NEUTRAL ATOMS

The stunning rise of quantum computing's dark horse

QUANTONATION VENTURES

QUANTO
NATION

by Dylan Barry

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Acknowledgments

We extend special thanks to the following individuals for volunteering their time to be interviewed and for offering substantive comments on this white paper. They are listed below in alphabetical order.

Dr Alain Aspect (Institut d'Optique, Université Paris-Saclay & a Co-Founder of Pasqal), Dr Immanuel Bloch, (Max-Planck Institute of Quantum Optics, Ludwig Maximilian University of Munich), Dr Antoine Browaeys, (Institut d'Optique, Université Paris-Saclay & Chief Scientific Officer at Pasqal), Dr Jean Dalibard, (Collège de France), Dr Thierry Lahaye, (Institut d'Optique, Université Paris-Saclay & Scientific Advisor at Pasqal), Dr Julien Laurat, (Sorbonne Université & Chief Scientific Officer at Welinq), Dr Mark Saffman, (University of Wisconsin-Madison & Chief Scientist for Quantum Information at Infleqtion).

Editorial

Prof. Aspect, Quantonation Partner Christophe Jurczak, researchers and students Aspect's lab at Institut d'Optique, circa 1994. *Courtesy of Patrizia Vignolo*

After an early start working on ion traps at the Max Planck Institute for Quantum Physics in Germany with pioneer Prof. Herbert Walther, and a brief detour into high-power ultrashort pulsed lasers at École Polytechnique, I embarked on my scientific journey in 1992 in the then-emerging field of cold (neutral) atom physics with Prof. Alain Aspect at the Institut d'Optique in France.

It was an exciting time to witness the birth of a new discipline. My Ph.D. work brought me into contact with giants in the field—Aspect himself still very close to me and Quantonation in 2025, Bill Phillips on my jury and co-author of a paper, and Claude Cohen-Tannoudji through his weekly courses at the Collège de France that inspired generations of physicists. All three were awarded the Nobel Prize, Aspect in 2022, Phillips and Cohen-Tannoudji together along Chu in 1997. Back then, our work was deeply rooted in fundamental science. Applications were a distant thought, and the pursuit of knowledge for its own sake was our guiding light.

Fast forward 25 years, and the landscape has changed dramatically. Neutral atom physics has become the foundation of critical technologies like metrology, atomic clocks, gravimeters, other quantum sensors, and quantum simulators. What was once a niche area of research is now a thriving global community.

Meanwhile, in the race for quantum computing, other platforms—ion traps, superconducting circuits, and photonic systems—captured the spotlight. Investors and even respected scientists from different disciplines questioned whether neutral atoms could rise to the challenge of digital quantum computing while their performance in the analog domain was uncontested. But to me, the distinctions between these platforms are less about the specific characteristics of the carriers of quantum information – the qubits - and more about the level of control over the quantum many-body system (the collection of qubits) one can achieve while growing up its size, from units to hundreds, thousands and much more elementary pieces. Critically, it's the degree of abstraction that determines how each technology is positioned for various classes of computational applications, from low-level analog (comparable to "bare-metal" in the language of supercomputers) to digital with error mitigation and digital with error-correction, a.k.a. fault-tolerant quantum computing.

Neutral atoms stand out for their scalability, their versatility and widespread applicability. The elegance of this platform lies in its ability to straddle diverse use cases. It is this combination of attributes that positions neutral atoms as a fertile ground for innovation in quantum computing. And this is what has driven us at Quantonation to invest in two trailblazers in the neutral atoms quantum computing and networking space, Pasqal and WeLinQ

Yes, challenges remain—primarily in industrializing the technology and turning it into a range of market-ready products. But history has shown us that new technologies often emerge from unlikely corners. Neutral atoms, once seen as a long shot, have earned the title of the "dark horse" in quantum computing, promising to redefine what we thought possible. Dylan Barry has done extensive research and interviewed luminaries in that space to give a very clear perspective that we're glad to share with our investors.

The journey of neutral atoms—from physics laboratories to the cusp of quantum computing—offers a vivid reminder of how curiosity-driven research can evolve into transformative technology. And this is just the beginning.

Christophe Jurczak
January 2025

Table of contents

1. INTRODUCTION

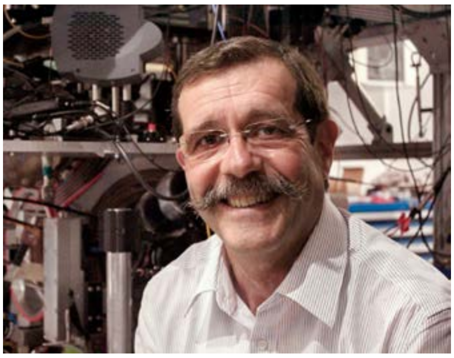
The last decade has witnessed remarkable progress on quantum computing.

One dramatic—and notably unexpected—development has been the stunning rise of *Neutral Atom Quantum Computing*.

Quantum computers use the famously counter-intuitive properties of quantum mechanics to run certain classes of mathematical calculation exponentially faster than any conceivable classical computer. But where different quantum computing paradigms differ is in the specific quantum systems they use to encode the fragile quantum states used in a computation.

Neutral atom quantum computers do exactly what they say on the tin. They use the various quantum states of *neutral atoms*—atoms with no net electric charge—to perform their quantum computations. Neutral atoms are an ideal platform for quantum computing for three reasons. The first is that each neutral atom of a given isotope is identical, quantum mechanically-speaking. Conveniently, nature does not make any manufacturing errors.

The second is that neutral atoms are robust and can consequently be kept in a coherent quantum state—a fragile state of affairs—for comparatively long periods of time. That is important for performing longer and more sophisticated quantum computations. Finally, the third, and most important, is that quantum computers made out of neutral atoms are straightforward to scale up into larger-and-larger quantum computers, and consequently have greater-and-greater amounts of quantum memory available for computing.



> **«The rise of neutral atom quantum computing over the last decade-and-a-half has been nothing short of remarkable—and it shows no sign of slowing down.»**

Dr Alain Aspect
Institute d'Optique, Université Paris-Saclay & Co-Founder of the startup Pasqal. Notably, Dr Aspect was awarded the 2022 Nobel Prize in Physics.

Pasqal's Quantum Computer at TGCC supercomputing center (France)

