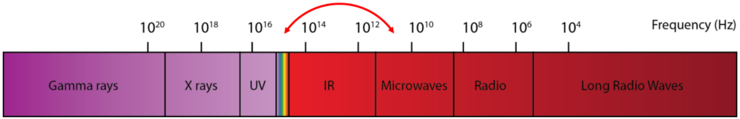
at 7 GHz, 40 mK $\Longrightarrow 10^3$ faster than SQL linear amplifier readout

SMPDs for itinerant photons

A Single Photon Microwave Counter (SMPD) architecture is significantly different whether it is meant for **cavity photons** or **itinerant (traveling) photons**.
We are interested in the itinerant version due to the magnetic fields involved.

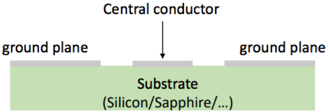


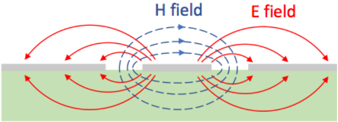
- detection of individual microwave photons is a challenging task because of their**low energy** $\sim 10^{-5}$ eV
- a solution: use "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ~GHz range
- or: rely on a single **current-biased Josephson junction**



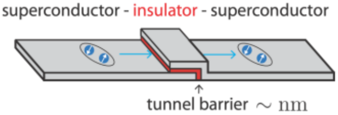
SUPERCONDUCTING CIRCUITS and the JOSEPHSON JUNCTION

SC circuits are solid state electrical circuits fabricated using techniques borrowed from conventional integrated circuits.

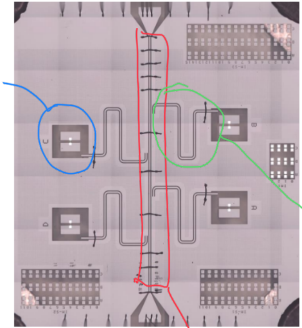


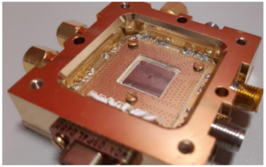


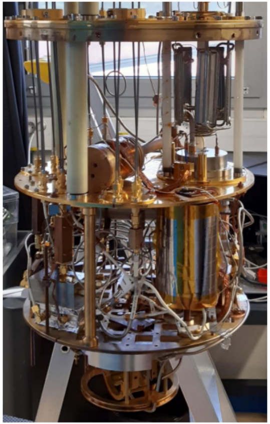
Devices useful for circuit QED are fabricated starting from a **non-dissipative, non-linear element**: the Josephson tunnel junction



Superconducting circuits

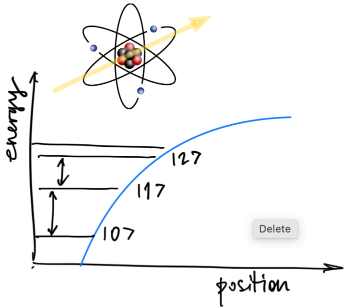






$\hbar\omega \gg kT$

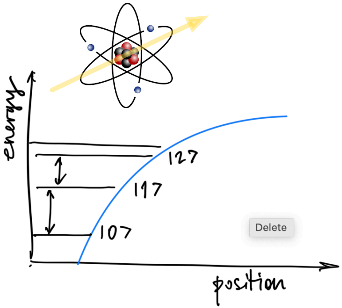
ARTIFICIAL ATOMS: the TRANSMON QUBIT

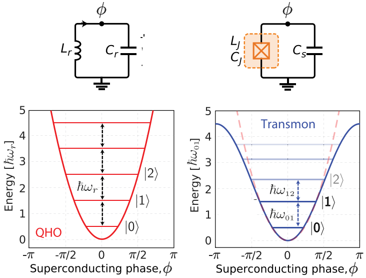


$E_{01} = E_1 - E_0 = \hbar\omega_{01} \;\neq\; E_{02} = E_2 - E_1 = \hbar\omega_{21}$
$\rightarrow$ good **two-level atom** approximation

control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos \omega_{01} t$

ARTIFICIAL ATOMS: the TRANSMON QUBIT





$E_{01} = E_1 - E_0 = \hbar\omega_{01} \neq E_{02} = E_2 - E_1 = \hbar\omega_{21}$
$\rightarrow$ good **two-level atom** approximation

control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos \omega_{01} t$

toolkit: capacitor, inductor, wire (all SC)
$\omega_{01} = 1/\sqrt{LC} \sim 10\,\text{GHz} \sim 0.5\,\text{K}$
$\rightarrow$ simple LC circuit is not a good **two-level atom** approximation

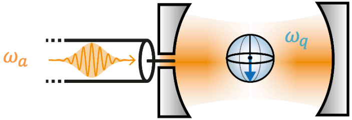
$I_J = I_c \sin\phi \qquad V = \frac{\phi_0}{2\pi}\frac{\partial\phi}{\partial t}$

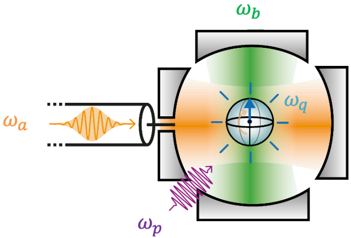
$V = \frac{\phi_0}{2\pi}\frac{1}{I_c\cos\phi}\frac{\partial I_J}{\partial t} = L_J \frac{\partial I_J}{\partial t}$

$L_J = \frac{\phi_0}{2\pi}\frac{1}{I_c\cos\phi}$ NL Josephson inductance

quantum engineers and **particle physicists** joining efforts

A practical transmon-based counter has been recently developed (Quantronics group CEA, Saclay) that we will apply to haloscope signal readout.



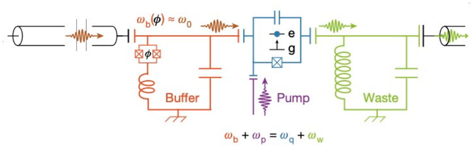


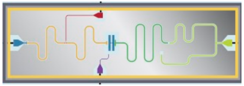
$$\omega_a + \omega_p = \omega_q + \omega_b$$

R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)
E. Albertinale *et al*, Nature 600, 434 (2021)

Quantronics Group
Research Group in Quantum Electronics, CEA-Saclay, France

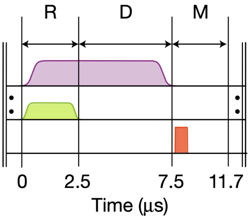
transmon-based SMPD





R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)
E. Albertinale , Nature 600, 434 (2021)

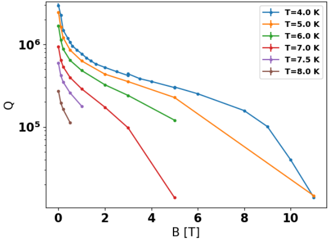
Quantronics Group
Research Group in Quantum Electronics, CEA-Saclay, France



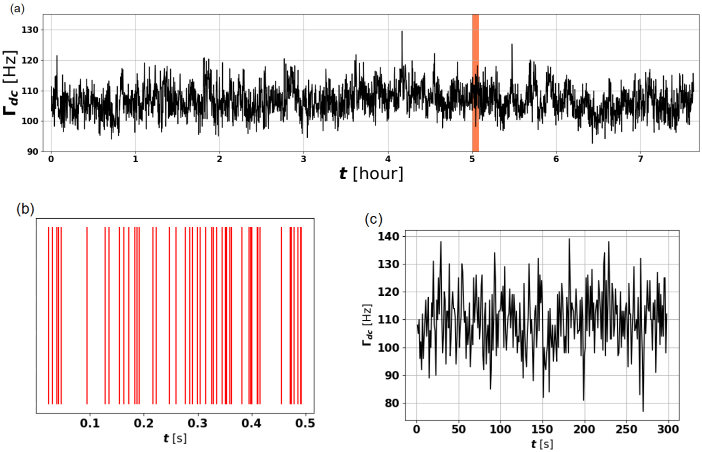
- a three-step process repeated several times
- qubit reset (R) performed by turning on the pump pulse + a weak resonant coherent pulse to the waste port
- detection (D) step with the pump pulse on
- measurement (M) step probes the dispersive shift of the buffer resonator to infer the qubit state

