Measurements, memories and time

Quantum measurement: a dialog of big and small

Wednesday, 28th September 2016

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Universita' di Pavia

FQxI Foundation,
"The physics of what happens"

QUit quantum information theory group

www.qubit.it

Quantum measurement

- What is it?
- Measurement problem
- Subjectivity of the Born rule
- What is the role of time?
- Quantum metrology

What is a quantum measurement?

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Quantum measurement

def: extraction of (classical) information from a quantum system

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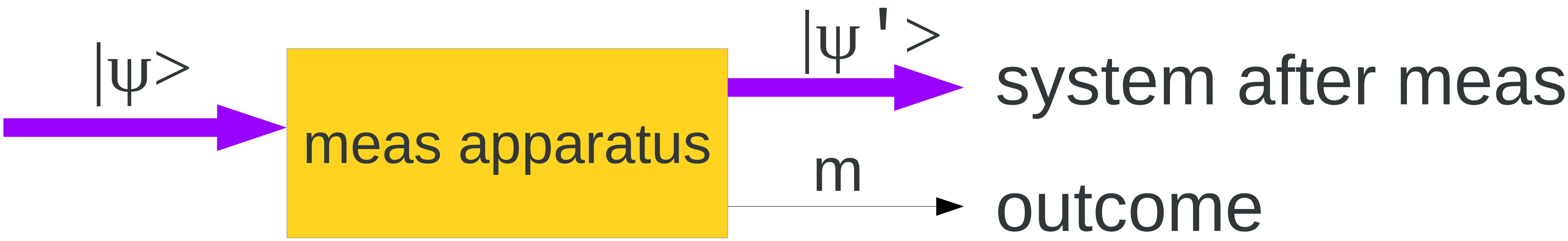

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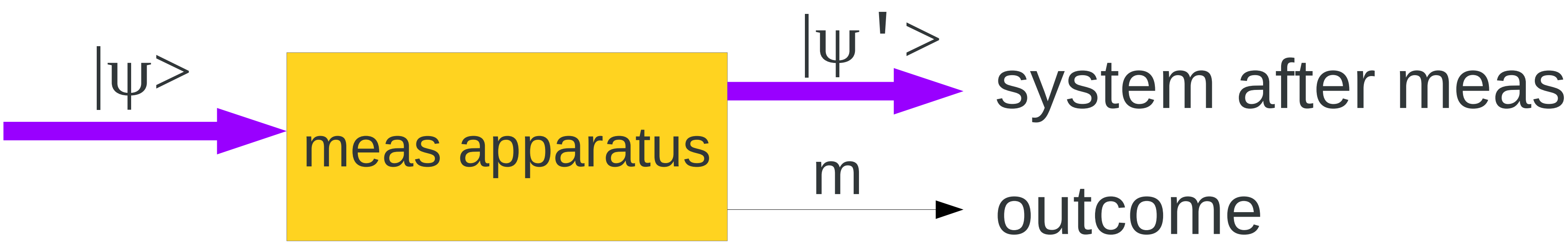

basically: a system-memory interaction (a **correlation**) (memory=where m is stored)

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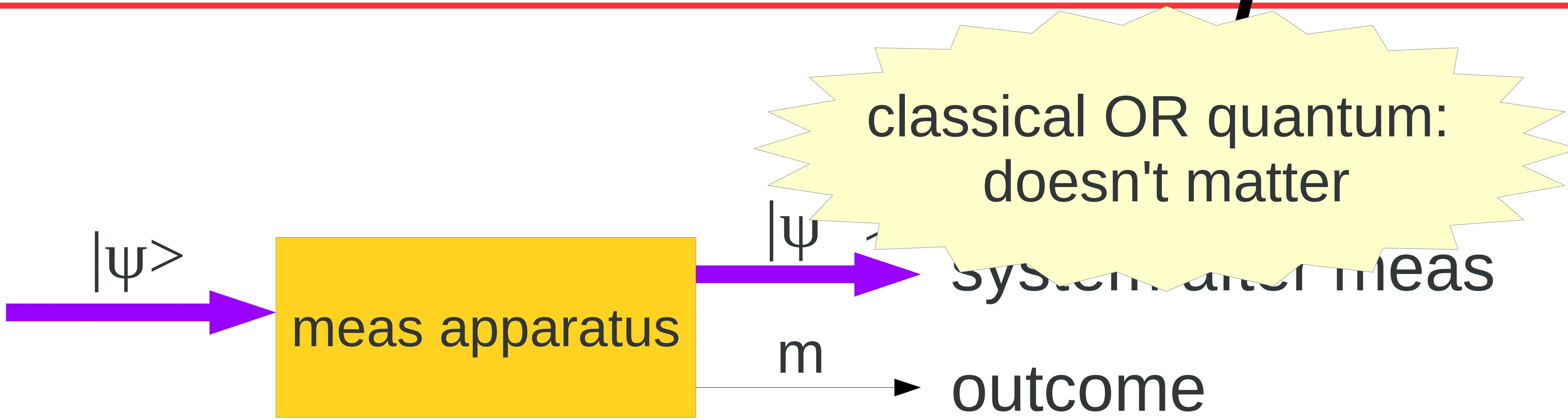

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no need for consciousness: a fully automated (stupid) apparatus can perform a measurement.

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no need for consciousness: a fully automated (stupid) apparatus can perform a measurement. The moon is there even if **we** don't look at it.

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We cannot directly compare things at different times, but only different records at the same time. We cannot know the past except through its records in the present, so it is only present records that we can really test.

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measurement problem

Quantum mechanics

Quantum mechanics

1. States postulate

2. tensor product postulate

3. Schroedinger eq: an isolated q system evolves **unitarily** (hence reversibly and deterministically).

4. Measurement postulate: during a measurement the probability of an outcome is the **Born rule**

Parenthesis

uantum mechanics

Born rule vs. “collapse” of the wave fn

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B.R.+ $p(x,y)=p(x|y)p(y) \Rightarrow$ collapse

[Ozawa quant-ph/9705030]

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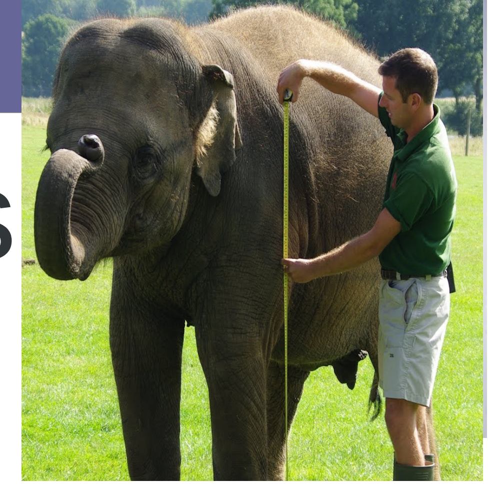

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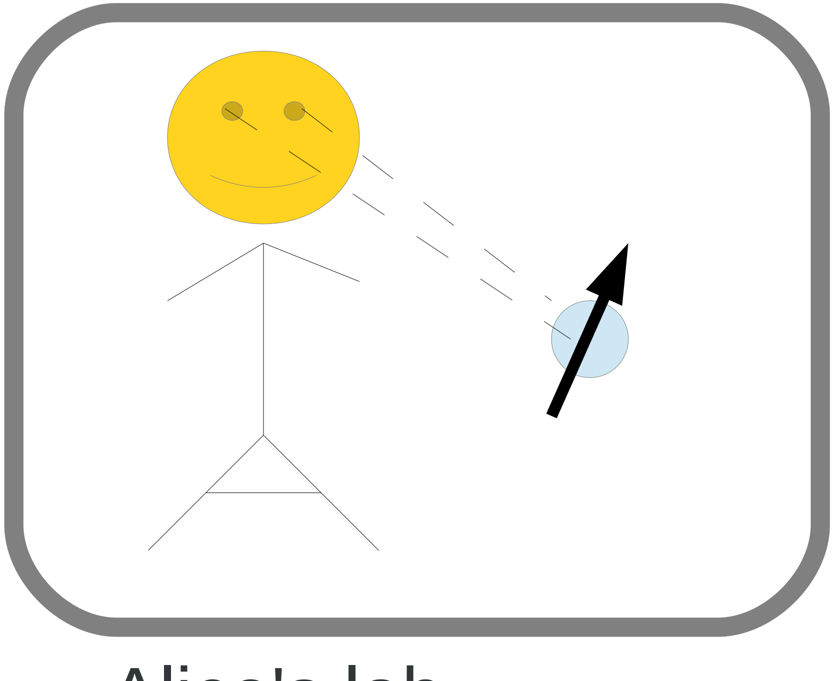

