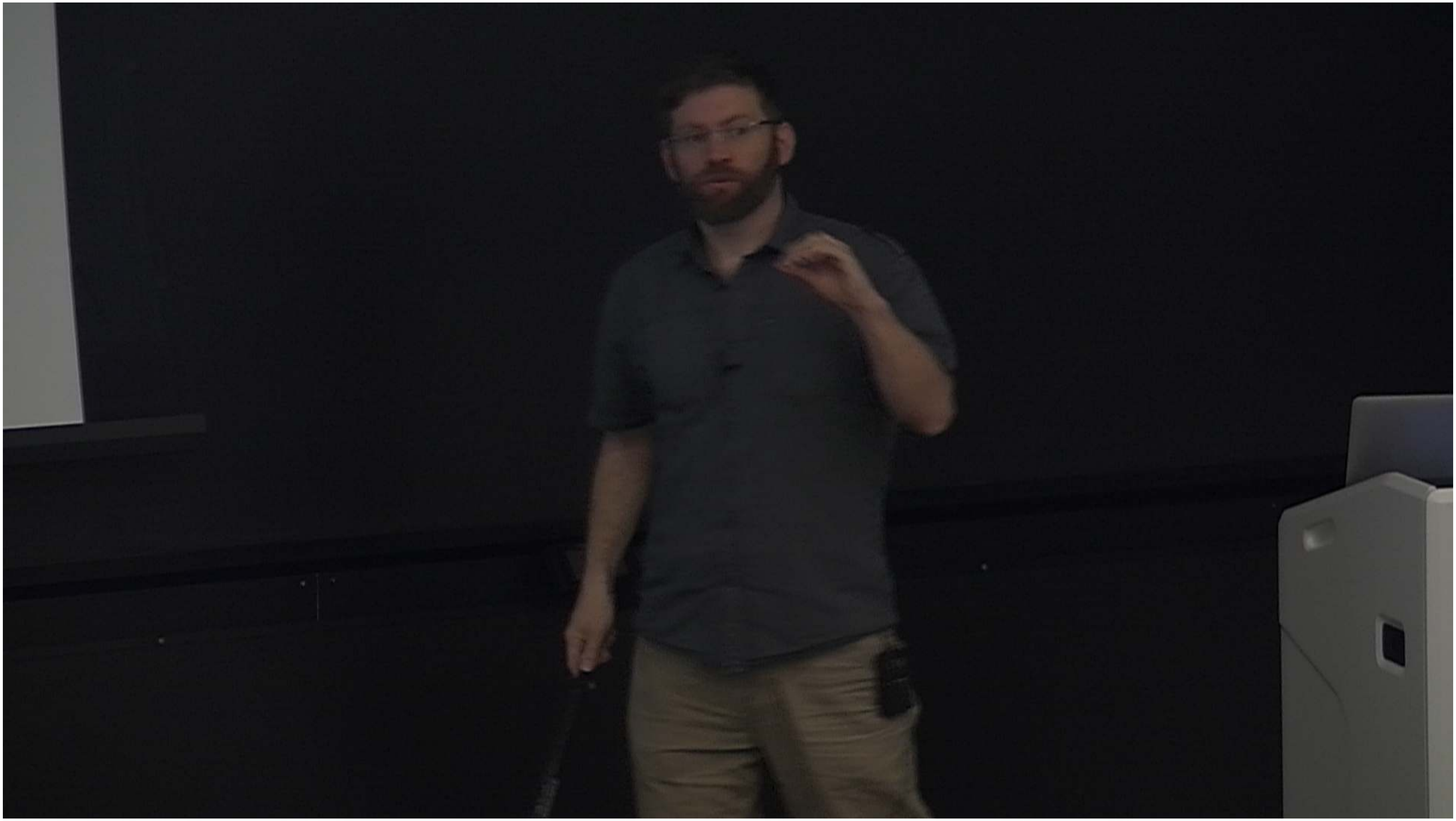
Title: Reassessing claims of nonclassicality for quantum interference phenomena

Date: Jun 16, 2016 02:00 PM

URL: http://pirsa.org/16060102

Abstract:



Methodological desiderata for understanding nonclassicality

Bad form	Good form
I can't see how to make sense of this observable phenomenon in a classical theory	I've proven a **theorem** showing that a formal notion of classicality is inconsistent with the observable phenomenon

Methodological desiderata for understanding nonclassicality

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I can't see how to make sense of this observable phenomenon in a classical theory	I've proven a **theorem** showing that a formal notion of classicality is inconsistent with the observable phenomenon
I can't explain the phenomenon using a classical system with the expected classical phase space and Hamiltonian; this quantum system has no classical counterpart	I've allowed **arbitrary** classical state spaces and dynamics (i.e., been liberal in what counts as classical)

What was the point of Werner's local hidden variable model establishing the impossibility of violating certain Bell inequalities with certain entangled states?

An attempt to clarify what is the precise quantum phenomenology that is in tension with a local explanation when one is maximally permissive about the form of such an explanation

What was the point of Werner's local hidden variable model establishing the impossibility of violating certain Bell inequalities with certain entangled states?

An attempt to clarify what is the precise quantum phenomenology that is in tension with a local explanation when one is maximally permissive about the form of such an explanation

Appropriate response: we need to identify the precise quantum phenomena that *are* in tension with locality

This talk has the same sort of objective:

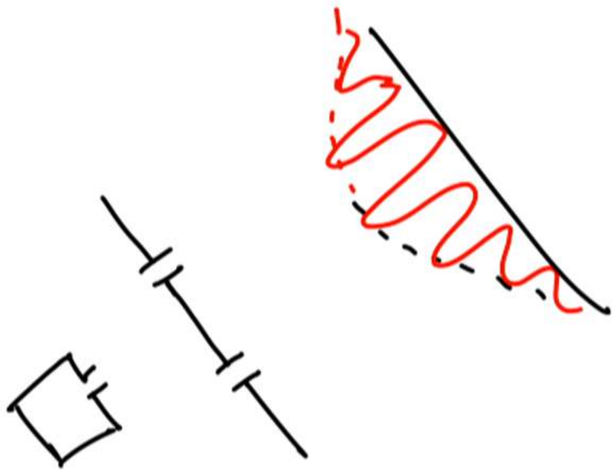
An attempt to clarify what is the precise quantum phenomenology that is in tension with a classical and local explanation

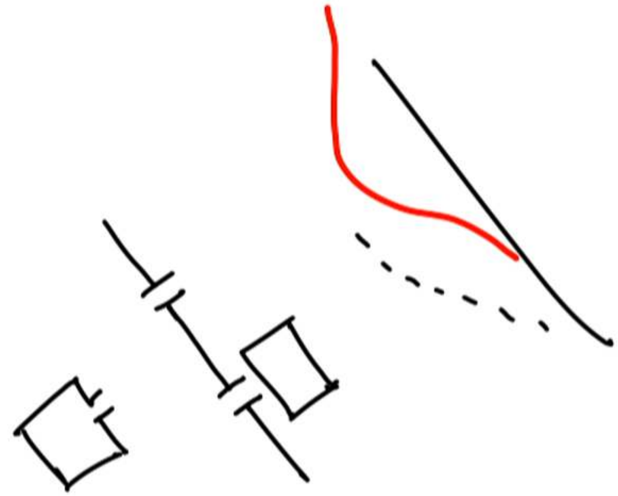
The conclusion:

The “core” phenomenology of wave-particle duality, Elitzur-Vaidman bomb-testing, Wheeler’s delayed choice, reality of the empty wave, and others can be understood in a local and classical way

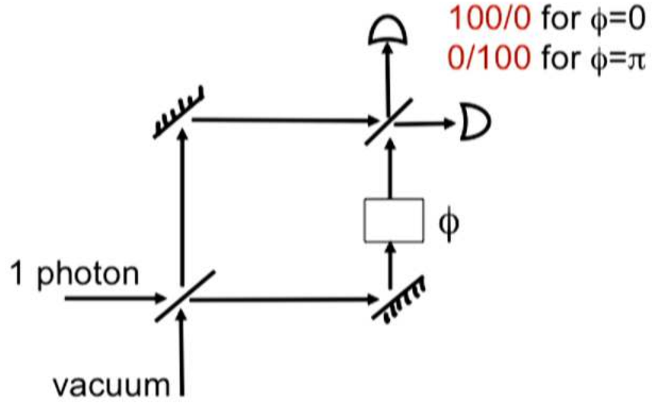
Appropriate response: we need to identify the precise quantum phenomena that *are* in tension with classicality and locality

Wave-particle duality





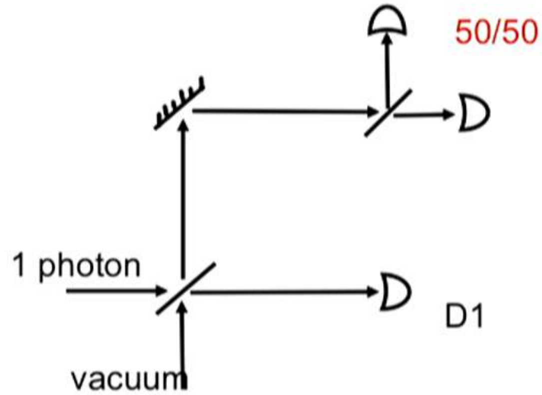
Mach-Zehnder Interferometer



$$|1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\phi = 0} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{BS} |1\rangle|0\rangle$$

$$|1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\phi = \pi} |1\rangle|0\rangle + |0\rangle|1\rangle \xrightarrow{BS} |0\rangle|1\rangle$$

