

# An Armchair Guide:

To Quantum Mechanics



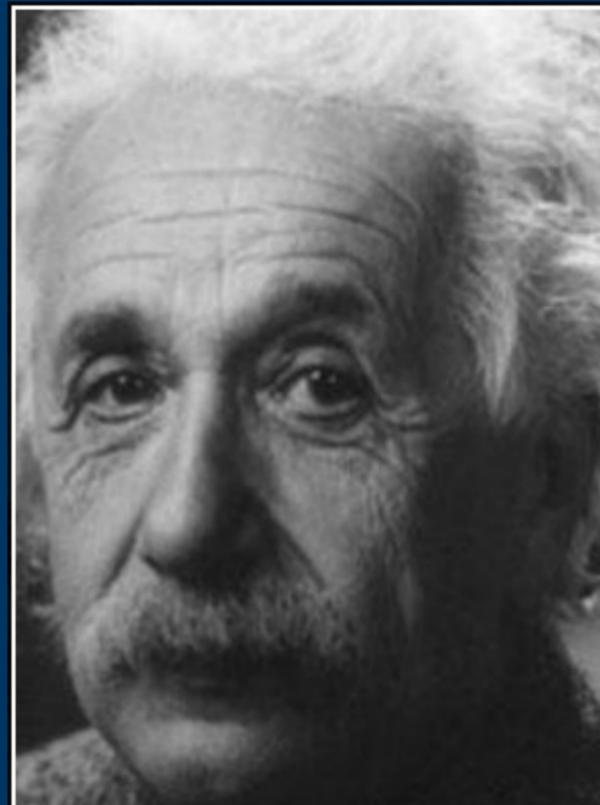
Jonathan Allday



# Session 3:

## Spooky action at a distance

When the left hand has an implicate influence on the right....



I cannot seriously believe in it [quantum theory] because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance [spukhafte Fernwirkungen].

— *Albert Einstein* —

AZ QUOTES

# Revision

Photon at a beam splitter

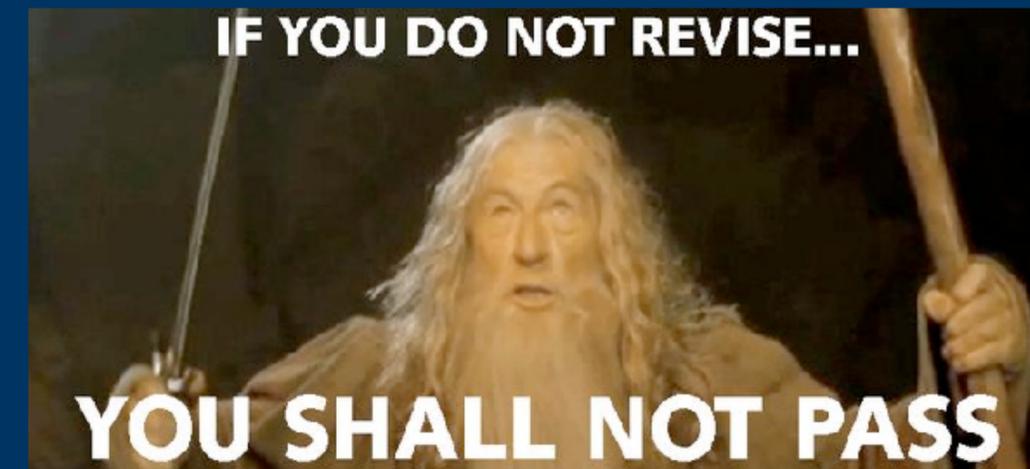


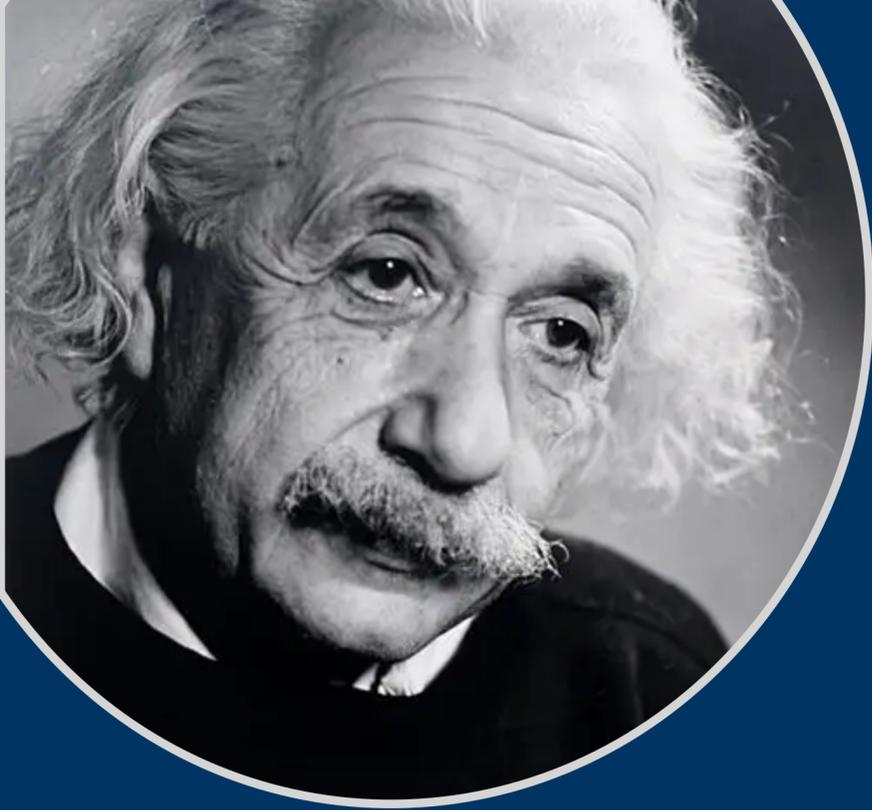
Either **reflects** or **transmits**

As a **whole** - does not split in two...

**Nothing** about the photon **prior to arriving** allows us to **predict** what it will do

Inherently **random**....



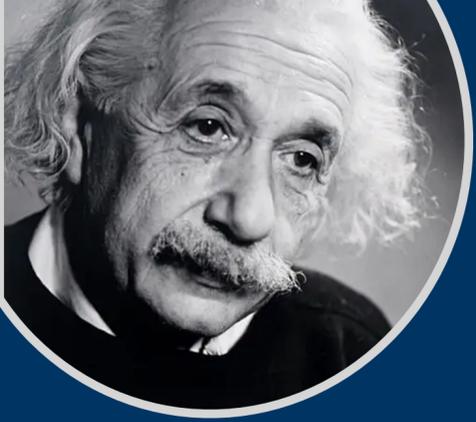


# The big guy is not happy...

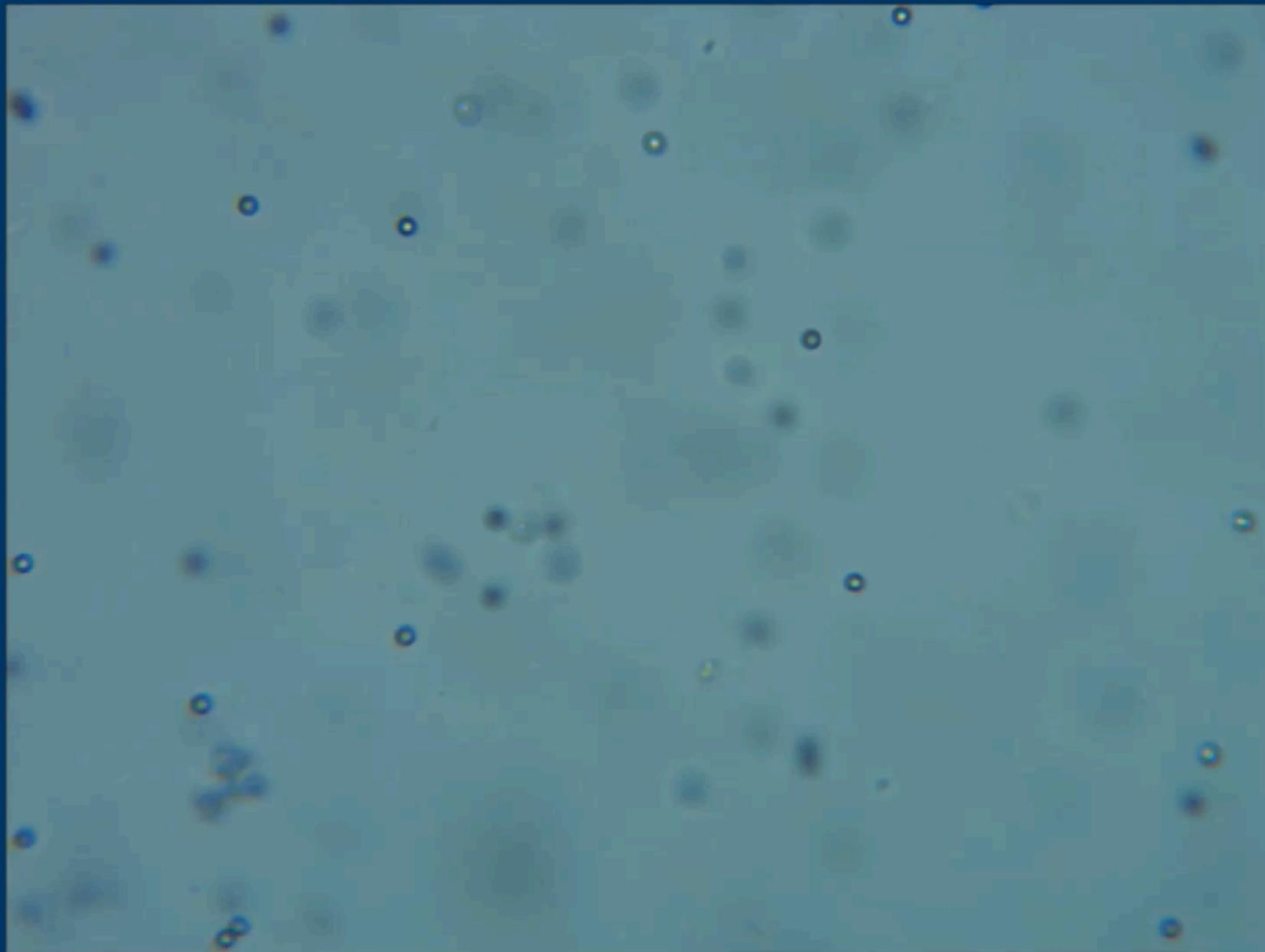
Quantum mechanics is certainly **imposing**. But an **inner voice** tells me that it is **not yet the real thing**. The theory **says a lot**, but does not really **bring us any closer to the secret of the 'Old One'**. I, at any rate, am convinced that **He does not throw dice**.

Within the framework of **statistical quantum theory** there is no such thing as a **complete description of the individual system**. ... The attempt to conceive the quantum-theoretical description as the complete description of individual systems leads to **unnatural theoretical interpretations**

The present **quantum theory** is unable to provide the **description of a real state of physical facts**, but only of **an (incomplete) knowledge of such**



“the trajectories are confused and complicated so often and so rapidly that it is impossible to follow them”



## Brownian Motion

Jiggling of tiny particles in a liquid

Apparently random

Analysed by Einstein

Evidence for atoms...

Invisible (hidden?) objects

Striking the larger visible ones

Not random...