Pilot SMPD-haloscope experiment

- copper cavity **sputtered with NbTi**
  magnetron sputtering in INFN-LNL
- right cylinder resonator, TM_{010} mode
  $\nu_c \sim 7.3\,\text{GHz}$ to match the new generation SMPD bandwidth
  (7.280 - 7.380) GHz
- **system of sapphire triplets** to tune the cavity frequency
  $\sim$ 10 MHz tuning without impacting Q
- **nanopositioner** to change the sapphire rods position



the dark count is a **inhomogeneous Poisson process**



REAL SMPDS HAVE FINITE EFFICIENCY η AND DARK COUNTS $\Gamma_{dc} > \Gamma_{sig}$

$\delta N_{dc} = \sqrt{\Gamma_{dc}\tau}$ uncertainty in the number of dark counts collected in an integration time τ

$\Sigma = \frac{\eta\Gamma_{sig}\tau}{\sqrt{\Gamma_{dc}\tau}} = \eta\Gamma_{sig}\sqrt{\frac{\tau}{\Gamma_{dc}}}$ the dark count contribution to the fluctuations dominates

$R_{\text{counter}} = \frac{\Delta\nu_c}{\tau} = \frac{\Delta\nu_c \eta^2 P^2_{a\gamma\gamma}}{h^2\nu^2\Sigma^2\Gamma_{dc}}$ $R_{\text{lin}} = \frac{Q_a}{Q_c}\left(\frac{P_{a\gamma\gamma}}{\Sigma\, k_B T}\right)^2$ scan rates lin. amp. and counter

$$\frac{R_{\text{counter}}}{R_{\text{lin}}} = \left(\frac{k_B T_{sys}}{h\nu}\right)^2 \frac{\eta^2 \Delta\nu_a}{\Gamma_{dc}}$$

quantum advantage can be demonstrated even with high dark count rates Γ_{dc}
$\eta \approx 0.4$, $\Gamma_{dc} \approx 100\,\text{Hz} \Longrightarrow$ potential improvement of a factor 11 compared to SQL scan rate

Scan rate

For a target sensitivity $g_{a\gamma\gamma}$, the parameter space scan rate is given by:

$$\frac{df}{dt} \propto \frac{B^4\, V_{\text{eff}}^2\, Q_L}{T_{sys}}$$

A haloscope optimized at best goes at:

$$\left(\frac{df}{dt}\right)_{\text{KSVZ}} \sim \text{GHz/year}$$

$$\left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 20\,\text{MHz/year} \qquad \odot\,\odot$$

Take-home: to probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim 100$ years with 4-5 complementary haloscopes

Studio e caratterizzazione di nuovi dispositivi per la rivelazione di particelle basati sull’uso di magneti a singola molecola nell’esperimento NaMaSSte

INFN Istituto Nazionale di Fisica Nucleare
CSN5

(**Na**no**Ma**gnets for quantum **S**ensing and Data **St**orag**e**)

Alberto Cini*, Giuseppe Celardo, Fabio Cinti, Maria Fittipaldi, Giuseppe Latino, Lorenzo Sorace, Angelo Rettori
Francesca Brero, Elio Giroletti, Alessandro Lascialfari, Manuel Mariani, Margherita Porru
Paolo Arosio, Francesco Orsini
Jonathan Frassineti, Samuele Sanna
Paolo Santini

* Università di Firenze & INFN Sezione di Firenze

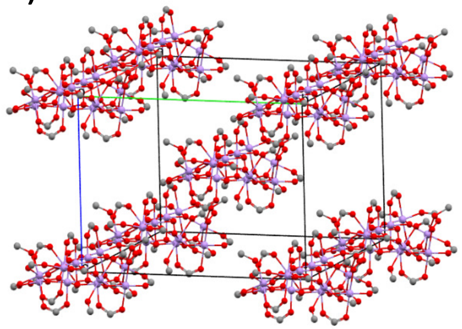
Firenze Unit Pavia Unit Milano Unit Bologna Unit Parma Unit

Nanomagneti molecolari

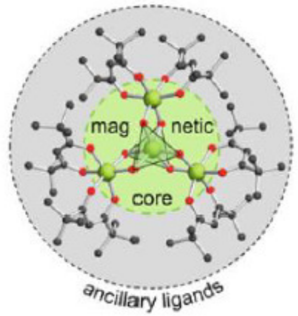
Materiali cristallini composti da molecole identiche magneticamente isolate, denominati ‘’magneti a singola molecola’’ (MSM)

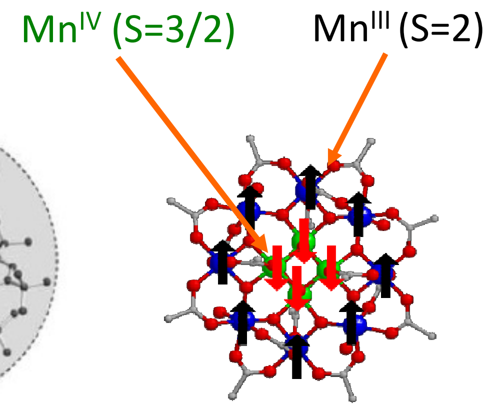
MSM:

1. Presentano un **core magnetico** costituito da un numero finito (n≥1) di centri paramagnetici (forti interazioni di scambio intramolecolari)
2. Sono schermati da leganti organici (deboli interazioni intermolecolari)



Mn_{12} crystal



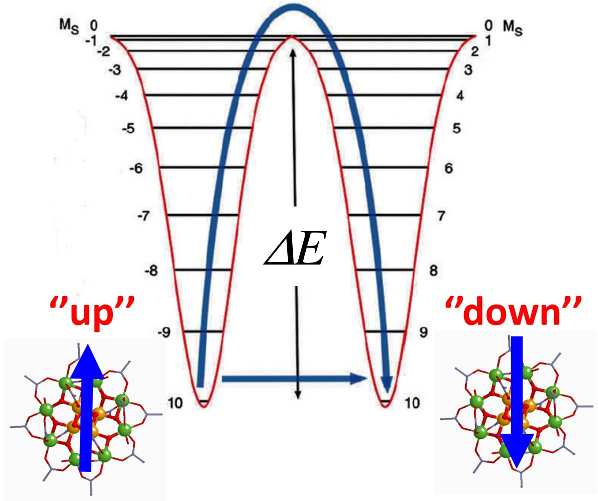


Mn_{12} core

→
- **Elevato valore di spin *S***
- **Forte anisotropia uniassiale → bistabilità magnetica a bassa T**
- **Tunneling quantistico della magnetizzazione**

MSM di ″riferimento″ (il più studiato), Mn_{12}:

$$S_{tot} = 10;\ \Delta E \approx 65\ \mathrm{K};\ \tau = \tau_0 \exp(\Delta E / k_B T),\ \tau_0 \approx 10^{-7}\mathrm{s}$$



Potenziali applicazioni:
- **Memory storage**
- **Quantum information**
- **Quantum sensing**

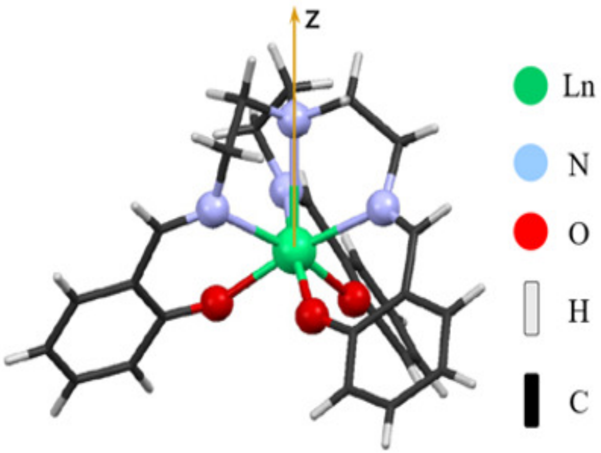
Gatteschi, Sessoli, *Angew. Chem. Int. Ed.* **42** (2003)

