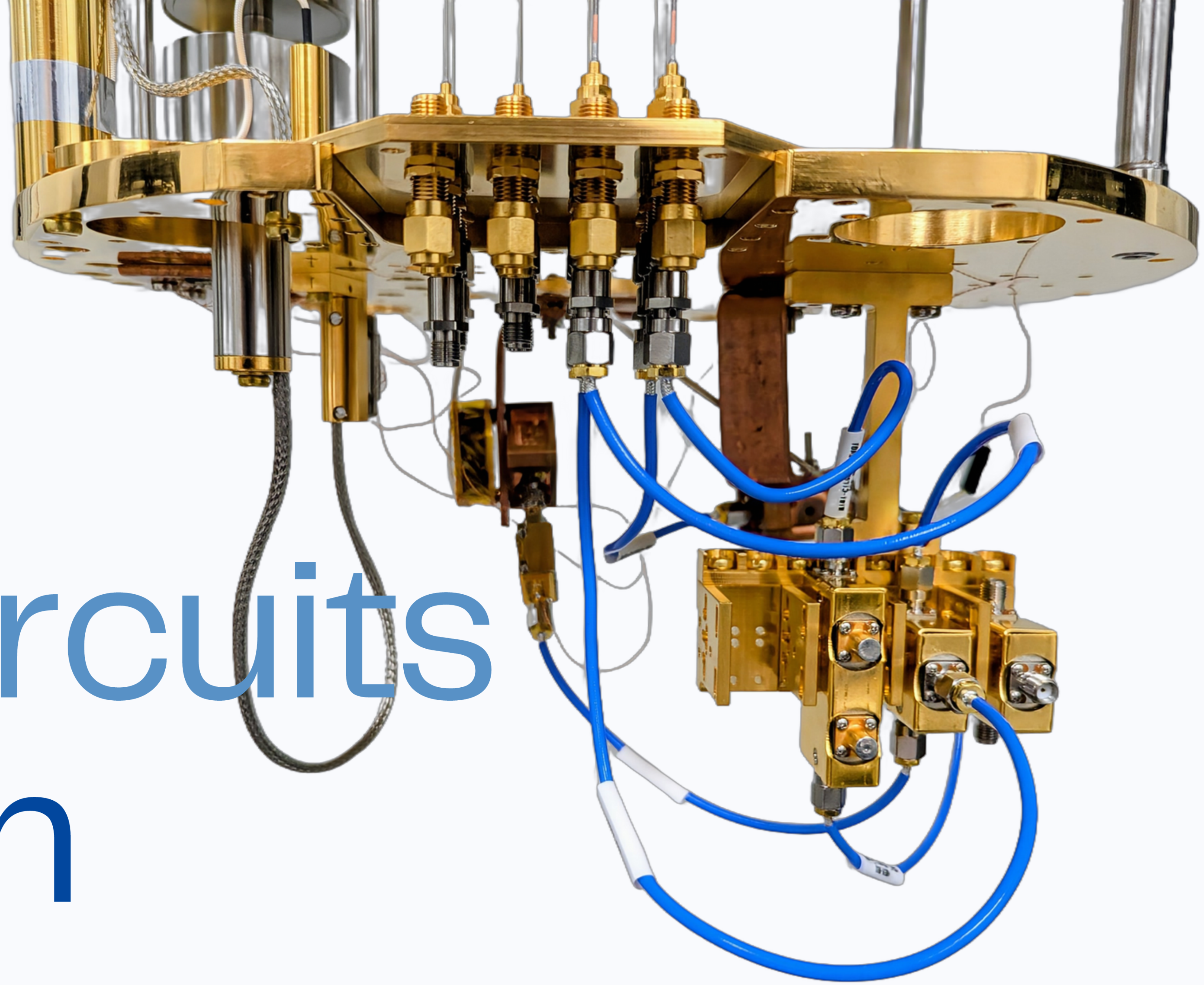
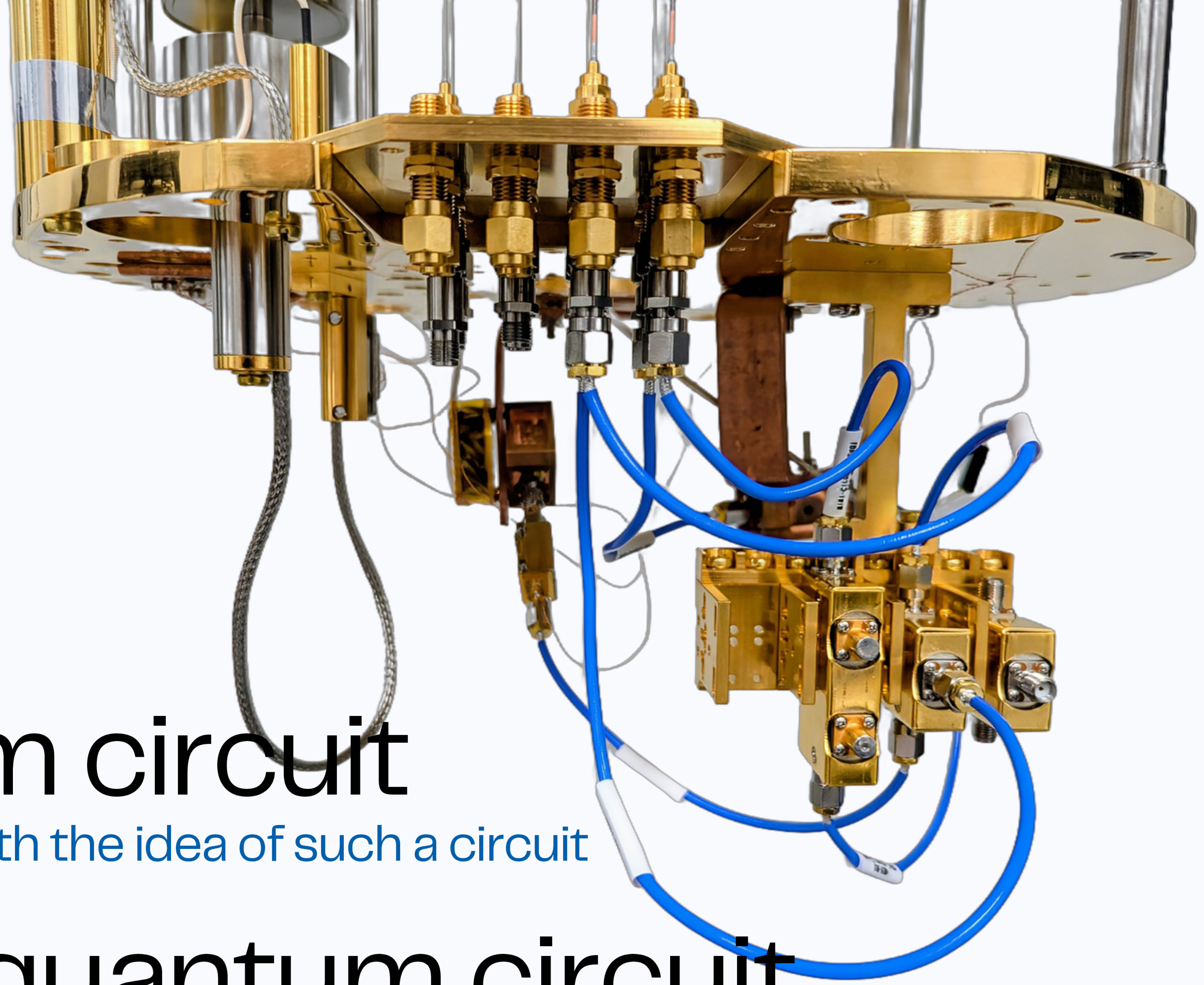
FONDAZIONE BRUNO KESSLER
FOR A HUMAN-CENTERED AI



quantum circuits introduction

Quantum sensing school, UNIPD - 15/07/2025

Nicolò Crescini

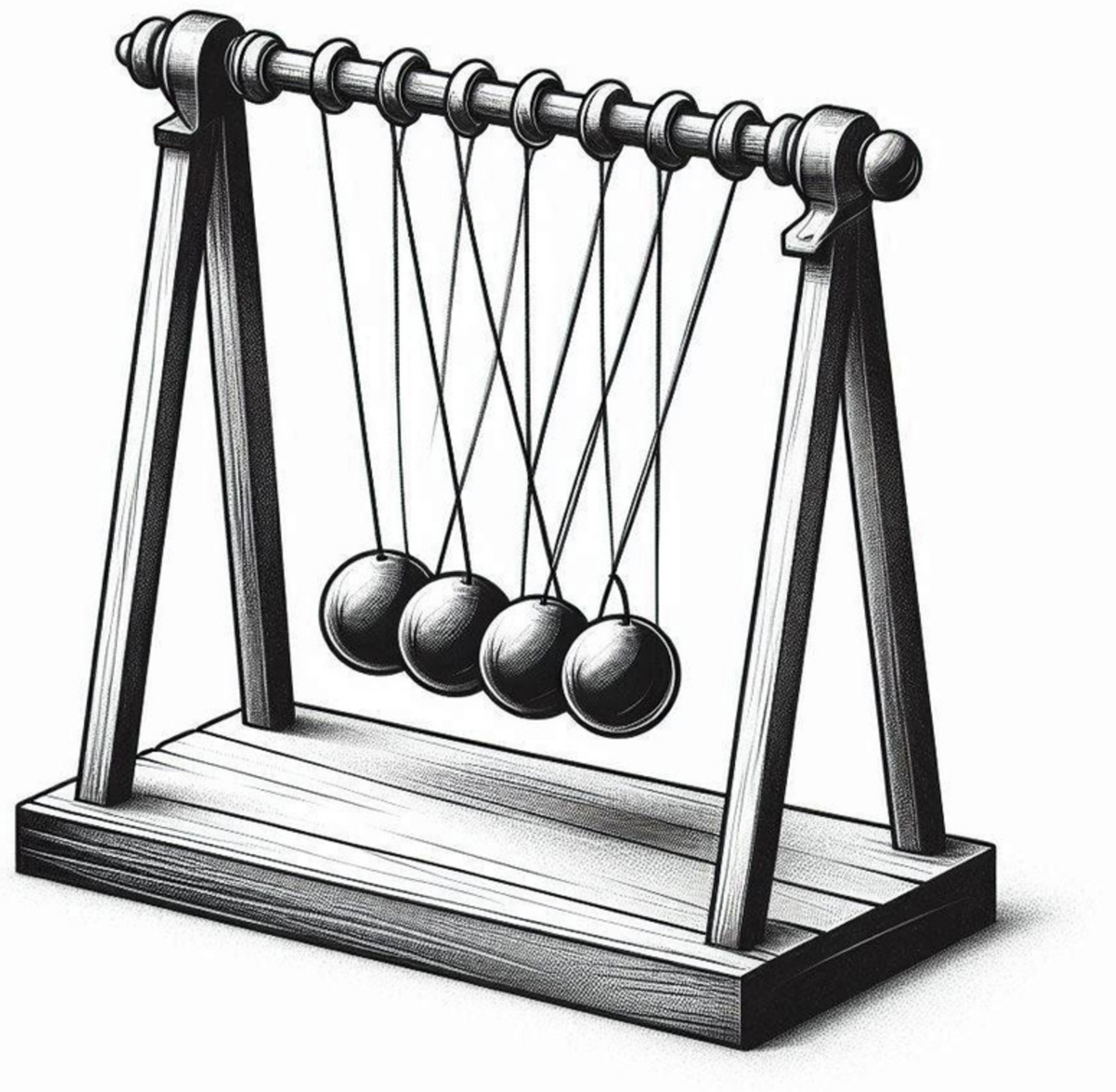


Outline:

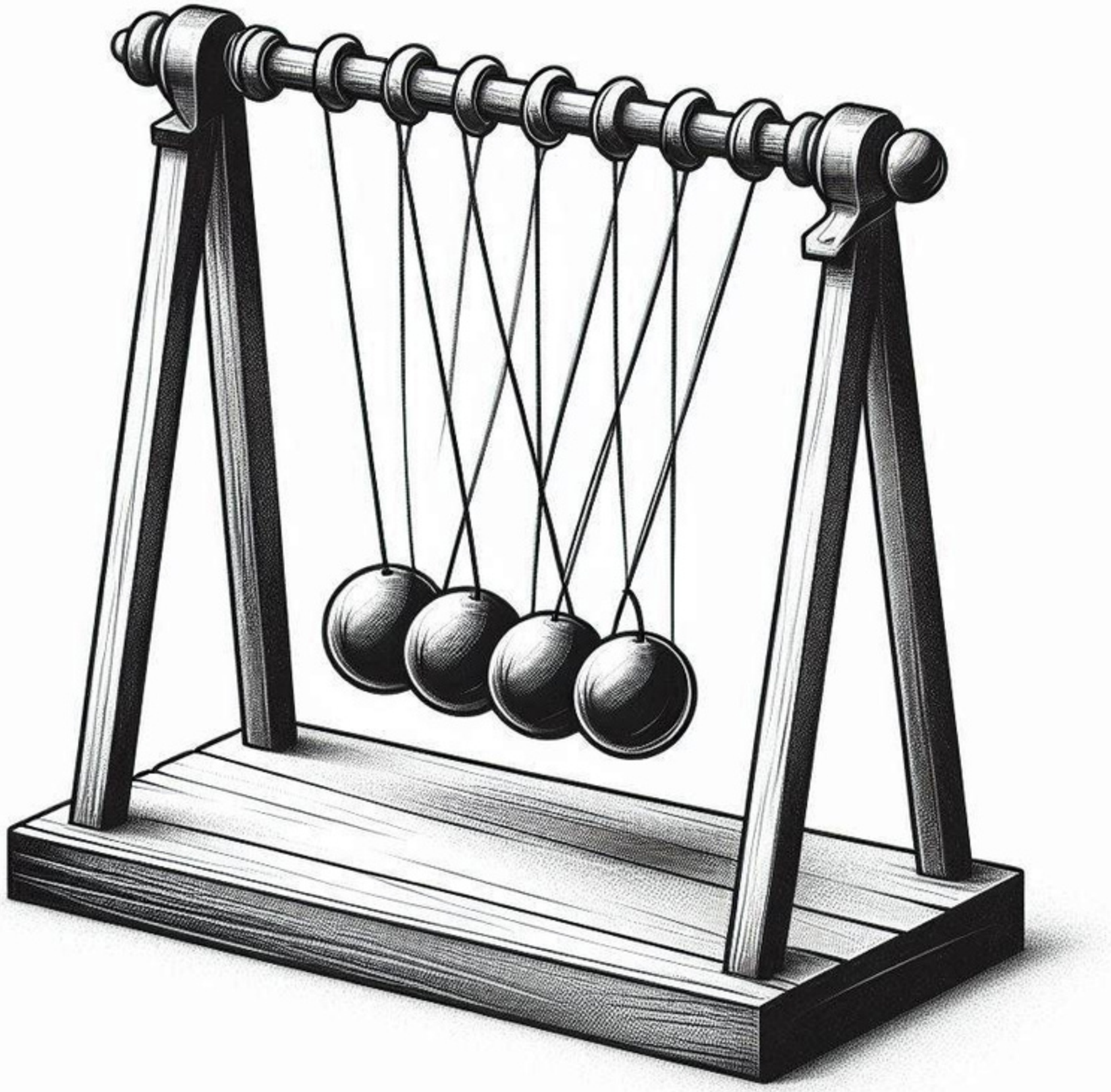
- whats is a quantum circuit
  what does it mean and how to come up with the idea of such a circuit
- what to do with a quantum circuit
  extremely sensitive sensors, and the promise of quantum computing
- how to craft a quantum circuit
  how it is practically realised, and how to talk to a quantum circuit

whats is a quantum circuit

what does it mean and how to come up with the idea of such a circuit



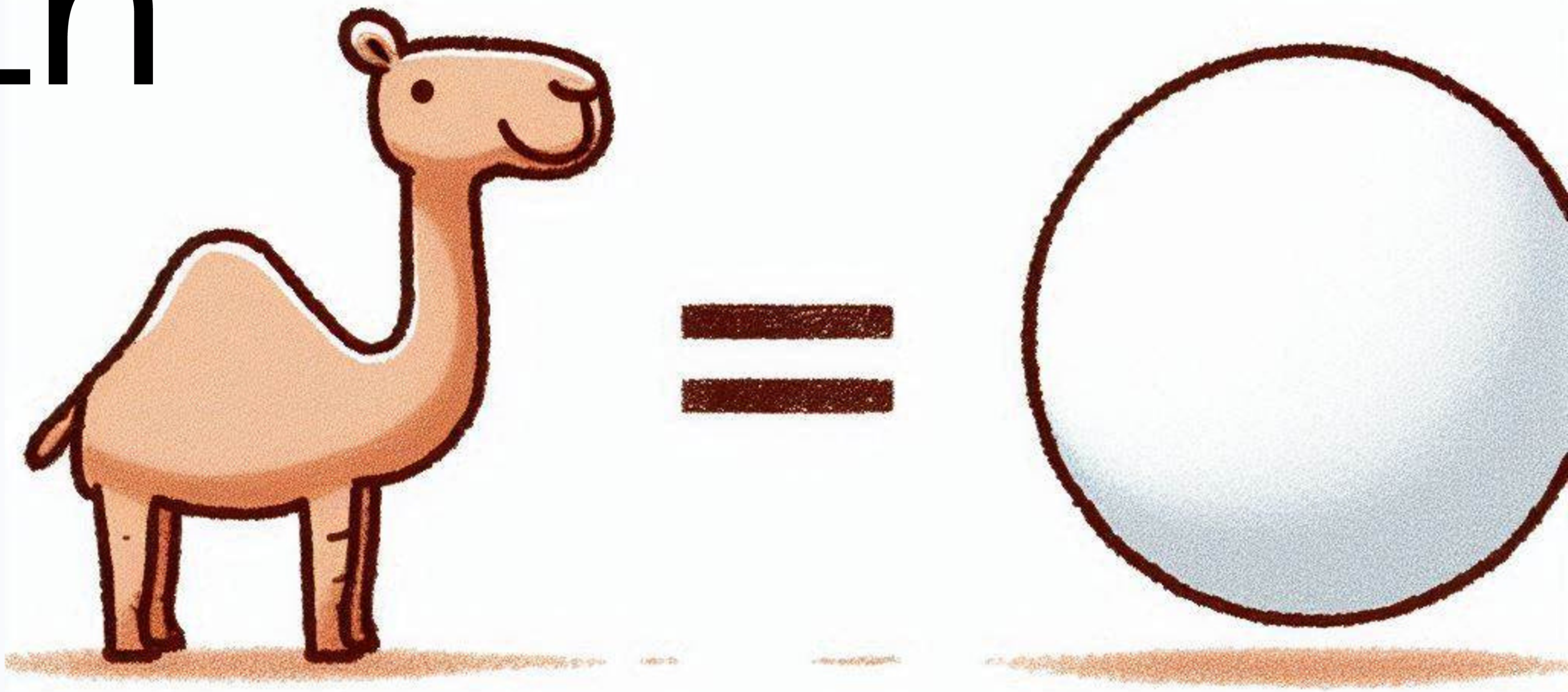
physics is about
simple things

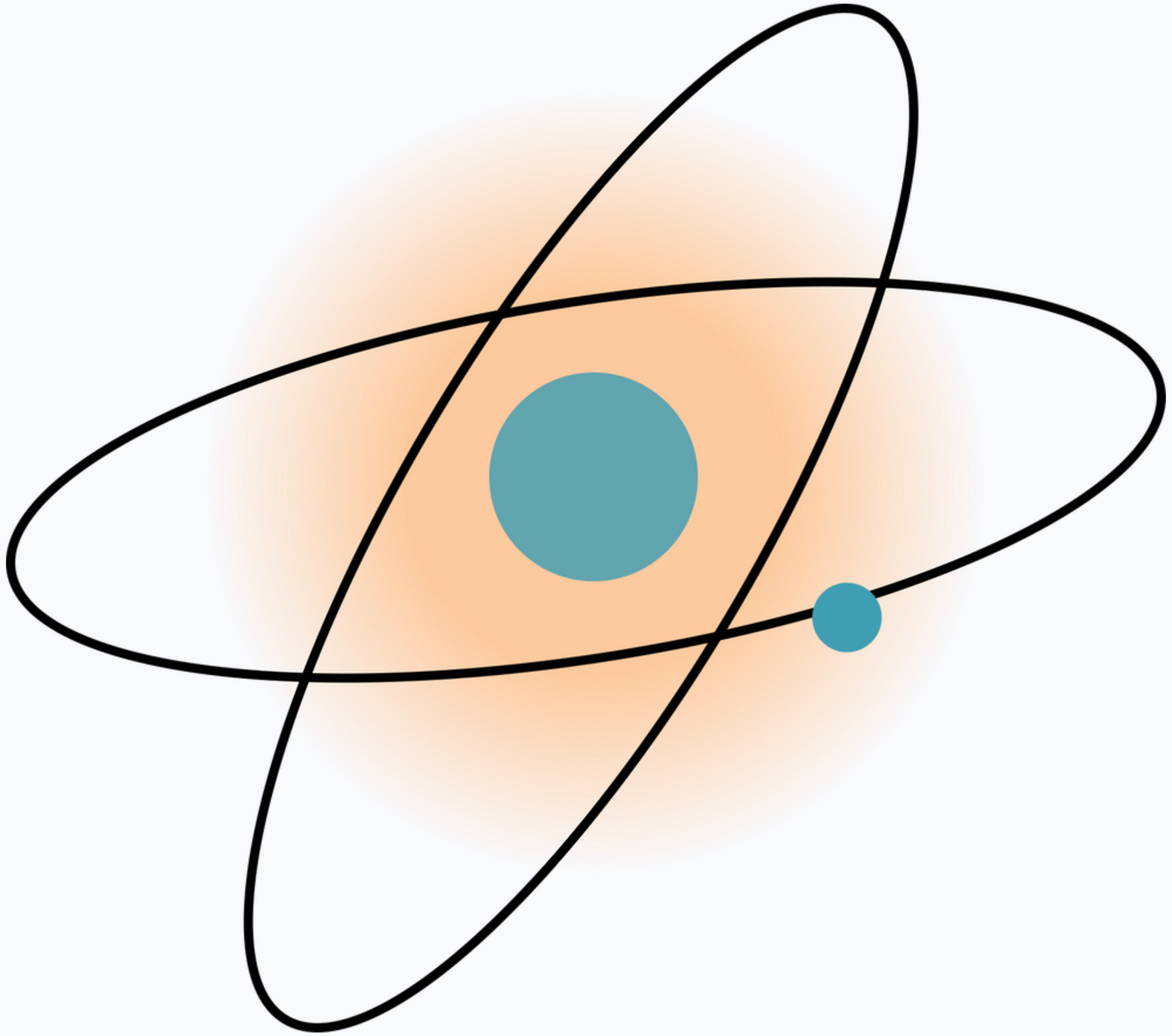


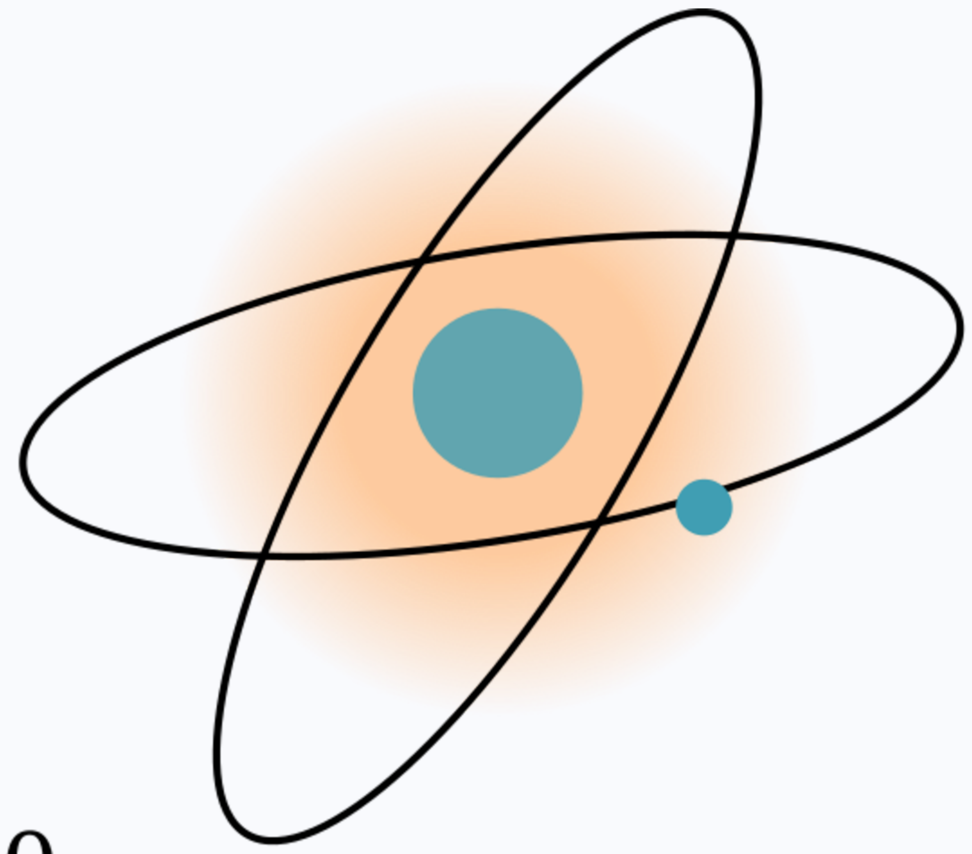
physics is about
simple things

the most complicated thing ever built by humans
is just a few millimeters big

we need simple things to use math



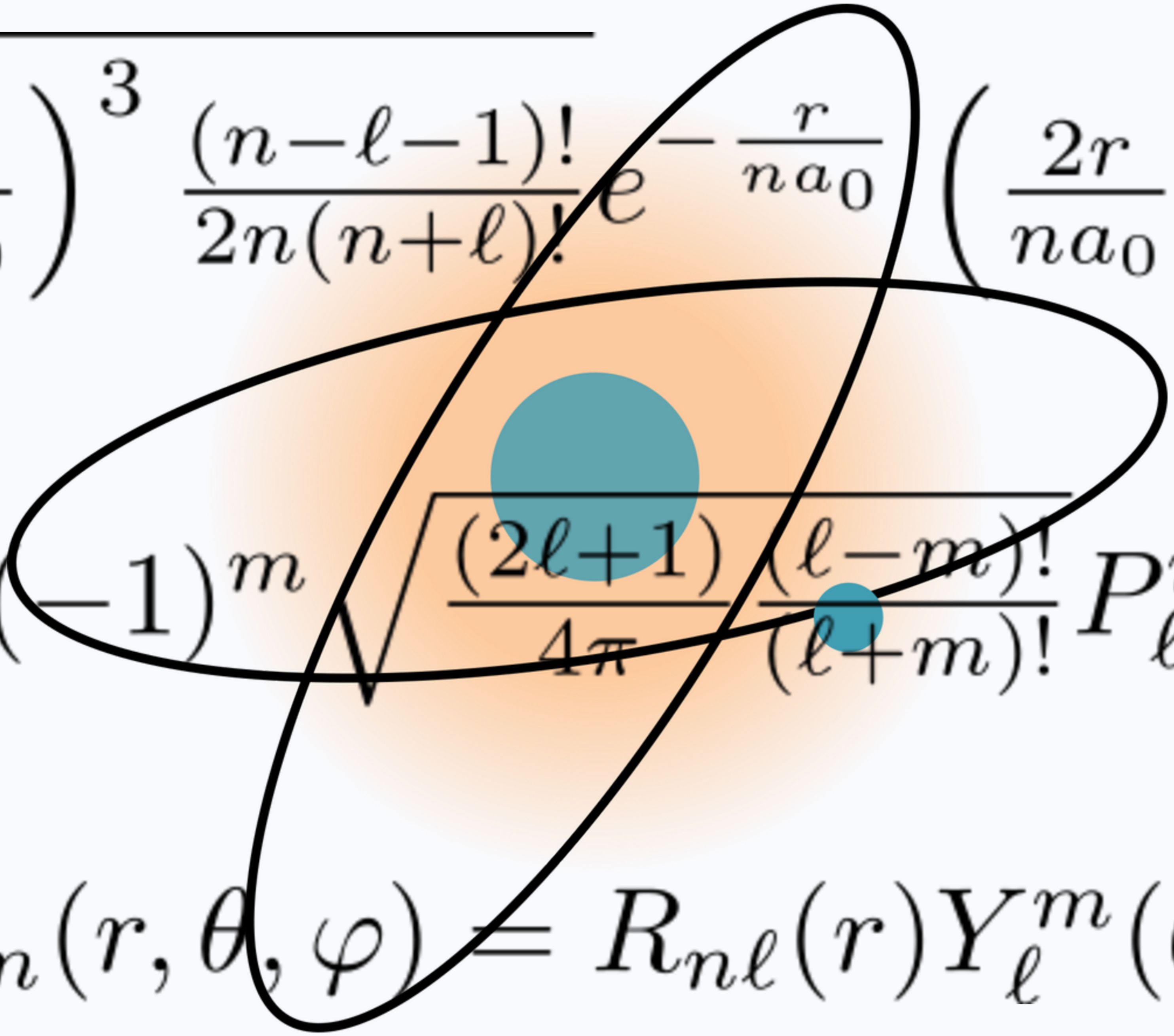




1920

QED

$$R_{n\ell}(r) = \sqrt{\left(\frac{2}{na_0}\right)^3 \frac{(n-\ell-1)!}{2n(n+\ell)!}} e^{-\frac{r}{na_0}} \left(\frac{2r}{na_0}\right)^{\ell} L^{2\ell+1}_{n-\ell-1}\left(\frac{2r}{na_0}\right)$$

