# Strategies for Non-Qubit Quantum Computing

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*Presented at:* **Washington Quantum Computing Meetup (on OrionX YouTube)**

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# Overview

- Review the deep history of qubits
- Question a few forgotten assumptions
- Propose a few new approaches

# Part I. Humble Origins: The Methane Modeling Problem

# First Mention of the Methane Modeling Problem

**1970: A. Schlüter (Technische Hochschule Darmstadt) on quantum modeling of one methane molecule:**

> *"Computational physics is primarily used to solve … [the quantum mechanics of electrons, atomic nuclei…, and the electromagnetic field]. … Take, for example, … how a methane molecule is structured, what vibrations it can perform, what light it absorbs or emits.*
>
> *In principle, … **we only need to write down the quantum mechanical Schrödinger equation** for one carbon nucleus and four hydrogen nuclei [and] electrons, [then] insert the known values… This will be a long equation. …*
>
> *… a direct numerical solution to the methane problem … looks … hopeless. The Schrödinger equation … is a differential equation in 42 dimensions. … [If you replace] continuous space with a latticework of points with 10 points [too few] on each edge … **the latticework contains a total of $10^{42}$ points** …*
>
> *Nothing [but making] simplistic assumptions [helps] … [E.g.,] in the case of the methane, [one can assume] that the so-called inner electrons of carbon do not contribute directly to the chemical bond."*

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[1] A. Schlüter, *Electronic Computers in Physics* [in German], Physikalische Blätter **26** (8), 343–348 [Aug.] (1970). https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/phbl.19700260802. pp. 333-338.

# The High Cost of Digital Quantum Modeling

**1975: R. P. Poplavskiı on the astronomical energy cost of digitally modeling one molecule of methane:**

> *"It is known that the exponent describing the probability of the corresponding fluctuation is equal to the minimum work that needs to be done on the system to transfer it from the initial equilibrium state to another one determined by the fluctuation.* ***Thus, these probabilities are two-state or binary digits****. It should be emphasized that, despite the fact that the above estimate takes into account only thermal noise, it is valid in all cases. Indeed, if the estimate is accurate for $kT \gg h\nu$, then if it is necessary to take into account quantum noise, it can be taken as the upper estimate (in terms of the number of operations).* ***This estimate … strongly limits the capabilities of the modern digital computer structure [for modeling quantum phenomena].***
>
> *To concretize this statement, let us refer to [****A. Schlüter's**** example of modeling one methane model]. For the mechanical calculation quanta of a methane molecule, grid method calculations require using $10^{42}$ points. If we assume that only 10 elementary operations need to be performed at each point, and that all calculations are performed at an ultra-low temperature ($T = 3 \times 10^{-3}{}^{\circ}K$), then even the calculation of one methane molecule will require the expenditure of* ***all energy produced on Earth over about a century****."*

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[1] R. P. Poplavskiĭ, *Thermodynamic models of information processes* [in Russian], Soviet Physics Uspekhi **18** (3), 222, (1975). https://www.mathnet.ru/php/archive.phtml?wshow=paper&jrnid=ufn&paperid=9965&option_lang=eng

# Biology Builds Reliability from Complexity

**1974: J. J. Hopfield on cellular use of composite chemical pathways to achieve high-fidelity outcomes**

> *"The specificity with which the genetic code is read in protein synthesis, and with which other highly specific biosynthetic reactions take place, can be increased above the level available from free energy differences in intermediates or kinetic barriers by a process defined here as kinetic proofreading. A simple kinetic pathway is described, which results in this proofreading when the reaction is strongly but nonspecifically driven, e.g., by phosphate hydrolysis. Protein synthesis, amino acid recognition, and DNA replication all exhibit the features of this model. In each case, known* ***reactions which otherwise appear to be useless or deleterious complications are seen to be essential to the proofreading function****.*
>
> *…*
>
> *The basis of good reading discrimination may often lie in proofreading and the kinetic complexity of biosynthetic pathways, and not in the existence of some particular intermediate with an extremely large free energy difference between correct and incorrect substrates. Understanding the meaning of biosynthetic pathways in such cases will involve the nuances of minor pathways, competitive rates, and side reactions. The dominant direct reaction pathway need not by itself contain the explanation of large specificity."*

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[1] J. J. Hopfield, *Kinetic Proofreading: A New Mechanism for Reducing Errors in Biosynthetic Processes Requiring High Specificity*, Proceedings of the National Academy of Sciences **71** (10), 4135–4139 [Oct.] (1974). https://www.pnas.org/doi/abs/10.1073/pnas.71.10.4135

# First Quantum Computing Efficiency Hypothesis

## 1980: Uri Manin proposes that "superposed quantum automata" achieve spectacular energy efficiency

*"Molecular biology furnishes examples of the behaviour [such as DNA replication that are best described] in terms initially devised for discrete automata. … We need a mathematical theory of quantum automata [that provides] mathematical models of deterministic processes with quite unusual properties, [since] the quantum state space has far greater capacity than the classical one. [The] quantum version [of a classical system with N states] allows superposition (entanglement) [of] $c^N$ states. When we join two classical systems, their number of states $N_1$ and $N_2$ are multiplied, [but] in the quantum case, we get exponential growth $c^{N_1 N_2}$.*

*… since there is no unique decomposition of a quantum system into its constituent parts, **a state of the quantum automaton can be considered in many ways as a state of various virtual classical automata**. … R. P. Poplavskii [describes how classical emulation of the] quantum-mechanical computation of one molecule of methane requires $10^{42}$ grid points [and would] use all the energy produced on Earth during the last century.*

*… The quantum automaton … model of evolution is the unitary rotation in a finite dimensional Hilbert space, and the decomposition of the system into its virtual parts corresponds to the tensor product decomposition of the state space ("quantum entanglement"). … We must accommodate interaction … described by density matrices and probabilities [since a classical continuously evolving system governed by differential equations can imitate a discrete automaton only if its phase space is extremely elaborate: it must include many stability domains, or attractors, separated by low energy barriers.]*

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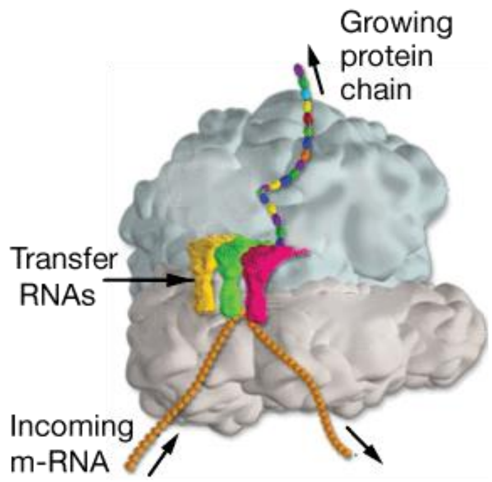
[1] Y. I. Manin, *Computable and Uncomputable* (Introduction, pages 14-15 only, in English), Soviet Radio (1980). https://sarxiv.org/ref.1980-10-09.p14-15.engl.pdf.

