Qubits: Physical platforms and applications

Maria Longobardi

maria.longobardi@unibas.ch

Swiss National Science Foundation

Universität Basel

NCCR SPIN

Outline

Lesson 1: QC Overview - What is the mathematical language of qubits?

Lesson 2: How do we evaluate physical qubits' performance?

Lesson 3: How do different platforms realize qubits?

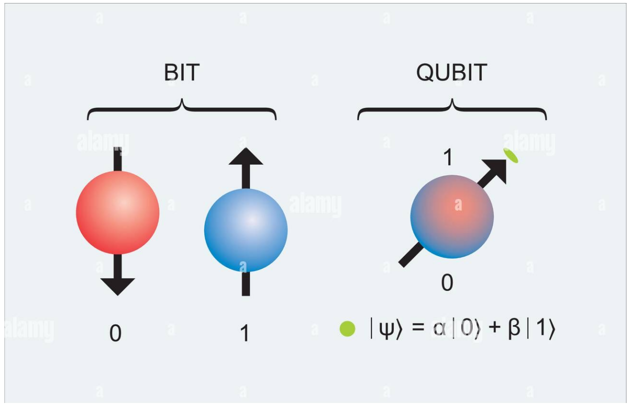
Lesson 4: Qubits as a sensor
Overview of the quantum markets and talent development

Bits vs Qubits

Classical bit: one of two states, 0 or 1.

Qubit: quantum two-level system with basis states $|0\rangle$ and $|1\rangle$

and superpositions $\alpha|0\rangle + \beta|1\rangle$.



computational basis
$|0\rangle$ $|1\rangle$

Qubits

A qubit $|\psi\rangle$ is the special case d=2: $\mathcal{H} \simeq \mathbb{C}^2$,

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle.$$

The coefficients $\boldsymbol{\alpha}$ **and** $\boldsymbol{\beta}$ **are complex amplitudes**.

A physical state must be **normalized**:

$$|\alpha|^2 + |\beta|^2 = 1$$

Measurement in the computational basis gives:

$$P(0) = |\alpha|^2, \qquad P(1) = |\beta|^2$$

The quantum state contains amplitudes.
The measurement returns **one classical outcome.**

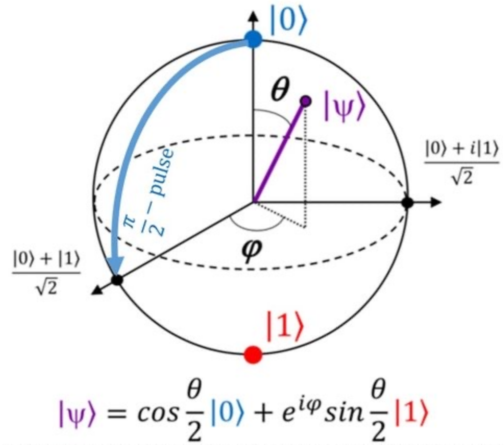
Complex Hilber Space
2-dimensional

Bloch sphere

A **single pure qubit state** can be represented on the Bloch sphere.

Spherical coordinates

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



Bloch Sphere

The polar angle $\boldsymbol{\theta}$ **controls the population balance between** $|\mathbf{0}\rangle$ **and** $|\mathbf{1}\rangle$.
The azimuthal angle $\boldsymbol{\phi}$ **is the relative phase.**

Equatorial states

The Bloch sphere is therefore not just a picture of "superposition".

<u>It is a compact way to visualize amplitudes, phase, and measurement axes.</u>

Pauli Matrices

The three Pauli matrices are:

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

They are Hermitian (observable):

$$X = X^{\dagger}, \qquad Y = Y^{\dagger}, \qquad Z = Z^{\dagger}$$

They are also unitary (reversible):

$$X^{\dagger} X = I, \qquad Y^{\dagger} Y = I, \qquad Z^{\dagger} Z = I$$

Hermitian means they can represent **observables**.

Unitary means they can also act as **reversible quantum gates.**

As observables, they correspond to measurements.

As gates, they implement specific reversible qubit transformations.

Pauli Matrices as gates

The Pauli matrices can also act as single-qubit gates.

The X gate **flips the computational basis states**: $X|0\rangle = |1\rangle$ $X|1\rangle = |0\rangle$

The Z gate **changes the relative phase**: $Z|0\rangle = |0\rangle$ $Z|1\rangle = -|1\rangle$

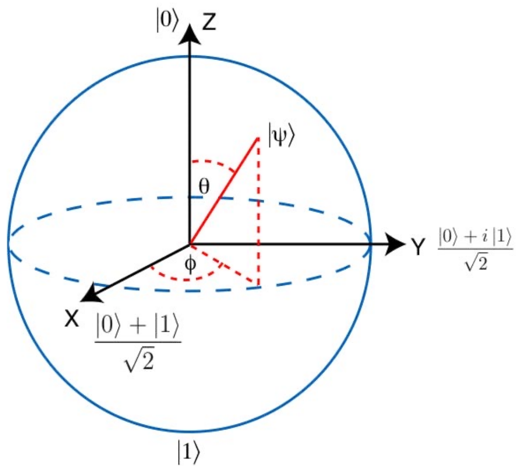
The Y gate **combines a bit flip with a phase change**:

$$Y|0\rangle = i|1\rangle, \qquad Y|1\rangle = -i|0\rangle$$

X_π: 180° rotation around the X-axis

Y_π: 180° rotation around the Y-axis

Z_π: 180° rotation around the Z-axis



Pauli Matrices do not commute (order matters)

Different Pauli matrices generally do not commute:

$[X, Y] = 2iZ$ $[Y, Z] = 2iX$ $[Z, X] = 2iY$

This means that the order of operations matters.

Applying X and then Y is not the same as applying Y and then X.

Physically, this reflects the fact that measurements and rotations along different axes are incompatible.

For example:

measuring Z gives information about the computational basis
measuring X gives information about a different basis

A qubit cannot have definite values of X, Y, and Z at the same time.

From theory to the lab

DiVincenzo Criteria (2000)

The DiVincenzo criteria summarize what a physical quantum computer must provide:

1. scalable, well-characterized qubits

2. initialization to a simple fiducial state

3. coherence times long compared with gate times

4. a universal set of quantum gates (single qubit rotation and at least two-qubit entanglement)

5. qubit-specific measurement

David DiVincenzo

Two-level quantum system is not enough

The central hardware challenge is to preserve quantum coherence while still allowing control, coupling, and measurement.

Basic sequence

1. **Initialization**: set $|0\rangle$

2. **Spectroscopy**: sweep the drive frequency to find the qubit transition.

3. **Rabi oscillations**: once you know the transition frequency, drive resonantly and vary pulse duration.

4. **Ramsey/echo**: characterize coherence.

Characterization and controlling

Requirement	**Tested by**
It has a well-defined transition frequency	Spectroscopy
It can be coherently controlled	Rabi oscillations, gate calibration
It preserves quantum information	T_1, Ramsey, T_2^*, ${T_2}^{echo}$ Hahn echo, dynamical decoupling
It can be measured reliably	Readout fidelity, QND tests
It performs accurate gates	Randomized benchmarking, tomography, leakage and crosstalk tests

Spectroscopy

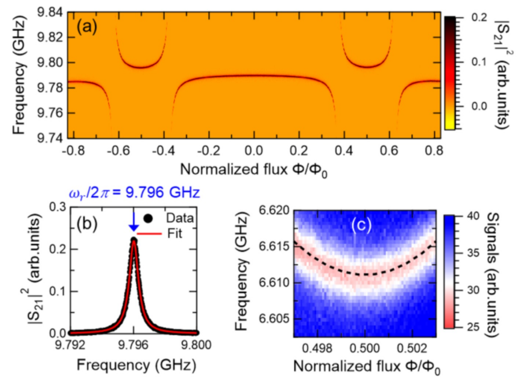
Before controlling a qubit, we must identify its transition frequency:

$$hf_q = E_1 - E_0$$

A spectroscopy experiment scans the drive frequency and measures when the qubit absorbs energy.

Spectroscopy tells us: f_q. the **qubit transition frequency**.

Fig. 2: Spectroscopy of resonator and qubit.



Commun Mater **2**, 98 (2021)

It also gives information about linewidth, frequency stability, and whether the system behaves as a clean two-level quantum system.

Why it matters

If the transition is not well-defined, the qubit cannot be addressed reliably.

A broad or unstable transition usually indicates noise, disorder, unwanted coupling, or poor device stability.

Rabi oscillations, Gate calibration

A qubit must be controllable.
Rabi oscillations demonstrate that an external drive can rotate the qubit state in a controlled way

A resonant drive (often microwave or laser) induces coherent rotations between the two qubit states:
$|0\rangle \leftrightarrow |1\rangle$

$$\theta = \Omega_R t$$

and $P_1(t) = \sin^2\left(\frac{\Omega_R t}{2}\right)$

The Rabi frequency $\boldsymbol{\Omega_R}$ tells us how fast the qubit rotates on the Bloch sphere:

By changing the **pulse duration**, we control the rotation angle on the Bloch sphere.

The Rabi experiment allows us to calibrate the pulse durations for:

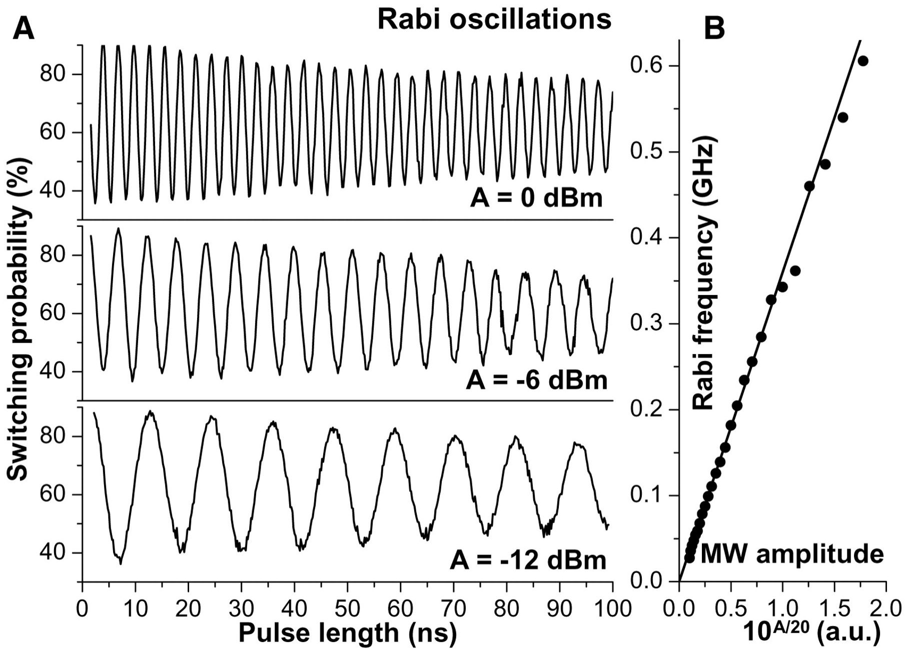
$$X_\pi, \qquad X_{\pi/2}$$

where X_π flips the qubit and $X_{\pi/2}$ creates an equal superposition.

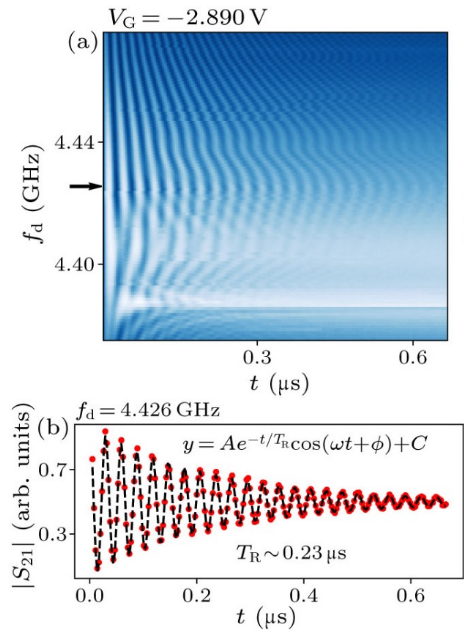
A $X_\pi - pulse$ flips the state:
$$|0\rangle \rightarrow |1\rangle$$

A $X_{\pi/2} - pulse$ creates superposition:
$$X_{\pi/2}|0\rangle = \frac{|0\rangle - i|1\rangle}{\sqrt{2}}$$

Rabi oscillations



Science **299**,1869-1871(2003)



Chinese Phys. Lett. **40** 047302

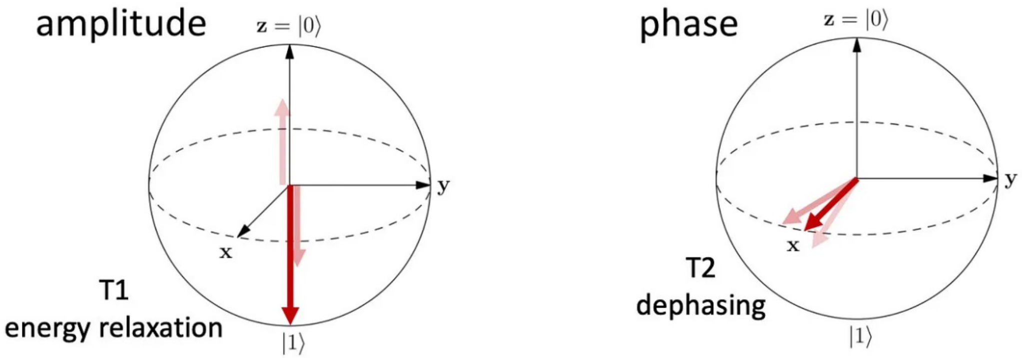
$$\theta = \Omega_R t$$

Decays

T_1= population/energy decay

.

T_2= phase coherence decay



Source: IBM

Energy relaxation time T_1

It measures how the population of the excited state decays

T_1 tells you how long the qubit remains in the excited state before relaxing to the ground state.

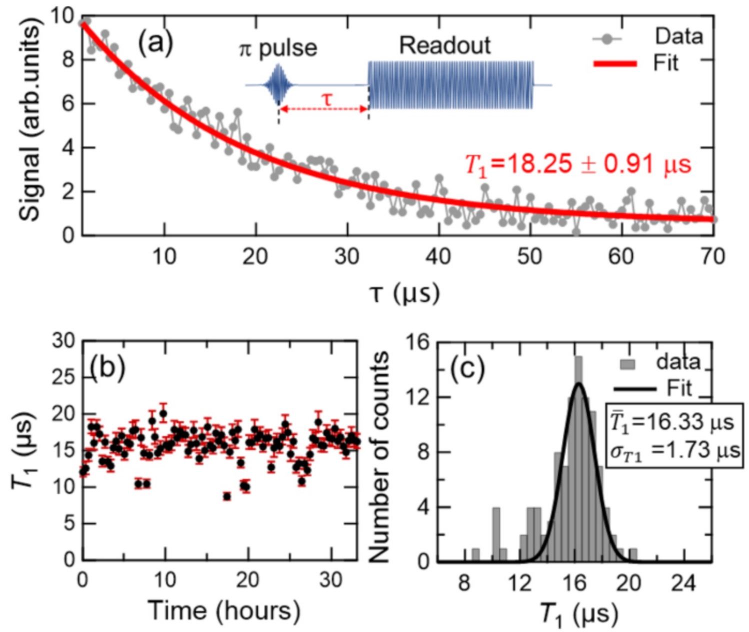
. $X_\pi \rightarrow$ wait t $\rightarrow$ measure

$$|0\rangle \longrightarrow X_\pi \longrightarrow |1\rangle \text{ wait } t \longrightarrow measure$$

$$P_1(t) = P_1(0)e^{-t/T_1}$$

X_π: 180° rotation around the X-axis (flipping)

Fig. 3: Energy relaxation time T_1 and its temporal variation.



Commun Mater **2**, 98 (2021)

Ramsey: coherence during free evolution

Rabi tells us how to rotate the qubit.

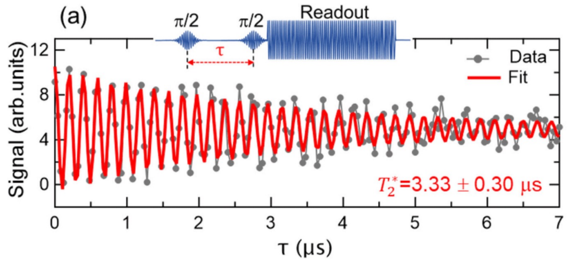
Ramsey tells us whether a superposition keeps its phase during free evolution.

A typical Ramsey experiment uses two calibrated $\pi/2 - pulses$ separated by a waiting time:

$$X_{\pi/2} \rightarrow \text{wait } t \rightarrow X_{\pi/2} \rightarrow measure$$

The first $\pi/2 - pulse$ creates a superposition.
During the waiting time, the relative phase freely evolves.
The second $\pi/2 - pulse$ converts phase information into a measurable population.

The Ramsey signal decays as the phase becomes uncertain.
From the decay of the Ramsey fringes, we extract: T_2^*



Commun Mater **2**, 98 (2021)

What we learn

Ramsey shows that the qubit phase remains coherent and experimentally measurable during free evolution.

