Quantum Technologies

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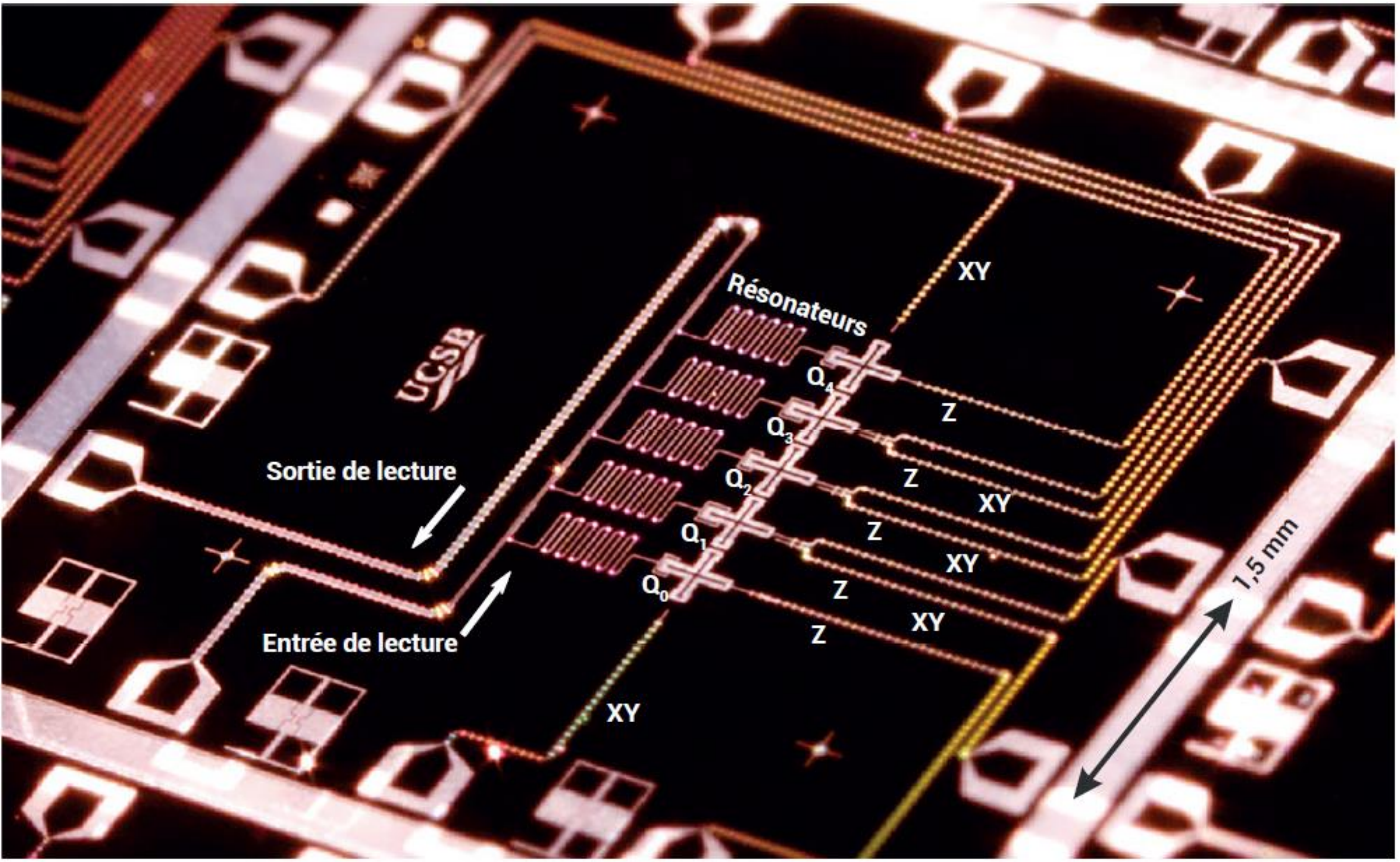
What are we talking about?

