# NMI-Q / BIPM Workshop:

## Accelerating the Adoption of Quantum Technologies Through Measurements and Standards

# Opening Remarks

## Tim Prior – NMI-Q

# National Metrology Institute (NMI) Summit on Developing Good Practice for Industry-Relevant Quantum Measurements and Standards

**Goal:** Leverage the combined expertise of the world's National Metrology Institutes to accelerate the development and adoption of quantum technologies through coordinated development and sharing of measurement "best practices" in support of future standardization.

**Organizing committee:**

- NRC-Canada (Kevin Thomson)
- NPL-UK (Tim Prior)
- NIST-US (Barbara Goldstein)
- NMIJ-Japan (Nobu-Hisa Kaneko)
- NMIA-Australia (Jan Herrmann)
- PTB-Germany (Nicolas Spethmann)
- INRIM-Italy (Davide Calonico)

# Agenda – Day 1 - Morning
# **Opportunities & Challenges**

| | |
|---|---|
| 09:00 | Registration |
| 09:30 | Welcoming remarks |
| | NMI-Q – Tim Prior |
| | BIPM – Martin Milton, Director |
| | CIPM – JT Janssen |
| 10:00 | Keynote: The emerging quantum economy - the promise & the barriers |
| | Sir Peter Knight |
| 10:45 | Framing the workshop: motivation and goals - Barbara Goldstein |
| 11:15 | Break |
| 11:45 | Panel: Building a quantum economy - what will it take, and what are the challenges? |
| 12:45 | Lunch |

# Opening Remarks

## Martin Milton

## BIPM Director

# Opening Remarks

JT Janssen

CIPM and Conference Chair

10:00 – 10:45

# Keynote: the emerging quantum economy: the promise & the barriers – Sir Peter Knight

# The Emerging Quantum Economy: promises and barriers a personal view


- Peter Knight
- UK NQTP Scientific Advisory Board
- And NPL Quantum Metrology Institute



- Thanks to Qureca, McKinsey, and colleagues for slides

# Promises and Challenges

## Promises

Dynamic and creative research ecosystem

Strong governmental support

Active NMI leadership

International

Active investor community

## Challenges:

Quantum Tech ≠ quantum computing

Hype

Export regulations inhibiting markets

Patient capital and the risk of early exit M&A


The quantum technology ecosystem in 2023
Summary of Quantum Technology Monitor findings
$106B
potential quantum technology market size by 2040[1]
350
start-ups in the ecosystem[2]
Quantum computing
$9B–$93B
estimated market size by 2040
$5.4B
invested as of Dec 2022
223
start-ups as of Dec 2022
Quantum communications
$1B–$7B
estimated market size by 2040
$1.0B
invested as of Dec 2022
72
start-ups as of Dec 2022
Quantum sensing
$1B–$6B
estimated market size by 2040
$0.4B
invested as of Dec 2022
23
start-ups as of Dec 2022
$34B
total government investment announced
Potential economic value from quantum computing
$620B–$1,270B
across four industries by 2035: chemicals, life sciences, finance, and automotive[3]
Quantum-capable talent
50
QT master's degree programs
180
universities with QT research groups
Scientific progress
1,589
QT-related patents granted in 2022
44,155
QT-related publications in 2022

# UK NATIONAL QUANTUM PROGRAMME

A Brief Timeline

Launch The UK National Quantum Technologies Programme (NQTP)

2013 → 2014 → 2019 → 2023 → 2024 - 2034

**PHASE 0:**

Workshop at Chicheley Hall

**PHASE 1:**

Focus on converting research and excellence into technology prototypes and plugging the skills deficit

£380m investment over 5 years.

**PHASE 2:**

Focus on driving commercialisation and economic impact (investment, supply chain growth, international collaboration)

Additional £350m over 5 years plus £153m for industry-led activities.

National Quantum Computing Centre (NQCC) launched Sept 2020

**PHASE 3**

Publication of UK Quantum Strategy affirms UK continued commitment to quantum technologies for the next 10 years. Strategy provides an additional investment of £2.5 billion, starting in 2024

So far, NQTP has provided awards to over 123 businesses and 38 universities and RTOs collaborating in over 95 projects

# THE UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME (NQTP): PARTNERS AND GOVERNANCE

**Department for Science, Innovation & Technology**

UK Quantum Strategy lead department

Parent department of UKRI and sponsor for NPL

**UKRI Engineering and Physical Sciences Research Council**

Funds research and training in quantum, including:
(1) a national network of research hubs;
(2) centres for doctoral training;
(3)-domestic and international research grants;
(4)-fellowships.

**UKRI Innovate UK**

Delivering a national challenge programme to develop new commercial quantum products involving academia, industry and Government

**UKRI Science and Technology Facilities Council**

Delivering the Quantum Technologies for Fundamental Physics programme;

Home of the National Quantum Computing Centre

**NPL National Physical Laboratory**

Home of the Quantum Metrology Institute (QMI)

Leads activities to test, validate and commercialise new quantum R&D

**Ministry of Defence**

Government lead for defence applications of quantum technologies

**[dstl]**

Responsible for delivering MOD R&D programme in quantum technologies

Provides specialist technical support to national quantum programme partners

**GCHQ**

One of the UK's Intelligence and Security Agencies

Home of the National Cyber Security Centre (NCSC): conducts research and provides advice on 'post-quantum' security

# COORDINATING BODIES

Programme Board
Provides coordination and strategic direction for the programme with representation from each of the partner agencies.. Chaired by Dame Lynn Gladden, Executive Chair, EPSRC.

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Strategic Advisory Board
Provides independent advice to help steer the strategic direction of the programme and policy on quantum technologies, and is made up of eminent figures from across industry, academia and Government. Chaired by Sir Peter Knight.

Department for
Science, Innovation
& Technology

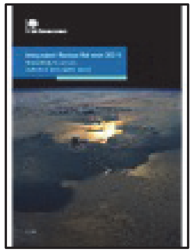
# In the UK: Quantum is critical area of emerging tech

## Government policy context

Government aim to make **UK a Science and Technology superpower** by **2030**

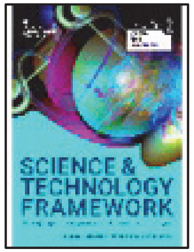
Commitment to **increase R&D** spend by **33%** to **£20bn** per annum by **2024/25**

New **Cabinet Committee - National Science and Technology Council**



**Integrated Review**


**Innovation Strategy**




**Science & Technology Framework**

## Science & Technology Framework

### 5 Critical Technologies

- **Artificial Intelligence**
- **Engineering biology**
- **Future telecoms**
- **Semi-conductors**
- **Quantum technologies**

### 10 cross-cutting strands:

| | |
|---|---|
| Identifying Critical Technologies | Procurement |
| Signaling UK Strengths and Ambitions | International Opportunities |
| Investment In R&D | Access to Physical & Digital Infra |
| Talent and Skills | Regulations and Standards |
| Financing Innovative S&T Companies | Innovative Public Sector |

# UK Quantum strategy: 4 Main Goals

## Ensure

Ensure the UK is home to world-leading quantum science and engineering, growing UK knowledge and skills

## Support

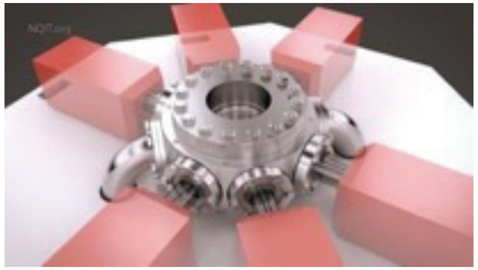
Support business, making the UK the go-to place for quantum businesses and an integral part of the global supply chain, as well as a preferred location for investors and global talent

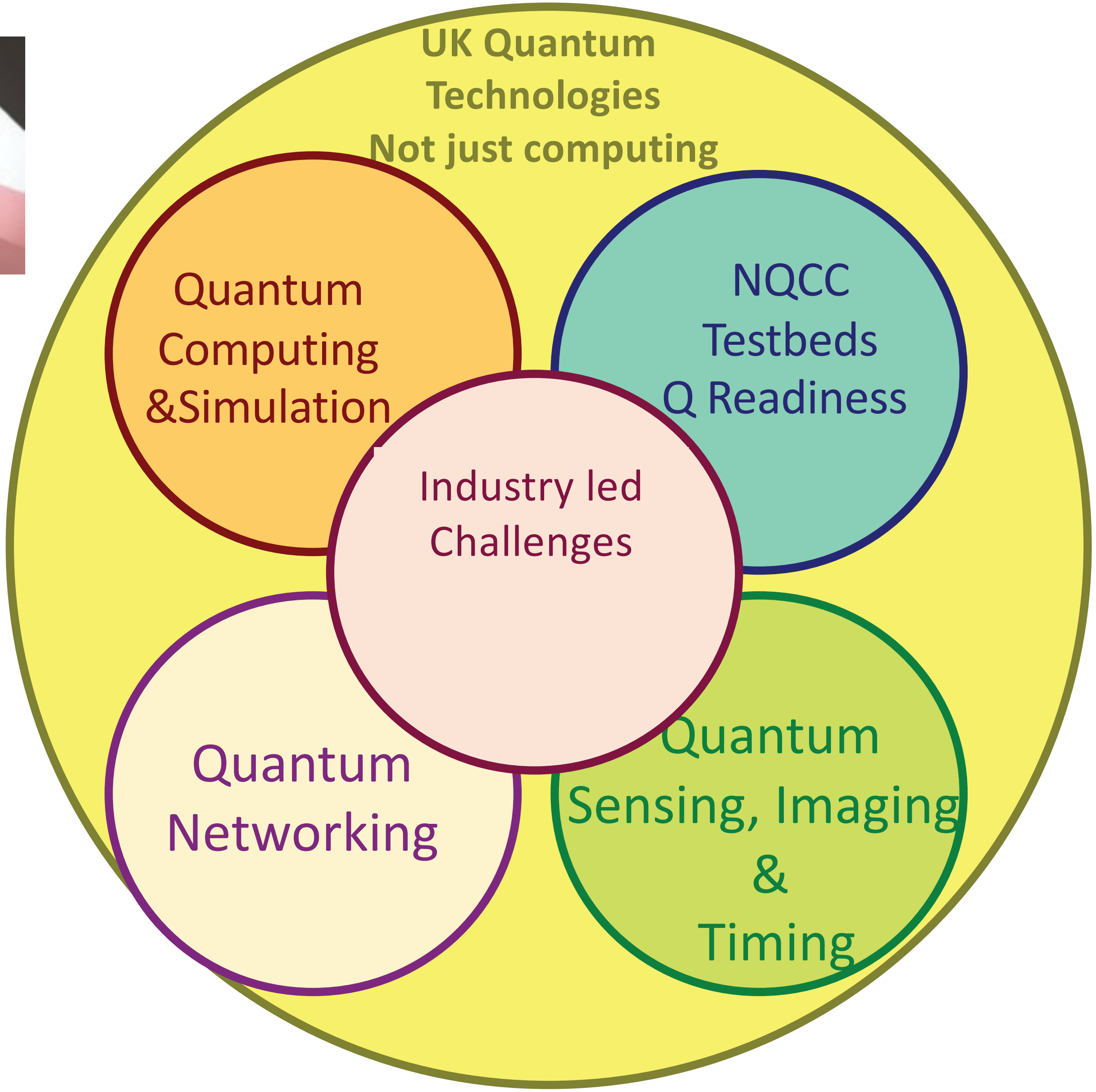
## Drive

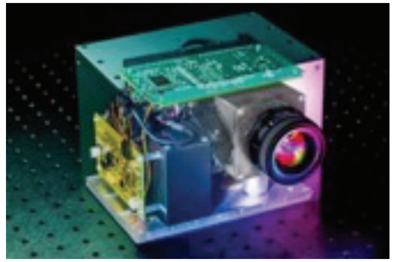
Drive the use of quantum technologies in the UK to deliver benefits for the economy, for society and for our national security

## Create

Create a national and international regulatory framework that supports innovation and the ethical use of quantum technologies, and protects UK capabilities and national security




UK Quantum
Technologies
Not just computing
Quantum
Computing
&Simulation
NQCC
Testbeds
Q Readiness
Industry led
Challenges
Quantum
Networking
Quantum
Sensing, Imaging
&
Timing



Department for Science, Innovation & Technology

# UK Real world applications and products

Wearable brain scanner with better sensitivity and lower cost

Putting quantum technologies in space to secure future communications

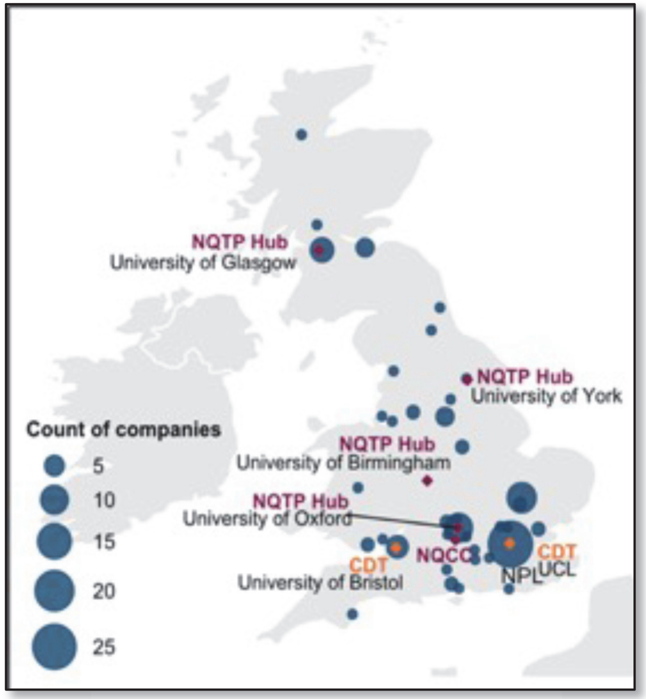
Measuring emissions and greenhouse gases more accurately than ever before

First commercial trial of a quantum secured communications network in the world

Gravity gradient sensor ‘seeing’ the invisible underground

Department for Science, Innovation & Technology

# 10-year UK National Quantum Technologies Programme has resulted in a thriving Quantum sector…




**World leading research and skills:** 1st in Europe and 3rd in the world for the quality and impact of quantum research. More than 470 PhDs, 125 MSc candidates, and 85 apprenticeships funded through the NQTP

**Thriving business community:** UK is second for the number of quantum companies (11% of the world's quantum companies)

**High-levels of private investment:** UK is second in attracting private equity investment (12% of global private investment)

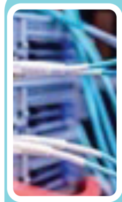
**Broad capabilities:** Quantum companies spanning computing, communications, sensing, timing, and imaging

**Highly collaborative community:** 180 quantum organisations working together through IUK challenges, and 140 Hub industry partners

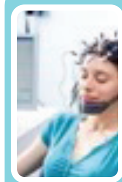
Department for Science, Innovation & Technology | UKRI Engineering and Physical Sciences Research Council | UKRI Innovate UK | UKRI Science and Technology Facilities Council | UKRI National Quantum Computing Centre | NPL | Ministry of Defence | [dstl] | GCHQ

# UK Quantum Missions: vision for 2024-2035

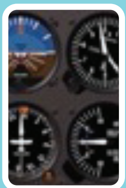
By 2035, there will be accessible, **UK-based quantum computers capable of running 1 trillion operations** and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy.



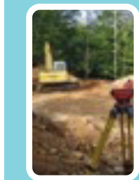
By 2035, the UK will have deployed the **world's most advanced quantum network at scale**, pioneering the future quantum internet.



By 2030, every **NHS Trust will benefit from quantum sensing-enabled solutions**, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment.



By 2030, **quantum navigation systems, including clocks, will be deployed on aircraft**, providing next-generation accuracy for resilience that is independent of satellite signals.



By 2030, **mobile, networked quantum sensors will have unlocked new situational awareness** capabilities, exploited across critical infrastructure in the transport, telecoms, energy, and defence sectors.

Department for Science, Innovation & Technology

# UK translation activity

## The UK Quantum Technologies Challenge is delivered across a range of funding programmes to drive collaboration, catalyse private investment and build UK industrial leadership.

**Collaborative Research & Development (CR&D) Projects.**
Up to 3 years and £10M grant. These are organised around the commercial advancement of a quantum product or service. Consortia are typically comprised of full technology chains, from research organisations to component manufacturers, systems integrators and end-users. Innovation progresses to system demonstration in end-user trials at the final stages of the project.

**Technology Projects.**
Up to 3 years and £10M grant. These projects are primarily focused on the removal of technical barriers that are shared across the quantum industry to accelerate commercialisation. Consortia bring together a range of businesses with the support of research organisations to address these common challenges.

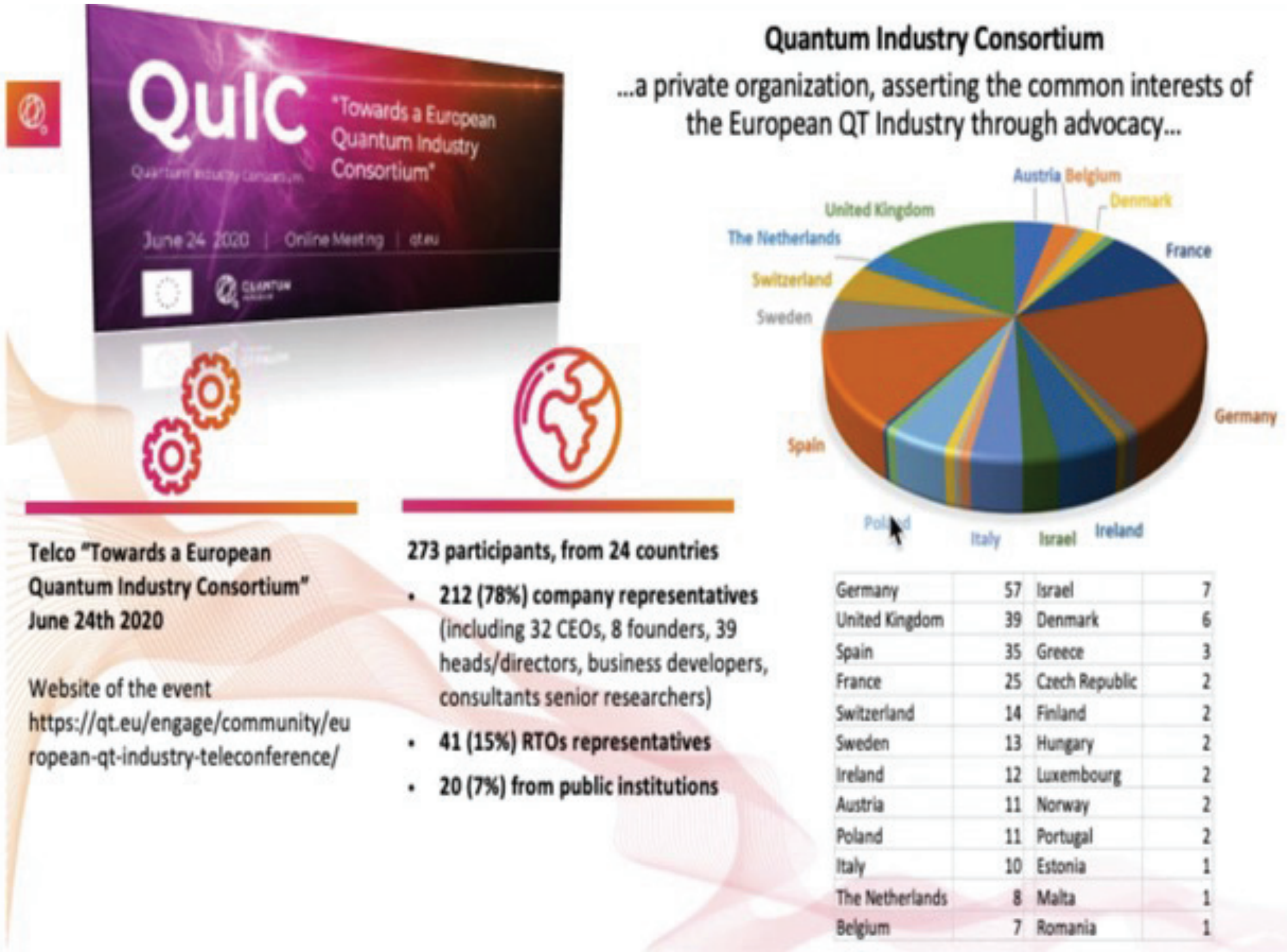
**Feasibility studies.**
Up to 1.5 years and £0.5M. These are earlier stage innovation projects that focus on advancing user defined quantum products, services and devices, components or supply chain elements for the current or future quantum technologies market.

**Investor partnership.**
Delivered in partnership with IP Group, this programme sees project grant funding aligned with direct equity investment to accelerate and de-risk private investment into quantum technology companies with high growth potential.

### INTERNATIONAL

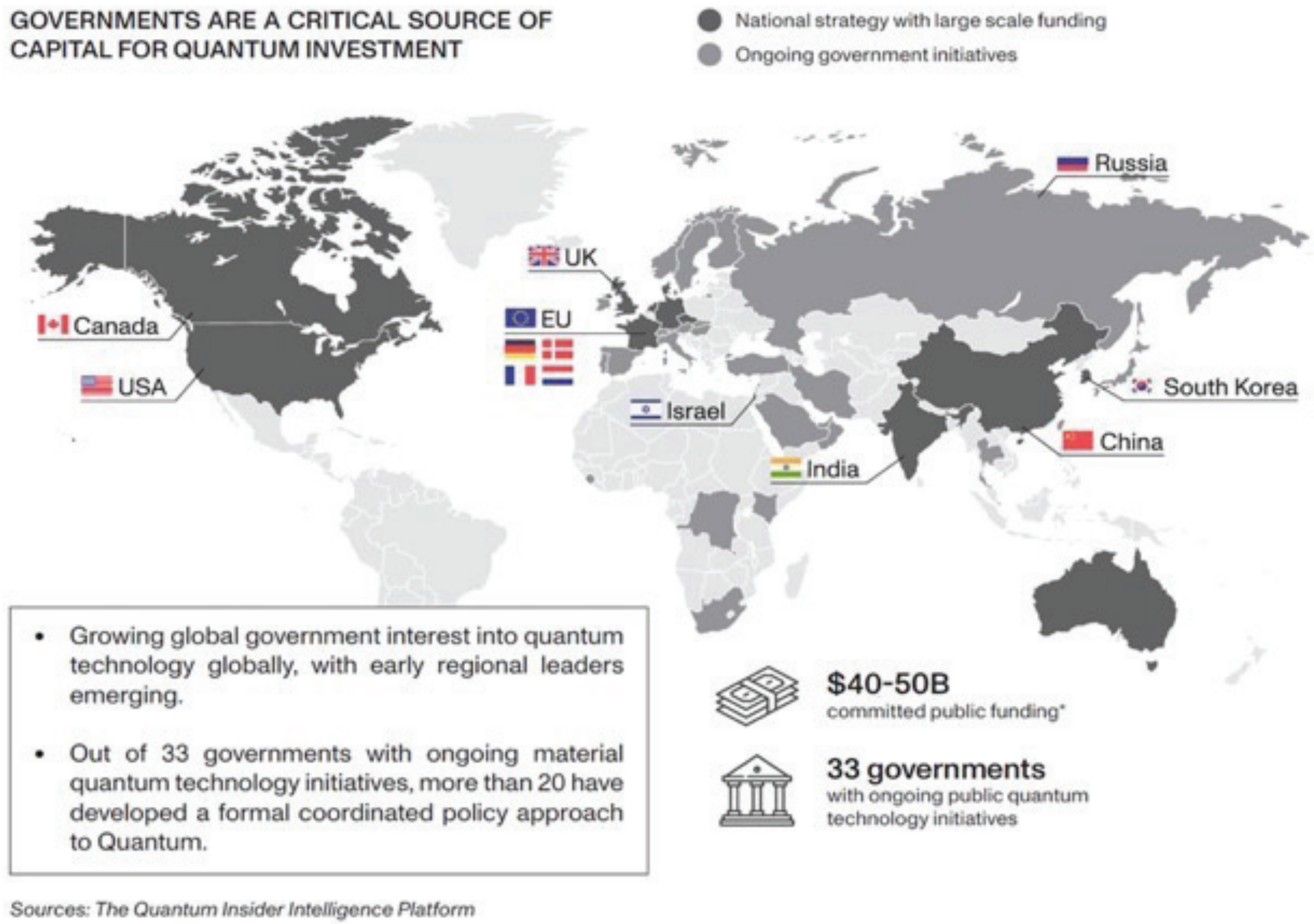
**UK-Canada programme.**
Projects up to 3 years and £0.5M. Building mutually beneficial international collaboration in commercial quantum technologies innovation, involving both industry and academia. These projects are laying the technical foundations for advancing commercial ties between UK and Canada, both nations with a deep and rich heritage in quantum science and technology. In partnership with the Natural Sciences and Engineering Research Council of Canada.

**Europe translation activity**

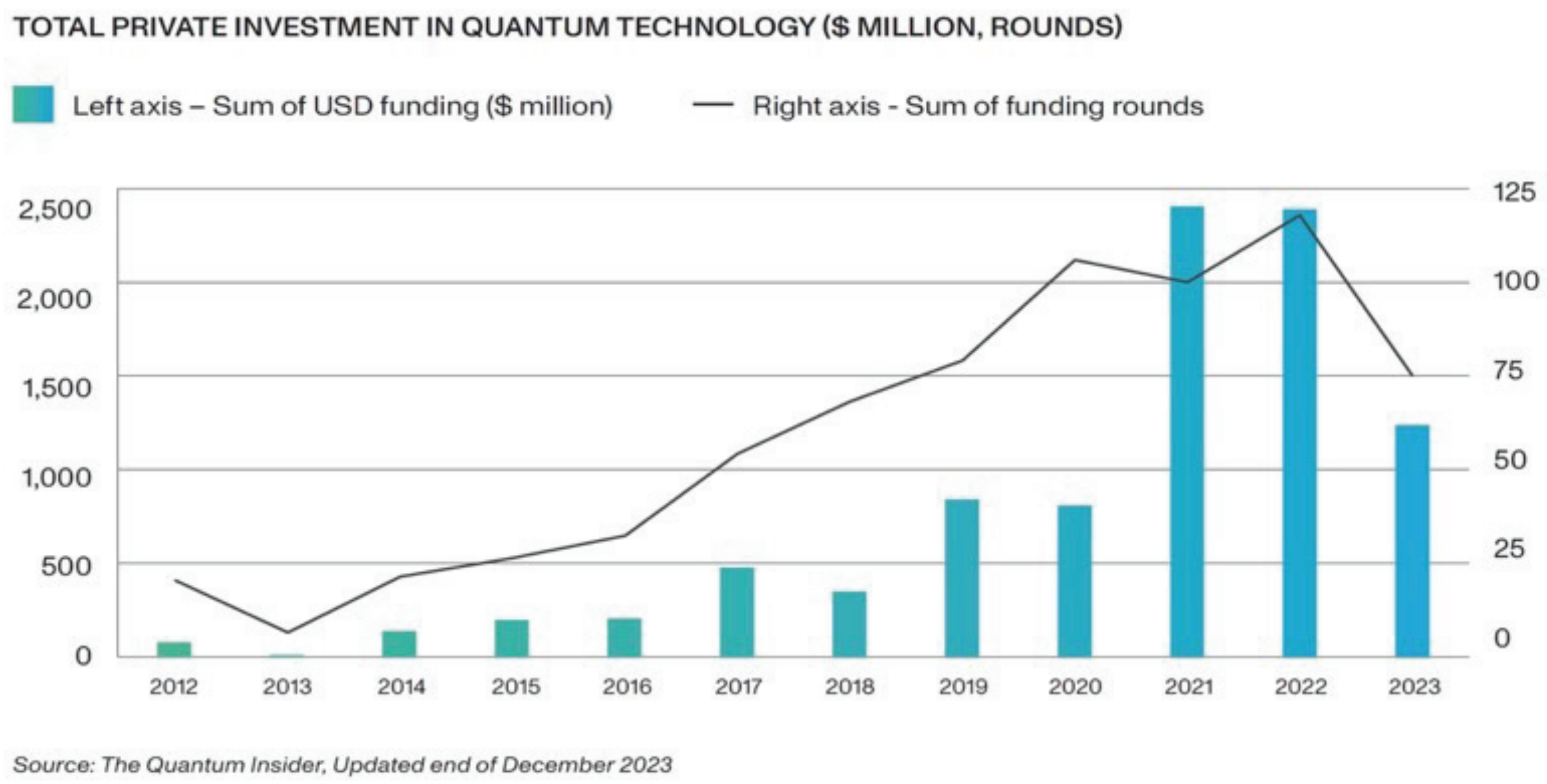



And in the US: QEDC

# World investment



# Are we seeing a quantum winter?



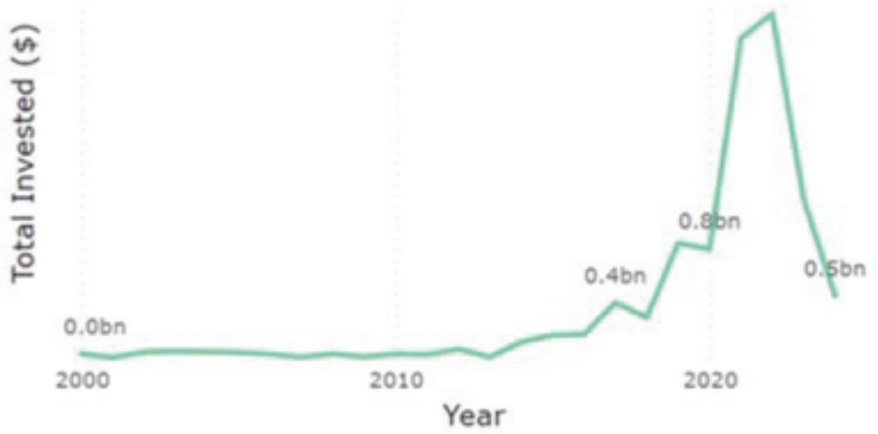



Figure 2a: Global trend of private investment ($) 2012 - 2024

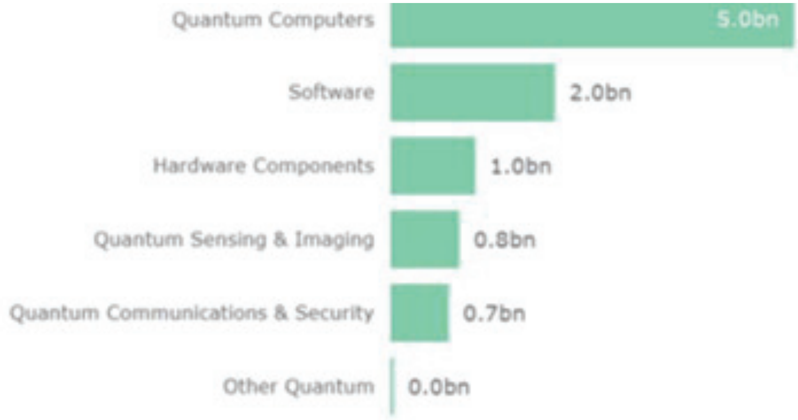



Figure 2b: Primary areas of investment ($) globally 2012 - 2024

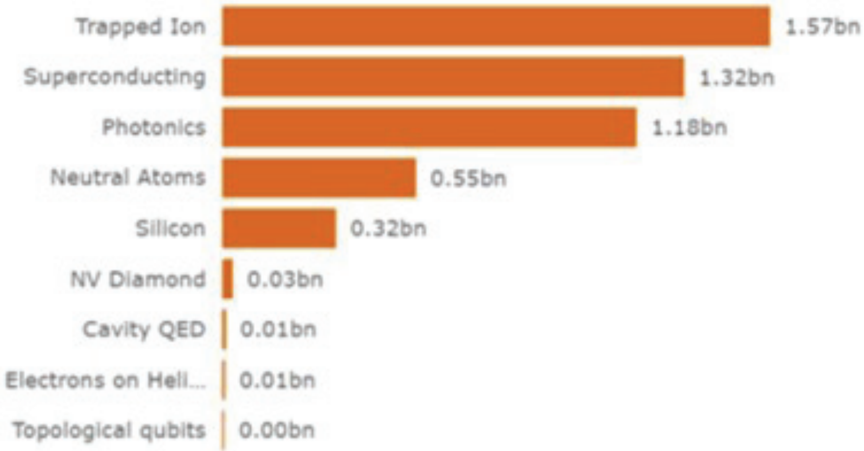



Figure 2c: Global investment ($) in Quantum Computing Technologies 2012 - 2024

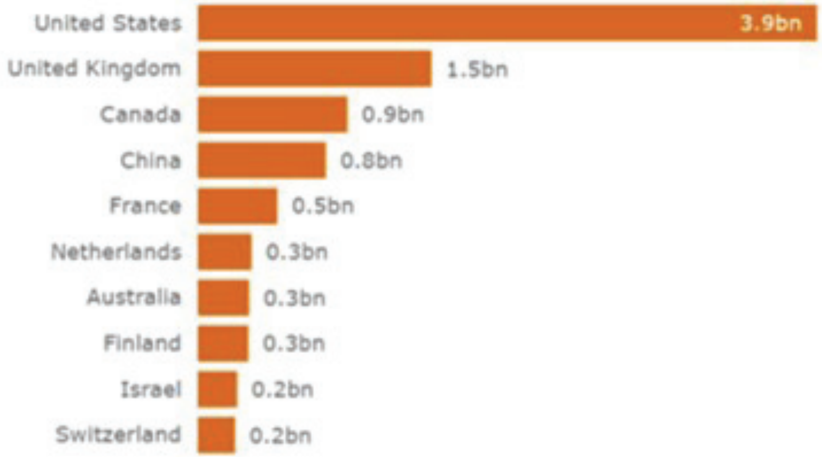



Figure 2d: Top 10 Ranking of Investment ($) by Country 2012 - 2024

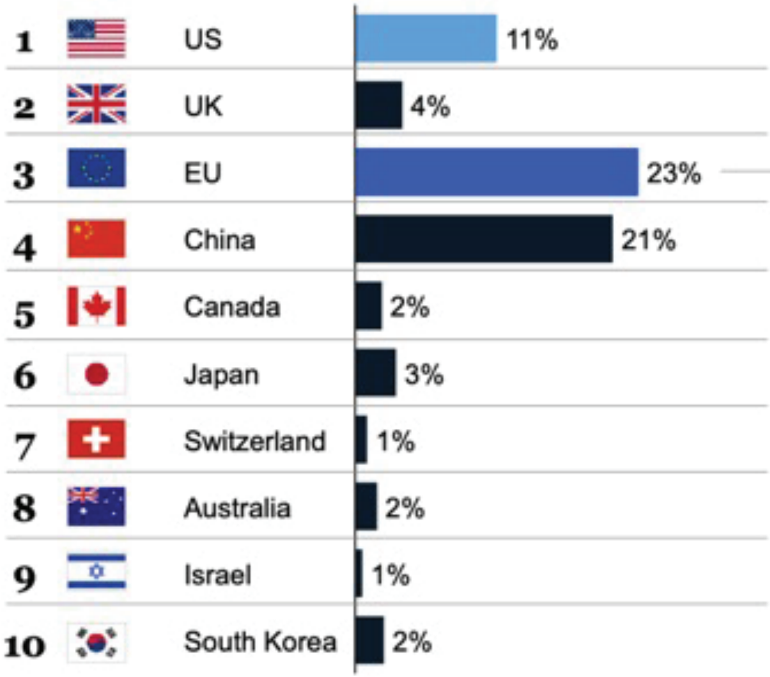
# The European Union leads in quantum-relevant publications, but the United States outcompetes in impact

**As of 2020**

**XX** Rank of country's h-index

**Top 10 countries worldwide 2020, by h-index**

Share of articles and country's h-index[2] in quantum-relevant publications




**Top 5 EU countries**

Share of articles and H index, 2020

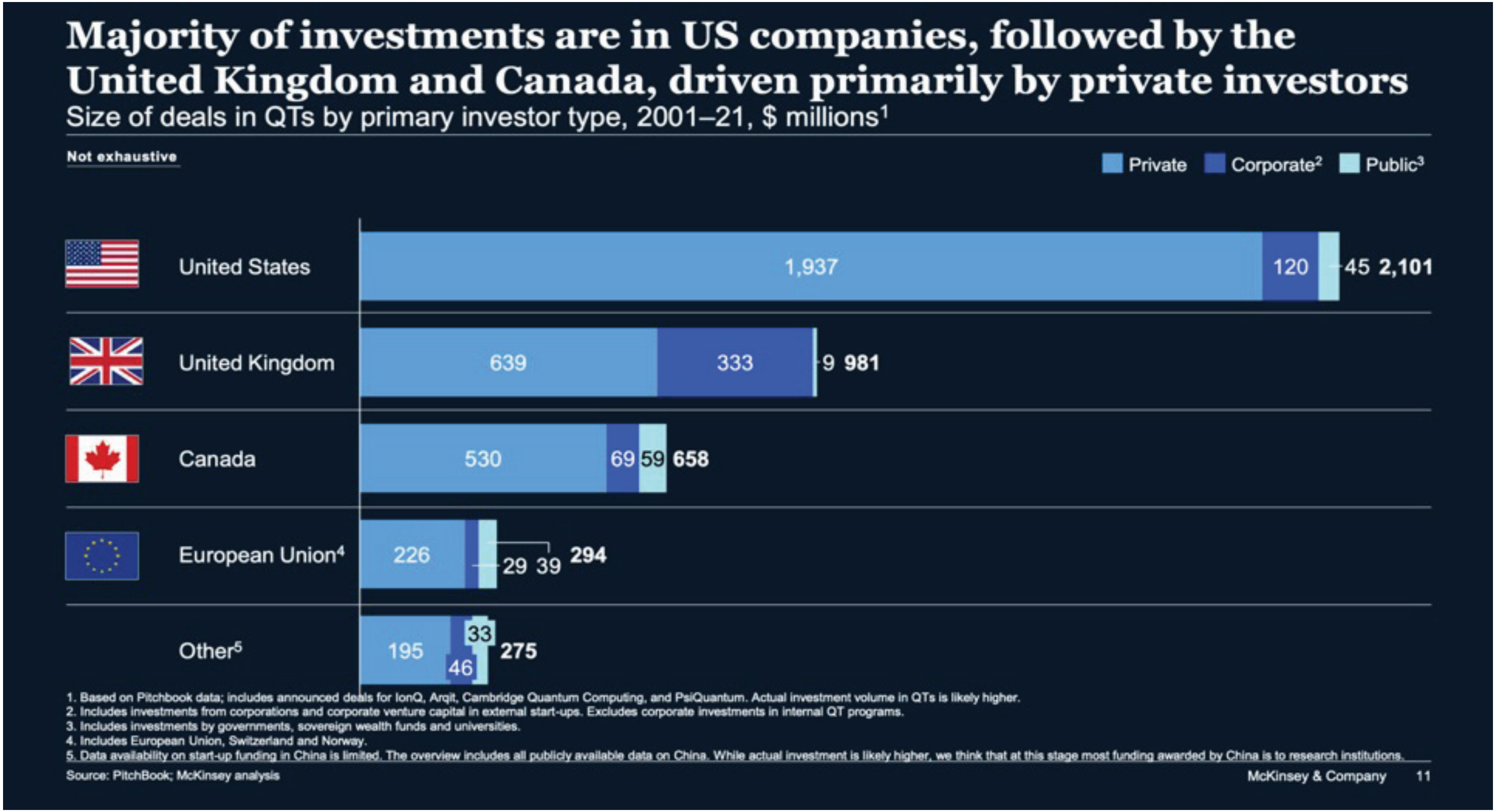

1. Quantum relevant publications defined as publications in physics, mathematics, and statistics, and information and communications technology
2. The h-index is the number of articles (h) in a country that have been cited at least h times

Source: SCImago Journal & Country Rank; McKinsey analysis

## Key takeaways

US publications have the **highest impact** measured by h-index indicating a leading position in academic research

The EU is leading in terms of **published articles** in 2020 in quantum-relevant fields, followed by China and the US


Majority of investments are in US companies, followed by the United Kingdom and Canada, driven primarily by private investors
Size of deals in QTs by primary investor type, 2001–21, $ millions1
Not exhaustive
Private
Corporate2
Public3
United States
1,937
120
45
2,101
United Kingdom
639
333
9
981
Canada
530
69
59
658
European Union4
226
29
39
294
Other5
195
46
33
275
1. Based on Pitchbook data; includes announced deals for IonQ, Arqit, Cambridge Quantum Computing, and PsiQuantum. Actual investment volume in QTs is likely higher.
2. Includes investments from corporations and corporate venture capital in external start-ups. Excludes corporate investments in internal QT programs.
3. Includes investments by governments, sovereign wealth funds and universities.
4. Includes European Union, Switzerland and Norway.
5. Data availability on start-up funding in China is limited. The overview includes all publicly available data on China. While actual investment is likely higher, we think that at this stage most funding awarded by China is to research institutions.
Source: PitchBook; McKinsey analysis
McKinsey & Company
11

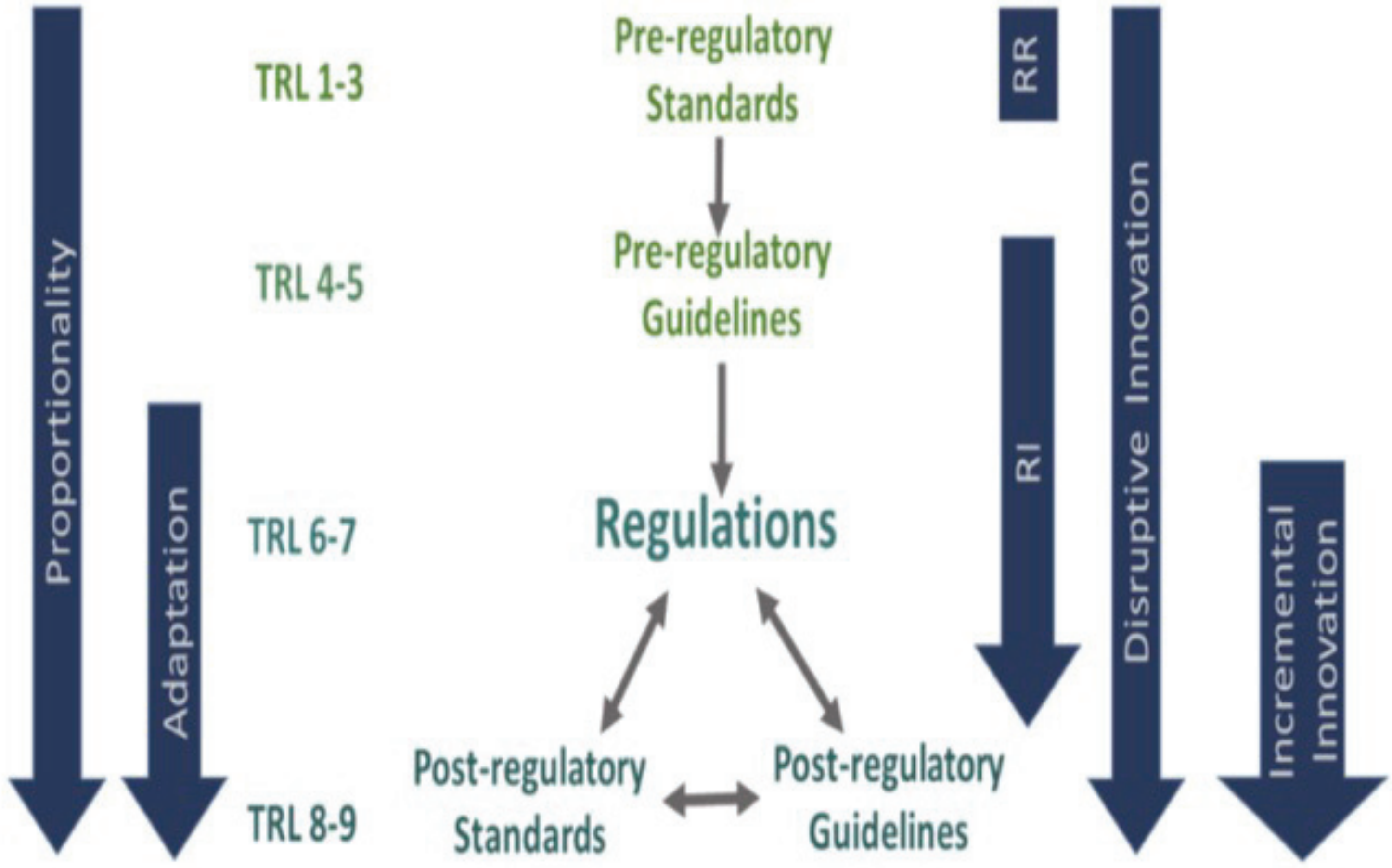
# Standards?

NPL
National Physical Laboratory

“The great thing about (international) standards is that there are so many to choose from!”
Andrew S Tannenbaum – Computer Scientist


Picture: Joachim Lonien
Brussels, 2019-03-28

Regulatory framework



**TRL 1-3 (Pre-regulatory Standards)**: focus on consensus standards.

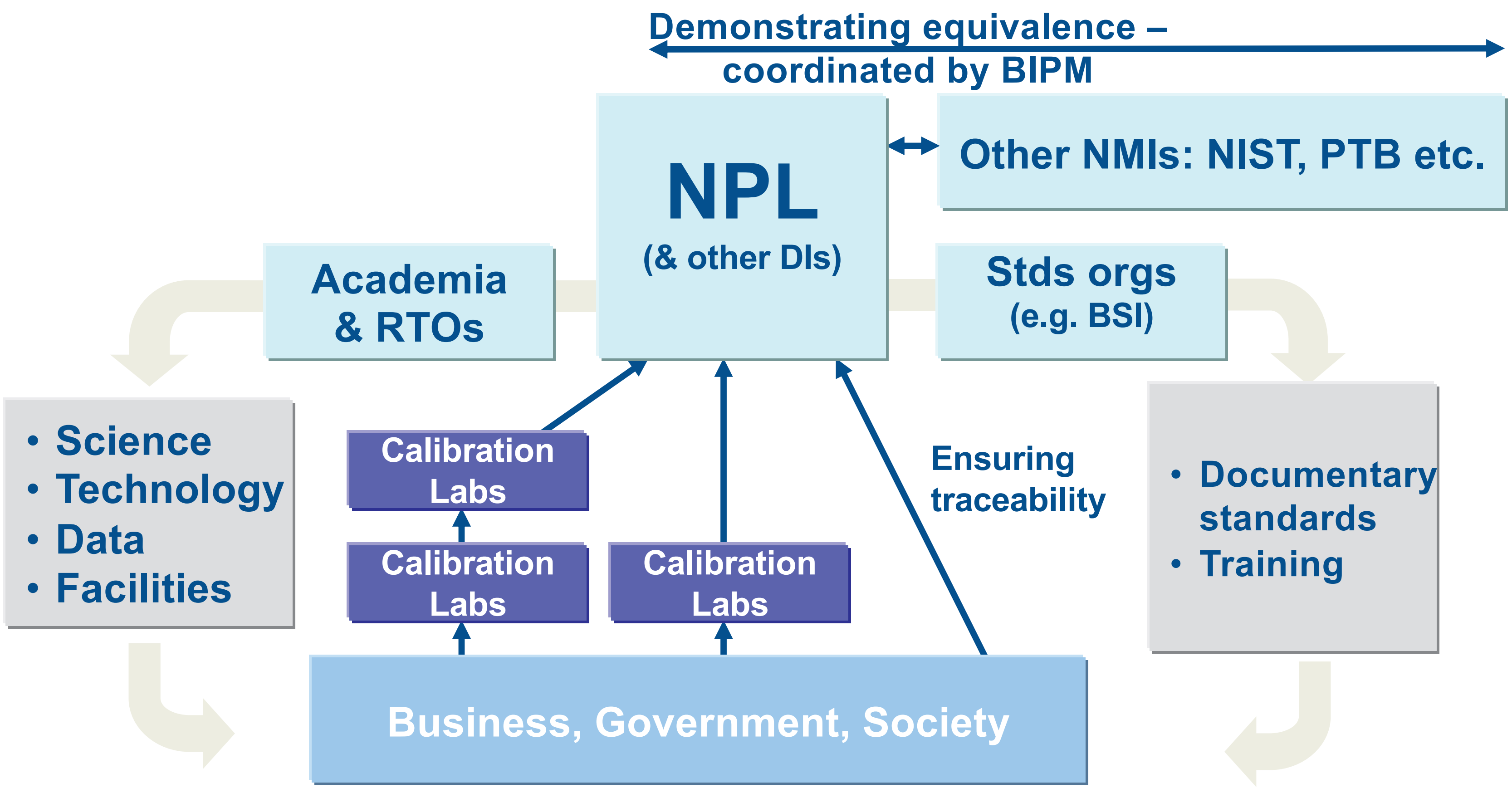
These standards can underpin an understanding of the quantum technology's properties, identifying potential benefits and risks and determining future optimal development and management strategies.

**TRL 4-5 (Pre-regulatory Guidelines)**: Building upon the initial standards, more defined guidelines can emerge. These could subsequently lay the groundwork for a future regulatory system. Importantly, decision-makers should remain receptive to the idea that these guidelines alone might suffice in ensuring the safety, quality, and efficacy of the quantum product or process – rendering legally based regulations unnecessary.

**TRL 6-7 (Regulations)**: Decision points at this stage involve discerning the relevance of existing regulatory systems or, in the case of exceptionally transformative quantum innovations, contemplating a fresh regulatory approach. Legally based regulations should be articulated in broad terms, focusing on desired outcomes, and bolstered by subsequent standards and guidelines, ensuring proportionality towards quantum-related products and processes and adaptability in the face of future changes.

- **TRL 8-9 (Post-regulatory Standards and Guidelines)**: Here, standards (including technology and interoperability standards, along with consensus standards) and guidelines can be crafted to facilitate compliance

# Providing confidence in measurement




Calibrated instrumentation, agreed procedure, trained practitioner, (verification/accreditation)

# Quantum Sensors and Timing: Opportunities in PNT

## Map Matching for Positioning

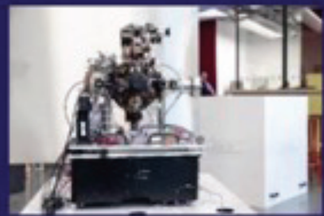
Gravity gradient

Magnetic Fields

→ Providing absolute position without any communication (including under water)
→ Collision alert (?)