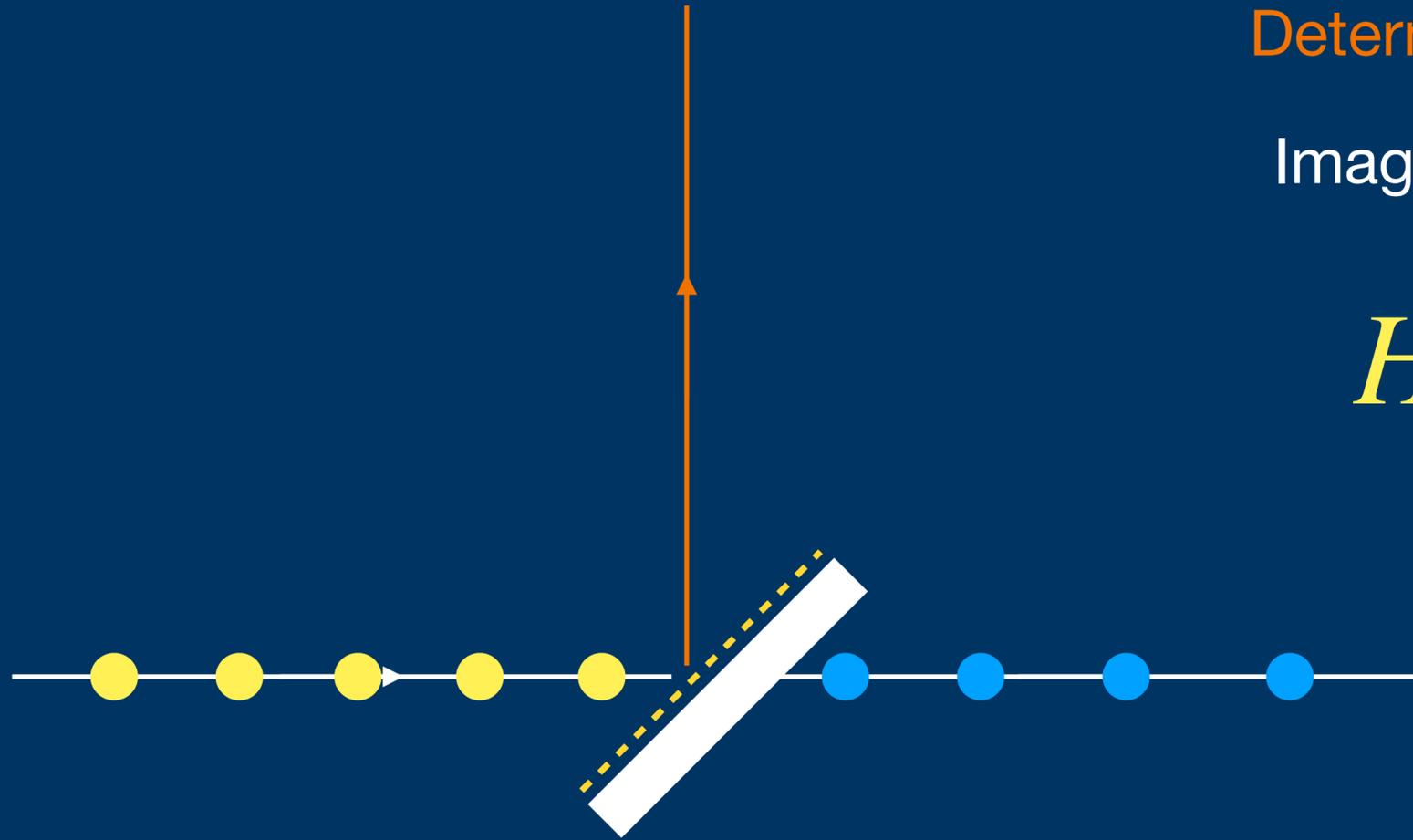
# Hidden variables

Some **physics** **underneath** what we **know**

**Determines** what is **happening**

Imagine a **hidden quantity**,  $H$

$H = 0$  Transmission



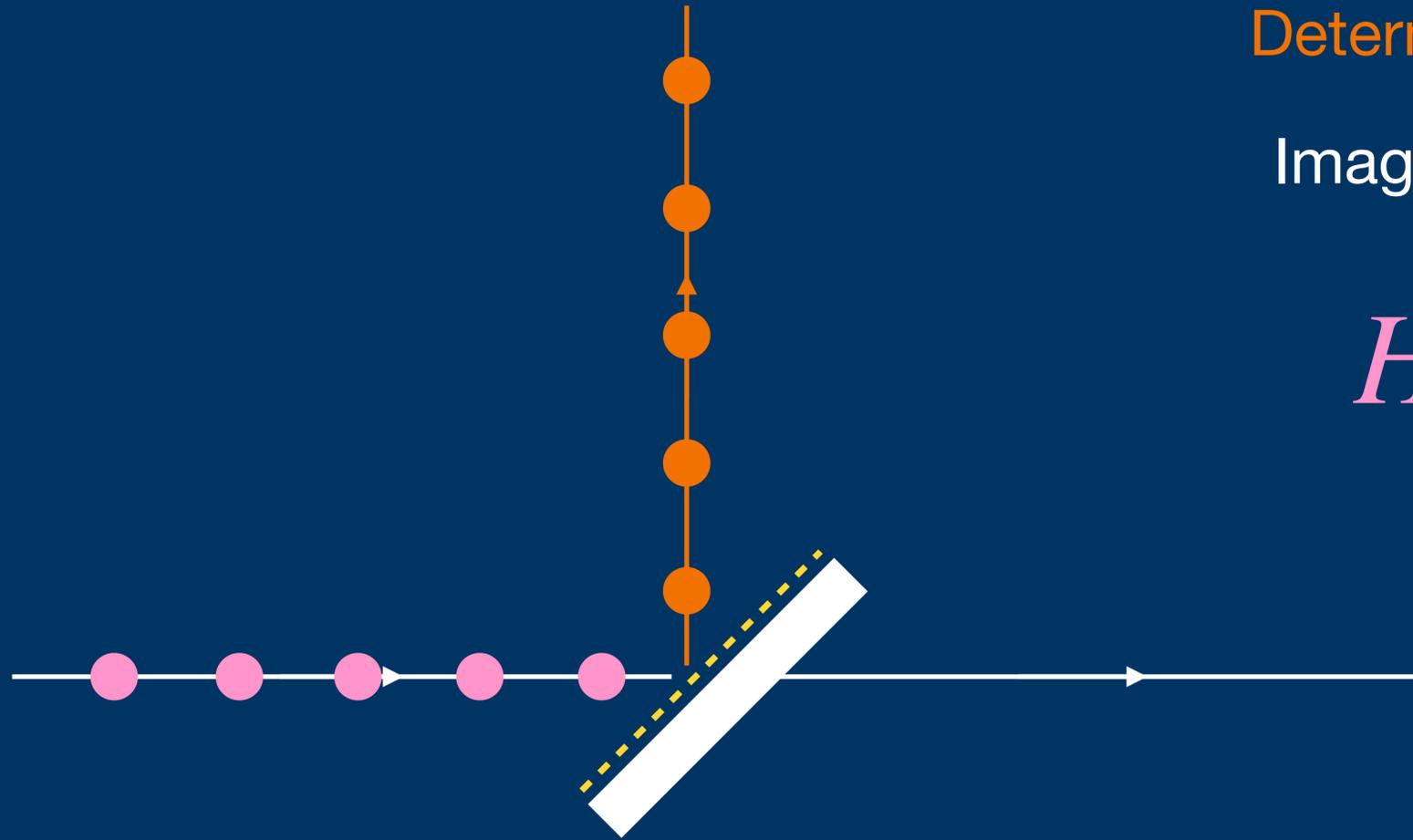
# Hidden variables

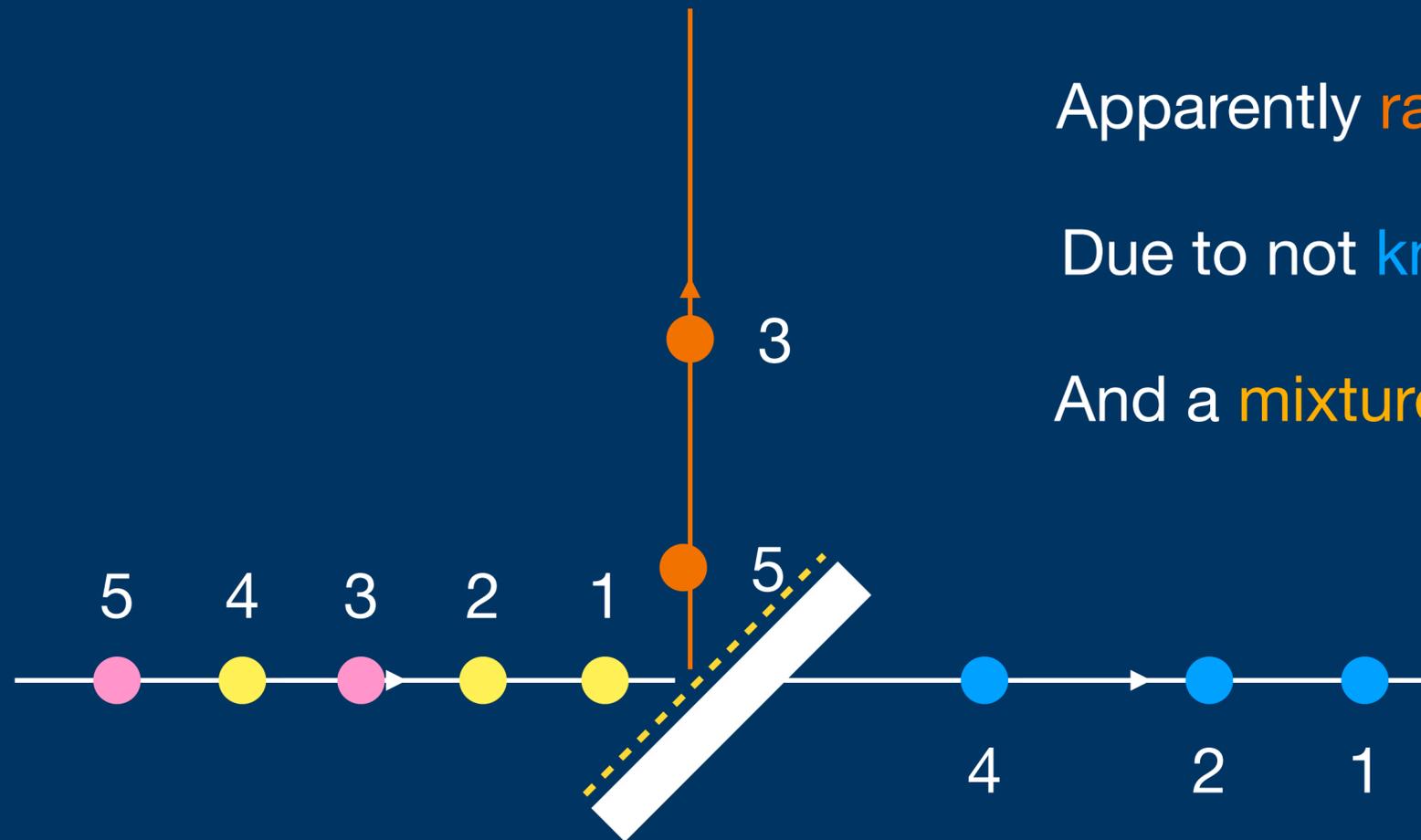
Some **physics** **underneath** what we **know**

**Determines** what is **happening**

Imagine a **hidden quantity**,  $H$

$H = 1$  Reflection





Apparently **random** outcomes

Due to not **knowing** the value of **H**

And a **mixture** present in the **beam**



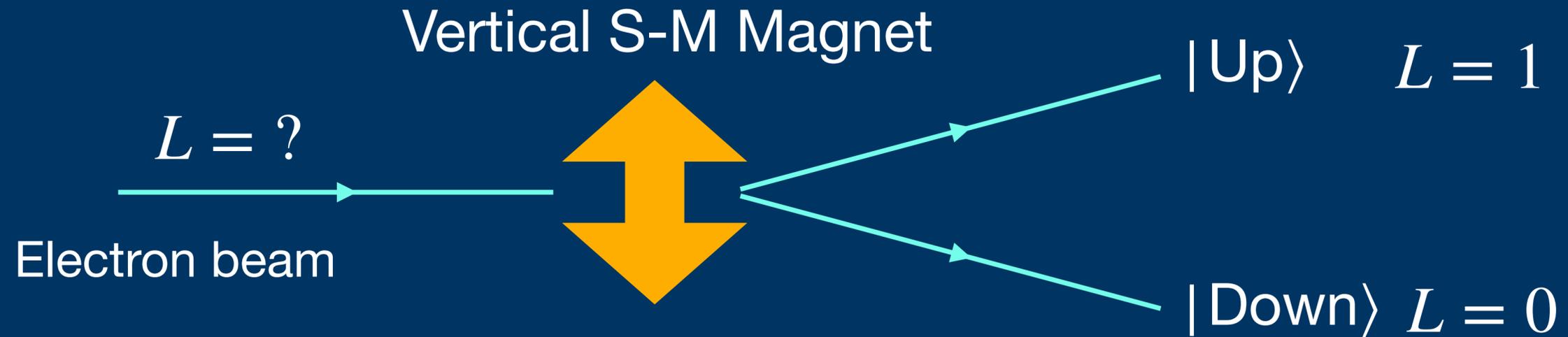
# Apply same idea to spin...

$$L = 1$$

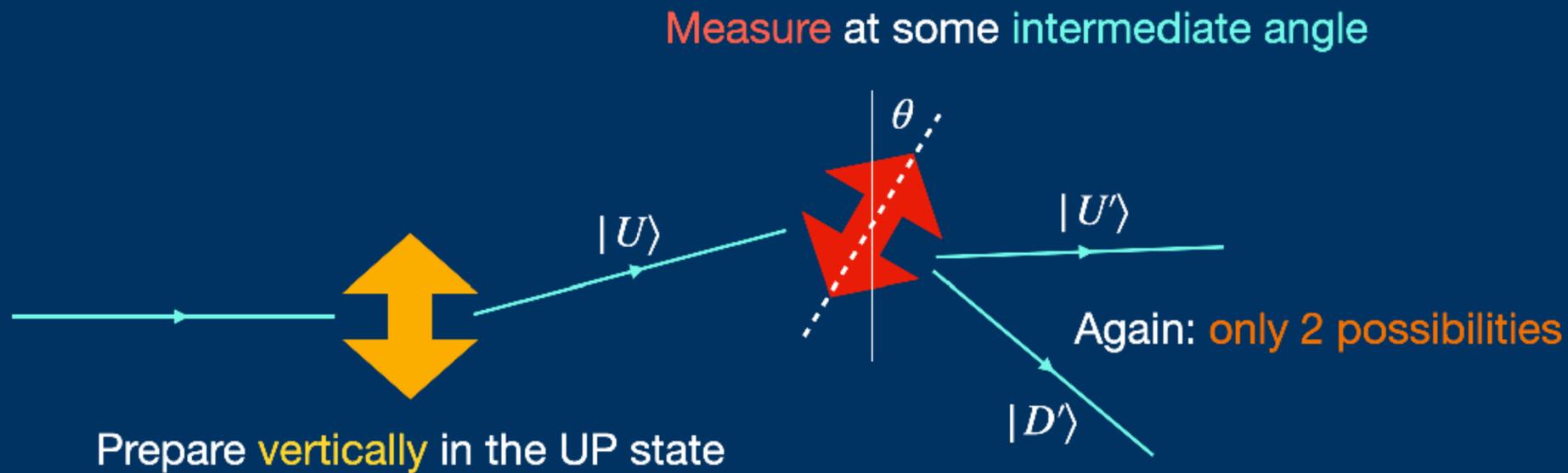
Up

$$L = 0$$

Down



# Theory has to work hard for spin...



If  $\theta = 30^\circ$

$ U'\rangle \rightarrow 93.4\%$	$ U'\rangle \sim \cos^2(\theta/2)$
$ D'\rangle \rightarrow 6.7\%$	$ D'\rangle \sim \sin^2(\theta/2)$

If  $\theta = 0$  (vertical)

$L = 1 \rightarrow |UP\rangle$

$L = 0 \rightarrow |DOWN\rangle$

If  $\theta \neq 0$  (Not vertical)

