Quantum Technologies applied to 2∞ physics

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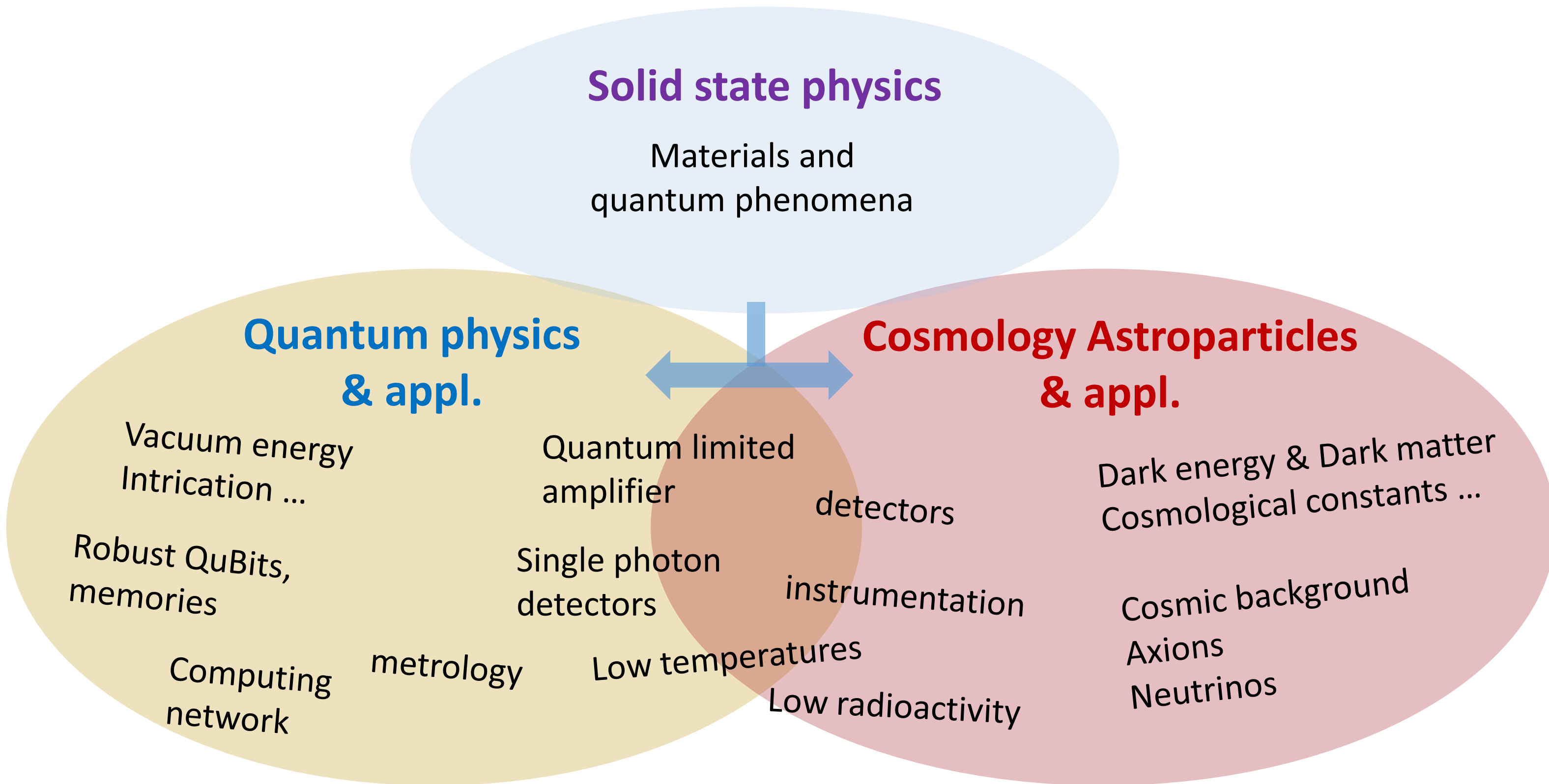
Quantronics Group, Service de Physique de l’Etat Condensé, **CEA Saclay**

QT / 2∞

What do they have in common?



Qu-tech ➔ **reaching the « quantum limit »**

Advanced electronics
Shields from radioactivity ← **Cosmology – astroparticles**

“Quantum Detectors”

What are we talking about?

Quantum Sensing, C.L. Degen et al.

“ Use of a *quantum system*, *quantum properties* or *quantum phenomena* to perform a measurement of a physical quantity” Rev. Mod. Phys. **89**, 035002 (2017)

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Device based on quantum physics (eg solid state…)?
➔ ~ all of them

Device that operates in the quantum regime ?
i.e. kT<< characteristic energies

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More specifically: detectors that exploit

- Quantum coherence
- Superposition
- Entanglement
- Squeezing
- backaction evasion

“Quantum Detectors”

Synopsis

General scope: single ‘X’ (atom, electron, …) devices

Key feature: quantum coherence

Figure of merit: strong sensitivity to external disturbances

Famous examples:
Atom clocks, squids, cold atom gravimeters, gravitational wave detectors

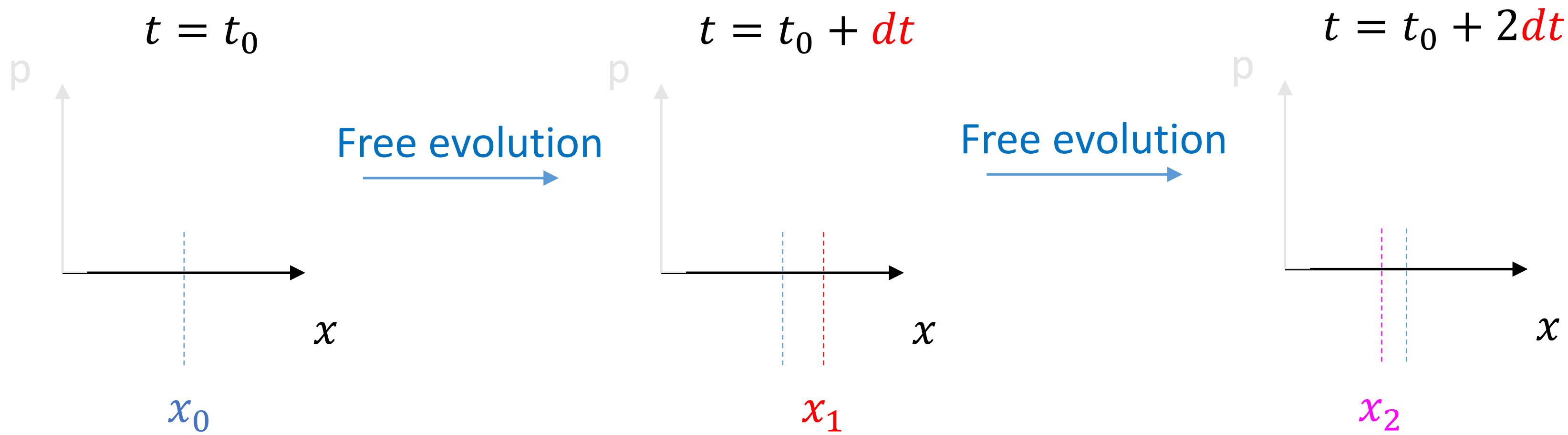
Already exploited to measure:
magnetic and electric fields, time and frequency, gravity field (eg rotations…), temperature, pressure…

Today's menu

- What does a « quantum measurement » mean ?
  A bit of definitions
- Two strategies for em field measurements:
  click or flux
- How to build a superconducting quantum circuit
  low losses and some nonlinearity
- 2 nice examples of QT detectors applied to **2**∞
  The parametric amplifier and the single microwave photon counter

Measurement in quantum mechanics

Measure the position x of a free particle with super high precision



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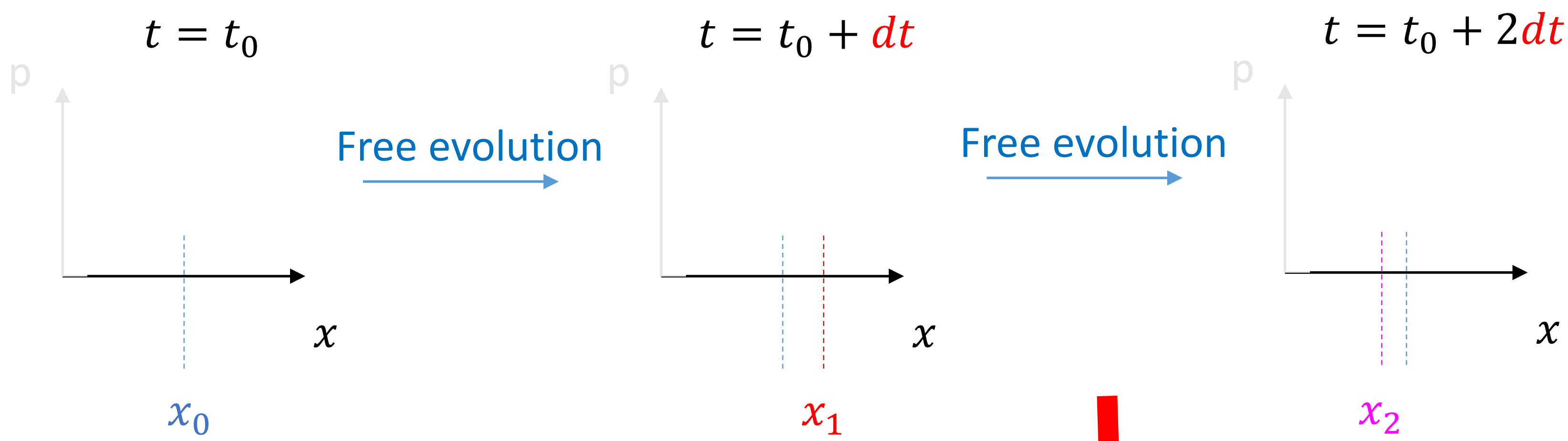
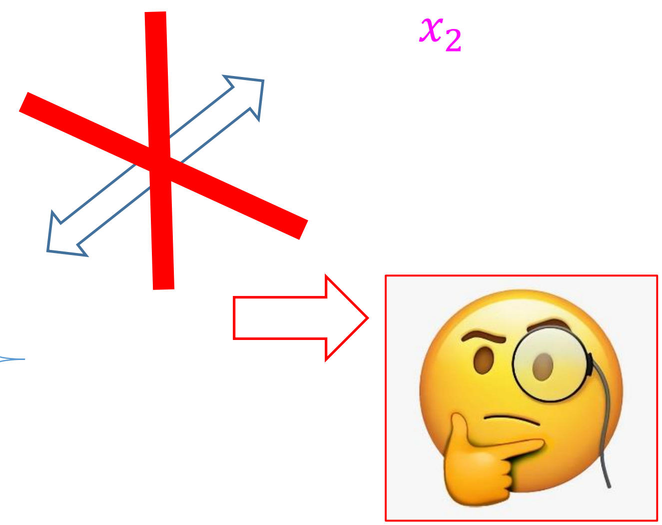


