Quantum Ghosts Go Bump In The Night

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May 21, 2014

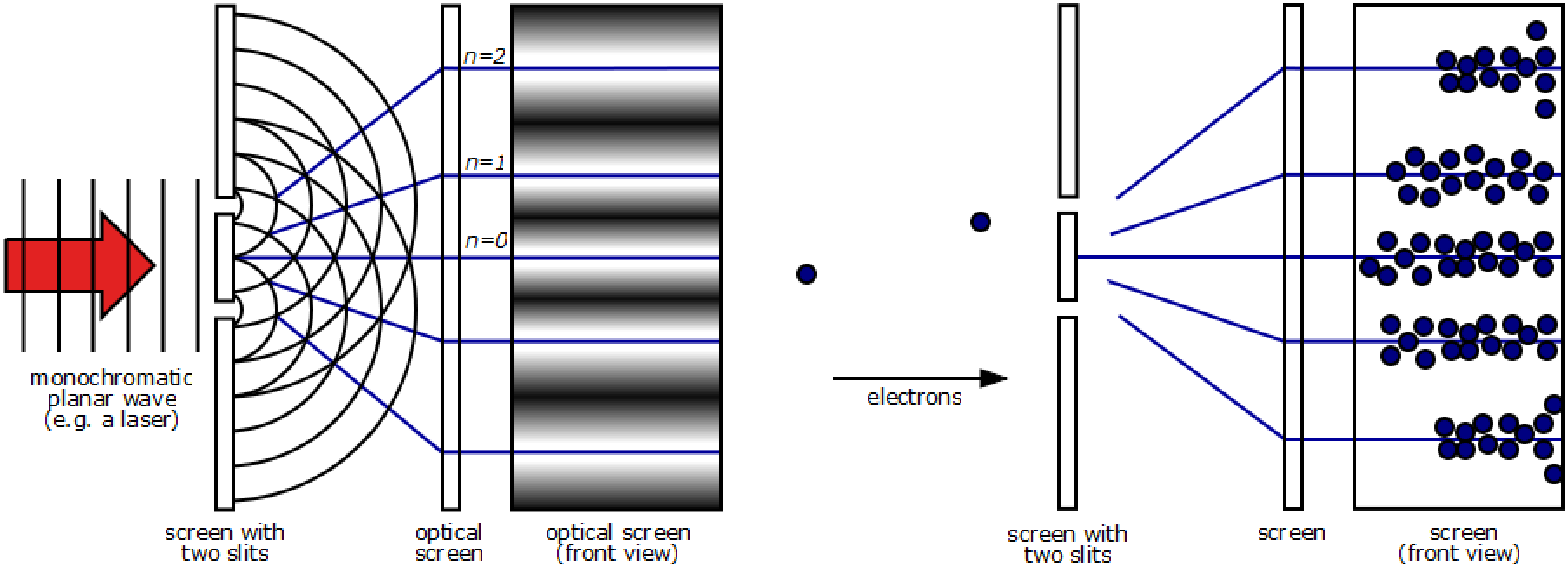
Warning

I can safely say that nobody understands quantum mechanics. ... Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.

Richard Feynman

Feynman's only mystery

- Feynman on interference: "We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot explain the mystery in the sense of ***explaining*** how it works. We will ***tell*** you how it works."



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Quantum Interference with matter

- "Quantum interference experiments with large molecules", O. Nairz, M. Arndt, A. Zeilinger, Am. J. Phys. 71 (4), April 2003, 319-325

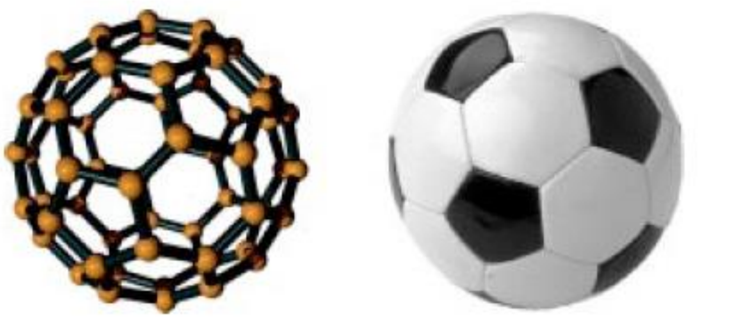


Fig. 2. The fullerene molecule C_{60}, consisting of 60 carbon atoms arranged in a truncated icosahedral shape, is the smallest known natural soccer ball.