# Manin's Hypothesis: "virtual classical automata"

- Manin: *"The quantum state space has far greater capacity than the classical one."*
- This is valid for computation *only* if the many-worlds idea is correct
  - It assumes computational power exists *independently* of the observer
  - An alternative: Superpositions are *observer-imposed* views of single items

**Manin:**

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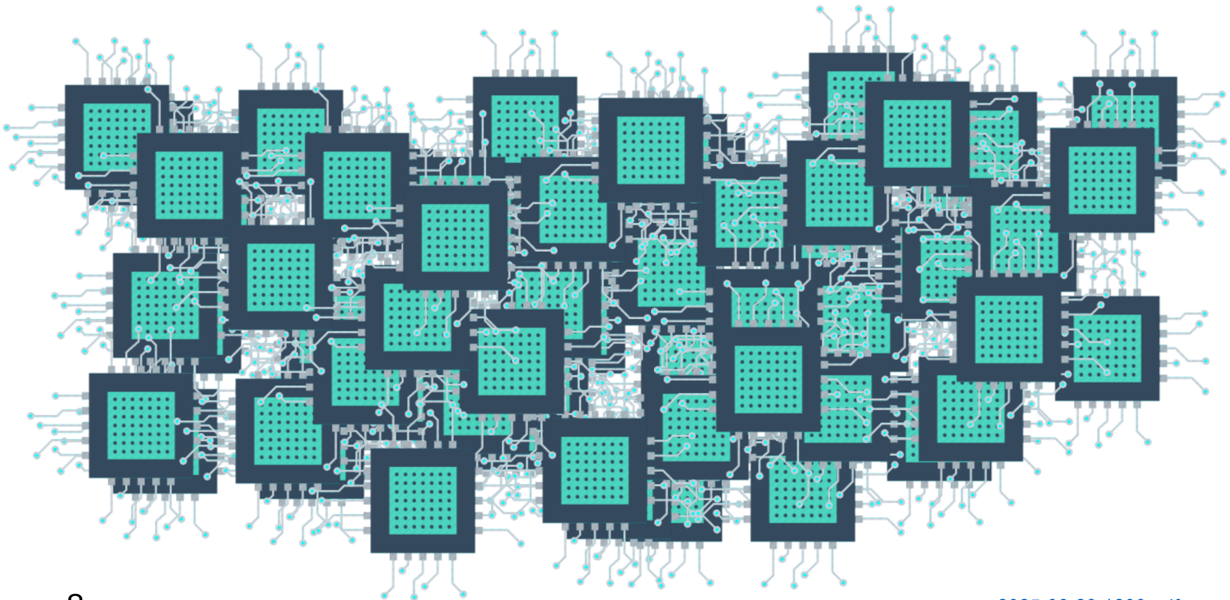

# Feynman’s Universal Quantum Simulator

**1982: R. Feynman on his interpretation of quantum computing (quite different from others)**

> *“Now I explicitly go to the question of how we can simulate [quantum-mechanical effects] with a computer — a universal automaton. … But the full description of quantum mechanics for a large system with $R$ particles is given by a function $\psi(x_1, x_2 \dots x_R, t)$, which we call the amplitude, to find the particles $x_1, x_2, \dots x_R$, … Because it has too many variables, it cannot be simulated with a normal computer with a number of elements proportional to $R$ [particles] or proportional to $N$ [locations in space]. …*
>
> ***Can you do it with a new kind of computer — a quantum computer?*** *… If we disregard the continuity of space and make it discrete … as an approximation … it does seem to be true that all the various field theories … can be simulated … with* ***little latticeworks of spins and other things****. … I believe … that with a suitable class of quantum machines you could imitate any quantum system, including the physical world.*
>
> *… It has been found that there is a kind of universal [Turing] computer that can do anything. [In] the same way, we should try to find out what kinds of quantum mechanical systems … will simulate everything. What, in other words, is the universal quantum simulator?”*

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[1] R. Feynman, *Simulating physics with computers*, International Journal of Theoretical Physics **21** (6), 467–488 (1982). https://catonmat.net/ftp/simulating-physics-with-computers-richard-feynman.pdf

# Origin of the Word "Qubit"

## 1992: Ben Schumacher's creation of the word "qubit" in a joke he made to Bill Wootters

*"In the spring of 1990 at the Santa Fe Institute, Bill (Wootters) and I discussed the idea that, by using suitable code words and decoding observables, [perhaps] you could reach the Holevo bound for classical information transfer over a quantum channel. I don't think I knew that Holevo had previously conjectured this; Bill will have to speak for himself. We worked on this for a couple of years. The problem proved to be horribly difficult. …*

*After a couple of years of struggling with the problem, I was pretty discouraged. I drove Bill back to the airport in Columbus, which takes about an hour. As often happens when nothing is working, the talk turned a little crazy. Maybe, we said, we are asking the wrong questions.* ***Maybe in quantum mechanics, the old ideas of information are just not appropriate. Maybe we need a new idea of "quantum information." And we could measure it in "qubits"! The idea of measuring something in "qubits" (like Noah's ark) struck us as immensely funny, and we laughed a good deal.*** *…*

*During the drive back, I started thinking about our joke. It occurred to me that it was not a bad idea, actually. I understood several things immediately — such as the fact that "quantum coding" could not be a copying process because of the no-cloning theorem, and the fact that* ***the qubit would be a generic two-level system****. When I got back to Gambier, I spent the summer cooking up the data compression theorem. …*

*Bill Wootters: Ben's recollections sound entirely right to me. In the course of our discussion in the car, Ben suggested that maybe we needed to think about a new kind of information that is fundamentally quantum mechanical. And I remember very clearly that [Ben Schumacher] is the one who came up with "qubit" as a unit of this information. 'And we could measure it in qubits!' were very likely his exact words, including the exclamation point!"*

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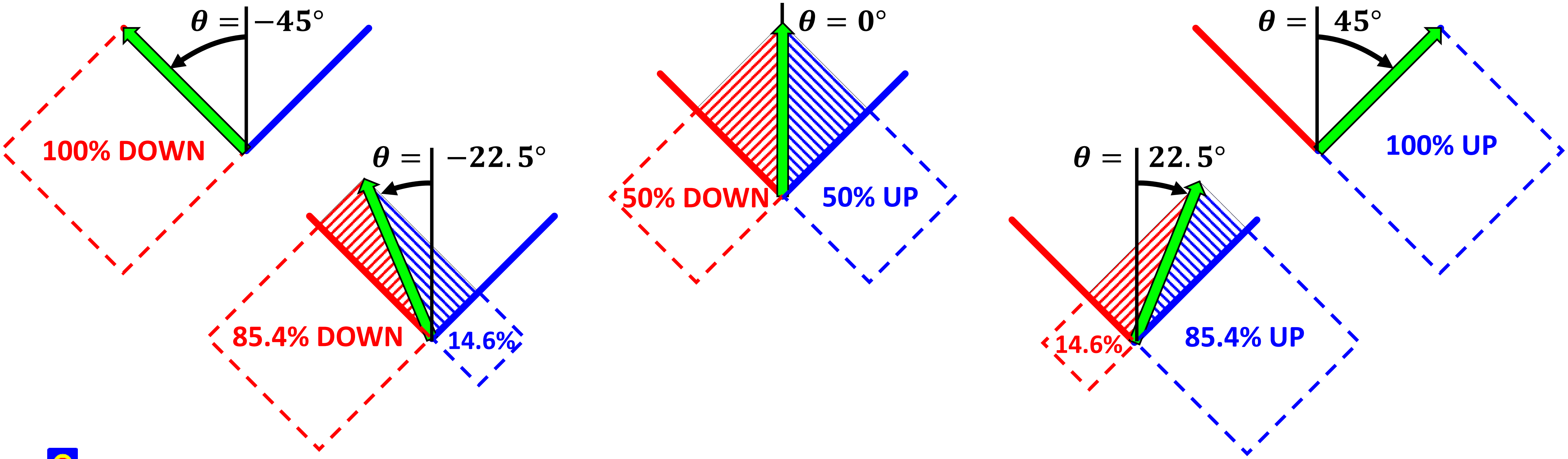
[1] C. A. Fuchs, M. Schlosshauer, and B. C. Stacey, *My Struggles with the Block Universe* [page 851: qubit origin story]," arXiv preprint arXiv:1405.2390 [May 10] (2015). https://arxiv.org/pdf/1405.2390.pdf#page=909

# "The qubit would be a generic two-level system"

- When Ben Schumacher invented the qubit in 1992, he noted that "the qubit would be a generic two-level system" (vs. 1-level bit?)
- What does this mean? It is a superposition of two object states.
- An alternative: One object with viewing angles, e.g. $-45° \leq \theta \leq 45°$