$$x_1 = x_0 + \frac{p}{m} dt$$

$$x_2 = x_1 + \frac{p}{m} dt$$

Free evolution : p conserved



Measurement in quantum mechanics

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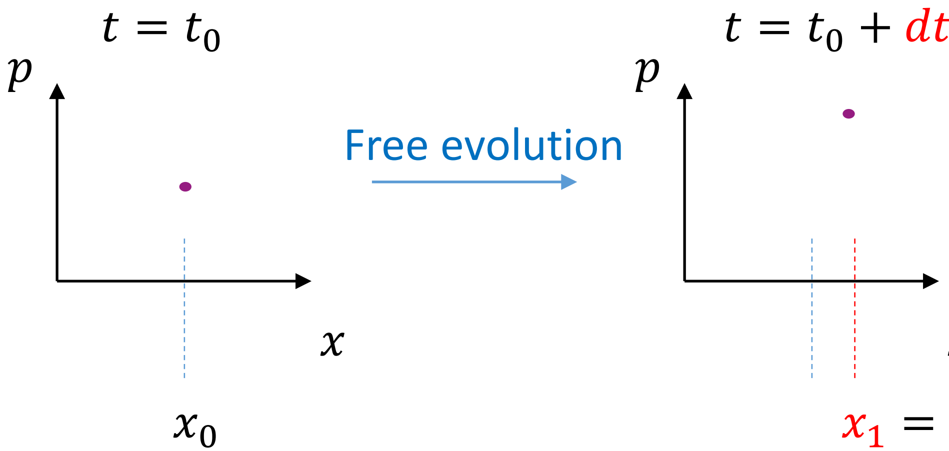


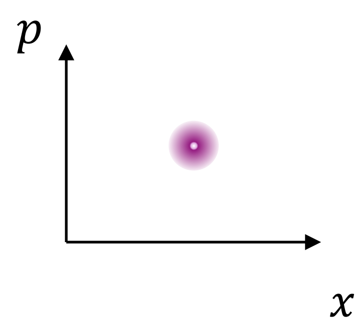
$$x_1 = x_0 + \frac{p}{m} dt$$

$\boldsymbol{x}$ measurement has given an unpredictible (and non reproducible) kick on $\boldsymbol{p}$

Conversely, measuring $\boldsymbol{p}$ would push $\boldsymbol{x}$ in an unpredictible (and non reproducible) way

« measurement back-action »

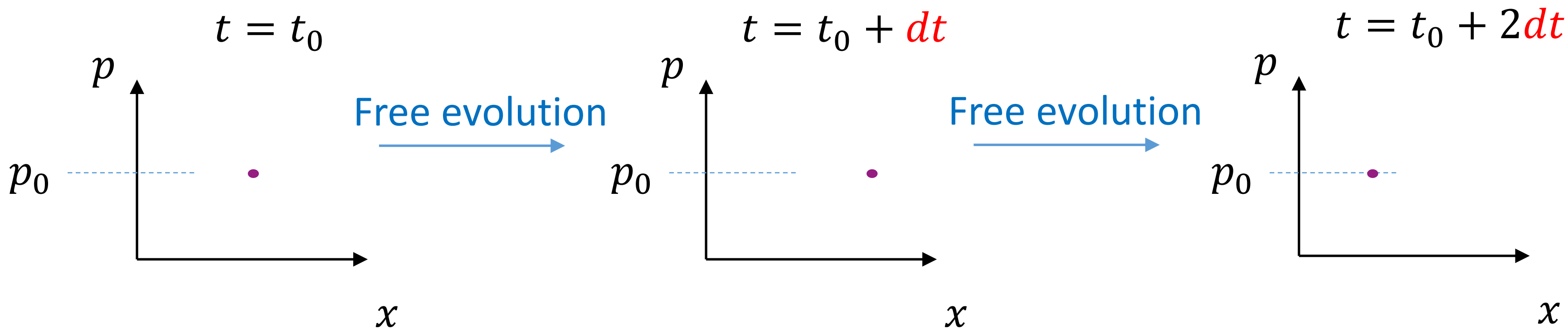
$$[\hat{x}, \hat{p}] \neq 0$$

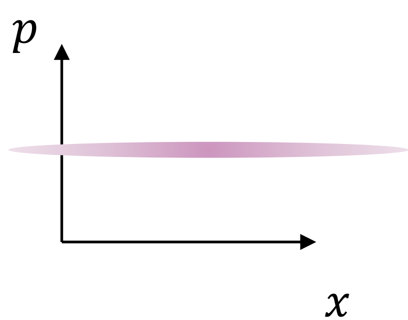


$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

Measurement in quantum mechanics

Measure the momentum p of a free particle with super high precision





$$x_1 = x_0 + \frac{p}{m} dt$$

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Free evolution : p conserved

« Quantum Non Demolition measurement of p »

Measurement in quantum mechanics

Quantum non demolition $[\hat{a}(t), \hat{a}(t+dt)] = 0$

V. Braginsky, Y. I. Vorontsov, and K. P. Thorne, Science 209, 547 (1980), see also Caves, Unruh

Free particle

$$[\hat{x}(t), \hat{x}(t+dt)] = i\,\hbar\, dt/m$$

$$[\hat{p}(t), \hat{p}(t+dt)] = 0$$

$$\hat{H}\,|n\rangle = E_n|n\rangle$$

p and E are continuous QND observables

Oscillator

$$[\hat{x}(t), \hat{x}(t+dt)] = \frac{i\,\hbar}{m\omega}\sin(\omega\, dt)$$

$$[\hat{p}(t), \hat{p}(t+dt)] = i\,\hbar\, m\omega \sin(\omega\, dt)$$

x and p are stroboscopic QND observables !

amplitude

E and $x \pm i\,\frac{p}{m\,\omega}$ are continuous QND observables !

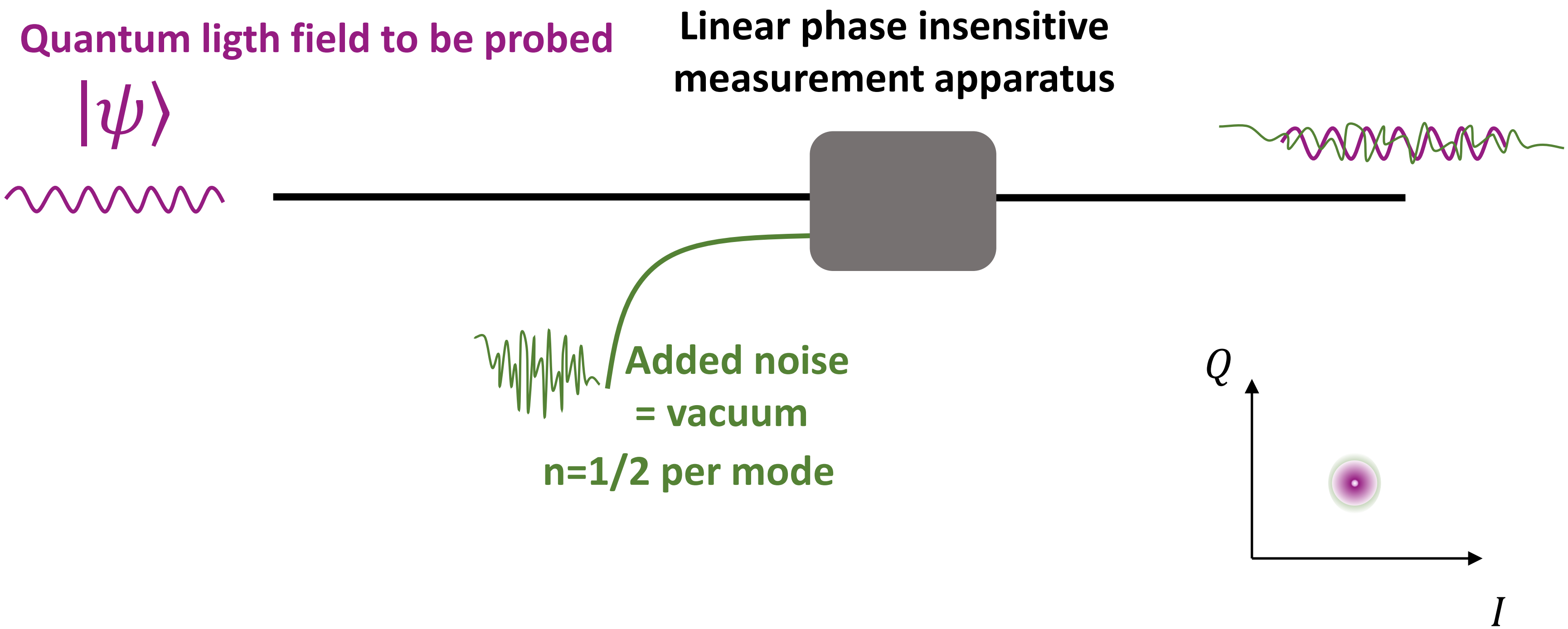
⚠ Quadratures do not commute

Measure one quadrature of the amplitude : « Backaction evading measurements »

Measuring small (coherent) fields

Noise added by vacuum fluctuations

Caves, Phys. Rev. D **1981**, 23, 1693–1708

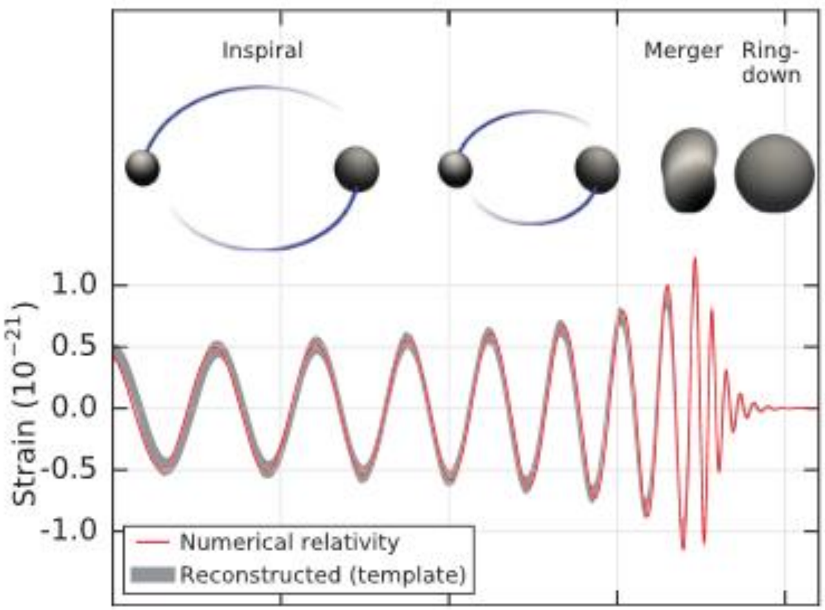


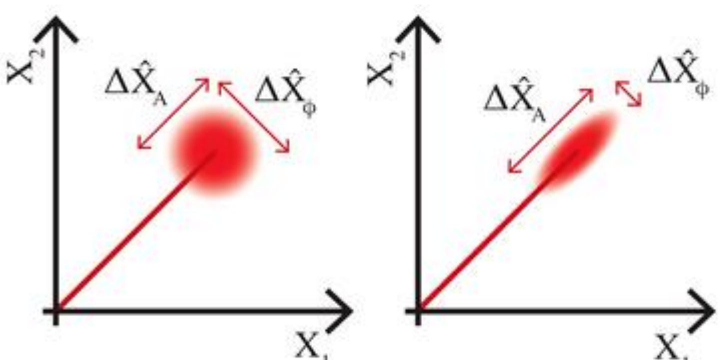
« Standard quantum limit »