$L = 1 \rightarrow |UP'\rangle \sim \cos^2(\theta/2)$

$L = 0 \rightarrow |DOWN'\rangle \sim \sin^2(\theta/2)$

Outcome has to depend on  $L$  and  $\theta$

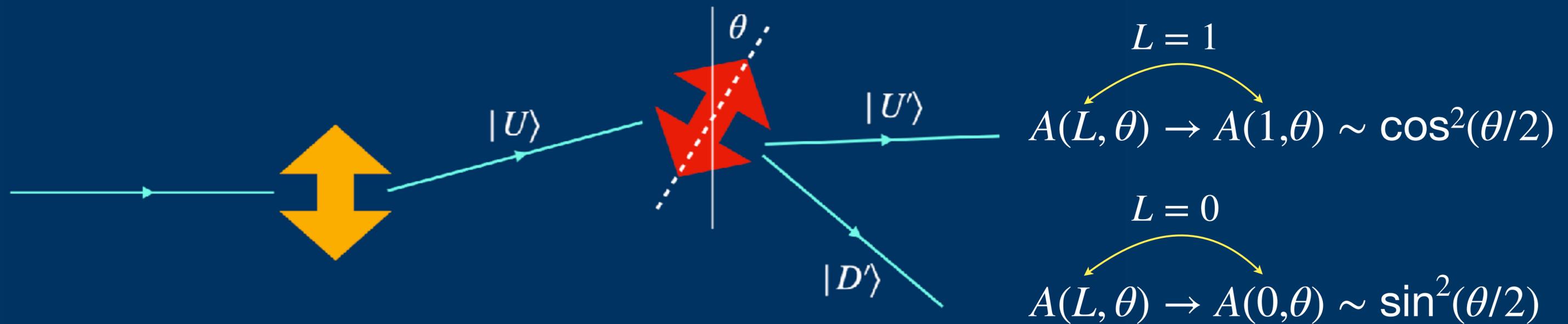
Imagine some mathematical expression

That depends on  $L$  and  $\theta$

Just imagine the possibility

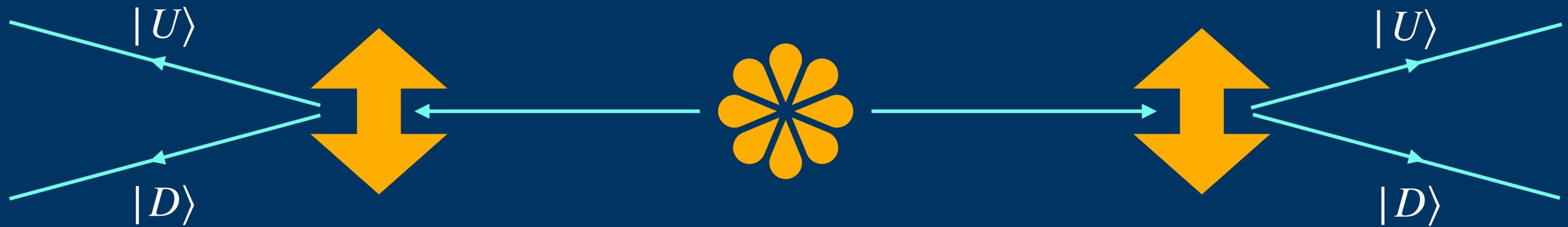


Measure at some intermediate angle



Prepare **two particles** with total spin = 0

Send them off in **opposite directions** to S-G magnets



This side must manifest  $|D\rangle$

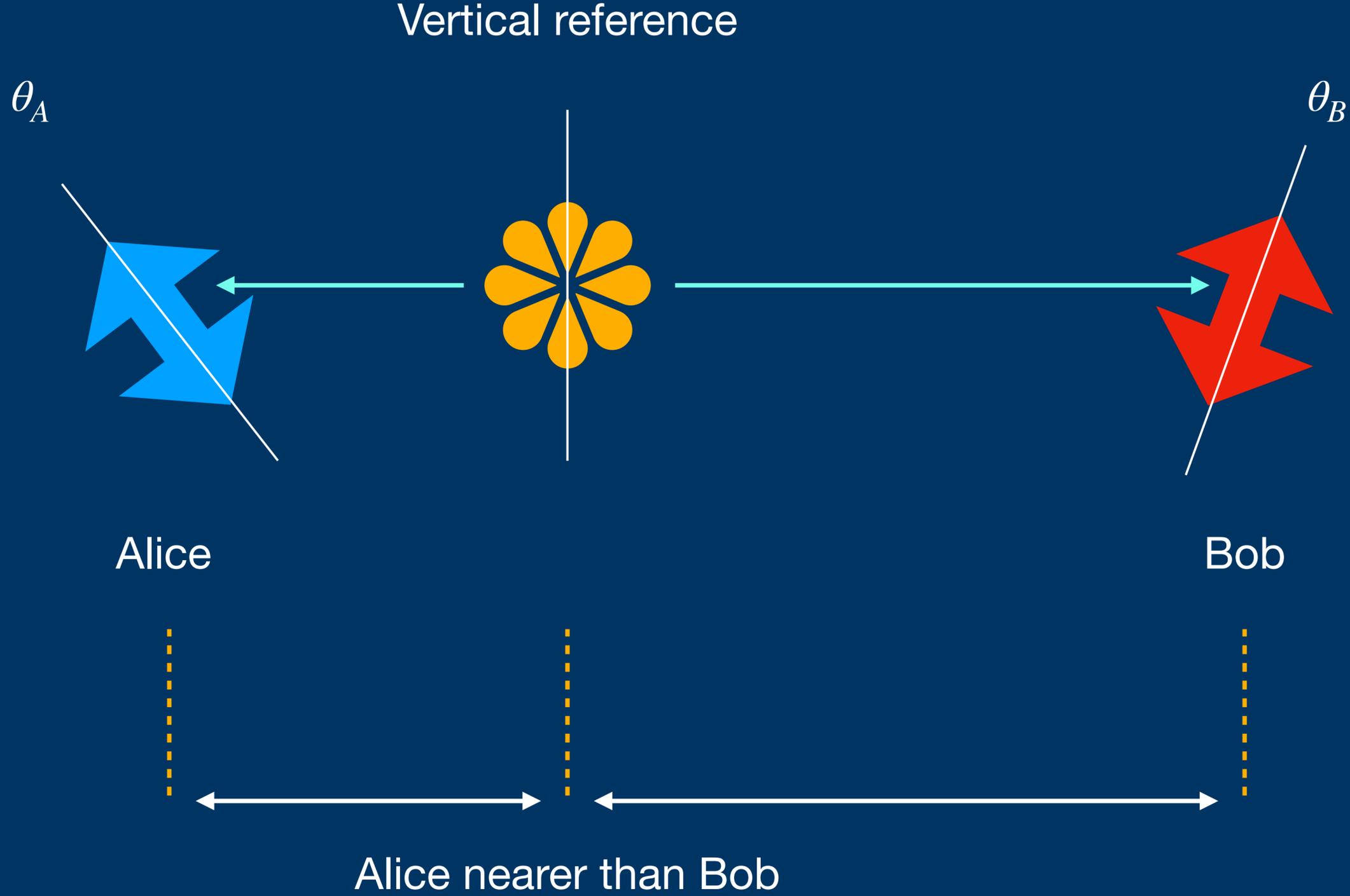
If this side manifests  $|U\rangle$

And vice-versa

About **any angle!!**

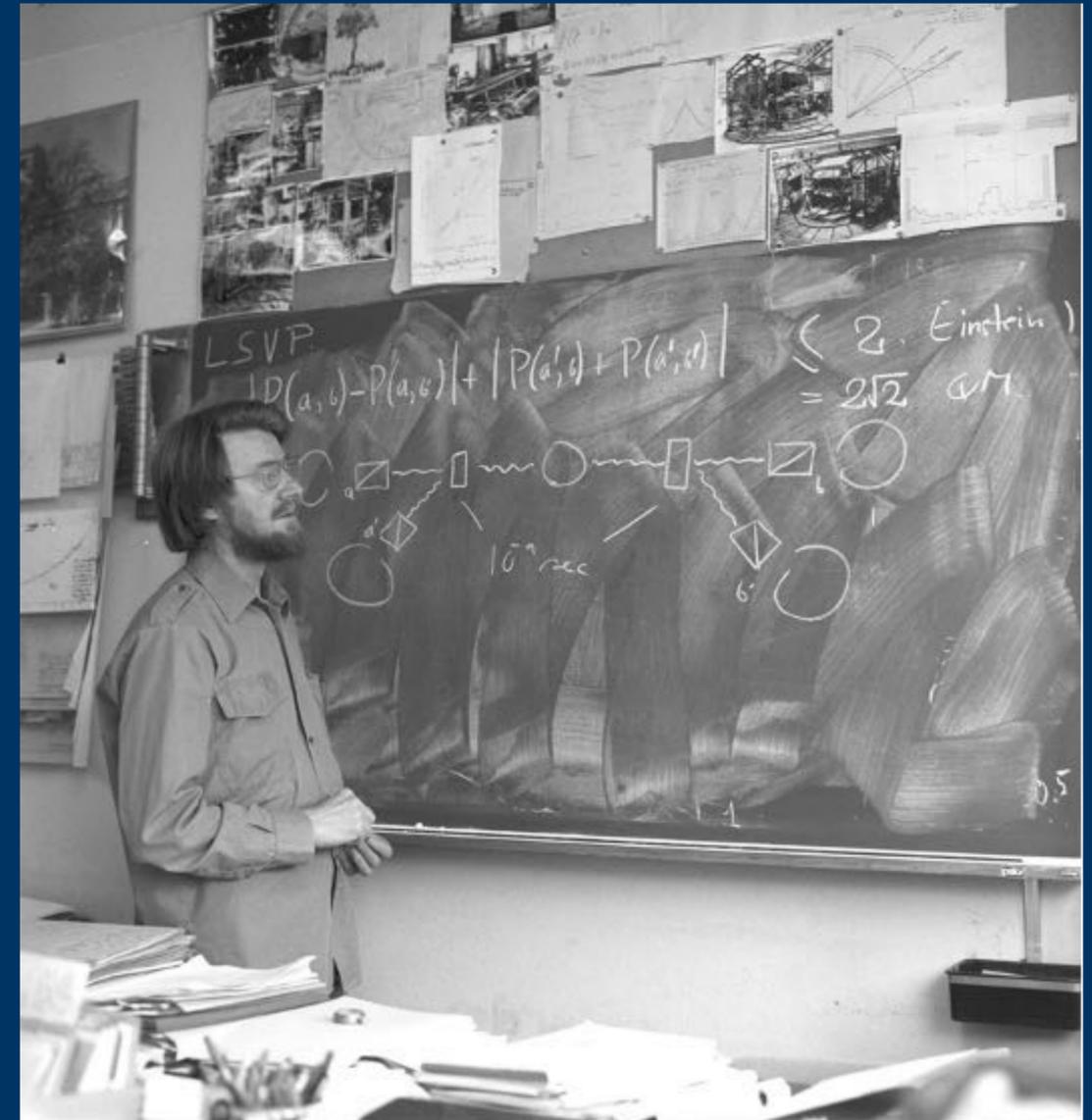
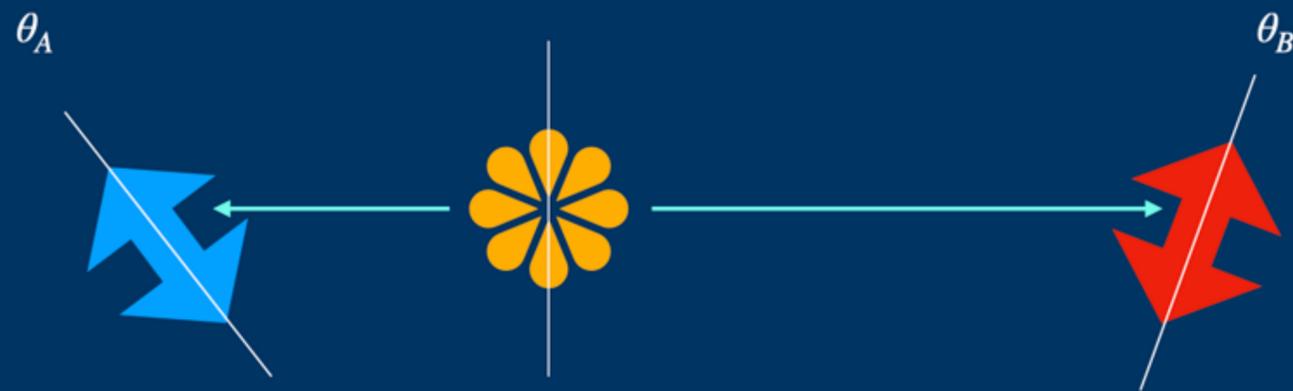


# Typical Experimental Arrangement



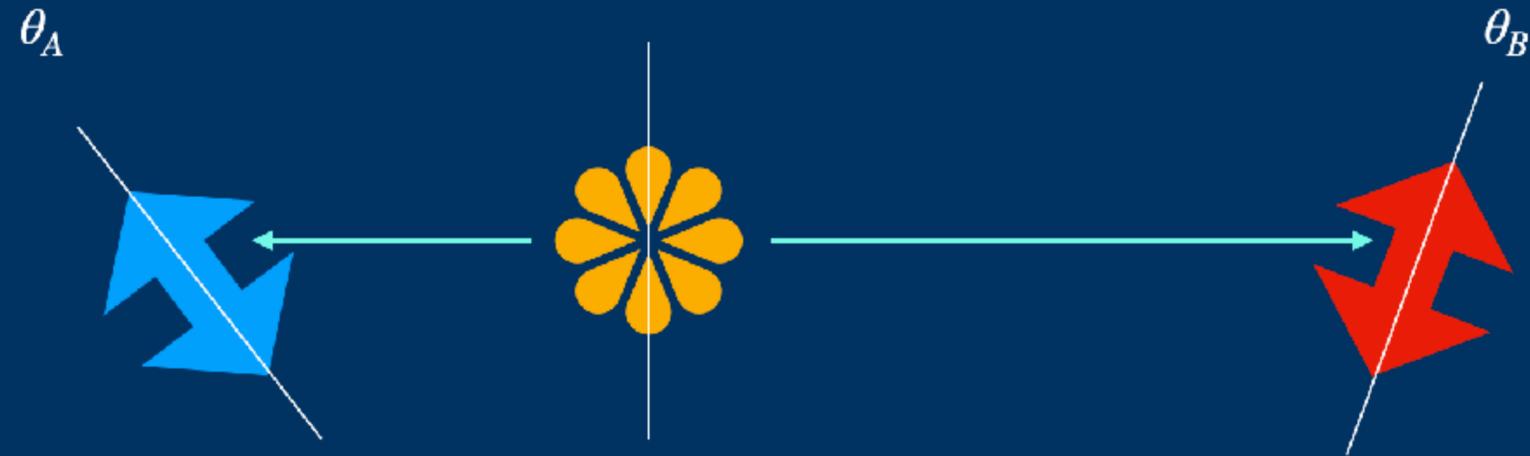
# John Stuart Bell

- Pondering **hidden variable** possibilities
  - Some **physics** that we **don't know** **determines** the outcomes
  - This physics is a / are hidden quantities / variables
- Bell's question
  - *Can a hidden variable theory reproduce the results of QM?*



John Stuart Bell (1928 - 1990)

# Scope of experiment



- Alice and Bob
  - Each measure spin component along a set angle
  - Angles can be adjusted
  - Indeed, changed 'in flight'
  - Alice's measurement before particle reaches Bob

If Alice and Bob measure along the same angle:

If Alice  $|UP\rangle \rightarrow$  Then Bob  $|DOWN\rangle$

If Alice  $|DOWN\rangle \rightarrow$  Then Bob  $|UP\rangle$

} Certain

If Alice and Bob measure  $90^\circ$  apart

If Alice  $|UP\rangle \rightarrow$  Then Bob  $|UP\rangle/|DOWN\rangle$

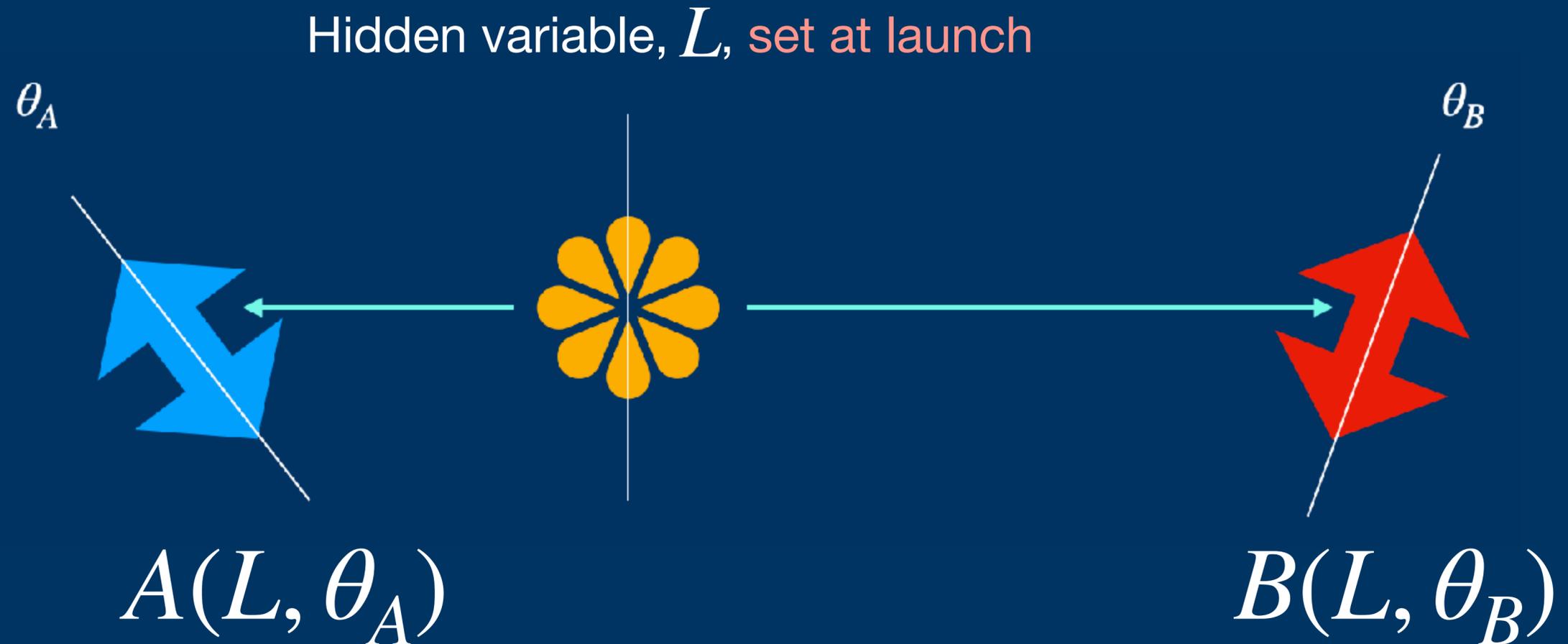
If Alice  $|DOWN\rangle \rightarrow$  Then Bob  $|UP\rangle/|DOWN\rangle$

} Random

If Alice and Bob measure  $\phi$  apart

Results are correlated

# Scope of experiment

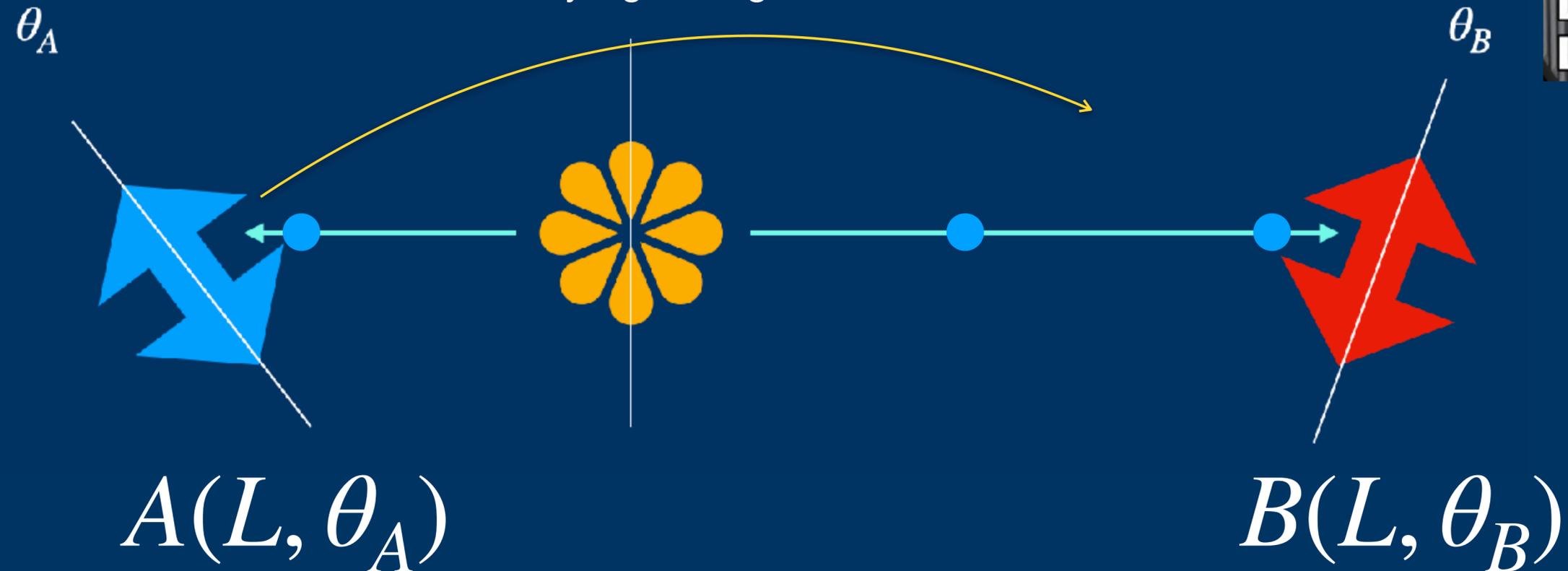


Each measurement probability determined by a combination of  $L$  and  $\theta$

# Locality is baked in...

Hidden variable,  $L$ , set at launch

No time for any signal to get from Alice to Bob



Alice sets her angle just before particle arrives

Bob sets his angle just before particle arrives

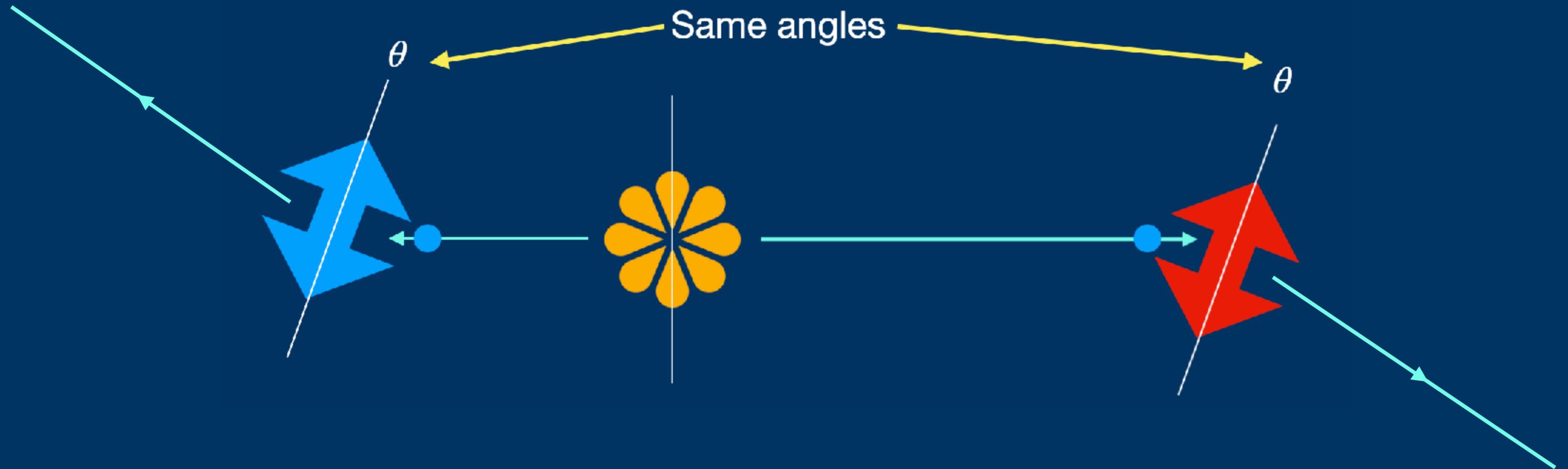
Sends the setting to Bob

Without knowing Alice's angle

No time for any signal to get from Alice to Bob

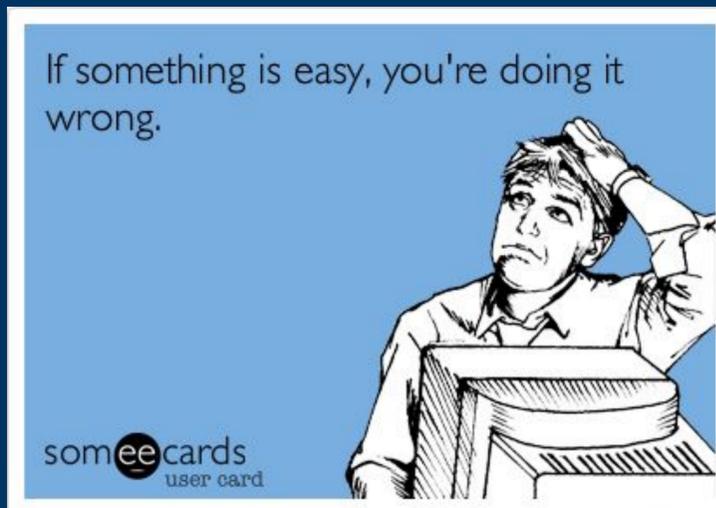
# Easy bit...