NAMASSTE: scopi

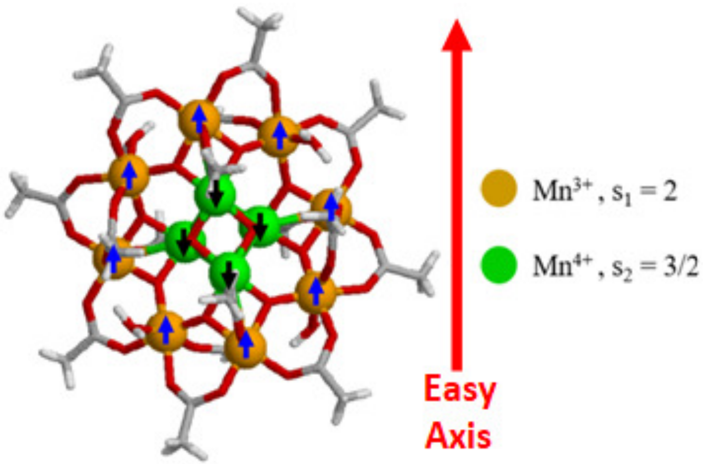
Progettare, sintetizzare e caratterizzare nuovi MSM per due differenti applicazioni:

- come sistemi di immagazzinamento di **memoria ad alta densità** (magneti a singolo ione (SIM))
- come **sensori di alta sensibilità** (considerando MSM, in particolare Mn12), potenzialmente idonei per la rivelazione di **materia oscura** (sensibilità in energia fino a ~ 10^{-3} eV): hidden photon [1], …..

Scopi da raggiungere mediante una combinazione innovativa di tecniche sperimentali
Magnetometria (SQUID), NMR, EPR e μ-SR, in sinergia con studi teorici



Ln-based SIM

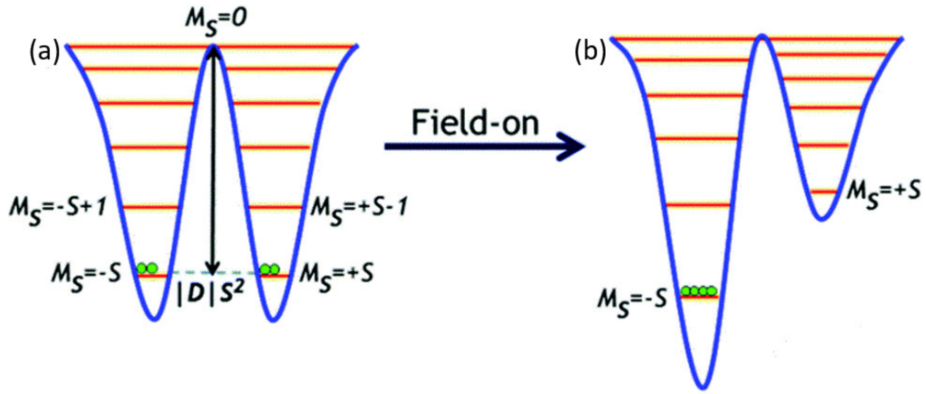


Mn_{12} MSM

[1] Bunting *et al. Phys. Rev. D* **95**, 095001(2017)

MSM come sensori

Il corrente approccio di rivelazione [1] si basa sull'idea che una particella incidente possa indurre una **''valanga magnetica''** nei cristalli di MSM immersi in un campo magnetico. Questo effetto è dovuto al rilascio dell'energia Zeeman, immagazzinata negli stati metastabili del MSM, legata alla presenza di un campo magnetico esterno.



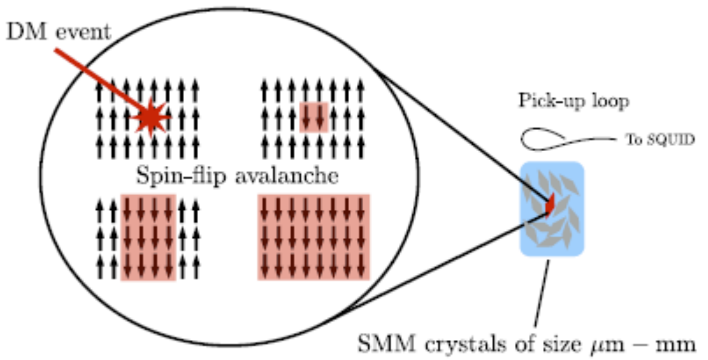
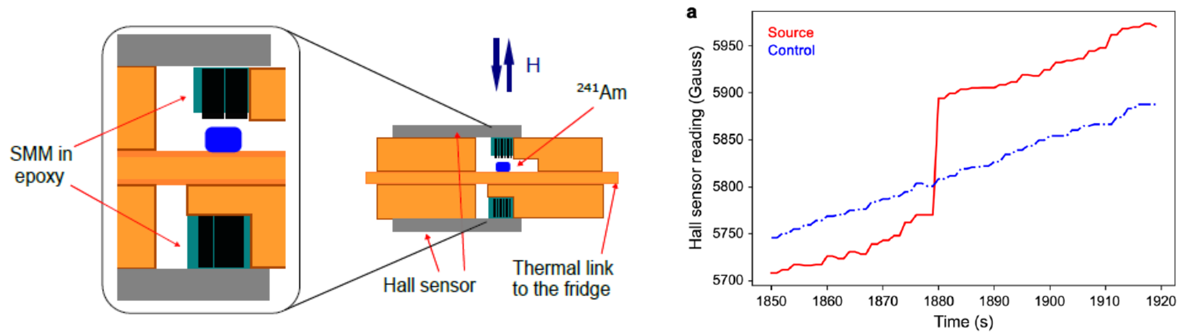


FIG. 1. DM detector concept based on magnetic deflagration in molecular nanomagnet crystals. A DM event that deposits energy in the form of heat ignites a spin-flip avalanche in the crystal which is detected by the change in magnetic flux through a pick-up loop.

[1] Bunting *et al. Phys. Rev. D* **95**, 095001(2017)

Studio preliminare usando particelle α [2]:
osservazione di valanghe indotte → prima evidenza di possibilità d'uso del Mn_{12} come sensore



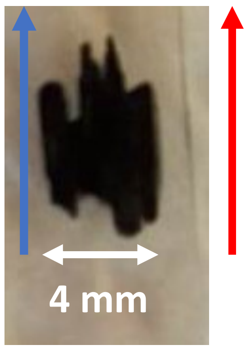
[2] Chen *et al.* arXiv:2002.09409v2

Attività in corso

Utilizzo di diverse tecniche per studiare il MSM Mn12 sotto l'effetto di sorgenti di radiazioni di bassissima attività:

- **Magnetometro di precisione (SQUID)**
  per riprodurre i recenti risultati riportati in letteratura e individuare le condizioni di setup ottimale