## Inertial Sensors for Navigation

Acceleration and Rotation



→ Low drift
→ Low bias
→ Ingredients for INS

## Clocks for Timing

→ On board holdover
→ GNSS spoofing alert


→ Time references
→ Transportable time

UK
Quantum Technology Hub
Sensors and Timing

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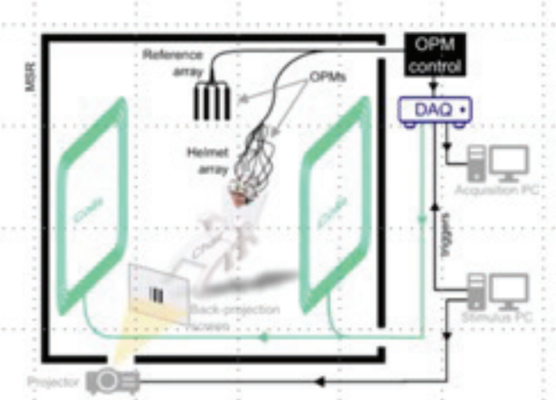
TECHNOLOGIES
PROGRAMME

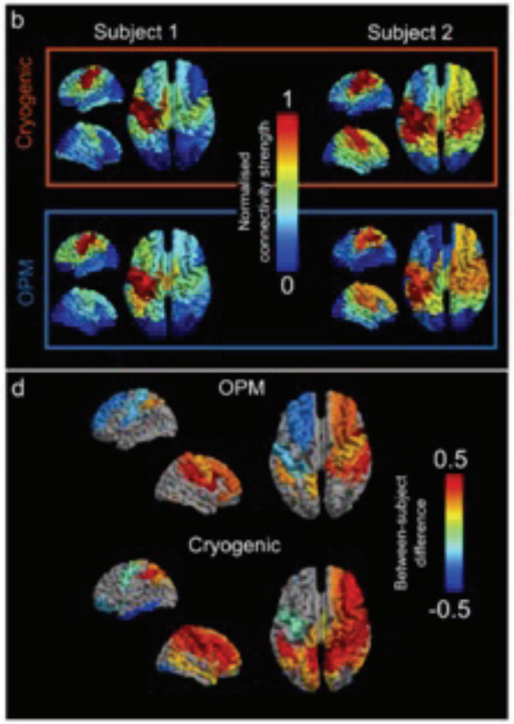
# What's in your head: MEG

## Quantum-Magnetoencephalography – Spin off from QT




Cerca:
Joint venture spin-off between Magnetic Shields and Nottingham University
Founded in 2020

First systems delivered internationally
£6M turnover in first year
>£50M requests for quotations



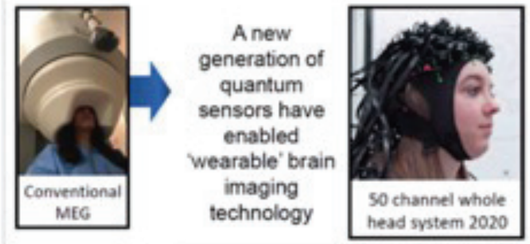

**Impact Opportunities:**

Epilepsy: 60M people worldwide

Dementia: 1% GDP

Schizophrenia: 1% of population

Trauma: 100.000 / year in UK




UK Quantum Technology Hub Sensors and Timing

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

# Now for timing?

# Financial regulation –
# EU requirements for time stamping of trades

European Securities and Markets Authority

- Markets in Financial Instruments Directive II

  Traceability to UTC

  HFT algo 100µs to UTC, 1µs resolution

  Electronic 1ms to UTC, 1ms resolution

  operators of trading venues and their members or participants are required to synchronise the clocks they use for any reportable events with UTC (Article 50 of Directive 2014/65/EU and Article 1 of Commission Delegated Regulation (EU) 2017/574)

3rd Jan 2018

# Do not expect fast breakthroughs!
# Example: Cesium Atomic Clock Development

**1955**
**First cesium atomic clock (NPL, UK)**

**1956**

**First commercial atomic clock (National Company, Inc., USA)**

**1964**
**First portable cesium clock (HP, USA)**


**1967**
**SI second redefined in terms of caesium transition frequency**

**1976**

**Smaller, more rugged caesium atomic clock (HP, USA)**

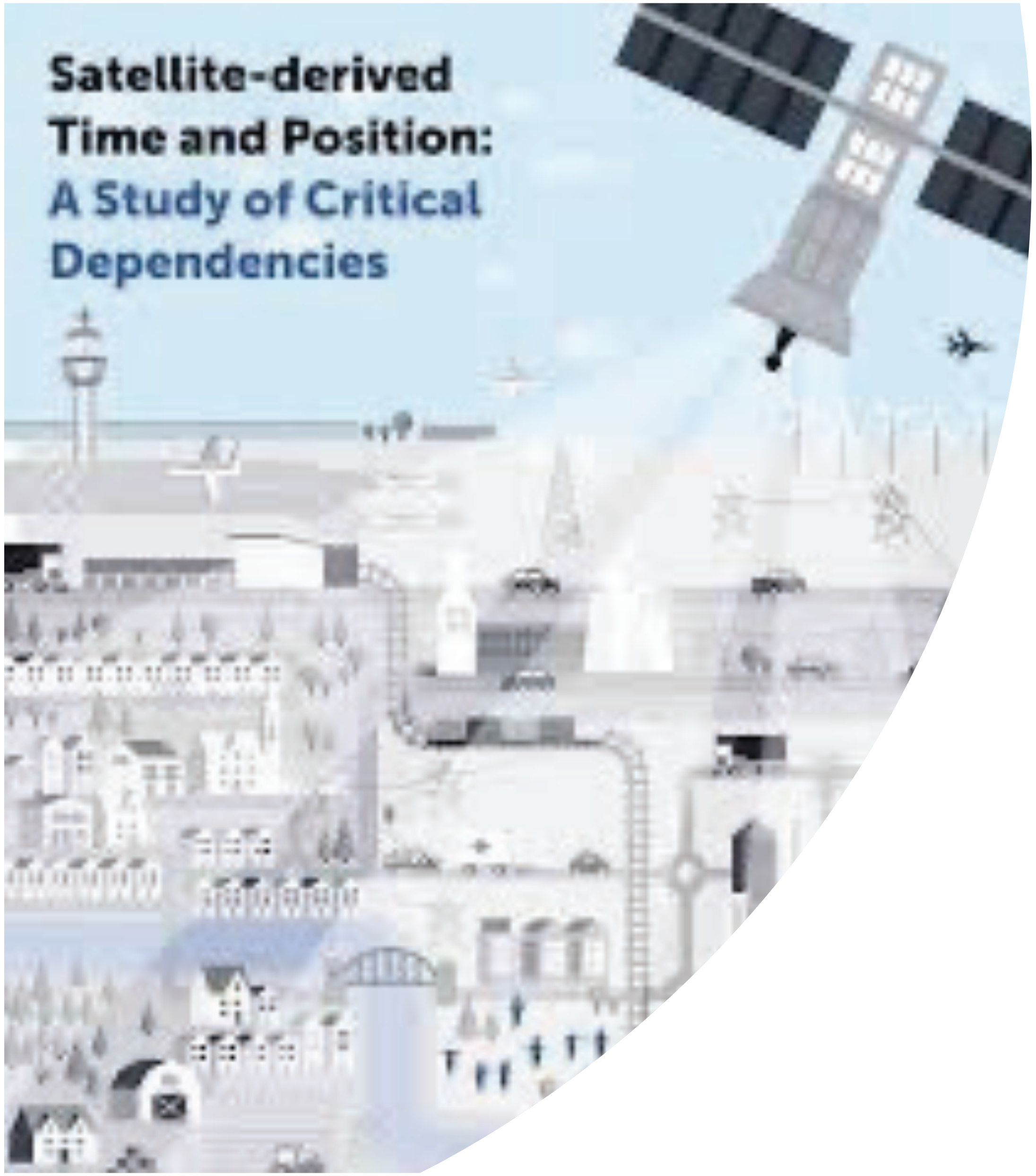
**2011**
**First commercial chip-scale atomic clock (Symmetricom Inc., USA)**


***Accuracy 3 µs / day***
***16 cm³, 35 g, 155 mW***

**2016**
**Cesium fountain primary standards**

**(Courtesy Peter Knight, ESA Meeting Dec 2016, modified)**

*From: W.Kaenders, FiO 2017 (Washington, DC) FW1B*




# PNT

Peter Knight

Joint chair of the UK PNT Strategy Group

reporting to CO and DNSA

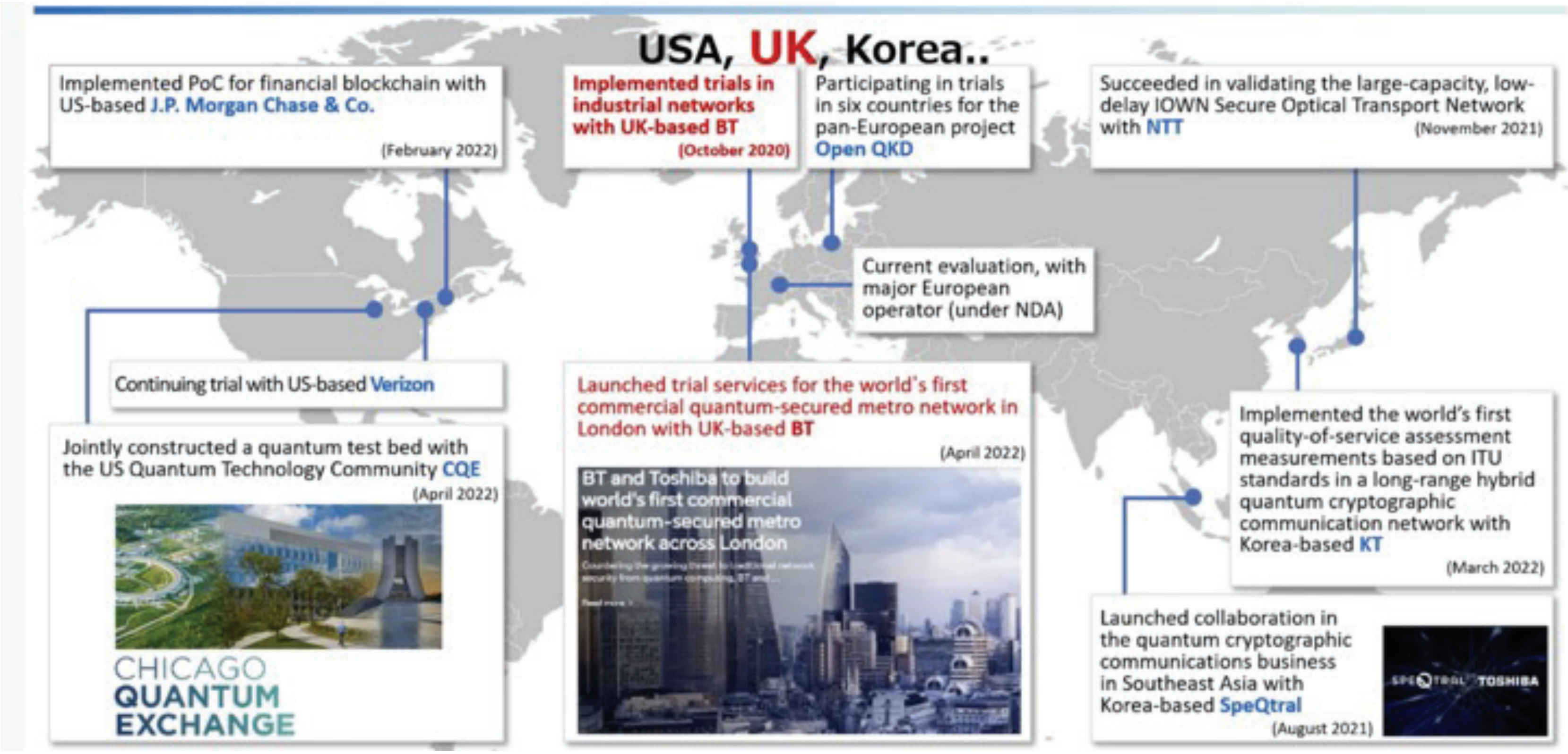
and one coauthor of the Government Office of Science report on GNSS

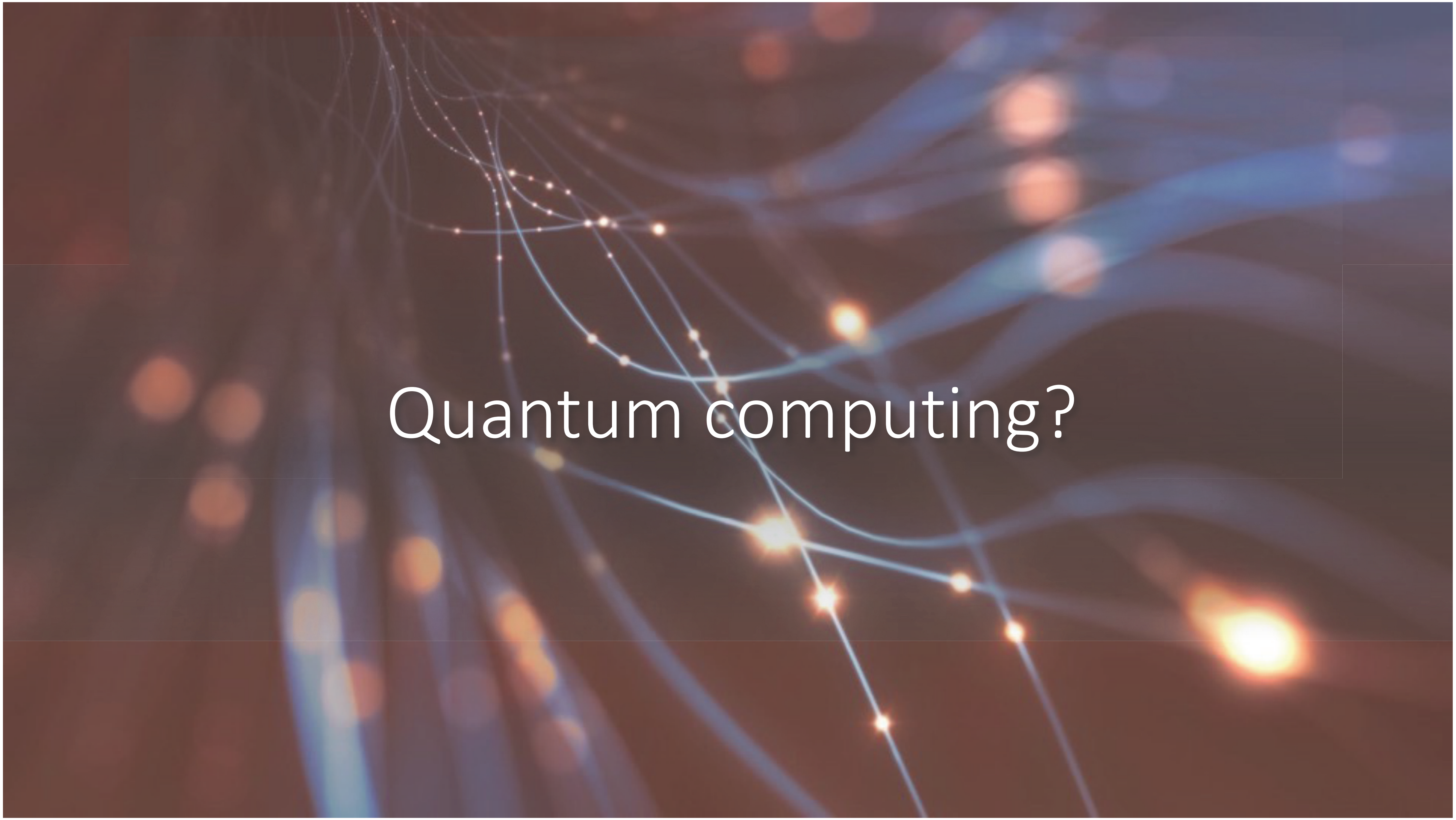
Timely: Wed 18th Nov, The Times: General Sir Patrick Sanders, commander of Strategic Command, focused on the importance of positioning, navigation and timing (PNT) signals provided by satellites. “The economy would be projected to lose £1 billion every day if we did not have access to these crucial timing signals,”. A world without satellite-enabled navigation would be “incredibly challenging” because societies have lost skills like manual map-reading and navigating by the stars.

# Quanta and information in transit

- We cannot make a measurement on a quantum state without perturbing the state
- We cannot measure a single photon, extract all the quantum information and transmit an exact copy of that photon
- Hence we can build ways to transfer quantum information that we can know if anyone (Eve) has tried to extract information
- Either we disregard keys when Eve is listening (BB84) or we can use entanglement QKD where each bit of the key is destroyed if Eve tries to measures that bit
- These issues also provide counter measures & weaknesses of quantum key distribution approaches

# And for quantum communications: Toshiba experience

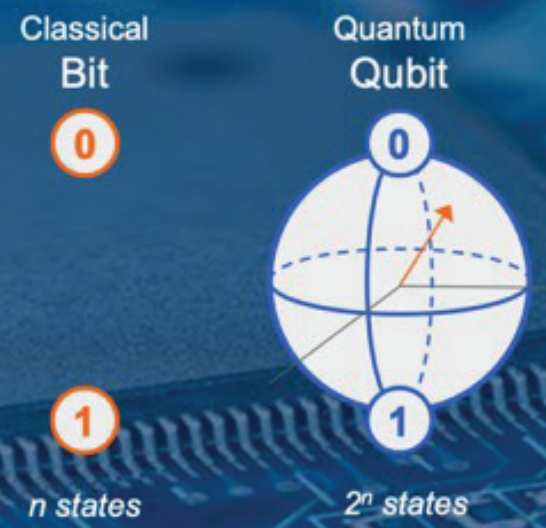




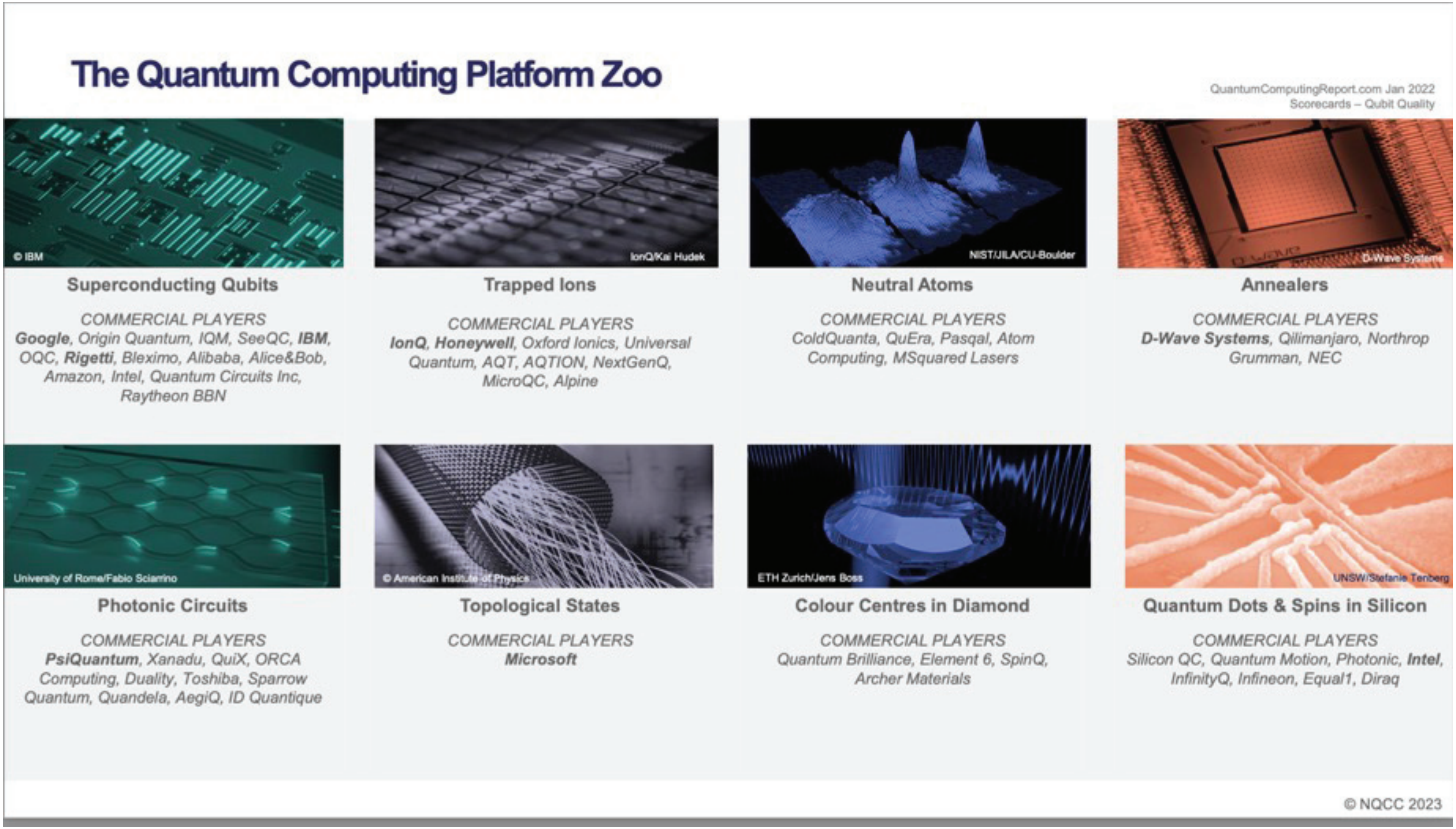
# Quantum computing?

# Quantum Information

- Classical
  - Silicon (Ge, GaAs)
  - Encoded - electrical
  - Lifetime – 1bn operations per s for 1bn years
- Quantum
  - **trapped ions**, neutral atoms, **superconducting circuits**
  - semiconductors, photonic circuits, diamond, exotic metals
  - Encoded - electrical, microwave, optical
  - Lifetime ~1ms




| Qubits *N* | Memory in bits | Time for quantum gate operation |
|---|---|---|
| **20** | 16 MB | milliseconds on smartphone |
| **40** | 16 TB | minutes on supercomputer |
| **60** | 16 EB | long long time |
| **80** | size of visible universe | age of the universe |



The Quantum Computing Platform Zoo
QuantumComputingReport.com Jan 2022
Scorecards – Qubit Quality
© IBM
Superconducting Qubits
COMMERCIAL PLAYERS
Google, Origin Quantum, IQM, SeeQC, IBM, OQC, Rigetti, Bleximo, Alibaba, Alice&Bob, Amazon, Intel, Quantum Circuits Inc, Raytheon BBN
IonQ/Kai Hudek
Trapped Ions
COMMERCIAL PLAYERS
IonQ, Honeywell, Oxford Ionics, Universal Quantum, AQT, AQTION, NextGenQ, MicroQC, Alpine
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Quantum Brilliance, Element 6, SpinQ, Archer Materials
UNSW/Stefanie Tenberg
Quantum Dots & Spins in Silicon
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Silicon QC, Quantum Motion, Photonic, Intel, InfinityQ, Infineon, Equal1, Diraq
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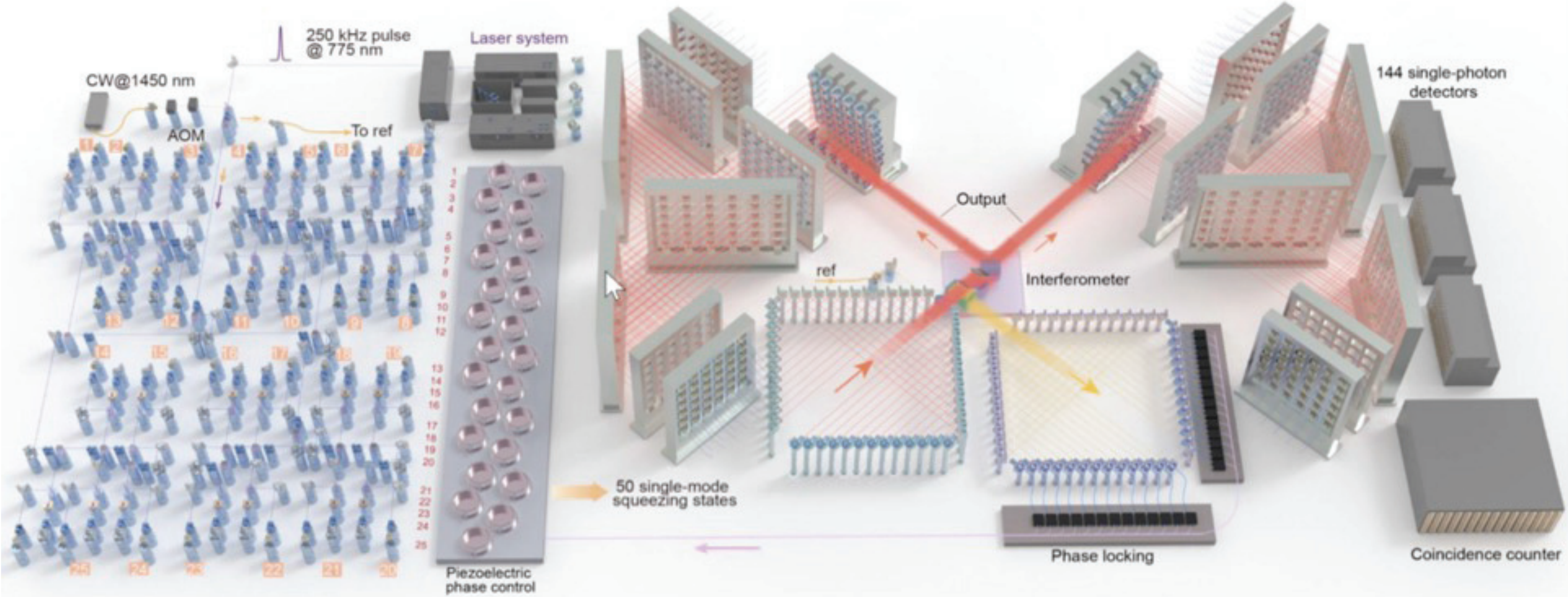
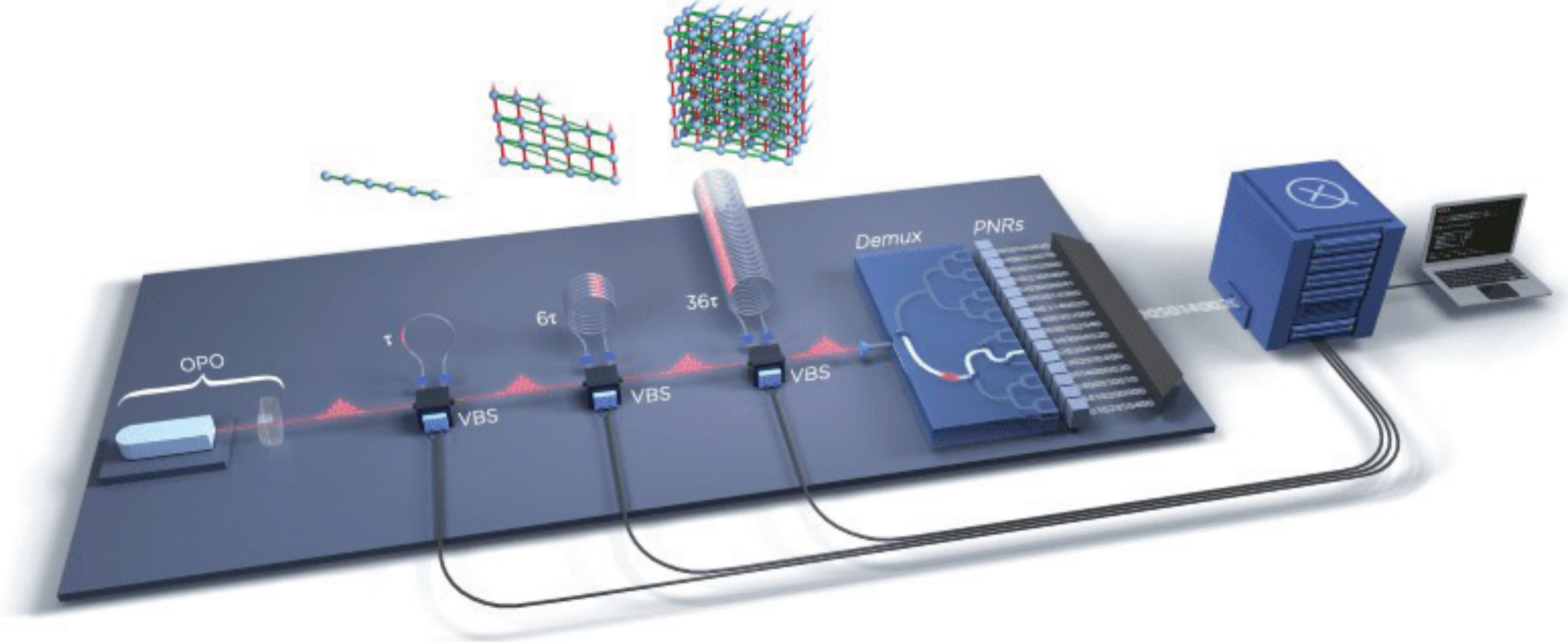
# Gaussian boson sampling

**Jiuzhang 2.0**



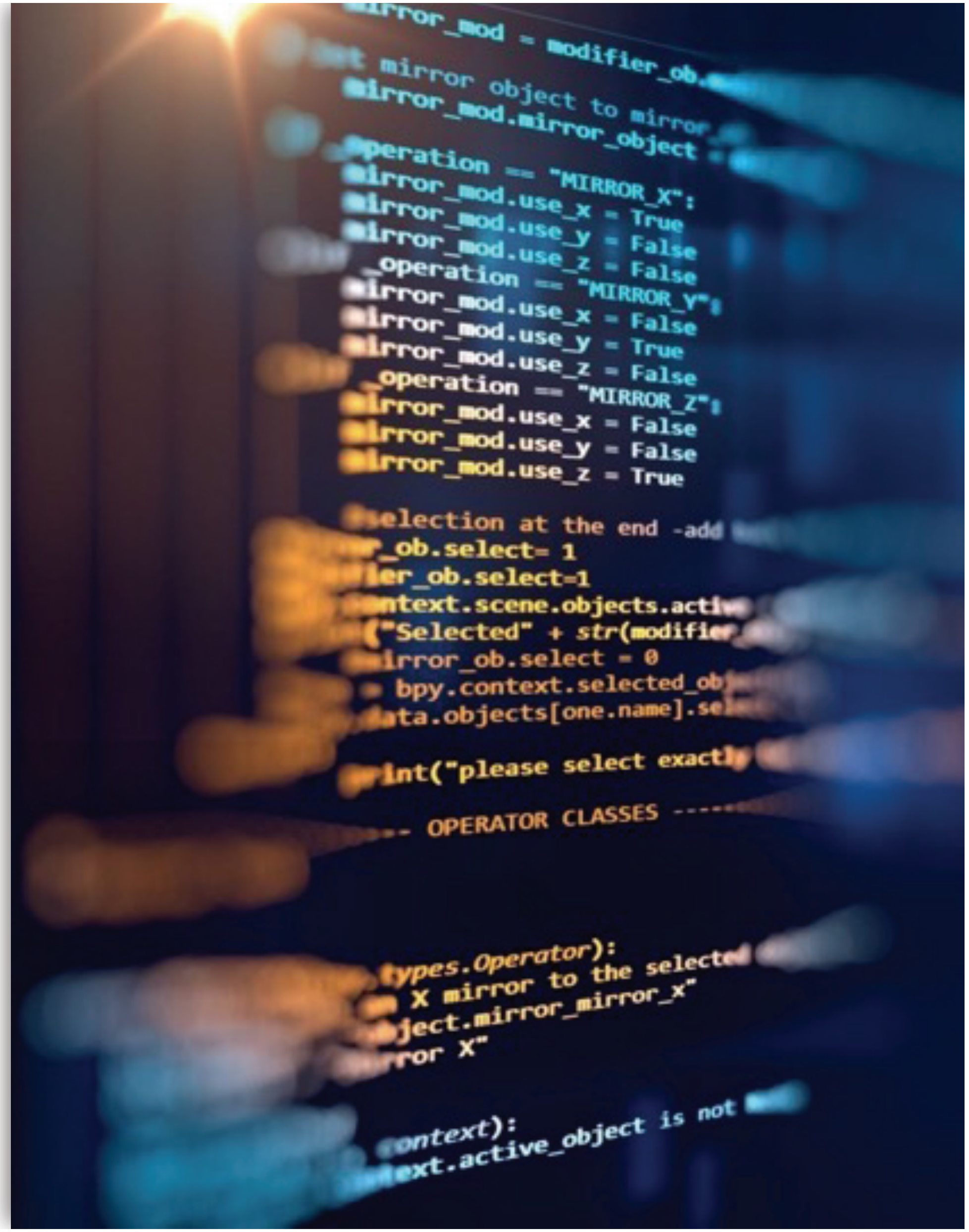
# Xanadu Borealis Gaussian boson sampling




Borealis differs from Jiuzhang - size: with 216 distinct modes compared w 144

# Drowning in data- error correction

- Running a program on an error-corrected quantum computer generates a very fast continuous stream of QEC data.
- A commercial-grade quantum computer would stream about 100 Terabytes of QEC data per second.
- That’s the equivalent of Netflix’s total global streaming rate.
- This flood of data must be processed in real-time by sophisticated algorithms, whose task is to identify the underlying errors and issue corrective measures.

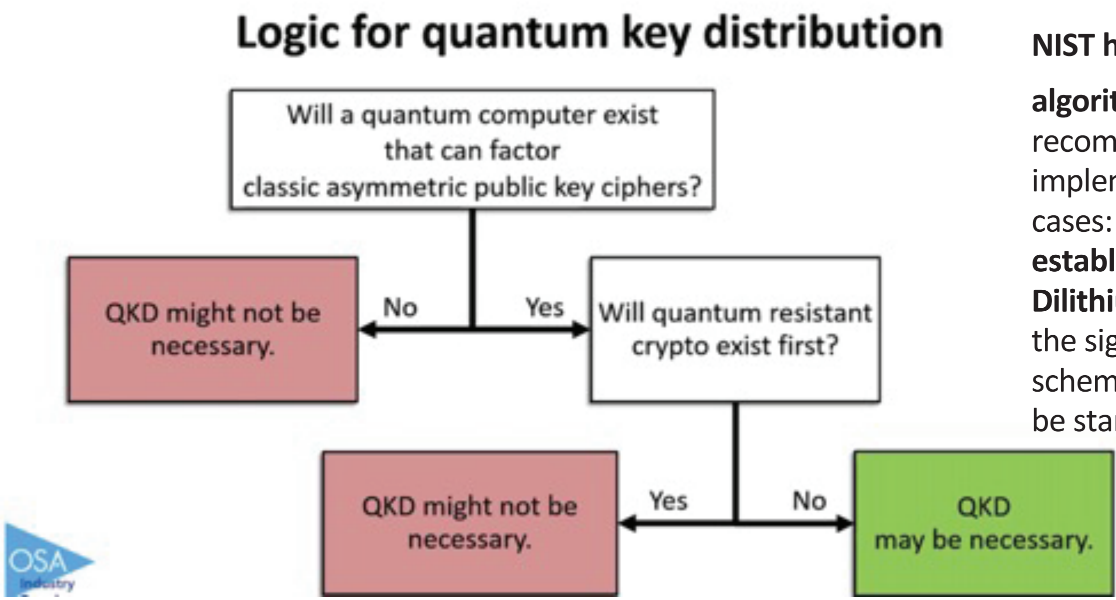


# Why worry: the Mosca equation

- How long does your information require to be secure (x years)?
- How long to re-tool existing infrastructure with quantum safe or resistant solutions (y years)?
- How long until a large-scale quantum computer is built (z years)?

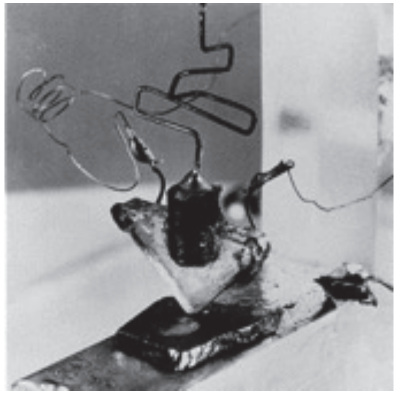
Mosca's Theorem: If x + y > z then worry

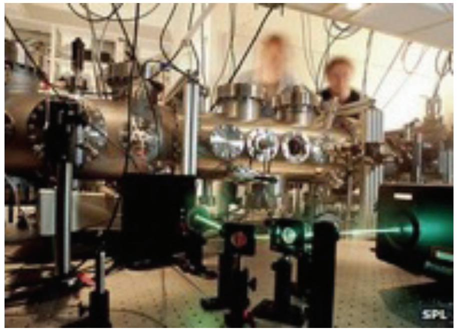

# NIST PQC: candidates now announced

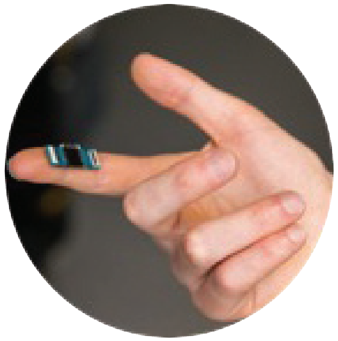



**NIST has identified four candidate algorithms for standardization**. NIST will recommend **two primary algorithms** to be implemented for most use cases: **CRYSTALS-KYBER (key-establishment)** and **CRYSTALS-Dilithium (digital signatures)**. In addition, the signature schemes **FALCON** and **SPHINCS$^+$** will also be standardized.

Care- one candidate Rainbow broken…do we have confidence…







## The Transistor and the Integrated Circuit: lessons for quantum

- First transistor invented in 1947.
- Miniaturization of the technology, in line with Moore's Law, is astounding.
- Complexity of integrated circuits has increased more than a billion-fold since the 1960s.
- The price of an individual transistor is now less than one millionth of the cost in the late 1960s.
    - Had the cost of automobiles fallen at the same rate, a new car today would cost less than one pence
    - We are on a similar journey with Quantum Tech devices!

# Summary: a quantum powerhouse

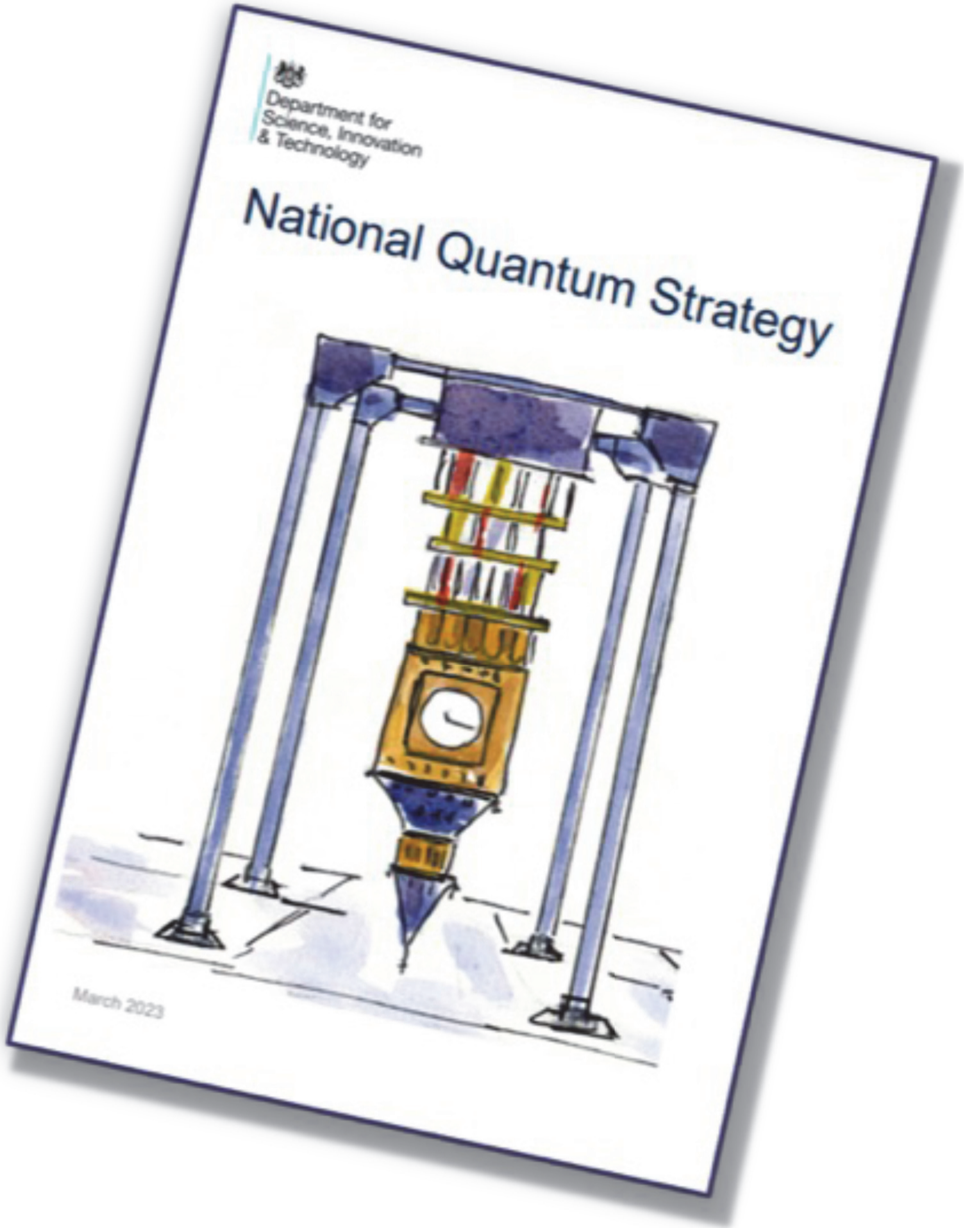
Breadth

Depth

Community building

Partnership

Thank you for listening



10:45 – 11:15

## Framing the workshop: motivation and goals

Barbara Goldstein

With: Davide Calonico, Jan Herrmann, Nobu-Hisa Kaneko, Tim Prior, Nicolas Spethmann, Kevin Thomson

# Emerging technologies demand innovations in metrology

**Agility** to keep up with rapidly changing technical landscape

**Ability** to make a measurement at all

- traceability may lag if needed at all

**Comparability and interoperability**

across vendors, quickly, continuously

**Accelerated delivery**

formal standards may be obsolete by the time they’re published


# NMIs

- first to develop
- first to benefit

Examples:

- Josephson junctions for voltage standards
- Ion traps for clocks


**What does industry need from us to develop quantum technologies?**

Examples:

- Josephson junctions for voltage standards… and superconducting qubits
- Ion traps for clocks … and computing

And these technologies need entirely new ways to measure & characterize

# Metrology Institutes are uniquely poised to accelerate the quantum economy

We bring:

- Measurement expertise
- Ties to industry, academia, standards development organizations
- Innovation
- **Objectivity, neutrality and long history of international collaboration**
    - **Culture of rigor** – the "metrology mindset"
    - **Infrastructure for collaboration** and mutual recognition

# Metrology Institutes are expanding their role to meet new demands

We are:

- Establishing consortia
- Launching incubators
- Contributing to national strategies
- Establishing testbeds
- Conducting pre-standard and standardization work

*But can we do more together?*

# The Standards Landscape

# Standards come in lots of flavors

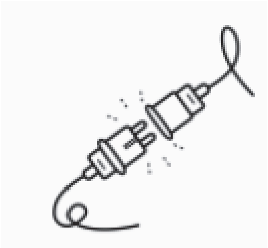
Physical standards & measurement protocols


Architectures

Procurement

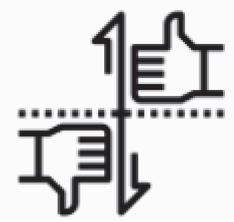
Use Cases

Guidelines,
Best practices

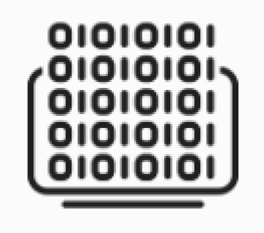


Interoperability

Terminology



Benchmarks
& metrics



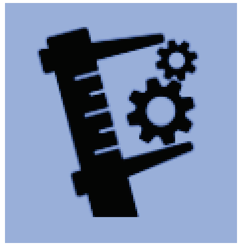
Software
algorithms &
languages

Certification
& test
protocols

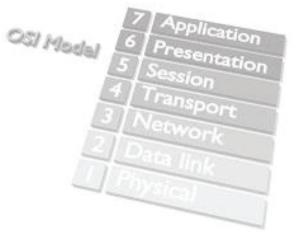
Regulatory standards

# Standards come in lots of flavors

NIST



**Physical standards & measurement protocols**




Architectures

Procurement

Interoperability

Terminology

Use Cases

Guidelines, Best practices

Benchmarks & metrics

Certification & test protocols

Regulatory standards

Software algorithms & languages

# Standards fuel the technology lifecycle

## Scientific revolutions don’t require standards; industrial revolutions do

| | Standards |
|---|---|
| **Inventing** | Terminology<br>Test & measurement |
| **De-risking** | Characterization & performance<br>Metrics & benchmarks<br>IT Security |
| **Product Dev.** | Interface |
| **Marketing, selling, supporting** | Interoperability<br>Testbeds<br>Certification<br>Procurement<br>Supply chain comm |
| **Re-thinking / recycling** | Industry 4.0 |

- Terminology → Provide a common language to bridge stakeholder communities
- Characterization & performance → Provide performance ground truth
- Metrics & benchmarks → Manage the hype; Compare competing technical approaches
- Interface / Interoperability → Create market opportunities through a plug & play framework
- Certification → Establish consumer confidence
- Supply chain comm / Industry 4.0 → M2M logistics support, Performance-to-design loopback

# When standards work, they…

- Create a common language
- Create fair & open, plug & play markets
- Enable protection of health, safety and environment
- Spur innovation

$ Create business opportunities

# When standards don't work, they…

- **Multiply!**
- Give unfair advantage
- Create barriers to trade
- Entrench inferior technologies
- Stifle innovation
- Impede interoperability of products and systems

***Another mouth to feed!***

Image by brgfx on Freepik

# Ingredients for success in standards

**Existence of:**
- Companies, suppliers
- Products
- Use cases
- Roadmaps
- Testbeds


NMIs contribute to all 3!

**Existence of:**
- Proven science
- Metrology
- Adjacent standards

**Existence of:**
- Balanced, global expert pool
- Standards Setting Organizations
- End users for standards

**We can help standards be:**
- Science-based
- Industry-driven

# The busy, evolving & **de-centralized** quantum standardization landscape

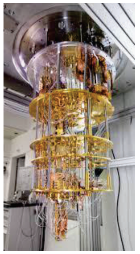
**TRL 1** — **Basic Research**

**TRL 2, 3** — **Feasibility Research**

**TRL 4, 5** — **Prototype Development**

**TRL 6, 7, 8, 9** — **Mature Technology**

**Beyond TRLs** — Market Established



**Quantum memory**

**Quantum repeaters**

**Quantum computers**

**Quantum networks**

**Randomness generation**

**Single Photon Sources & Detectors**

**Quantum sensors**

**Quantum Key Distribution**

**Quantum annealers**

**Post quantum encryption algorithms**

**Technologies** ⟷ **Standards**

**Terminology**
IEEE P7130
ISO/IEC JTC1 WG14

**Architectures, Roadmaps**
IETF/IRTF QIRG
ITU-T
C/CLC JTC 22

**Benchmarks**
QED-C prototypes

**Measurement protocols**

**Use Cases**
IETF/IRTF QIRG

**Software languages**

**Security, Algorithms**
NIST post-quantum crypto

**ISO/IEC JTC-3**

**Guidelines, Best practices**

**Physical Standards**
NIST, NRC, NPL, etc.

**Interoperability**
IEEE 1913 NETCONF/YANG
IEC TC86 – cables, fibres
ITU-T

**Procurement**

**Regulatory standards**

**Certification/test protocols**
ETSI QKD
ISO/IEC JTC1 SC27 QKD

*Barbara Goldstein, NIST*

# Standards for quantum technologies
# - What will it take?

## Us!  Working together

**To:**

- **Inform standards activities** with vetted, sound science
  - i.e.: pre-standardization research
- **Explore new ways to characterize, measure and benchmark**
- **Establish testbeds** to test the viability of candidate standards
- **Leverage** our rich history of **objectivity** & infrastructure for **international collaboration**

**Introducing NMI-Q**

# During this workshop we'll…

- Hear from industry consortia
- Explore the relationship between measurements, standards and emerging technologies
- Share how our Institutes are already supporting emerging technologies
- Work together to answer:
  - What more should we work on together?
  - How should we work together?

**NMI-Q is ours to define**

# 11:15 – 11:45

# Break

# Agenda – Day 1 - Morning
# **Opportunities & Challenges**

| | |
|---|---|
| 09:00 | Registration |
| 09:30 | Welcoming remarks |
| | NMI-Q – Tim Prior |
| | BIPM – Martin Milton, Director |
| | CIPM – JT Janssen |
| 10:00 | Keynote: The emerging quantum economy - the promise & the barriers |
| | Sir Peter Knight |
| 10:45 | Framing the workshop: motivation and goals - Barbara Goldstein |
| 11:15 | Break |
| 11:45 | Panel: Building a quantum economy - what will it take, and what are the challenges? |
| 12:45 | Lunch |

11:45 – 12:45

# Panel: Building a quantum economy: what will it take, and what are the challenges?

Moderator – Nicolas Spethmann

# Panel: Building a quantum economy: what will it take, and what are the challenges?

- Q-STAR – Taro Shimada (on-line)
- UK Quantum – Jonathan Legh-Smith
- QuIC – Thierry Botter
- QED-C – Celia Merzbacher (on-line)
- Quantum Industry Canada – Lisa Lambert

13:45 – 14:30 (After Lunch)

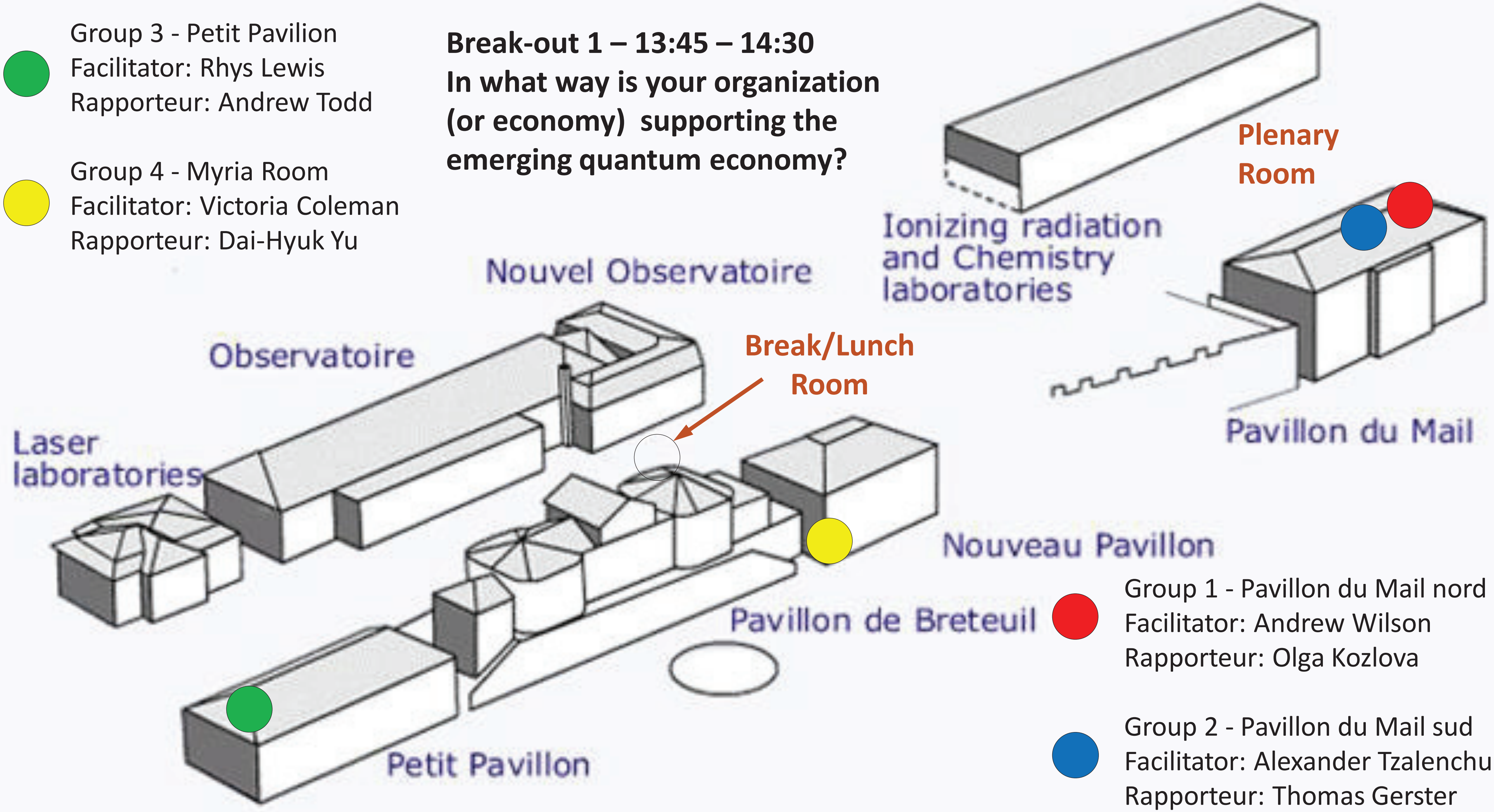
# Break-out 1: In what ways is your organization supporting the emerging quantum economy?

Moderator – Kevin Thomson

Group 3 - Petit Pavilion
Facilitator: Rhys Lewis
Rapporteur: Andrew Todd

Group 4 - Myria Room
Facilitator: Victoria Coleman
Rapporteur: Dai-Hyuk Yu

**Break-out 1 – 13:45 – 14:30**
**In what way is your organization (or economy) supporting the emerging quantum economy?**




Group 1 - Pavillon du Mail nord
Facilitator: Andrew Wilson
Rapporteur: Olga Kozlova

Group 2 - Pavillon du Mail sud
Facilitator: Alexander Tzalenchuk
Rapporteur: Thomas Gerster

**Groups 3 and 4 should wrap-up five minutes early to get back to the plenary room**

# Break-out 1: In what ways is your organization supporting the emerging quantum economy?

- Active research program – Quantum for Metrology / Metrology for Quantum
- Direct funding to enable industry
- Test beds
- Role in standardization / standards
- Role as an advisor in government / industry
- Reference materials
- Priority in quantum if not currently active

# 12:45 – 13:45

# Lunch

Group 3 - Petit Pavilion
Facilitator: Rhys Lewis
Rapporteur: Andrew Todd

Group 4 - Myria Room
Facilitator: Victoria Coleman
Rapporteur: Dai-Hyuk Yu

**Break-out 1 – 13:45 – 14:30**
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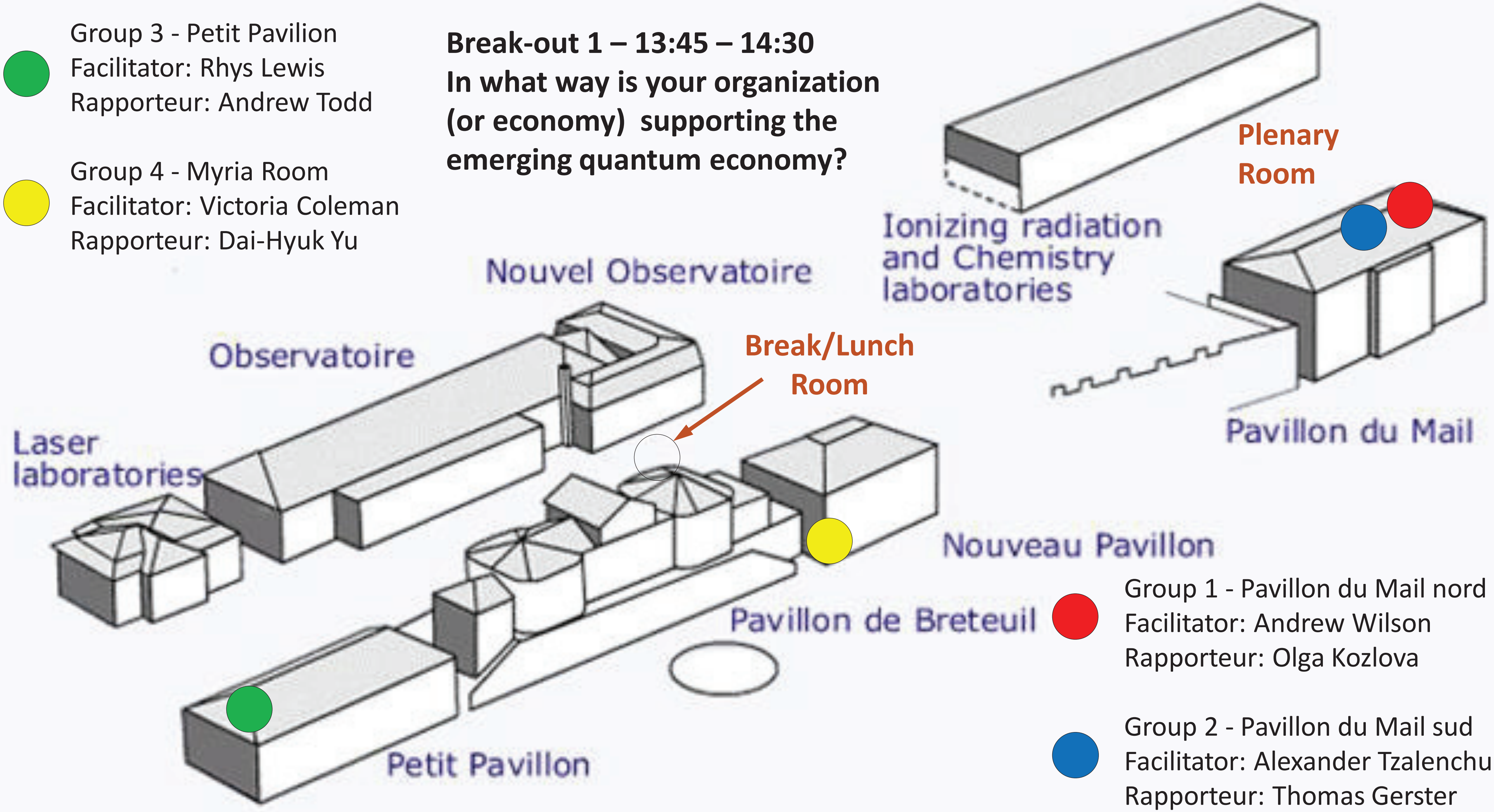


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**Groups 3 and 4 should wrap-up five minutes early to get back to the plenary room**

13:45 – 14:30

# Break-out 1: In what ways is your organization supporting the emerging quantum economy?

*Break-out groups 3 and 4 finish up 5 minutes early to get back to plenary*

## Break-out 1: In what ways is your organization supporting the emerging quantum economy?

- Active research program – Quantum for Metrology / Metrology for Quantum
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- Reference materials
- Priority in quantum if not currently active

14:30 – 14:45

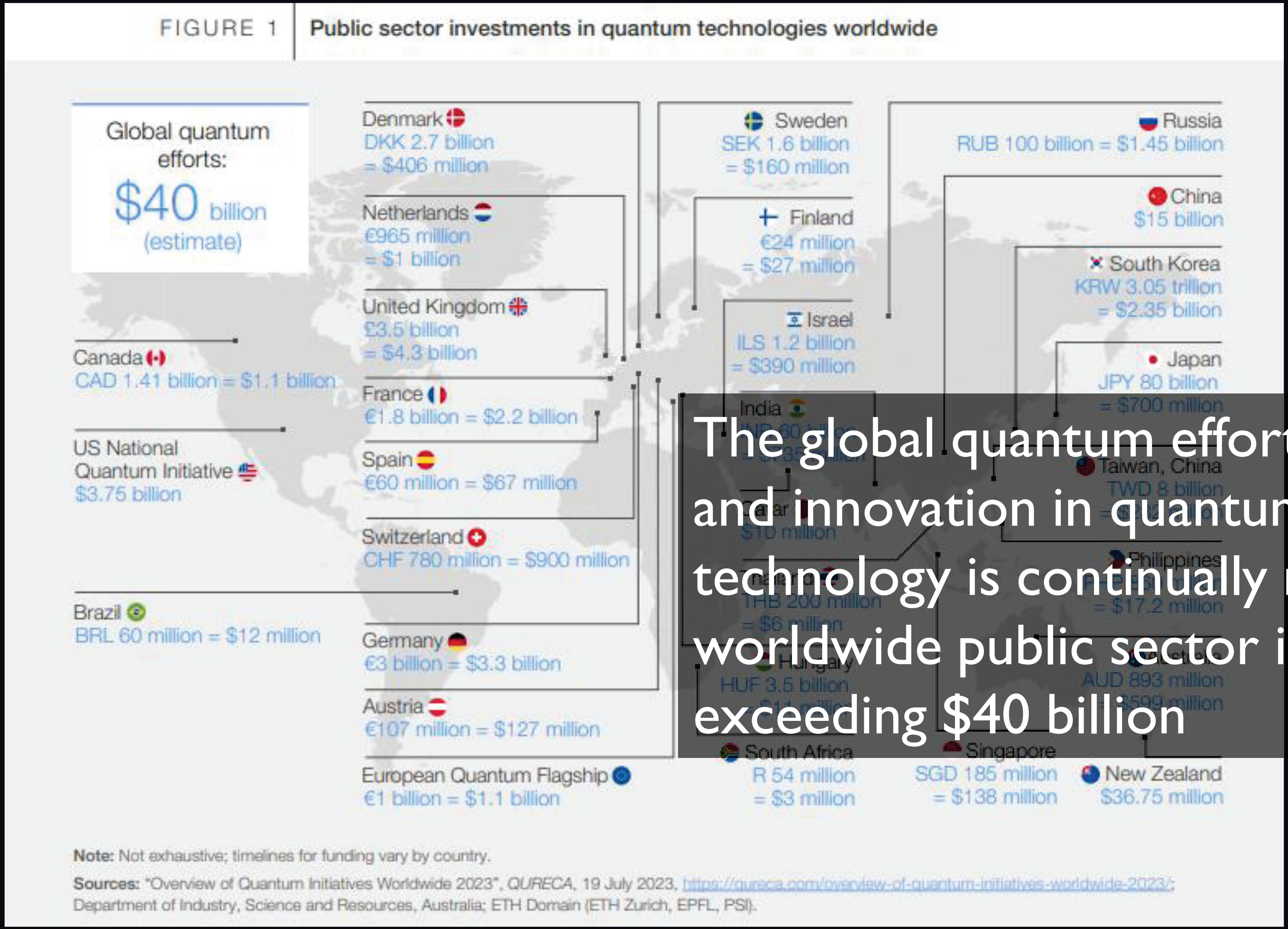
# Report out from Break-out 1: In what ways is your organization supporting the emerging quantum economy?