M. Le Bellac, Reflets de la Physique, 67 (2020) 4-8.



1. Image optique d'un processeur intégré avec cinq qubits supraconducteurs. Les cinq qubits (Q_0 à Q_4, au centre de la figure) sont en forme de croix et disposés suivant un réseau linéaire. À leur gauche on trouve cinq résonateurs formés de guides d'ondes résonants utilisés pour la mesure des qubits individuels. Le câblage dédié au contrôle et à la manipulation des qubits est situé à droite. Afin de minimiser la décohérence, l'énergie thermique doit être largement inférieure à la différence $\Delta E = E_1 - E_0$ entre les deux niveaux d'énergie E_0 et E_1 du qubit, et le processeur est maintenu à une température T = 20 mK grâce à un réfrigérateur à dilution, de sorte que $k_BT << \Delta E$. Source : R. Barends *et al.*, *Nature*, **508** (2014) 500.

2015 : Toy Quantum computers with 5 Qubits

$$\alpha_0|00000\rangle + \alpha_1|00001\rangle + \alpha_2|00010\rangle + \alpha_3|00011\rangle + \cdots + \alpha_{31}|11111\rangle$$

2020 : Bigger toys with 50 Qubits

In 10 years : dedicated quantum computers with ~1000 Qubits, is this any useful for us?

Later, the ‘revolution’ (maybe) universal programable quantum computer with 10^5 - 10^6 Qubits

What are we talking about?

Disruptive technology (potentially…), are we (IN2P3) missing something important?

- **Quantum computing and algorithms *('software')***
  How can IN2P3 science benefit from the new potentialities of quantum computers?

- **Quantum sensing *('hardware')***
  A **quantum device** operates in the quantum limit (single particle detection, or shot-noise limited) or profits from quantum properties (superposition, entanglement).
  We are using or developing quantum sensors at IN2P3:
  - Solid State detectors for Dark Matter detection
  - Superconducting detectors for CMB observation
  - Quantum 'squeezed' light for gravitational waves detection
  - Atomic magnetometers and atomic clocks for precision experiments…

Workshop in Marseille, summer 2021

22 participants in Marseille
18 participants on zoom

7 contributions

- Simulating quantum complex many-body problems
  D. Lacroix (IJCLab)
- Quantum Machine Learning for physics of 2 infinities
  A. Sartirana (LLR)
- Application of quantum technologies for GW detectors
  E. Tournefier (LAPP)
- In-vacuum squeezer for Advanced Virgo+
  N. Leroy (IJCLab)
- Precise clock generation for Hyper-Kamiokande
  M. Guigue (LPNHE)
- Solid State Quantum Technology for Astroparticles
  S. Sengupta (IJCLab)
- Kinetic Inductance Detectors for millimetric cosmology
  F. Levi-Bertrand (Institut Néel)

Workshop in Marseille, summer 2021

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2 talks on the institutional landscape

- Quantum technologies at CNRS, GDR IQFA Ingéniérie Quantique, Aspects Fondamentaux et Applications (INP, INSIS, INS2I)
  S. Tanzini (CNRS)
- CERN Quantum Technology Initiative
  A. Di Meglio (CERN)

4 invited review talks on Quantum Technologies (QT)

- QT and Dark Matter — H. Le Sueur (CEA)
- QT in GW detectors — E. Capocasa (APC)
- QT & millimetric detection — F. Levi-Bertrand (Néel)
- Intro quantum computing — T. Meunier (Néel)

Institutional talks look like this...

Organizations and Projects

QUANTUM FLAGSHIP

QuantHEP

esa

Industry

Google

IBM

IBM Q-Net

intel

aws

Amazon Braket

Microsoft

Xanadu

AtoS

PASQAL

CQC

Cambridge Quantum Computing

IQ

DESY.

EPFL

ETH zürich

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

lrz

TUM

INFN

Istituto Nazionale di Fisica Nucleare

Universidad de Oviedo

QuTech

Academia, Research Labs and Agencies

ICEPP

Fermilab

OAK RIDGE

National Laboratory

Quantum computing @ IN2P3

2019: national IN2P3 workshop on Quantum Computing (70 participants)
Then creation of a group of people interested in quantum computing (theoreticians and engineers), see https://qc.pages.in2p3.fr/web/
2 exploratory lines at the moment

- N body nuclear problem: a quantum computer for a quantum problem?
- Quantum machine learning: how to exploit the HHL algorithm (quantum speedup for solving a certain class of linear systems).

