Topology, Physics, and Complexity

Michael H. Freedman
Microsoft, Station Q

Thanks to John Cloutier
for slide preparation.

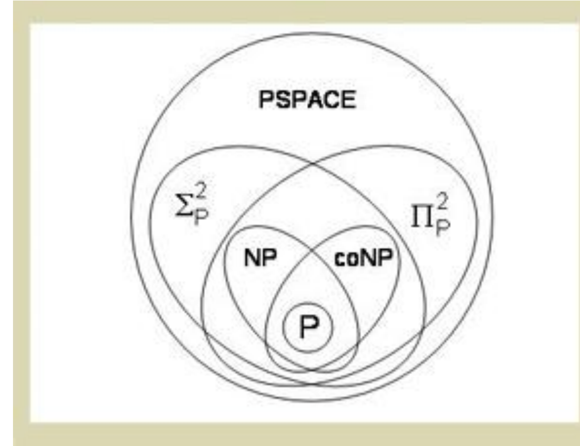
Topology

Topology

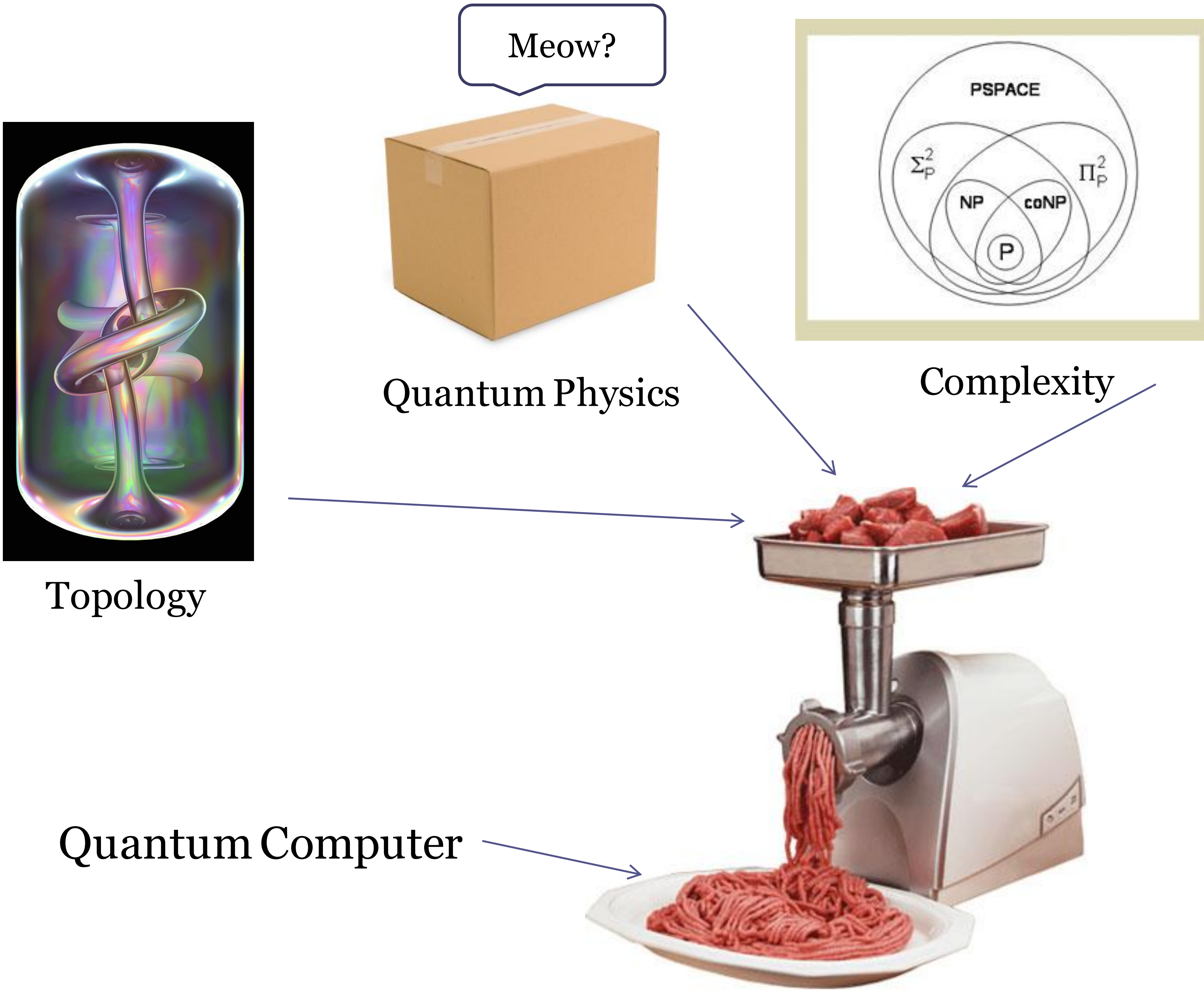
Quantum Physics

Topology

Quantum Physics



Complexity


Meow?
PSPACE
Σ_P^2
Π_P^2
NP
coNP
P
Quantum Physics
Complexity
Topology
Quantum Computer

Quantum computation is a new paradigm in which computational work obeys different scaling laws than those that are known to hold in present day "classical" computers.

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- Computation increasingly defines the limit of what we know in science.
- As far as we know, there are exactly two regimes of computation: Classical and Quantum.
- Sometime in this century, we will pass from the first to the second.
- I will explain why this is happening and what some of the consequences will be, though most are presently unknown.

I recommend to you Gregory Clark (Economics, U.C. Davis), a great "monist."

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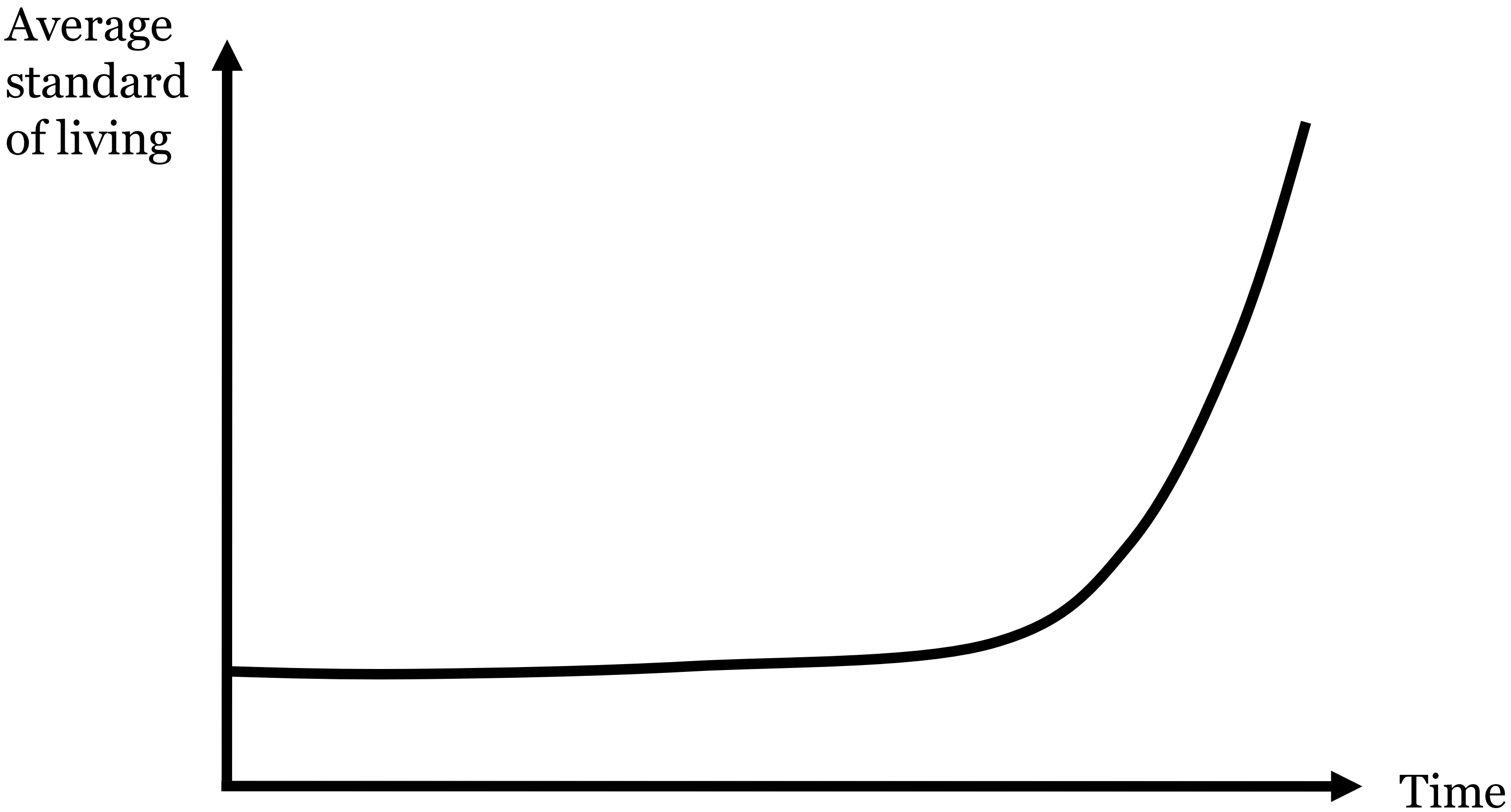
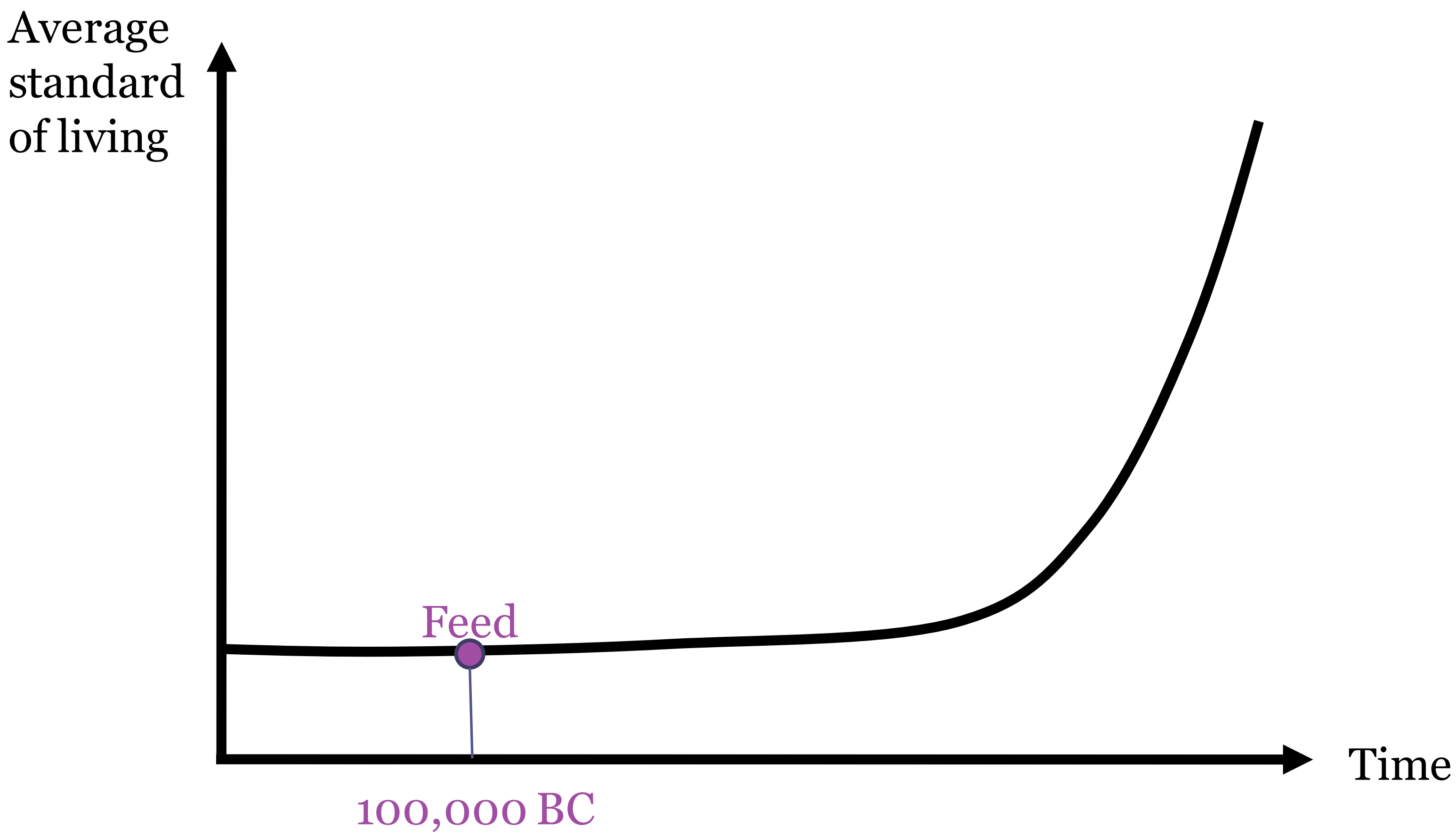
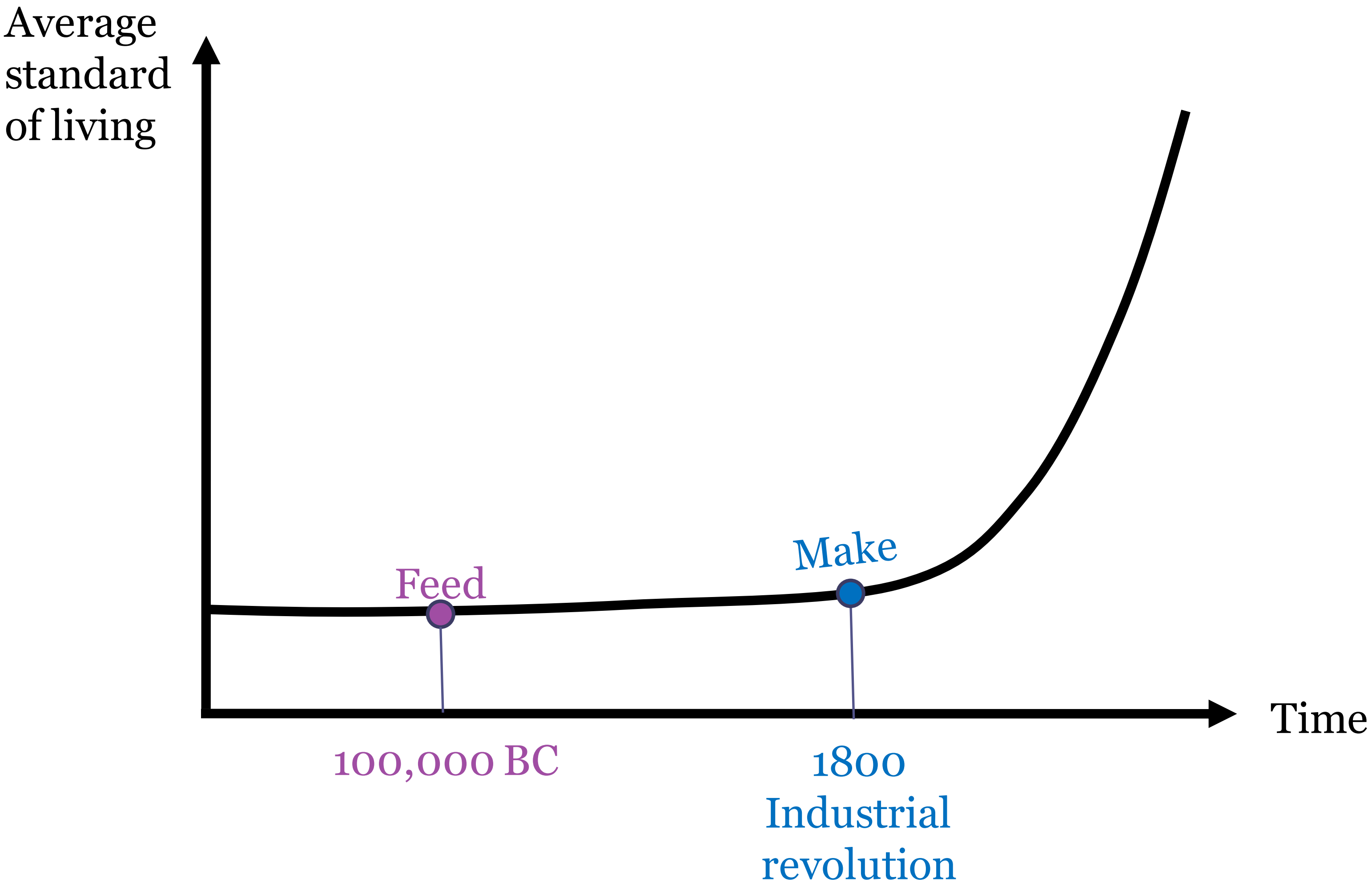
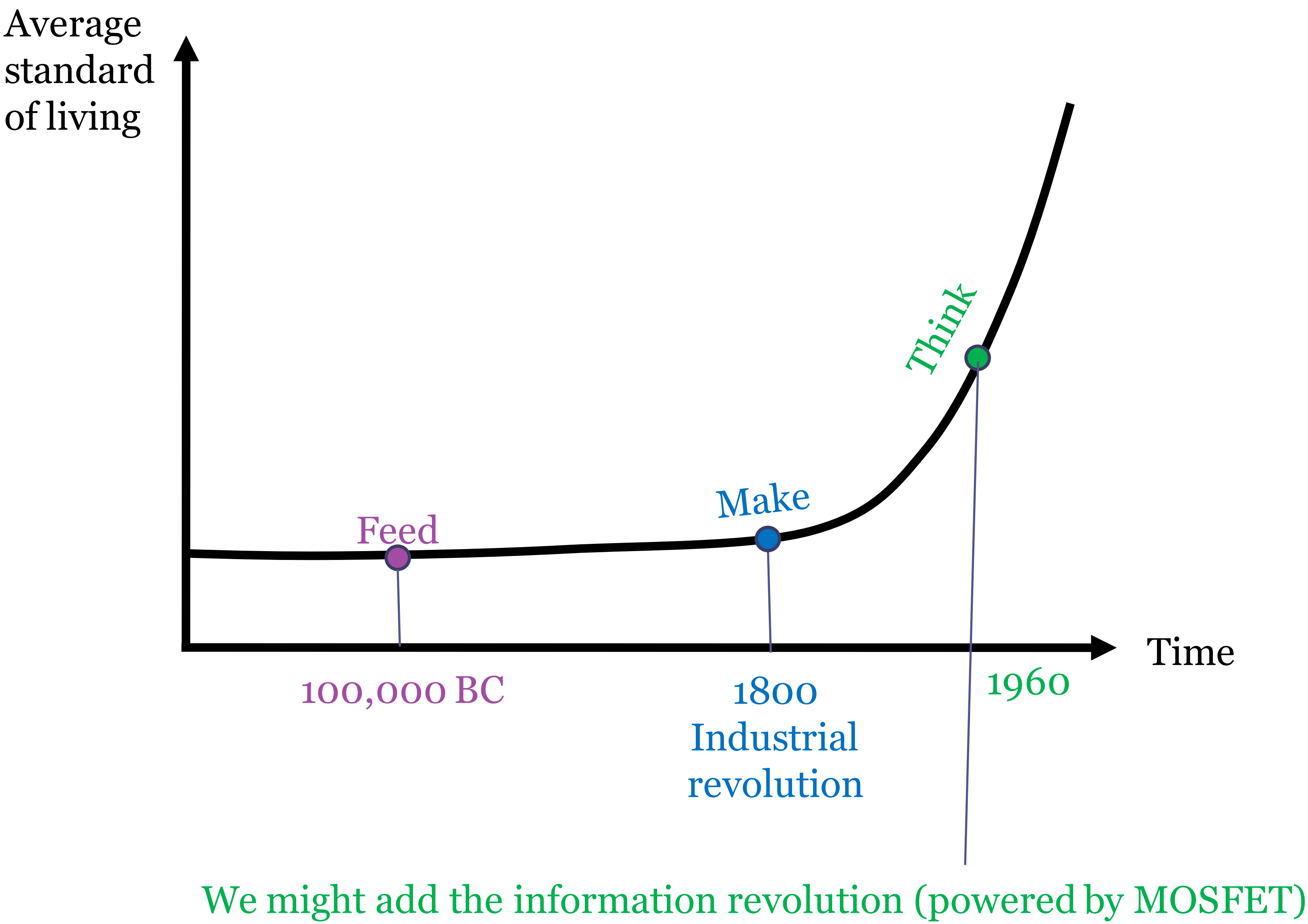
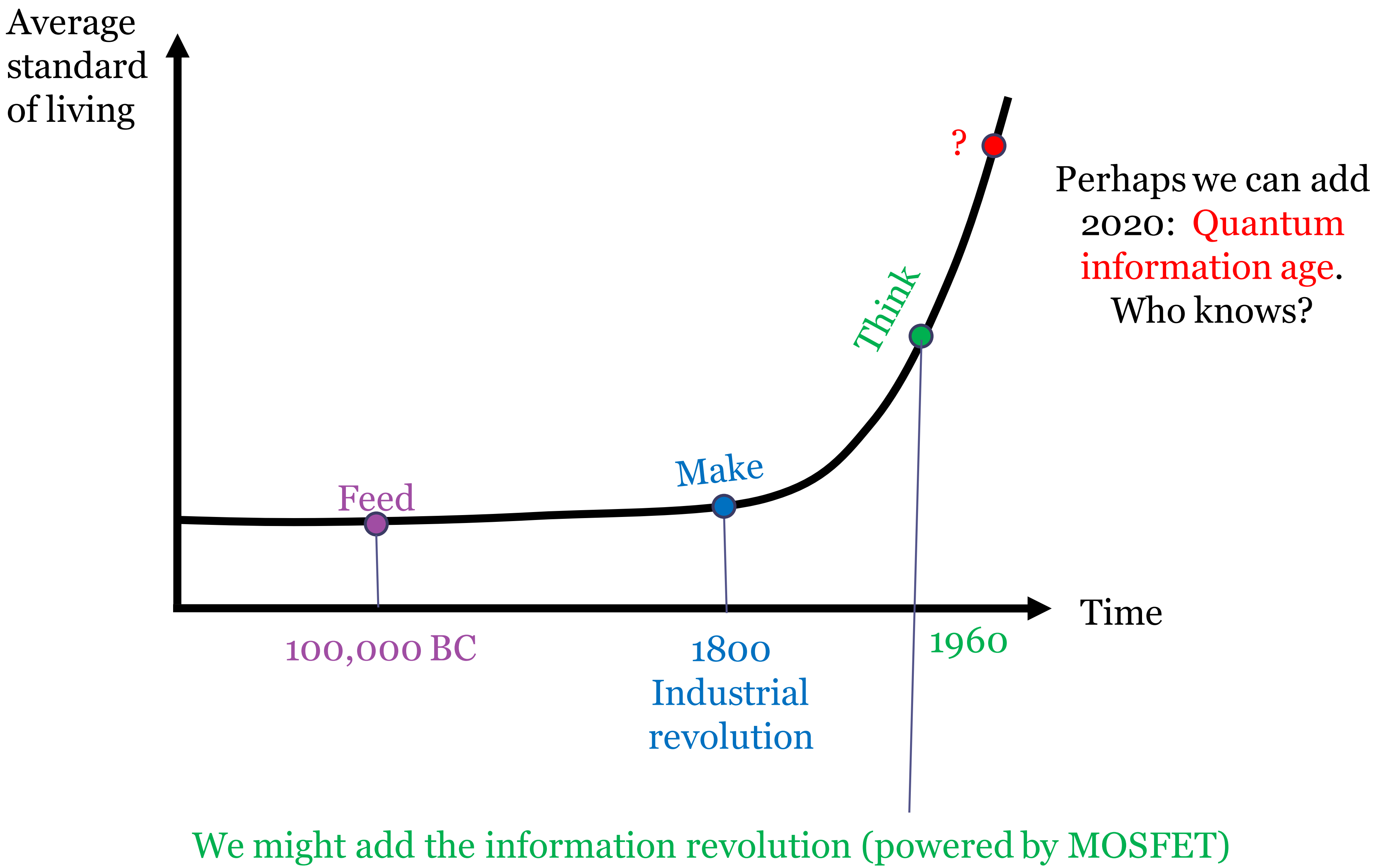
For the first time in history, ingenuity was not nullified by corresponding population growth.


Average
standard
of living
Time


Average standard of living
Feed
Time
100,000 BC


Average standard of living
Feed
Make
Time
100,000 BC
1800 Industrial revolution


Average
standard
of living
Think
Make
Feed
Time
100,000 BC
1800
Industrial
revolution
1960
We might add the information revolution (powered by MOSFET)



Average standard of living
?
Perhaps we can add 2020: Quantum information age. Who knows?
Think
Make
Feed
Time
100,000 BC
1800
Industrial revolution
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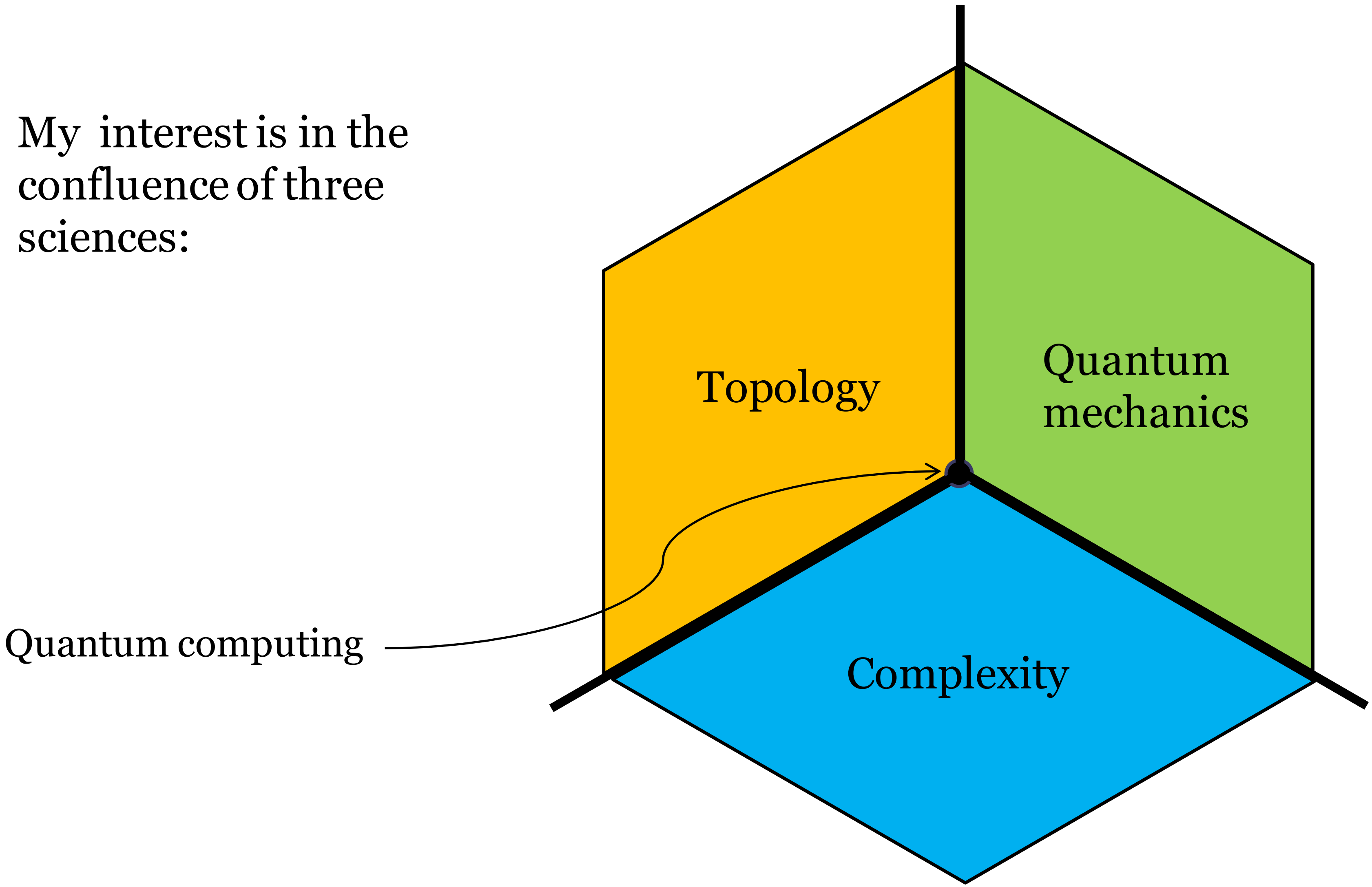
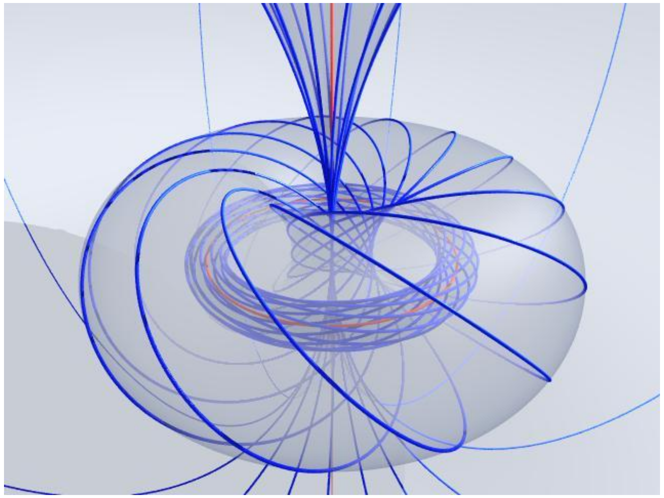
We might add the information revolution (powered by MOSFET)

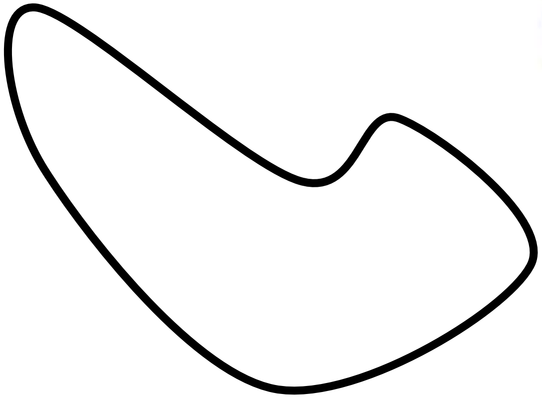
My interest is in the confluence of three sciences:



Topology

Central topic: Manifolds.





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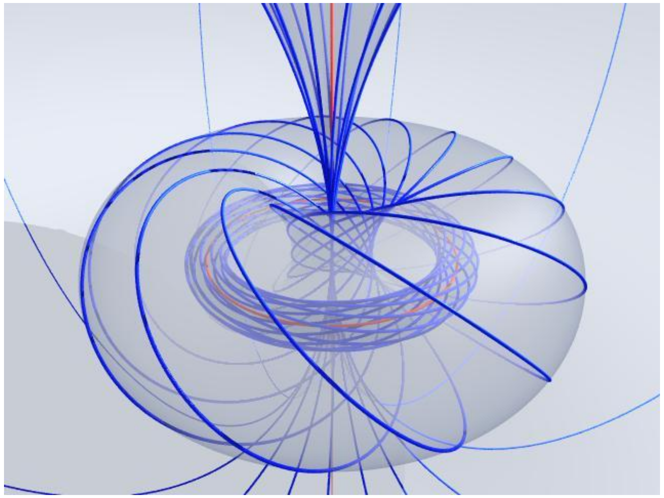

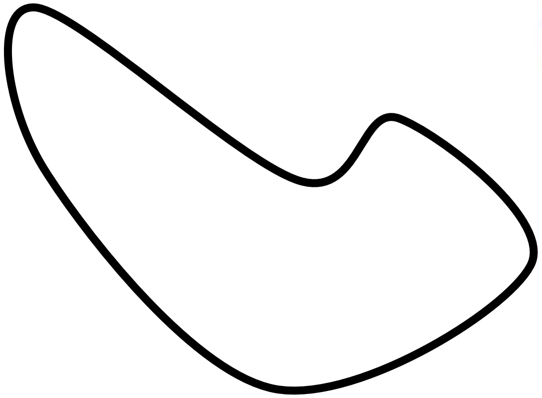

Manifolds personify the classical 19th century view of the world.

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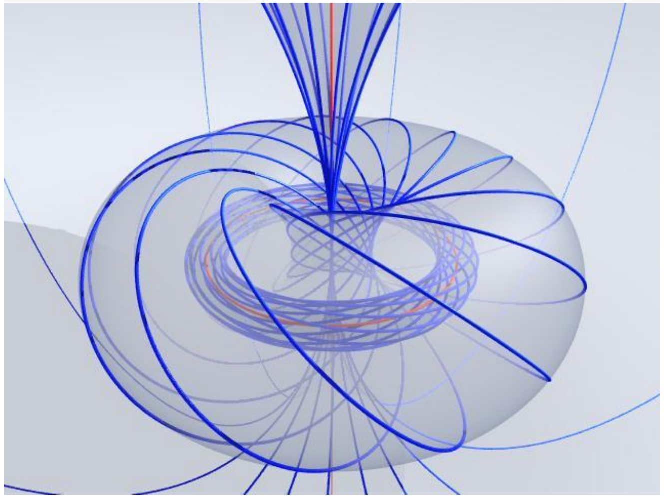

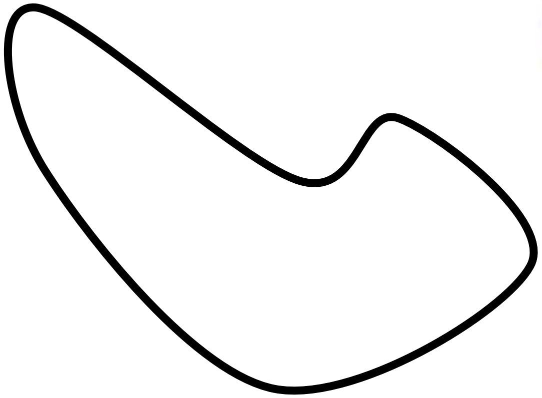

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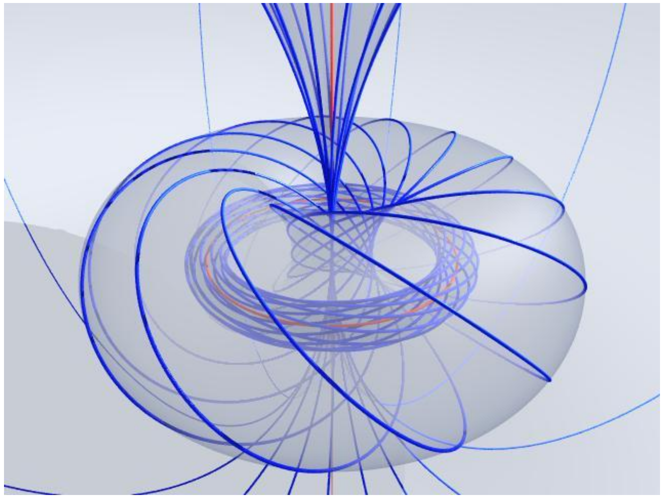

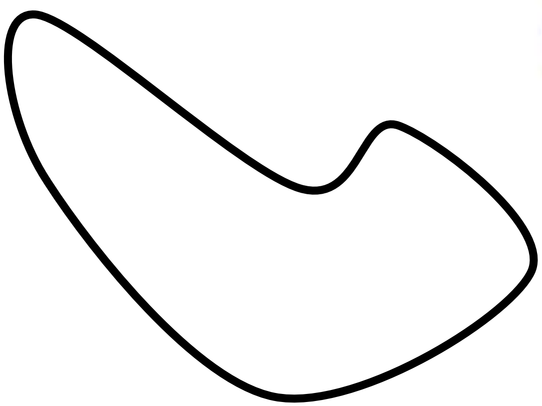

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They live resolutely in "position space."