Hidden variable,  $L = 1$ , set at launch



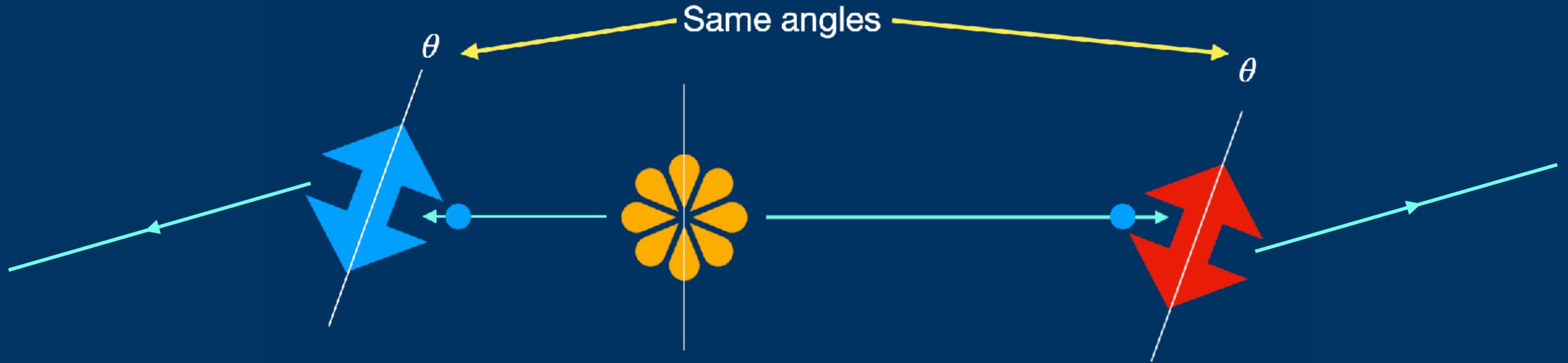
$$A(1, \theta) = 1$$

$$B(1, \theta) = 0$$



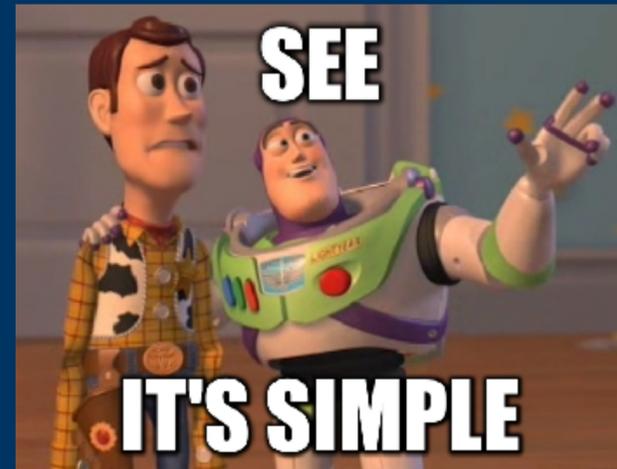
# Easy bit...

Hidden variable,  $L = 0$ , set at launch



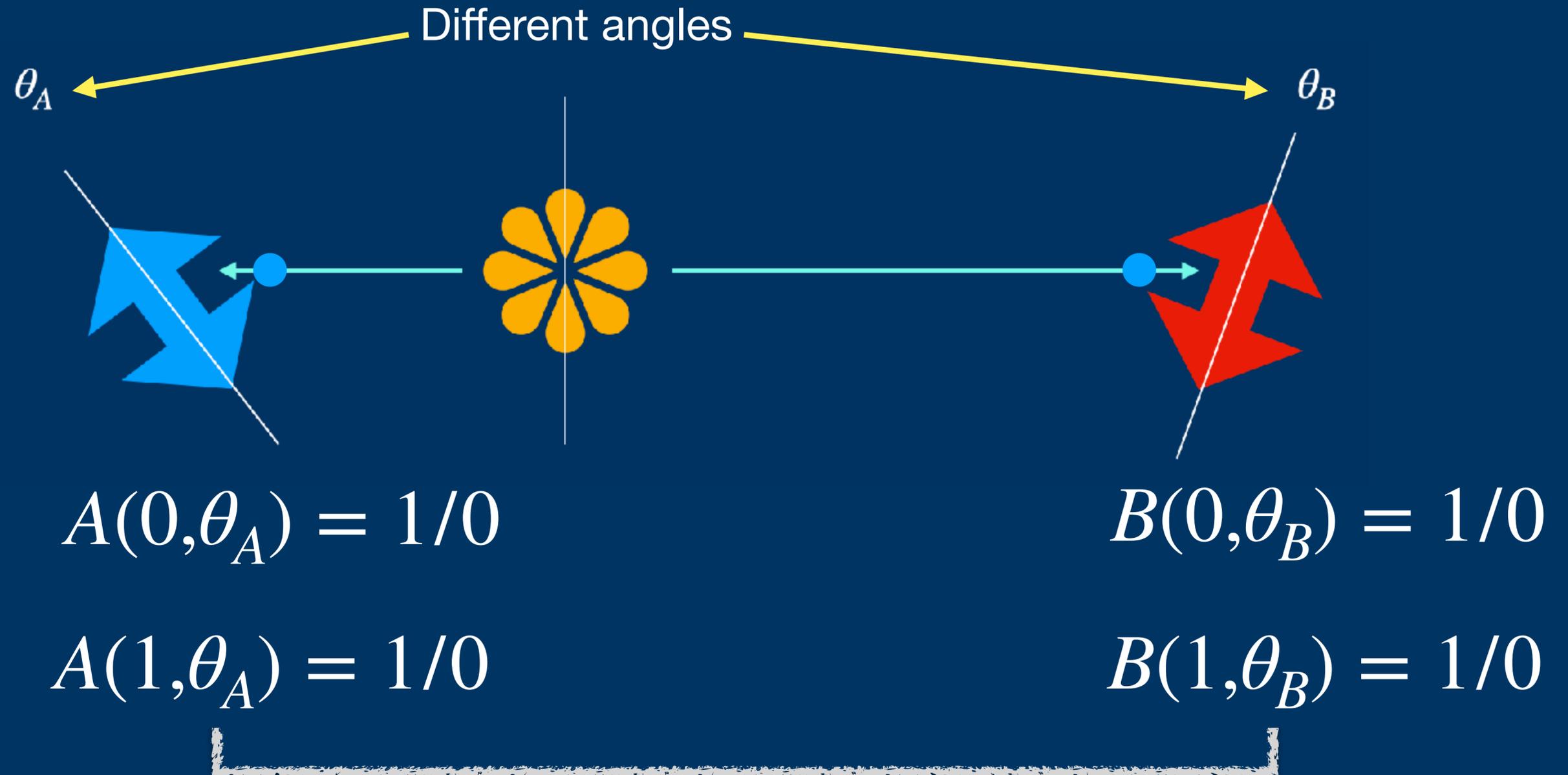
$$A(0, \theta) = 0$$

$$B(0, \theta) = 1$$



# Hard bit...

Hidden variable,  $L = 0/1$ , set at launch



Any correlation can only be the result of chance

Bell was able to **construct** a **measure** of **correlation**

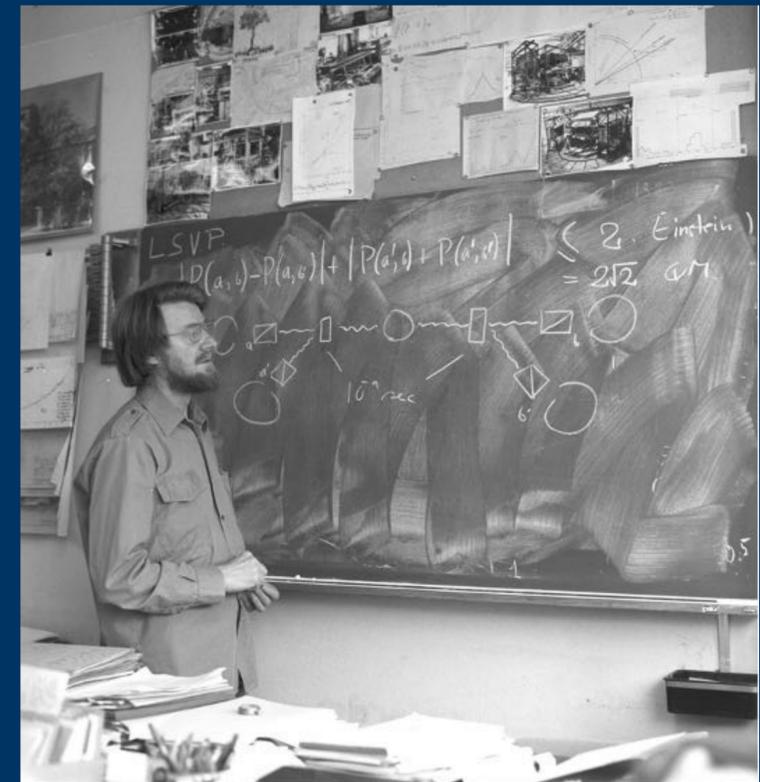
Based on:

The existence of two expressions

$$A(L, \theta_A) \quad B(L, \theta_B)$$

A **probability distribution** for  $L$

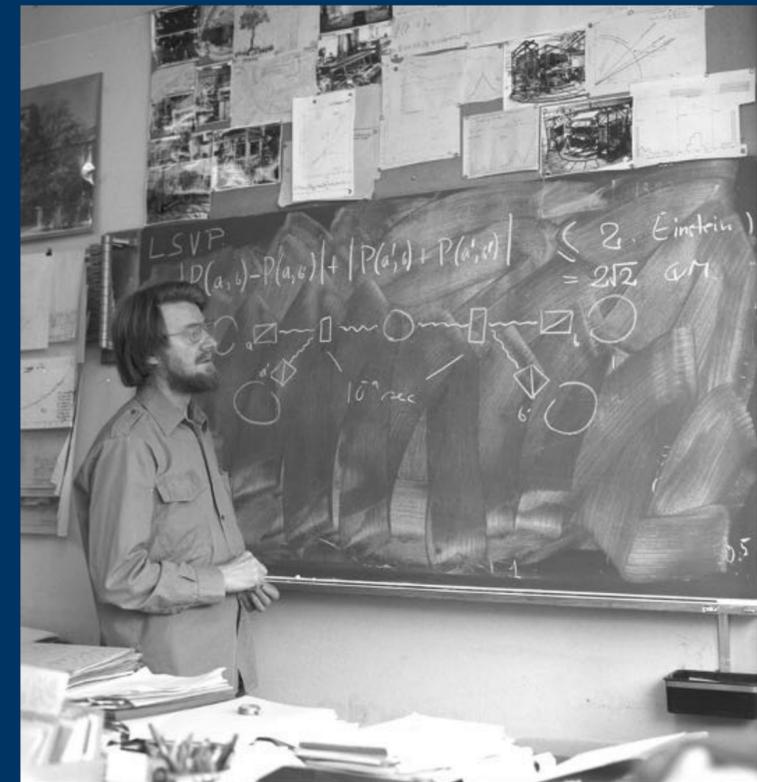
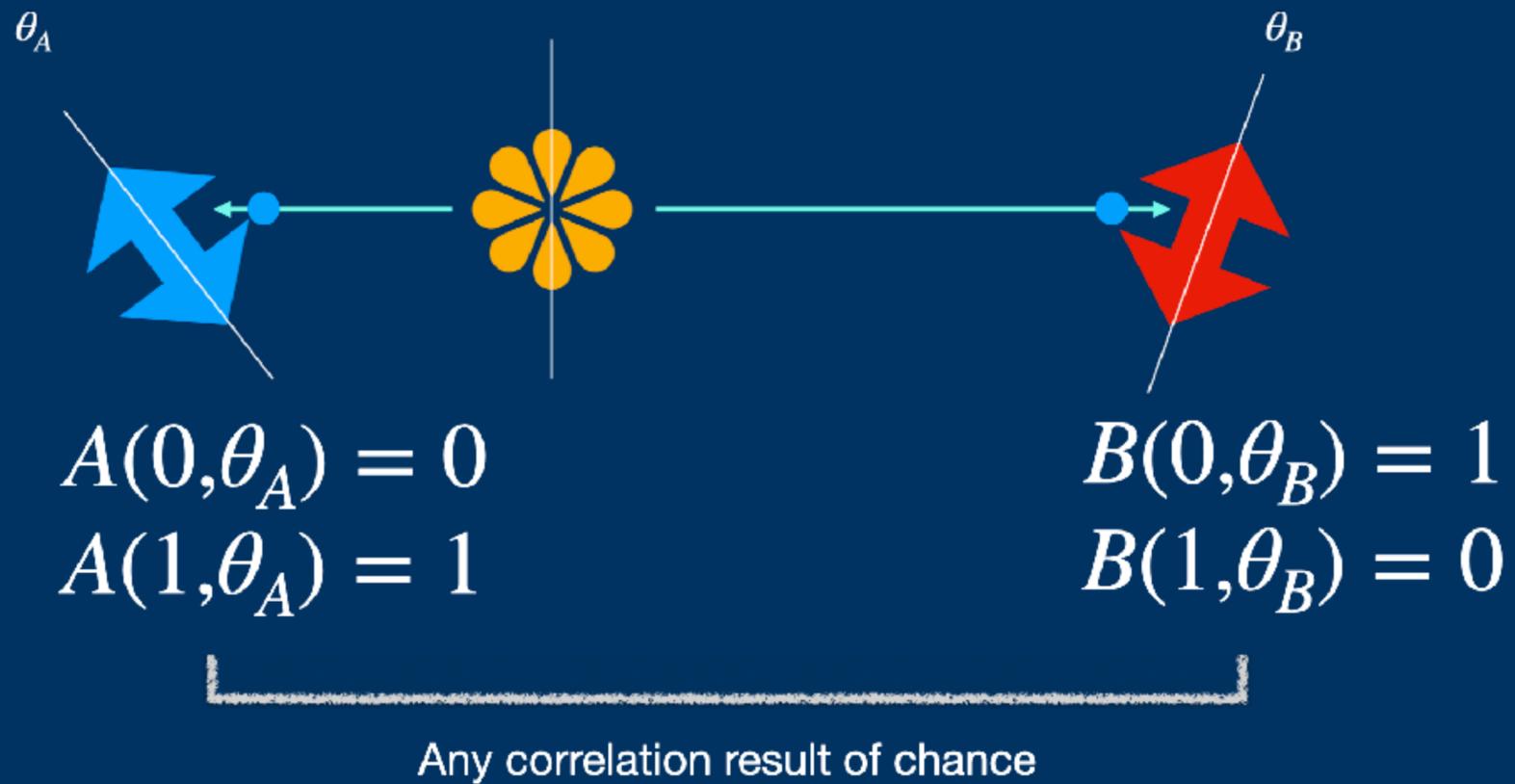
Did not need to now **what they are**, just that they **can be built**



John Stuart Bell (1928 - 1990)