14:45 – 15:45

# Panel: International quantum standardization

Moderator – Tim Prior


Overall, the global QT market is projected to reach $106 billion by 2040
Potential economic value from quantum computing estimate to be > $1 trillion




The global quantum effort leading to research and innovation in quantum science and technology is continually rising, with current worldwide public sector investments exceeding $40 billion

# The European Union leads in quantum-relevant publications, but the United States outcompetes in impact

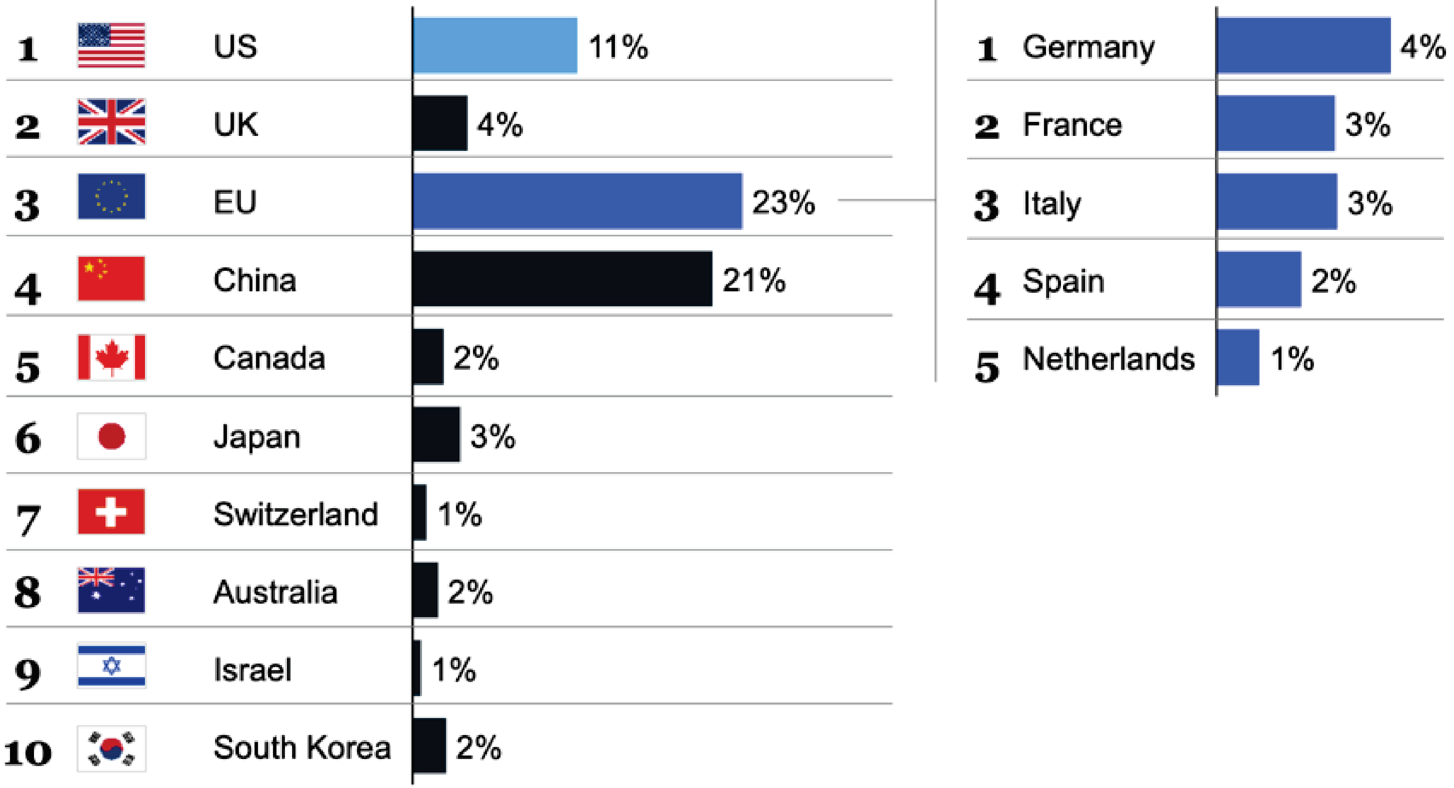
UK per capita in good leading position

As of 2020

**XX** Rank of country's h-index

**Top 10 countries worldwide 2020, by h-index**
Share of articles and country's h-index[2] in quantum-relevant publications

**Top 5 EU countries**
Share of articles and H index, 2020



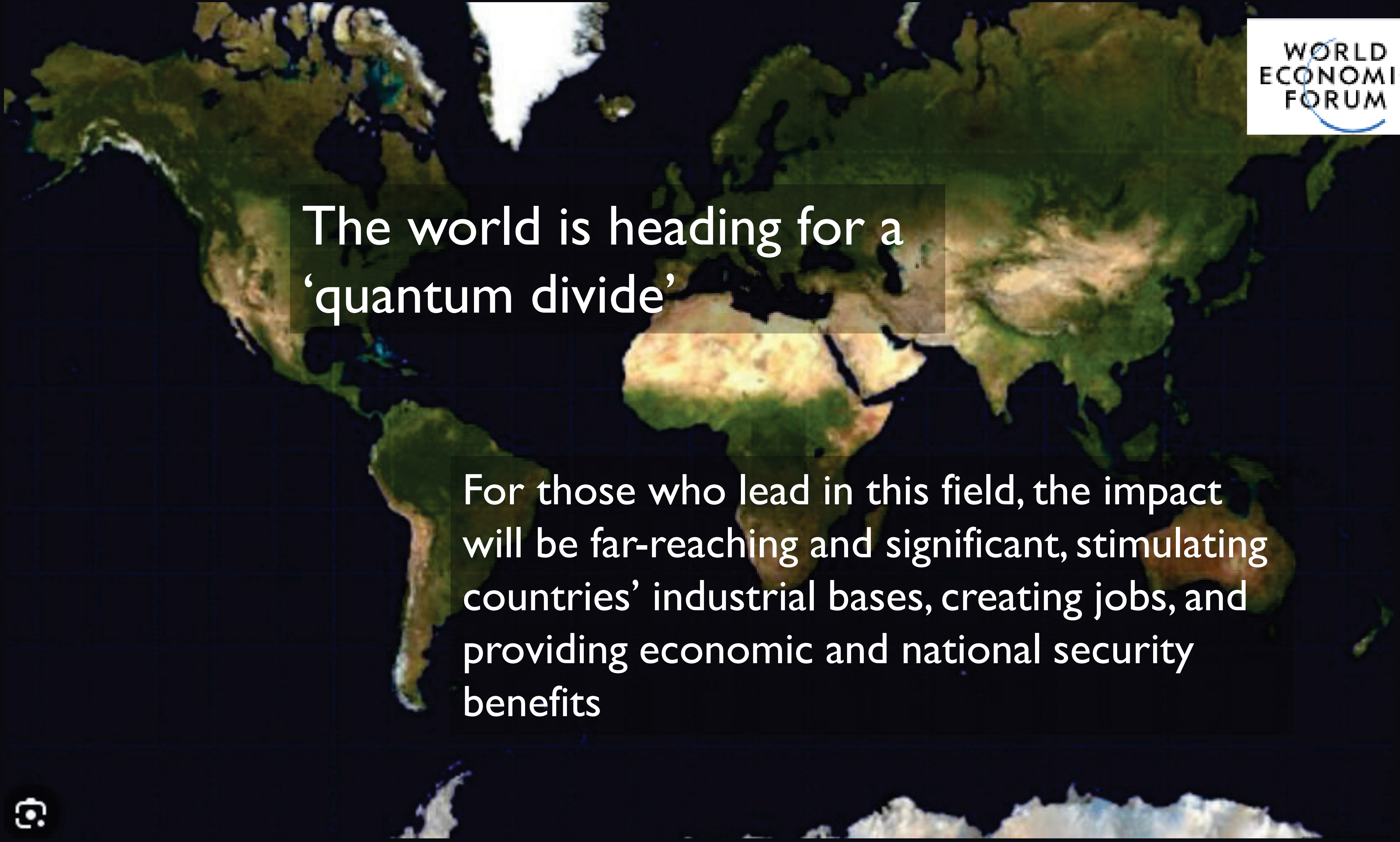

## Key takeaways

US publications have the **highest impact** measured by h-index indicating a leading position in academic research

The EU is leading in terms of **published articles** in 2020 in quantum-relevant fields, followed by China and the US

1. Quantum relevant publications defined as publications in physics, mathematics, and statistics, and information and communications technology
2. The h-index is the number of articles (h) in a country that have been cited at least h times

Source: SCImago Journal & Country Rank; McKinsey analysis



# The world is heading for a 'quantum divide'

For those who lead in this field, the impact will be far-reaching and significant, stimulating countries' industrial bases, creating jobs, and providing economic and national security benefits

In collaboration with IBM and SandboxAQ

# Quantum Economy Blueprint

INSIGHT REPORT

JANUARY 2024

WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

> The Australian Government will be an active participant in global standards-setting bodies to promote the development of standards that support a thriving, accessible and safe quantum ecosystem; and ensure Australia's regulatory frameworks foster quantum-related research, support investment in quantum companies and support exports while protecting Australia's national interests."
>
> Australian Government Department of Industry, Science and Resources, *National Quantum Strategy*, 2023.

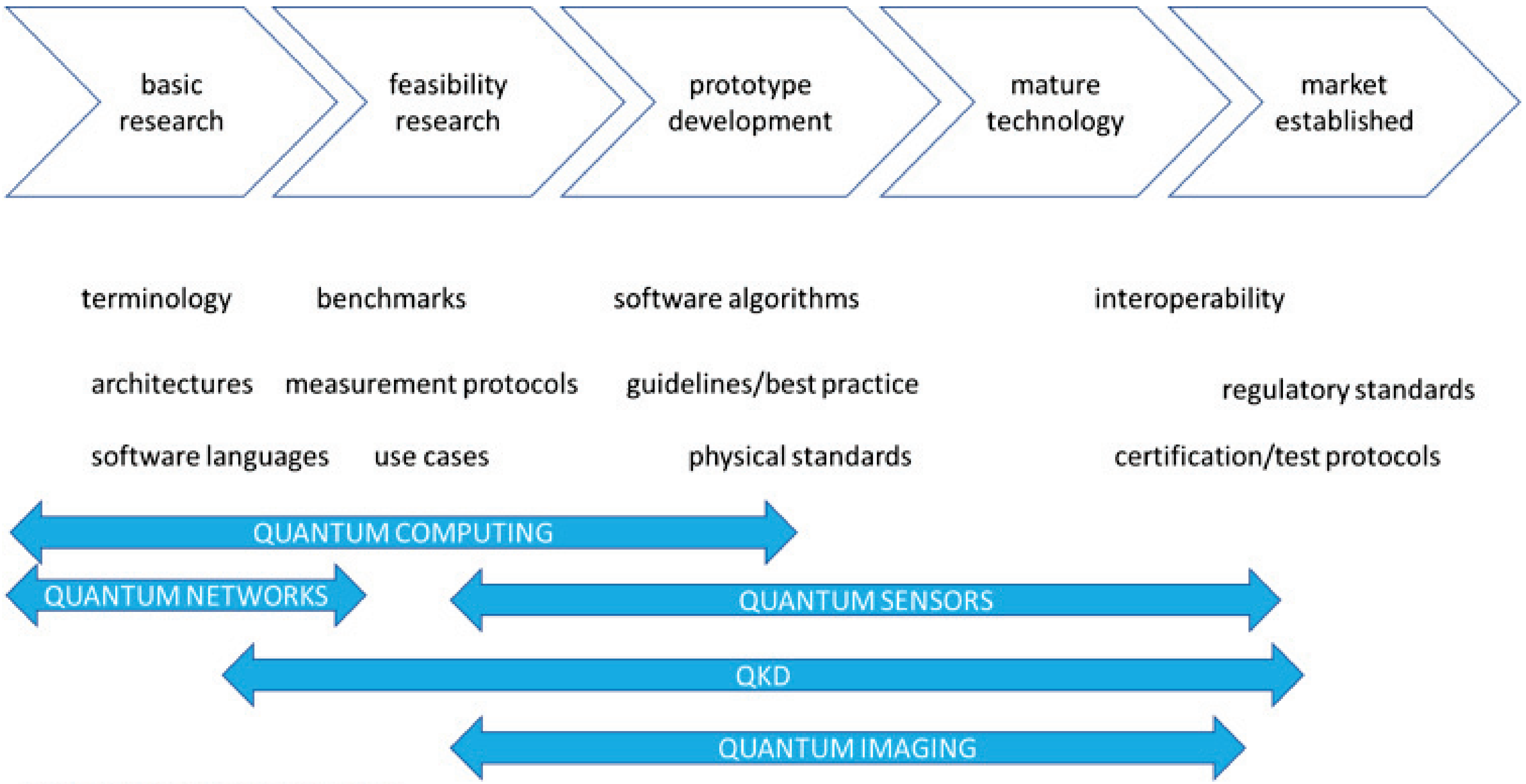
> The supply chain that underpins the quantum sector – while still nascent – is already truly global. Based on a survey of 54 relevant UK companies, 85% are importing elements of their supply chain to develop quantum technologies. In the UK, 33 companies are a key part of this global supply chain.
>
> UK Department for Science, Innovation & Technology, *National Quantum Strategy*, 2023.

> There is a critical concern for Argentina, Brazil and other countries in the Global South related to the widening technology gap with developed countries, in spite of the fact that many countries in this region are scientifically and technologically mature. It is important to create awareness of this issue and to find ways to revert this trend.
>
> Karen Hallberg, Professor of Physics, Balseiro Institute and Principal Researcher, National Council on Scientific and Technological Research (CONICET), Bariloche Atomic Center (CNEA), Argentina

> Promote quantum industry by training human resources and widely disseminating information. Promote quantum industrialization by developing a programme to recruit and train human resources in quantum and related fields; make clear in Japan and internationally that implementation of quantum technology is essential for future society.
>
> QSTAR Japan

## Standardisation Readiness Level – A growing NMI Roadmap

NPL National Physical Laboratory | QMI Quantum Metrology Institute




NIST National Institute of Standards and Technology U.S. Department of Commerce

Credit: Barbara Goldstein, NIST

# Panel: International quantum standardization

- NIST – Barbara Goldstein
- NPL – John Devaney
- PTB – Thomas Gerster
- Fujitsu – Kazutomo Hasegawa

# 15:45 – 16:15

# Break

16:15 – 17:30

# Panel: The role of the metrology community in advancing emerging technologies

Moderator – JT Janssen

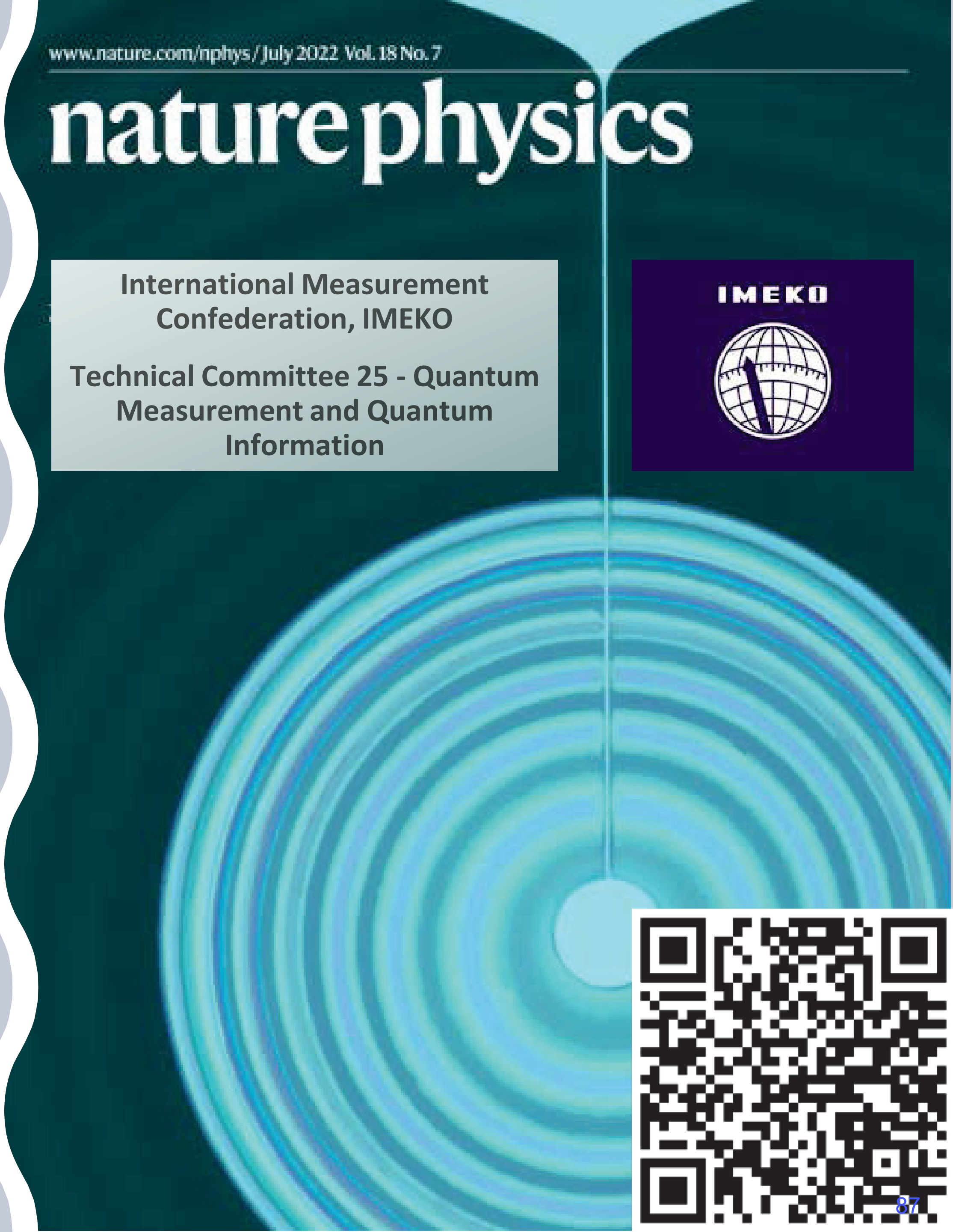
Panel: The role of the metrology community in advancing emerging technologies

# Talk: The expanding role of NMIs in the quantum era

Alexander Tzalenchuk

# The Expanding Role of National Metrology Institutes in the Quantum Era

Alexander Tzalenchuk, Nicolas Spethmann, Tim Prior, Jay H. Hendricks, Yijie Pan, Vladimir Bubanja, Guilherme P. Temporão, Dai-Hyuk Yu, Damir Ilić and Barbara L. Goldstein

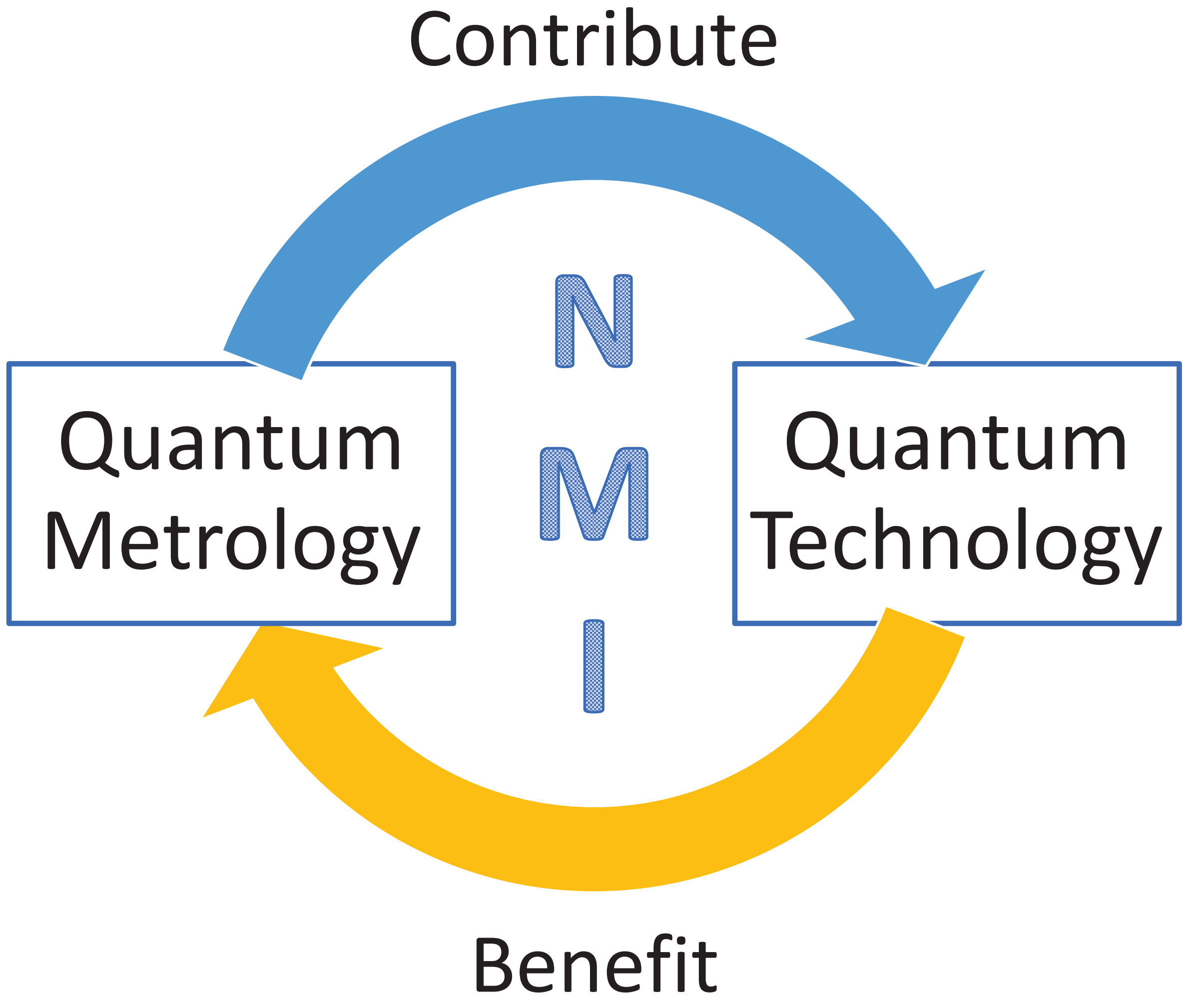



International Measurement Confederation, IMEKO

Technical Committee 25 - Quantum Measurement and Quantum Information

IMEKO

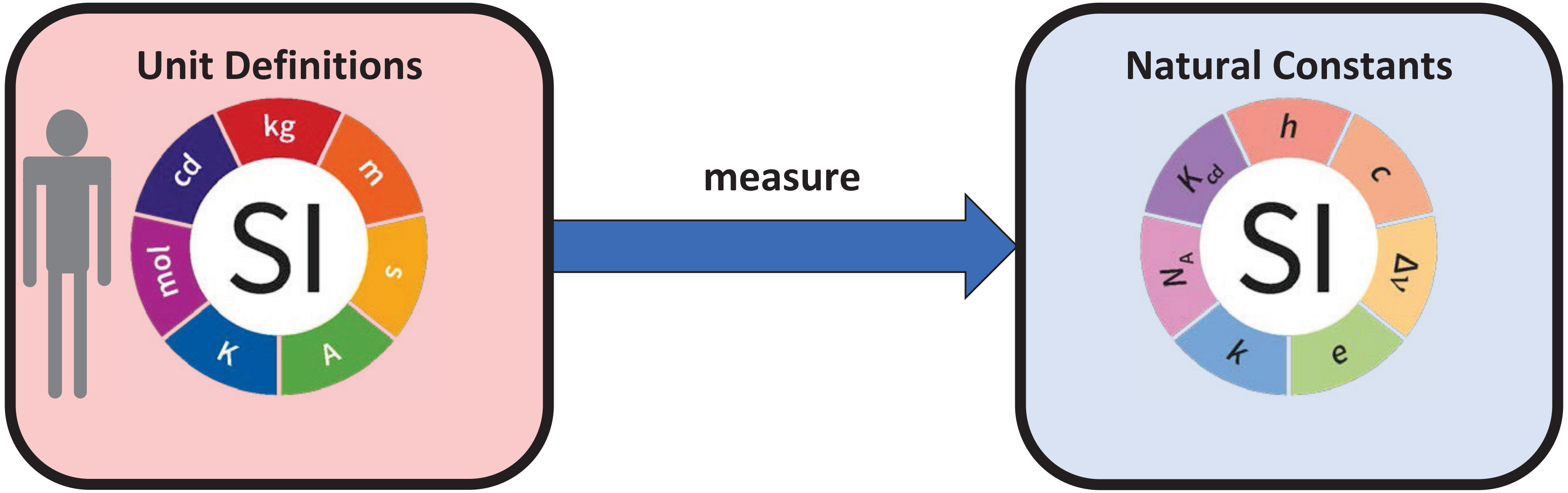
# Talk outline



# Discoveries and applications in metrology

- Time metrology. Masers and atomic clocks. [**1944 -** Isidor Isaac Rabi , **1964 -** Charles H. Townes, Nicolay G. Basov, Aleksandr M. Prokhorov]
- Frequency standards. Ion traps, laser cooling. BEC. [**1989 -** Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul, **1997 -** Steven Chu, Claude Cohen-Tannoudji, William D. Phillips, **2001 -** Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman]
- Lasers, interferometry and spectroscopy, frequency combing [**1907** - Albert Michelson, **2005 -** Roy J. Glauber, John L. Hall, Theodor W. Hänsch]
- Dimensional and functional metrology on the nano-scale. Scanning probe microscopy [**1986 -** Ernst Ruska, Gerd Binnig, Heinrich Rohrer]
- The Josephson effect and the volt [**1973 -** Leo Esaki, Ivar Giaever, Brian D. Josephson]
- Quantum Hall effect and the ohm [**1985 -** Klaus von Klitzing]
- Graphene [with the first application in resistance standard **2010 -** Andre Geim & Konstantin Novoselov]
- Quantum control and clocks [**2012** – Serge Haroche & David Wineland]

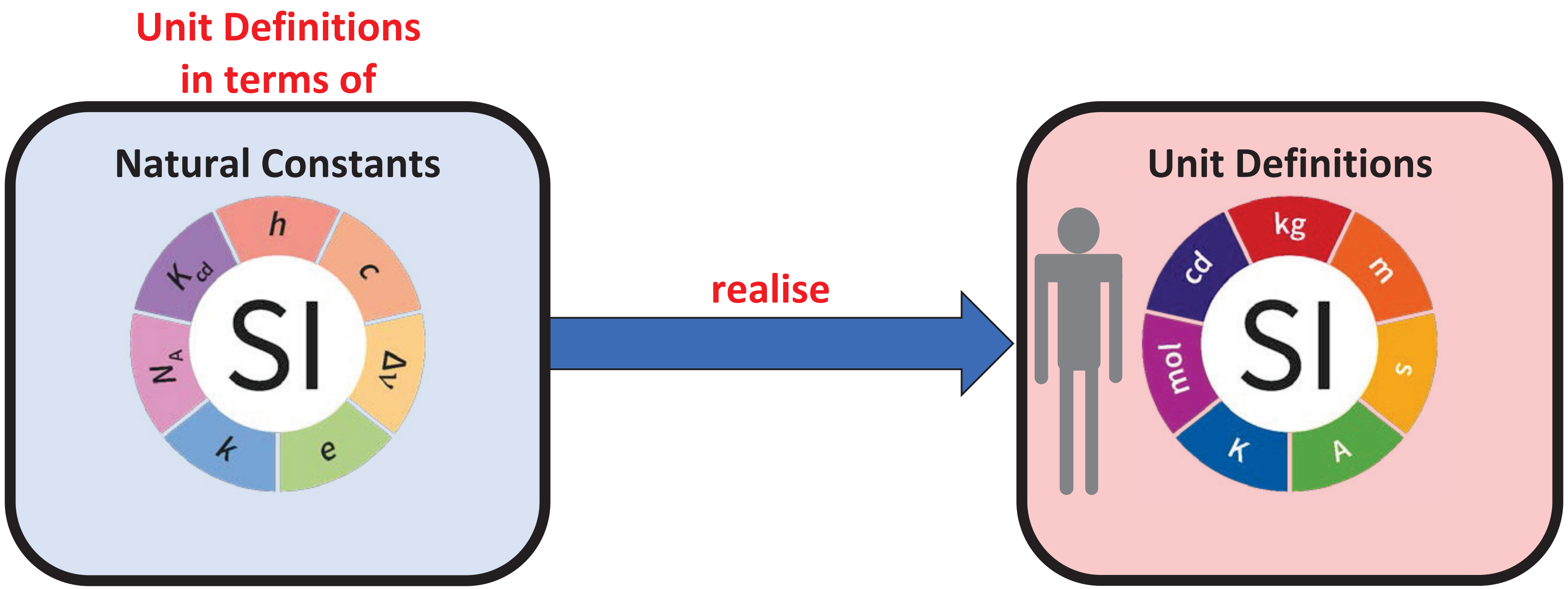
# SI redefinition




**’Old’:**

1. Defined units in terms of artefacts or classical physics laws (e.g. the metre prototype)
2. Measured constants of nature in terms of the units as accurately as possible

# SI redefinition



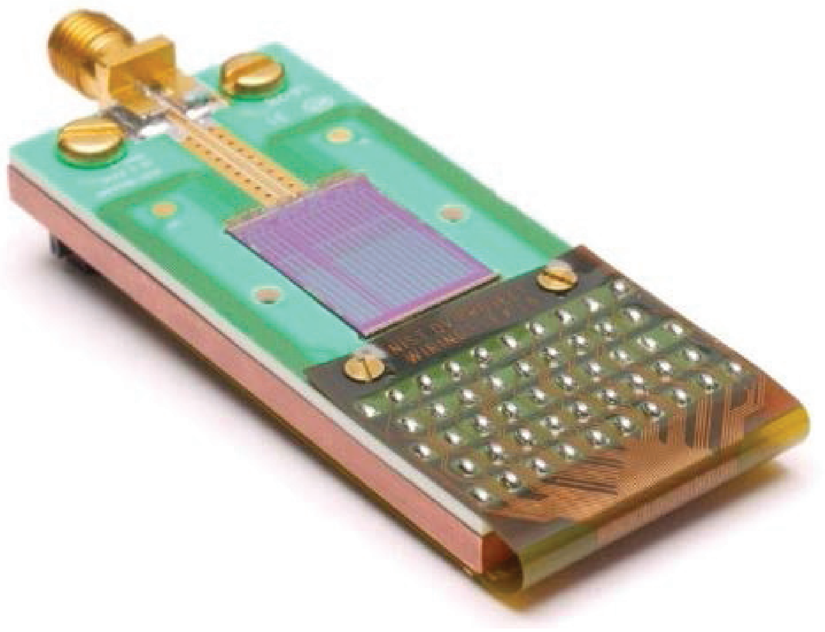

**’Old’:**

1. Defined units in terms of artefacts or classic physics laws (e.g. the metre prototype)
2. Measured constants of nature in terms of the units as accurately as possible

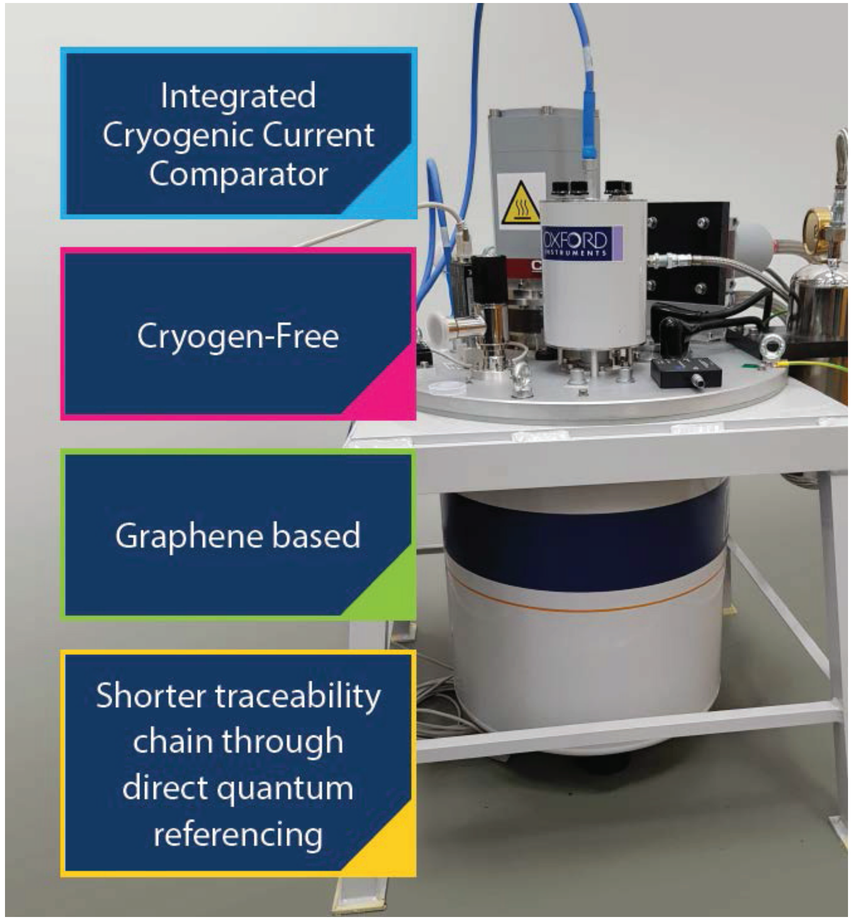
**‘New’:**

3. Fixed the numerical value of constants (e.g., the speed of light)
4. Realised the units in terms of the value of the constants

# We may and (often) we can realise units (almost) anywhere anytime

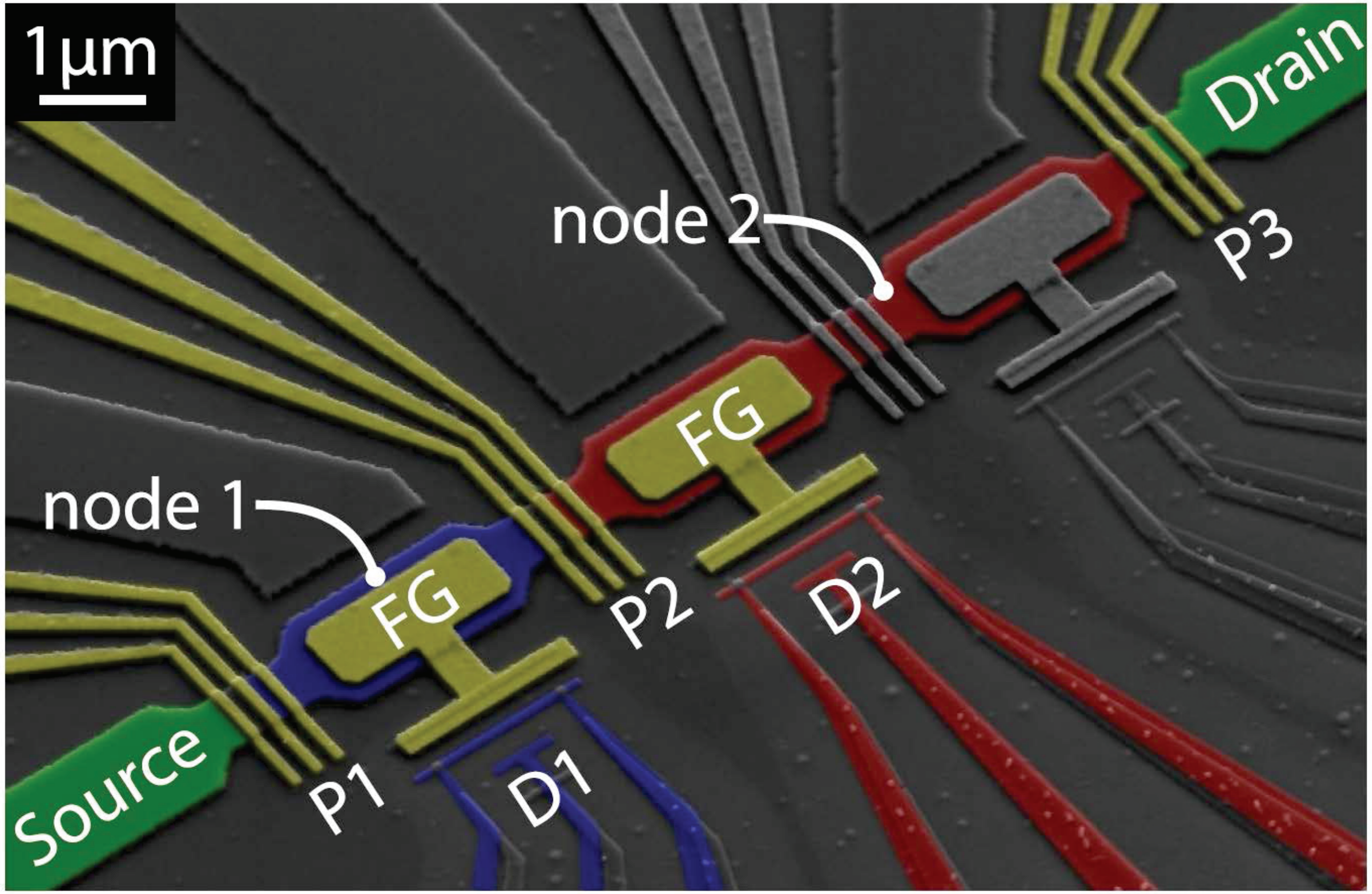


NIST: 10 V programmable Josephson voltage standard (PJVS)



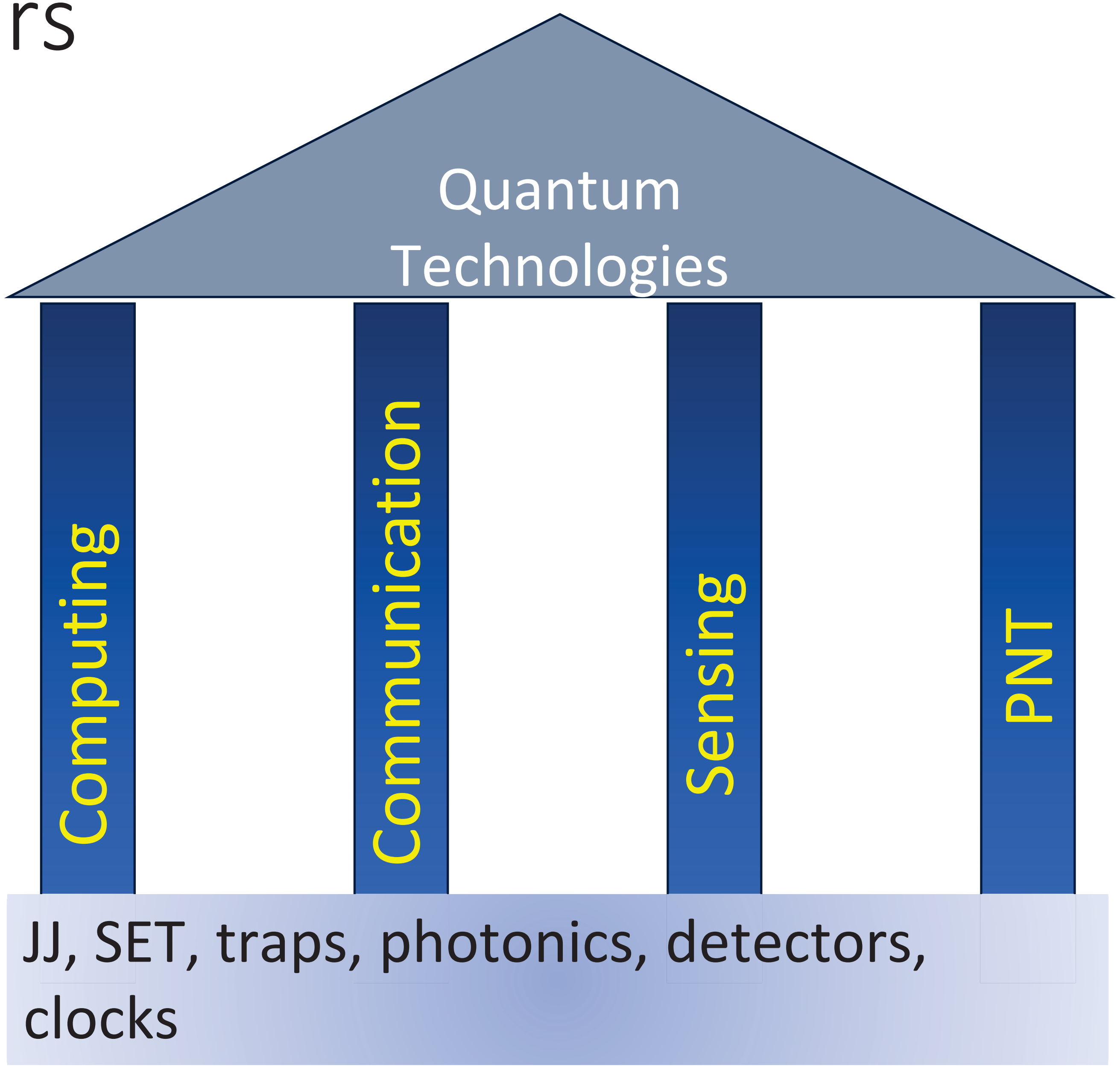

NPL: table-top quantum Hall system

# We may and (often) we can realise units (almost) anywhere anytime

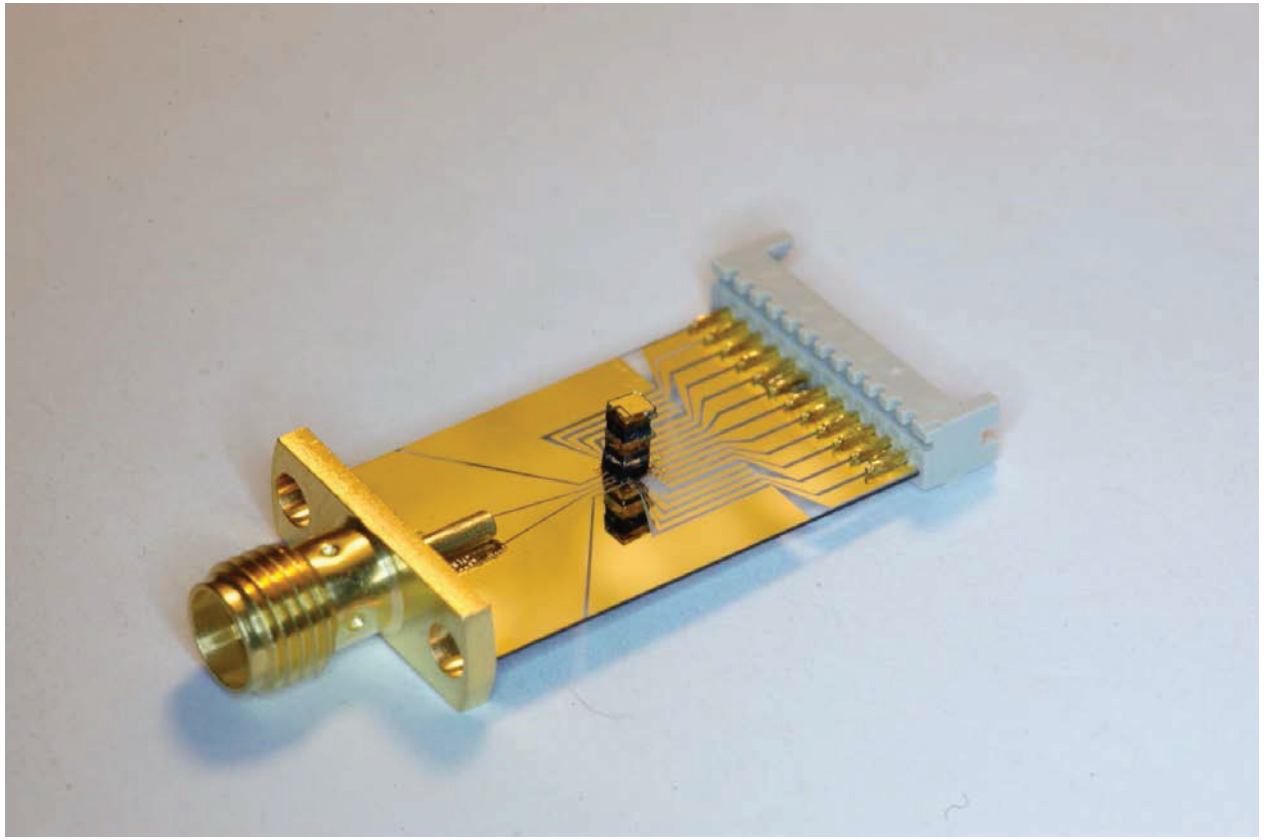


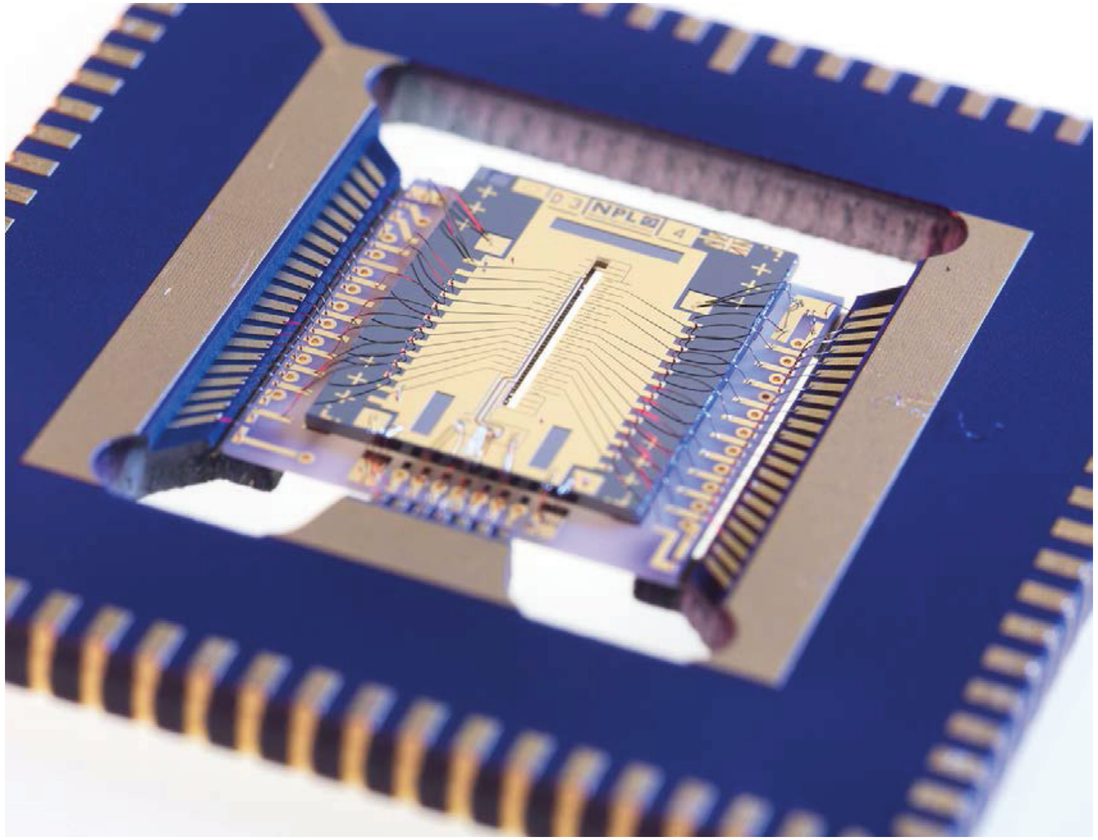

PTB: self-referenced single-electron quantized current source

# Four pillars



# From quantum standards to quantum sensors

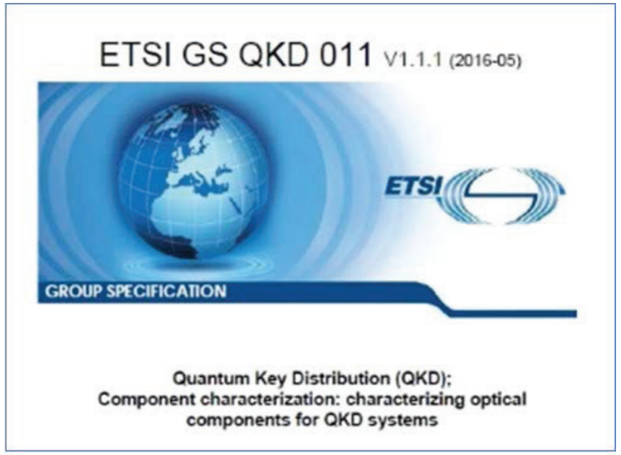





NIST’s chip-scale atomic magnetometer

NPL’s microfabricated 3D ion trap

# Photonics and quantum communications


ETSI GS QKD 011 V1.1.1 (2016-05)

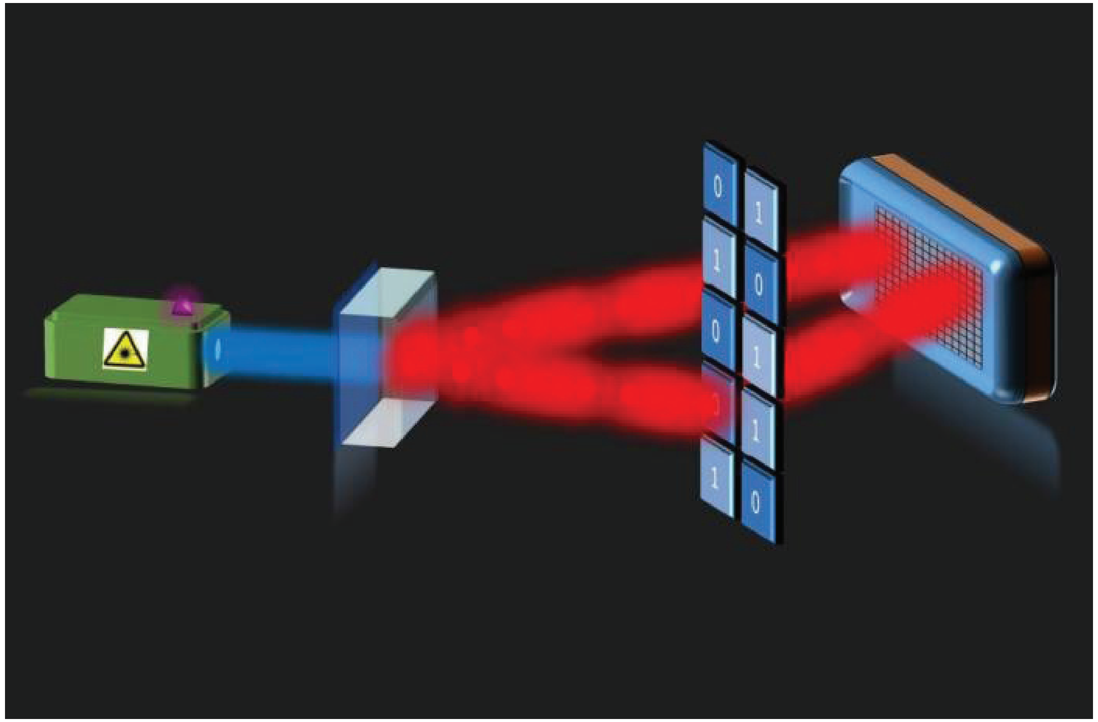
GROUP SPECIFICATION

Quantum Key Distribution (QKD);
Component characterization: characterizing optical components for QKD systems


ETSI GR QKD 003 V2.1.1 (2018-03)

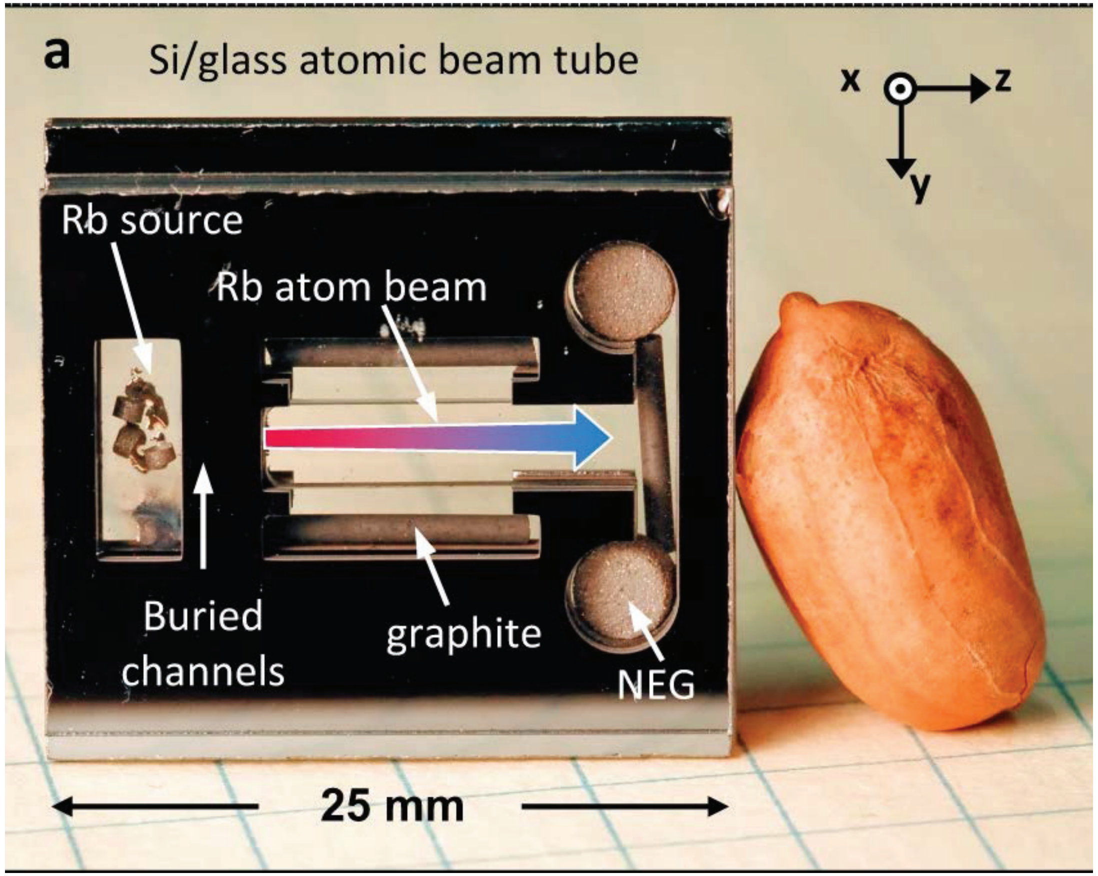
GROUP REPORT

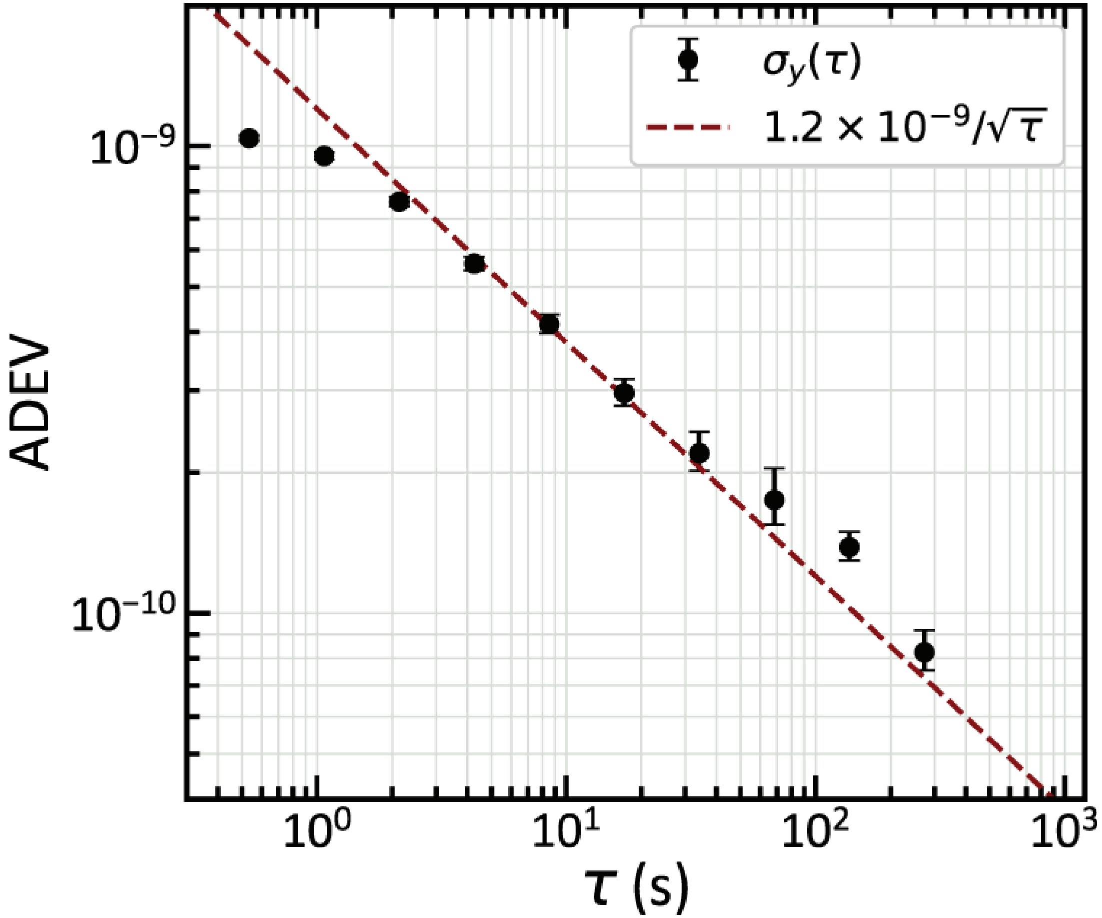
Quantum Key Distribution (QKD);
Components and Internal Interfaces



INRIM: Quantum imaging and quantum sensing

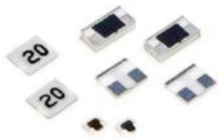
# Timing



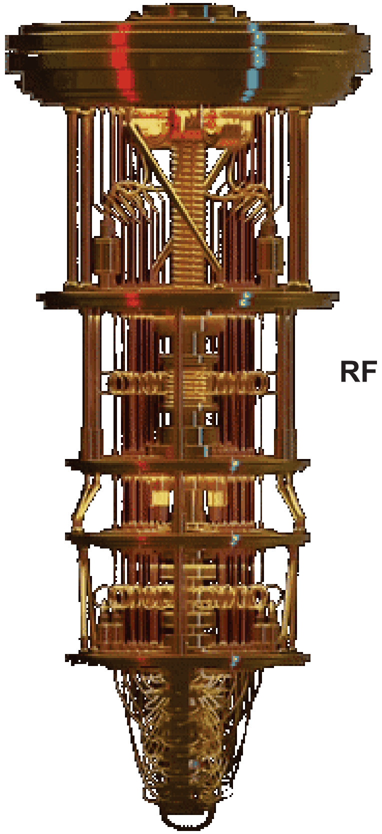

NIST: chip-scale atomic beam clock
from Martinez, G.D., Li, C., Staron, A. et al. Nat Commun 14, 3501 (2023).