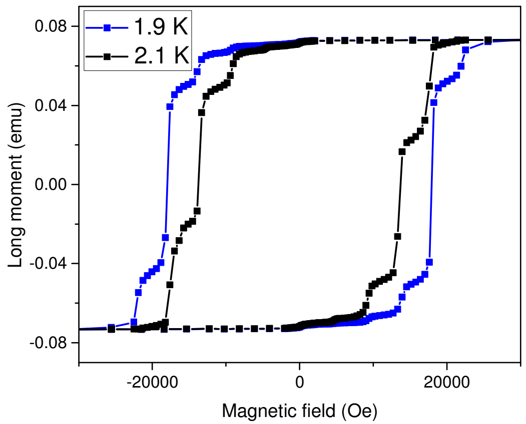
Incidenza prevista: ~ 1 α al min



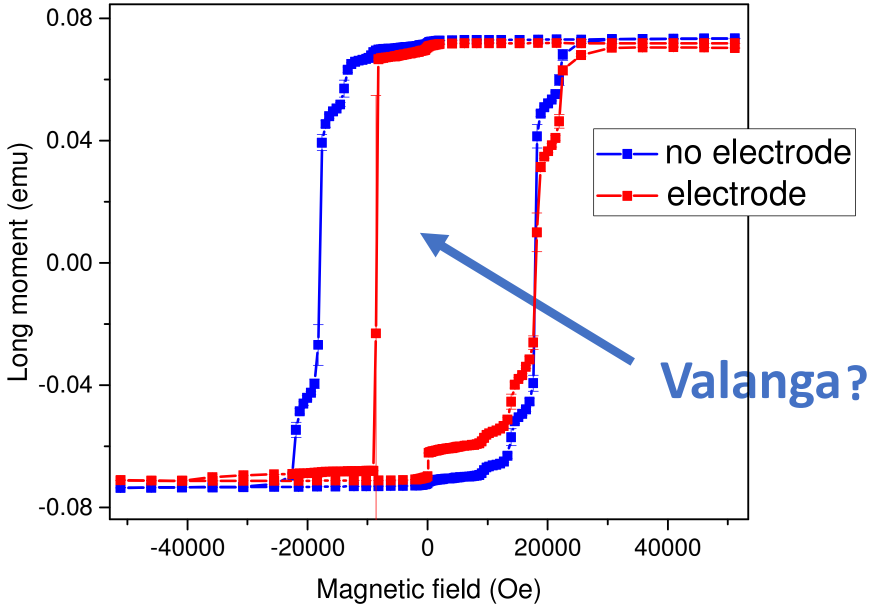
Asse facile magnetico

Campo magnetico

Isteresi senza sorgente α



Isteresi con sorgente α



- **Electron Paramagnetic Resonance (EPR)**
- **Nuclear Magnetic Resonance (NMR)**

Tecniche di sonde locali: questo approccio (basato su studio di perturbazione dei tempi di rilassamento) è atteso essere più sensibile rispetto alle tecniche magnetometriche come SQUID, basate sulla misura della variazione di magnetizzazione nell'intero volume del sensore

- **Studio teorico su modellizzazione dell'interazione radiazione-MSM**

Backup (I)

Bunting *et al., Phys. Rev. D* 95, 095001(2017):

→ I MSM come sensori competitivi per la rivelazione di Dark Photon a basse masse

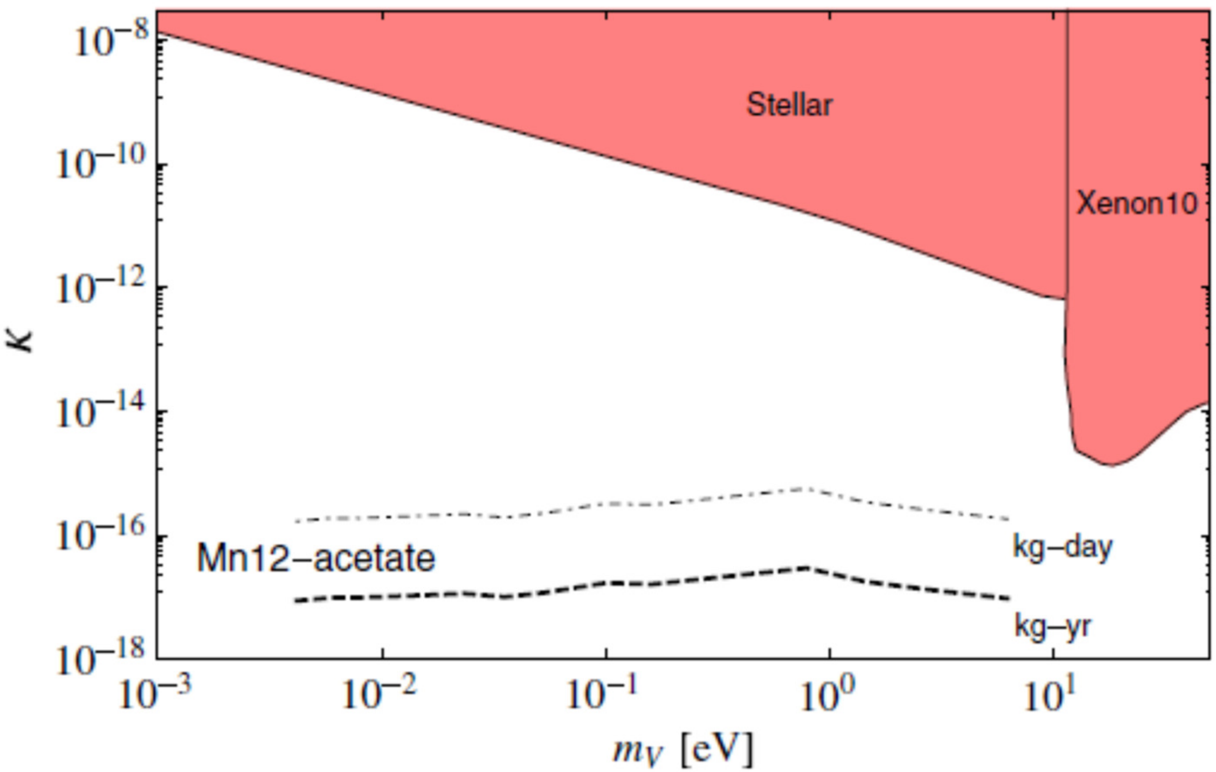


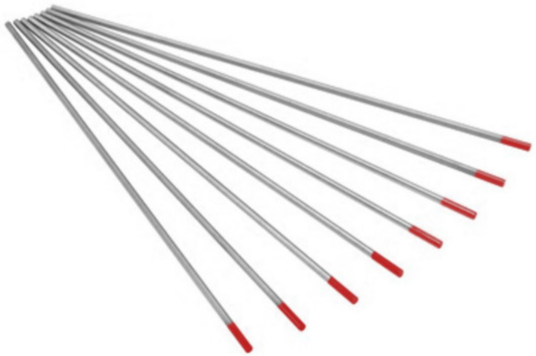
FIG. 6. Estimated sensitivity to absorption of dark vector DM in Mn_{12}-acetate, assuming an aggressive sensitivity of 1 event/kg year (dashed), and a sensitivity of 1 event/kg day (dot-dashed). The absorption data from Refs. [62,65] (described in the appendix) has been smoothed, an interpolation used in the region $m_V \sim 0.2$–0.5 eV, for which no data was available, and we use the approximation $\kappa \simeq \kappa_{\rm eff}$ (see text).

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ^\mu_{\rm em}A_\mu$$

Backup (II) - MSM come sensori: sorgenti di radiazioni

Richiesta: sorgenti α/β di bassissima attività, da adattare alle ridotte dimensioni degli strumenti usati