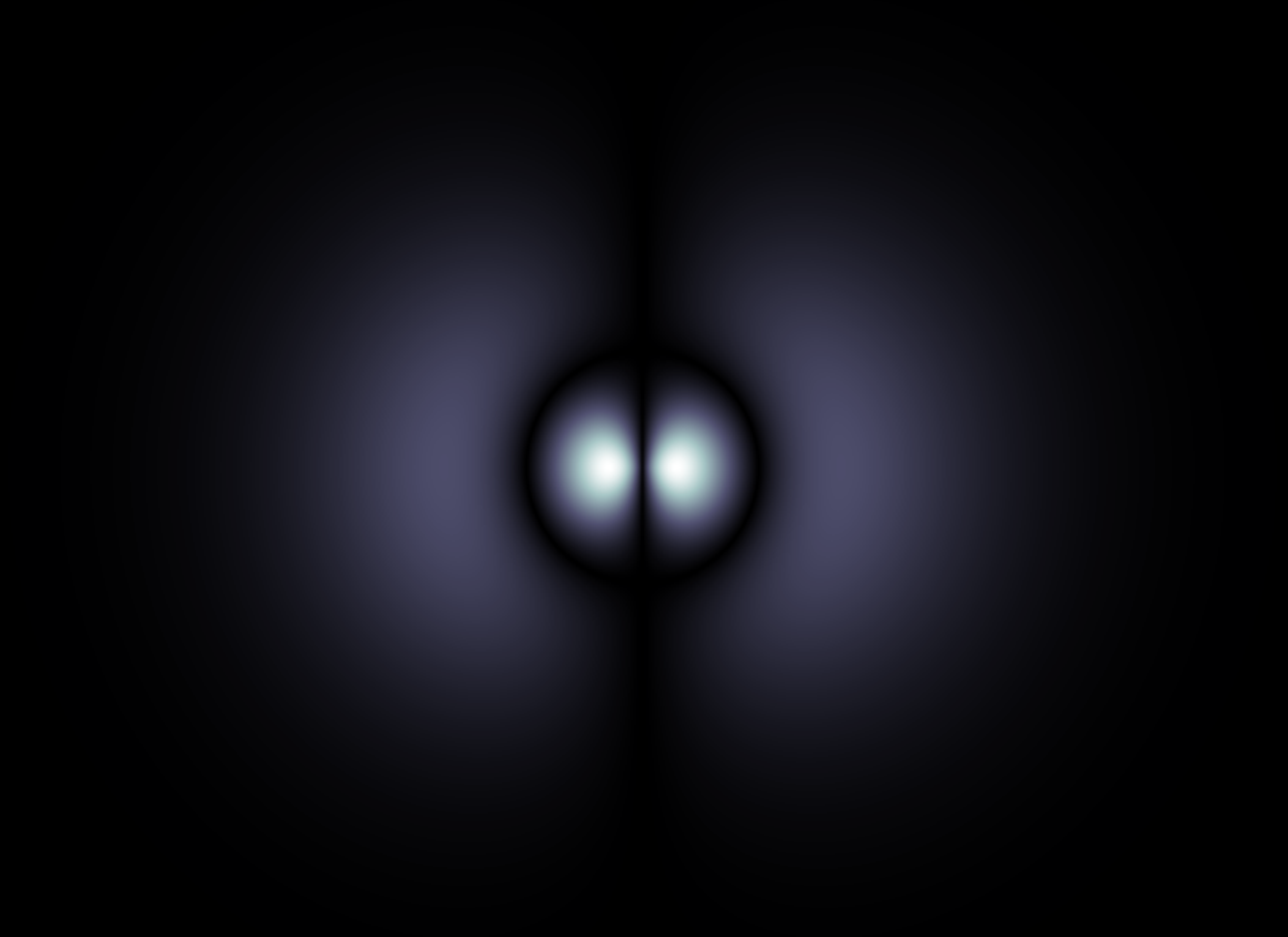


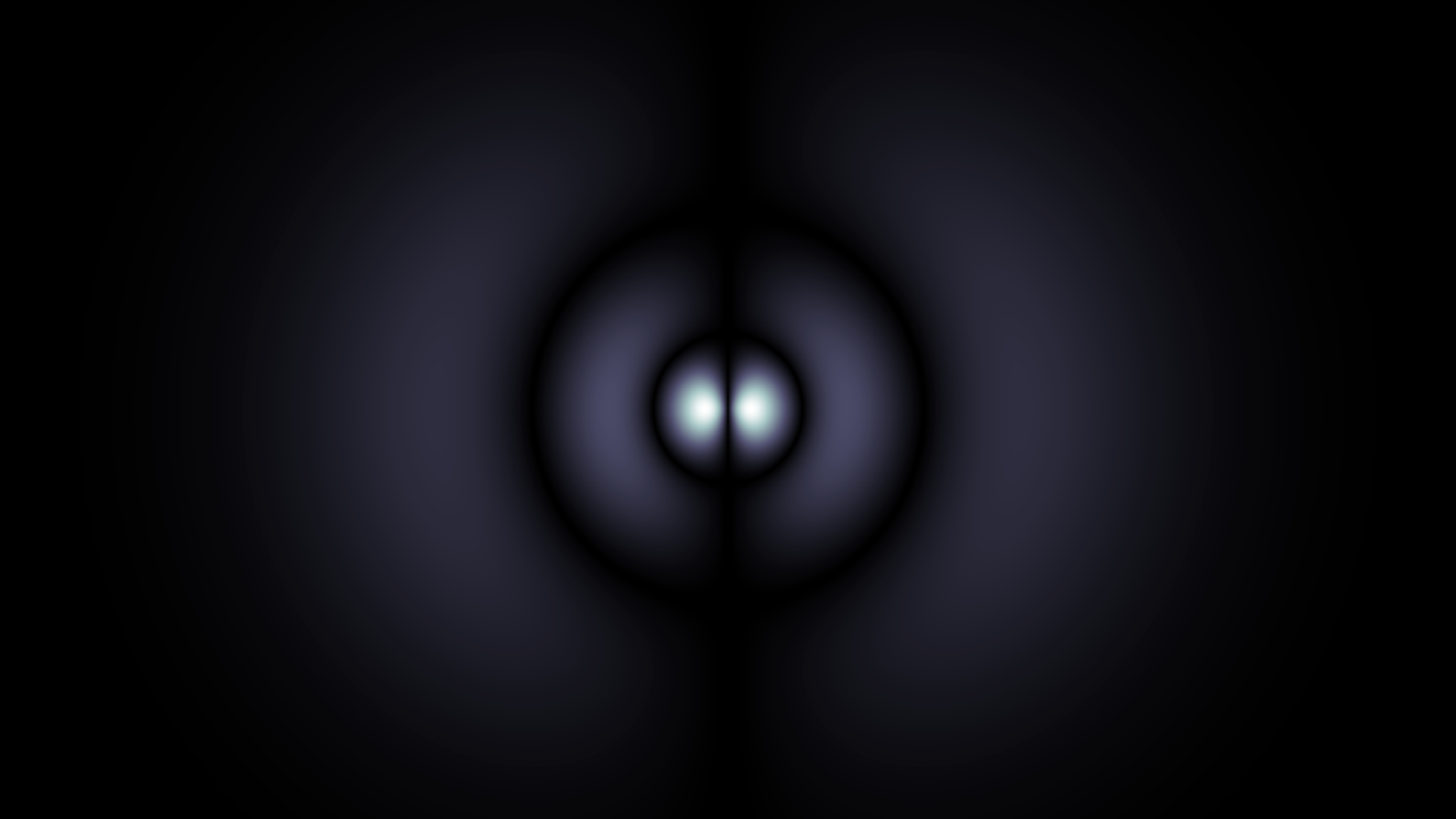
$$Y_\ell^m(\theta,\varphi) = (-1)^m \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}} P_\ell^m(\cos\theta) e^{im\varphi}$$

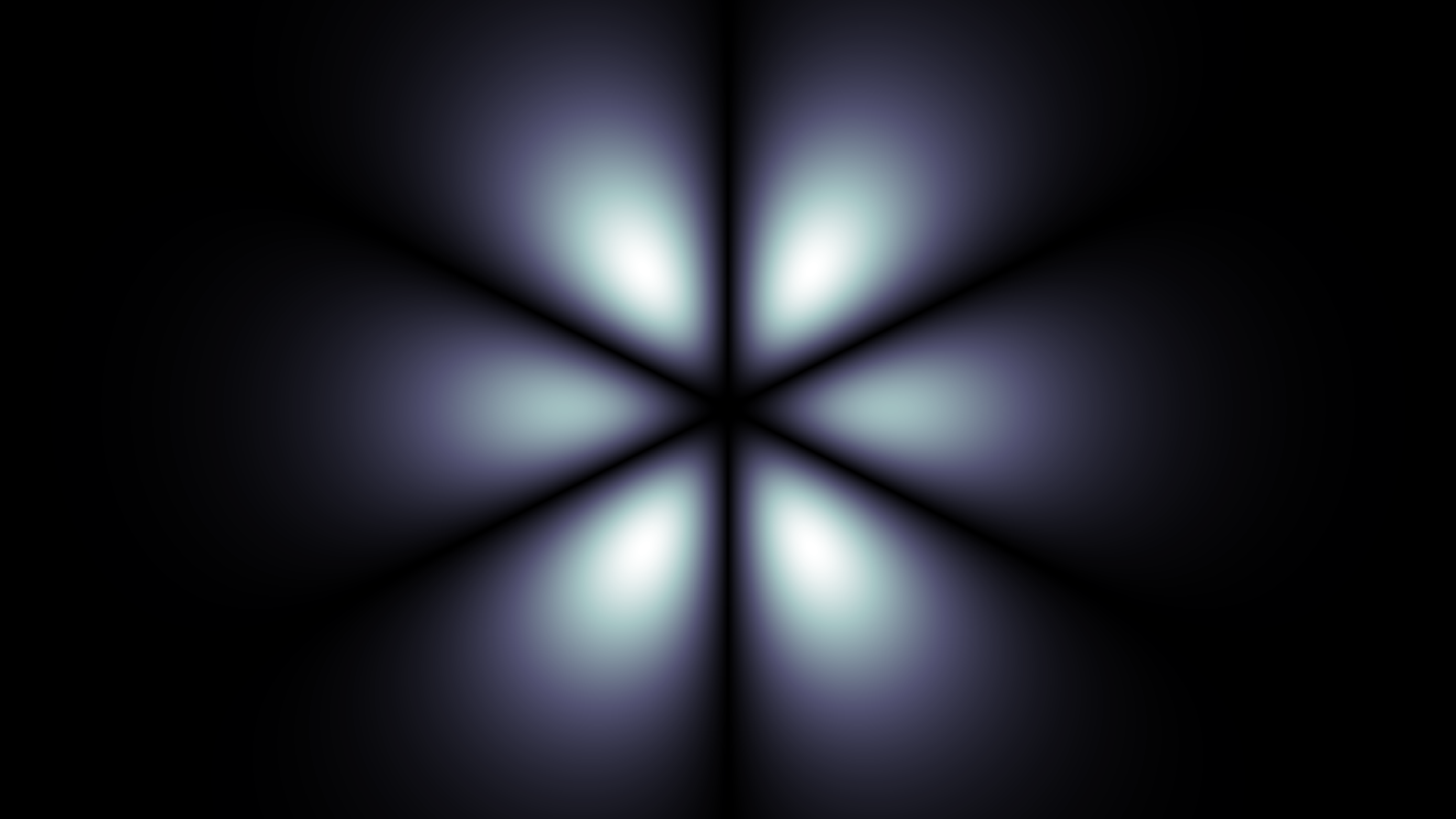
$$\psi_{n\ell m}(r,\theta,\varphi) = R_{n\ell}(r) Y_\ell^m(\theta,\varphi)$$