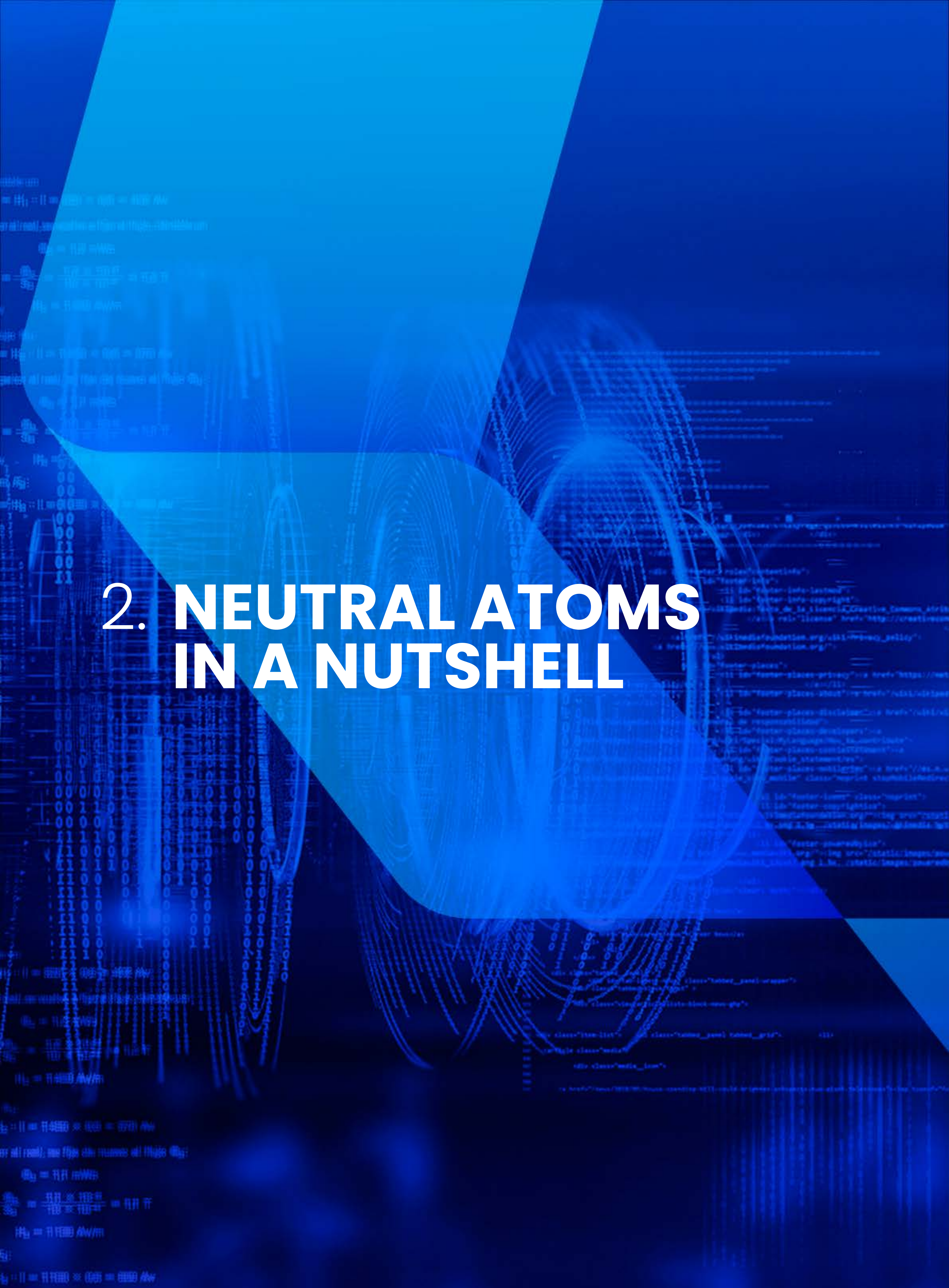
> **«Neutral atoms were a genuine dark horse. From the year 2000 to about the year 2015, most of the attention in quantum computing was focused on the trapped-ion and superconducting qubit approaches. Neutral atom quantum computing, by contrast, was a small field with only a handful of dedicated research groups.»**

Dr Mark Saffman
University of Wisconsin-Madison & Chief Scientist
for Quantum Information at the startup Infleqtion.

Nevertheless, for most of the last 25 years, neutral atoms have remained a dark horse paradigm of quantum computing. That reflects a simple truth. Neutral-atom quantum computing is exceedingly hard. The advantages that neutral atoms offer result from the fact that they are *electrically neutral*, which means they do not interact directly with *electromagnetic fields*. This makes their quantum properties comparatively stable, but that comes at a cost. Doing anything with neutral atoms means relying on finely-tuned laser light with resolutions down to atomic-scales. These sophisticated optical techniques present steep technical challenges and it is consequently only over the last decade that the necessary laser-optical techniques have reached the threshold at which neutral-atom quantum computing has become possible at competitive scales.

But neutral atom quantum computers have become more than just competitive. In only a handful of years, they have gone from the niche obsession of a handful of research groups to a leading paradigm in quantum computing. A series of neutral-atom companies have thrust onto the scene, raising hundreds of millions of dollars and producing some of the largest quantum processors now available on the market. Neutral atom quantum computing is many things, but a dark horse of quantum computing it is no longer.

This white paper by *Quantonation* builds on the paper "Quantum Computing with Neutral Atoms", published in 2020, providing a brief introduction of neutral atom quantum computing, detailing the unprecedented ascent of neutral atoms over the last decade, before exploring what the future holds in store for the paradigm.[1]



2. NEUTRAL ATOMS IN A NUTSHELL

THE NEUTRAL ATOM

It is worth starting with a brief introduction to neutral atoms and how they can be used to perform quantum computations. Recall that every atom consists of both an atomic nucleus, made up of protons and neutrons, and a cloud of electrons that surround that nucleus in discrete orbitals.

If the number of positively-charged protons in the nucleus is equal to the number of negatively-charged electrons that orbit the nucleus, the atom is left with no net electric charge. The result is a *neutral atom*. To perform quantum computations with a collection of neutral atoms, physicists take advantage of the excitability of an atom's *valence electrons*. These are the electrons that occupy the outermost electron orbitals of the atom in question.

Each valence electron wants to occupy its *ground state*, the lowest energy state that is available to it. This corresponds to the electron orbital most tightly-bound to the atomic nucleus that remains as yet unfilled. But—if given a kick of just the right energy from a photon—a valence electron can also be excited into the empty electron orbitals above it. These are a valence electron's possible excited states, and there are generally a number of them.

THE NEUTRAL ATOM QUBIT

These states can be used to represent *qubits*. The qubit, short for *quantum bit*, is the quantum equivalent of a classical *bit*, an abstract variable that can hold either the value 0 or 1. This is the smallest unit of data a classical computer can process.

Like a bit, a qubit has only two measurable states. These are labelled $|0\rangle$ and $|1\rangle$, by analogy to the states of a classical bit. Using a neutral atom to represent a qubit is as simple as taking a valence electron and giving the label $|0\rangle$ to its ground state and $|1\rangle$ to one of its possible excited states.

The neutral atom can then be excited from $|0\rangle$ to $|1\rangle$ using a pulse of light with a frequency tuned to the precise difference in the energy between the two states. By adjusting the properties of that light, a neutral atom can then be placed into a *quantum superposition* of states, which is a statistical blend of two or more states. That is enough on its own to run simple quantum gates, the elementary operations that constitute a quantum computation.

To run more complicated gates, however, one extra ingredient is necessary. That is the ability to set up *quantum entanglement* between two or more qubits, a class of peculiar correlations between quantum states. Fortunately, there is an elegant way to entangle neutral atoms with a procedure known as a *Rydberg Blockade*. Take a neutral atom and use a pulse of laser light to excite it into a *Rydberg state* $|r\rangle$, a highly-excited state in which the valence electron used to encode the qubit states is kicked up to an orbital with a radius particularly far out from the nucleus, smearing the outermost valence electron out over a much larger region of space.

This puffs up the neutral atom in question to one thousand times its ground state radius, creating what is known as a *Rydberg atom*. Notably, when two or more neutral atoms are pressed together in close proximity—within a distance known as the *Rydberg radius*—only one of the neutral atoms in question can be excited into a Rydberg state at a given time. In other words, the presence of one Rydberg atom blocks the creation of others around it. Hence the term "*Rydberg blockade*". The Rydberg Blockade has the convenient effect of neatly entangling the quantum states of the neutral atoms in question, and—using a sequence of laser pulses—that entanglement can be transferred down to the qubit states $|0\rangle$ to $|1\rangle$ as well.

THE NEUTRAL ATOM QUANTUM COMPUTER

That is the theory of neutral atom quantum computing in a nutshell. The quantum states of the valence electrons orbiting a neutral atom can be used to represent the quantum states of a qubit. These qubits can then be used to perform quantum computations by exciting them with precise pulses of laser light and pressing pairs of them into a gentle embrace to establish quantum entanglement between them. With a sufficient collection of qubits, that is enough to run any quantum algorithm.

There is obviously a considerable amount of additional physics makes this possible in practise. Many of those details will become clear in the following section which recounts the story of neutral atom quantum computing from past to present day.