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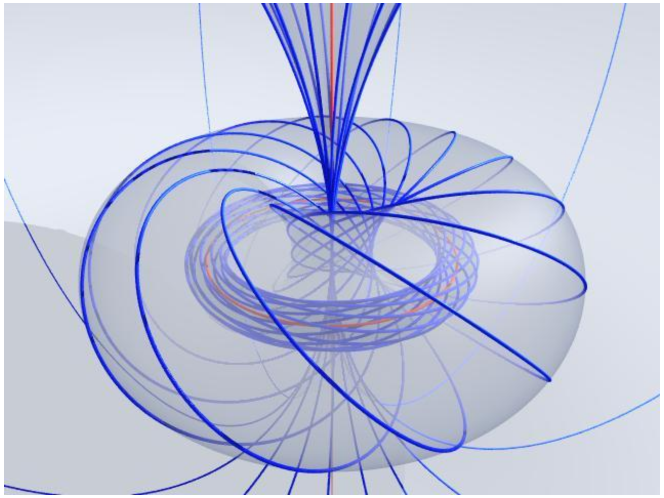

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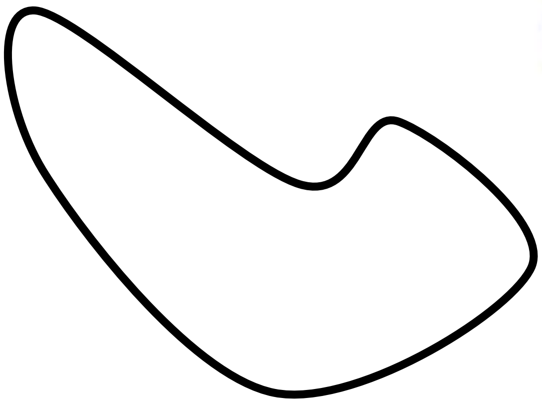

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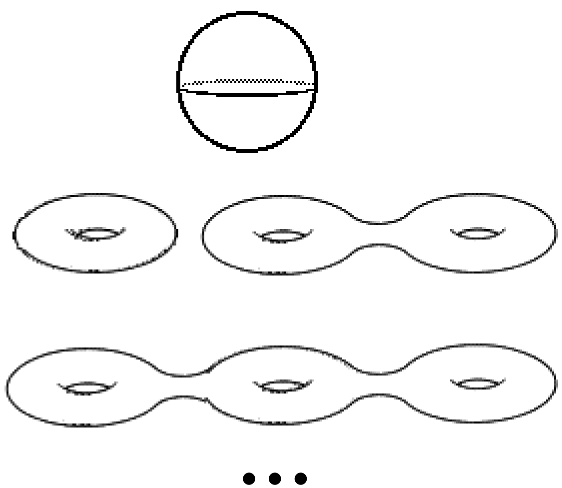
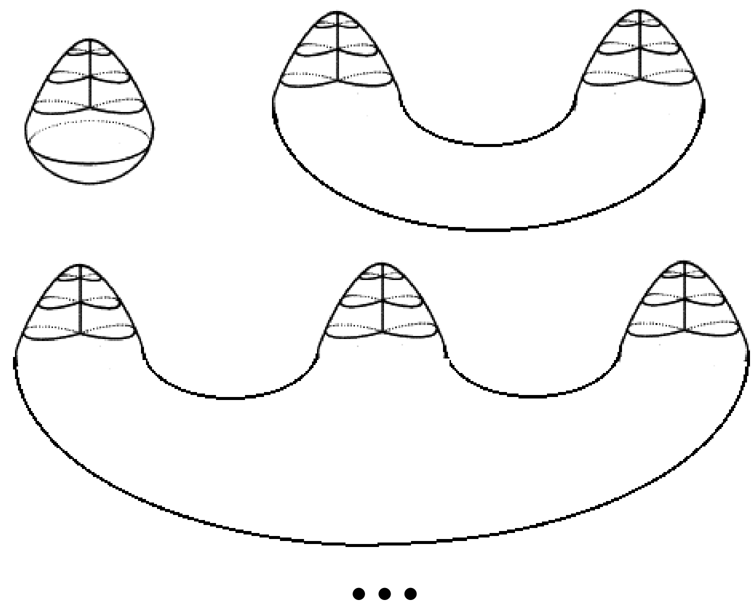
They are a direct extension of Kant’s world view.

The local $\Longrightarrow$ global question manifolds imply has been perhaps the most captivating problem in mathematics.



Orientable



Non-orientable

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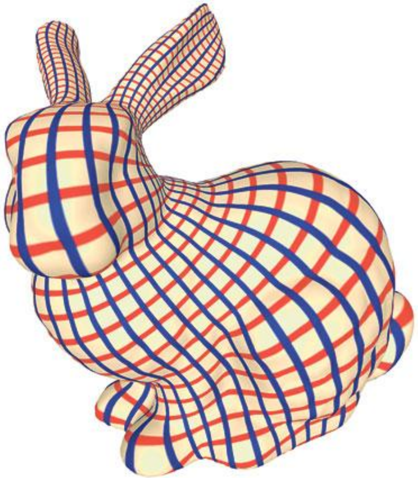

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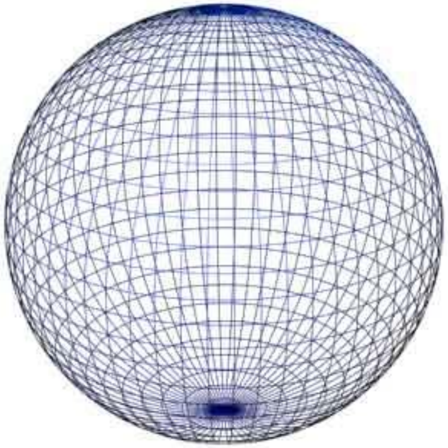

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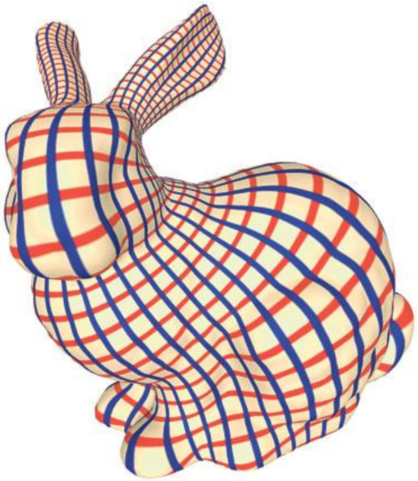

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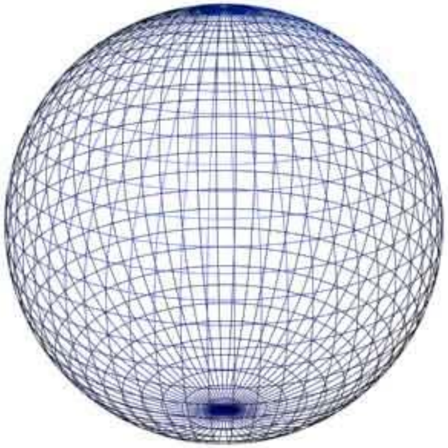

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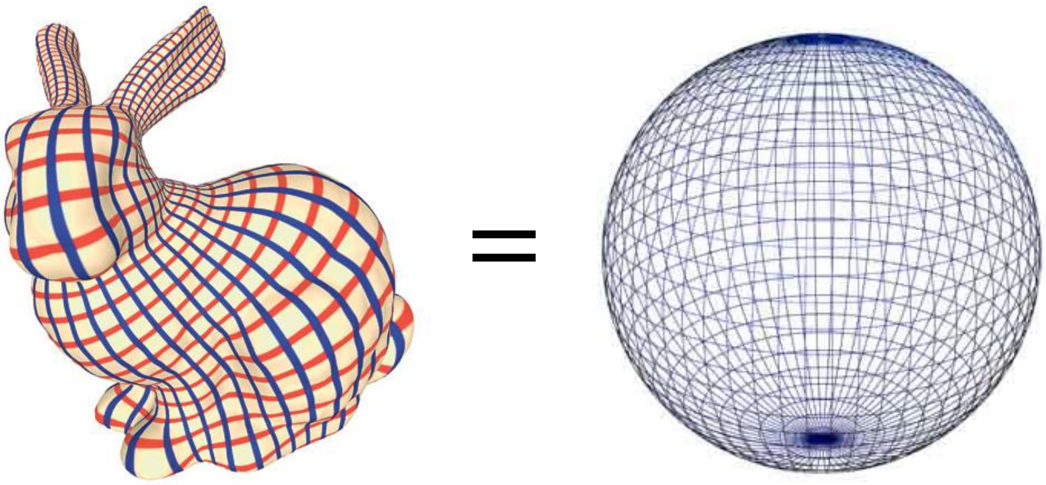

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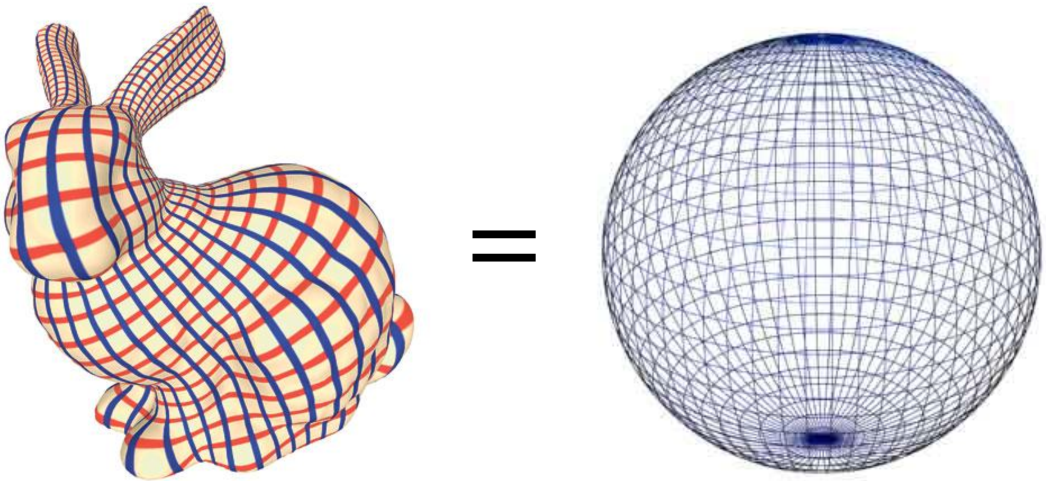

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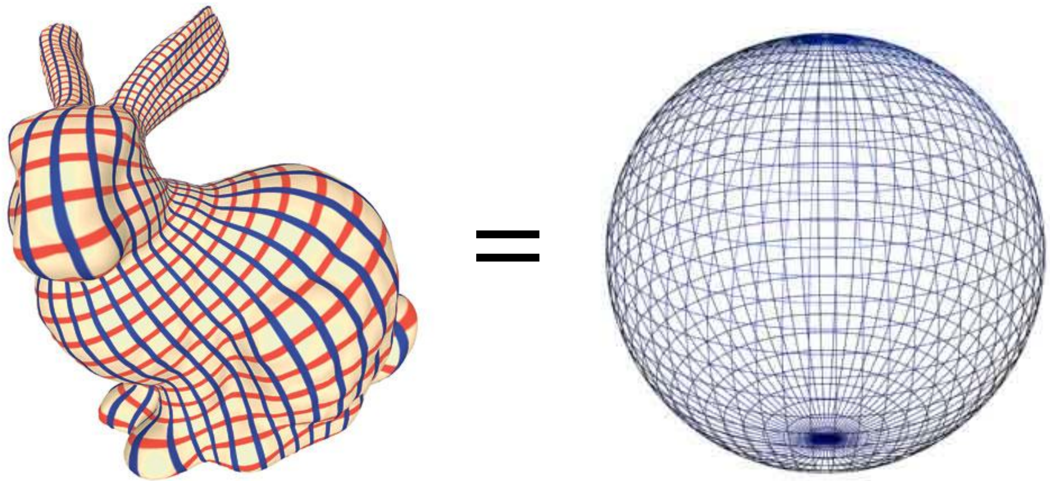

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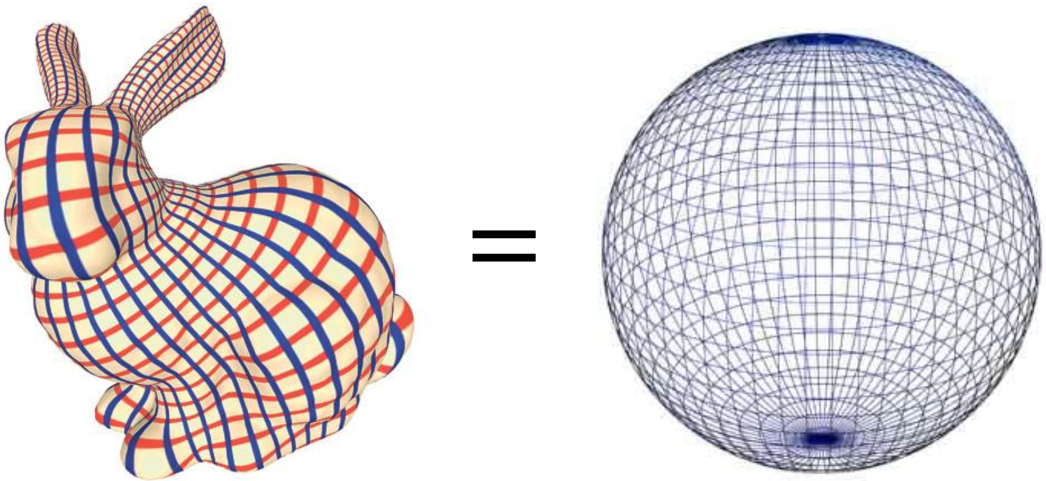

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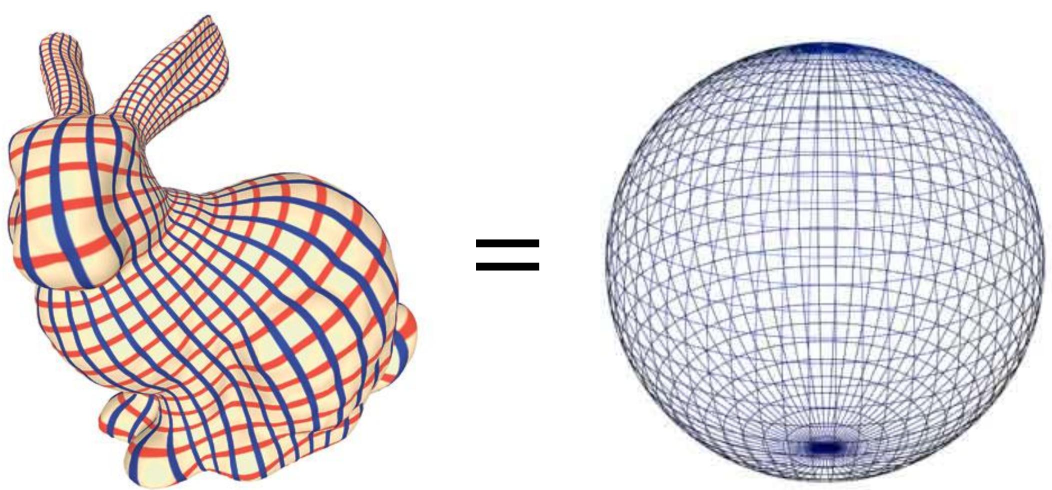

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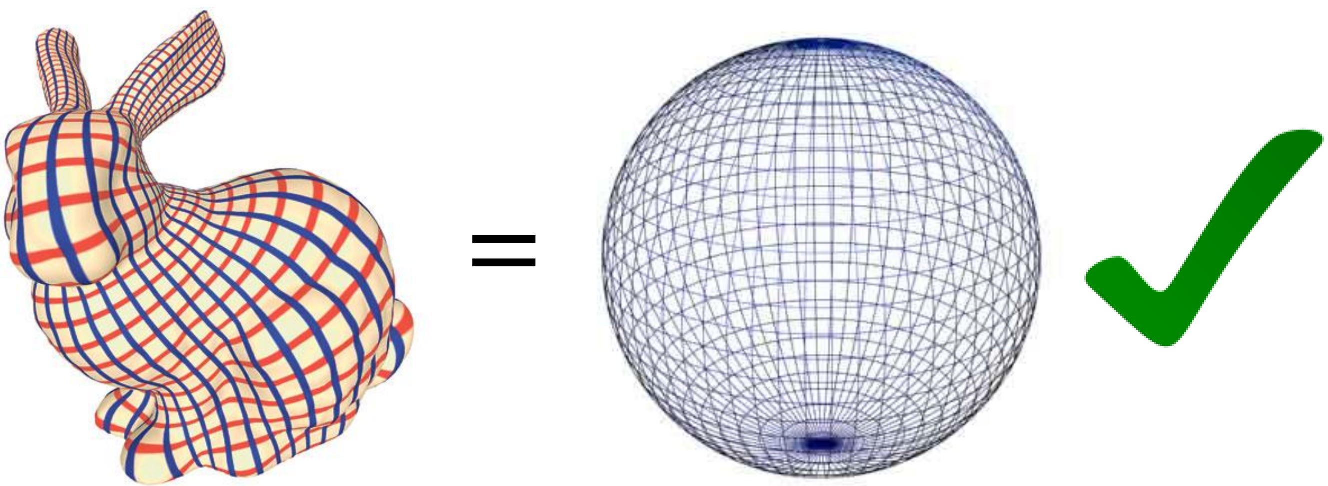

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“homeomorphic” vs. “diffeomorphic”

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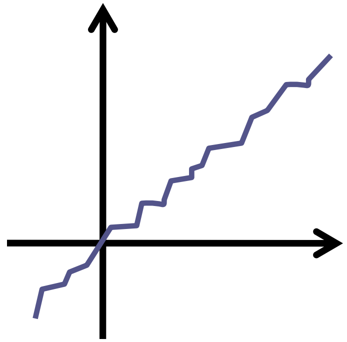

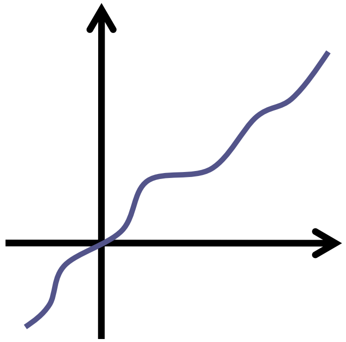

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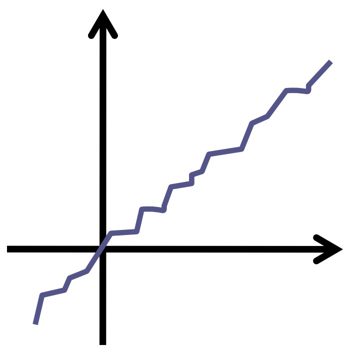
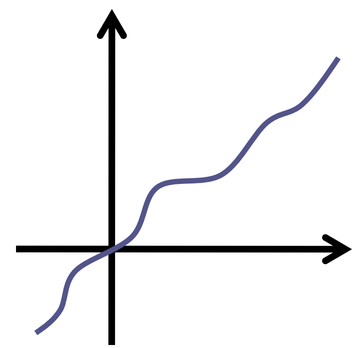
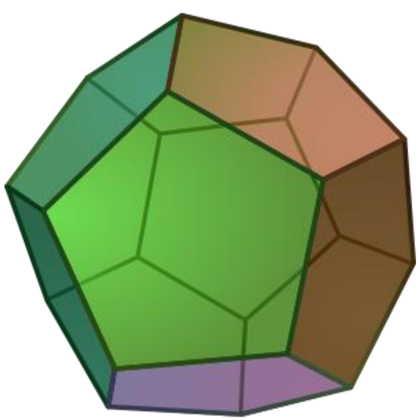
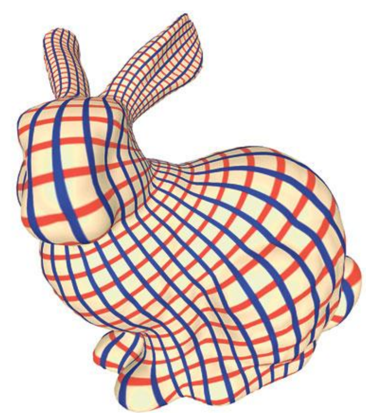
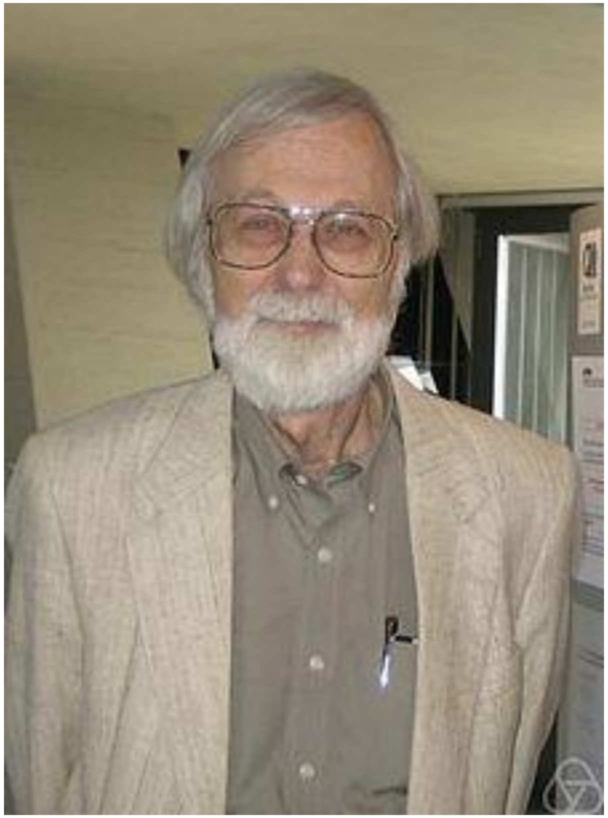








My favorite paper in topology: Milnor 1956



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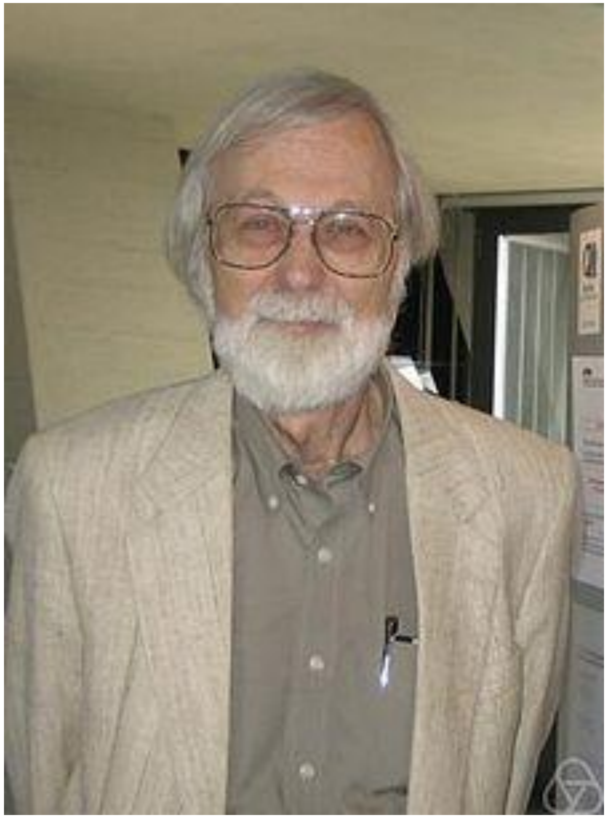

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left/right Quaternion multiplication

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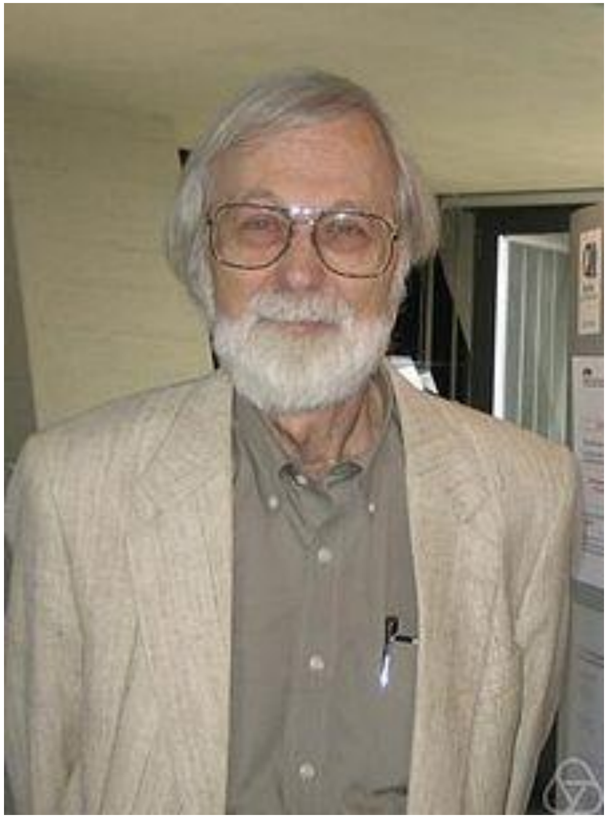


$$(S^3 \times D^4) \cup (S^3 \times D^4) = \Sigma^7 \neq S^7$$

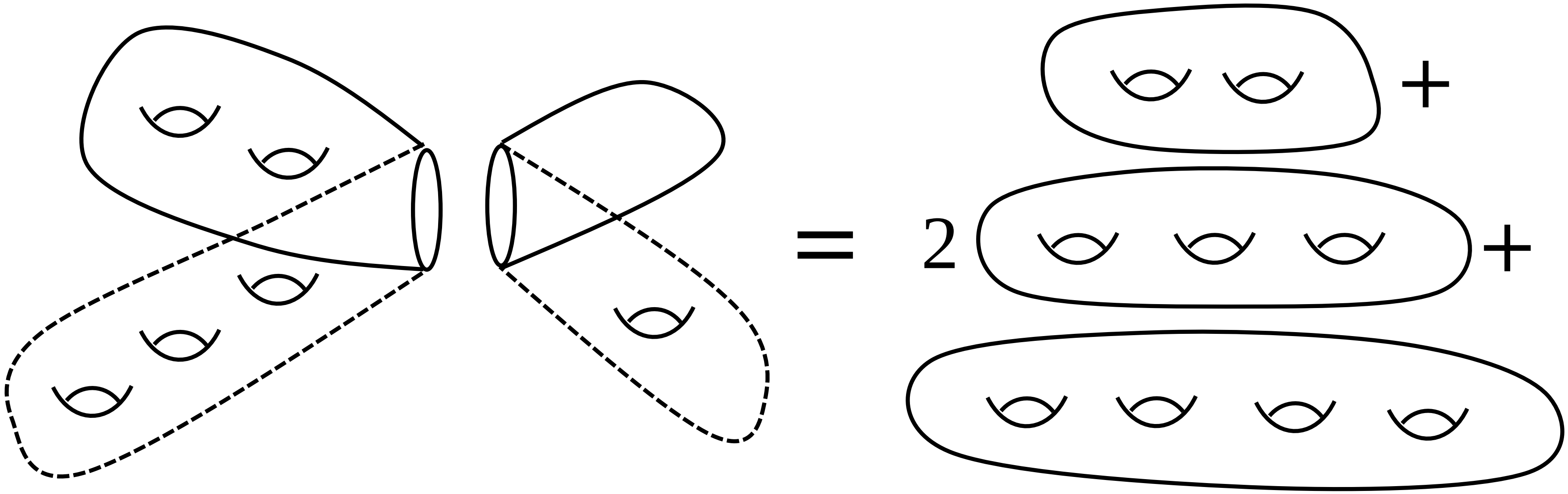
left/right Quaternion multiplication

But, $\Sigma^7 \equiv S^7$, that is, Σ^7 is homeomorphic but not diffeomorphic to S^7.

Gluing $\xrightarrow[\text{+quantum physics}]{\text{fifty years}}$ manifold superpositions

For N^{d-1}

$$\mathcal{M}_N \times \mathcal{M}_N \longrightarrow \mathcal{M}$$



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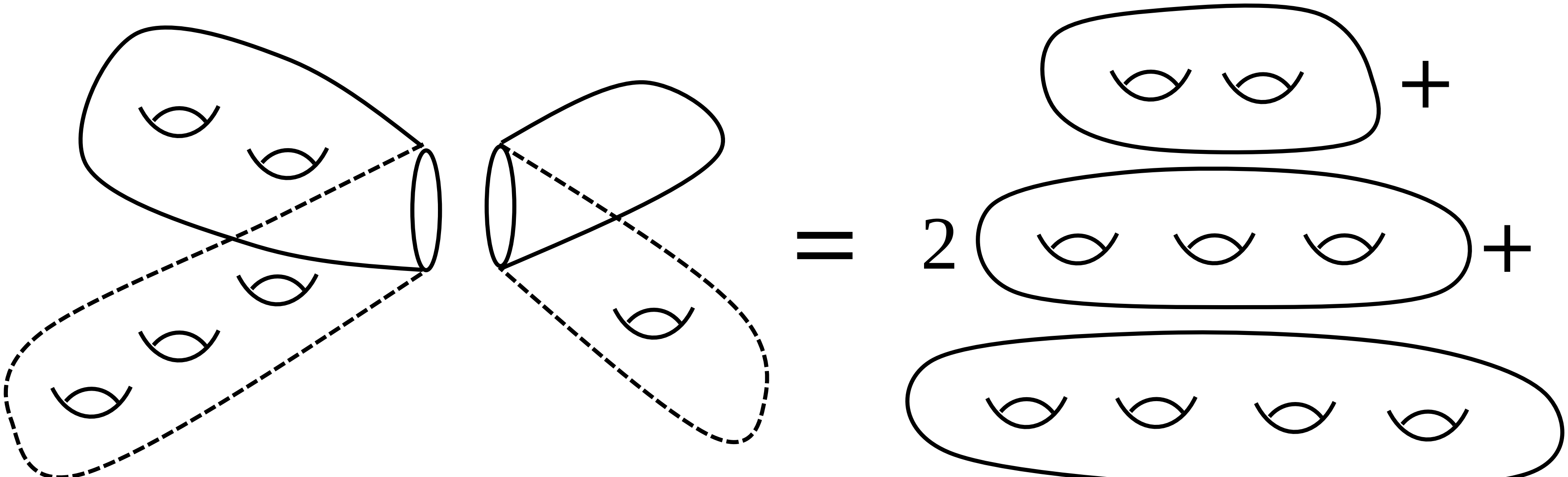

$$\langle \Sigma a_i A_i \,, \Sigma b_j B_j \rangle = \Sigma a_i \bar{b}_j A_i \bar{B}_j$$

<u>Theorem</u>:

For d = 1, 2, 3, if $v \in \mathcal{M}_N$ and $\langle v, v \rangle = 0$, then $v = 0$

(uses Perelman)

$\langle \ , \ \rangle$ is "positive" or "Euclidean"

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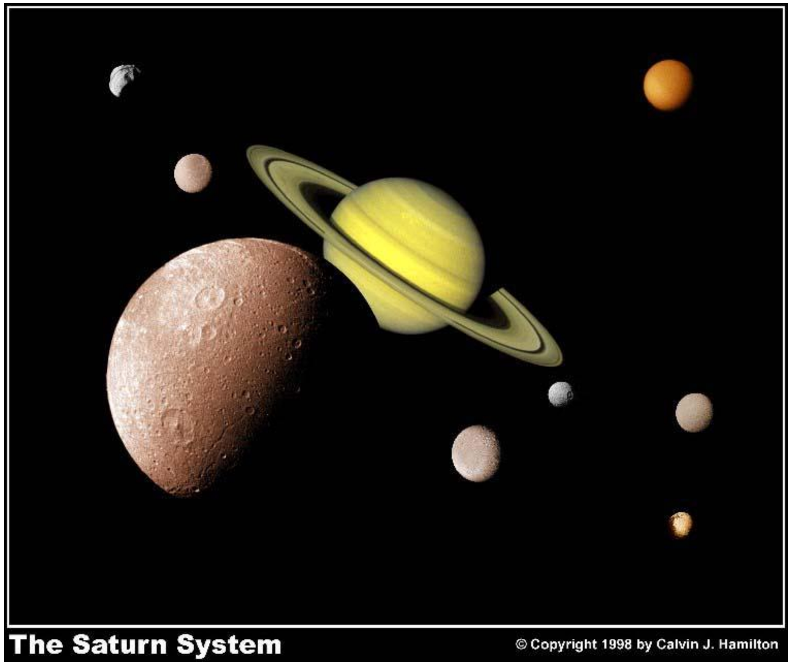
For $d = 4, 5, \ldots$ $\exists\, 0 \neq v \in \mathcal{M}_N$ and $\langle v, v \rangle = 0$

v "light like"

Physics

1756: <u>Lagrangian formulation</u>: L = kinetic – potential energy
Classical trajectories are least (critical) action paths.

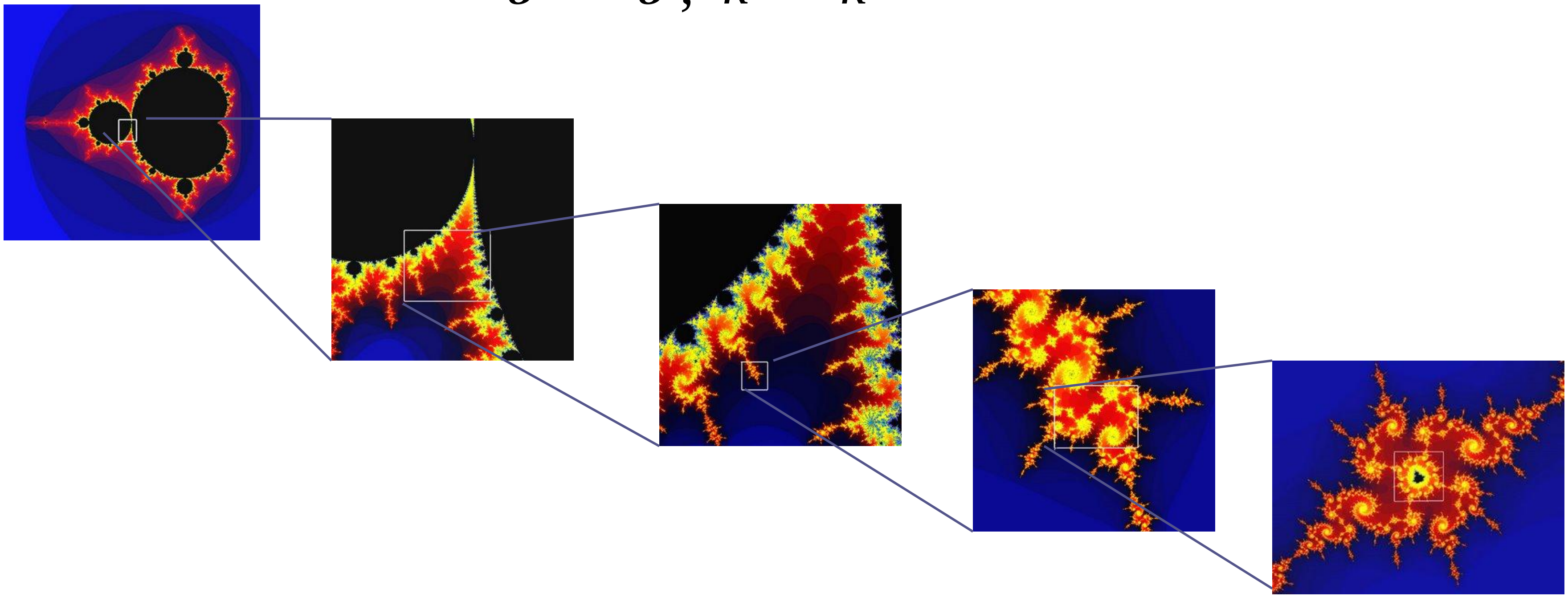
Today, all physical systems are described by writing a Lagrangian



1970: Wilson, Renormalization: How does the Lagrangian evolve when re-expressed using longer length scales, lower frequencies, colder temperatures:

The terms with the fewest derivatives dominate:

$$\varepsilon >> \varepsilon^2, \ k >> k^2$$



Chern-Simons Action: $AdA + \frac{2}{3}(A \wedge A \wedge A)$

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In condensed matter at low enough temperatures, we expect to see systems in which topological effects dominate and geometric detail becomes irrelevant.

Shockingly, in our $1/r^2$ - world, the Chern-Simons action does not depend on distance (i.e. the metric) but describes a purely topological interaction.

- We can enter a world in which all that matters are topological interactions.