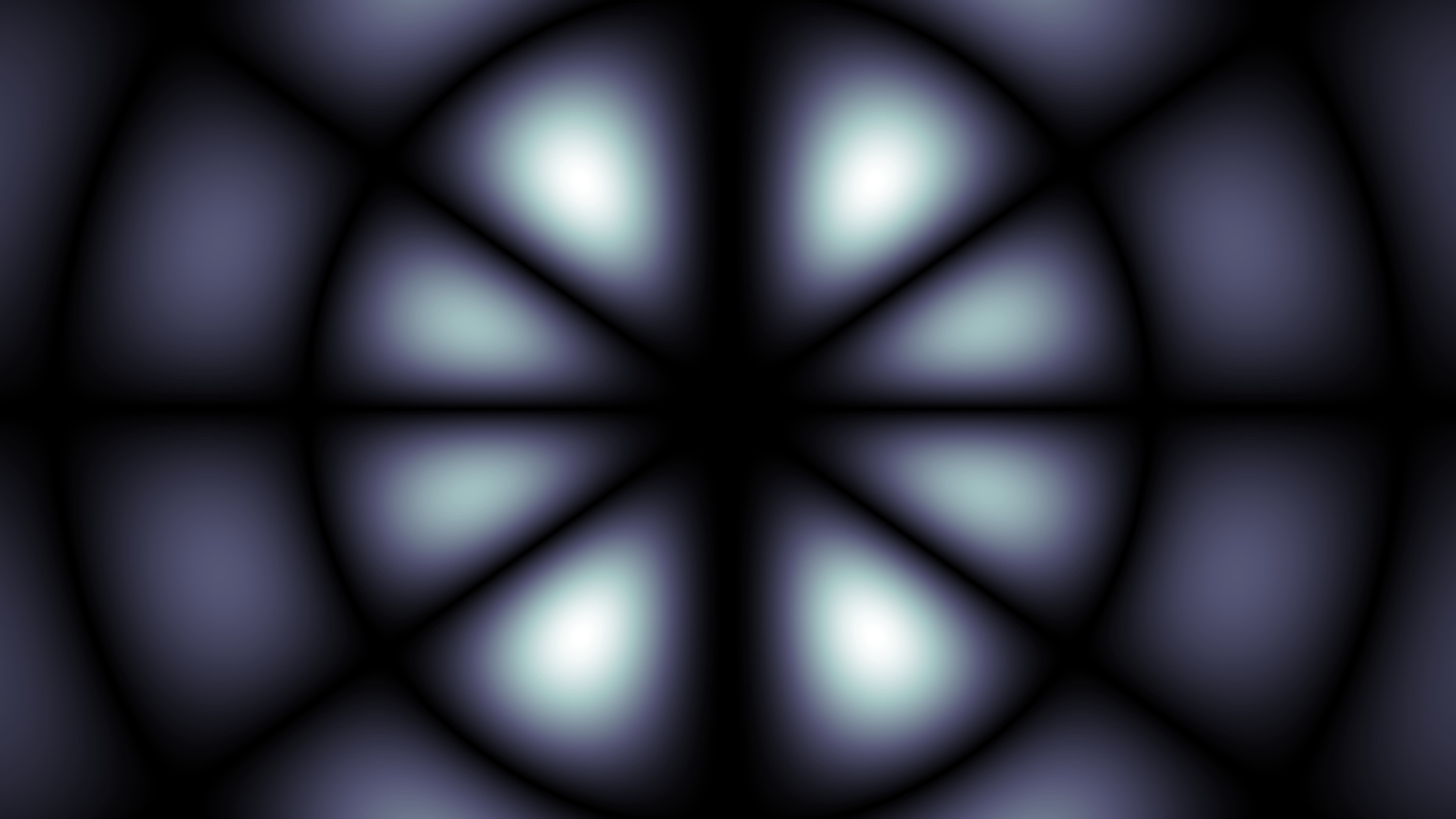
energy

levels

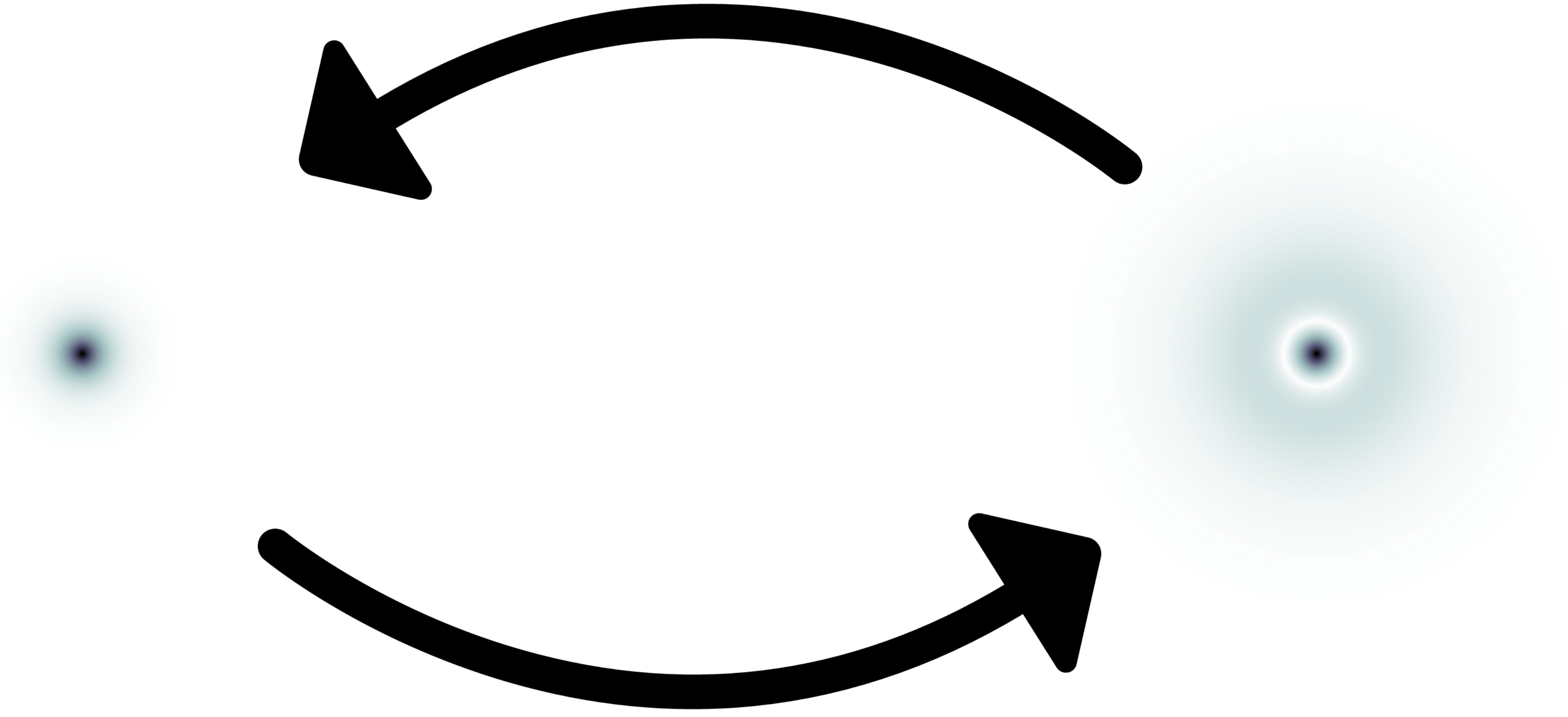


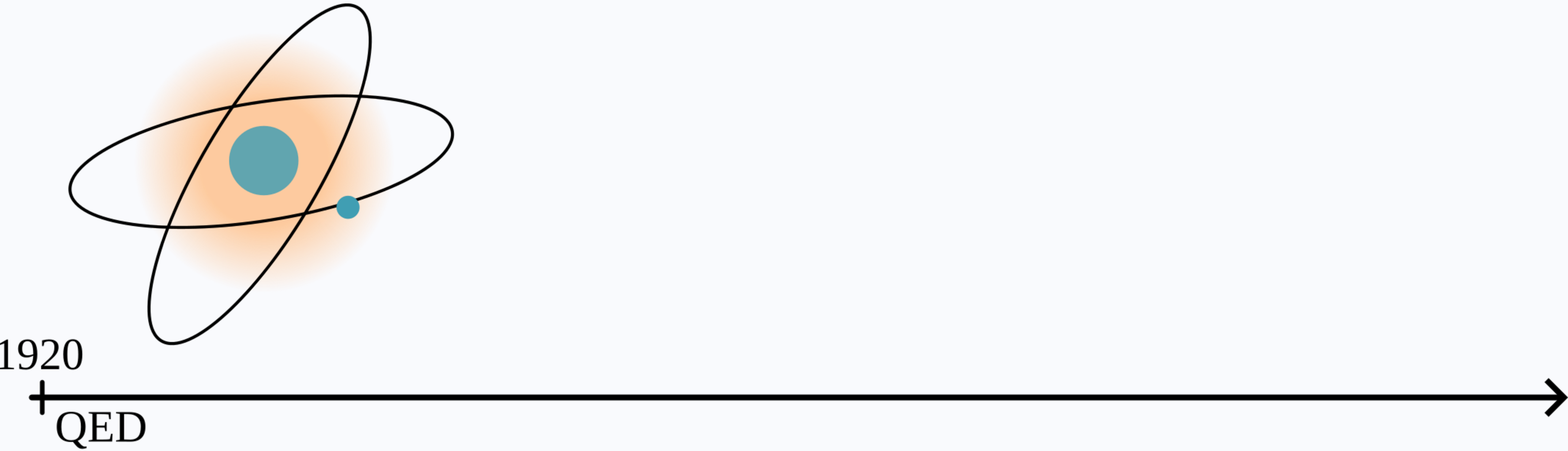


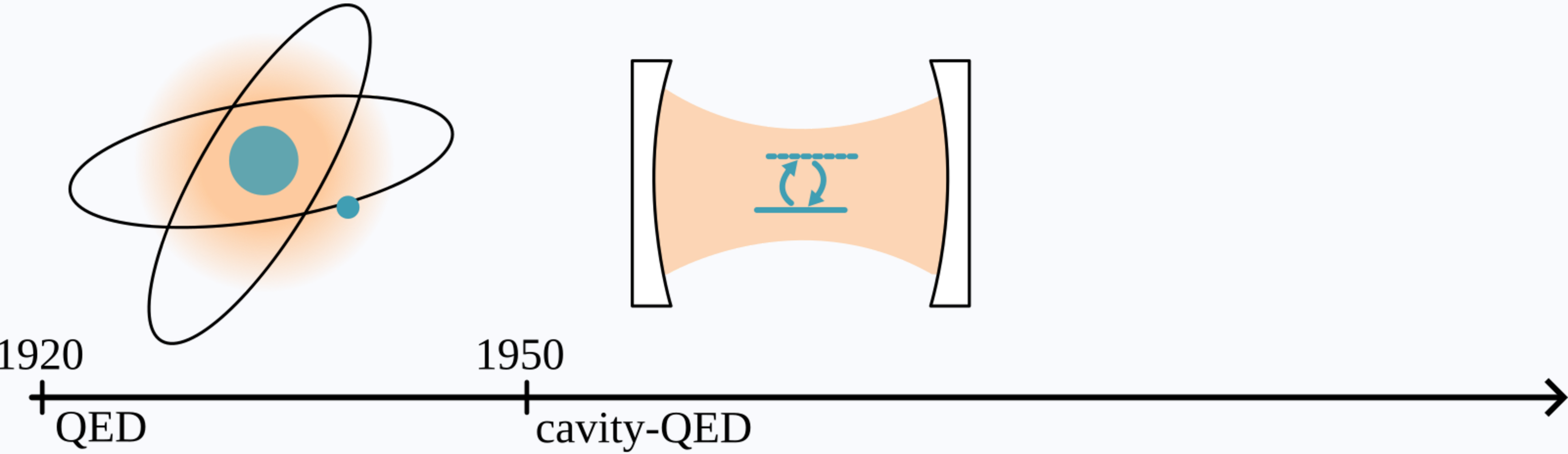


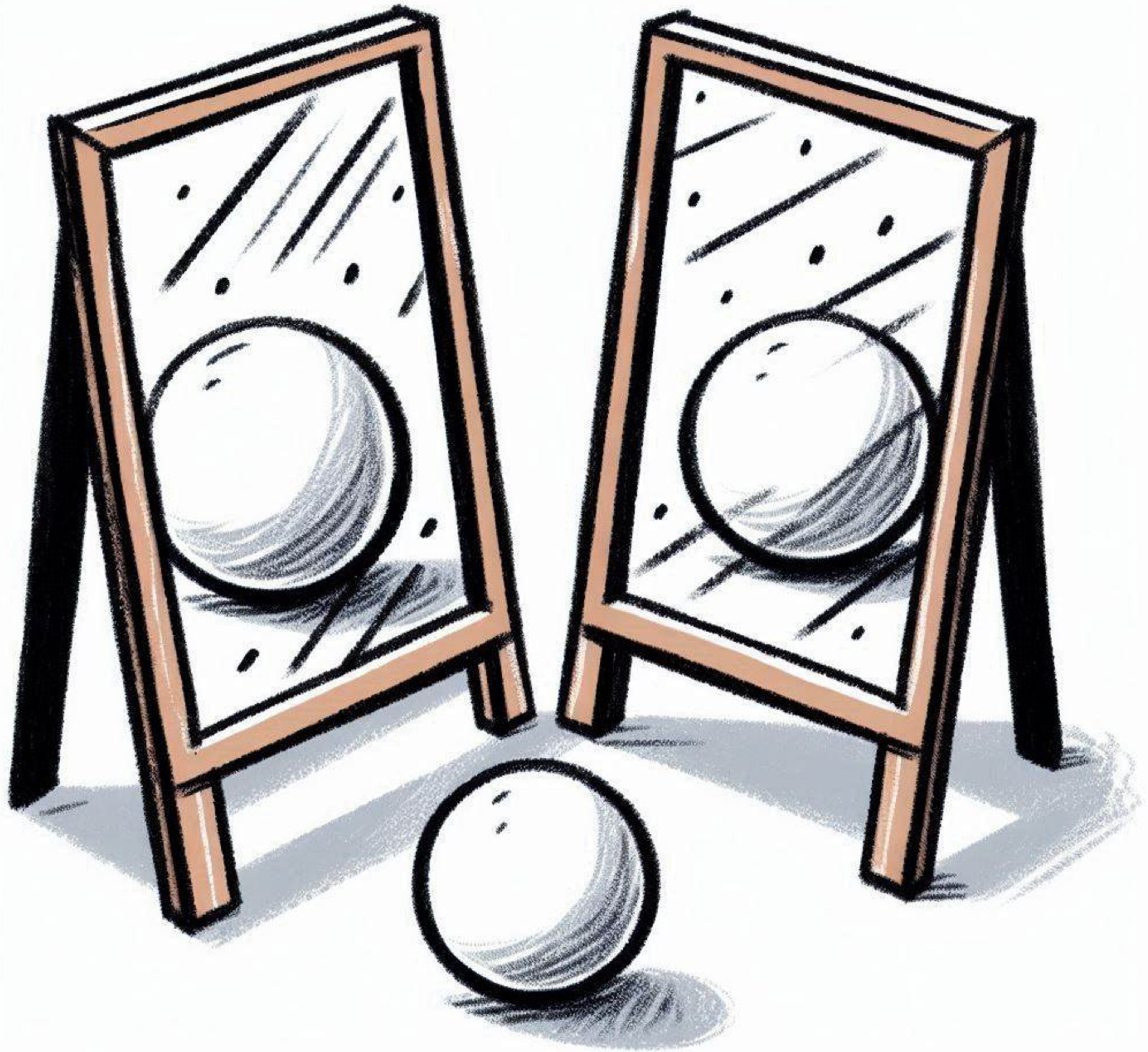


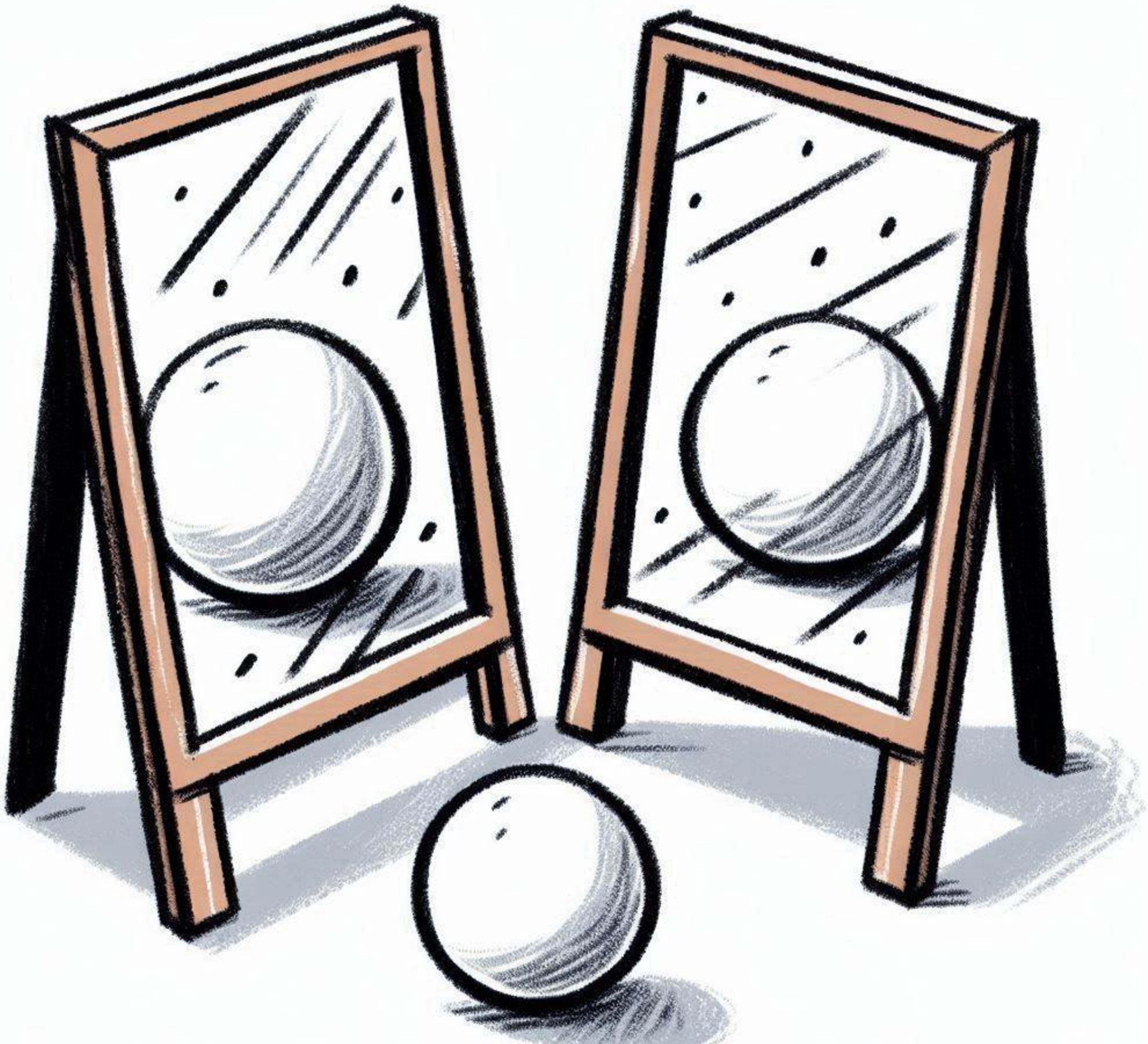
light is a gateway between energy levels

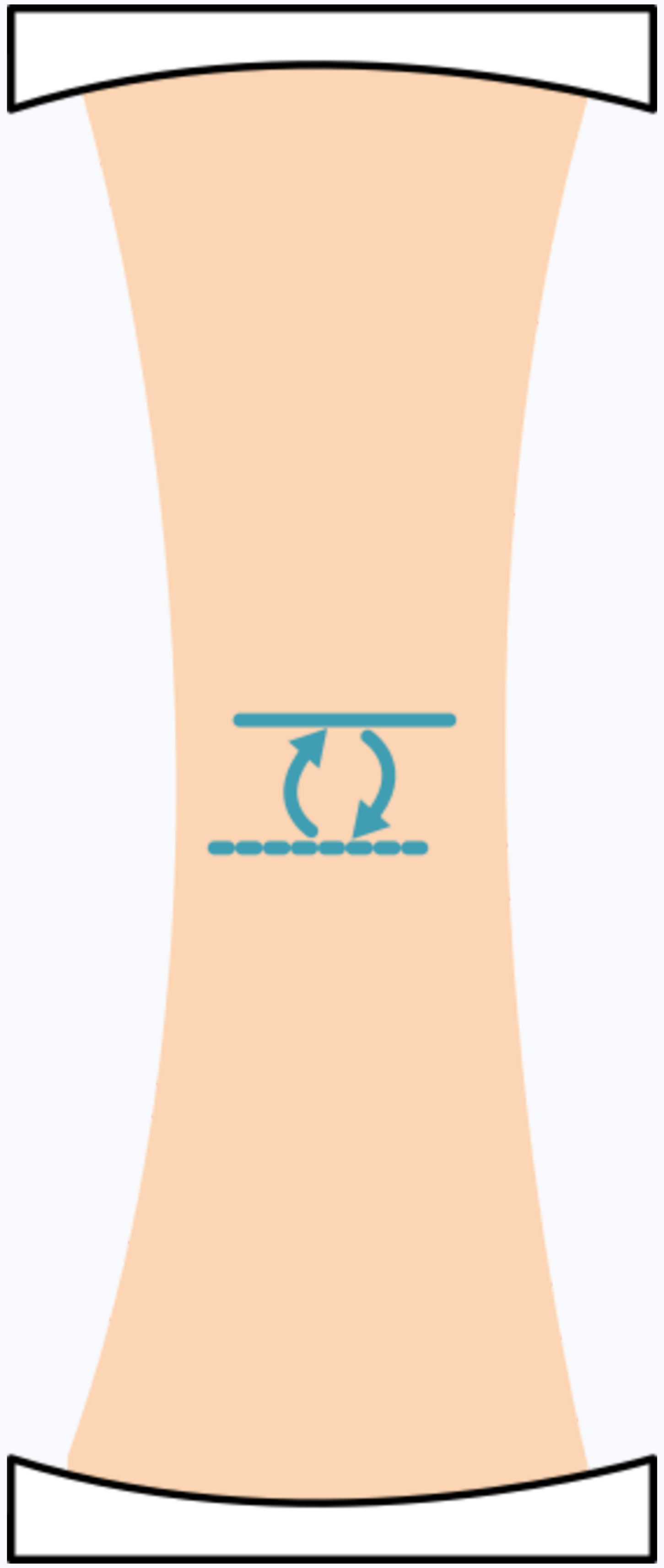


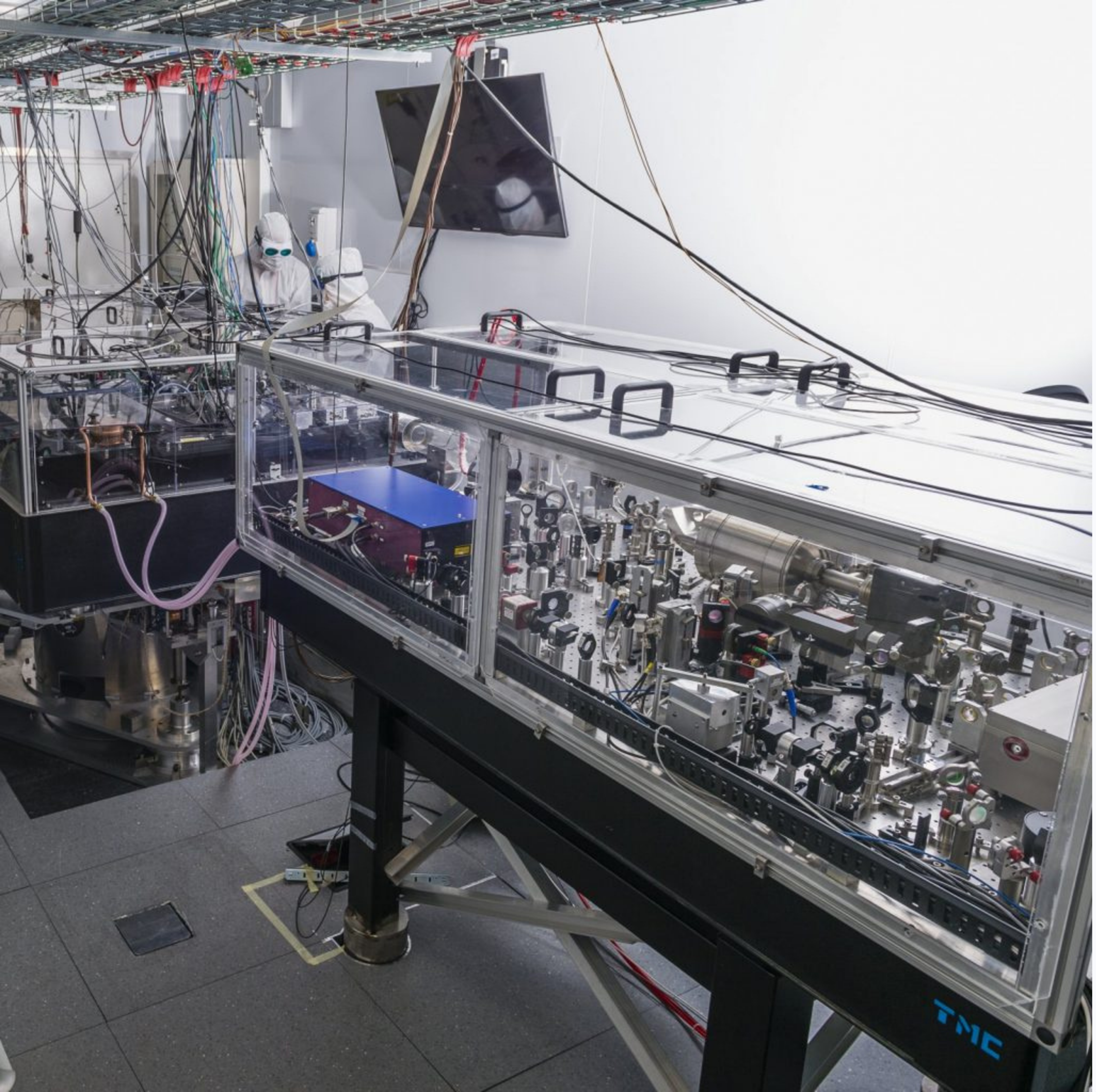

1920
QED

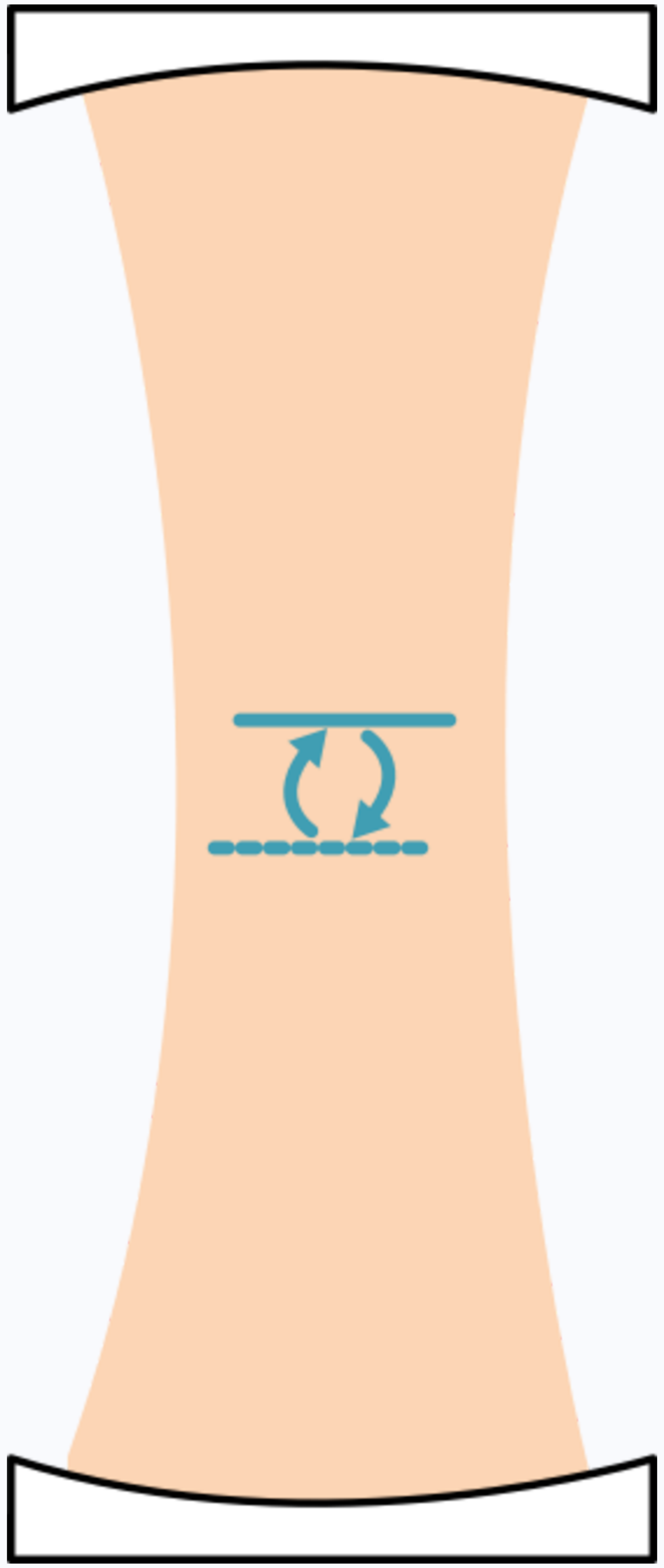

1920
QED
1950
cavity-QED

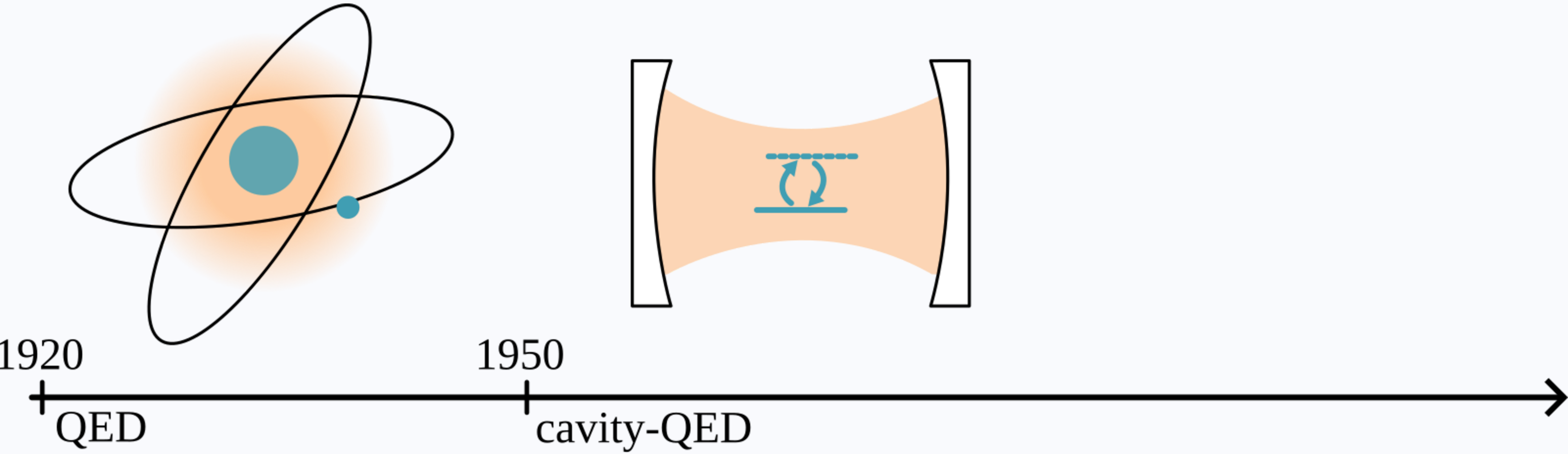


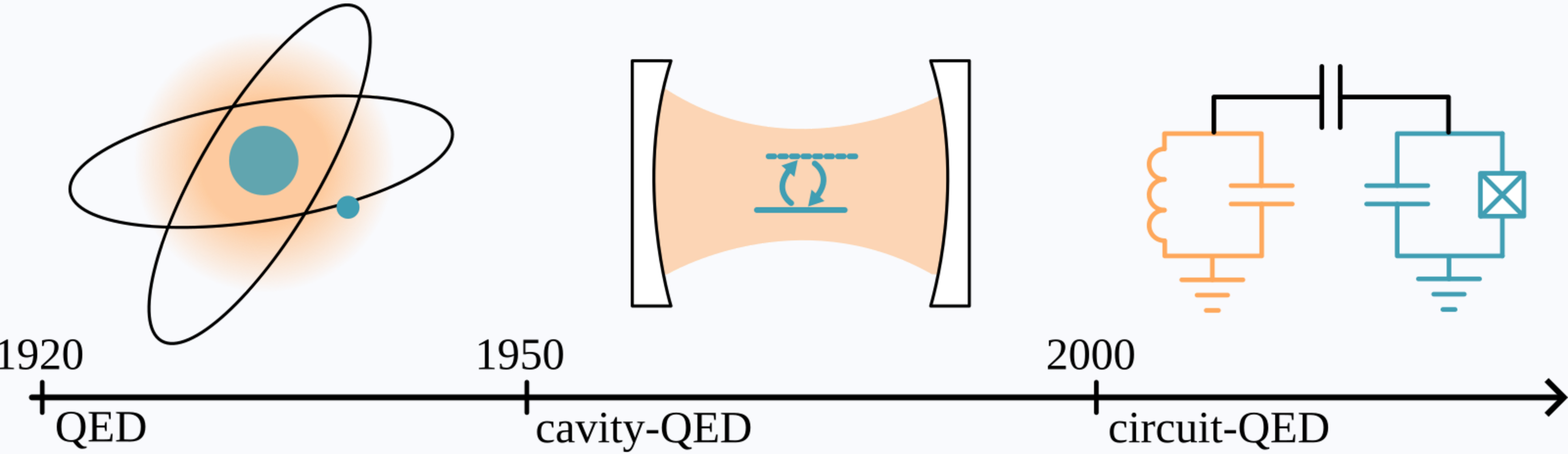





TMC




1920
1950
QED
cavity-QED


1920
1950
2000
QED
cavity-QED
circuit-QED

analogies and approximation

$\cong$

analogies and approximation

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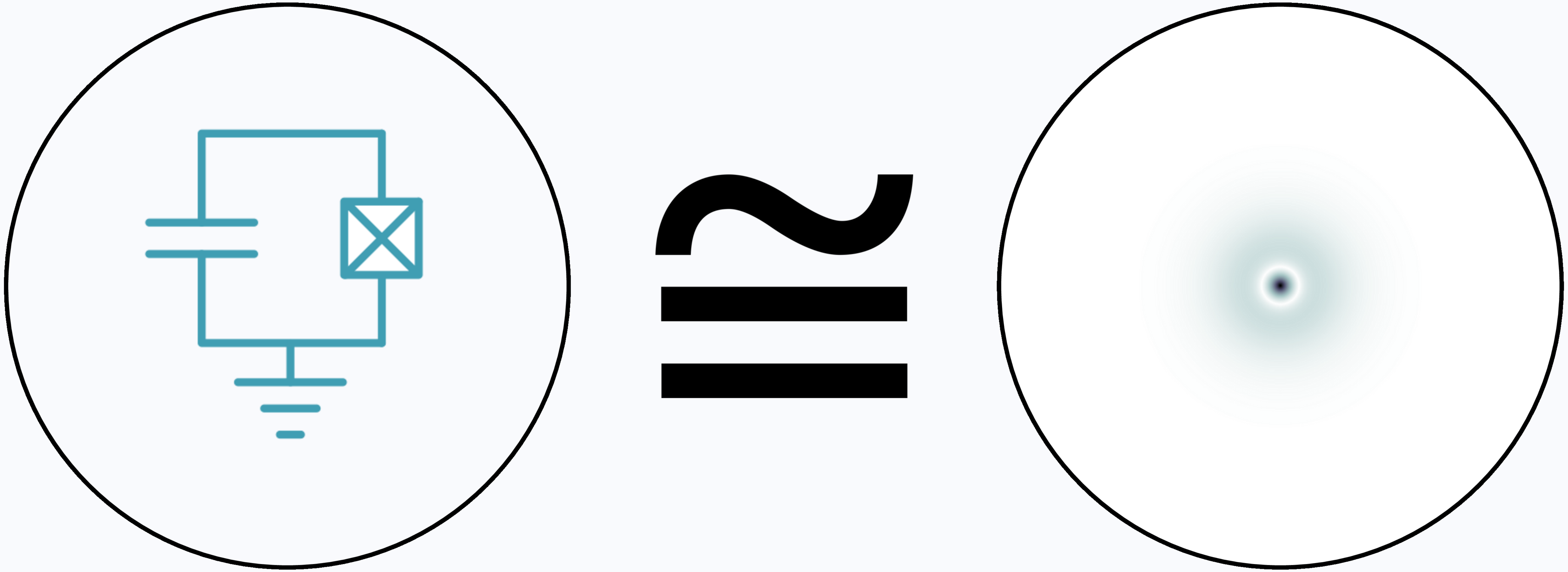
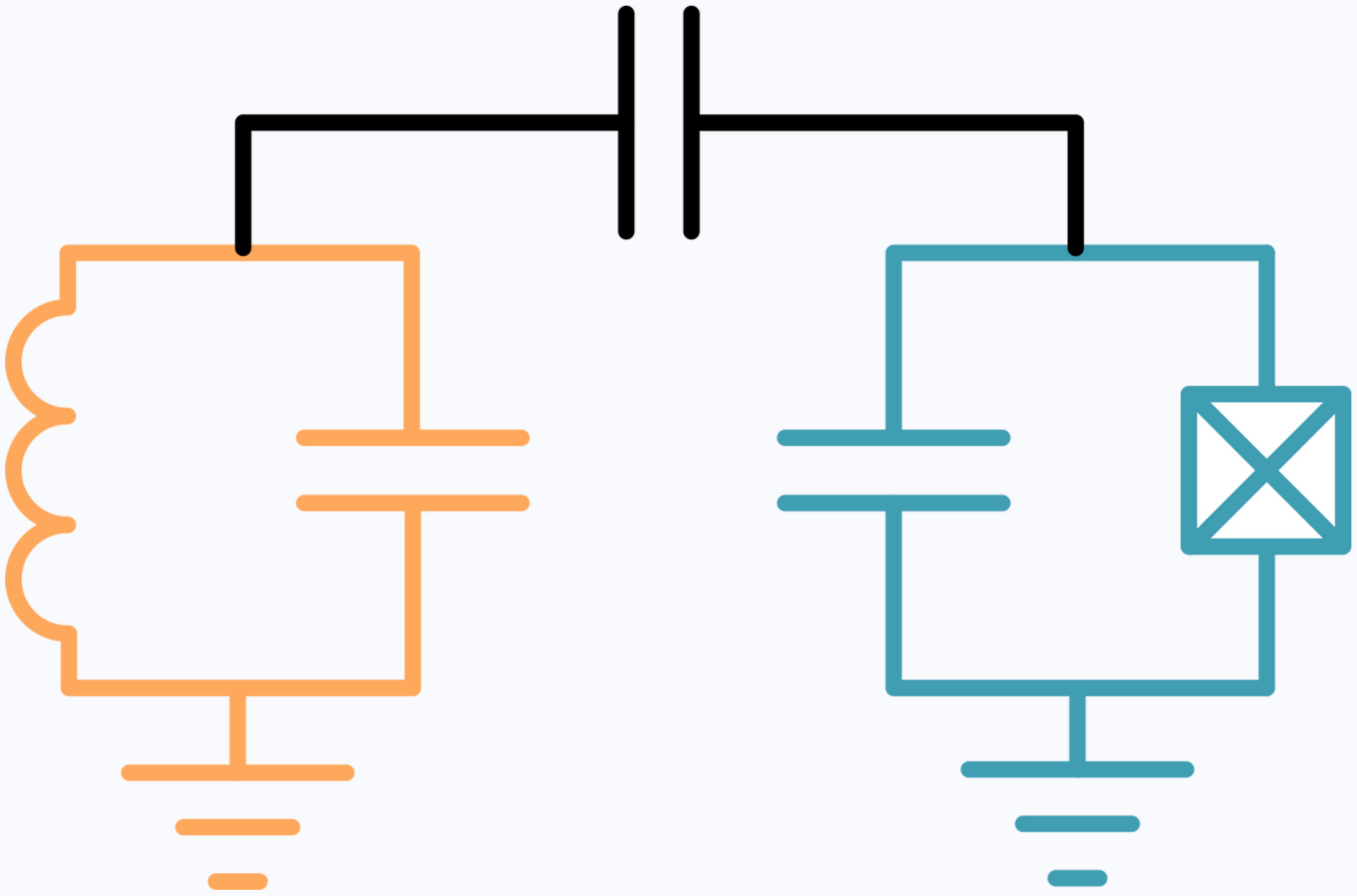
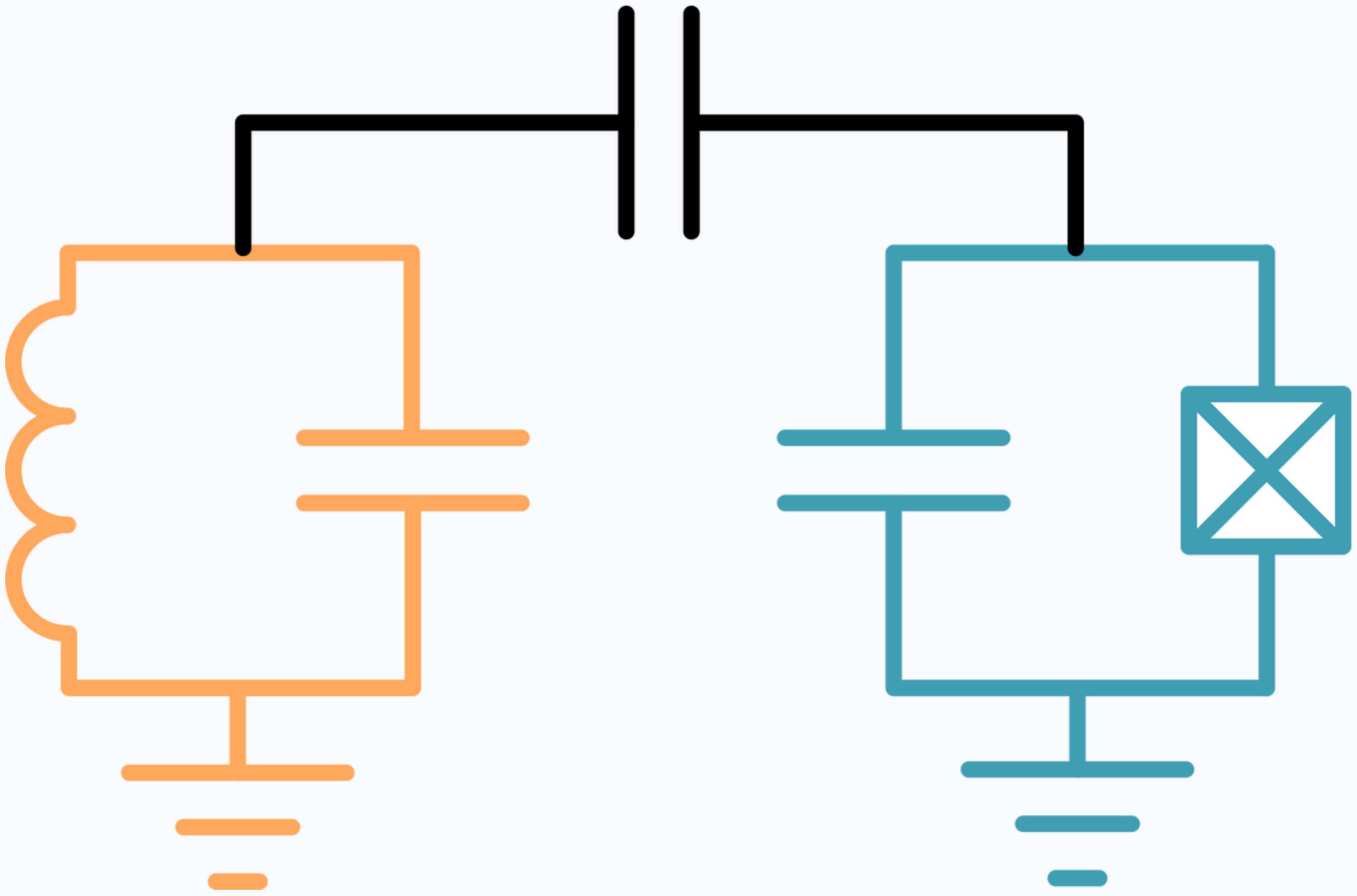
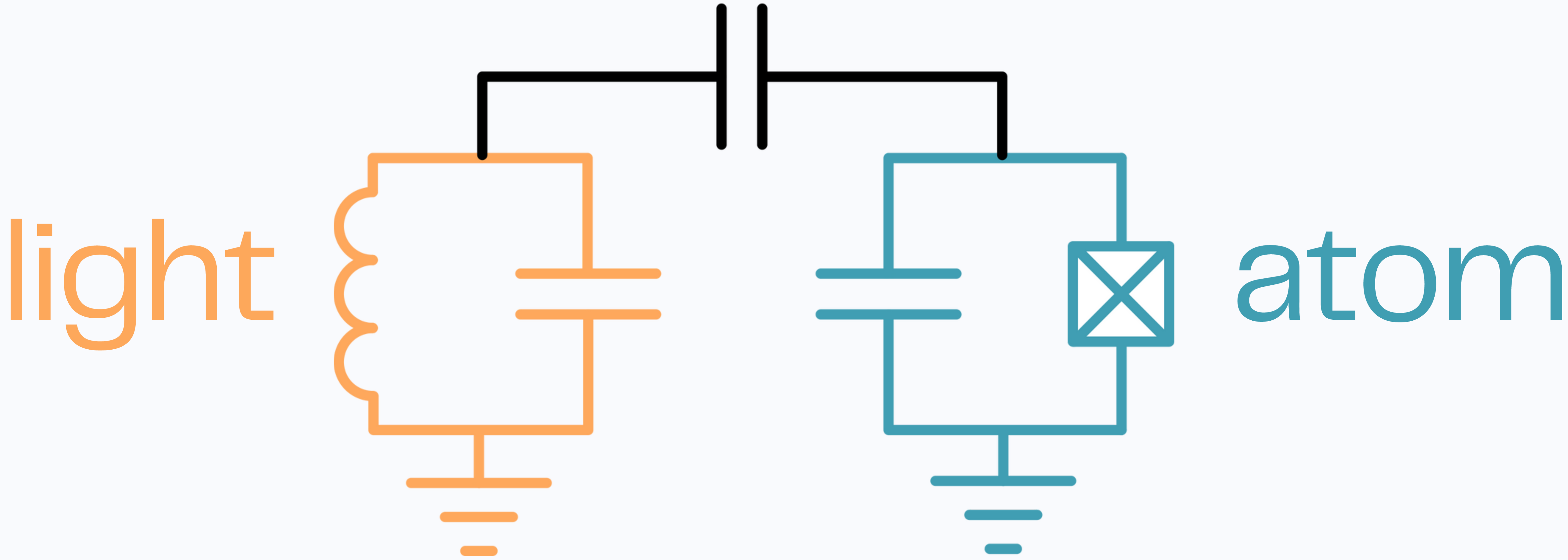
analogies and approximation