=> There is a discussion forum on these emerging topics already

Survey on quantum sensing @ IN2P3

Solid State physics

- The Astroparticle Solid State Detectors group @IJCLab

Developing innovative detectors for Dark Matter (Edelweiss), neutrino physics (CUPID, CROSS, Ricochet) and CMB (QUBIC). Expertise on nanofab, TES (Transition Edge Sensors), SSED (Superconducting Single Electron Detector).

- The GIS Grenoble collaboration on KIDs for CMB

Development of superconducting detectors for millimetric cosmology. Collaboration with

Atomic, Molecular and Optical Physics

- "Squeezed" light to reduce the quantum noise in GW detectors.

Collaboration with

- Accurate timing with atomic clocks for neutrino exps.

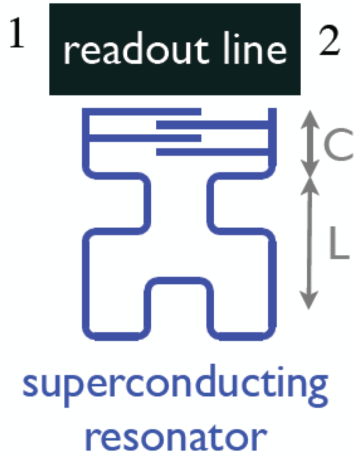
Collaboration with SYRTE

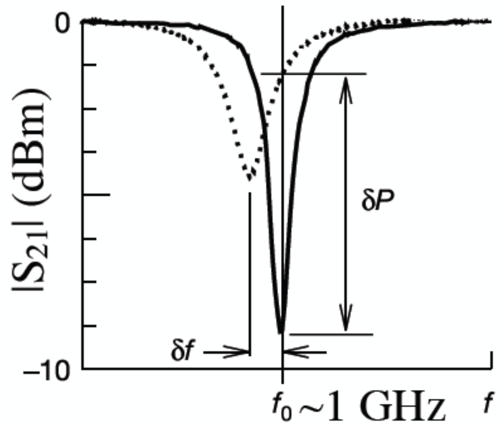
- Not discussed in Marseille: Expertise on quantum magnetometers (links with LKB) and on ion traps

KIDs and millimetric detection for CMB

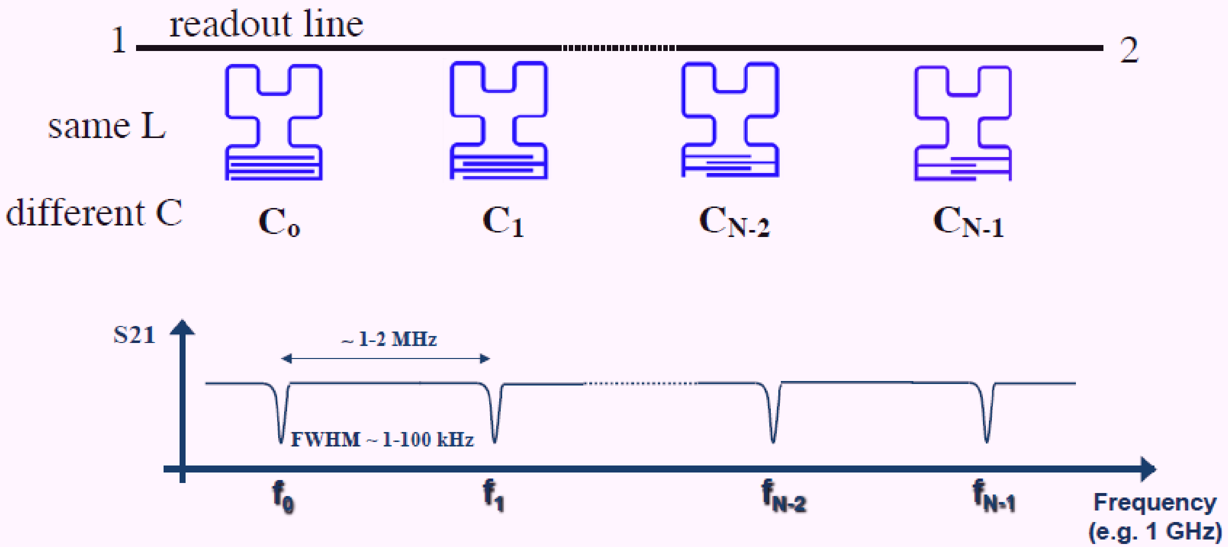
Kinetic Inductance Detectors:

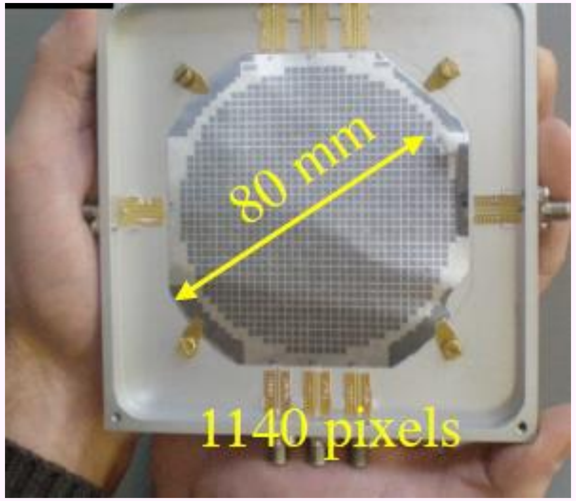
incident radiation (mm wavelength)
-> absorbed in superconductor
 -> breaks cooper pairs
  -> changes the inductance
   -> changes the resonant freq $f_0 \approx \frac{1}{\sqrt{LC}}$



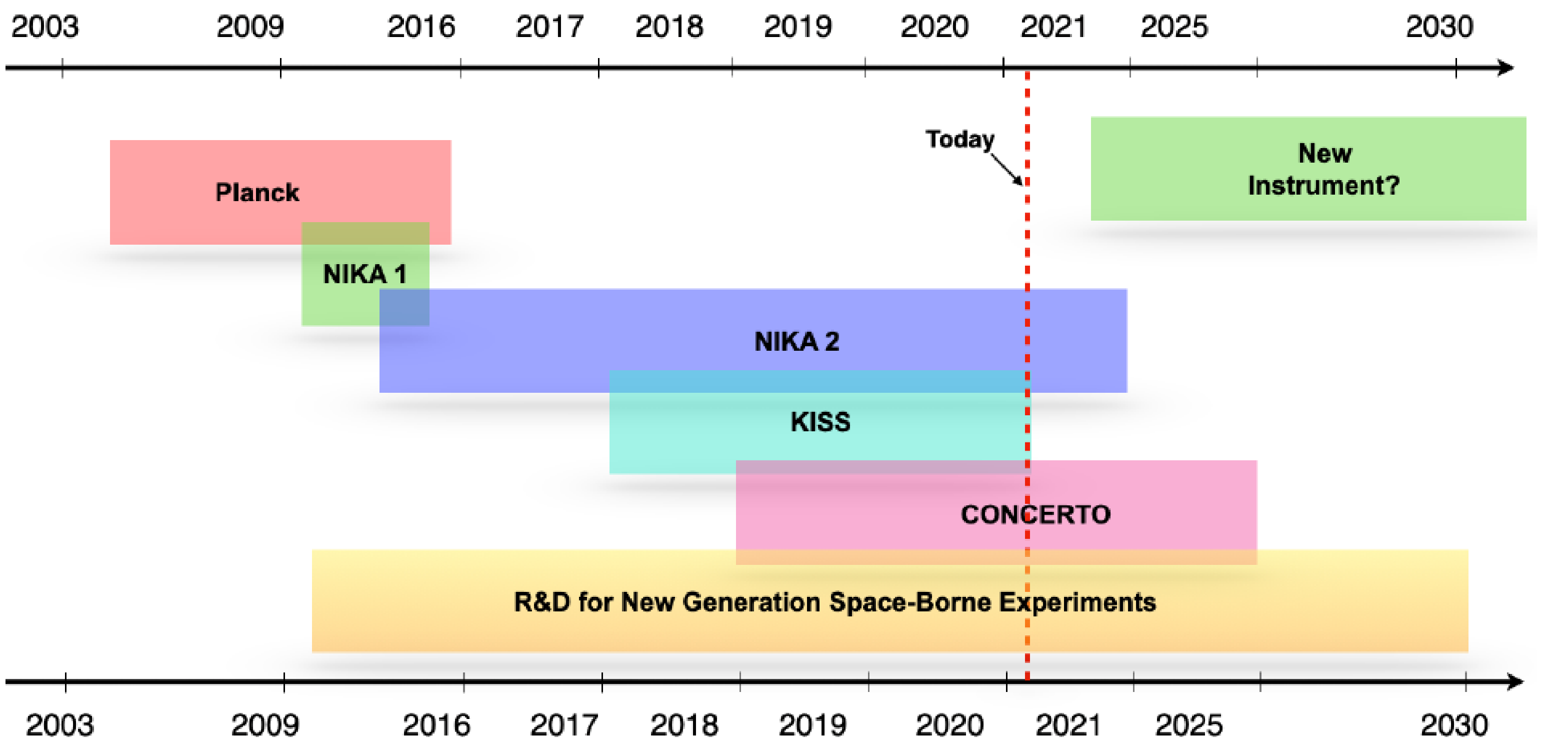


Readout with frequency multiplexing! -----> Camera with many pixels (here, NIKA2)





KIDs for CMB: THE ROADMAP



Mid-term goal (2023-2025)

* Design studies for S4-like instrument
