THEMATIC NOTEBOOK

QUANTUM TECHNOLOGIES AT CNRS

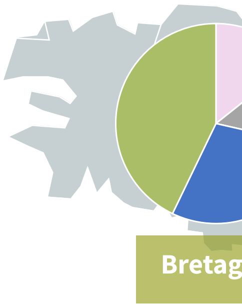
CNRS RESEARCH STRENGTHS IN QUANTUM TECHNOLOGIES

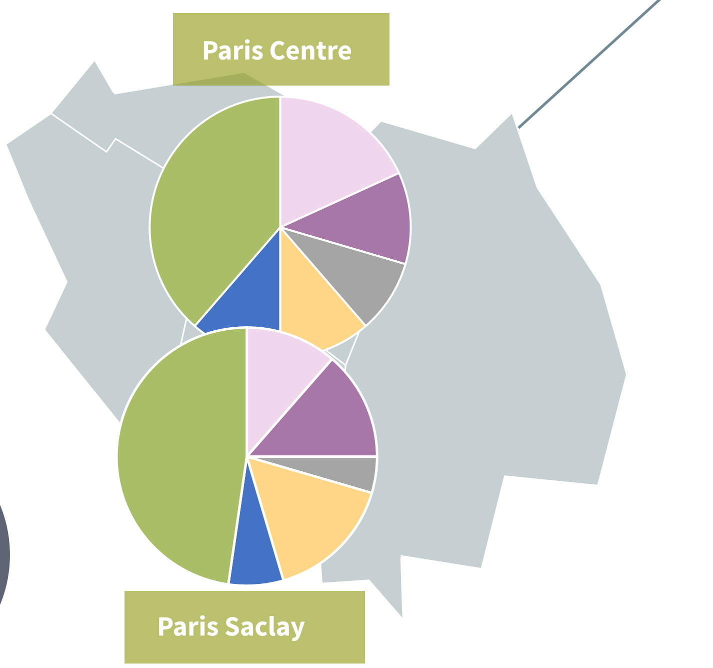
From diodes, transistors and lasers to medical imaging and secure information systems... quantum physics has brought unprecedented technological advances that have revolutionised our daily lives. In the context of highly competitive international research and industrial development, the CNRS represents one of France's major assets to effectively address tomorrow's challenges in quantum technologies and to help positioning France to the forefront of the international competition.

Quantum physics foundations have been discovered at the beginning of the last century. They serve now as concepts and tools for developing disruptive quantum technologies. Those discoveries notably enabled researchers to understand the laws that govern matter, light, and their interactions. Along this race mapping quantum foundations and applications, three Nobel prizes in Physics were awarded to French researchers, and four CNRS gold medals have been attributed to this field over the 25 past years*.

The extraordinary experimental progress made over the past decades made it possible to observe quantum objects - photons, atoms or ions - which we have learned to control both individually and collectively. This means that scientists can prepare and manipulate such objects using the concepts of superposition of quantum states and entanglement. The vast range of applications that these developments have opened up makes today's quantum technologies one of the most promising and competitive sectors and one in which the CNRS has undeniable assets to exploit. These include its network of laboratories throughout France, a multidisciplinary approach combining fundamental research, innovation, and technology transfer, as well as the undoubted excellence of the organisation's work. This level of excellence is based on extremely strong fundamental research in the field of quantum science and technologies whose quality makes it a worldwide reference. The CNRS's cross-disciplinary approach now enables the operational implementation of applications in potential use cases, notably through a genuine ecosystem combining academic research, start-ups, and major industrial groups.

*The Nobel Prize winners in physics are Claude Cohen-Tannoudji (1997), Albert Fert (2007) and Serge Haroche (2012), who respectively developed methods for cooling and trapping atoms with lasers, spintronics, and quantum electrodynamics in cavities. Albert Fert and Serge Haroche were awarded the CNRS gold medal in 2003 and 2009, respectively. Alain Aspect and Jean Dalibard were awarded the CNRS gold medal for their pioneering work on quantum entanglement and ultra-cold quantum matter, respectively in 2005 and 2021.