# Part II. Fourier Transforms and Quantum Computing

# Quantum Fourier Transforms and the Shor Algorithm

**1994: Don Coppersmith finds a better quantum way to do the Fourier transform step of Shor's algorithm**

> "**Abstract**. *We define an approximate version of the* ***Fourier transform*** *on $2^L$ elements, which is computationally attractive in a certain setting, and which may find application to* ***the problem of factoring integers with a quantum computer****, as is currently under investigation by Peter Shor.*
>
> …
>
> ***A definite advantage is in the computational complexity.*** *Shor's proposal, using a mixed-radix Fourier Transform with $1 \approx 5n^2$ the product of small prime powers, appears to require about $(\log n)^3$ elementary operations (spin-spin interactions). The radix-$2^L$ FFT requires only $(\log n)^2$ elementary operations. The AFFT requires only $(\log n)(\log \log n + \log 1/\epsilon)$ operations, where a final precision of $\epsilon$ is required. So, the Fourier transform is no longer the bottleneck of the computation.*"

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[1] D. Coppersmith, *An Approximate Fourier Transform Useful in Quantum Factoring*, IBM Research Report RC 19642 [Jul. 12] (1994). https://arxiv.org/abs/quant-ph/0201067

# The Fourier and Inverse Fourier Transforms

## Fourier transform

$$\hat{f}(\boldsymbol{k}) = \int_{-\infty}^{\infty} f(\boldsymbol{x}) e^{-i2\pi \boldsymbol{k}\cdot\boldsymbol{x}} d\boldsymbol{x}, \quad \forall \xi \in \mathbb{R}$$

## Inverse Fourier transform

$$f(\boldsymbol{x}) = \int_{-\infty}^{\infty} \hat{f}(\boldsymbol{k}) e^{i2\pi \boldsymbol{k}\cdot\boldsymbol{x}} d\boldsymbol{k}, \quad \forall x \in \mathbb{R}$$

# Quantum Mechanics as Fourier-Duality Mechanics

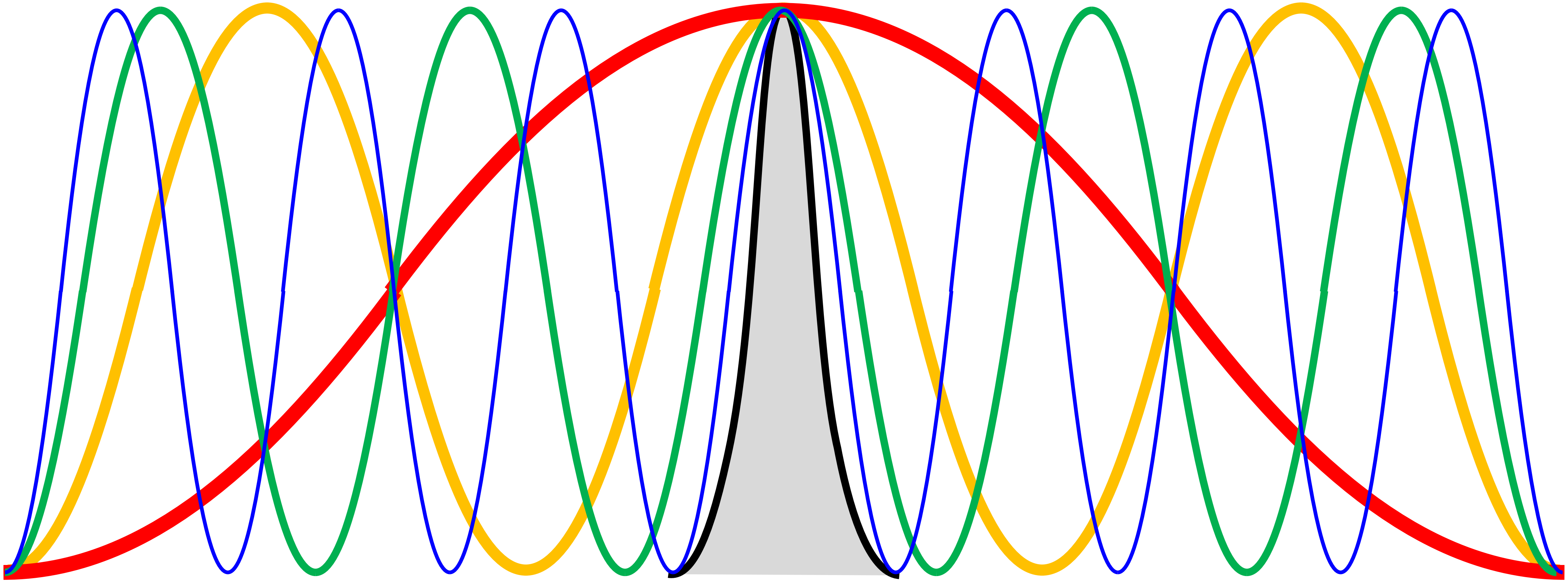
**Position Wave Function as a Fourier Transform of Momentum States (e.g., of emission spectra)**

$$\psi(\boldsymbol{r}) = \frac{1}{\left(\sqrt{2\pi}\right)^3} \int_{\boldsymbol{k}-space} \phi(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \mathrm{d}^3\boldsymbol{k}$$

**Momentum Wave Function as an Inverse Fourier Transform of Position States (e.g., of crystals)**

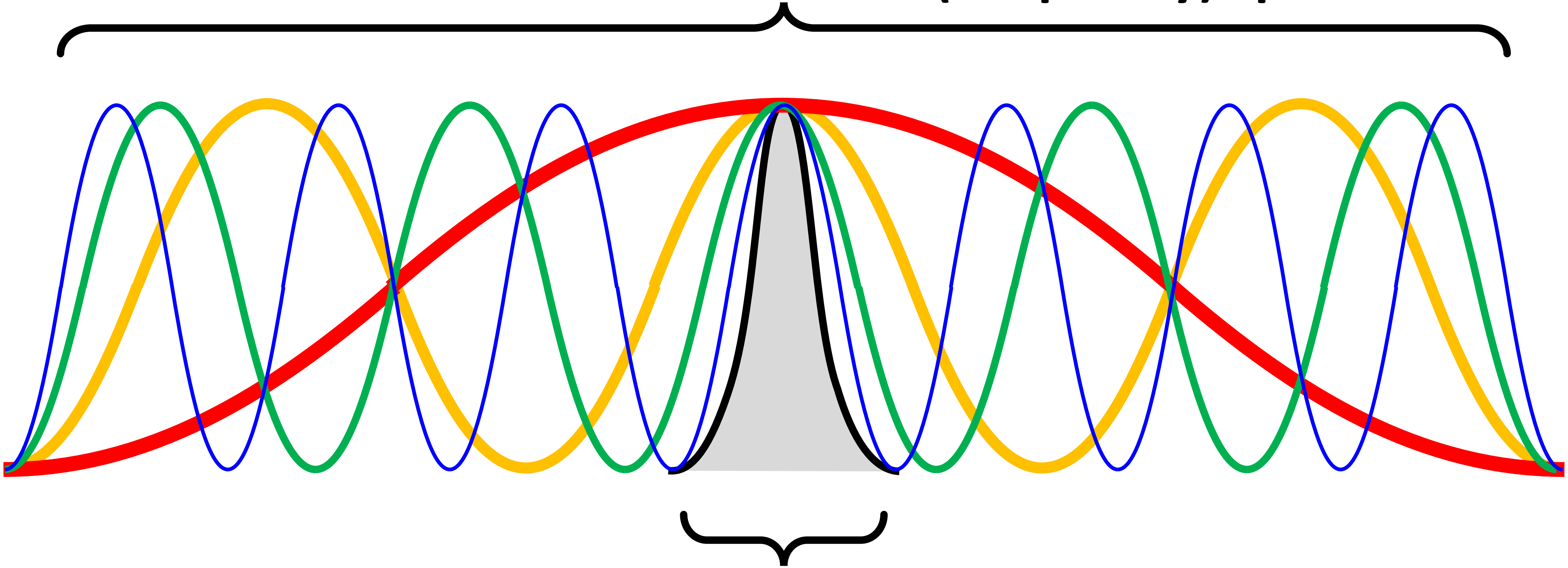
$$\phi(\boldsymbol{k}) = \frac{1}{\left(\sqrt{2\pi}\right)^3} \int_{\boldsymbol{r}-space} \psi(\boldsymbol{r}) e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \mathrm{d}^3\boldsymbol{r}$$