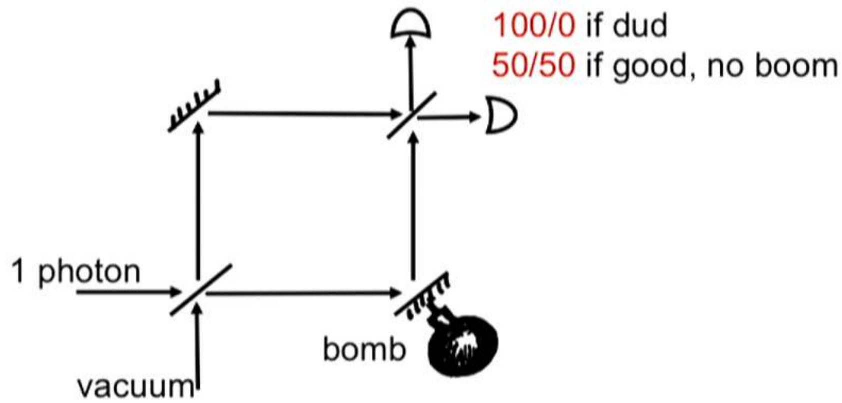
Mach-Zehnder Interferometer



No click at D1

$$|1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle \longrightarrow |1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle$$

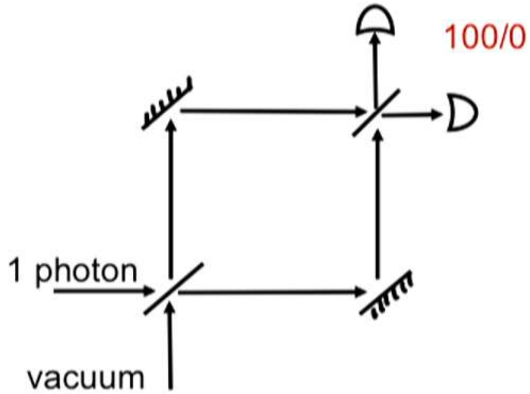
Elitzur-Vaidman bomb-testing



	BS		Dud		BS	
$\|1\rangle\|0\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle - \|0\rangle\|1\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle - \|0\rangle\|1\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle$
	BS		Good, no boom		BS	
$\|1\rangle\|0\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle - \|0\rangle\|1\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle$	$\Longrightarrow$	$\|1\rangle\|0\rangle - \|0\rangle\|1\rangle$

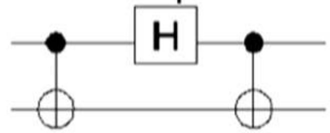
Again, but in the Hamiltonian picture

Mach-Zehnder Interferometer



$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},\ Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},\ Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Beam splitter



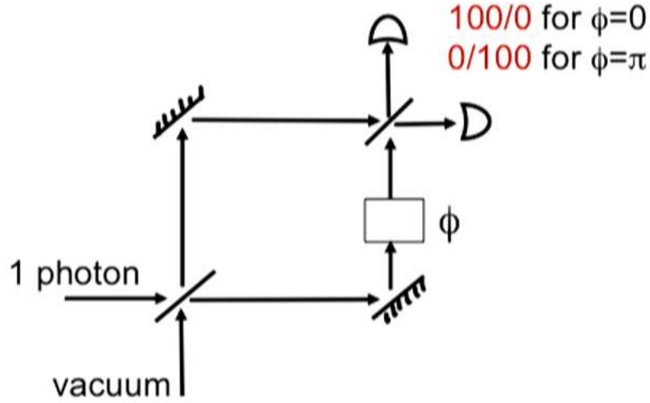
ZI → -XX
XI → -XZ
IZ → YY
IX → IX

$$|1\rangle|0\rangle \overset{BS}{\Longrightarrow} |1\rangle|0\rangle - |0\rangle|1\rangle \overset{BS}{\Longrightarrow} |1\rangle|0\rangle$$

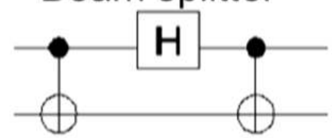
<ZI,-IZ> <-XX,-ZZ> <ZI,-IZ>

Mach-Zehnder Interferometer

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},\ Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},\ Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

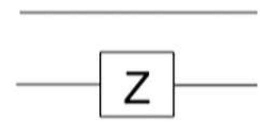


Beam splitter



ZI → -XX
XI → -XZ
IZ → YY
IX → IX

π phase shift



ZI → ZI
XI → XI
IZ → IZ
IX → -IX

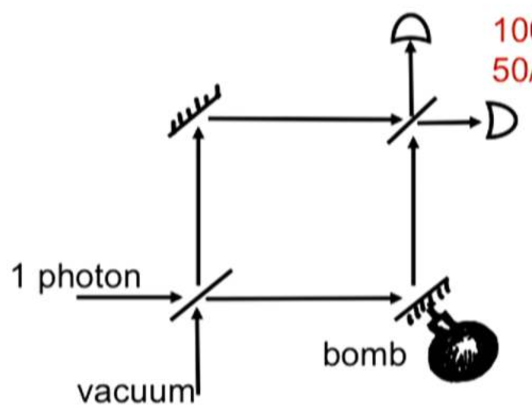
$$|1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\phi = 0} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{BS} |1\rangle|0\rangle$$

<ZI,-IZ> <-XX,-ZZ> <-XX,-ZZ> <ZI,-IZ>

$$|1\rangle|0\rangle \xrightarrow{BS} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\phi = \pi} |1\rangle|0\rangle + |0\rangle|1\rangle \xrightarrow{BS} |0\rangle|1\rangle$$

<ZI,-IZ> <-XX,-ZZ> <XX,-ZZ> <ZI,-IZ>

Elitzur-Vaidman bomb-testing



100/0 if dud
50/50 if good, no boom

$|1\rangle|0\rangle \xrightarrow{\text{BS}} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\text{Dud}} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\text{BS}} |1\rangle|0\rangle$

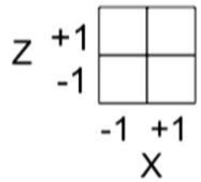
<ZI,-IZ> <-XX,-ZZ> <-XX,-ZZ> <ZI,-IZ>

$|1\rangle|0\rangle \xrightarrow{\text{BS}} |1\rangle|0\rangle - |0\rangle|1\rangle \xrightarrow{\text{Good, no boom}} |1\rangle|0\rangle \xrightarrow{\text{BS}} |1\rangle|0\rangle - |0\rangle|1\rangle$

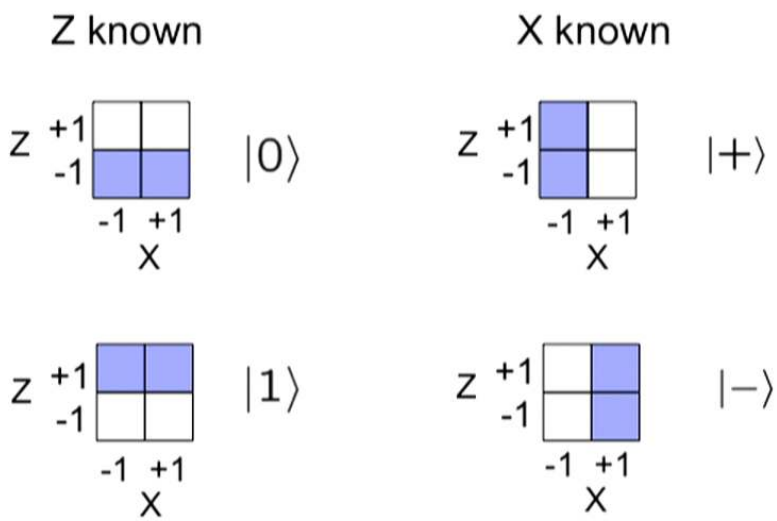
<ZI,-IZ> <-XX,-ZZ> <ZI,-IZ> <-XX,-ZZ>

A classical model using discrete fields

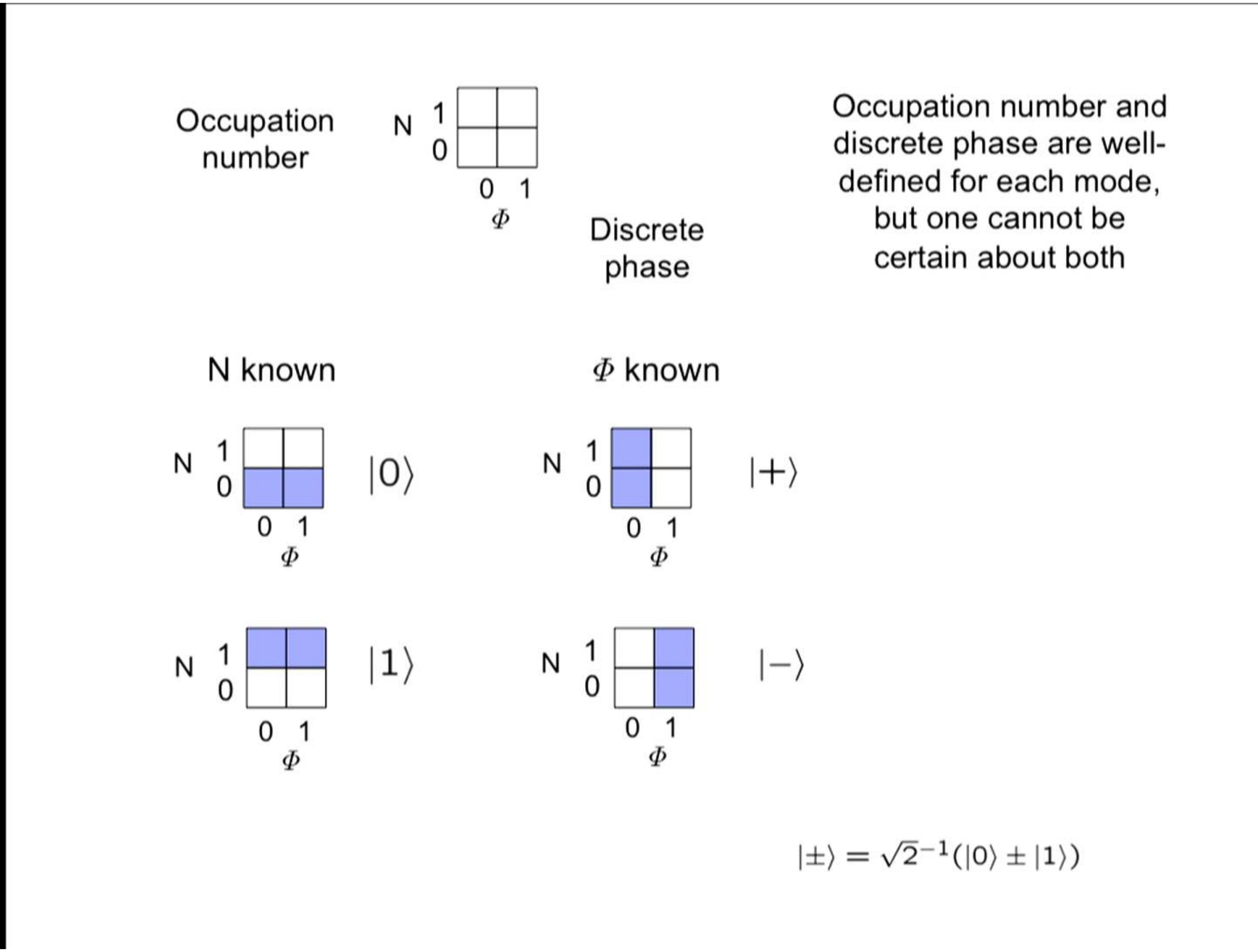
Joint work with Elliot Martin and Matt Leifer