# Computing and comms: component calibration



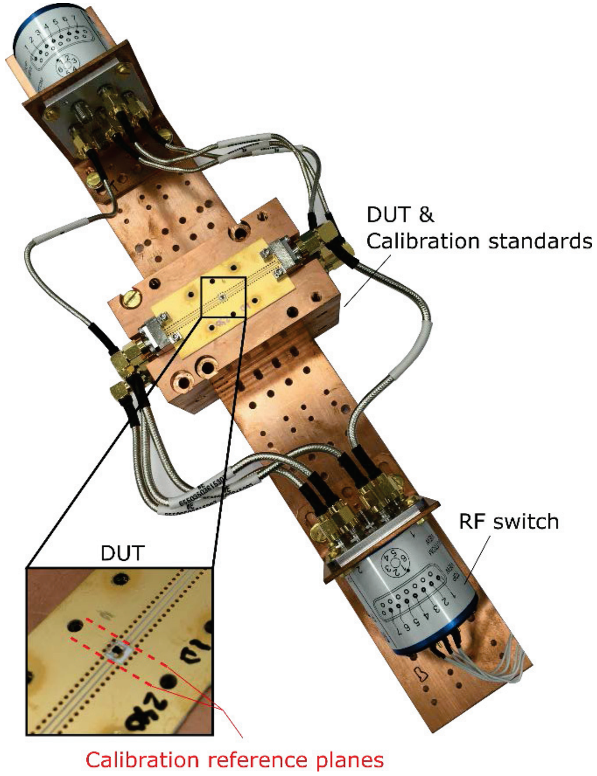
**RF Integrated Circuits**

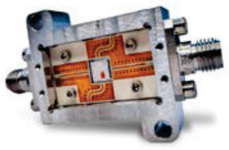
**Materials**



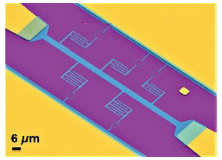
**RF Cables & Interconnects**

**Cryo-electronics**



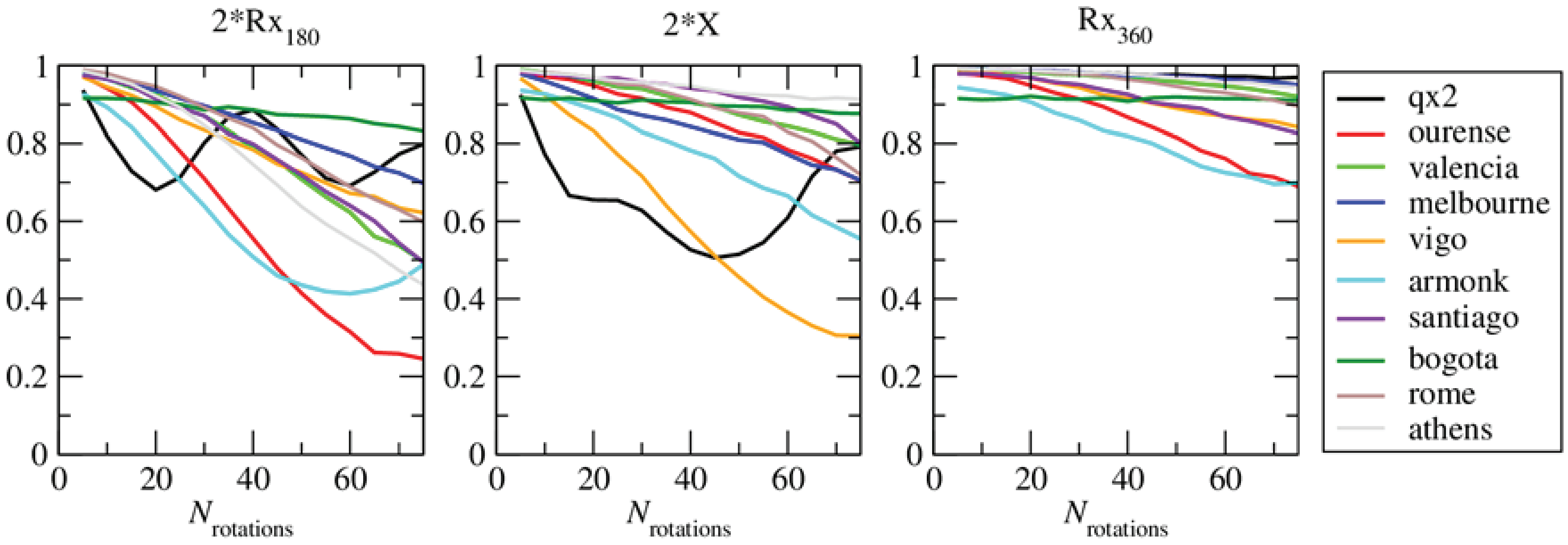
**Coaxial Devices**




**Quantum Integrated Circuits**

# Difficult questions...

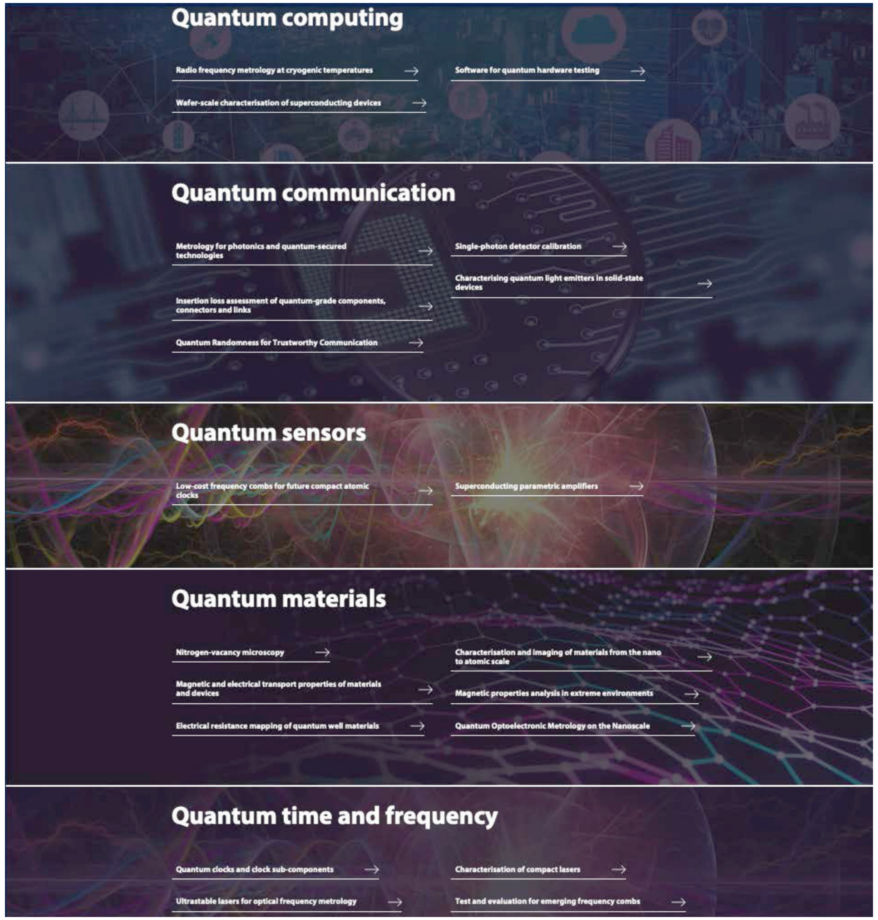
Such as: which quantum computing hardware is the best? Requires a well-defined approach that removes benchmarking ambiguity and tests properties relevant for real applications




Example: three equivalent ways to repeatedly rotate a qubit by 360 degrees, different hardware is the apparent winner for each approach. Detailed examination helps identify and mitigate noise sources.

# Quantum testbeds, innovation and T&E programmes

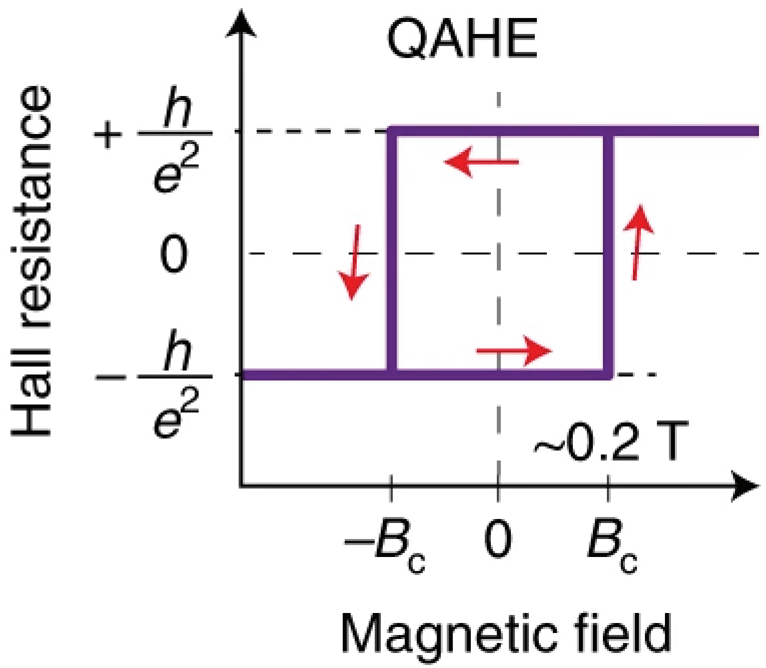
addressing the barriers to innovation and accelerating the commercialisation of quantum technologies.




- NMIJ
- NIST
- PTB
- NPL
- KRISS
- …

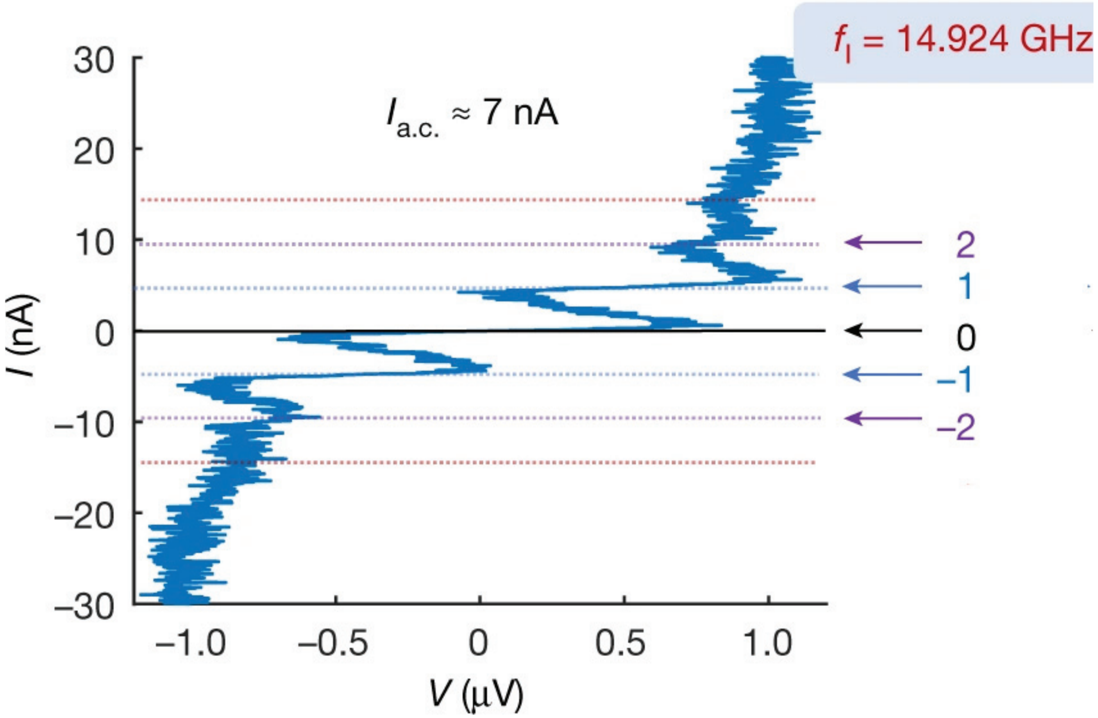
# More is coming

QAHE - an alternative way to realise the ohm?




Okazaki, Y., *et al. Nat. Phys.* **18**, 25–29 (2022).

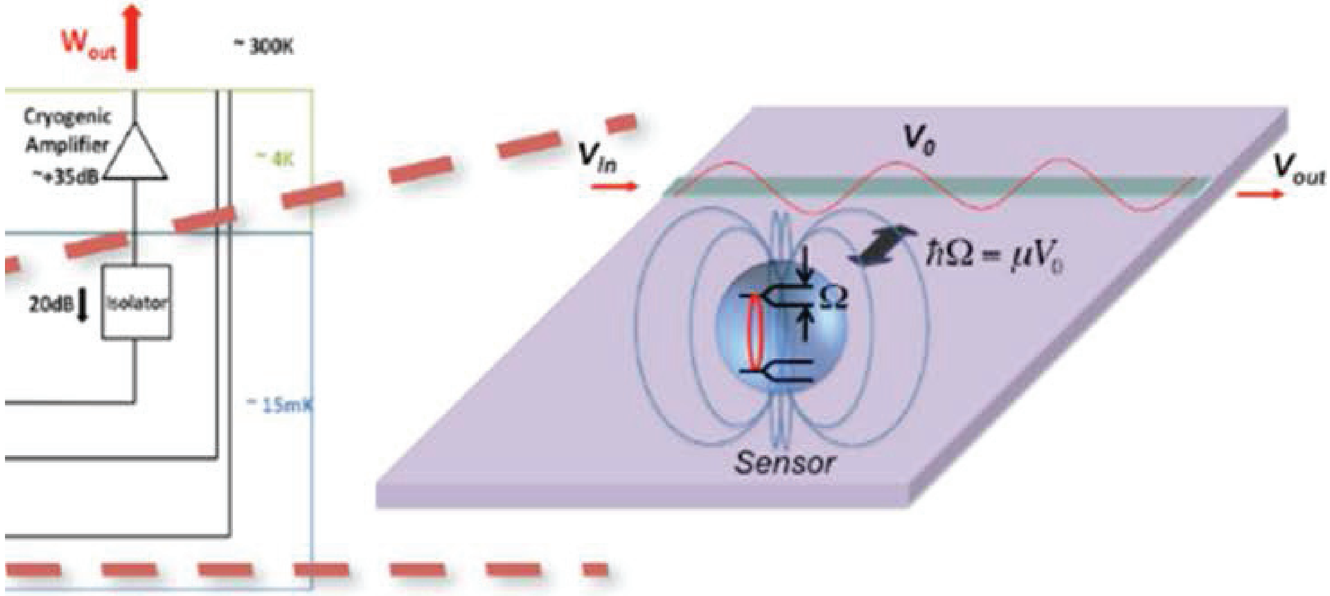
QPS - an alternative way to realise the ampere?

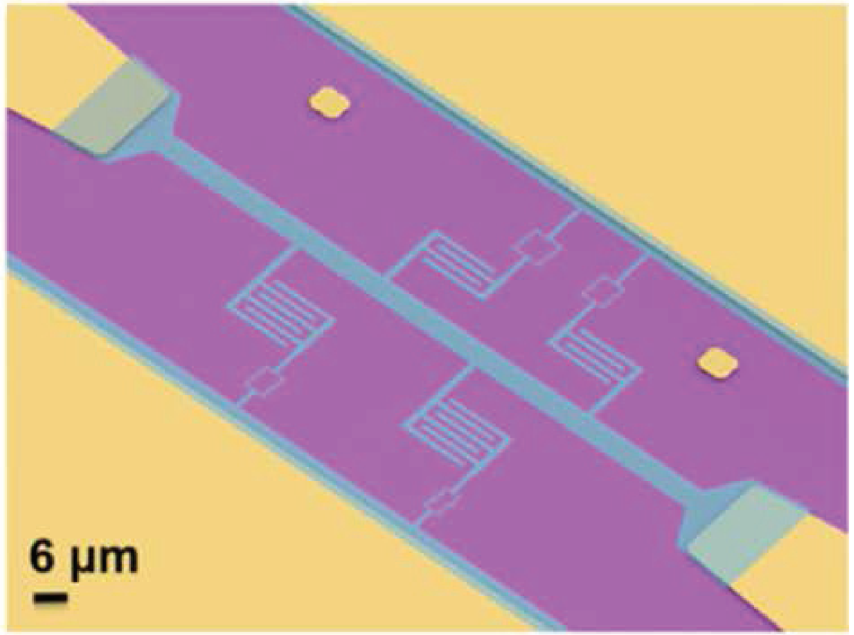



R. Shaikhaidarov, *et al. Nature* **608**, 45–49 (2022).

# Beyond SI base units

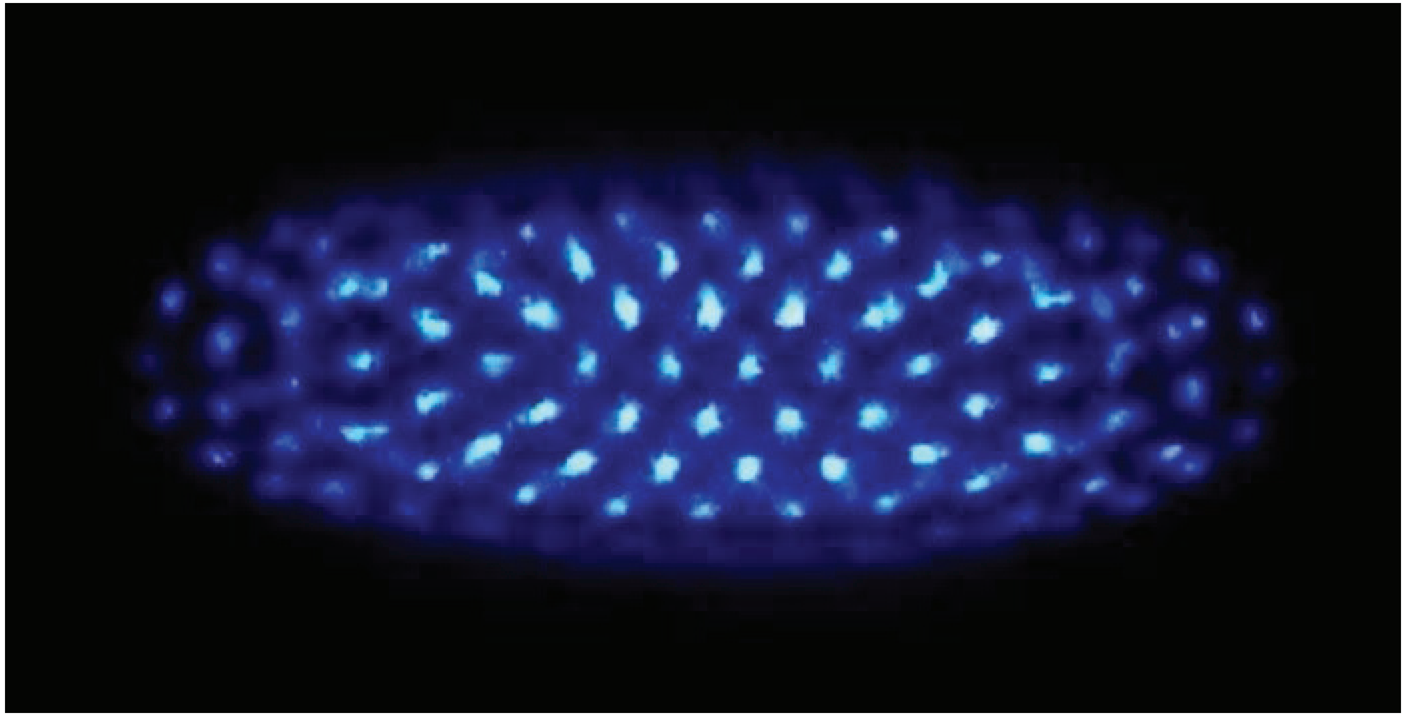
## qubit as an absolute sensor of microwave power




T. Hönigl-Decrinis, et al. Phys. Rev. Applied 13, 024066 (2020)

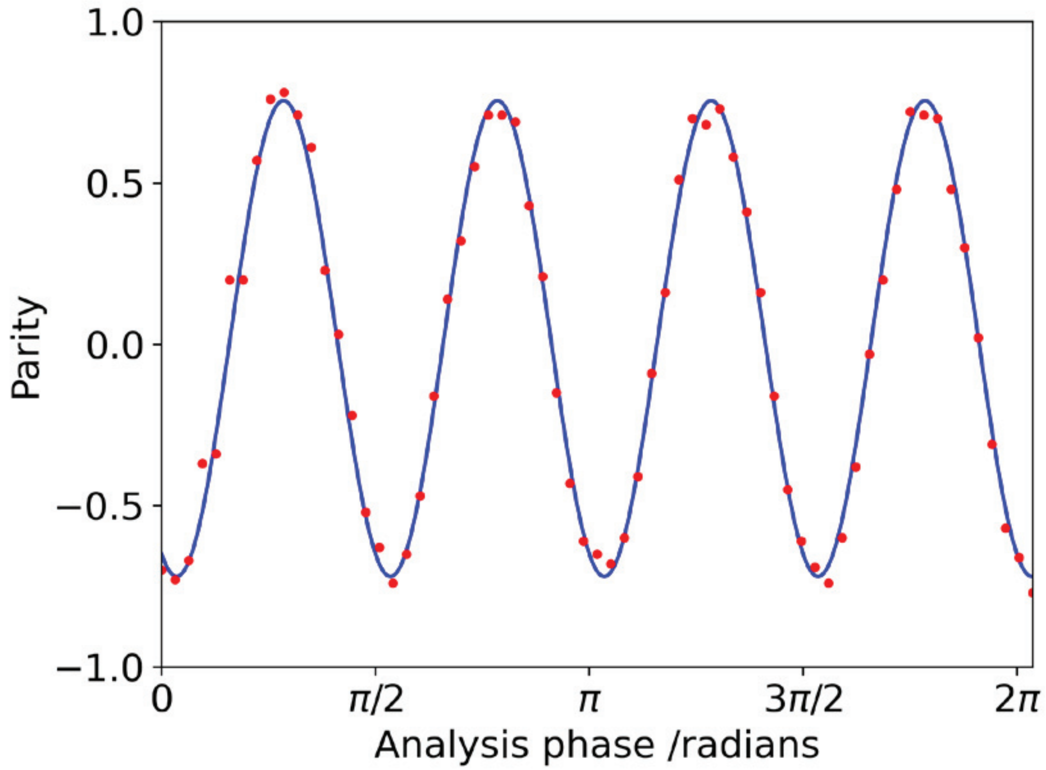
# Future SI: Towards redefinition of the second



PTB: Yb multi-ion optical clock

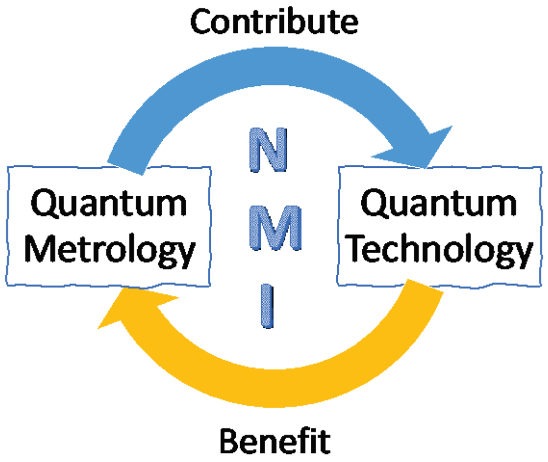
# Quantum advantage

- Can entanglement be usefully scaled?
- Can sensors be quantum-networked?




A ‘parity scan’ graph, used to determine the fidelity of generating the 4-ion entangled state (akin to a Ramsey fringe)

# Conclusions:



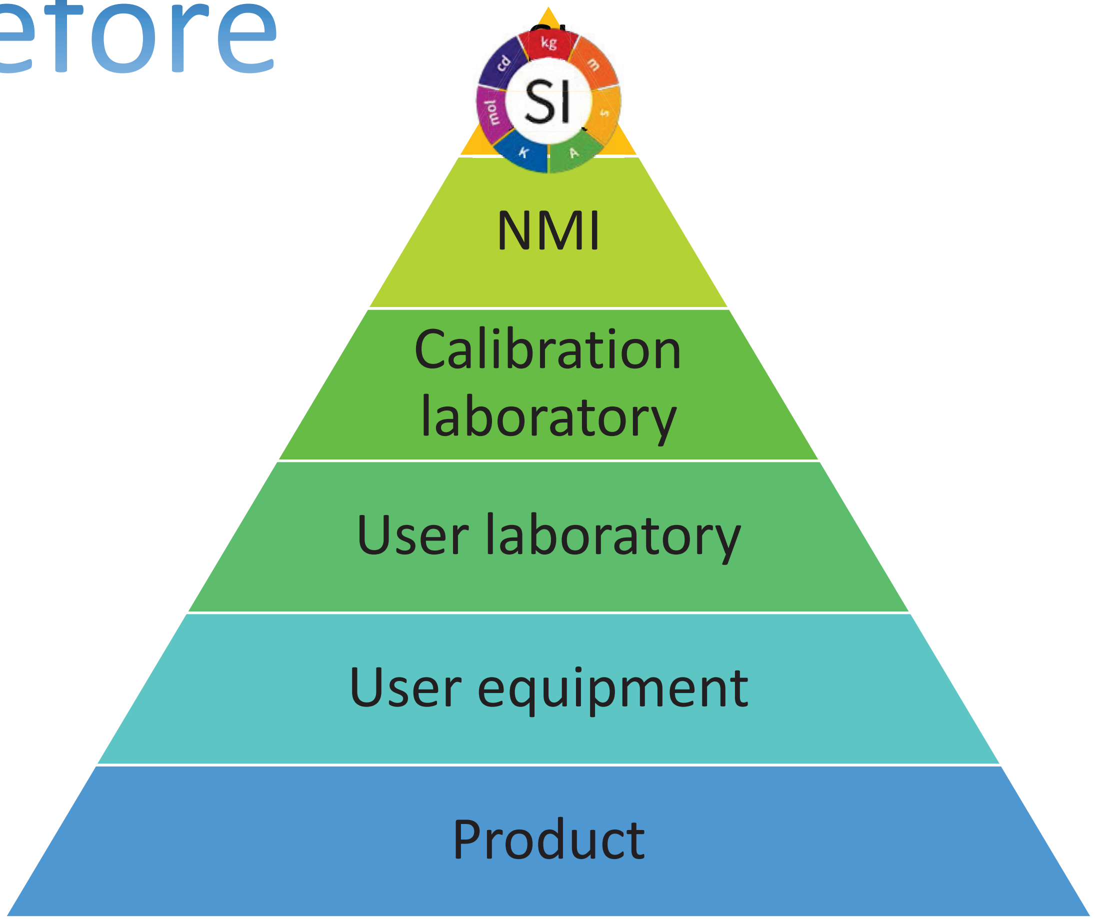

NMIs' expertise in quantum metrology can be beneficially applied to advance emerging quantum technologies and support industry.

Emerging quantum technologies pose new measurement challenges, but also offer previously unknown measurement solutions.

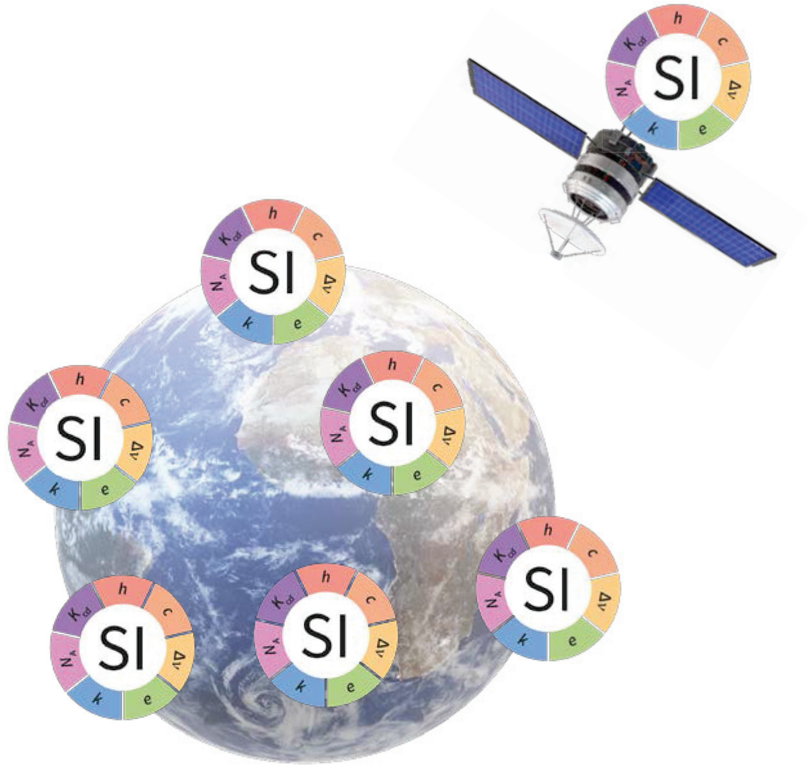
By nature of metrology and good will NMIs have a long history of collaboration. Let's do quantum together!

# Democratized traceability

## Before




## Now




Question to the panel:
Who owns traceability?

# Panel: The role of the metrology community in advancing emerging technologies

- AIST/NMIJ – Takashi Usuda
- NMIA – Victoria Coleman
- NIST – Jim Kushmerick
- NRC – Georgette Macdonald
- PTB – Cornelia Denz

# G-QuAT of AIST and quantum hardware components evaluation

Takashi Usuda

# G-QuAT of AIST and Quantum Hardware Components Evaluation

## -Resilient Supply Chain of Quantum Hardware Components-

NMIJ AIST
Takashi Usuda

21 March 2024

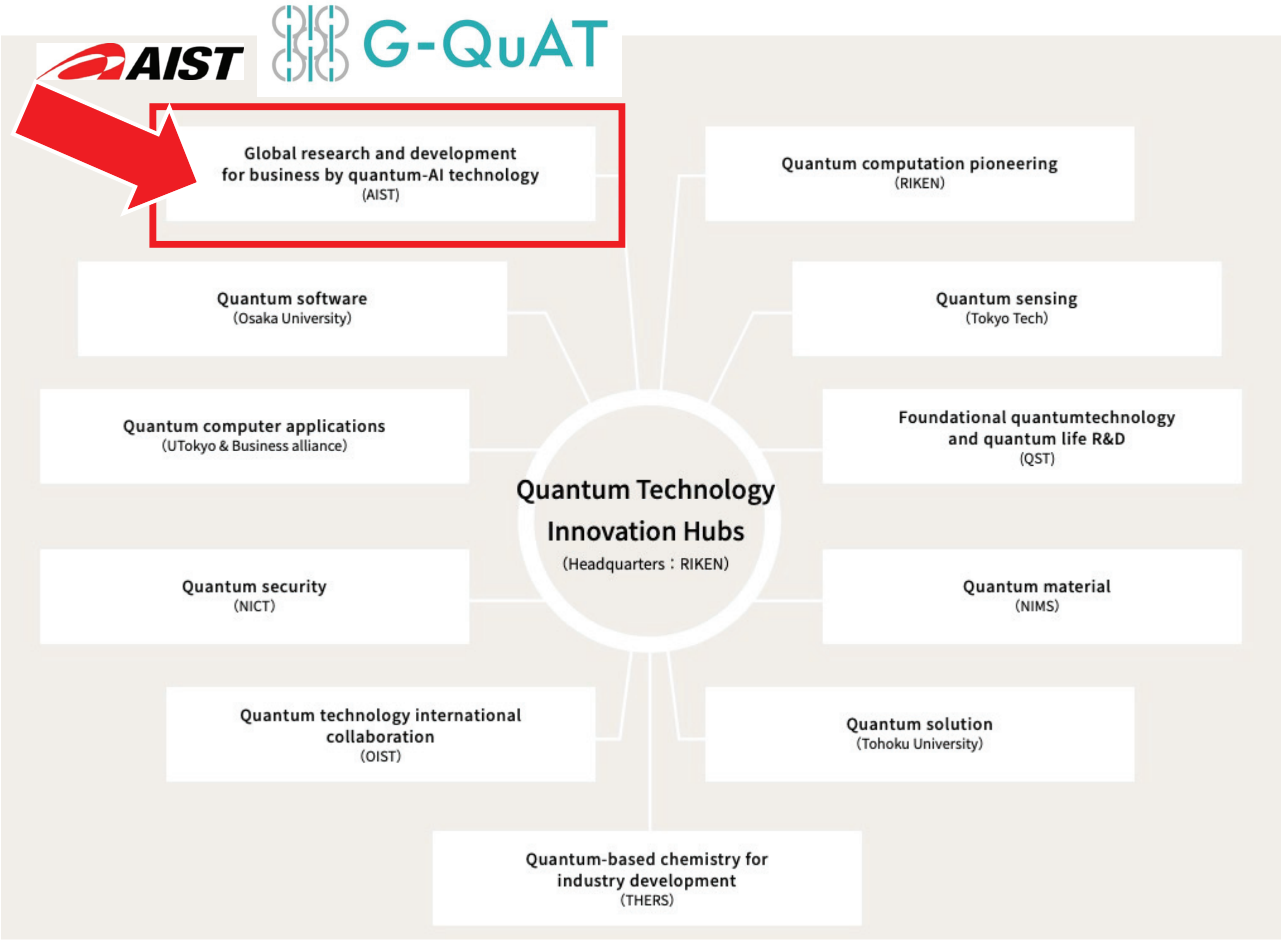
# Quantum Technology Innovation Hubs (QIH)

Vision of Quantum Future Society

-Future Society to be Realized through Quantum Technology and Strategies for Its Realization- April 2022

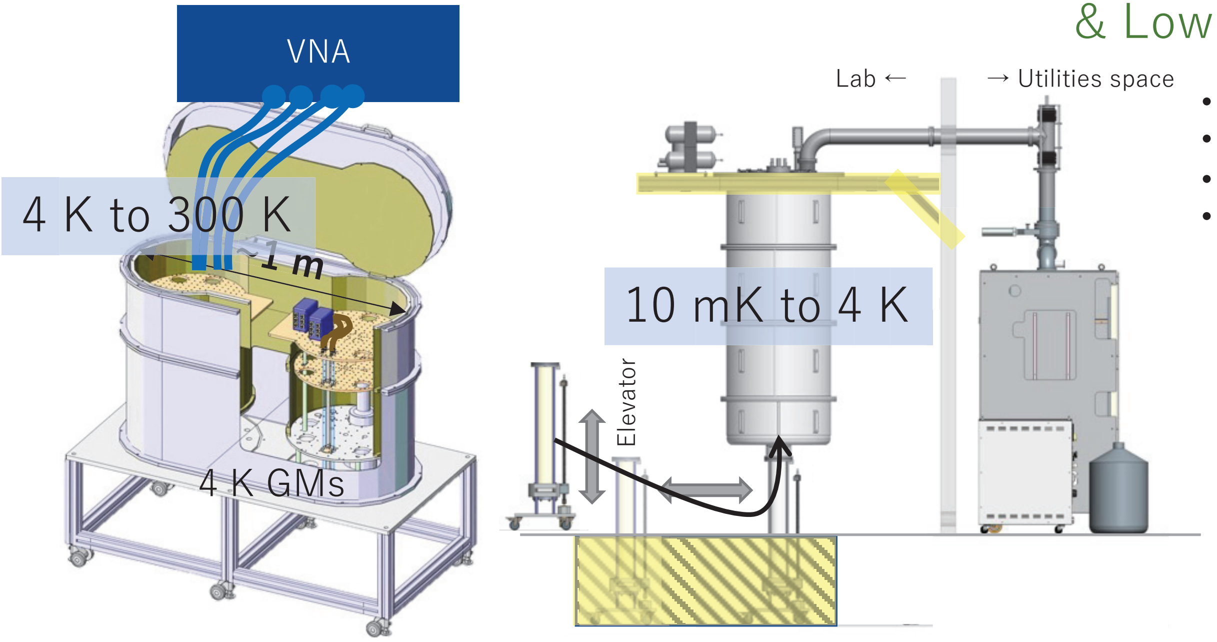
Global Research and Development Center for Business by Quantum-AI technology (G-QuAT)

- Quantum-AI Cloud Research Team
- Quantum Application Team
- Quantum Hardware Components R&D Team
- Quantum Device Measurement Team
- Quantum Device Research Team
- Quantum Sensing Research Team



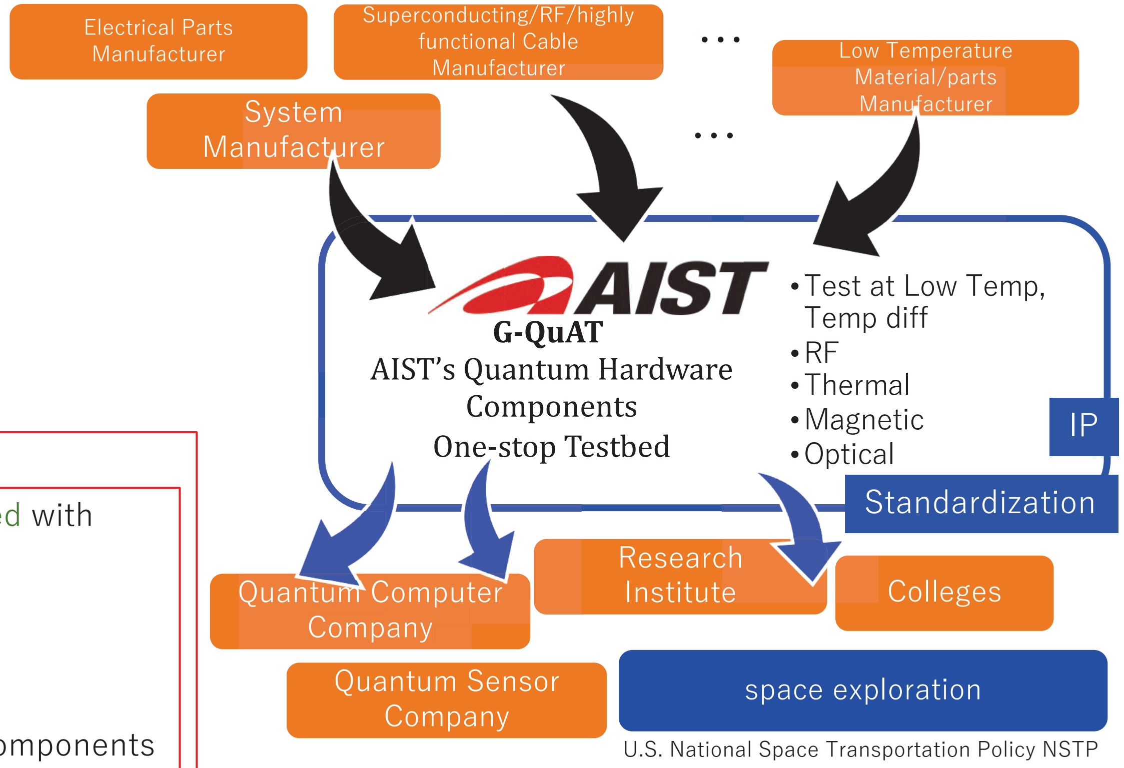

出典：量子技術イノベーション拠点WEBページ、https://qih.riken.jp

# Hardware Testbed for Cryogenic Quantum Computer/Sensor Components -Supply Chain of Quantum Components/parts-




## G-QuAT One-stop Testbed for Traceable Testing/Calibrations & Low temperature annealing

- Two tandem GMs (4 K)
- One single GM (4 K)
- Eleven dilution fridges (10 mK to 4 K (maximize throughput by bottom-load system))
- 4 K prober




- Active parts (AMPs)
- Passive parts
- Chip carriers (RF), Chip elements
- Cables (superconducting, resistive)
- Connectors (high density)
- Cryo-CMOS
- Superconducting circuits (AQFP, RSFQ)
- Other electrical comportments/parts
- Screening of qubits (dilution fridge)
- Thermal, optical, electrical properties of various devices

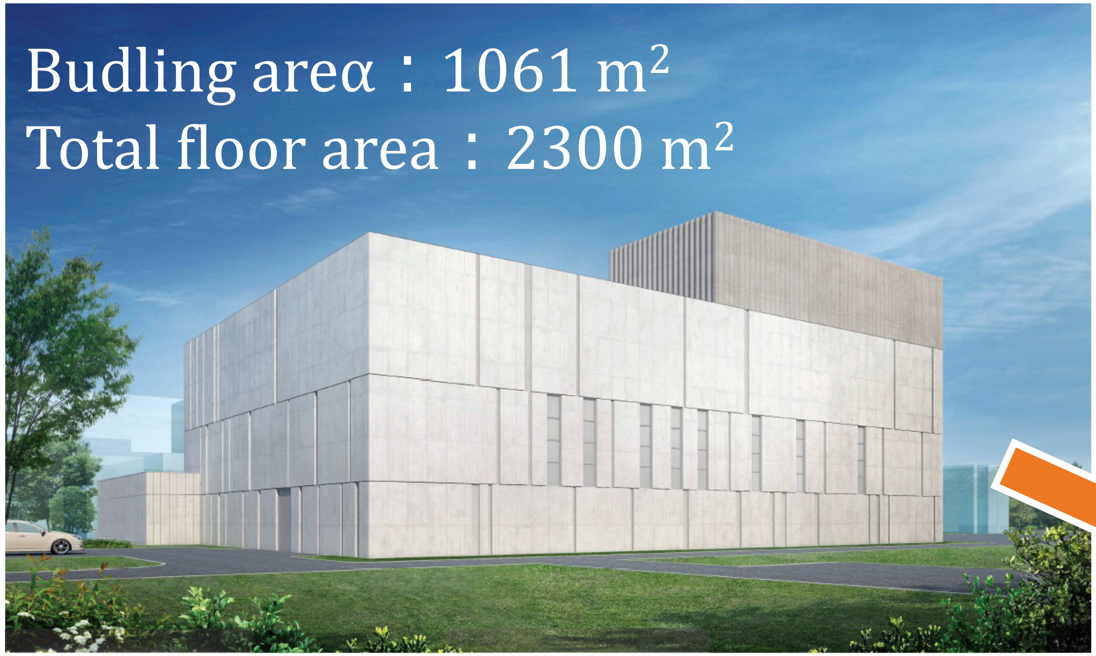
### Components/parts Carriers

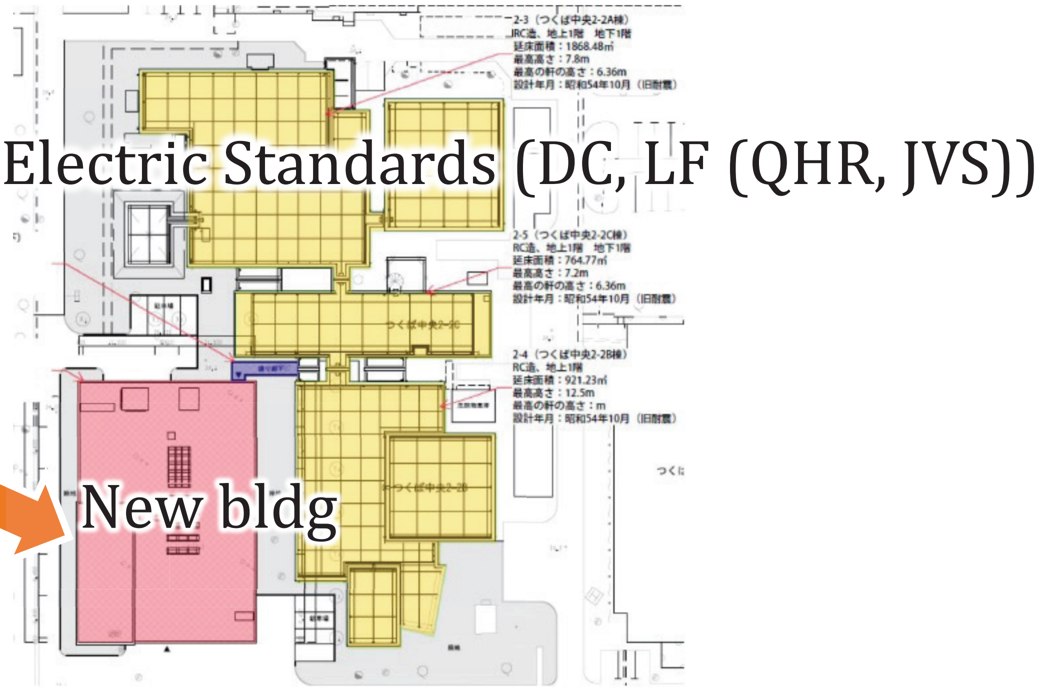
Low temp testing/calibration and annealing testbed with dedicated
- Cryocoolers
- Components carriers (several types)
- scanners/switches/probe heads/probe cards
- VNAs and Impedance meters

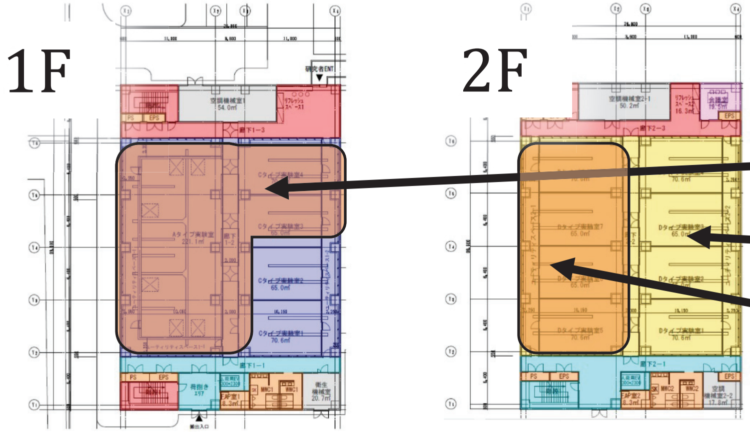
for the required size/shape and RF bands of the components

# New Quantum Hardware Components Testbed Bldg

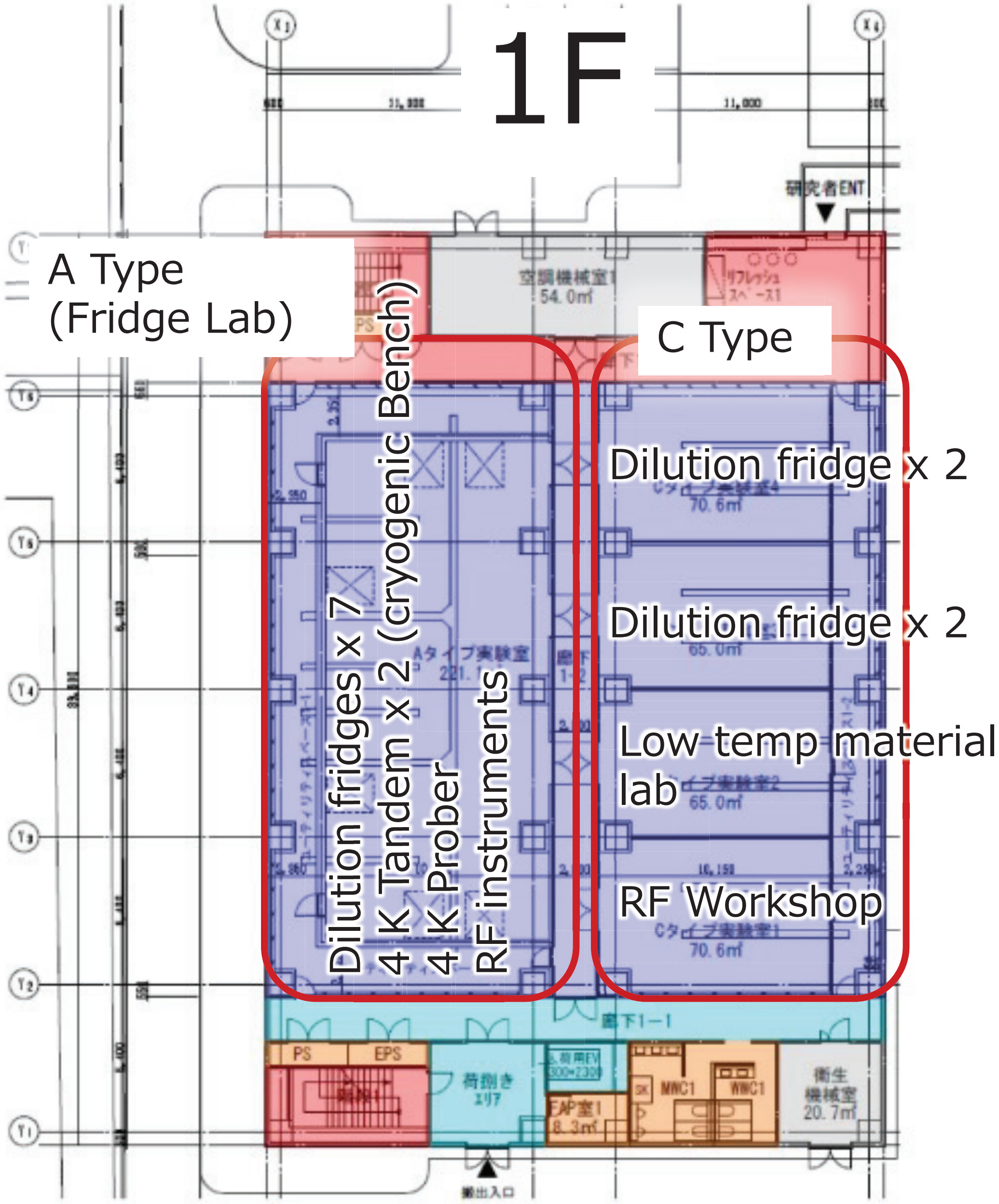
Completion: March 2025

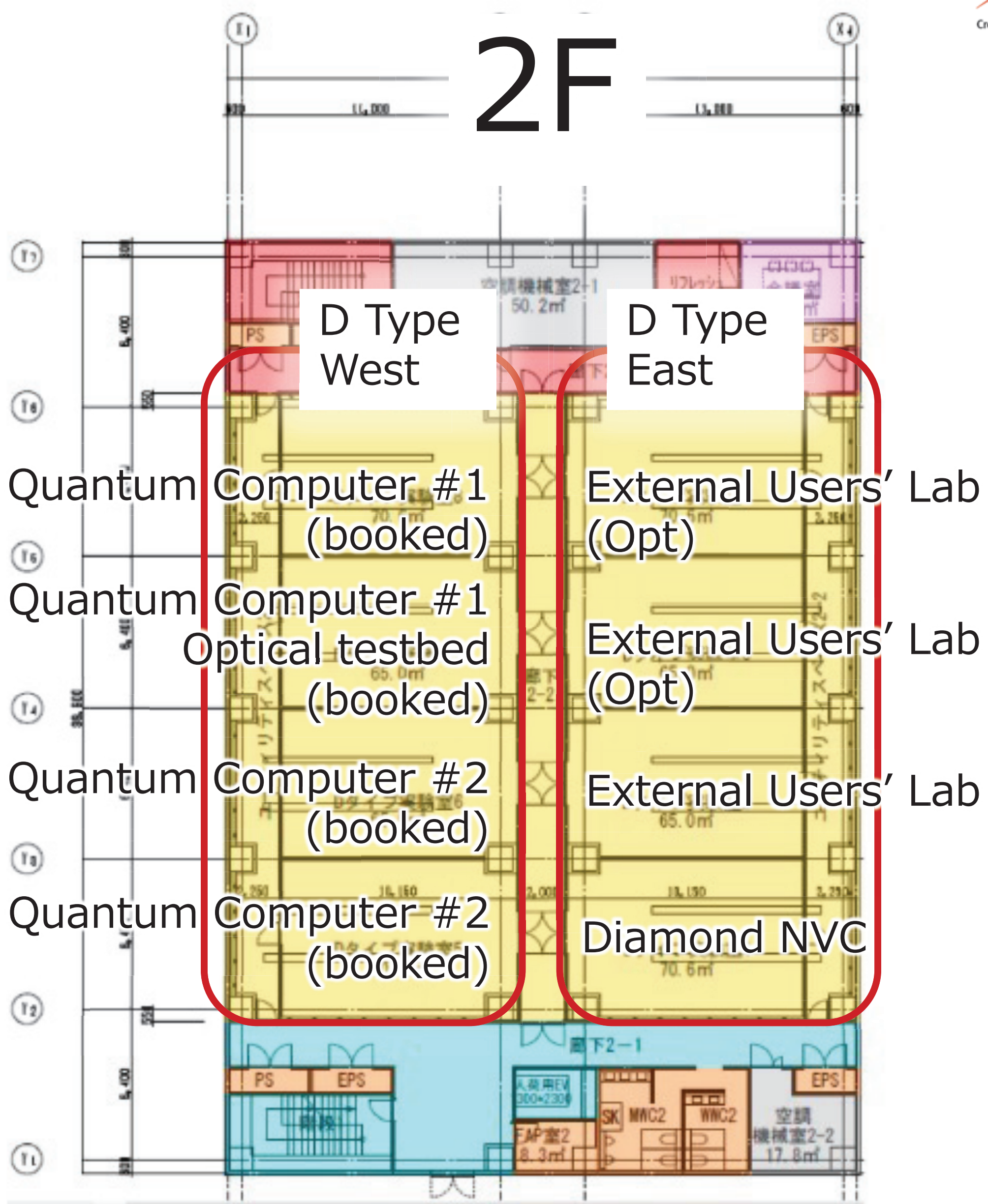


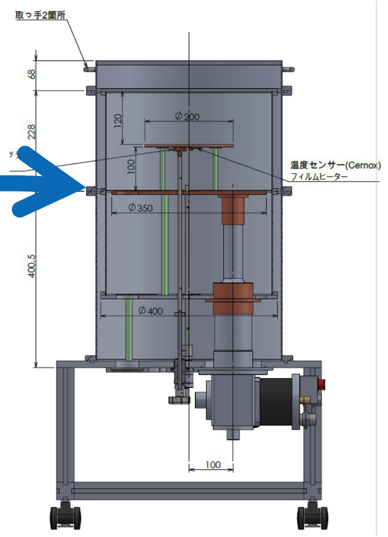



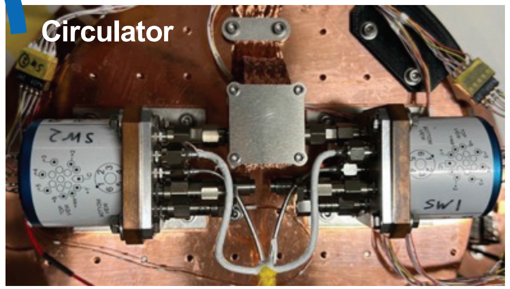

- Testbed (Low temp, RF, thermal)
- Collaboration rooms
- Quantum computers (optical), Testbed (RT, optical)

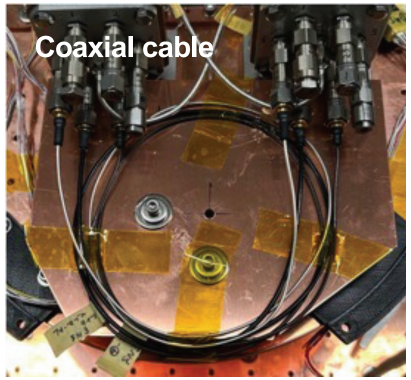

1F
A Type
(Fridge Lab)
Dilution fridges x 7
4 K Tandem x 2 (cryogenic Bench)
4 K Prober
RF instruments
C Type
Dilution fridge x 2
Dilution fridge x 2
Low temp material lab
RF Workshop

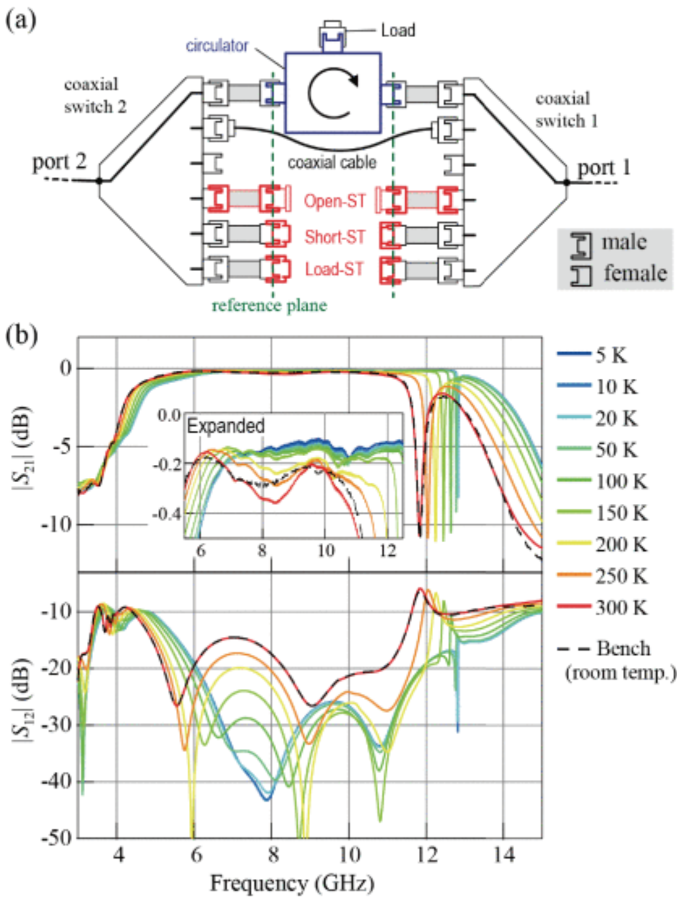

2F
D Type
West
D Type
East
Quantum Computer #1
(booked)
Quantum Computer #1
Optical testbed
(booked)
Quantum Computer #2
(booked)
Quantum Computer #2
(booked)
External Users' Lab
(Opt)
External Users' Lab
(Opt)
External Users' Lab
Diamond NVC

# Measurement results of actual components

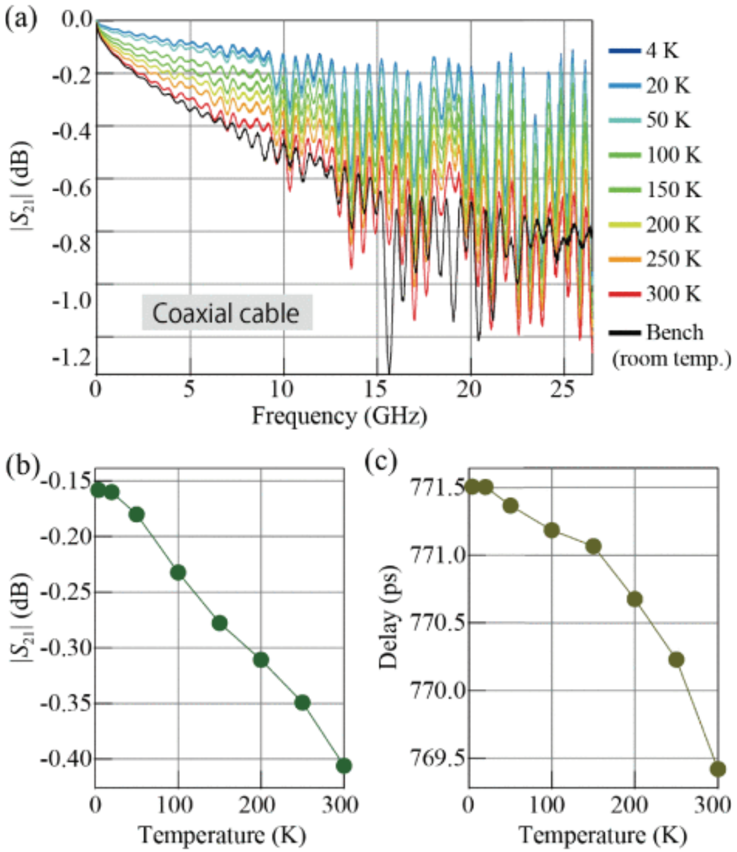





※bench: conventional method without RF switch at RT




T. Arakawa and S. Kon, *IEEE TIM* 2023
DOI: 10.1109/TIM.2023.3315393

# Summary

What we do

- List low temperature components/parts/materials w/ their specs that are necessities in the quantum computer development (→ roadmap)
- Evaluate/measure/calibrate them in the adequately real conditions (4 K, 10 mK or with temperature gradient (10 mK to 60 K)) with common traceability (standards)
- All are "low temperature annealed" simultaneously
- Simulations with low-temperature electronic/thermal and measurements, those for combinations of components and consistency check
- Measurements of combined sets of typical existing components, those of developed components with various typical existing components
- Establishment of a reference model of evaluation of quantum computers components

What the industry benefits

- All components can be combined without extra/additional measurements/treatments (good matching)
- Feed-back to manufacturers→Better components
- Engineers/Researchers (of quantum computer manufacturers) are supplied with calibrated/tested components
- No hassle on trial-and-error measurements/selection/matching of components
- One-stop testing based on standards and international standardization (e.g., IEC)
- Collaboration platform between companies/institutes
- Solution business to all low temperature fields
    - Including: space exploration (宇宙基本計画（内閣府, Basic Plan for Space, Cabinet Office）, Starlink (Space X), 国家宇宙輸送計画(U.S. National Space Transportation Policy NSTP, NASA戦略的宇宙技術投資計画 (Strategic Space Technology Investment Plan SSTIP), and basic research (physics (elementary particle and solid-state physics), chemistry, geophysics).
- The project is planned to include the activities towards "Standardizations"

# Experiences in advancing standardisation for emerging technologies – nanotechologies

Victoria Coleman

# Quantum information science at NIST

James Kushmerick

# Quantum Information Science at NIST

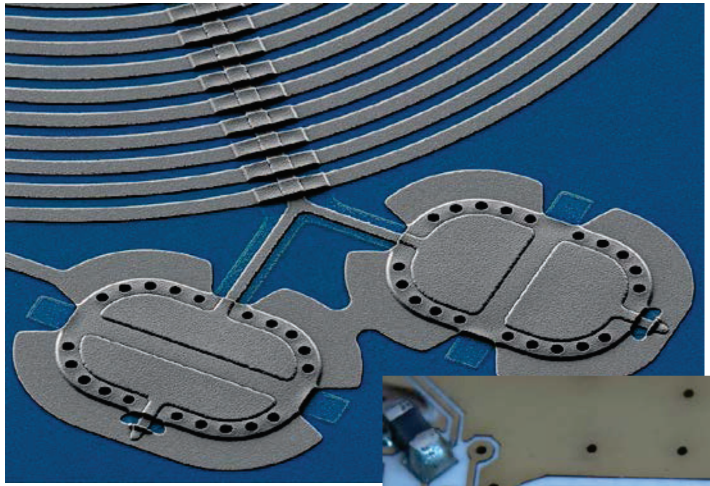
*Dr. James Kushmerick*
*Physical Measurement Laboratory Director*

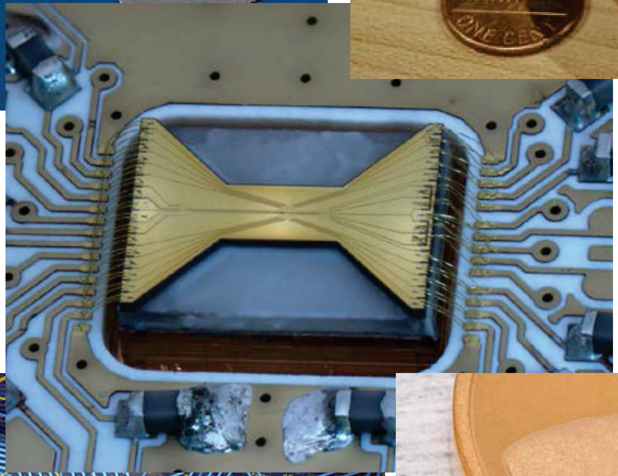
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

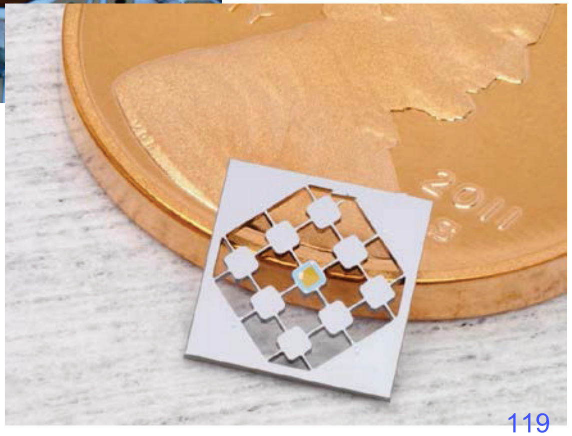
# QIST Research @ NIST

## NIST QIST R&D activities span the full NQI Program:

- Quantum Sensing and Precision Measurement e.g. optical atomic clocks (compact and high-performance) for time keeping and navigation, nano-mechanical and opto-mechanical devices, atomic magnetometers, chemical and biological systems.
- Quantum Networking e.g. quantum repeater, quantum transduction, optical networks (both quantum and classical, fiber and free-space), single photon sources and detectors.
- Quantum Computing e.g. improving qubit performance across all major platforms, benchmarking, error correction, new technologies for scaling.
- Fundamental Quantum Science e.g. quantum simulation, understanding complex quantum systems, searches for 'beyond Standard Model' physics e.g. dark matter, tests of gravity and quantum mechanics.
- Enabling Technologies e.g. integrated photonics, meta-materials, optical frequency combs, and control electronics.
- Risk Mitigation e.g. post-quantum cryptography.