# Peak Matching: A Lazy Way to Do Fourier Transforms



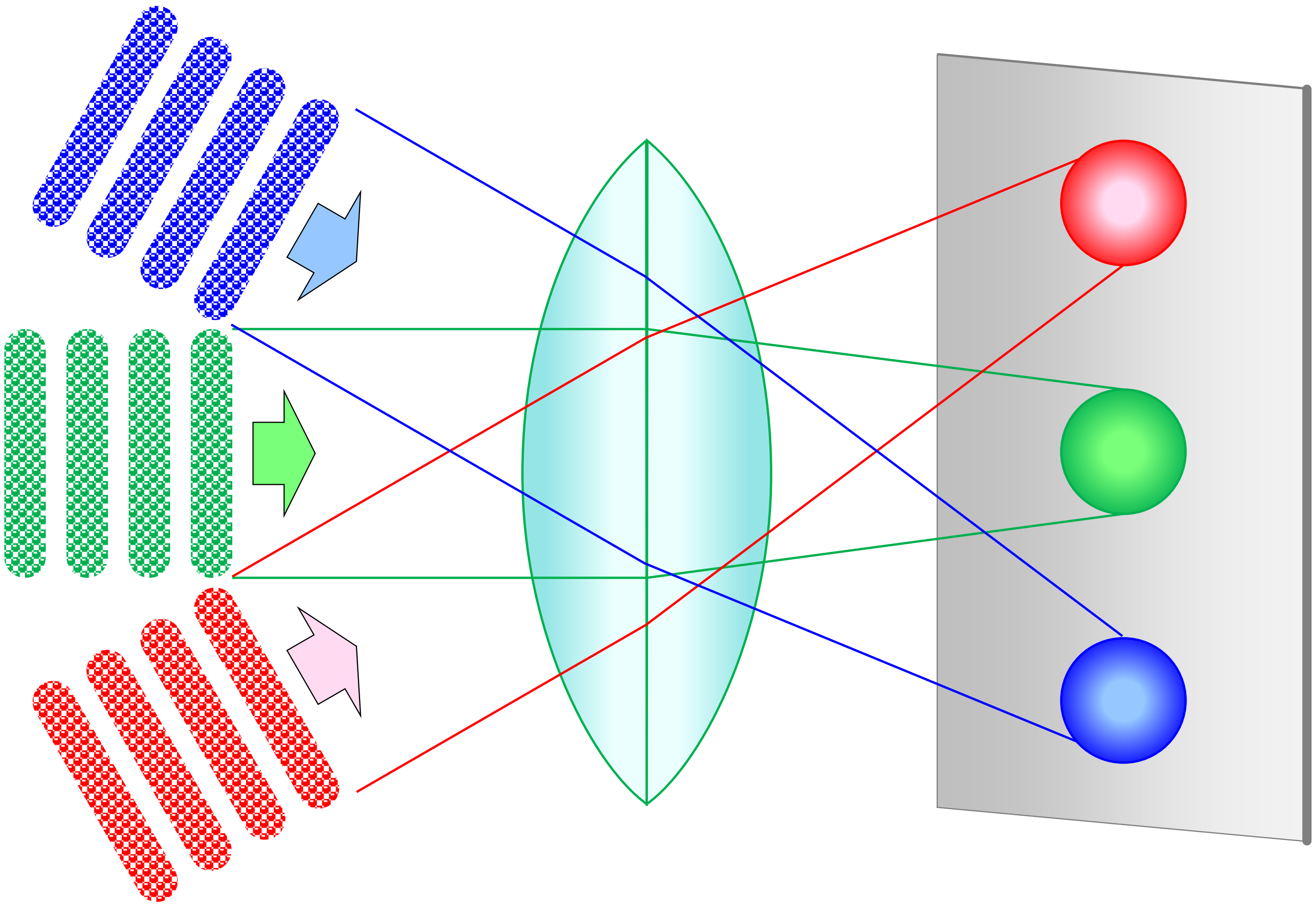
# Fourier is the Source of Quantum Uncertainty