THE DETAILS DON'T MATTER



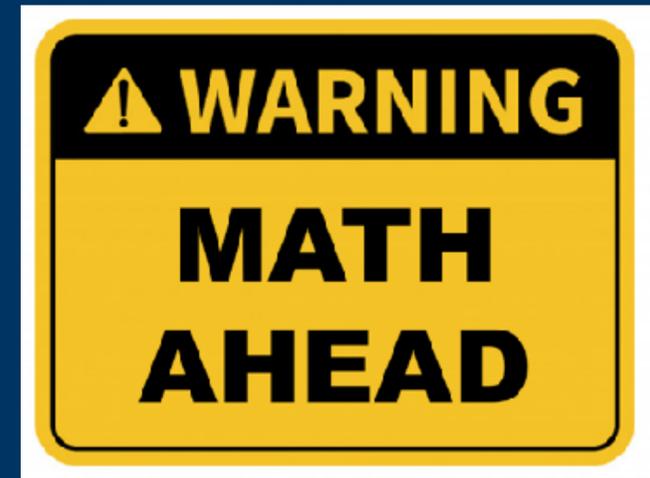
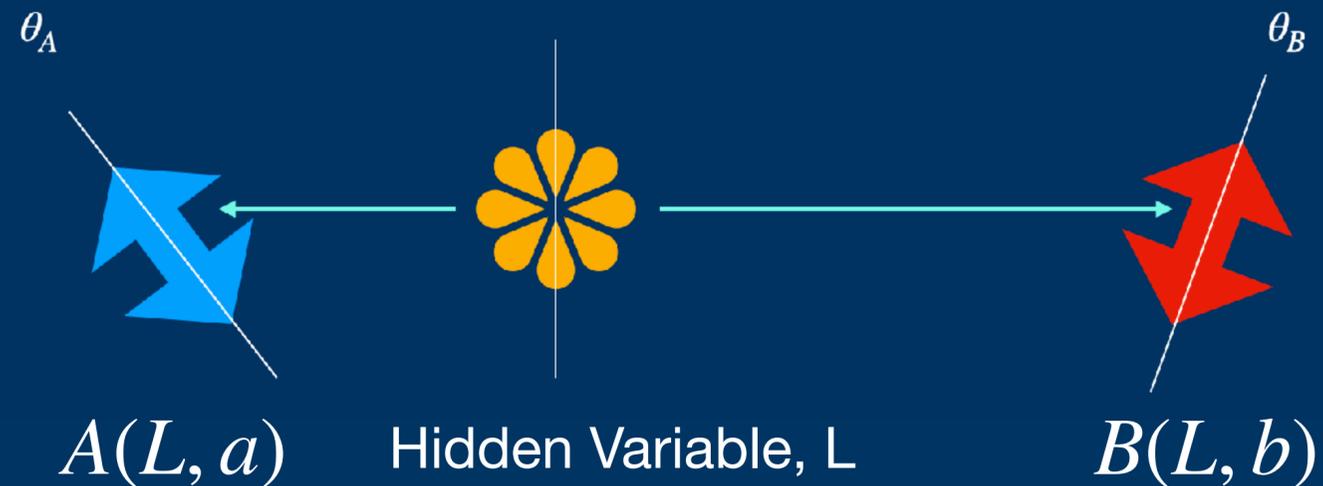
John Stuart Bell (1928 - 1990)

Alice can be set to one of **two angles**:  $(a, a')$

Just to **make** the **calculation** a bit **easier**

**Bob** can be set to one of **two angles**:  $(b, b')$

# Experimental Protocol



Alice and Bob set to angles  $a, b$

Run experiment for a period and count:

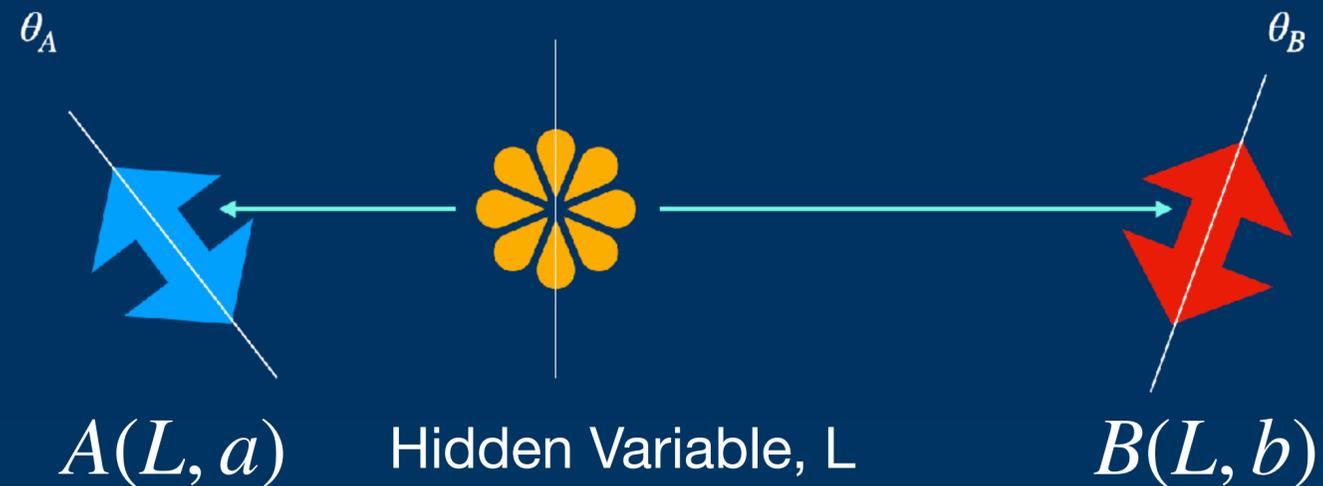
$N_{++}$  = the number of times get UP (+1) at both

$N_{--}$  = the number of times get DOWN (+1) at both

Ponder....

If both angles the same ( $a=b$ ), both of these must be zero...

# Experimental Protocol



Alice and Bob set to angles  $a, b$

Run experiment for a period and count:

$N_{++}$  = the number of times get UP (+1) at both

$N_{--}$  = the number of times get DOWN (-1) at both

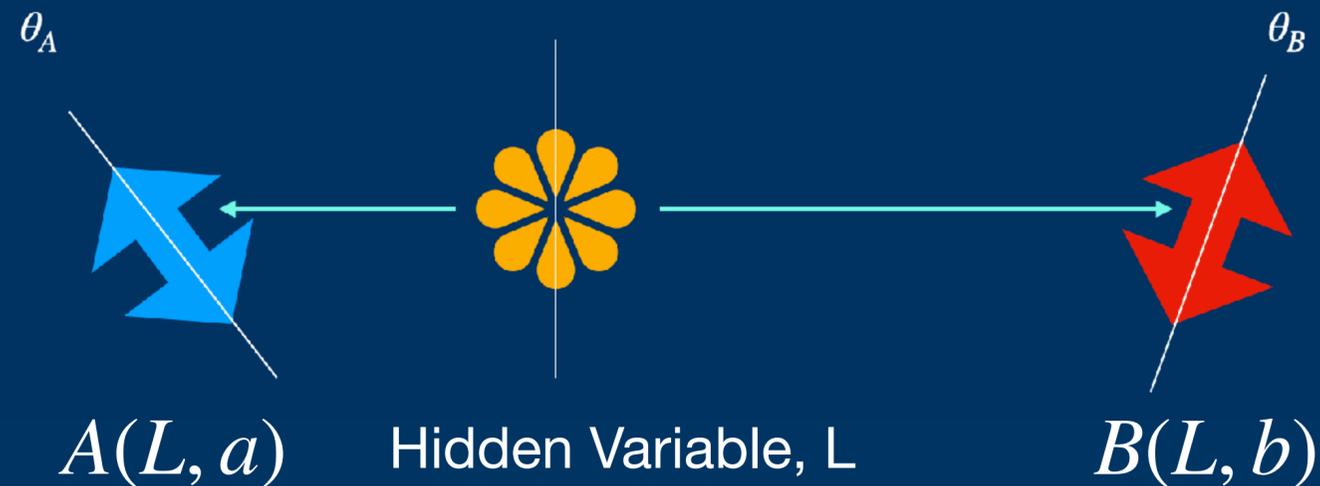
Experimental Counts

	Alice	Bob
$N_{++}$	1	1
$N_{--}$	-1	-1
$N_{-+}$	-1	1
$N_{+-}$	1	-1

$N_{-+}$  = the number of times:  
 Alice gets UP (+1)  
 Bob DOWN (-1)

$N_{+-}$  = the number of times:  
 Alice gets DOWN (-1)  
 Bob UP (+1)

# Experimental Protocol



Experimental Counts

No times Alice UP, BOB DOWN

No times Alice DOWN, BOB UP

No times Alice UP, BOB UP  
No times Alice DOWN, BOB DOWN

	Alice	Bob
$N_{++}$	1	1
$N_{--}$	-1	-1
$N_{-+}$	-1	1
$N_{+-}$	1	-1

$$E(a, b) = \underbrace{(+1)(+1)}_{\text{Multiplied by +1}} N_{++} + \underbrace{(-1)(-1)}_{\text{Multiplied by -1}} N_{--} + \underbrace{(-1)(+1)}_{\text{Multiplied by -1}} N_{-+} + \underbrace{(+1)(-1)}_{\text{Multiplied by +1}} N_{+-}$$

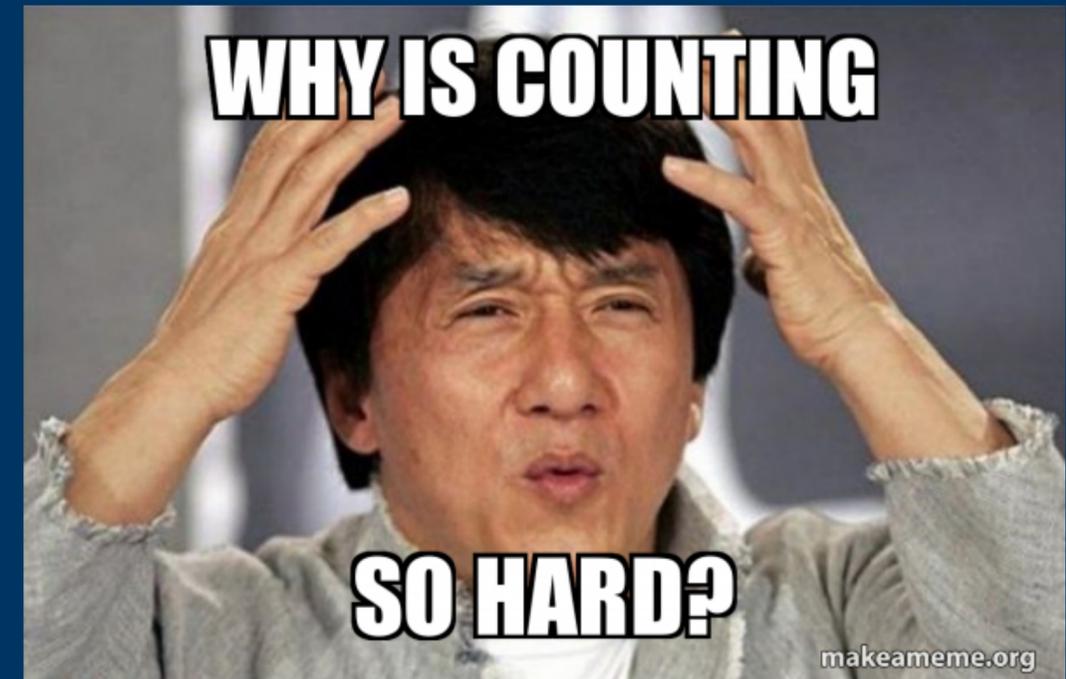
$N_{++} + N_{--} + N_{-+} + N_{+-}$

Multiplied by +1, -1, +1, -1

# Experimental Protocol

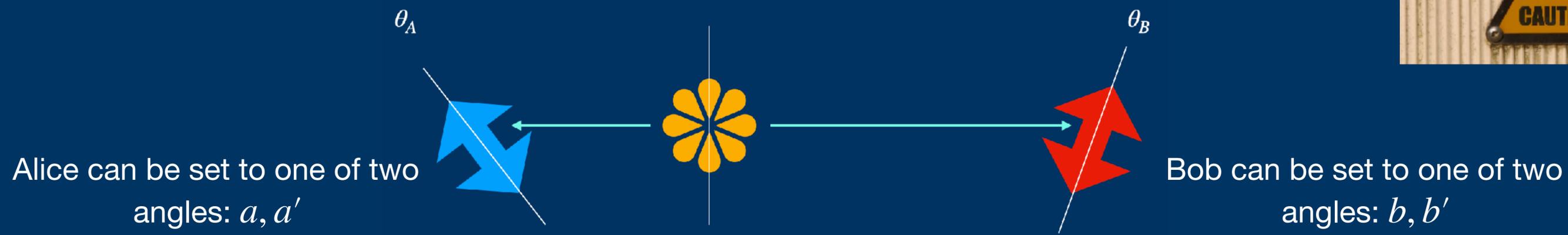
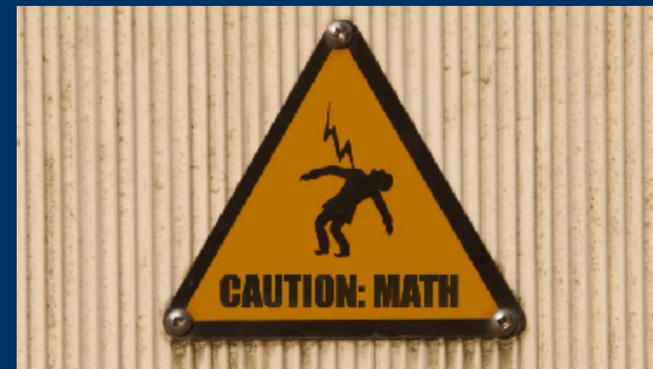
Experimental Counts

	Alice	Bob	
N++	1	1	800
N--	-1	-1	600
N-+	-1	1	540
N+-	1	-1	380



$$E(a, b) = \frac{(+1)(+1) 800 + (-1)(-1) 600 + (-1)(+1) 540 + (+1)(-1) 380}{800 + 600 + 540 + 380}$$
$$= \frac{800 + 600 - 540 - 380}{2320} = 0.21$$

# Then we fiddle with the angles....



Experimental Counts

	Alice	Bob
N++	1	1
N--	-1	-1
N-+	-1	1
N+-	1	-1

Run the experiment and accumulate counts for **each combination**  $(a, a', b, b')$

Ideally, **changing the angles while the particles are in flight**

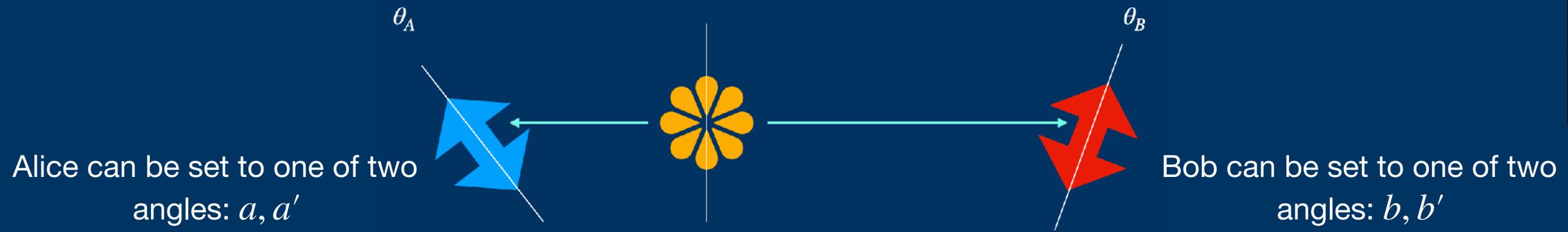
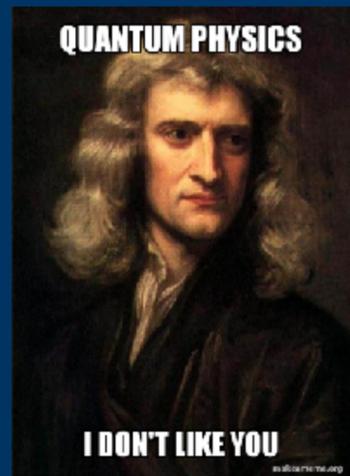
$$E(a, b)$$

$$E(a, b')$$

$$E(a', b)$$

$$E(a', b')$$

# The dark magic happens....



$$S_e = |E(a, b) - E(a, b')| + |E(a', b) + E(a', b')|$$

What is it?

An **experimental** way to **measure** the **correlation**

What is it?