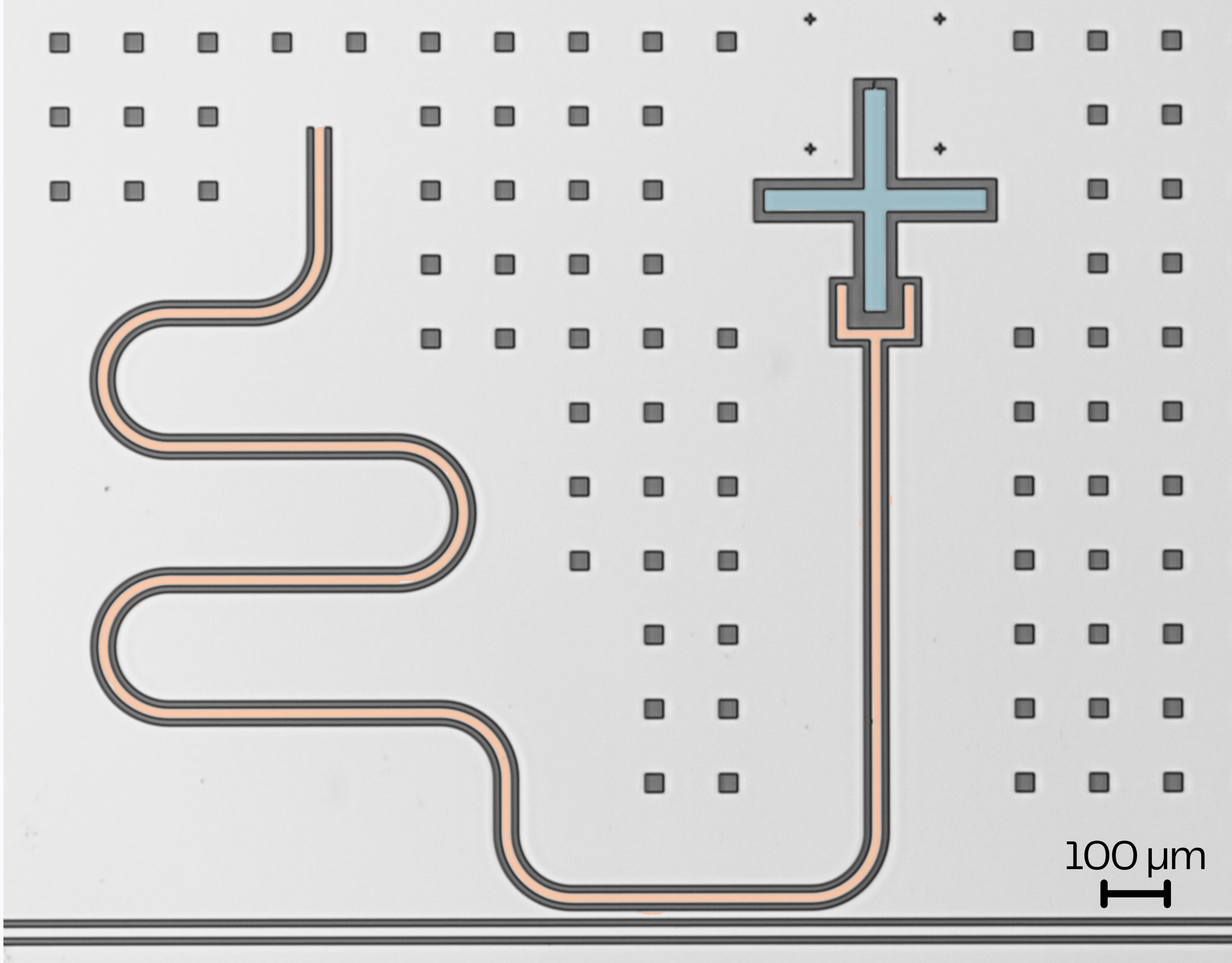


light

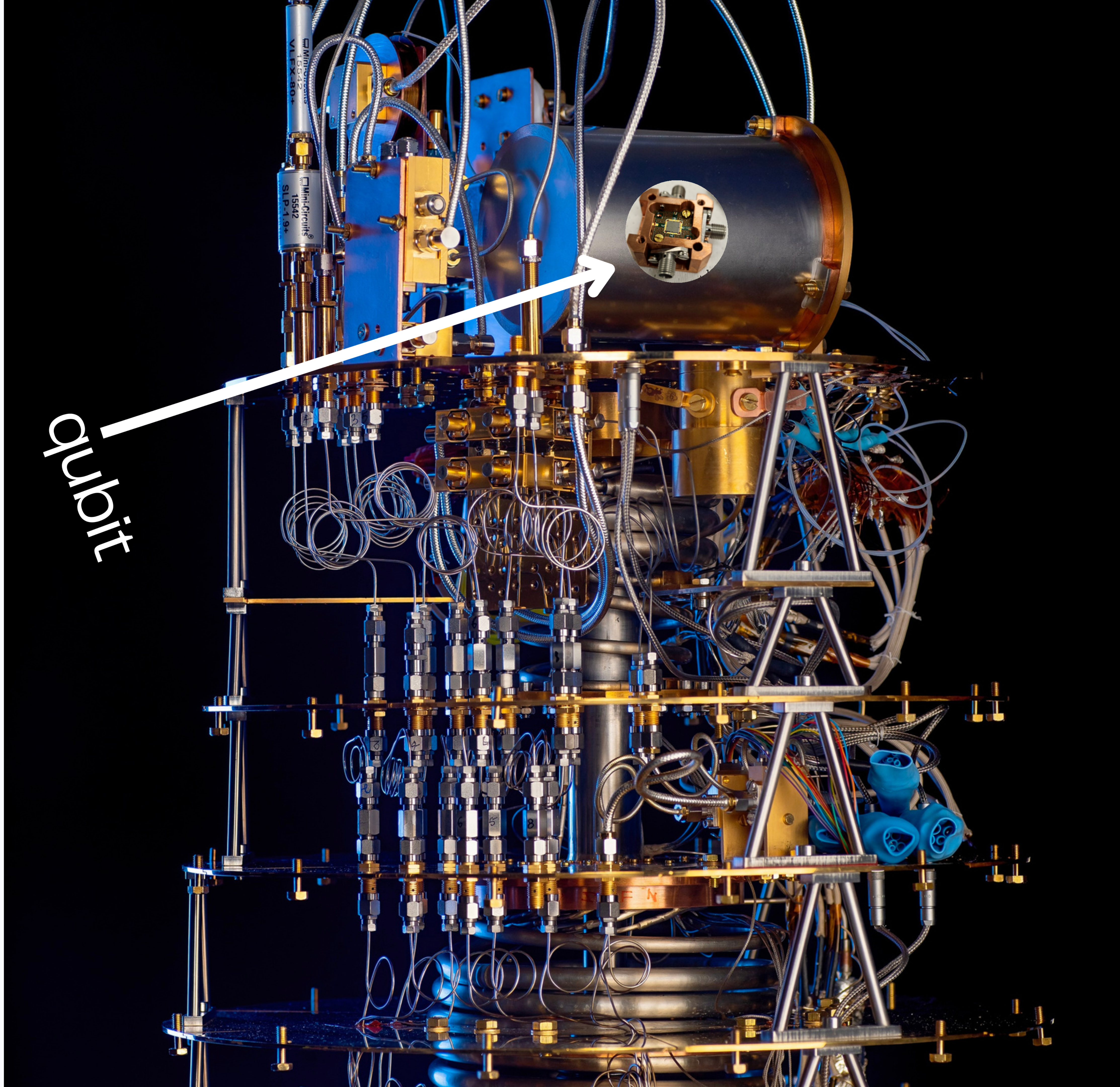


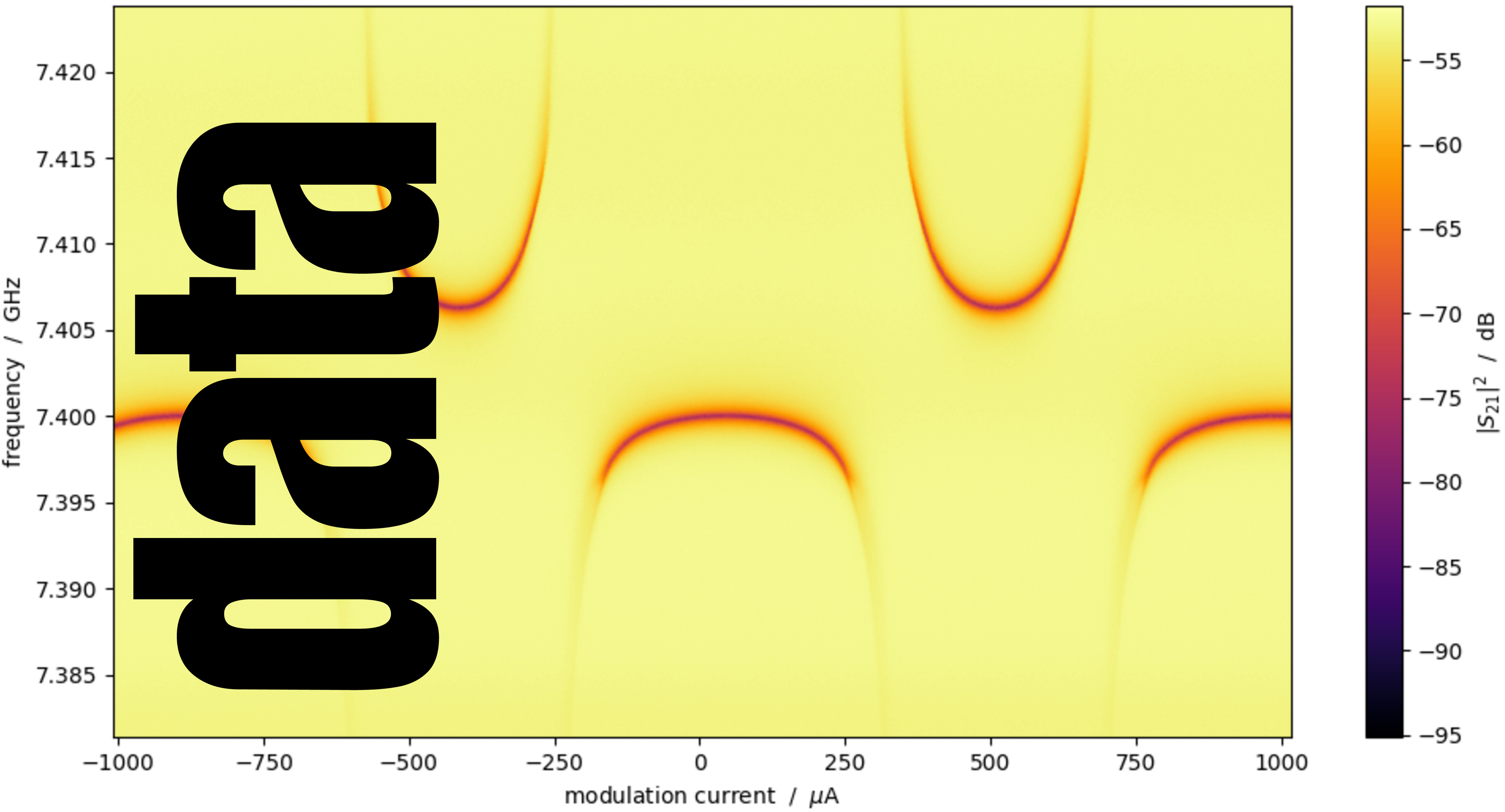

light
atom

circuit



meas.



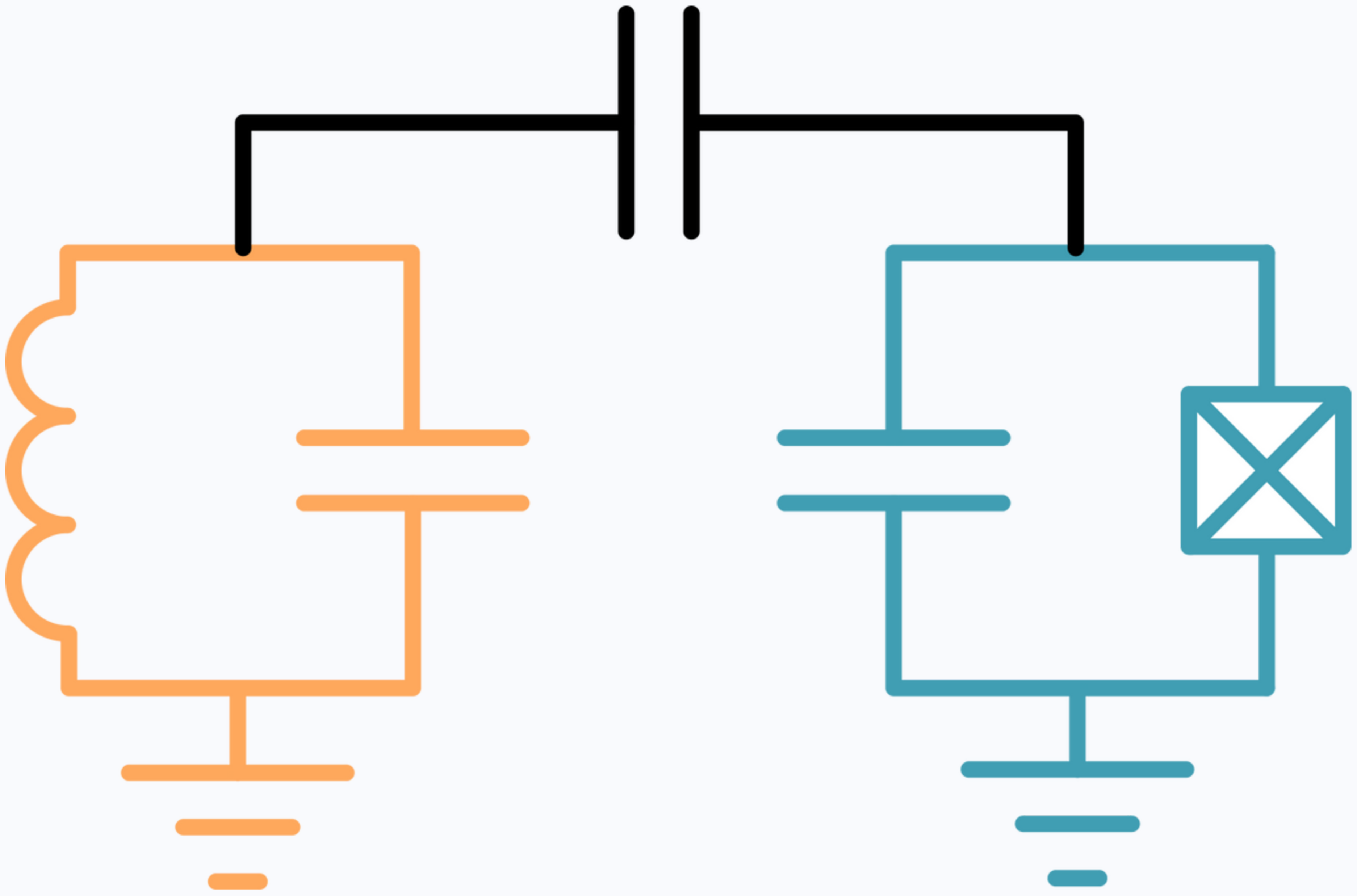

data
frequency / GHz
7.420
7.415
7.410
7.405
7.400
7.395
7.390
7.385
−1000
−750
−500
−250
0
250
500
750
1000
modulation current / μA
$|S_{21}|^2$ / dB
−55
−60
−65
−70
−75
−80
−85
−90
−95

end of the first part

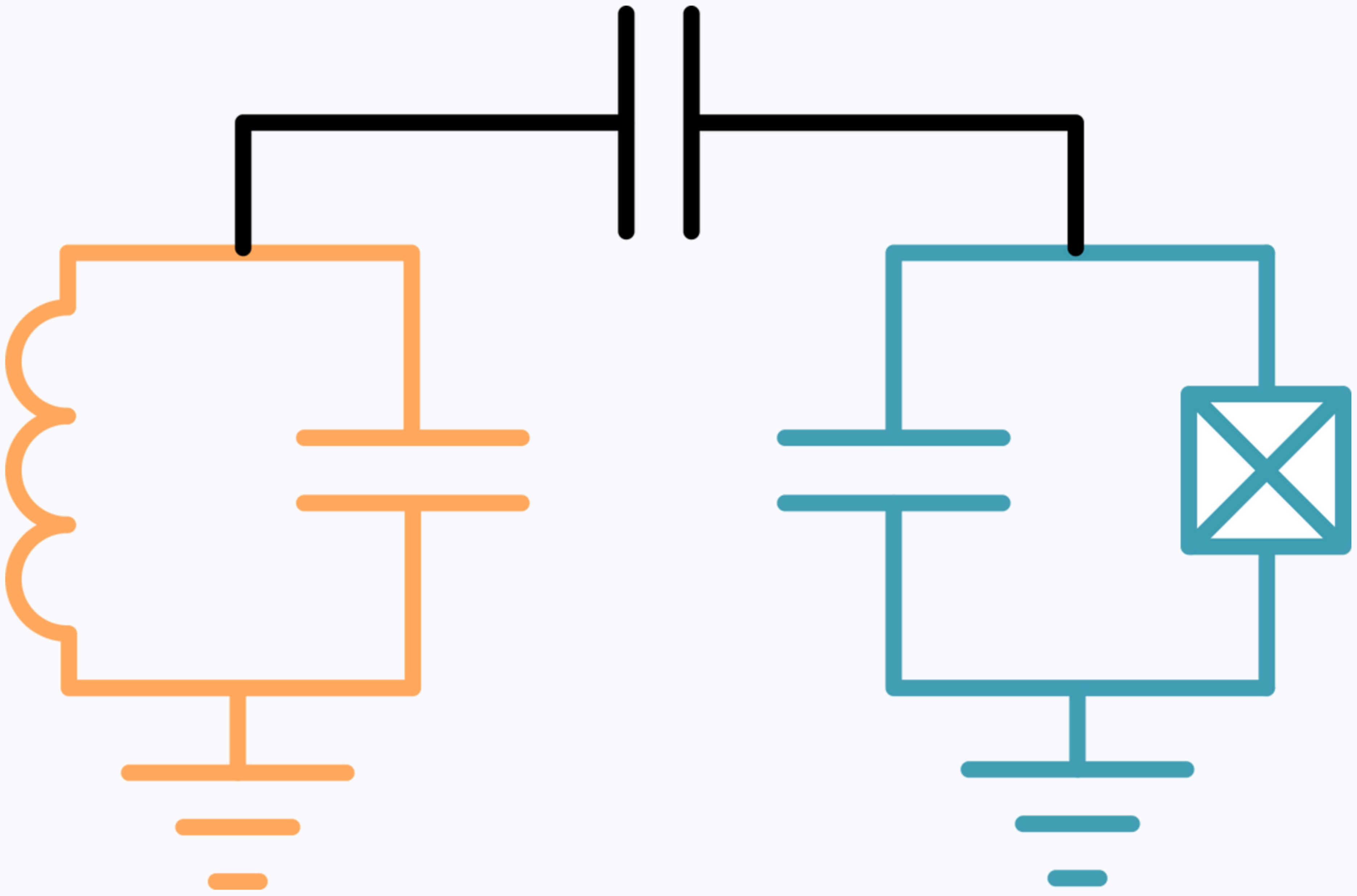
questions?