Strategy: Prepare vacuum in a « squeezed state » to reduce measurement noise

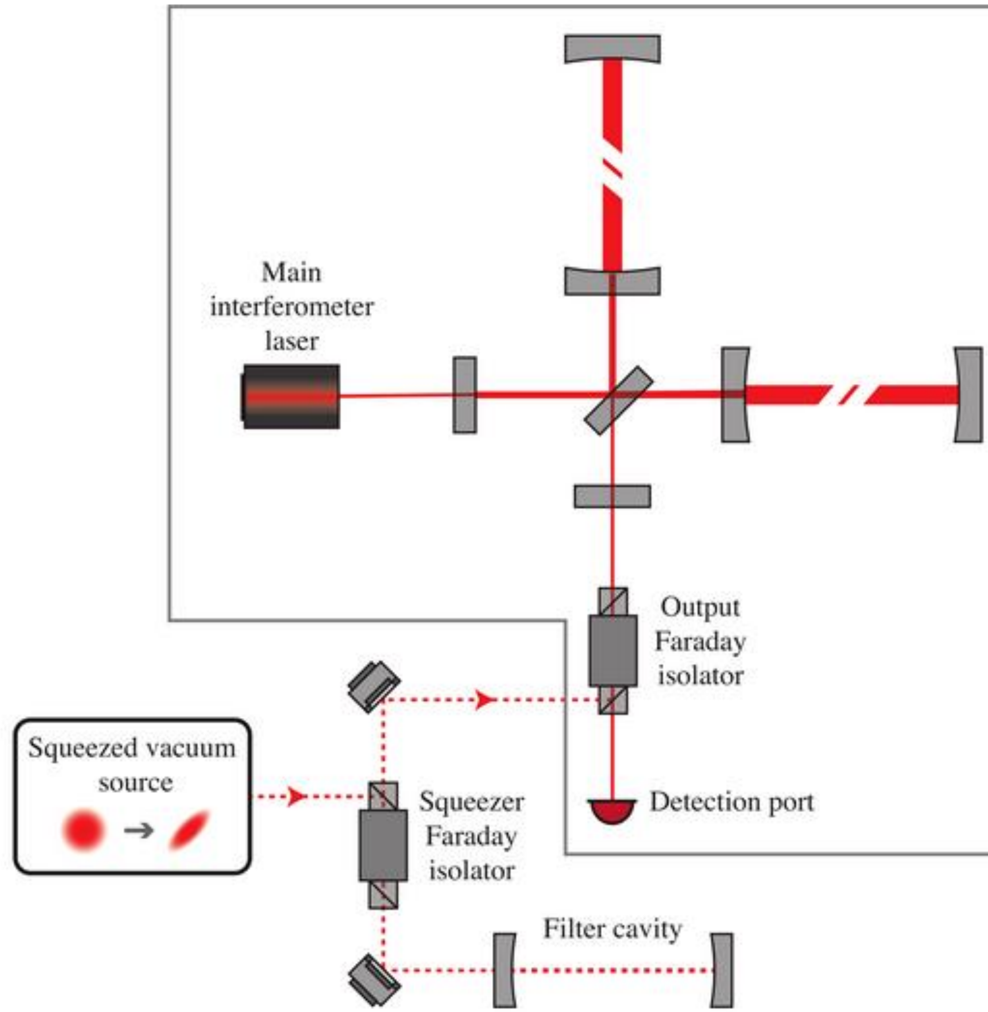
GW detectors use squeezing in order to beat standard quantum limit

PRL **116**, 061102 (2016)





Galaxies 2022, 10(2), 46



Click detector versus flux detector

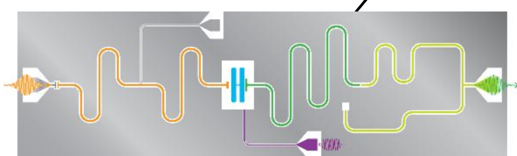
quantum

Example of photon - em detection

Quantum ligth field

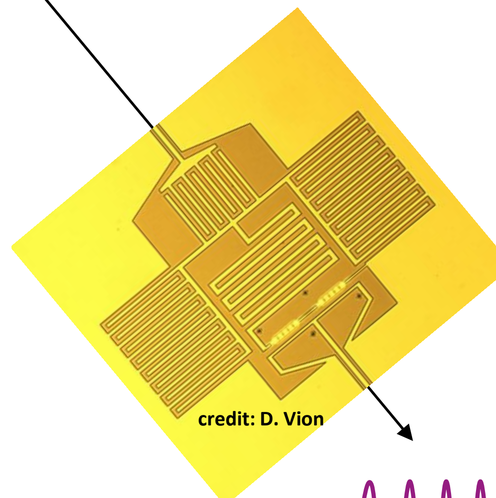
$|\psi\rangle$

Photon detector



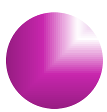
credit: E. Flurin

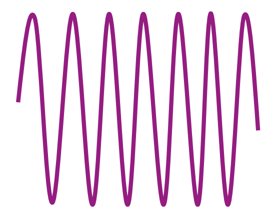
Field detector



credit: D. Vion

particle like





wave like

Particle number $\in \mathbb{N}$

Amplitude $\in \mathbb{C}$

quantum

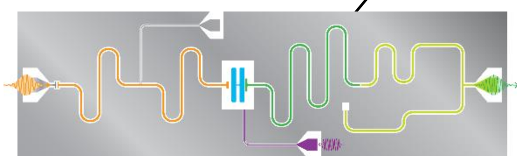
Click detector versus flux detector

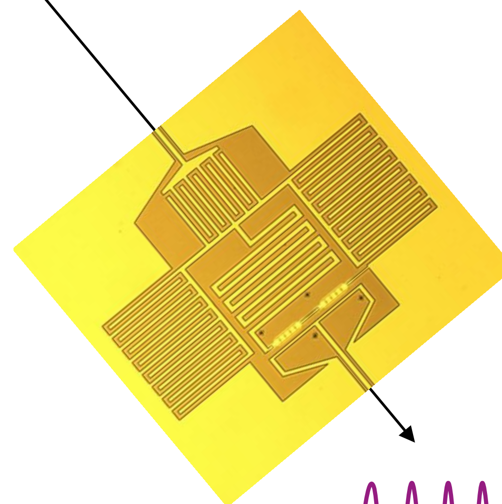
Example of photon - em detection

Quantum ligth field

$|\psi\rangle$

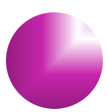
Photon detector

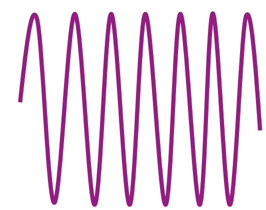




Field detector

particle like





wave like

Uncertainty principle

Particle number ∈ ℕ

Amplitude ∈ ℂ

2∞: Rare events, incoherent ➔ needs mostly **click detectors**

Click detector versus flux detector

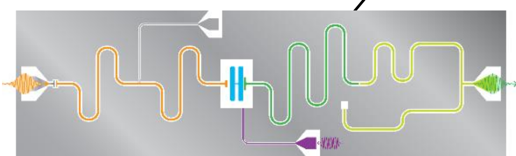
quantum

Example of photon - em detection

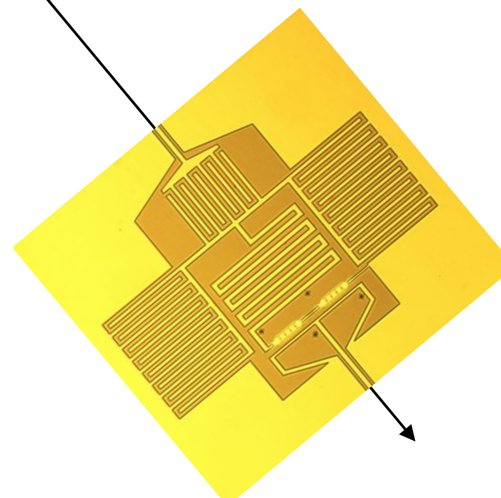
Vacuum

$|0\rangle$

Photon detector



Field detector



t

Absence of click

t

Vacuum fluctuations

quantum

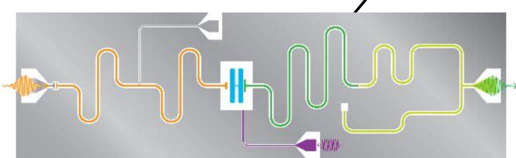
Click detector versus flux detector

Example of photon - em detection

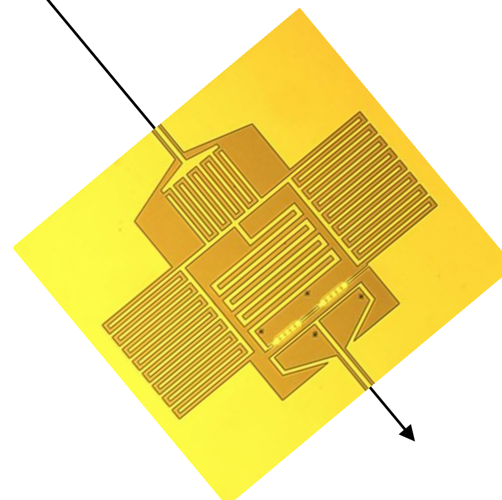
Single photon

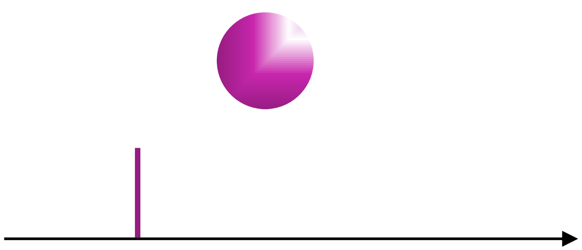
$|1\rangle$

Photon detector



Field detector





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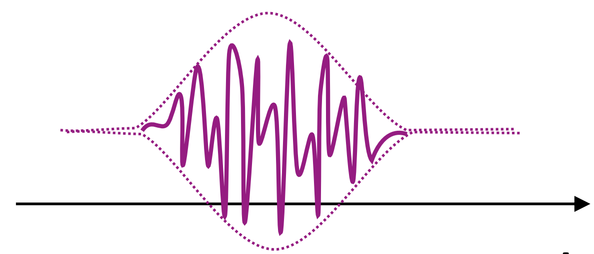
single click