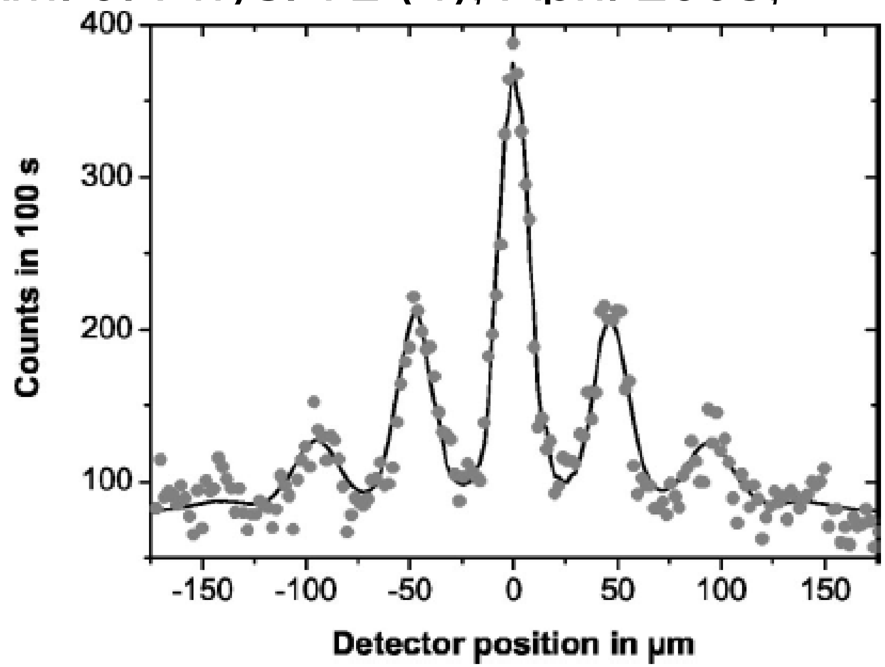


Fig. 7. Far-field diffraction of C_{60} using the slotted disk velocity selector.

Recently repeated with 1298 AMU phtalocyanin ,
a 114 atom molecule, Juffmann et al., Nature, Feb. 2012.