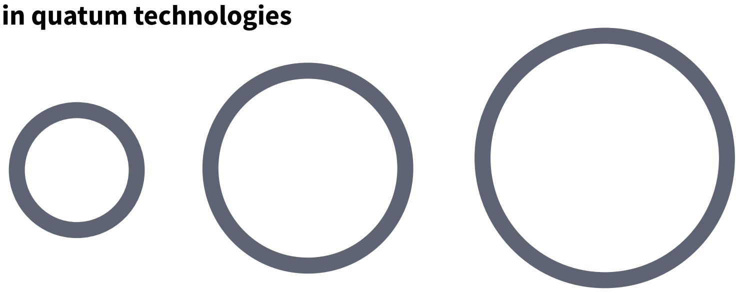




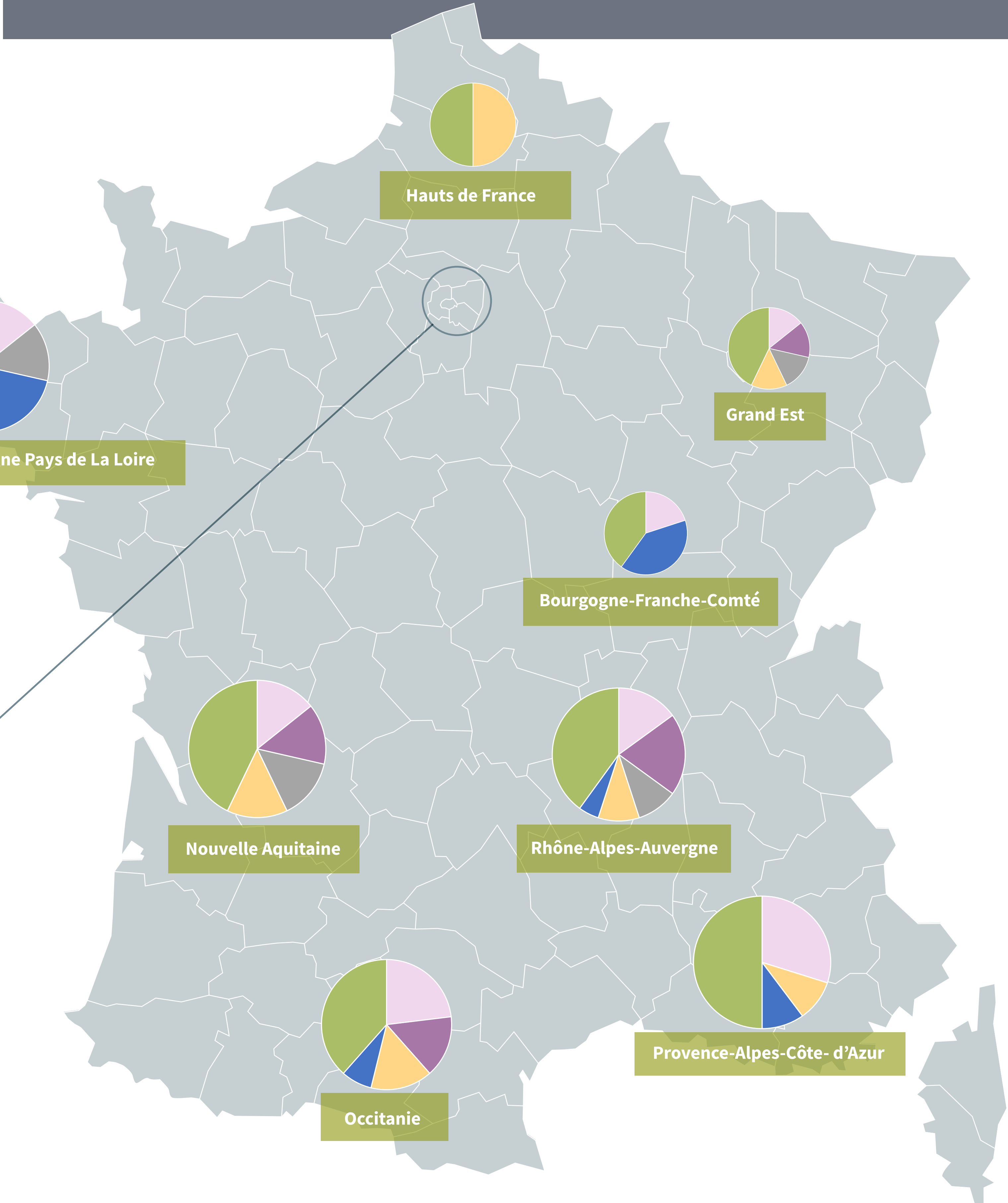
Research themes:

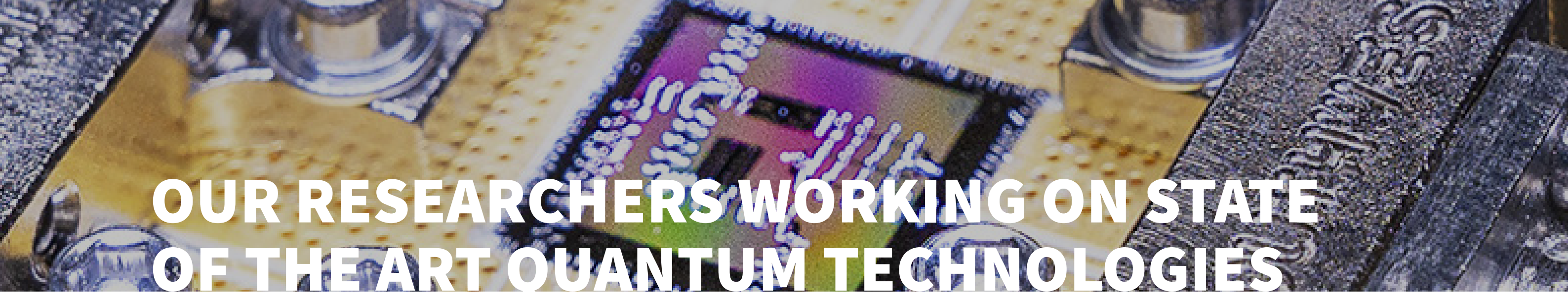
- **Quantum communication**
- **Quantum computing hardware**
- **Quantum computing software**
- **Quantum simulation**
- **Quantum metrology and sensors**
- **Basic sciences**

Number of laboratories involved in quatum technologies



Less than 5 **Between 5 and 10** **Between 10 and 15**


Hauts de France
Grand Est
ne Pays de La Loire
Bourgogne-Franche-Comté
Nouvelle Aquitaine
Rhône-Alpes-Auvergne
Provence-Alpes-Côte- d'Azur
Occitanie

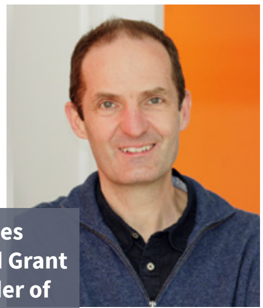


OUR RESEARCHERS WORKING ON STATE OF THE ART QUANTUM TECHNOLOGIES

"Quantum sensors open up a wide range of applications in fields ranging from geosciences to health. Thanks to their fundamental properties, quantum sensors are ideally suited to setting new standards in their respective fields and pushing back performance limits. Their development requires a constant exchange between quantum physicists, industrial partners ready to take on new technological challenges and, of course, end users who open up new challenges."