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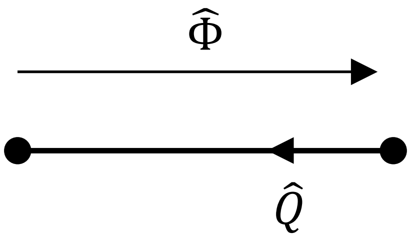
Excess fluctuations

(superconducting) circuit description

for Quantum Technologies



$$\hat{\Phi}(t) = \int_{-\infty}^{t} \hat{V}(t')dt'$$ flux - « position »

$$\hat{Q}(t) = \int_{-\infty}^{t} \hat{I}(t')dt'$$ charge - « momentum »

$$[\hat{\Phi}, \hat{Q}] = i\hbar$$ conjugate variables

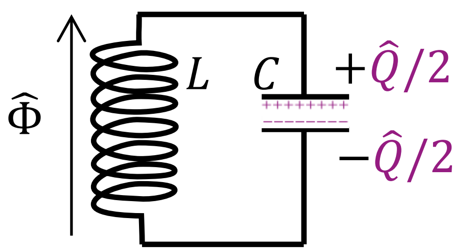
dimensionless variables :

$$\hat{\varphi} = 2\pi \frac{\hat{\Phi}}{h/2e}$$ "phase"

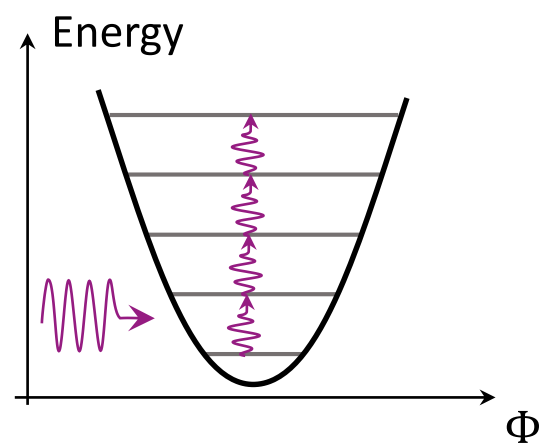
$$\hat{N} = \hat{Q}/2e$$ # Cooper pairs

$$[\hat{\varphi}, \hat{N}] = i$$

simplest quantum object : **harmonic oscillator**



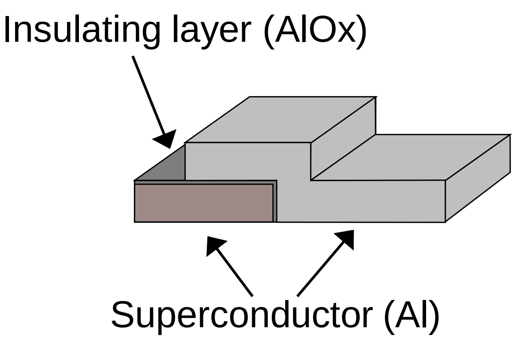
$$H = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C}$$

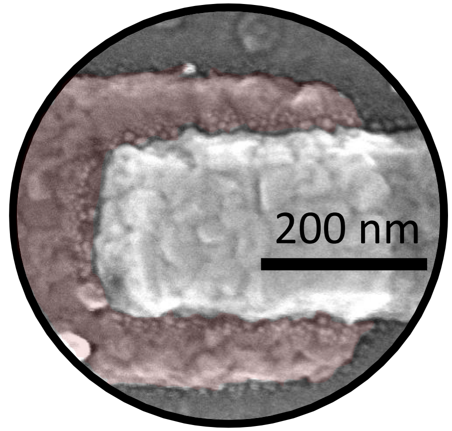


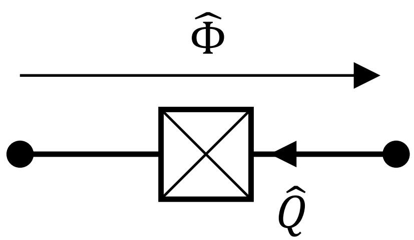
need to add non-linearity !

Josephson Junction

THE non-linear element at the root of most superconducting quantum devices

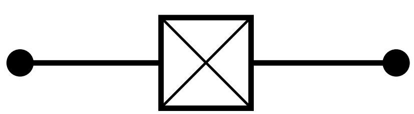
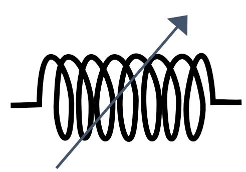






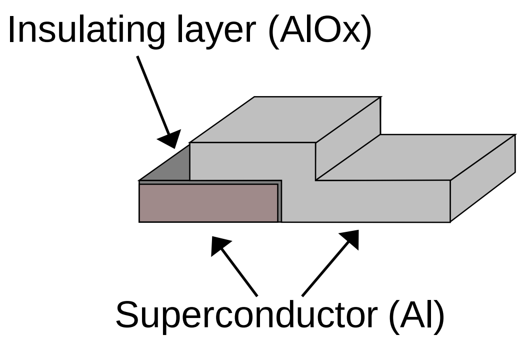
potential term ~~$\frac{\hat{\Phi}^2}{2L}$~~ becomes $E_J \cos(\hat{\Phi}) \equiv \frac{\hat{\Phi}^2}{2L(\Phi)}$

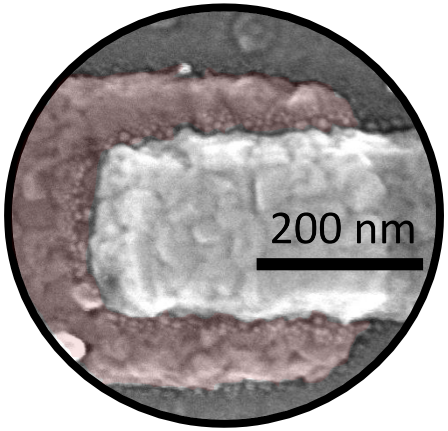
(analogous to a pendulum)