# NIST's Joint Research Institutes

JILA
CU-Boulder and NIST

29 research groups with
~250 postdocs & students
https://jila.colorado.edu/

Established in 1962 as a Joint Institute of NIST and the University of Colorado

University of Colorado **Boulder**

JOINT QUANTUM INSTITUTE

35 research groups with
~180 postdocs & students
https://jqi.umd.edu/

Established in 2006 as a Joint Institute of NIST and the University of Maryland

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

16 research groups with
~80 postdocs & students
https://quics.umd.edu/

Established in 2014 as a Joint Institute of NIST and the University of Maryland

University of Maryland 1856

# Quantum Economic Development Consortium

**Enable and grow a robust U.S. quantum industry and supply chain**

Identify and develop strategies to address gaps in the following

- Enabling technologies (cryogenics, electronics, lasers, etc.)
- Standards, benchmarks and performance metrics
- Workforce

Identify economically important applications and use cases

Facilitate industry coordination and interaction with government

Provide government with a collective industry voice, e.g., to guide R&D investments, inform regulatory policy, and develop a quantum-ready workforce

Established by NIST, managed by *SRI International*, and led by the US quantum industry.

QED-C®

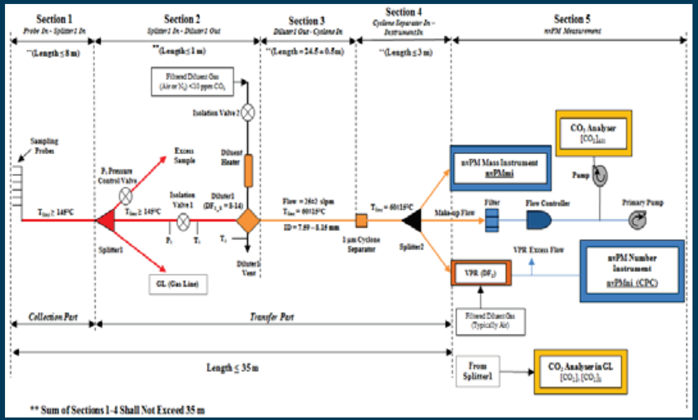
# Experiences in advancing standardisation for emerging technologies

Georgette Macdonald

# ICAO/SAE-E31
# Civil Aviation Emissions




- *Particulate emissions regulated by opacity measurement (visibility) from 1960s to 2010s*
- *Better engine design and awareness of Black Carbon (nano particles) drove new measurement and emission standards*
- *National regulations require international standards*
- *International Civil Aviation Organization developed standards policy, Society for Automotive Engineering managed technical standards development*
- *Development through collaboration of government labs, industry and universities over ~20 years*
- *ARP6320A published in 2021*




National Research Council Canada

Transport Canada

Pratt & Whitney
A United Technologies Company

Missouri S&T

ETH

AVL

Artium Technologies Inc.

ICAO

SAE INTERNATIONAL

....

# Metrology for the emerging quantum industry

Cornelia Denz

Panel: The role of the metrology community in advancing emerging technologies

# Metrology for the emerging quantum industry

Cornelia Denz, PTB

# Grand challenges & innovation | Transformative fields

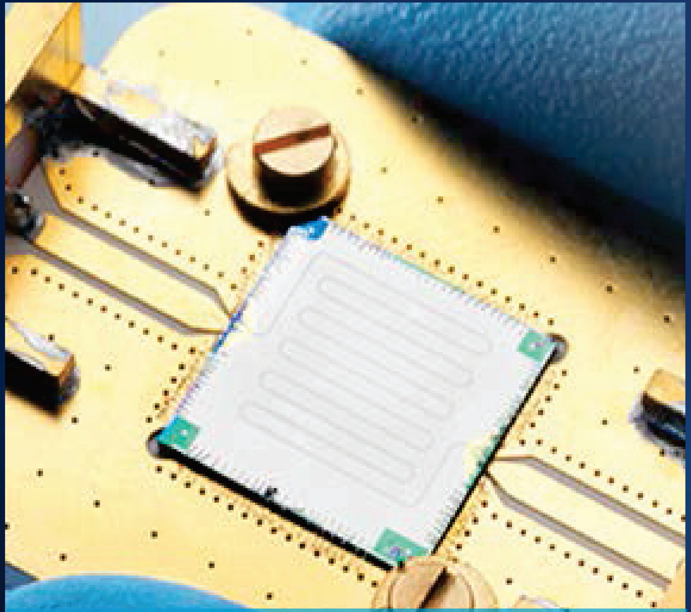
- Emerging fields need basic research for innovations ▶ **Science-oriented approach**
- Innovations in turn need interdisciplinary expertise ▶ **Project-oriented approach**
- Traceability & uncertainty definitions are lacking ▶ **New frontiers in metrology**

**Emerging needs in metrology require also innovations with respect to industry services, legal metrology & societal trust in metrology**

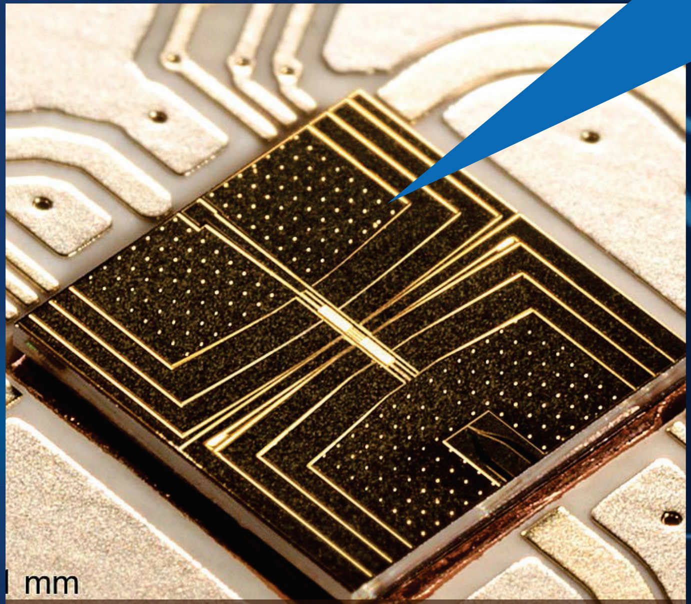
# Grand challenges & innovation | Example QT

- QT has many metrological themes ▶ **Quantum s**
  - ▶ Objective **tests & characterizations** to suppo
  - ▶ **Quantum innovations in precision metrolog**

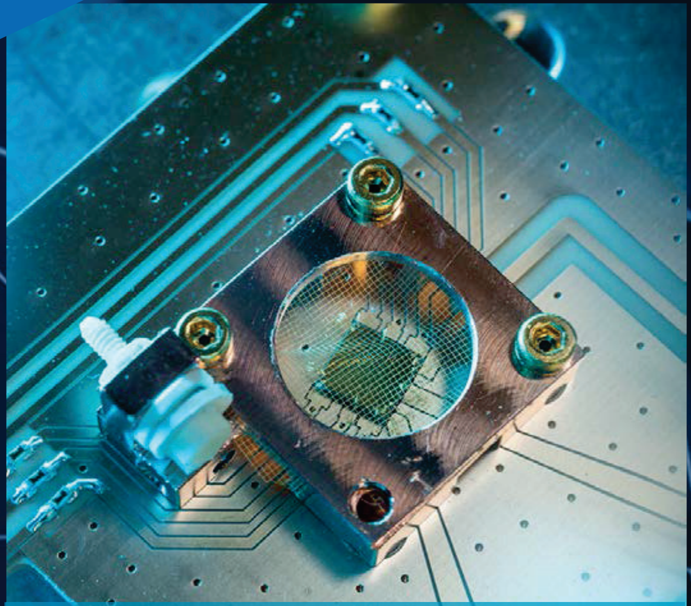
**Developing quantum technologies for industrial needs as e.g. miniaturization & robust operation also initiates novel scientific approaches**



**Quantum Hall circuits: AC QHR** © PTB




**Ion computer chip** © PTB



**Chip for photonic encryption** © PTB

# Industry-related QT innovations | Technology centers

- **Example I: Quantum Technology Competence Center (QTZ)** ▶ A **PTB center** to allow partners from industry & academia to access QT expertise & infrastructure
  - ▶ **Support of QT areas with economic potential and standardization needs**
  - ▶ **Transfer of basic research to applied QT with potential future commercial use**
  - ▶ **Cooperation with SMEs & startups**

**In QTZ, cutting-edge approaches interface scientific and industrial needs**

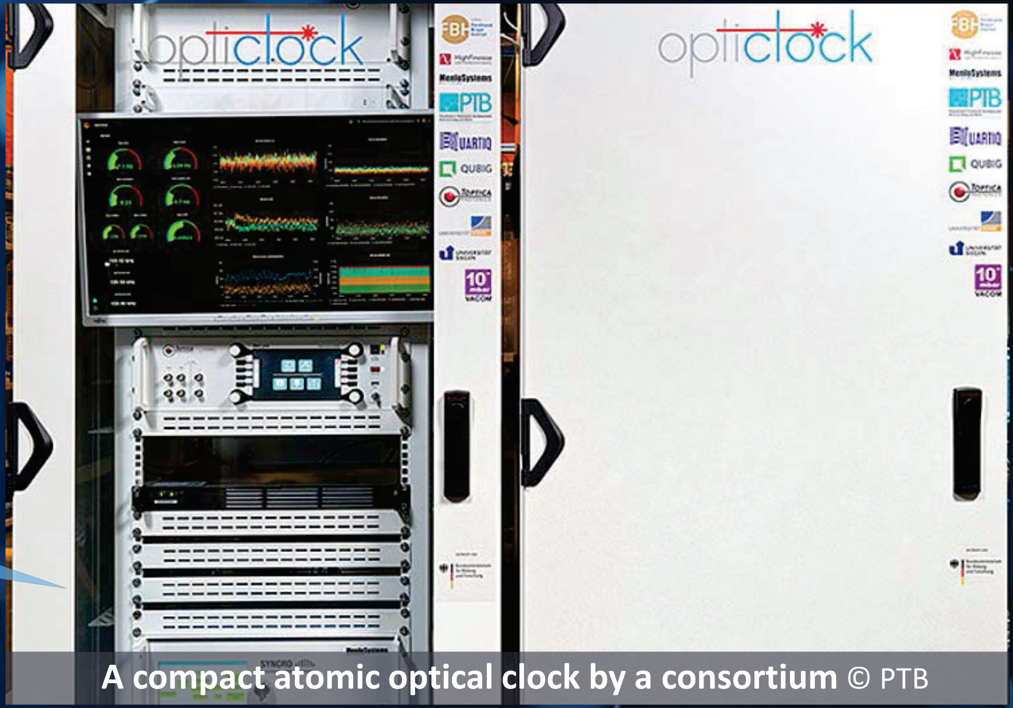
**Local centers as QTZ allow international networking by scientific, legal and regulatory sandboxes as e.g. with CIPM, IMEKO, Cen-Cenelec, ...**


**New home of QTZ: Lummer-Pringsheim building, Braunschweig** © PTB

# Industry-related QT innovations | Testbed examples

- **Metrology Testbed I: Ion traps**
  - Key metrological technology that supports development of **optical atomic clocks, quantum computers, quantum simulation**
- **Goals of QTZ in ion trap applications**
  - **Compact & robust test facilities**
  - **Qualification & certification for industry**
  - **Reliable and reproducable specifications**
  - **Development of standards**

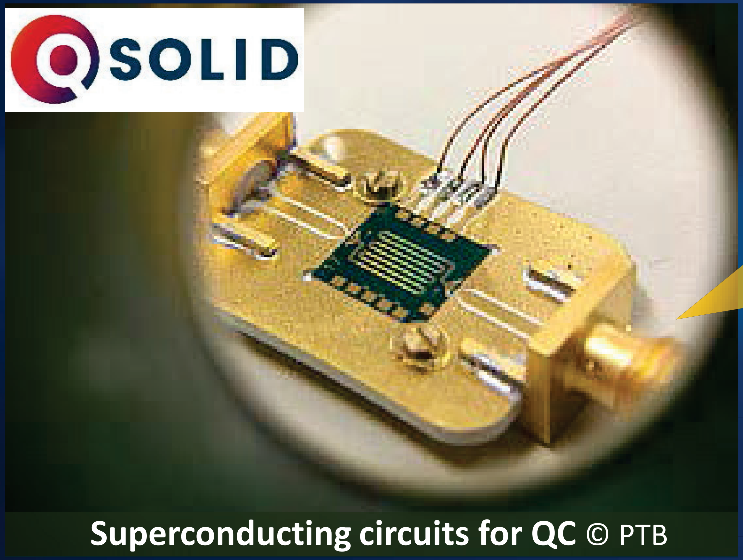
**Opticlock: user-friendly and reliable optical atomic clock system by a mixed metrology-industry consortium**



A compact atomic optical clock by a consortium © PTB

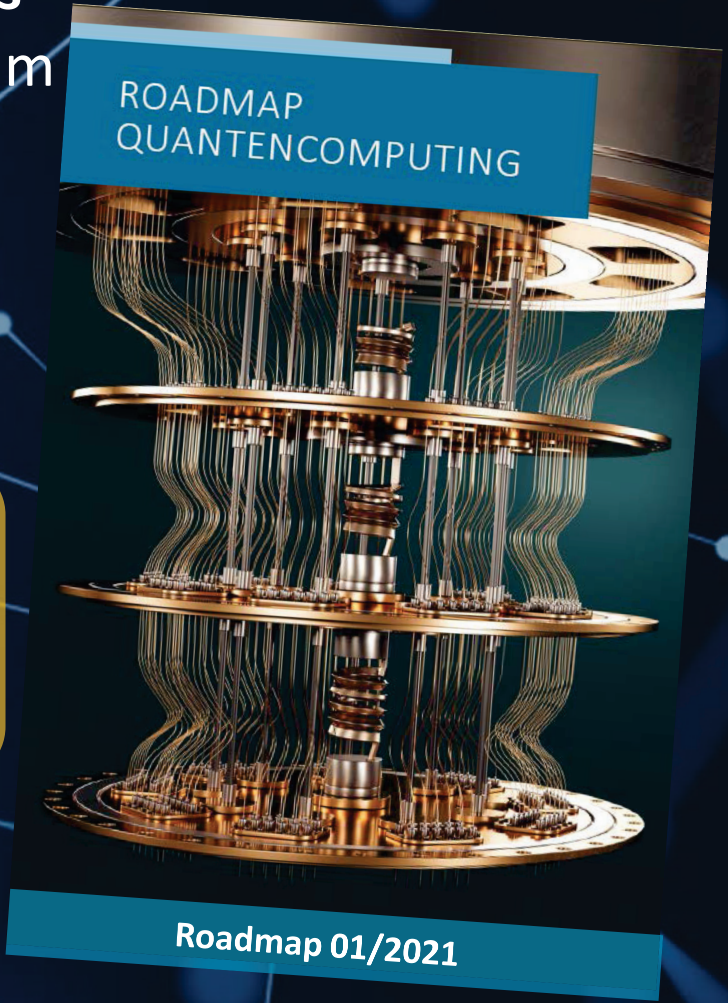
# Industry-related QT innovations | Testbed examples

- **Metrology Testbed II: (Superconducting) quantum computers**
  - Independent research & development of different quantum computer realizations  is key for future digitalization
  - **Collaborative project QSolid for quantum computers**
  - **Test facility for enhanced error correction**
  - **Further fields: SQUIDs & op magnetometers**



**Superconducting circuits for QC** © PTB

**Testbeds enable metrology NMIs to advance industry-relevant quantum technologies in different areas: information, measurement industry, medicine,  circular economy**



# Industry-related QT innovations | Testbed examples

## Metrology Testbed III: Quantum Communication

- A testbed for radiometry and fibre applications
- (Non classical) light sources, detectors, fibre links
- Sandbox & testing facility for QKD components

**Quantum communication testbed established in the region connecting technology centers**

# Industry-related QT innovations | Incubator example

**PTB Quantum Technology Center | A PTB incubator**

QT expertise and infrastructure for academia and industry

- ▶ **Demonstrators & testbeds, education & training, start-ups & industry support**

**Quantum valley lower saxony | A regional incubator**

Construction of an ion quantum computer (QVLS Q1)

- ▶ **QC testbed: 50 Qubits till 2025**

Innovation cluster (QVLS-iLabs) & pre-standards

- ▶ **Regional QT industry with > 20 companies**

QVLS High Tech Incubator (QVLS-HTI)

- ▶ **Promotion of 12 startups**

Leibniz Universität Hannover | Technische Universität Braunschweig | PTB

**Ecosystem for breakthroughs in quantum technologies: Research institutions, companies, and startups are joining forces to efficiently coordinate developments from the research lab to commercialization**

Niedersächsisches Ministerium für Wissenschaft und Kultur | Quantum Valley Lower Saxony

# Emerging quantum industry | Joint leverage for standards

**International metrological expertise is indispensable for standards**

- Metrological support for an internationally emerging quantum ecosystem
- Common development of secure, reliable, traceable quantum technologies
  - **Network of local high tech incubators create a common understanding**
  - **Clusters of regional user facilities connect metrology to industrial needs**
  - **Interconnection of national tech transfer in direct cooperation with industry**
  - **Global reference measurements in applied testbeds**

- **Continuous quantum innovations by fundamental research**
- **Establishing metrological services for the quantum ecosystem**
- **Developing standards for the emerging quantum industry**

17:30

# Day 1 wrap-up, adjourn – Jan Herrmann

# Day 1 Recap:

- Industry needs application-driven quantum standardisation, and it needs it fast.
- Quantum standardisation needs collaboration.
- NMIs are uniquely positioned to contribute to, to drive and to facilitate such standardisation.
- We have a track record of being quantum ‘pushers’ and ‘pullers’.
- We are seen as being independent.
- We have an established culture and framework of collaboration, but we need to think about how we can be agile and responsive in the context of a very dynamic technology landscape.
- So tomorrow, let’s look at what we can do together, and how we can work together.

# Reception Sponsored by NPL

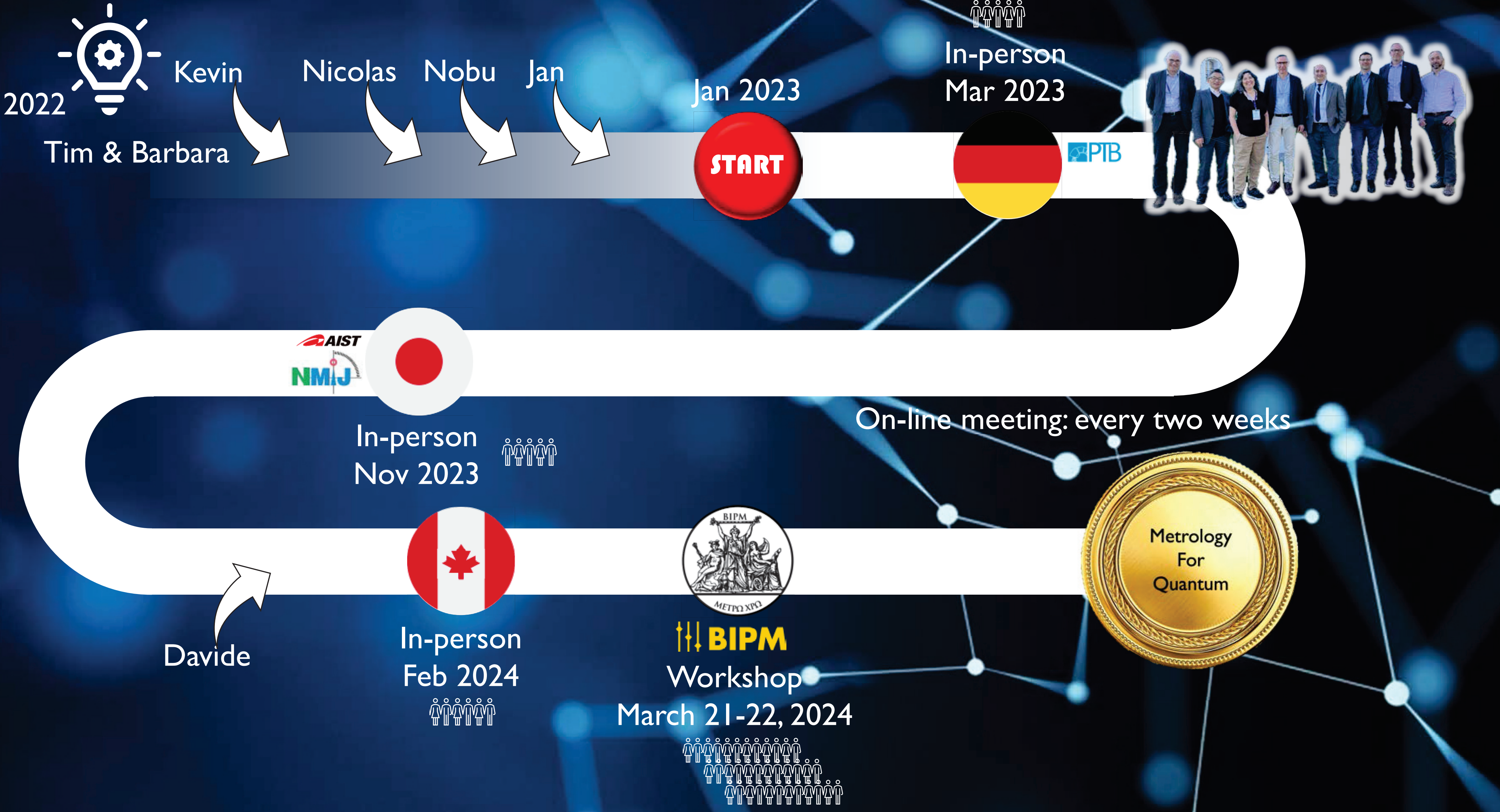
# Agenda – Day 2 – Morning (updated)
## Solutions

| | |
|---|---|
| 08:45 | Day 1 recap, framing Day 2 |
| 09:00 | Presentations: NMI Collaborations in Quantum |
| | EMN-Q, Qu-Test – Ivo Degiovanni |
| | SQMS, Metrology gaps for superconducting quantum devices – Florent Lecocq |
| | LNE, Metrology gaps for quantum, benchmarking – Felicien Schopfer |
| | Quantum Photonics – Angela Gamouras (NRC) / John Lehman (NIST) |
| 10:00 | Survey Results |
| 10:15 | Break with group photo |
| 10:45 | Break-out 2: What should NMIs/DIs do together? |
| 11:45 | Report back |
| 12:00 | Examples of frameworks for NMI collaboration – Jan Herrmann, NMI-Q |
| 12:15 | Lunch |

08:45 – 09:00

# Day 1 recap, framing Day 2 – Nobu Kaneko

# NMI-Q



2022
Tim & Barbara
Kevin
Nicolas
Nobu
Jan
Jan 2023
START
In-person
Mar 2023
PTB
On-line meeting: every two weeks
AIST
NMIJ
In-person
Nov 2023
Metrology
For
Quantum
Davide
In-person
Feb 2024
BIPM
BIPM
Workshop
March 21-22, 2024

# Day 1 recap

Welcome remarks, keynote, & framing talk

→ Guide all of us toward the same "goal"

Goal: Leverage the combined expertise of the world's NMIs to accelerate the development and adoption of quantum technologies through coordinated development and sharing of measurement "best practices" in support of future standardization.

→ Ready to be on the same page and develop consensus on how to move forward as a community

Panels

I: industry consortia: needs application-driven quantum standardization and test cases

II: standardization: needs collaboration and benchmark. NMIs are independent, uniquely positioned, have track record of being quantum 'pushers' and 'pullers,' have established culture and framework of collaboration, but we need to think about how we can be agile and responsive in the context of a very dynamic technology landscape

III: NMIs' directors: showed NMI quantum activities and directors' positions

Break-out I

Active discussion: economies' quantum programs - ice breaker

→NEEDS MORE TIME!

## TODAY: What and how we can do together

# Agenda – Day 2 – Morning (updated)
## Solutions

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09:00 – 10:00

# Presentations: NMI collaborations in quantum

Moderator – Nobu Kaneko

# Presentations: NMI collaborations in quantum

- EMN-Q, Qu-Test – Ivo Degiovanni
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- LNE, Metrology gaps for quantum, benchmarking – Felicien Schopfer
- Quantum photonics - Angela Gamouras (NRC) and John Lehman (NIST)

09:00 – 09:10

# European Metrology Network for Quantum Technologies (EMN-Q) and the Qu-Test Project

Ivo Pietro Degiovanni

# European Metrology Network for Quantum Technologies (EMN-Q) and the Qu-Test Project

**Ivo Pietro DEGIOVANNI**

EMN-Q Chair & INRIM

*BIPM Workshop on*
*Accelerating the Adoption of QT*
*through Measurements and Standards*
*BIPM – March 21-22, 2024*

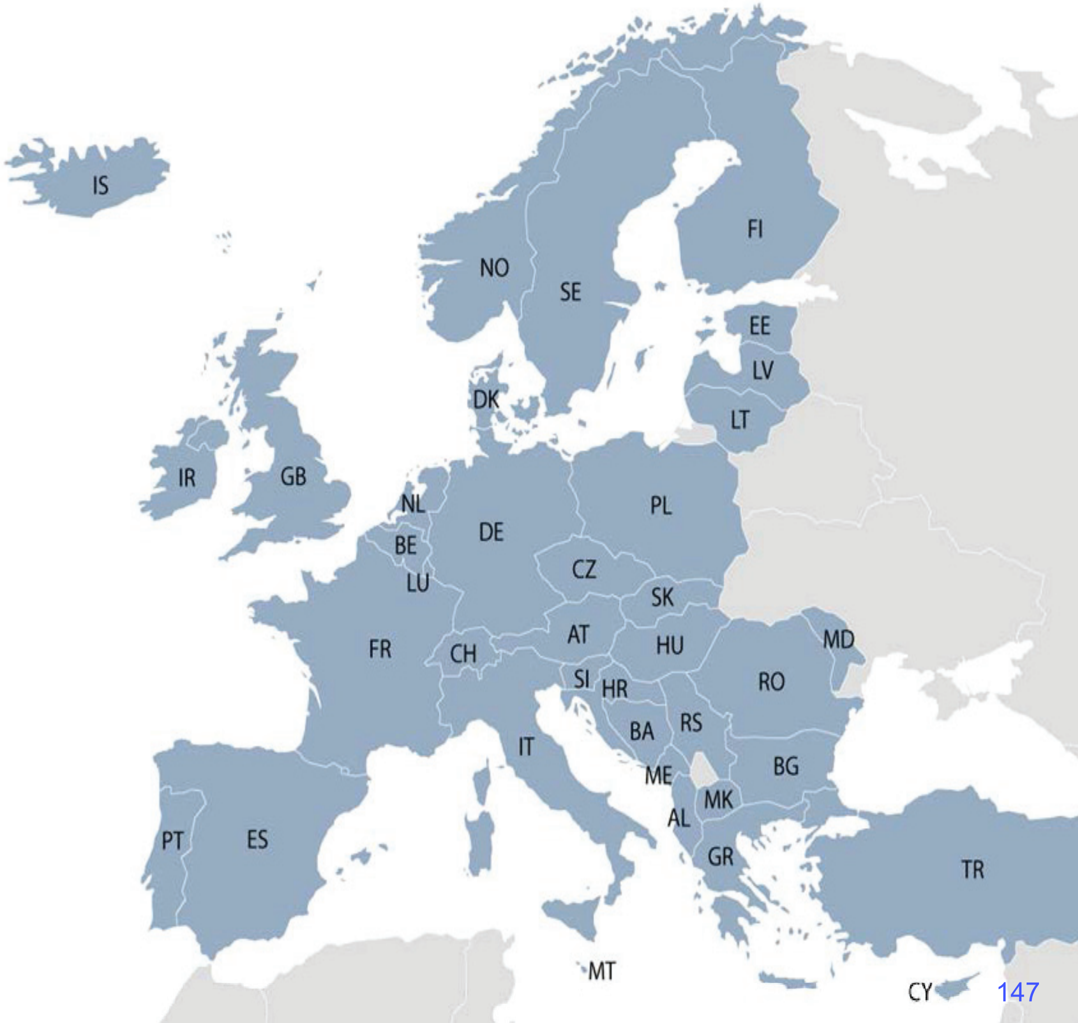
# Outline

- EMN-Q
- QU-TEST project

# EURAMET

## EURAMET, the Regional Metrology Organisation (RMO) of Europe

- **38 National Metrology Institutes** (Members)
- **77 Designated Institutes** (Associates)
- **16 international Liaison Organisations** (e.g. IAEA, BIPM, WMO, EA, Eurachem, Eurolab)
- Providing stakeholders with **world-leading measurement solutions and standards**
- Securing **world-wide trust** and **acceptance** of measurements, for all aspects of business and society
- Implementing **Metrology Research Programmes**



# EURAMET

## EURAMET, the Regional Metrology Organisation (RMO) of Europe

- Technical/scientific collaboration in EURAMET is organised within **ten Technical Committees.**

Acoustics, Ultrasound and Vibration
Electricity and Magnetism
Flow
Ionising Radiation
Length
Mass and Related Quantities
Metrology in Chemistry
Photometry and Radiometry
Thermometry
Time and Frequency

- In addition, **two Committees deal with ‘horizontal’ topics.**

Quality
Interdisciplinary Metrology

As new structural backbones, EURAMET recently establishes

**European Metrology Networks (EMNs)**

- to strengthen stakeholder interaction and to work towards a sustainable, coordinated European metrology landscape.
- Strong emphasis on interactions with stakeholders!
- 15 EMNs are already existing or proposed.

# EMN for Quantum Technologies: EMN-Q

EMN-Q Strategic Agenda (22 Oct. 2020)

QUANTUM TECHNOLOGIES

EURAMET

**Rationale**

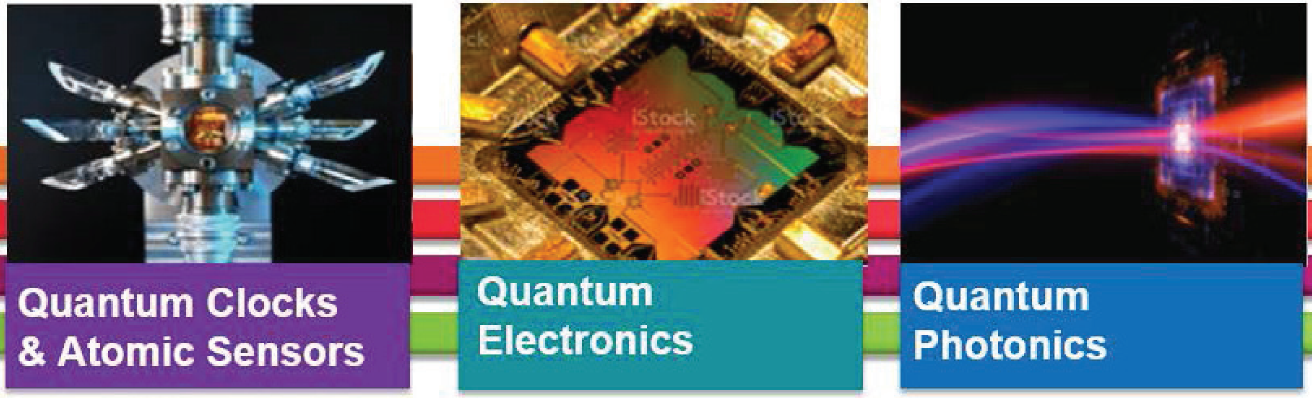
- **To align with industrial requirements, those of the EC Quantum Technologies Flagship,** national and inter-governmental quantum technology (QT) programmes, and of any **relevant stakeholders;**
- **to contribute to QT developments** through NMI's and DI's research and innovation activities;
- **to give input into the standardisation & certification** of QT;
- **to promote of the benefits of metrology** to the stakeholders.

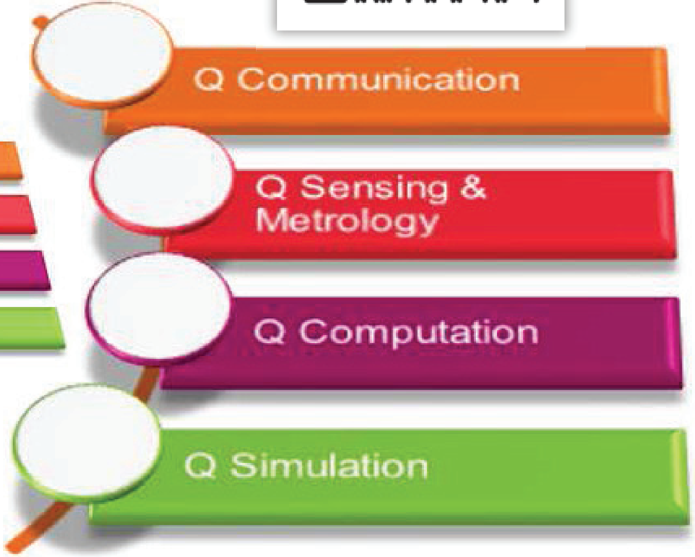
**Vision**

**EMN-Q aims at being the recognised European unique reference point representing European metrology for Quantum Technologies.**

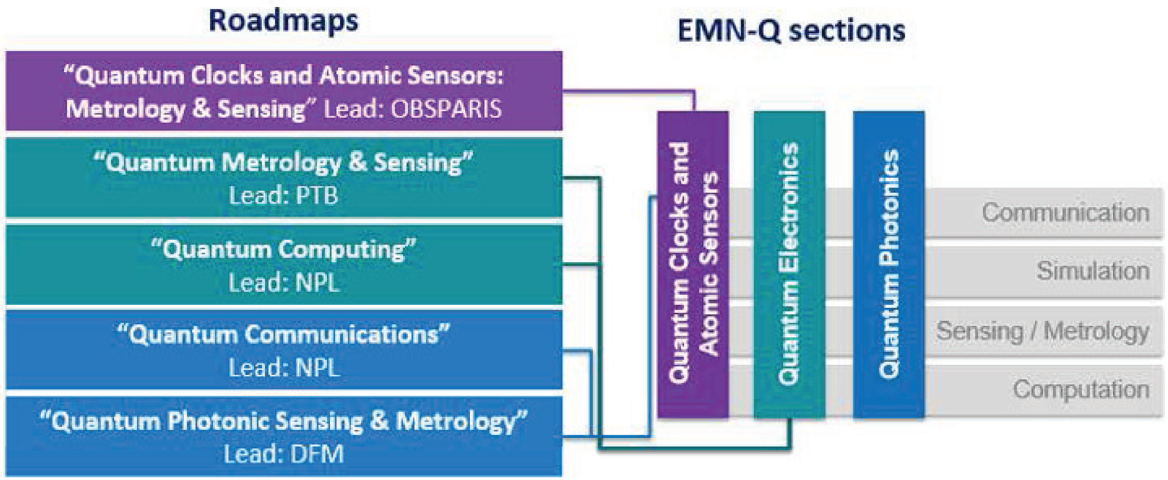
Today, EMN-Q has **18 EURAMET Members and Partners** from 15 countries.

# EMN-Q Structure and Organisation




- EMN-Q has drafted 5 strategical roadmaps in the 3 sections, related to the Quantum Flagship pillars.
- Roadmap drafts were circulated among the EMN-Q community and EURAMET TCs, and feedback was collected.




EMN-Q Strategic Research Agenda

*download and provide your feedback!*

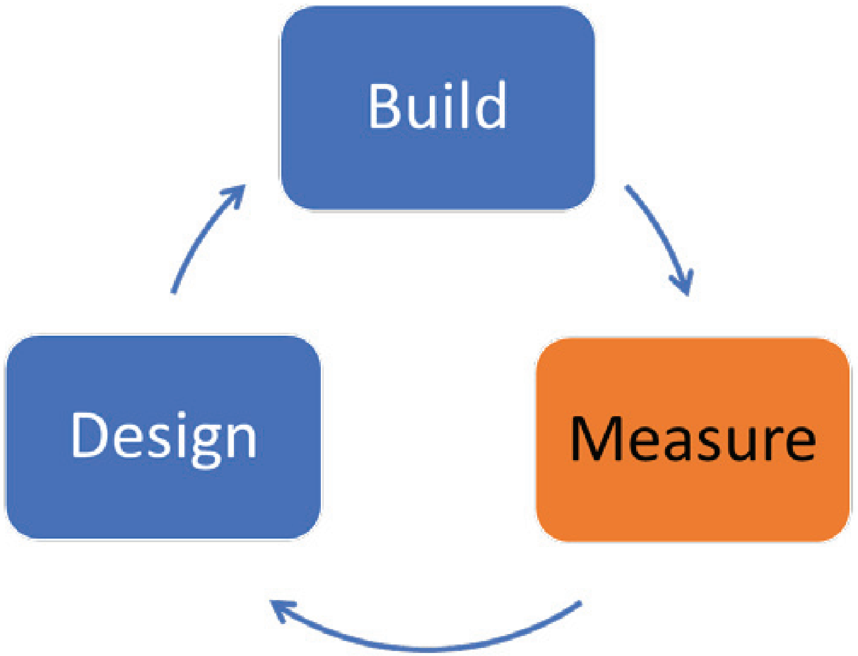
# QU-TEST

SUPPORTING OPEN TESTING
AND EXPERIMENTATION FOR QUANTUM
TECHNOLOGIES IN EUROPE

Funded by European Union l Horizon Europe

# Why is testing important?

Reliable testing is crucial to move from hardware R&D to commercialization both for supplier and purchaser of quantum technologies.




Our goals with Qu-Test

- **Improving** test facilities for quantum devices
- **Harmonization** of procedures and methodologies
- **Cooperation** with quantum industry
- **Providing access** to testing capabilities

Funded by European Union l Horizon Europe

# The consortium

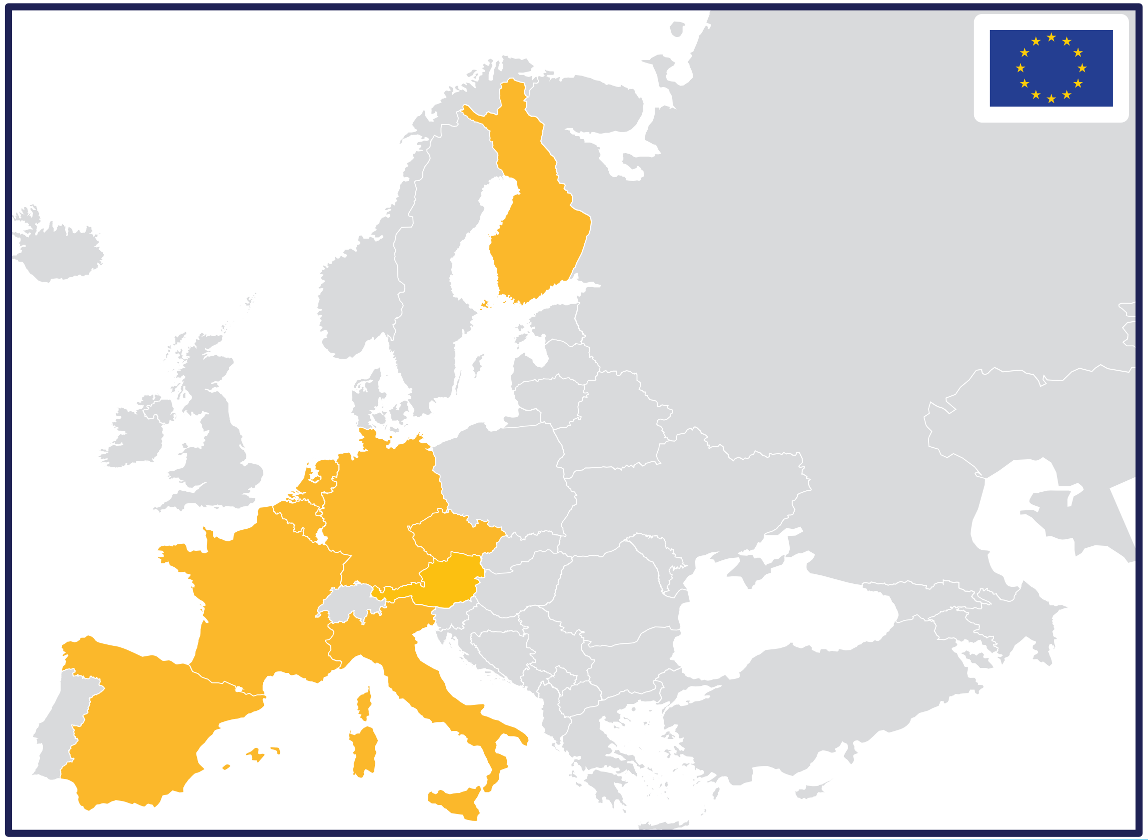
QU-TEST
QUANTUM TECHNOLOGIES
EURAMET

Service providers (RTOs and NMIs):

TNO
Fraunhofer
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
AIT AUSTRIAN INSTITUTE OF TECHNOLOGY
l'Observatoire de Paris
VTT
LNE
cea
PTB
imec
INSTITUT d'OPTIQUE GRADUATE SCHOOL

QU-TEST

***kick-off in April 2023***
***3.5 years***



Business services: AMIRES, SONNENBERG HARRISON

Use case companies: SILENT WAVES, ALICE & BOB

SINGLE QUANTUM Excellence in photon detection
QUANDELA
infineon
exail
QUANTUM OPTICS JENA
CryoConcept an Air Liquide affiliate
SENER Aeroespacial
AUREA TECHNOLOGY
Alea Quantum Technologies

# The consortium

QUANTUM TECHNOLOGIES

EURAMET

QU- TEST

Computing

- Solid-state cryogenic computing components and devices
- Photonics quantum computing components and devices
- Characterization of ion traps

Comms

- Characterisation of light generation and light detection on device level
- Evaluation of components and system on QRNG and QKD protocol level
- Experimentation and Prototyping for quantum communication

Sensing

- Metrology Applications of Q-Clocks
- Neutral atoms: Hot & Cold
- Non-classical light for quantum-enhanced imaging and sensing
- Solid State Spins (e.g., NV centers in diamond)

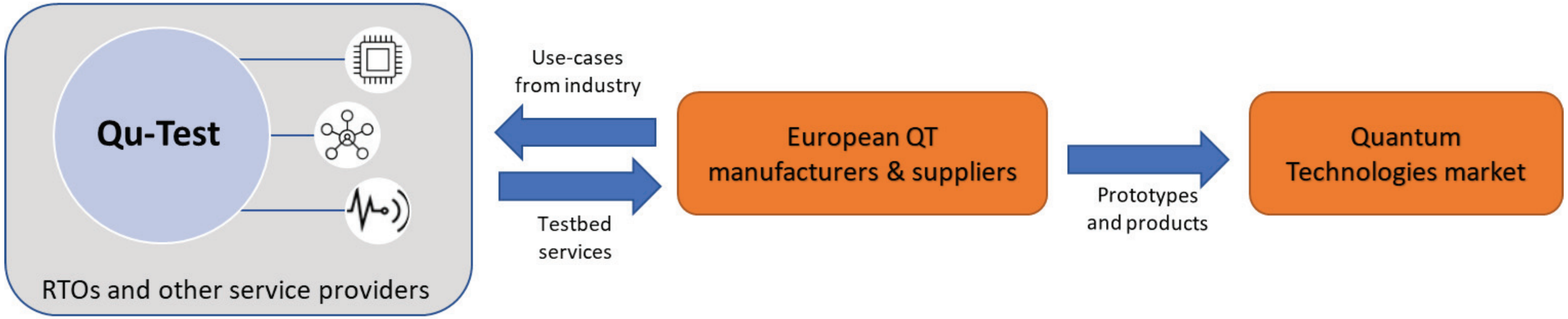
# Objectives

**Objective 1:** To create a federalized network of **testing and experimentation** services answering the needs of the industry.

**Objective 2:** To upgrade, upscale and integrate the **testing and experimentation** infrastructures and associated processes

**Objective 3:** To set-up an open-access distributed **testing and experimentation** infrastructure to make services available to clients in all 27 EU countries.

**Objective 4:** To validate the relevance of the service offering and robustness of the Single-Entry-Point network.




Funded by European Union I Horizon Europe

# Thanks for your attention!

09:10 – 09:20

# Metrology gaps for superconducting quantum devices

Florent Lecocq

# Metrology gaps for superconducting quantum devices

SQMS

Florent Lecocq

03/13/2024

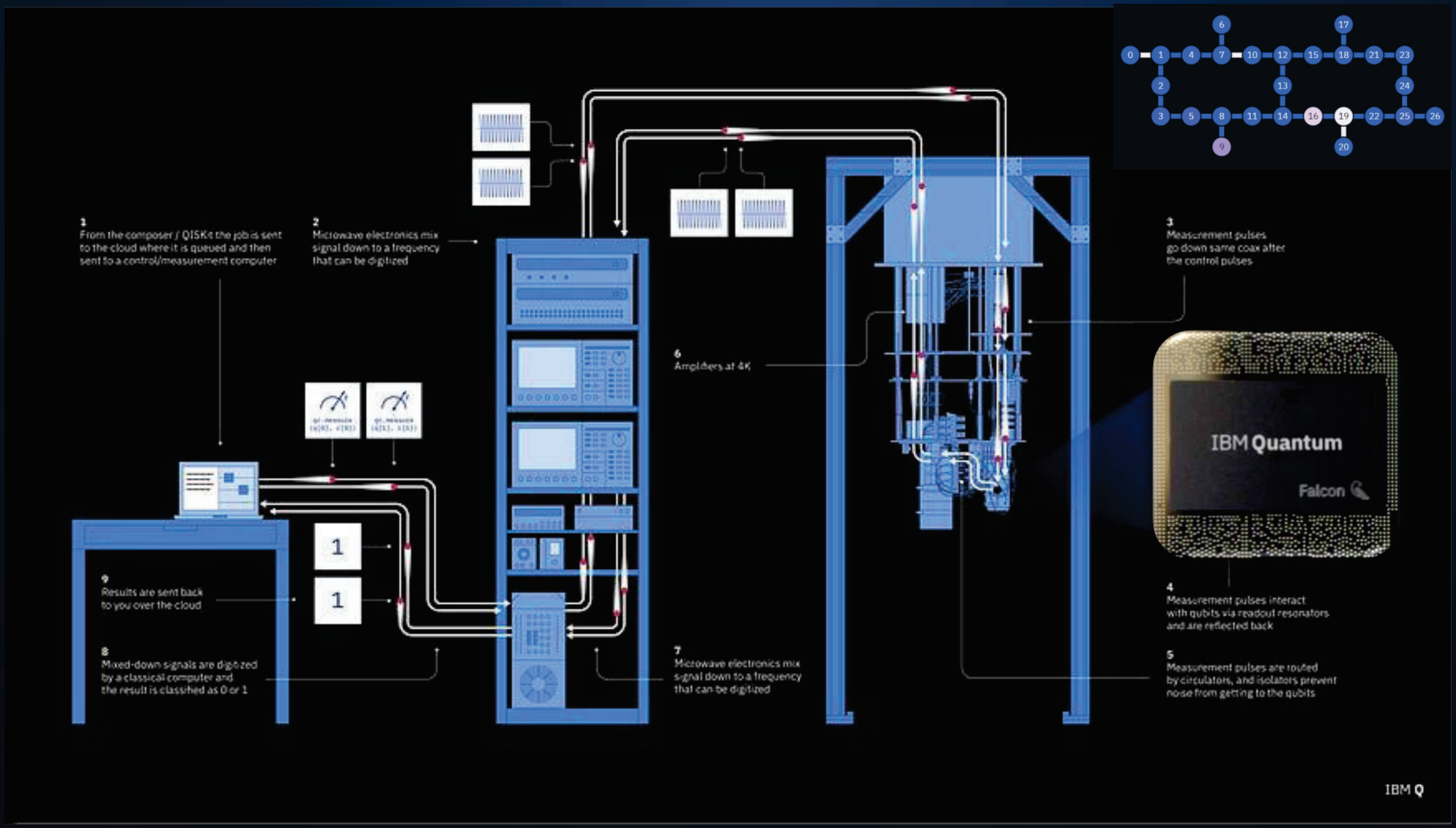
NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

University of Colorado Boulder

NIST Boulder
Advanced Microwave Photonics Group

# Benchmarking quantum computers

A difficult task!