**Broad location in momentum (frequency) space**

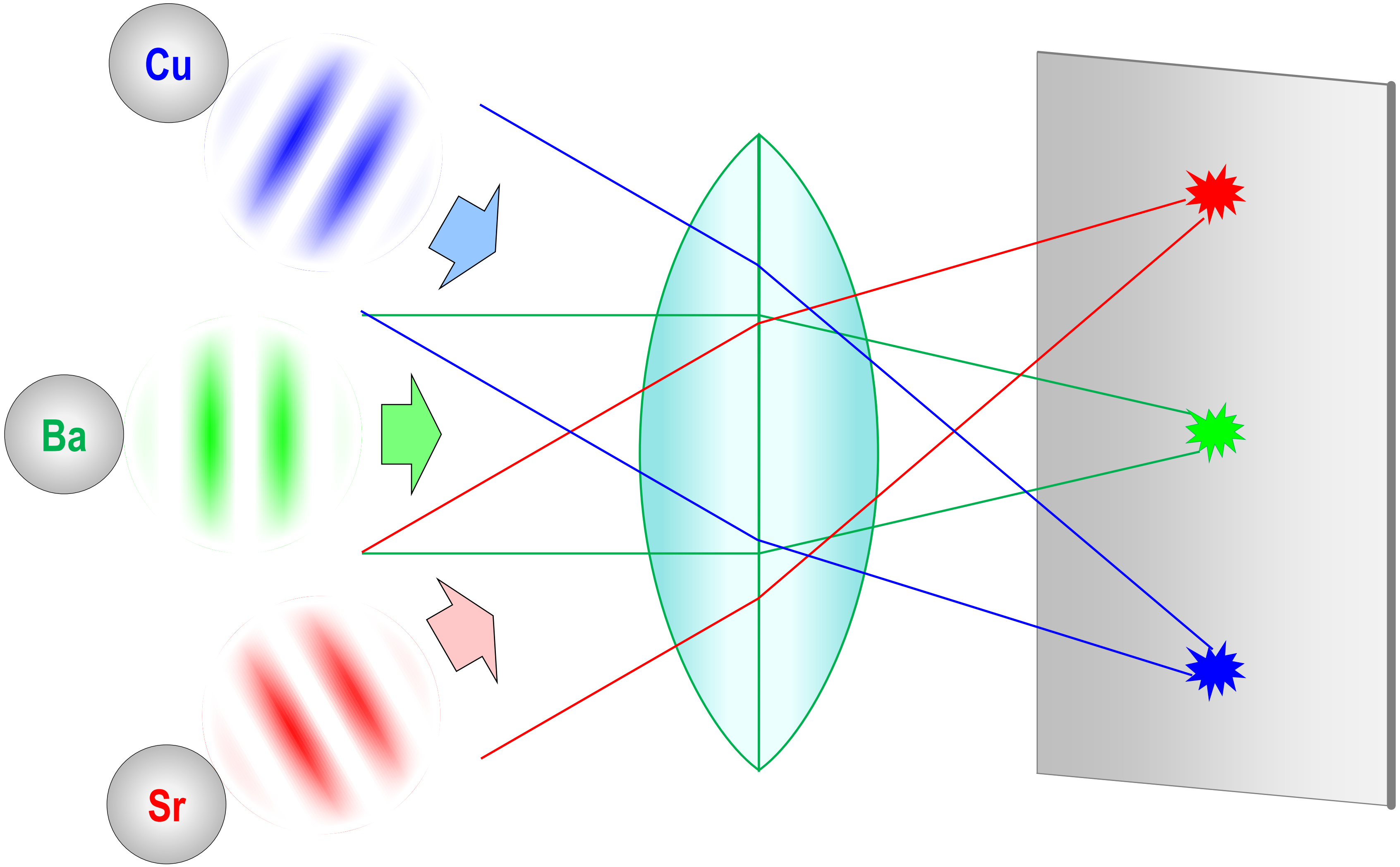


**Narrow location in position (xyz) space**

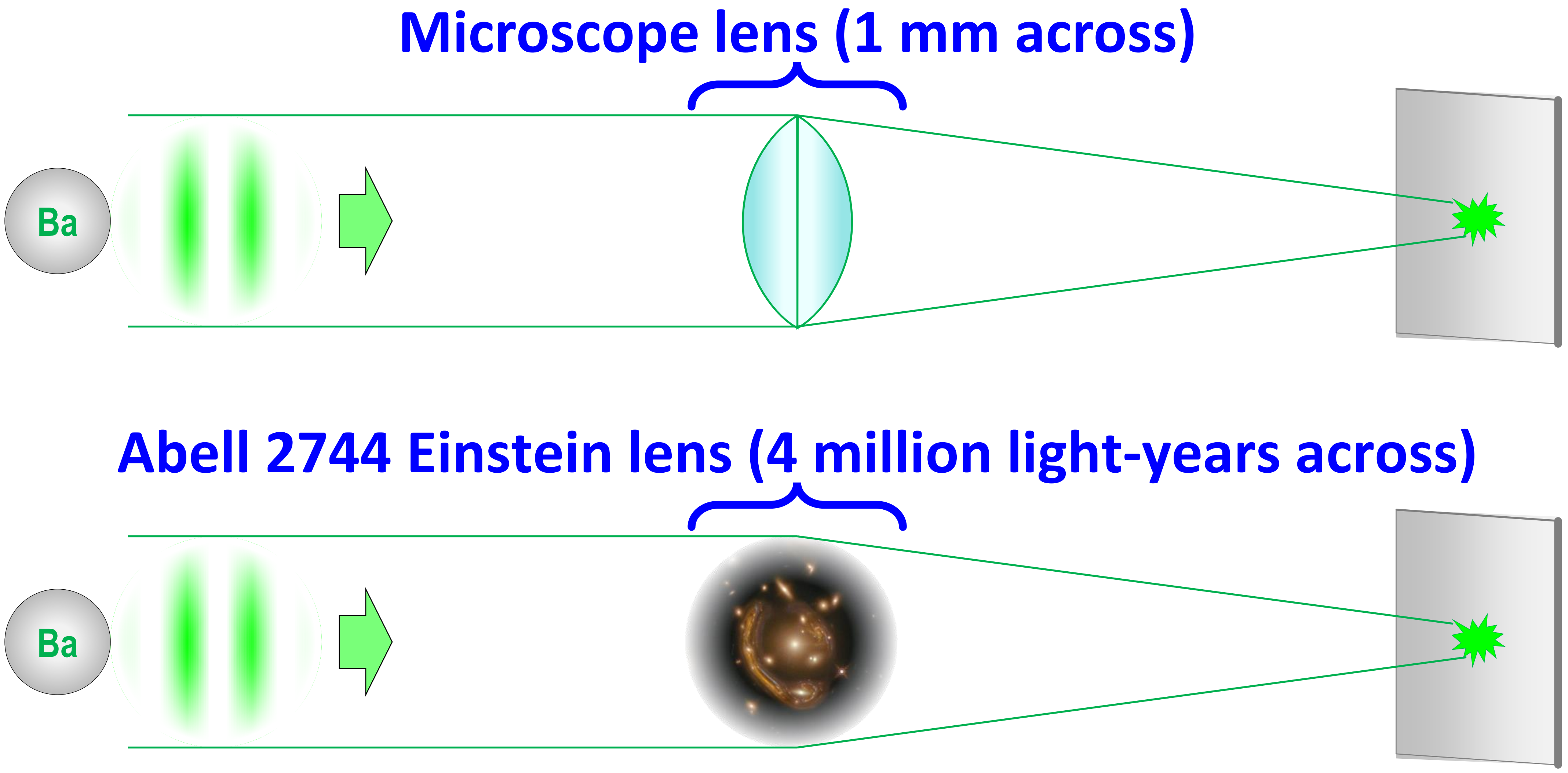
# Lenses are Fourier Transformers of Plane Waves



# Lenses Are Also *Quantum* Fourier Transformers



# The Lens-Scale Issue: *Photon Fourier Don't Care!*



# How Can Photons Scale Over 25 Orders of Magnitude?

- When a four-trillion-sun galaxy cluster focuses *one* photon to a point, it means the photon "saw" the entire cluster (!)
- How is this possible? How can *one photon* interact meaningfully with four trillion suns' mass spread across millions of light-years?
- The correct answer: We don't know how. It's just what we observe.
- Important limitations:
  - One photon only gives a direction — nothing more.
  - The more such photons you see, the more details you see
  - The resolution issue is related to those of quantum computing
- Summary: **Fourier is almost "free," but the *details* cost energy**

# How Relevant Is Fourier to Quantum Computing?

- While photon Fourier transforms are remarkable for…
  - Scalability over at least 25 orders of magnitude
  - Vanishingly small energy requirements to perform the transform
  - Extreme speed (literally the speed of light)
- … these are not proof of its value to quantum computing
- The 1994 Coppersmith Quantum Fourier Algorithm contribution to Shor’s algorithm demonstrates proves a strong relevance
- Question: Are we missing further opportunities by focusing to much on differential smoothness with its enormous digitization costs?

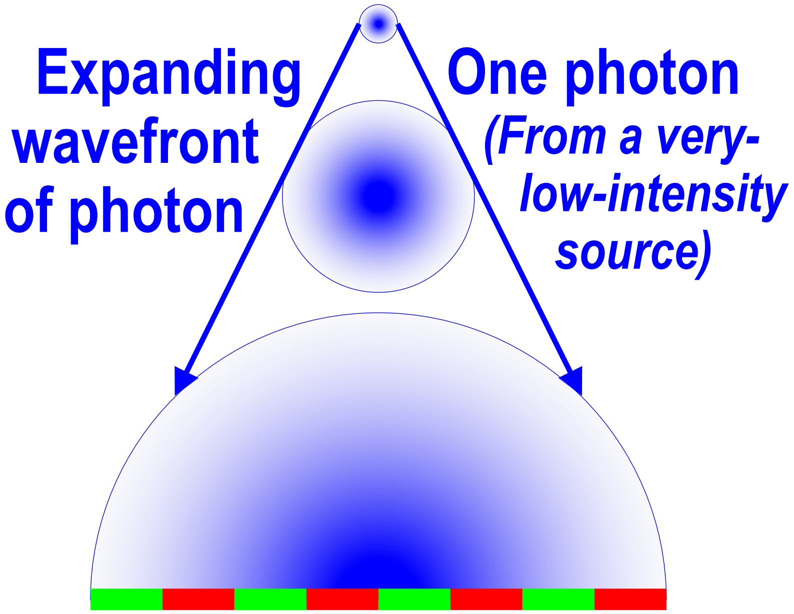
# Part III. Computers, Entanglement, and Observation

# Rethinking Use of the Digital Computer Model

- Poplavskiı, Manin, Feynman, Schumacher, and Wootters all assume a complex phase space that mimics a classical computer:
  - Poplavskiı: "Thus, these probabilities are two-state or binary digits."
  - Manin: "[imitate digital] only if its phase space is extremely elaborate"
  - Feynman: "simulated … with little latticeworks of spins and other things"
  - Schumacher-Wootters: "The qubit would be a generic two-level system."
- Only Hopfield diverges: "useless or deleterious complications are seen to be essential to the proofreading process"
- Question: Must we recreate a digital computer to access quantum computing processes such as quantum Fourier transforms?