T_2,echo (slow noise)

T_2,echo is measured by inserting a **refocusing π pulse** in the middle of the free-evolution period.

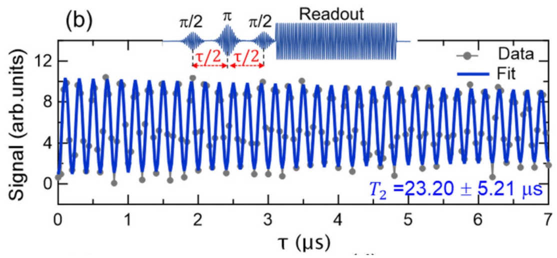
The purpose of the π pulse is to partially cancel slow or quasi-static dephasing noise.

The Hahn echo pulse sequence is:

$X_{\pi/2} \rightarrow$ wait $\frac{t}{2}$ $\rightarrow X_{\pi}$ $\rightarrow$ wait $\frac{t}{2}$ $\rightarrow$ $X_{\pi/2}. \rightarrow.$ measure

The measured signal is often fit with:

$$P_1(t) = \frac{1}{2}\left[1 + Ce^{-\left(\frac{t}{T_{2,echo}}\right)^n}\right]$$

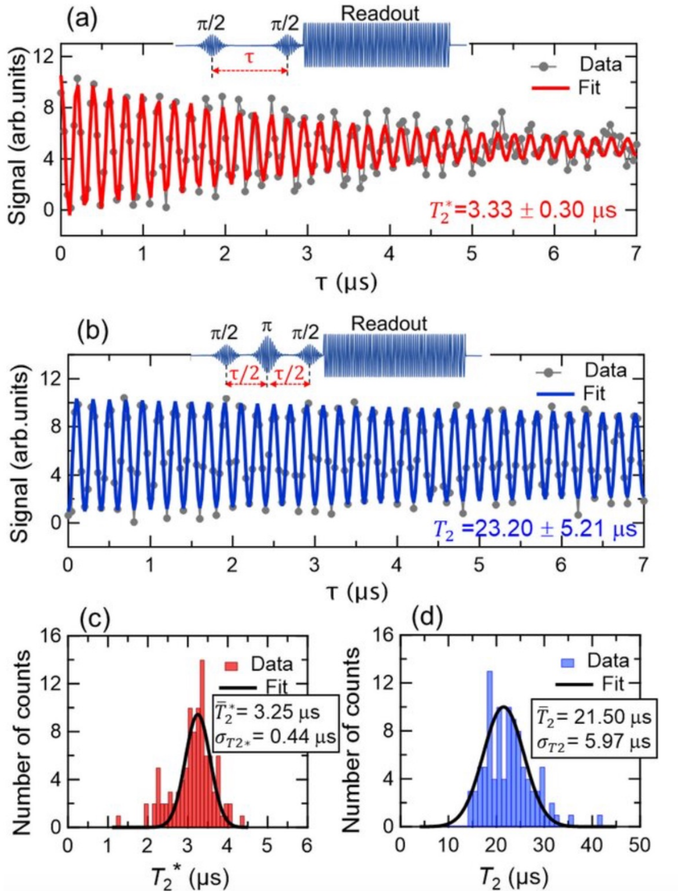


where C is the contrast and n depends on the noise spectrum (different noise spectra can produce different decay shapes)

Commun Mater **2**, 98 (2021)

n=1 corresponds to a simple exponential decay.

.



If: $T_2^{echo} \gg T_2^*$ much of the Ramsey decay comes from slow, reversible dephasing.

If: $T_2^{echo} \approx 2T_1$ coherence is mainly limited by irreversible energy relaxation.

If: $T_2^{echo} \ll 2T_1$ additional dephasing mechanisms remain

Commun Mater **2**, 98 (2021)

We discussed how to define, control and manipulate qubits

Typically qubits are operated at mK

Josephson junction

Josephson-junction qubits typically operate in the microwave regime:

$$f_{01} = \frac{\omega_{01}}{2\pi} \sim 1 - 10\text{GHz}$$

This range is useful because it is below the junction plasma frequency ω_{p} and compatible with microwave electronics.

To suppress thermal excitation, the qubit energy must exceed thermal energy: $\boldsymbol{\hbar\omega_{01} \gg k_B T}$

The operating temperature is typically: $T_{op} \approx 10\ mK$

This is not the superconducting transition temperature.

$$T_{op} \ll T_{\mathrm{C}}$$

Superconducting qubits operate at mK to remain superconducting and to keep thermal excitations low.

Spin qubits

Spin qubits are operated at mK to make quantum-dot energy scales resolvable and stable.

Thermal energy must be smaller than the relevant energies:

$$k_{BT} \ll EC, EV, EZ, Delta_{\mathrm{orb}}$$

E_C = charging energy
E_V = valley splitting
E_Z = Zeeman splitting
Delta $_{\_orb}$ = orbital level spacing

Low temperature is needed to: stabilize single-electron occupation, enable Coulomb blockade, suppress thermal excitation, improve initialization and readout fidelity

Typical operation: T = 10–100 mK (Some devices can operate around 1–4 K).

Cryogenic operation keeps electrons in well-defined quantum-dot states and prevents thermal energy from washing out spin, charge, valley, and orbital energy splittings.

Hot Spin qubits

nature electronics

ARTICLES

https://doi.org/10.1038/s41928-022-00722-0

Check for updates

A hole spin qubit in a fin field-effect transistor above 4 kelvin

Leon C. Camenzind[1,3], Simon Geyer[1,3], Andreas Fuhrer[2], Richard J. Warburton[1], Dominik M. Zumbühl[1]✉ and Andreas V. Kuhlmann[1,2]✉

The greatest challenge in quantum computing is achieving scalability. Classical computing, which previously faced such issues, currently relies on silicon chips hosting billions of fin field-effect transistors. These devices are small enough for quantum applications: at low temperatures, an electron or hole trapped under the gate can serve as a spin qubit. Such an approach potentially allows the quantum hardware and its classical control electronics to be integrated on the same chip. However, this requires qubit operation at temperatures above 1 K, where the cooling overcomes heat dissipation. Here we show that silicon fin field-effect transistors can host spin qubits operating above 4 K. We achieve fast electrical control of hole spins with driving frequencies up to 150 MHz, single-qubit gate fidelities at the fault-tolerance threshold and a Rabi-oscillation quality factor greater than 87. Our devices feature both industry compatibility and quality, and are fabricated in a flexible and agile way that should accelerate further development.

Hot Spin qubits

Silicon FinFETs can host hole spin qubits operating above $\sim 4\text{K}$.

The paper demonstrates:

fast electrical control of hole spins

with driving frequencies up to:

$$\sim 150\text{MHz}$$

They also report high-quality single-qubit gates and very clear Rabi oscillations.

The main message is:

A silicon transistor-like device can operate as a spin qubit above 4 K, combining industrial compatibility with good qubit performance.

Hot Spin qubits

The big problem in quantum computing is scaling up: making not just one good qubit, but millions or billions of controllable devices.

Classical computing solved scaling by using **silicon chips** with billions of tiny transistors called **FinFETs**.

Can we use similar silicon transistor structures to make qubits?

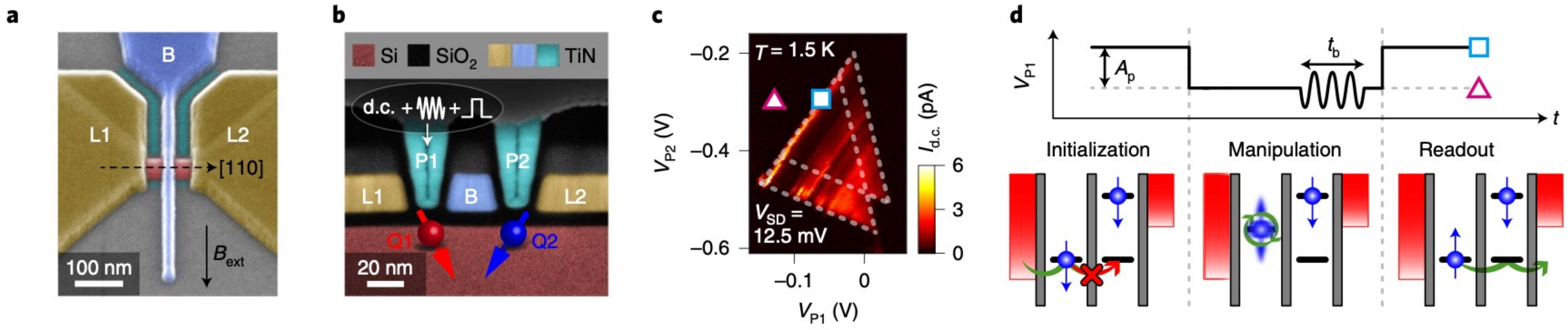
At low T, a single electron or hole trapped under the gate of a FinFET can behave like a **spin qubit**.

This is attractive because it could eventually allow the quantum device and part of the classical control electronics to be integrated more closely.

But there is a problem: **classical control electronics produce heat**.
If the qubits only work at very low millikelvin temperatures, the cooling power is extremely limited.

So, for scalable integration, it would be very useful if qubits could work **above 1K**

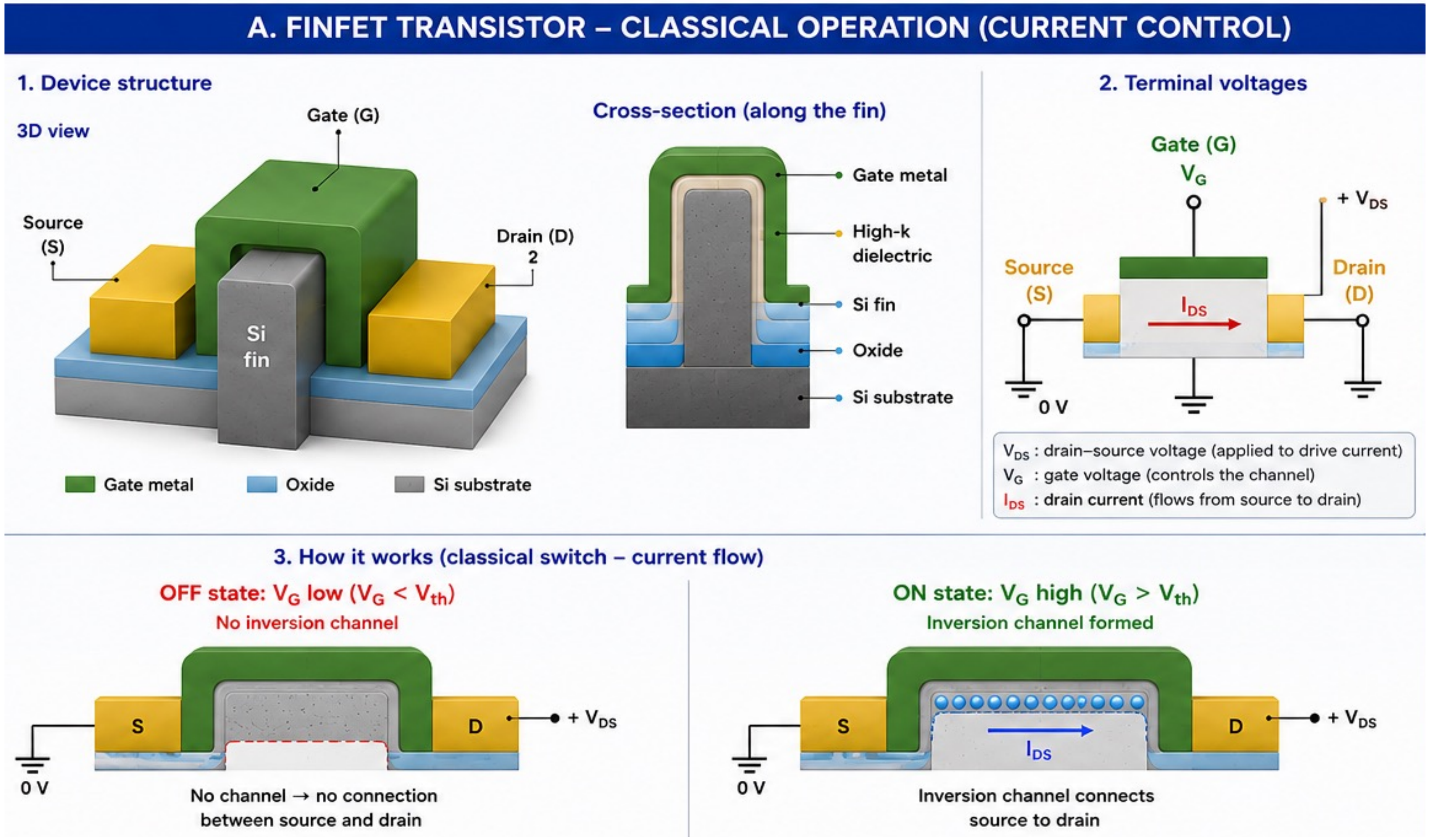
Hot Spin qubits



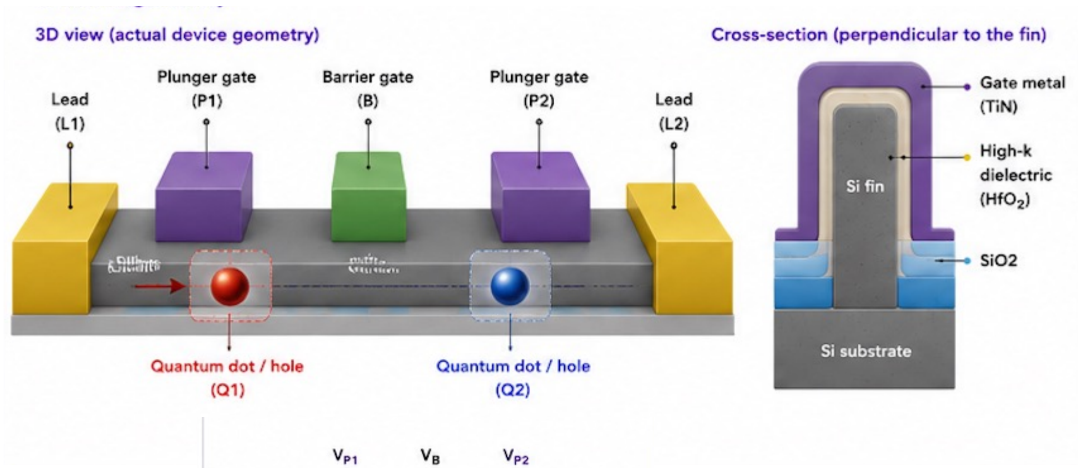
Pauli spin blockade is important because it gives a way to read out the spin state electrically.

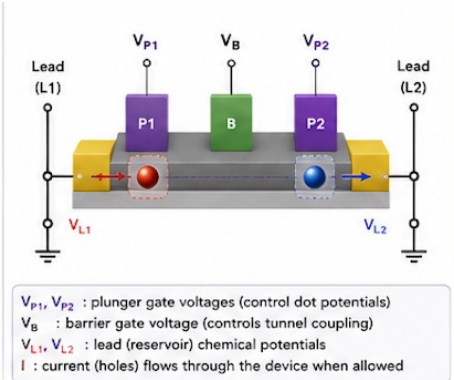
For a spin qubit, the hard part is not only controlling the spin.
You also need to **measure whether the spin is** $|0\rangle$ **or** $|1\rangle$.
Pauli spin blockade converts the spin information into a charge/current signal, which is much easier to detect.