* Development of first large arrays of on-chip spectrometers

Long term goal (2025-2030)

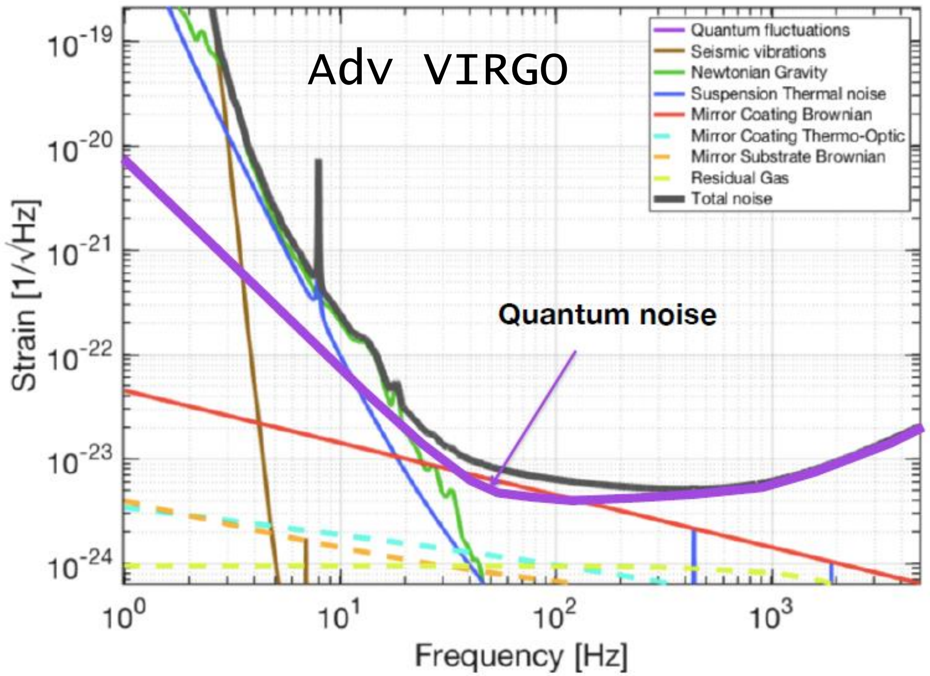
* Be ready to deploy S4-like instruments
* Be a valid candidate to cover the focal plane of the next generation space mission

Quantum noise & GW detection

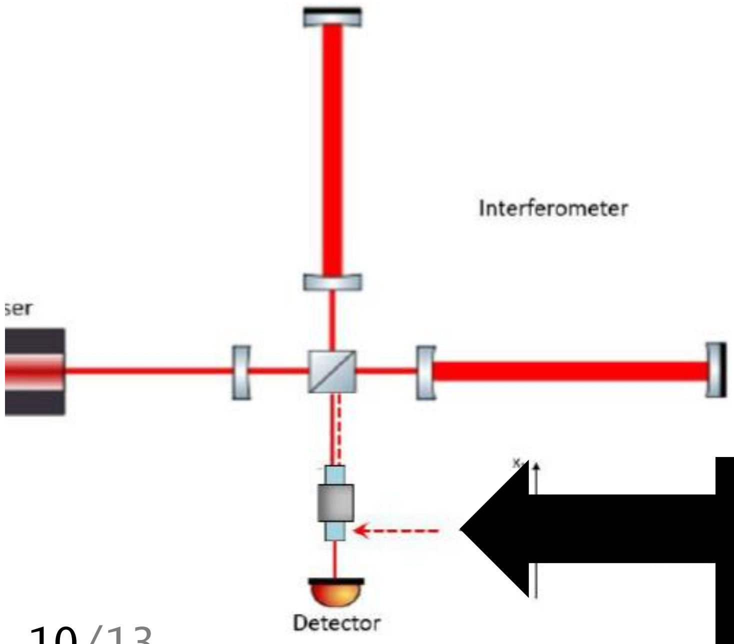
Quantum properties of light:

phase φ and photon number N are quantum variables and $\Delta N\,\Delta\varphi > \frac{1}{2}$ (Heisenberg)