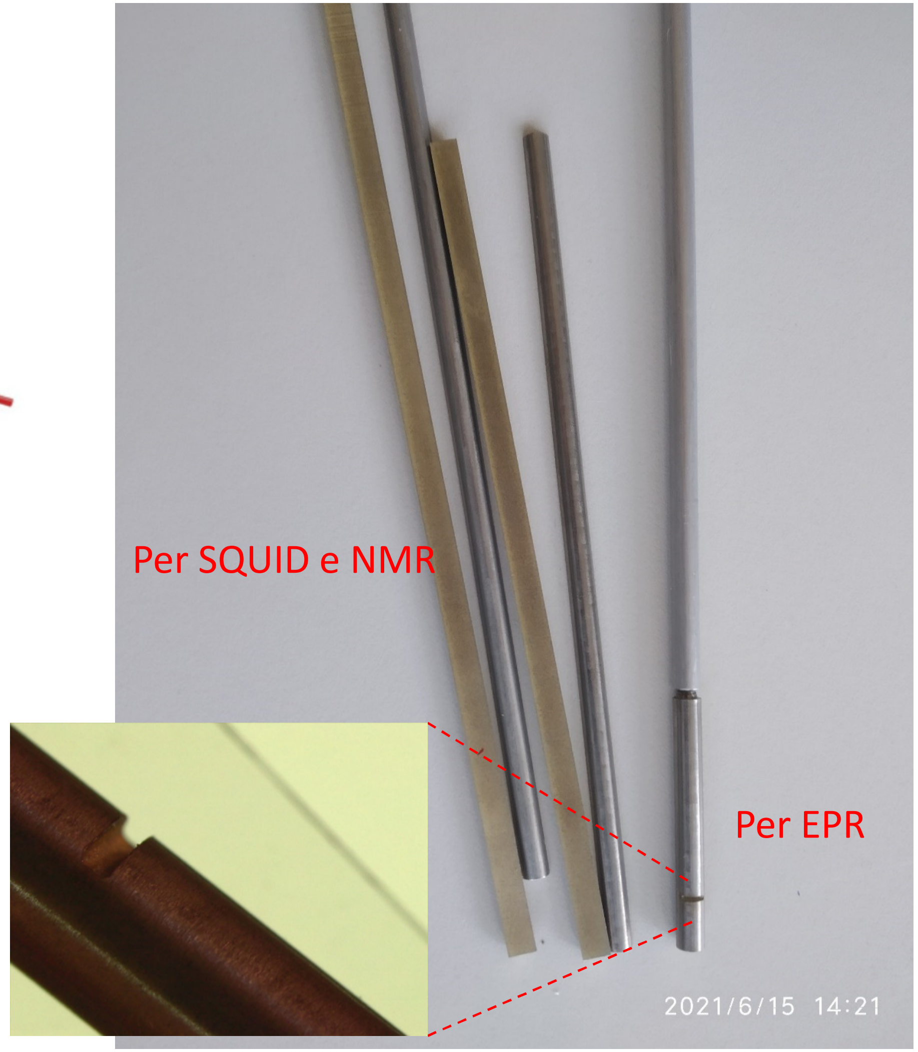
- soluzione: realizzate con elettrodi per saldatura speciale di W contenente Th al 2% (<u>prodotto commerciale con attività al di sotto dei limiti di legge</u>)



- attività α superficiale misurata (@ PV): 0.22 dec/(mm^2 min)
  (con addizionale attività β/γ di circa x20)

- Lavorazione (@ PV) con taglio meccanico di precisione per adattarle alle specifiche necessità tecniche degli strumenti:
  → per EPR: barretta cilindrica (D = 4 mm), con piccolo taglio trasversale per allocare il sensore (sorgente usata come porta-campione)
  → per SQUID e NMR: barretta semi-cilindrica (D = 4 mm)

- Recente acquisizione/lavorazione addizionale:
  elettrodi di W, identici ai precedenti, ma *senza* drogaggio con Th;
  → <u>possibilità di effettuare misure con e senza sorgente nelle identiche condizioni sperimentali</u>



INFN Workshop on future detectors 2022

Bari 17-19/10/2022

Toward single-photon detector based on Josephson effect for dark matter search

Alessandro D'Elia, Ph.D.

INFN-LNF

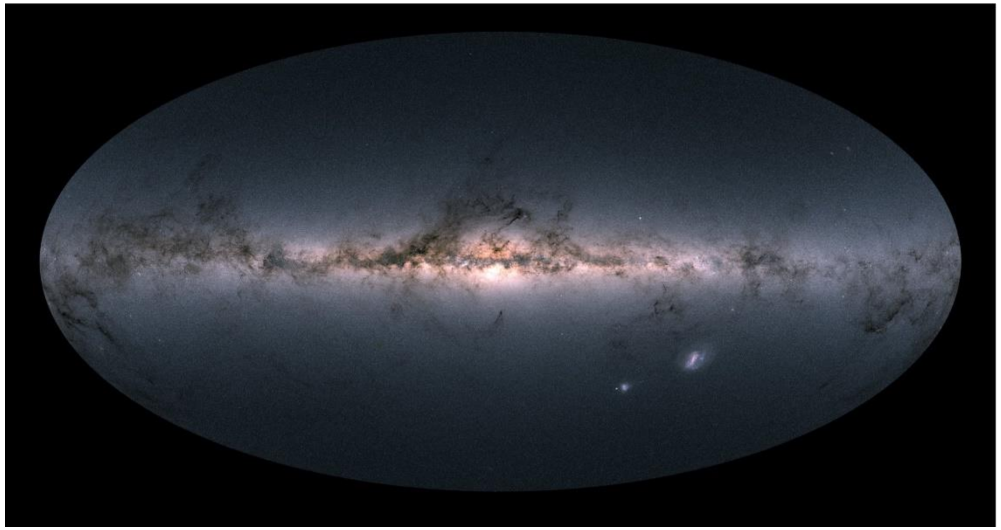
SUPERGALAX

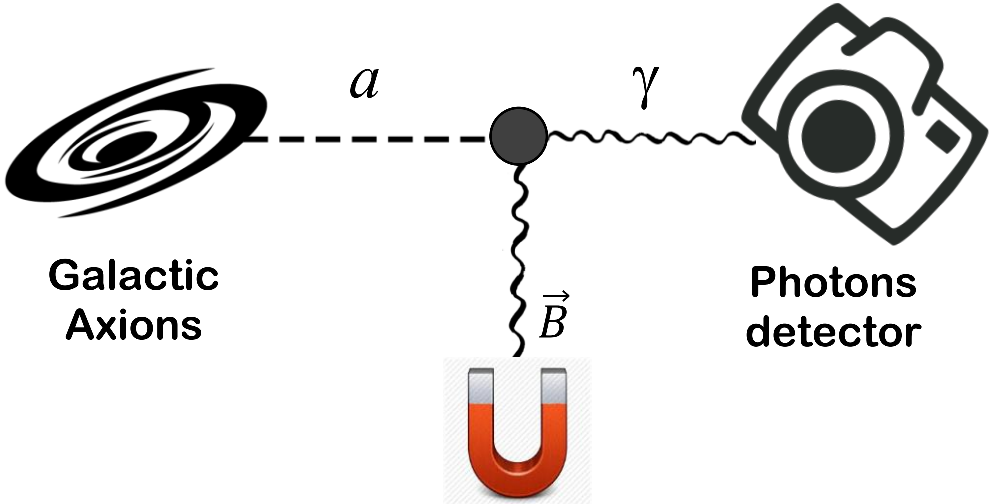
INFN Istituto Nazionale di Fisica Nucleare