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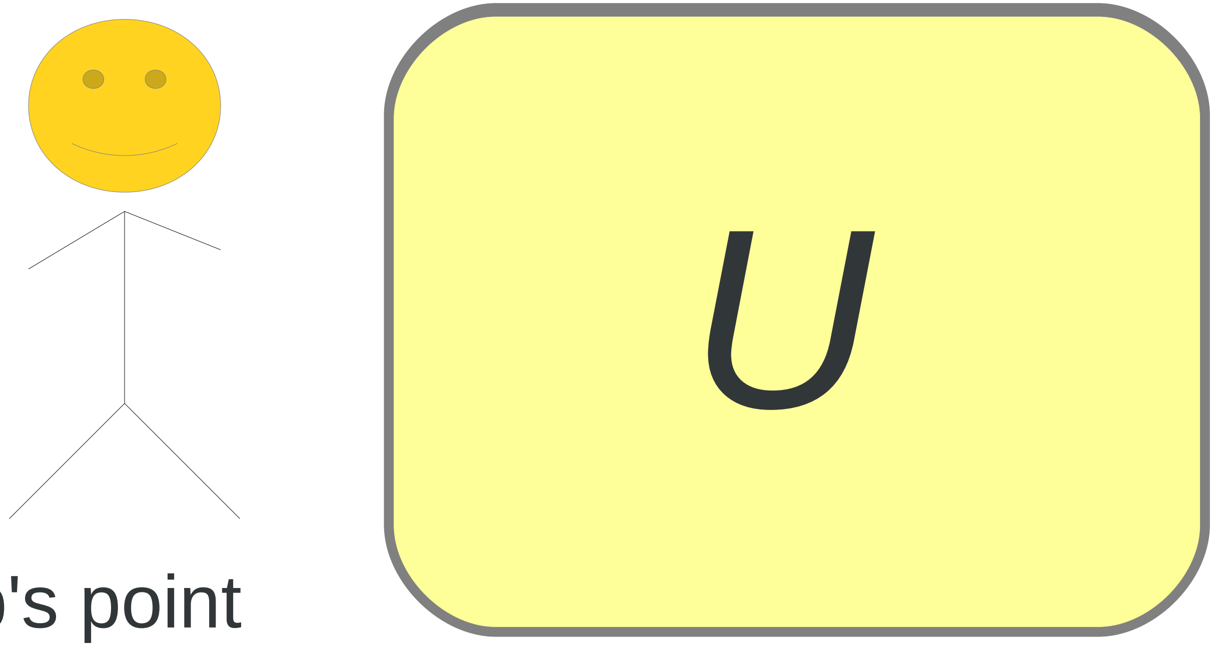

Bob's point of view

Alice's lab

whether the scientist sees a definite outcome depends on who you ask. Alice: yes, Bob: no

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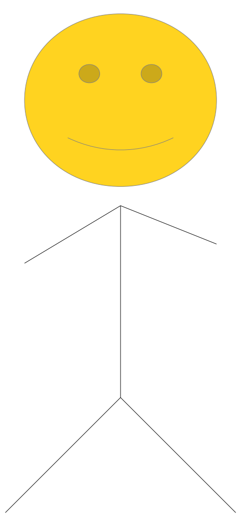

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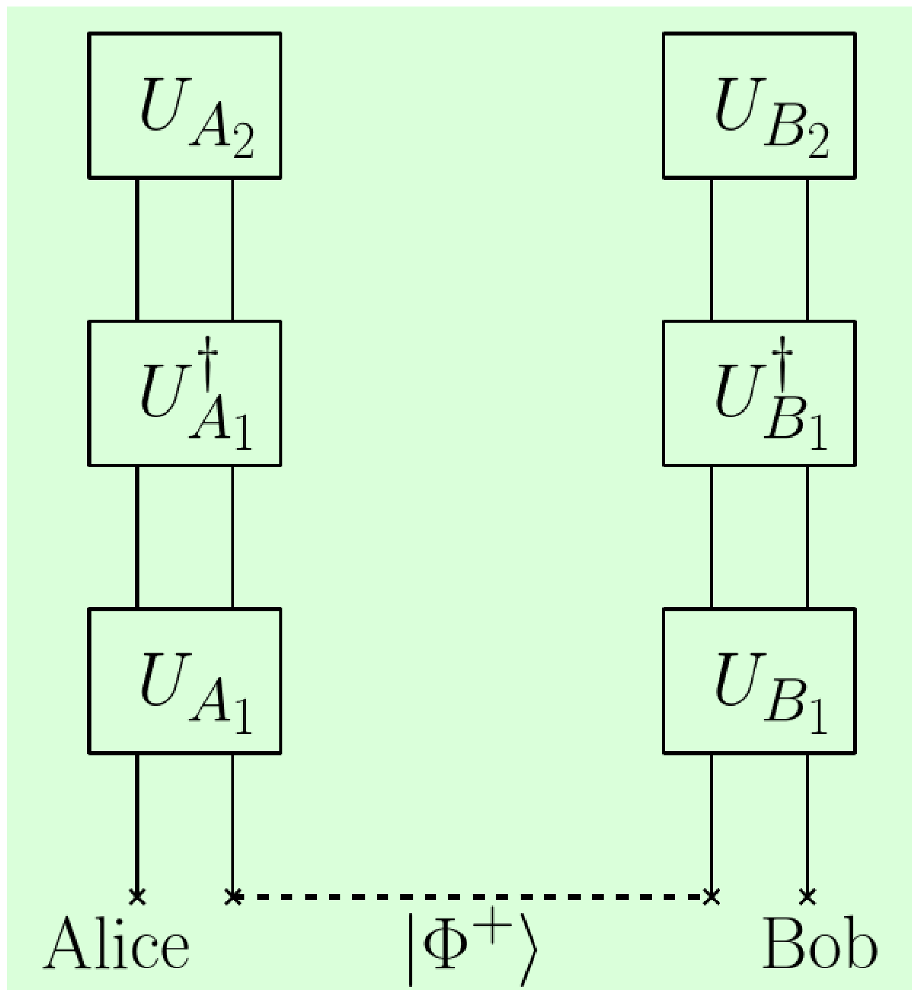

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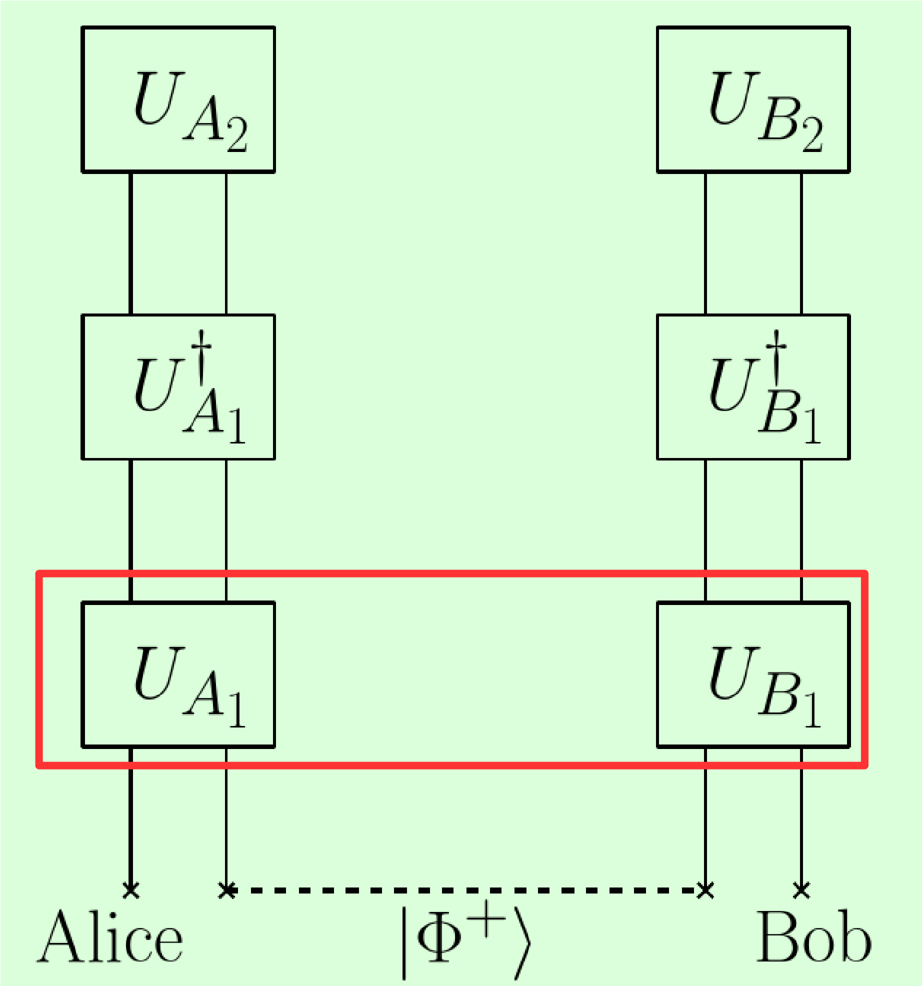