3. THE RISE OF NEUTRAL ATOM QUANTUM COMPUTING

BLACKBOARD TO LABORATORY

The story of neutral atom quantum computing starts at the turn of the century. In 1999—25 years ago this year—Ivan Deutsch at the University of New Mexico, Poul Jessen at the University of Arizona and collaborators published a seminal paper proposing the use of ultracold neutral atoms, manipulated by nothing more than light, as a basis for quantum computing.[2,3]

Neutral atoms were in the zeitgeist at the time. In the years from 1985 to 1990, the physicists Steven Chu, Claude Cohen-Tannoudji and William "Bill" Philips had independently demonstrated that lasers could be used to cool neutral atoms to temperatures close to 0°K (-247.15°C), the coldest temperature in the universe. They did this by immersing atoms in a bath of laser light—called optical molasses—in which atoms are slowed down to a standstill as if trapped in a viscous liquid like honey, or (as the title suggests) molasses.[4,5,6,7]

Bill Phillips and collaborators then demonstrated in 1990 that the same techniques can be used to capture atoms by a lattice of counterpropagating lasers, called an optical lattice, trapping them in place at a sequence of regularly-spaced intervals.[8] The physicists Eric Cornell and Carl Weiman then famously used these techniques in 1995 to establish the first *Bose-Einstein Condensate* (BEC)—a peculiar quantum phase of matter—in a gas of neutral rubidium atoms.[9,10,11] For these pioneering discoveries, Chu, Cohen-Tannoudji and Philips were awarded the 1997 Nobel Prize in Physics, and Cornell and Weiman were awarded the 2001 Nobel Prize in Physics.

Deutsch and Jessen's proposal for a quantum computer was to trap a collection of ultracold neutral atoms in an optical lattice and then use each of the neutral atoms to represent a qubit. This is an elegant approach to quantum computing—using nothing but atoms and light to perform computations—and it consequently set off a cascade of work on neutral atom qubits.

Notably, in the year 2000, the physicists Dieter Jaksch, Ignacio Cirac, Peter Zoller, Mikhail Lukin and others published in a landmark paper in which they proposed using the Rydberg blockade mechanism, described in the prior section, to establish entanglement between pairs of neutral atom qubits.[12,13,14] Lukin's is a name that will pop up repeatedly in this white paper.

It was not long before experimentalists were creating rudimentary collections of neutral atom qubits in the laboratory. Thanks to the Nobel Prize winning work of Chu, Cohen-Tannoudji and Philips, preparing a gas of ultracold neutral atoms had by this time become routine. Heat up a sample of an alkali metal like Rubidium or Caesium in a vacuum chamber and you get a gas of hot atoms. These neutral atoms—each moving at thousands of metres per second—can then be slowed to a standstill, the same as cooling them down, using a *magneto-optical* trap. This is a changing magnetic field set up in the middle of several optical molasses beams.

Timeline of Relevant Nobel Prizes

Year	Laureates	Awarded
1997	Steven Chu, Claude Cohen-Tannoudji & William Phillips	LASER COOLING OF ATOMS
2001	Carl Wieman, Eric Cornell & Wolfgang Ketterle	BOSE-EINSTEIN CONDENSATES
2018	Gerard Mourou, Donna Strickland & Arthur Ashkin	OPTICAL TWEEZERS
2022	Alain Aspect, John Clauser & Anton Zeilinger	QUANTUM ENTANGLEMENT
2023	Pierre Agostinie, Ferenc Krausz & Anne L'Huillier	ULTRAFAST LASER PULSES

The earliest attempts to turn such a gas of neutral atoms into a quantum computer followed Deutsch, Jessen and company's original prescription. If an optical lattice is turned on within a magneto-optical trap, the atoms can be made to settle into the regularly-spaced potential wells of the lattice at random, creating a sparse and haphazard arrangement of neutral atom qubits suspended at fixed points in space. The physicists Immanuel Bloch, Markus Greiner and colleagues were experimental pioneers of this approach, creating many of the first arrays of neutral atom qubits in this manner, and even creating limited entanglement by coordinating controlled collisions between adjacent neutral atoms.[15,16,17,18,19,20]

These optical lattice arrays did not yet provide the precision control necessary to perform quantum computations with quantum gates, but did provide a platform for pioneering quantum simulation experiments. It would take another Nobel Prize-winning technique to make that kind of precision control possible. In 1986, the physicist Arthur Ashkin showed that a tightly-focused beam of laser light can be used to pluck a microscopic particle out of suspension in a vacuum chamber and move it from place to place.[21,22,23,24,25] This technique—known as the *optical tweezer*—would win Ashkin the 2018 Nobel Prize for Physics. It turns out that an array of optical tweezers, each trapping a single neutral atom qubit that can then be moved around with incredible precision, is the perfect platform for performing quantum gates with neutral atoms qubits.

The use of optical tweezers to manipulate neutral atom qubits was pioneered by the physicists Antoine Browaeys, Philippe Grangier and their groups at the *Institut d'Optique of Université Paris-Saclay*.[26,27,28,29] Simultaneously, Mark Saffman at the *University of Wisconsin-Madison* was busily pioneering the implementation of Rydberg blockade-based entanglement gates of neutral atom qubits.[30,31,32,33] This combination of techniques, paired with a set of fluorescence-imaging techniques developed by Dieter Meschede at *Universität Bonn* and others,[34,35,36,37] would lead to a dramatic period of progress in the years before 2010 when physicists were able to perform simple quantum gates with neutral atom qubits for the first time.

By the start of 2010, experimentalists had successfully used small arrays of neutral atom qubits to demonstrate each of the quantum logic gates needed for general quantum computation. The last of these was a quantum gate, called a CNOT gate, that establishes quantum entanglement between a pair of neutral atom qubits. It was first demonstrated by Saffman and colleagues in a preprint posted in 2009.[38]

This was exciting progress. Nevertheless, performing more complicated quantum algorithms on large collections of neutral atoms was still out of reach. This was due to two considerable obstacles. The first obstacle was the fact that, like in an optical lattice, when an optical tweezer array is switched on in a magneto-optical trap the atoms fill the array haphazardly. This means that experimentalists have to rely on chance to arrive at arrangements of neutral atom qubits that can be used to perform specific quantum gates.

This is feasible for a handful of neutral atoms, but it cannot be scaled up to run more complicated quantum algorithms on larger numbers of neutral atom qubits. Fortunately, there was a convenient solution to this problem. Whatever partial arrangement the neutral atoms happen to settle into on their own, a second set of fast-moving optical tweezers could be used to rearrange those neutral atoms, one-by-one, into a neat—and, importantly, completely filled—pattern designed to run some large-scale quantum algorithm.

This technique was perfected by Antoine Browaeys and his group at the *Institut d'Optique*, who described their work in a series of papers published between 2016 and 2018 in which they reported using a fast-moving array of optical tweezers to create tightly-packed arrangements of 50 to 75 neutral atoms in 2D, and later 3D optical tweezer arrays.[39,40] Mikhail Lukin and Markus Greiner at Harvard University and Vladan Vuletic at the Massachusetts Institute of Technology (MIT) developed similar techniques over a similar period.[41,42] The efforts of the Browaeys group culminated in 2018—the year of Arthur Ashkin's Nobel Prize—in a famous paper in which the group reported using the approach to assemble a collection of neutral atoms into the shape of the Eiffel Tower.[43]

The second serious obstacle in the way of more complicated quantum algorithms was the high rate of error involved in running quantum gates with neutral atoms, a problem that would be solved by the same two groups of researchers. In 2018, Browaeys and collaborators identified noise—specifically the *phase noise*—in the lasers used to excite neutral atom qubits between states as a major bottleneck on the performance of neutral atom quantum gates.[44] Shortly thereafter, Mikhail Lukin and collaborators found ways to reduce the phase noise of their lasers that led to a dramatic reduction in error rates.[45]

That improved the accuracy—also known as the *fidelity*—with which two neutral atom qubits could be entangled with one another from a previous state of the art figure of 75% (meaning the atoms are correctly entangled 75% of the time) all the way up to 97.5%. That was an improvement of an order of magnitude, lowering the rate of error from 25% down to 2.5%. This discovery was another bombshell.

The journal *Science* captured the mood in an often-quoted editorial piece in which it described neutral atoms as a "dark horse candidate" to win the race to the first industrial-scale quantum computers.[46] Neutral atoms had now officially arrived.

«The industrialisation of neutral atom quantum computing has been important to the recent progress in the field. The incentives are different from academia, with constant pressure to deliver a product that will provide a commercial advantage, and the resources available are considerably greater.»

Dr Antoine Browaeys
Institute d'Optique, Université Paris-Saclay &
Chief Scientific Officer at the startup Pasqal.