 $\rightleftharpoons$  non linear inductor

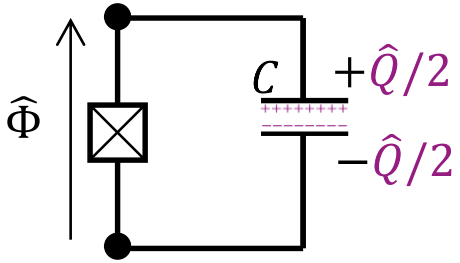
Josephson Junction

dissipationless nonlinear inductor

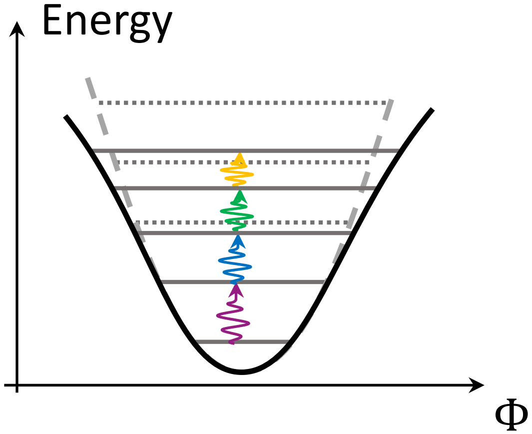


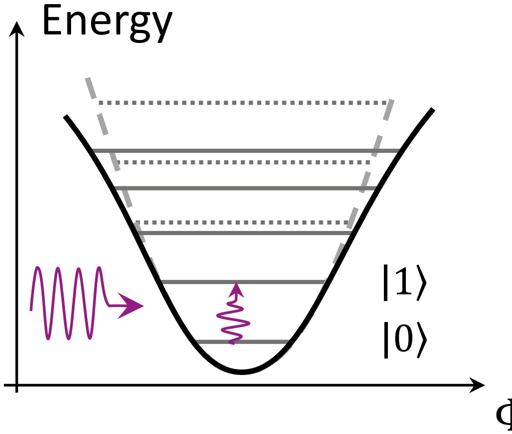


QuBit: non-linear **oscillator**



$$H = E_J \cos(\hat{\Phi}) + \frac{\hat{Q}^2}{2C}$$



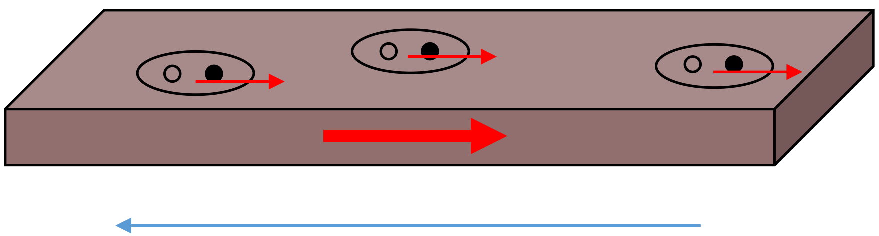


effective two level system

Josephson / kinetic Inductance

property of the superfluid condensate

$|\Psi\rangle = \Delta\, e^{i\varphi}$

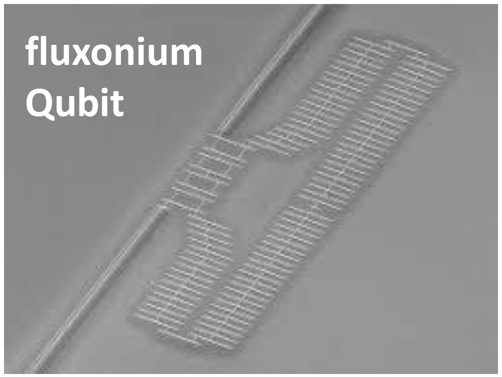


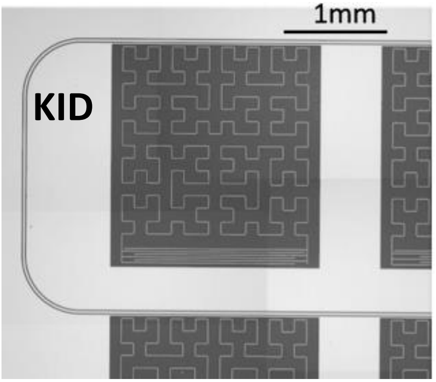
$\nabla\varphi$

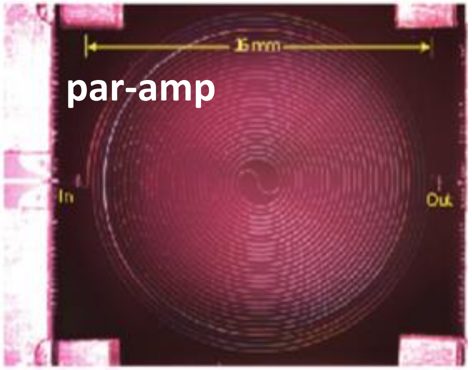
kinetic inductance

$$\left.\frac{\partial I}{\partial \phi}\right|_{I=x} \equiv L_K^{-1}$$

Used in many fields: **quantum technologies and cosmology / astroparticles**



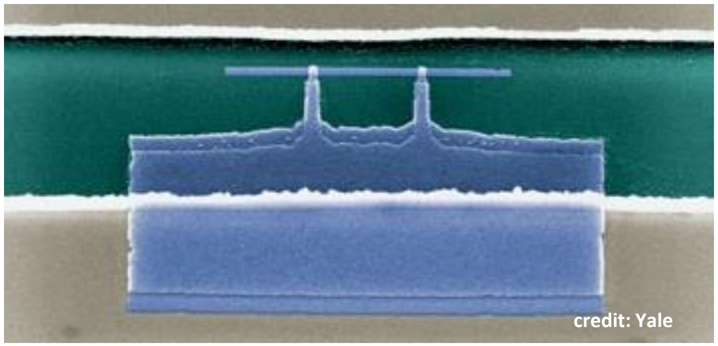




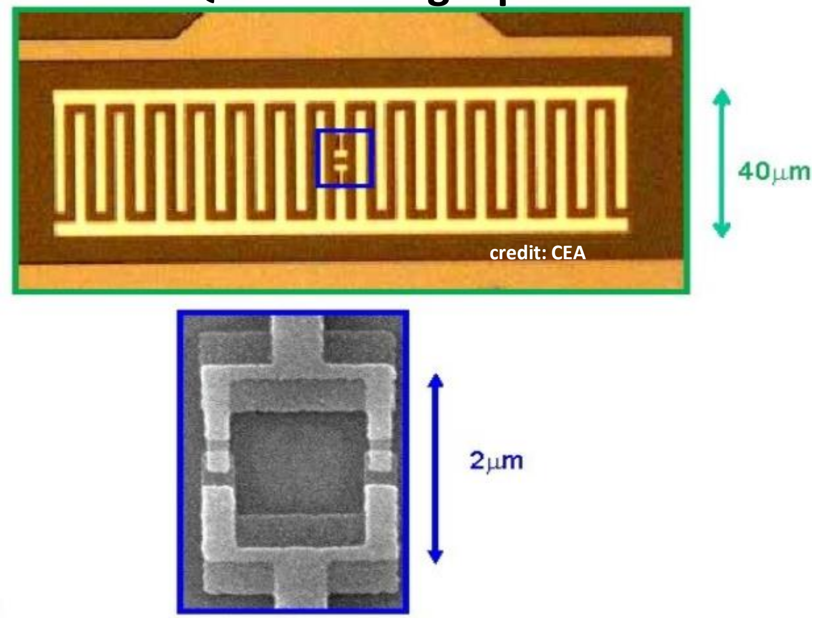
Famous examples

Superconducting quantum devices used for Dark Matter Search

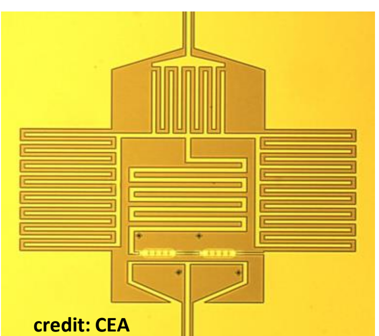
Cooper pair box Electrometer