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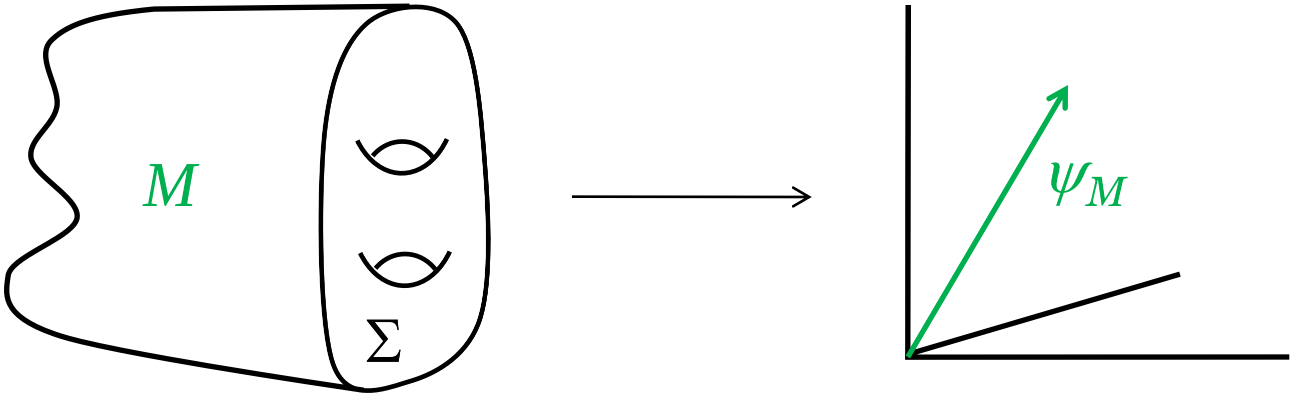
- Consistent with the previous theorem, mathematicians expect the 2-D quantum physics at low temperatures to contain complete knowledge of 3-D topology.
- To the contrary, 3-D quantum physics must be completely ignorant of the light-like vectors which capture what is most interesting in four dimensional topology: Donaldson-Seiberg-Witten theory.

Dictionary

Dictionary

3-manifold M with $\partial M = \Sigma \xrightarrow{\int_M dA \exp CS(A)}$ (dual) physical state $\psi_M \in Hilb_\Sigma$



manifold   vector in $Hilb_\Sigma$

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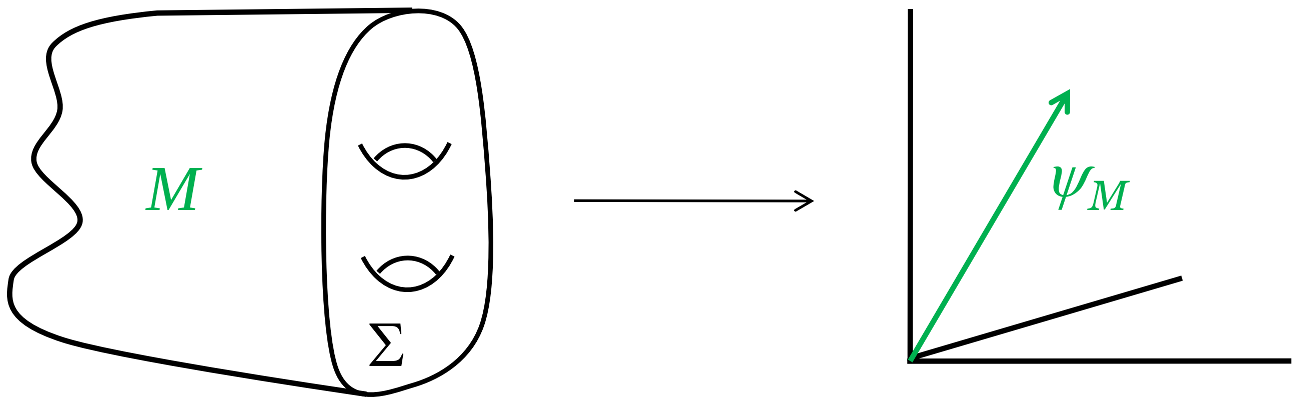

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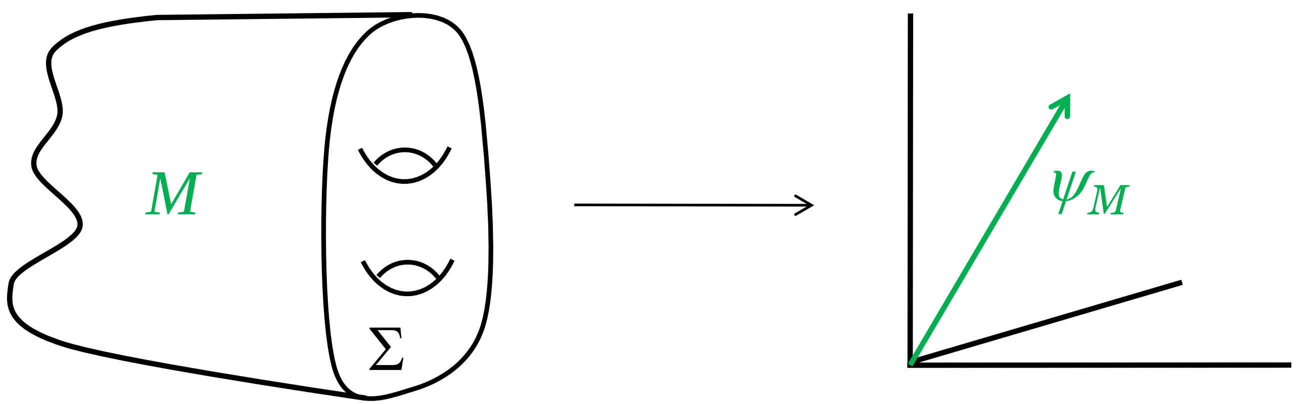
v = light like $\longrightarrow$ zero



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Super conductivity

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Fractional Quantum Hall Effect (FQHE)

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Fractional Quantum Hall Effect (FQHE)

What is it?

Renormalization implies exotic low temperature physics:

Super conductivity

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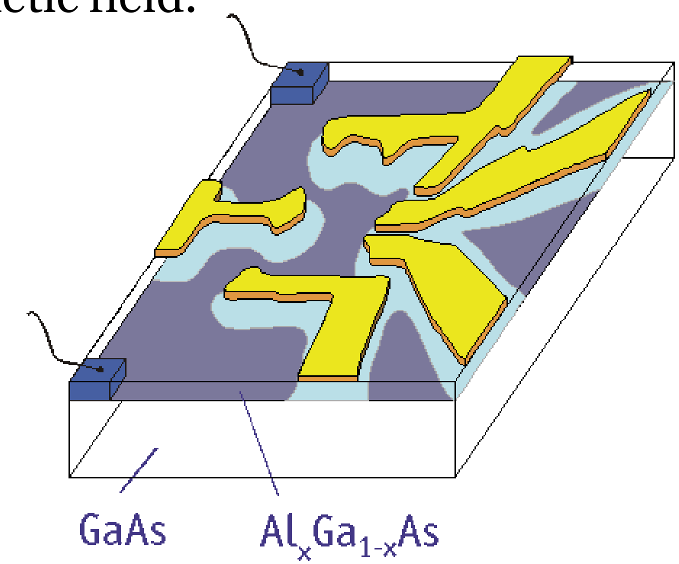
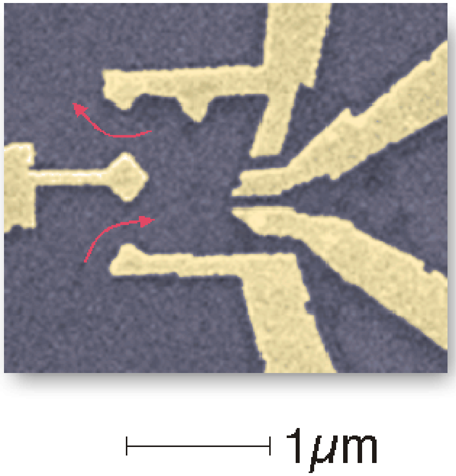
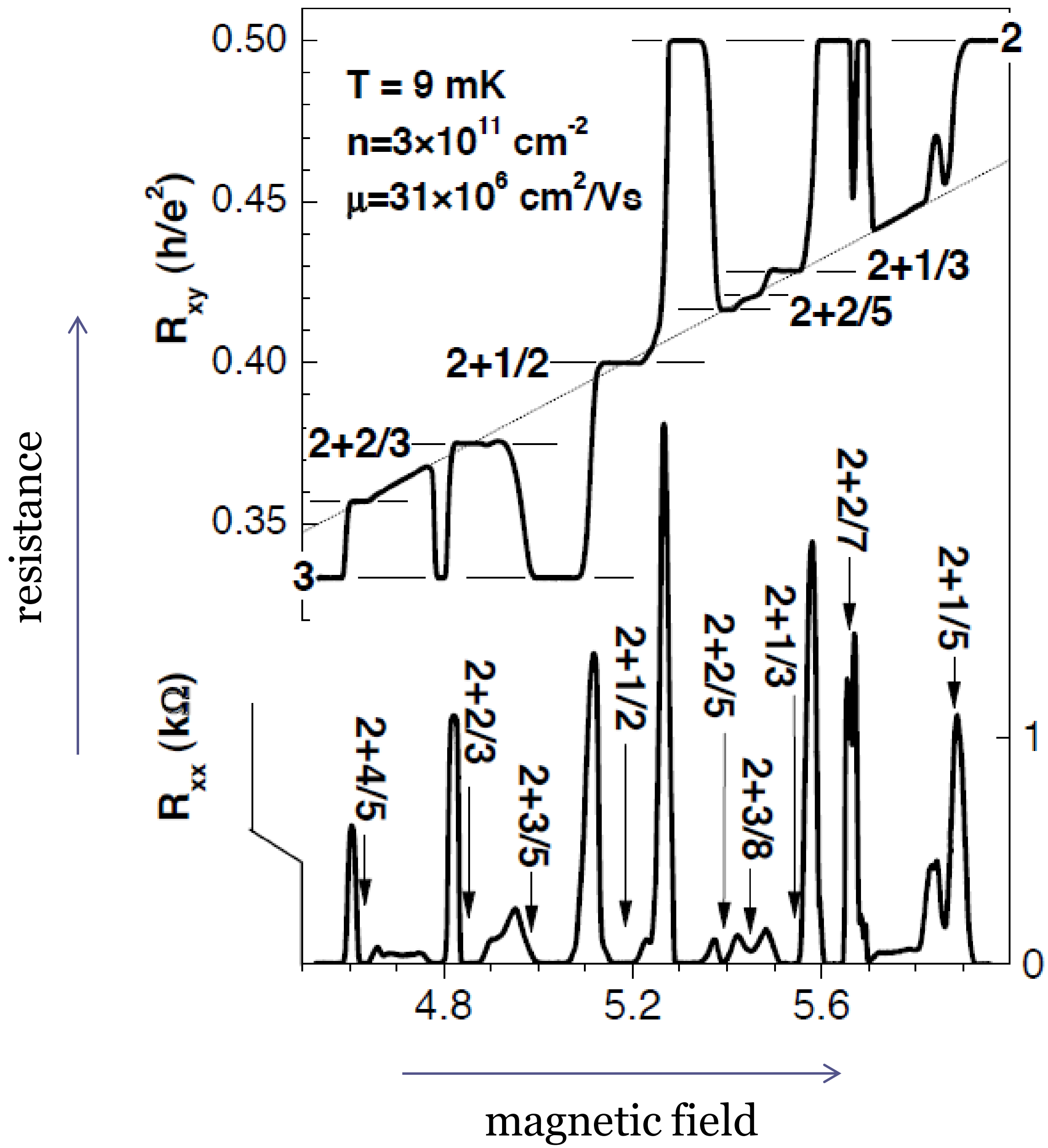
What is it?

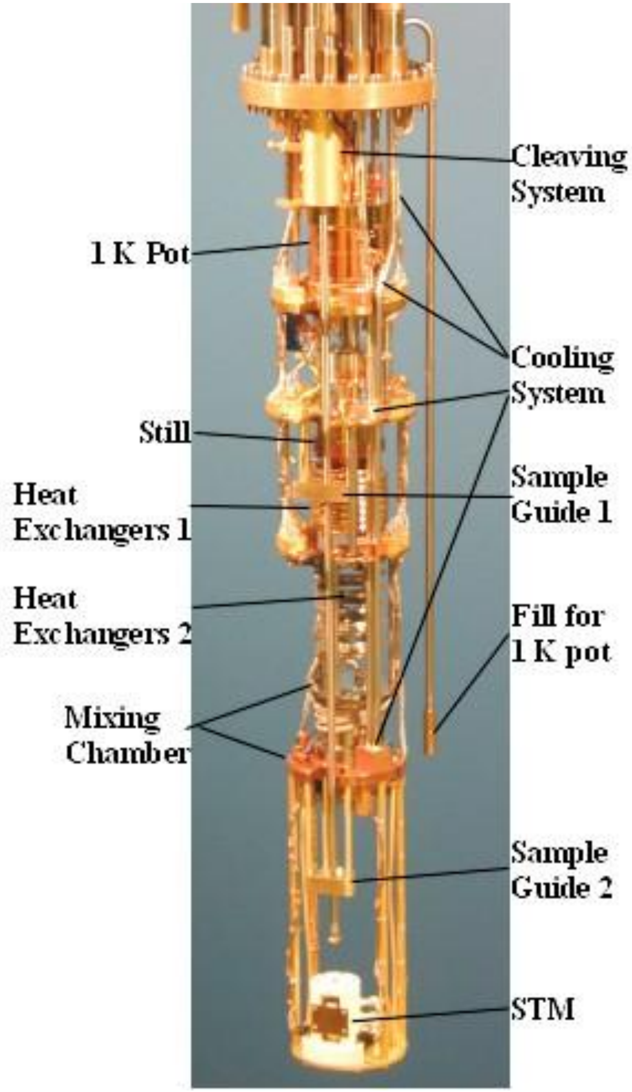
A two-dimensional electron gas trapped by a chemical potential in a AlGaAs – GaAs crystal interface and subjected to a strong transverse magnetic field.







T = 9 mK
n=3×10^11 cm^-2
μ=31×10^6 cm^2/Vs
R_xy (h/e^2)
0.50
0.45
0.40
0.35
2
3
2+1/3
2+2/5
2+1/2
2+2/3
R_xx (kΩ)
1
0
2+4/5
2+2/3
2+3/5
2+1/2
2+2/5
2+3/8
2+1/3
2+2/7
2+1/5
4.8
5.2
5.6
resistance
magnetic field



There is some hope now that a quantum computer can be built around the $\nu = 5/2$ plateau.

How could this work in principle?

The key new idea is superposition.

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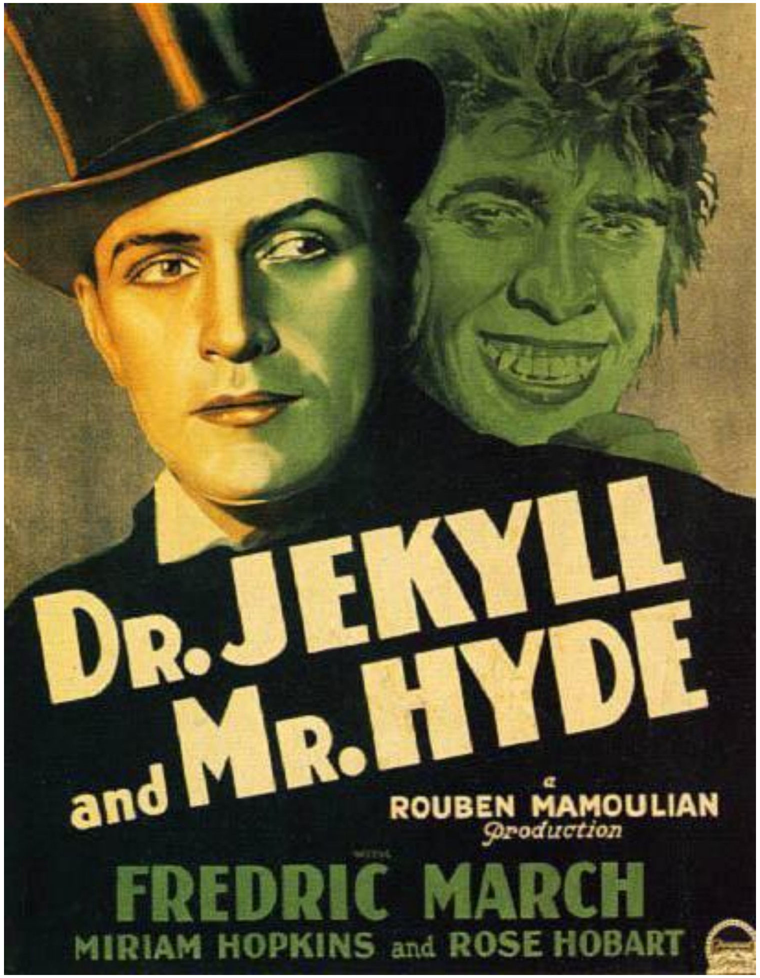

- Superposition means that a state ψ may be written as a linear combination of eigen-states ψ_i, which typically are classical configurations

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- The coefficients α_i, called amplitudes, are "square roots" of probabilities:

$$\sum |\alpha_i|^2 = 1$$

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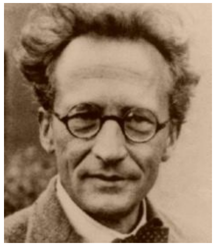
Plank

Born

Bohr

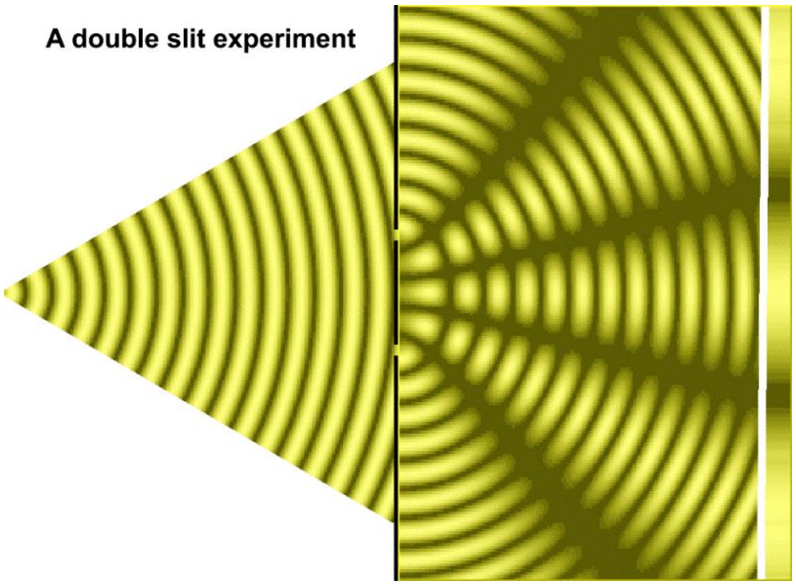
Heisenberg

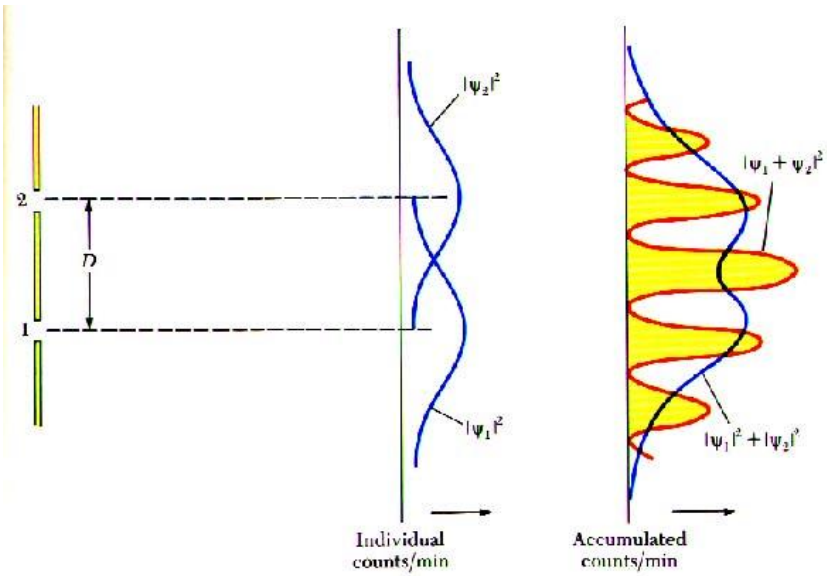


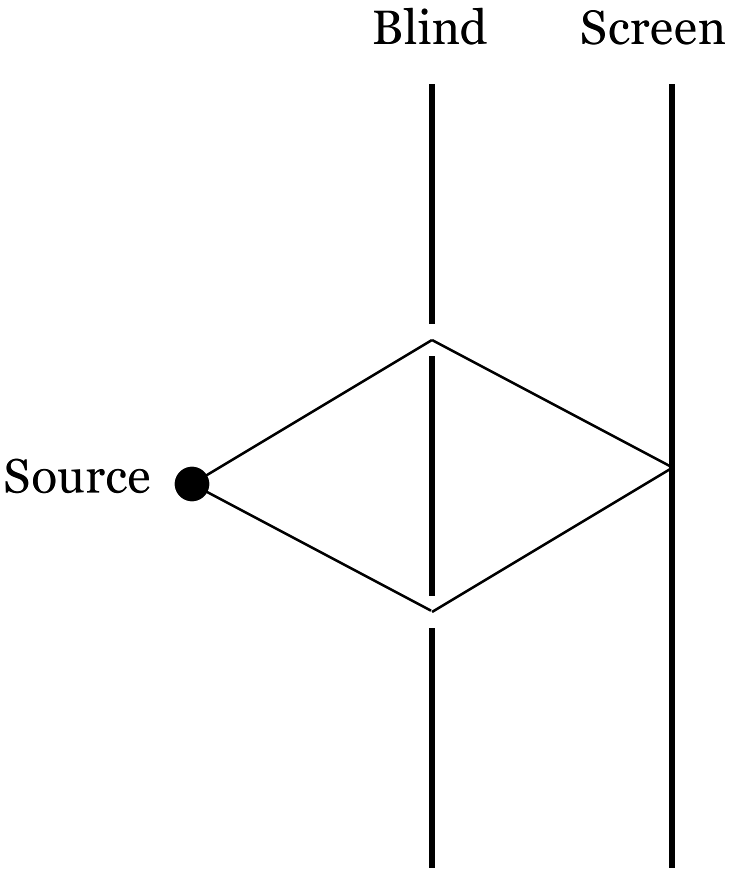
Schrodinger

Diffraction, Scattering, Atomic Spectra

- The double slit experiment shows amplitudes at work.







$$|\alpha + \beta|^2 \neq |\alpha|^2 + |\beta|^2$$

Observed pattern

Prediction if one mistakenly adds probabilities

How do amplitudes, opposed to probabilities, enhance computational power?

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In a cleverly designed algorithm

Peter Shor

factoring

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useless computational paths can often be arranged to cancel out – like the dark spots ("nodes") in the double slit experiment – and not consume computational resources.

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useless computational paths can often be arranged to cancel out – like the dark spots ("nodes") in the double slit experiment – and not consume computational resources.

This is possible because amplitudes, unlike probabilities, can be negative (or even imaginary).

How might this work in detail?

- In 3-dimensions, exchange is order = 2, allowing only bosons and fermions.

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- In 2-dimensions, exchange is infinite order and braiding will alter the state of a collection of anyons by a Jones representation.

Vaughan Jones

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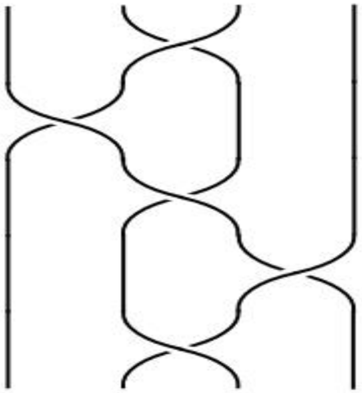
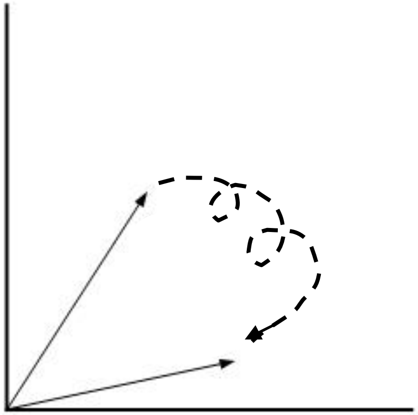
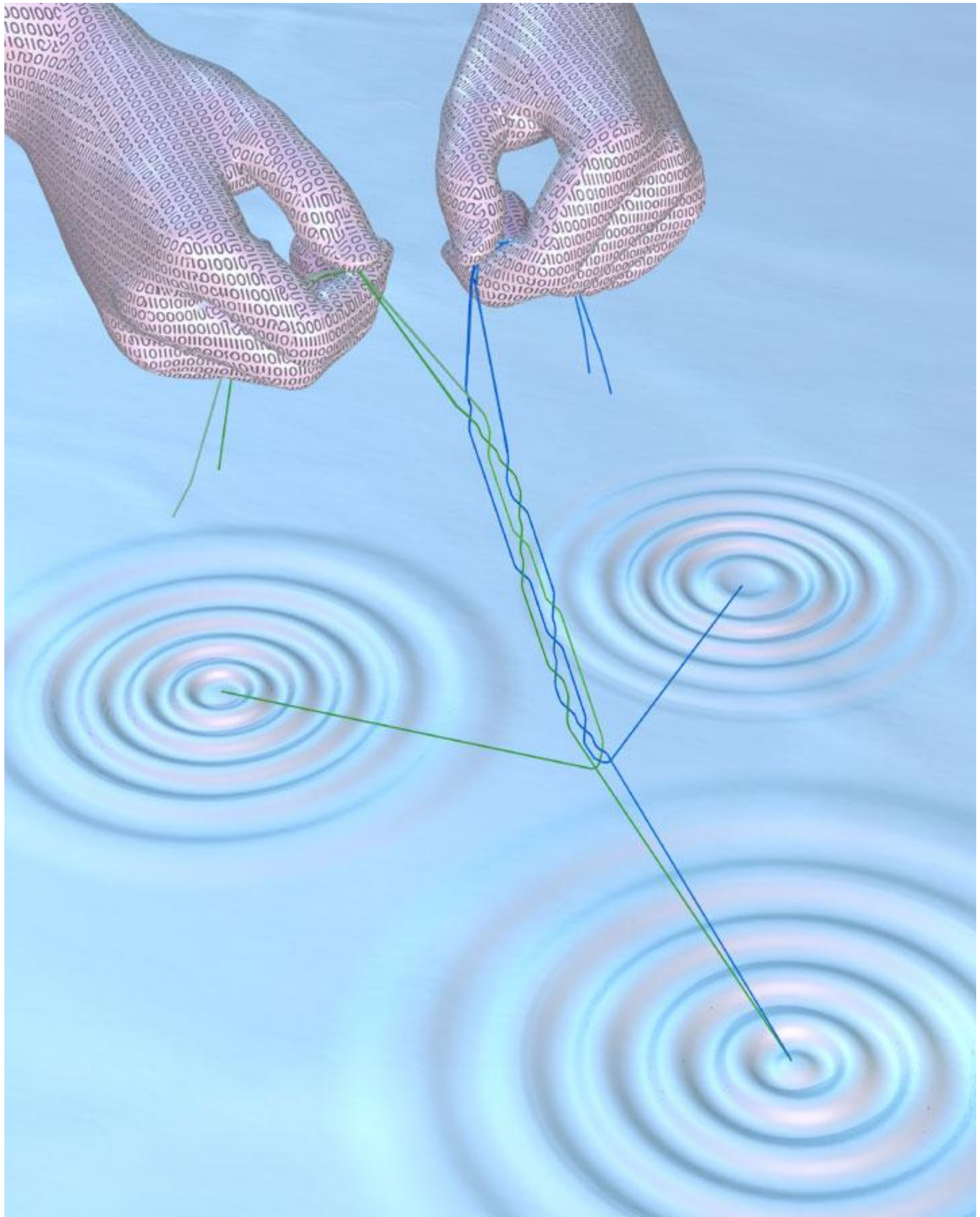


Braid picture

Time



Hilbert Space



How will we affect this braiding?

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1. Atomic force microscope (AFM) tip.

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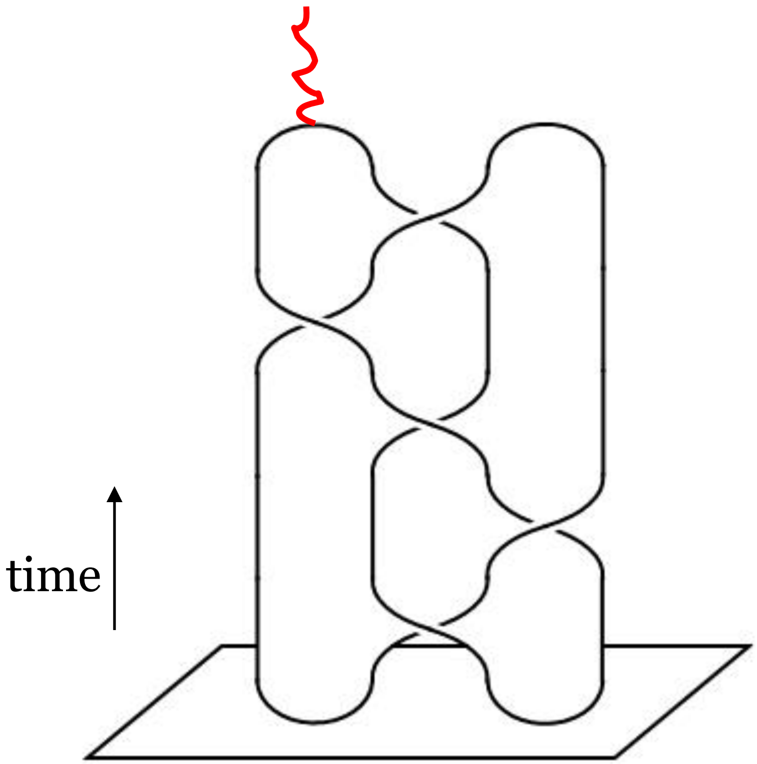
2. A sweeter solution uses “edge state” tunneling shown here in the context of a quasi-particle interferometer.

Strategy 1:

The entire computation is a closed braid.



Measurement (death of H) (or not)

↑

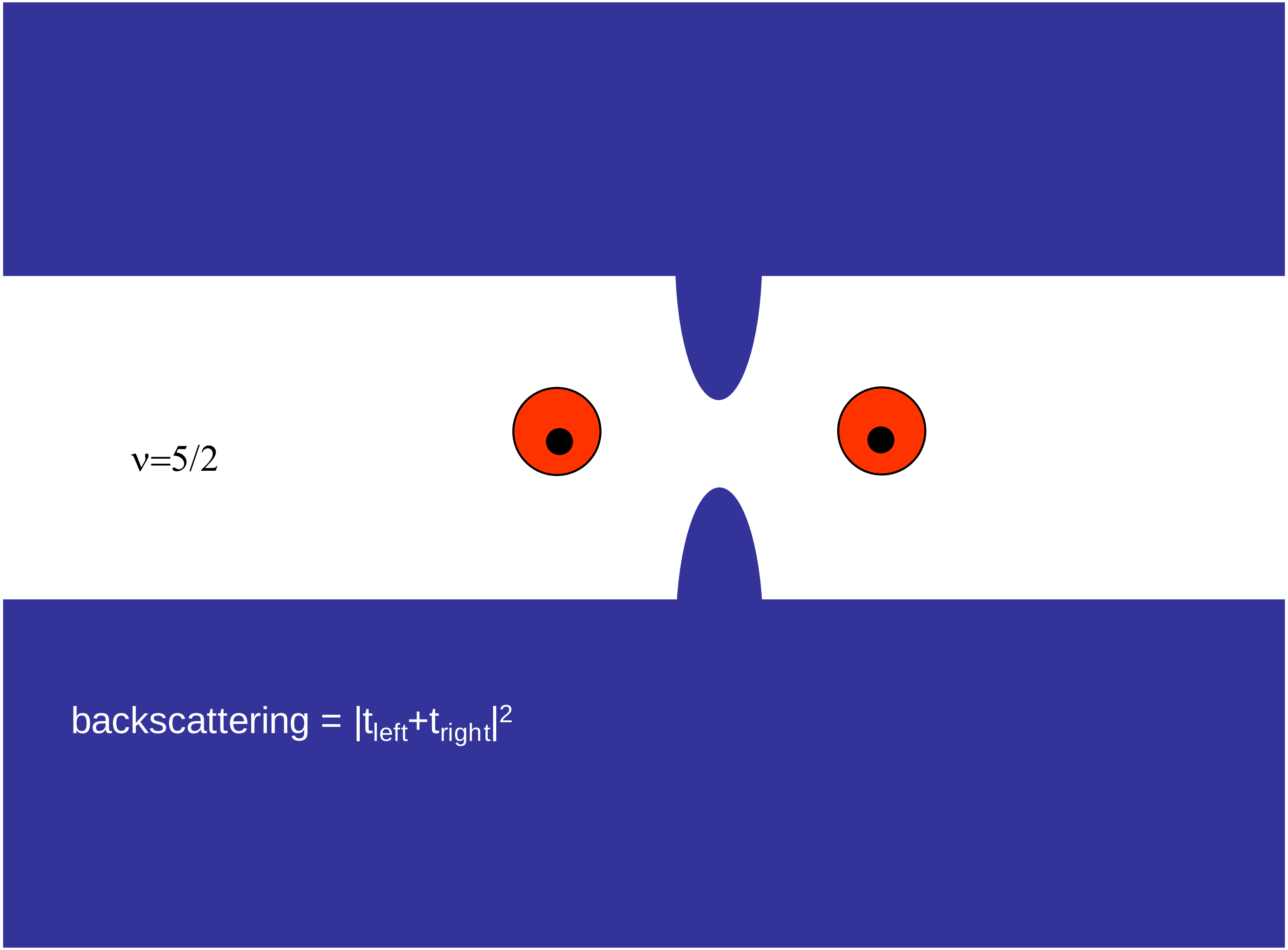
Braiding = computation

↑

Birth of Hilbert space H

Strategy 2:

On closer examination, we can leave the topological charges fixed and simulate braiding by measuring tunneling currents with “interferometers.”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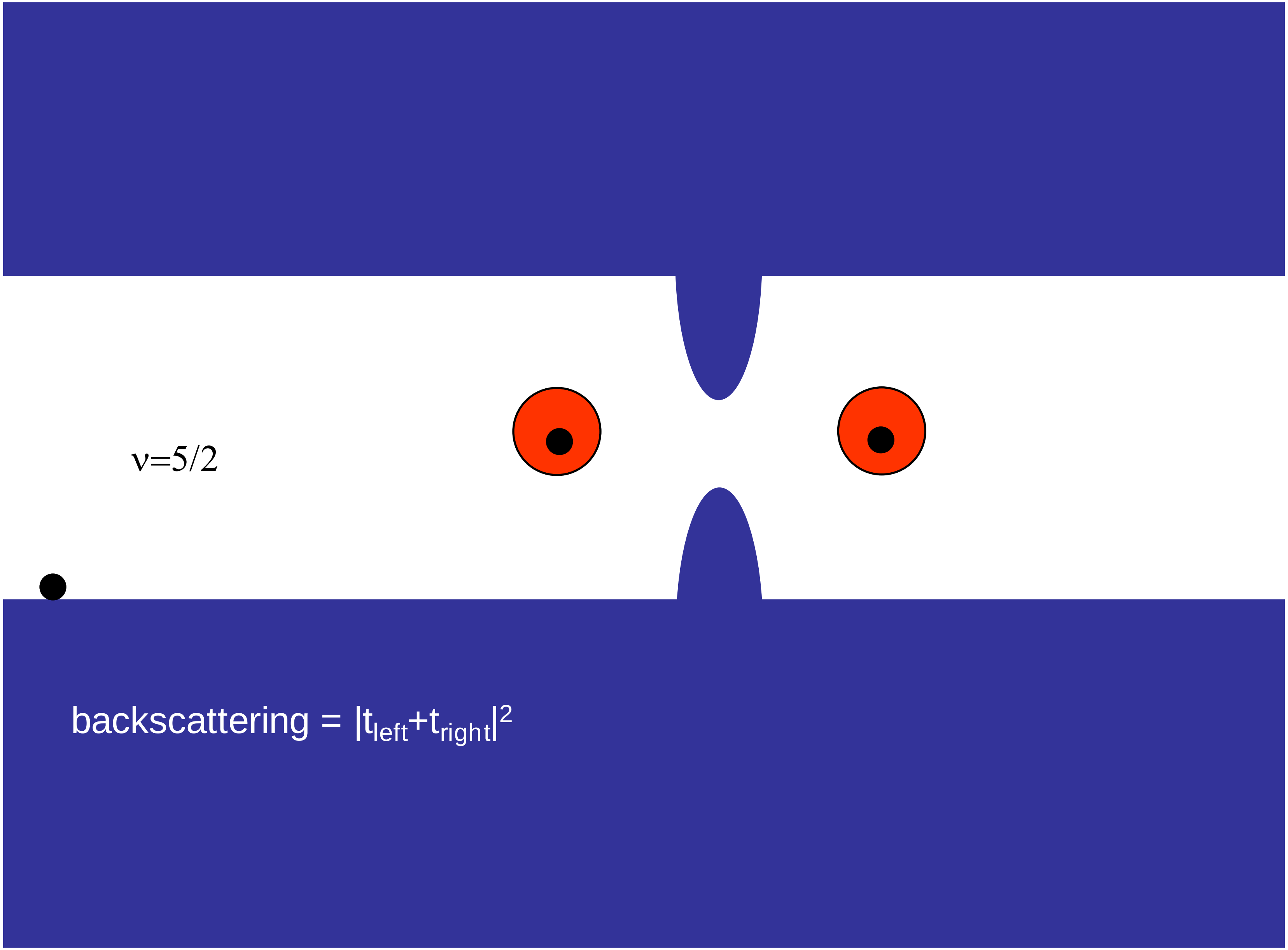
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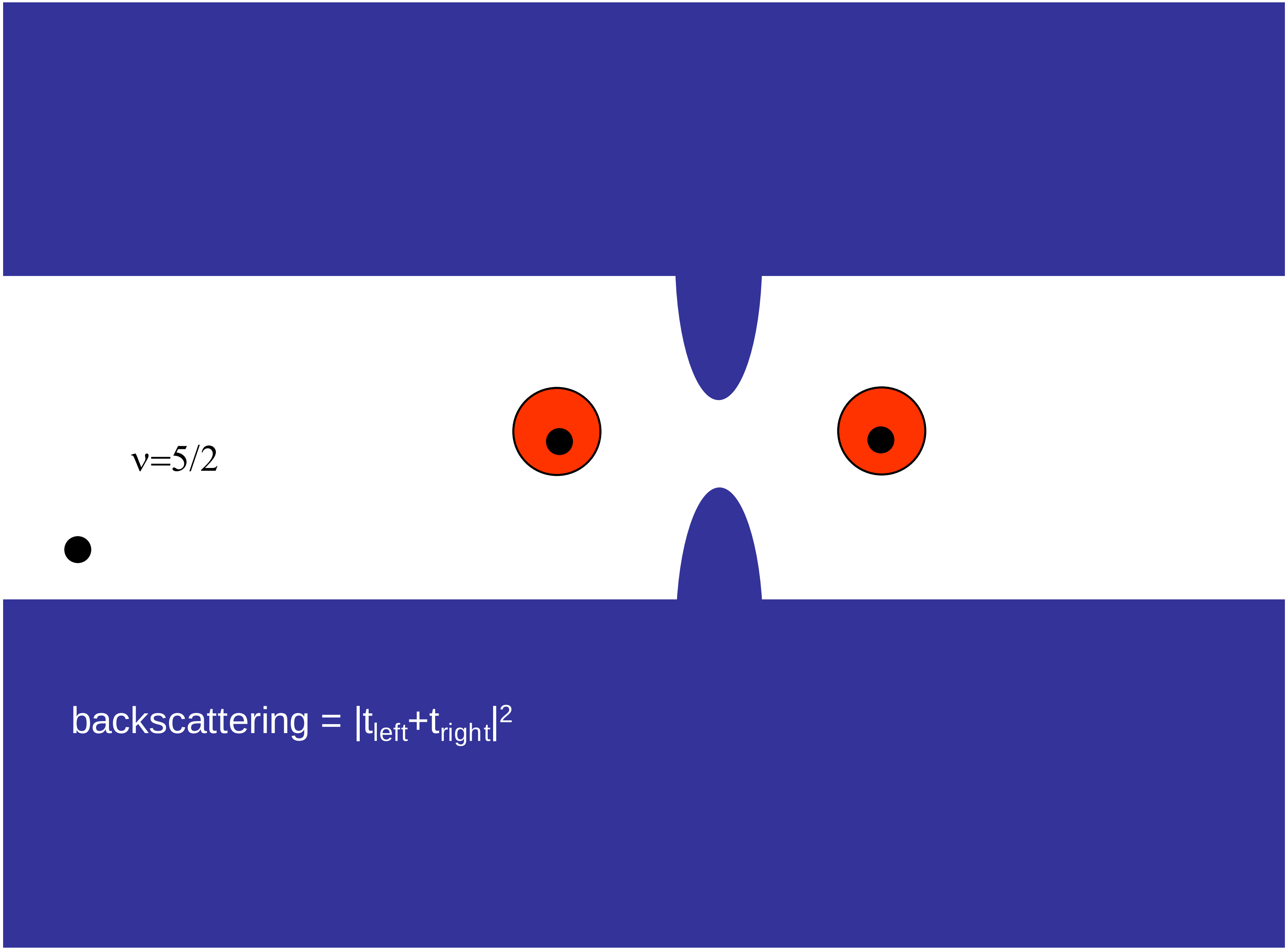
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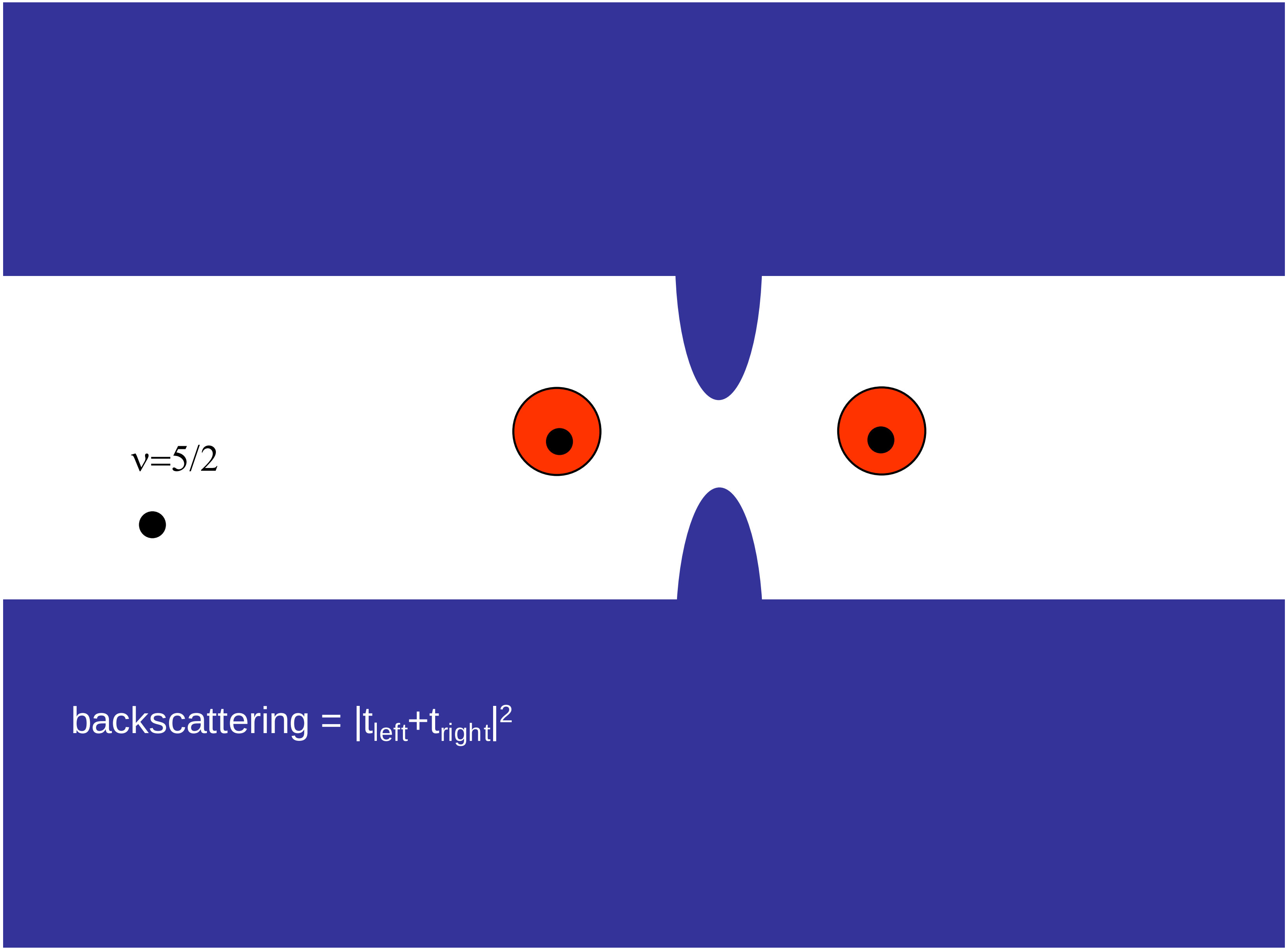
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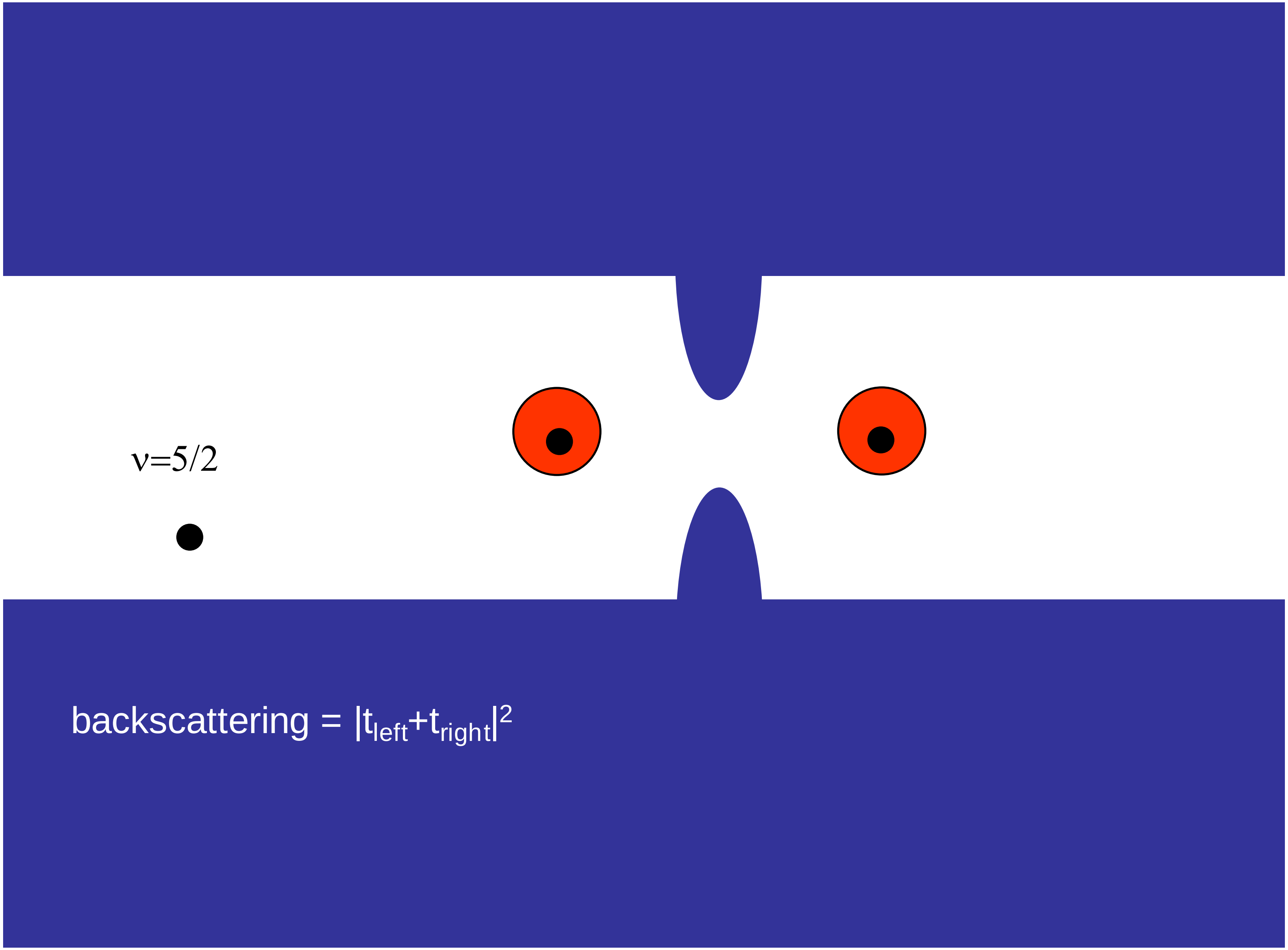
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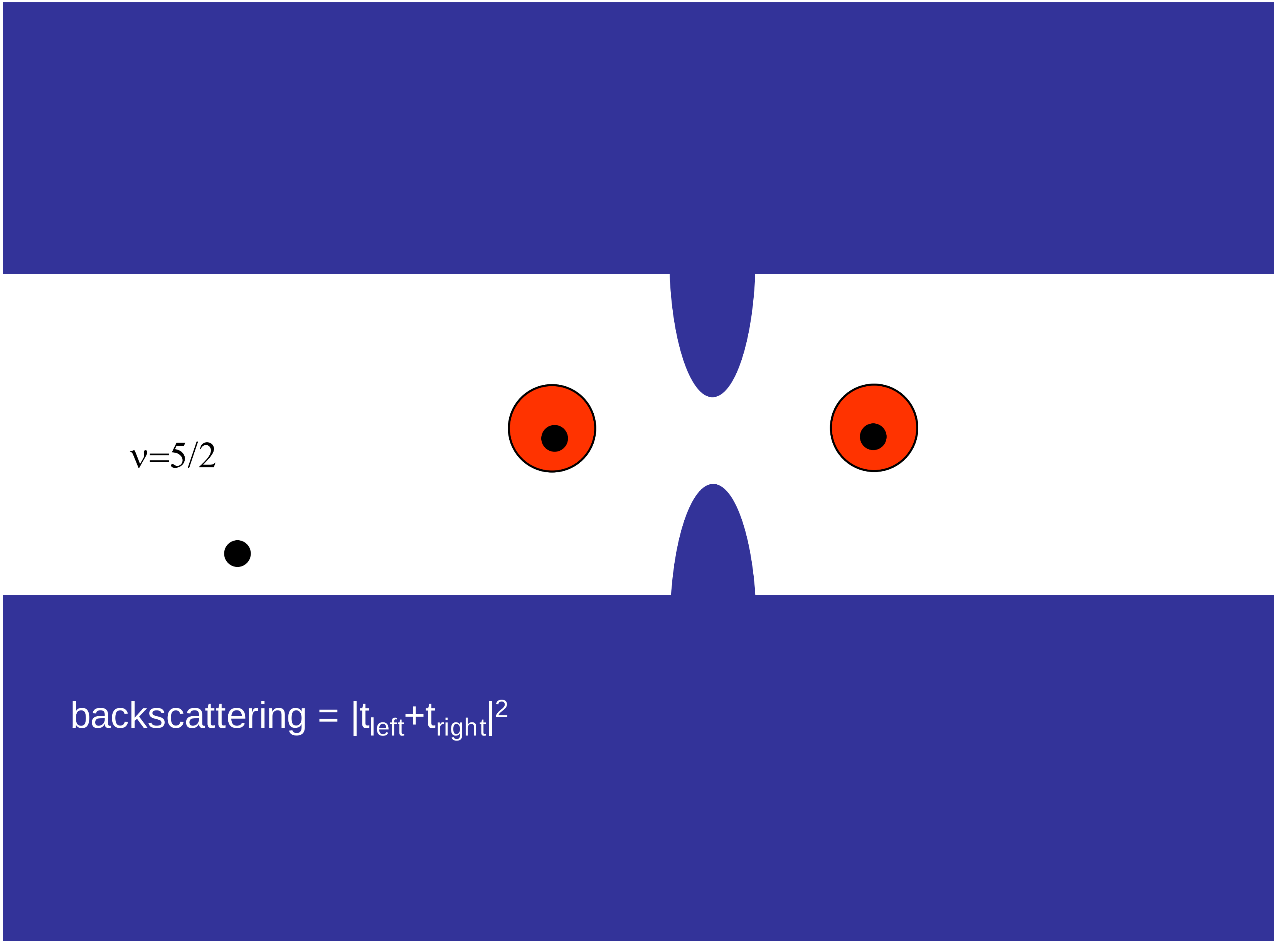
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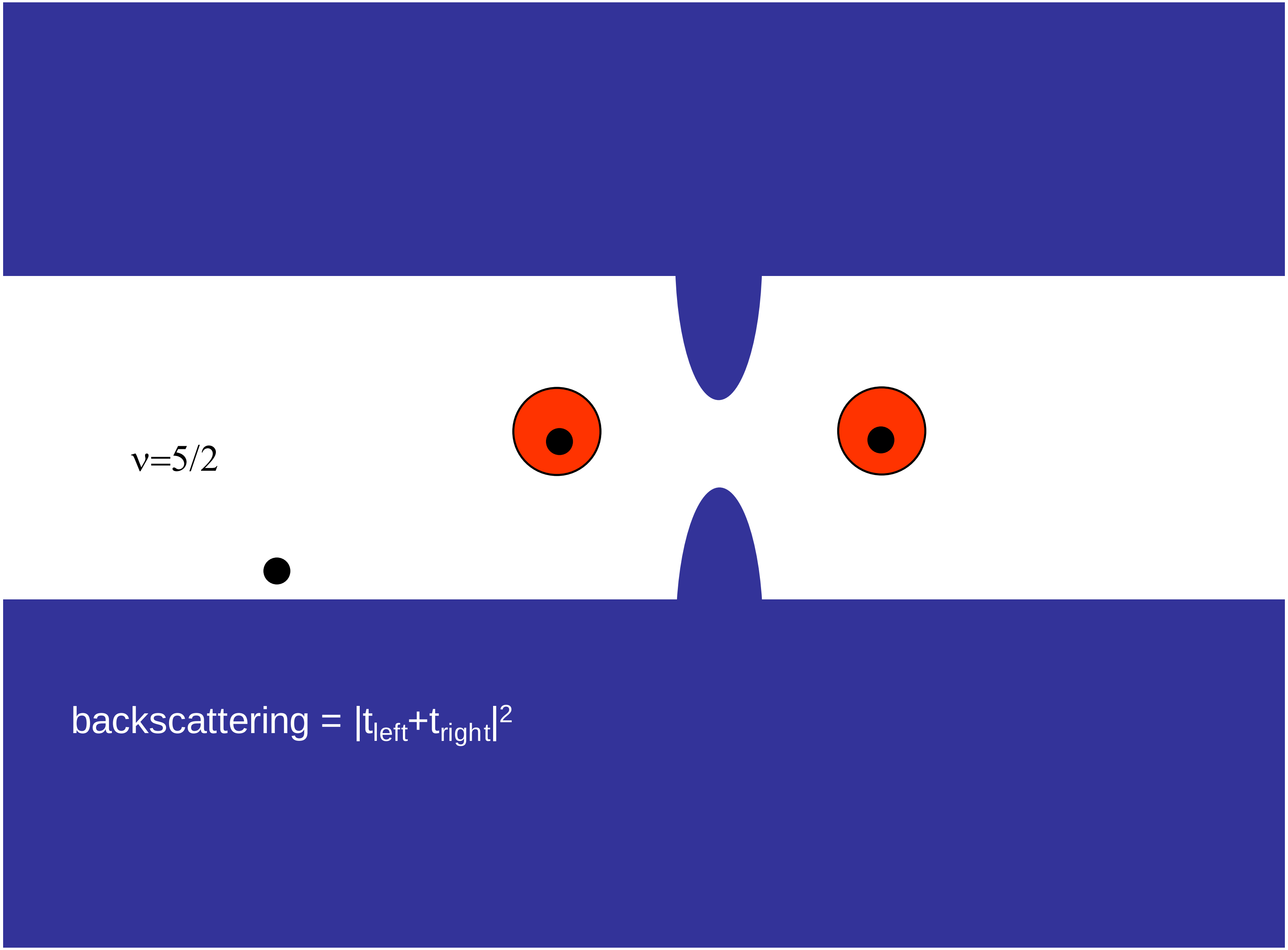
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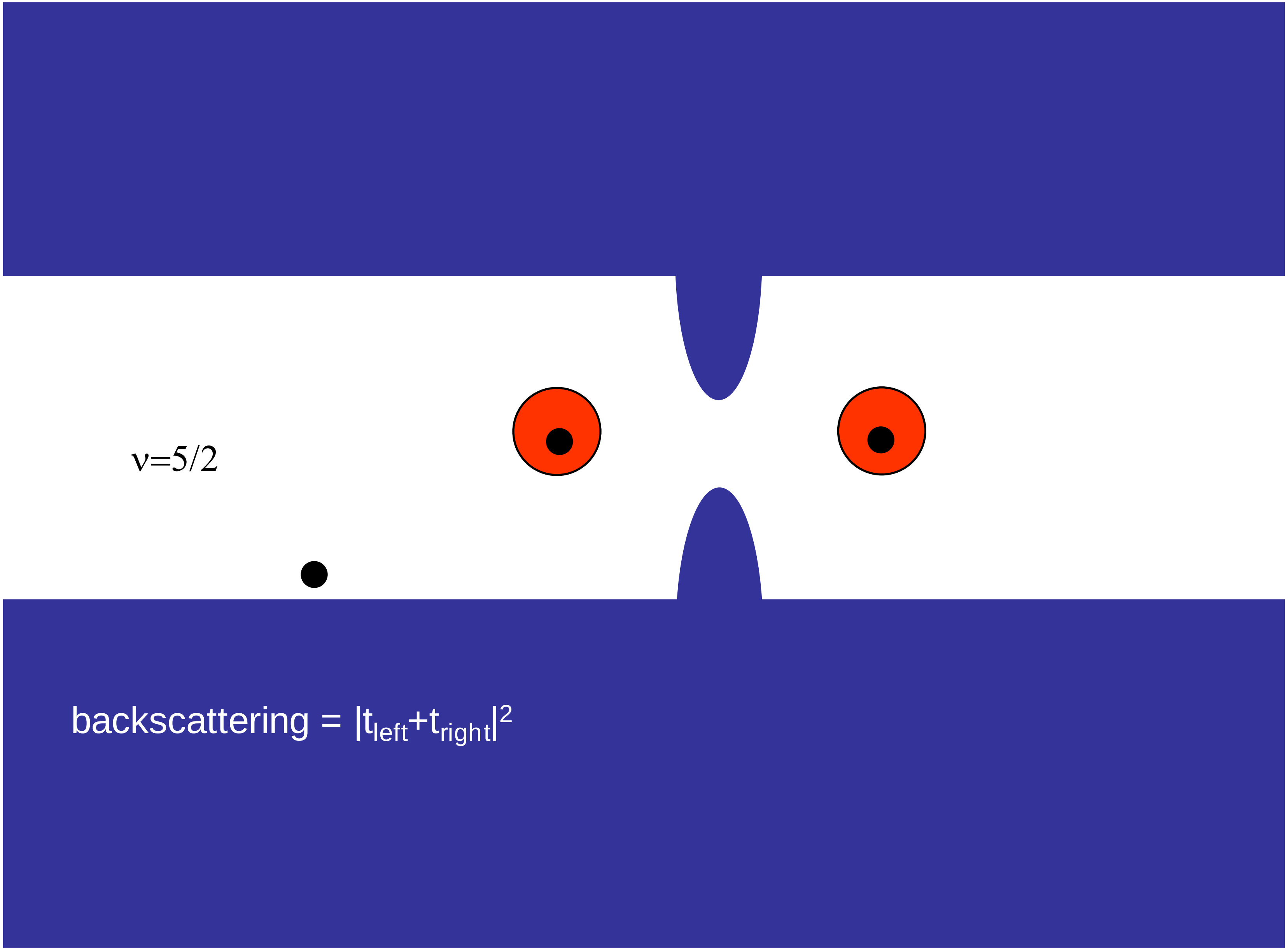
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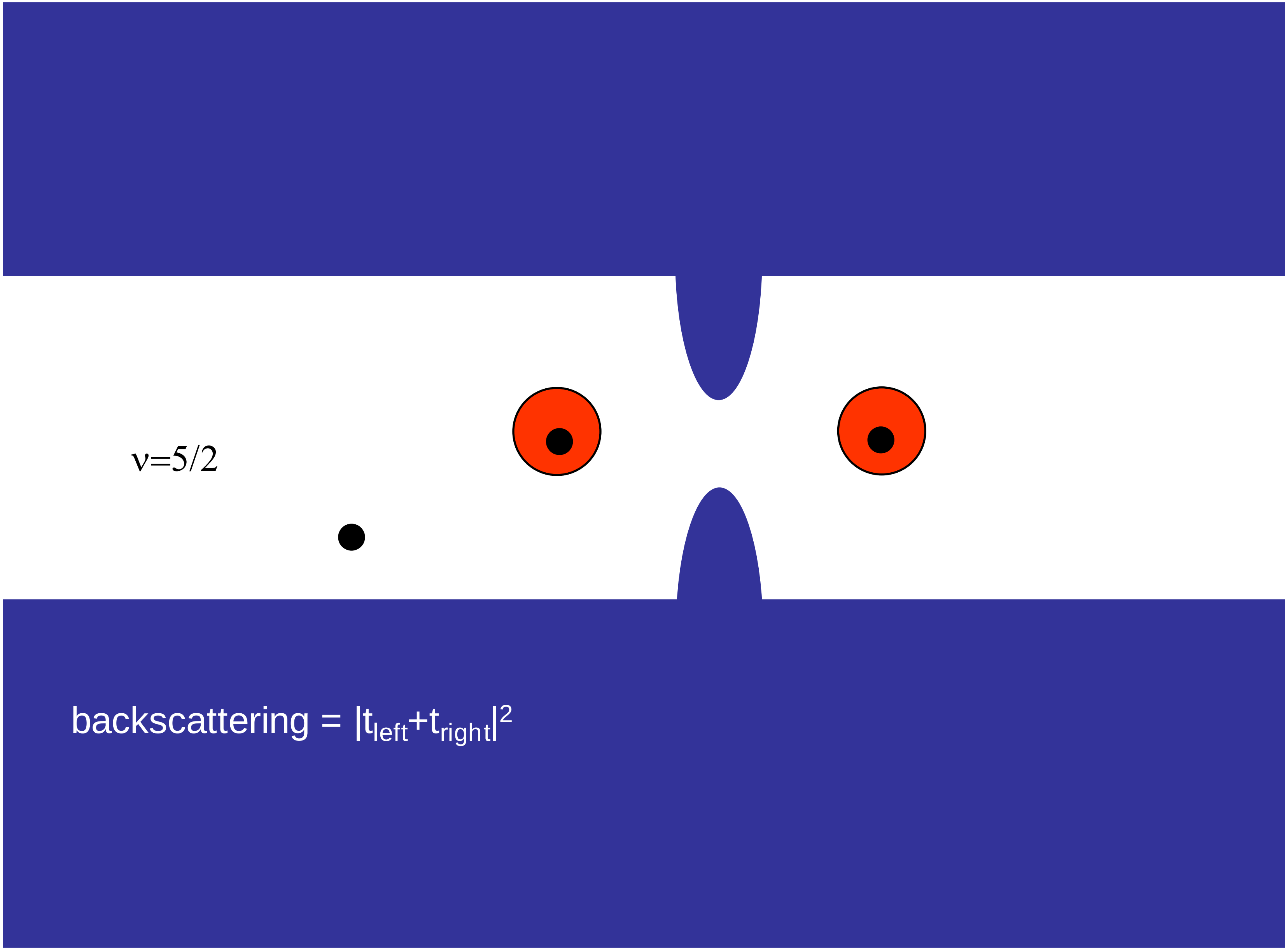
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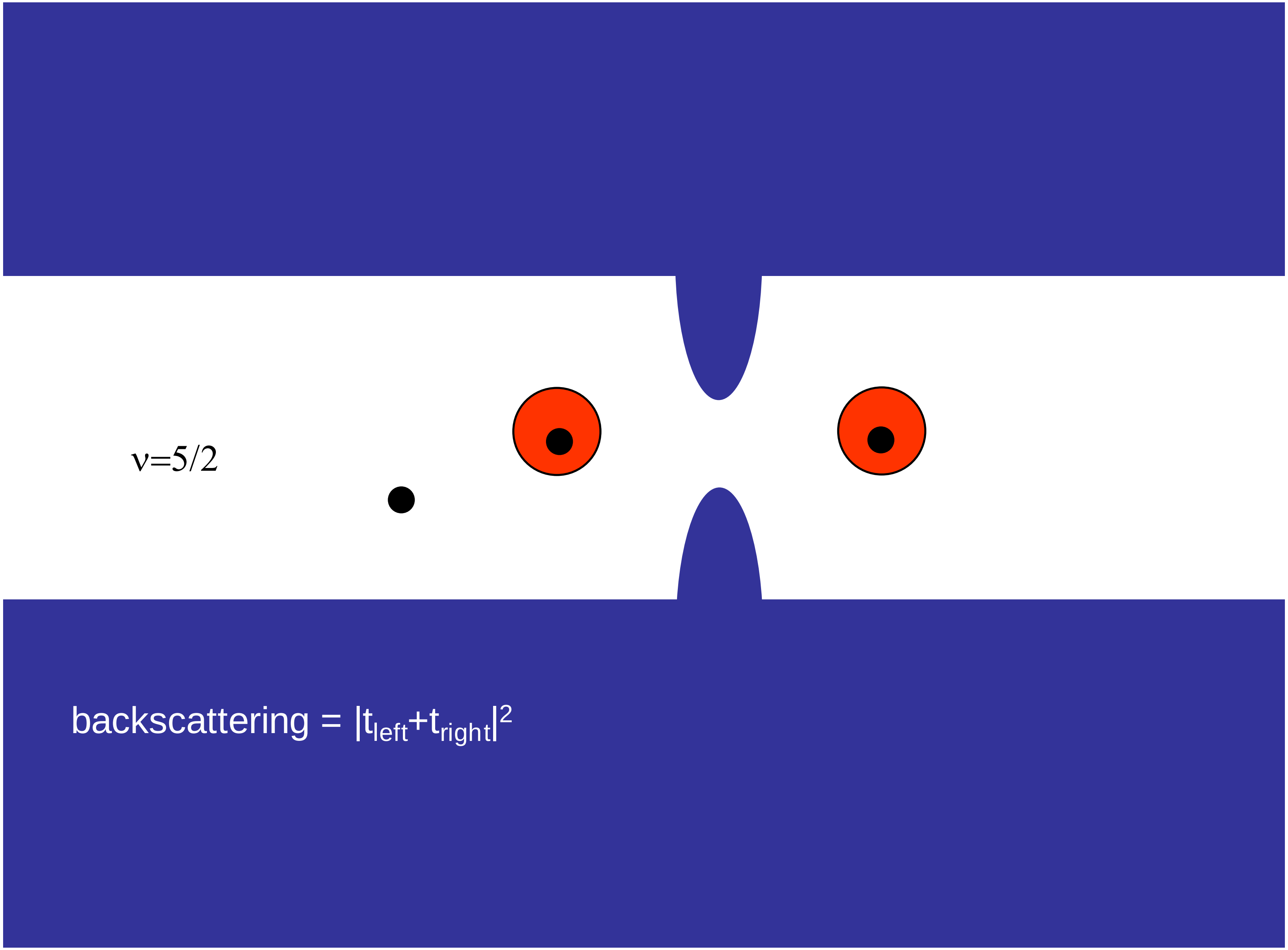