LABORATORY TO BOARDROOM

It is difficult to overstate how much of a surprise these advances came as for those outside of the small community of neutral atom quantum computing researchers.

The narrative for the preceding 25 years had generally focused on two commercially relevant paradigms of quantum computing—*Superconducting Quantum Computing and Trapped Ion Quantum Computing*—with none of the competing quantum computing paradigms offering a genuine commercial threat.

The major commercial players consequently bet big on those paradigms. IBM and Google, for example, invested heavily in superconducting qubits, while Honeywell invested heavily in trapped ion qubits. The *annus mirabilis*—Latin for "miraculous year"—of 2018, however, brought neutral atoms within striking distance of both the accuracy and scale of competing approaches to quantum computing. Neutral atoms were now serious business—and they were about to become big business.

Within a handful of months, five neutral atom quantum computing companies, M Squared Lasers, Infleqtion, Atom Computing, QuEra Computing Inc. and Pasqal were founded or entered the industry. Mikhail Lukin, Markus Greiner, and Vladan Vuletic were founding members of QuEra; Antoine Browaeys and Thierry Lahaye were founding members of Pasqal; and Mark Saffman has since joined Infleqtion (originally known as ColdQuanta). The company planqc—a sixth startup—has more recently joined this new collection.

That cohort of companies has since raised over $500m in investment financing, primarily from venture capitalists. That has done two things. The influx of capital into neutral atom quantum computing has dramatically accelerated the rate of progress in the years since. But much of that work is now proprietary, meaning that it goes on behind closed doors. It would consequently be a handful of years before the true impact became public.

The dam ultimately broke in 2022, a second *annus mirabilis*. Like 2018, it would boast a Nobel Prize. In October, Alain Aspect won the 2022 Nobel Prize for Physics for a series of pioneering experiments in 1981 and 1982 that proved the existence of quantum entanglement.[47,48,49] That work laid the foundations for what would become quantum computing. It had been a whirlwind year for Aspect, who was one of the founders of the startup Pasqal.

Pasqal had already offered access to prototype neutral atom quantum processors for a handful of years, but—in 2022—it upped the ante. In a matter of months, it launched the first cloud-based platform for neutral atom quantum computing— PASQAL Cloud Services—in private beta, and announced that its processors would soon be made available on Azure Quantum, Microsoft's cloud quantum computing platform.[50] Pasqal then announced that it had signed the first major contracts to deliver and install an on-premises neutral atom quantum computer, agreeing to supply a pair of 100+-qubit quantum processors to clients in Germany and France as part of the European Union's project on hybrid high-performance computing.[51]

The best, however, was left for last. In September—the month before Aspect won his Nobel Prize—Pasqal unveiled a 324-qubit quantum processor, named *Fresnel*. It was, at the time that it was unveiled, not just the largest neutral atom quantum computer, but the largest quantum computer of any description yet announced.[52] That drove the other companies to reveal their hands. In November, QuEra Computing Inc. unveiled a 256-qubit quantum processor, named *Aquila*, while M Square Lasers unveiled a 200-qubit quantum processor, named *Maxwell*.[53,54] Aquila was immediately placed on Braket, Amazon's cloud quantum computing platform, where it remains the largest quantum computer available on the cloud.

Neutral Atom Quantum Computing Companies

Company	Investment	Processor	Processor Details	Processor Type	Headquartered	Founded
M Squared Lasers	$20m (Non-VC)	Maxwell	200-qubit prototype array (2022).	Analog, Hyperfine Qubit	Glasgow, Scotland	2006
Infleqtion	Seed: $17m Series A: $32m Series B: $110m	Sqorpius	1,600-qubit prototype array (2024).	Gate-based, Hyperfine Qubit	Boulder, Colorado	2007
Atom Computing	Seed: $5m Series A: $15m Series B: $70m	Phoenix	1,180-qubit prototype array (2023).	Gate-based, Nuclear-Spin Qubit	Berkeley, California	2018
QuEra Computing	Seed: $17m Series A: $30m	Aquila	256-qubit commercial processor available on the Cloud (2022).	Analog, Hyperfine Qubit	Boston, Massachusetts	2018
Pasqal	Series A: $27m Series B: $110m	Fresnel	1,110-qubit prototype array (2024). 200-qubit commercial processor available for on-premises installation (2023). 100-qubit commercial processor available on the Cloud (2022).	Analog, Hyperfine Qubit	Paris, France	2019
planqc	Series A: $55m	-	1,200-qubit prototype array (2024). 1,000-qubit commercial processor available for on-premises installation (2023).	Gate-based, Hyperfine Qubit	Munich, Germany	2021

50,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75

BOARDROOM TO CABINET OFFICE

«Neutral atoms are a fantastic platform for both analog quantum simulation and digital (meaning quantum gate-based) quantum computation. It also allows for hybrid approaches between the two in a way that combines the best of both worlds.»

Dr Immanuel Bloch
Max-Planck Institute of Quantum Optics.

The last two years, 2023 and 2024, have steadily built upon that momentum. The procurement of neutral atom quantum processors by the European Union started a broader wave of government interest in neutral atom quantum computers. The United States,[76,77] United Kingdom,[78,79] Germany,[75,80] Denmark[81], Japan,[82,83] South Korea[84,85] and Saudi Arabia71 have signed contracts to either procure a quantum processor or form a strategic partnership with a neutral atom quantum computing company to advance their domestic quantum ecosystems. The most ambitious such announcement was made by planqc, which recently announced a contract with the Leibniz Supercomputing Centre near Munich to build and deploy a 1,000-qubit neutral atom quantum processor.[75]

But the main milestones over the last eighteen months have been technical ones. There have been a series of demonstrations of the scope to scale up neutral atom quantum processors well into the thousands of qubits. Each of Atom Computing, Pasqal, Infleqtion and planqc have prepared 1,000+-qubits on their quantum processors as a proof of principle. That means that the first 1,000+ qubit quantum processor is likely to be announced by one of those startups in the next year or so. There are no obvious technical obstacles to scaling up beyond that either, meaning that a 10,000+ qubit quantum processor is a legitimate aspiration for the industry.

The fidelity of neutral atom qubits has also continued to improve. Mikhail Lukin, Markus Greiner and Vladan Vuletic—the founders of QuEra Computing Inc.—and collaborators have improved the fidelity with which two neutral atom qubits can be entangled to 99.5% on as many as 60 atoms in parallel.[86] That is as good as has been achieved by any competing approach with as many atoms at the same time. It also crossed the threshold required to perform *quantum error correction* using a *surface code*, a family of particularly important quantum error correction codes.

The team have since done just that, using up to 280 neutral atom qubits to encode 48 error-corrected *logical qubits* which could be entangled with one another with a fidelity of 99.9%.[87] This is the most logical qubits encoded by any quantum computing approach to date, a result that firmly delivered neutral atoms into the fault tolerant era of quantum computing.

Benjamin Bloom and collaborators at Atom Computing have since gone one step further, entangling 24 error-corrected logical qubits in single quantum state, a landmark demonstration that puts neutral atoms at the frontier of the discipline.[88]

That is where neutral atom quantum computing stands today. The approach is now unambiguously one of a handful leading approaches to quantum computing on almost any metric one cares to name.

4. NEUTRAL ATOMS COMPARED TO OTHER APPROACHES

THE QUANTUM COMPUTING ZOO

Before looking towards the future prospects of neutral atom quantum computing, it is worth presenting in detail at how the current state-of-the-art compares to the most important competing paradigms.

There are about a half-dozen well-established approaches to quantum computing, which are conventionally divided into three primary categories: *Atomic Quantum Computing, Solid-State Quantum Computing and Photonic Quantum Computing.*

ATOMIC QUANTUM COMPUTING

The atomic approaches include *Neutral Atom Quantum Computing*, but the most established of the atomic paradigms is actually *Trapped Ion Quantum Computing*.

This uses chains of ions trapped by electromagnetic fields to represent its qubits, where ions are just atoms with unequal numbers of protons and electrons, leaving them with a net positive or negative electric charge. Like a neutral atom qubit, a trapped ion qubit is encoded in the states of atomic electrons. But to perform a quantum computation, a chain of trapped ions is set to oscillate like a taut string.