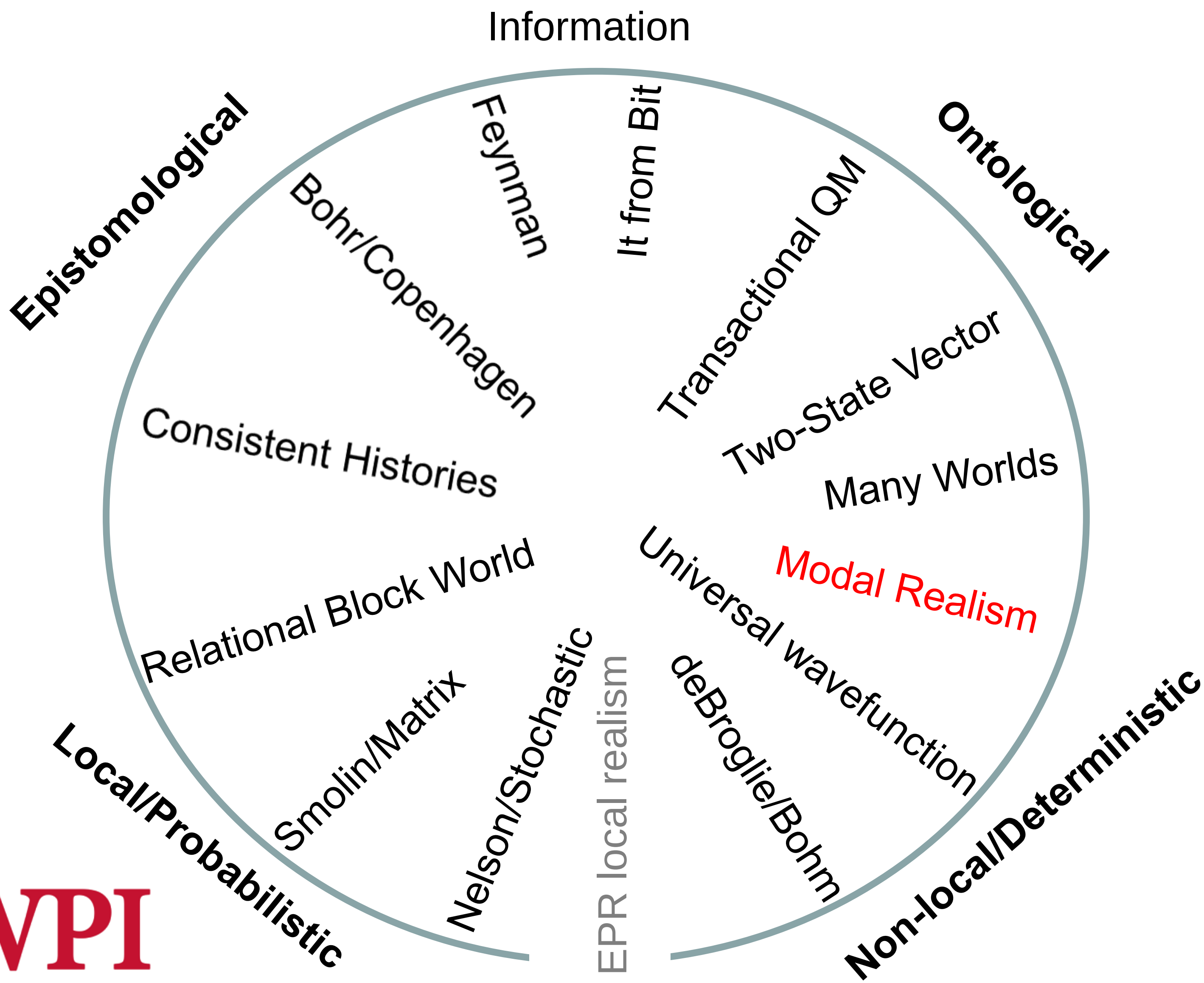
More quantum weirdness

- Wave/Particle Duality (Interference)
- Non-commutivity of measurements
- Superposition States
- Entanglement
- Contexuality
- Quantum Cheshire Cat
- **Interaction Free Measurements**