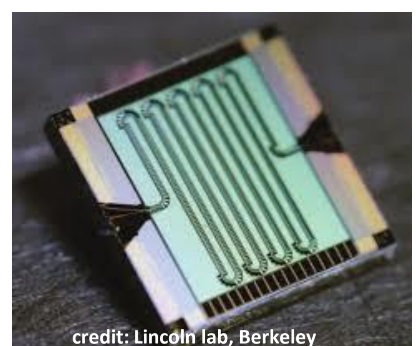
Transmon Qubit ➔ Single μw Photon Det



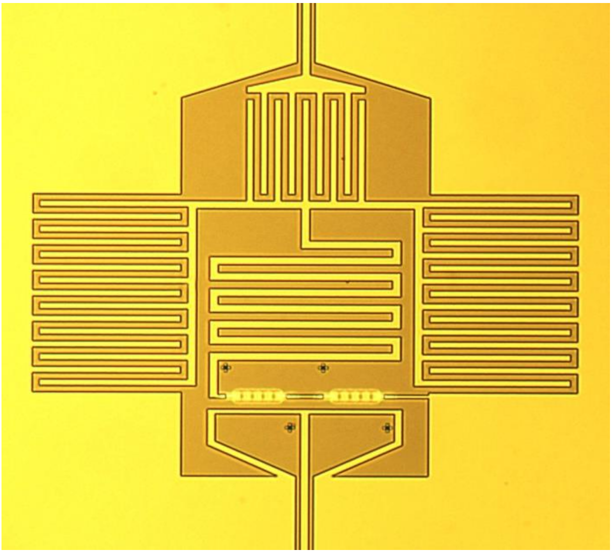
Josephson Parametric Amplifier



TWPA

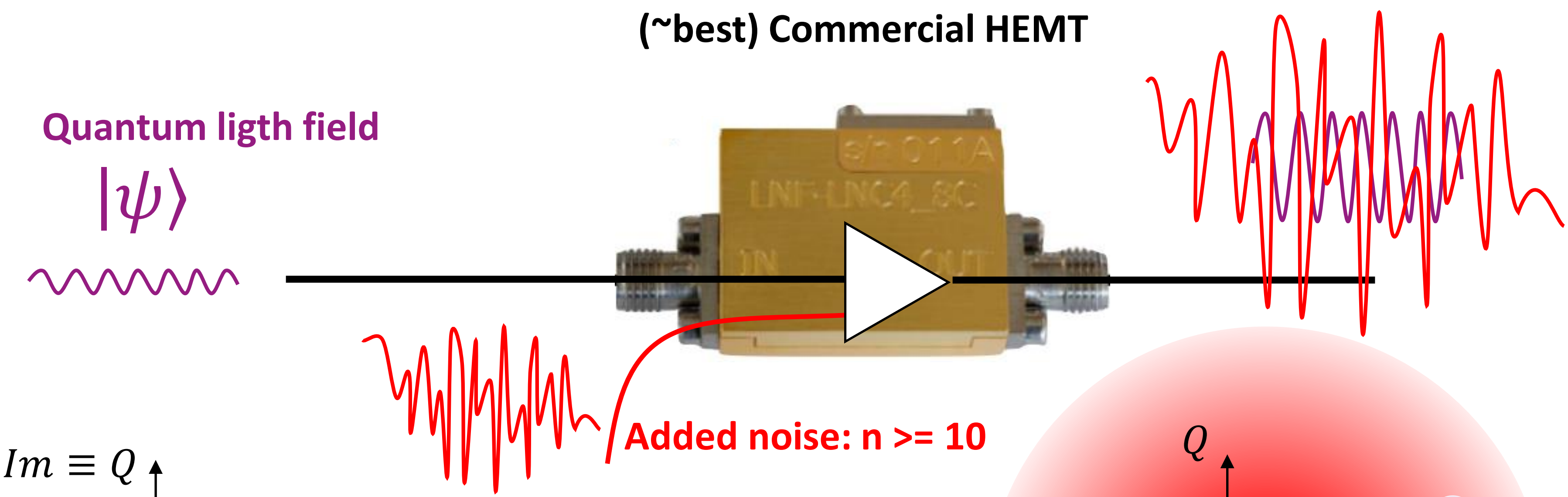


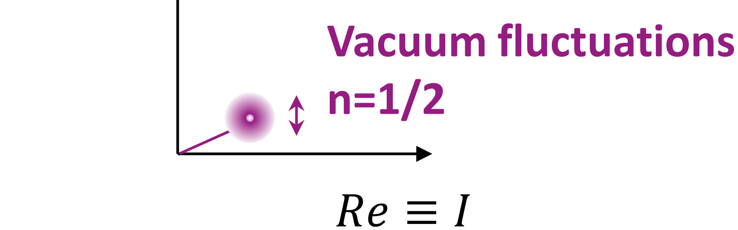
Parametric Amplifier

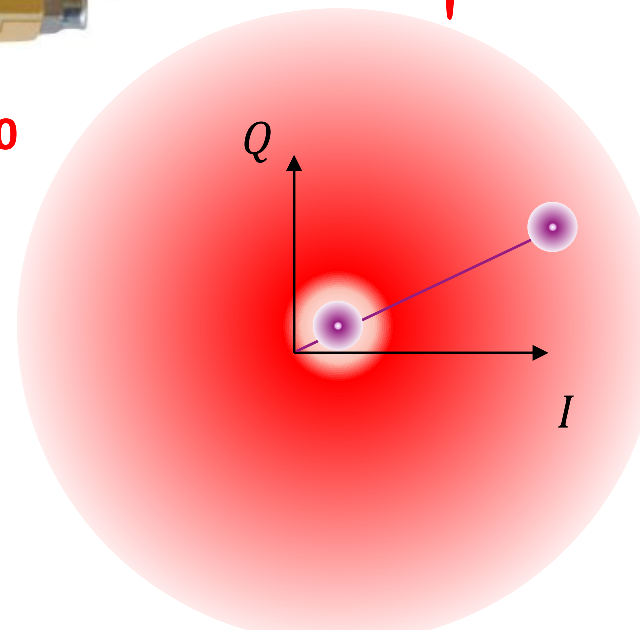


Example of 3 wave mixing

Measuring small microwave (coherent) fields



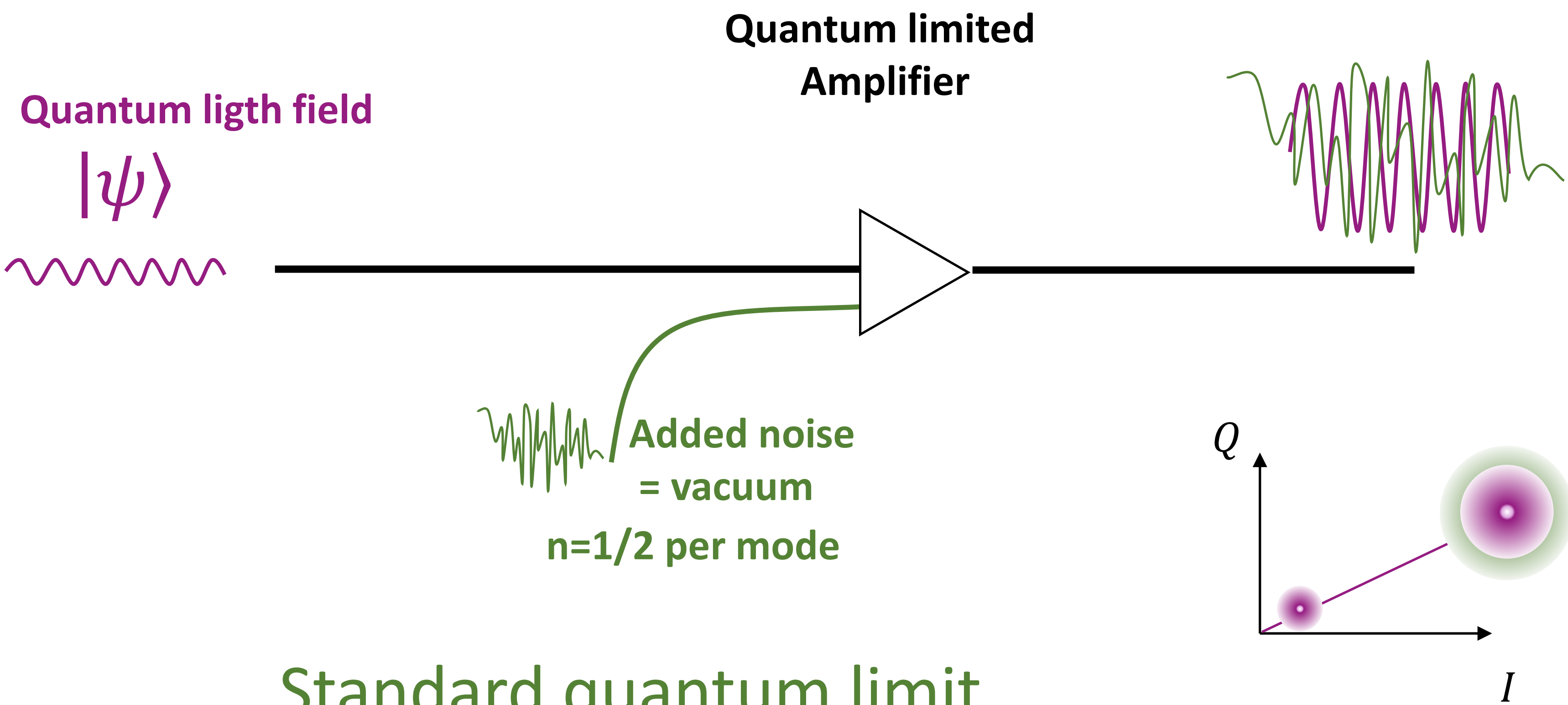




Amplifier figure of merit: $\mathbf{T_N}$

noise power per unit bandwidth [W/Hz] = $\mathbf{k_B T_N = n\, h\nu}$

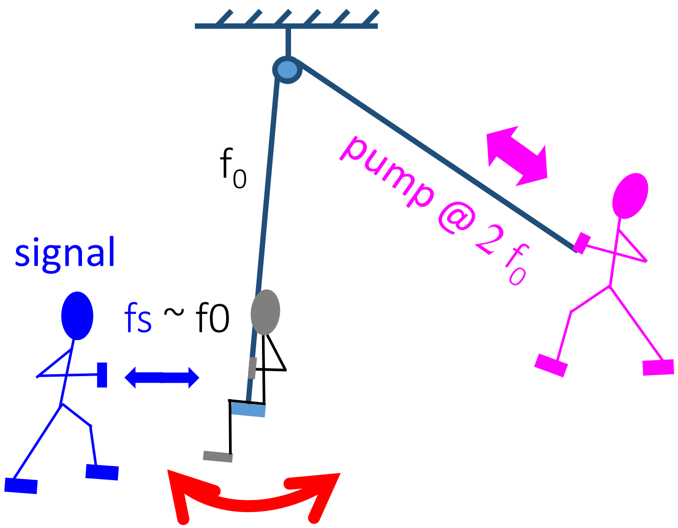
Measuring small microwave (coherent) fields

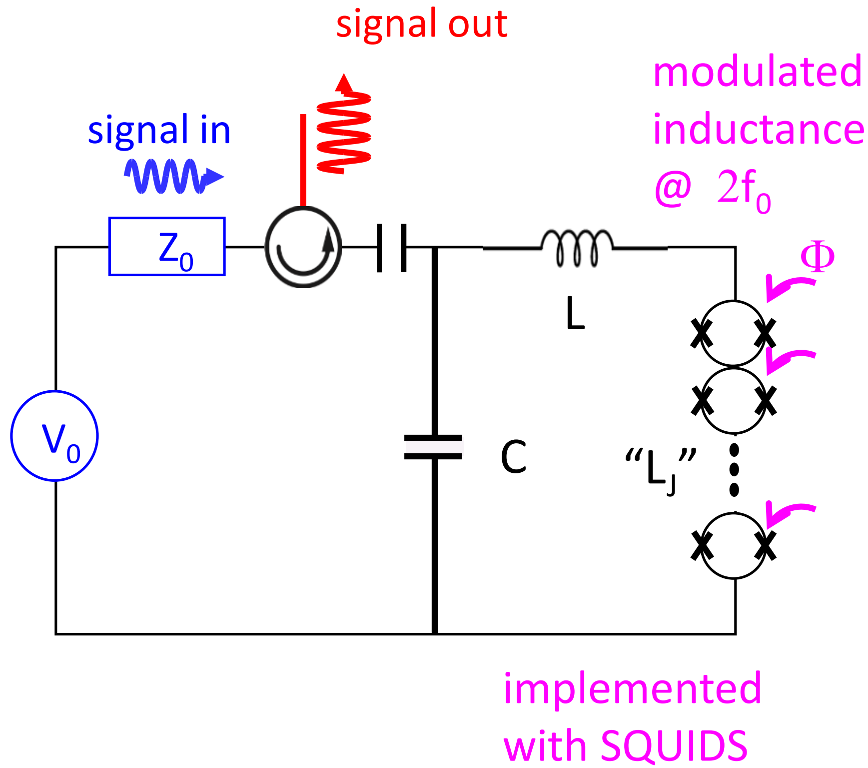


Standard quantum limit

Josephson quantum limited amplifiers

Principle of parametric amplifiers





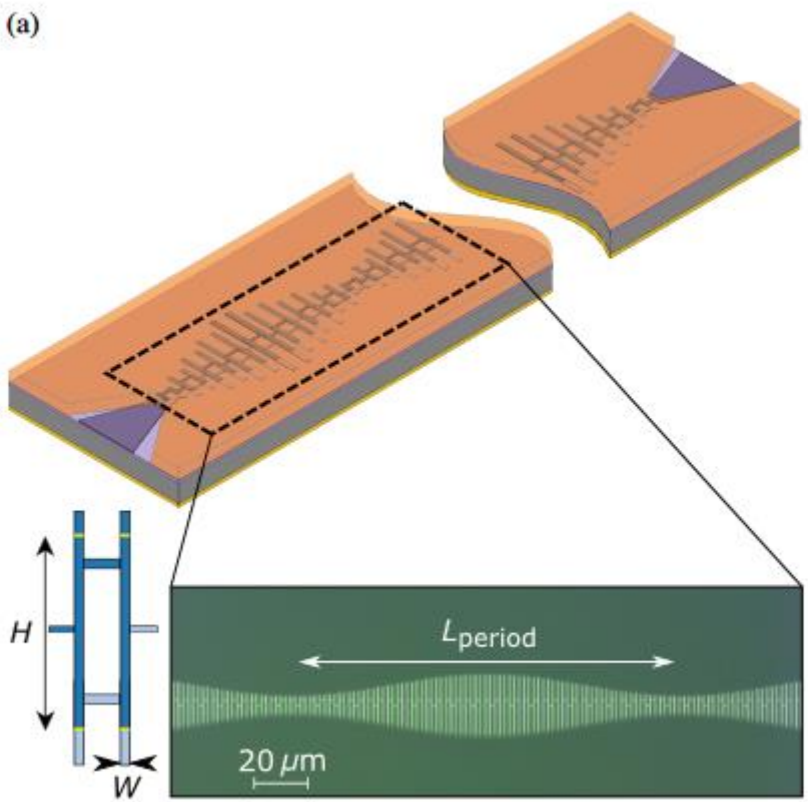
3 wave mixing

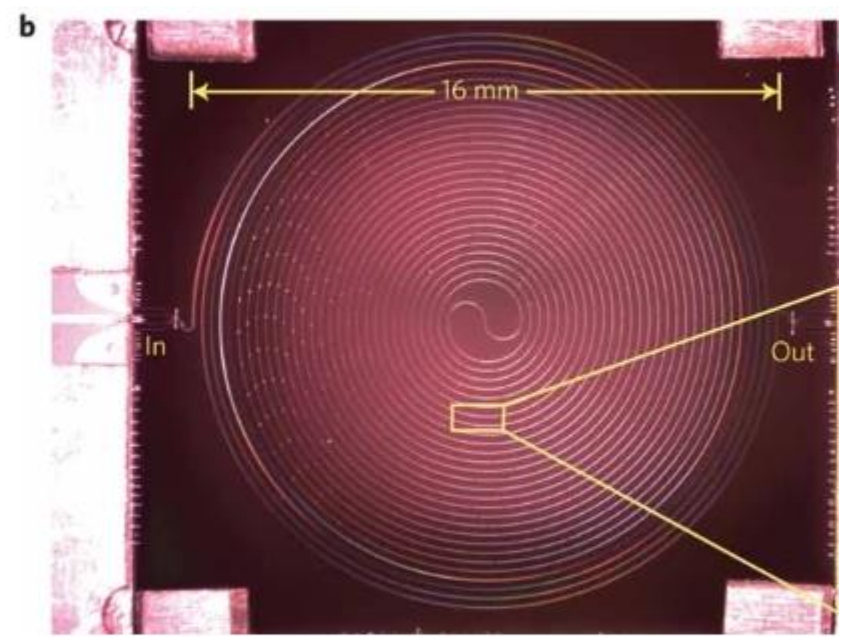
$$\omega_p = \omega_s + \omega_i$$

Nice example : travelling wave parametric amplifier

PHYS. REV. X 10, 021021 (2020)

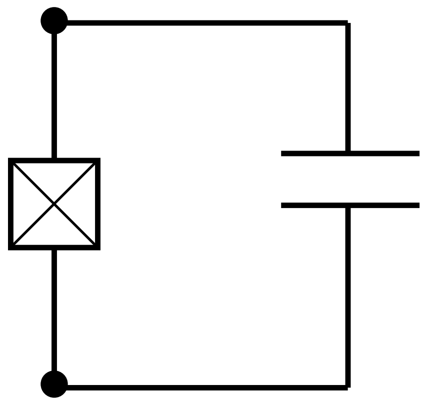
Nature Physics volume 8, pages 623–627 (2012)