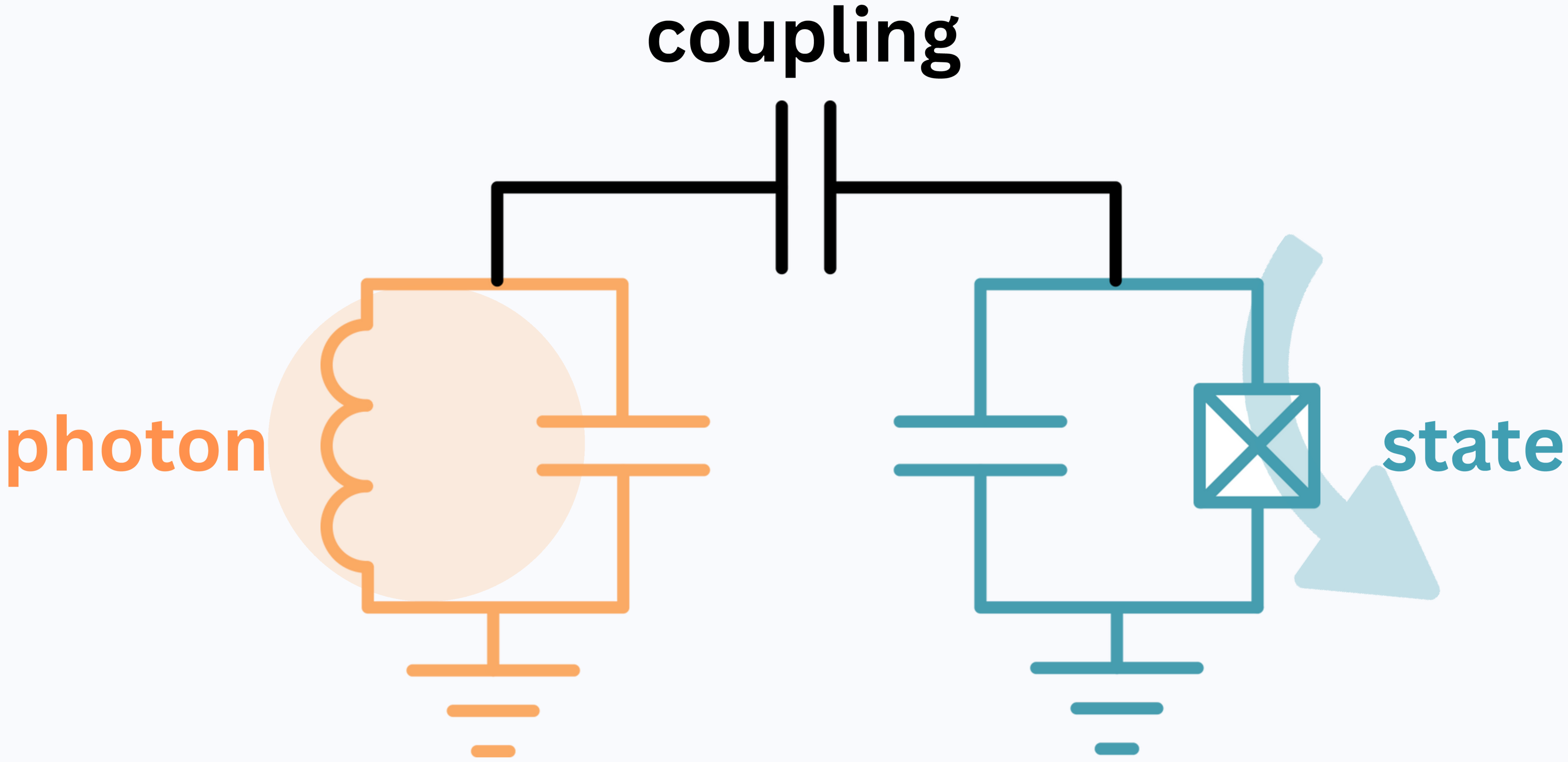
what to do with a quantum circuit

extremely sensitive sensors, and the promise of quantum computing



sensors




coupling
photon
state

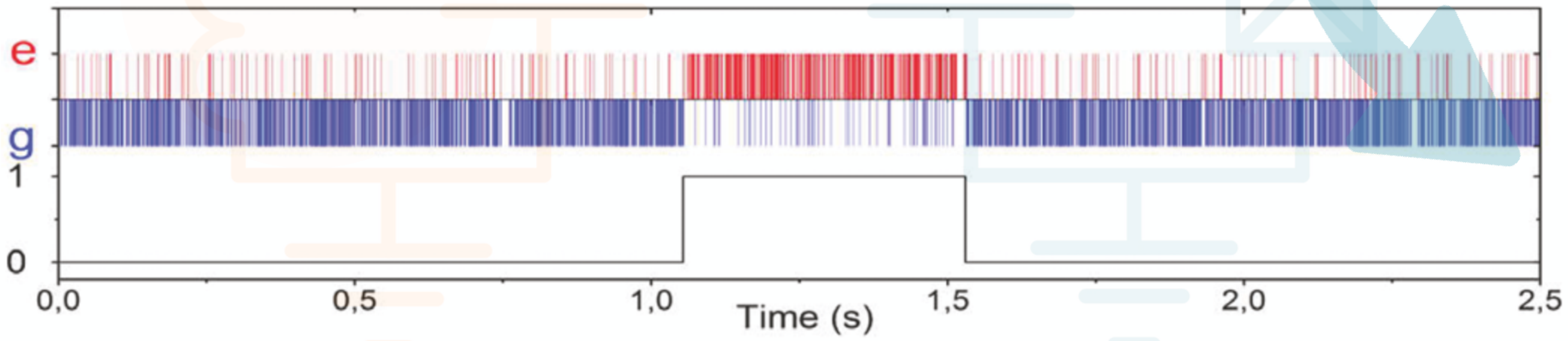
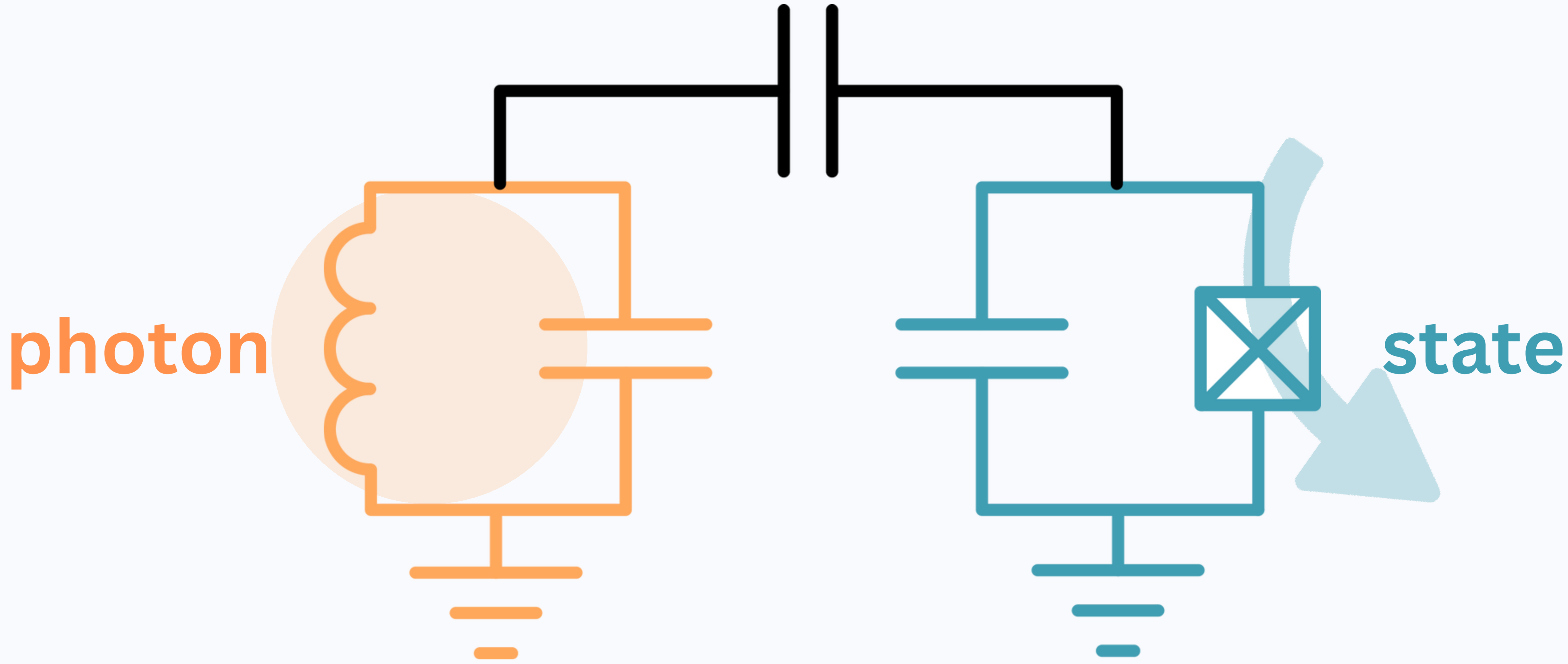
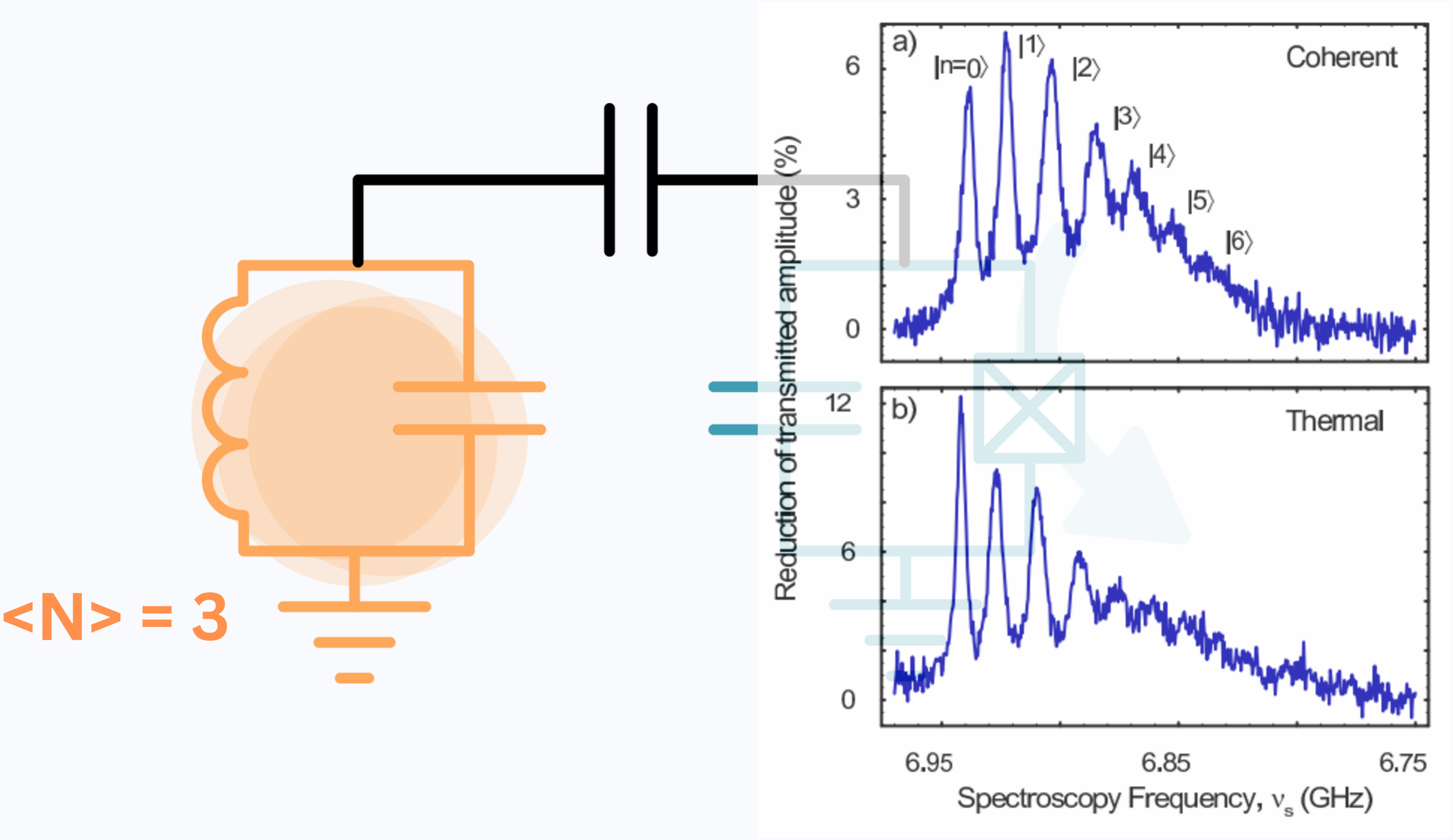
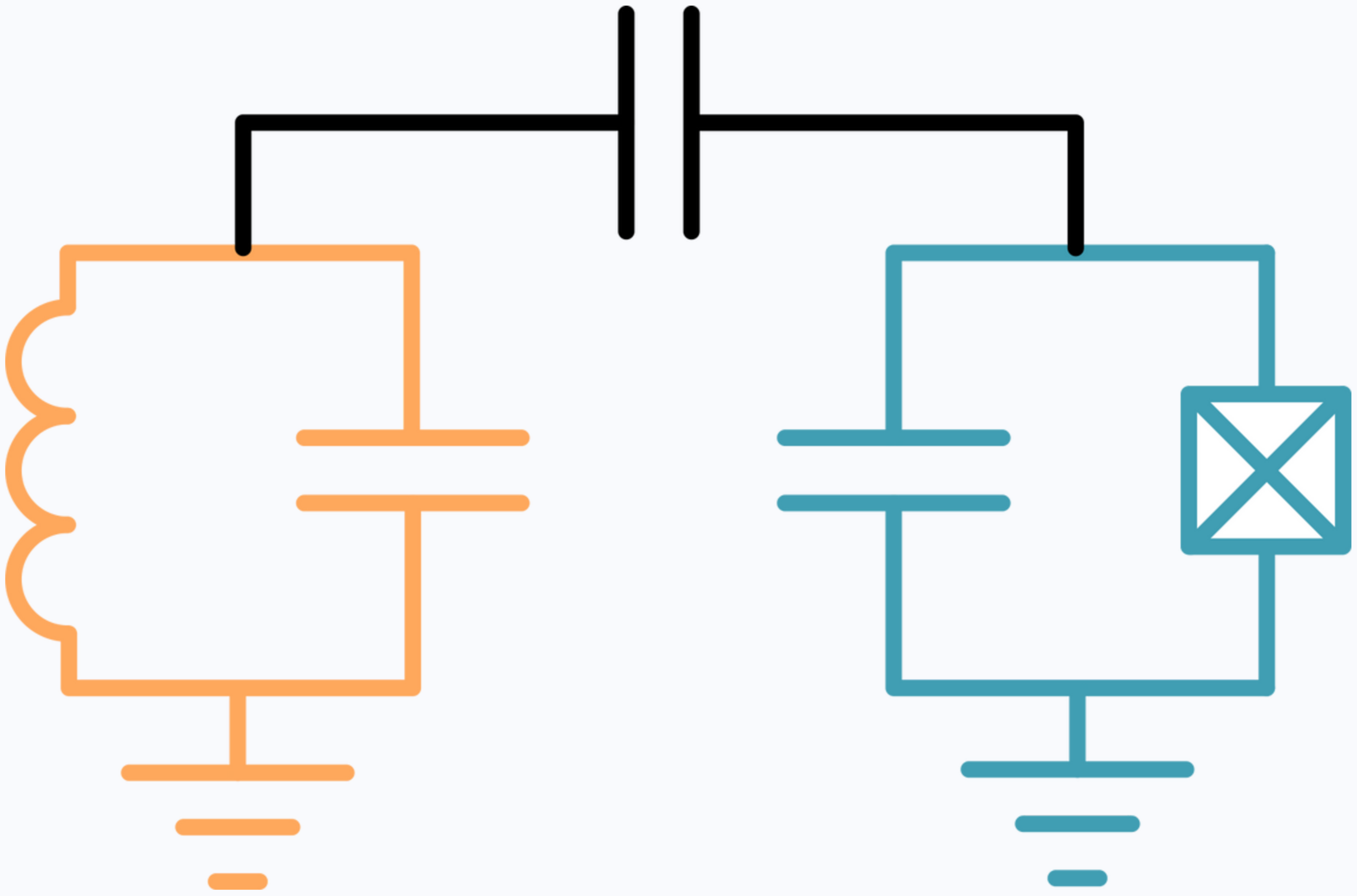


FIGURE 11. QND detection of a single photon: the sequence of single atom events (upper trace) detects the sudden change of the photon number (lower trace), revealing the birth, life and death of a single light quantum (reprinted with permission from [50], © Macmillan Publishers Ltd).


photon
state



<N> = 3
a)
|n=0⟩
|1⟩
|2⟩
|3⟩
|4⟩
|5⟩
|6⟩
Coherent
b)
Thermal
Reduction of transmitted amplitude (%)
6
3
0
12
6
0
6.95
6.85
6.75
Spectroscopy Frequency, νs (GHz)



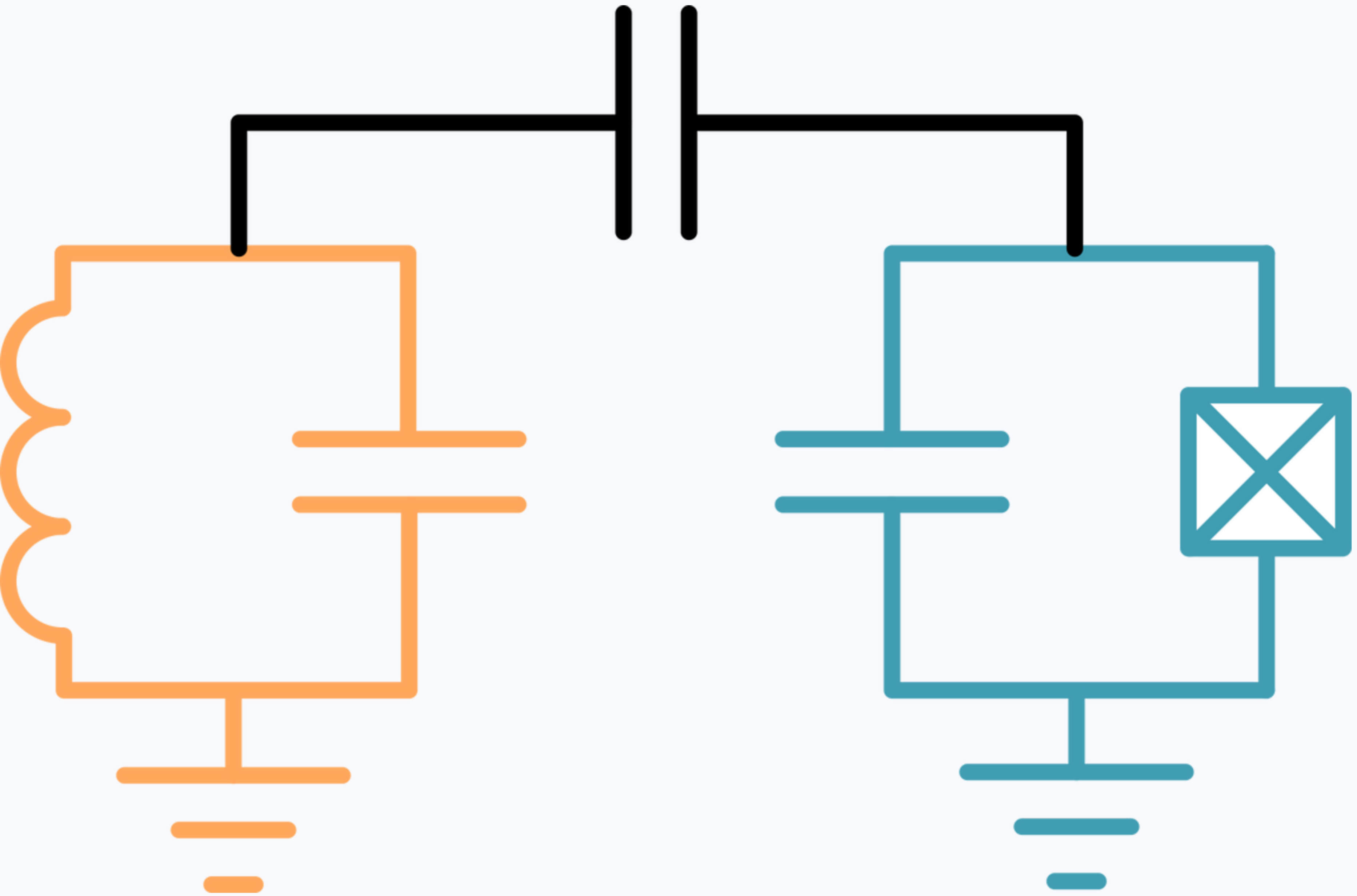
computing

bits:

a, b, c, d = 0, 1

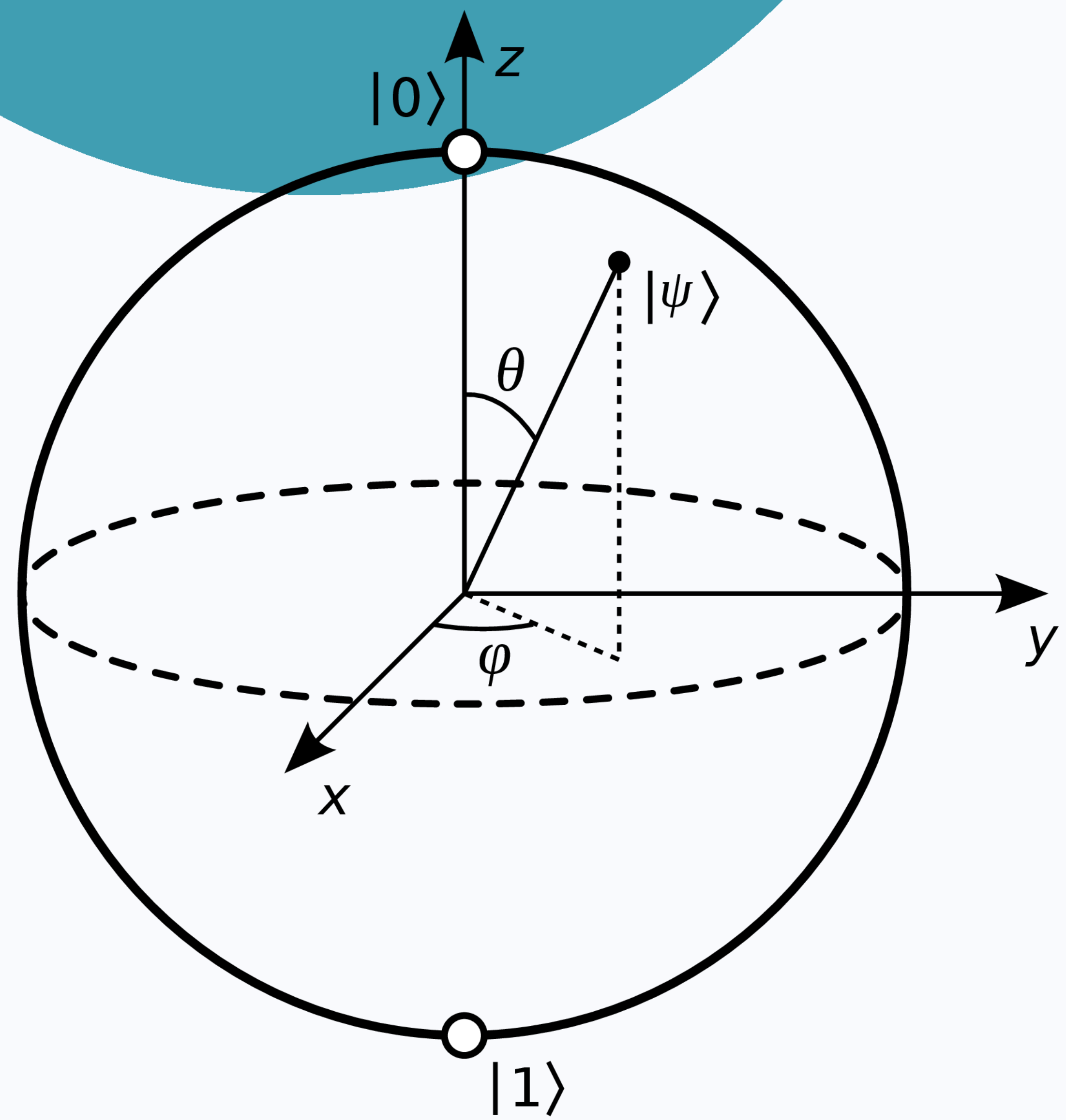
quantum bits:

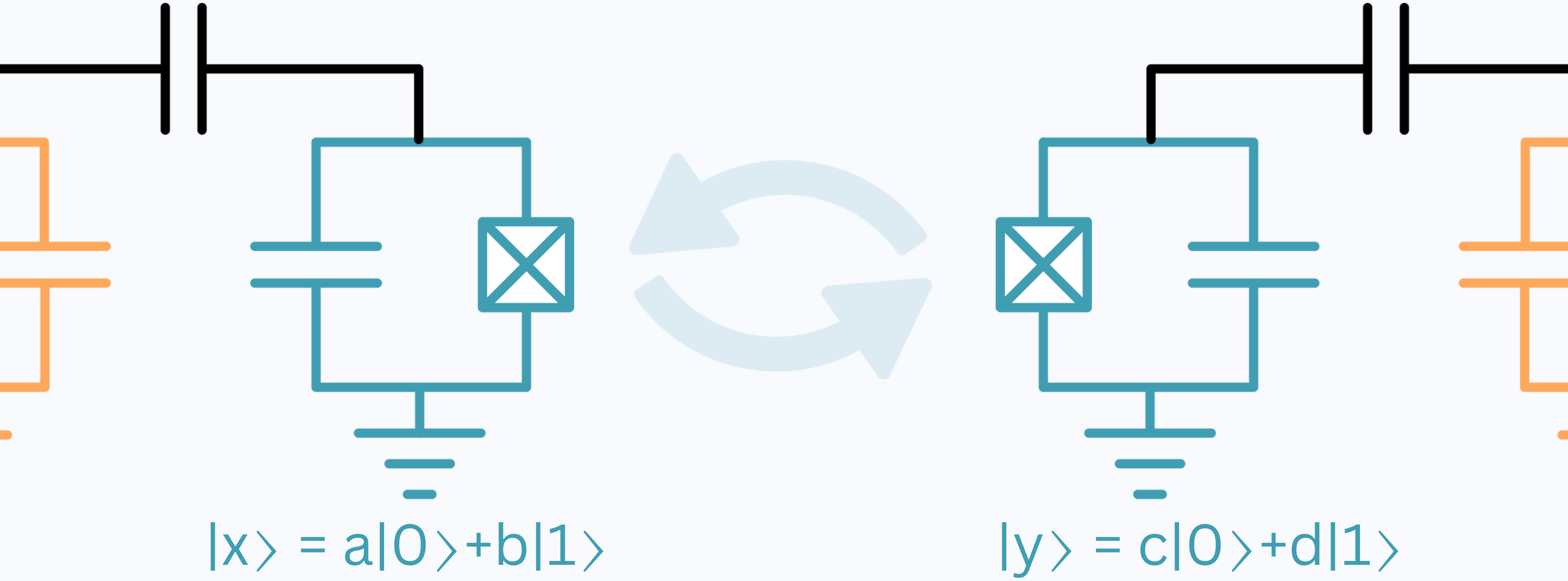
a, b, c, d = complex



$$|x\rangle = a|0\rangle + b|1\rangle$$

$$a^2 + b^2 = 1$$



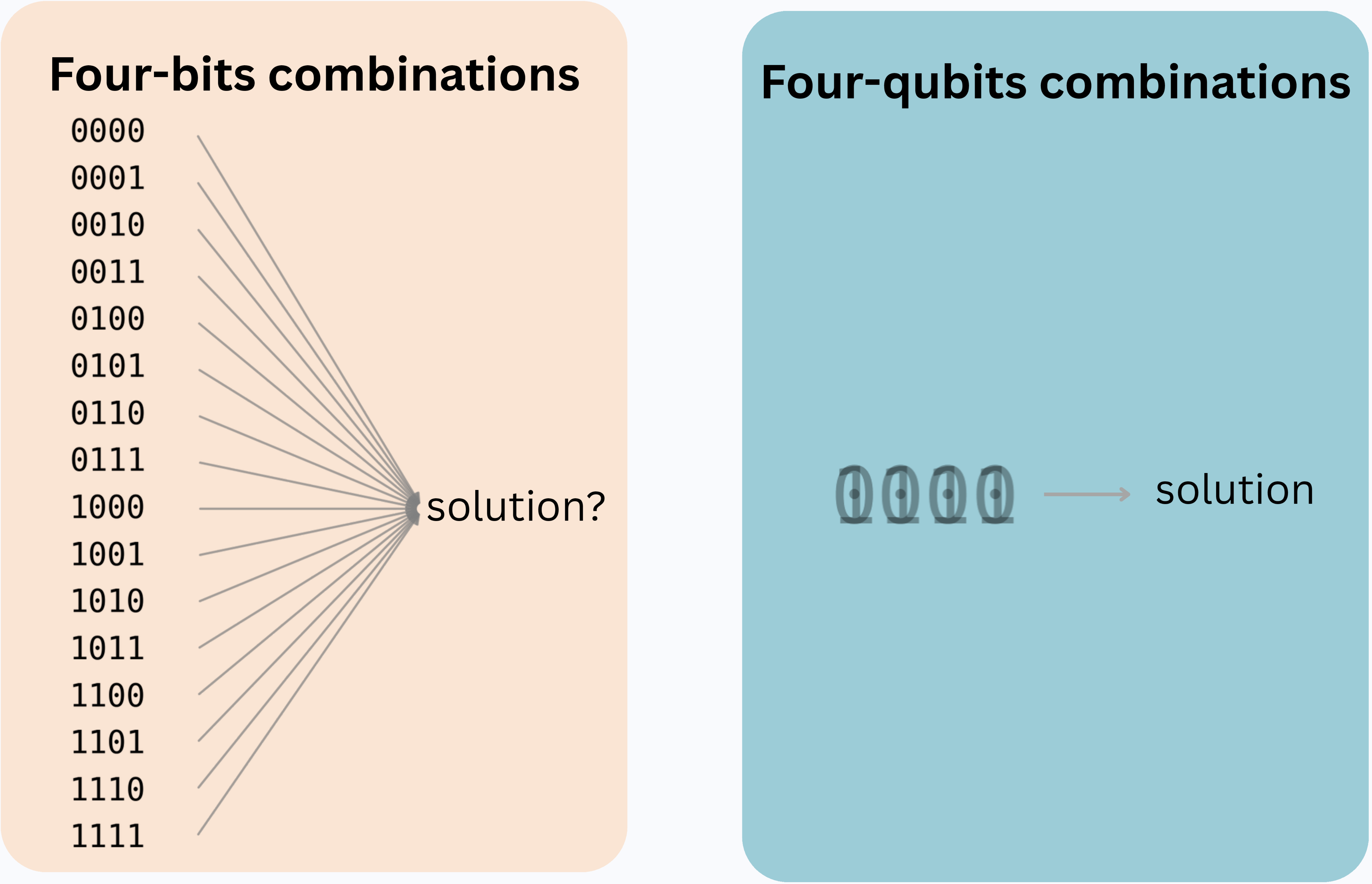


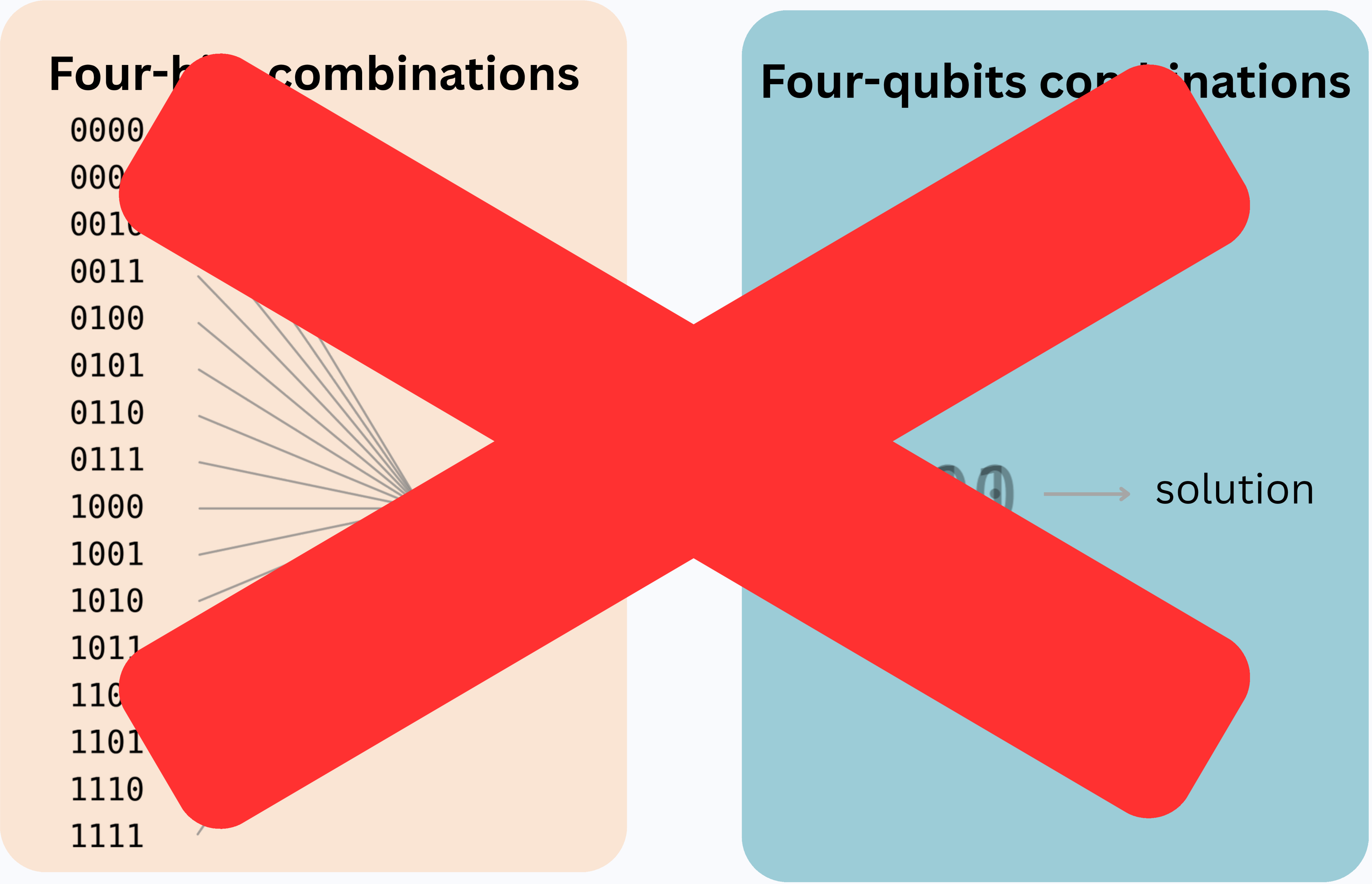
$|x\rangle = a|0\rangle + b|1\rangle$
$|y\rangle = c|0\rangle + d|1\rangle$

Bits

0000
0001
0010
0011
0100
0101
0110
0111
1000
1001
1010
1011
1100
1101
1110
1111

Qubits


Four-bits combinations
0000
0001
0010
0011
0100
0101
0110
0111
1000
1001
1010
1011
1100
1101
1110
1111
solution?
Four-qubits combinations
solution



Four-b combinations
0000
000
001
0011
0100
0101
0110
0111
1000
1001
1010
1011
110
1101
1110
1111
Four-qubits co inations
solution

Example: searching algorithms

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Bits

0101
0110
0111
1000
1001
1010

f( ) = Yes/No

Qubits

f( ) = Yes/No

What is the average number of trials to find the answer?