Arnaud Landragin, CNRS senior researcher, director of the SYRTE (Time Space Reference Systems) laboratory, awarded the CNRS innovation medal in 2020

"Many groups, including ours at LCF, develop experimental techniques to produce synthetic quantum systems atom by atom. The level of control we have over these means we can study open problems such as magnetism of certain materials, transport properties, and so forth. Several start-ups (including Pasqal) have embarked on this adventure and are also studying problems which interest industry. Improving these systems will probably enable us to build a quantum computer one day."



Antoine Browaeys, CNRS senior researcher at the Charles Fabry laboratory (LCF), beneficiary of an ERC Advanced Grant 2020, awarded the CNRS silver medal in 2021, co-founder of the Pasqal start-up

"At the C2N, we develop semiconductor components emitting single photons that represent a key technological breakthrough for the development of optical quantum computing and quantum communication networks. The Quandela start-up is promoting and transferring this technology by marketing it to international quantum technology researchers and engineers. This experience of interdisciplinarity and intersectorality led me to create Quantum - the centre for quantum science and technology at Paris Saclay University."

Pascale Senellart-Mardon, CNRS senior researcher at the Centre de nanosciences et de nanotechnologies (C2N), beneficiary of an ERC Consolidator Grant in 2011, awarded the CNRS silver medal in 2014, co-founder of and scientific advisor for Quandela

"PCQT marks the second stage of the dynamic started by the creation of a Parisian CNRS research federation in 2013. PCQT is expanding thematically by focusing on the full spectrum of quantum technologies, and institutionally by welcoming the Inria (National Institute for Research in Computer Science and Control), Sorbonne University, Université de Paris and Université PSL. The aim is to federate research forces in Paris in the fields of quantum computing, communication, cryptography and sensors by developing their synergies in training matters and their relations with the Parisian and regional innovation ecosystems."

Eleni Diamanti, CNRS senior researcher at the Computer Science Laboratory in Paris (LIP6), beneficiary of an ERC Starting Grant in 2017, deputy director of Paris Centre Quantum Technologies (PCQT)

"The Quantum Engineering Grenoble (QuEnG) programme is constructing an ecosystem for quantum technologies, from the humanities to physics, from philosophers to industrialists, namely the whole continuum of knowledge and economic activity. The underlying challenge is to promote dialogue between different fields of expertise to define new questions and fields of knowledge together, rather than to provide solutions to pre-existing problems."

CNRS senior researcher at the Institut Néel and coordinator of the QuEnG programme and the newly created QuantAlps federation

SCIENTIFIC POLICY

The CNRS is involved in the European Quantum Flagship operation launched in 2018 in the context of the H2020 framework programme and is a major player in how the three main pillars of quantum technologies are structured in Europe. These are quantum computing and simulation, quantum communication, and quantum metrology and sensors. Research at CNRS covers all of these fields and the organisation is one of the three scientific institutions* which steer the national acceleration strategy for quantum technologies launched in January 2021. The aim is to organise France's industrial and academic research forces to make the country a major player in quantum technologies.

* CNRS, CEA (French Alternative Energies and Atomic Energy Commission), Inria

A COLLABORATIVE ANTICIPATORY POLICY

With its partner organisations and universities, the CNRS contributes to building a network throughout France in anticipation of the work required to effectively structure research forces in the field of quantum technologies. Today, the organisation's cross-disciplinary approach enables applications to be implemented operationally. This is made possible thanks to the CNRS's genuine ecosystem bringing together academic research, start-ups and large industrial groups which promotes and facilitates synergies between the academic sphere and the most promising civil and military industrial sectors. This approach makes it possible to:

- support both fundamental and applied research, i.e. when already well established in the main quantum technology pillars,
- guarantee 1) the emergence of new concepts, 2) the value chain, 3) the creation of new start-ups, and 4) major industrial groups' interest in the integration, implementation of applications, as well as in defining use cases.

The aim of this strategy as a whole is to contribute effectively to national and broader European sovereignty in quantum technologies.

THE MAIN THEMATIC AXES IN QUANTUM TECHNOLOGIES

Processing information more efficiently

Medium- and long-term efforts are still required to push quantum computers forward. The aim of this research area is to implement high-performance hardware architectures based on the generation, manipulation and read-out of registers made up of a large number of qubits, the logical unit of quantum information. This makes it possible to run massively parallel operations as such quantum systems are provably more efficient than the existing conventional solutions. However, defining fields of application for this type of computer also requires appropriate quantum algorithms to be written at the same time. Currently, researchers have only identified a small number of algorithms for which quantum computation is more advantageous than conventional alternatives. Considerable research efforts have been made in this field, both in the academic world and at major industrial computing and Internet companies like Google, IBM, Intel, Microsoft and ATOS. All these companies are investing considerable resources in quantum computers while several French start-ups such as Quandela with photons, Pasqal with atoms, and Alice&Bob with superconductoing circuits are also positioning themselves in this sector.

Ultra-secure communication of information

Today's conventional communication methods enable information to be disseminated and routed at very high speeds and over almost unlimited distances. However, these current methods remain fallible in terms of data security which is regarded as a strategic challenge as it affects many civilian and military fields. Today, the protocols employed to cipher and decipher data use increasingly long public keys at a time when the power of (conventional) computers capable of breaking those keys is continually increasing. Unlike standard systems, quantum cryptography is used to set up private keys between various users which are then used in classical encryption protocols. This relies on the distribution of randomly generated and measured photonic qubits. This genuine quantum randomness guarantees the inviolability and durability of the keys and of the resulting communication protocols. Some cities such as Tokyo or Vienna already have a permanent local quantum cryptography network. In France, the city of Nice is currently developing its network, a Paris-Saclay/Paris-Centre link is being developed and the start-up company Quandela is marketing single photon sources.