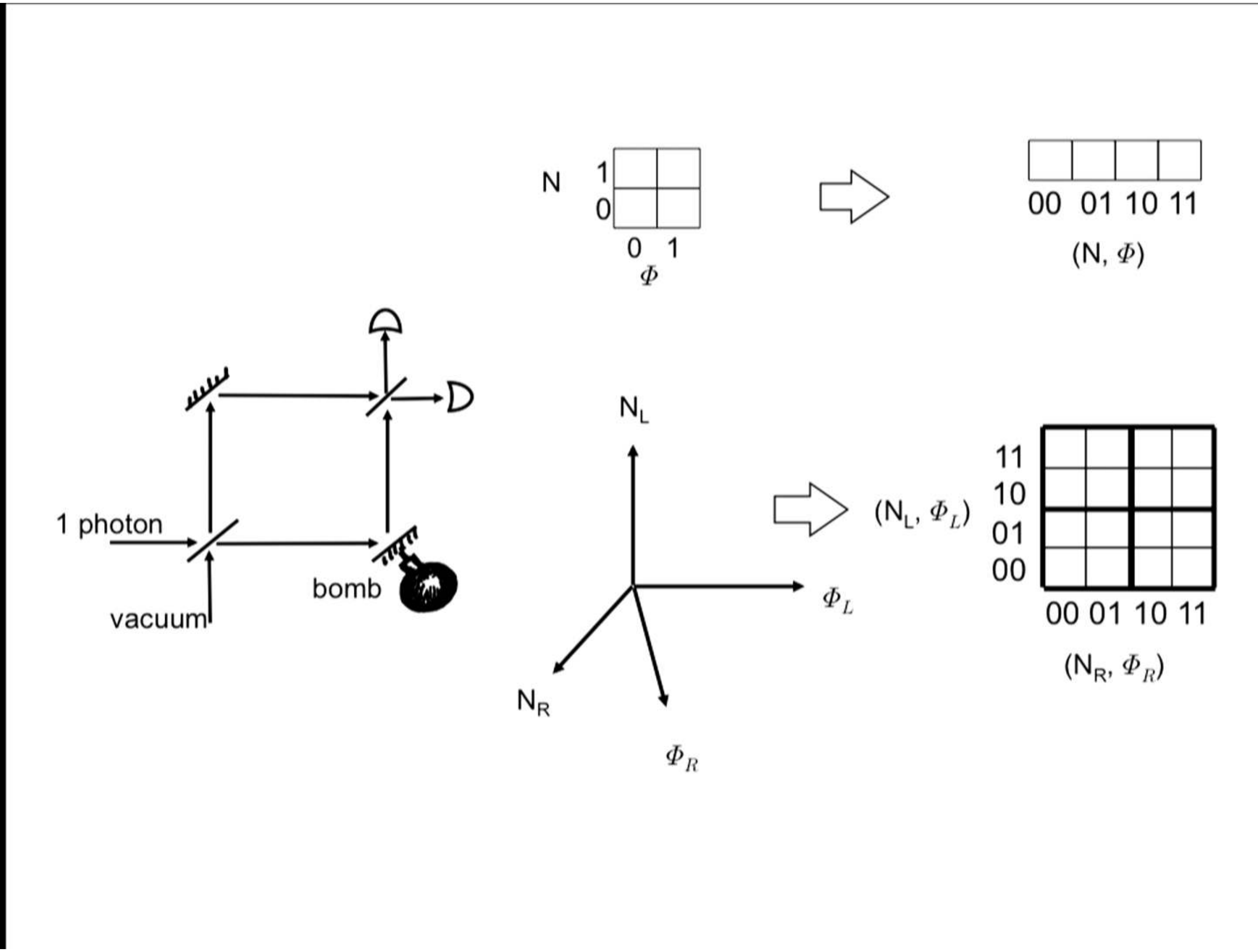


Z and X are well-defined for each mode, but one cannot be certain about both

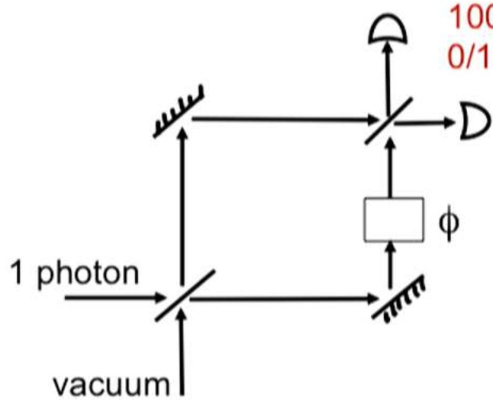


$$|\pm\rangle = \sqrt{2}^{-1}(|0\rangle \pm |1\rangle)$$

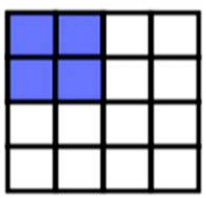

Occupation number
N
1
0
0 1
Φ
Discrete phase
Occupation number and discrete phase are well-defined for each mode, but one cannot be certain about both
N known
Φ known
|0⟩
|+⟩
|1⟩
|−⟩
|±⟩ = √2⁻¹(|0⟩ ± |1⟩)


N
1
0
0 1
Φ
00 01 10 11
(N, Φ)
1 photon
vacuum
bomb
N_L
Φ_L
N_R
Φ_R
(N_L, Φ_L)
11
10
01
00
00 01 10 11
(N_R, Φ_R)