<u>Bad metrics *on their own*</u>:

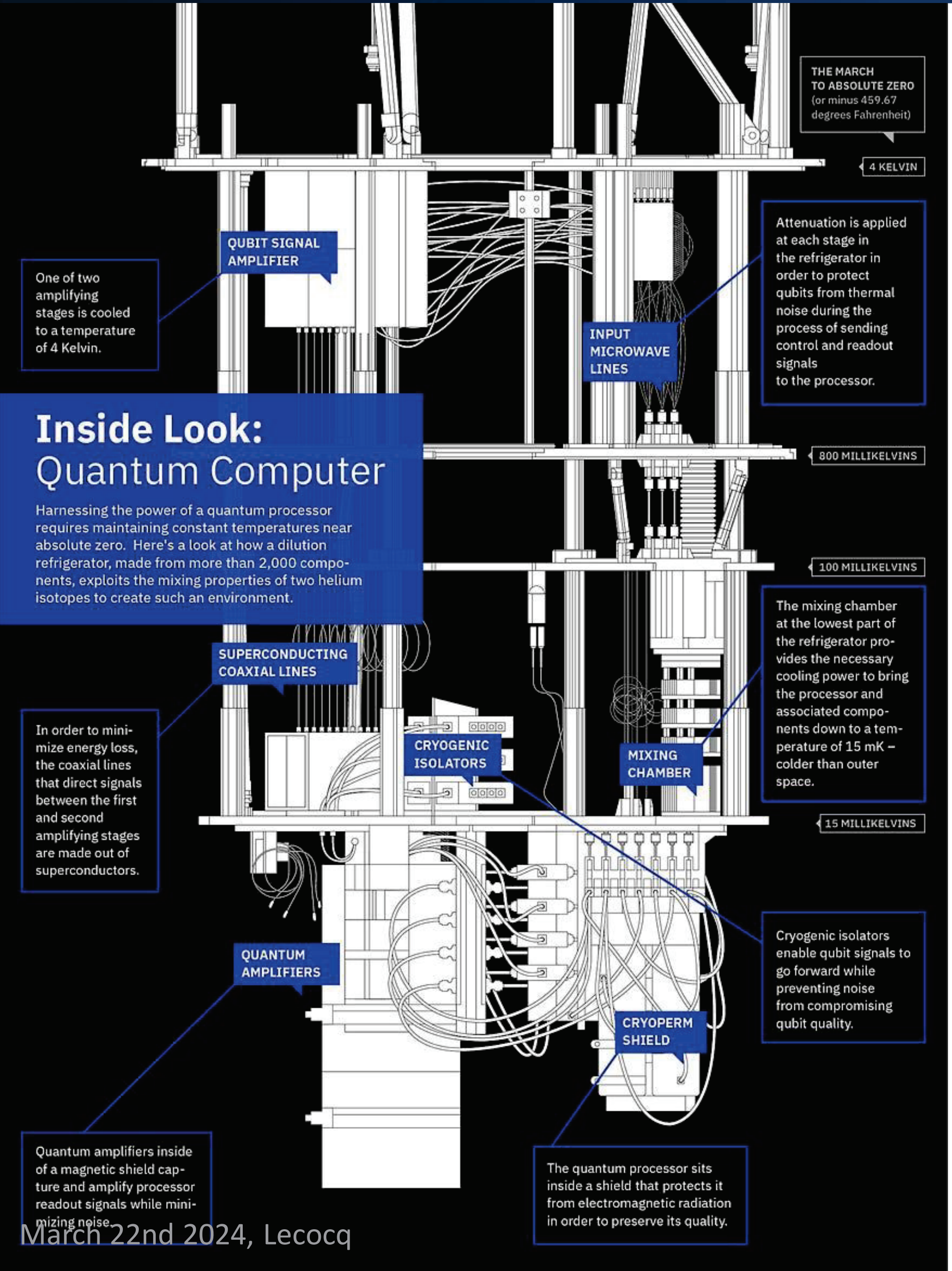
- # of qubits
- Coherence times
- Gate fidelity

<u>Better metrics</u>:

- Quantum volume
- Specific algo benchmarking

<u>Eventually impossible if classical comparison needed</u>

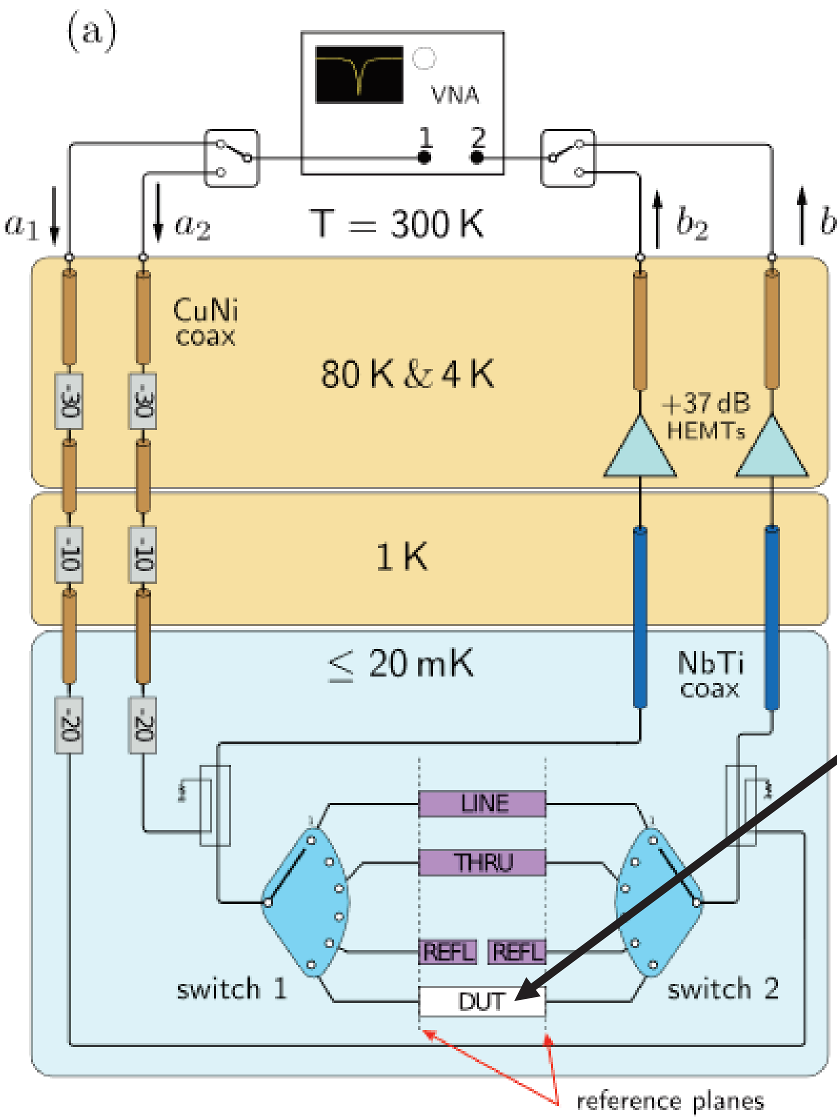
# Metrology for hardware at ultracryogenic temperatures




| Category | Sub category | Metrics |
|---|---|---|
| Cryogenics | Dil Fridges | • Cooling power<br>• Energy efficiency |
| Signal delivery | • Cables<br>• Filters<br>• Attenuators<br>• Isolators | • Heat load<br>• Crosstalk<br>• Scattering parameters<br>• Thermalization<br>• Isolation |
| Shielding | • Magnetic<br>• Thermal<br>• Radiation | • Efficacy vs frequency<br>• Heat load<br>• Thermalization |
| Readout chain | Quantum amplifiers | • Gain<br>• Added noise<br>• Power handling |
| Quantum processor | • Qubits<br>• Resonators<br>• Integrated circuitry | • Coherence (T1,T2)<br>• Gate fidelity<br>• Connectivity<br>• Crosstalk |

Non-exhaustive list

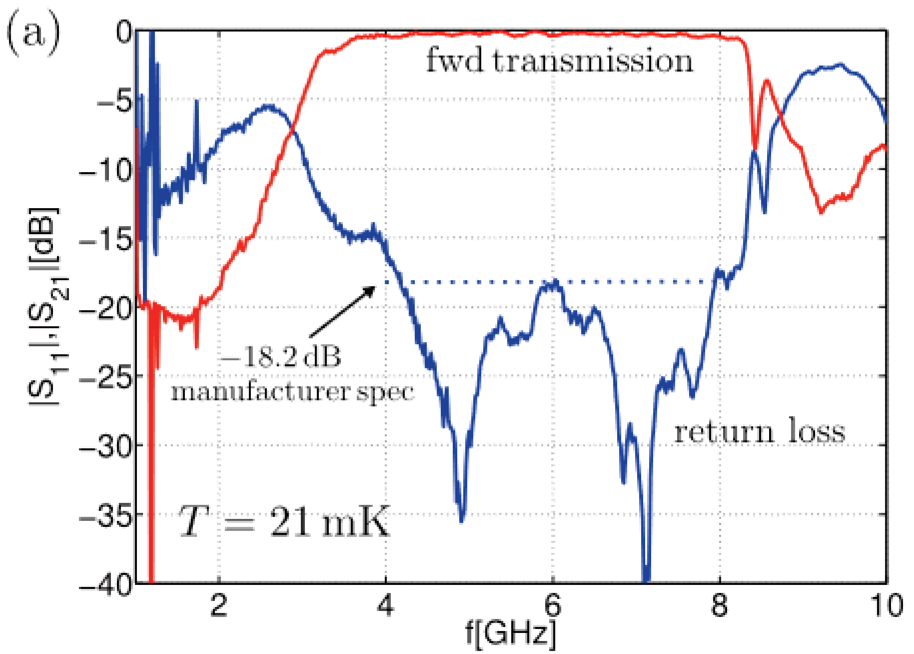
# Cryogenic components calibrations




REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 034704 (2013)

## Two-port microwave calibration at millikelvin temperatures

Leonardo Ranzani,[1,a)] Lafe Spietz,[1] Zoya Popovic,[2] and José Aumentado[1,b)]
[1]*National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[2]*University of Colorado at Boulder, Boulder, Colorado 80309, USA*

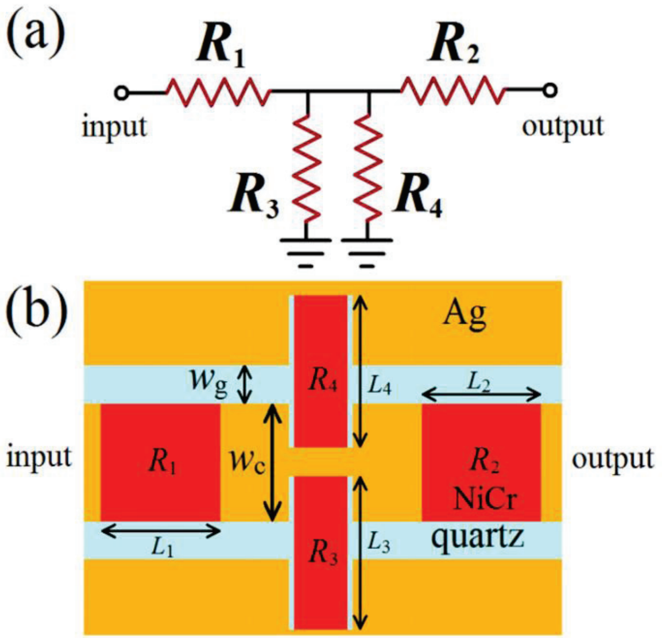



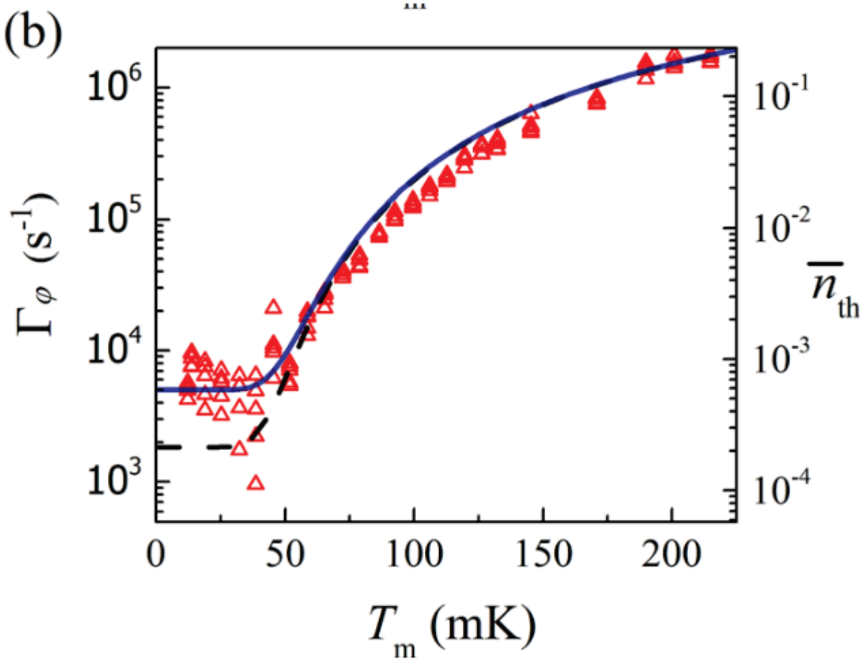
# Using qubit themselves to measure components

JOURNAL OF APPLIED PHYSICS **121**, 224501 (2017)

## Microwave attenuators for use with quantum devices below 100 mK

Jen-Hao Yeh,[1,2,a)] Jay LeFebvre,[1,2,b)] Shavindra Premaratne,[1,2] F. C. Wellstood,[2,3] and B. S. Palmer[1,2]
[1]*Laboratory for Physical Sciences, 8050 Greenmead Drive, College Park, Maryland 20740, USA*
[2]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[3]*Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA*




Using qubit coherence to measure attenuator thermalization and power handling

New Partnership between XMA/QED-C/NIST:

# Metrology for hardware at ultracryogenic temperatures

Typically companies do not have access to mK temperatures

↓

Partnership with NMIs can help! (e.g. QED-C)

| Category | Sub category | Metrics |
|---|---|---|
| Cryogenics | Dil Fridges | • Cooling power<br>• Energy efficiency |
| Signal delivery | • Cables<br>• Filters<br>• Attenuators<br>• Isolators | • Heat load<br>• Crosstalk<br>• Scattering parameters<br>• Thermalization<br>• Isolation |
| Shielding | • Magnetic<br>• Thermal<br>• Radiation | • Efficacy vs frequency<br>• Heat load<br>• Thermalization |
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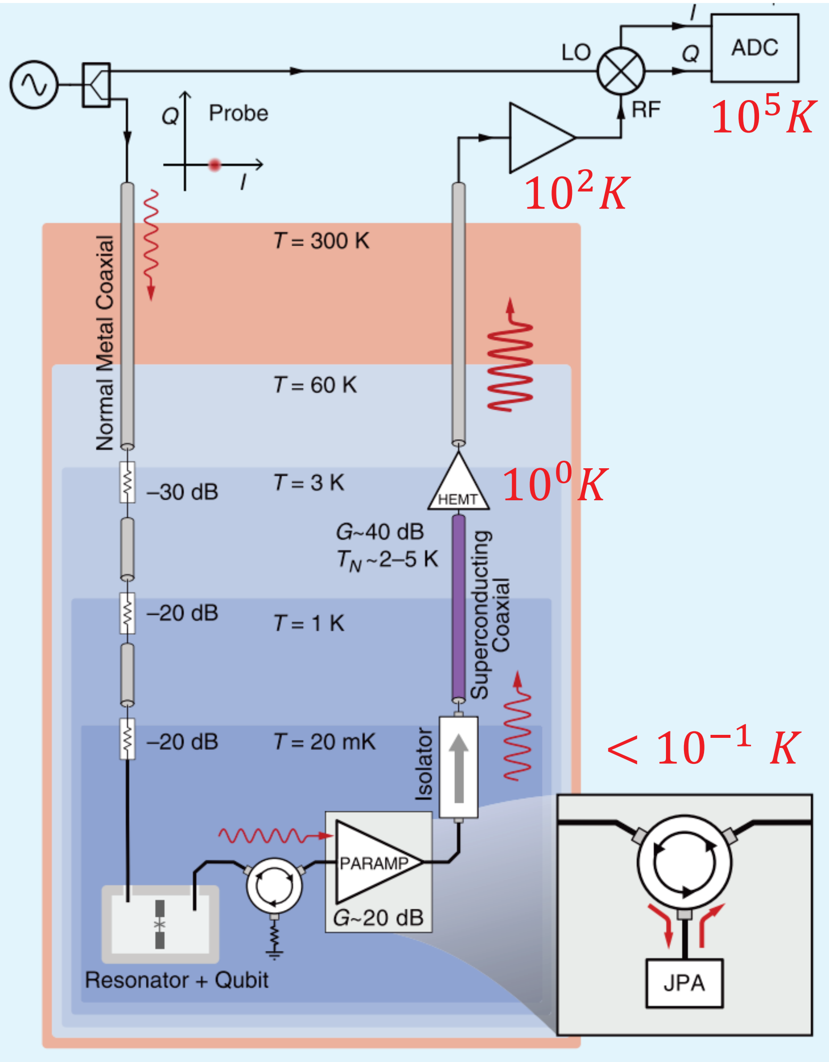
Non-exhaustive list

# Quantum amplifier calibration



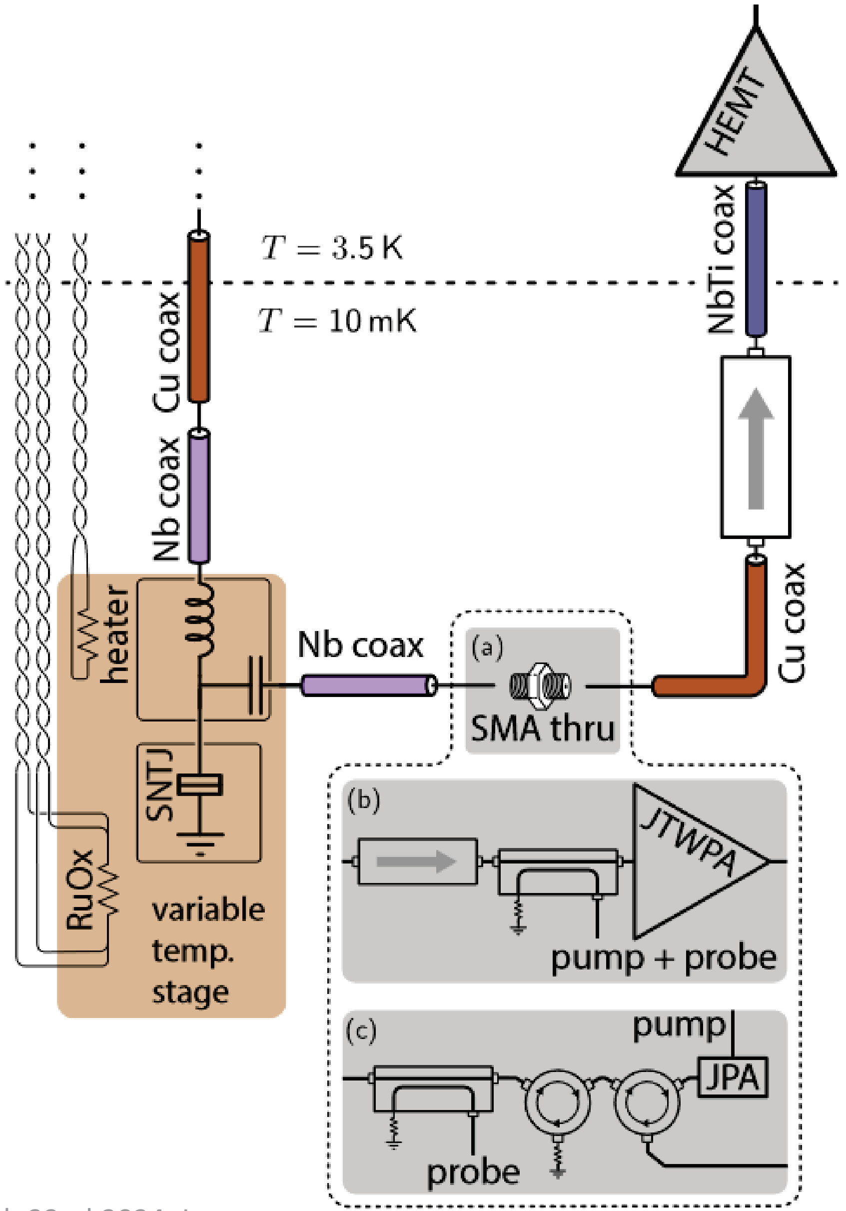

*J. Aumentado, **IEEE MW magazine** 21 (2020)*

Ultralow noise parametric amplifiers are a cornerstone of quantum computers

Field is plagued by calibration error
(no one can ever have a “quantum limited” amplifier)

Nascent industry

# Quantum amplifier calibration



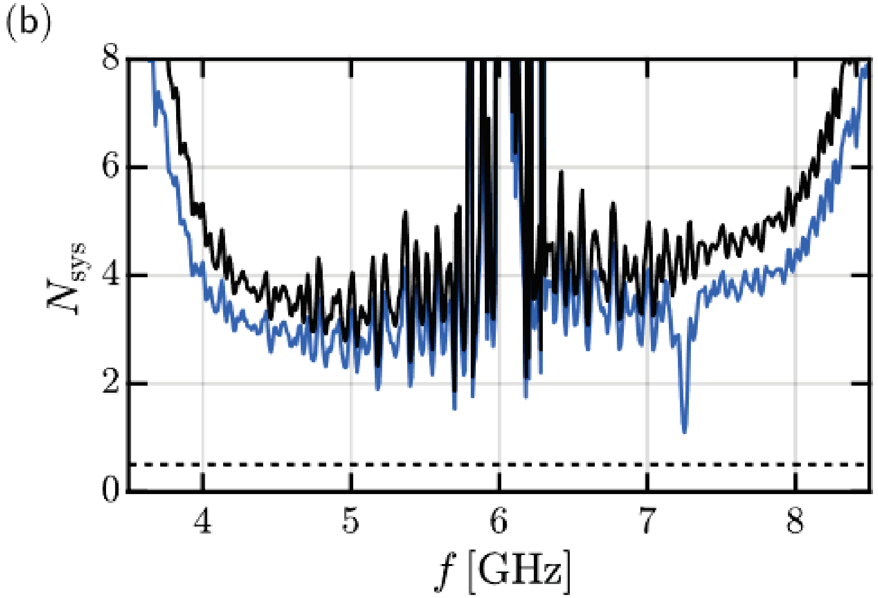

NMIs can define the best practices and metrics

Review of Scientific Instruments ARTICLE

## Low-noise cryogenic microwave amplifier characterization with a calibrated noise source

Published Online: 7 March 2024

M. Malnou,[1,2,a)] T. F. Q. Larson,[1,2] J. D. Teufel,[1] F. Lecocq,[1] and J. Aumentado[1]



# Metrology for hardware at ultracryogenic temperatures

NIST

Qubit coherence remains a critical metric

How do we report decoherence times?

How do we identify the sources of decoherence?

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Non-exhaustive list

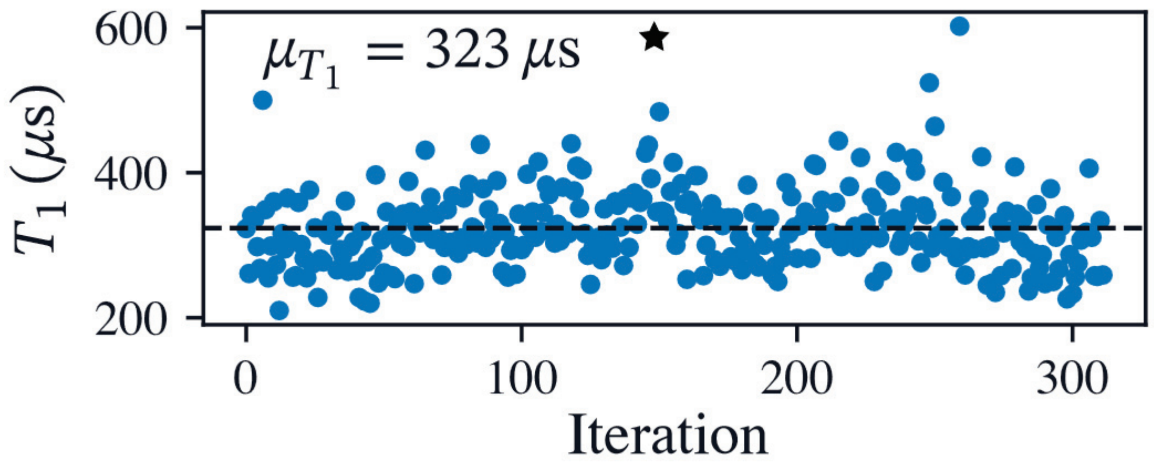
# Measuring and reporting qubit coherence

Coherence fluctuates over time

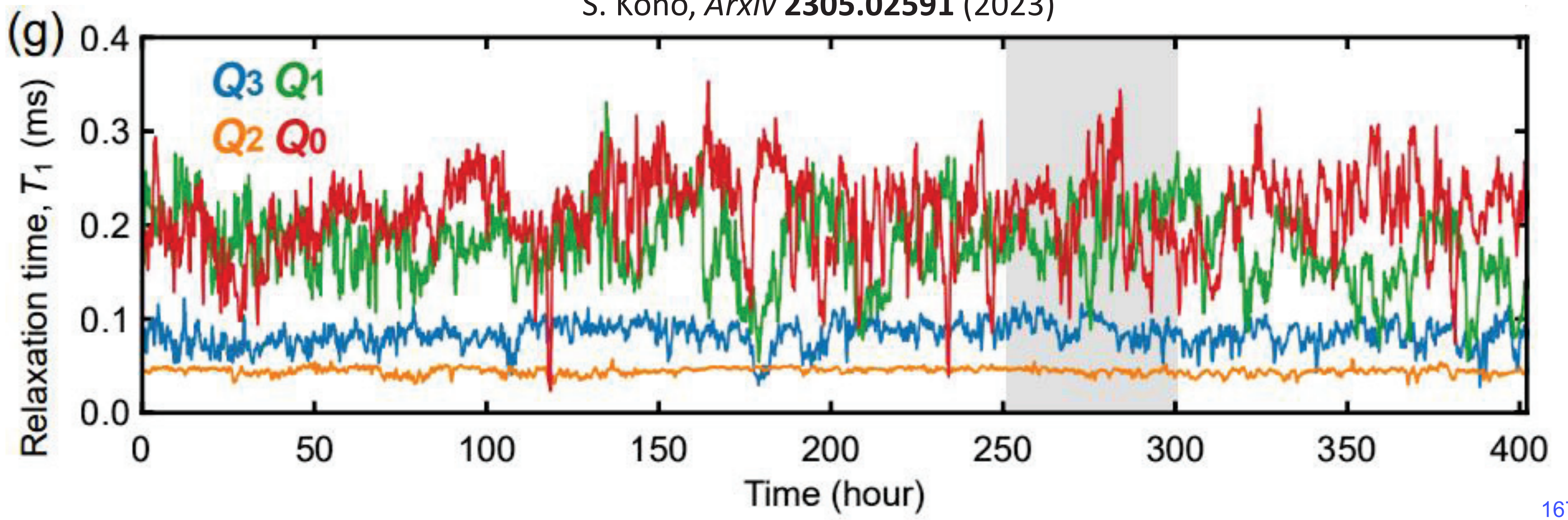
Reporting max/mean T1 is usually not enough

Histogram/Time traces are better

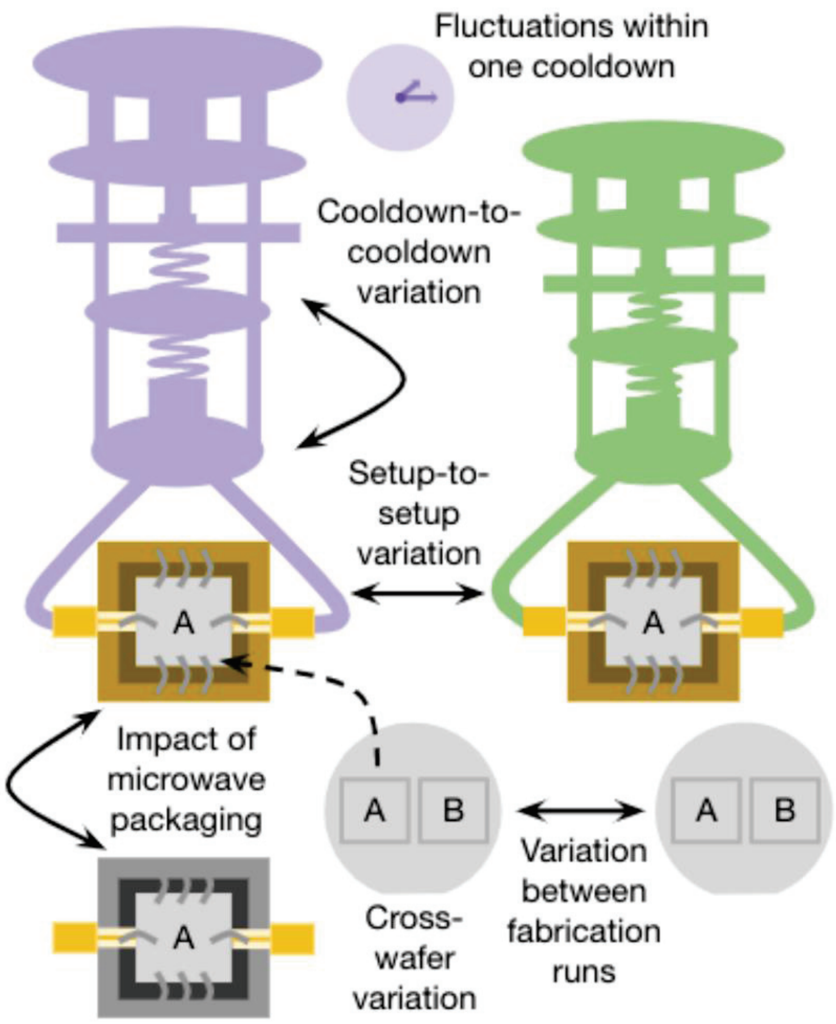
M. Bal, *Arxiv* **2304.13257** (2024)




S. Kono, *Arxiv* **2305.02591** (2023)

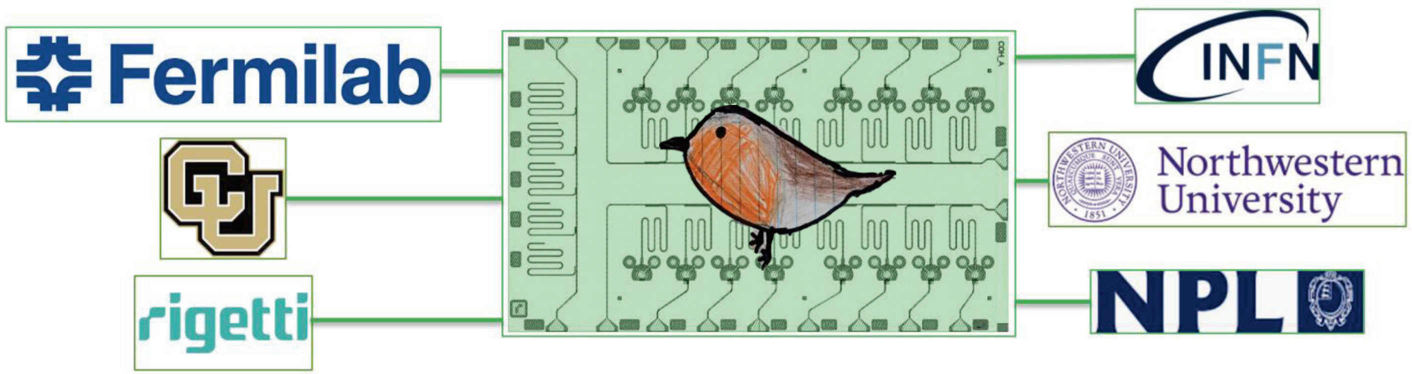


# The SQMS Round Robin




McRae *et al*, Appl. Phys. Lett. **119**, 100501 (2021)

Disentangle some sources of loss by sending an identical device at multiple location within the SQMS center




Goal is to standardize:

- Measurement protocol
- Measurement electronics
- Measurement code
- Data analysis

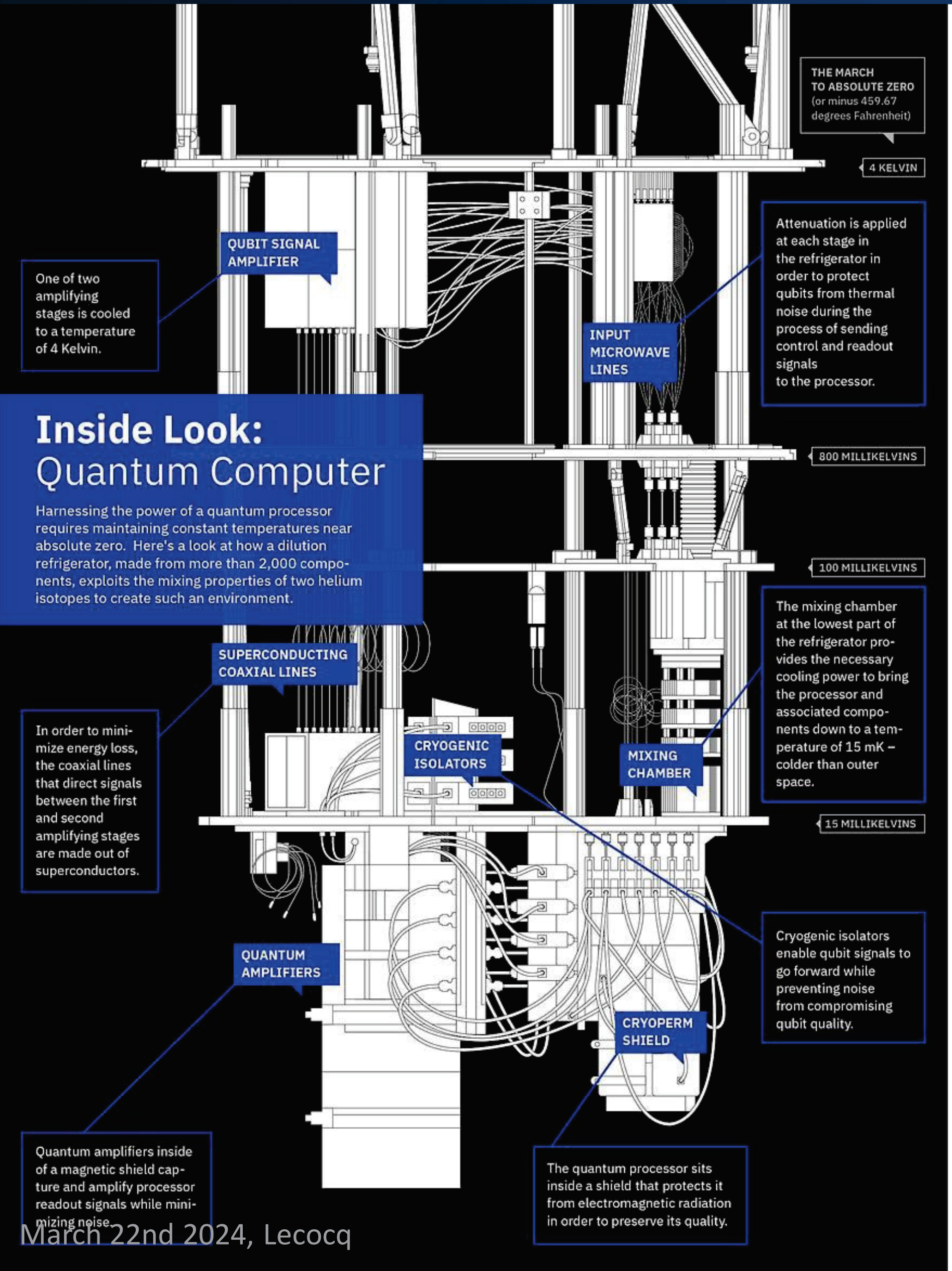
# Conclusion

Quantum computing is not mature enough for standardization yet

But NMIs and other government agencies could/should help:

- define the right metrics
- define good practices
- support nascent quantum industry

# Metrology at ultracryogenic temperatures

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Non-exhaustive list

09:20 – 09:30

# Metrology gaps for quantum - benchmarking

Félicien Schopfer

RÉPUBLIQUE FRANÇAISE
*Liberté*
*Égalité*
*Fraternité*

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

# MetriQs-France

## Measurement, evaluation and standardization of quantum technologies


Félicien Schopfer
LNE


22 March 2024

STRATÉGIE NATIONALE QUANTIQUE

MetriQs France

FRANCE 2030

anr agence nationale de la recherche

BIPM Workshop "Accelerating the Adoption of Quantum Technologies through Measurements and Standards"

Bureau International des Poids et Mesures

# MetriQs-France

National Program for
Measurement, Evaluation, and Standardization
of Quantum Technologies

STRATÉGIE NATIONALE QUANTIQUE

FRANCE 2030 — anr agence nationale de la recherche

MetriQs France

RÉPUBLIQUE FRANÇAISE — LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS — LNE

- *Independent and trusted third party*
- *Expert in quantum*
- *Expert in metrology, testing, standardization, certification…*

Develop, exploit, and promote **measurement capabilities of reference** - *validated, harmonized, widely recognized* -

→ Characterization and performance assessment of quantum technologies

→ Reliability, impartiality and comparability

⇒ Metrology, Test & Evaluation, International Standardization…

⇒ **Innovation + Establishment of the quantum industry**

⇒ ***Trust*** *in QT*
⇒ ***Adoption*** *of QT*

## ➢ Collaborative R&D Projects

- **R&D on metrology gaps** [QC Benchmarks, Characterization of quantum components and enabling technologies…]
- **Standardization** [AFNOR, CEN-CENELEC, ISO/IEC, IEEE…]
- **Collaborations** EU and International
- …

- Research Organizations
- Large industry
- Startups
- AFNOR
- LNE
- …

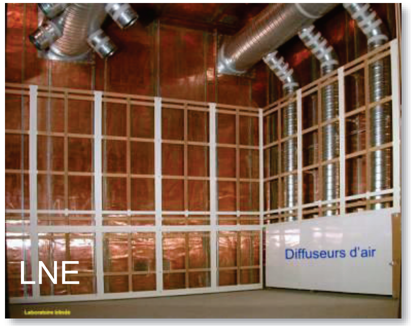
## ➢ Measurement & Testing Infrastructure

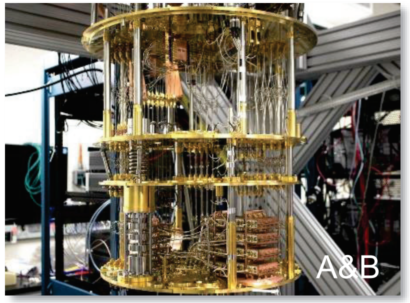
- **Quantum metrology platform** at LNE/French Metrology Network
- Network of **trusted platforms for characterization and testing**

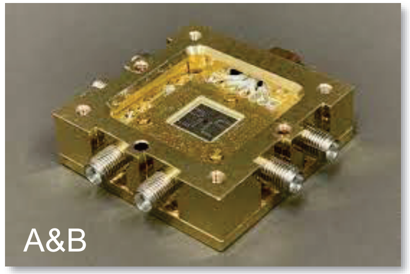
# Measurement & testing infrastructure

Infrastructure of reference, expert, independent, and open
**Metrology R&D et Services for Quantum Technologies**

- *State-of-the-art equipment (Investment program)*
- *Controlled experimental conditions*
- *Expert & skilled metrology staff*




**LNE** / French metrology network
**Quantum metrology platform**

**LNE – Trappes**
Characterization of solid-state qubits and enabling technologies (electronics and cryogenics)

**LNE-SYRTE-OP - Trappes**
Quantum gravimetry

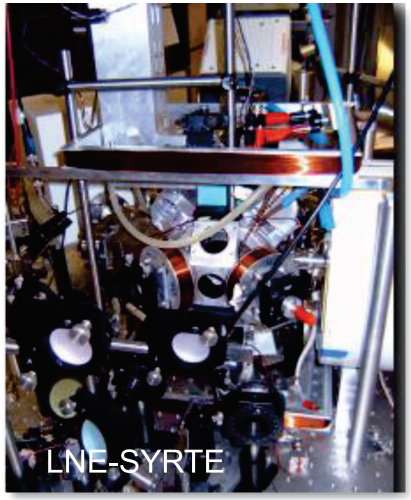
**LNE-CNAM - Saint-Denis**
Thermometry and optomechanical sensors at very low temperature

**LNE-SYRTE-OP - Paris**
Atomic clocks

Network of trusted characterization platform for quantum technologies

**Platform #1**

**Platform #X**


+ Additional services to be deployed resulting from **R&D projects**

# BACQ Project: Application-oriented benchmarks for quantum computers

BACQ
MetriQs-France

⇒ Developing a **measuring instrument** for the **quantum computing practical performance**.

*Unbiased, "universal", long-lasting, widely-used and recognized, to serve as common reference.*

## Purposes

- ⇒ **Comparing classical *vs.* quantum** [Analog, gate-based, NISQ to FTQC]
- ⇒ Measuring the **progress towards a practical quantum advantage**
- ⇒ Supporting **the development of useful QC** technologies

## Scientific approach to the challenge

- **A set of benchmarks** based on the resolution of reference problems:
  *Optimization; Linear systems solving;*
  *Quantum physics simulation; Factorization*
- **Aggregation of technical metrics** (computational – *pb size, time, fidelity, accuracy*…- and energetic) and **multicriteria notation** related to a quality of service

## Key figures

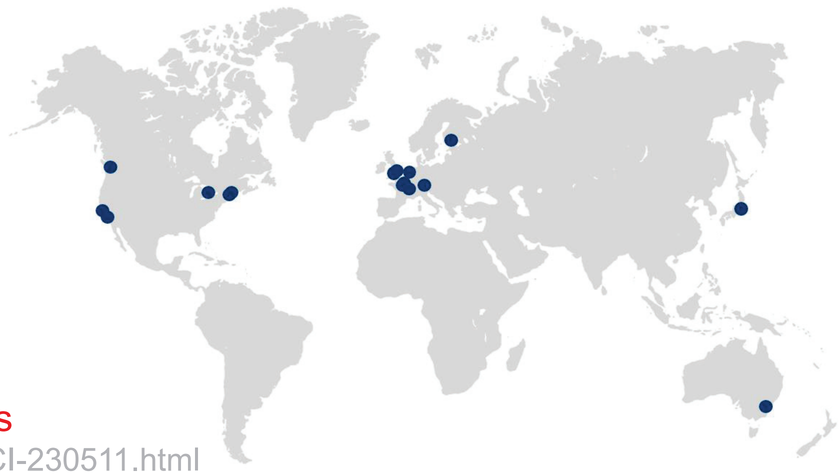
- ✓ **3 years**: Sept. 2023 – Aug. 2026
  + FastTrack action Q-score/MaxCut
- ✓ **6 partners** → **7.2 FTE / year**
- ✓ **3.9 M€ budget**

https://arxiv.org/abs/2403.12205

## ➢ Dialogue and collaborations

### ➢ With QPU providers

- Quandela, IQM, Quantinuum, Pasqal, Alice&Bob, QuEra, Quantum brilliance, IBM, …(~20)
- Superconducting circuits, spins, photons, neutral atoms, trapped ions, NV...



### ➢ With benchmarking initiatives

- R&D teams and projects:
  Fraunhofer IKS (DE), TNO (NL), TUDelft (NL), Qilimanjaro (ES), QuIC (EU), QED-C (US), Hamiltonian Library Project (US), UF/Metriq…

### ➢ With end-users *(more to come)*…

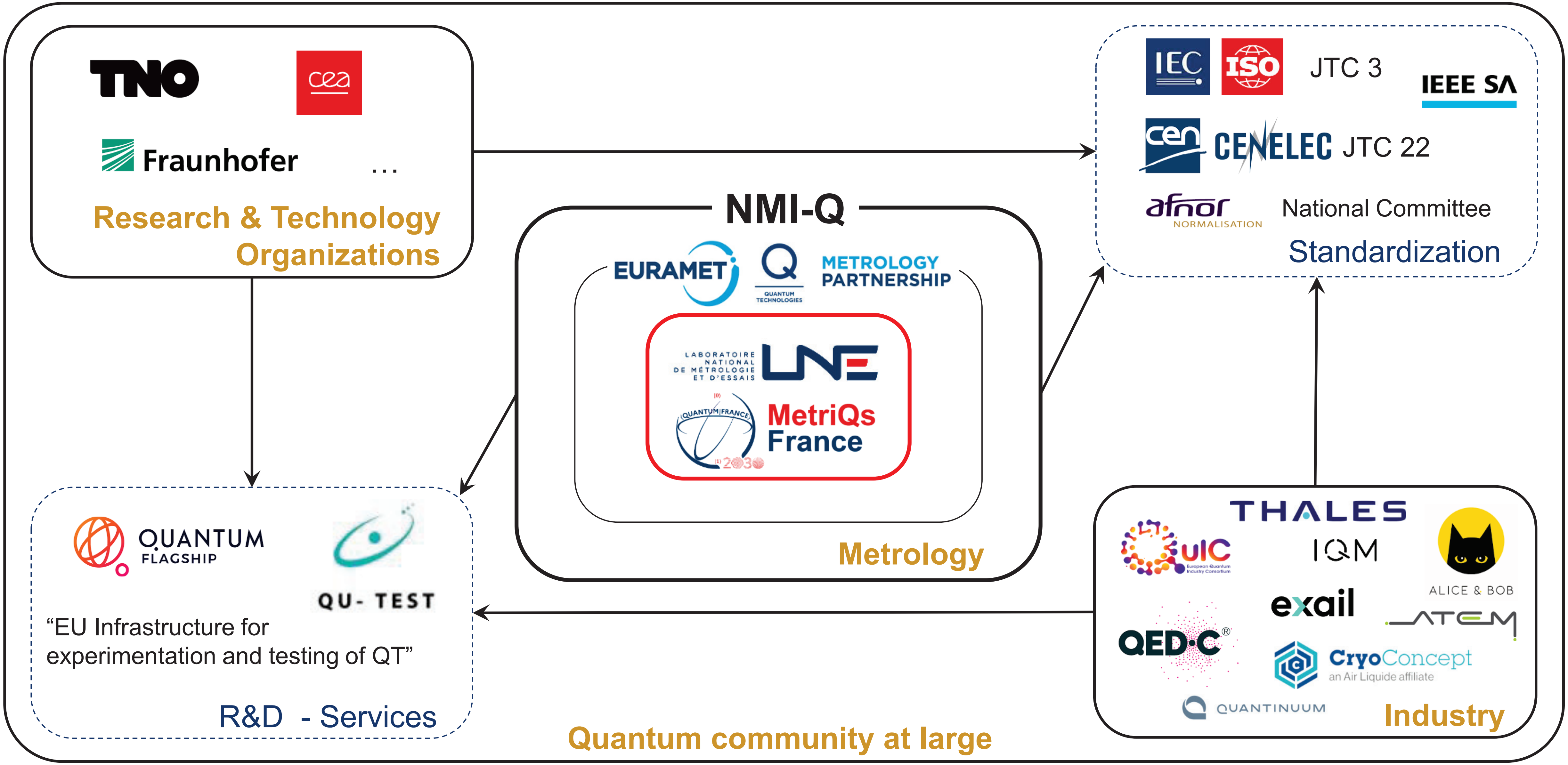
- HPC centres, multiple industries, etc

Annual International Seminar on QC Benchmarks
https://teratec.eu/Seminaires/TQCI/2023/Seminaire_TQCI-230511.html

LNE THALES Building a future we can all trust EVIDEN an atos business cea cnrs Teratec

# EU and international collaborations

*"For widely-shared and recognized measurement capabilities to serve quantum technologies industry"*



# Main takeaway

- Let's **build on the national quantum metrology initiatives**, like **MetriQs-France**, to develop **collaborations** between **NMIs**, **Research Organizations** and **Industry**

To progress towards **internationally harmonized & recognized measurement capabilities**, **benchmarks** and **standards** for quantum technologies.

⇒ To establish **trust in quantum technologies** and accelerate their worldwide **adoption by industry, market and society**.

Characterization of gravimeters, including cold atom quantum devices, at LNE-Trappes (2022)

felicien.schopfer@lne.fr

09:30 – 09:50

# NMI Collaborations in Quantum Photonics Standards Development

Angela Gamouras & John Lehman

# NMI Collaborations in Quantum Photonics Standards Development

John Lehman & Angela Gamouras

NIST National Institute of Standards and Technology U.S. Department of Commerce

NRC·CNRC National Research Council Canada Conseil national de recherches Canada

# Single-Photon Technology

Biotechnology
- Bioluminescence
- Single molecule detection
- DNA sequencing

Metrology
- Quantum standards
- Primary radiometric standards
- Quantum enhanced measurements

Quantum Information Processing
- Cryptography
- Random numbers
- Simulation
- Computing

Photonics
- Optoelectronics
- Optical comms

Physical Science
- Astrophysics
- Nuclear particle detection
- Spectroscopy

Medical Physics
- Imaging
- Radioactive monitoring
- Clinical tomography

Meteorology
- Remote sensing
- Environmental monitoring
- Lidar

Sensing
- Surveillance
- Low-light

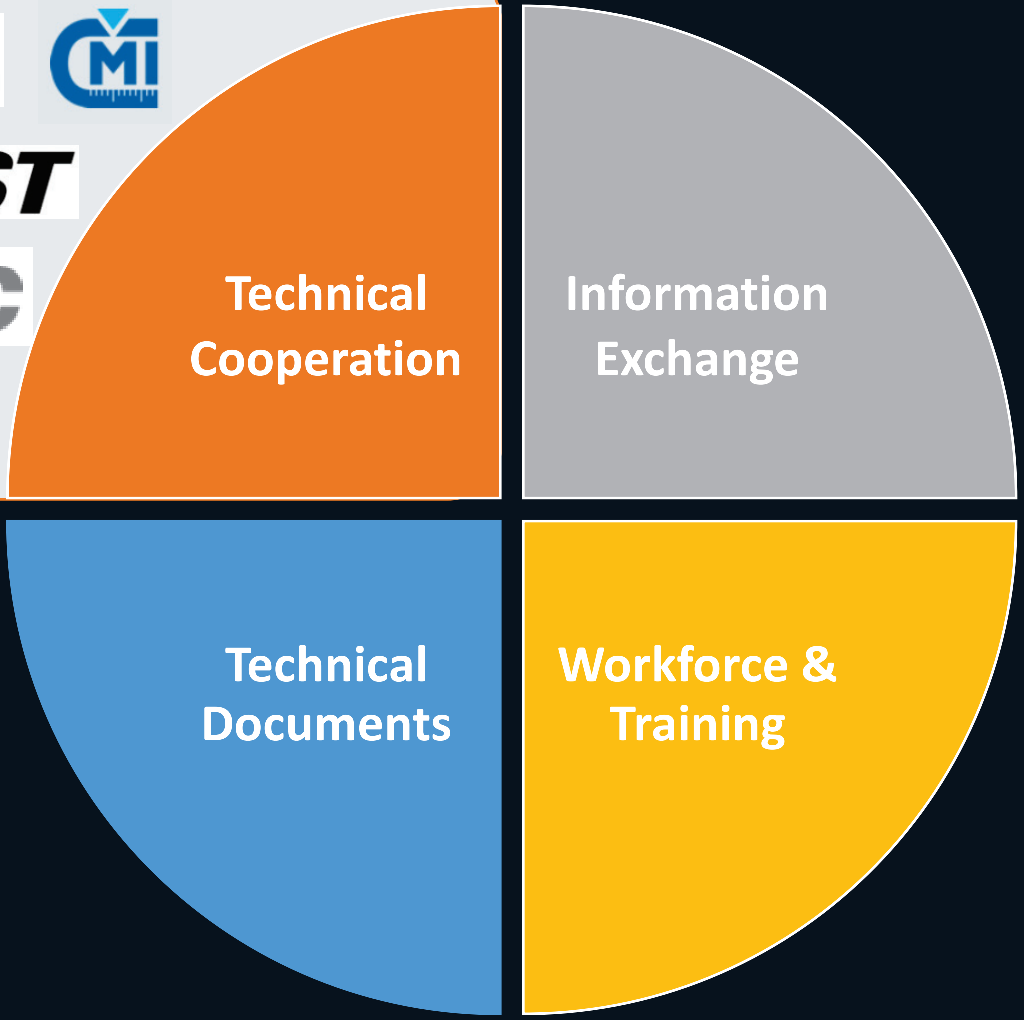
Chunnilall, et al., Optical Engineering 53(8), 081910 (August 2014)

# Outline and Framework

< NIST | NRC >

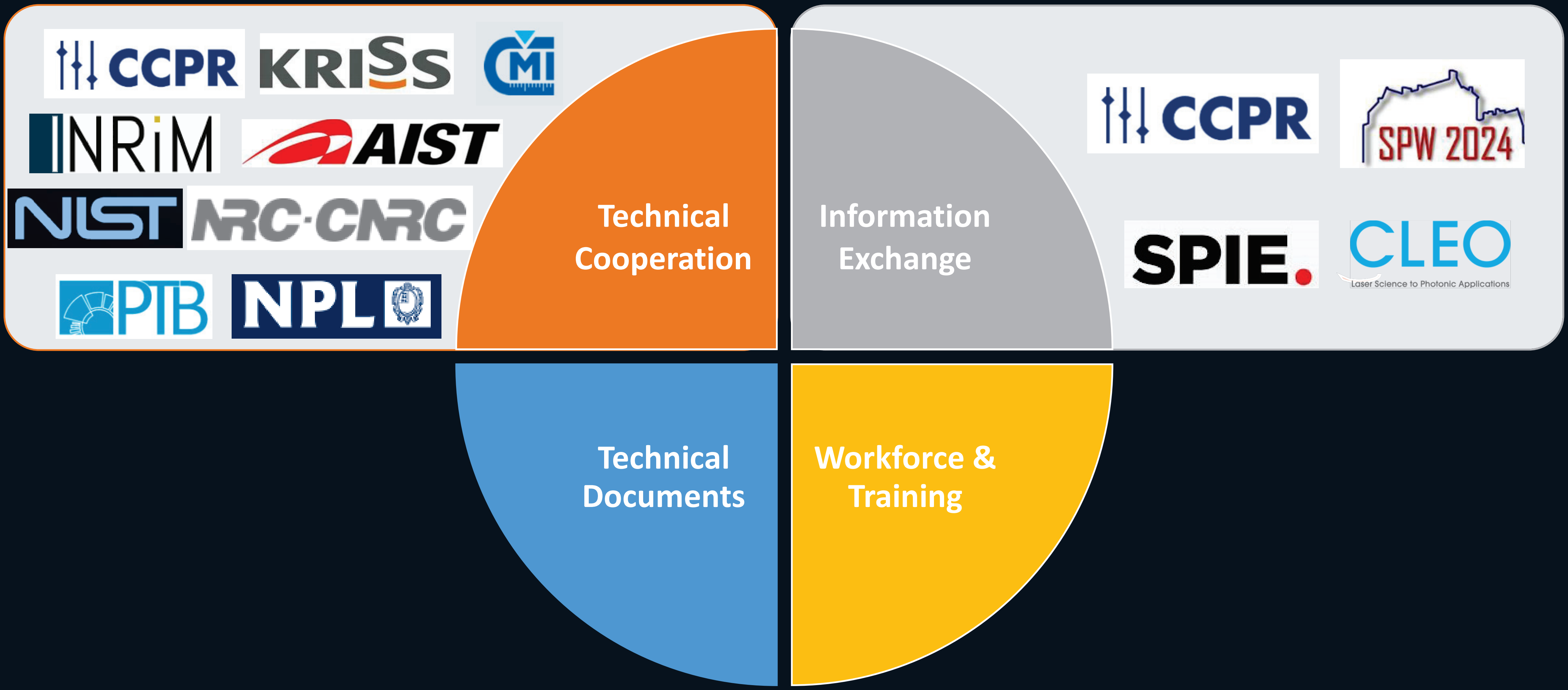
# Outline and Framework





# Outline and Framework

< NIST | NRC >



# Outline and Framework

< NIST | NRC >

CCPR KRISS CMI INRiM AIST NIST NRC·CNRC PTB NPL

**Technical Cooperation**

**Information Exchange**

CCPR SPW 2024 SPIE. CLEO Laser Science to Photonic Applications

**Technical Documents**

**Workforce & Training**

⟨Q|School CLEO Laser Science to Photonic Applications SPIE.

# Outline and Framework

< NIST | NRC >

**Technical Cooperation**

CCPR, KRISS, CMI, INRiM, AIST, NIST, NRC-CNRC, PTB, NPL

**Information Exchange**

CCPR, SPW 2024, SPIE., CLEO Laser Science to Photonic Applications

**Technical Documents**

CCPR, ISO JTC 1 IEC INFORMATION TECHNOLOGY STANDARDS, ETSI, Single-Photon Sources and Detectors Dictionary, cie, IEC/ISO JTC 3 Quantum technologies

**Workforce & Training**

⟨Q|School, CLEO Laser Science to Photonic Applications, SPIE.

# Timeline 2003 - 2018

< NIST | NRC >

2003 Single Photon Workshop (Alan Migdall et al.)

2006 The "last" Symposium on Optical Fiber Measurements (SOFM)

2015 CCPR TG-7 questionnaire & pilot study single-photon detector (SPD) detection efficiency

2016 CCPR TG-7 pilot study, 11 participants, free space SPD (ongoing)

2016 NIST/PTB synchrotron based single photon detector calibration

2017 NIST/PTB Verification of calibration methods

2017 NIST special test SPD calibration

2018 NRC/NIST free space SPD comparison began

# Timeline 2019 - 2021

< NIST | NRC >

2017 BIPM Workshop "The Quantum Revolution in Metrology"  28-29 September 2017

2018 NPL/NRC/NIST Quantum Standards Meeting NIST Gaithersburg

2019 NPL/NRC/NIST Quantum SI Workshop NIST Boulder

2019 NIST/PTB MOU for faint light radiometry/radiometers (Beyer/Lehman)

2019 3rd Germany-USA-DE Joint Meeting, Federal Ministry of Education and Research, Berlin

2021 QED-C Workshop Single-photon measurement infrastructure: Needs and priorities

2021 National Quantum Initiative Funding to NIST

2021 New Developments and Applications in Optical Radiometry (NEWRAD)

# Timeline 2022 - 2024

< NIST | NRC >

2022 NIST/NRC/CU Quantum dot source & faint light radiometry

2022 NIST/NRC Calibration and comparison of detection efficiency

2023 NIST Detector Calibration for Customers ISO17025

2023 NIST/NPL single photon detector comparison (APD)

2023 NIST Single Photon Dictionary

2023 NEWRAD Teddington

2023 Single Photon Short Course (INRIM, NIST, NRC, NPL)

2024 Single Photonics Short Course

2024 Single Photon Workshop

# Directions: NMI Collaboration

< NIST | NRC >

## Quantum SI workshop for single-photon metrology

NIST, Boulder, Colorado

February 28, March 1, 2019

**Purpose:**

The purpose of the workshop is to bring together subject matter experts in single photon science and engineering from the national metrology institutes, NPL, NRC, and NIST, to engage in development, metrology, standardization, and dissemination of scales.