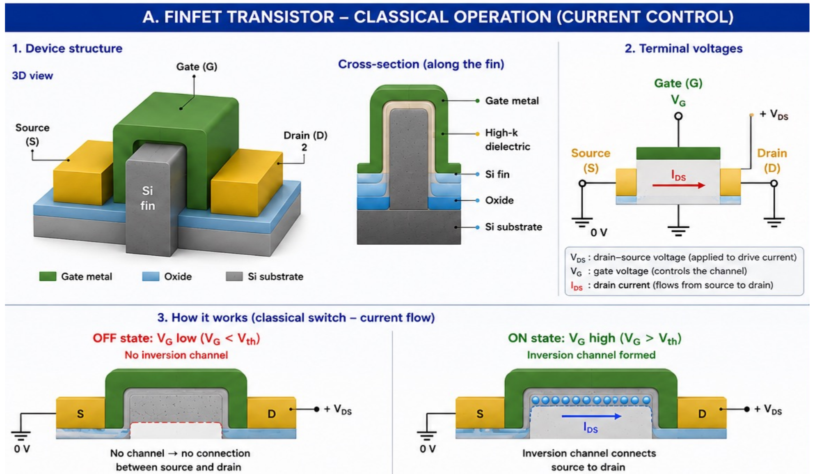
Hot Spin qubits



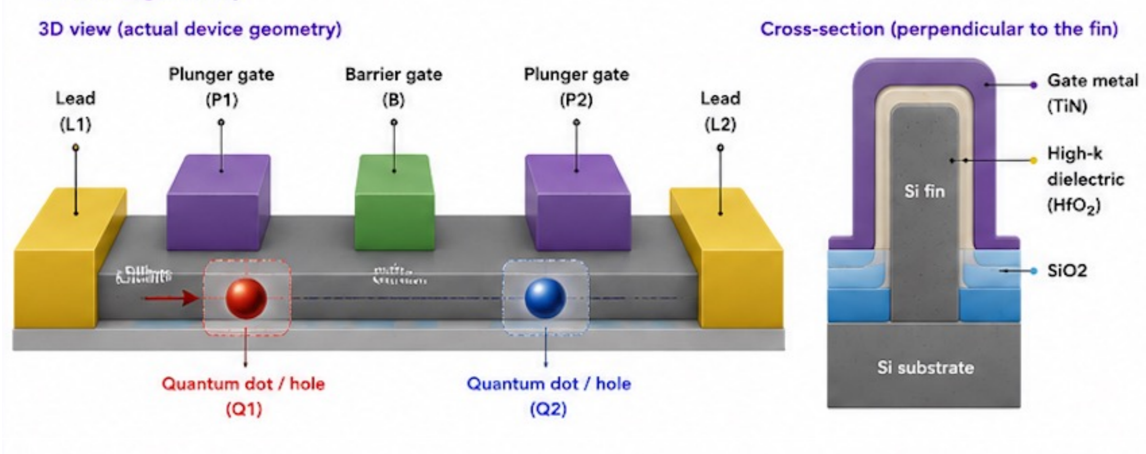
Hot Spin Qubits





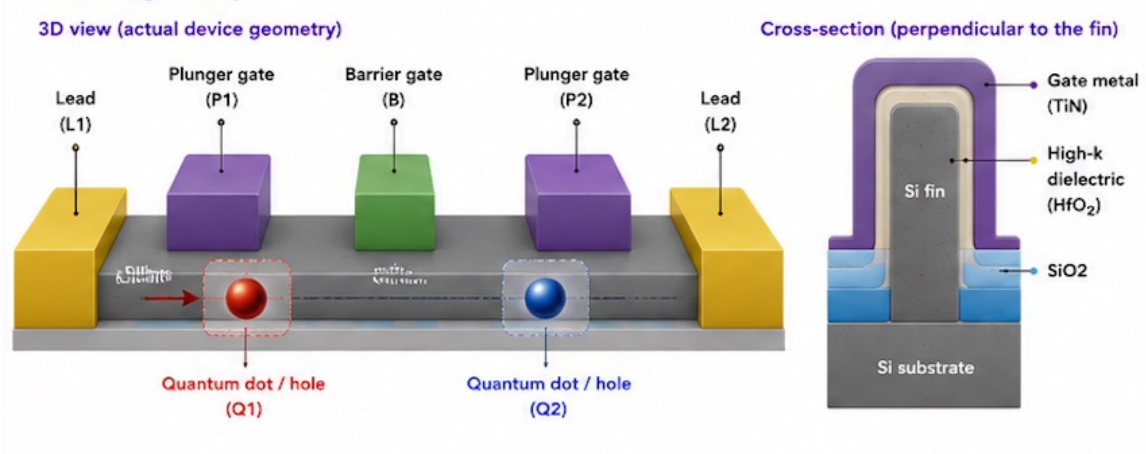


Hot Spin Qubits



Step	What you change	Purpose
Load holes	V_{P1}, V_{P2}	Load holes into the quantum dots
Isolate (1,1)	V_B	Isolate the dots / control tunnelling
Operate	V_B + AC gate pulse	Couple the dots / rotate the spin
Readout	V_{P1}, V_{P2} detuning	Move to the (1,1) → (0,2) readout point and detect Pauli spin blockade

Hot Spin Qubits



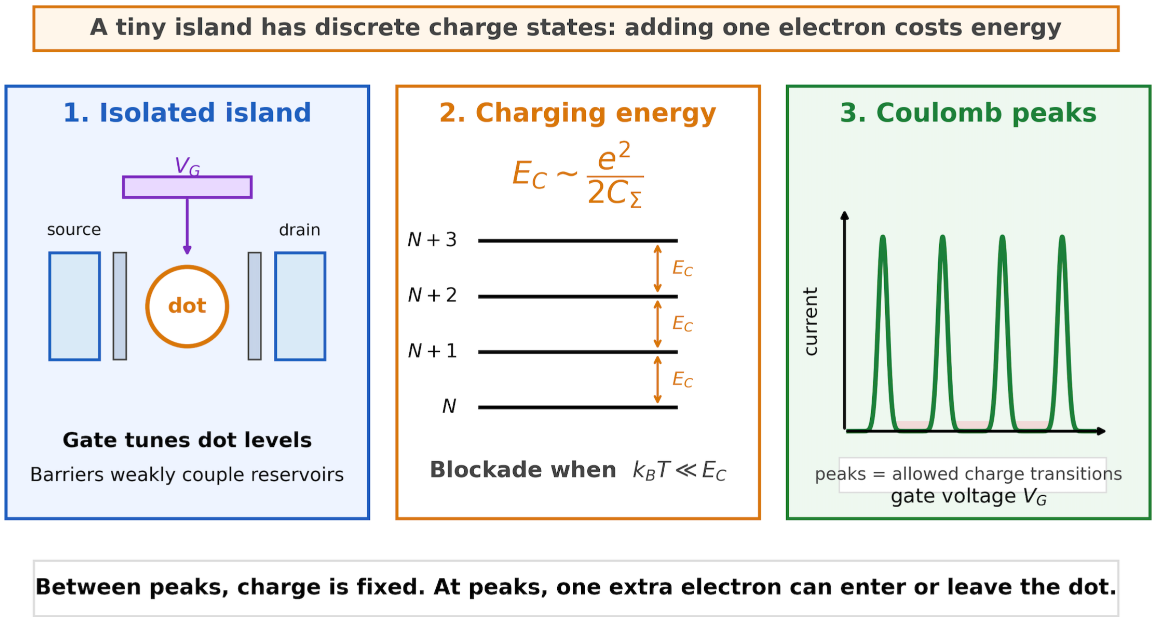
Step	**What you change**	**Purpose**
Load holes	V_{P1}, V_{P2}	Load holes into the quantum dots
Isolate (1,1)	V_B	Isolate the dots / control tunnelling
Operate	V_B + AC gate pulse	Couple the dots / rotate the spin
Readout	V_{P1}, V_{P2} detuning	Move to the $(1,1) \rightarrow (0,2)$ readout point and detect Pauli spin blockade

Coulomb blockade

Coulomb blockade is extremely useful for quantum dots and spin qubits.

It is the mechanism that lets us **control electrons one by one**.

Adding one electron costs the charging energy: $E_C \sim \frac{e^2}{2C_\Sigma}$



Pauli spin blockade for readout

Pauli spin blockade occurs in a double quantum dot.

A charge transition is allowed for a singlet configuration but blocked for a triplet configuration.

Typical transition:

$S(1{,}1) \rightarrow S(0{,}2)$

A spin state itself is hard to measure directly.
A charge movement is much easier to measure.

Pauli spin blockade maps spin symmetry onto charge motion.
S(1,1) → S(0,2) allowed: charge moves
T(1,1) → S(0,2) blocked: charge stays

triplet cannot become a singlet without a spin change.
If the two-spin state is triplet-like, charge motion is blocked by spin selection rules.

This makes Pauli spin blockade a central readout mechanism for singlet-triplet and two-spin devices.

Pauli spin blockade for readout

Allowed

$S(1,1)$ → $S(0,2)$

dot 1: ↑ | dot 2: ↓ → dot 1: 0 | dot 2: ↑ ↓

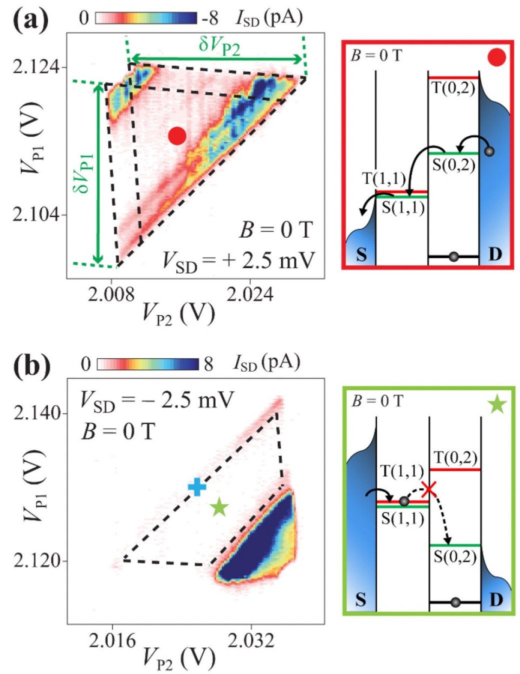
same spin symmetry
different charge distribution
charge moves

Blocked

$T(1,1)$ ✗ $S(0,2)$

dot 1: ↑ | dot 2: ↑ ✗ dot 1: 0 | dot 2: ↑ ↓

spin symmetry mismatch
triplet cannot become
low-energy singlet



Pauli spin blockade maps spin symmetry onto charge motion.

S(1,1) → S(0,2) allowed: charge moves

T(1,1) → S(0,2) blocked: charge stays

SCIENTIFIC REPORTS -1 : 110 –
DOI: 10.1038/srep00110

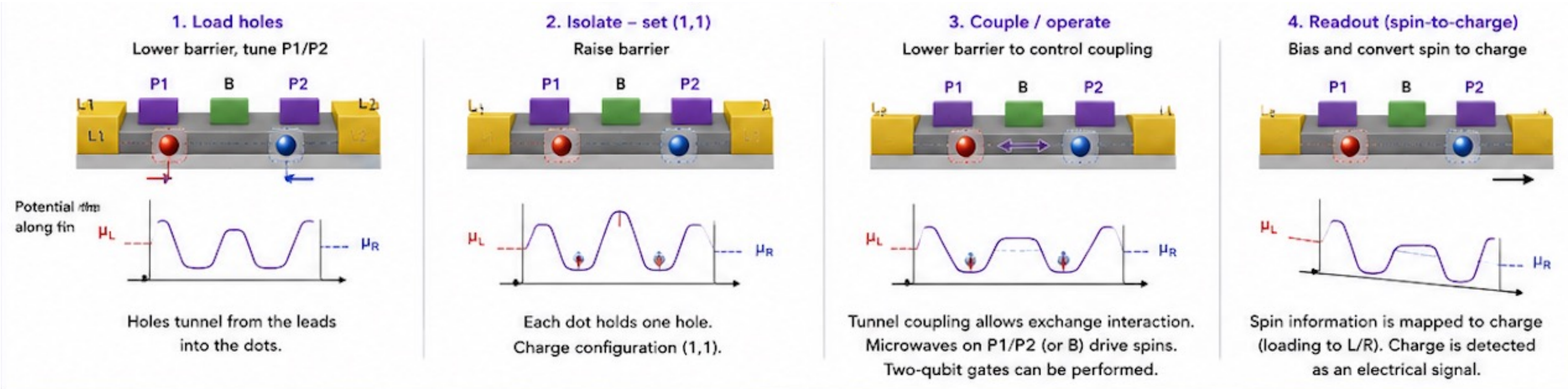
Pauli spin blockade protocol

Pauli spin blockade then maps this spin information onto a charge/current signal

1)Tune the double dot in the few-charge **Coulomb-blockade regime**.
The occupation is well defined, for example (1,1), (0,2), or (2,0).
2) **Initialize** into a known charge/spin configuration.
For example, load one hole in each dot.
3) **Apply control pulses** or microwave/electric drive.
This rotates the spin state or changes the singlet/triplet probability.
4) **Pulse to the readout** point near the spin-blockade transition.
This is where (1,1)→(0,2) or (1,1)→(2,0) is energetically allowed for a singlet but blocked for a triplet.
5) **Measure current**.
If charge moves, the state was singlet-like. If charge is blocked, the state was triplet-like.
6) **Convert** the signal into a singlet/triplet or spin-state probability.

charge transition observed → singlet-like state
charge transition blocked → triplet-like state

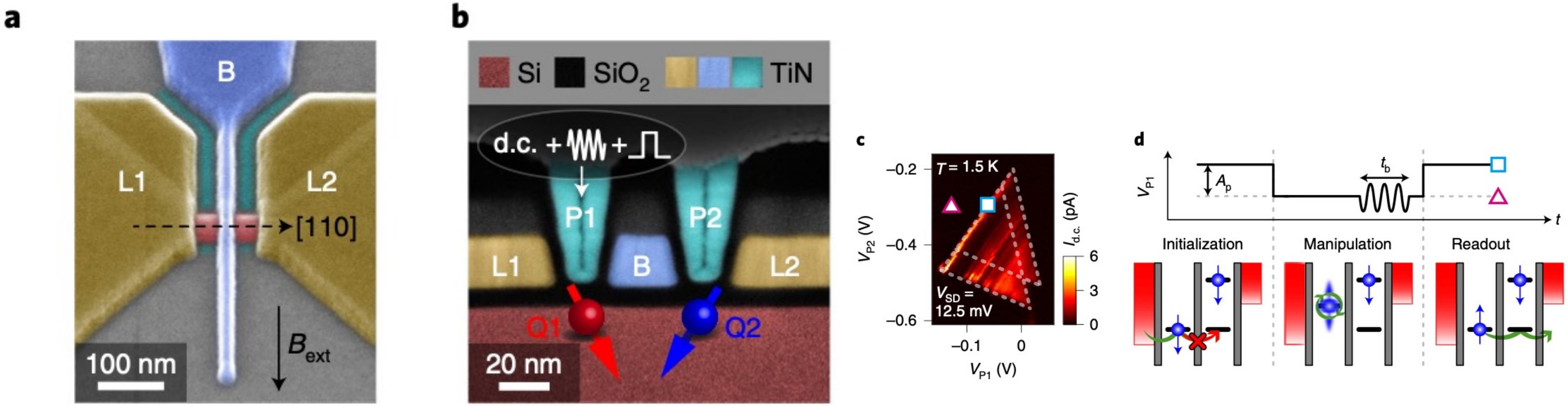
Hot Spin Qubits

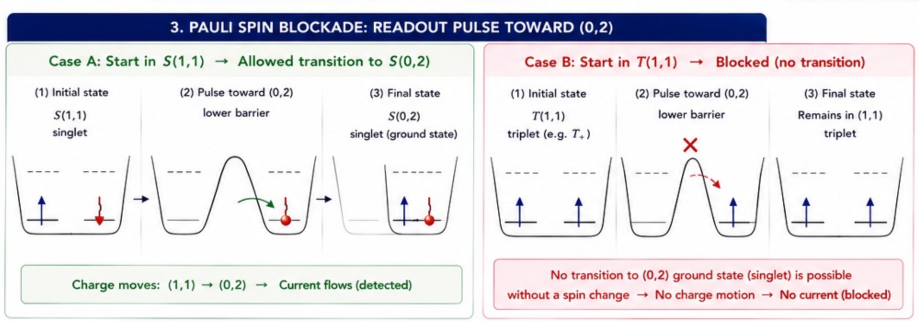


An AC pulse rotates the spin through spin-orbit coupling, and the two-spin state has a certain probability to be singlet-like or triplet-like.

<u>Pauli spin blockade then maps this spin information onto a charge/current signal</u>

Hot Spin qubits





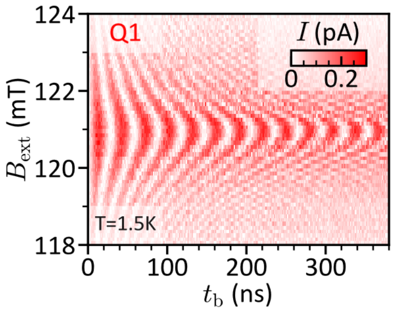
The narrow central silicon fin is the active region. Gates around it define where holes are confined.