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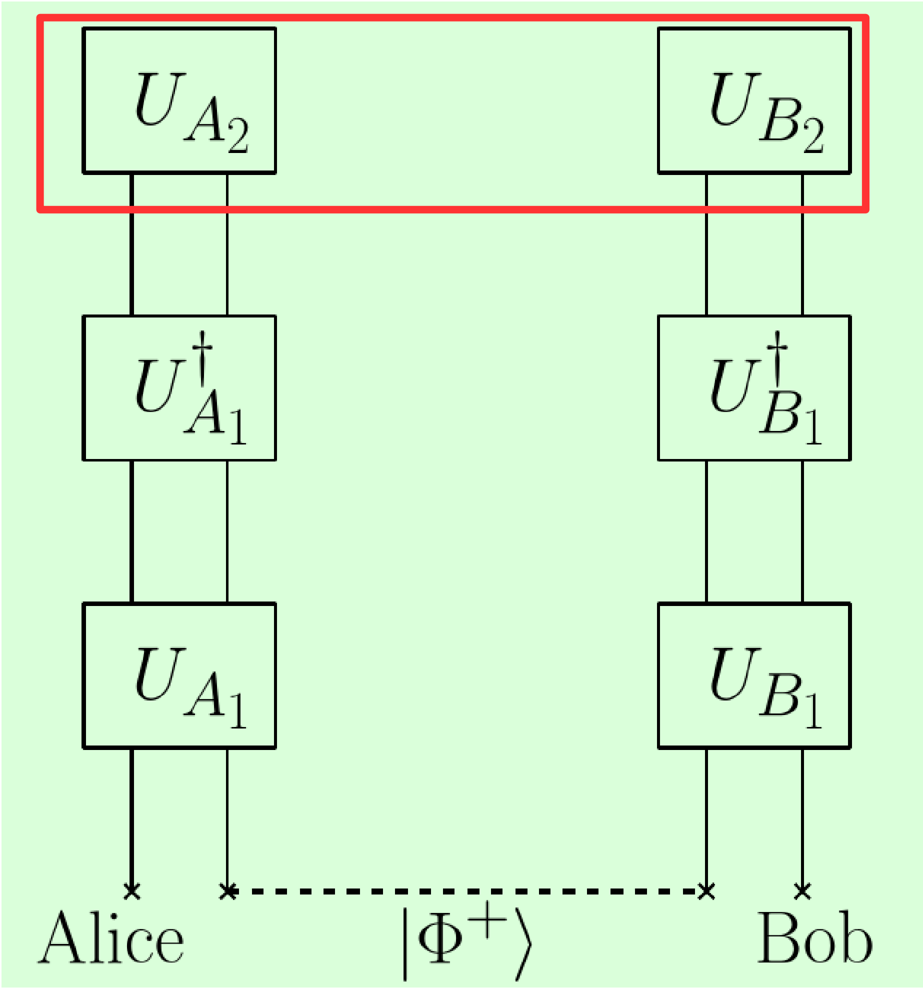

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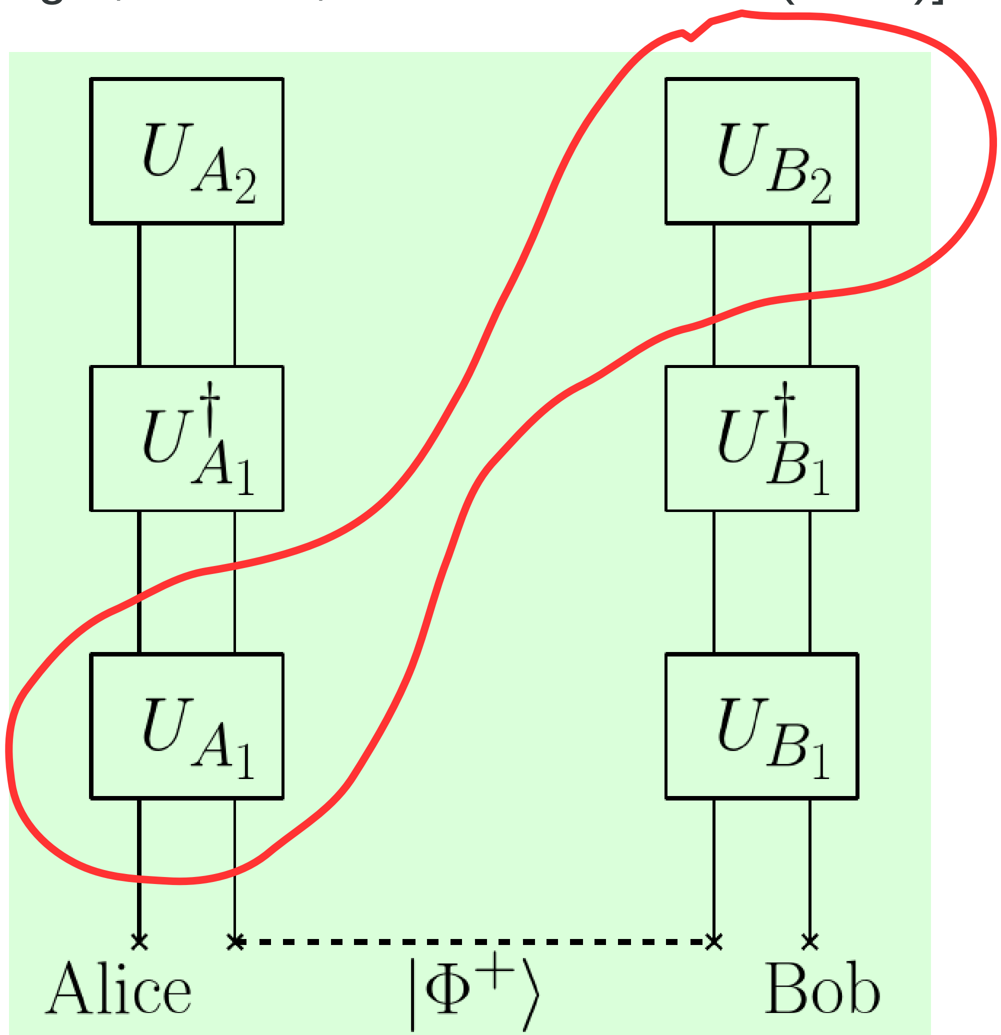

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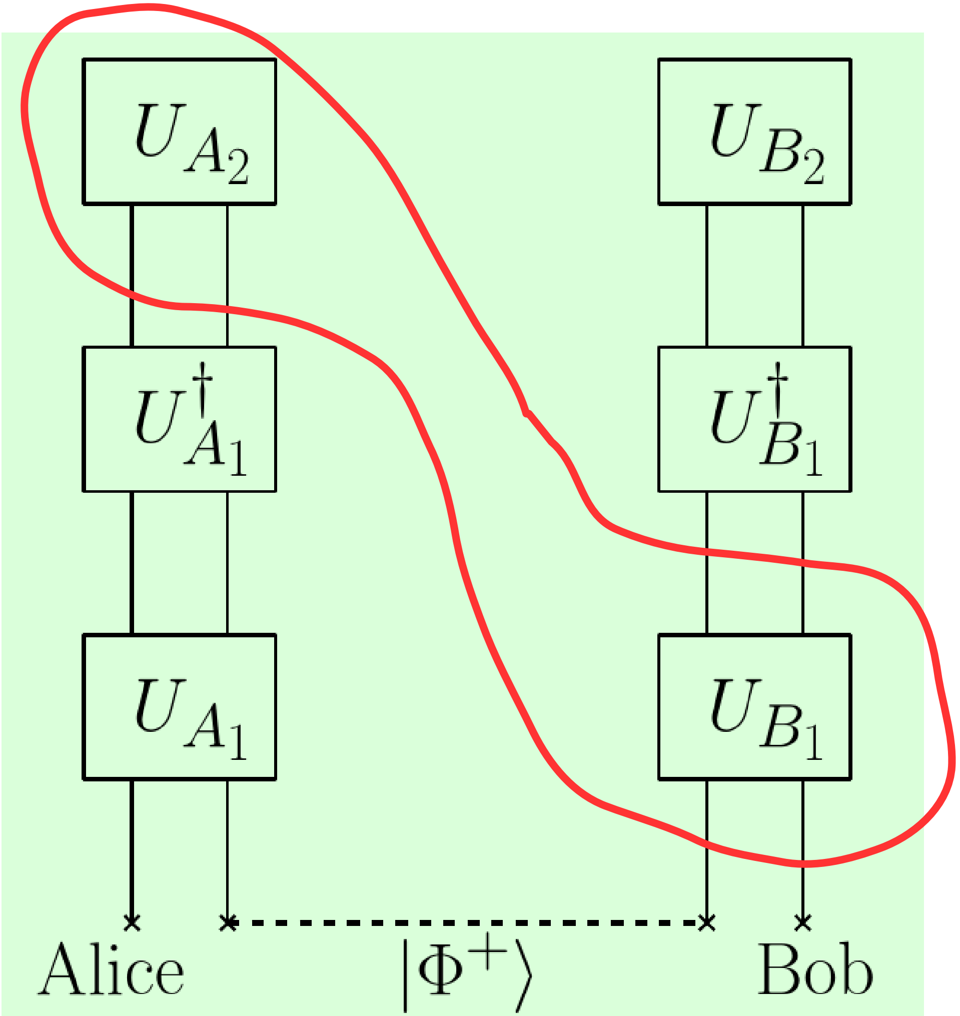