# Encoding Complex Images into Single Photons (1 of 2)

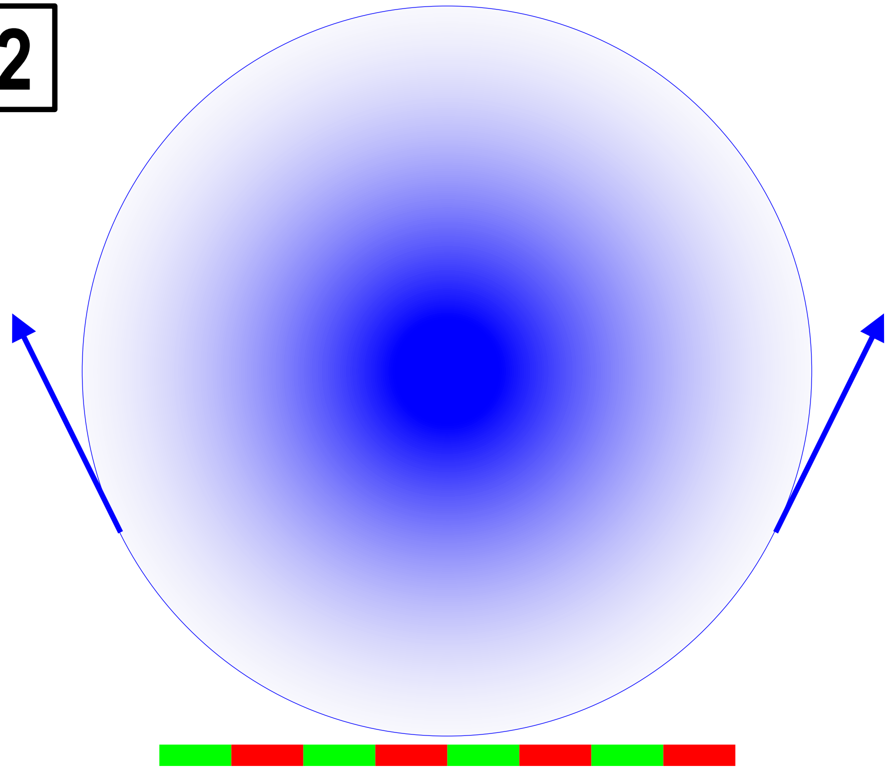
**Step 1**




Digitally controllable 2D mirror array

***Digital multi-mirror device in all-flat, full-coherence, specular reflection mode***

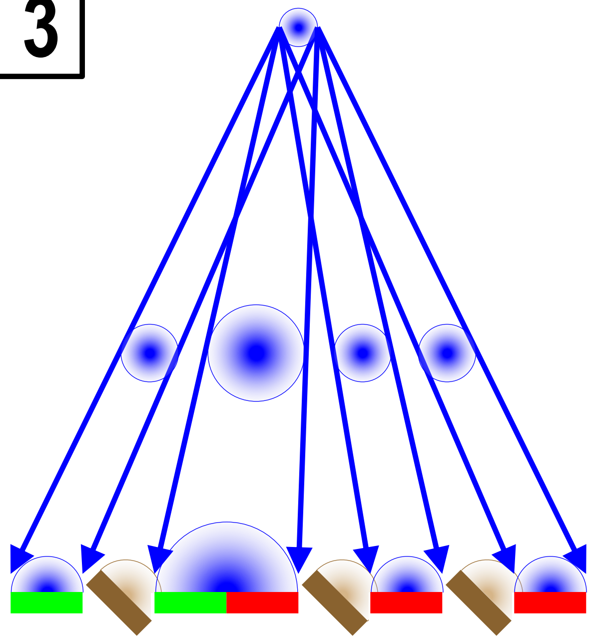
**Step 2**



***No signals* (no qubits) except mirror location are encoded onto the reflected photon.**

# Encoding Complex Images into Single Photons (2 of 2)

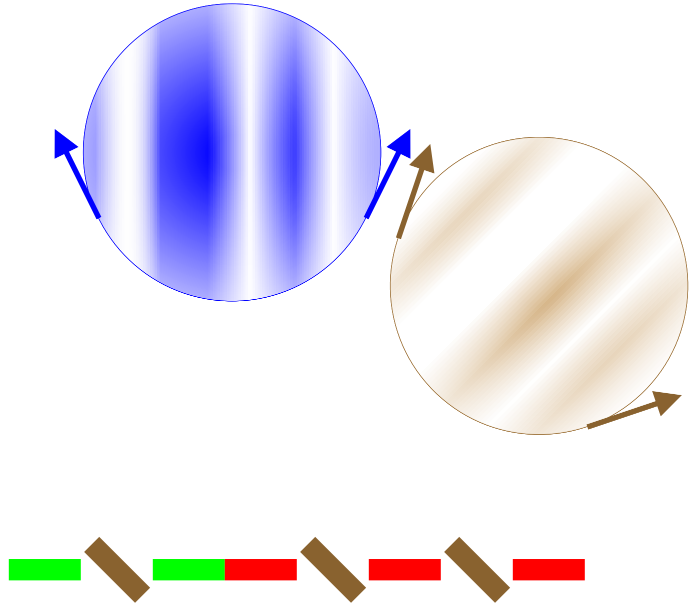
## Step 3



Tilted mirrors split photon into two patterns

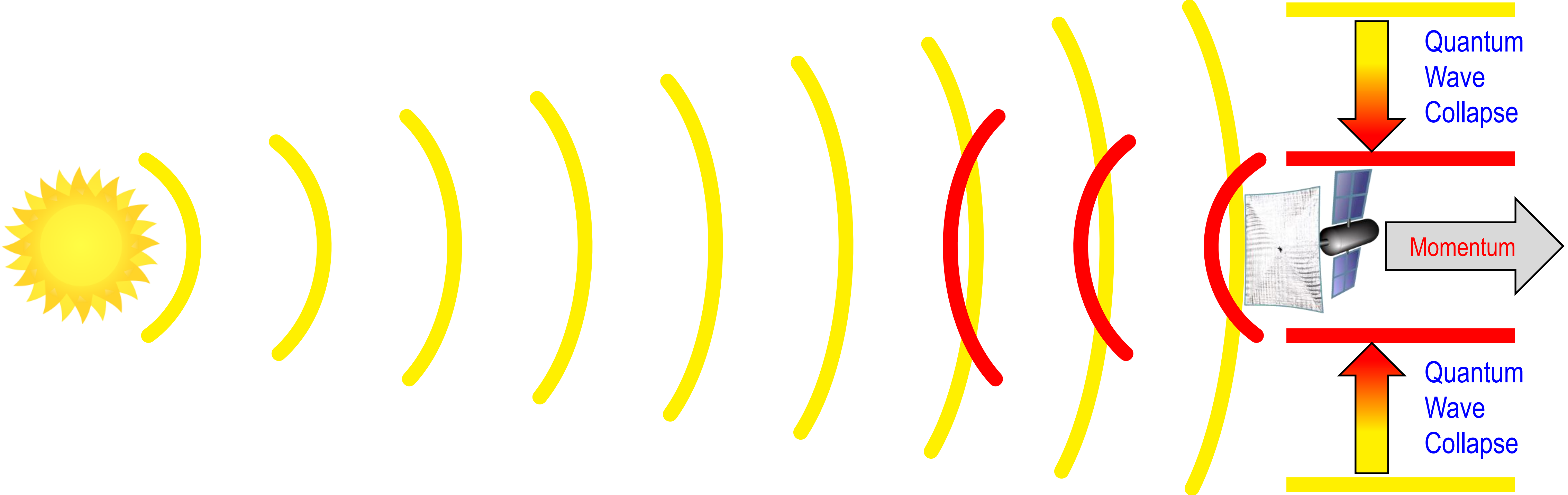
***Selected coordinated groups of mirrors reflect photons coherently in either of two directions.***