Hot Spin qubits

The device still shows coherent spin control and measurable Ramsey coherence at T = 4.2 K

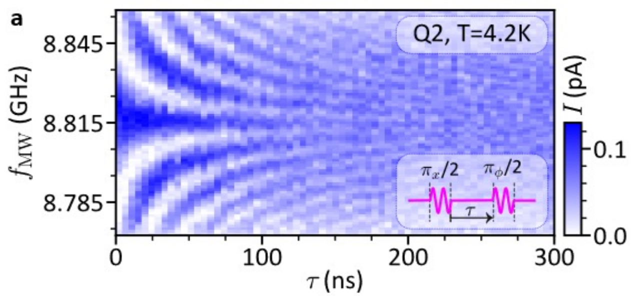
Rabi: (driven spin rotation)

- f_{Rabi} ~ 150 MHz (<u>VERY FAST</u>)
- Q-factor > 100 cycles

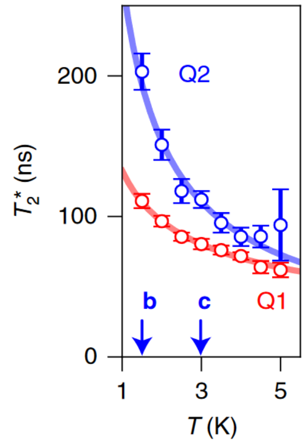


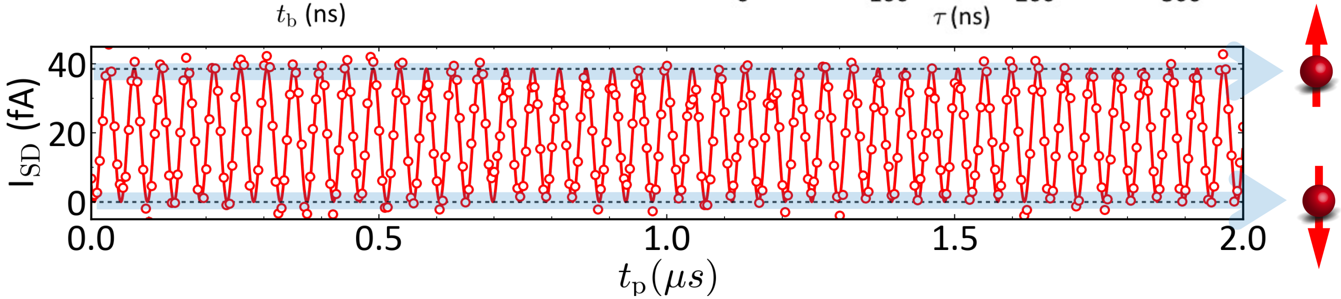
Ramsey: (phase coherence during free evolution)

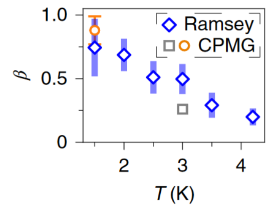
- T_2^* ~ 440 ns
- Q^*-factor ~ 40 cycles



High T > 4 K







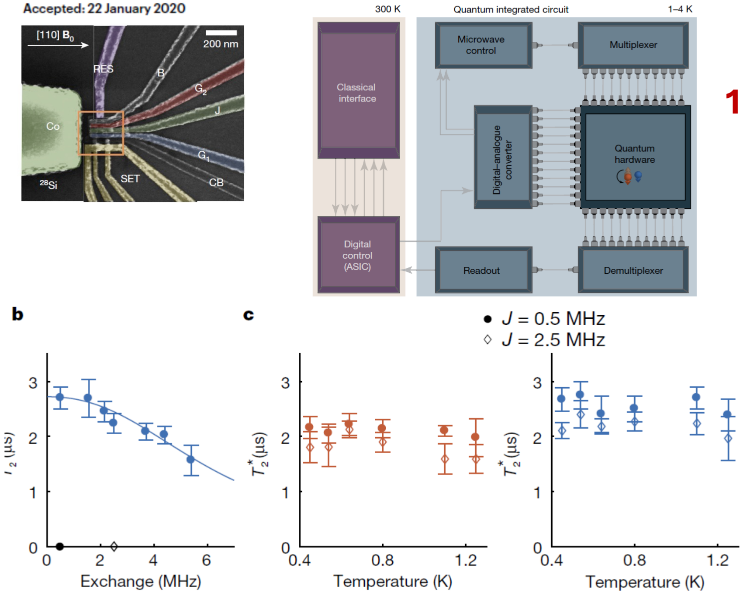
Hot Spin qubits

Operation of a silicon quantum processor unit cell above one kelvin

Sydney

https://doi.org/10.1038/s41586-020-2171-6
Received: 19 June 2019
Accepted: 22 January 2020

C. H. Yang[1✉], R. C. C. Leon[1], J. C. C. Hwang[1,6], A. Saraiva[1], T. Tanttu[1], W. Huang[1], J. Camirand Lemyre[2], K. W. Chan[1], K. Y. Tan[3,7], F. E. Hudson[1], K. M. Itoh[4], A. Morello[1], M. Pioro-Ladrière[2,5], A. Laucht[1] & A. S. Dzurak[1✉]



1 K

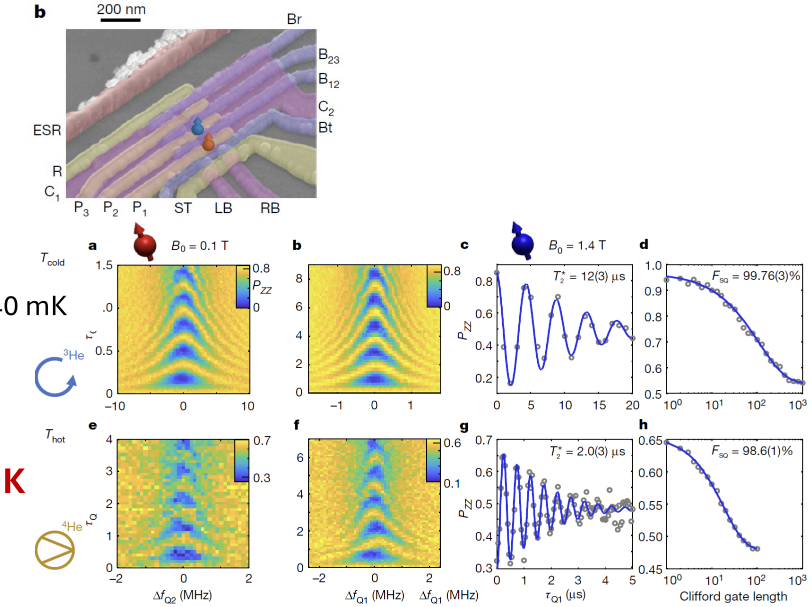
Nature **580**, 350 (Apr 2020)

Universal quantum logic in hot silicon qubits

Delft

https://doi.org/10.1038/s41586-020-2170-7
Received: 22 October 2019
Accepted: 22 January 2020

L. Petit[1], H. G. J. Eenink[1], M. Russ[1], W. I. L. Lawrie[1], N. W. Hendrickx[1], S. G. J. Philips[1], J. S. Clarke[2], L. M. K. Vandersypen[1] & M. Veldhorst[1✉]



40 mK

1.5 K

Nature **580**, 355 (Apr 2020)

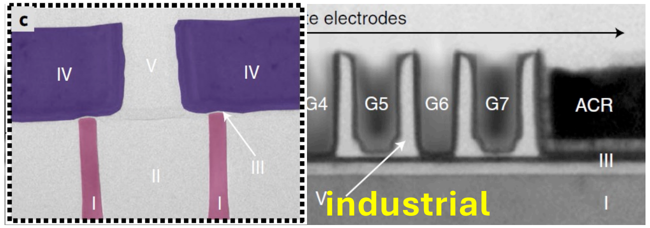
Hot Spin qubits

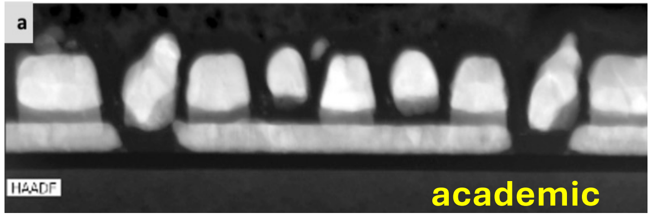
ARTICLES
https://doi.org/10.1038/s41928-022-00727-9
nature electronics
Check for updates

OPEN

Qubits made by advanced semiconductor manufacturing

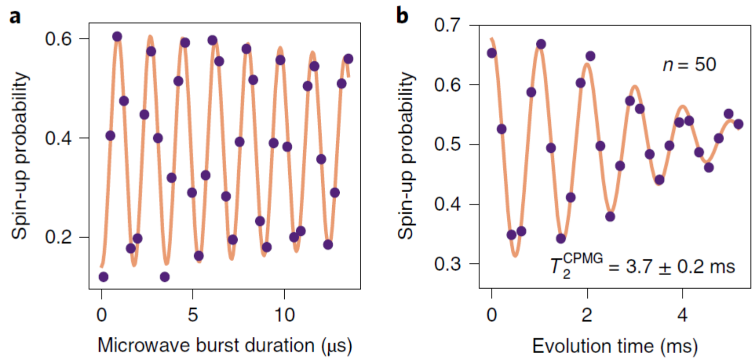
A. M. J. Zwerver[1], T. Krähenmann[1], T. F. Watson[2], L. Lampert[2], H. C. George[2], R. Pillarisetty[2], S. A. Bojarski[2], P. Amin[2], S. V. Amitonov[1], J. M. Boter[1], R. Caudillo[2], D. Correas-Serrano[2], J. P. Dehollain[1], G. Droulers[1], E. M. Henry[2], R. Kotlyar[2], M. Lodari[1], F. Lüthi[2], D. J. Michalak[2], B. K. Mueller[2], S. Neyens[2], J. Roberts[2], N. Samkharadze[1], G. Zheng[1], O. K. Zietz[2], G. Scappucci[1], M. Veldhorst[1], L. M. K. Vandersypen[1] ✉ and J. S. Clarke[2] ✉





- gate length 50 nm
- large aspect ratio fins
- trenches filled with oxide
- electrons (vs holes)
- **full industrial all-optical process 300 mm Intel**

micromagnets for spin manipulation



Nature Electronics **5**, 184 (March 2022)

Qubit as a sensor

Qubits as sensors

Qubits are fragile

but

that fragility is sensitivity

Quantum sensors turn the environmental sensitivity of quantum systems into a measurement advantage.

DiVincenzo Criteria (2000)

David DiVincenzo

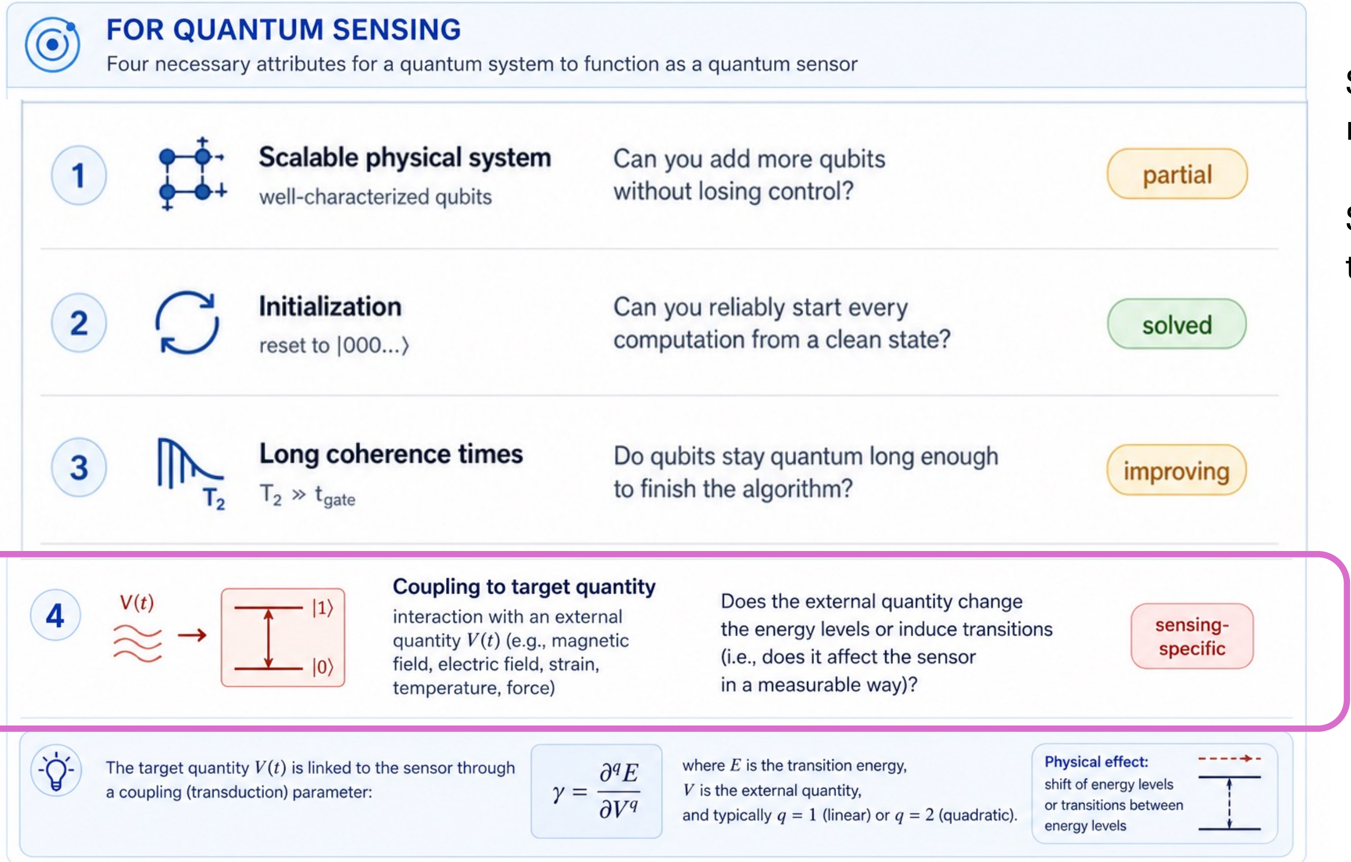
#	Criterion	Question	Status
1	**Scalable physical system** well-characterized qubits	Can you add more qubits without losing control?	partial
2	**Initialization** reset to |000...⟩	Can you reliably start every computation from a clean state?	solved
3	**Long coherence times** $T_2 \gg t_{gate}$	Do qubits stay quantum long enough to finish the algorithm?	improving
4	**Universal gate set** single + two-qubit gates	Can you implement any quantum algorithm with available gates?	solved
5	**Qubit-specific measurement** readout fidelity > 99%	Can you read one qubit without disturbing the others?	partial
	FOR QUANTUM COMMUNICATION		
6	**Stationary ↔ flying qubit** processor ↔ photon interface	Can you transfer a qubit from a chip onto a photon to send it?	open
7	**Faithful transmission** quantum networks	Can you send qubits between distant locations without errors?	open

Scalable, stable and measurable qubits

that can be used to send information

- **solved** — achieved on all major platforms
- **partial / improving** — works but not at scale
- **open** — no platform has achieved this yet

Criteria for sensing



Scalable, stable and measurable qubits

Strong coupling to the target

Qubits as sensors

Quantum sensing is not one technology

It is a family of platforms optimized for different observables and environments.

Market reports typically segment the field into

atomic clocks, magnetometers, gravimeters, gyroscopes/accelerometers, RF sensors, single-photon detectors, quantum imaging….

Qubits as sensors

Quantity	Example quantum sensor	Typical application
Magnetic field	NV centers, SQUIDs, atomic magnetometers	brain signals, materials, geophysics
Electric / RF field	Rydberg atoms, NV centers	antenna calibration, communications, RF imaging
Gravity	atom-interferometer gravimeters	underground mapping, geophysics
Acceleration / rotation	atom interferometers, quantum gyroscopes	inertial navigation
Time / frequency	atomic clocks, optical clocks	GPS, telecom, synchronization
Temperature / strain / pressure	NV centers, optomechanical sensors	nanoscale imaging, materials

Qubits as sensors

The same coupling channel can be viewed in two opposite ways:

In quantum computing, uncontrolled environmental coupling is noise and should be minimized or corrected.

In quantum sensing, a specific coupling to the target quantity is intentionally enhanced or exploited.

In quantum computing, one protects the qubit from the environment

Quantum sensing uses the fragility of quantum systems as a resource: the environment perturbs the quantum state, and that perturbation becomes the measurement signal.

Qubits as sensors (external field)

A qubit is a two-level quantum system whose evolution is governed by a Hamiltonian.

If an **external parameter λ changes the Hamiltonian**, the final qubit state becomes sensitive to **λ.**

$$H(\lambda) = H_0 + \lambda G$$

λ=quantity to be measured
G=coupling operator (with qubit)

After an evolution time t: $U_\lambda(t) = e^{-iH(\lambda)t/\hbar}$

and an initial state becomes: $|\psi\lambda(t) >= U\lambda(t)|\psi_0 >$

The parameter λ changes the Hamiltonian, so the qubit accumulates a λ-dependent evolution that can be measured.

Qubits as sensors

Key idea: I want to measure the effect of the external parameter

$\lambda \rightarrow H(\lambda) \rightarrow$ phase / population change → measurement signal

A qubit is a sensor when an external field or perturbation changes its Hamiltonian and leaves a measurable imprint on the final quantum state.

Qubits as sensors (protocol)

Most quantum-sensing protocols follow the same structure:

initialize → prepare superposition → interact with signal → readout

λ = external parameter to be sensed

For example, λ could be: $B,\ E,\ T,\ a,\ \Omega,\ p$ magnetic field, electric field, temperature, acceleration, rotation rate, pressure, etc.

For a phase sensor:

$$|\psi_0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

During sensing time t, the parameter λ changes the energy splitting between the two states: $\Delta E = \Delta E(\lambda)$
This produces a relative phase

$$\phi(\lambda) = \frac{\Delta E(\lambda) t}{\hbar}$$

The final measurement converts phase into population: phase shift → probability change

Qubits as sensors (protocol)

This type of sequence is then central to sensing:

$$X_{\pi/2} \quad \rightarrow \quad \text{sensing time } t \quad \rightarrow \quad X_{\pi/2} \quad \rightarrow \quad \text{measure}$$

quantum sensors work by converting a tiny field-induced phase shift into a measurable population difference.