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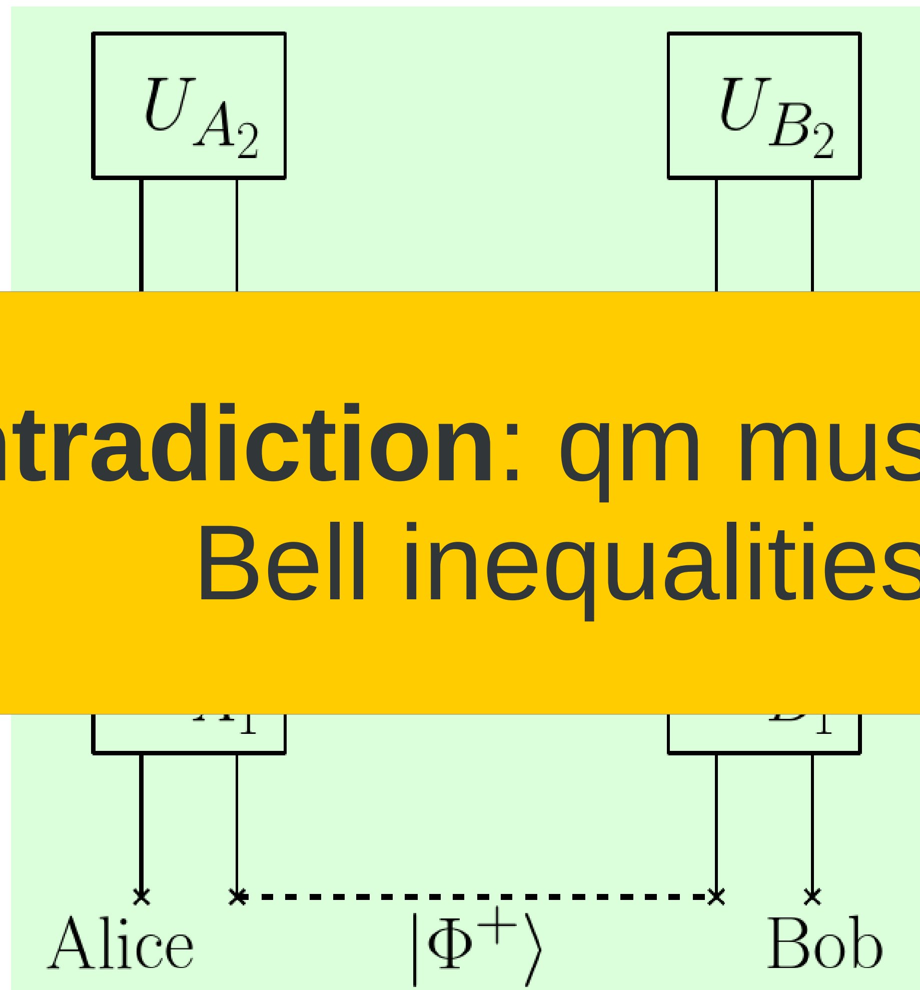

contradiction: qm must violate Bell inequalities!

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if we erase the memory, the measurement hasn't happened

(remember the importance of the memory in a measurement)

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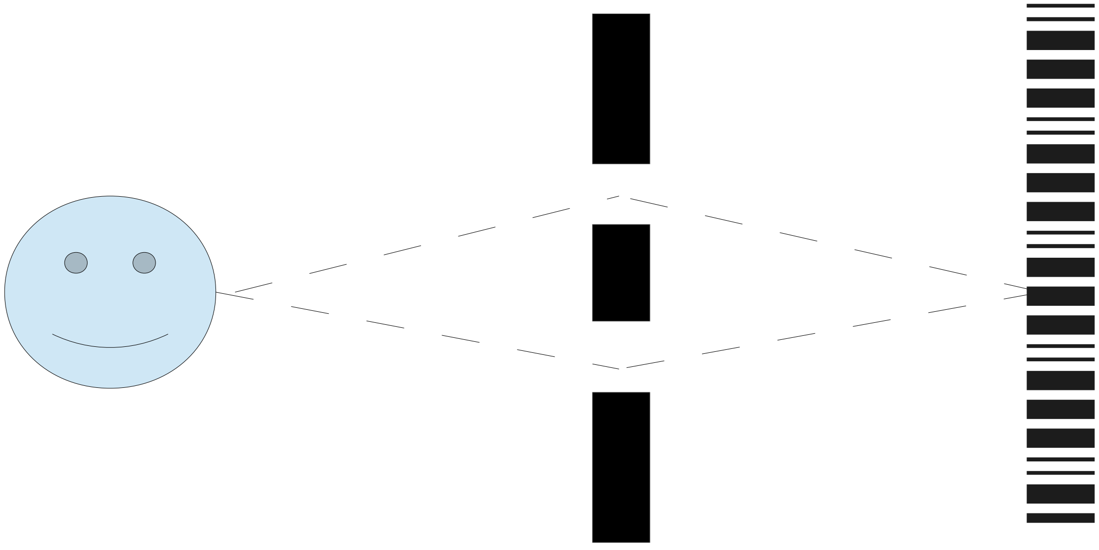
person going through a double slit



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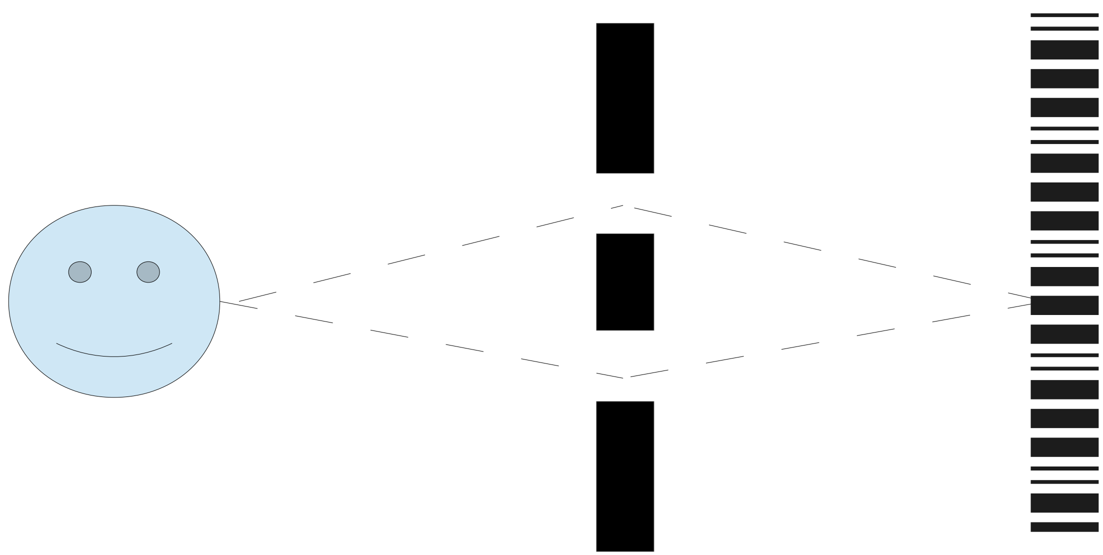

If he remembers where he passed, no interference. If he doesn't, can we say that he passed through ***one*** slit? If so, which one?

measurement problem

Preposterous!!!

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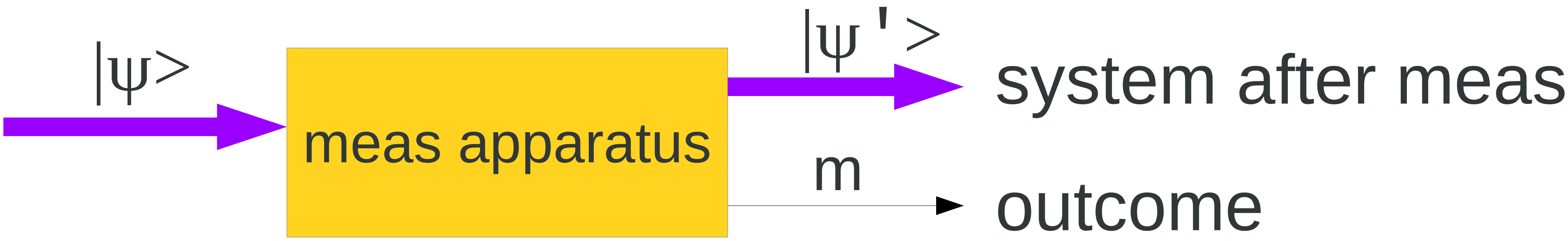
we'll keep unmodified qm for the rest of the talk

Back to the measurement...