COLD LNF Cryogenic Laboratory for Detectors

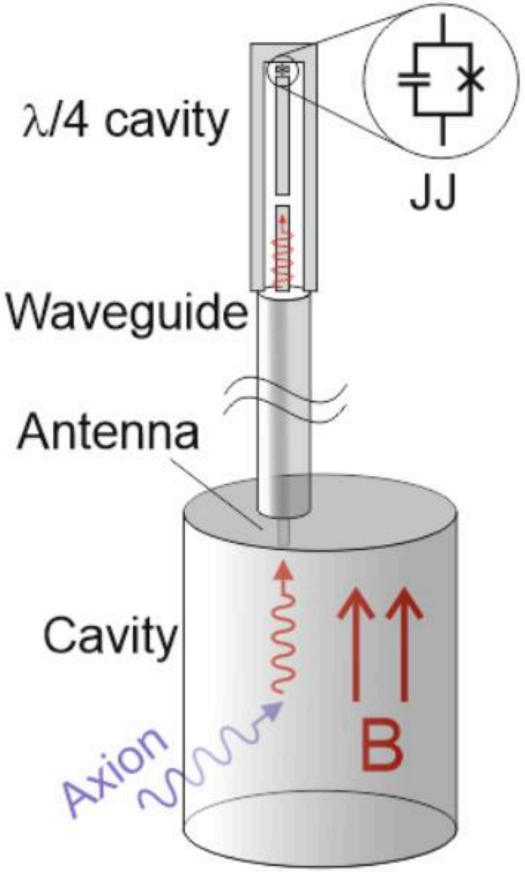
alessandro.delia@lnf.infn.it

Dark matter search





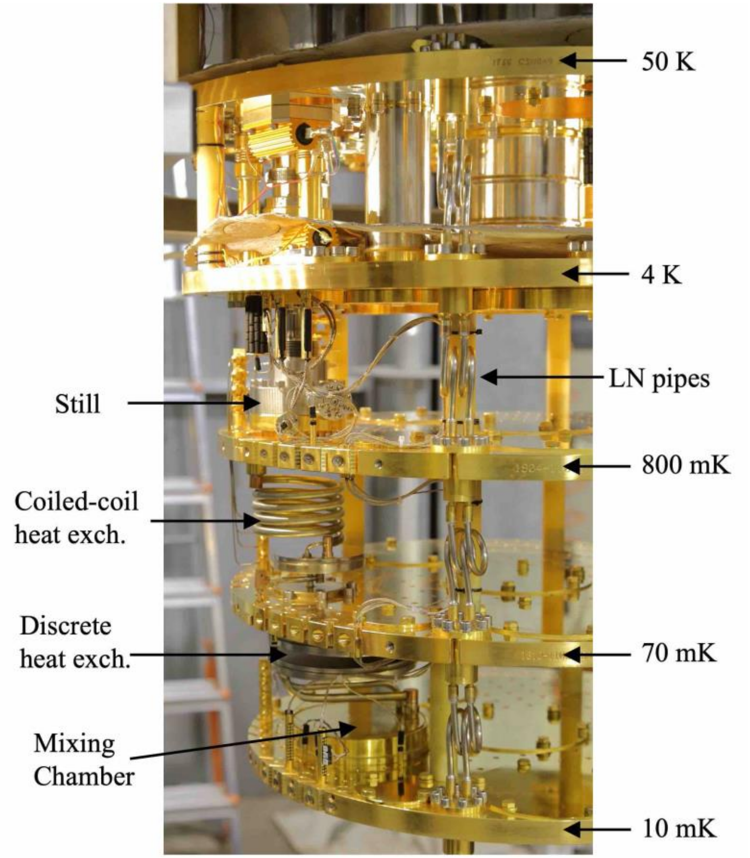
We need for a single photon detector with ultra low noise



COLD laboratory cryostat

LEIDEN CRYOGENICS

$$T_{base} = 8\,mK$$



Magnet 9 T

SUPERGALAX

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.

SUPERGALAX → *Study the changes induced in a Transmission line when a Coherent array of Qubits "sees" a photon*

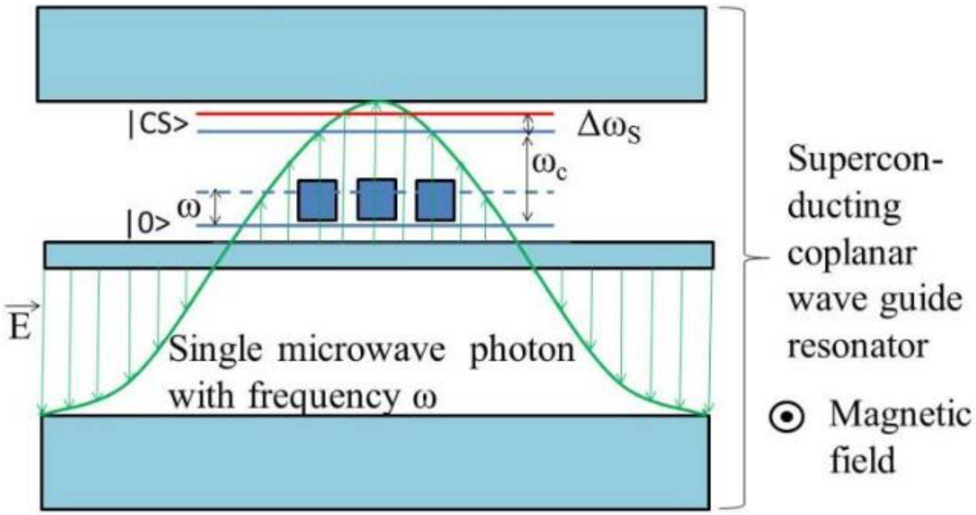
↓

Exploit AC Stark effect to shift the qubit array collective mode

↓

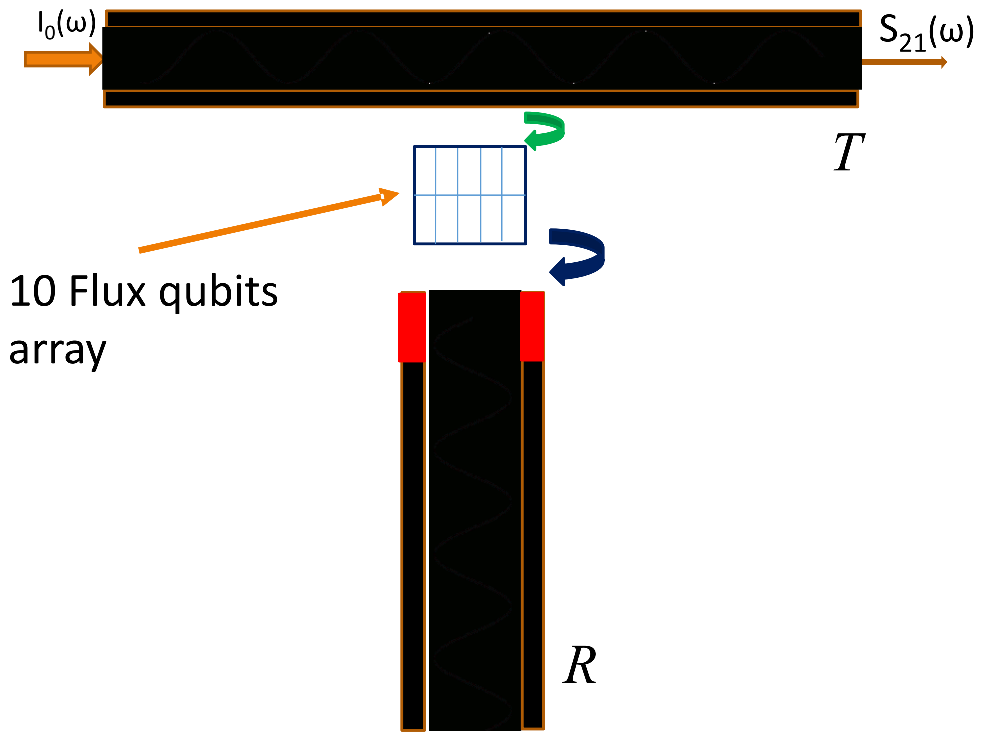
We try to detect this small $\Delta\omega_s$

Using a Qubits array th predicted scaling of the signal to noise ratio goes as N instead of $\sqrt{N}$