SOLID-STATE QUANTUM COMPUTING

The solid-state approaches include *Superconducting Quantum Computing, Solid-State Spin Quantum Computing and Topological Quantum Computing*. The superconducting paradigm makes use of electrical circuits made of semiconductor components like inductors and capacitors cooled down to cryogenic temperatures at which electrons experience no electrical resistance. The electrons then oscillate to-and-fro in the circuit at discrete frequencies that characterise quantum states. The circuit acts like a synthetic atom which can then be used to represent a qubit.

The solid-state spin paradigm makes use of the quantum spin of electrons trapped in semiconductor nanocrystals, known as *quantum dots*, to represent each qubit. These electrons can then be excited between quantum spin states—*up* and *down*, respectively—using an oscillating electromagnetic field. Two electron spin qubits in a quantum dot cannot boast the same spin, which can be used to entangle them in a manner similar to a Rydberg Blockade. The topological paradigm, by contrast, makes use of the collective excitations of electrons in a superconducting nanowire to represent qubits. These qubits have the advantage of being spread out over the nanowire which, at least in principle, makes them more robust than other qubits.

PHOTONIC QUANTUM COMPUTING

The photonic approaches include both *Discrete-Variable Quantum Computing and Continuous Variable Quantum Computing*. The discrete variable paradigm makes use of the discrete quantum states of a photon to represent a qubit, including the *angle of polarisation* of a single photon, or—as is more common—the number of individual photons that take one of a discrete number of specially designed paths.

The continuous variable paradigm makes use of the continuous quantum states of a photon to represent a so-called *qumode*—the continuous equivalent of a qubit—including the *frequency* or *relative-phase* of a single photon or a beam of photons.

In either case, the photons are then passed through an optical circuit containing optical components like mirrors, waveguides, phase-shifters, and beam splitters to apply a series of quantum gates to them before they are measured at the end.

HOW NEUTRAL ATOMS COMPARE IN THEORY

There are several unique theoretical advantages that neutral atoms have over the competing quantum computing paradigms. Three of these were mentioned in the introduction, which we will repeat here.

Every individual neutral atom—and consequently every individual neutral atom qubit—is perfectly identical, which means that there is no need for the calibration or quality-control of individual qubits. This is a considerable advantage over the solid-state qubits, which are industrially-fabricated and have to be both carefully calibrated and quality-controlled to work.

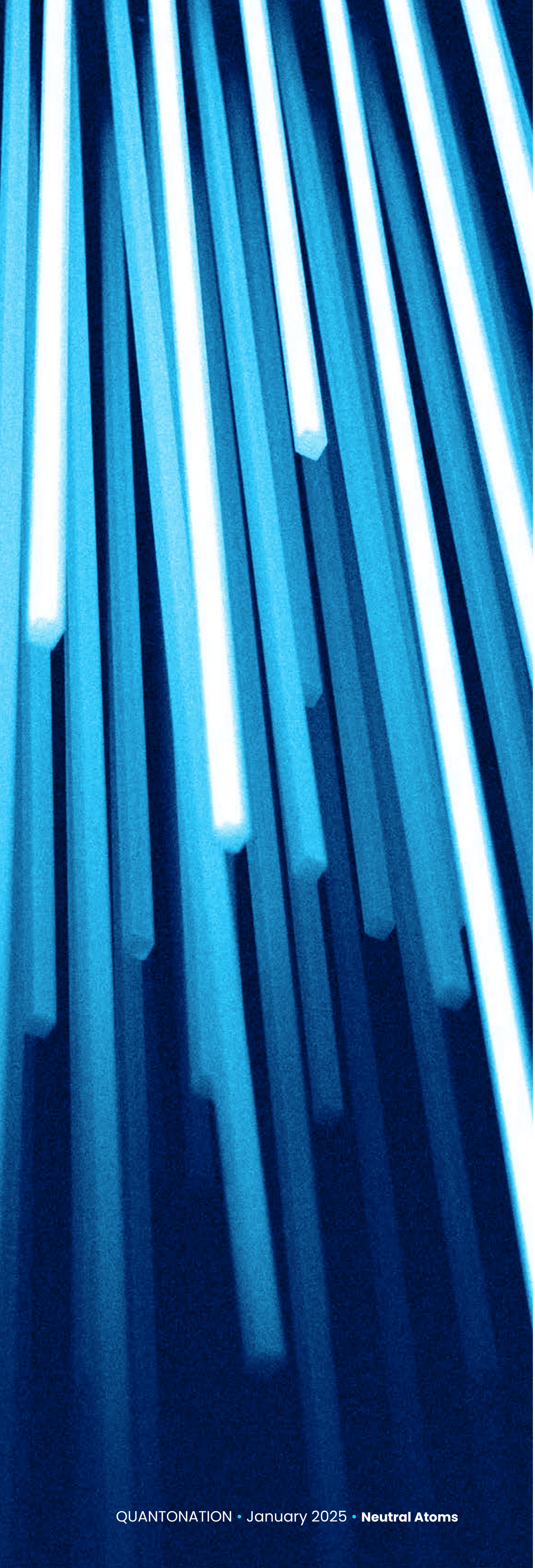
Neutral atoms are robust and have a long *coherence time*, which is the expected lifetime of a coherent quantum state. In theory, that gives a neutral atom quantum computer a greater window of time in which to perform sequences of quantum gates, and means that they should boast a greater *quantum circuit depth*, which is a measure of the length and the complexity of the quantum computations that a quantum computer is capable of running. That is a considerable advantage over the various solid-state qubits, which have comparatively shorter coherence times.

Neutral atoms can also be scaled up to large arrays of qubits more easily than the other paradigms. There are no serious obstacles to scaling up optical lattice arrays to the tens of thousands of neutral atom qubits while maintaining their *all-to-all connectivity*, which means that every qubit can be made to interact directly with any other in the lattice by simply moving them about with some optical tweezers. That all-to-all connectivity is attractive because it improves the over-all fidelity of quantum computations performed by a quantum computer and—as has recently become clear—makes more powerful quantum error correcting schemes possible. That is a considerable advantage over almost all of the other quantum computing paradigms, which either lack the all-to-all connectivity that neutral atoms offer (the solid-state paradigms), or boast that connectivity but face some considerable challenges in scaling up to greater volumes of qubits (the trapped-ion paradigm).

That covers the advantages described in the introduction. But there are other advantages that are also worth mentioning. Perhaps the most important is one pointed out by Deutsch and Jessen themselves.[3] There is a profound tension in quantum computing between the desire for qubits that are strongly interacting and qubits that are weakly interacting.

The more strongly qubits interact, the simpler it is to entangle them. That makes running quantum gates comparatively straightforward. But it comes at a cost. The more strongly qubits interact, the more susceptible they are to quantum noise in the environment, which destroys the fragile quantum states needed for quantum computing. Poul and Jessen called this tension the *Tao of Quantum Computing*, a reference to the Taoist striving for balance between the concepts of *Yin* and *Yang*.[3]

Neutral atoms offer this balance. Most approaches to quantum computing start at one of two extremes. They either take strongly interacting qubits and then go to great lengths to isolate the qubits from the ambient noise in their environment. This involves expensive techniques like ultra-cold cryogenic refrigeration in solid-state approaches. Or they take weakly interacting qubits and go to great lengths to make them interact with one another. This is true of the photonic approaches.



Neutral atom qubits, by contrast, can simply be switched back and forth between weakly interacting qubit states, the states |0⟩ and |1⟩, and a strongly interacting Rydberg state, the state |r⟩. They consequently benefit from the advantages of both strongly interacting and weakly interacting qubits without suffering from any of the disadvantages of either. Neutral atoms are, in principle, the perfect qubits.

Finally, neutral atom quantum computers have some interesting advantages when it comes to integrating with other quantum technologies. The same techniques that are used to create neutral atom quantum computers—neutral atoms arrays manipulated by precise laser light—underpin the emerging infrastructure of quantum networks, including quantum memories and devices that rely on them (quantum switches, routers and repeaters).