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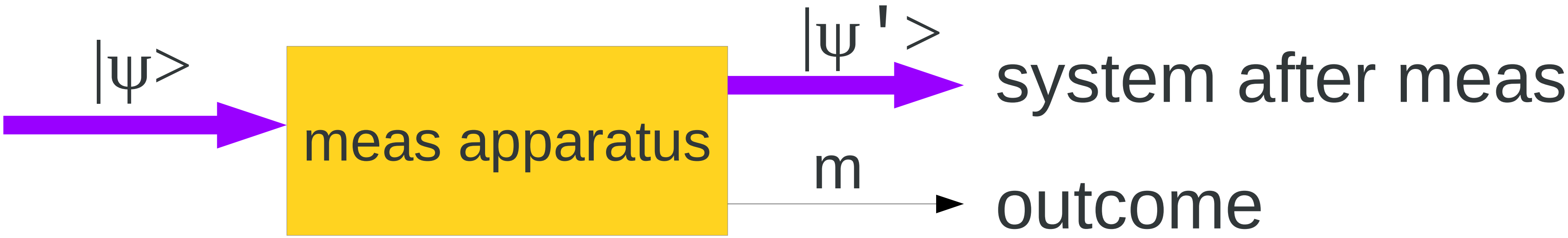
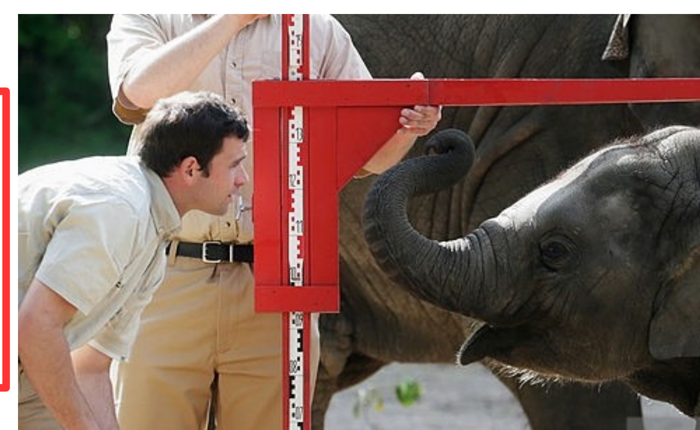


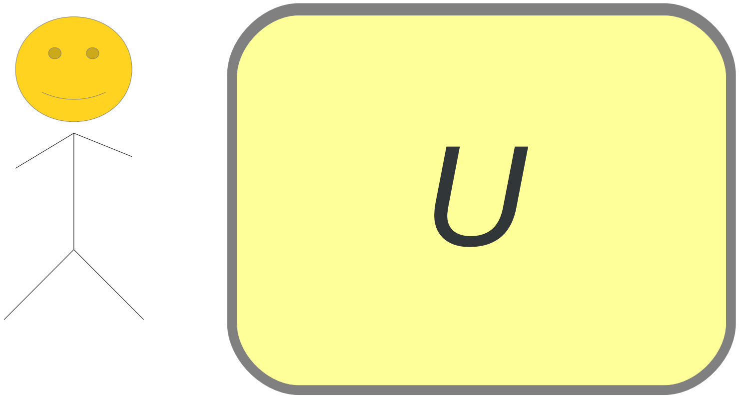
can we formalize this transformation?

Yes (von Neumann)

use 2 stages



stage 1: pre-measurement interaction



measurement formalization

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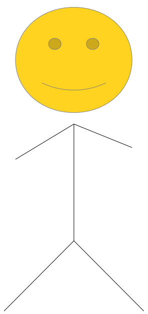

U

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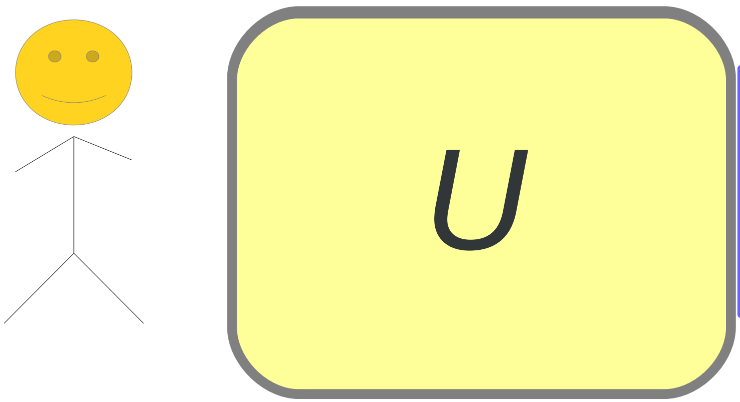

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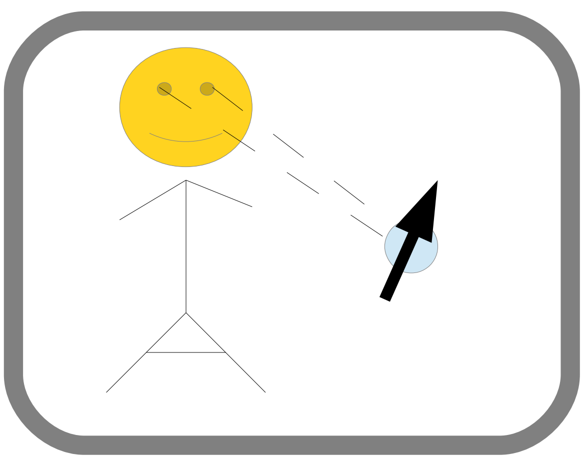
stage 2: wave function “collapse” (Born rule takes over)



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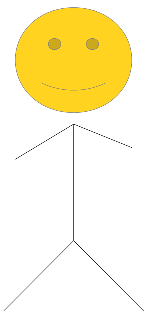

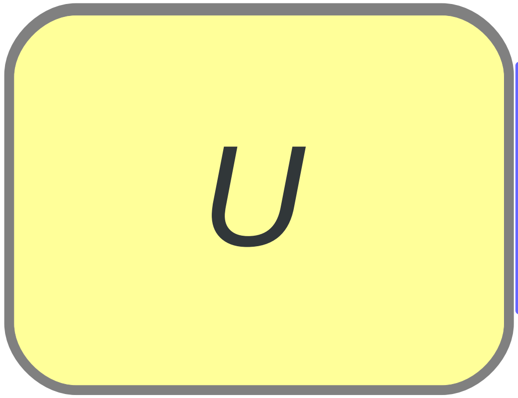

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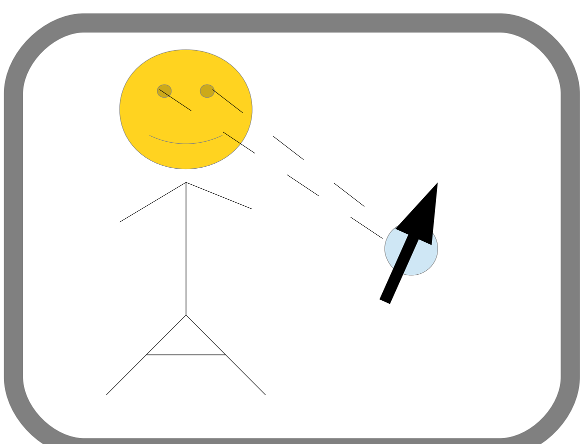

$$\text{Outcome } a \text{ , } p(a) = |\psi_a|^2$$

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connection to my research [PRD **92**, 045033]

Timeless quantum mechanics and measurements:

Rovelli's evolving constants of motion

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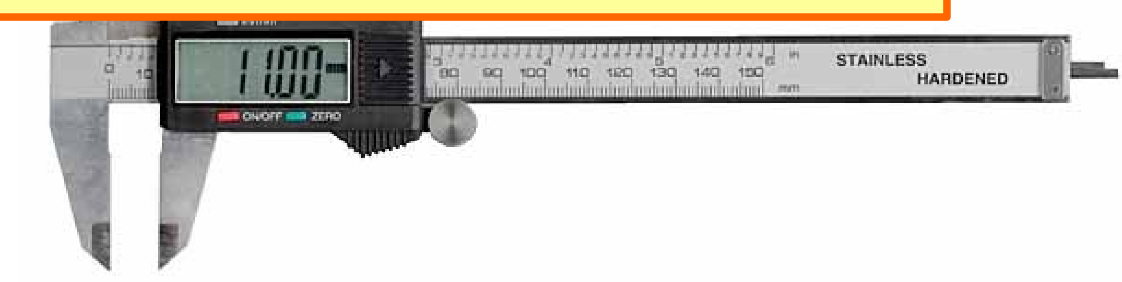
connection measurement-time problem. Ask for details...

connection to my research

Quantum measurements: only foundational relevance?