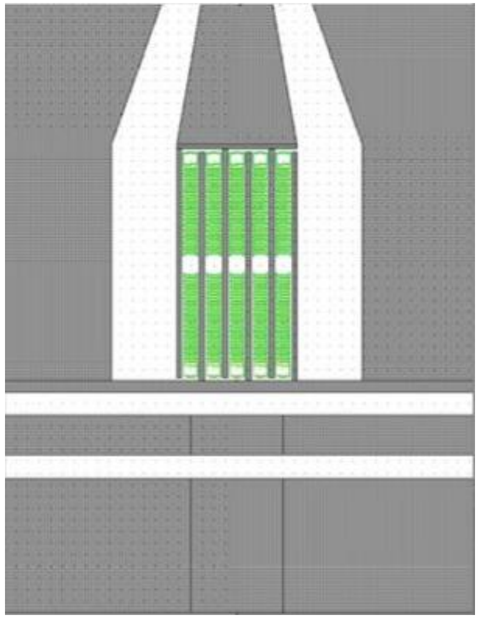


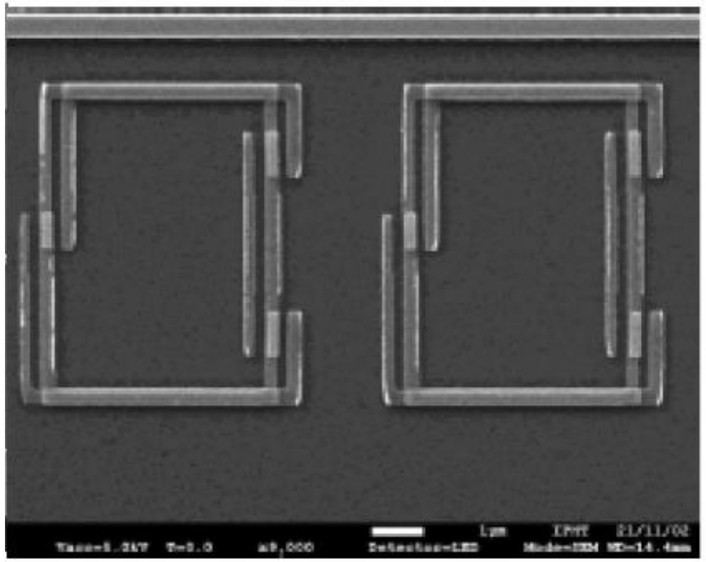
SUPERGALAX outline

Two uncoupled resonators at the same resonant frequency both coupled to an array of qubits



Leibniz-Institut fuer Photonische Technologien

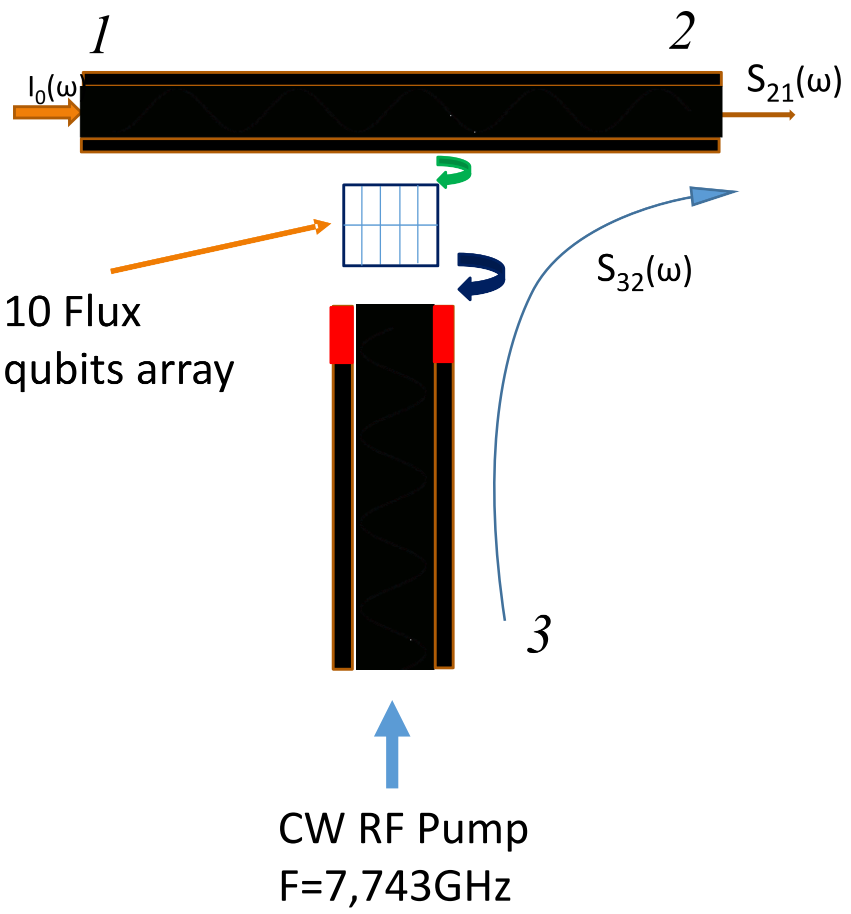


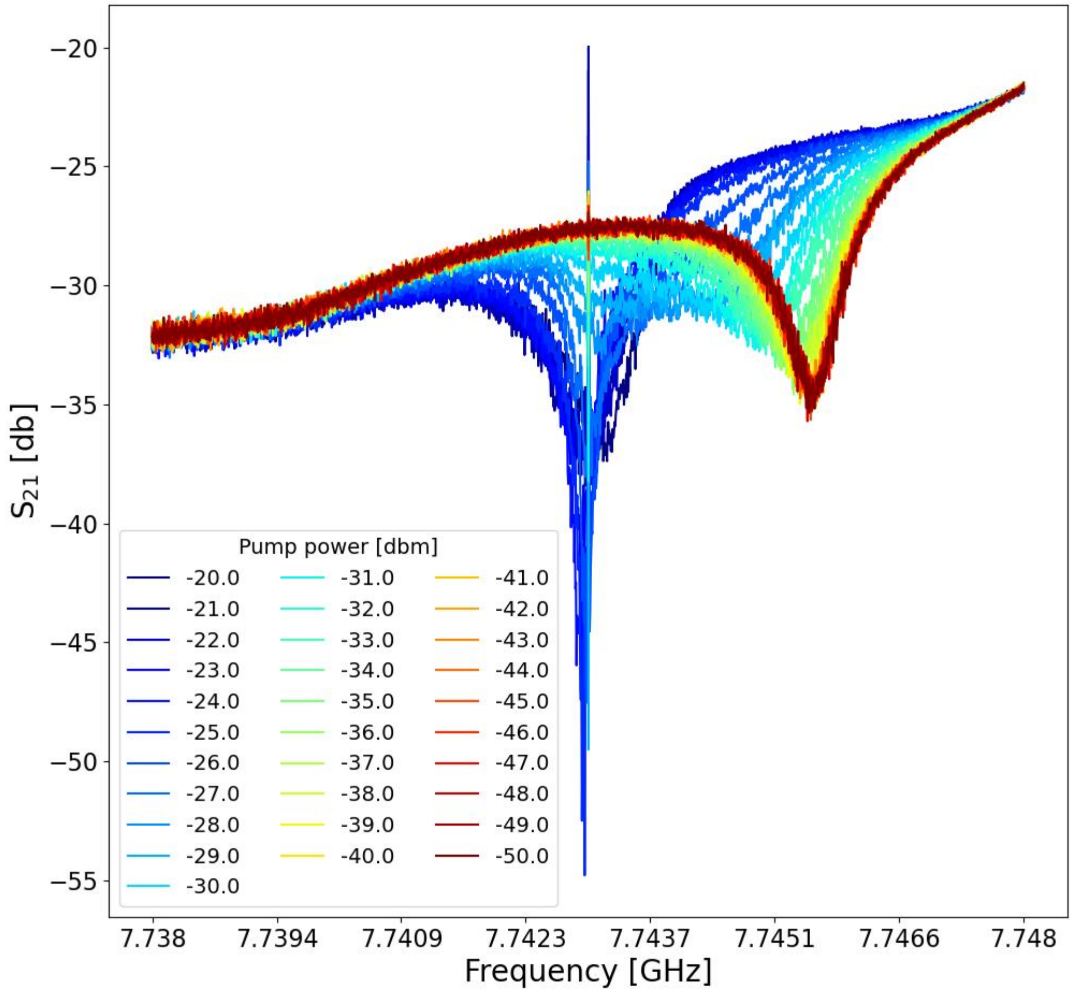


Study the change in S_{21} transmission when sending photons trough resonator R

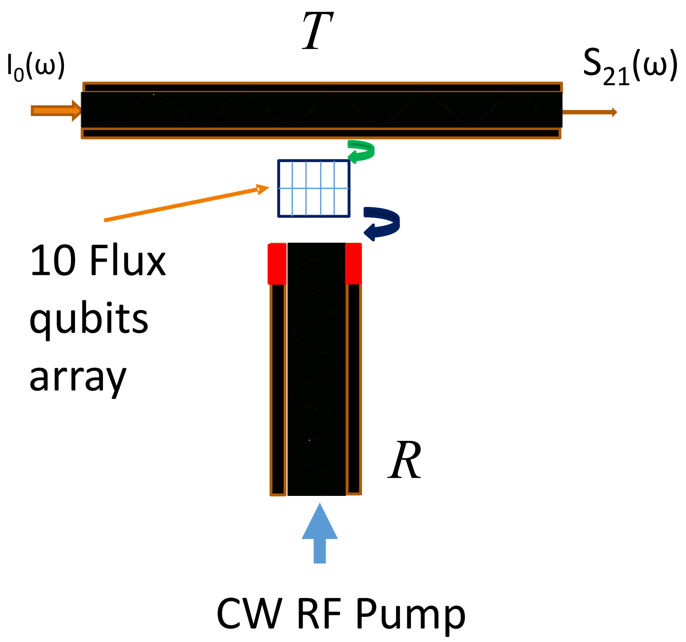
Application of magnetic field to tune the Qubits array not yet possible!