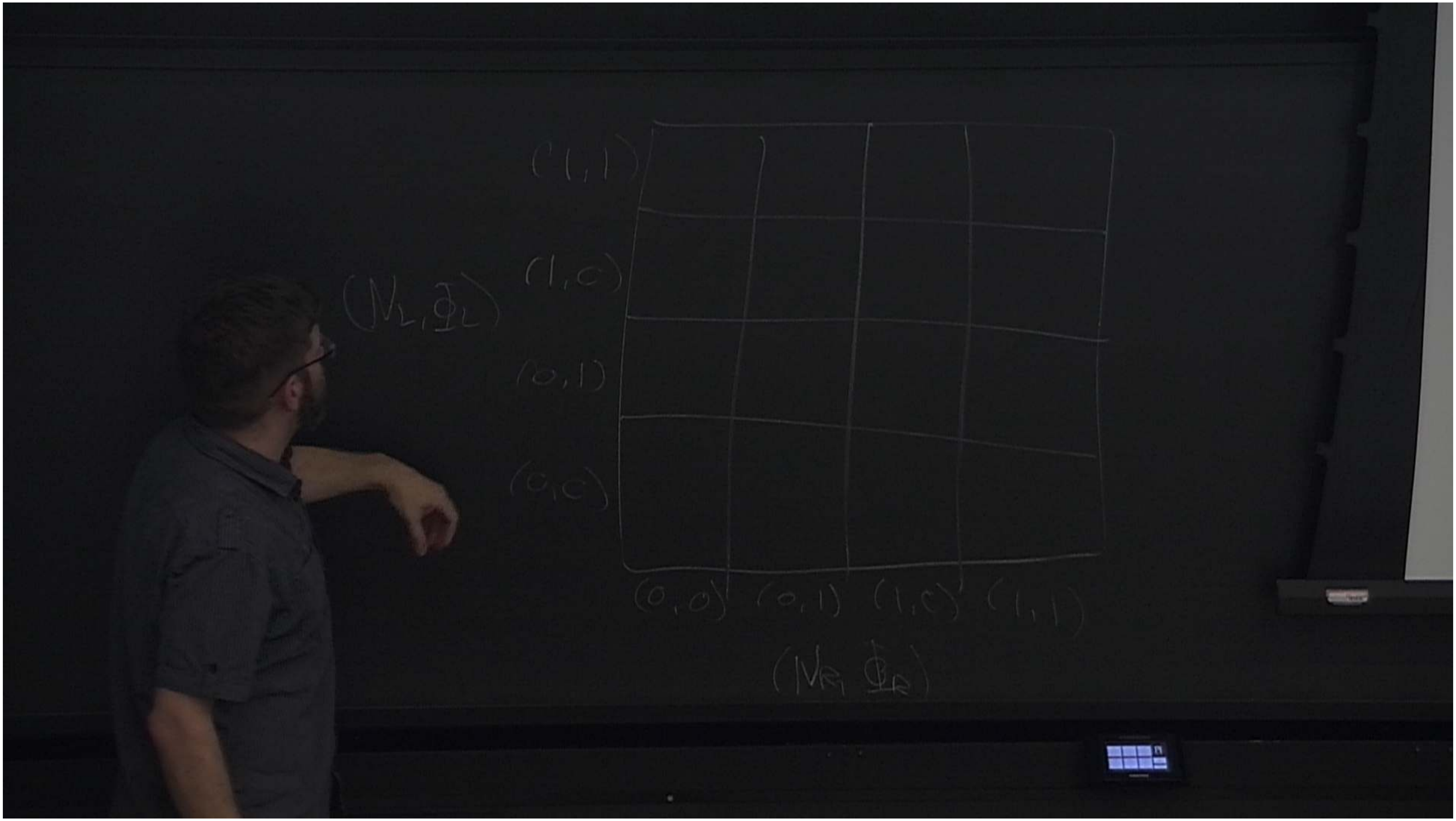
Mach-Zehnder Interferometer



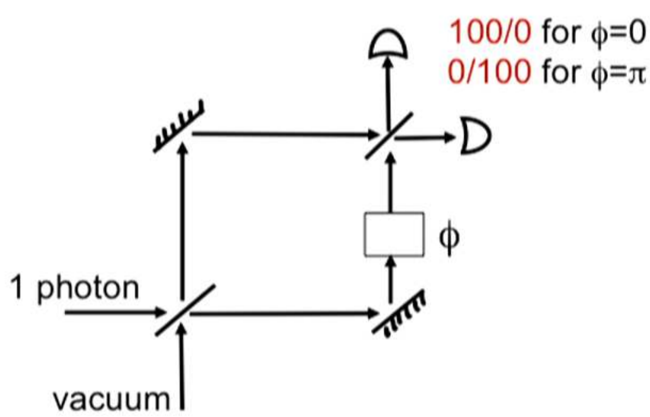
$|1\rangle|0\rangle$



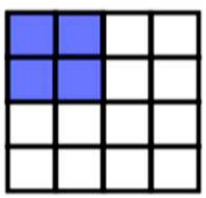
$N_L = 1,$
$N_R = 0$


(1,1)
(1,0)
(0,1)
(0,0)
(0,0) (0,1) (1,0) (1,1)

Mach-Zehnder Interferometer

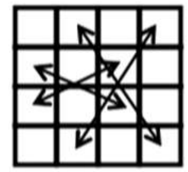


$|1\rangle|0\rangle$



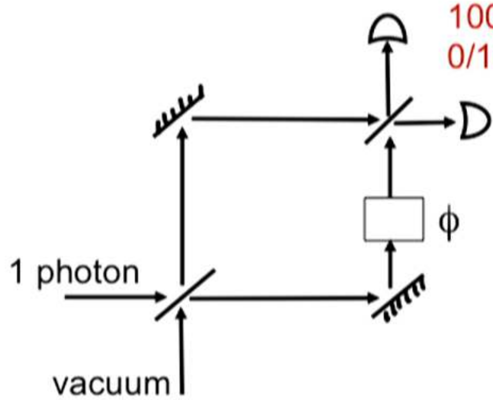
$N_L = 1,$
$N_R = 0$

Beam splitter

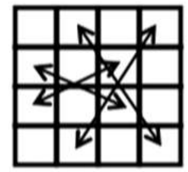


$N_L \rightarrow \Phi_L \oplus \Phi_R$
$\Phi_L \rightarrow N_L \oplus \Phi_R$
$N_R \rightarrow (N_L \oplus \Phi_L) \oplus (N_R \oplus \Phi_R)$
$\Phi_R \rightarrow \Phi_R$

Mach-Zehnder Interferometer

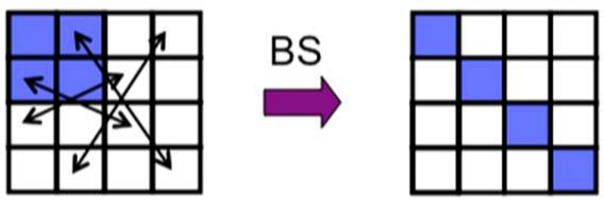


Beam splitter



$\mathrm{N_L} \rightarrow \Phi_L \oplus \Phi_R$
$\Phi_L \rightarrow \mathrm{N}_L \oplus \Phi_R$
$\mathrm{N_R} \rightarrow (\mathrm{N}_L \oplus \Phi_L) \oplus (\mathrm{N}_R \oplus \Phi_R)$
$\Phi_R \rightarrow \Phi_R$

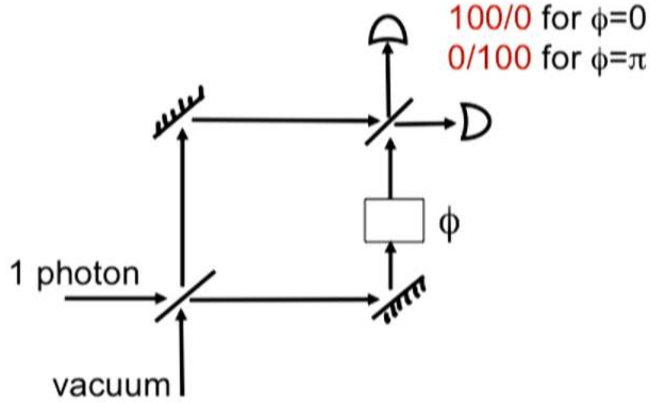
$|1\rangle|0\rangle$ $\qquad$ $|1\rangle|0\rangle - |0\rangle|1\rangle$



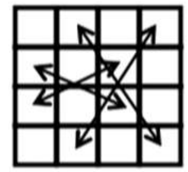
$\mathrm{N_L} = 1,$
$\mathrm{N_R} = 0$

$\mathrm{N}_L \oplus \mathrm{N}_R = 1,$
$\Phi_L \oplus \Phi_R = 1$

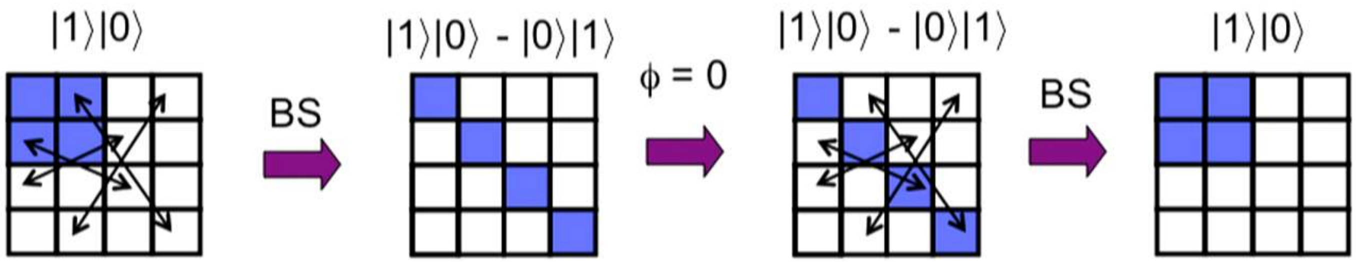
Mach-Zehnder Interferometer



Beam splitter



$N_L \rightarrow \Phi_L \oplus \Phi_R$
$\Phi_L \rightarrow N_L \oplus \Phi_R$
$N_R \rightarrow (N_L \oplus \Phi_L) \oplus (N_R \oplus \Phi_R)$
$\Phi_R \rightarrow \Phi_R$



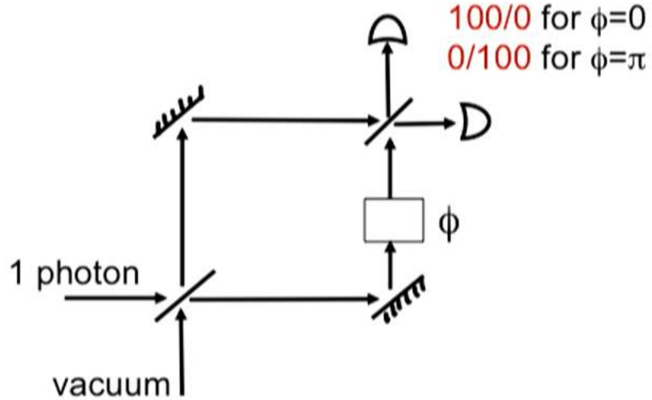
$N_L = 1$, $N_R = 0$

$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 1$

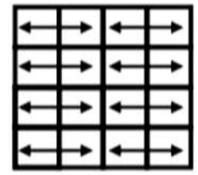
$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 1$

$N_L = 1$, $N_R = 0$

Mach-Zehnder Interferometer

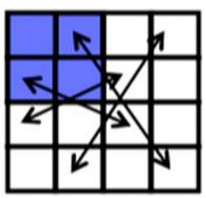


π phase shift



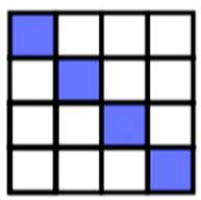
$N_L \rightarrow N_L$
$\Phi_L \rightarrow \Phi_L$
$N_R \rightarrow N_R$
$\Phi_R \rightarrow \Phi_R \oplus 1$