No! Practical aspects of q. technologies:

Quantum METROLOGY



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Quantum Metrology: estimation of a parameter with increased precision (thanks to quantum effects, e.g. entanglement)

Usually: $\sqrt{N}$ enhancement: the error goes as $1/N$

Example: quantum metrology

Phys. Rev. Lett. **96**, 010401 (2006)

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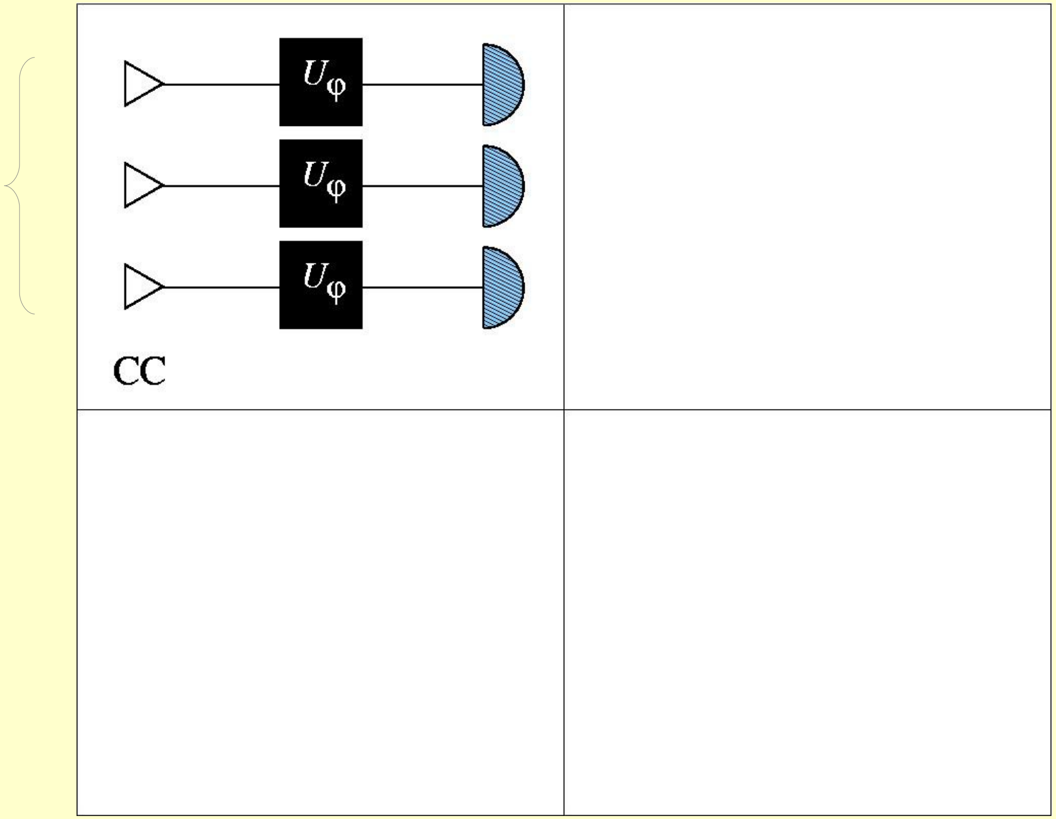
Parallel strategies

N probes



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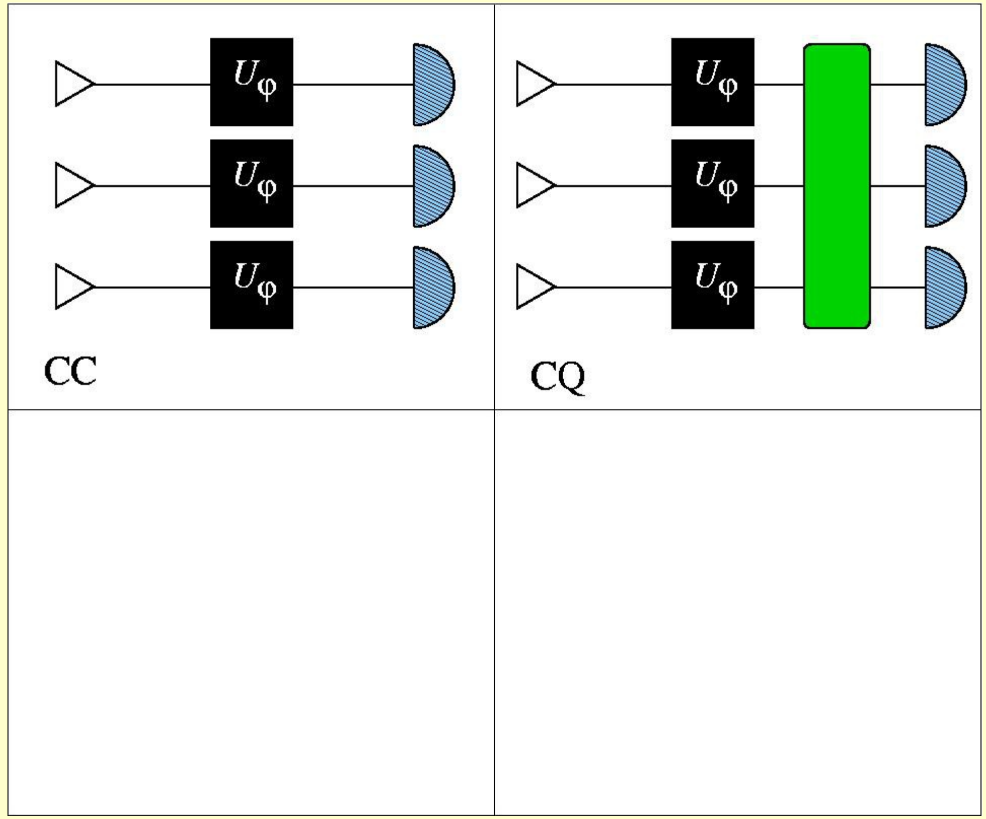

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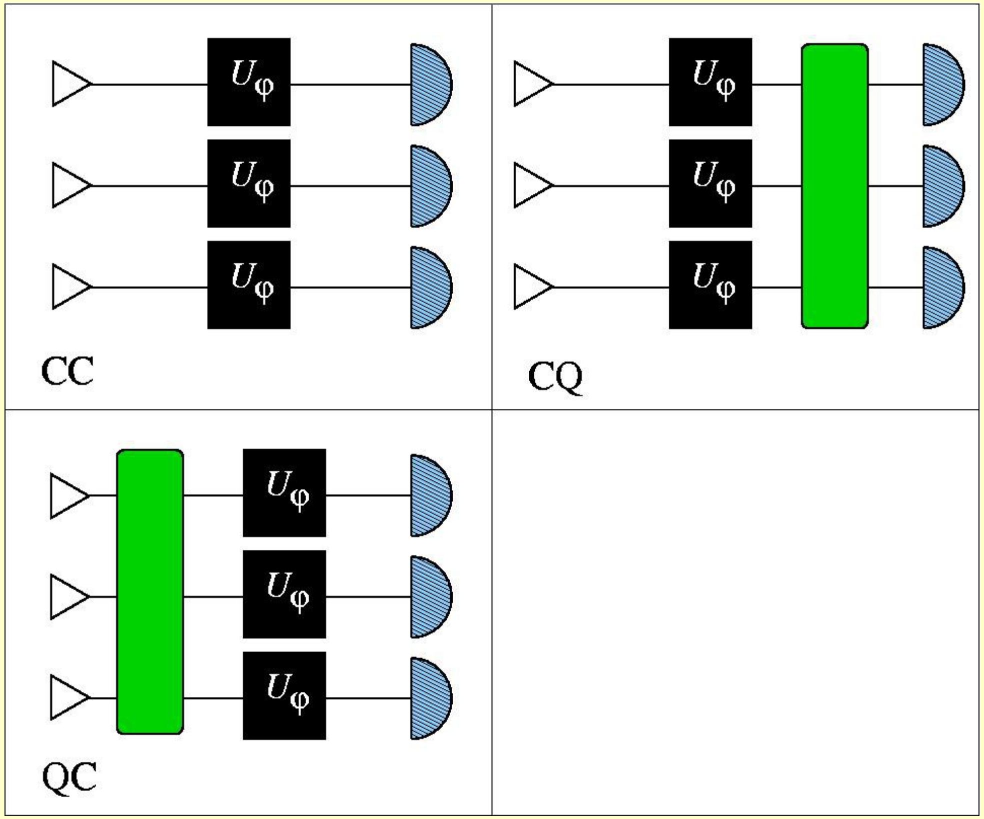