Ultra-sensitive sensors for unparalleled accuracy in measurements

Quantum states are highly sensitive to the environment which makes it possible to develop highly accurate sensors which are most often based on atomic and photonic interferometers. For example, cold atom accelerometers and gyrometers are based on atomic interferometry. When such devices are embedded onboard ships or airborn systems, they are able to measure the acceleration or rotation of the system highly accurately and reliably. Other systems exist with various applications such as cold atom gravimeters, atomic clocks or magnetometers. The latter are based on colour centres in diamond capable of mapping fields with unequalled sensitivity and precision, therefore showing high potential for use in cell biology. Some of these sensors have found tangible applications and been the subject of technology transfer to industry like cold-atom inertial sensors with the Muquans (now iXBlue) company in Bordeaux. These quantum instruments are continually being made more compact and moving from proof-of-concept laboratory demonstrations to the integration of prototypes.

© Quantum coherence - Cyril Frésillon/CNRS Photothèque/Institut Néel du CNRS

FUNDAMENTAL RESEARCH INTO QUANTUM TECHNOLOGIES

Basic research, whether theoretical and/or experimental, aims at being implemented into applications in the coming 5 to 10 years. Much of this work concerns condensed matter or more generally quantum or topological matter and is based on the micro- and nano-structuring of materials. This is giving rise to new and even exotic quantum properties. These mean new functionalities can be envisaged in the fields of electronic transport, spintronics, light-matter interfaces and so forth, aimed at future applications in all the main pillars of quantum technologies. Another major part of the research in this area involves the theory of NISQ machines designed on lattices of cold atoms, trapped ions, or superconducting circuits made of Josephson junctions.

SCIENTIFIC LEADERSHIP:

The means required to animate communities working on quantum technologies and encouraging interdisciplinarity are based on structuring research networks (GdRs) and technological platforms.

RESEARCH NETWORKS

(Groupements de recherche, GdRs)

The GdR is a CNRS structure that, as the name suggests, creates a federating network with a scientific and/or R&D community based on a given theme.

The Quantum Engineering, Fundamental Aspects to Applications Research Network (IQFA).

IQFA brings together the French research community working on quantum technologies. All forms of quantum information are concerned whether such information is individually or collectively communicated, processed, simulated or manipulated, and whether it uses photons, atoms, trapped ions, electrons, superconducting circuits, etc.

400 RESEARCHERS
60 LABORATORIES

The Research Network on Cold Atoms (AF)

The scientists associated with the AF Research Network exploit experimental and theoretical developments to work on fundamental and applied questions concerning the issue of laser cooling or evaporation of atoms.

200 RESEARCHERS
22 LABORATORIES

The Mesoscopic Quantum Physics Research Network (MESO)

This Research Network's themes of activity concern coherent electronic transport in conductors of all dimensionalities and nature (hybrid systems, topological insulators, graphene, superconductors, etc.). Recent developments in the field involve the manipulation of quantum states in systems of this kind and their behaviour at high frequency.

320 RESEARCHERS
35 LABORATORIES

The Quantum Optomechanics and Nanomechanics Research Network (MECAQ)

The MecaQ Research Network aims to bring together the French research community whose work is linked to nanomechanics and optomechanics, notably in the regime in which quantum fluctuations play an important role. Metrology, ultra-sensitive measurements or quantum information are among the research topics dealt with by scientists in this network.

120 RESEARCHERS
32 LABORATORIES

LABEX FIRST-TF NATIONAL NETWORK

The Training, Innovation, Research, Services and Transfer in Time-Frequency Research Network coordinates the work of the French T/F community.

It thus ensures this is both constructive and complementary to the strategies of the universities and establishments hosting the laboratories (network hubs) and those of the national organisations like the CNRS, the LNE (National Metrology Laboratory), the CNES (National Centre for Space Studies) and the DGA (France's defence procurement agency).

24 LABORATORIES
28 COMPANIES
3 TECHNICAL AGENCIES
5 OTHER STRUCTURES AROUND THE 5 FOUNDING LABORATOIRES: SYRTE, FEMTO-ST, LPL, UTINAM, GEOAZUR.

THE CNRS INSTITUTIONAL TECHNOLOGY PLATFORM RENATECH +

Renatech is a network of high-end technological facilities whose objective is to provide the whole national research and industrial community with micro- and nano-manufacturing resources that are easy to access and to use, and whose performance is at the highest international level.

THE NATIONAL QUANTUM STRATEGY

The National Quantum Strategy announced by President Emmanuel Macron on January 21st 2021 is partly based on the Forteza report*, submitted to the government in January 2020. This report confirmed the excellence of French research but also stated that France has fallen behind in terms of investment, particularly for transfer to industry. This report proposed 37 measures aimed at defining an ambitious national strategy in the field of quantum technologies, several of which have been taken up.

"Quantum technologies are among the keys to the future that France must have in hand", said Emmanuel Macron at the presentation of the National Quantum Strategy on January 21st 2021 at the Centre for Nanoscience and Nanotechnology (C2N).

© Élysée - screenshot - CNRS Info

AN AMBITIOUS PLAN

The National Quantum Strategy provides for actions in favour of research, industry and training with 1.8 billion euros of funding from the 4th 'Investments for the Future' Programme (PIA4) and the 'France Relance' recovery plan. The aim of this intensive R&D programme in the three main pillars of quantum technologies – quantum computation and simulation (hardware and software), quantum communication and metrology, and quantum sensors – is to identify the technological avenues most likely to find a market in the next five years. This plan is intended to respond to the quantum sector's many strategic challenges. It is also the basis for a strategy aimed at speeding up the process of structuring French forces in this area and development of the so-called "enabling" technologies required to implement future quantum systems (e.g. advanced materials, cryogenics). Currently, quantum technologies are essentially the subject of fundamental research which is why the State designated the CNRS, the CEA and the Inria to establish part of this strategy.