It tells us **how connected** Alice's and Bob's **results are**

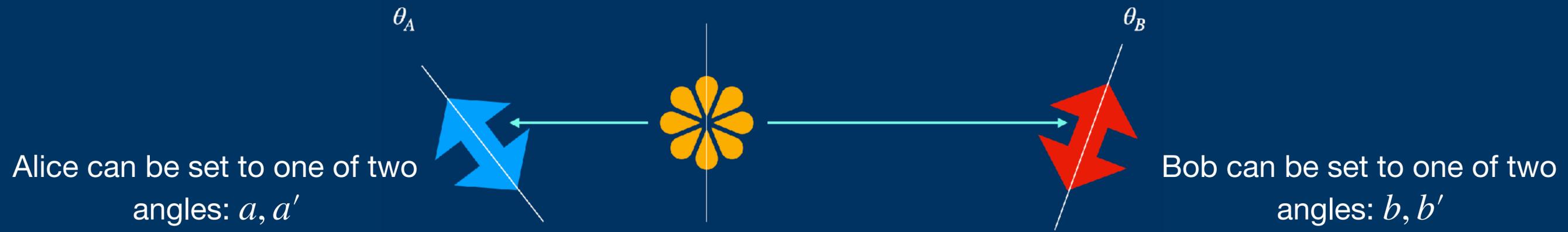
$$E(a, b)$$

$$E(a, b')$$

$$E(a', b)$$

$$E(a', b')$$

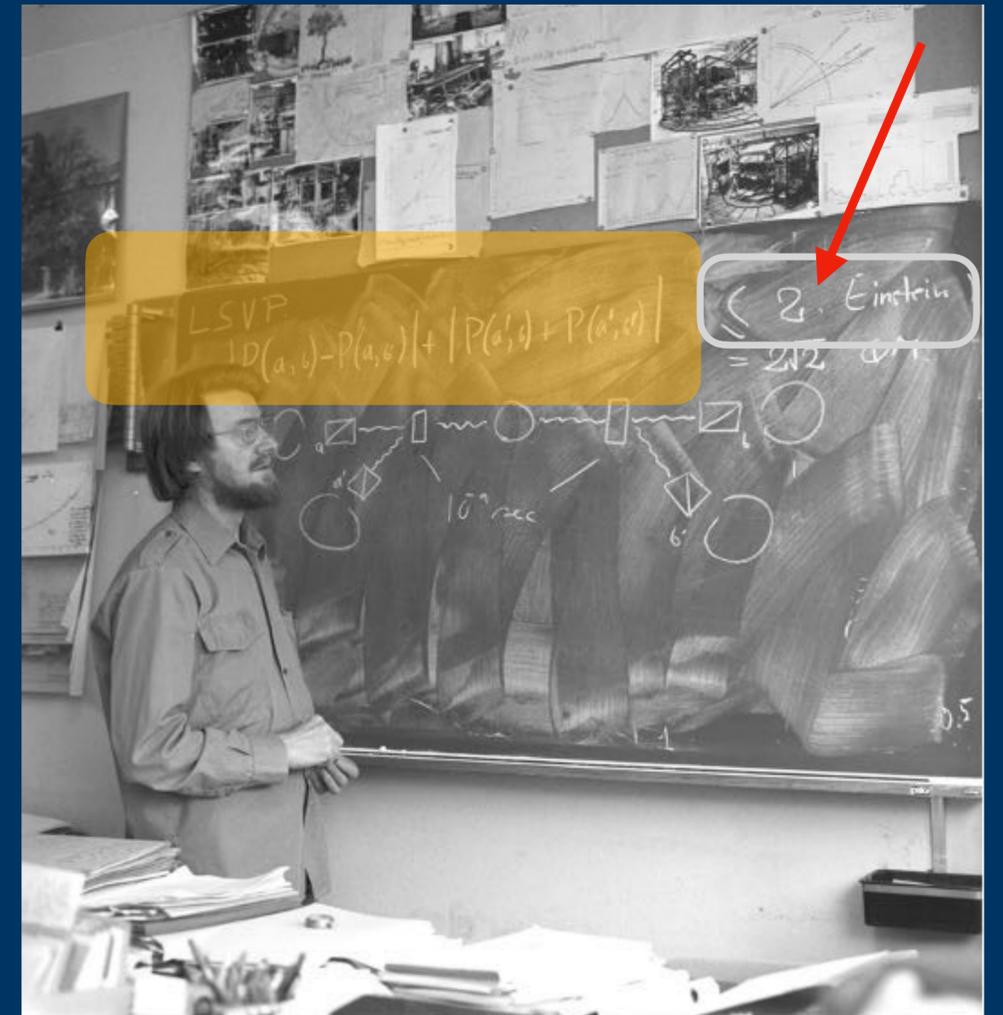
# The dark magic happens....



$$S_e = |E(a, b) - E(a, b')| + |E(a', b) + E(a', b')|$$

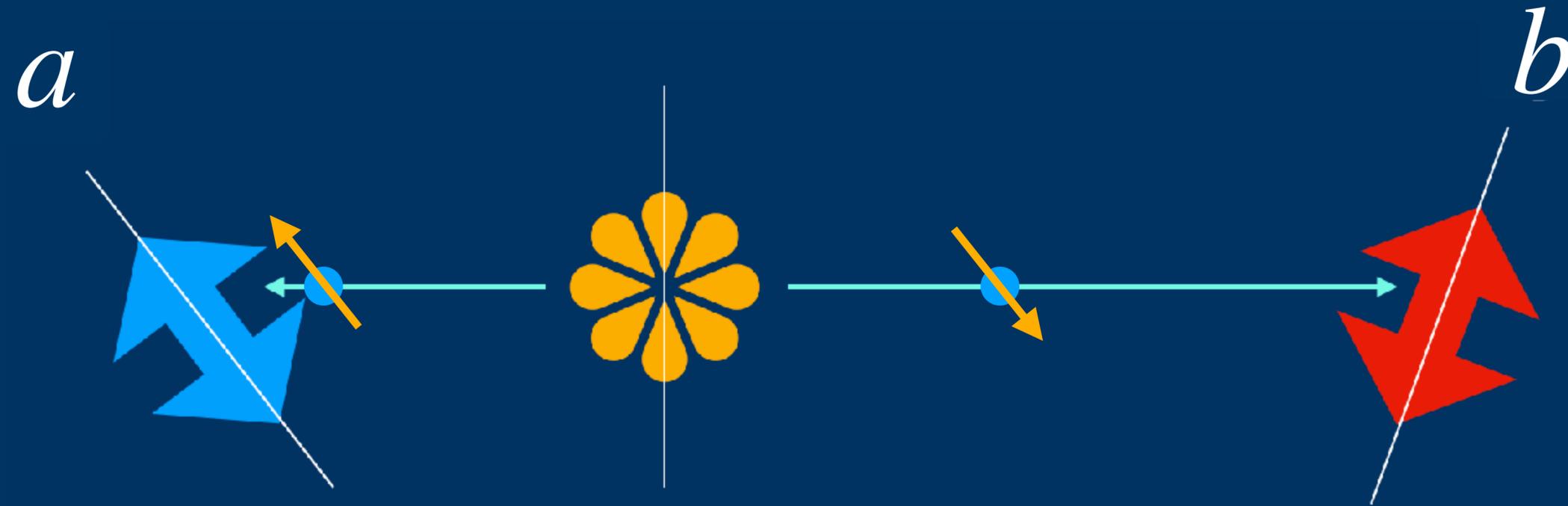
For a **local hidden variable theory**

Bell calculated  $S_H \leq 2$



Clauser, Horne, Shimony and Holt (CHSH) parameter

# Quantum theory



Measurement at Alice manifests

$$|UP'\rangle/|DOWN'\rangle$$

Along Alice's angle, a

Makes the other particle

$$|DOWN'\rangle/|UP'\rangle$$

Along that angle...

When particle arrives at Bob

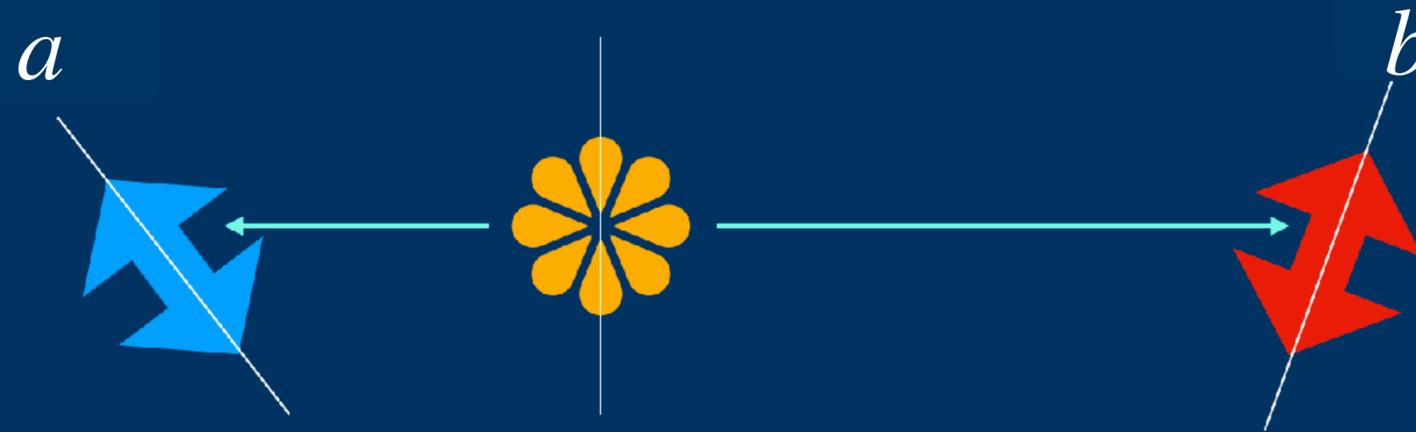
$$|UP''\rangle/|DOWN''\rangle$$

$$|UP''\rangle \sim \cos^2(\theta/2)$$

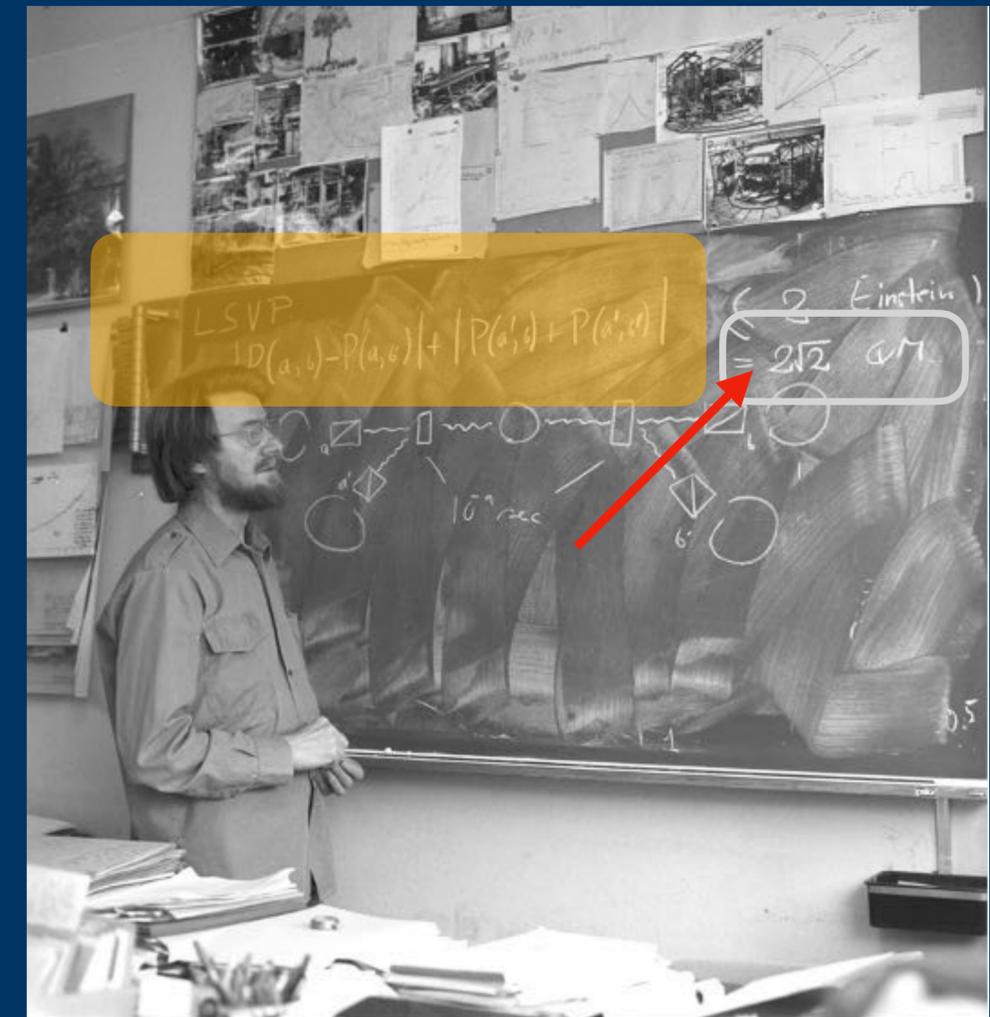
$$|DOWN''\rangle \sim \sin^2(\theta/2)$$

$$\theta = a - b$$

# So...



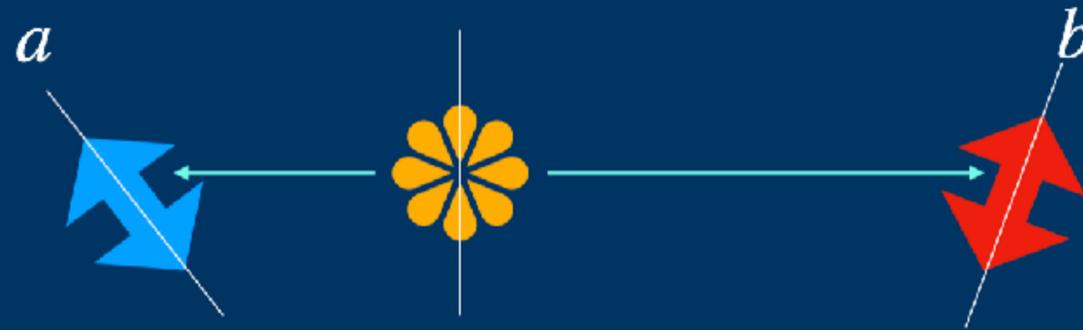
- The number  $S$  is something we have to find out by experiment...
  - What nature actually does...
- Bell was able to calculate maximum value it could be for a hidden variable theory:
  - $S_H \leq 2$
  - Extent to which correlations could happen 'by accident' in a hidden variable theory
- Can also calculate the quantum prediction
  - Adroit choice of angles  $a = 0^\circ$ ;  $a' = 45^\circ$ ;  $b = 22.5^\circ$ ,  $b' = -67.5^\circ$
  - Gives  $S_Q = 2\sqrt{2}$



Crucial Question -  
what does nature  
give us?

NB Angles are different for electrons, these are for photons...

# Aspect's Experiment



- 1980 - 1982 Experimental series
  - First robust measure of  $S_e$
  - Corrected for efficiencies and lens apertures
  - $S_e = 2.697 \pm 0.015$ 
    - $S_e = (2.712 - 2.682)$
  - Clearly greater than 2
    - The prediction for  $S_H$
  - Corrected QM prediction  $S_Q = 2.70 \pm 0.05$

Nature **disagrees** with local HV

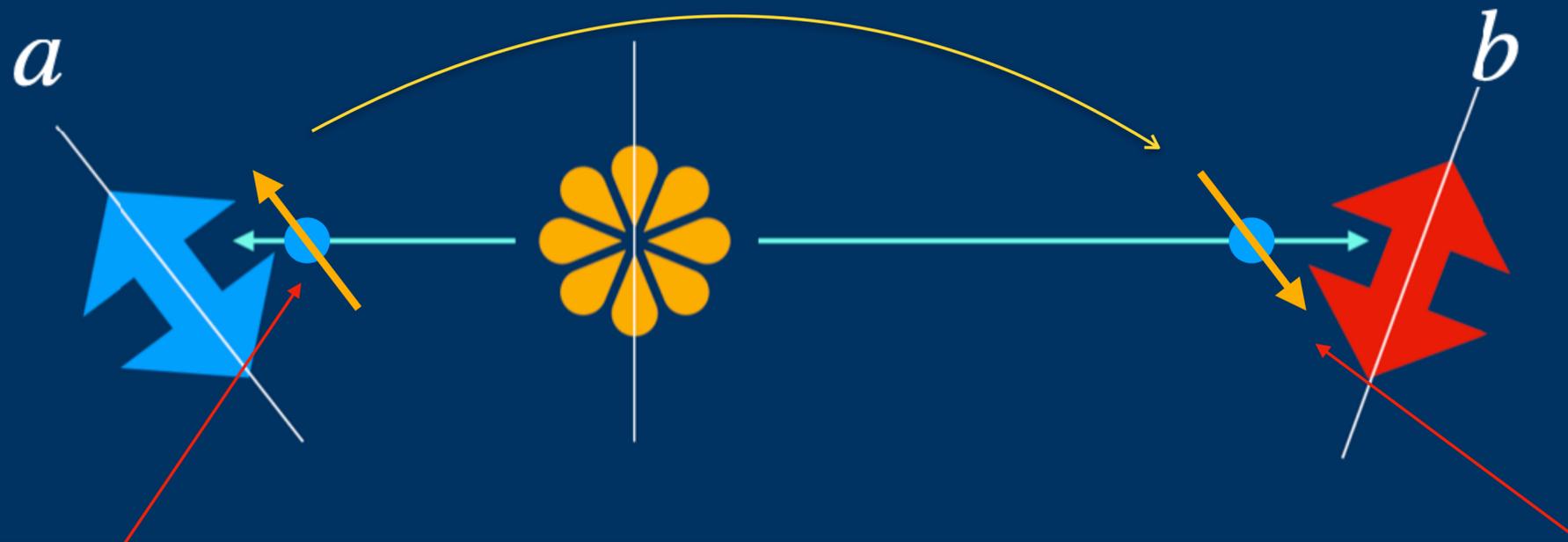
Nature **agrees** with QM



Alain Aspect (1947-)  
Nobel Prize 2022

# So, what's the punchline?

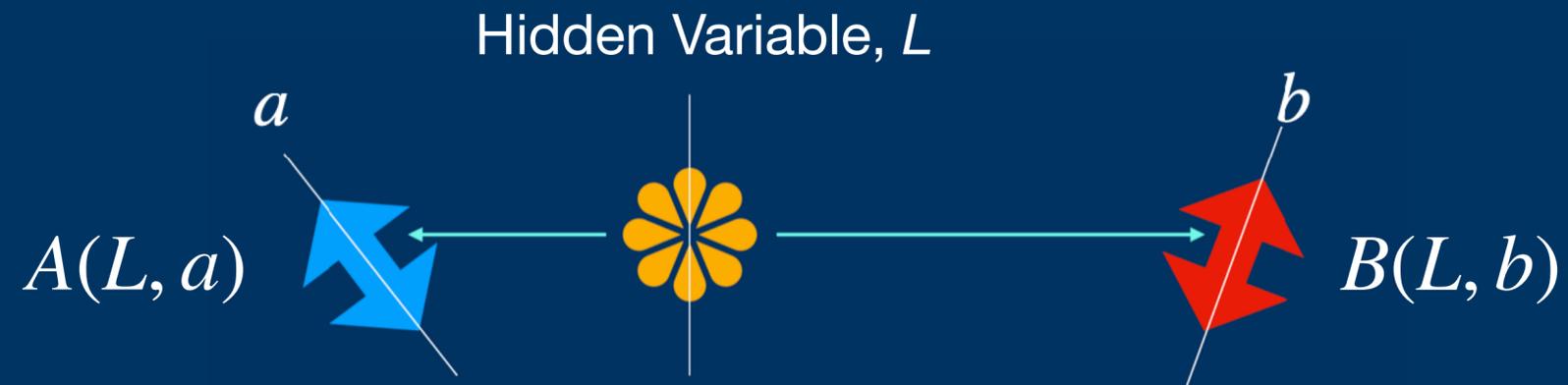
No time for any signal to get from Alice to Bob



- Particle spin component gets measured by Alice
  - Gets the result +1

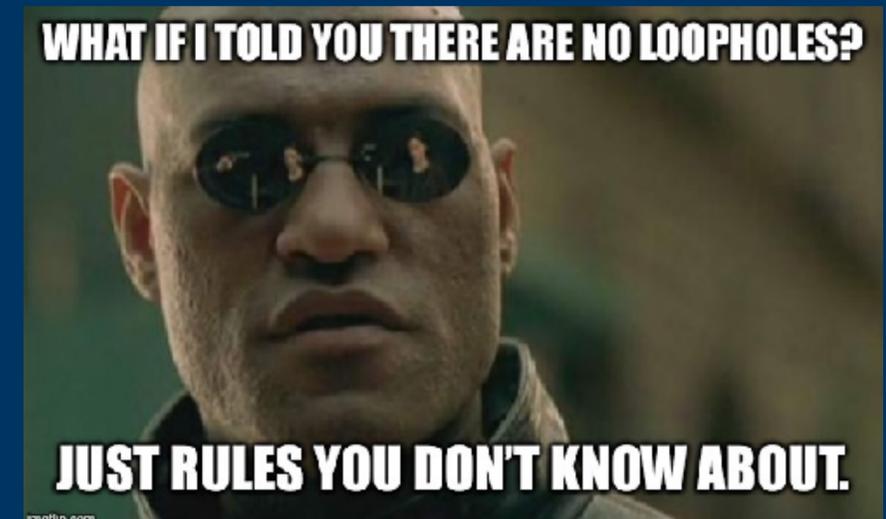
- Particle spin component gets measured by Bob
  - More or less likely to get +1
  - Depending on the angles  $a, b$
  - How does Bob / Bob's particle
    - 'know' the angle of Alice
    - The result at Alice?