O(N)

O(?)

Example: searching algorithms

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Bits

0101
0110
0111
1000
1001
1010

f( ) = Yes/No

Qubits

f( ) = Yes/No

What is the average number of trials to find the answer?

O(N)

O(1)

Example: searching algorithms

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Bits

0101
0110
0111
1000
1001
1010

f( ) = Yes/No

Qubits

f(0000) = Yes/No

What is the average number of trials to find the answer?

O(N)

Example: searching algorithms

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Bits

0101
0110
0111
1000
1001
1010

f( ) = Yes/No

Qubits

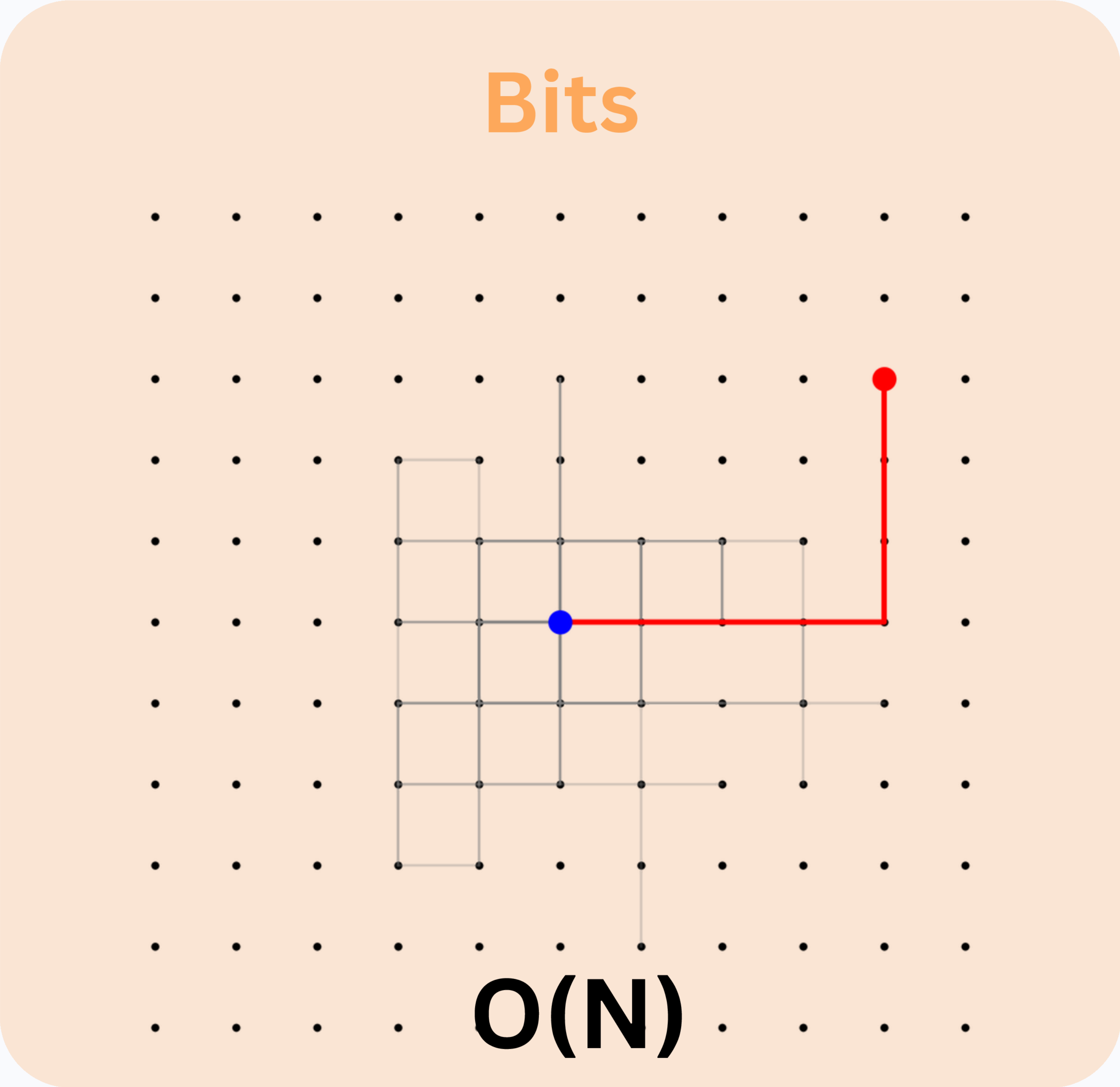
f( ) = Yes/No

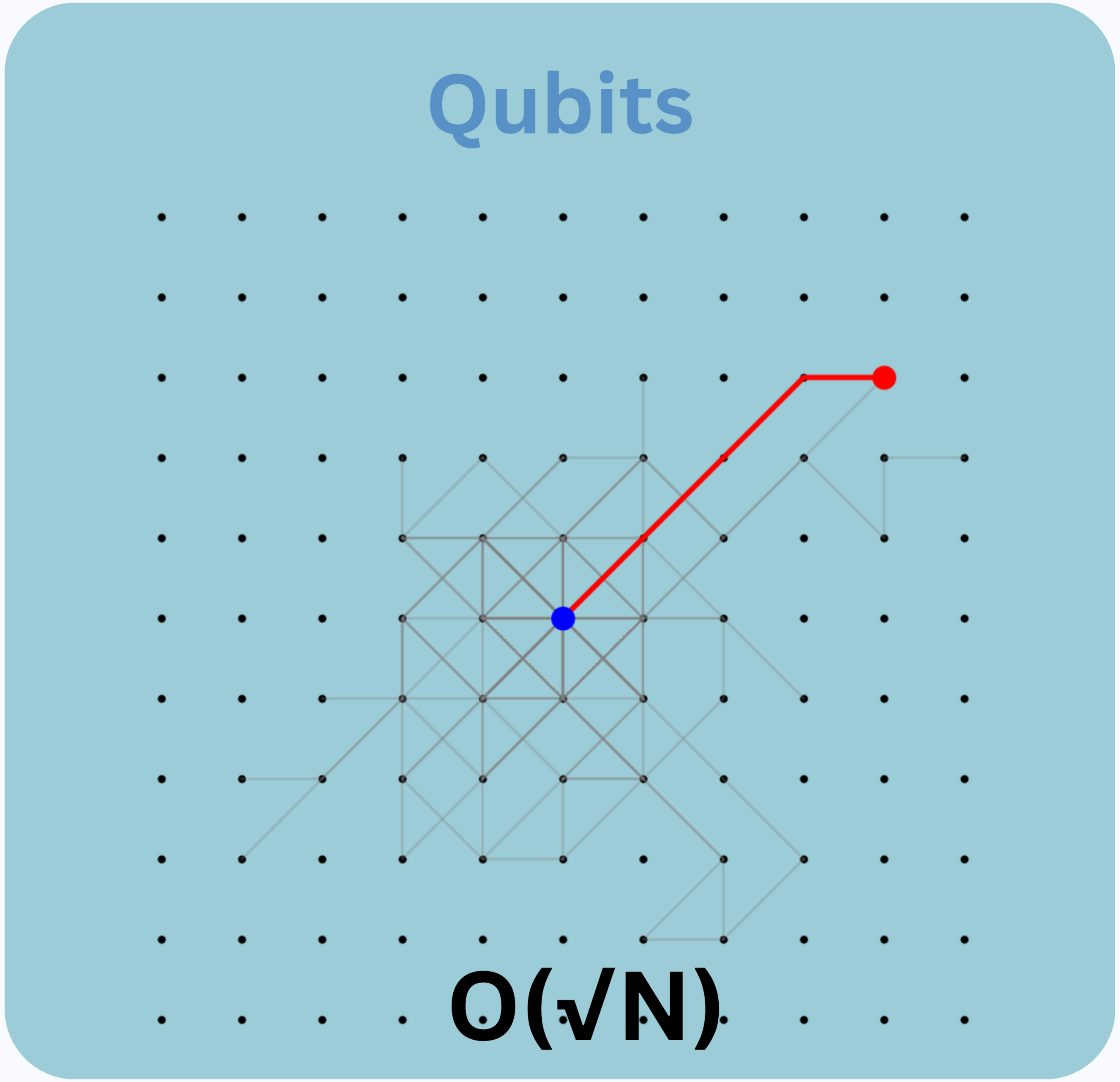
What is the average number of trials to find the answer?

O(N)

O(√N)

Ok, but why is that?





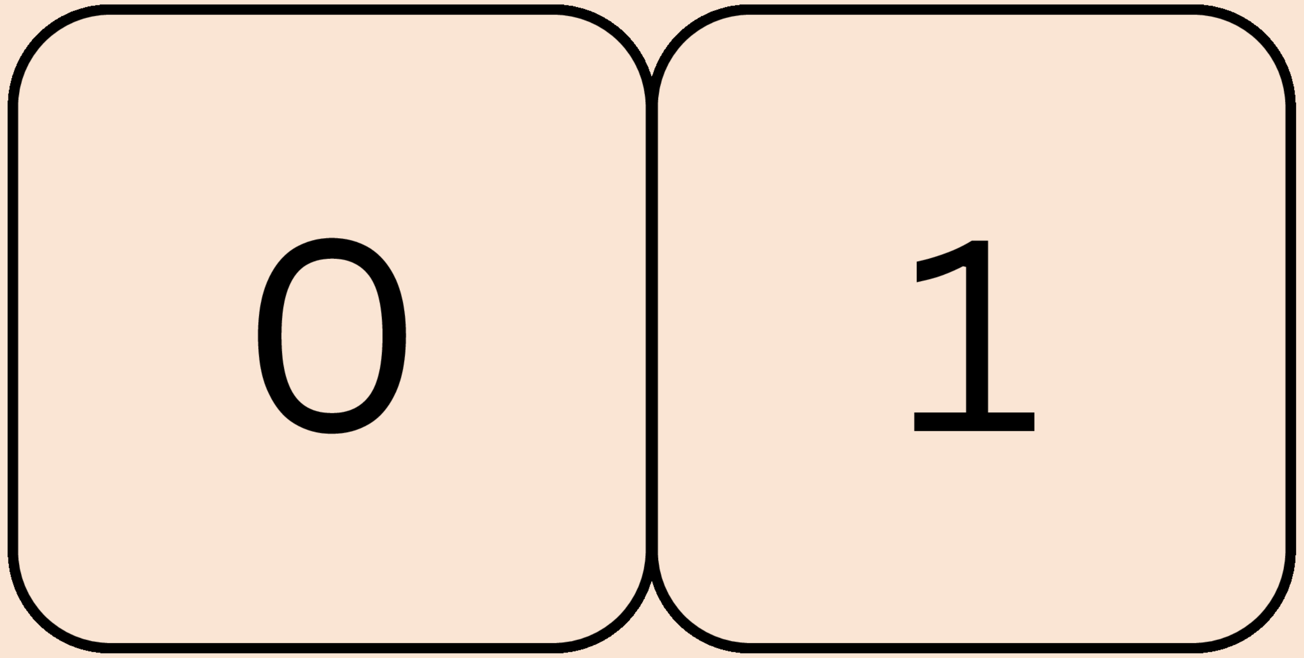
Bits	Qubits
0000 0001 0010 0011 0100 0101 0110 0111 1000 1001 1010 1011 1100 1101 1110 1111	

Why does this fail?

The take home message

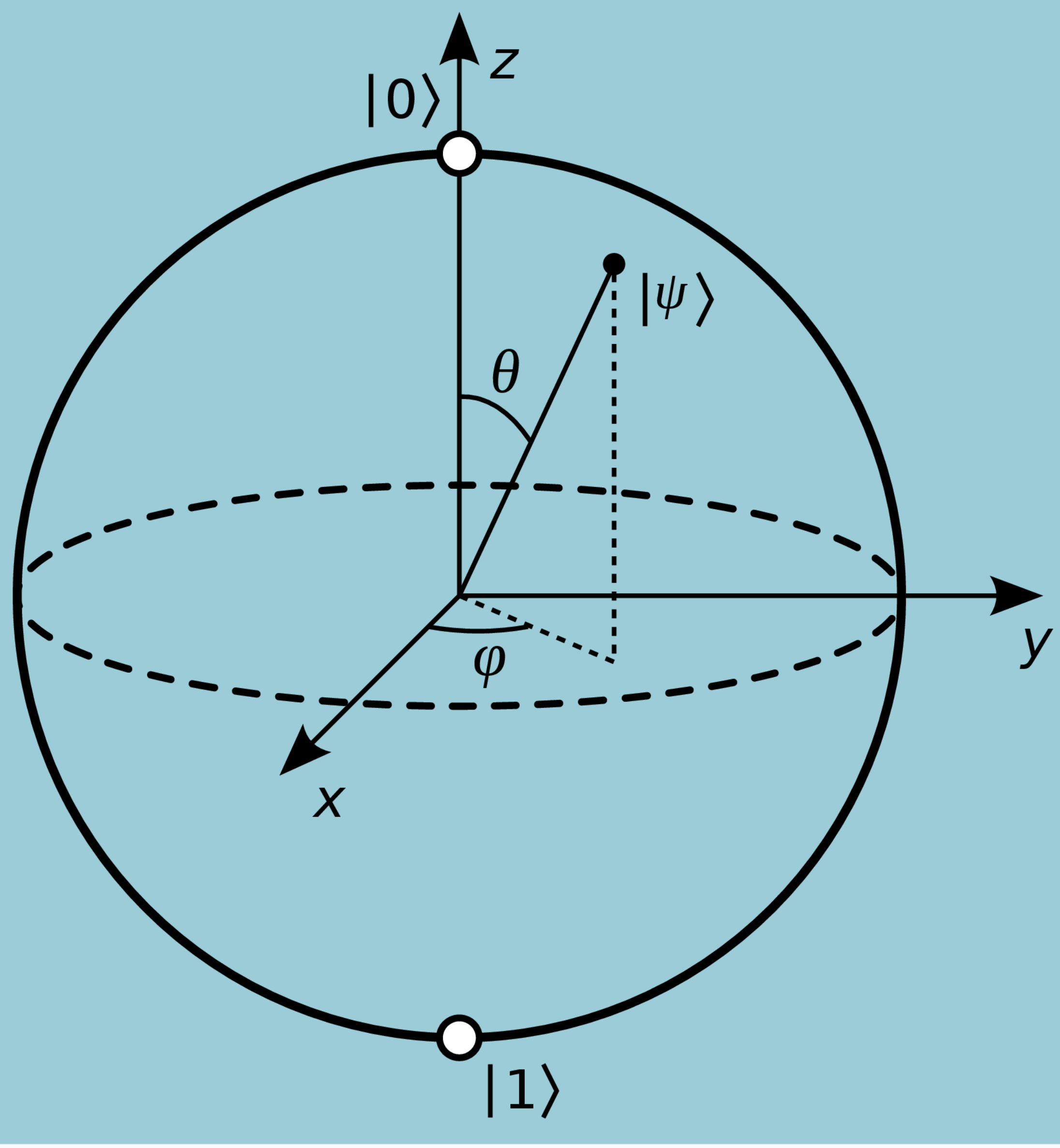
Bits

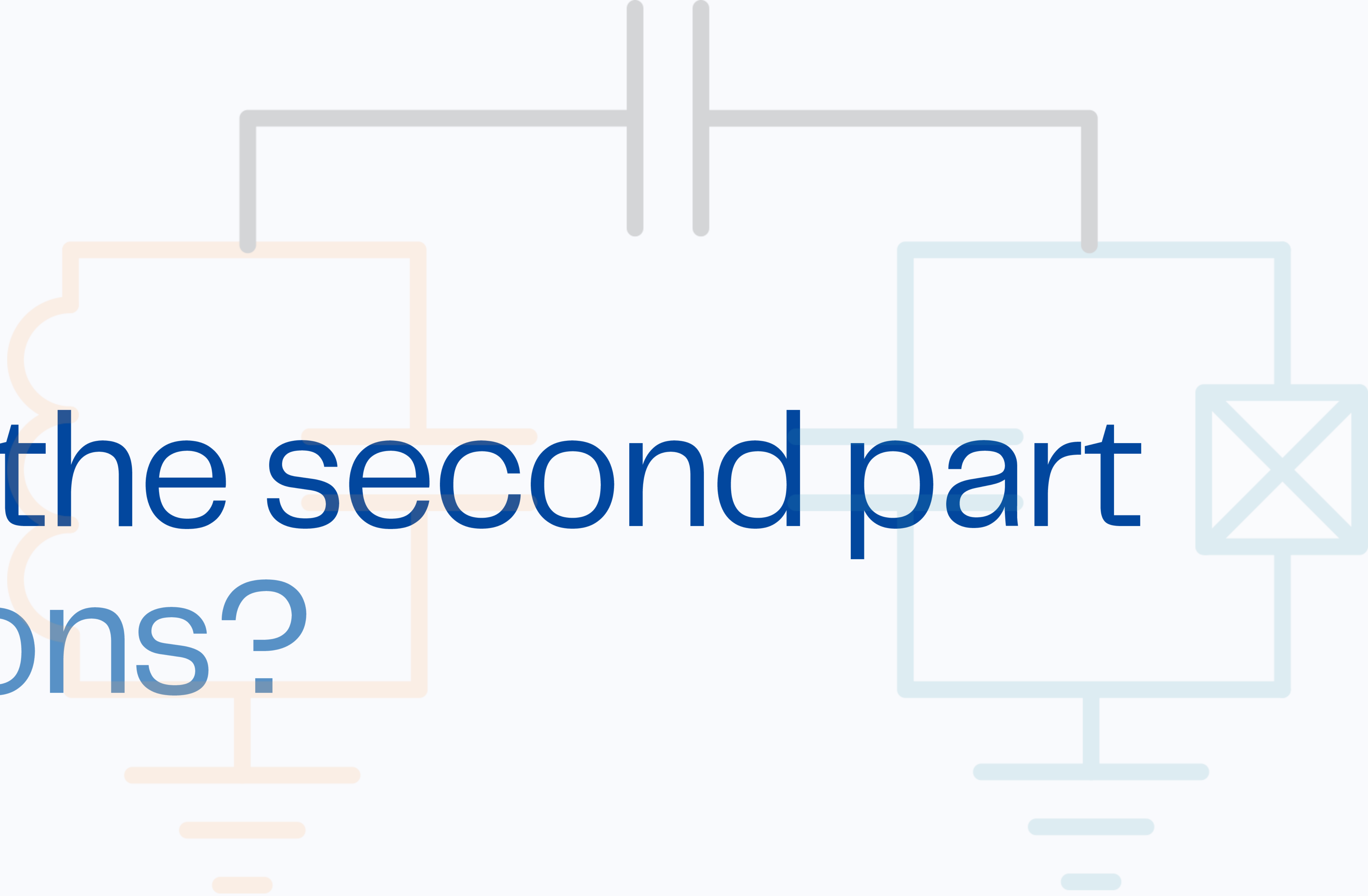
Conditional gates, binary logic



Qubits

Flipping and rotating a vector



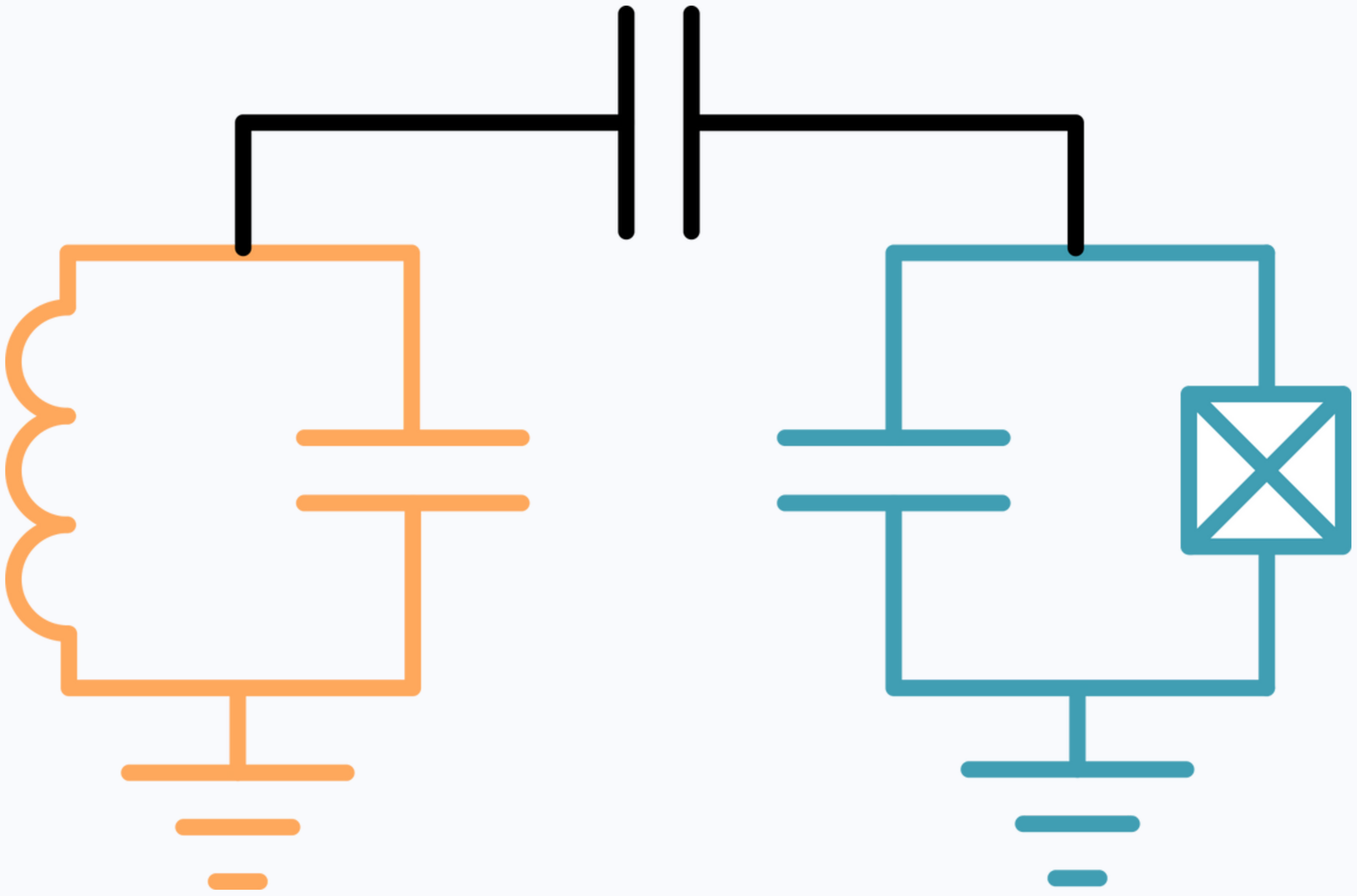


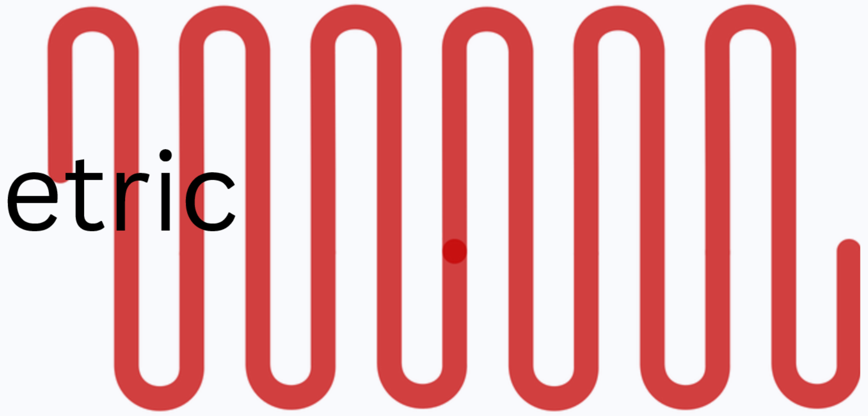
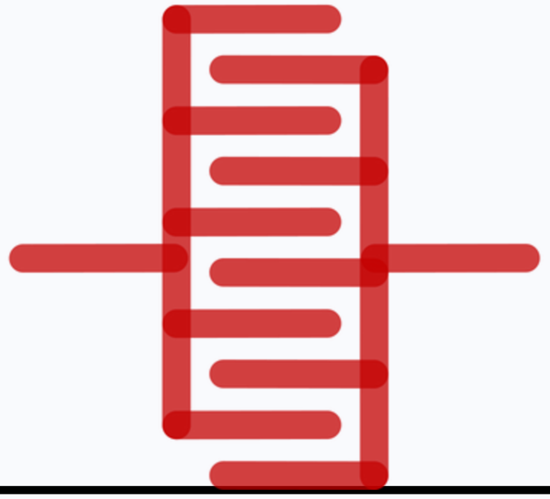
end of the second part