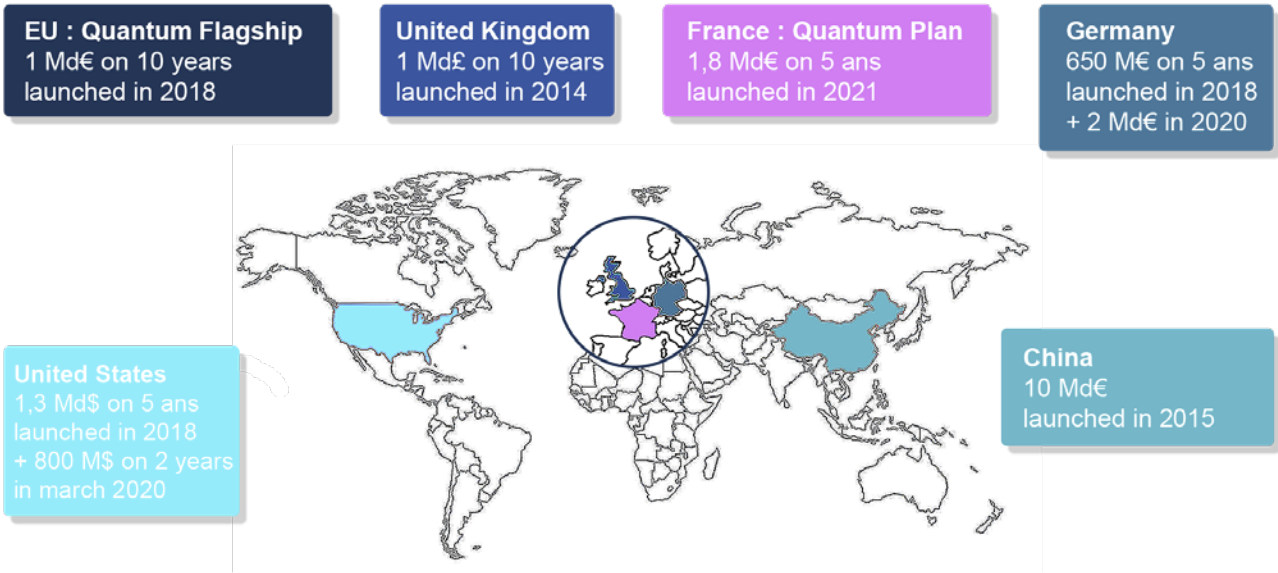
ENSURING NATIONAL SOVEREIGNTY

The Strategy thus aims to ensure national sovereignty, particularly when faced with the United States and China who are investing massively in the field and digital giants like Google or IBM who are multiplying their research efforts, obtaining major results and allocating substantial budgets.

* The report 'Quantum technologies, the technology revolution that France will not miss' submitted by the member of Parliament Paula Forteza, the researcher Iordanis Kerenidis (CNRS) and the former CEO of Safran, Jean-Paul Herteman, to the Prime Minister Édouard Philippe in January 2020.

THE NATIONAL QUANTUM STRATEGY - AMBITIOUS AND AWAITED

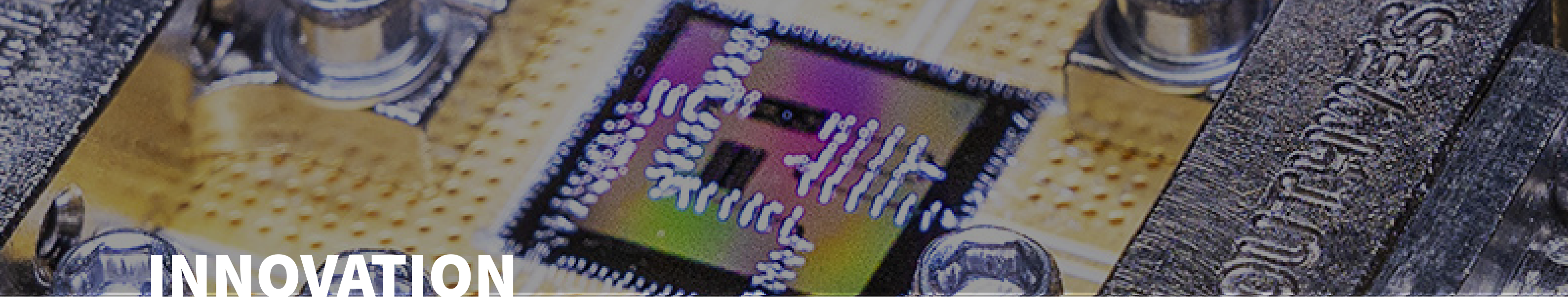
Here are some of the Government's investments in quantum technologies around the world



© CNRS - Sources: government sites, Forteza report and Olivier Ezratty

A clean room where carbon-nanotube chips are manufactured. These are destined to be integrated into a processor used to develop a quantum processor.