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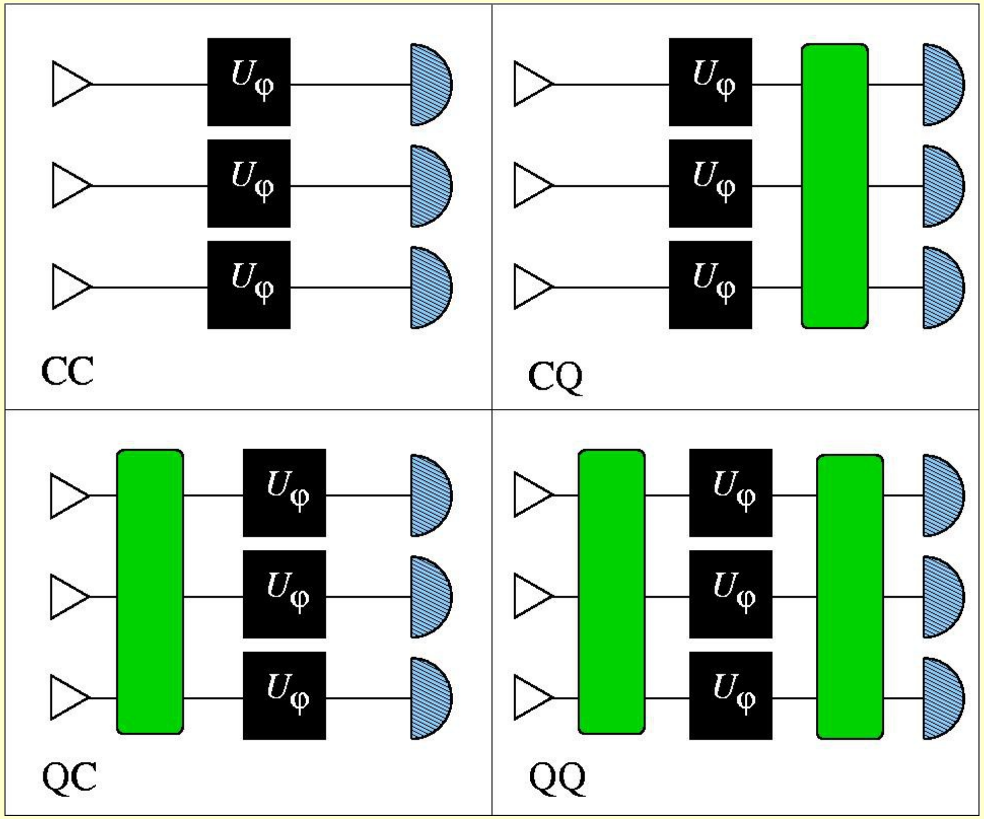

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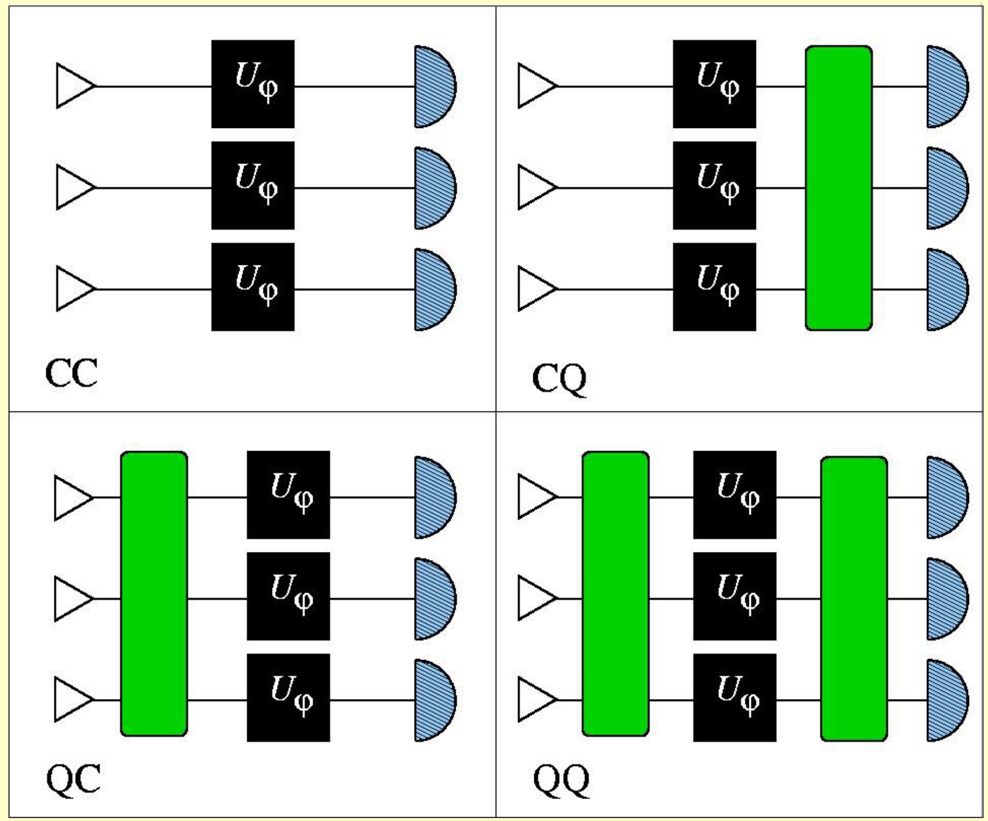

→ $\frac{1}{\sqrt{N}}$

→ $\frac{1}{N}$

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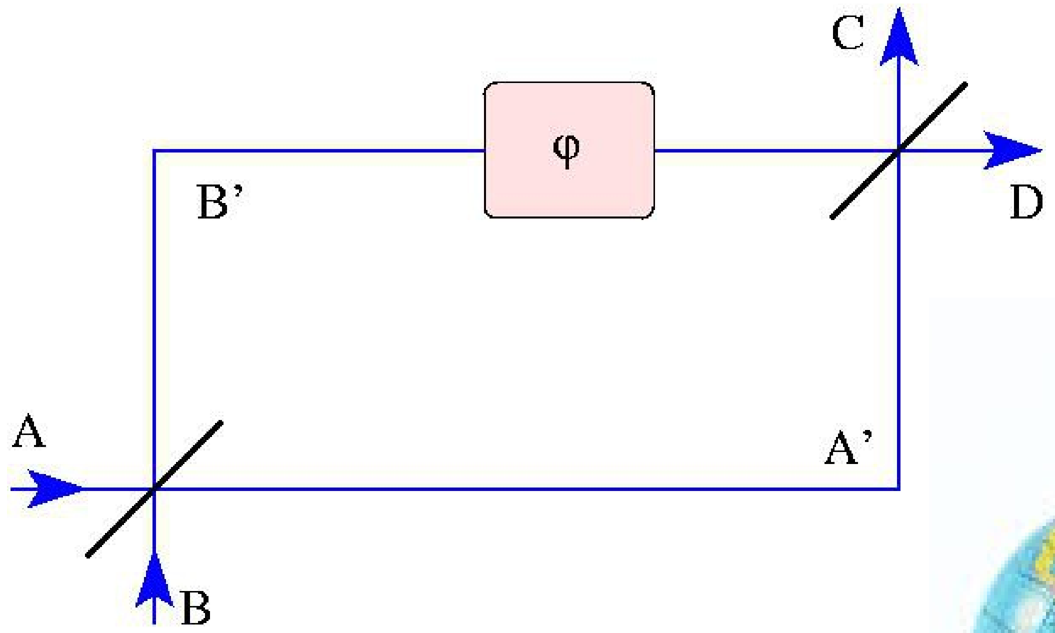
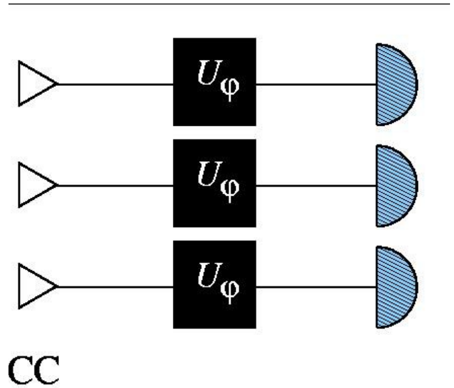
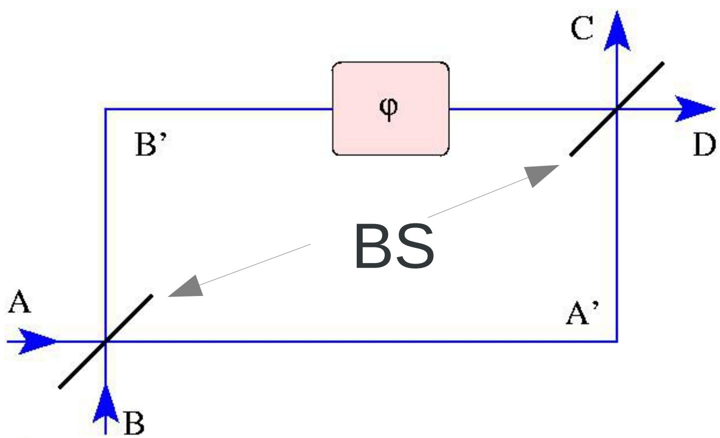
An example:

Measuring the phase in an optical interferometer



Classical strategy:



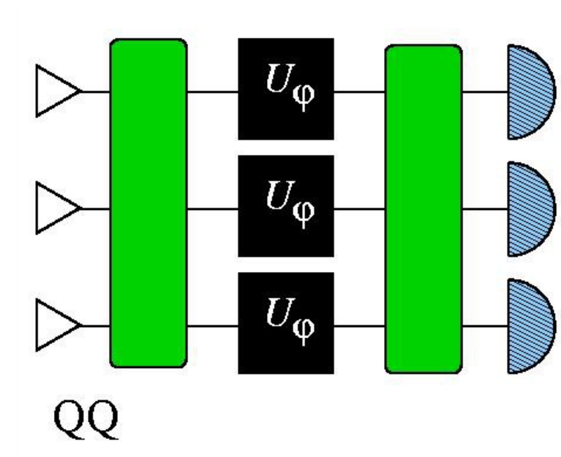


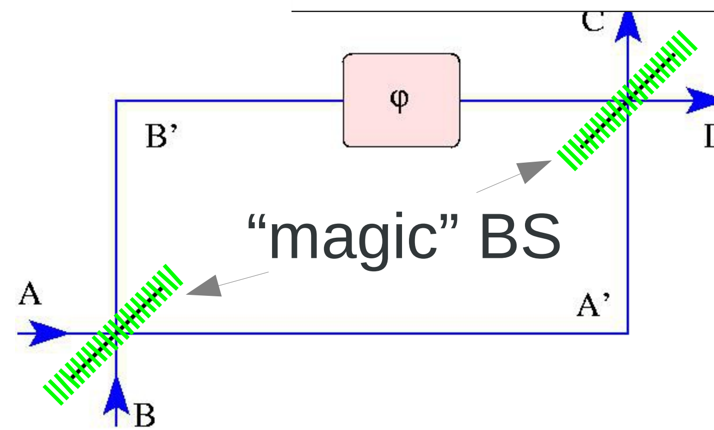
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad \mathrm{x}\ N$$

each of the N photons is treated independently in the interferometer

$$\Rightarrow \Delta\varphi = 1/\sqrt{N}$$

Quantum strategy:





$$\frac{1}{\sqrt{2}}(|0\rangle^{\otimes N} + e^{iN\varphi}|1\rangle^{\otimes N})$$

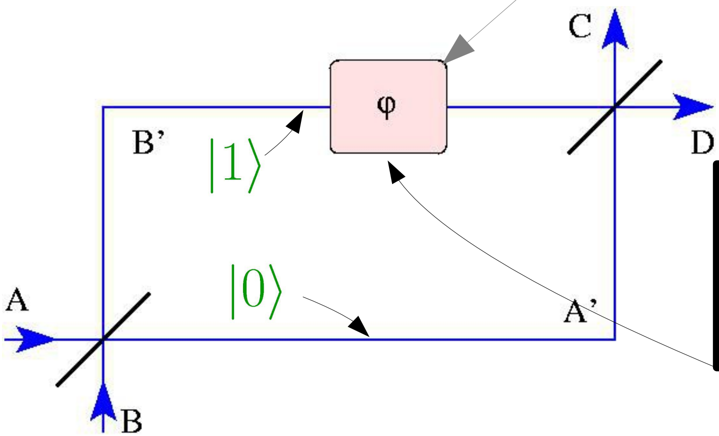
the N photons are “collectively” employed (i.e. they are entangled) in the interferometer

$$\Rightarrow \Delta\varphi = 1/N$$

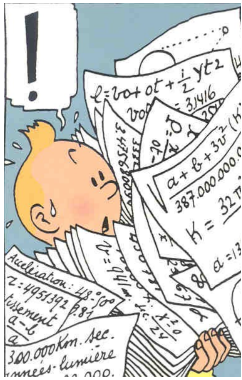
Example

estimation of a phase φ from a Mach-Zehnder interferometer

[or a Ramsey interferometer or a discrete FT, see Rosetta stone: J. Mod. Opt. 49, 2325 (2002)].



N photons at the input A $\rightarrow$ NP_φ at output C and $N(1-P_\varphi)$ at output D. What's φ?



Beam splitter:

$$|0\rangle \leftrightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$
$$|1\rangle \leftrightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Phase shift:

$$|0\rangle \rightarrow |0\rangle$$
$$|1\rangle \rightarrow e^{i\varphi}|1\rangle$$

$$\Rightarrow \quad P_\varphi = |\langle\Psi_{in}|\Psi_{out}\rangle|^2 = \frac{1}{4}|(\langle 0| + \langle 1|)(|0\rangle + e^{i\varphi}|1\rangle)|^2 = \cos^2(\varphi/2)$$

and the variance of the mean (from the variance of a binomial): $\Delta^2 P_\varphi = P_\varphi(1-P_\varphi)/N$

so that from error propagation:

$$\Delta\varphi = \frac{\Delta P_\varphi}{|\partial P_\varphi/\partial\varphi|} = \frac{\sqrt{\cos^2\frac{\varphi}{2}\sin^2\frac{\varphi}{2}}}{\sqrt{N}|\cos\frac{\varphi}{2}\sin\frac{\varphi}{2}|} = \frac{1}{\sqrt{N}}$$

ENTANGLEMENT does it better!!

Instead of using N times the state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ in the interferometer, use ONCE the N photon state:

$$\frac{1}{\sqrt{2}}(|0\rangle^{\otimes N} + |1\rangle^{\otimes N}) \longrightarrow \frac{1}{\sqrt{2}}(|0\rangle^{\otimes N} + e^{iN\varphi}|1\rangle^{\otimes N})$$

Now, the overlap between input and output states is:

and $\Delta^2 P'_\varphi = P'_\varphi(1 - P'_\varphi)$

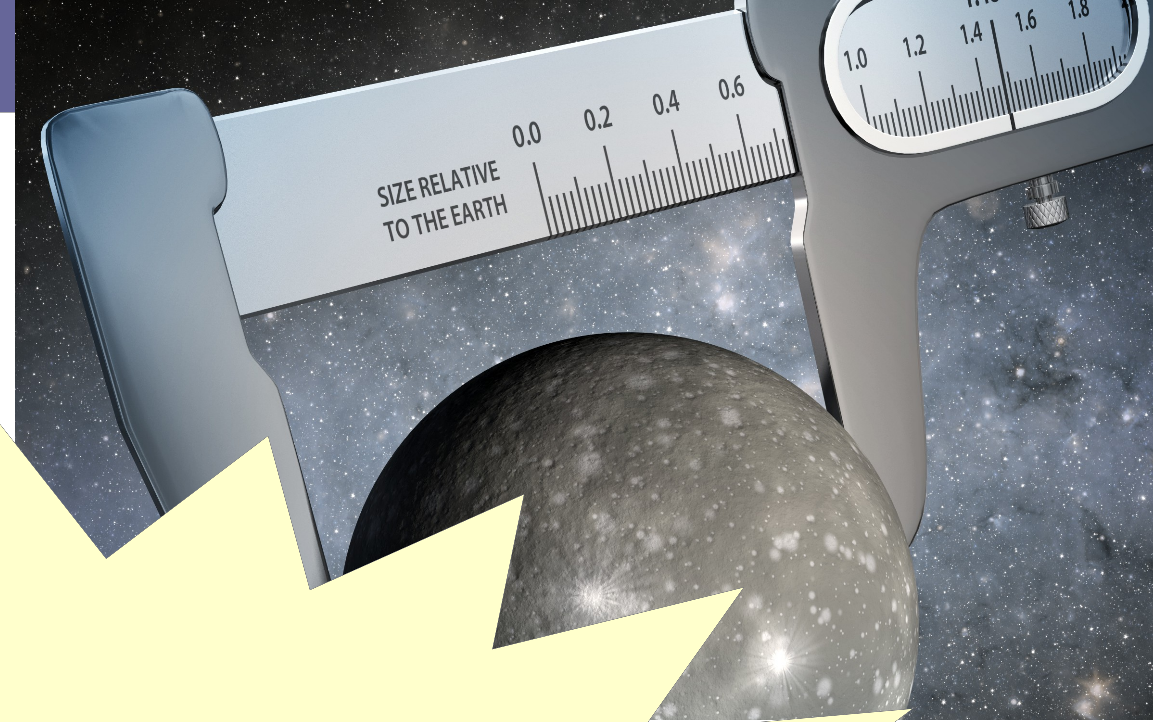
$$\Rightarrow \quad \Delta\varphi = \frac{\Delta P'_\varphi}{|\partial P'_\varphi/\partial\varphi|} = \frac{\sqrt{\cos^2\frac{N\varphi}{2}\sin^2\frac{N\varphi}{2}}}{N|\cos\frac{N\varphi}{2}\sin\frac{N\varphi}{2}|} = \frac{1}{N}$$

A $\sqrt{N}$ gain over the classical strategy!!!!!

N.b. We are using a "modified" MZ: the necessary state cannot be obtained from a conventional beam splitter.

Quantum measurement

- What is it? → role of memory
- Measurement problem
- Subjectivity of the Born rule
- What is the role of time?
- Quantum metrology



Measurement: correlation between q system and **memory**

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