This means that where quantum networking devices use the same atomic species as quantum processors (for example, caesium or rubidium) they can be seamlessly integrated because the frequencies of the light involved in exciting the atoms on both ends is the same, whereas other quantum computing approaches will require frequency conversion between frequencies. This will give neutral atoms a leg up in distributed quantum computing, the connecting up of multiple neutral atom quantum computers to work together in parallel, in the same manner that distributed classical computers work today.

The same principles have the potential to allow neutral atom quantum computers to integrate comparatively seamlessly with atomic clocks and other emerging quantum metrological devices, like quantum accelerometers and gravitometers, which could potentially feed quantum data directly into neutral atom quantum computers for direct quantum processing.

HOW NEUTRAL ATOMS COMPARE IN PRACTICE

The state-of-the-art for each contemporary approach is tabulated on the following page against a suite of non-exhaustive but commonly-used performance metrics. The photonic paradigms - which do not differ much - are treated as one category.

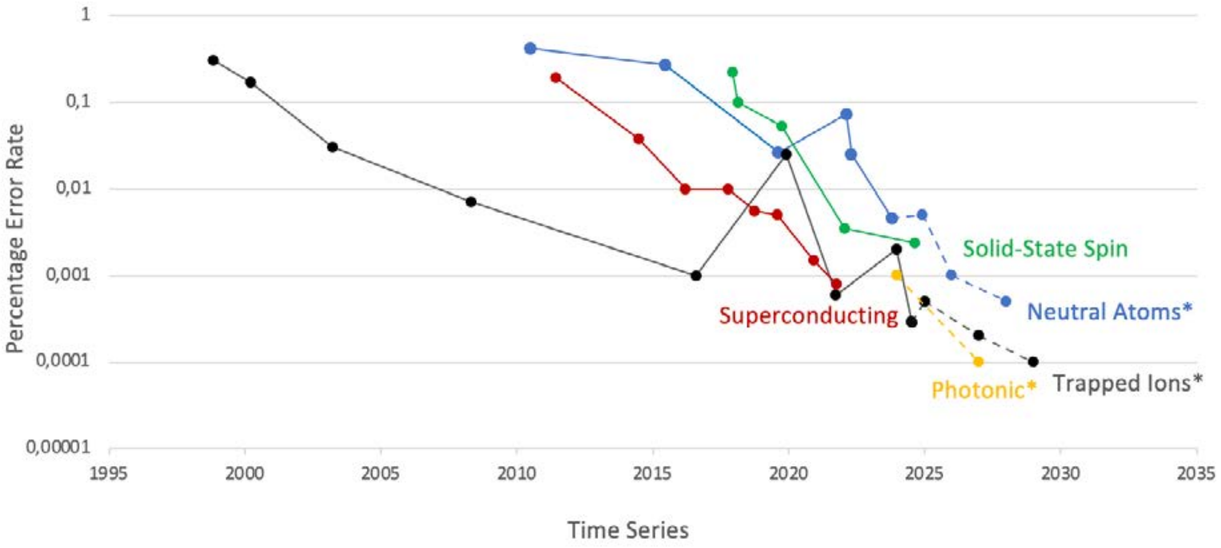
Quantum Computing Paradigms Compared

		Atomic		Solid-State		Photonic	
		Neutral Atoms	**Trapped Ions**	**Superconducting**	**Solid-State Spin**	**Topological**	**Photonic**
Sizes	**Qubit size**	(1 µm)^2	(1 µm)^2	(100 µm)^2	(100 nm)^2	(No data)	(100 µm)^2
Numbers	**Current qubit numbers**	1,600	56	1,121	12	0	216
	Potential qubit numbers *	>10,000	>100	>1,000	>1,000,000	(No data)	>100,000
	Logical qubit numbers	48	12	12	1	0	12
Architectures	**Qubit connectivity**	All-to-All	All-to-All	Nearest-Neighbour	Nearest-Neighbour	Nearest-Neighbour	All-to-All
Fidelities	**1-qubit gate**	99.97%	99.99%	99.99%	99.90%	(No data)	99.99%
	2-qubit gate	99.55%	99.99%	99.91%	99.65%	(No data)	99.22%
	State Preparation & Measurement	99.44%	99.99%	99.99%	99.34%	(No data)	99.98%
Speeds	**1-qubit gate**	2.5 µs	5 µs	4 ns	10 ns	(No data)	3 ns
	2-qubit gate	400 ns	500 ns	12 ns	10 ns	(No data)	3 ns
	State Preparation	400 ms	3.5 ms	100 ns	300 ns	(No data)	100 ms
	State Measurement	500 µs	500 µs	100 ns	1 µs	(No data)	(No data)
Coherence Times	**Trap lifetime**	1.5 hrs	18 hrs	N/A	N/A	N/A	N/A
	Relaxation time (T1)	4 s	100 s	2.5 ms	10s	(No data)	N/A
	Dephasing time (T2)	1 s	1 s	1.5 ms	100 µs	(No data)	N/A
Temperatures	**Cryogenic requirements**	4 K	4 K	15 mK	1 K	(No data)	10 K
Maturity	**Relative maturity**	Mature	Highly Mature	Highly Mature	Immature	Highly Immature	Immature

* In a single system without networking between quantum processors.

41,61,86,87,89,90,91,92,93,94,95,96,97,98,99,100,101.102,103,104,105,106,107,108,109,110,111,112,113,114,115,116

Time Series Comparison of Two-Qubit Entanglement Fidelities



* The dotted lines reflect the trajectory implied by published commercial roadmaps.

Data provided by Riverlane

The most important takeaways from the table are that neutral atoms now lead the industry in demonstrated numbers of both physical qubits and logical qubits, with qubit numbers in prototype processers now well above the 1,000-qubit mark.

The most mature approaches, trapped ions and superconducting qubits, continue to lead neutral atoms on gate fidelities. But the rate of improvement has been so steep that this gap looks likely to close. The gap in gate fidelities compared to the solid-state qubits is also overstated because of the difference in their connectivity.

All-to-all connectivities—in which each qubit can be directly entangled with any other—preserve their fidelities better than the nearest-neighbour connectivities.

Neutral atoms have overtaken the gate speeds of trapped ions, but they remain several orders of magnitude slower than the gate speeds possible with any of the superconducting, solid-state spin or photonic qubits. This is less of an issue than it might first appear, however. The solid-state approaches boast exceptionally short coherence times, which is the amount of time a qubit can be expected to preserve a quantum state. This means that the number of quantum operations that can be run in a coherence time window, the quantum circuit depth, remains comparable.

Neutral atoms do face a handful of unambiguous obstacles, however. The most glaring concerns the overall speed of the neutral atom computation cycle, which lags considerably behind the other paradigms. This is due in large part to how the qubits are measured at the end of a quantum computation. The conventional way of measuring the states of an array of neutral atom qubits is known as *destructive readout*, which requires expelling the neutral atom qubits in one of the pure states—either $|0\rangle$ or $|1\rangle$—from the optical lattice. The remaining neutral atoms are then observed by bathing them in light of a specific frequency to make them fluoresce.

But destructive readout has two disadvantages. The first is that it requires both the reloading and rearranging of the neutral atoms in an optical lattice after each quantum computation. This makes the state preparation speed of a neutral atom quantum computer orders of magnitude slower than the competing approaches. The second is that any neutral atom qubits lost from the optical lattice during the course of the quantum computation, which is not an uncommon occurrence, will be measured with the state of the neutral atom qubits that are later expelled from the lattice during the measurement. That erodes the measurement fidelity as well. These problems also only grow larger the more neutral atom qubits are involved.

There are other important—but less dramatic—drags on the rate of computation. The repeated use of fluorescence imaging throughout the state preparation and readout process—even in non-destructive readout schemes—slows things down. This is because it takes a comparatively long time to collect enough photons, which are emitted from an atom one-by-one, to establish the location or the state of a qubit with the sufficient degree of fidelity.