# Can we get out of it?



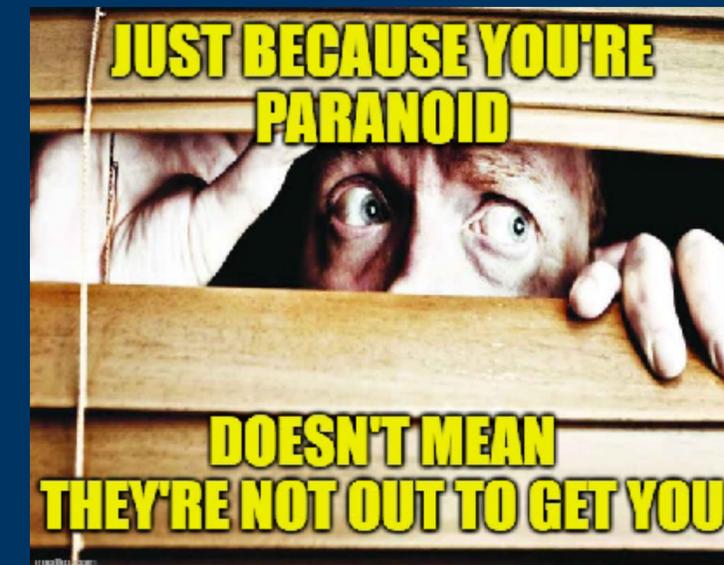
Possible experimental **loopholes**:

- **Detection loophole** - you **miss** significant **particles**
- **Locality loophole** - some influence is travelling from **Alice** to the **Bob**
- **Memory loophole** - something is happening **in the environment**
- **Free choice loophole** - our **angle selection** is **influenced**



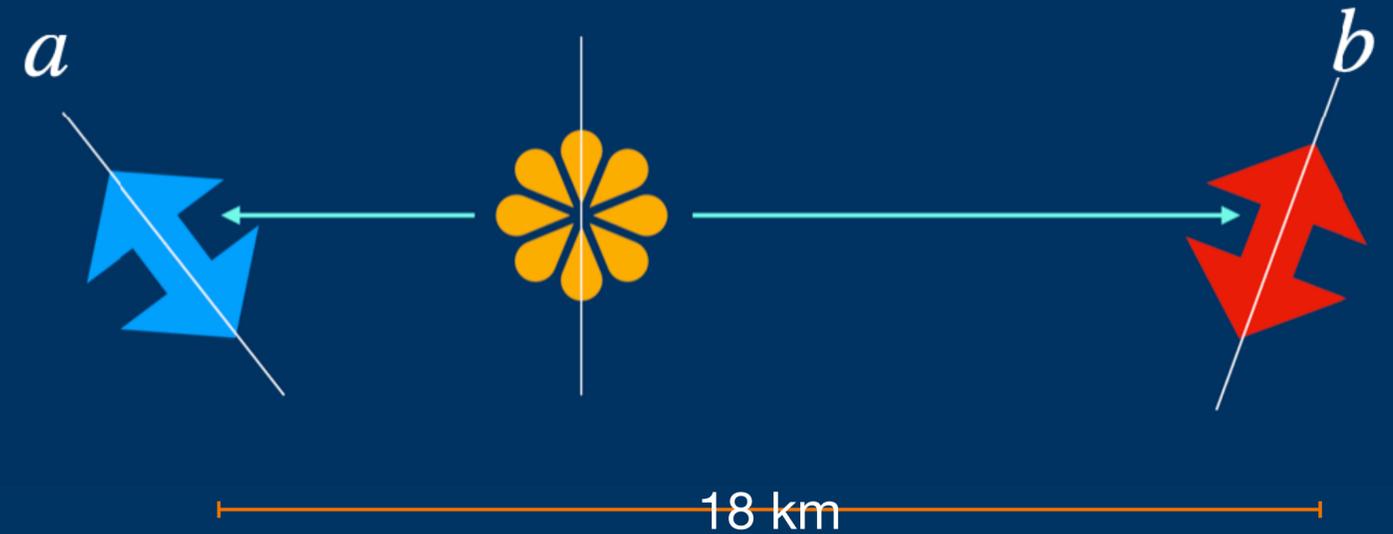
# Detection Loophole

- **Detectors** cannot be 100% efficient
  - they **miss** particles from time to time
  - **compensate** for this by **adjusting** the value of  $S_H$
- **Conspiracy** problem
  - In principle, the events **missed** could be of a **different statistical nature** which, **if included** in the results, **agree with** the upper limit on  $S_H$
  - **'fair sample' hypothesis**: missed events **same nature** as those that **are seen**
- As **technology has improved** so **detector efficiency** for photons, for example, has increased from **20-30%** up to **93%**
- This **closes the loophole**

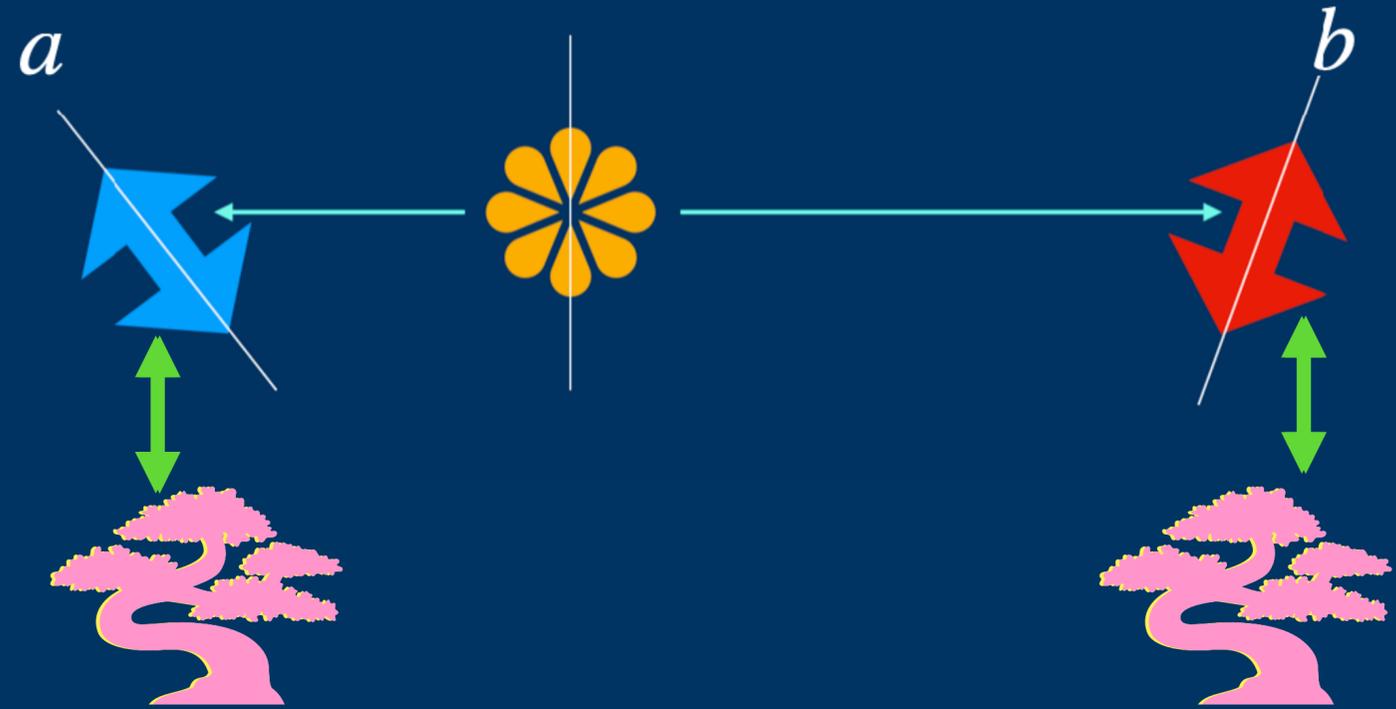


# Locality Loophole

- Need **balance** between
  - the **speed** at which the particles travel
  - the **distance** between the detectors
  - the **rate** at which the detectors can take their measurements
- **measurement** at **B** lies **outside** the **causal radius** of **A**
- Then **no classical / explicate** way events at **A** can **influence B**
- As **technology** has **improved**, A and B **further apart**
  - **without** significant **particle loss** during flight
- This loophole has effectively been **closed** by an **experiment** performed with an **A-B separation of 18km**
- The **implicate layer** is not **bounded by space-time** in the same way



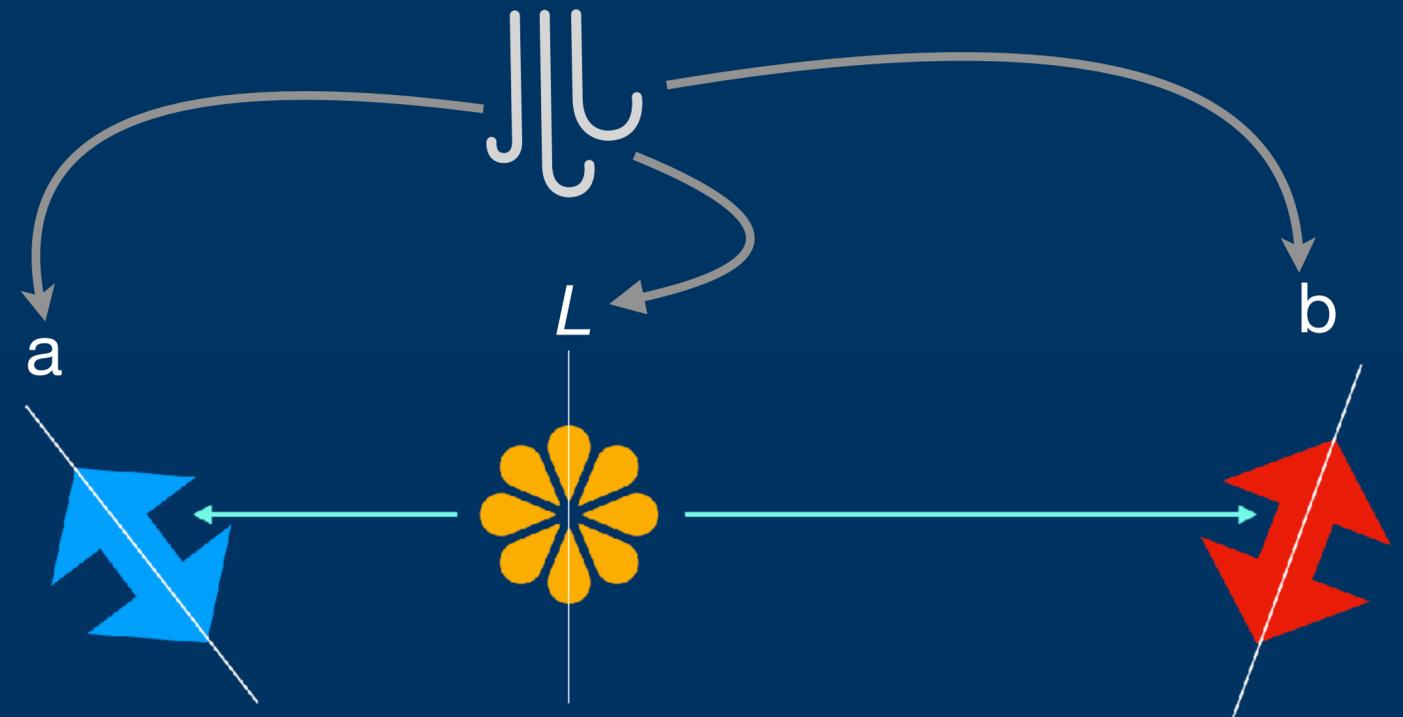
# Memory Loophole



- If **A** and **B** remain in **fixed locations**
  - **conditions local** to the two detectors could have an influence on successive measurements
  - Also the **physical parameters in the locations** might be **varying with time**
  - However, **provided each successive measurement uses a different random setting**,
    - this should have **no effect** on the outcome.
  - Results from the first **experiments** to close the **detection**, **locality** and **memory** loopholes in the same protocol were published in **2015**.



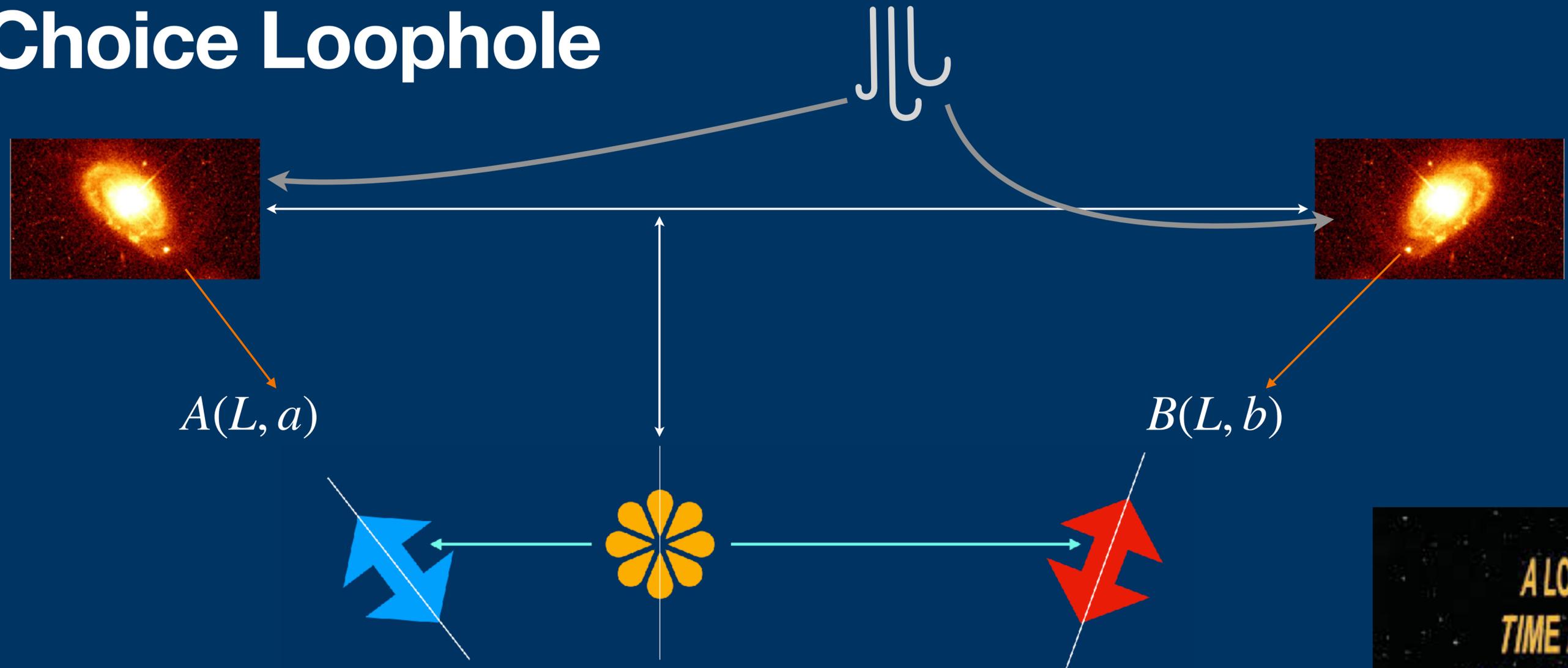
# Free Choice Loophole



- Assumption:
  - detector settings  $a, a', b, b'$  are
    - independent of  $L$  (we can choose...)
  - Some events in the history of the universe might influence both the detector settings and  $L$
  - hence violate  $S_H$
  - Overcome this loophole using quantum systems
    - generate random numbers that determine the detector settings
      - invalid
        - do not know if these systems are similarly determined!