© Hubert Raguet/C12 Quantum Electronics/LPENS/CNRS Photothèque

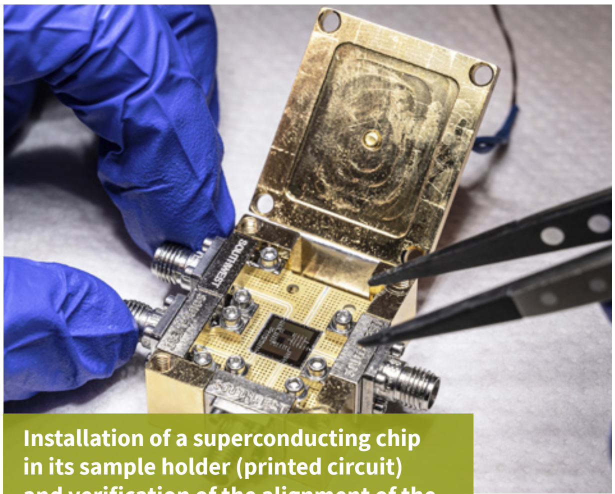


INNOVATION

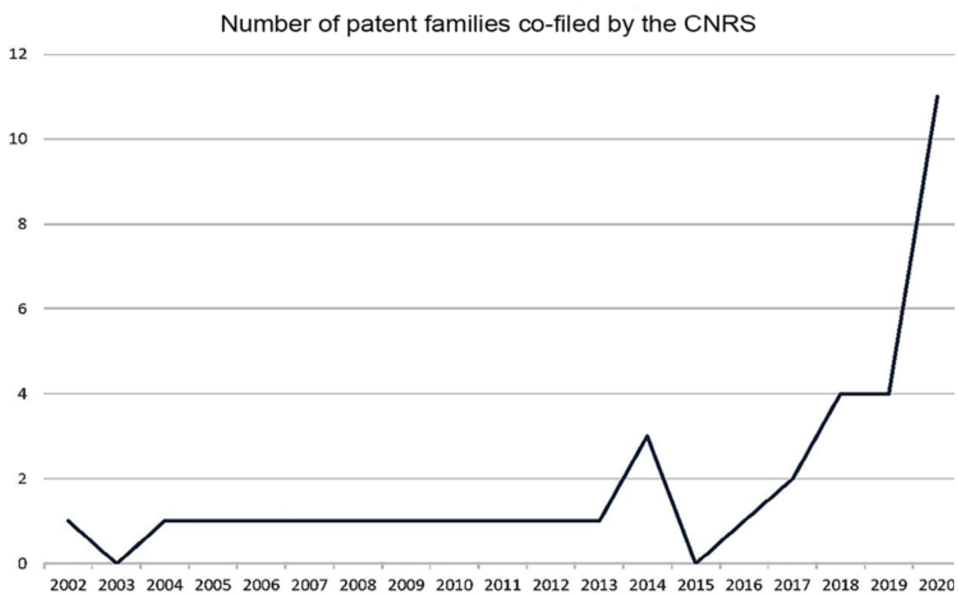
The CNRS has made the transfer of knowledge to companies and society a priority working theme along with the economic impact of these transfers. The dedicated ecosystem for technology transfer and innovation set up by the organisation has proved to be beneficial in the field of quantum technologies with several start-ups already positioned in this promising sector.

The strong growth in the number of patent families co-filed over the last five years testifies to the success of the transfer of quantum physics research carried out in CNRS laboratories and those of its partners. This has also led to the creation of innovative start-ups, positioned on various aspects of this major research field. These are listed in the following pages, illustrating the diversity of research conducted in this area. Four of these start-ups have benefited from the CNRS RISE business creation support programme.

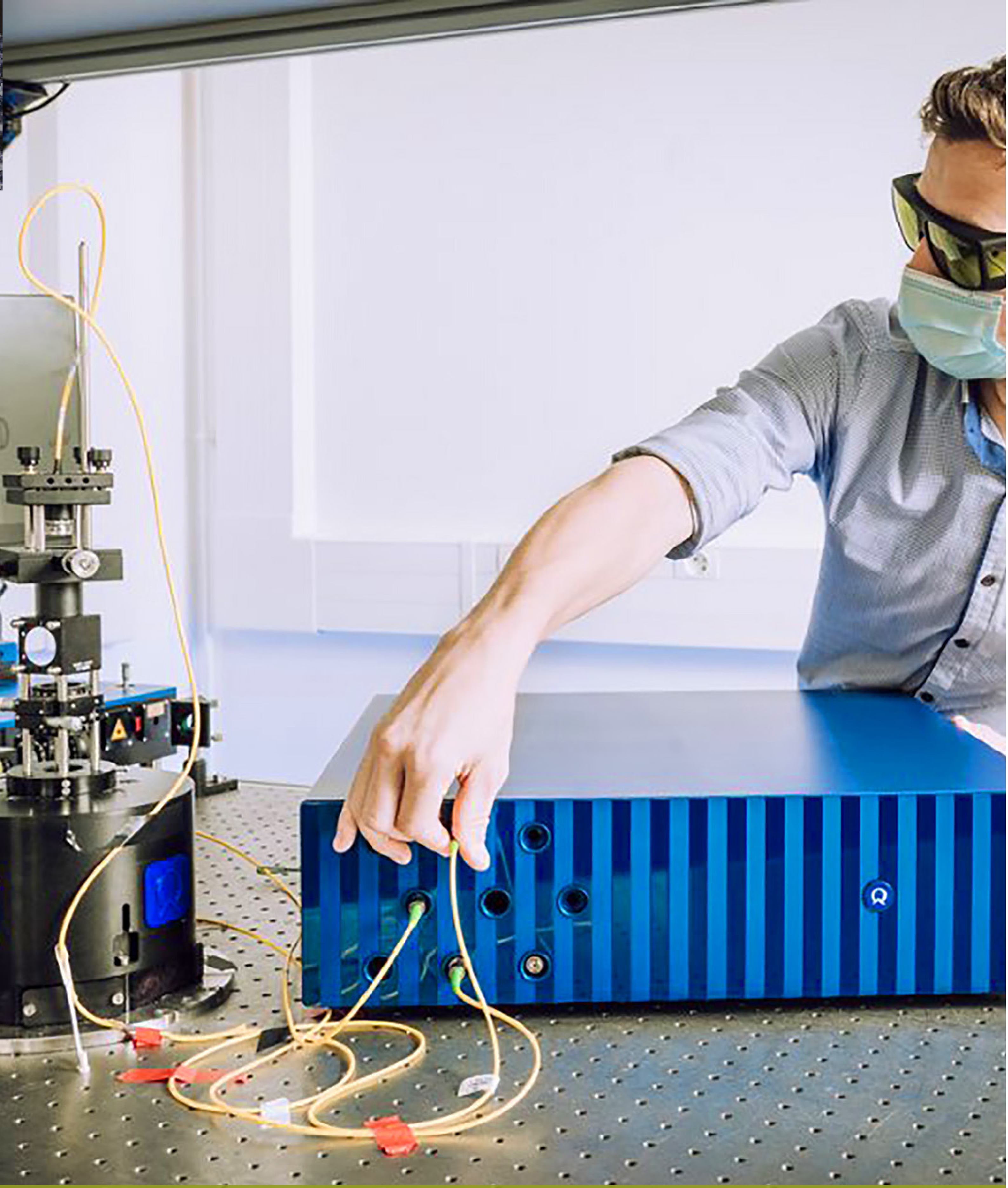
Between 2016 and 2020 almost one million euros were invested in the CNRS's prematurity programme, which aims at detecting and supporting the most promising research projects in quantum science and technologies. This programme has already financed around ten projects in this sector and should thus enable other innovations to emerge in the next few years.