> *Anyone who is not shocked by quantum theory has not understood it.*
>
> Niels Bohr

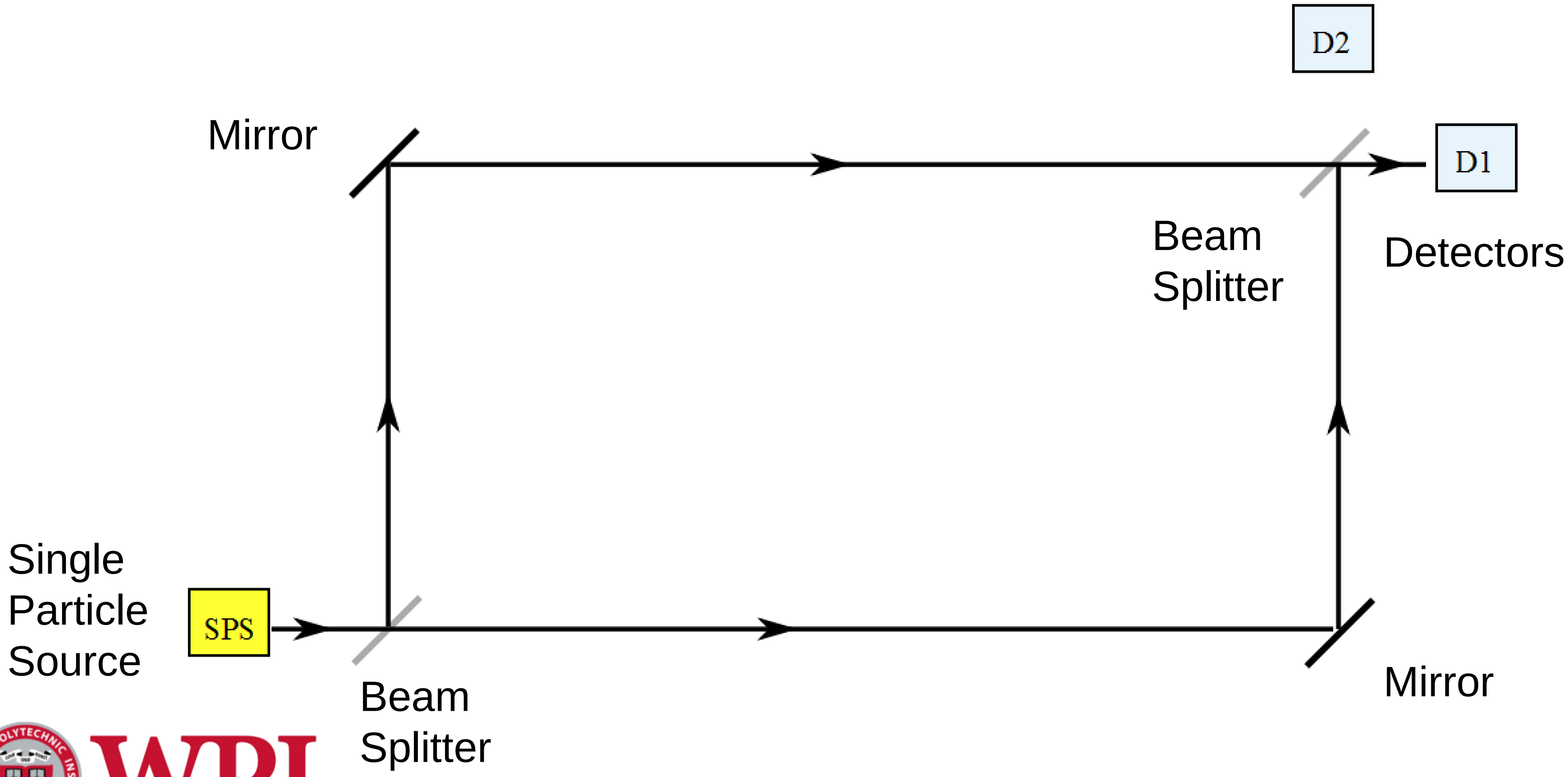
The weirdest thing about QM: We know exactly how to compute answers, we just don't know why it works or what it means about reality.