The constant rearrangement of neutral atom qubits with optical tweezers is also a comparatively sluggish process. This is a difficult issue to solve without sacrificing the all-to-all connectivity of neutral atom quantum processors, one of the reasons that they are so attractive in the first place.

Finally, neutral atom quantum computers do not lend themselves to being placed on microchips in quite the same way that the solid-state approaches, and even the photonic approaches, promise to. This is an obstacle to potential mass-production.

«I would not have imagined in my wildest dreams that we would be where we are today. It is hard to predict whether the rate of progress will continue at such a dramatic rate, but both the sheer number of research groups now working on neutral atoms and the vibrancy of the neutral atom startup scene bode well for the future.»

Dr Thierry Lahaye
Institute d'Optique, Université Paris-Saclay &
Scientific Advisor at the startup Pasqal.

AREAS OF ACTIVE IMPROVEMENT

Fortunately, researchers are actively working on overcoming these obstacles and there are several exciting fronts of innovation that have the potential to make marked improvements to the performance of neutral atom quantum computers.

One of the fronts is the exploration of alternative atomic species as neutral atom qubits. Traditionally, neutral atom quantum computers use Rubidium or Caesium atoms, but physicists have started to explore the use of alkaline-earth metals like neutral Ytterbium and Strontium atoms instead, in which it is most convenient to encode qubit states in the quantum states of the nucleus rather than in the states of atomic valence electrons.[117,118,119,120]

These atomic species provide several advantages as neutral atom qubits. They are known to be comparatively robust, boasting exceptionally long coherence times for neutral atom qubits, and they are particularly suited to a handful of recently proposed schemes for quantum error correction and the non-destructive readout of qubit states at the end of quantum calculations. There are even advantages to using multiple species of atoms in combination, because it reduces the odds that laser pulses intended for one neutral atom qubit will accidentally excite a second one, a phenomenon known as *cross-talk*.

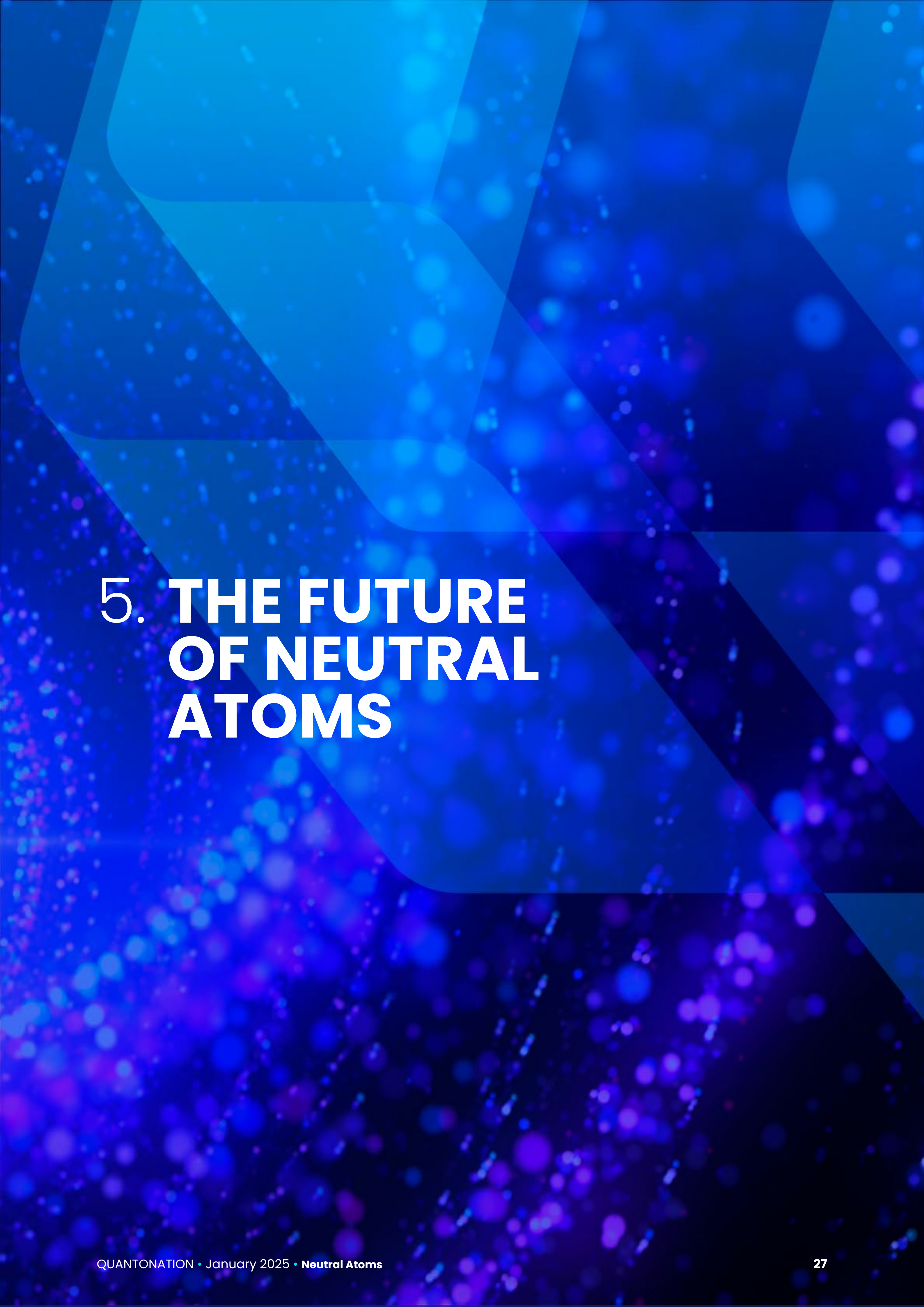
There is also a considerable amount of work in the field exploring ways to move from destructive-readout methods, which require the reloading of atom arrays from scratch after each computation cycle, to non-destructive readout methods, which would allow atom arrays to stay intact between computation cycles. That would dramatically improve the cycle speeds of neutral atom quantum processors by reducing their state preparation times. These schemes require the continuous reloading of atom arrays during computation—on which there has been important recent progress—which has the added benefit of addressing the aforementioned problem of atom loss as an important impediment to improving the fidelities of neutral atom quantum processors.[121,122,123]

There are also several focuses of innovation involving the optical techniques used in neutral atom quantum computing. Interestingly, optical lattices have started re-emerge as part of hybrid systems, used in tandem with optical tweezers.[124,125] This has been precipitated by the advent of powerful optical lattices enhanced by resonating optical cavities. Compared to optical tweezers, these cavity-enhanced optical lattices make dramatically more efficient use of the laser power used to create them, providing a pathway to larger neutral atom arrays than are currently possible with optical tweezers alone.[126,127]

These cavity-enhanced optical lattices also allow for higher-fidelity fluorescence imaging of a neutral atom array by reducing the rate of atom loss during the measurement process. For these reasons and others, cavity-enhanced optical lattices are part of many of the continuous reloading schemes mentioned above, with neutral atoms passed backwards and forwards between an optical lattice and an optical tweezer array in order to make use of the advantages of both, without having to suffer the disadvantages of either.

Finally, there is some exciting—but nascent work—on putting neutral atom arrays onto integrated nanophotonic chips, which might one day allow the paradigm to be miniaturised and—eventually—comparatively cheaply mass-fabricated in chip foundries. This is unlikely to make a considerable difference in the near-term but might be transformative in the long term.[128]

Taken together, none of the obstacles facing neutral atom quantum computing look genuinely insurmountable and they are almost all merely technical. The fact that the approach is still maturing means there are many workarounds yet to be explored, which bodes well for the future.



5. THE FUTURE OF NEUTRAL ATOMS

«Neutral atom quantum computers are particularly suited for integration with other emerging quantum technologies, in particular those in quantum networking, which take advantage of similar neutral atom technologies. One consequence of this is that neutral atom quantum computing lends itself to distributed quantum computing, computing with multiple quantum computer processors in parallel.»

Dr Julien Laurat
Sorbonne Université, Laboratoire Kastler Brossel &
Chief Scientific Officer at the startup Welinq.