Installation of a superconducting chip in its sample holder (printed circuit) and verification of the alignment of the connectors. This prototype Cat-Qubits chip was developed by the Alice&Bob start-up.



A total of over thirty patents have been filed since 2002.



The optical fibre in the hand of the experimentalist carries single photons (photonic qubits) from a semiconductor source (quantum dot, not shown) placed in the black cryostat to the left of the picture. These single photons are collected using a confocal microscope positioned above the cryostat chamber. The single photons are then filtered by separating the laser used for the optical excitation of the source. This step is carried out in the blue box called QFiber, which serves as an interface between the excitation laser, the photon source in the cryostat and the rest of the experiment. The Quandela start-up was founded in 2017 by Valérian Giesz, Niccolo Somaschi and Pascale Senellart (CNRS senior researcher) to work on these photonic qubits. This approach permits to exploit dozens of qubits simultaneously. The qubit is the unit of information storage that indicates quantum computers' computing power. The start-up produces miniaturised and stabilised sources based on quantum dots, themselves composed of a hundred of atoms.

QEC: QUANTUM ERROR CORRECTION

The Alice&Bob start-up, was founded in 2020 deriving from work carried out at the Physics Laboratory of the École Normale Supérieure. It produces cat qubits (named after Schrödinger's famous experiment involving a cat that is both dead and alive) with a feedback system that can correct the qubits' own errors. It aims to design the very first logical qubit with autonomous self-correction of errors.

CARBON NANOTUBES SERVING QUANTUM PROCESSING

The start-up C12 Quantum Electronic, was founded in 2020 and again results from research at the Physics Laboratory of the École Normale Supérieure. The start-up works on spin qubits in suspended carbon nanotubes as carbon is a material whose minimal interface with the external environment drastically reduces the failure rate. The company's aim is to design the first quantum processors based on carbon nanotubes.

QUANTUM BY ANALOGY

The Pasqal start-up, derived from the Charles Fabry Laboratory, was founded in 2019 and specialises in the arrangement of quantum simulators based on laser-cooled atoms.

PHOTONICS SERVING QUANTUM COMPUTING

The Quandela start-up, was founded in 2015 to develop work carried out at the Centre for Nanoscience and Nanotechnology. Its researchers work on photonic qubits by using miniaturised and stabilised sources based of quantum dots composed of a hundred atoms. The aim underpinning this research is to produce the first quantum computer based on photonic circuits.

SIMPLIFYING TO GAIN SPEED

The QuBit Pharmaceuticals start-up, was founded in 2019 as a result of work at the Laboratory of Theoretical Chemistry (LCT). It has optimised high-performance computing algorithms to gain several orders of magnitude in speed and reliability. These algorithms should enable molecules in silico to be designed, thus reducing the risk-taking involved in the preclinical phase.

QUANTUM DETECTION

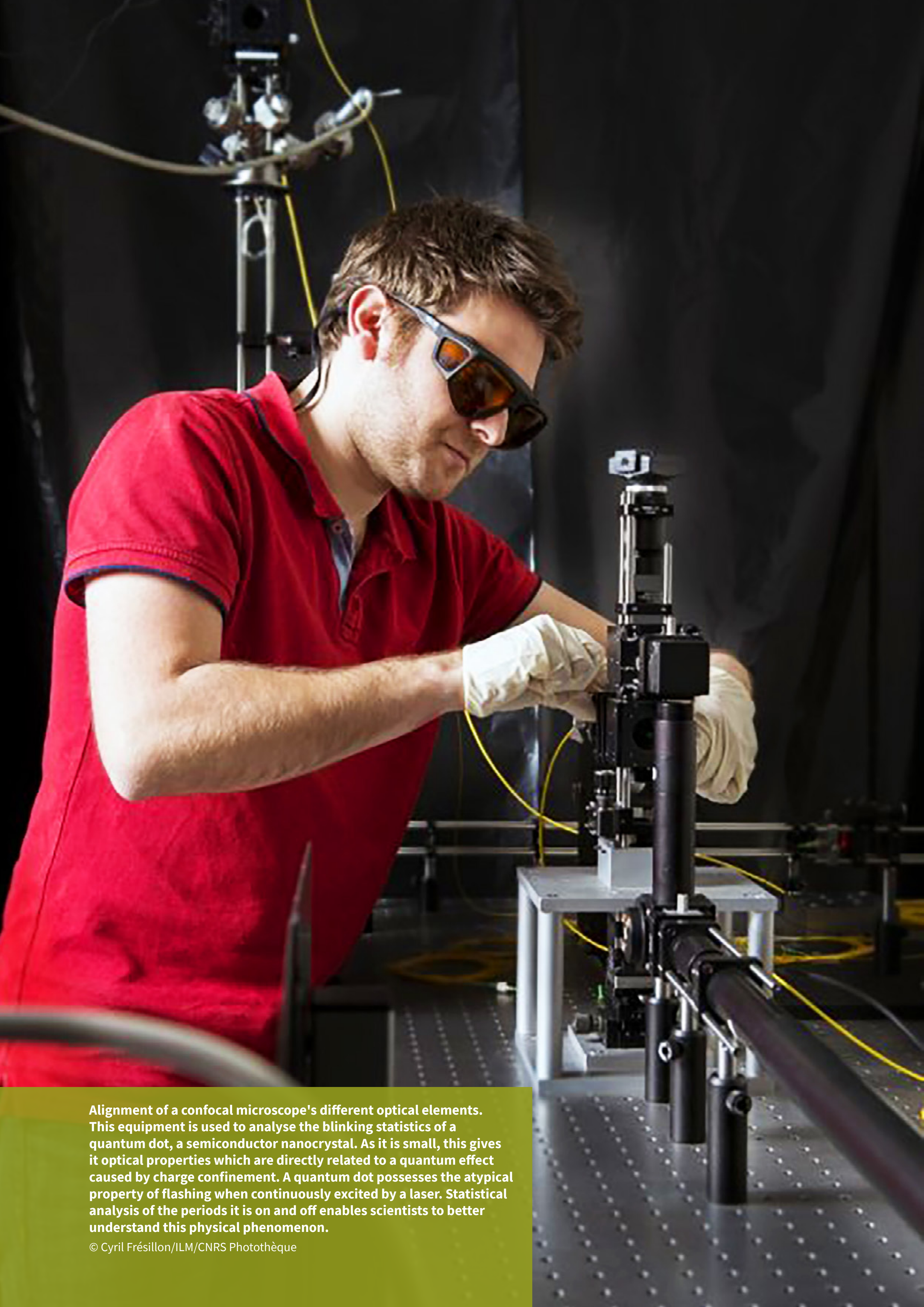
The Muquans start-up (now iXBlue), was founded in 2011 after a collaboration project involving the Photonics, Numerical and Nanosciences Laboratory (LP2N) and the National Metrology and Testing Laboratory - Time Space Reference Systems (SYRTE). It specialises in high-performance gravity detection, time and frequency applications and laser solutions, and aims to provide all-integrated quantum sensors based on cold atoms.