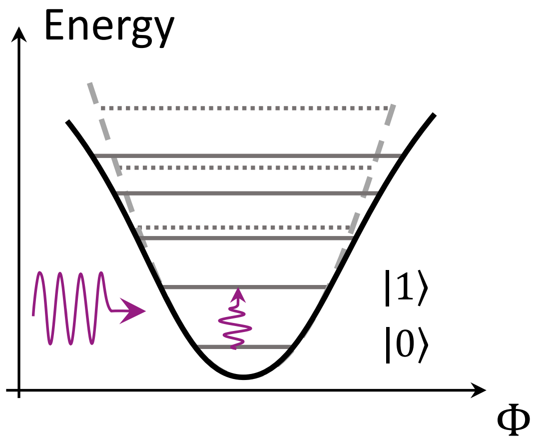


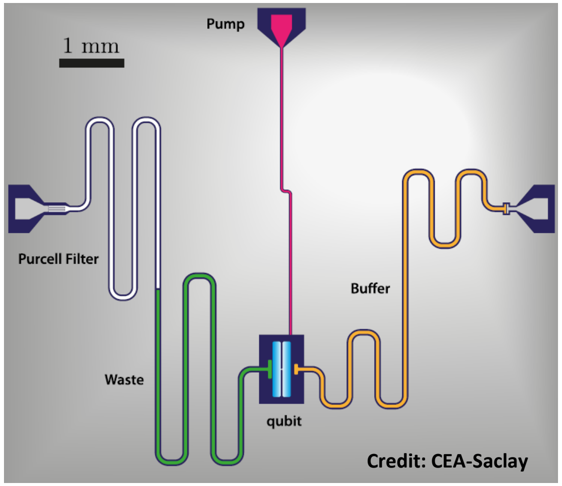


Single Microwave Photon Detector SMPD

Transmon QuBit



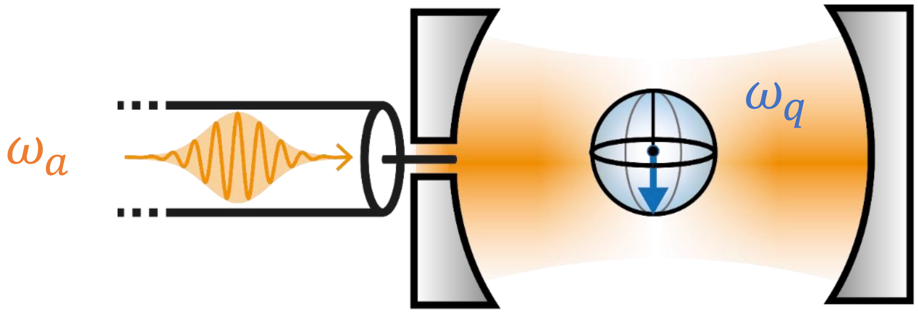




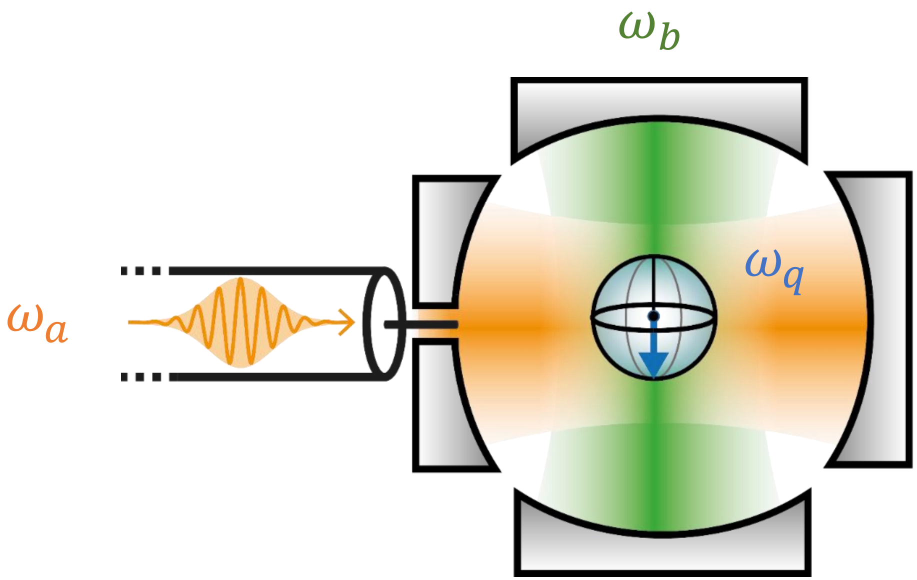
E. Flurin, P. Bertet, (SPEC, Université Paris-Saclay, CEA)
QUAX collaboration

Lescanne et al., PRX (2020)

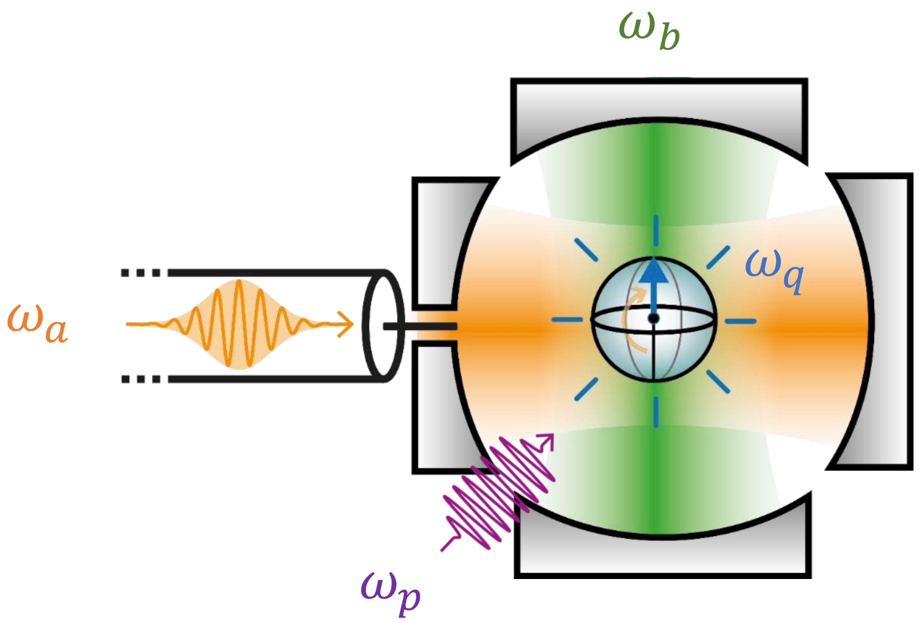
Single microwave photon counter : principle



Single microwave photon counter : principle

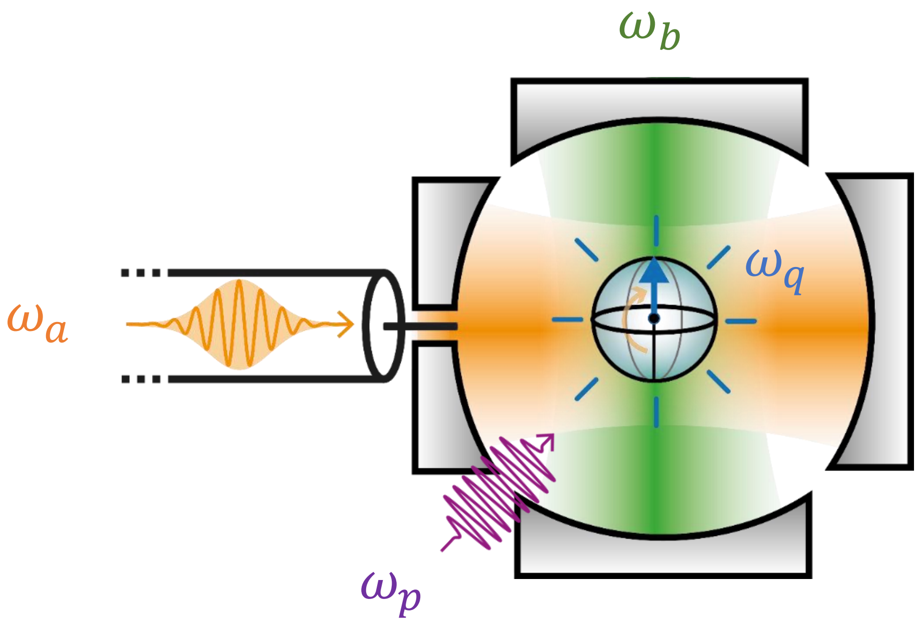


Single microwave photon counter : principle



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

Single microwave photon counter : principle

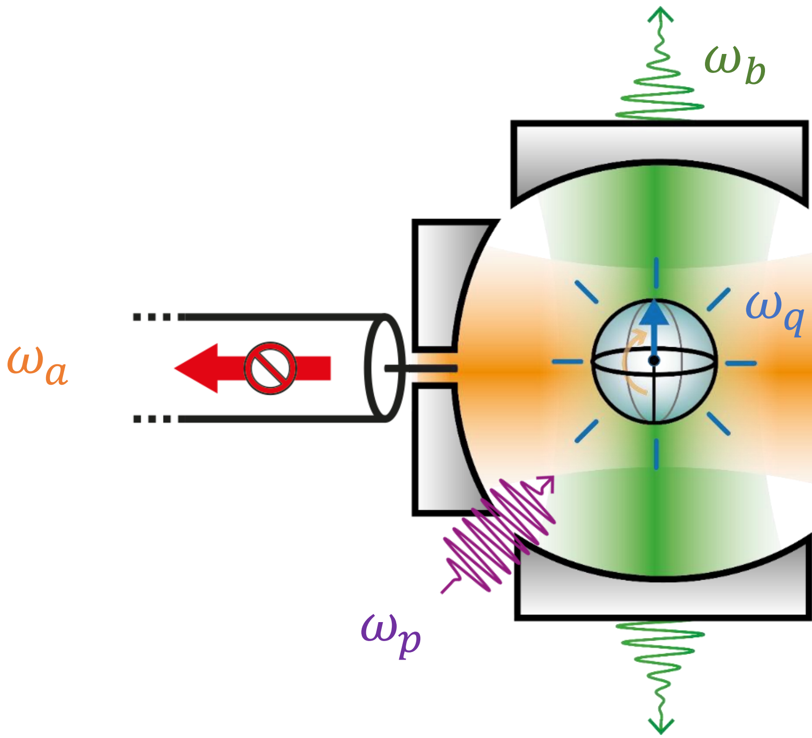


$$\boldsymbol{\omega_a + \omega_p = \omega_q + \omega_b}$$

Four-Wave mixing-based Photodetection

$$\hat{H} = g_4 \cdot (\xi \, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^* \, \hat{a}^+\hat{\sigma}\hat{b})$$