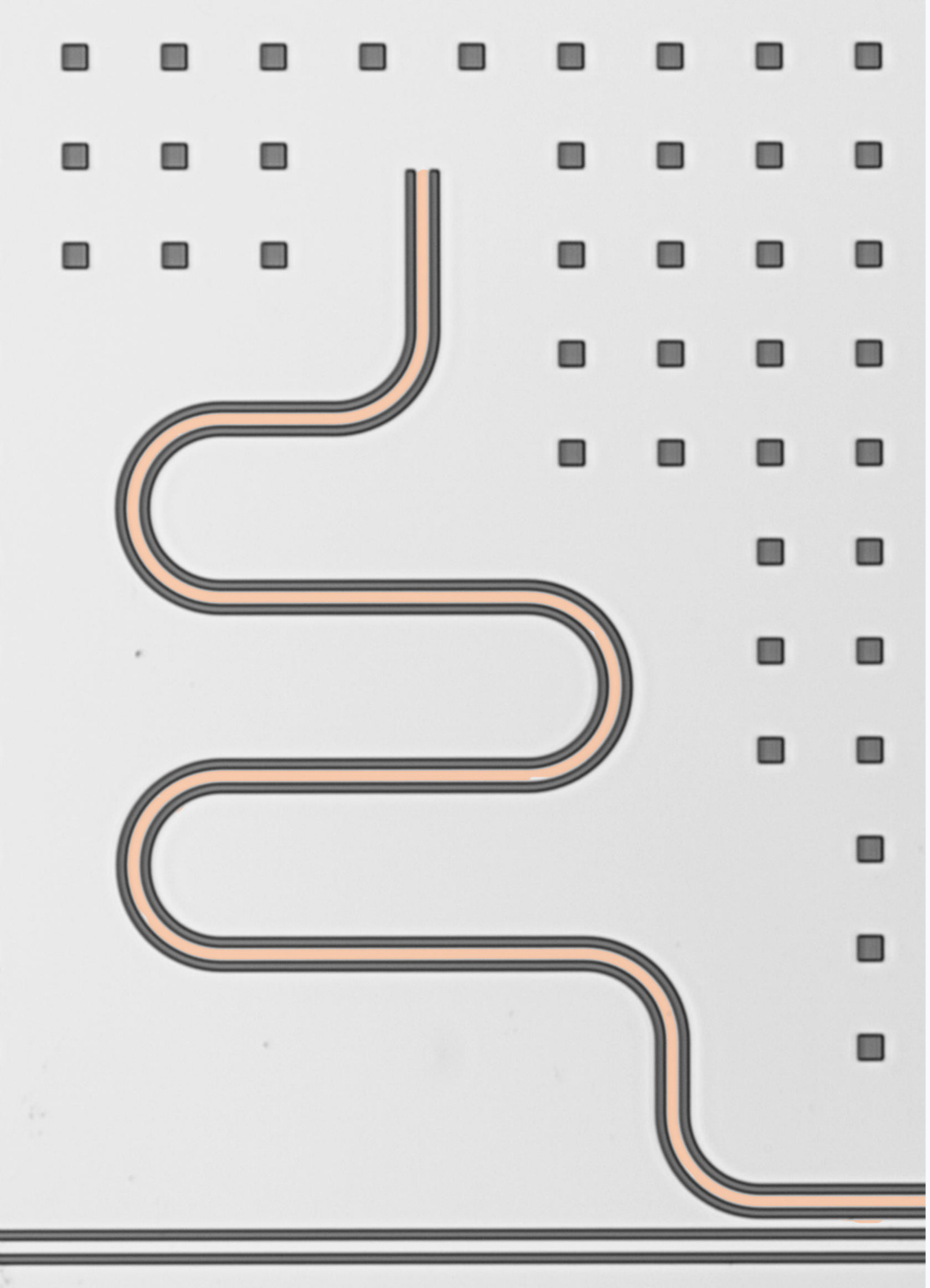
questions?

how to craft a quantum circuit

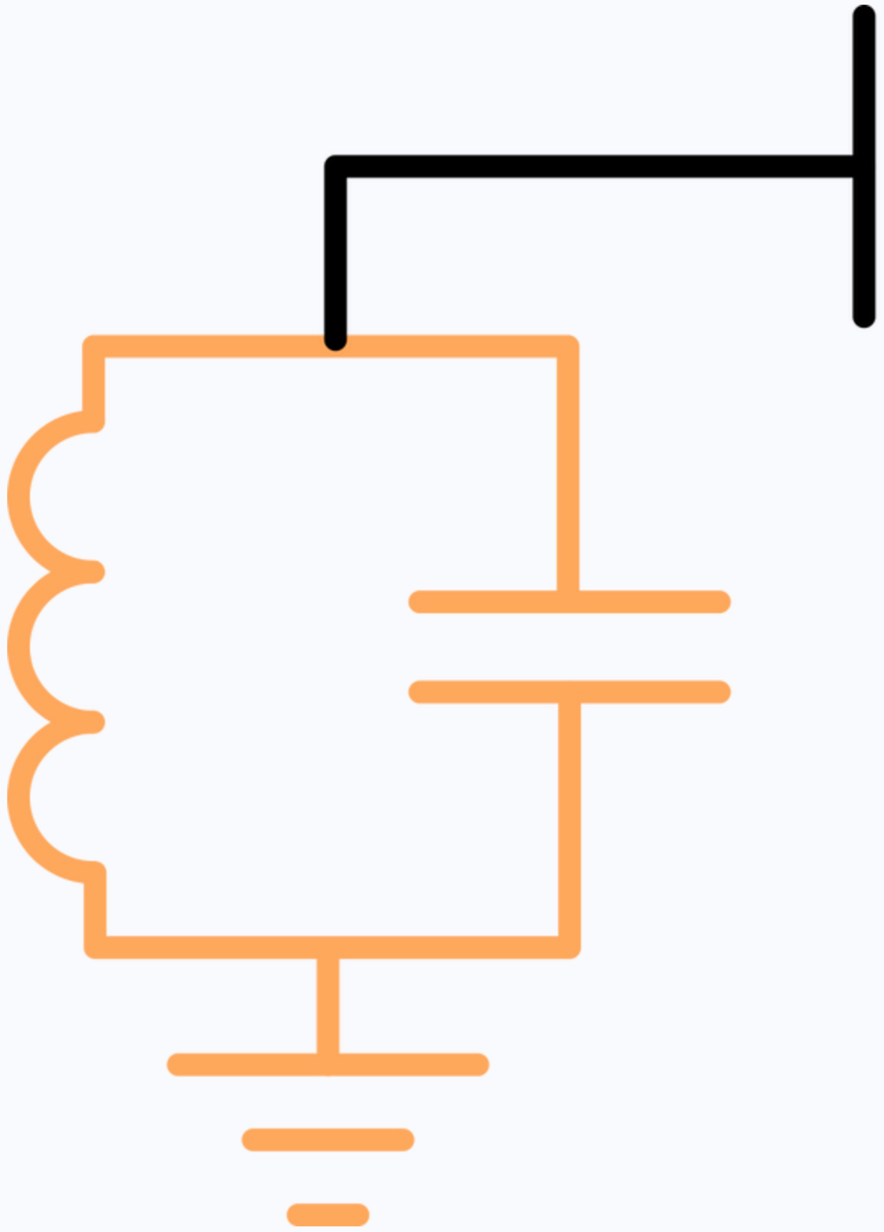
how it is practically realised, and how to talk to a quantum circuit

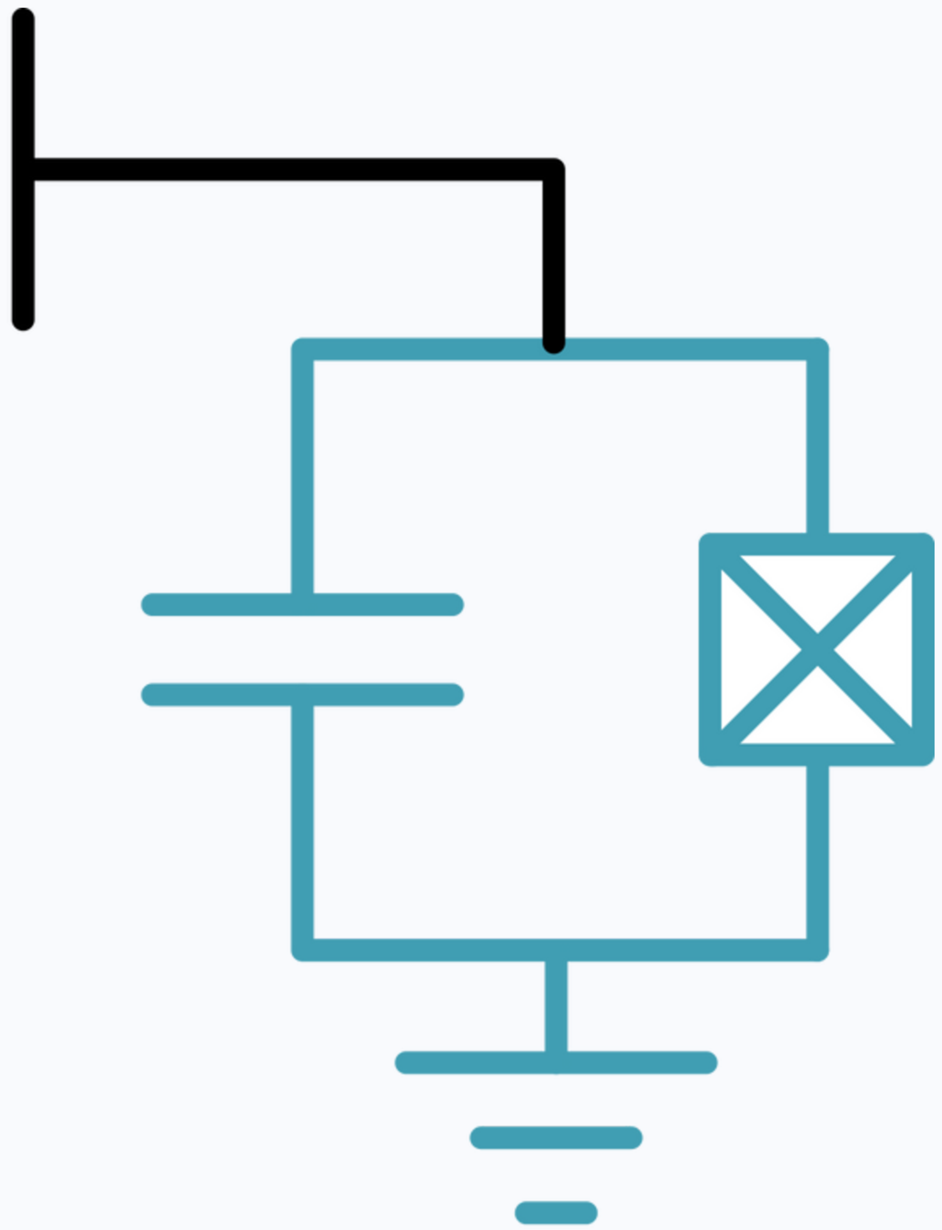


Inductors	Capacitors	Resistors
Geometric 	Geometric 	Metallic materials: • gold • chromium (also inductive) • platinum
Nonlinear inductors 	Nonlinear capacitors 	• high impedance • probably, with high currents • heating is a problem
Large junction low impedance	Small junction high impedance	Impedance/dissipation engineering