$|1\rangle|0\rangle$



BS

$|1\rangle|0\rangle - |0\rangle|1\rangle$

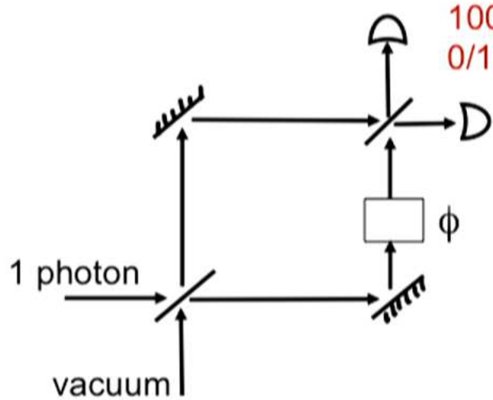


$\phi = \pi$

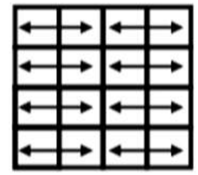
$N_L = 1$,
$N_R = 0$

$N_L \oplus N_R = 1$,
$\Phi_L \oplus \Phi_R = 1$

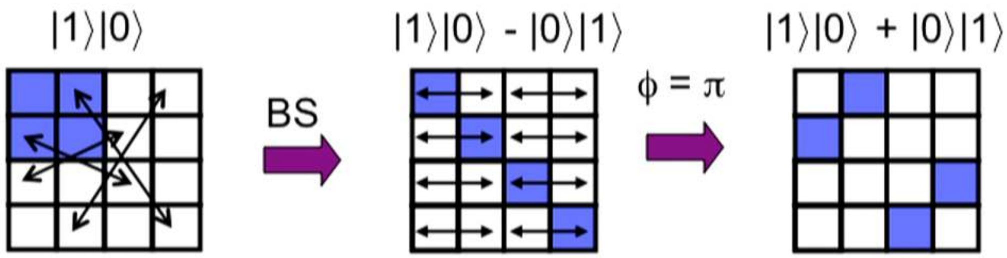
Mach-Zehnder Interferometer



π phase shift



$N_L \rightarrow N_L$
$\Phi_L \rightarrow \Phi_L$
$N_R \rightarrow N_R$
$\Phi_R \rightarrow \Phi_R \oplus 1$

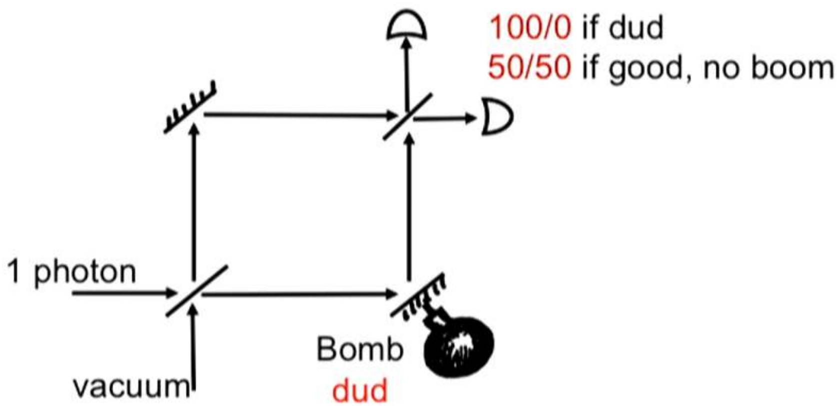


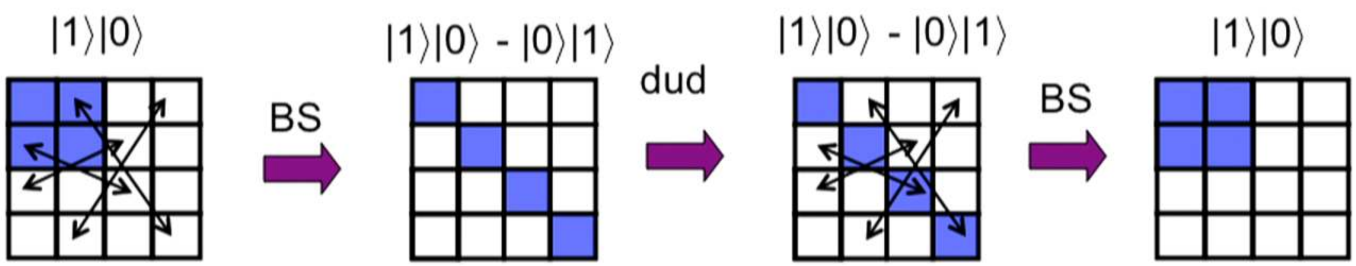
$N_L = 1$, $N_R = 0$

$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 1$

$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 0$

Elitzur-Vaidman bomb-testing





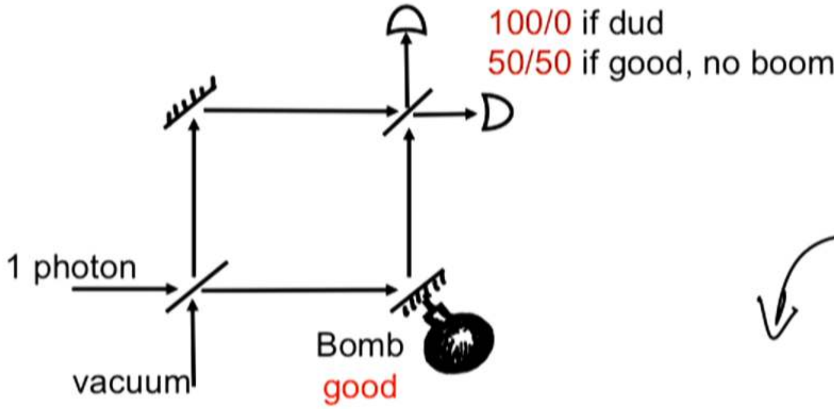
$N_L = 1$, $N_R = 0$

$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 1$

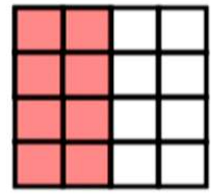
$N_L \oplus N_R = 1$, $\Phi_L \oplus \Phi_R = 1$

$N_L = 1$, $N_R = 0$

Elitzur-Vaidman bomb-testing

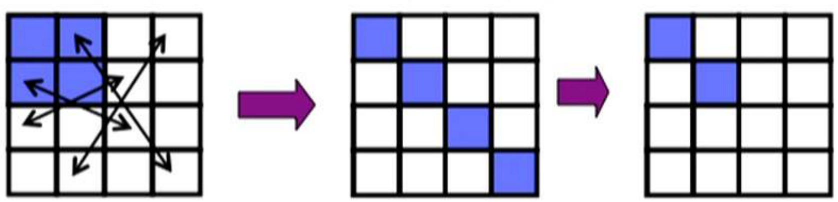


Finding vacuum
on right mode



N_R =0

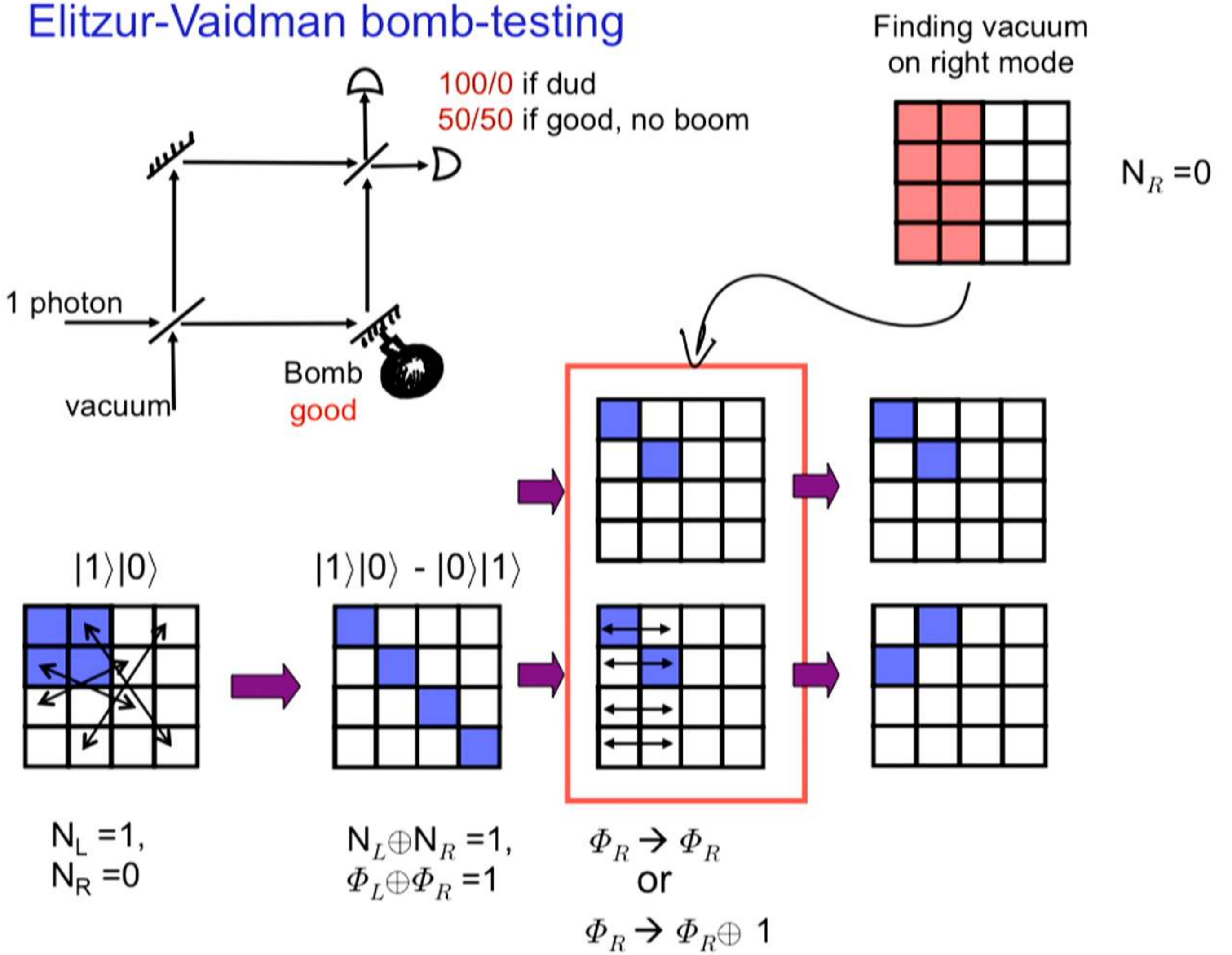
$|1\rangle|0\rangle$ $|1\rangle|0\rangle - |0\rangle|1\rangle$