# Directions: International Engagement

< NIST | NRC >

**3rd Germany – United States Science and Technology Joint Meeting Commission**

**November 5 & 6, 2019, Federal Ministry of Education and Research (BMBF), Berlin**

Workshop on Quantum Information Sciences

Highlighted the longstanding cooperation with PTB

---

Additional State Dept meetings were planned before Covid

# Directions: Workforce Development

< NIST | NRC >

## CUbit Quantum Initiative

About | Structure of CUbit | Industry Partners | Education & Workforce Training | People | News | Events

### ⟨Q|School Single Photonics Short Course: Sources, Detectors and Measurements

**August 6–9, 2024**
University of Colorado Boulder

Getting to Class | Teachers & Speakers | REGISTRATION OPENING SOON! | Course Program | Sponsorship Levels

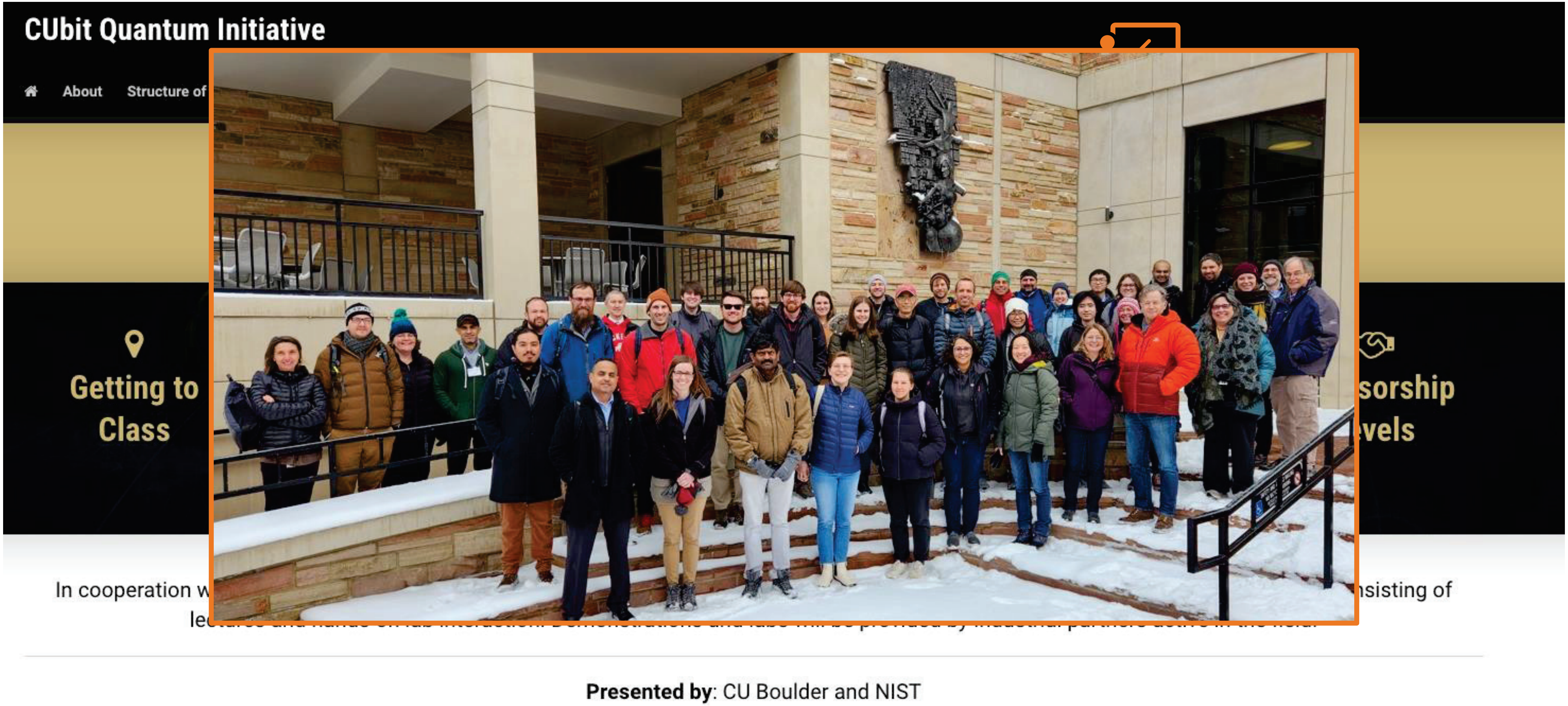
In cooperation with researchers and metrologists from around the world, the University of Colorado Boulder will present a short course consisting of lectures and hands-on lab interaction. Demonstrations and labs will be provided by industrial partners active in the field.

**Presented by**: CU Boulder and NIST

https://www.colorado.edu/initiative/cubit/single-photonics-and-quantum-radiometry-short-course

# Directions: Workforce Development

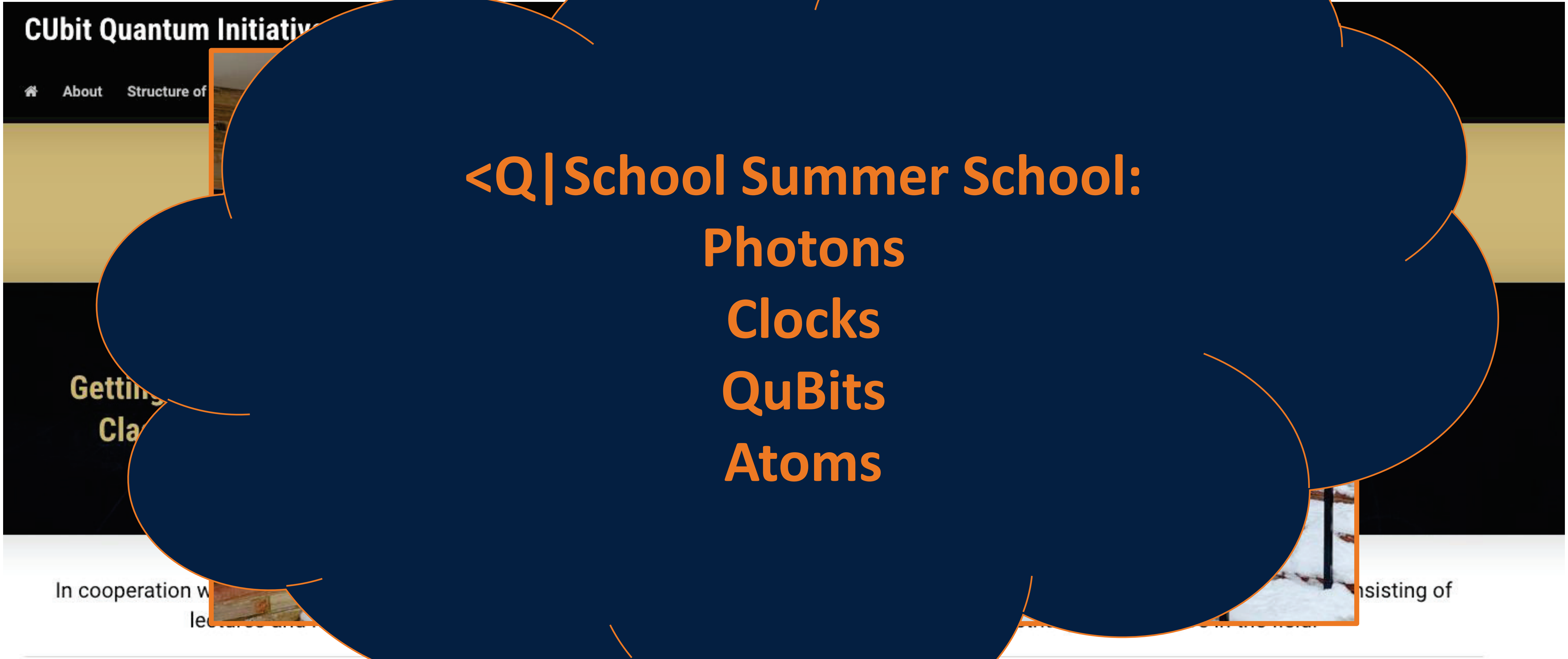
< NIST | NRC >




https://www.colorado.edu/initiative/cubit/single-photonics-and-quantum-radiometry-short-course

# Directions: Workforce Development

< NIST | NRC >




**<Q|School Summer School:**

**Photons**

**Clocks**

**QuBits**

**Atoms**

https://www.colorado.edu/initiative/cubit/single-photonics-and-quantum-radiometry-short-course

# Directions and Opportunities

< NIST | NRC >

SPIE Photonics west 2024 (893 presentations)
SPIE Photonics Europe (300 presentations)


CLEO
Laser Science to Photonic Applications

CLEO PacificRim 2024
August 4-9, 2024
Songdo ConvensiA, Incheon, Korea

NEWRAD 2023

CLEO EUROPE EQEC 2023

# Directions and Opportunities

< NIST | NRC >

## 1986 -2006

“The first transatlantic telephone cable to use optical fiber was TAT-8, which went into operation in 1988”

NIST Special Publication 1055

**Technical Digest: SOFM 2006**

***A NIST Symposium for Photonic and Fiber Measurements***

Sponsored by the National Institute of Standards and Technology
in cooperation with the IEEE Lasers and Electro-Optics Society
and the Optical Society of America

# Directions and Opportunities

< NIST | NRC >

Industry & academic engagement to monitor advances and demands in **quantum photonics**

→ Consortia

→ Collaborative discussion forums

QUANTUM INDUSTRY CANADA

Q-STAR

QuIC European Quantum Industry Consortium

QED-C

CCPR Discussion Forum on Few-Photon Metrology (CCPR-WG-SP-TG7)
→ NMI, industry and academic members

# Terminology Documentation

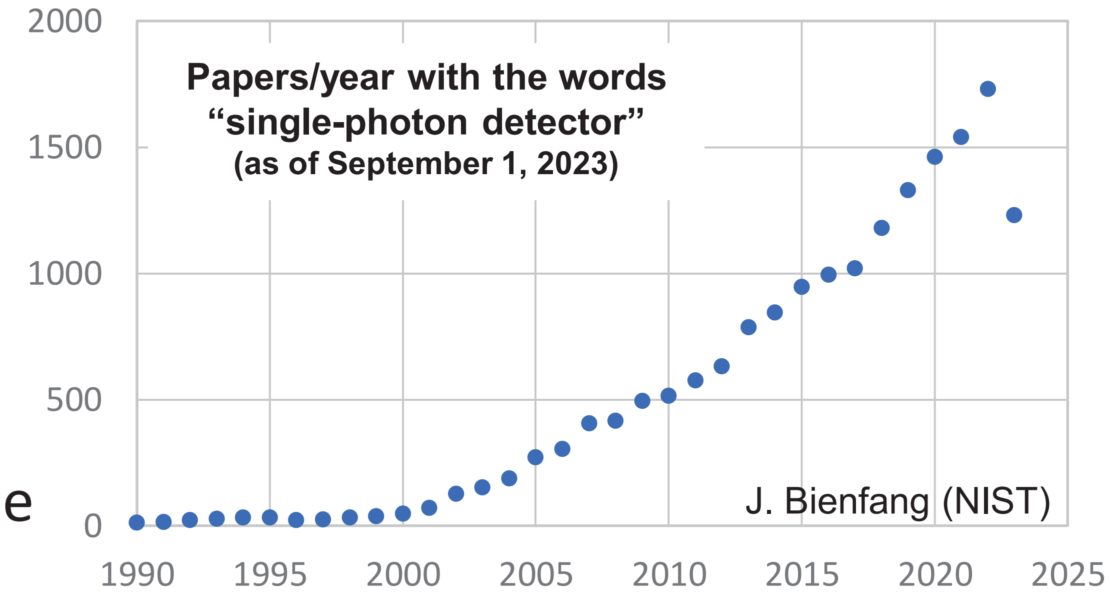
< NIST | NRC >

**Inconsistencies in terminology:**

**Usage**: no well-defined meaning

**Context**: different meanings in different fields

**Clarity**: Incomplete, comparisons difficult or impossible




CIE Reportership DR 2-87 Terminology in single/few photon metrology
12 contributors from 7 NMIs and research institutes

NIST Single-Photon Sources & Detectors Dictionary
https://nvlpubs.nist.gov/nistpubs/ir/2023/NIST.IR.8486.pdf

# Terminology Docu

< NIST | NRC >

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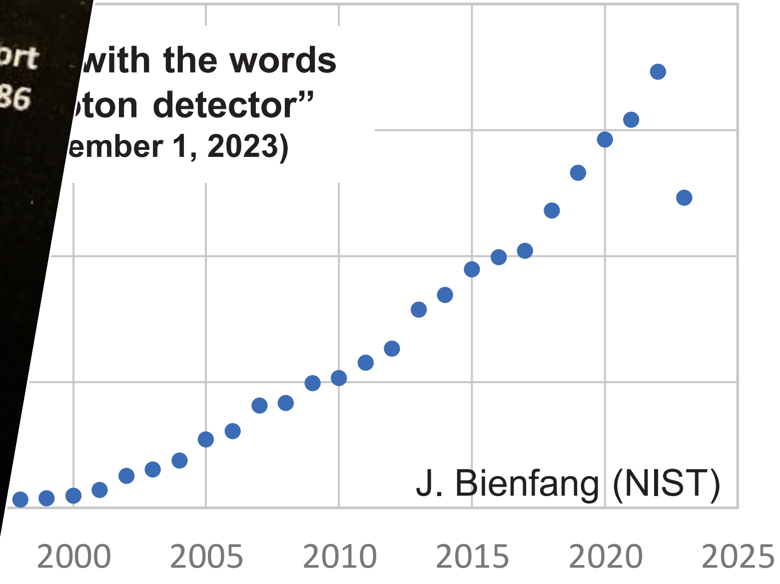


CIE Reporte e/few photon metrology
12 contribut

NIST Singl ionary
https://nvlpubs.nist.gov/ 86.pdf

# Terminology Docu

< NIST | NRC >

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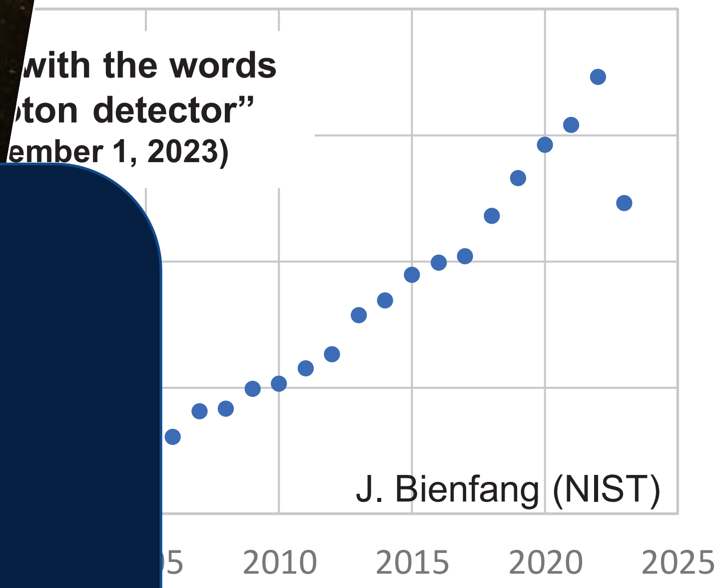



## Resources required!

CCPR

CIE Re ... oton metrology

12 contribut

QED·C

NIST Singl ... ionary

https://nvlpubs.nist.gov/ ... 86.pdf

# Direction: Documentary standards

< NIST | NRC >

**NMIs have contributed to:**

- Revision of ISO/IEC 18031 – Random Bit Generators  [approved]
- ISO/IEC 23837:2023 Security requirements, test and evaluation methods for QKD
- ETSI GS QKD 016:2023-04 Common Criteria Protection Profile – Pair of Prepare and Measure QKD Modules
- ETSI GR QKD 007 V1.1.1 (2018-12) QKD: Vocabulary
- ETSI GR QKD 003 V2.1.1 (2018-03) QKD: Components and Interfaces
- ETSI GS QKD 011 V1.1.1 (2016-05) QKD: Component characterization: characterizing optical components for QKD systems

# Direction: Documentary standards

< NIST | NRC >

Recent standards development activities:

June 2020

ISO JTC 1 IEC — INFORMATION TECHNOLOGY STANDARDS

ISO/IEC JTC 1/WG 14
Quantum Information Technology: standardization program on Quantum Computing

March 2023

cen CENELEC

CEN/CLC/JTC 22 (4 WGs)
Quantum Technologies

→ **Standardization Roadmap on Quantum Technologies**

Support deployment of quantum technologies in European industry

February 2024

IEC/ISO JTC 3 Quantum technologies

Quantum information, metrology, sources, detectors, communications and fundamental technologies

Information exchange: Discussion Forum on Few-Photon Metrology CCPR

# Direction: NMI Cooperation

< NIST | NRC >

Outcome of CCPR-WG-SP-TG7 Discussion Forum on Few-Photon Metrology

→ Single-Photon Radiometry TG (CCPR-WG-SP-TG11) CCPR

→ Pilot study on detection efficiency of single-photon detectors (11 participants)

## What next?

### Documentation

- ❑ Recommended measurement practices
- ❑ Pitfalls to avoid

### Technology

- ❑ Required uncertainties (per application)
- ❑ Develop shorter SI-traceability path

# SI-Traceability: Quantum Photonics

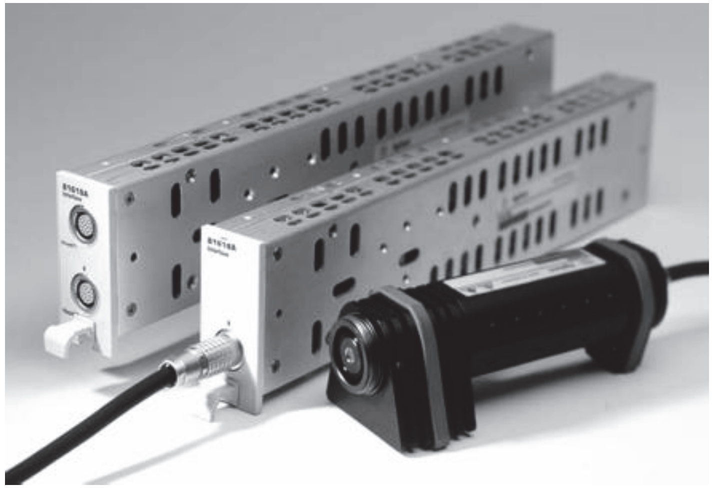
< NIST | NRC >

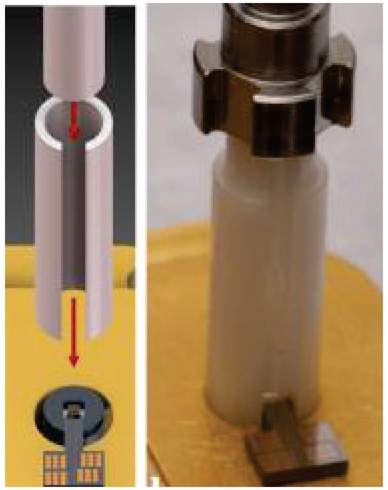
Underpinned by radiometry: optical power (cryogenic radiometer)

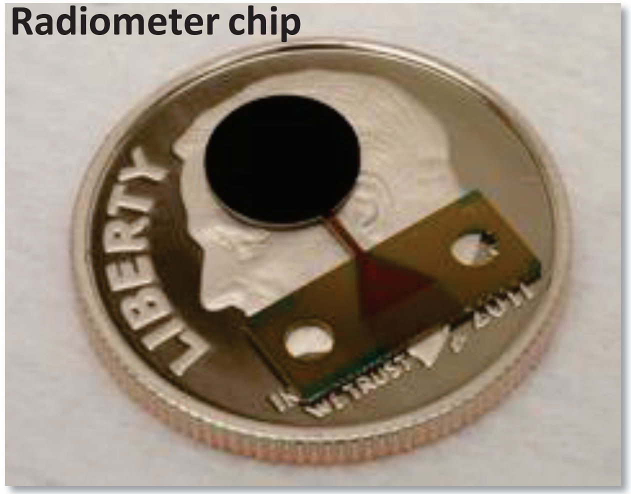
**Example: Technology ⟳ Metrology**

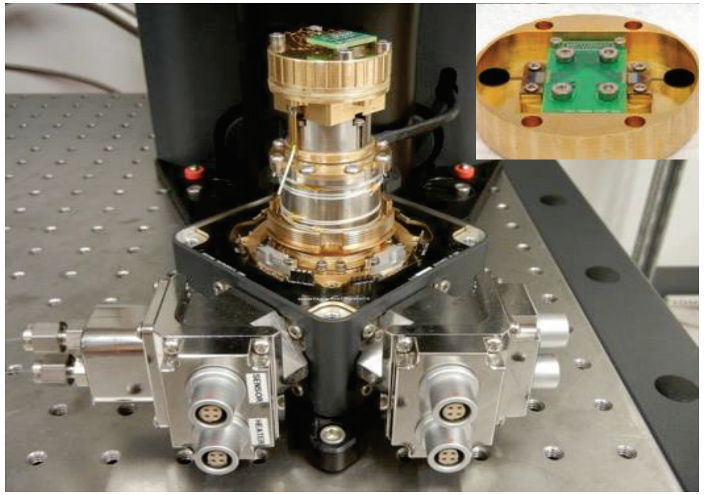
→ Shorter traceability chain for fibre-coupled photodetectors

**Impact:** telecommunications and information technology sectors







NIST

CENAM
CENTRO NACIONAL DE METROLOGÍA

CMI CZECH METROLOGY INSTITUTE

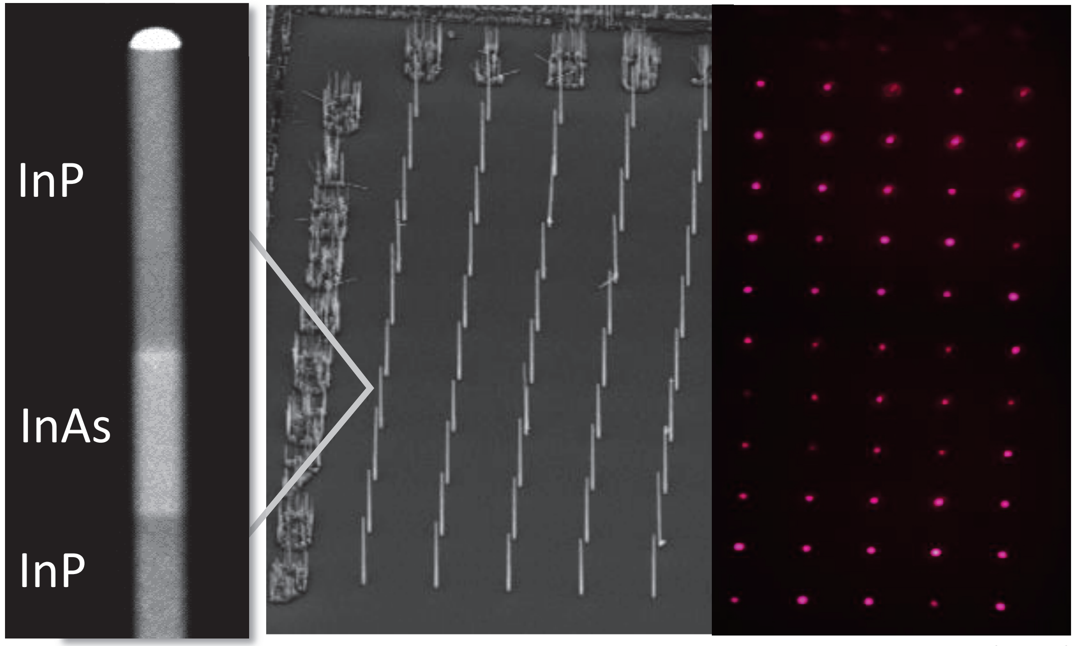
# SI-Traceability: Quantum Photonics

< NIST | NRC >

**What next?** Metrology solutions for future quantum photonics infrastructure

**Quantum photonics ⟲ Metrology**

## NRC quantum dot emitters




Sci. Rep. 12, 6376 (2022)

NRC·CNRC

## NIST faint-light radiometer

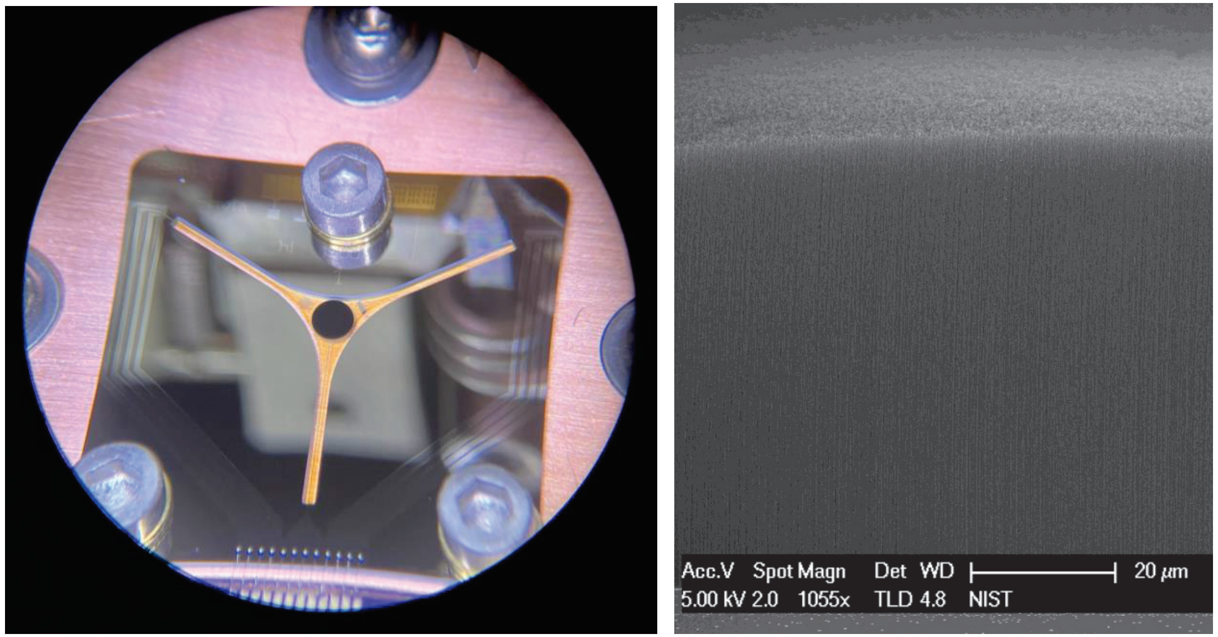
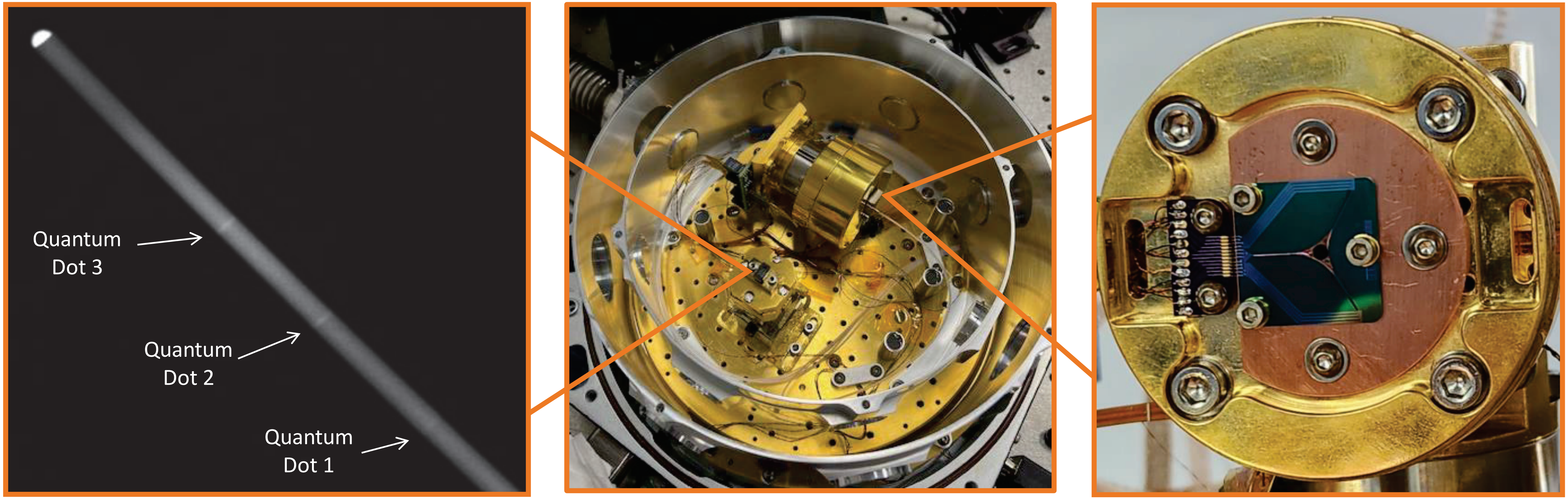



Photo: N. Tomlin

NIST

## **NMI collaboration:** Combining technologies




First measurements of NRC quantum dot emitters with a specialized faint-light sensor

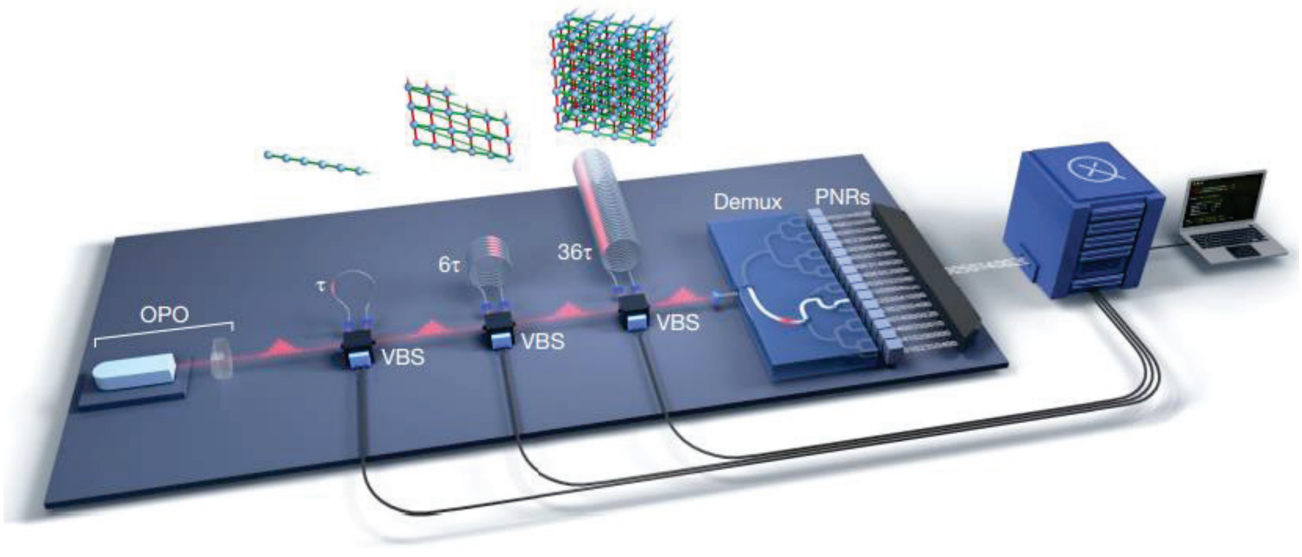
# SI-Traceability: Quantum Photonics

< NIST | NRC >

## What next?

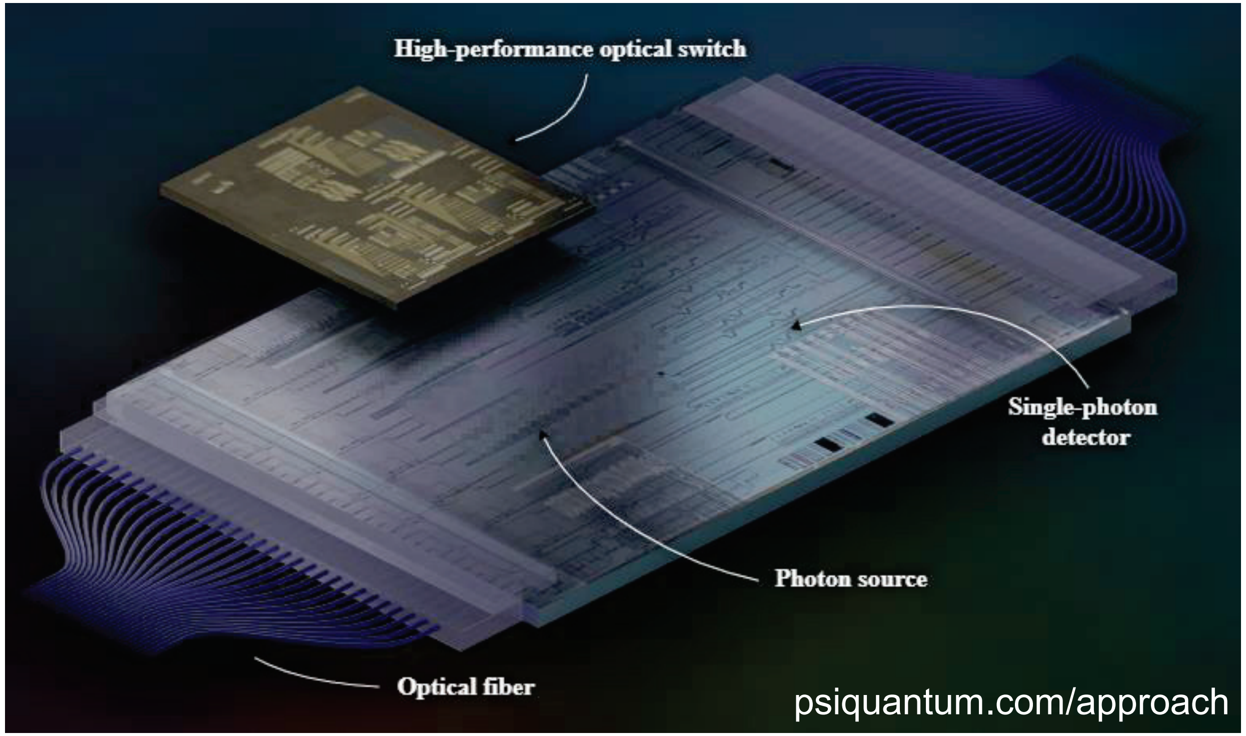
Metrology for photonic quantum computing, communications & networks

→ Mass testing of quantum photonic integrated circuits




Madsen et. al. Nature 606, 75 (2022)

XANADU




psiquantum.com/approach

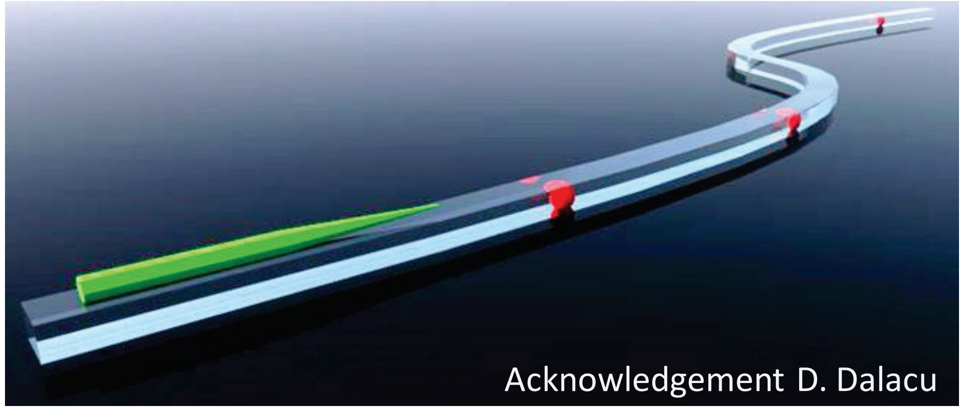
PsiQuantum

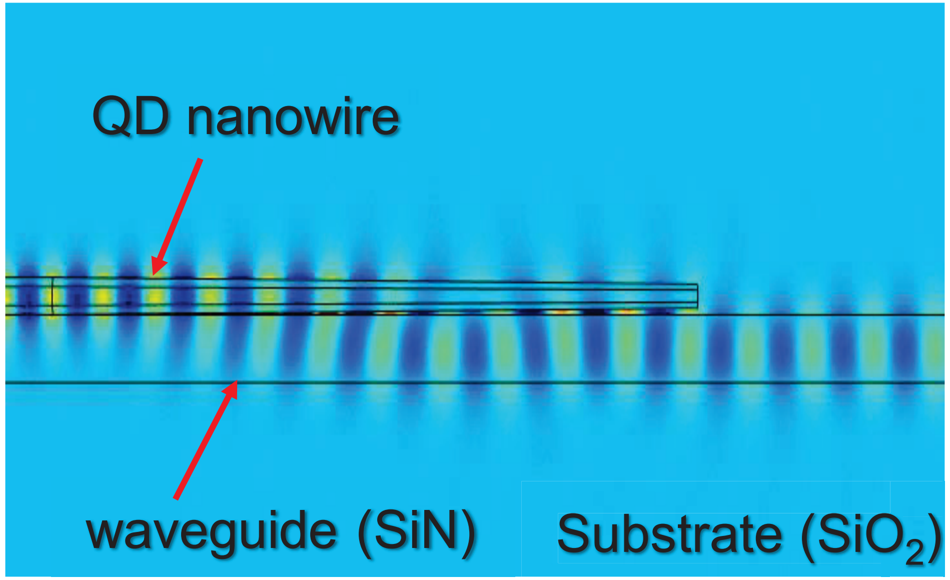
# SI-Traceability: Quantum Photonics

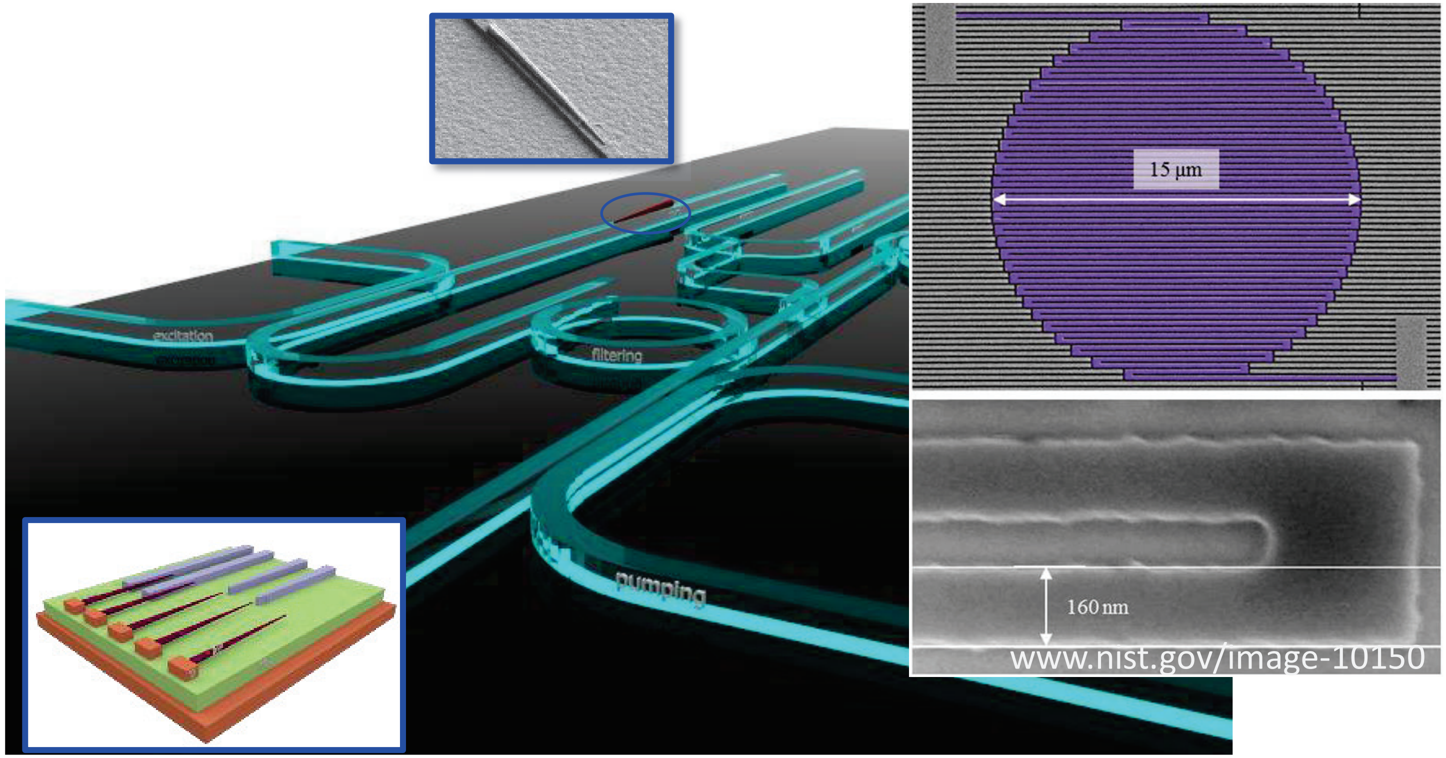
< NIST | NRC >

## NMI collaboration: combining technologies

## On-chip integration



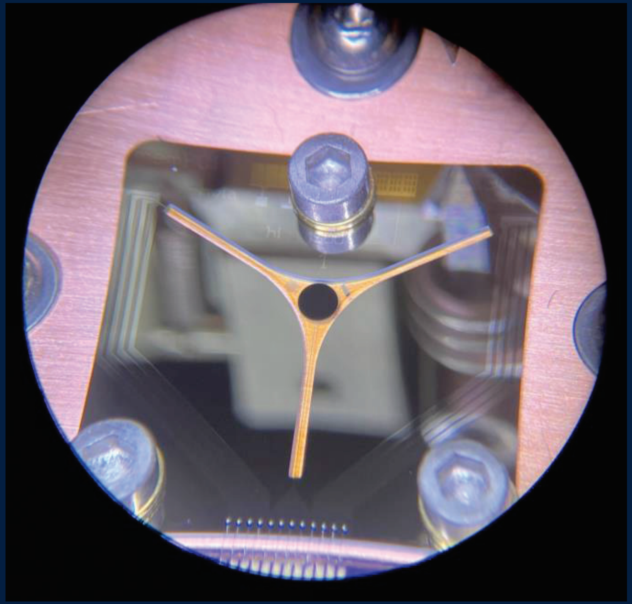



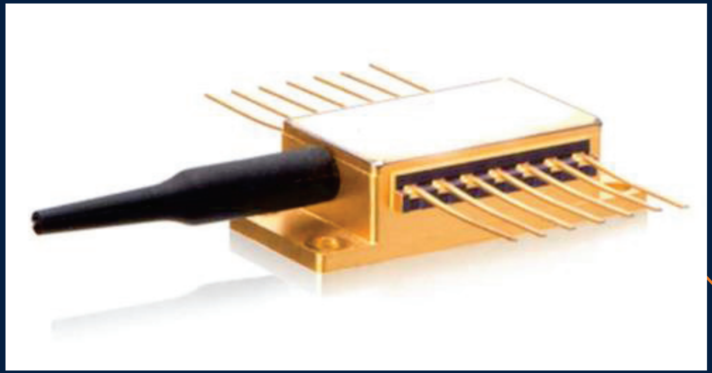

Quantum photonic integrated circuit development
→NRC quantum emitters & NIST single photon detectors

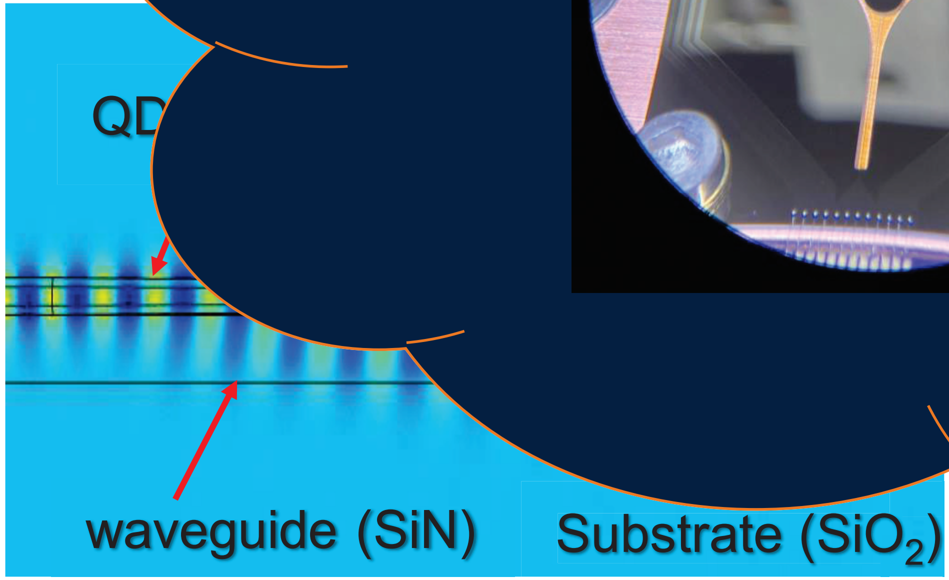
# SI-Traceability: Quantum Ph nics

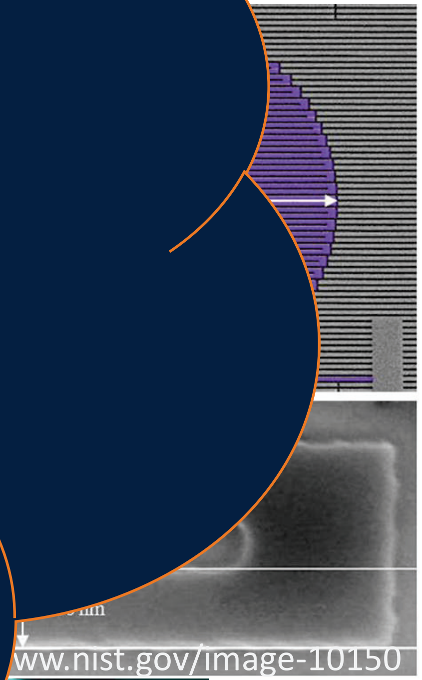
NMI collab ion

## Future SI-traceable QPIC calibrations








egrated circuit development

itters & NIST single photon detectors

# Strength in Collaboration

< NIST | NRC >

**Short Term Goals:**

Common language

- ❑ Terminology – make the single-photon dictionary a standard

Understanding of measurements

- ❑ Publish recommended measurement practice/pitfalls technical notes

**Long Term: Support quantum photonics measurements & future infrastructure**

- ❑ Identifying comparison activities (detectors, sources, etc.)
- ❑ Practical calibrations and SI-Traceability

# Summary



## Progress in quantum photonics standards activities

- ✓ Communication
- ✓ Collaboration
  - → Discussion Forums & Networks
  - → Motivation +
  - → Terminology documentation
  - → Technology Integration

# Questions

10:00 – 10:15

# Survey results

Nicolas Spethmann, Analysis by Pierre Gournay

## Questionnaire: Accelerating the Adoption of Quantum Technologies through Measurements and Standards

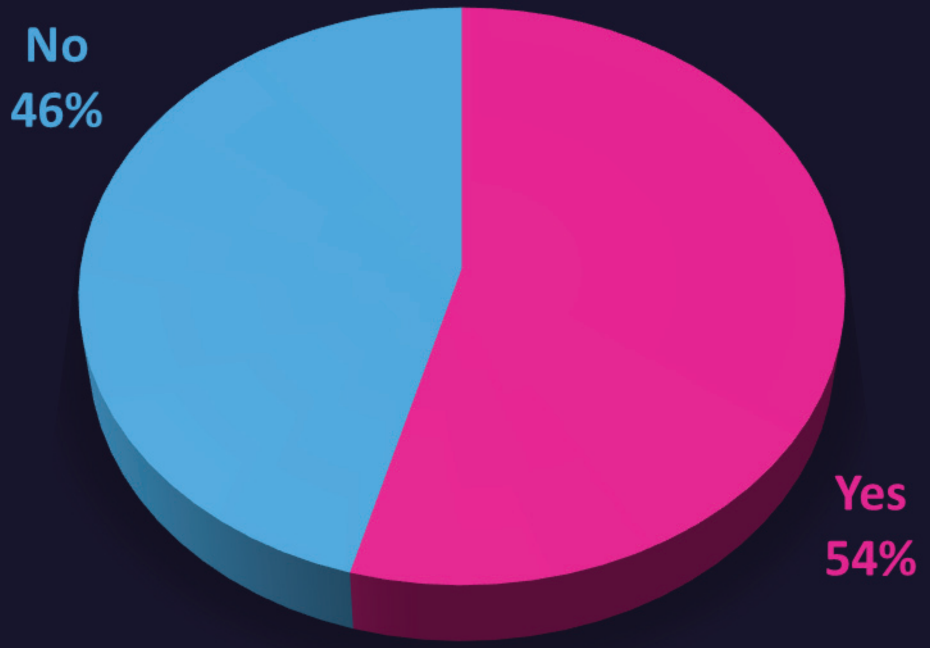
- 38 NMIs/DIs represented at the workshop
- of those, 92 % responded to the questionnaire

Survey goal was to get an overview of:

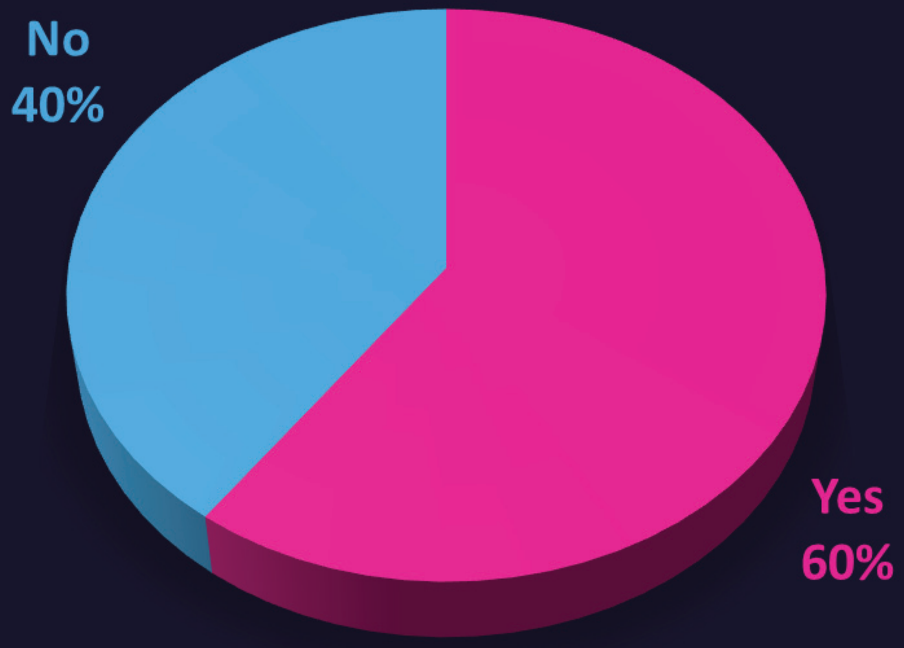
- existing activities of respective economies in quantum,
- topics and fields of quantum that are actively pursued,

to inform the discussion of the workshop.

## In your economy, do you have a domestic quantum strategy ?

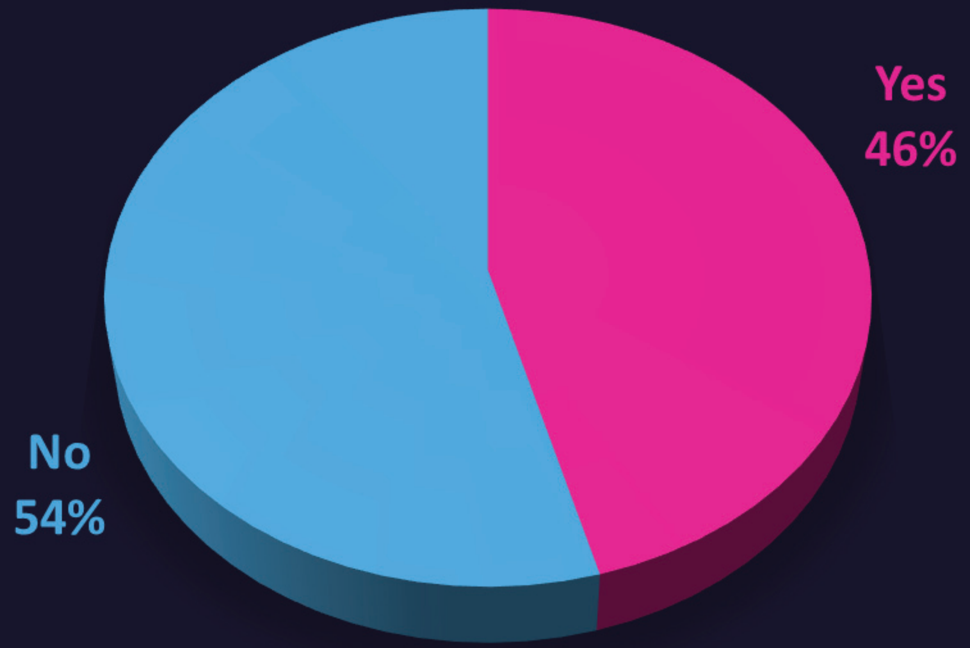



## In your economy, do you have a suite of domestic/regional/local quantum programs?



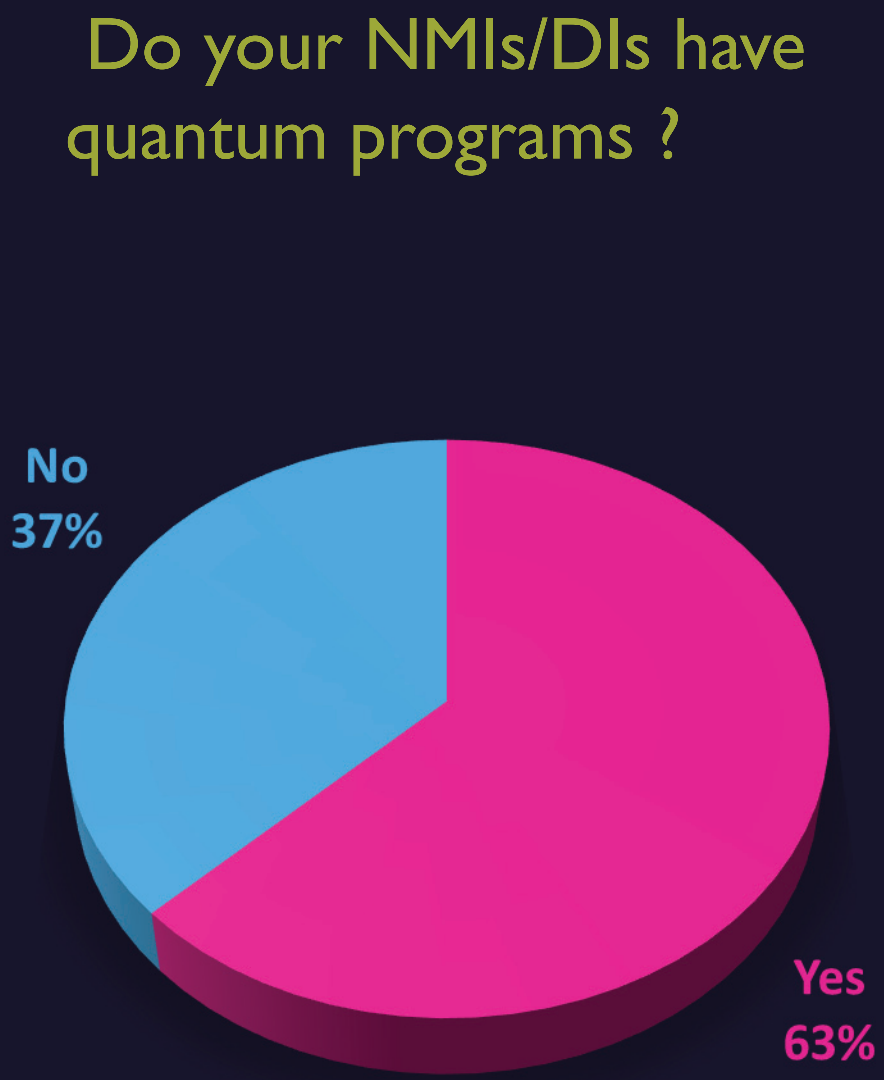

Links to further information at the end of this presentation

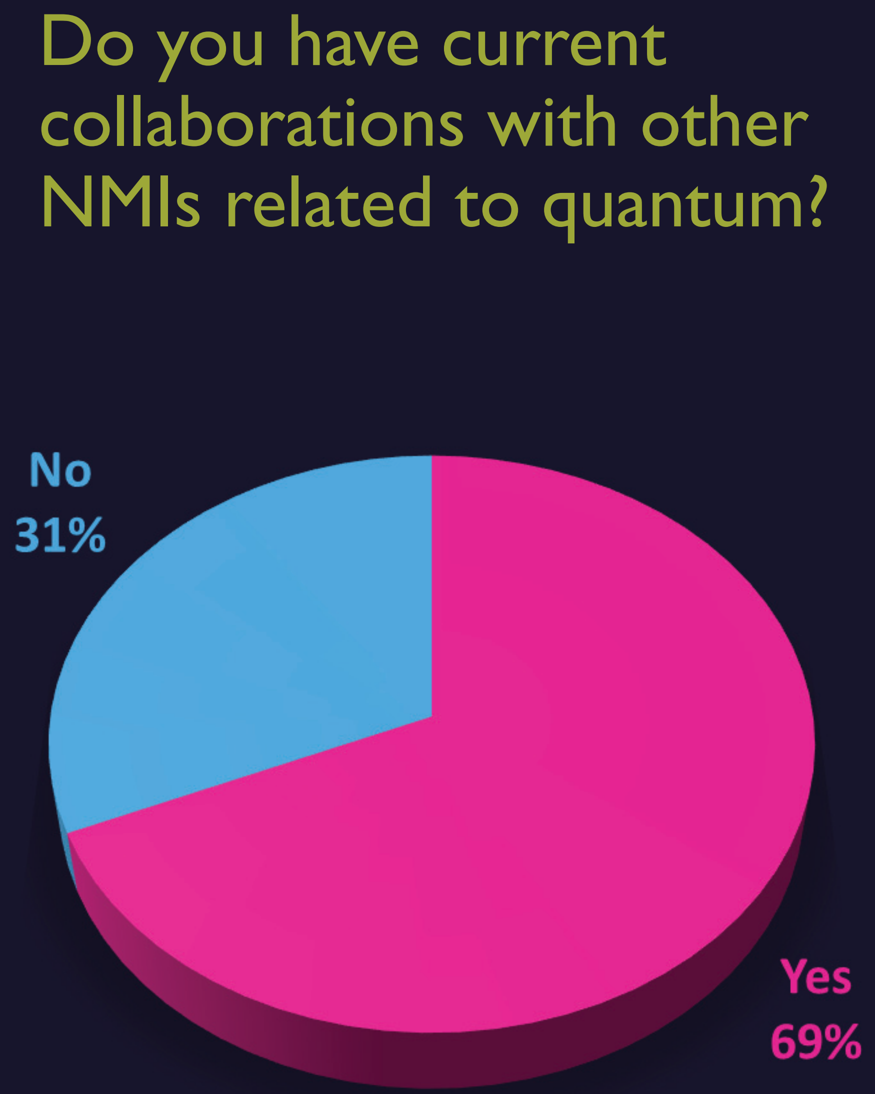
## In your economy, do you have Quantum-relevant roadmaps?