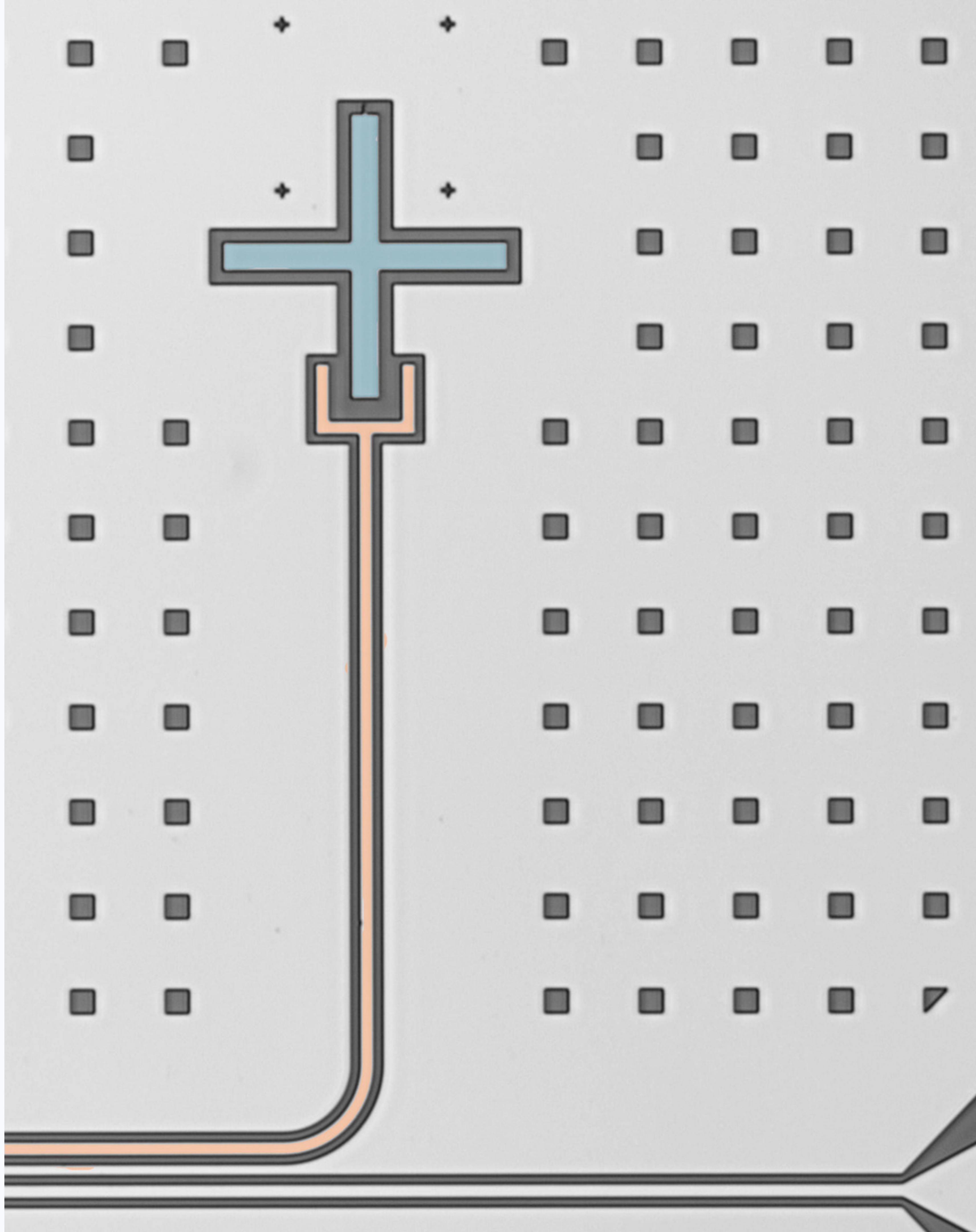


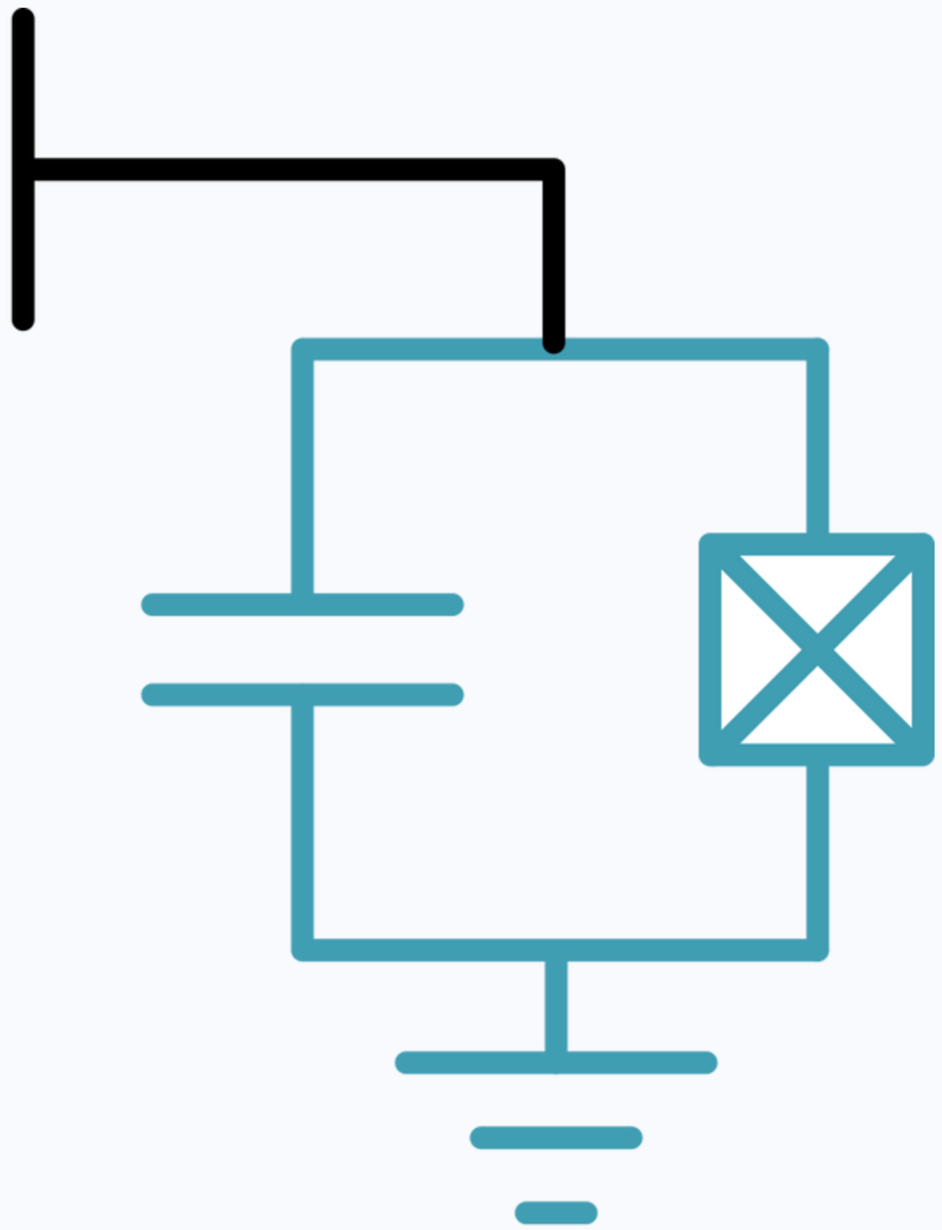
resonator



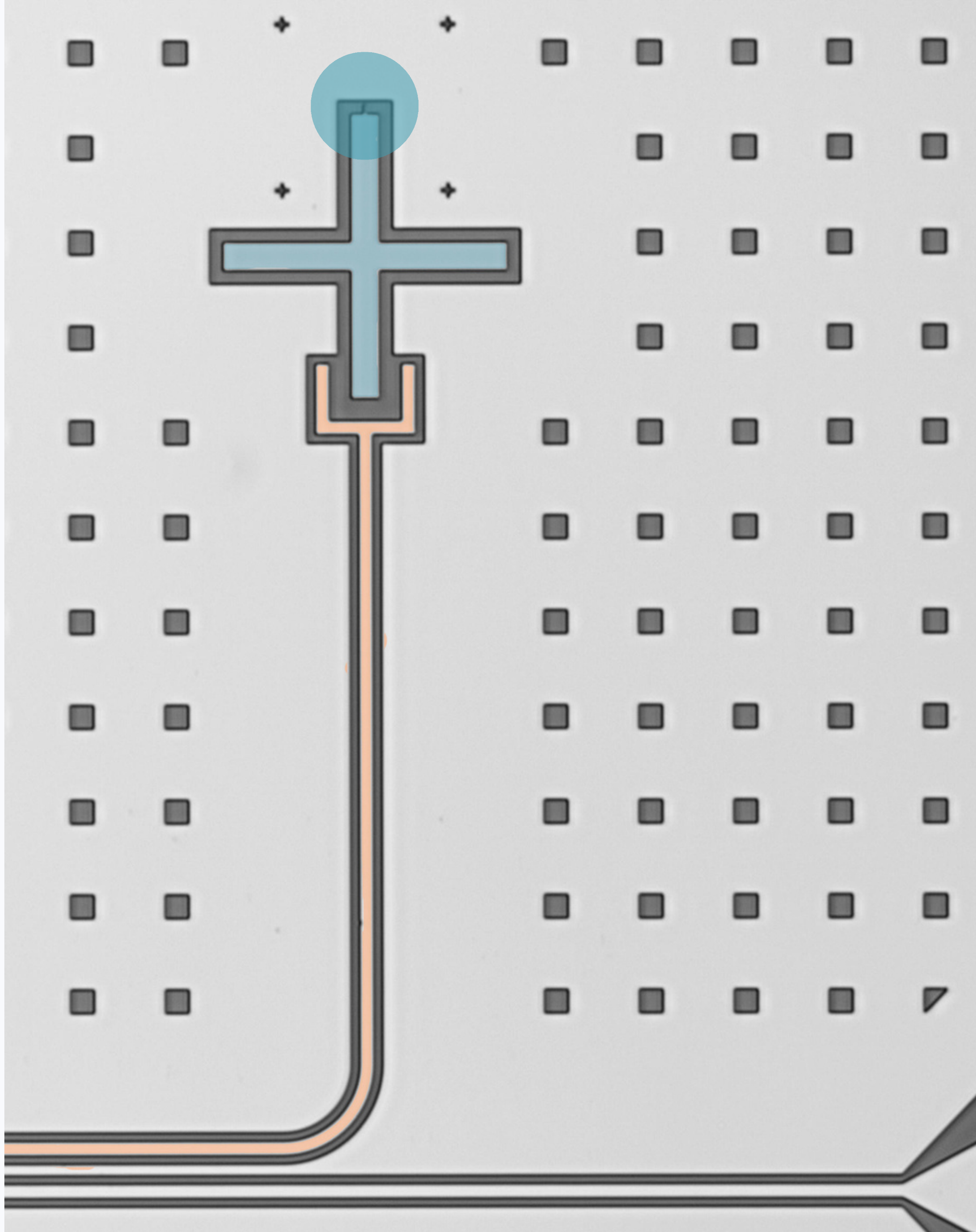


qubit

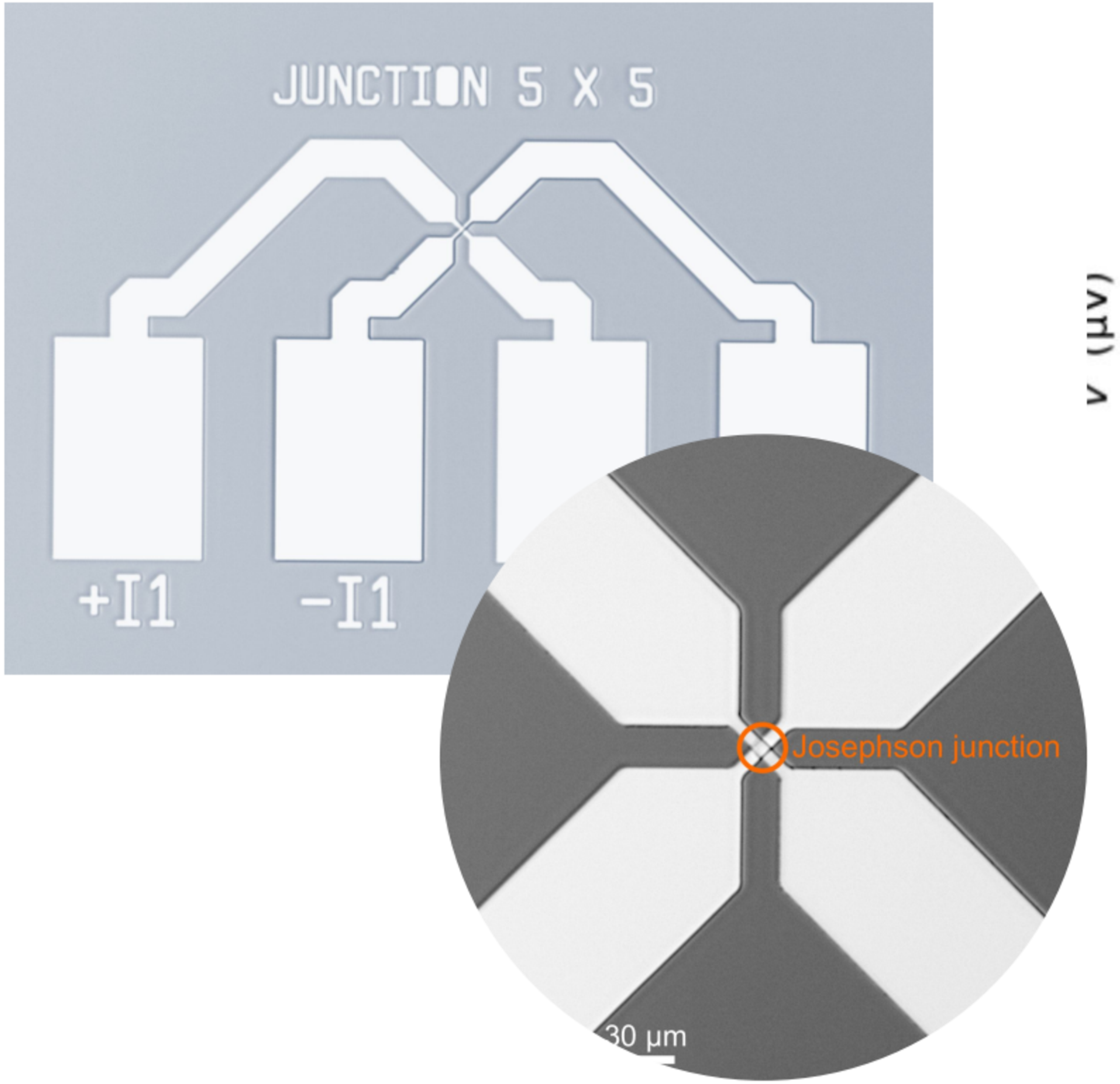


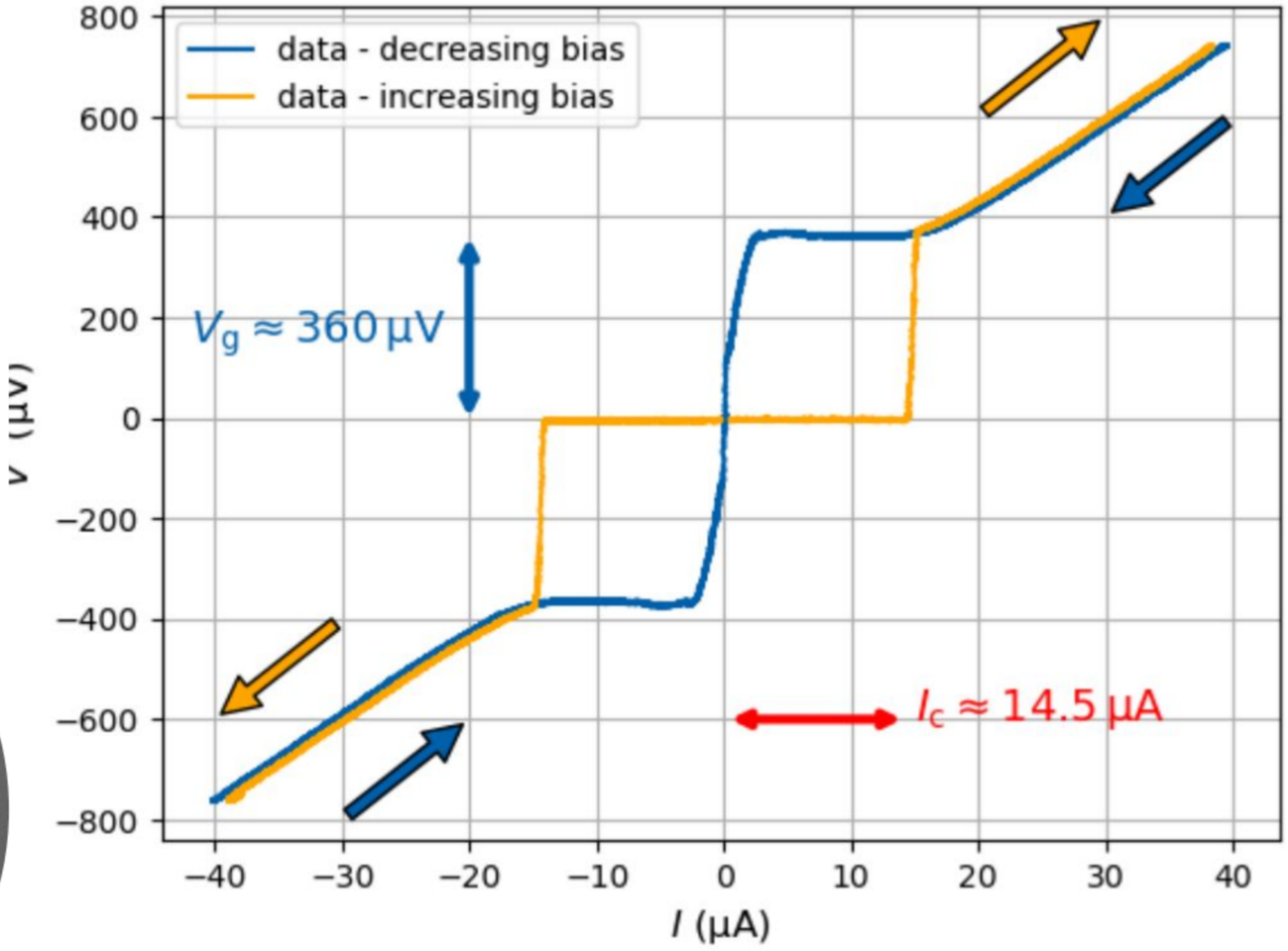


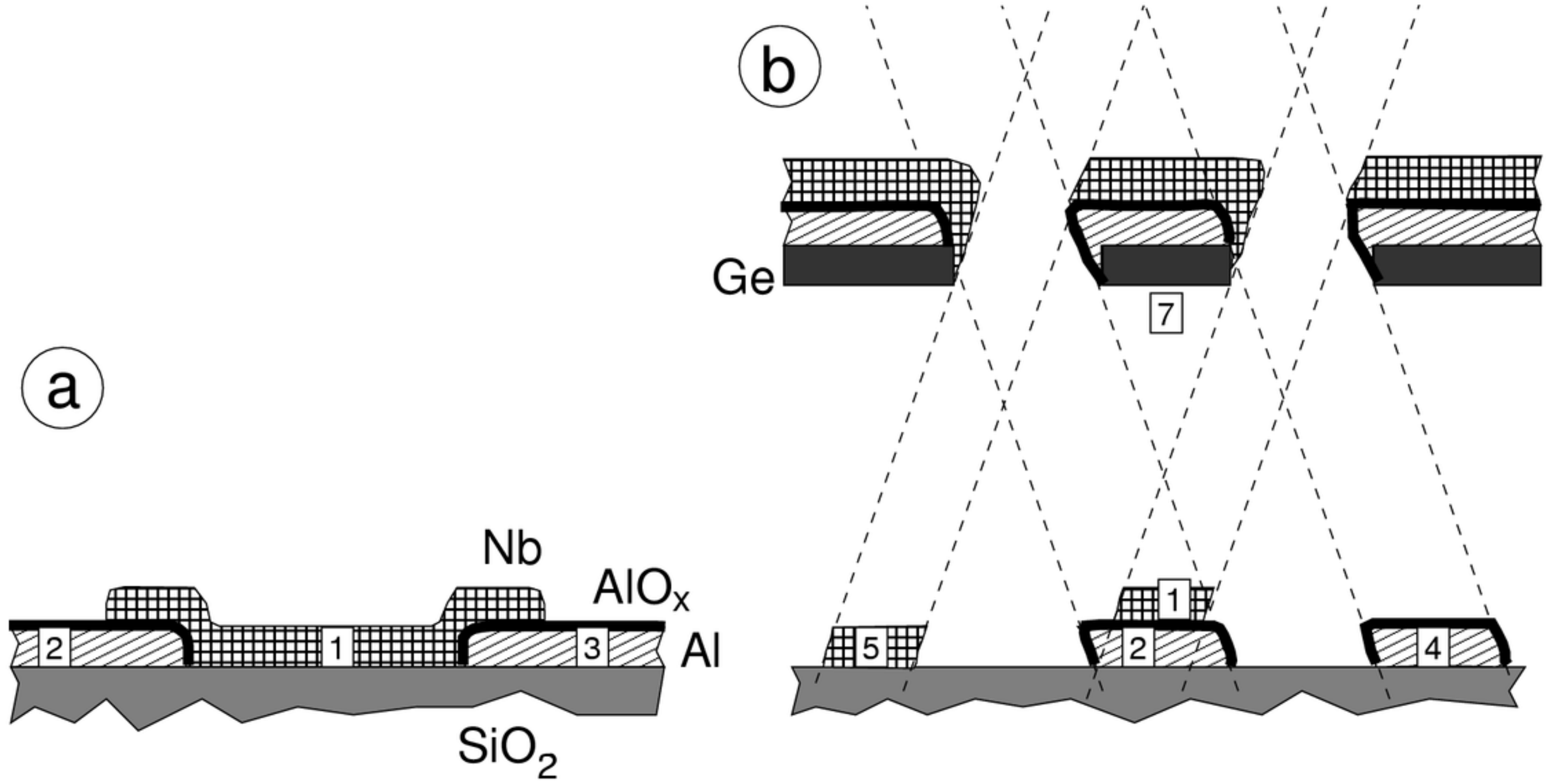
junction



Josephson junction



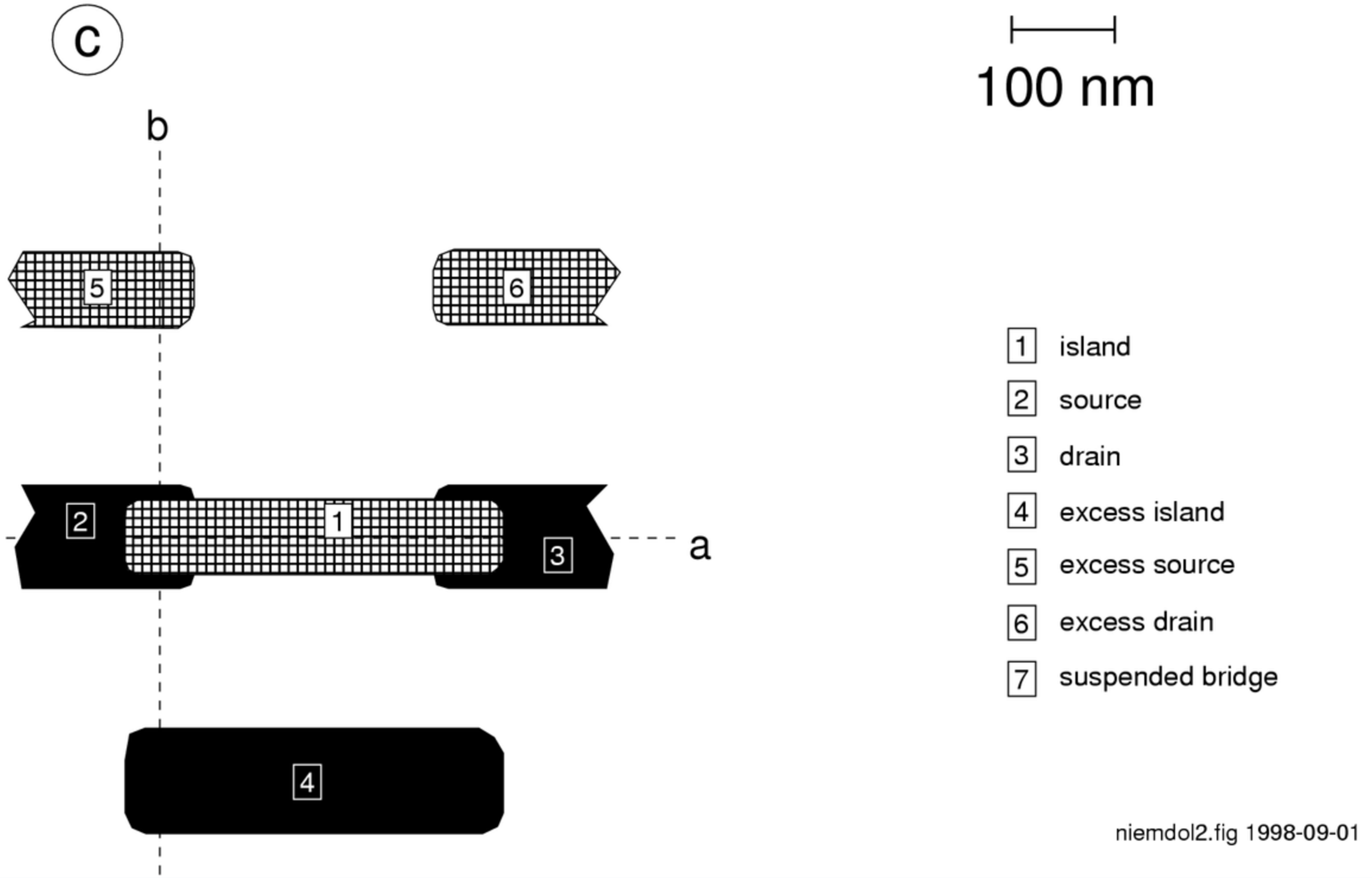


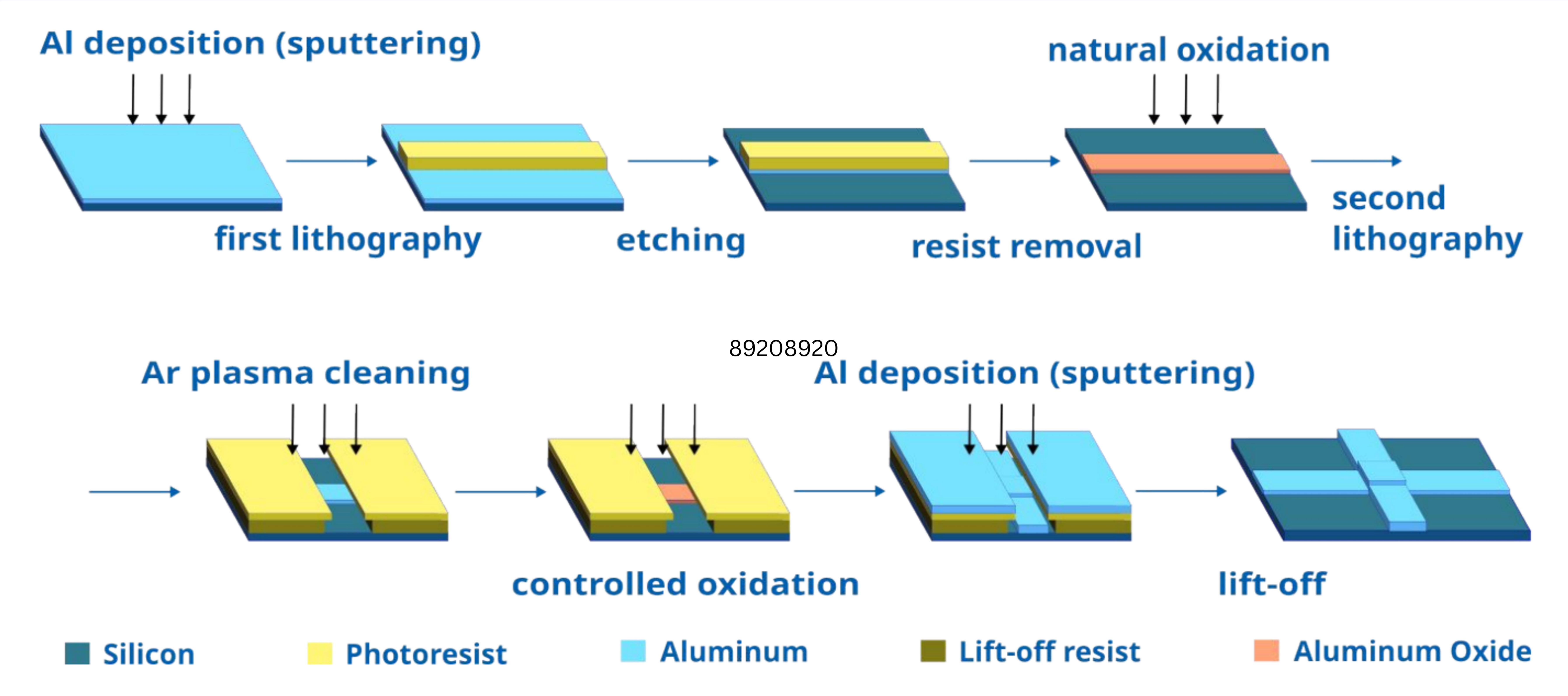


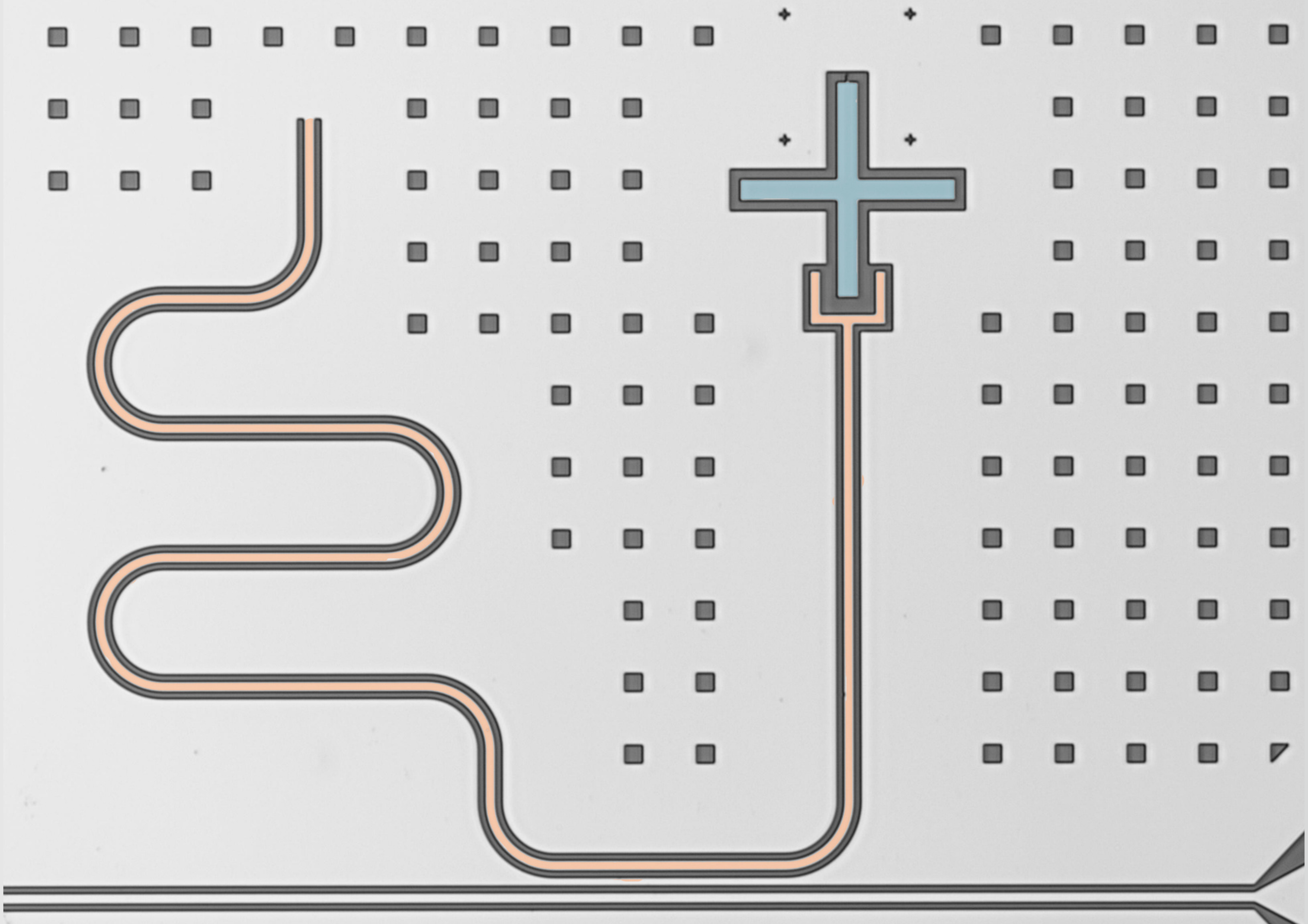
Double tilted evaporation

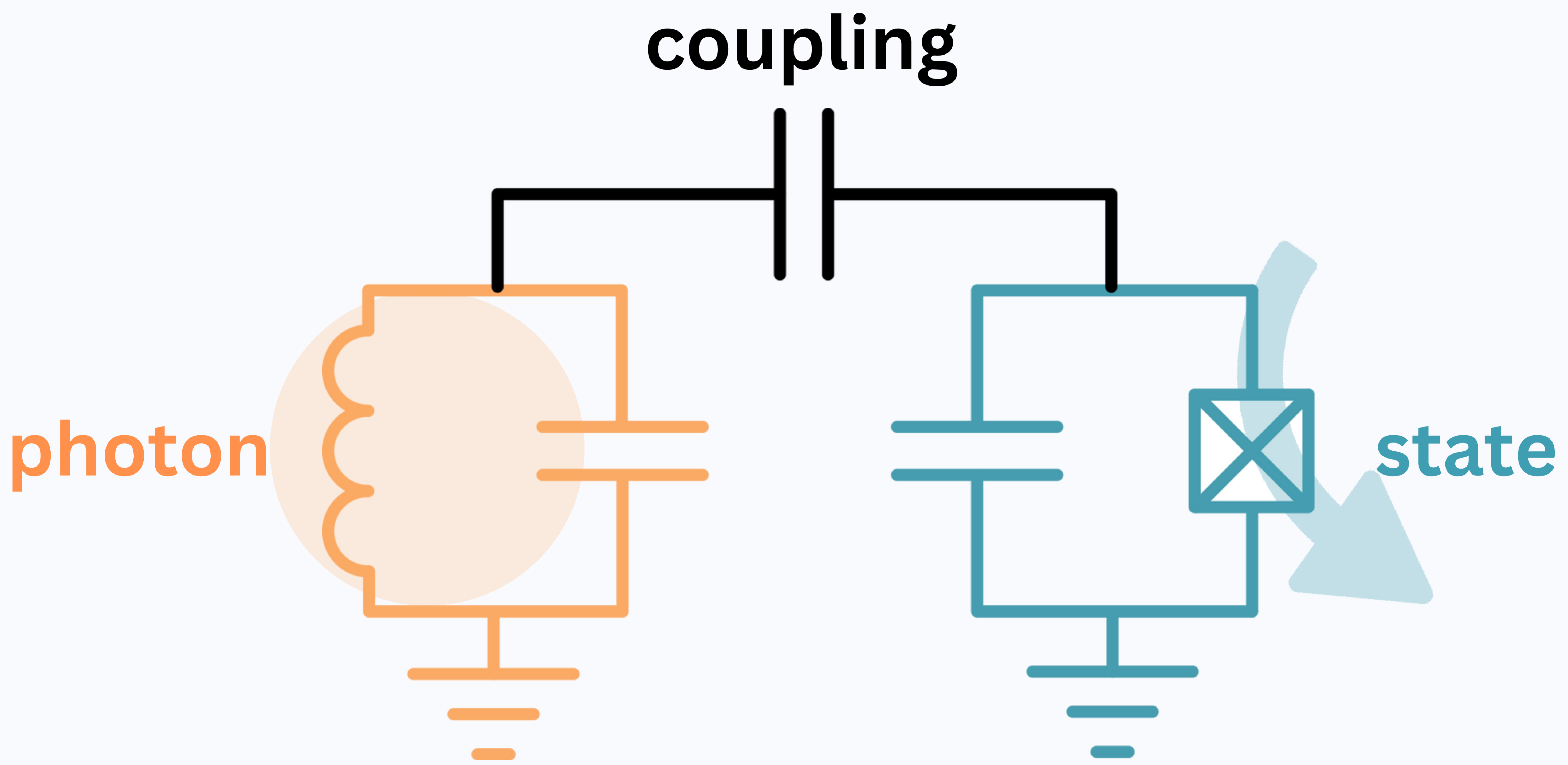
- based on resist bridges which are then removed
- the metal is not exposed to air: clean oxidation

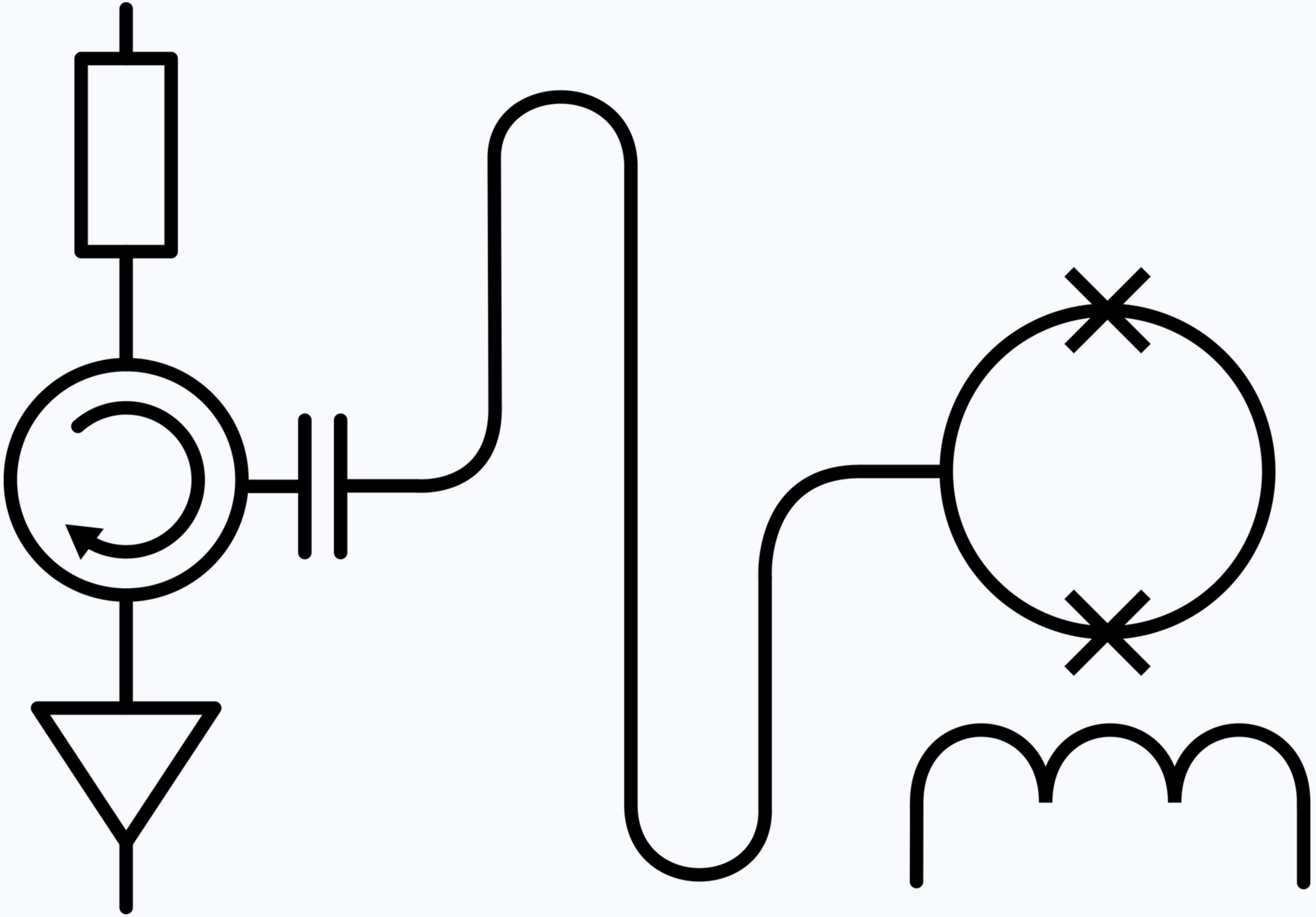
- design freedom is not absolute, there are limits
- excess metal deposition which can cause issues

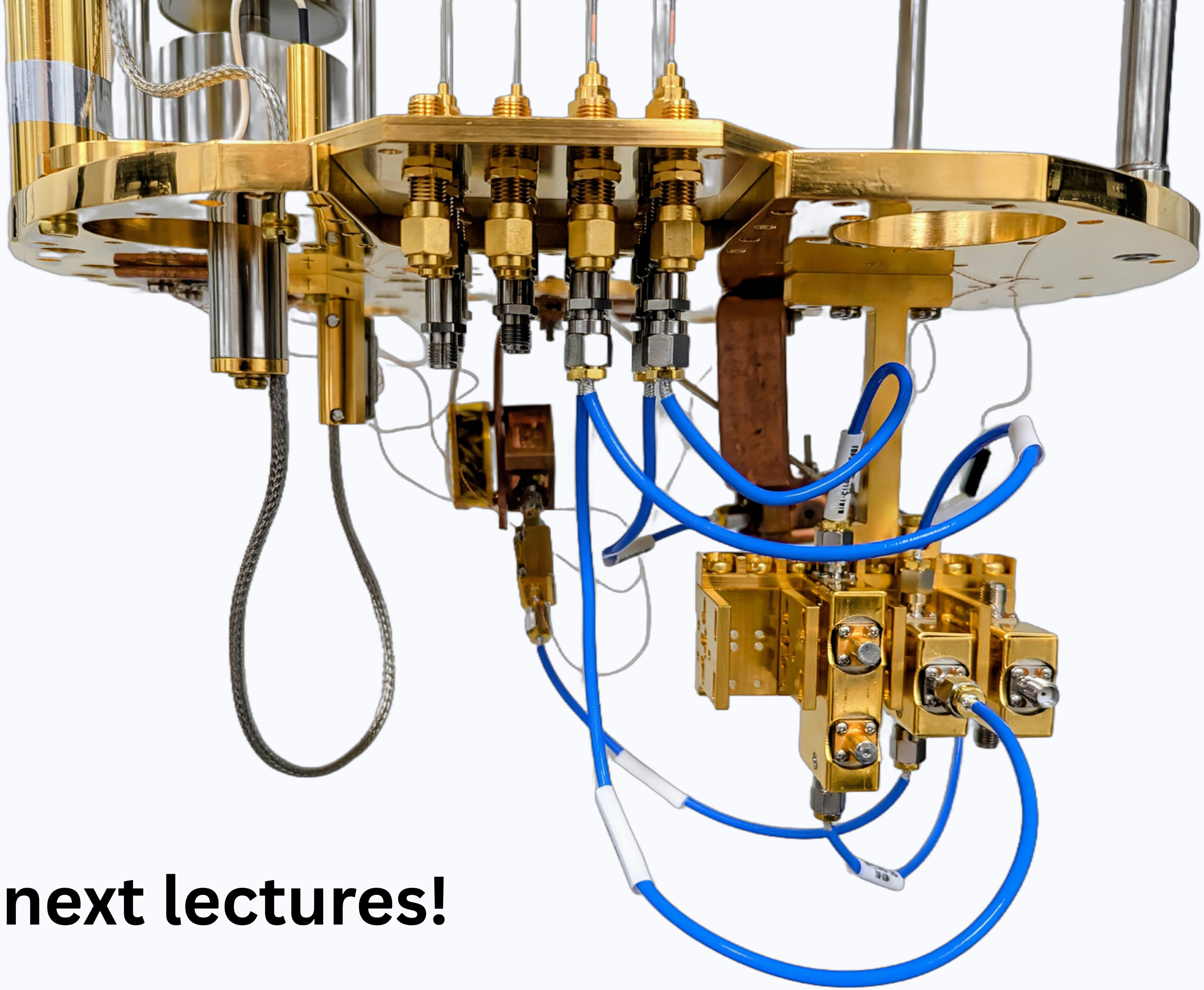



Al deposition (sputtering)
natural oxidation
first lithography
etching
resist removal
second lithography
89208920
Ar plasma cleaning
Al deposition (sputtering)
controlled oxidation
lift-off
Silicon
Photoresist
Aluminum
Lift-off resist
Aluminum Oxide




coupling
photon
state





Don’t miss the next lectures!

end of the third part

questions?

thank you for your time

Quantum sensing school, UNIPD

Nicolò Crescini