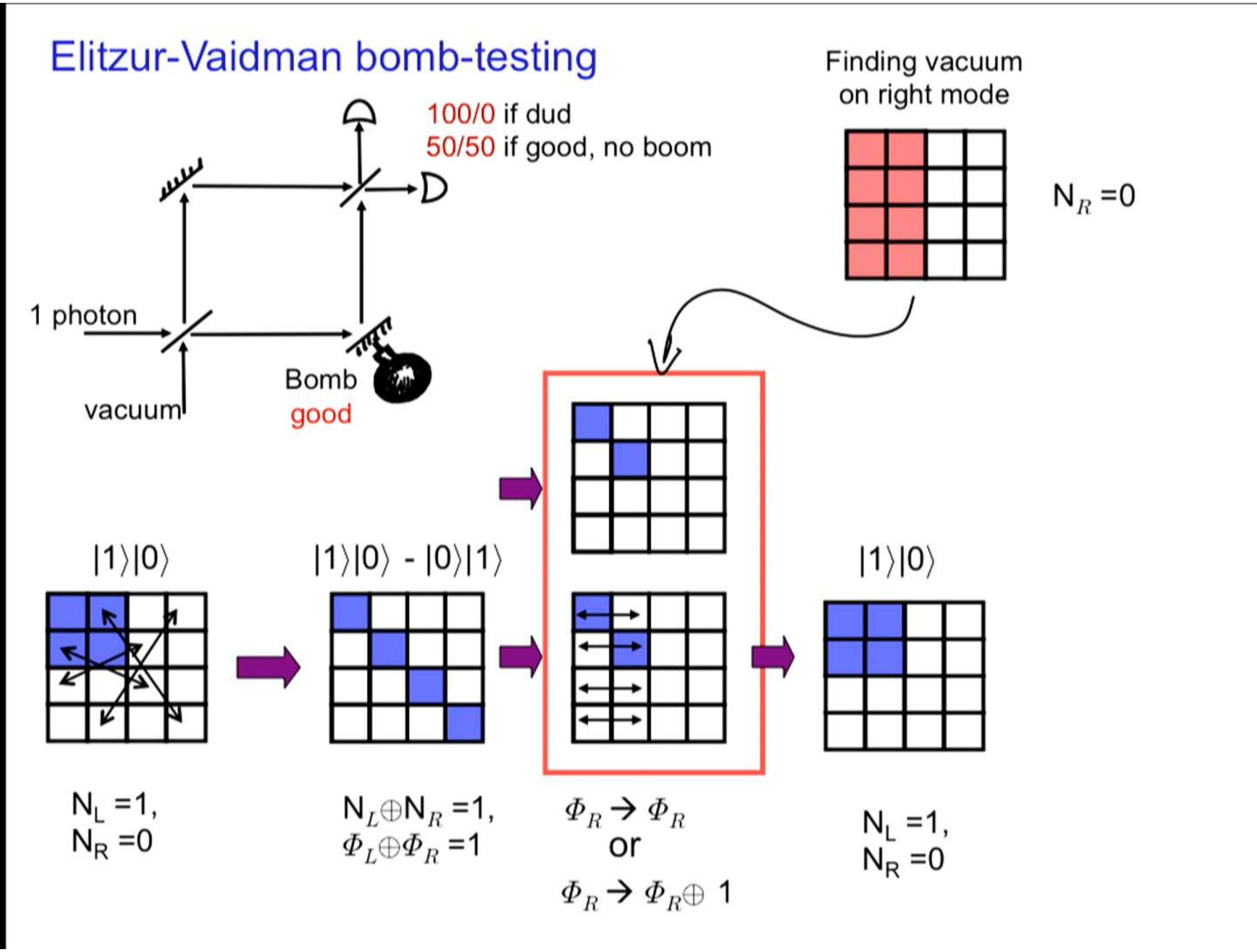


N_L =1,
N_R =0

$N_L \oplus N_R$ =1,
$\Phi_L \oplus \Phi_R$ =1

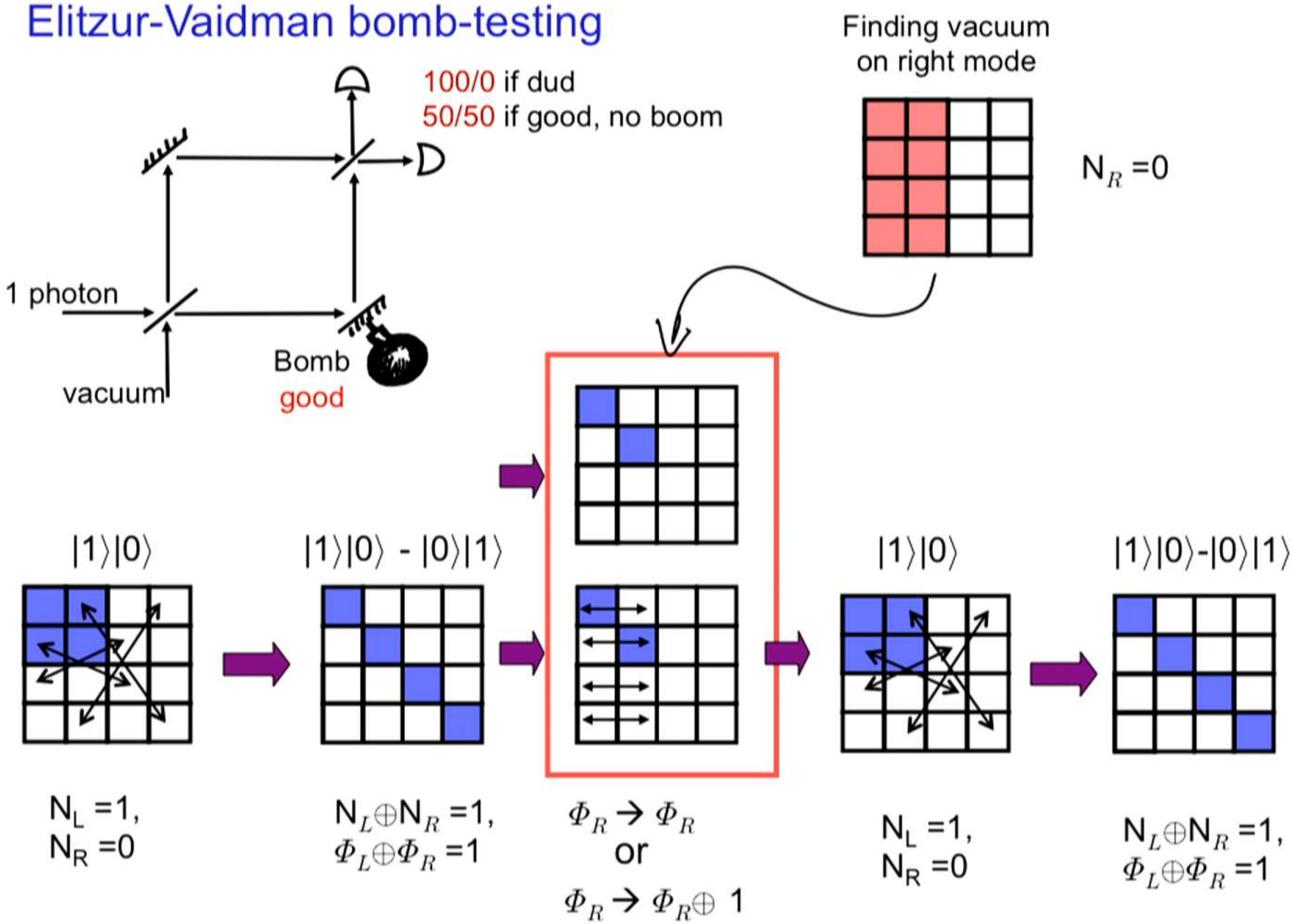
Elitzur-Vaidman bomb-testing



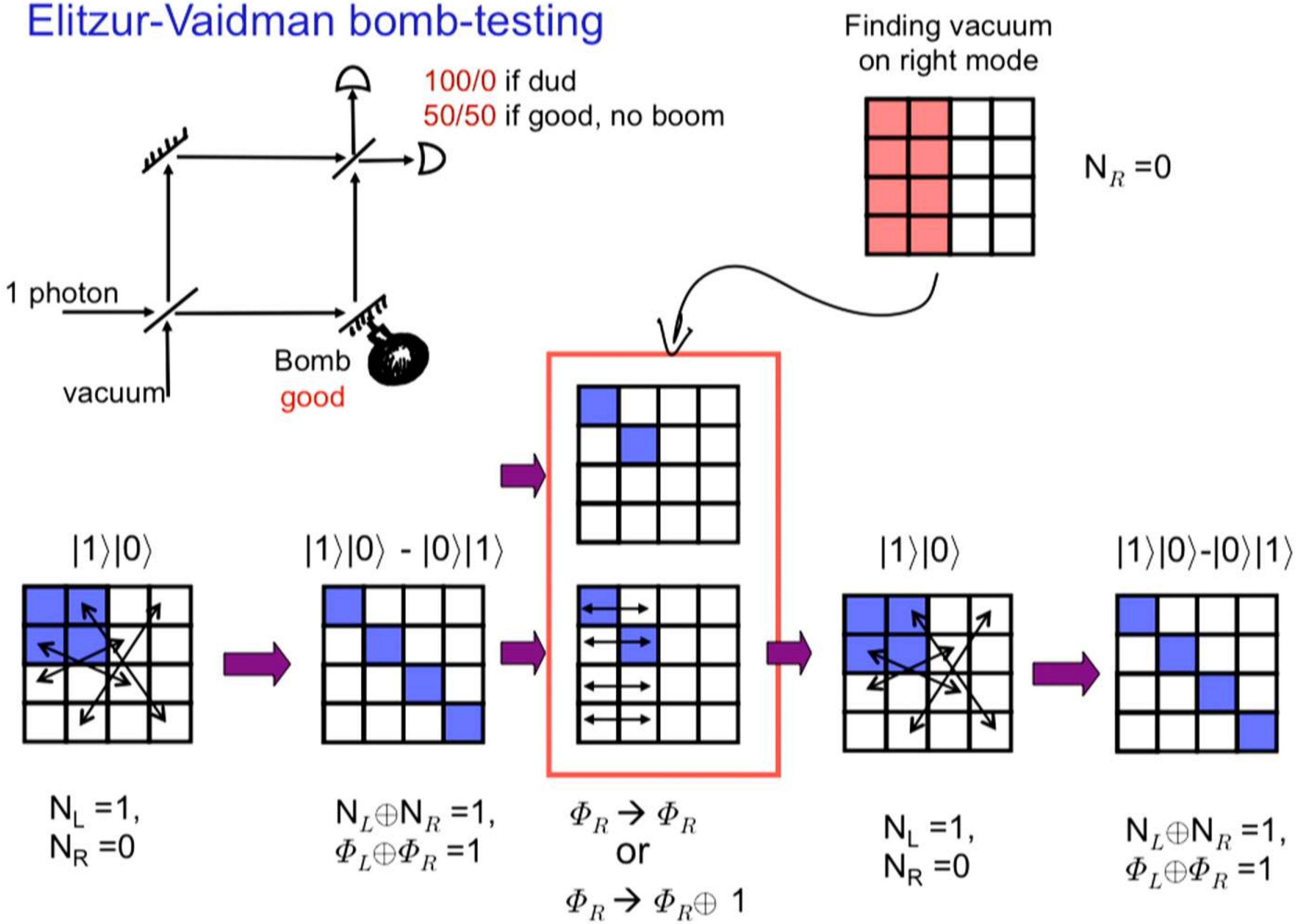


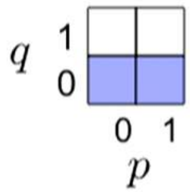
Elitzur-Vaidman bomb-testing
100/0 if dud
50/50 if good, no boom
1 photon
vacuum
Bomb
good
Finding vacuum
on right mode
$N_R = 0$
$|1\rangle|0\rangle$
$|1\rangle|0\rangle - |0\rangle|1\rangle$
$|1\rangle|0\rangle$
$N_L = 1$,
$N_R = 0$
$N_L \oplus N_R = 1$,
$\Phi_L \oplus \Phi_R = 1$
$\Phi_R \rightarrow \Phi_R$
or
$\Phi_R \rightarrow \Phi_R \oplus 1$
$N_L = 1$,
$N_R = 0$

Elitzur-Vaidman bomb-testing



Elitzur-Vaidman bomb-testing



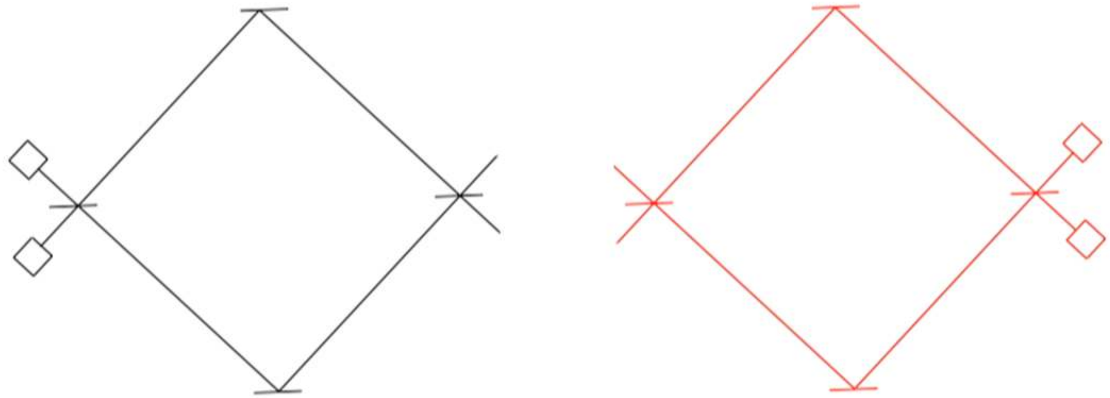


$|0\rangle$ -- vacuum

In this model, the quantum vacuum state is a stastical distribution over physical states with different phases

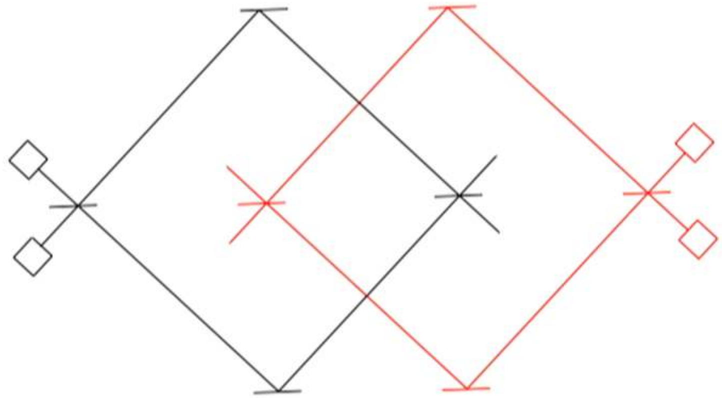
In this model, the vacuum mode can carry information

Hardy's reality of empty waves argument



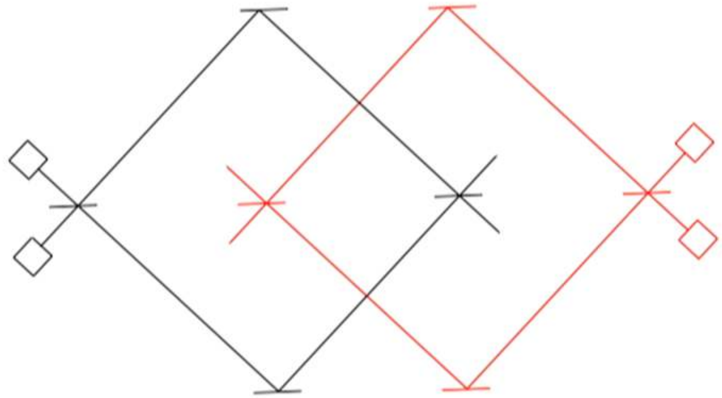