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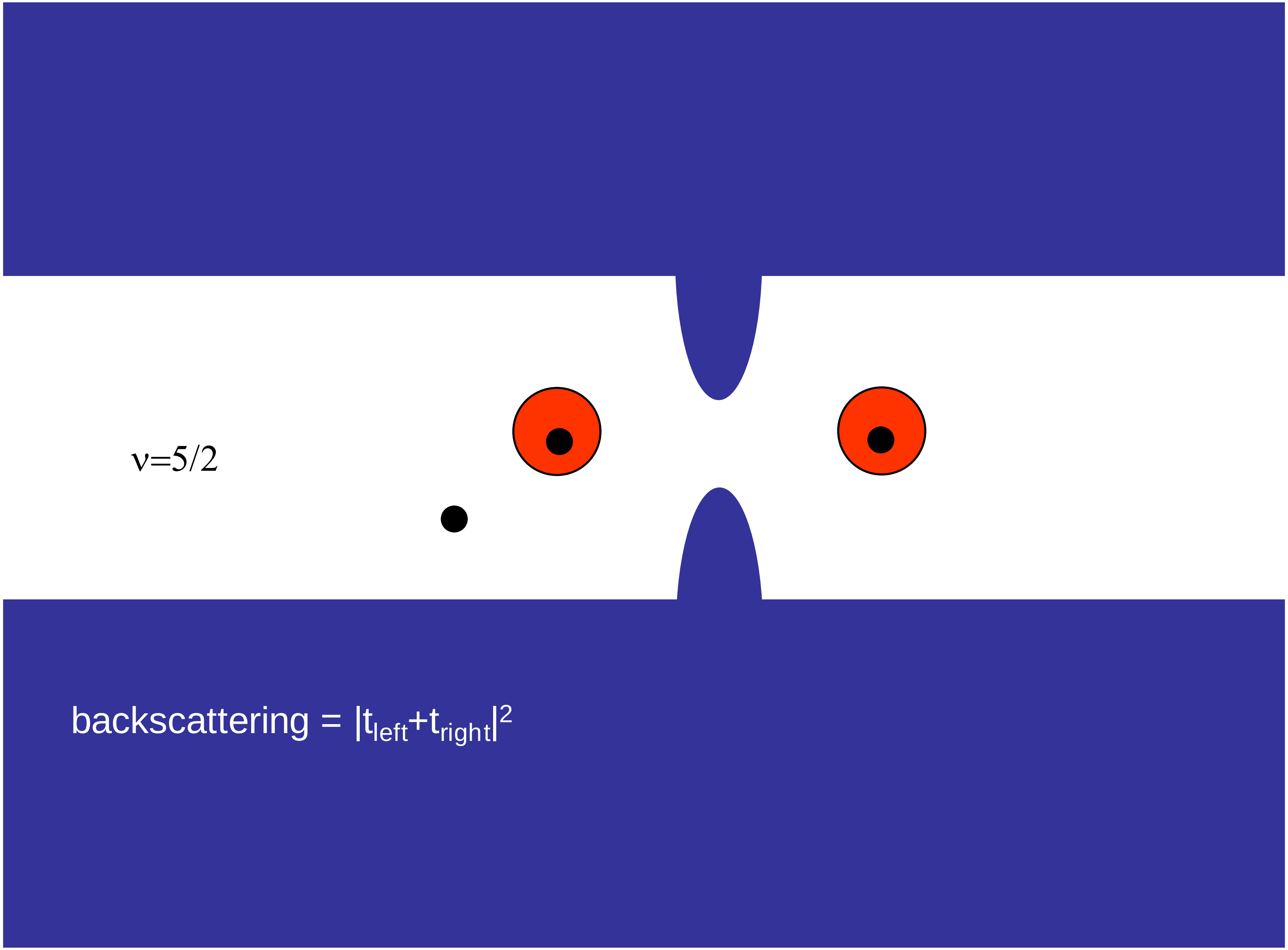
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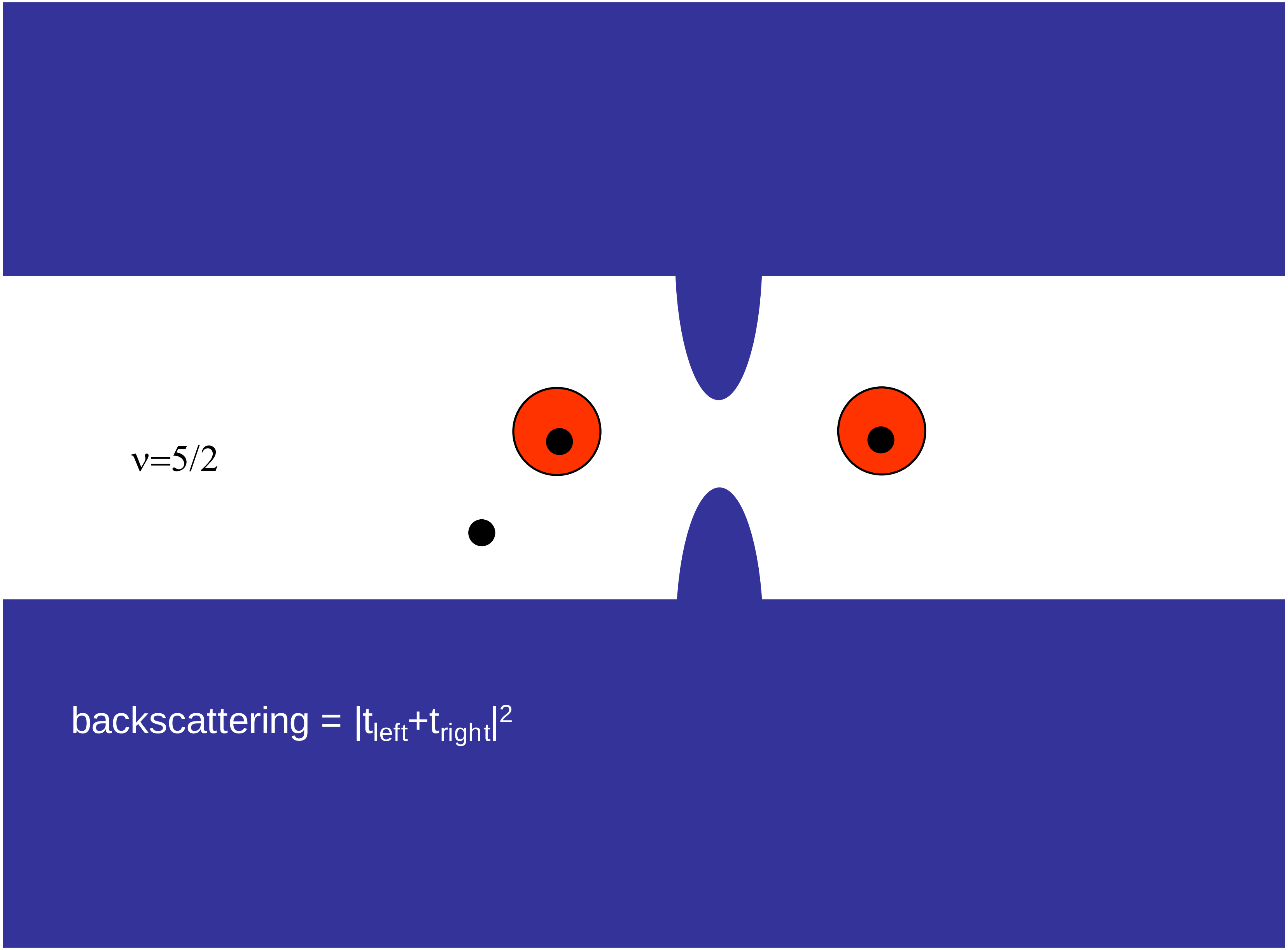
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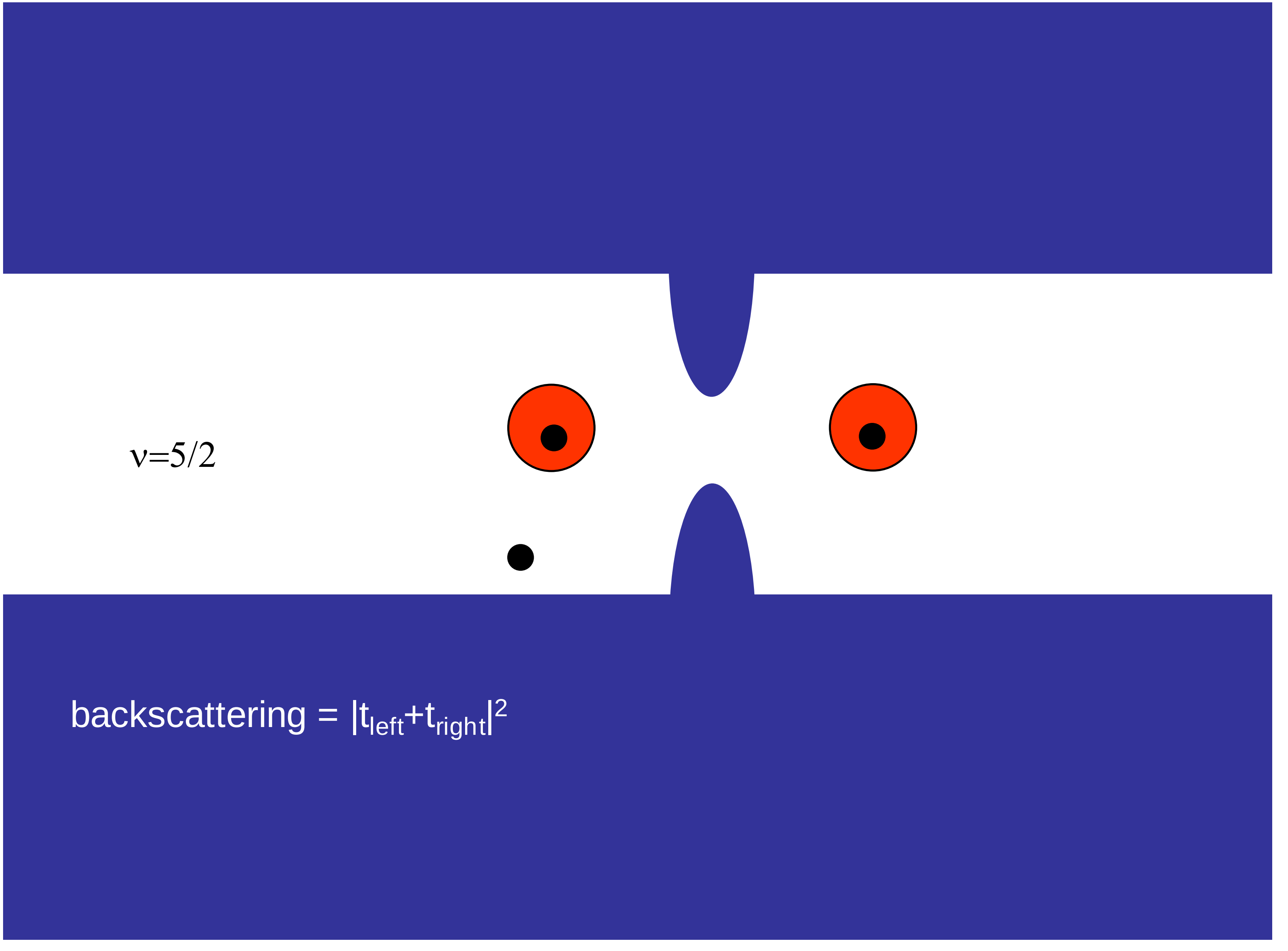
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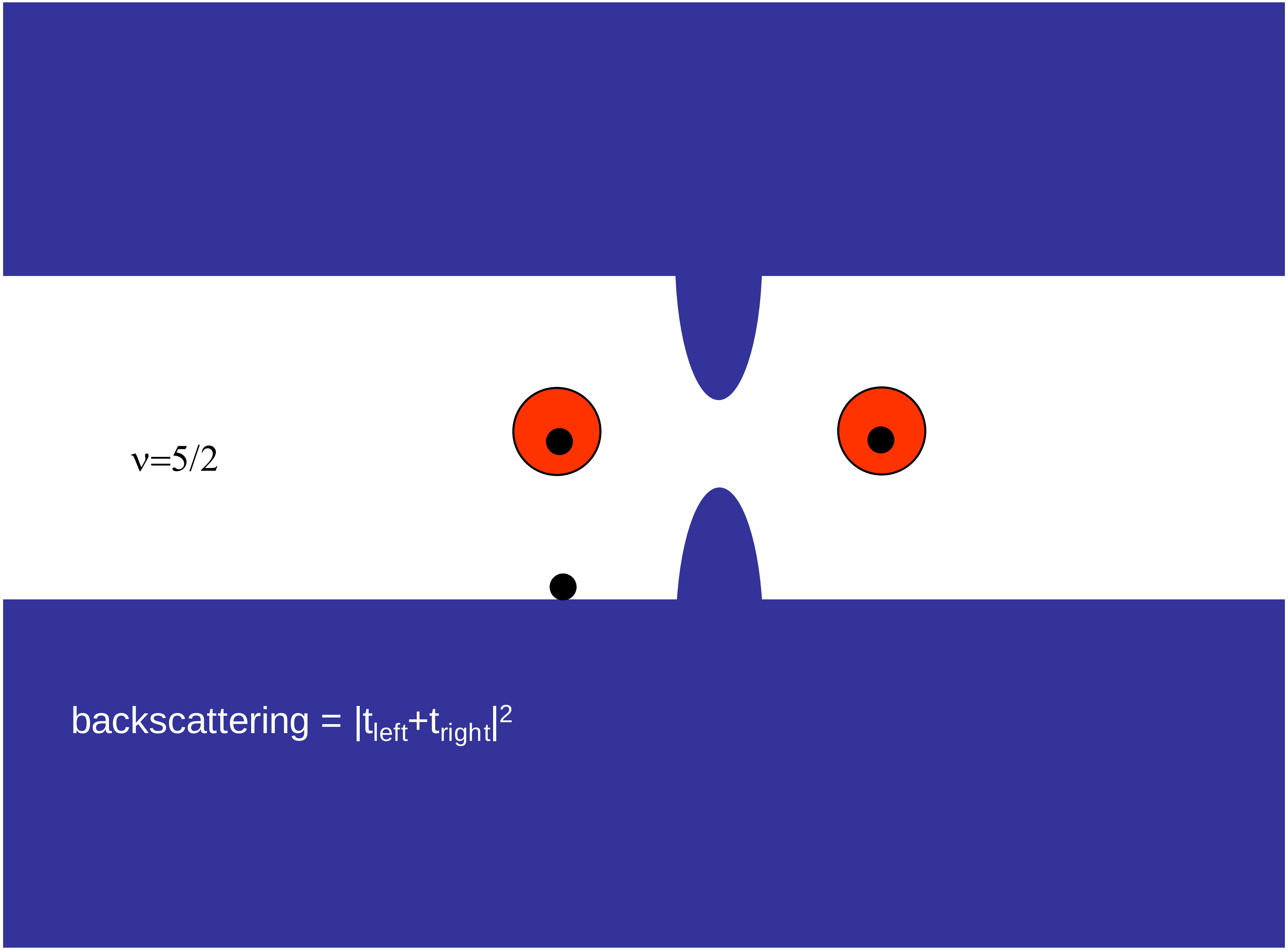
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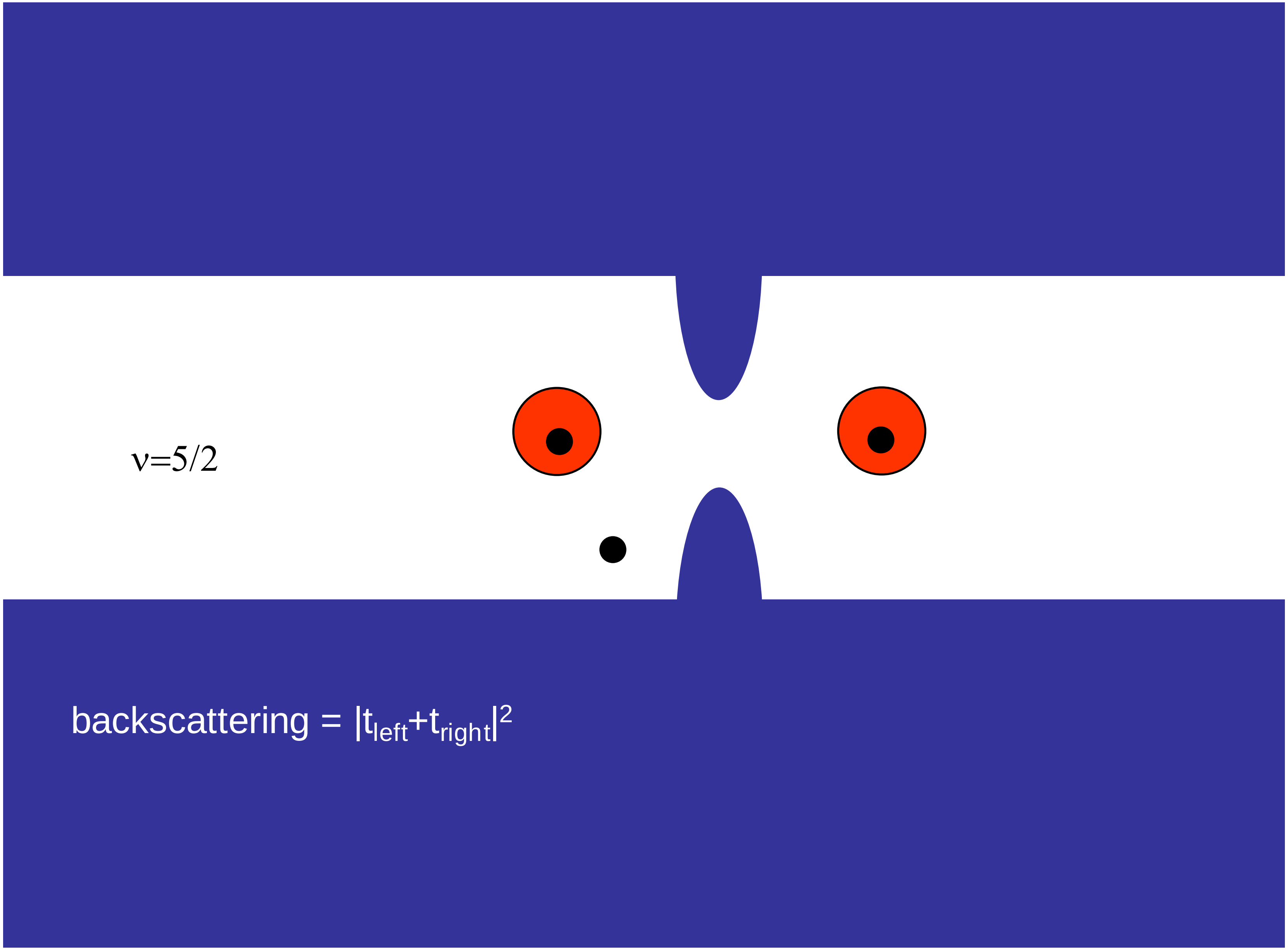
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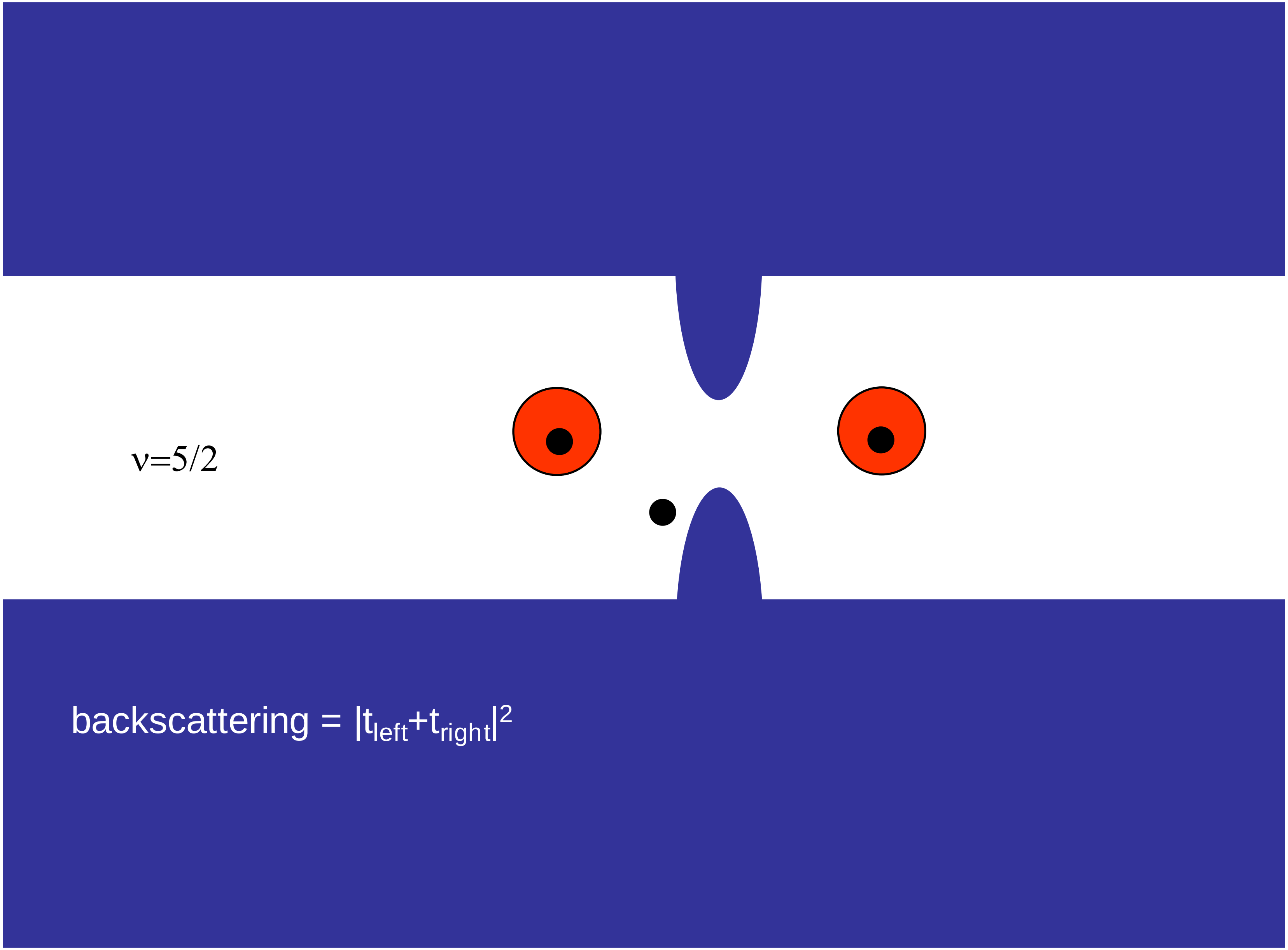
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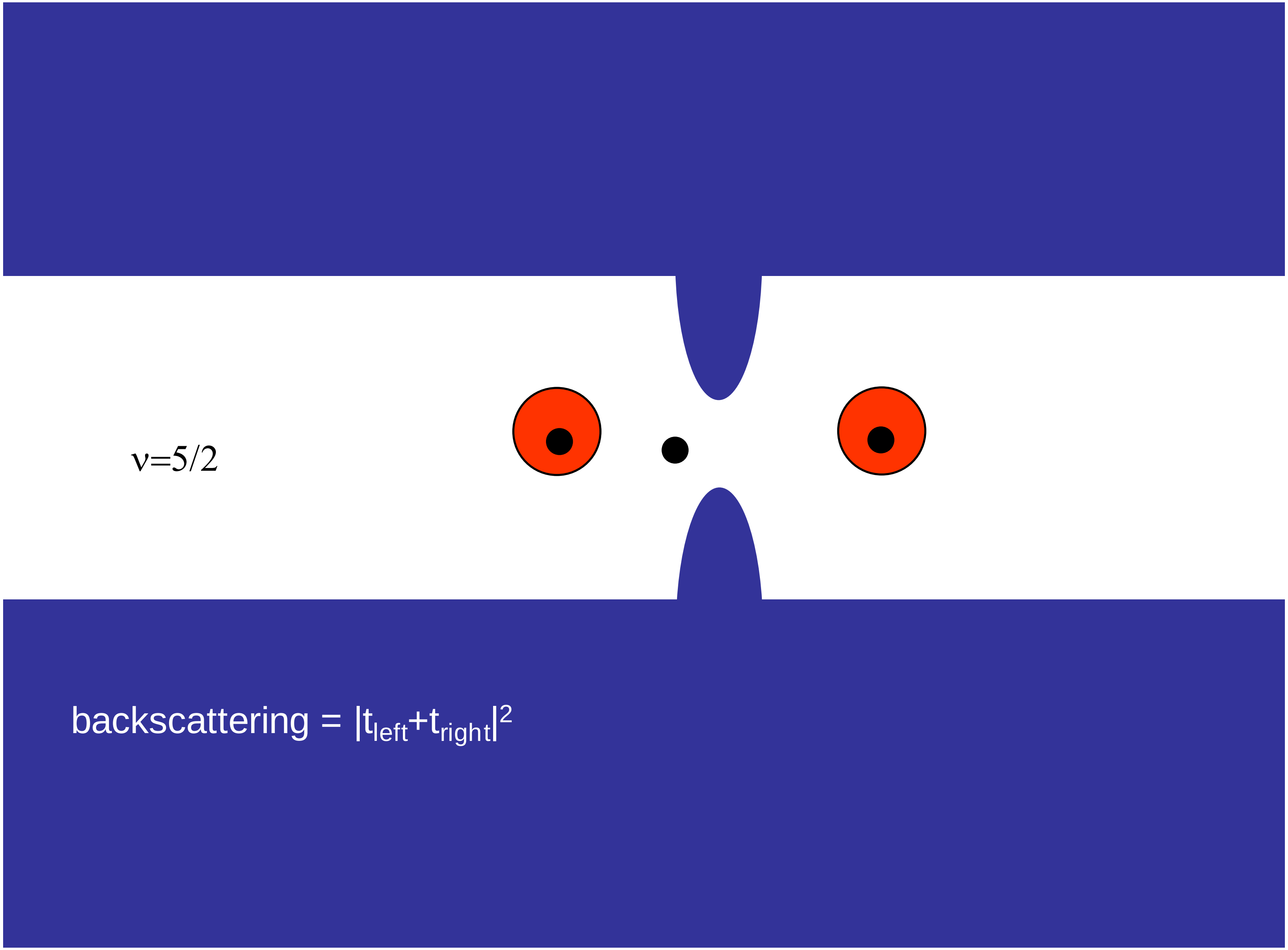
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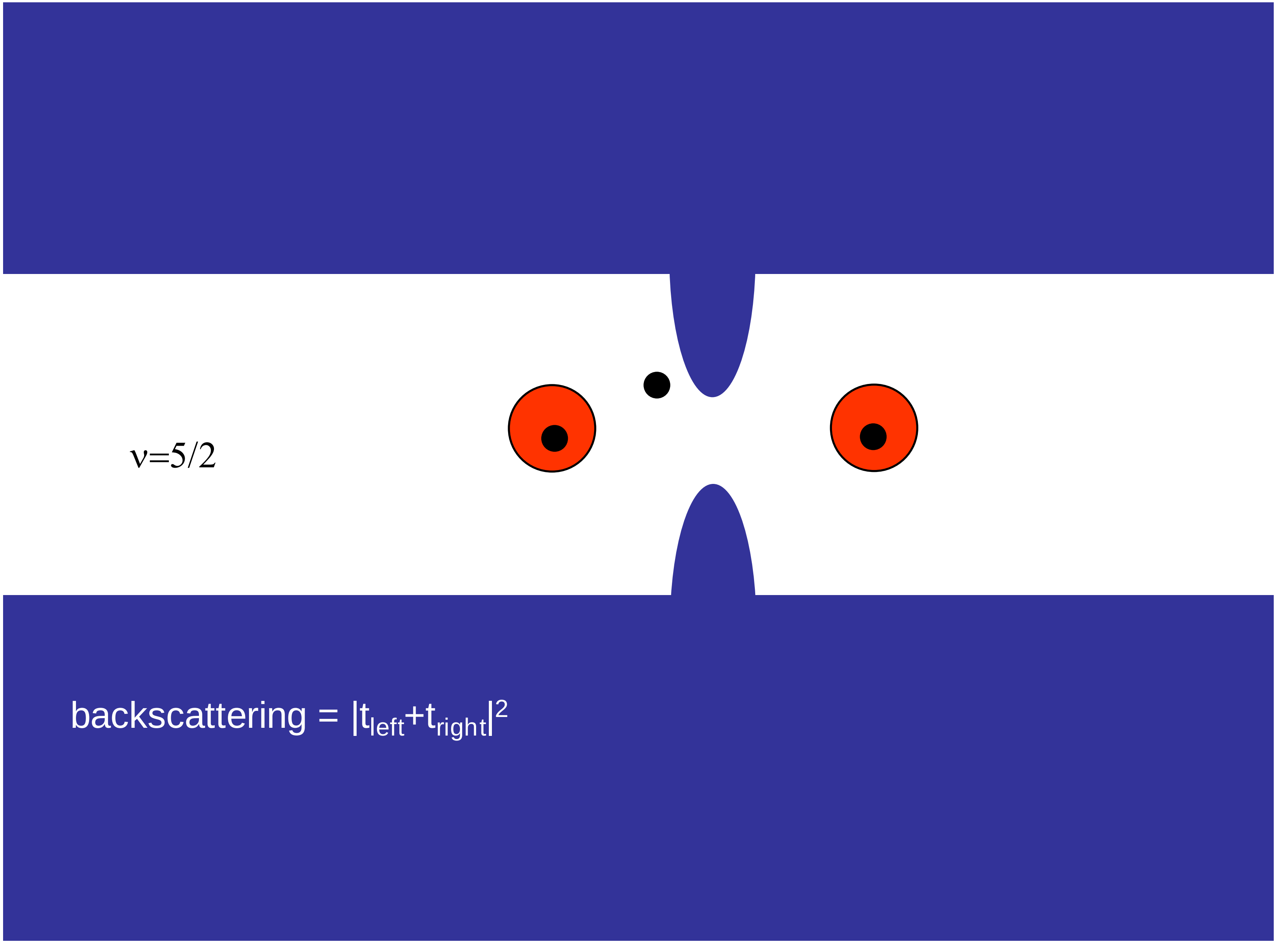
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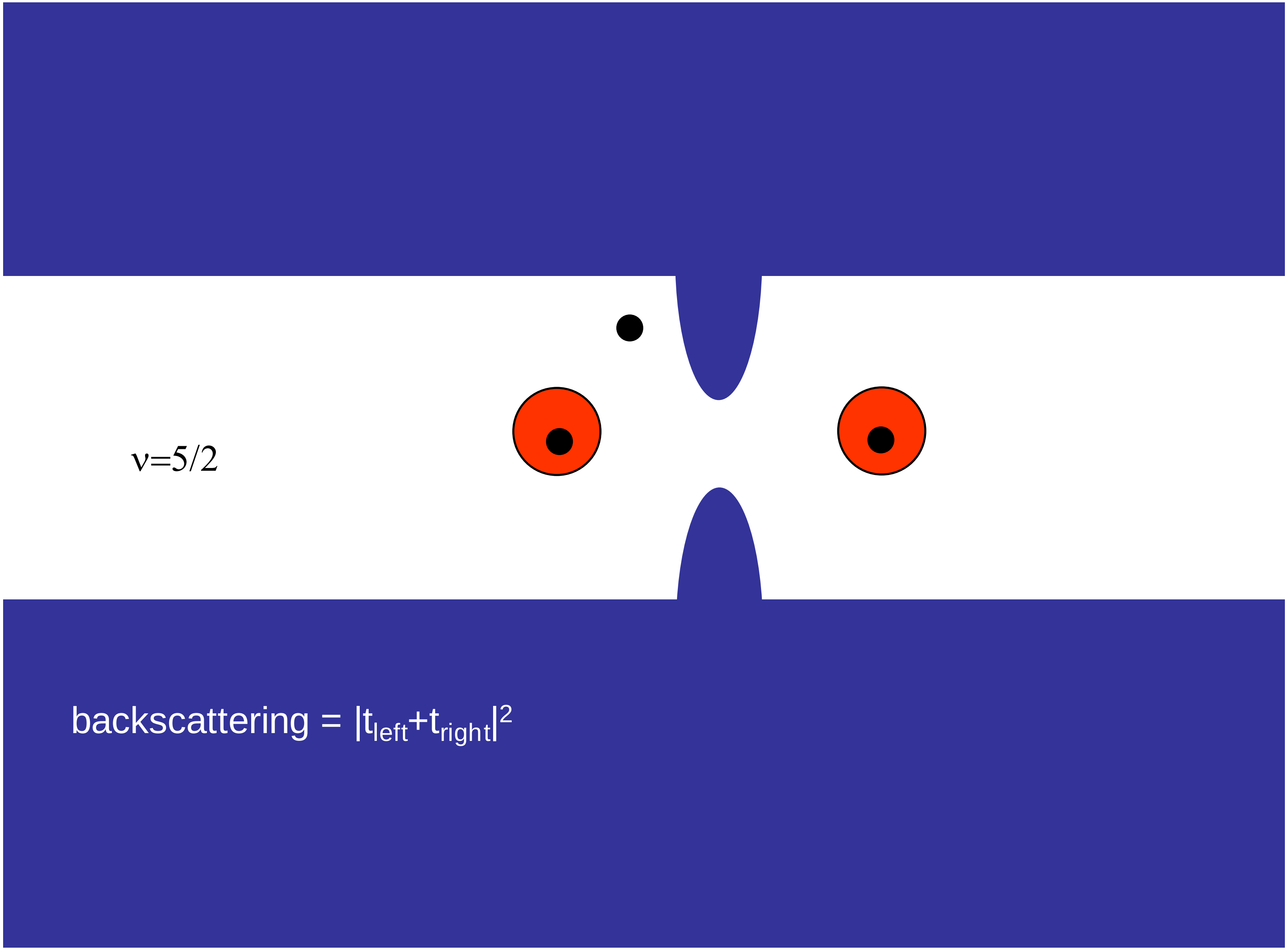
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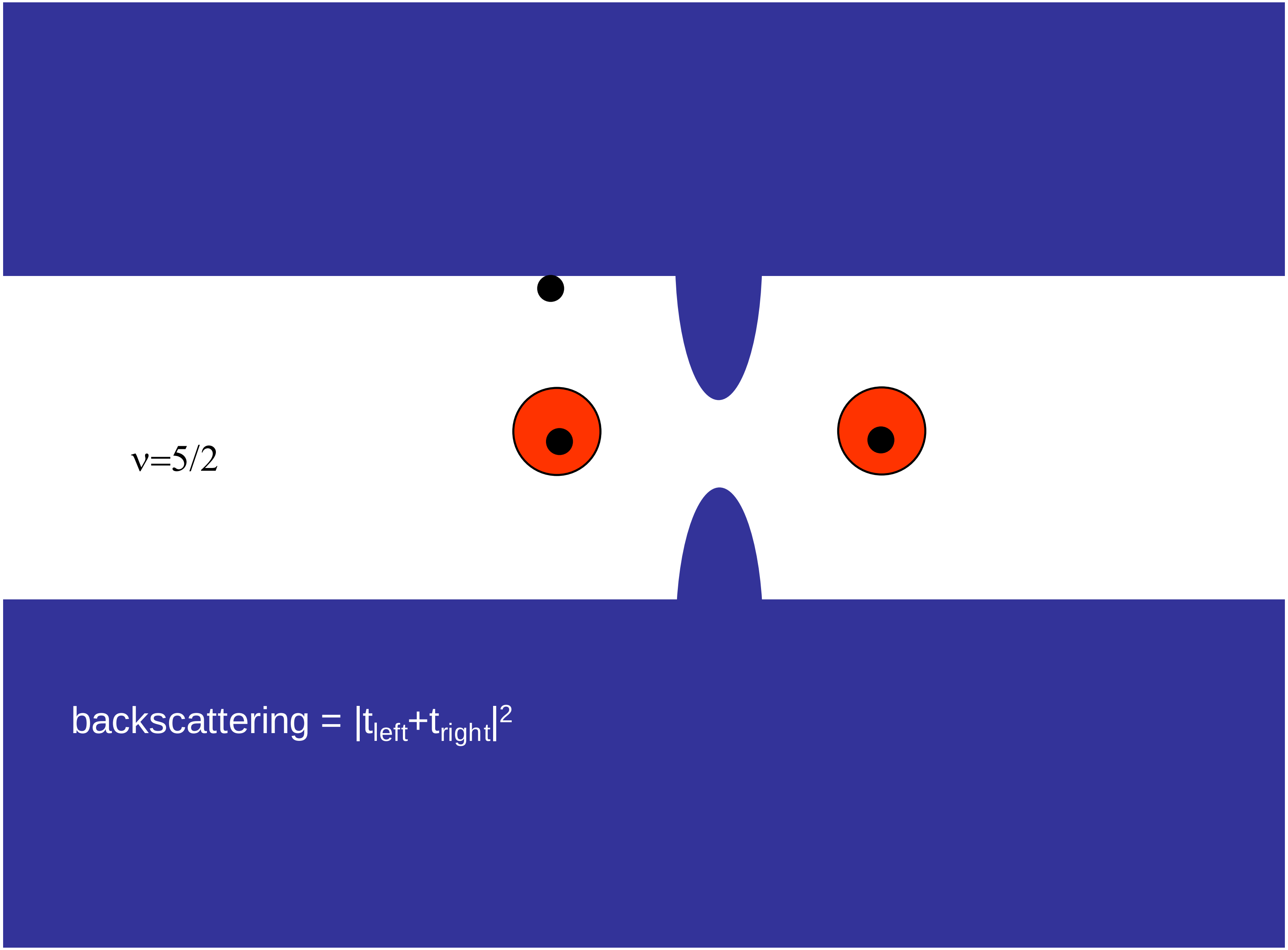