## Step 4



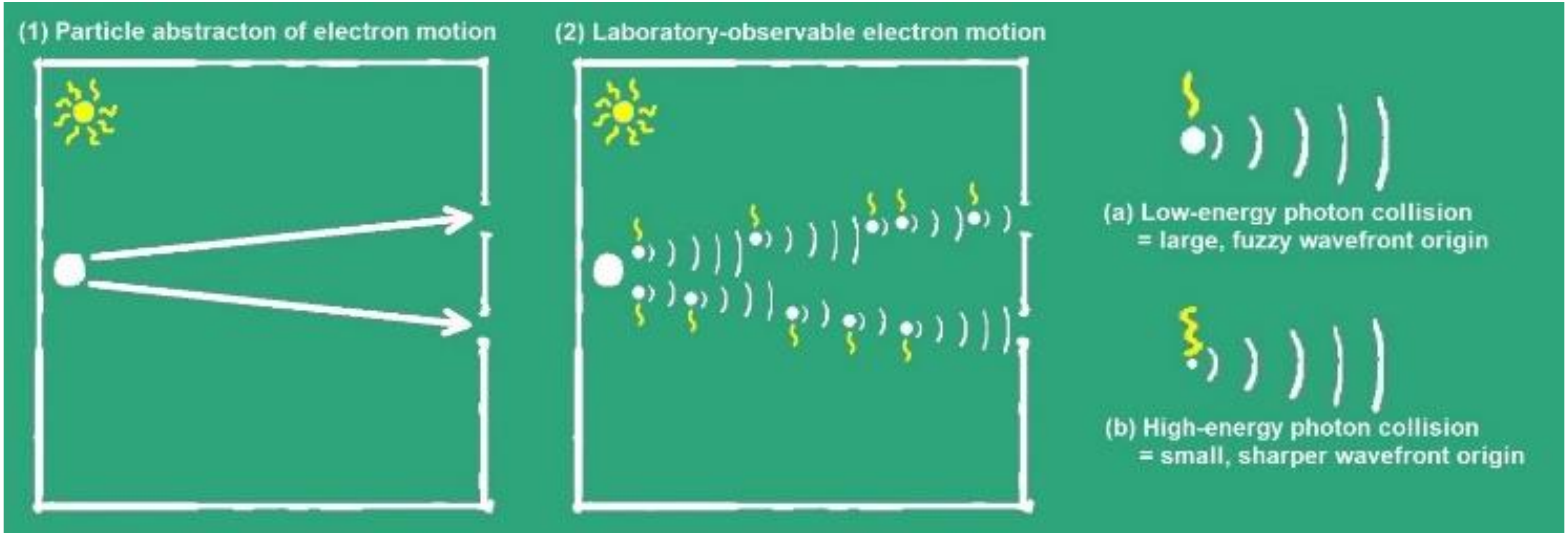
***Complementary patterns separate but remain entangled with each other, since the photon can be detected in either wavefront, but not both.***

# Do We Have the Observer Problem Backwards?



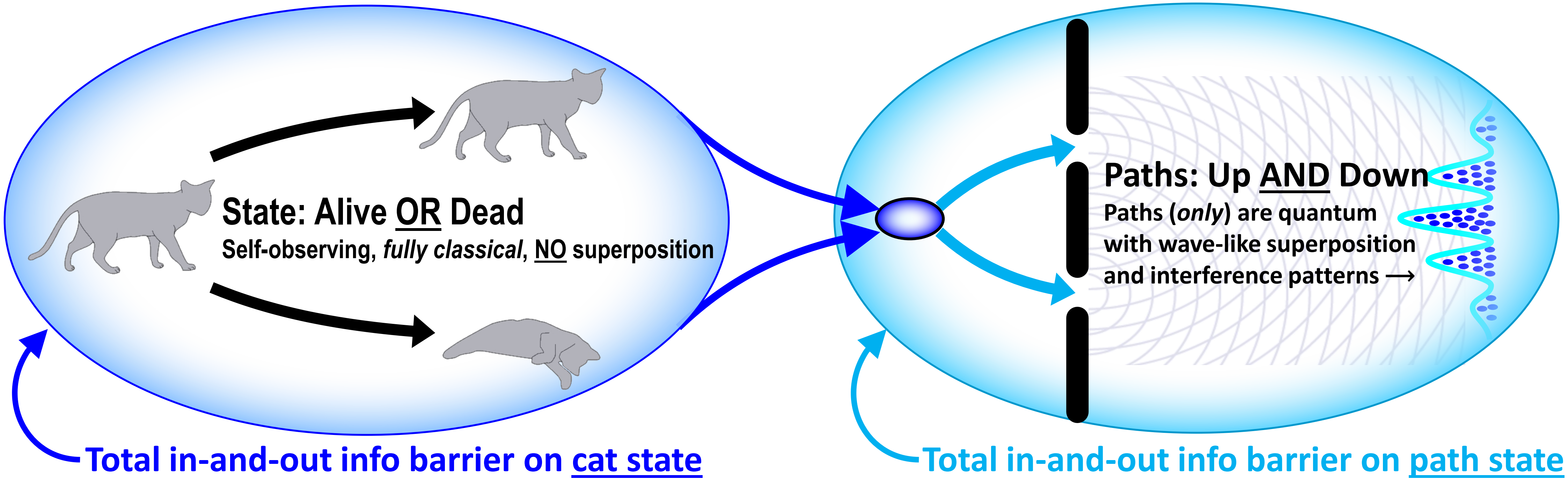

- ➢ Specularly reflected photon waves are not absorbed by atoms
- ➢ However, they *are* detected by the momentum they impart

# Minute Acceleration (Detection) and Classical Reality




- Immersion in acceleration ensures *non*-quantum physics behaviors
- There can be no parallel computing universes if wave collapse *creates* classical physics. This singular universe is all we get.

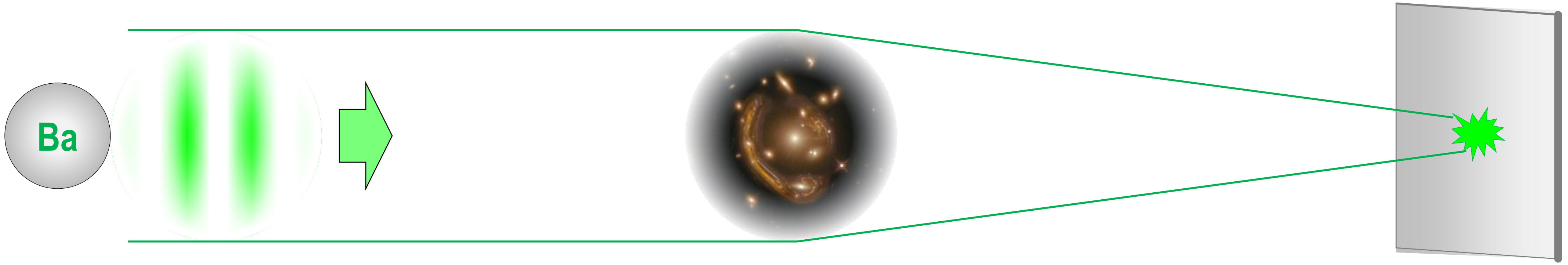
# Bottom-Up Reality with Spacetime Uncertainty




- ➢ Manin's concept of virtual automata cannot exist in such a universe
- ➢ A separate issue: Carefully accounting for the strong metrics boundaries created by acceleration supports uncertain spacetime

# But How Would a Singular Universe Compute?

- Without many-worlds, the source of quantum computation switches from multiple universes to massive, all-encompassing forms of entanglement at all physics scales, including (especially) classical
- Every action-reaction "bump" event, no matter how large or small:
  - Collapses *both* wavefunctions to a smaller size
  - Creates a new entanglement between them (both now "know" the other)
- The astonishing range and energy efficiency of photon Fourier transforms reflect the complexity of multi-level entanglements



# Entanglement Without Breaking Lightspeed

**2004: Asher Peres on why quantum state entanglement is real but never violates lightspeed**

*"In the [Einstein-Podolsky-Rosen paper], the authors complain that "it is possible to assign two different wave functions to … the second system." … They use the word "simultaneous" … four times — surprising … for people who knew very well that this term was undefined in the theory of relativity.*

*… One observer, … Alice, measures the $z$-component of the spin of her particle and finds $\pm\hbar/2$. She then … knows that if … distant observer, Bob, measures … the $z$-component of the spin of his particle, the result is … $-\hbar/2$. One can then ask: when does Bob's particle acquire the state with $s_z = -\hbar/2$?*

*… **When Alice measures her spin**, the information she gets is localized at her position and will remain so until she decides to broadcast it. **Absolutely nothing happens at Bob's location.** From Bob's point of view, all spin directions are equally probable, as can be verified experimentally by repeating the experiment many times with a large number of singlets without taking into consideration Alice's results."*