$$|1\rangle|0\rangle\ |1\rangle|0\rangle \xrightarrow{\text{BSs}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\ (|1\rangle|0\rangle - |0\rangle|1\rangle) \xrightarrow{\text{BSs}} |1\rangle|0\rangle\ |1\rangle|0\rangle$$

Hardy's reality of empty waves argument



$$|1\rangle|0\rangle\ |1\rangle|0\rangle \xrightarrow{\text{BS}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\ (|1\rangle|0\rangle - |0\rangle|1\rangle) \xrightarrow{\text{no gammas}} |1\rangle|0\rangle\ |0\rangle|1\rangle + |0\rangle|1\rangle\ |1\rangle|0\rangle$$

Hardy's reality of empty waves argument

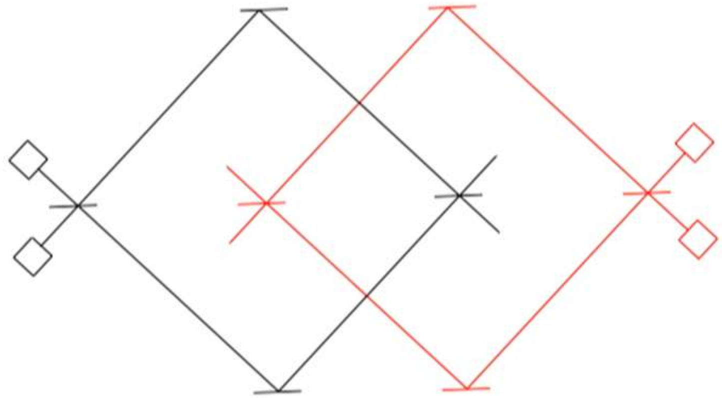


$$|1\rangle|0\rangle\ |1\rangle|0\rangle \xrightarrow{\text{BS}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\ (|1\rangle|0\rangle - |0\rangle|1\rangle) \xrightarrow{\text{no gammas}} |1\rangle|0\rangle\ |0\rangle|1\rangle + |0\rangle|1\rangle\ |1\rangle|0\rangle$$

$$\xrightarrow{\text{BS}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\ (|1\rangle|0\rangle + |0\rangle|1\rangle) + (|1\rangle|0\rangle + |0\rangle|1\rangle)\ (|1\rangle|0\rangle - |0\rangle|1\rangle)$$

$$= |1\rangle|0\rangle\ |0\rangle|1\rangle + |0\rangle|1\rangle\ |1\rangle|0\rangle$$