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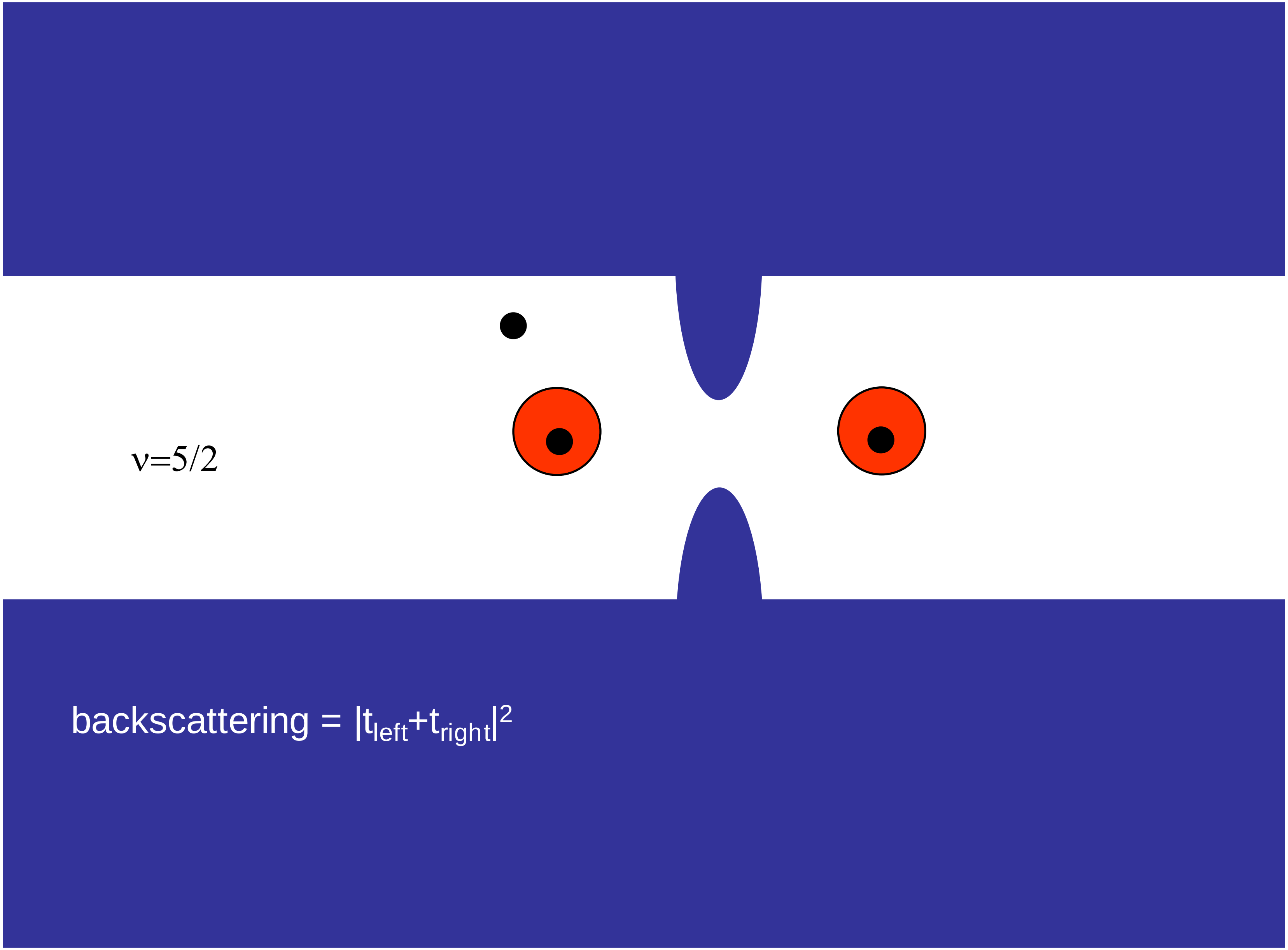
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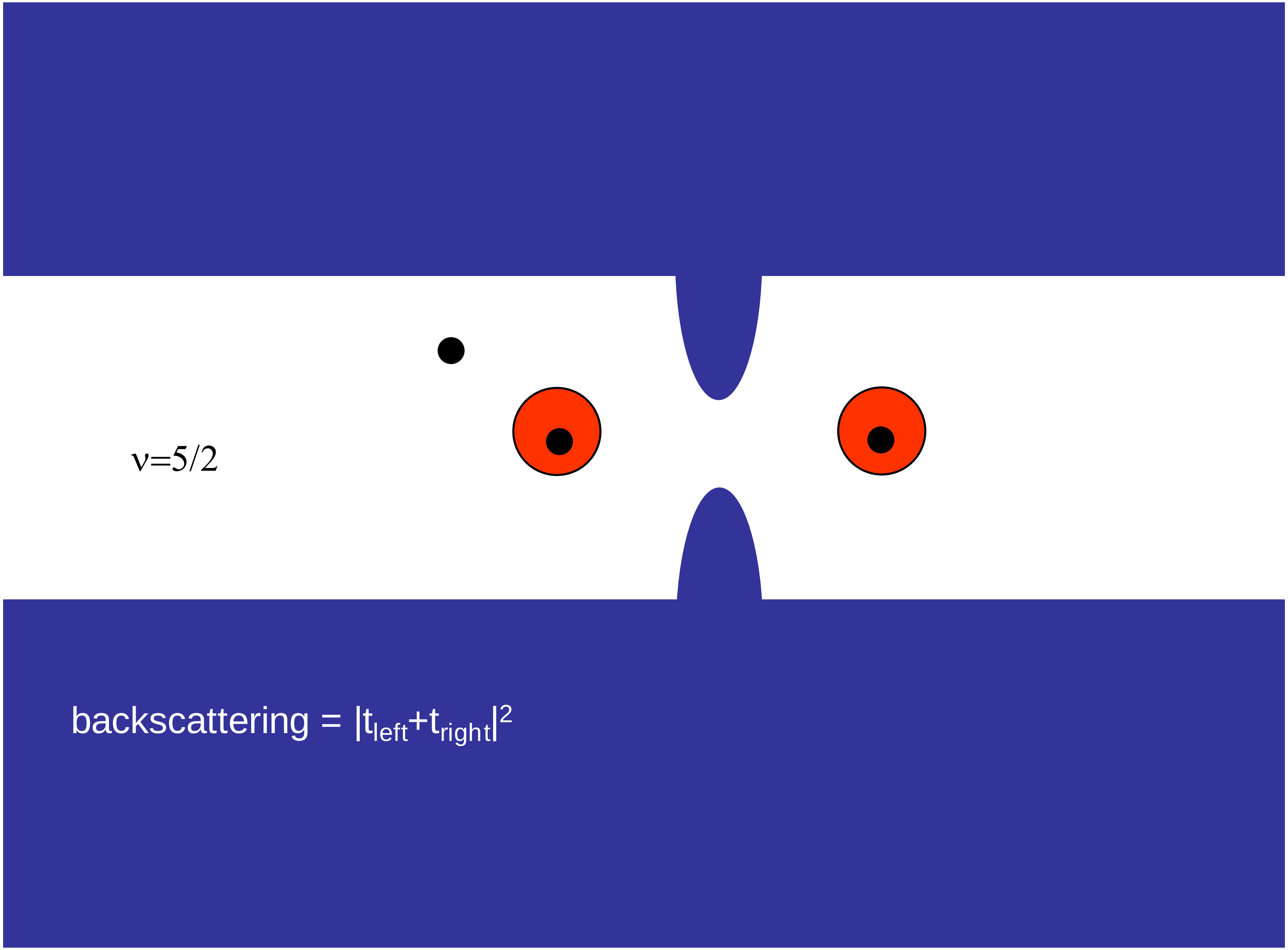
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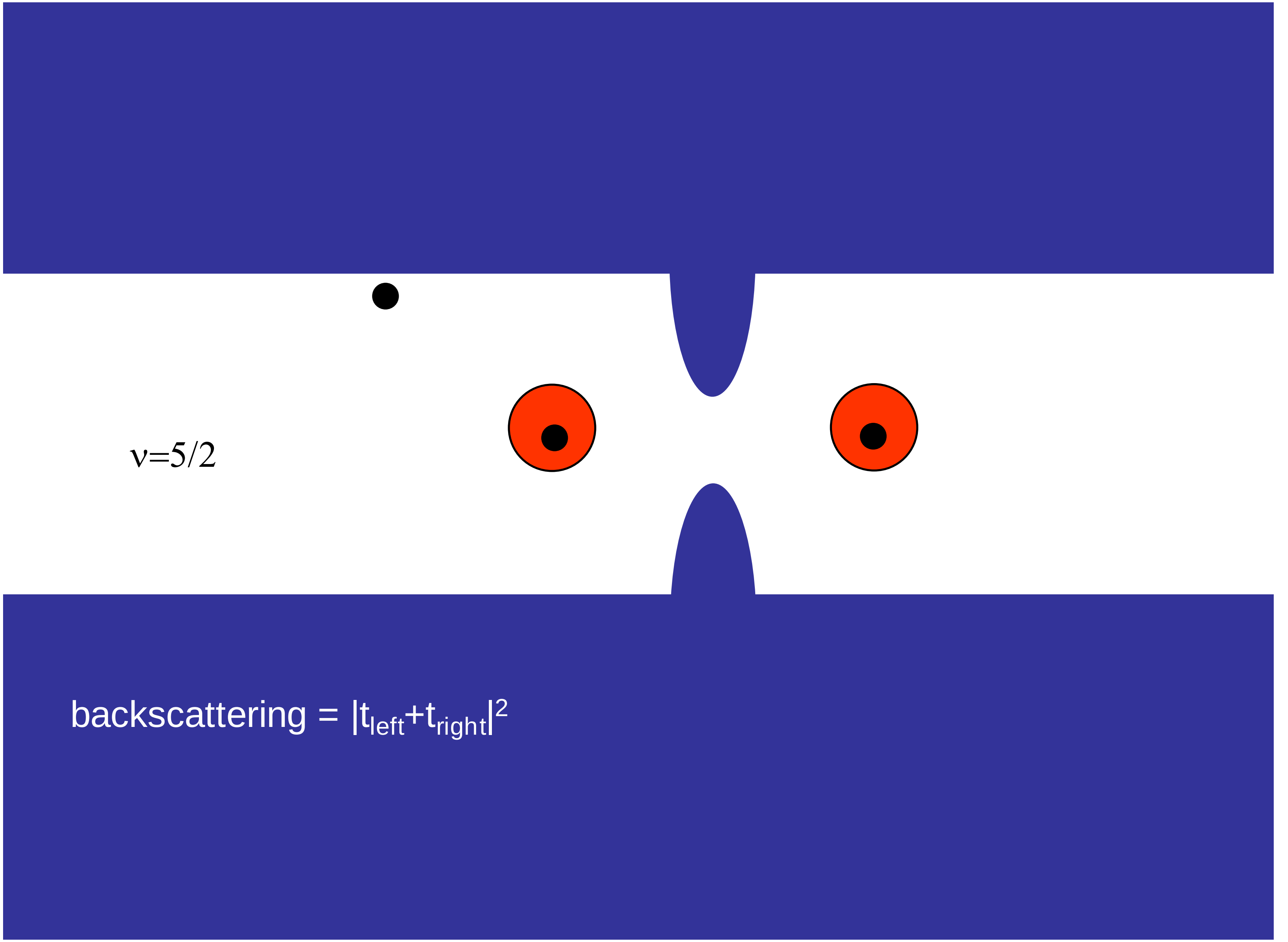
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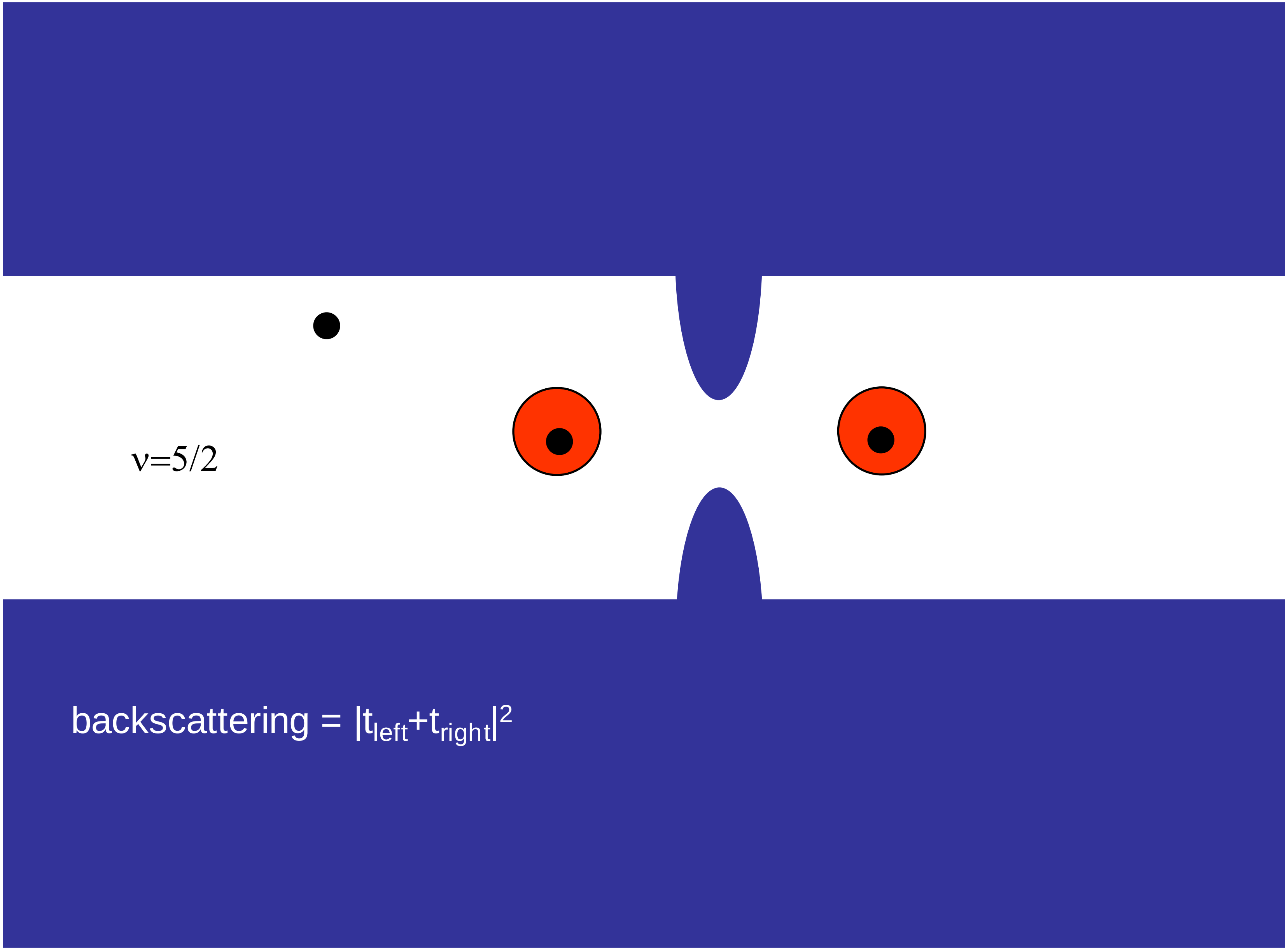

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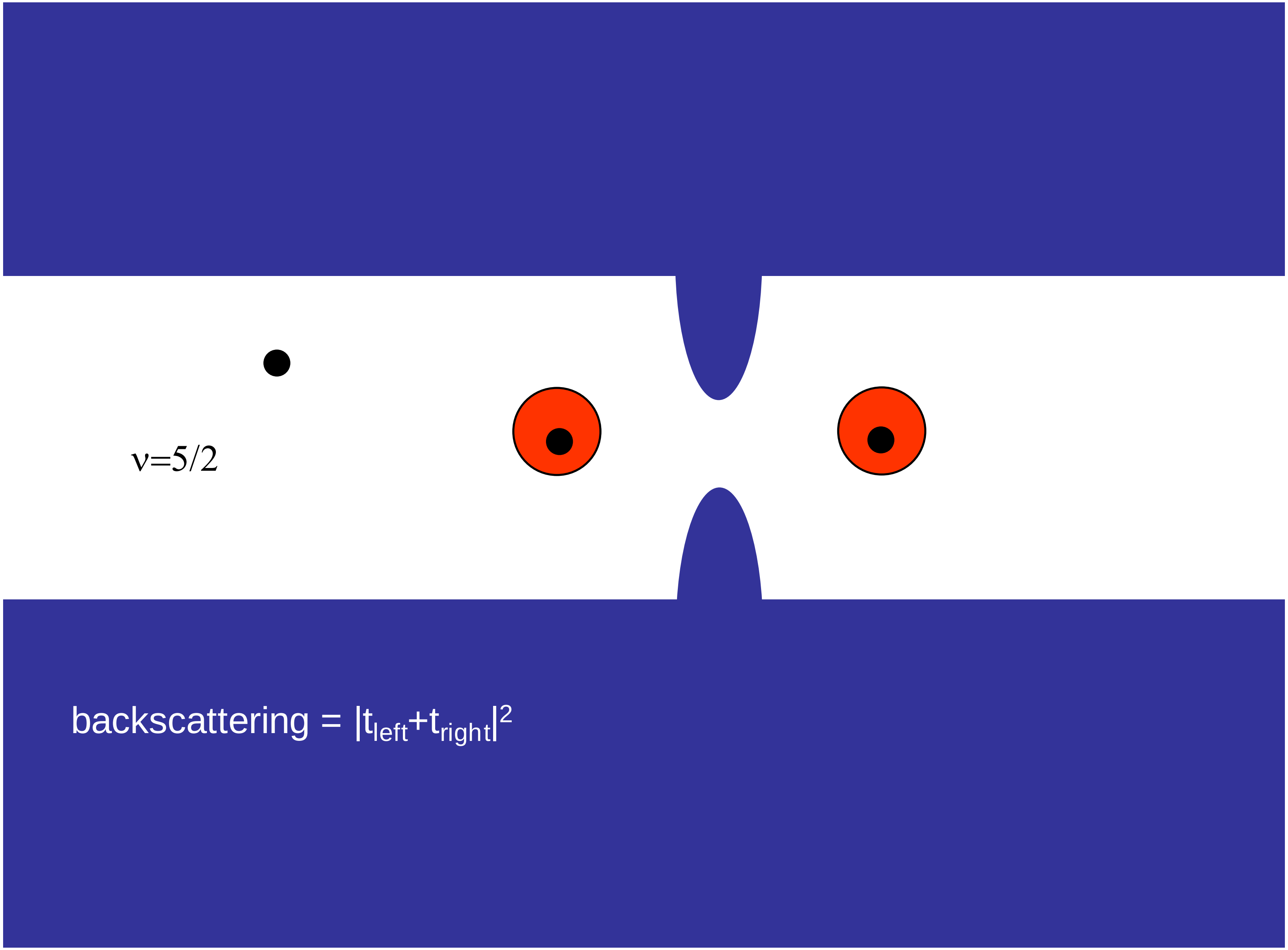
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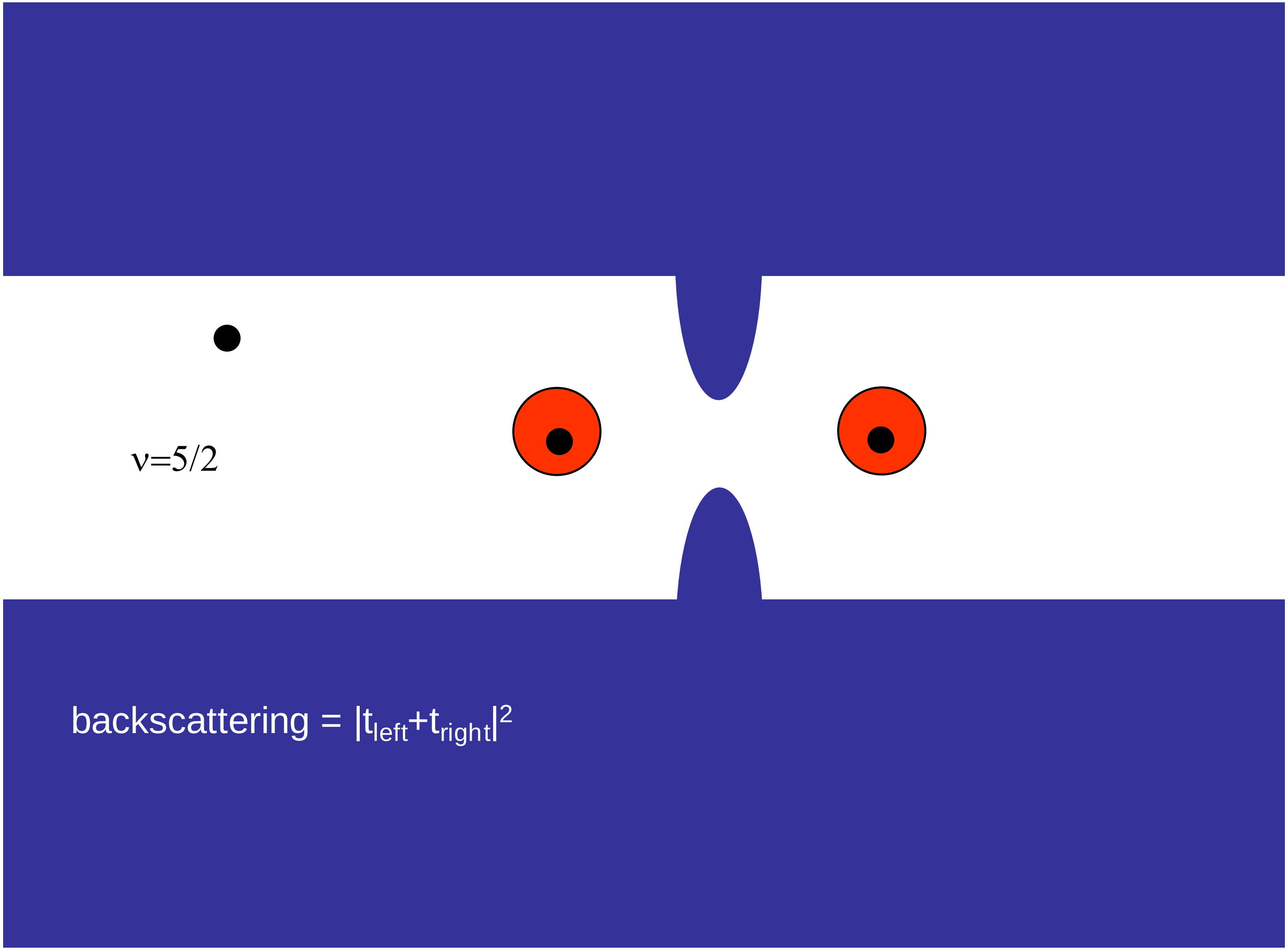
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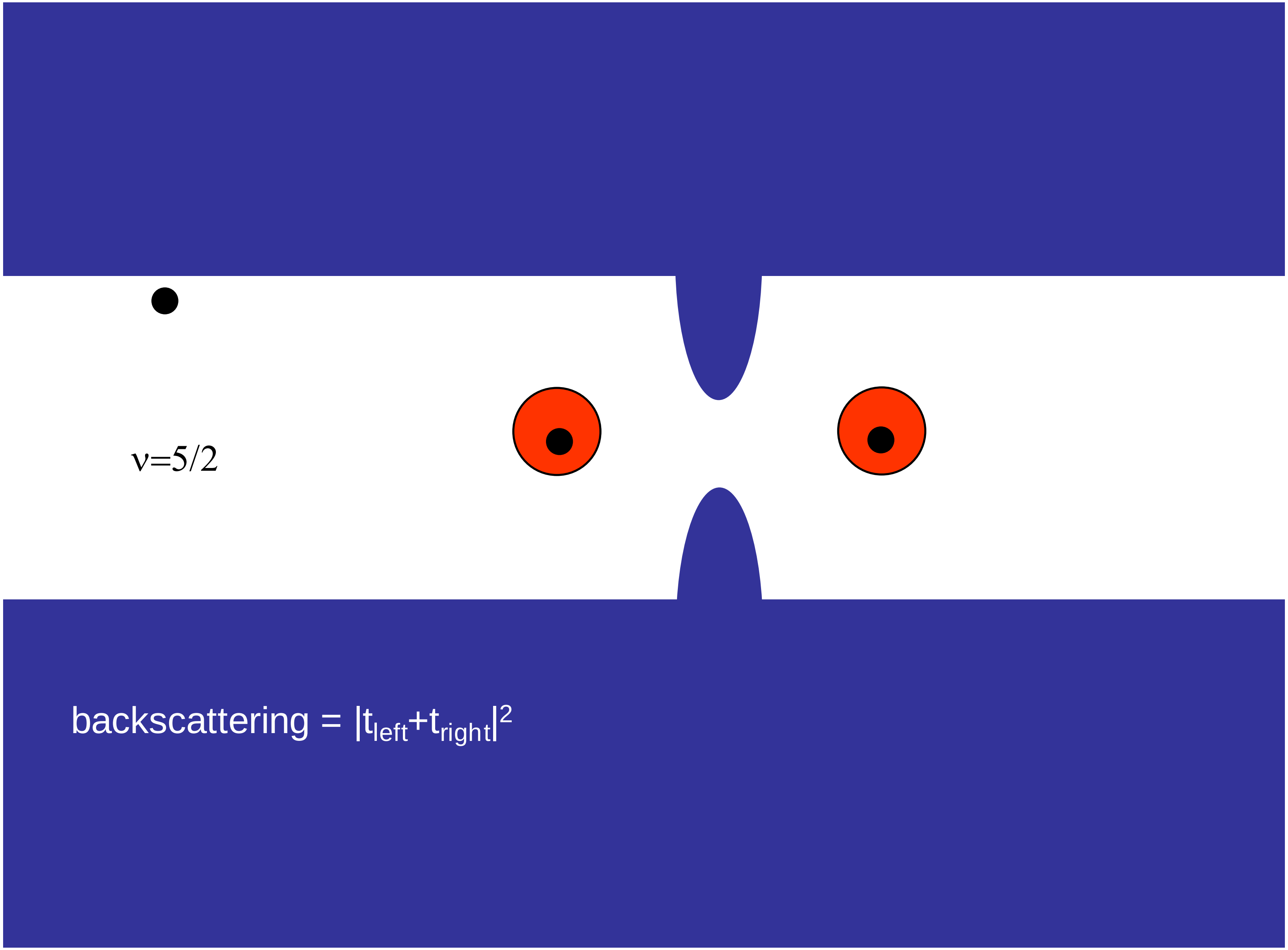
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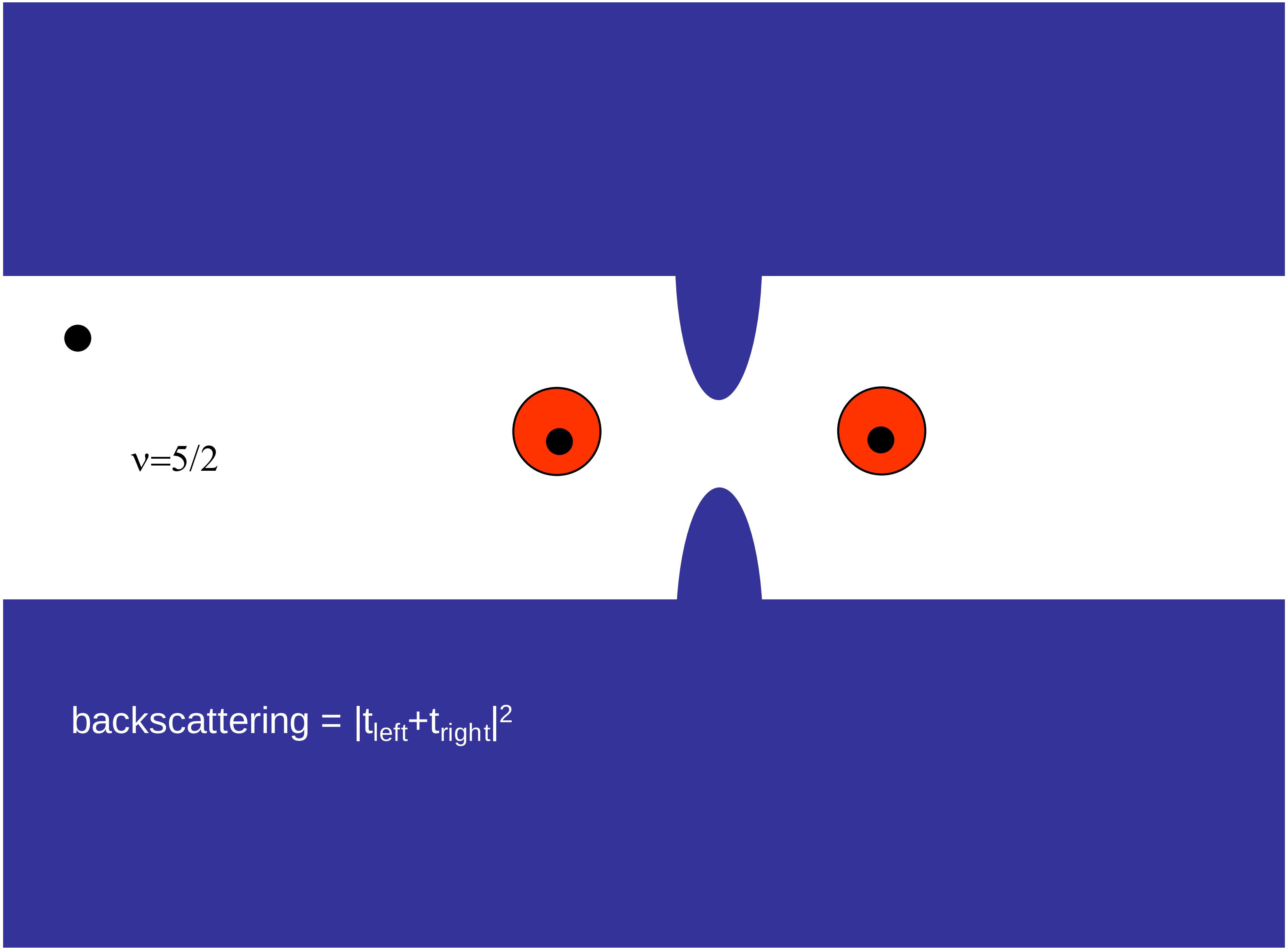
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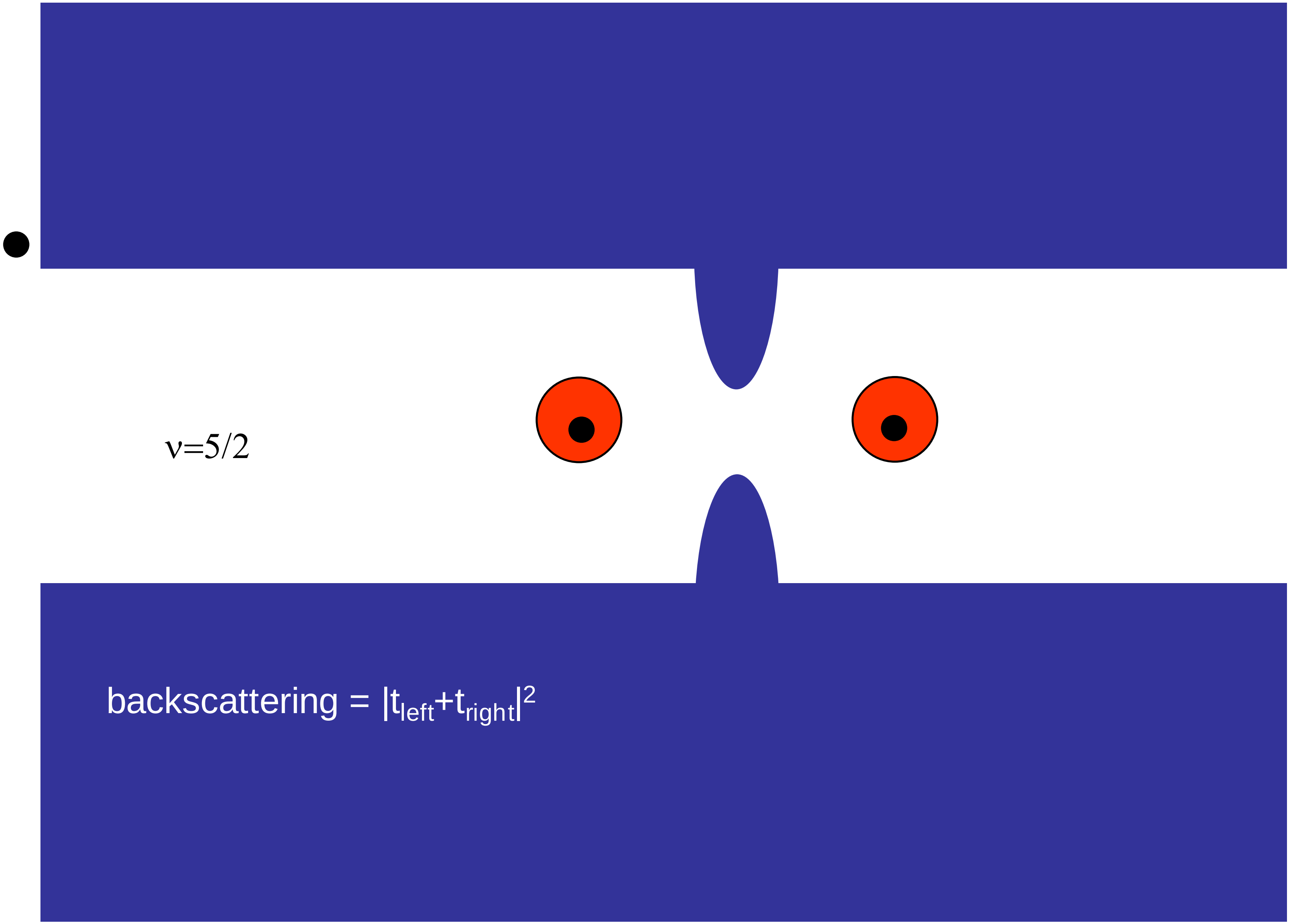
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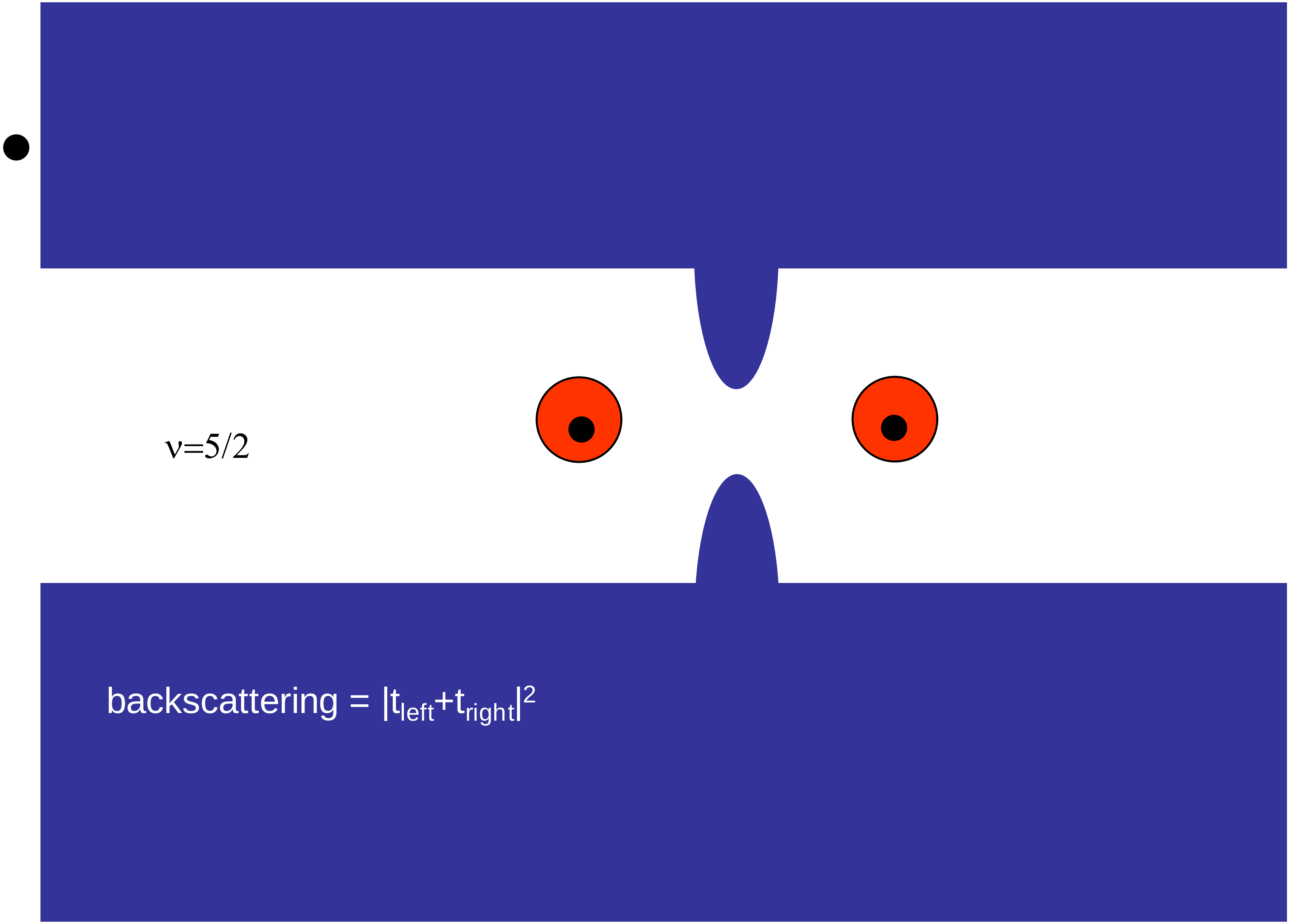