# Free Choice Loophole



- 2018 experiment

- Light from two separate quasars

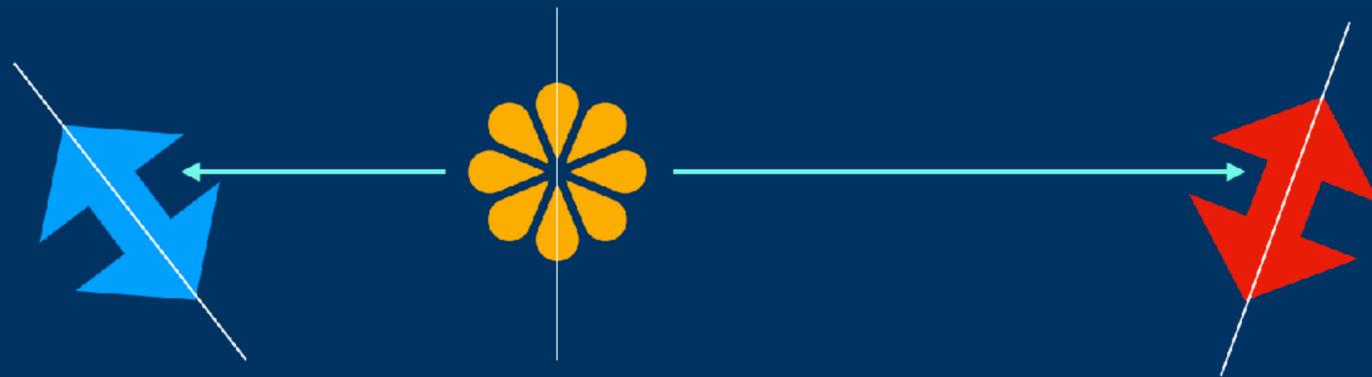
- Determined the separate detector angles

- distance between the two quasars and their distance from Earth:

- Any event that could influence detector settings happened more than  $7.9 \times 10^9$  years ago!



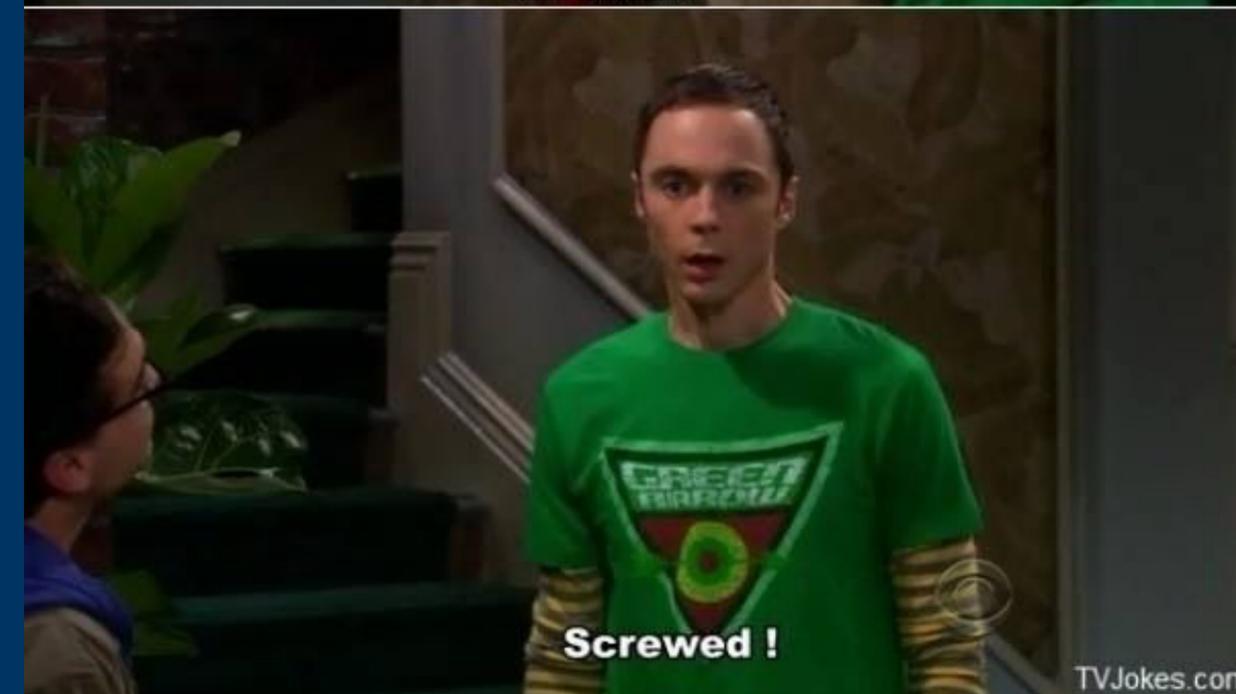
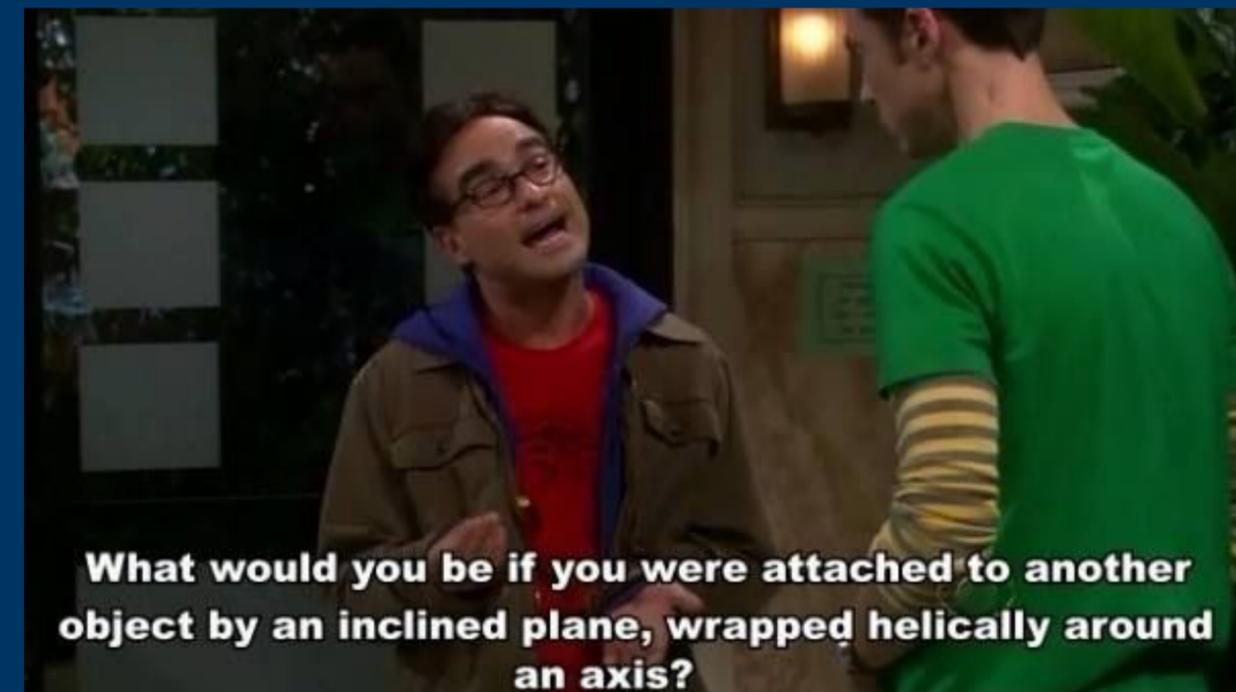
# Can we get out of it?



In short,  
no....

In longer short....

Still no...



Prepare **two particles** with **total spin = 0**

The **particles** are **entangled**...

**One** smoky dragon governing what happens to both

**Rather** than **one dragon each**

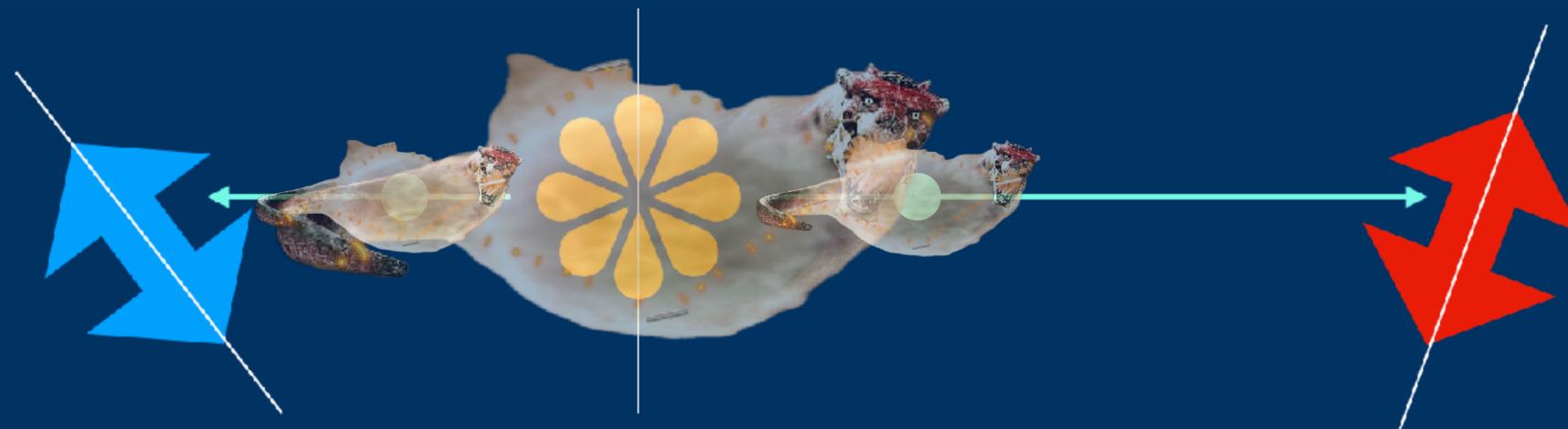
Technical definition:

$$\Psi(x_a, x_b, t) \neq \psi(x_a, t) \times \phi(x_b, t)$$

The dragon governing the behaviour of both

Be separated into two dragons

Cannot..



Undermines **reductionism**

Rather than **2 particles**

More of a **single 2-particle system**

However...

The **moment** Alice **makes** her **measurement**

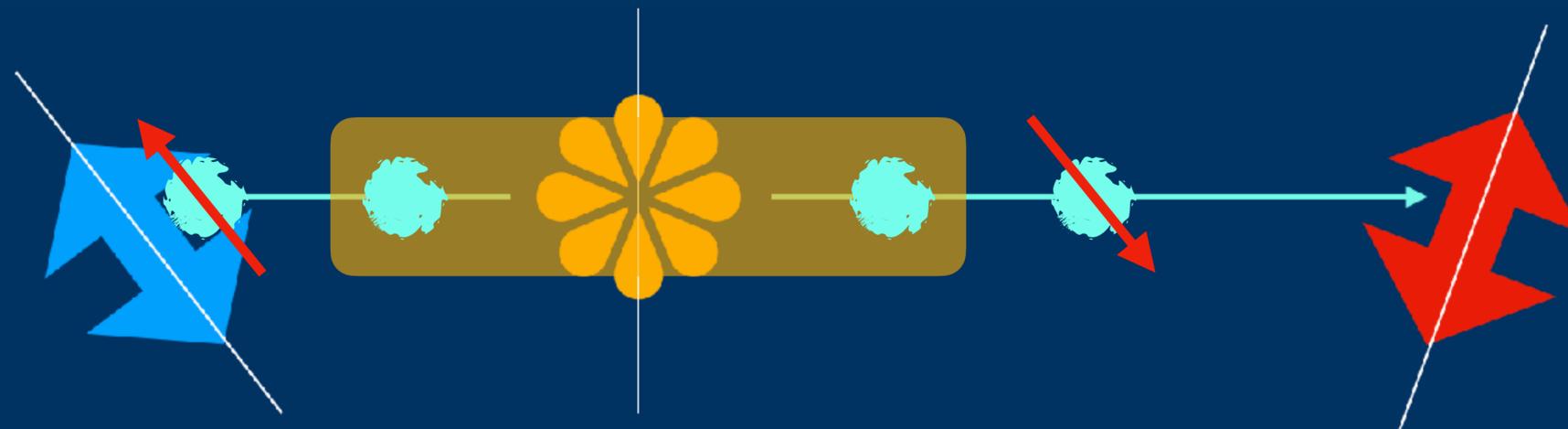
**Forces** a **choice** on the **particle** on the **way** to Bob

The situation

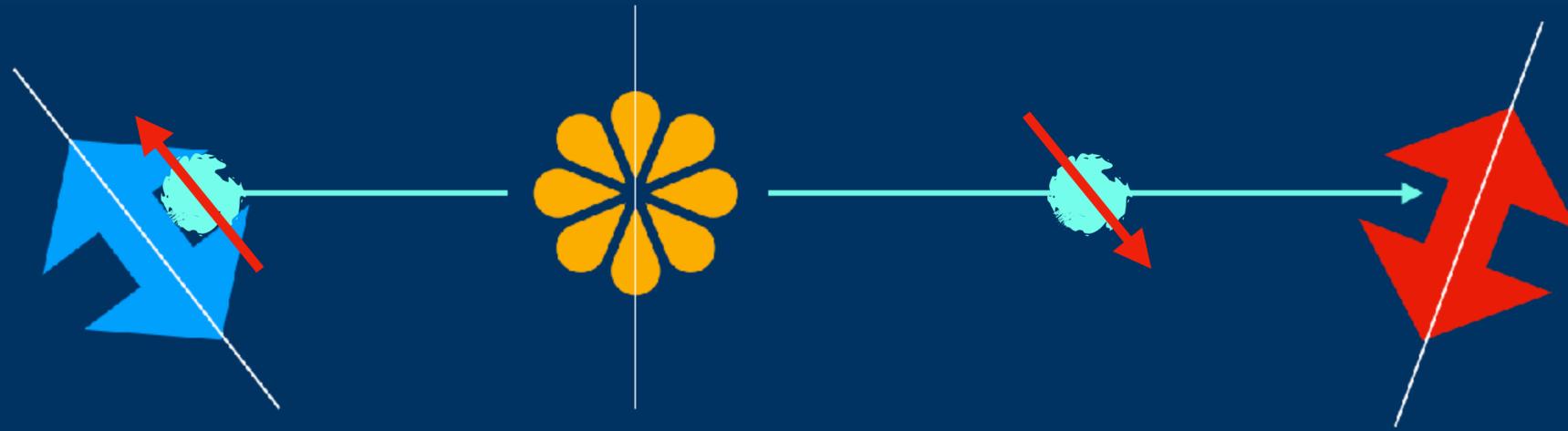
Be analysed in terms of parts

$$\Psi(x_a, x_b, t) \neq \psi(x_a, t) \times \phi(x_b, t)$$

Cannot..



The **entanglement** is now **dissolved**...



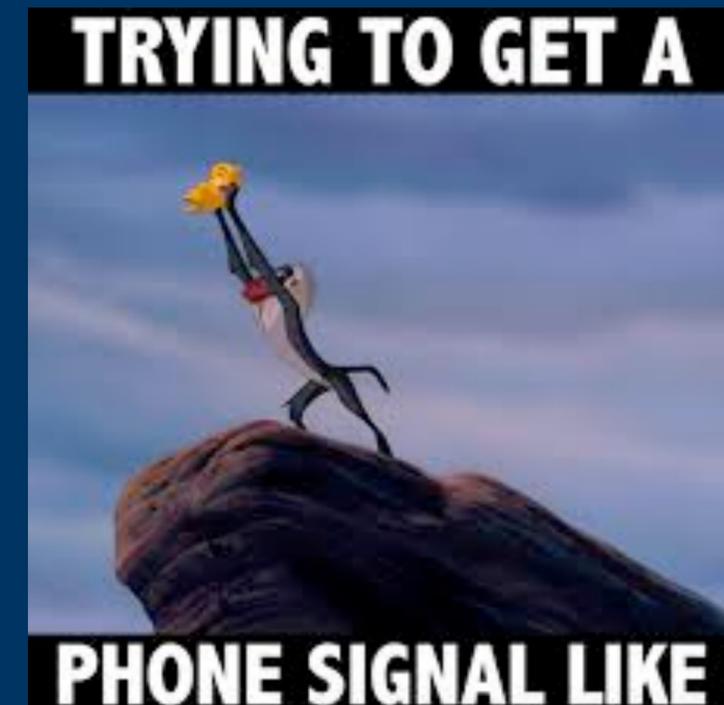
The entanglement can only be seen

In correlated repeat measurements

$$S_e = |E(a, b) - E(a, b')| + |E(a', b) + E(a', b')|$$

So can't be used to send signals

The entanglement is delicate....



**QUANTUM ENTANGLEMENT  
IS NOT HARD TO UNDERSTAND:  
SOCKS COME IN PAIRS.**

**IF YOU PUT A SOCK ON YOUR LEFT  
FOOT, THE OTHER SOCK OF THE PAIR  
INSTANTLY BECOMES THE "RIGHT SOCK," NO  
MATTER WHERE IT IS LOCATED IN THE UNIVERSE.**