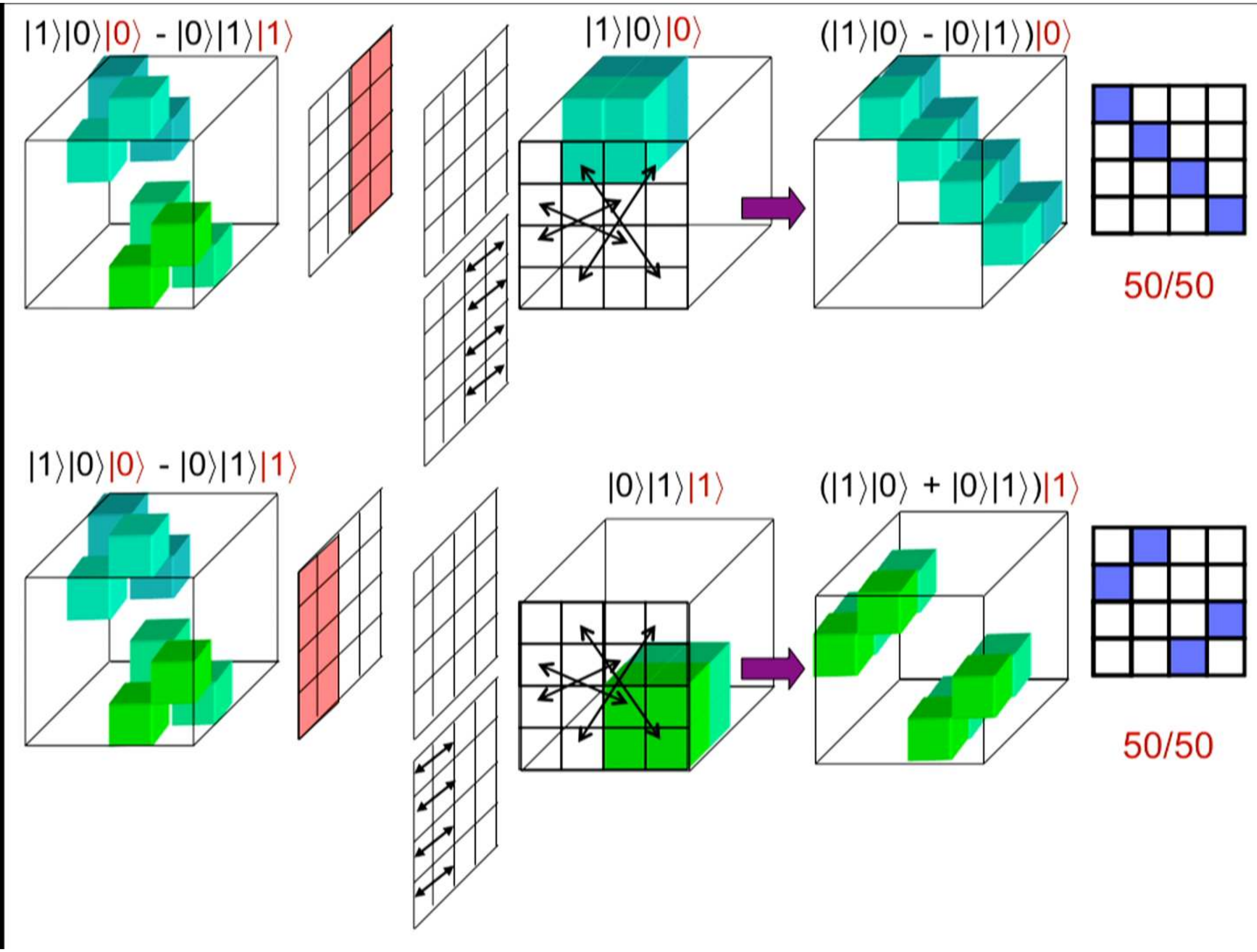
Hardy's reality of empty waves argument

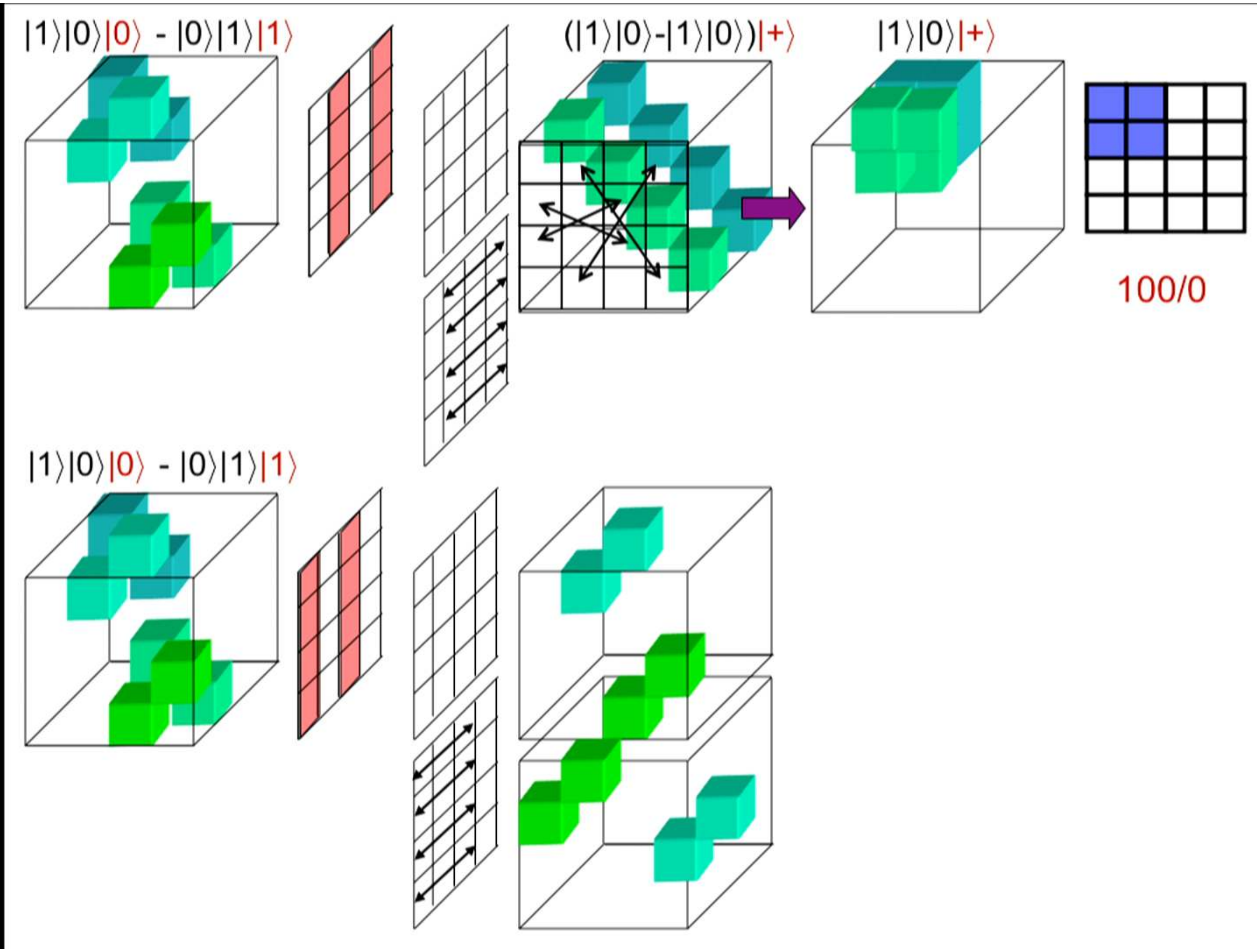


$$|1\rangle|0\rangle\ |1\rangle|0\rangle \xrightarrow{\text{BS}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\,(|1\rangle|0\rangle - |0\rangle|1\rangle) \xRightarrow{\text{no gammas}} |1\rangle|0\rangle\ |0\rangle|1\rangle + |0\rangle|1\rangle\ |1\rangle|0\rangle$$

$$\xRightarrow{\text{BS}} (|1\rangle|0\rangle - |0\rangle|1\rangle)\,(|1\rangle|0\rangle + |0\rangle|1\rangle) + (|1\rangle|0\rangle + |0\rangle|1\rangle)\,(|1\rangle|0\rangle - |0\rangle|1\rangle)$$

$$= |1\rangle|0\rangle\ |0\rangle|1\rangle + |0\rangle|1\rangle\ |1\rangle|0\rangle$$


|1⟩|0⟩|0⟩ - |0⟩|1⟩|1⟩
|1⟩|0⟩|0⟩
(|1⟩|0⟩ - |0⟩|1⟩)|0⟩
50/50
|1⟩|0⟩|0⟩ - |0⟩|1⟩|1⟩
|0⟩|1⟩|1⟩
(|1⟩|0⟩ + |0⟩|1⟩)|1⟩
50/50


$|1\rangle|0\rangle|0\rangle - |0\rangle|1\rangle|1\rangle$
$(|1\rangle|0\rangle-|1\rangle|0\rangle)|+\rangle$
$|1\rangle|0\rangle|+\rangle$
100/0
$|1\rangle|0\rangle|0\rangle - |0\rangle|1\rangle|1\rangle$

Methodological desiderata for understanding nonclassicality

Bad form	Good form
I can't see how to make sense of this experimental data in a classical theory	I've proven a **theorem** showing that a formal notion of classicality is inconsistent with the experimental data
I can't explain the data using a classical system with the expected classical phase space and Hamiltonian; this quantum system has no classical counterpart	I've allowed **arbitrary** classical state spaces and dynamics (i.e., been liberal in what counts as classical)

Categorizing nonclassical phenomena

Those arising in noncontextual models	Those not arising in noncontextual models
Interference Noncommutativity Entanglement Collapse No perfect state discrimination No cloning Steering Teleportation Tunneling Improvements in metrology Pre and post-selection effects Key distribution Others…	Noncontextuality inequality violations Bell inequality violations Computational speed-up Certain aspects of items on the left
Weakly nonclassical	Strongly nonclassical

Weakly nonclassical

Remote steering
Einstein 1935; Caves-Fuchs-Schack 2000; Harrigan-RWS 2010

Pre and post selection effects
Leifer-RWS 2004

Weak values
Karanjai-Cavalcanti-Bartlett-Rudolph 2015

Quantum multiplexing
RWS 2004

No error-free discrimination of nonorthogonal states
RWS 2004

Nonzero probability of wavepacket tunneling through a barrier
Bartlett-Rowe 1999

Strongly nonclassical

Failure of preparation noncontextuality = BI violation
Bell 1964; Barrett 2006 unpublished; Liang-RWS-Wiseman 2010

Pre and post selection effects with nonorthogonal pre and post selections
Leifer-Pusey 2015

Anomalous weak values
Pusey 2015

Probability of success in parity-oblivious multiplexing
RWS-Buzacott-Kheenn-Pryde-Toner 2008

Precise tradeoff of probability of discrimination with nonorthogonality
RWS-Wolfe (work in progress)

Precise dependence of tunneling probability on wavepacket width
RWS (work in progress)

References

RWS, “Quasi-quantization: classical statistical theories with an epistemic restriction”
Published in "Quantum Theory: Informational foundations and foils", eds. G. Chiribella and R. W. Spekkens
[arXiv:1409.5041 (quant-ph)]

M. Leifer, E. Martin, RWS, in preparation