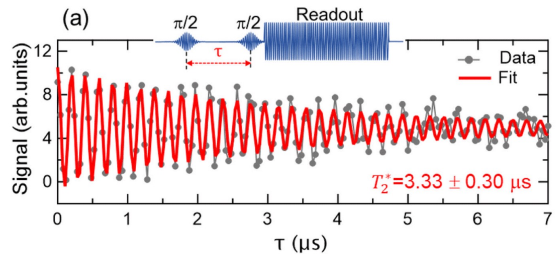
T_2^* Ramsey experiments

Standard pulse sequence: $X_{\pi/2} \rightarrow$wait $t \rightarrow X_{\pi/2} \rightarrow$ measure

$X_{\pi/2}$: 90° rotation around the X-axis
Used to create superposition states

A typical Ramsey signal can be written as:

$$P_1(t) = \frac{1}{2}\left[1 + Ce^{-\frac{t}{T_2^*}} \cos(\Delta\omega t + \phi_0)\right]$$



Commun Mater **2**, 98 (2021)

C is the contrast
$\Delta\omega$ is the detuning between the qubit and the drive reference
ϕ_0 is a phase offset

The decaying envelope gives T_2^*.

T_2^* is sensitive to slow frequency fluctuations, device drift, detuning noise, magnetic noise, charge noise, and flux noise.

Basic sensing (Ramsey)

The Ramsey sequence is the prototype of many qubit-based sensors:

$$X_{\pi/2} \;\rightarrow\; \text{sensing time } t \;\rightarrow\; X_{\pi/2} \;\rightarrow\; \text{measure}$$

During the sensing time, the **external parameter changes the qubit frequency**:

$$\omega_q(\lambda) = \omega_0 + \delta\omega(\lambda)$$

<u>The measured signal is:</u> $P_1(t) = \frac{1}{2}\left[\, 1 + Ce^{-t/T_2^*} \cos(\delta\omega(\lambda)t + \phi_0) \,\right]$

Sensitivity improves with longer coherent interrogation time, but the useful time is limited by dephasing:

$$t \lesssim T_2^*$$

Sensing time is limited by dephasing

or, with echo/dynamical decoupling:

$$t \lesssim T_2$$

Coherence time sets the measurement window of the sensor.

Sensitivity

The quantum sensor output is a probability

Sensitivity

A quantum sensor is useful when a small change in λ produces a measurable change in the outcome.

In a quantum sensor, the unknown parameter λ changes the measured probability: $P(\lambda)$

the local response is:

$$\frac{\partial P}{\partial \lambda}$$

how strongly the probability changes when λ changes a little

If the slope (λ) is large, the sensor is very responsive.

large slope ⇒ small change in λ gives a visible change in P

If the slope is small, the sensor is not very sensitive.

small slope ⇒ hard to detect small changes in λ

What is a good sensor? (uncertainty estimate)

The smallest resolvable change in λ can be estimated by:

$$\delta\lambda \sim \frac{\Delta P}{|\partial P/\partial\lambda|}$$

The uncertainty $in\ \lambda$ is the noise in the measured probability divided by how strongly the probability reacts to λ.

$\Delta P =$ noise / uncertainty $\quad\quad \left|\frac{\partial P}{\partial \lambda}\right| =$ sensitivity slope

A good sensor needs ΔP small and $\left|\frac{\partial P}{\partial \lambda}\right|$ large

for a strong response

low noise + steep slope $\Rightarrow$ small uncertainty $\delta\lambda$

Sensitivity limit (quantum limit)

Each single qubit measurement gives a random result:

$$0 \quad \text{or} \quad 1$$

So the experiment must be repeated many times.

If you repeat it N times, random statistical noise decreases as:

$$\Delta P \sim \frac{1}{\sqrt{N}}$$

Therefore:

$$\delta\lambda \propto \frac{1}{\sqrt{N}}$$

For ideal independent probes,
this is called the **standard quantum limit**.

For example:
100 repetitions improve precision by 10
10,000 repetitions improve precision by 100

It is the natural precision limit when you use independent qubits or independent repetitions.

Qubits as sensors

Entangled or squeezed states can improve scaling, but many practical sensors are limited by:

T_2, readout noise, technical noise, calibration drift

high sensitivity requires large response, low noise, long coherence, and stable calibration.

Qubits as sensors

Platform	Quantum degree of freedom	Typical measurand	Strength
Atomic clocks	atomic transition frequency	time / frequency	highest precision timing
Atom interferometers	matter-wave phase	gravity, acceleration, rotation	inertial and geophysical sensing
NV centers	defect spin in diamond	magnetic field, temperature, strain	room-temperature nanoscale sensing
SQUIDs	superconducting phase / flux	magnetic flux	ultra-sensitive magnetometry
Atomic magnetometers	atomic spin precession	magnetic field	biomagnetism, navigation
Rydberg atoms	high-n atomic states	RF / microwave fields	traceable field sensing
Optomechanical sensors	mechanical displacement	force, acceleration	precision displacement sensing

What is the best sensor?

The best sensor depends on the quantity to be measured

Spin qubits as a magnetic sensor

A spin couples directly to a magnetic field through the Zeeman interaction:

$$H_B = \frac{1}{2} g\mu_B \mathbf{B} \cdot \boldsymbol{\sigma}$$

$\boldsymbol{\sigma}$ Pauli matrices

If the field defines the z-axis:

$$H_B = \frac{1}{2} \hbar \omega_L Z$$

where (Larmor precession) $\omega_L = \frac{g\mu_B B}{\hbar}$

The spin processes in presence of the field B (according to the Larmor) and the magnetic field sets the spin-precession frequency.

Spin qubits as a magnetic sensor

Prepare the spin in a superposition:

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

Then you let it evolve for time t in presence of an unknown field B.

During a sensing time t, the spin accumulates a magnetic-field-dependent phase:

$$\phi(B) = \omega_L t = \frac{g\mu_B B}{\hbar} t$$

$$B \rightarrow \omega_L \rightarrow \phi(B)$$

A stronger magnetic field produces faster spin precession and a larger accumulated phase.

Measuring this phase allows us to estimate B.

How is the magnetic field measured?

The phase $\phi(B)$ is not measured directly.

A final $\pi/2$ pulse converts the accumulated phase into a population difference.

The measured probability (population) depends on B and can be written as:

$$P_1(B) = \frac{1}{2}[1 + C\cos\phi\,(B)] = \frac{1}{2}\left[1 + C\cos\left(\frac{g\mu_B B}{\hbar}t\right)\right]$$

The magnetic field is inferred from: precession frequency or accumulated phase or final population

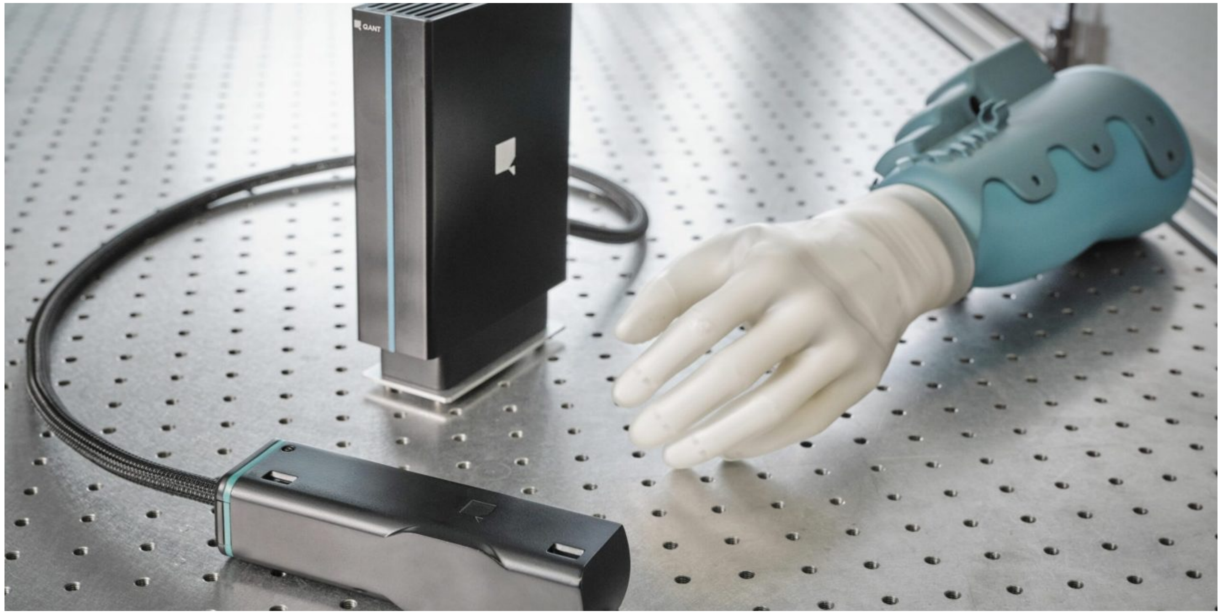
Measurement chain: $B \rightarrow \omega_L \rightarrow \phi(B) \rightarrow$ (Ramsey) $P_1(B) \rightarrow$ estimate B

A spin sensor converts magnetic-field strength into a change in spin-precession phase or population.

Magnetosensors

Sensor	Regime	Main use
NV centers	room temperature, nanoscale	magnetic imaging, materials, biology
Atomic magnetometersType equation here.	vapor cells	biomagnetism, navigation, shielding
SQUIDs	cryogenic	ultra-sensitive flux detection
Spin qubits	cryogenic / solid-state	local field probes, noise spectroscopy

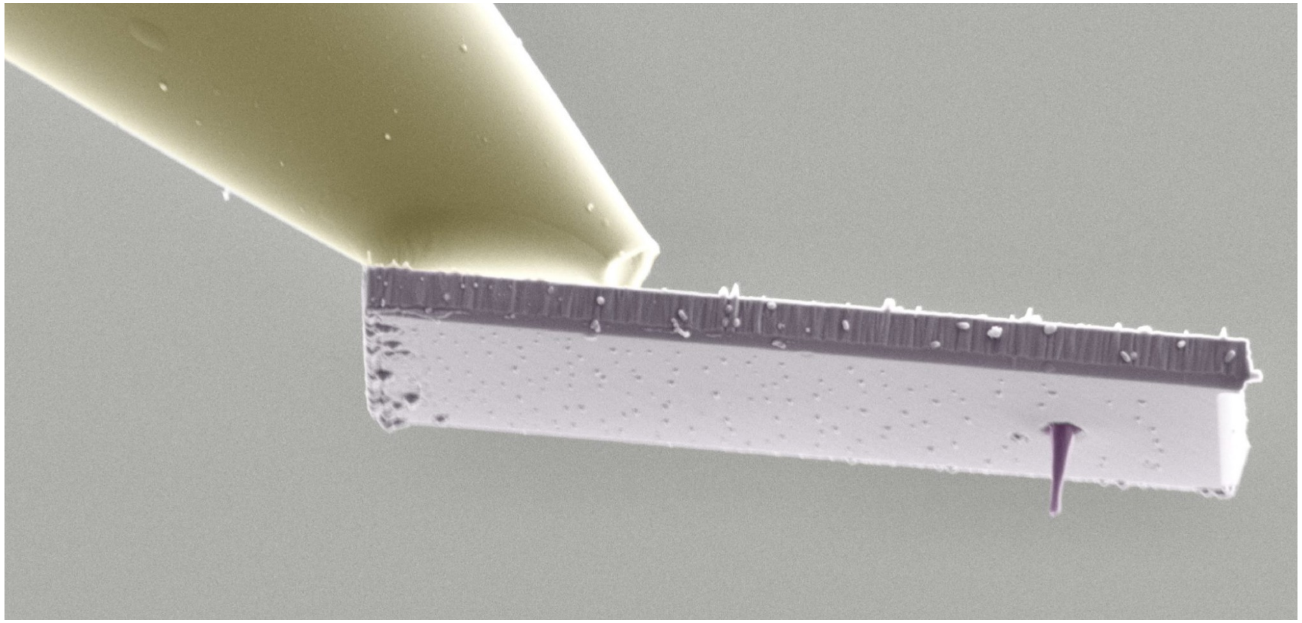
Magnetosensors



QANT

Quantum Magnetic Field Sensor to Control Prostheses, Exoskeletons and Avatars with Neural Signals

Magnetosensors



Quantilevers are diamond probes made with NV centers for scanning NV microscopy applications.

The quantum sensor is the NV center inside the diamond tip

Atom interferometers: sensing motion and gravity

Atom interferometers use matter waves instead of light waves.

Laser pulses split, redirect, and recombine atomic wave packets.

Standard pulse sequence:

$\pi/2 \;\rightarrow\; \pi \;\rightarrow\; \pi/2$

Note that this is not an Echo!

$\pi/2$ pulse = beam splitter
π pulse = mirror
$\pi/2$ pulse = recombiner

During the free-evolution time, acceleration or gravity changes the relative phase $\Delta\varphi$ between the two paths.

k_{eff} effective laser wave vector
T^2 time between pulses

$$\Delta\varphi \approx k_{eff} a T^2$$

For gravimetry

$$\boldsymbol{\Delta\varphi \approx k_{eff} g T^2}$$

Atom interferometers convert acceleration or gravity into a measurable matter-wave phase shift.

Atom interferometers: sensing motion and gravity

Applications:

gravimetry

gravity gradients

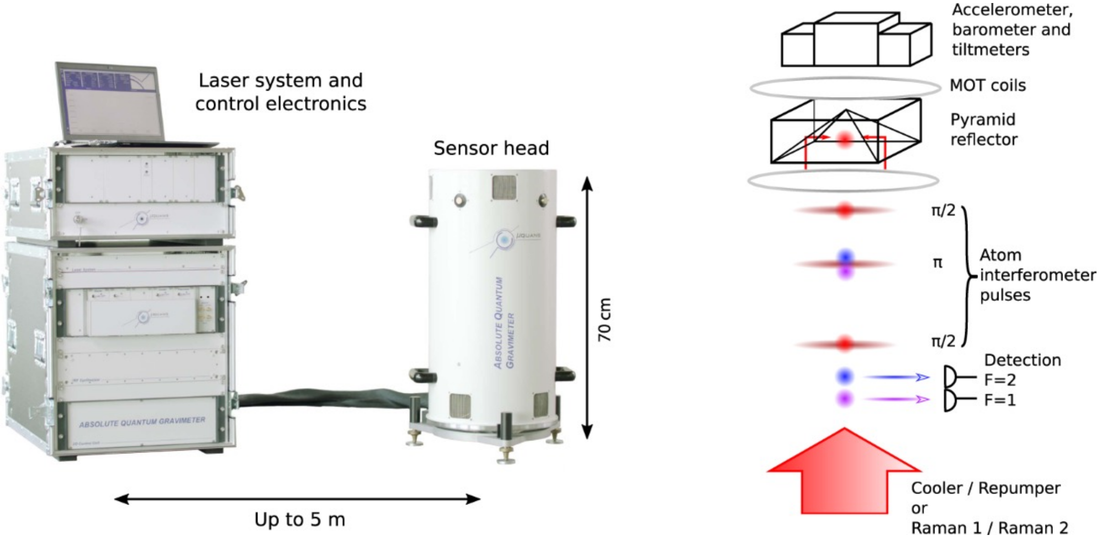
inertial navigation

geodesy and underground mapping

Quantum navigation analyses emphasize that gravimeters and magnetometers can reference Earth's gravitational and magnetic fields, offering navigation modes that do not rely on vulnerable radio-frequency signals.

Atom interferometers: sensing motion and gravity

quantum gravimeters AQG



Qubits as sensors

Qubits are fragile

but

that fragility is sensitivity

Quantum sensors turn the environmental sensitivity of quantum systems into a measurement advantage

Qubits as sensors

Quantum computing	**Quantum sensing**
implement algorithms	estimate physical parameters
gate fidelity and circuit depth	sensitivity, bandwidth, stability
qubit scaling	field deployment and calibration
output bitstrings	physical measurement signal

Quantum sensors exploit the same physical resources that make qubits powerful but the objective is different

From sensitivity to the deployment

High sensitivity is not enough for a real quantum sensor.

Deployment also requires:

robust packaging
calibration stability
field operation
cost control
data interpretation
integration with classical systems

This is why the quantum sensing market is already real, but highly segmented.

Market landscape

Quantum sensing is already a real market, but deployment depends on robustness, packaging, calibration, and cost.

The market is fragmented.

The strongest near-term impact is expected where classical sensors are limited by weak signals, inaccessible environments, long-term drift, or the need for GPS-independent reference signals.

Current market estimates vary because reports include different technologies such as atomic clocks, magnetometers, gravimeters, RF sensors, imaging systems, single-photon detectors, and components.

Market landscape

Source	Estimate
Global Market Insights	USD 414.6M in 2025; USD 478.8M in 2026; USD 1.3B by 2035
Mordor Intelligence	USD 0.86B in 2026; USD 1.57B by 2031
Persistence Market Research	USD 389.5M in 2026; USD 945.1M by 2033
IDTechEx	quantum sensors market to reach about USD 2.2B by 2045

Qubits as sensors? Hype or reality?