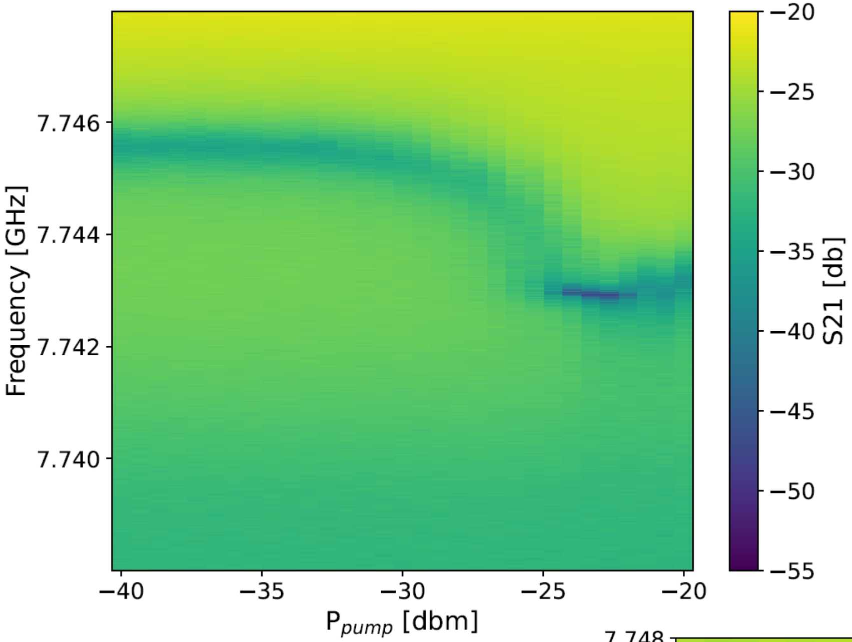
SUPERGALAX preliminary results

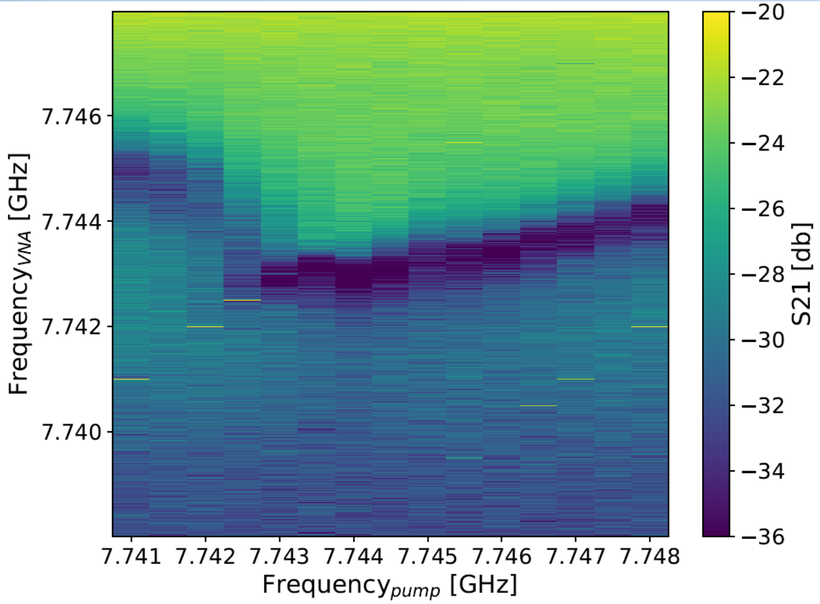


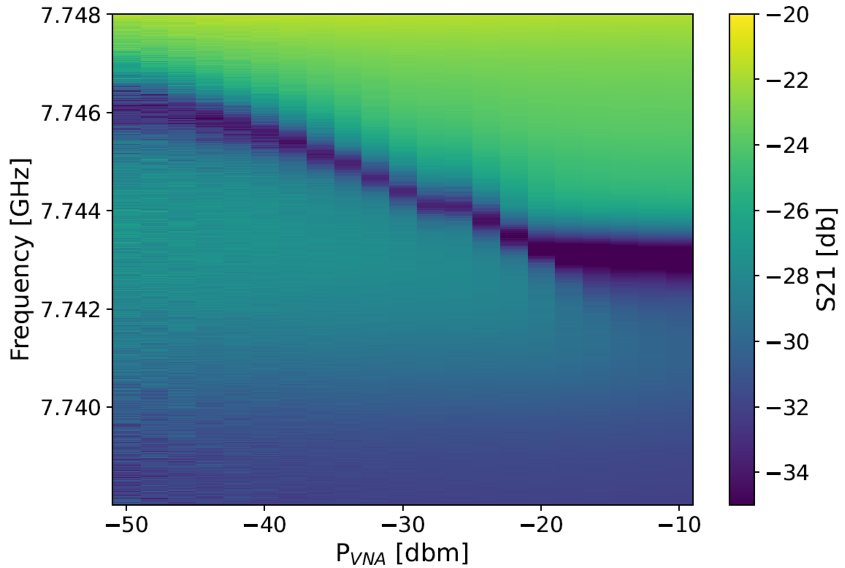


SUPERGALAX preliminary results









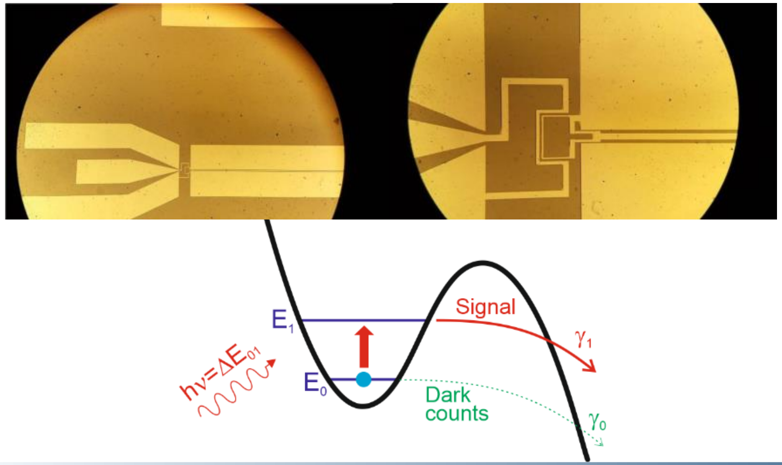
The transmission on the upper branch (S21) is modified of ~ 4 MHz when RF is injected in the R resonator

Conclusions and contacts

We demonstrated that the S_{21} of a transmission line is modulated up to ~ 4 MHz by pumping RF into a third line, coupled to a qubit array, and arranged in a «transistor-like» geometry.

Work in progress

Single photon detector with one Josephson junction terminated on a transmission line



Magnetic field resistant Josephson junction using van der Waals materials

Contacts

Acknowledgment

THANK YOU FOR YOUR ATTENTION!