Low frequency quantum noise =
radiation pressure noise
from ΔN

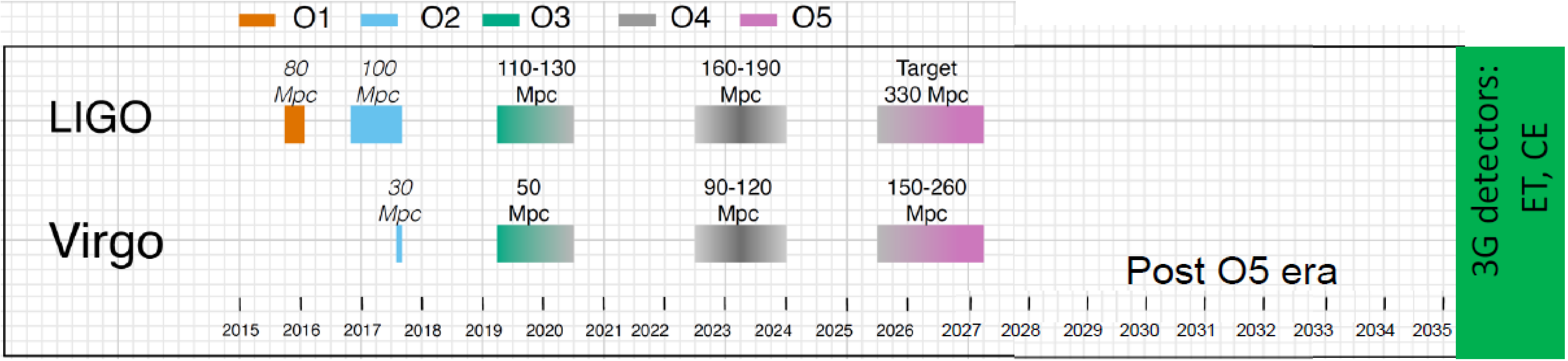


High frequency quantum noise =
shot noise from $\Delta\varphi$



SQUEEZING!! Inject non-classical light here (squeezed vaccum produced with non-linear OPO) to reduce $\Delta\varphi$ at the price of increasing ΔN (or vice-versa).

Quantum noise & GW detection: THE ROADMAP



Quantum noise reduction	3 dB (Achieved)	4.5 dB	6 dB	10 dB
Frequency dependent squeezing	No	100 Hz	100 Hz	3 Hz
Squeezing under vacuum	No	No	TBC	TBC

R&D

Reduce optical losses, improve quantum noise reduction

ANR ExSqueez
OPO under vacuum
CALVA@IJCLab

New frequency dependent squeezing schemes
(Q filter, EPR)

To conclude: SWOT

Strength

- **On algorithms, reservoir of quantum problems**
- Existing expertise on dedicated quantum sensing
- Expertise on enabling technologies
- **Established collaborations, each one with clear roadmap**

Weaknesses

- Lack of exchanges between the groups 'silo effect' -> GDR detector?
- **Not directly connected to the sources of funding targeting QT**
- Not involved in the IQFA GDR (yet)

Opportunities

- **CERN's quantum technology initiative**
- Well positioned to offer training on quantum algorithms
- Coordinate the response to calls for funding
- **GDR detector to foster quantum sensing**
- Getting involved in GDR IQFA

Threats

- No funding access due to lack of visibility
- Missing the opportunity to be at the initiative of a disruptive techno or algorithm

Recommendations

1. Support co-funding of PhD and postdocs on existing multi-institute collaborations on specific developments

2. Intensify networking on quantum technology community (IQFA, CERN Initiative, plan quantique…)

3. Stimulate the emergence of new detector concepts by deploying a technological watch on promising advances in quantum sensing