Single microwave photon counter : principle

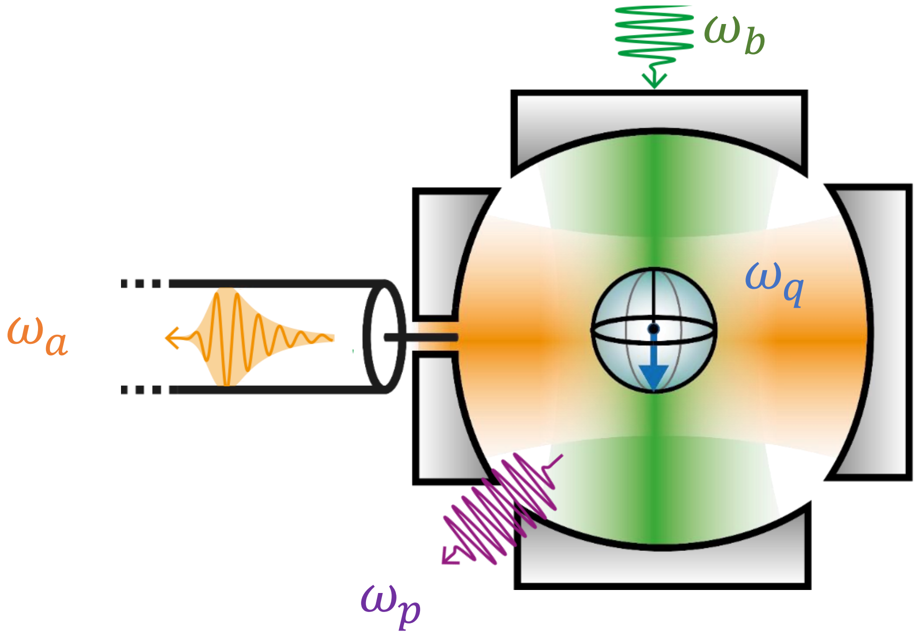


$\omega_a + \omega_p = \omega_q + \omega_b$

$$\hat{H} = g_4 \cdot (\xi\, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^* \hat{a}^+\hat{\sigma}\hat{b})$$

$$\hat{L} = \hat{a}\hat{\sigma}^+$$

Built-in detector reset



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

$$\hat{H} = g_4 \cdot (\xi\, \hat{a}\hat{\sigma}^+\hat{b}^+ + \xi^*\, \hat{a}^+\hat{\sigma}\hat{b})$$

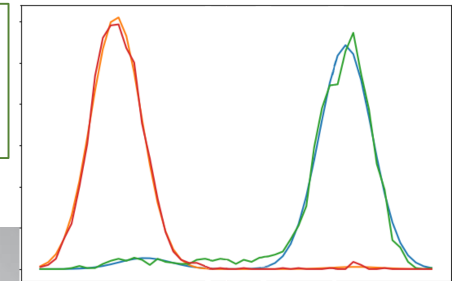
Implementation

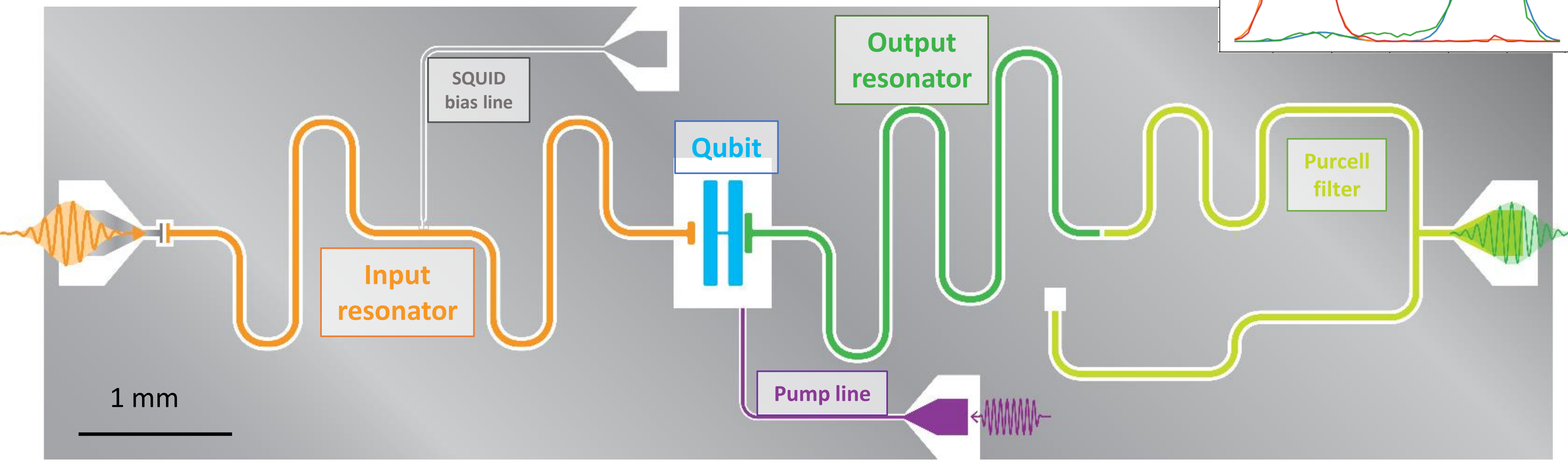
$f_{in} = 7,1\ \text{GHz}$
$Q_{in} = 7,5\ k$
$\chi_{in\ q}/2\pi$
$= 3,5\ \text{MHz}$

$f_q = 6,1\ \text{GHz}$
$T_1 = 8 - 9\ \mu s$
$T_2^* = 13\ \mu s$

$f_{out} = 7,6\ \text{GHz}$
$Q_{out} = 16\ k$
$\chi_{out\ q}/2\pi = 8,1\ \text{MHz}$

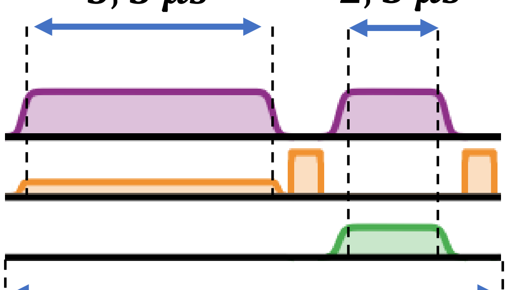
single shot measurement





detection
$3,5\ \mu s$

reset
$2,5\ \mu s$



cycle $10\ \mu s$

35% duty cycle

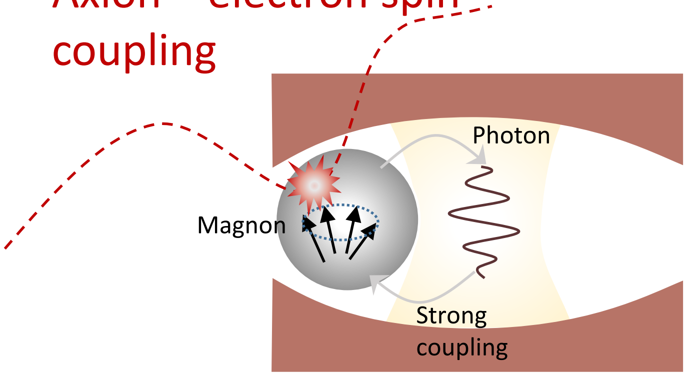
Dark count rate: $\alpha = 0.4\ ms^{-1}$

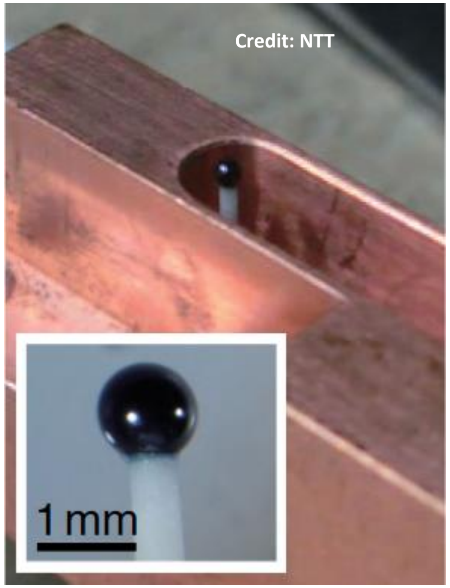
Total efficiency: 20%

Lescanne et al., PRX (2020)

Axion detectors (“haloscopes”)

Axion – electron spin coupling

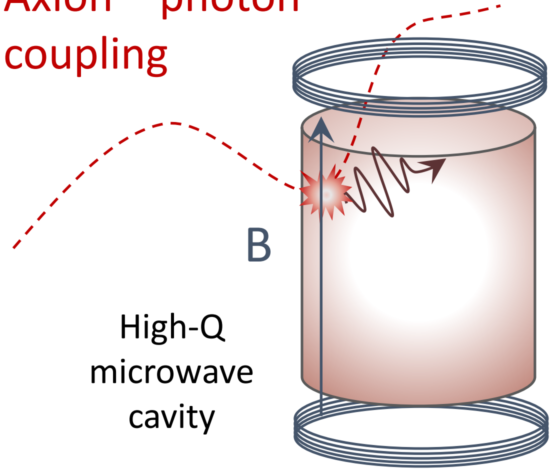




« Ferromagnetic haloscope »

Crescini, COMMUNICATIONS PHYSICS (2020)

Axion – photon coupling



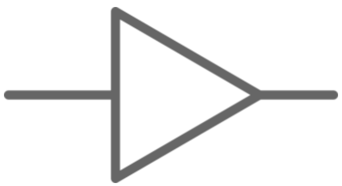
How to detect the photon ?

- Squid amplifier (ADMX)
  (J. Clarke) Rev. Mod. Phys., Vol. 75, No. 3, July 2003
- Josephson Parametric amplifier (HAYSTAC)
  (K. Lehnert) Phys. Rev. Lett. 118, 061302 (2017)
- Single microwave photon detector (QUAX)
  Lescanne et al., PRX 2020
  (D. Schuster) Dixit et al. PRL 2021

Dark matter Axion detection

Advantage of SMPD over linear detectors operated at the quantum limit $SNR = P_S/P_N$

Signal-to-noise with linear amplifier at the quantum limit



$$\mathrm{SNR}_{\mathrm{lin}} = \frac{P_{\mathrm{axion}}}{\hbar\omega/2}\sqrt{\frac{t_{\mathrm{lin}}}{\kappa_{\mathrm{axion}}}}$$

← axion linewidth $\sim 10\ \mathrm{kHz}$

Signal-to-noise with SMPD

axion power $\sim 1\ \mathrm{photon.s}^{-1}$

$$\mathrm{SNR}_{\mathrm{SMPD}} = \frac{P_{\mathrm{axion}}}{\hbar\omega}\sqrt{\frac{t_{\mathrm{SMPD}}}{\alpha_{\mathrm{DC}}}}$$

← darkcount $\sim 5 - 50\ \mathrm{click.s}^{-1}$

$$\frac{t_{\mathrm{lin}}}{t_{\mathrm{SMPD}}} = \frac{1}{4}\frac{\kappa_{\mathrm{axion}}}{\alpha_{\mathrm{DC}}} \sim 50 - 500$$

Thank you!

Quantronics Group, Service de Physique de l'Etat Condensé, **CEA Saclay**