The final question is what the future holds for neutral atom quantum computing. The outlook within the industry is bullish. Earlier this year, three companies - Pasqal, QuEra Computing and Infleqtion - published detailed company roadmaps to anchor market expectations for the next half decade. Those three roadmaps cannot be accused of lacking in ambition. [61,67,129]

They commit each of Pasqal, QuEra Computing and Infleqtion to unveiling their own 10,000+ qubit quantum processor sometime between 2025 and 2030 with the ability to encode more than 100 error-corrected logical qubits. No competing approach to quantum computing expects to scale the volumes of its qubits (either physical or logical) quite that fast quite that soon. Notably, QuEra Computing has committed to raising the number of logical qubits possible on its processors from 10 logical qubits in 2024, to 30 logical qubits in 2025 and 100 logical qubits in 2026. It will make logical qubits available on its Cloud-based processors later on in 2024.

Targets from Quantum Roadmaps

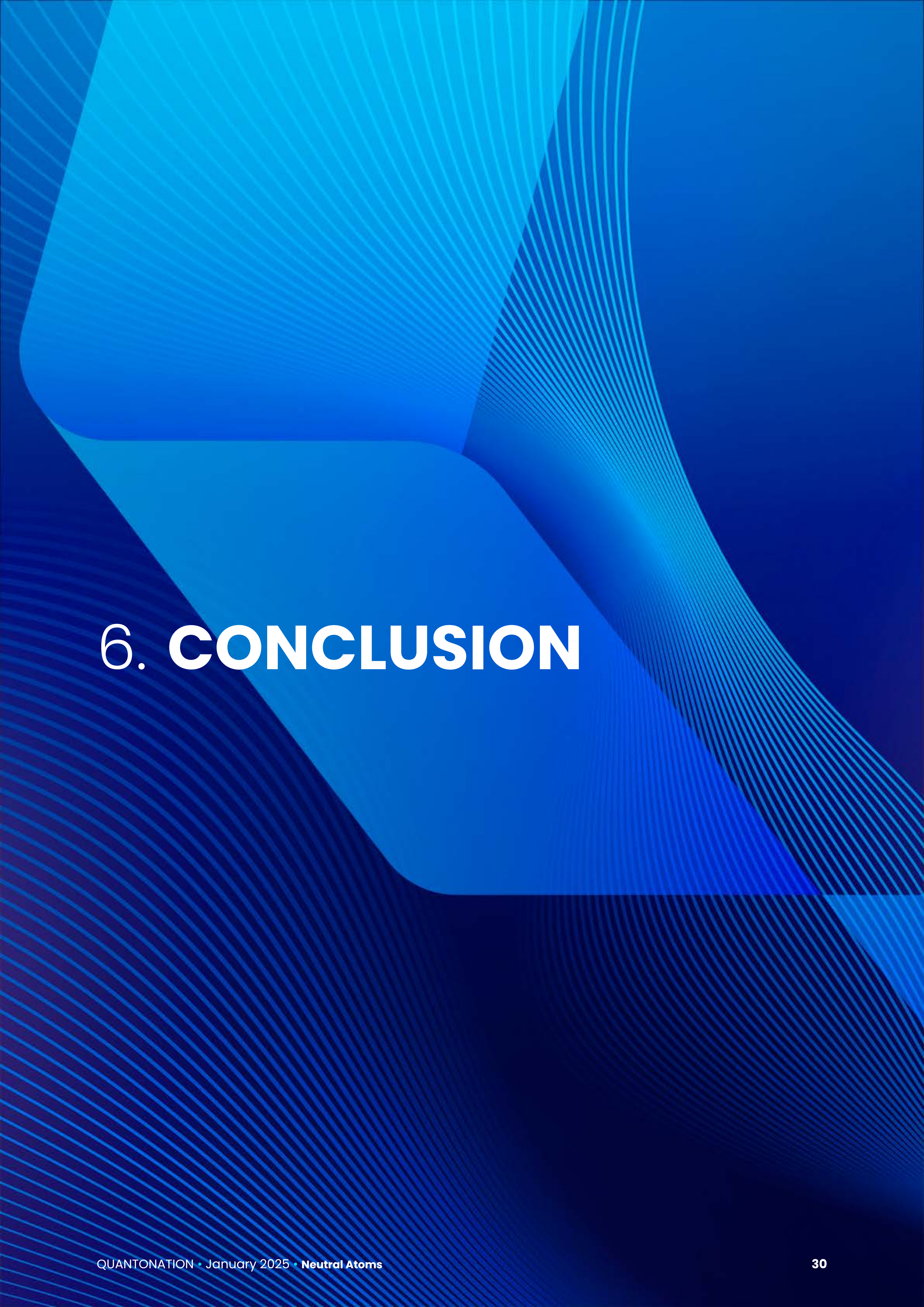
	QuEra Computing	Pasqal	Infleqtion
2024	256-qubits	1,000-qubits	1,600-qubits
2025	3,000-qubits		
2026	10,000-qubits	10,000-qubits	8,000-qubits
2027			
2028 +		100,000-qubits	40,000-qubits

The roadmaps also commit the companies to a series of aggressive timelines for the improvement of their computation speeds. Pasqal has committed to improve its *base repetition rate*, the rate of a complete cycle of computation on one of its quantum processors, from 3 cycles per second in 2024 to 10 cycles per second in 2026, and eventually 100 cycles per second after 2028. Infleqtion has committed to improve its *logical operations rate*, the speed at which its quantum processors perform quantum gates, from an undisclosed number in the present day to 10,000 operations per second in 2026 and later to 100,000 operations per second in 2028.

The roadmaps also commit the companies to a series of aggressive timelines for the improvement of their various fidelities. Infleqtion has set the most aggressive targets for the fidelities of its quantum gates, aiming to get its 2-qubit gate fidelity from 99.50% in 2024, up to 99.90% in 2026, and later up to 99.95% in 2028, with similarly ambitious targets for other gates. Neither QuEra Computing nor Pasqal have published numerical targets for gate fidelities, but Pasqal has committed to unveil its own high-fidelity gates in 2025. Finally, all three companies are now prioritising gate-based quantum computing. This is what Infleqtion and planqc have worked to from the start, but the commercial processors unveiled by QuEra Computing Inc. and Pasqal have so far been analog quantum computers, a simpler approach to quantum computing that is limited to specific types of computations.

That summarises the roadmaps currently published. It is fair to say that if these milestones are reached—which remains a big “if”—neutral atoms will be poised to take an unambiguous lead at the forefront of the quantum computing industry. But perhaps the greatest cause for optimism about the future of neutral atom quantum computing is the explosion of in interest in the field over the last decade. Between the years 2000 and 2015, the pioneering work on neutral atom quantum computing chronicled earlier in this white paper was done by a handful of research groups on both sides of the Atlantic. In the years since 2015, and in particular in the years since 2020, that has since expanded into hundreds of groups worldwide.

The sheer number of people now working on neutral atom quantum computing— both in academia and in industry—means that progress is likely to continue apace for the foreseeable future, and it should not be a surprise if some transformative innovations in the space are still to come..



6. CONCLUSION

That concludes this *Quantonation* white paper on the stunning and unexpected rise of neutral atom quantum computing. It was not that long ago that neutral atoms were barely considered to be a competitor in the quantum computing race.

But through the dogged persistence of a handful of dedicated researcher groups across the globe—notably in Paris, Boston, Boulder and San Francisco—neutral atoms have asserted themselves as not just a dark horse candidate with an outside shot of a come-from-behind victory, but one of a handful of genuine frontrunners.

Whether neutral atoms complete the fairy-tale ending and become the horse that ultimately wins the race is yet to be seen. There is a lot of race left to run, and the competition from competitors both emerging and established remains steep. But if there is one indisputable takeaway from the story of neutral atoms, it is that betting against them is the braver choice.

Quantonation has been fortunate enough to have a front seat to much of this story through its close relationship to *Pasqal*, and we look forward to continuing our bet on the promising future of neutral atoms.

«I am more optimistic about the future of neutral atom quantum computing than I was even five years ago. That is an incredibly exciting place to be.»

Dr Jean Dalibard
Collège de France.

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January 2025