## Do your NMIs/DIs have quantum programs ?

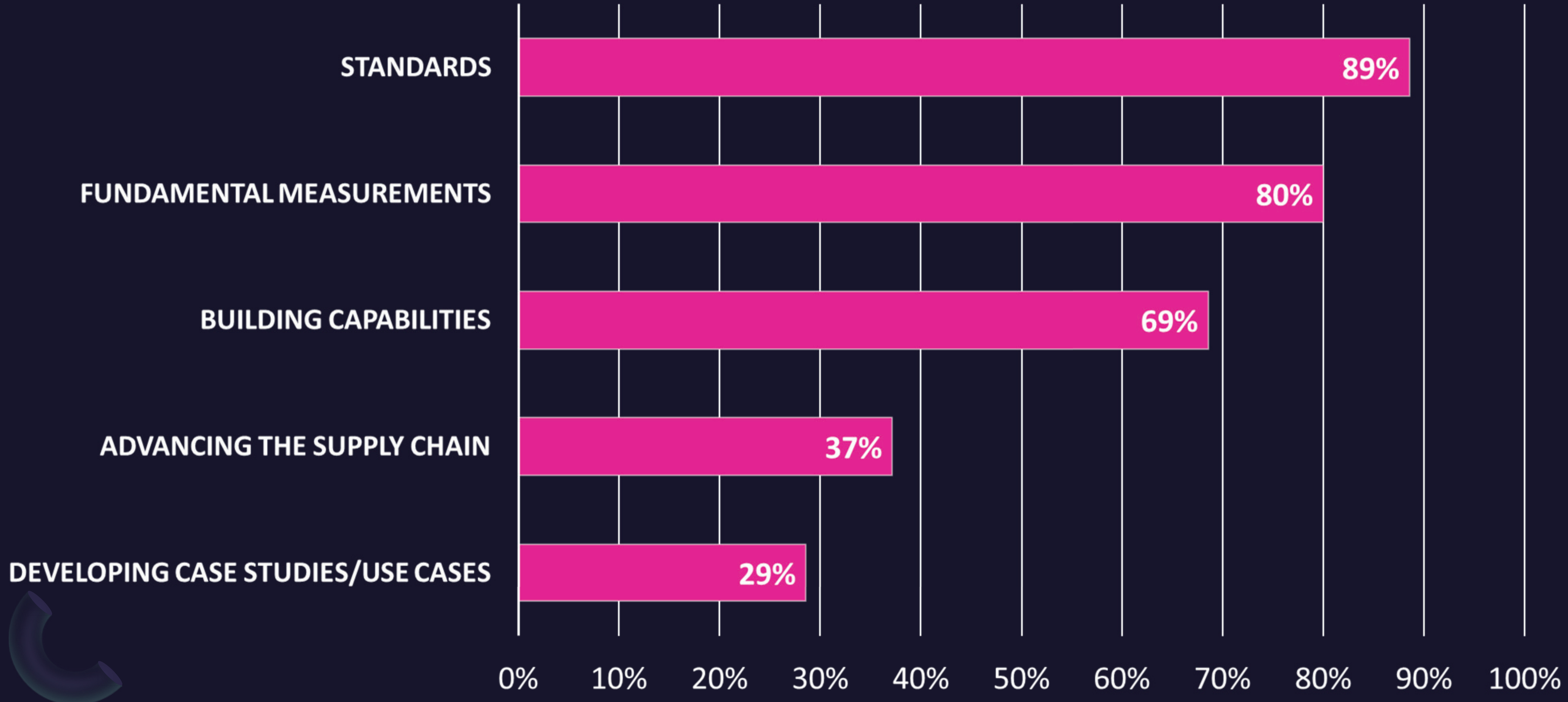

Links to further information at the end of this presentation




Links to further information at the end of this presentation

# What are your highest priorities for your quantum program(s)?



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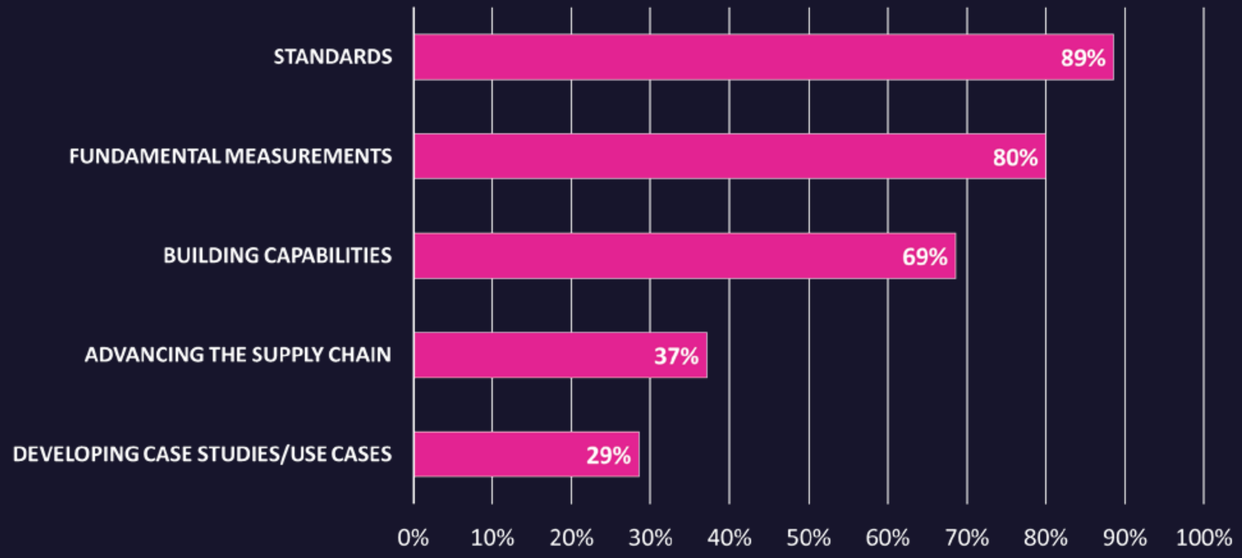


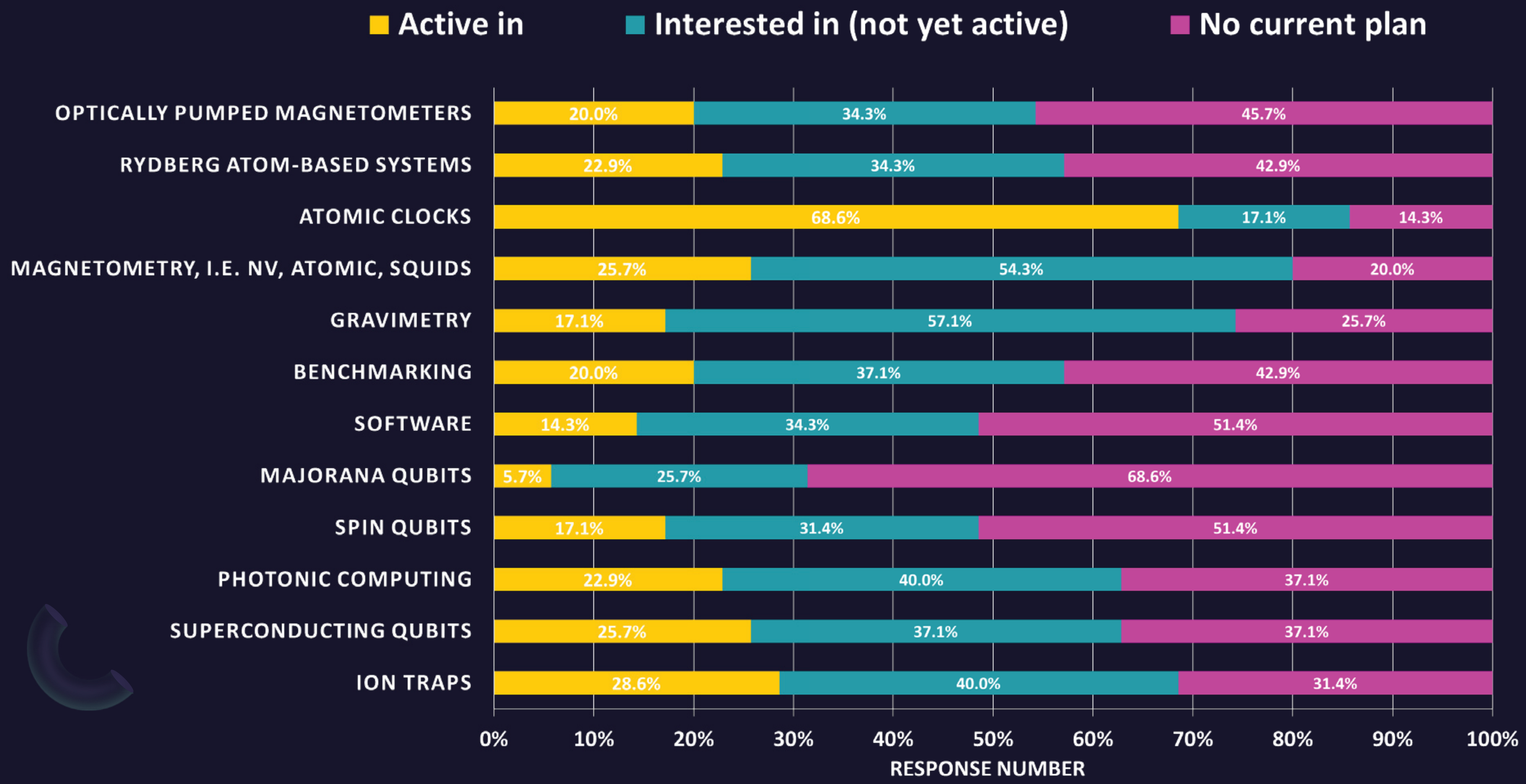

## Other proposed priorities:

- Health
- Environmental sensing
- Critical infrastructure
- Supporting supply chain resilience
- Developing skills and training

# What are your highest priorities for your quantum program(s)?
## *Other proposed priorities*

- Health
- Environmental sensing
- Critical infrastructure
- Supporting supply chain resilience
- Developing skills and training

# Please indicate which application areas you're active or interested in



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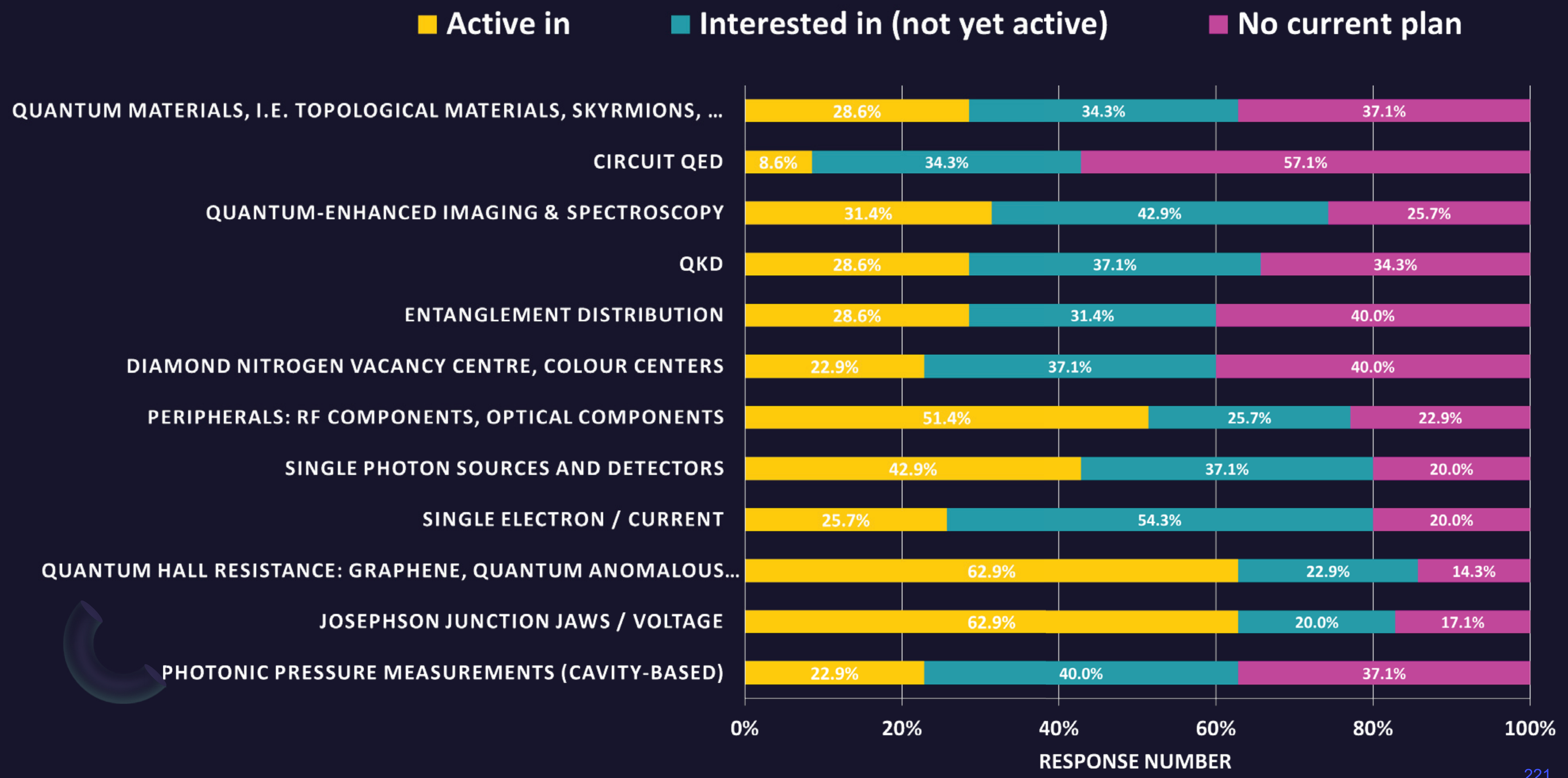


# How do you support & engage quantum industry?

**80 % NMIs/DIs responded with activities, including the following:**

- Collaborative research with industry and academia
- Testbeds, services and sharing facilities, characterization of components, traceability
- Proof-of-principle and novel measurement capabilities, evaluation of components
- Training (together with academia), awareness, communicate opportunities and challenges
- Participation in standardization
- "Creating critical mass" and synergies for industry's use of quantum

# Anything else you would like to share with the community?

- *"… open for collaboration with both scientific quantum community and quantum industry…"*
- *"…eager to offer the available standards and know-how for the quantum research and industry…"*
- *"...looking forward to development of the novel traceable tools and measurement techniques…"*
- *"…it is very challenging for small NMIs in developing economy to keep up with speed of research and technology development. Only through strategic capacity building and research collaborations that the gap between advanced NMIs and developing NMIs will not be wider at higher speeds..."*

# Observations from the questionnaire

- In the quantum technology application areas, there are
  - broadly established fields with significant activity and interest (clocks, Josephson junctions, quantum Hall, …)
  - less established fields with limited activity (Majorana qubits, …)
  - less established fields with high level of interest (gravimetry, magnetometry, …)
- Diversity of approaches and intensity of "quantum activities" across metrology community
- Engagement with quantum industry covers a spectrum of activities beyond 'core' metrology

10:45 – 11:45

# Break-out 2: What should NMIs/DIs do together?

Moderator – Davide Calonico

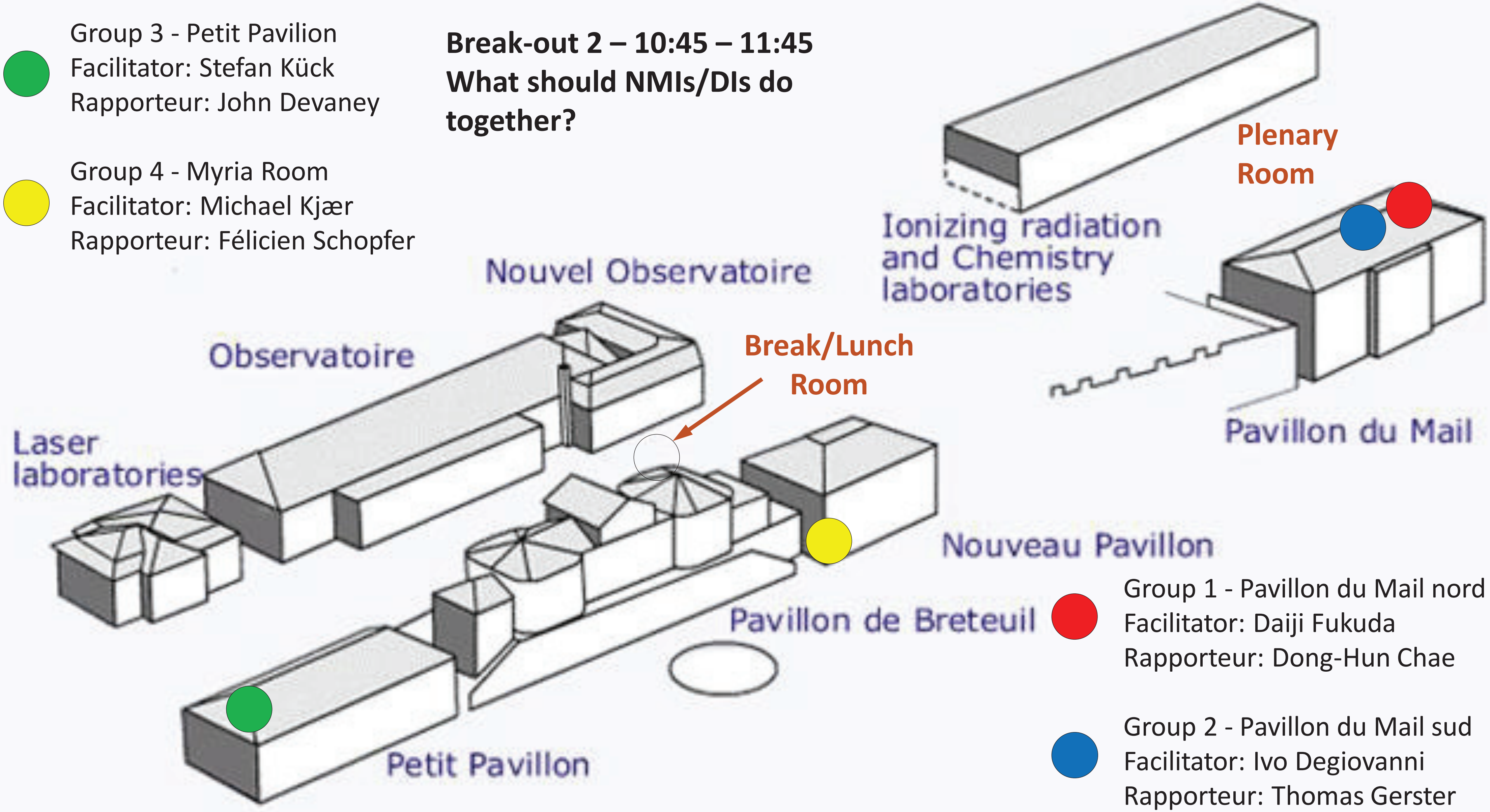
# Break-out 2: What should NMIs/DIs do together?

- What technologies and applications can we advance through cross-NMI collaboration?
- What activities and outputs should we produce?
- How can outputs be used?

**Break-out 2 – 10:45 – 11:45**
**What should NMIs/DIs do together?**

Group 3 - Petit Pavilion
Facilitator: Stefan Kück
Rapporteur: John Devaney

Group 4 - Myria Room
Facilitator: Michael Kjær
Rapporteur: Félicien Schopfer




Group 1 - Pavillon du Mail nord
Facilitator: Daiji Fukuda
Rapporteur: Dong-Hun Chae

Group 2 - Pavillon du Mail sud
Facilitator: Ivo Degiovanni
Rapporteur: Thomas Gerster

**Groups 3 and 4 should wrap-up five minutes early to get back to the plenary room**

# 10:15 – 10:45

# Group Photo & Break

**Break-out 2 – 10:45 – 11:45**
**What should NMIs/DIs do together?**

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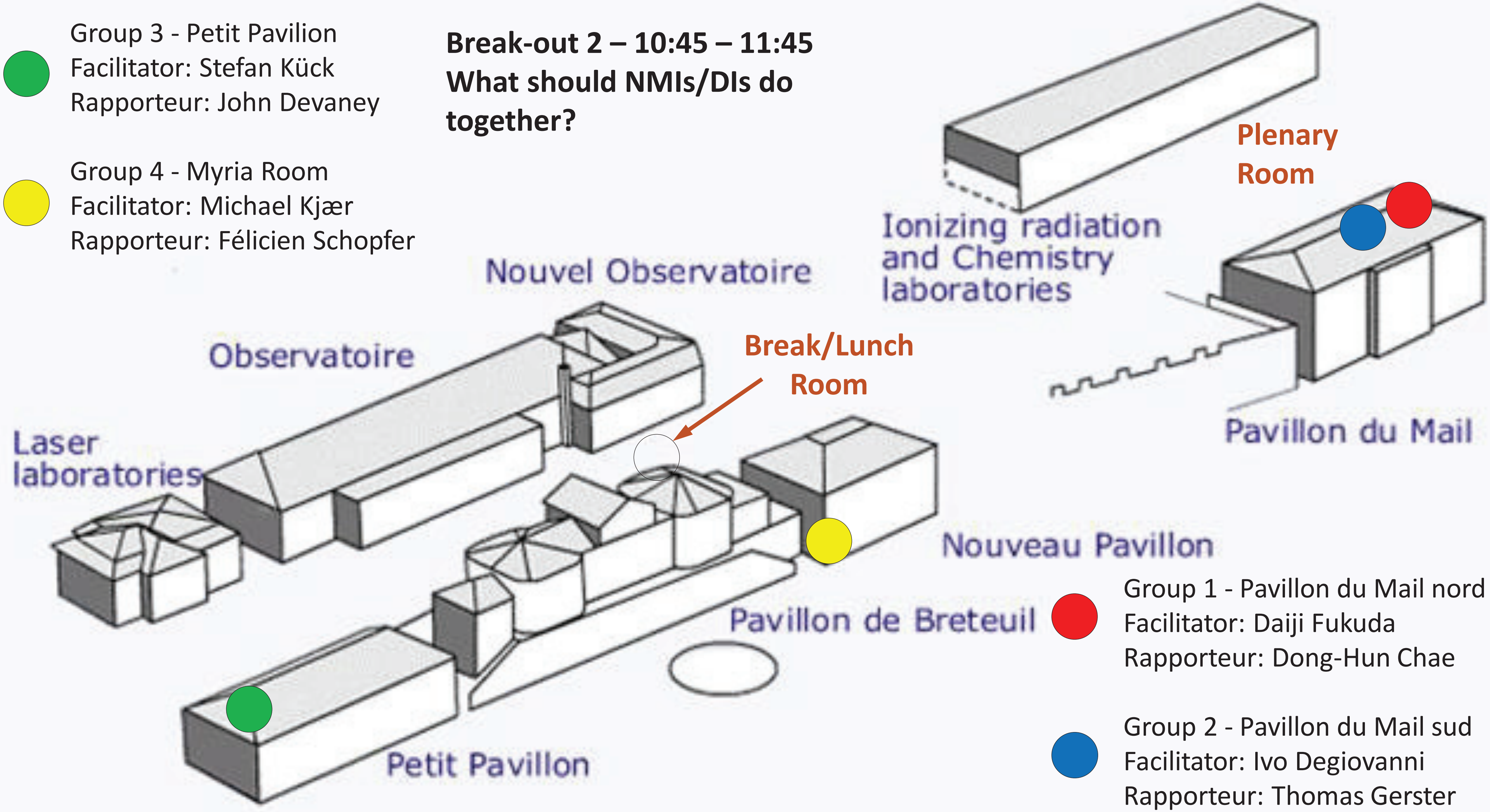


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**Groups 3 and 4 should wrap-up five minutes early to get back to the plenary room**

11:45 – 12:00

# Report out from Break-out 2: What should NMIs/DIs do together?

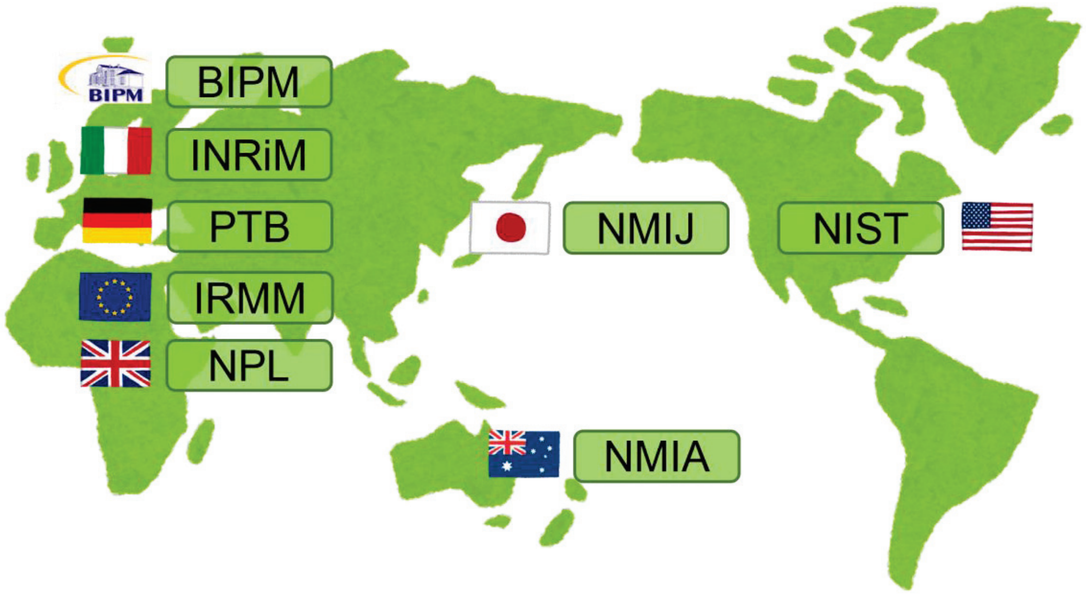
12:00 – 12:15

# Presentation Examples of frameworks for NMI collaboration – Jan Herrmann

# How can we work together?

## Examples of frameworks for NMI collaboration

International Avogadro Coordination Project




Versailles Project on Advanced Materials and Standards (VAMAS)

VAMAS

Canada . France . Germany . Italy . Japan . UK . USA . EC . Brazil . Mexico . Chinese Taipei . South Africa . Australia . Korea . India . China

1982 1983 2007 2008 2013

# Example 1: International Avogadro Coordination project for the re-definition of the kilogram

Naoki KURAMOTO, Prime Senior Researcher, Leader of Mass Standards Group, NMIJ

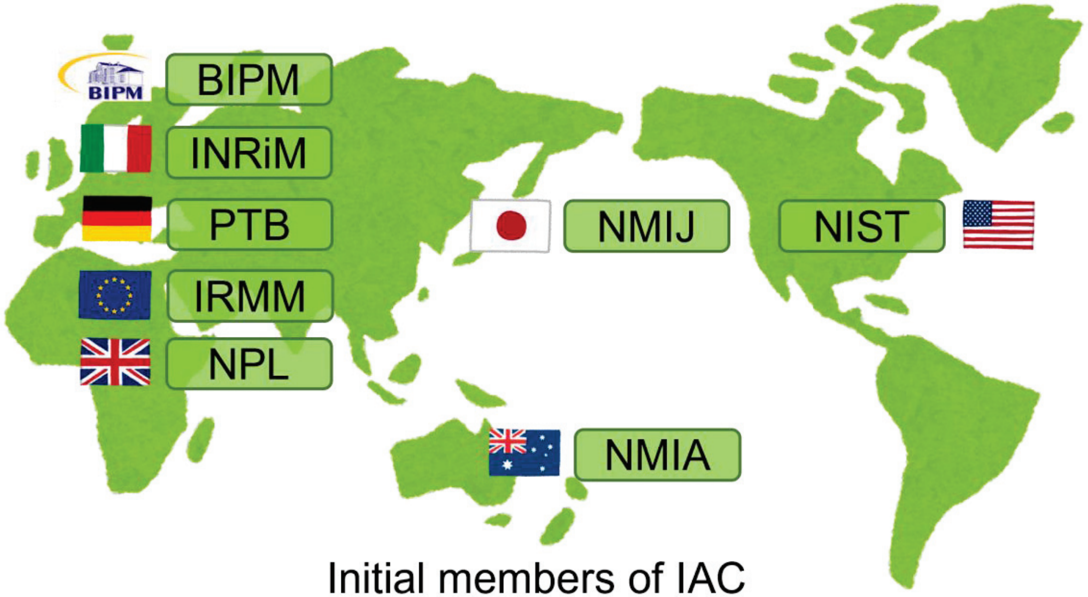
Background of the collaboration

- Resolution 7 of the 21st CGPM (1999)
  - NMIs were recommended to continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram.
- The Avogadro constant $N_A$: link the kilogram to atomic mass
  - X-ray crystal density method using Si crystal
  - The target of $u_r(N_A) = 2 \times 10^{-8}$
  - NMIJ-IRMM using $^{nat}Si$ crystal in 2003 : $u_r(N_A) = 2 \times 10^{-7}$

    → International cooperation among NMIs for the significant reduction of the uncertainty using $^{28}Si$-enriched crystal

# International Avogadro Coordination (IAC)

- Start : 2004
- Target : Accurate $N_A$ measurement using $^{28}$Si-enriched crystal




Initial members of IAC

Many independent papers from the members (extract)

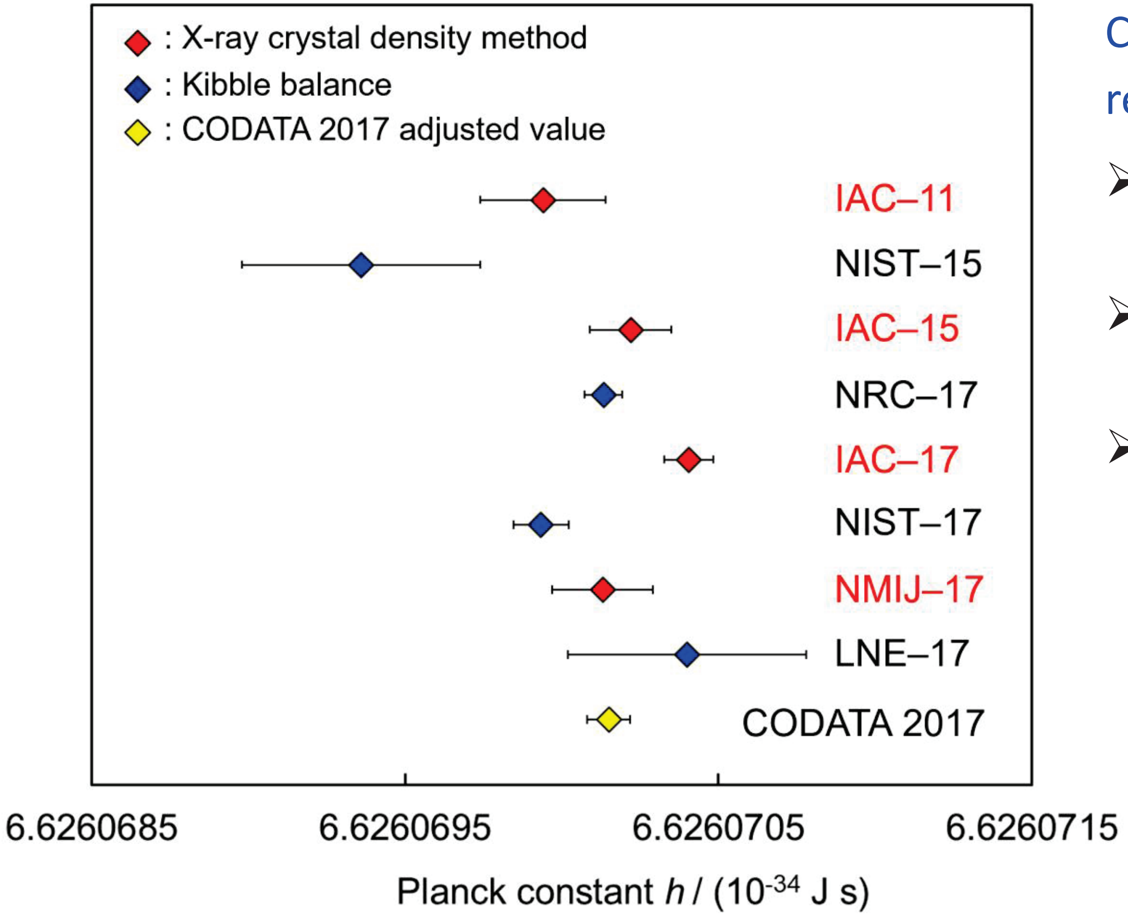
- Sphere volume
  - NMIJ : N. Kuramoto et al. Metrologia, **54**, 193 (2017)
  - PTB : A. Nicolaus et al. Metrologia, **54**, 693 (2017)
- Lattice constant
  - INRIM : E. Massa et al., J. Phys. Chem. Ref. Data, **44**, 031208 (2015)
  - NMIJ : A. Waseda et al., IEEE Trans. Instrum. Meas., **66**, 1304 (2017)
- Molar mass
  - PTB : A. Pramann et al., Int. J. Mass Spectrom., **299,** 78 (2011)
  - NMIJ : T. Narukawa et al., Metrologia, **51**, 161 (2014)

Many joint papers from the IAC (extract)

- Sphere diameter comparison among NMIJ, PTB and NMIA :
  N. Kuramoto, IEEE Trans. Instrum. Meas., **60**, 2615 (2011)
- Sphere mass comparison among BIPM, NMIA, PTB, NPL and NMIJ :
  A. Picard et al., Metrologia, **46**, 1 (2009)
- $N_A$ determination by PTB, NMIJ, NMIA, METAS, NIST, INRIM, BIPM and IRMM:
  B. Andreas et al., Phys. Rev. Lett., **106**, 030801 (2011)

Naoki KURAMOTO, NMIJ

# Determination of the Planck constant for the new definition of the kilogram




Collaboration by the IAC project played a decisive role in the redefinition of the kilogram.

- IAC-11, IAC-15
  - Y. Azuma et al., Metrologia, **52**, 360 (2015)
- IAC-17
  - G. Bartl et al., Metrologia, **54**, 693 (2017)
- NMIJ-17
  - N. Kuramoto et al., Metrologia, **54**, 716 (2017)

Naoki KURAMOTO, NMIJ

# Example 2: VAMAS

The Versailles Project on Advanced Materials and Standards (VAMAS) was established as one of 18 cooperative projects at the 1982 Economic Summit of the GATT 7 to stimulate trade in new technologies. Its membership has expanded over the years.

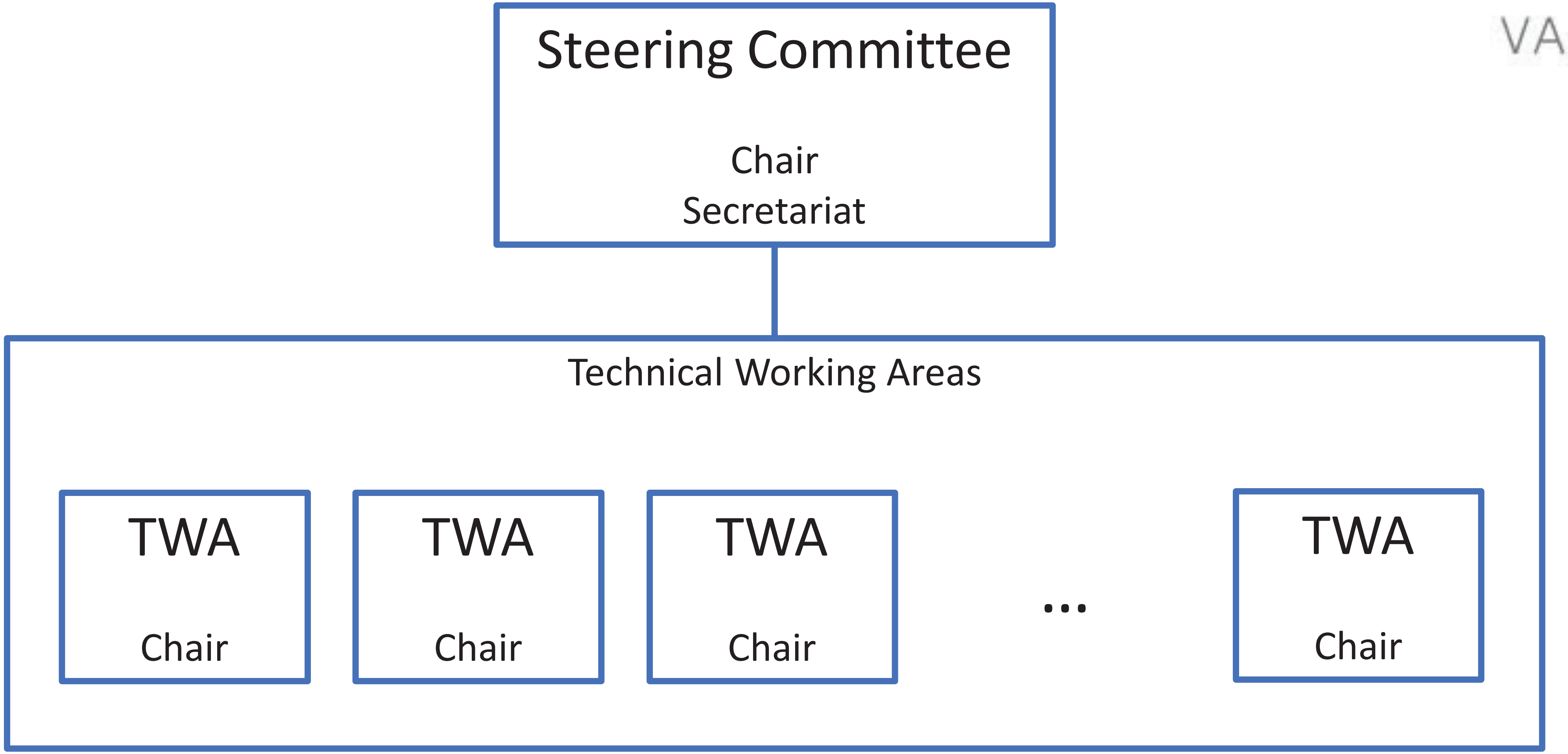
Canada . France . Germany . Italy . Japan . UK . USA . EC . Brazil . Mexico . Chinese Taipei . South Africa . Australia . Korea . India . China

1982 – 1983 | 2007 – 2008 | 2013

> “To support world trade in products dependent on advanced materials technologies by providing the technical basis for harmonized measurements, testing, specifications, and standards.”

vamas.org

# VAMAS – Structure



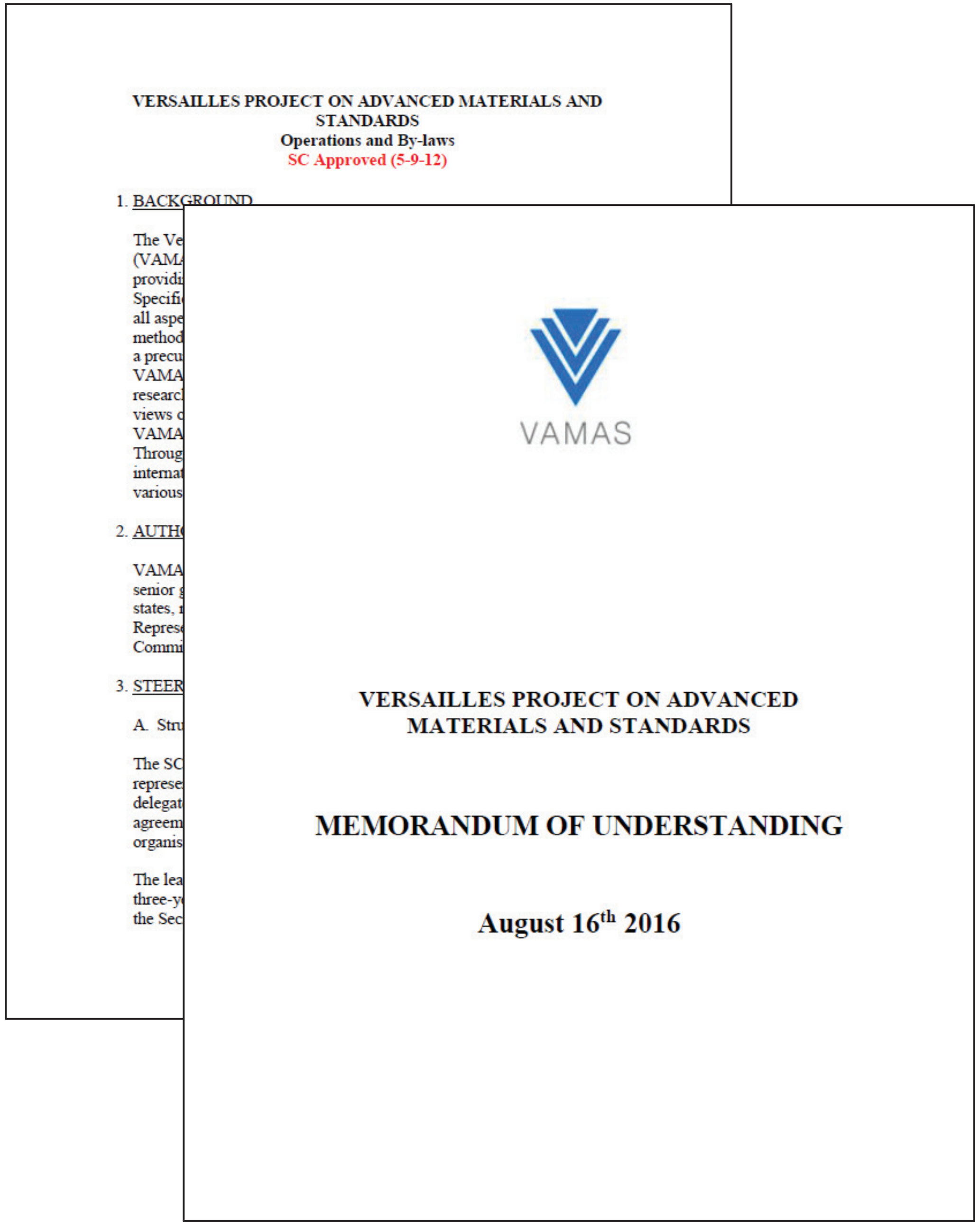
# VAMAS – Governance

## Membership

Economies/institutions may enter into this collaboration as parties through Memoranda of Understanding (MoUs). Such economies/institutions should make an application to the Steering Committee describing their proposed contribution to the purpose of VAMAS and their technical capabilities in the relevant fields.

## Steering Committee

Overall management of VAMAS is through a Steering Committee with up to three representatives from each of the member economies. The Chair and Secretariat of VAMAS alternate on a three-year cycle.


VERSAILLES PROJECT ON ADVANCED MATERIALS AND STANDARDS
Operations and By-laws
SC Approved (5-9-12)

1. BACKGROUND

VAMAS

VERSAILLES PROJECT ON ADVANCED MATERIALS AND STANDARDS

MEMORANDUM OF UNDERSTANDING

August 16th 2016

vamas.org

# VAMAS – Technical Working Areas

46 TWAs established; 17 currently active

| VAMAS – Active Technical Working Areas | |
|---|---|
| | |
| 2 – Surface Chemical Analysis | 37 – Quantitative Microstructural Analysis |
| 5 – Polymer Composites | 39 – Solid Sorbents |
| 16 – Superconducting Materials | 40 – Synthetic Biomaterials |
| 24 – Performance Related Properties of Electroceramics | 41 – Graphene and Related 2D Materials |
| 31 – Creep, Crack and Fatigue Growth in Weldments | 42 – Raman Spectroscopy and Microscopy |
| 33 – Polymer Nanocomposites | 43 – Thermal Properties |
| 34 – Nanoparticle Populations | 44 – Self Healing Ceramics |
| 36 – Printed, flexible and stretchable Electronics | 45 – Micro and Nano Plastics in the Environment |
| | |
| TWA 0 – Strategy and Impact | |

# VAMAS – Effective pre-normative research

VAMAS


vamas.org

# VAMAS – Connections

VAMAS

## BIPM (2008)

This MoU facilitates collaboration to identify key metrological traceability issues affecting the comparability and accuracy of the measurement of materials .

## ISO (2013) and IEC (2014)

These MoUs enable joint publications based upon the work of VAMAS to accelerate the development of documentary standards in advanced materials.

## World Material Research Institute Forum (2008)

This MoU encourages information exchange and possible joint work items between the two organisations.

## APMP (2020)

This MoU aims to foster the collaboration and lay the framework for cooperative activities to promote the development of metrology infrastructure in the Asia Pacific region with a key focus on the comparability and accuracy of the measurement of materials properties.

# VAMAS – Benefits

VAMAS has contributed to the development of national and international standards through

- Pre-standards work in rapidly developing technical areas
- Agreed nomenclature
- High quality data generation via inter-laboratory comparisons
- Precision data statements
- Provision of reliable material properties
- Contribution to the development of reference materials
- Development and validation of test methods and procedures
- Help establish the basis of new technical committees in standards bodies
- Effective transfer of results to standards bodies leading directly to international standards
- Increased proficiency of laboratories, including industrial laboratories

vamas.org

# NMI-Q – Benefits

VAMAS

NMI-Q can contribute to the development of national and international standards through

- Pre-standards work in rapidly developing technical areas
- Agreed nomenclature
- High quality data generation via inter-laboratory comparisons
- Precision data statements
- Provision of reliable component and system properties
- Contribution to the development of reference testbeds
- Development and validation of test methods and procedures
- Help establish the basis of new technical committees in standards bodies
- Effective transfer of results to standards bodies leading directly to international standards
- Increased proficiency of laboratories, including industrial laboratories

13:15 – 14:15 (after lunch)

# Break-out 3: How can we work together?

Moderator – Jan Herrmann

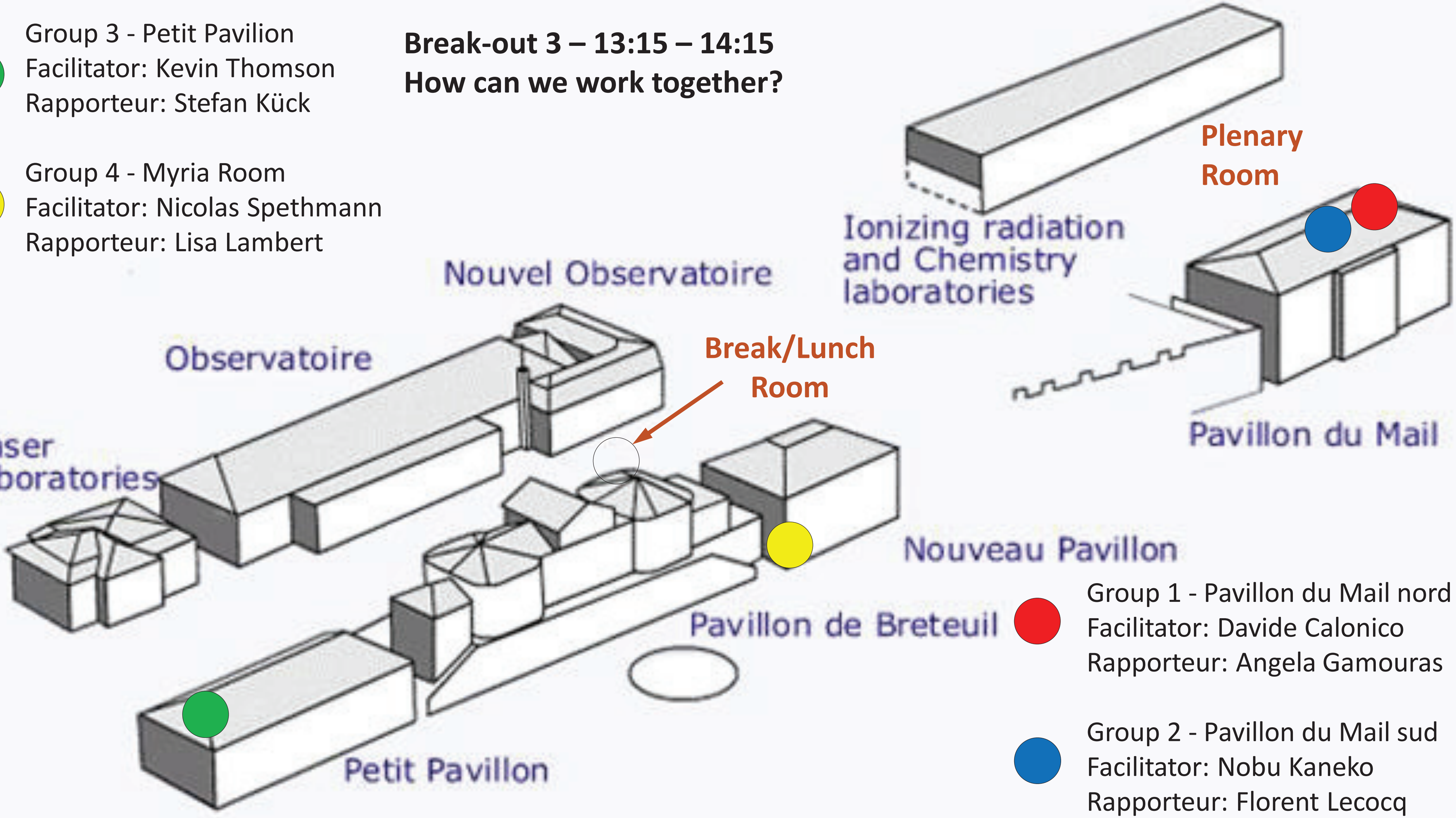
# Break-out 3: How should we work together?

- How do we organize ourselves?
- What constrains us from collaborating?
- How do we engage industry?
- Which other organizations do we need to include?
- How do we share our outputs?
- What is the role of CIPM/BIPM?

Group 3 - Petit Pavilion
Facilitator: Kevin Thomson
Rapporteur: Stefan Kück

Group 4 - Myria Room
Facilitator: Nicolas Spethmann
Rapporteur: Lisa Lambert

**Break-out 3 – 13:15 – 14:15**
**How can we work together?**

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Facilitator: Davide Calonico
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Group 2 - Pavillon du Mail sud
Facilitator: Nobu Kaneko
Rapporteur: Florent Lecocq

**Groups 3 and 4 should wrap-up five minutes early to get back to the plenary room**

Agenda – Day 2 – Continued
## Solutions

13:15 Break-out 3: How can we work together?

14:15 Report back

14:30 Panel: Wrap up – Main take-aways and suggestions for next steps

14:45 NMI-Q wrap-up – JT Janssen, Tim Prior and Barbara Goldstein

15:00 Adjourn

# 12:15 – 13:15

# Lunch

**Break-out 3 – 13:15 – 14:15**
**How can we work together?**

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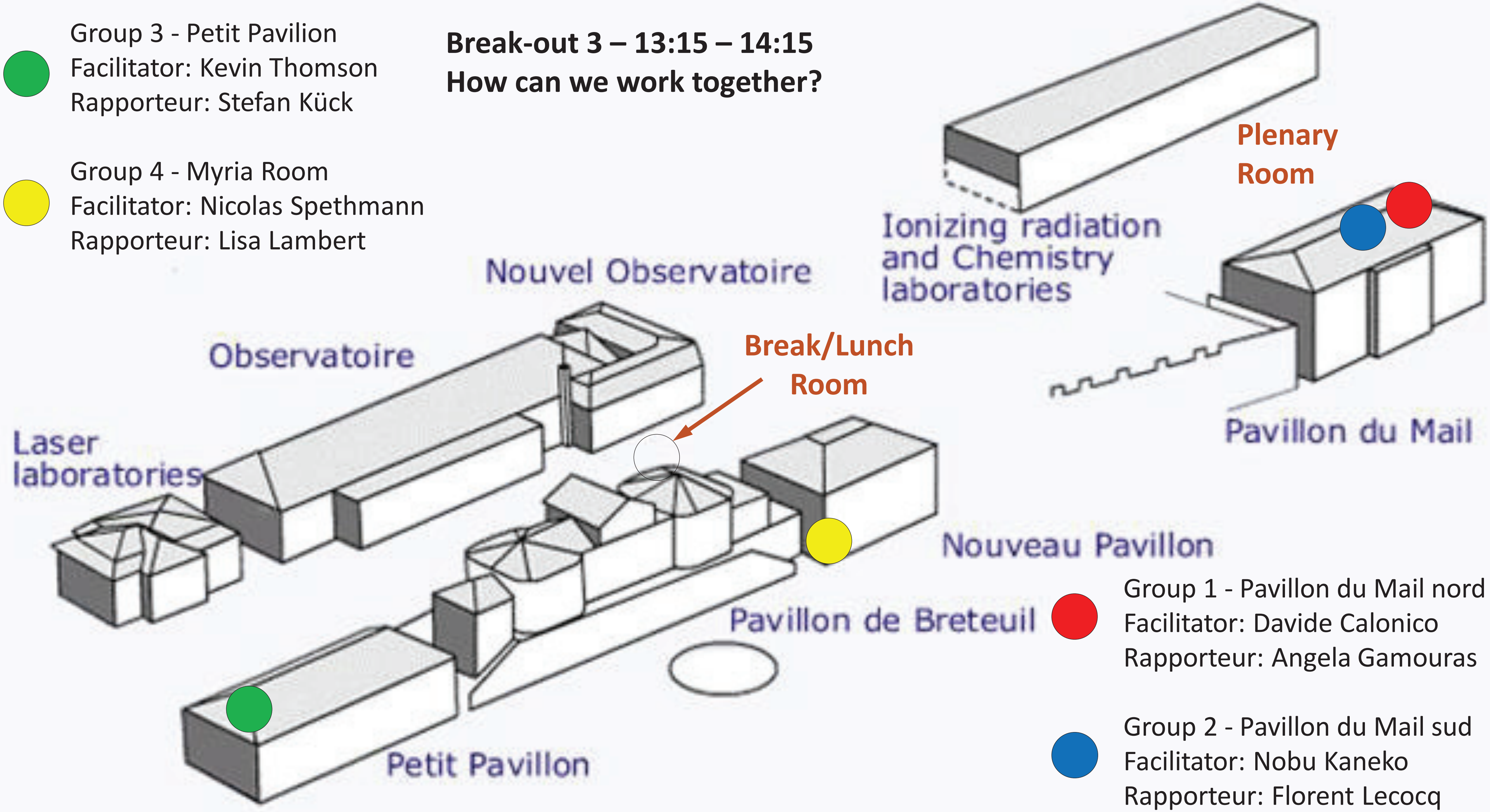


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14:15 – 14:30

# Report out from Break-out 3: How can we work together?

# Agenda – Day 2 – Continued
## **Solutions**

13:15 Break-out 3: How can we work together?

14:15 Report back

14:30 Panel: Wrap up – Main take-aways and suggestions for next steps

14:45 NMI-Q wrap-up – JT Janssen, Tim Prior and Barbara Goldstein

15:00 Adjourn

14:30 – 14:45

# Panel: Workshop wrap-up – Main take-aways and suggestions for next steps

Moderator – Nicolas Spethmann

# Panel: Workshop wrap-up – Main take-aways and suggestions for next steps

- NIST – James Olthoff
- CEM – Dolores del Campo Maldonado
- NRC – Andrew Todd
- INRiM – Ivo Degiovanni
- CIPM – Wynand Louw

14:45 – 15:00

# Closing Remarks

## JT Janssen, Tim Prior and Barbara Goldstein

15:00

## Adjourn

## Martin Milton