PREPARING FOR THE POST-QUANTUM ERA

The Cryptonext start-up, was founded in 2019 as a result of the collaboration between LIP6 and the Inria. It is one of the pioneers in rolling out post-quantum cryptography and aims to ensure the transition to a form of cryptography that can resist the quantum computing threat on conventional cryptography methods.

VeriQloud	**ACCELERATING QUANTUM COMMUNICATION** **The VeriQloud start-up**, founded in 2017 to transfer research results achieved at LIP6, works on accelerating the power of quantum communication networks by developing applications, software and architectures for future quantum information science.
LightOn	**AN OPTICAL COPROCESSOR FOR ARTIFICIAL INTELLIGENCE** **The LightOn start-up**, was founded in 2016 by three physicists from the Langevin Institute, the Statistical Physics Laboratory and the Kastler Brossel Laboratory. It has developed an optical coprocessor that speeds up machine learning in quantum information.
AQEMIA	**USING DEEP PHYSICS AND AI TO DISCOVER NEW MOLECULES** **The Aqemia start-up**, founded in 2019 at the École Normale Supérieure, is the fruit of eight years of academic research into a theory of quantum and statistical mechanics which calculates free energies. This research means Aquemia can invent innovative molecules by using machine learning and algorithms inspired by quantum physics.
AUREA TECHNOLOGY	**COUNTING PHOTONS TO DETECT LIGHT** **The AUREA Technology start-up**, was founded in 2010 as a result of work at the FEMTO-ST Institute and provides photon-counting modules with high quantum efficiency which can detect very low levels of light.

A reactor in which carbon nanotubes are synthesised from methane using a catalyst. These will later be integrated into a processor used to develop a quantum computer.



Alignment of a confocal microscope's different optical elements. This equipment is used to analyse the blinking statistics of a quantum dot, a semiconductor nanocrystal. As it is small, this gives it optical properties which are directly related to a quantum effect caused by charge confinement. A quantum dot possesses the atypical property of flashing when continuously excited by a laser. Statistical analysis of the periods it is on and off enables scientists to better understand this physical phenomenon.

LIST OF LABORATORIES MENTIONED:

Centre for Nanoscience and Nanotechnology (C2N, CNRS/Paris Saclay University)

GéoAzur (Research Institute for Development - IRD /Côte d'Azur Observatory/CNRS)

Franche-Comté Electronics Mechanics Thermal Science and Optics – Sciences and Technologies Institute (FEMTO-ST, CNRS/COMUE UBFC)

Langevin Institute (CNRS/ESPCI Paris)

Institut Néel (CNRS)

Charles Fabry Laboratory (LCF, CNRS/IOGS/Paris Saclay University)

Laboratory of Theoretical Chemistry (LCT, CNRS/Sorbonne University)

The Laser Physics Laboratory (LPL, CNRS/Sorbonne Paris Nord University)

École Normale Supérieure Physics Laboratory (LPENS, CNRS/ENS-PSL/ Sorbonne University/Université de Paris)

Computer Science Laboratory of Paris 6 (LIP6) (CNRS/Sorbonne University)

Kastler Brossel Laboratory (LKB, CNRS/Sorbonne University/ENS-PSL/Collège de France)

Time Space Reference Systems Laboratory (SYRTE, CNRS/Sorbonne University/ Paris-PSL Observatory/National Metrology and Testing Laboratory)

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Cover photo:
Prototype of a Cat-Qubit chip developed by the Alice&Bob start-up which is working on the development of a self-correcting qubits quantum computer (Cat-Qubits). Alice&Bob was co-founded in February 2020 by Théau Peronnin, CEO, originally from the ENS Lyon Physics Laboratory and Raphaël Lescanne, CTO, originally from the ENS Paris Physics Laboratory.