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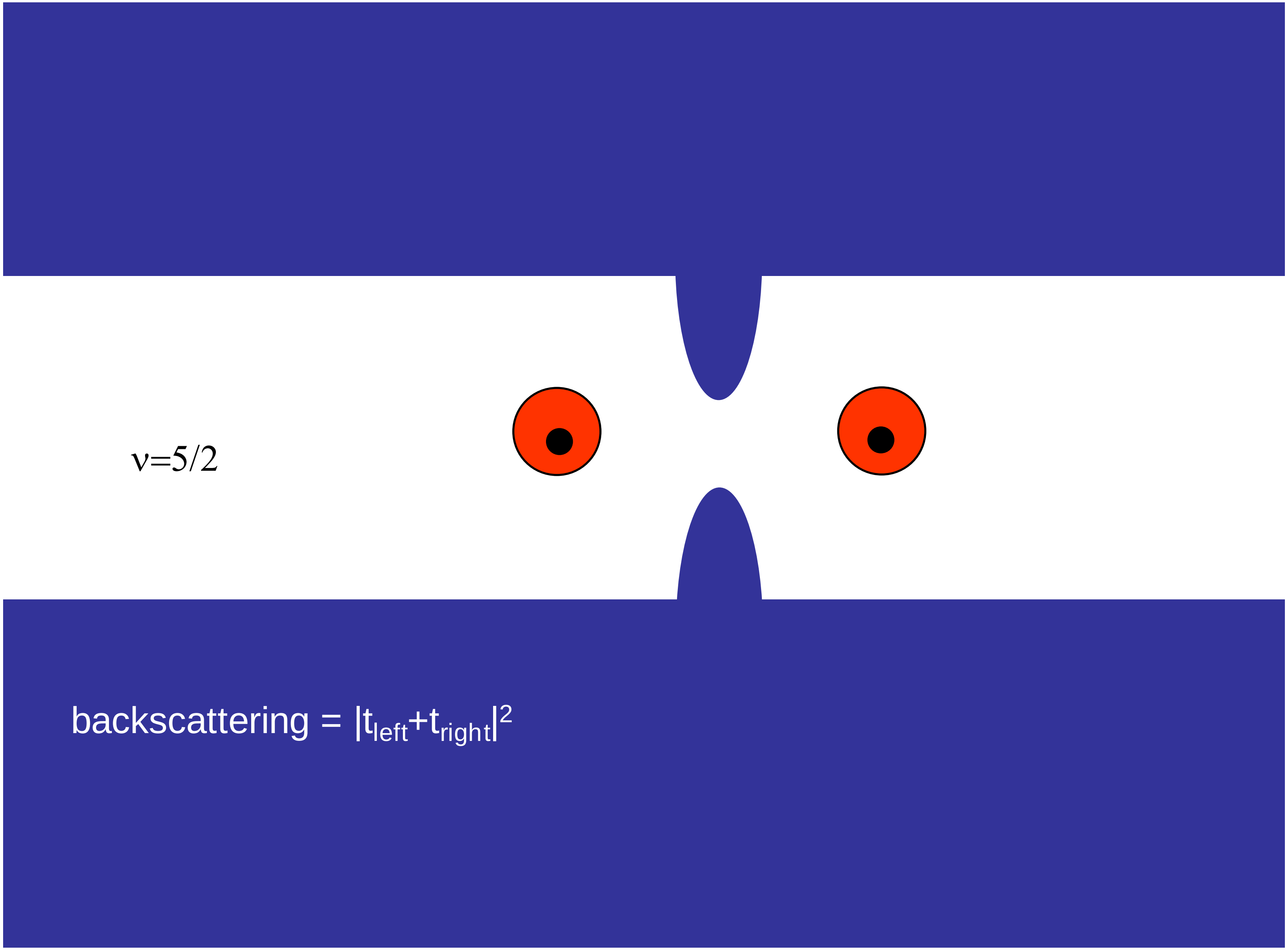
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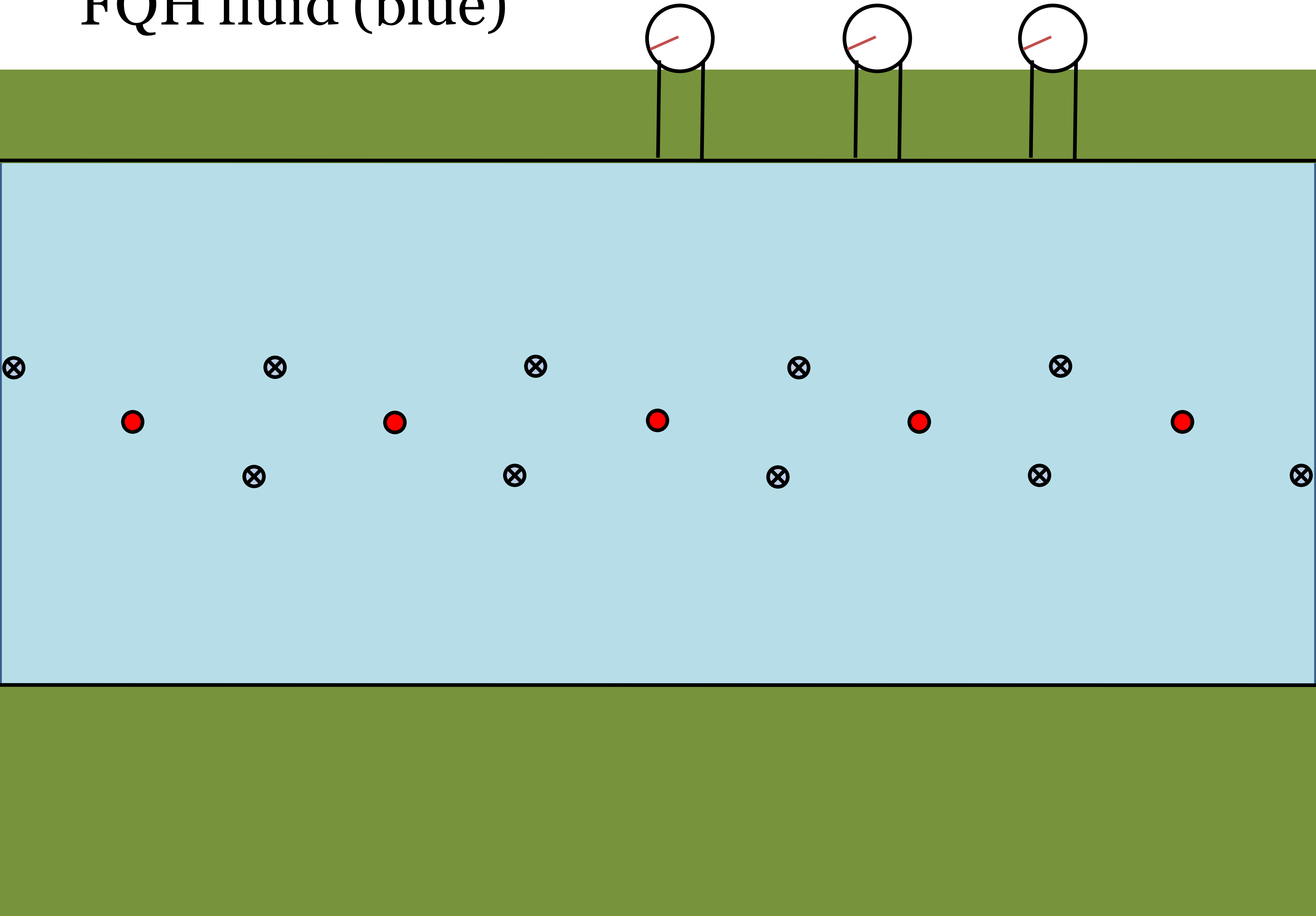
FQH fluid (blue)



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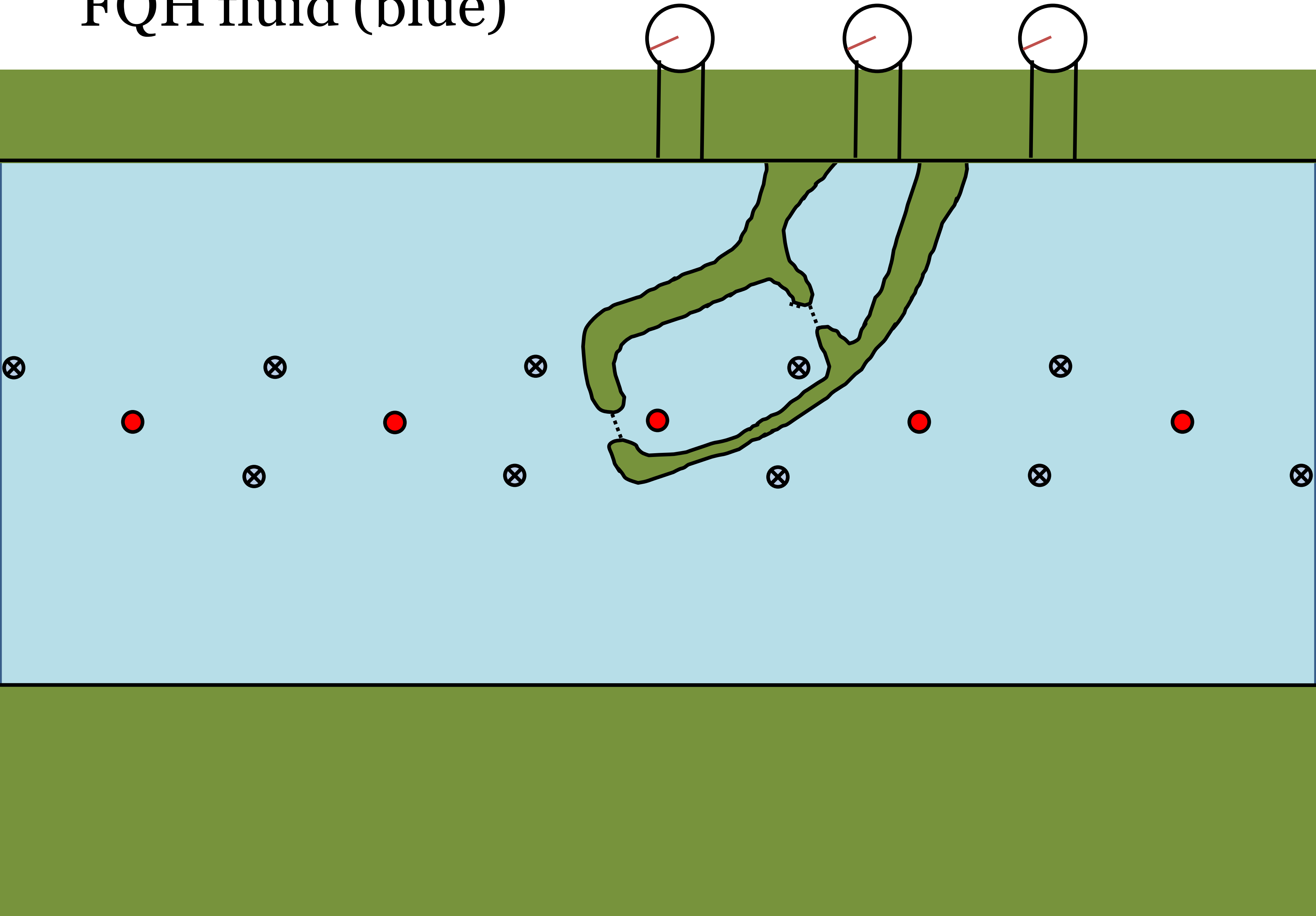

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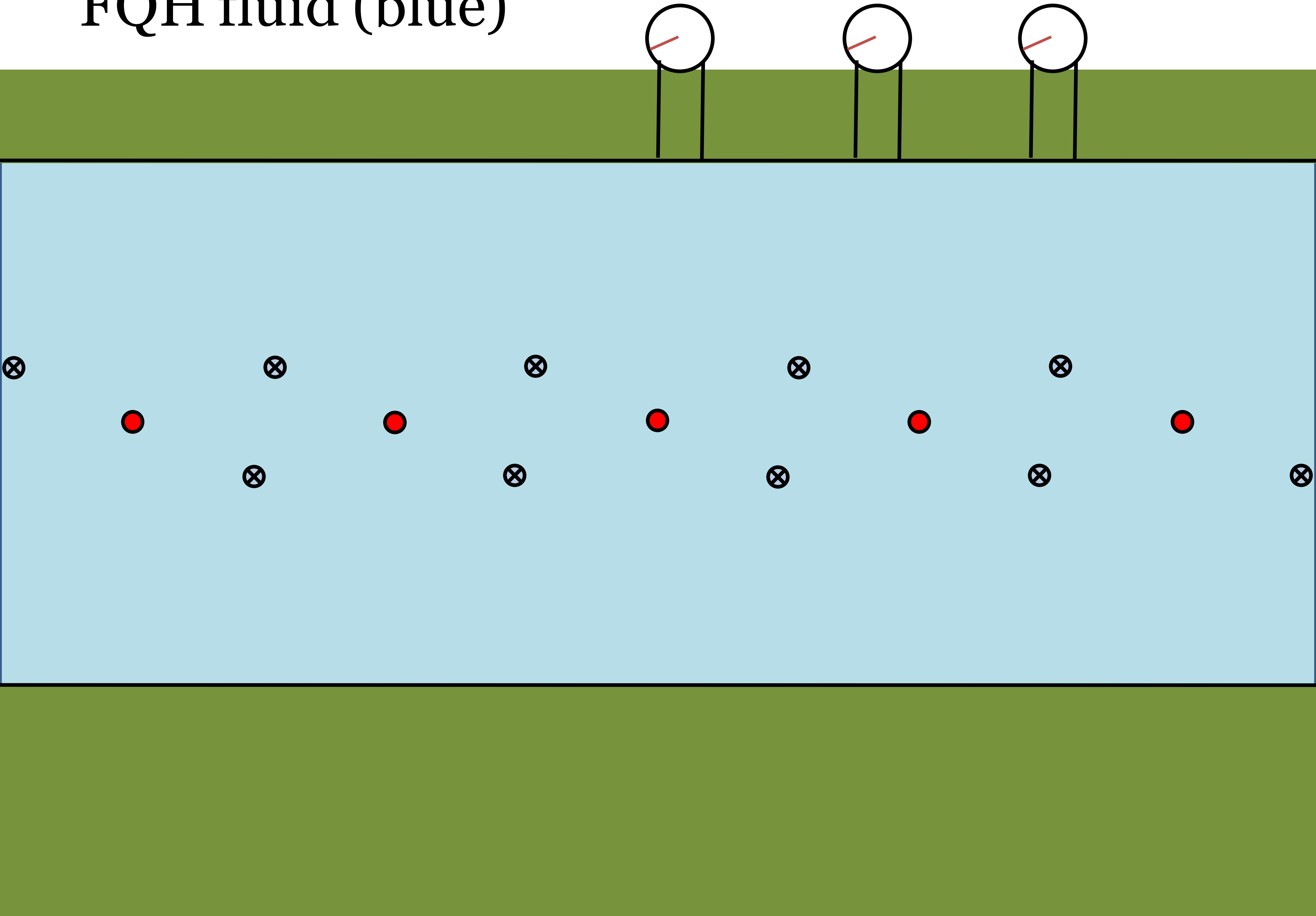

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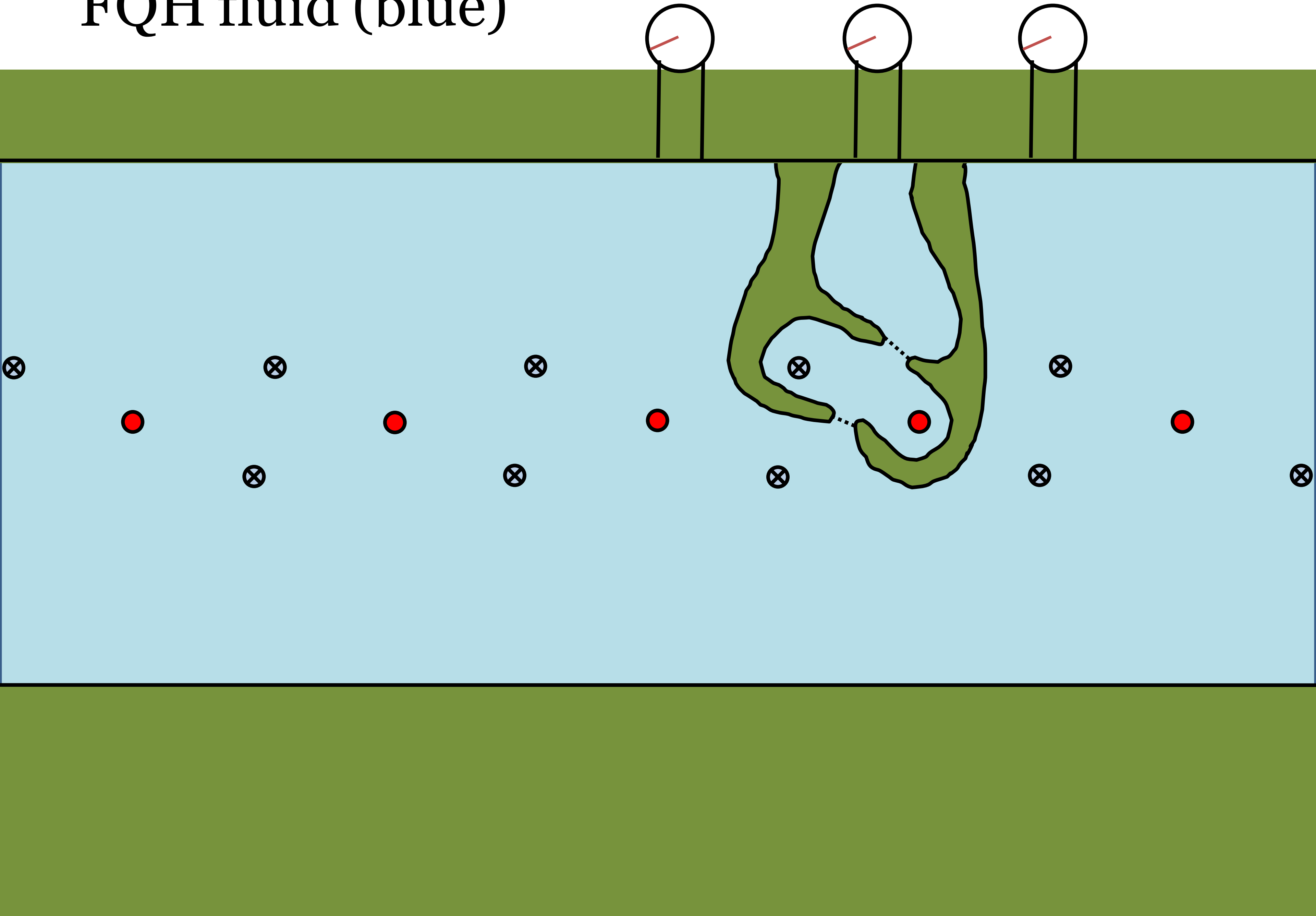

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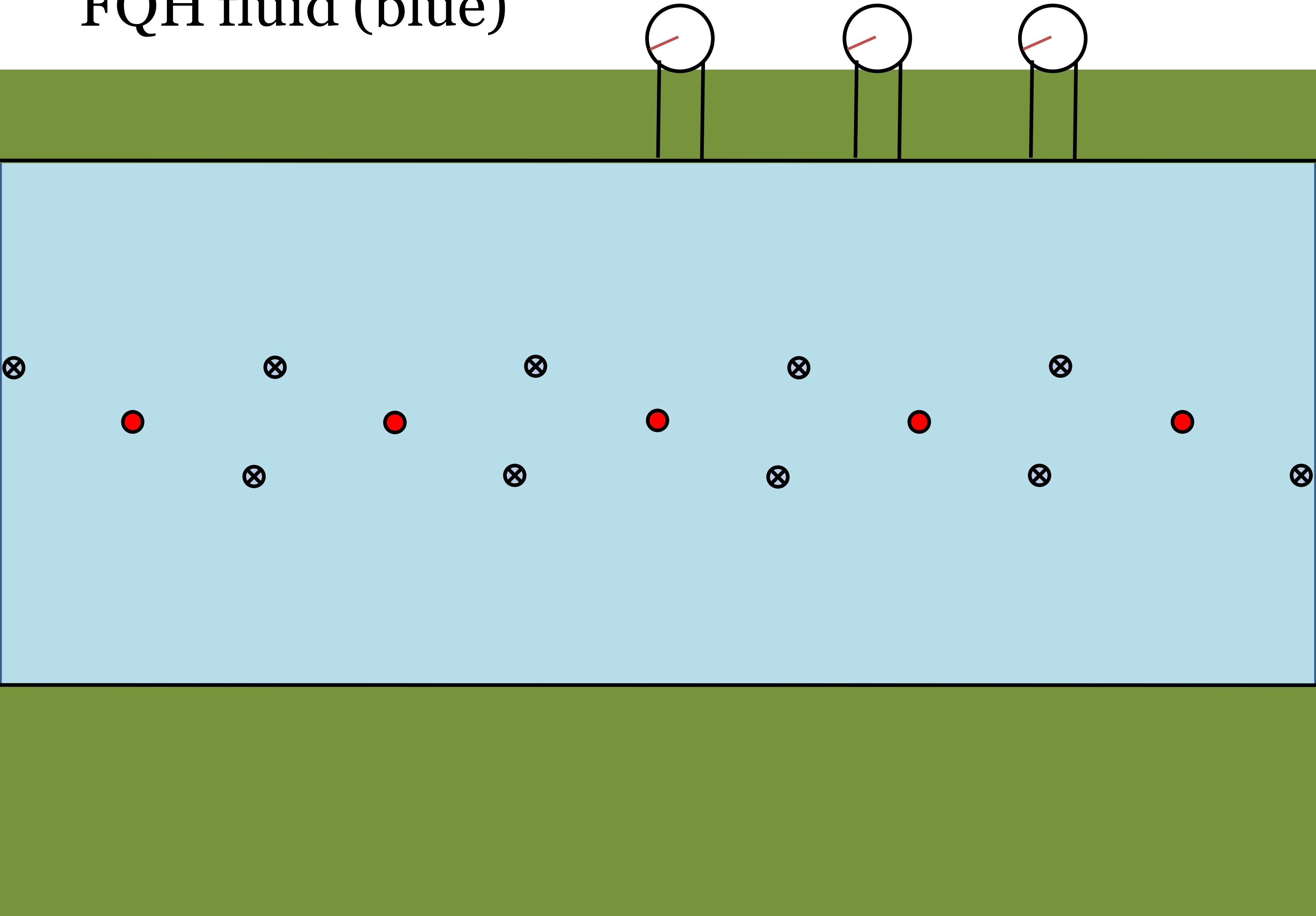

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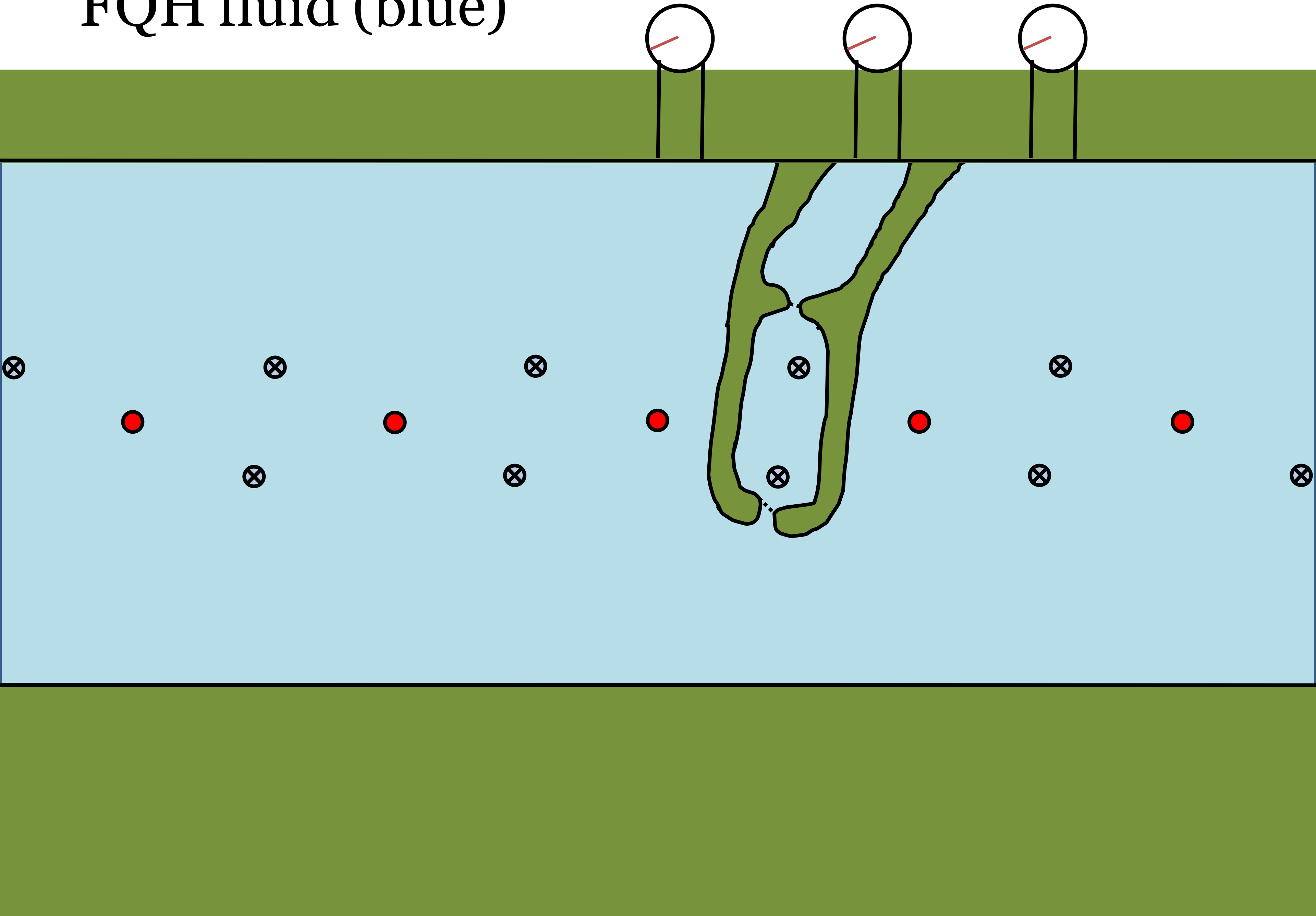

Use an ancilla and “forced measurements” to simulate braiding.

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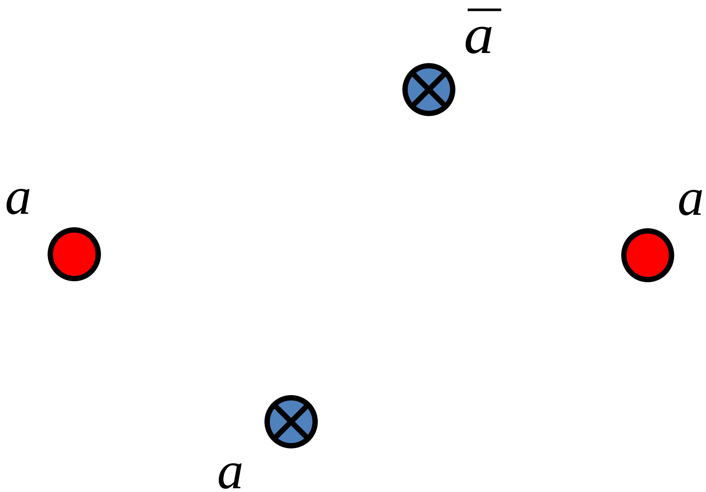

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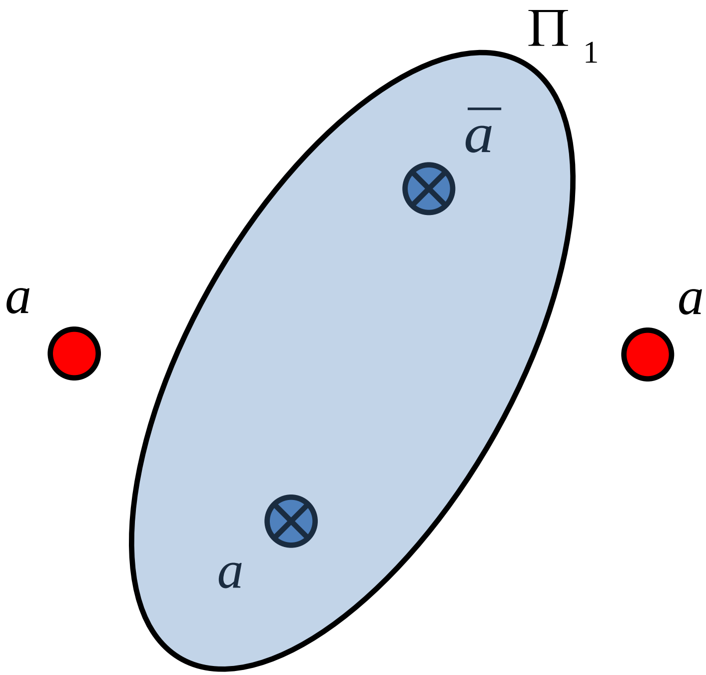

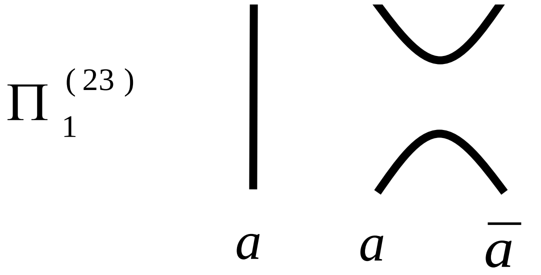

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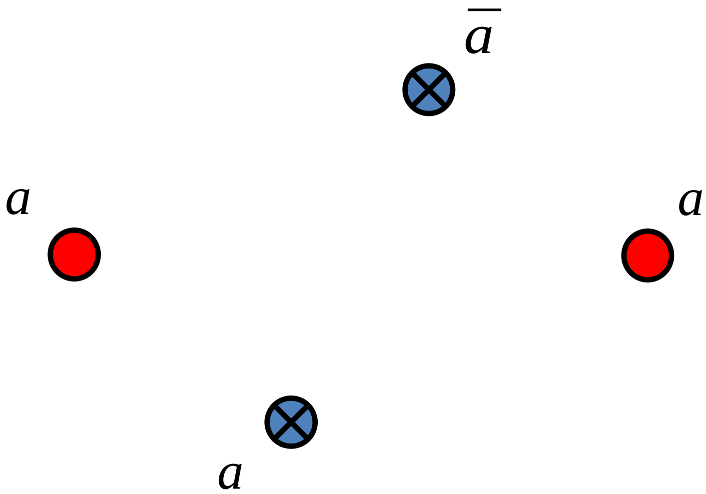
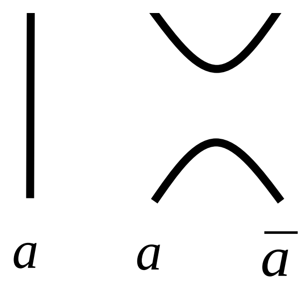


$\Pi_1^{(23)}$



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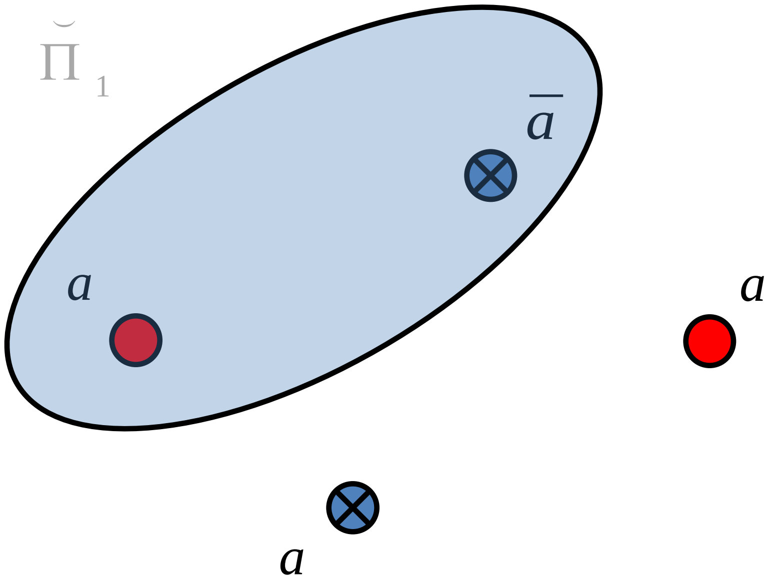

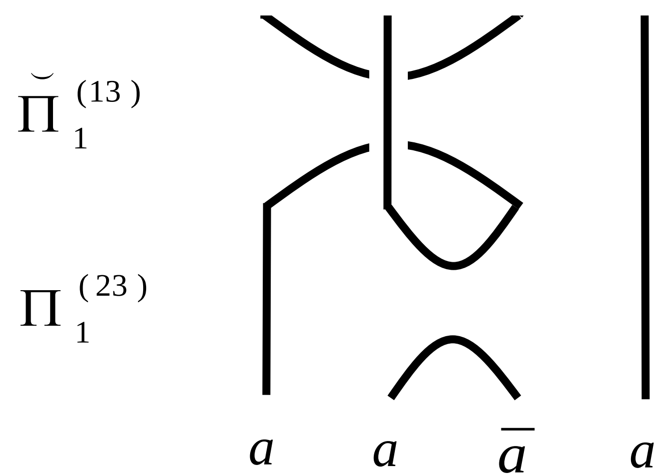

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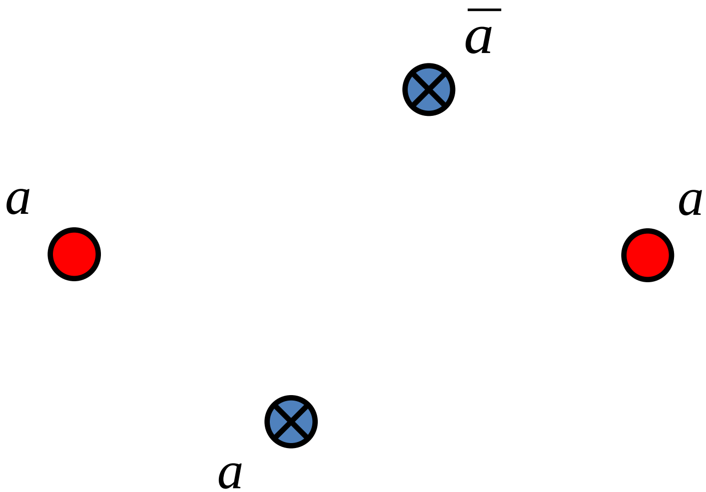

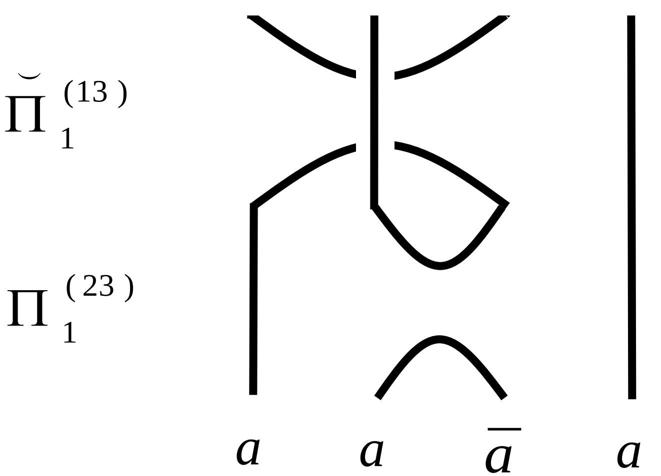

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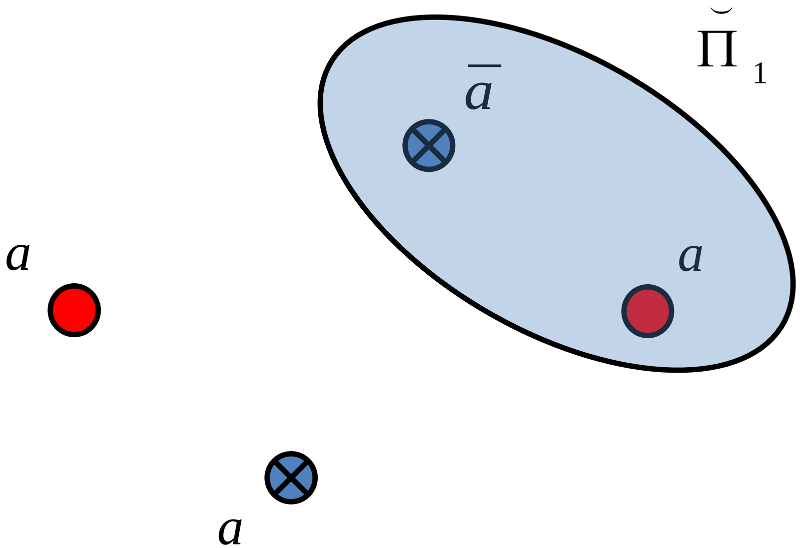