April 8, 2026 | 3 min read Add Us On Google

Is the 'Ghost Murmur' quantum device possible? Scientists are skeptical

Ghost Murmur was described as a futuristic CIA tool that could detect a heartbeat from vast distances. Physicists say the public story clashes with the basic limits of magnetic sensing

SCIENTIFIC AMERICAN

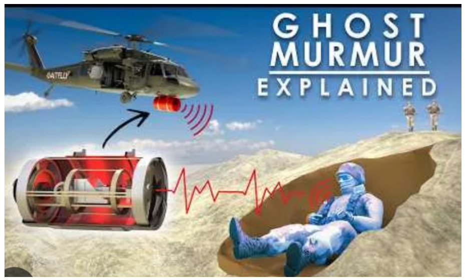
NEW YORK POST

POLITICS EXCLUSIVE

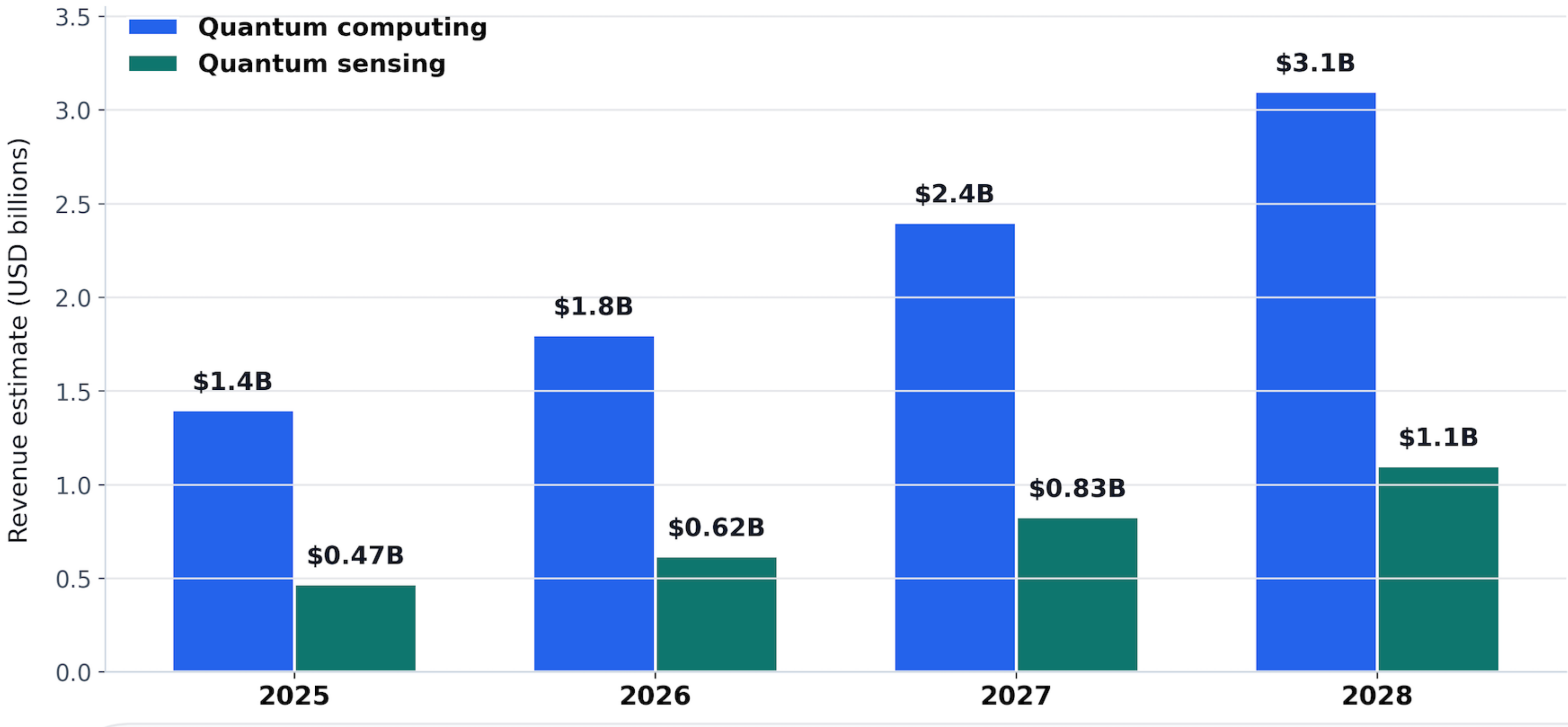
The secret, never-before-used CIA tool that helped find airman downed in Iran: 'If your heart is beating, we will find you'

By Steven Nelson
Published April 7, 2026, 1:47 p.m. ET

856 Comments



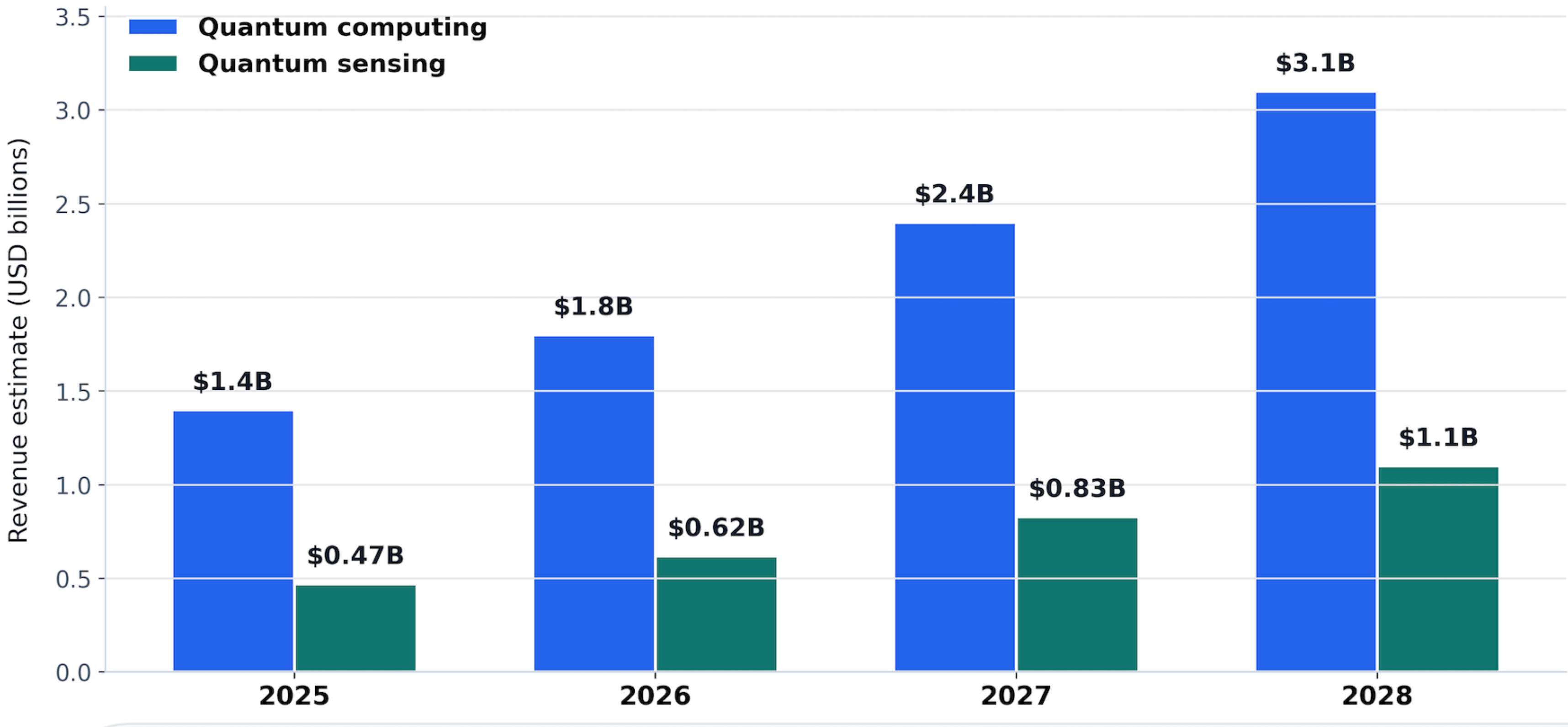
Quantum market: near-term



Source: QED-C 2026

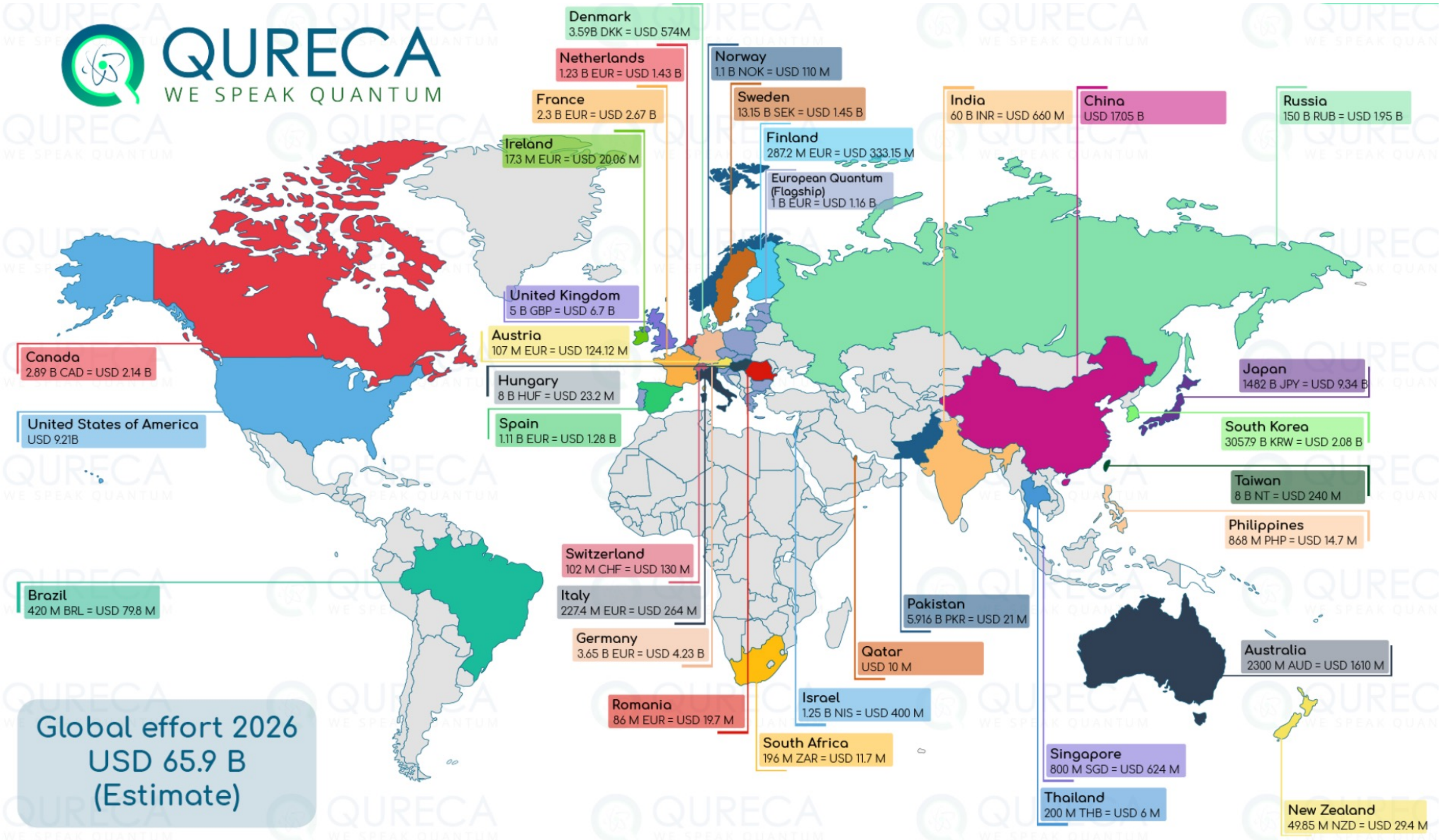
Quantum workforce and physics PhD

Quantum market: near-term



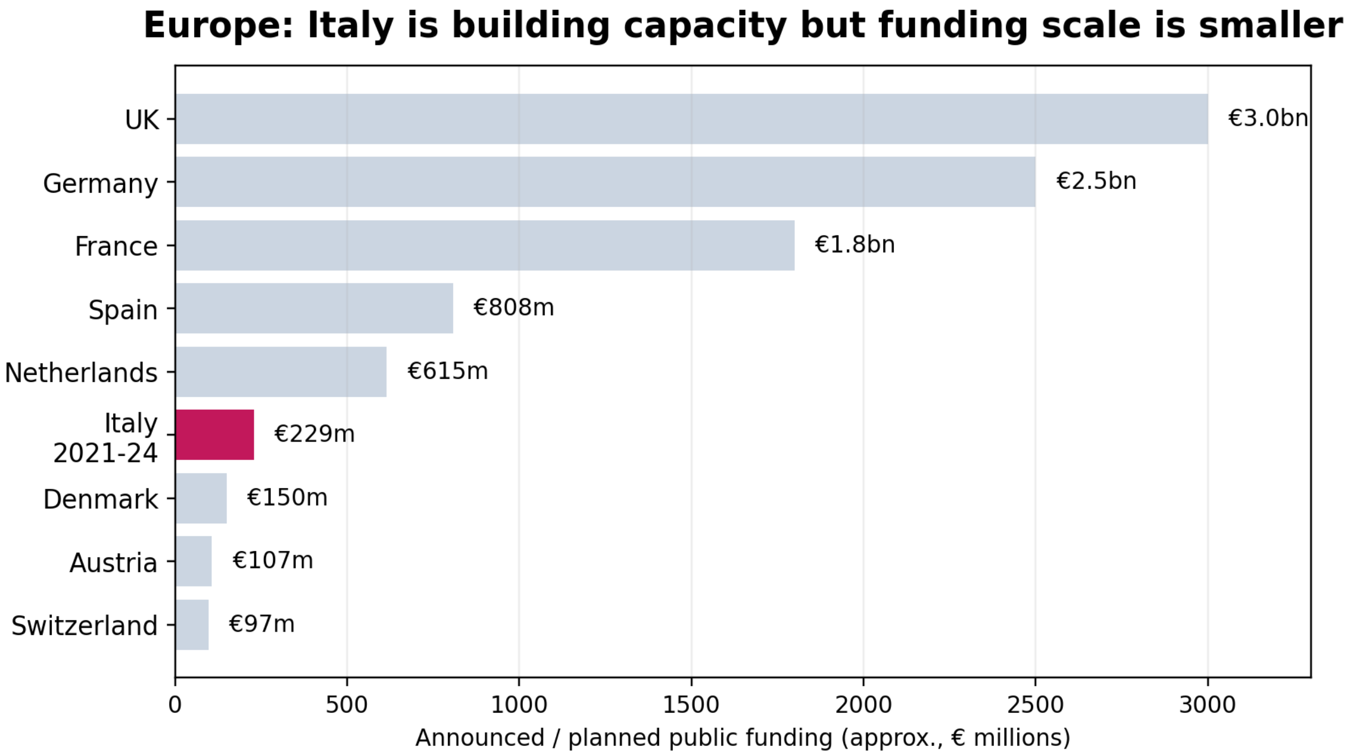
Source: QED-C 2026

Global Quantum Investments



Italy has invested **227.4 million €** during 2021-2024 to bolster quantum research, industrial applications, and workforce development

Global Quantum Investments



Italy: key data points

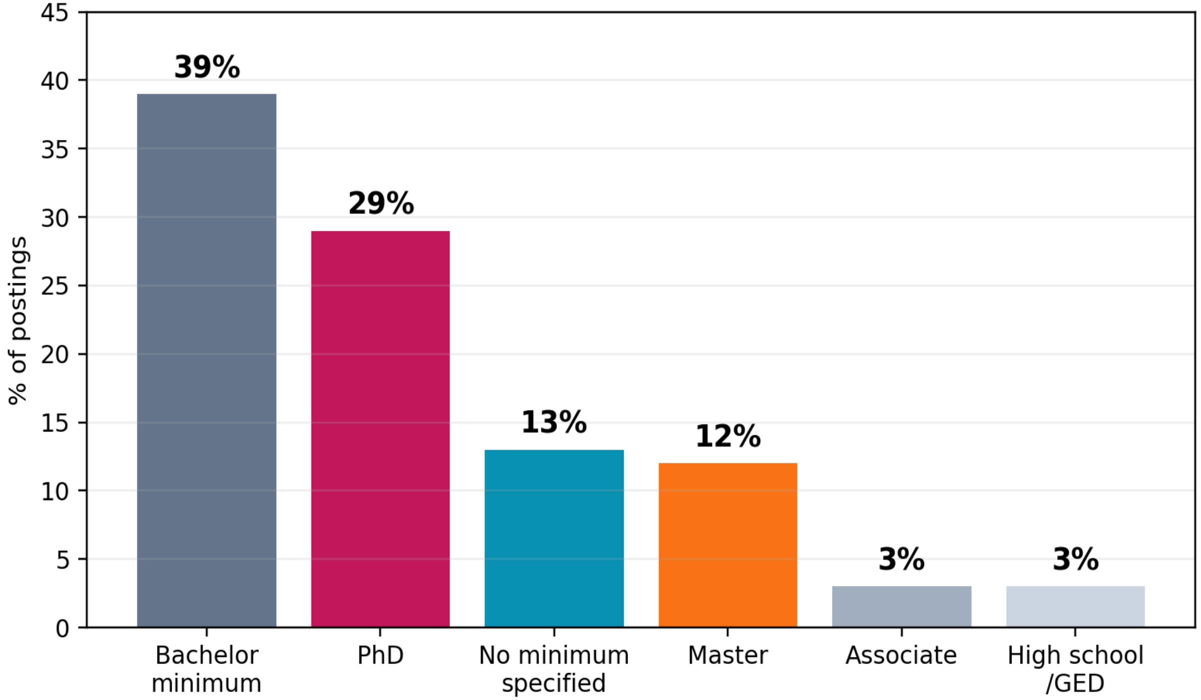
- €229m invested in 2021-2024
- 86% linked to PNRR projects
- +€70m EuroQCI/EuroHPC infrastructure
- Strategy suggests ~€200m/year for 5 years to approach leading scale