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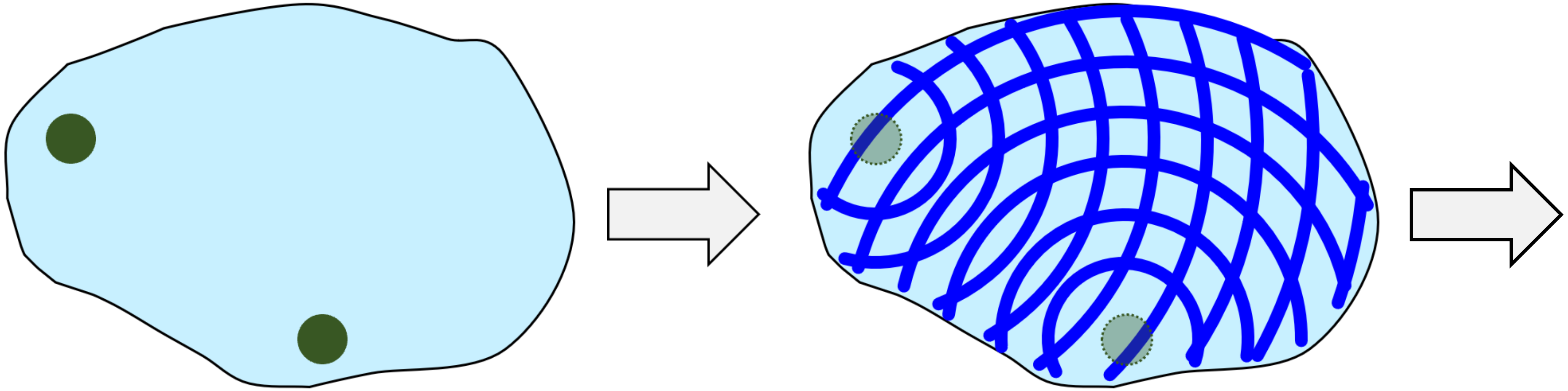
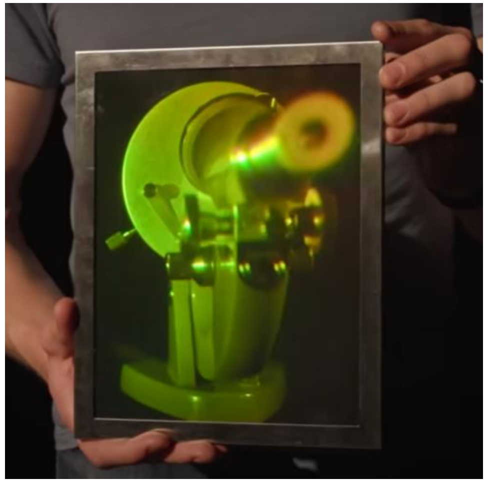
[1] A. Peres, *Quantum Information and General Relativity*, Fortschritte der Physik: Progress of Physics **52** (11-12), 1052–1055 (2004). https://arxiv.org/abs/quant-ph/0405127

# Part IV. Suggestions and Wrap-Up

# Suggestion: Think Holograms, Not Circuit Boards



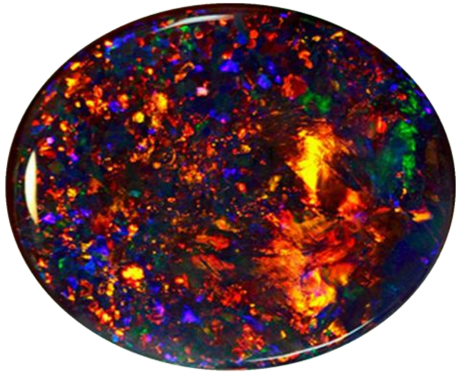


***The Microscope***, *Walter Spierings, 1984. Screen capture from "How Are Holograms Possible?," 3Blue1Brown, Oct 5, 2024,* *https://youtu.be/EmKQsSDlaa4?t=0m48s*

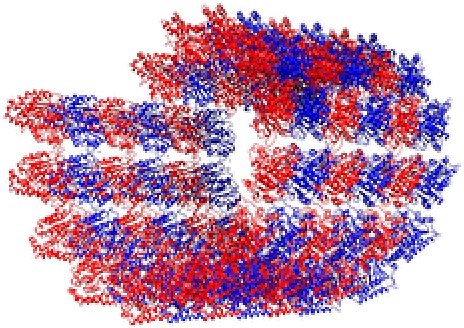
- Fourier duality is holographic duality using traditional position-momentum wave functions (no black holes!)
- If you think only in position (circuits) space, you lose access to the phenomenal power of photon Fourier transforms
- Lensing and repetition (diffraction gratings) are tools

# Suggestion: Stop thinking quantum is "cold only"

- The colors of opals and you reading this text are both examples of extraordinary levels of quantum mechanics in warm matter.



- Superradiance — a century-old quantum effect related to lasing — suppresses photon emissions at room temperature in organic microtubule networks.



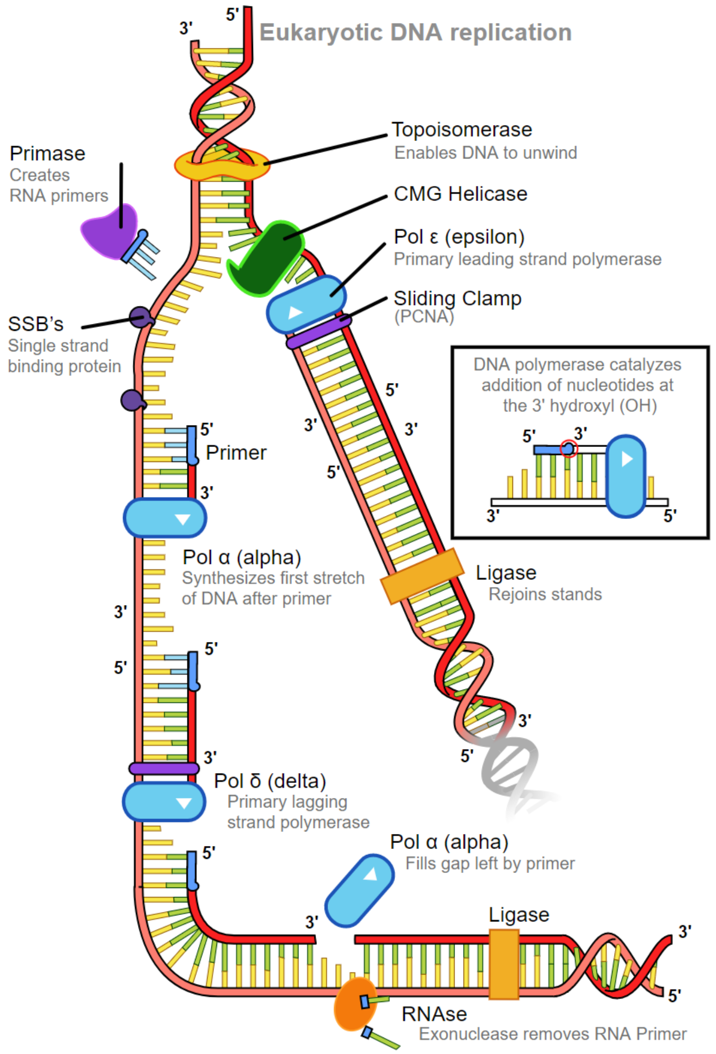
- Ordinary (and extraordinary) mirrors owe their reflective abilities to room temperature condensations of electrons in momentum space (versus position space).

# Suggestion: Don't Digitize Everything

- The original $10^{42}$ estimate for a methane molecule assumed that the *only* way to model it was with smooth differential equations

- The energy levels required to model the quantum world digitally are staggering in part *because* they assume reality is digital

- In contrast, biochemistry does all this at low energy in a chaotic environments. We need to know how.



# Wrap-Up

- The history of qubits begins with the necessarily endless task of digitizing a continuum. This is not a good start.
- Quantum computing never abandoned its intensely digital background set of assumptions, despite, e.g., the remarkable symmetry of position and momentum wave functions
- An obvious opportunity for greater energy efficiency: Photon-based quantum Fourier transforms
- Taking a more holographic approach, with lessons from molecular biochemistry, could open up novel quantum computing doors