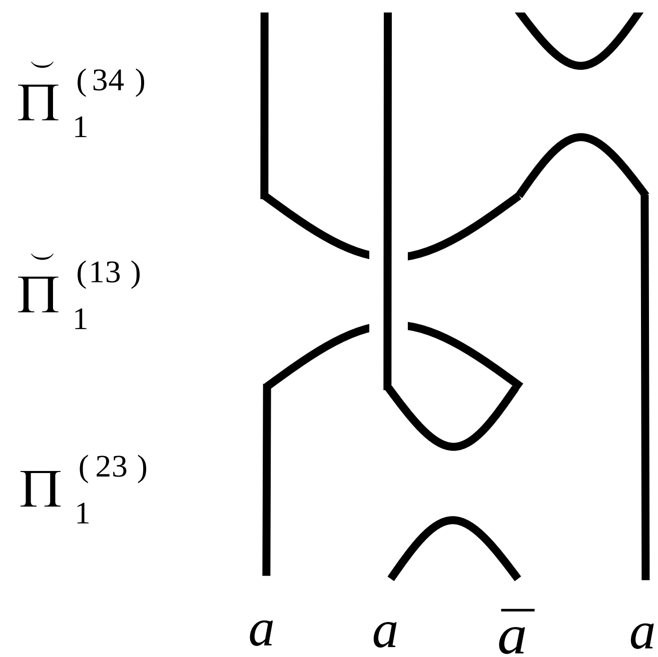

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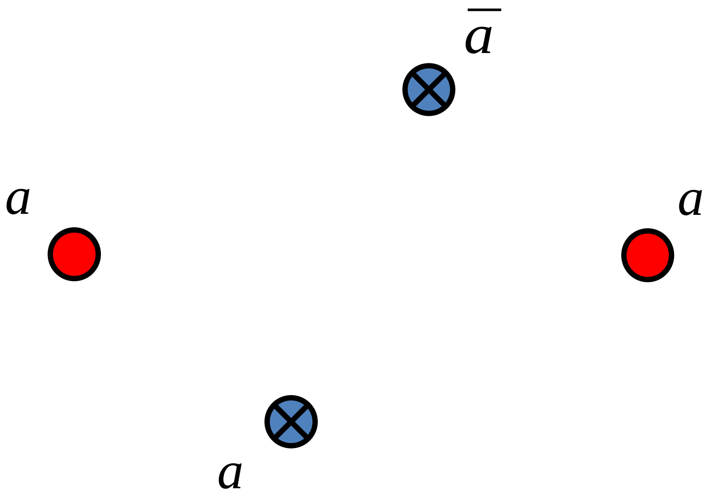

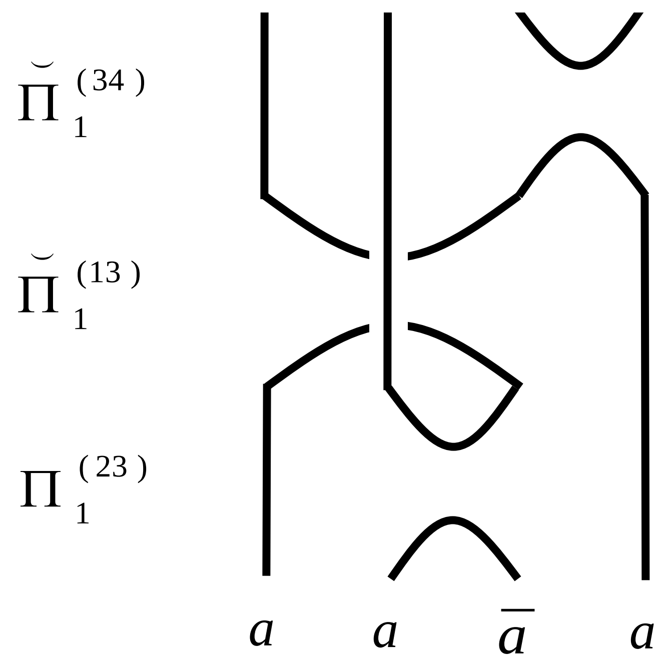

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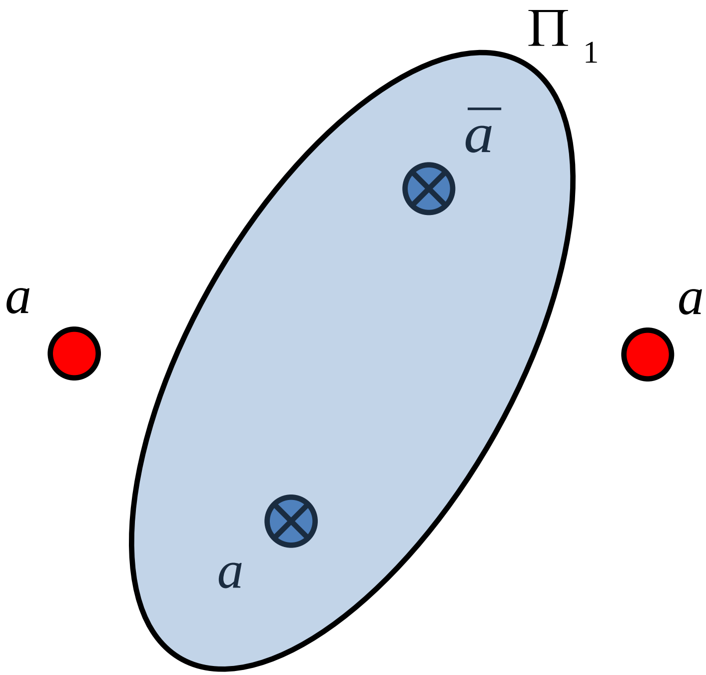
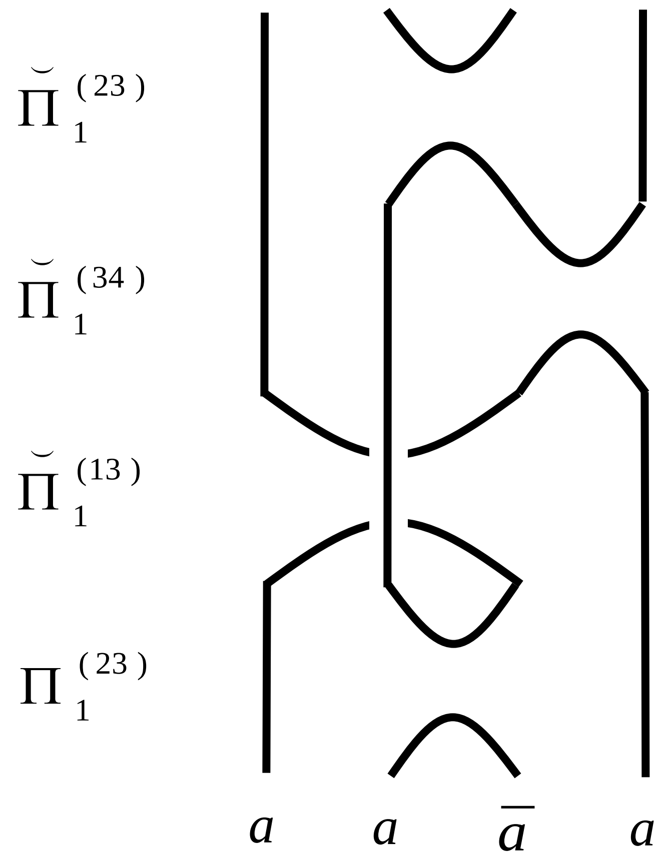
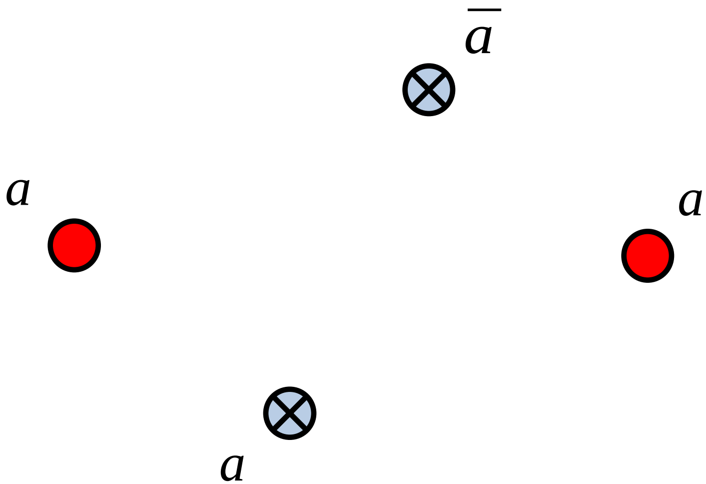
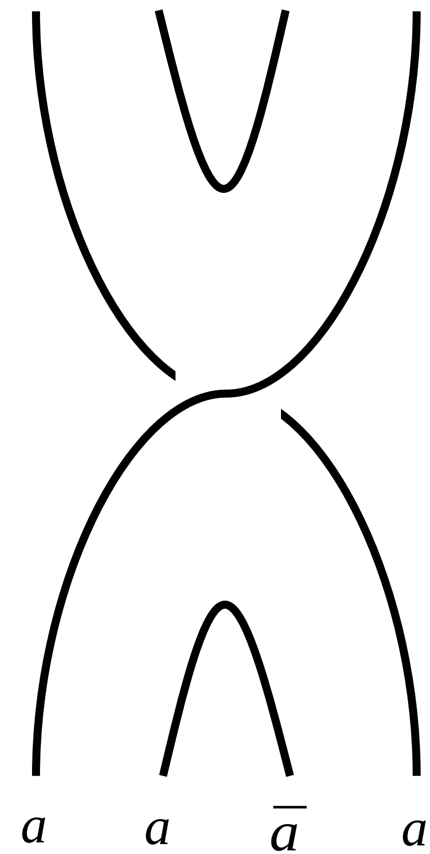




Measurement Simulated Braiding!



$$\breve{\Pi}_1^{(23)}\breve{\Pi}_1^{(34)}\breve{\Pi}_1^{(13)}\Pi_1^{(23)} = R^{(14)} =$$



What will a quantum computer do?

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"Everything that will ever be possible."

What will a quantum computer do?

"Everything that will ever be possible."

This very bold answer is supported by the belief that the underlying physics of our universe is quantum mechanical and once we leave behind our classical 0's and 1's and harness QM, physics will permit nothing further.

But what is “everything”?

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- What can be computed?

But what is "everything"?

- What can be computed?

- What can be known?

But what is “everything”?

- What can be computed?
- What can be known?
- Without quantum computers with which to play, we only have limited hints from theory:

What might a quantum computer do?

What might a quantum computer do?

- (1) Wreak havoc: Break all classical codes

Panic on Wall Street

- (2) Allow physicists to explore exotic states of matter

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  - Strongly correlated electron systems

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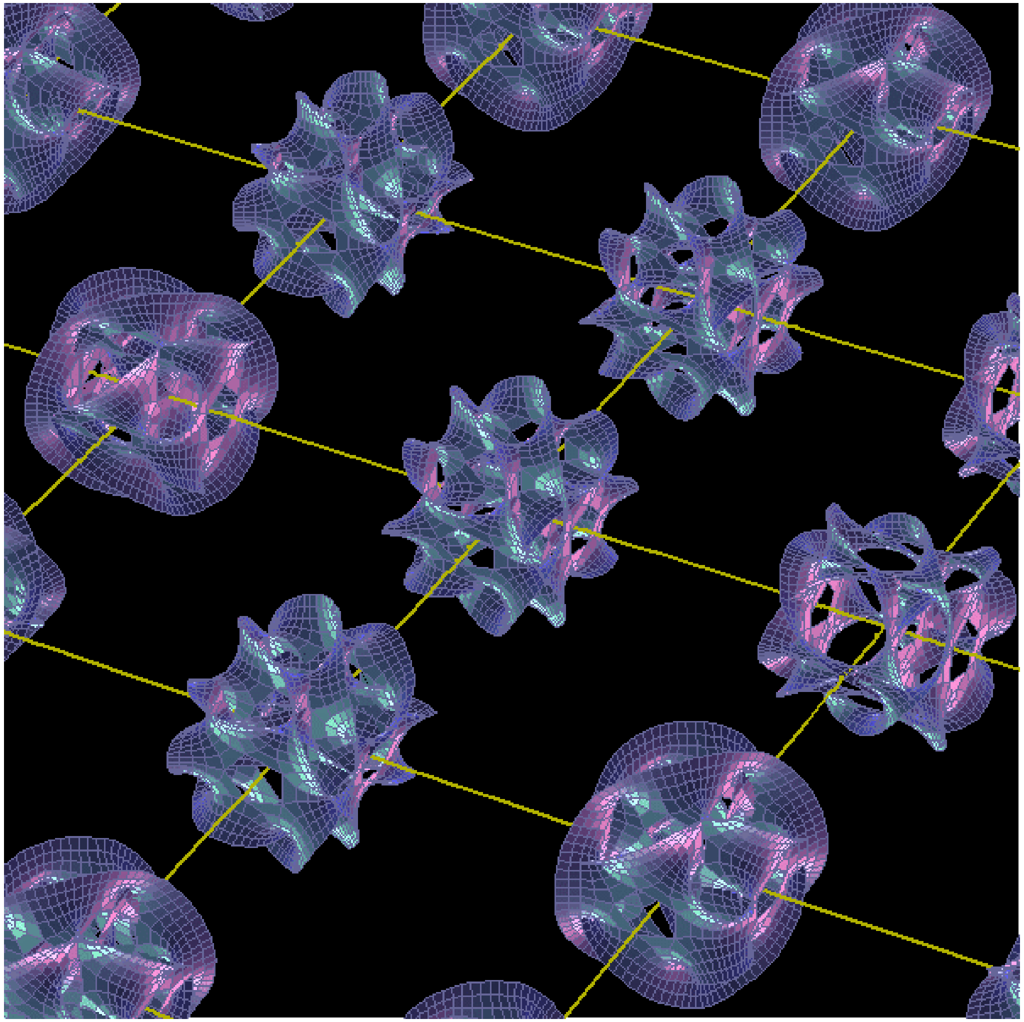
    - Exotic magnets

- (3) Compute string theories ?



• (4) Allow chemists / pharmacologists to design drugs?

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- (5) Artificial intelligence?

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  - In 1950, Alan Turing predicted :
    - Computing power would grow fast (it grew faster)
    - By 2000 we would have a hard time saying that machines were not thinking. (did not happen)

- Without claiming that *our* brains are quantum mechanical, "superposition" does appear to resemble the "background" of facts that guide our thoughts. Both are kinds of parallelism. Thus, the quantum computer might give AI a new lease on life.

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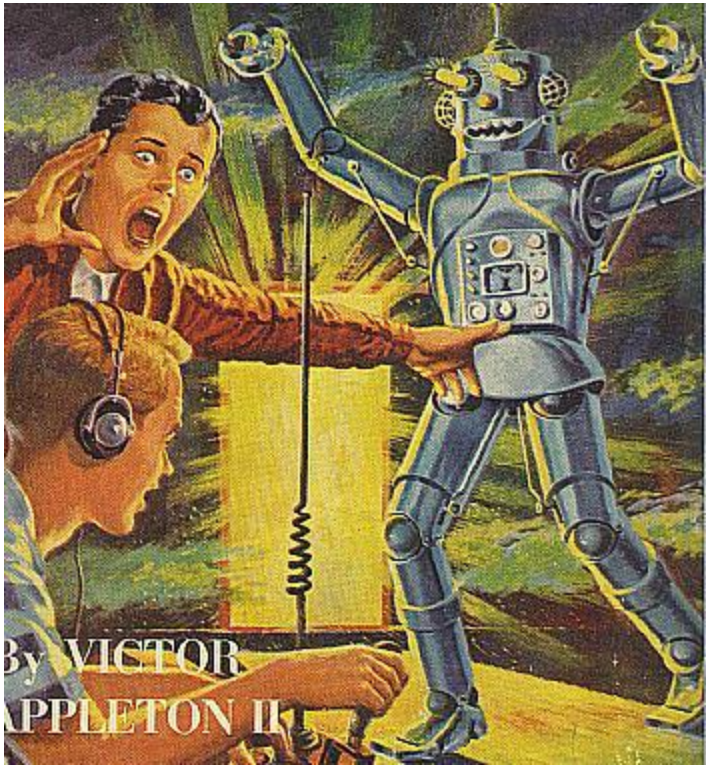
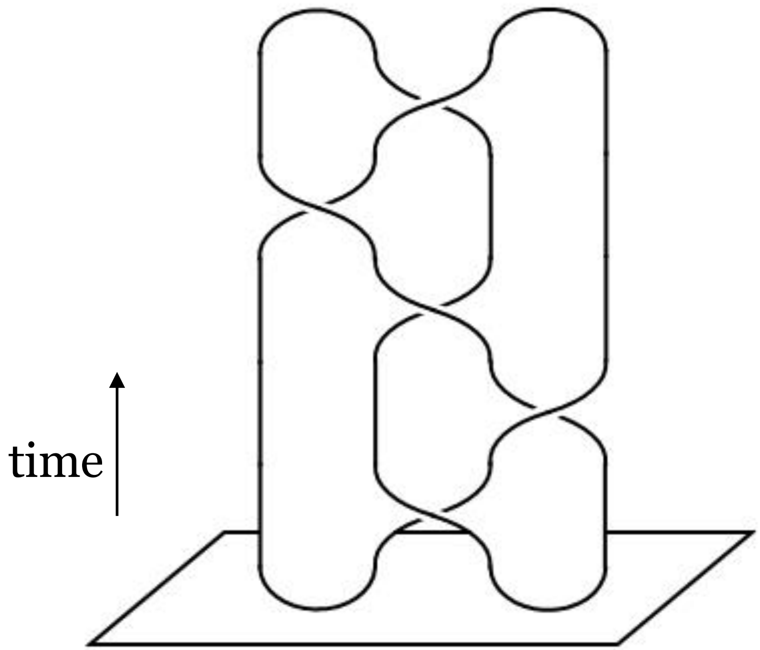


Recall: The "old" computation scheme



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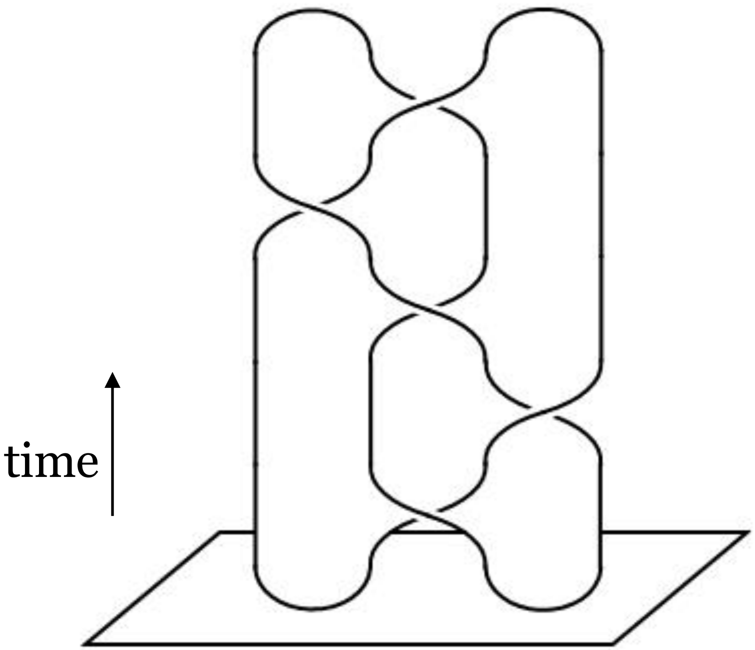

Initial ψ_0 out of vacuum

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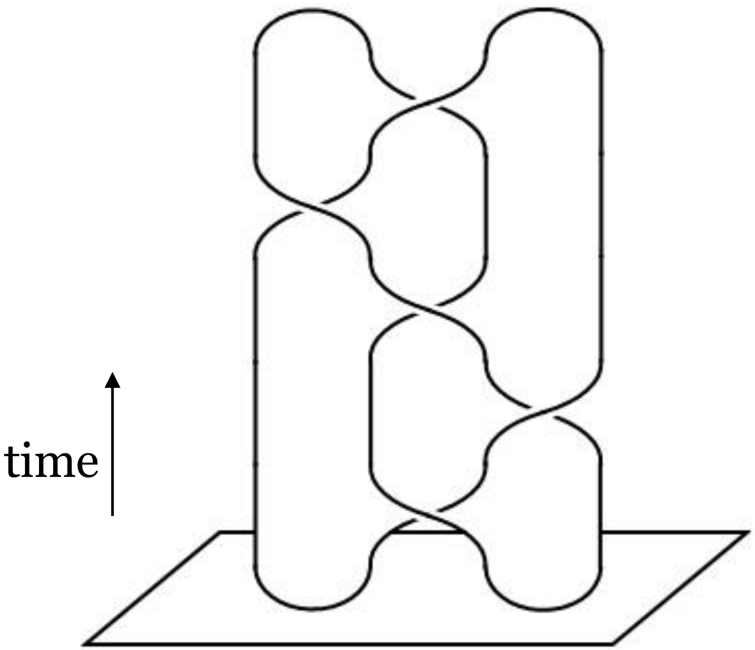

Braiding = program

↑

Initial ψ_0 out of vacuum

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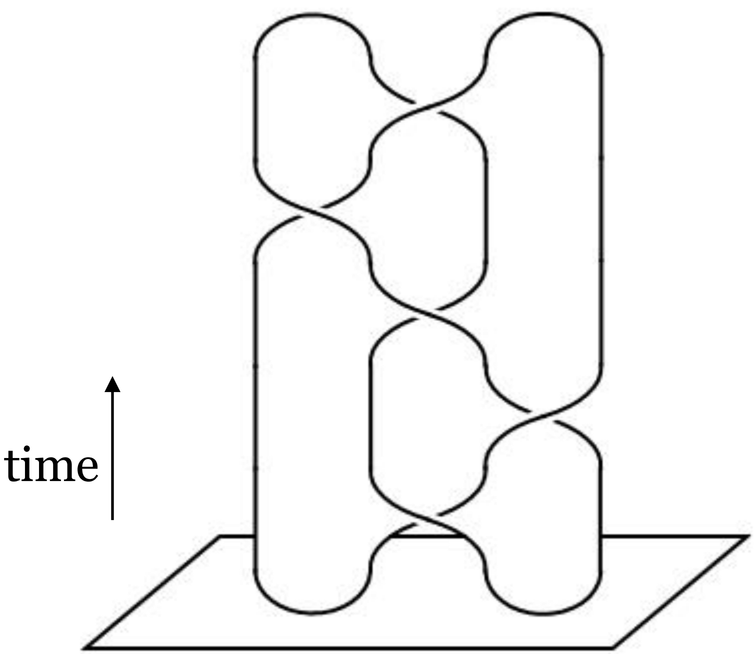


Measurement (return to vacuum)

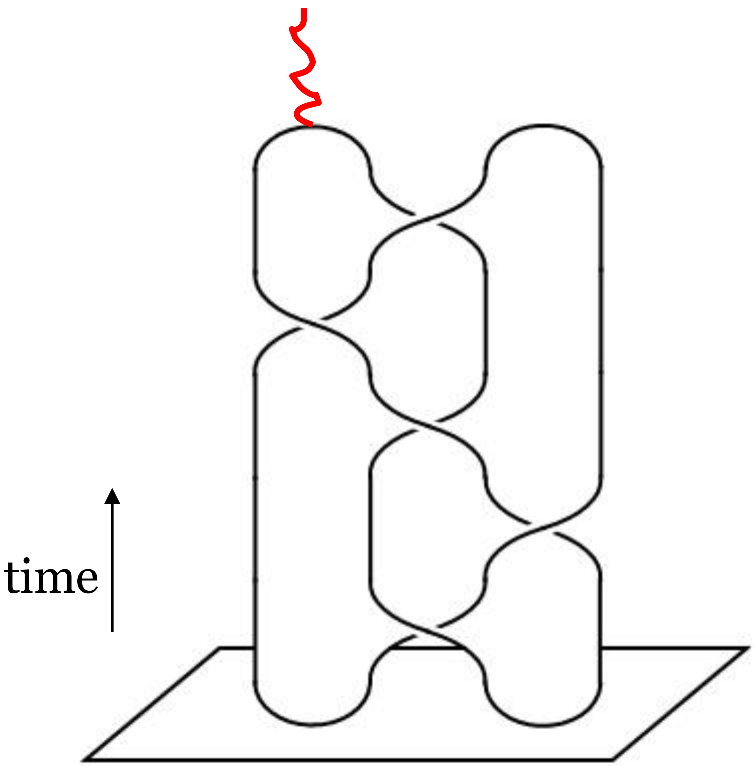
↑

Braiding = program

↑

Initial ψ_0 out of vacuum

Recall: The “old” computation scheme



Measurement (return to vacuum)
(or not)

↑

Braiding = program

↑

Initial ψ_0 out of vacuum

New Approach: measurement

↓

"forced measurement"

↓

motion

↓

braiding

New Approach: measurement

↓

"forced measurement"

↓

motion

↓

braiding

New Approach: measurement
↓
"forced measurement"
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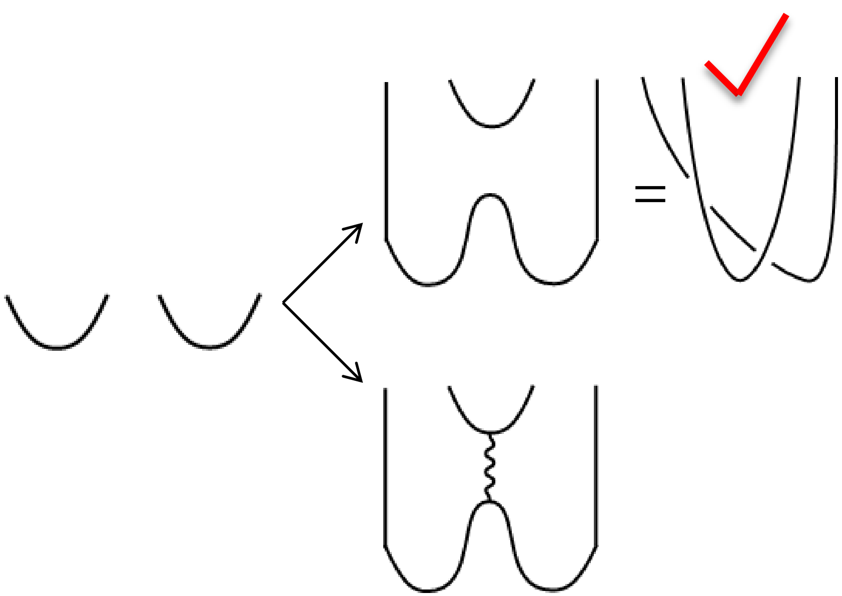
motion
↓
braiding



<u>New</u> Approach: measurement

↓

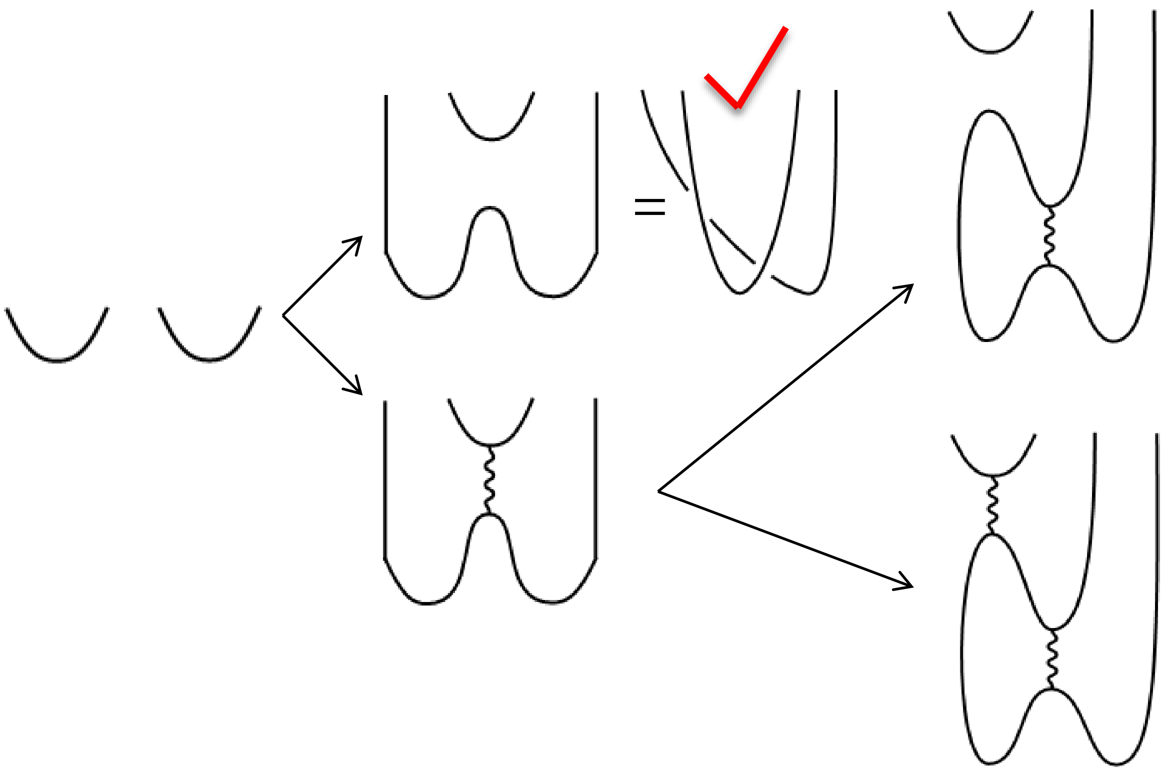
"forced measurement"

↓

motion

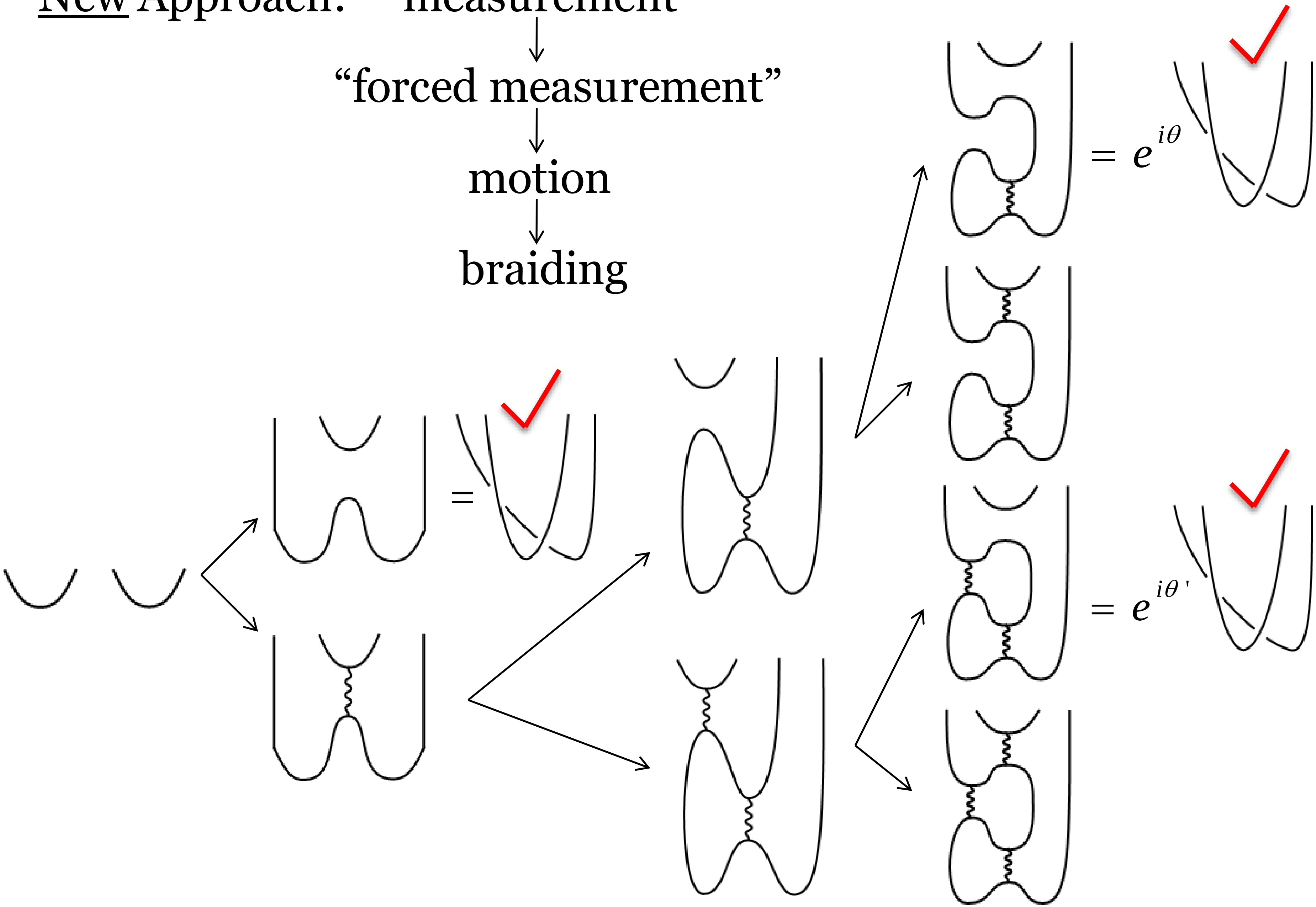
↓

braiding

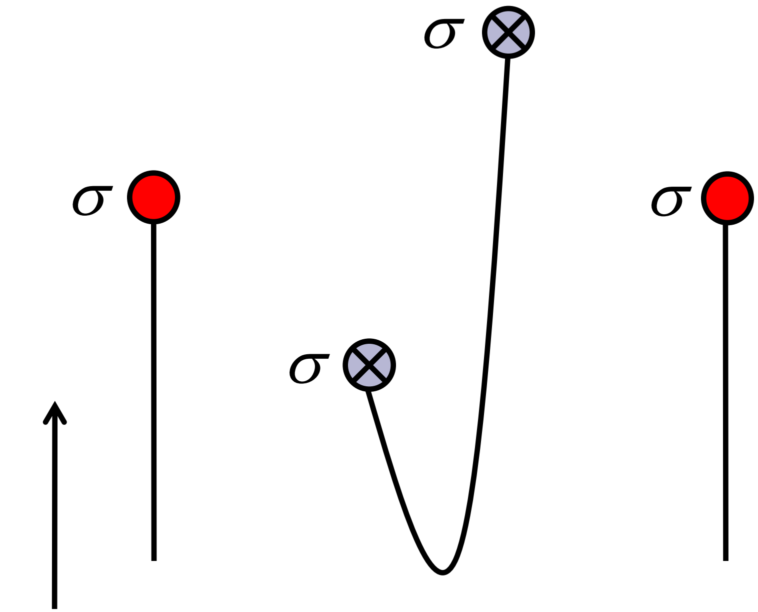


New Approach:

measurement
↓
"forced measurement"
↓
motion
↓
braiding



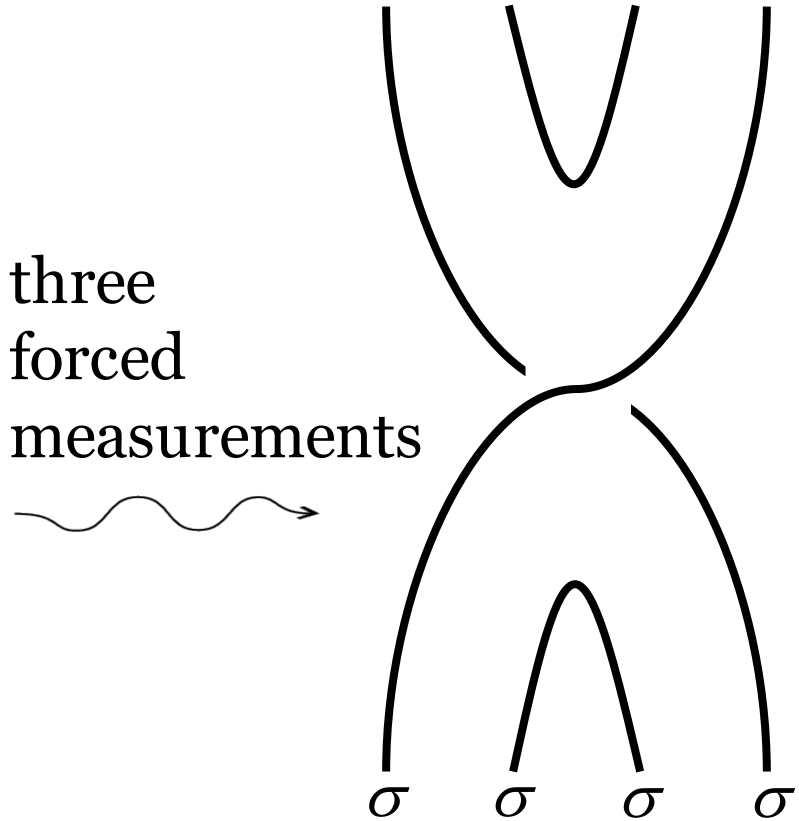
Forced Measurement ⟹ Braiding



time

ancilla birth

three
forced
measurements



In Detail