Italy has scientific strength; scale-up is the gap

Source: Italian Quantum Strategy 2025, Table 3 and funding framework; Quantum Flagship; MAECI

Quantum workforce

Degree requirements: PhDs matter, but the workforce is broader

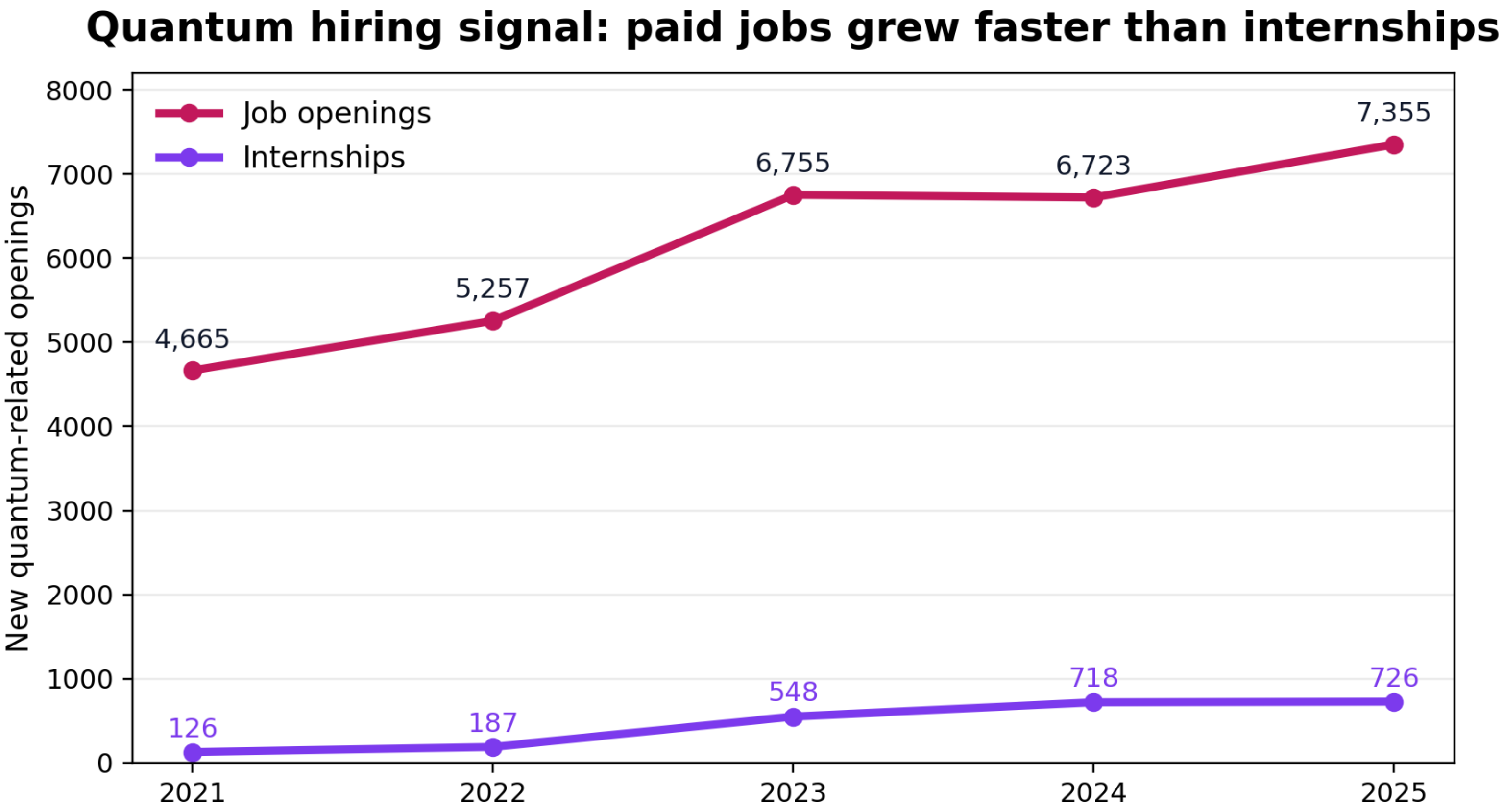


Strongest near the scientific core:
- qubit physics
- modelling / algorithms
- metrology
- benchmarking
- experiments

Add delivery evidence: code, documentation, calibration, teamwork.

The quantum workforce is not simply "more PhDs."
It is a mix of researchers, engineers, software profiles, operators and commercial roles

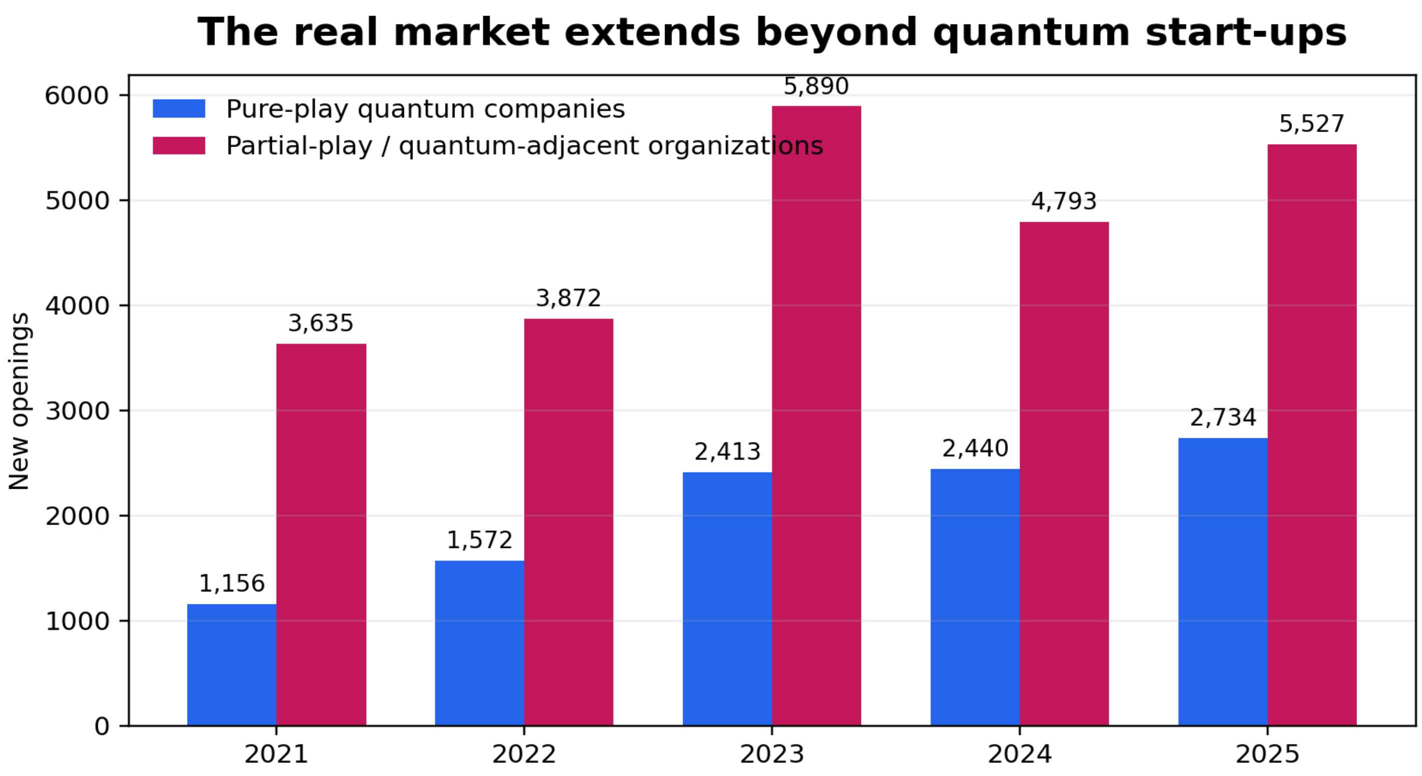
Quantum workforce



More paid, longer-term commitments than in earlier years.

Source: QED-C 2026

Quantum workforce: who is hiring?



Pure-play start-ups are not the only target.

Look also at:

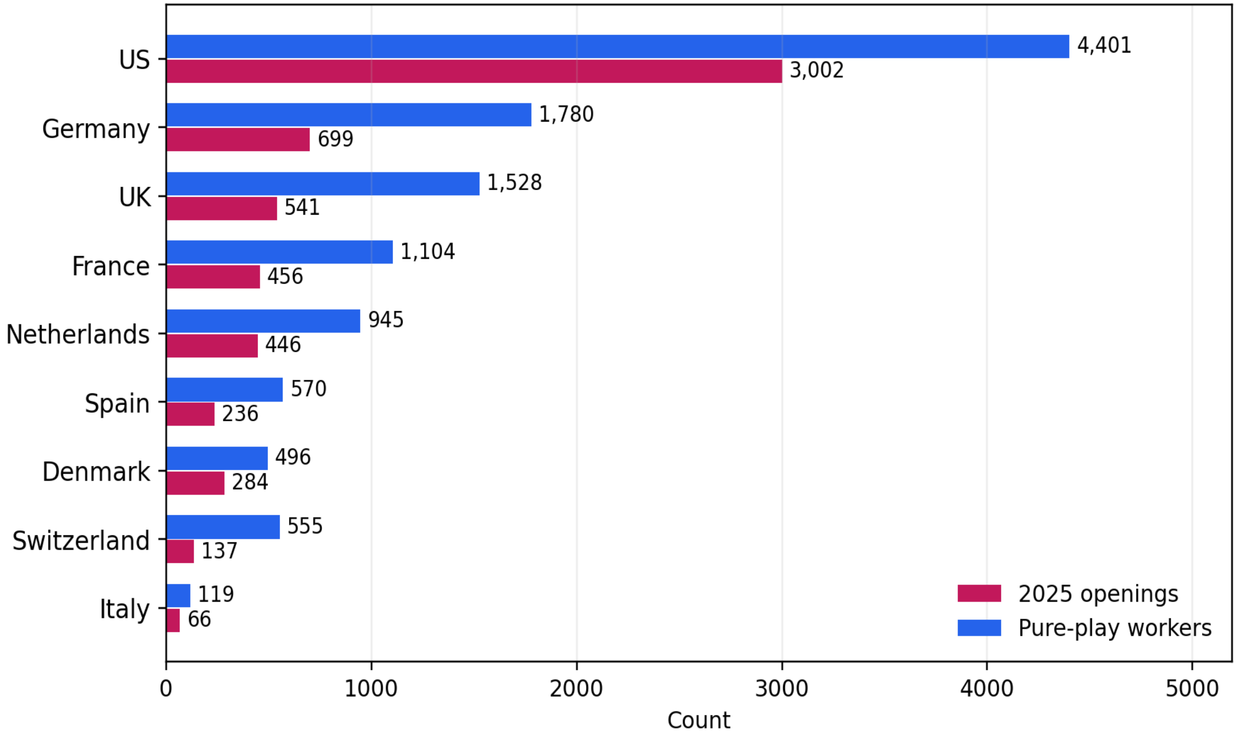
- semiconductors
- photonics / cryogenics
- RF electronics
- cloud / HPC
- cybersecurity
- sensing users

Pure-play quantum companies are not the only source of opportunities

Source: QED-C 2026

Quantum workforce: openings - geographical data

Europe has strong nodes, but opportunities are unevenly distributed



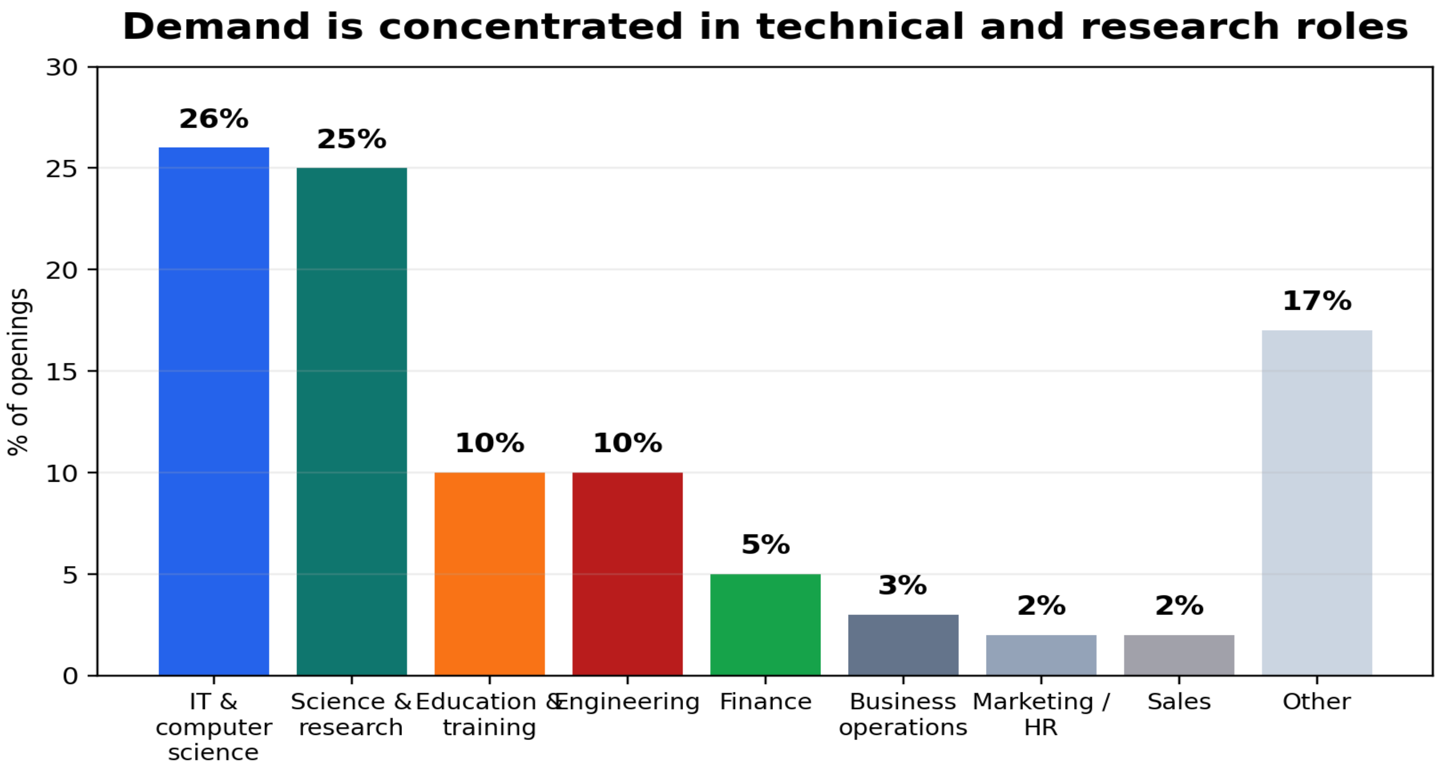
Italy is smaller in current openings, but has strong academic assets and a new national strategy.

Opportunity: connect research excellence with industrialization, infrastructure and mobility.

Young researchers may need international mobility or remote/hybrid collaboration to access opportunities

Source: QED-C 2026

Quantum workforce: roles



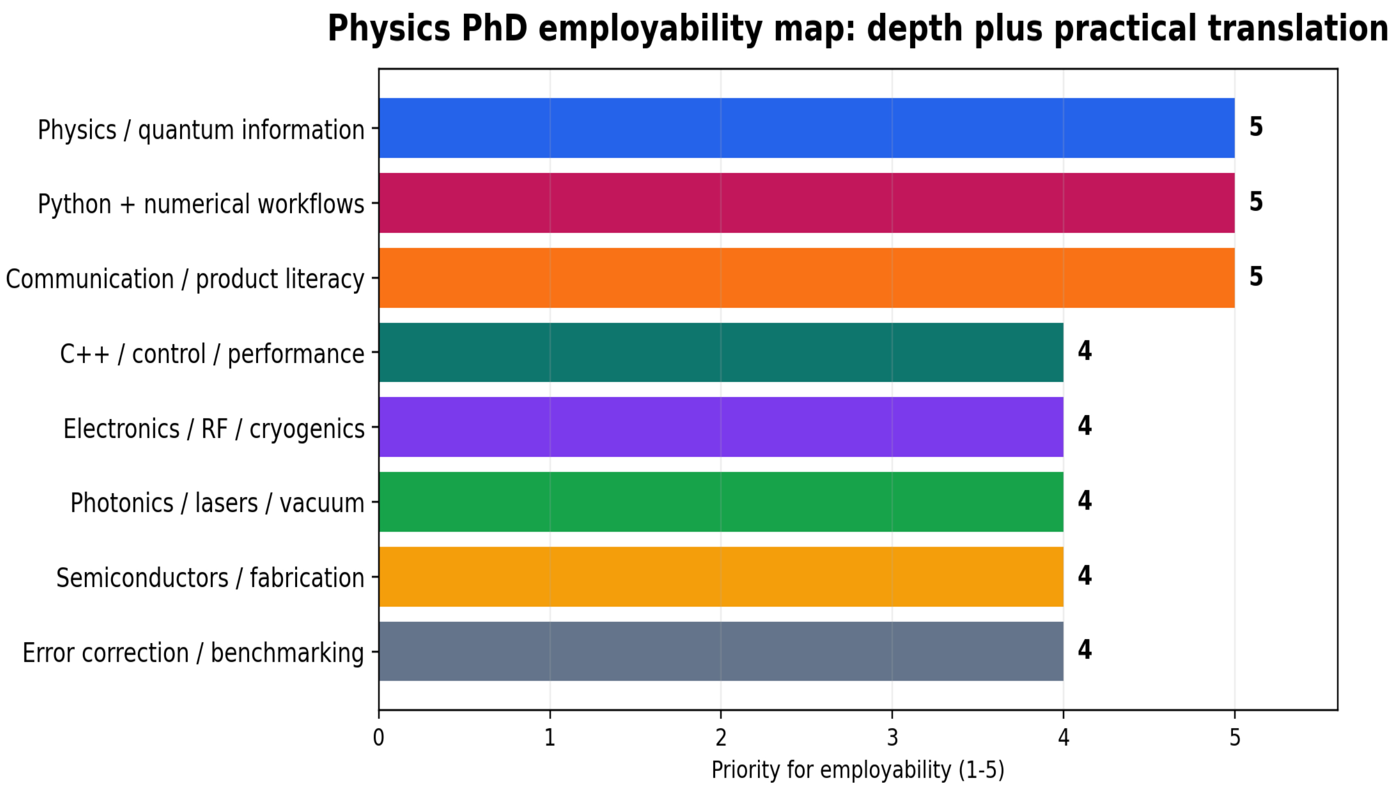
Technical/research roles dominate.

But a PhD physicist also needs evidence of:

- software
- systems
- teaching
- project delivery
- stakeholder skills

Source: EPO-OECD 2025 job posting analysis

Quantum workforce: PhD Physics



Do not present only as "quantum expert."

T-shaped profile:
- deep platform knowledge
- coding/data workflows
- calibration discipline
- communication/product literacy

PhD physicists are most valuable near the core of platform development, theory, modelling, experiments, benchmarking and error correction.

Sources:QED-C, EPO-OECD, QuIC workforce analyses

Quantum workforce: PhD Physics across sectors

	Academia	Industry / start-ups	Government labs	Public agencies / NGOs	Suppliers / enabling tech
Basic research	5	4	4	3	3
Hardware R&D	3	5	5	2	5
Engineering / product	1	5	3	2	5
Software / data	2	5	4	3	3
Teaching / training	5	2	3	4	2
Policy / standards	2	3	4	5	2
Commercial / user-facing	1	5	3	4	4
Stability	2	2	4	4	3
Publication pressure	5	1	3	1	1
IP / confidentiality	1	5	4	3	5

High
5
4
3
2
1

PhD physicists are most valuable near the core of platform development, theory, modelling, experiments, benchmarking and error correction.

Quantum workforce: PhD Physics across sectors

Dimension	Academia	Industry / start-ups	Government labs	Public agencies / policy	Suppliers / enabling tech
Primary output	Publications, grants, students, intellectual leadership	Products, prototypes, milestones, IP, revenue, customer value	Mission-driven research, national capability, strategic infrastructure	Funding, regulation, standards, procurement, diplomacy, ecosystem building	Reliable components, instruments, control systems, fabrication, service
Success metrics	Papers, citations, grants, student placement, scientific originality, intl reputation	TRL progress, product reliability, customer adoption, IP, speed, team delivery	Technical milestones, national strategy, publications/patents, security & mission impact	Policy impact, programme design, standards, international coordination	Quality, manufacturability, uptime, documentation, integration with customers
Role of a physics PhD	Deep expert, independent researcher, teacher, future PI or scientific leader	Specialist translating physics into robust engineering, software, or product capability	Scientist/engineer with mission, infrastructure, and long-term capability responsibility	Technical authority able to evaluate claims and design evidence-based programmes	Bridge between device physics and practical engineering constraints
Typical risk	Precarious pipeline, grant dependence, slow career progression	Market volatility, changing priorities, less freedom to publish	Security restrictions, bureaucracy, slower hiring	Distance from hands-on science, political cycles	May look less academically prestigious, but can be strategic and employable
Best preparation	Publication quality, teaching, grant writing, international reputation	Python/C++, Git, documentation, systems engineering, calibration, project delivery	Experimental depth, mission awareness, collaboration, security awareness	Science policy, standards, evaluation, communication, diplomacy	Instrumentation, electronics, photonics, cleanroom/ fabrication, reliability engineering

A physics PhD is valuable across the quantum ecosystem, but each path rewards a different translation of expertise

Quantum workforce: PhD Physics

Academia

PROVE

new knowledge
publications
grants + students

BUILD YOUR CV

Publications · Teaching · Grant writing
International reputation · Student outcomes

⚠ Precarious pipeline, slow career progression

Industry / start-ups

PROVE

reliable products
engineering delivery
customer value

BUILD YOUR CV

Python/C++ · CAD/control · Documentation
Calibration discipline · Project delivery

⚠ Market volatility, less freedom to publish

Government labs

PROVE

national capability
mission-driven R&D
standards + security

BUILD YOUR CV

Experimental depth · Mission awareness
Collaboration · Security clearance readiness

⚠ Security restrictions, slower hiring

Policy / agencies

PROVE

evidence-based programmes
regulation
diplomacy

BUILD YOUR CV

Science policy · Standards evaluation
Communication · Diplomacy · Economics

⚠ Distance from hands-on science

A strong physics PhD can play all of them, but not with the same CV.
translate your PhD differently for each sector

Quantum workforce: PhD Physics

Academia asks whether you can create new knowledge.

Industry asks whether your knowledge can survive constraints: time, budget, reproducibility, manufacturing, customers and team workflows.

Government and public-sector jobs ask whether you can connect technical reality to national capability, security, standards and public value.

These are different games.

A strong physics PhD can play all of them, but not with the same CV.

Key takeaway

- Workforce development is a **translation problem between physics, engineering, software, products and policy,** not just a pipeline problem.
- **Italy has strong science but limited openings** (119 in 2025) and low VC. **Mobility** to DE/NL/UK is essential for most.
- **Physics PhDs are essential near the scientific core**: qubit physics, theory, experiments, error correction, algorithms, metrology.
- EU produces 110k+ relevant STEM graduates per year: **the pipeline exists**, but applied/engineering translation is the bottleneck.
- **Industry needs evidence that a PhD can deliver**: clean code, reproducible workflows, documentation, calibration discipline, teamwork.
- **The strongest profile is T-shaped**: deep quantum physics + one practical specialization (sensing, HPC, photonics, policy…).

Build a T-shape Quantum profile

Coding
Python / C++ · Git · testing

Systems thinking
calibration · documentation

Sector literacy
markets · standards · IP

Communication
policy fluency · team delivery

TRANSLATION SKILLS

Your credibility

Physics depth gives you what engineers without a PhD can't easily replicate.

Italy's gap

Strong academic depth ; the problem is translation, not science.

D E P T H

Quantum Physics

your non-negotiable foundation

qubits · Hamiltonians · noise · measurement · algorithms · metrology · benchmarking

deep quantum physics
+ one practical specialization

Employers want both

Depth alone isn't enough; they need to see which sector your physics serves.

Evidence from job data

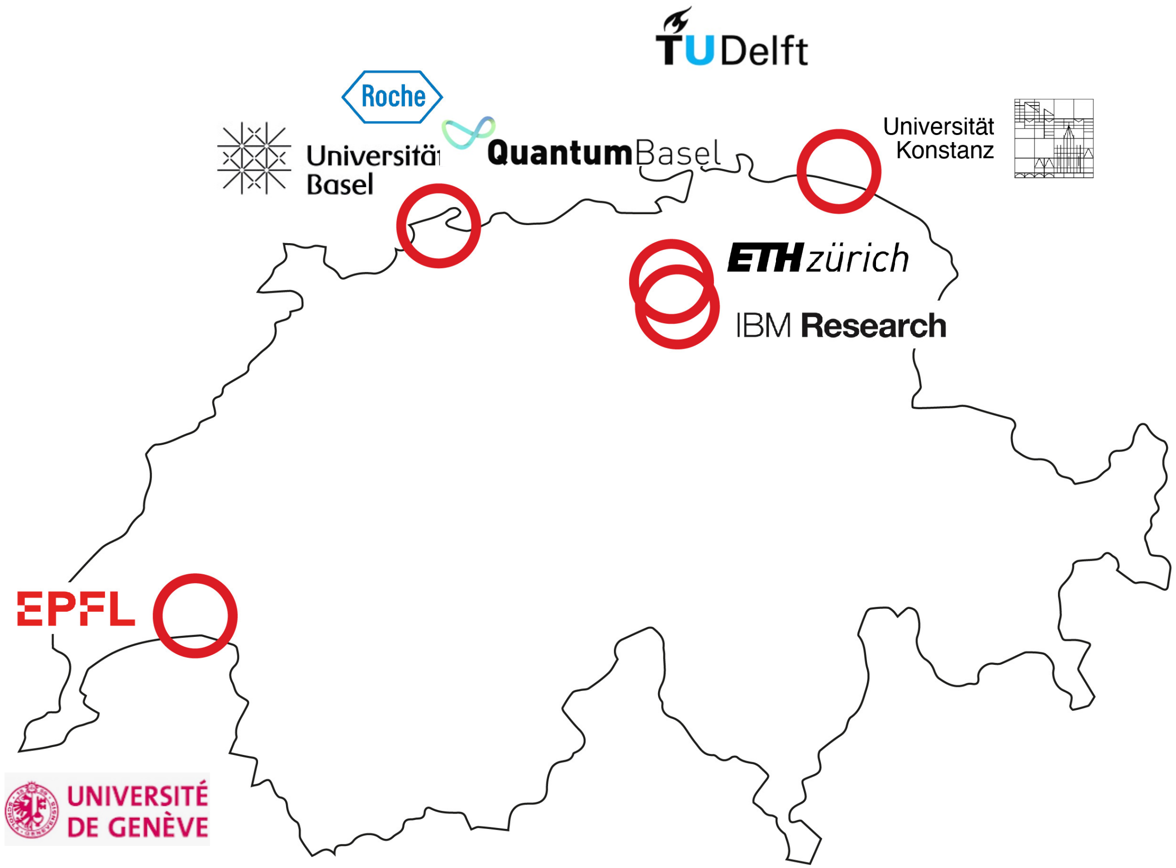
Python and communication score equal to quantum physics in hiring priorities.

"Physics PhD" is not a single job category.
It is a strong core that becomes employable when translated into a sector-specific capability.

And do not forget that

Mobility matters!

NCCR SPIN



New industry collaborations

intel
SemiQon
imec

Moth Quantum

Basel Precision Instruments

QAIventures

www.nccr-spin.ch

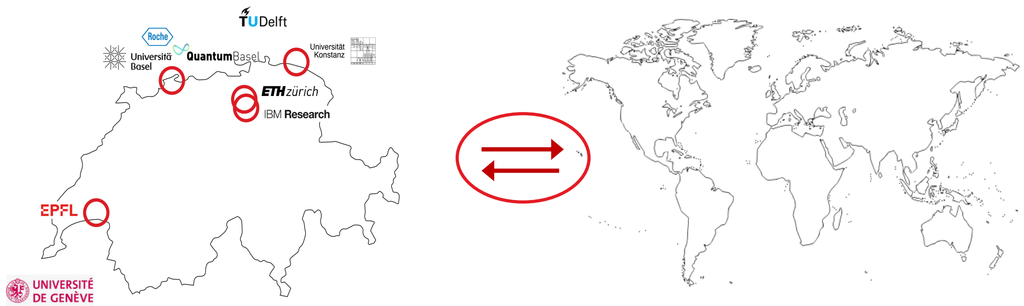
Mobility grants

QuantArt

Quantum Quest

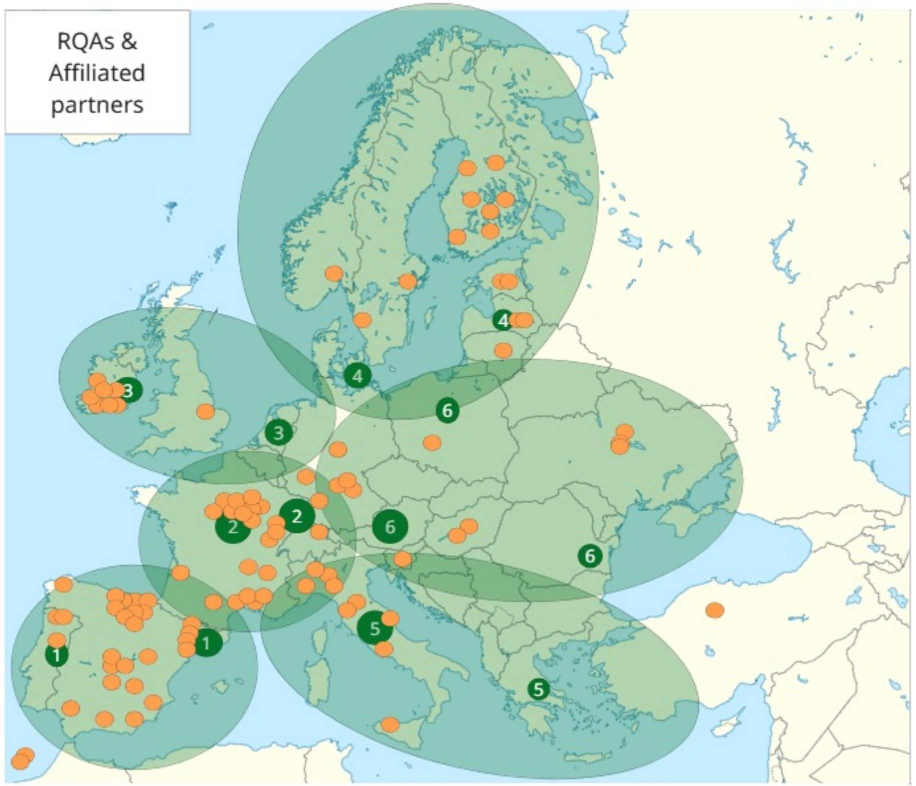
Birds of science

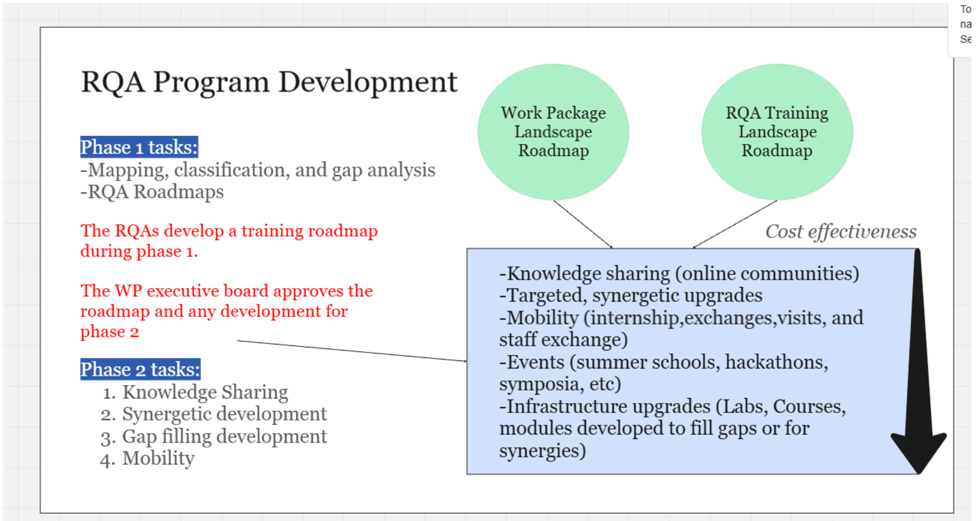
Senior researchers, Postdocs, PhD and Master's students
Academic and industry



mobility

Quantum Academy





Over 70 partners

Thank you
for your attention

Maria Longobardi

Maria.longobardi@unibas.ch