Wheel of Quantum Interpretation



Mach Zehnder Interferometer

- With correct arm lengths quantum interference can lead to 0 probability of D2 detections



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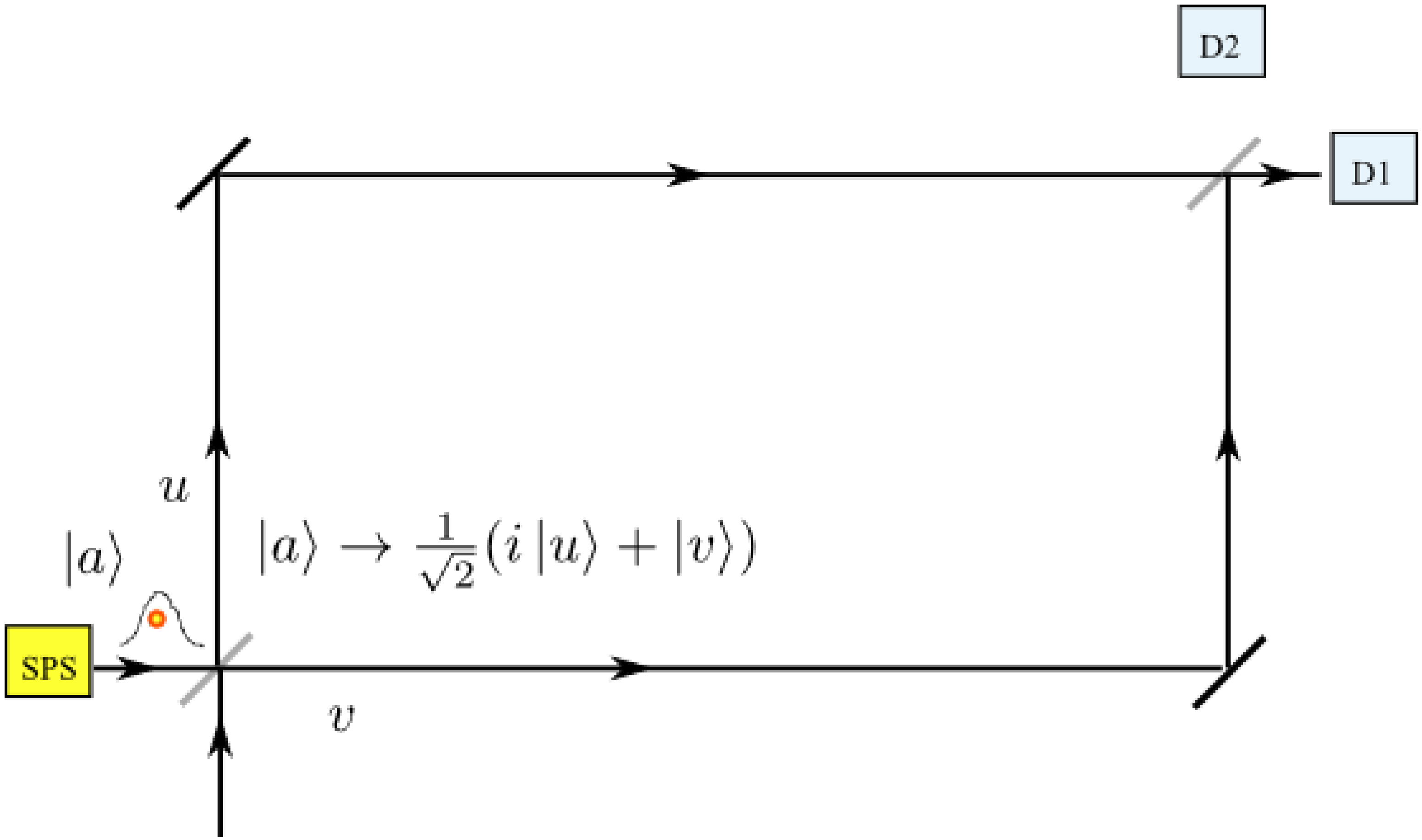
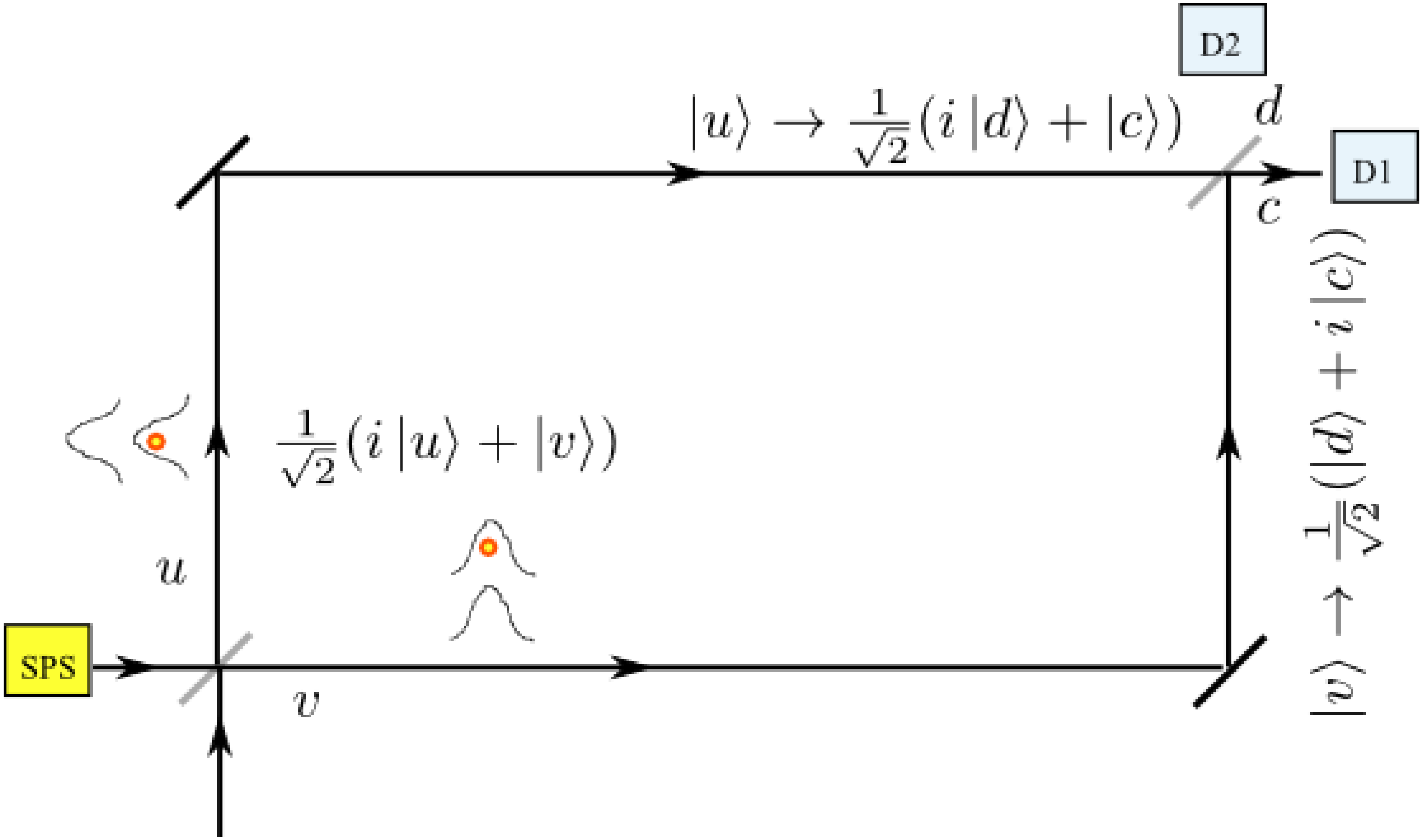
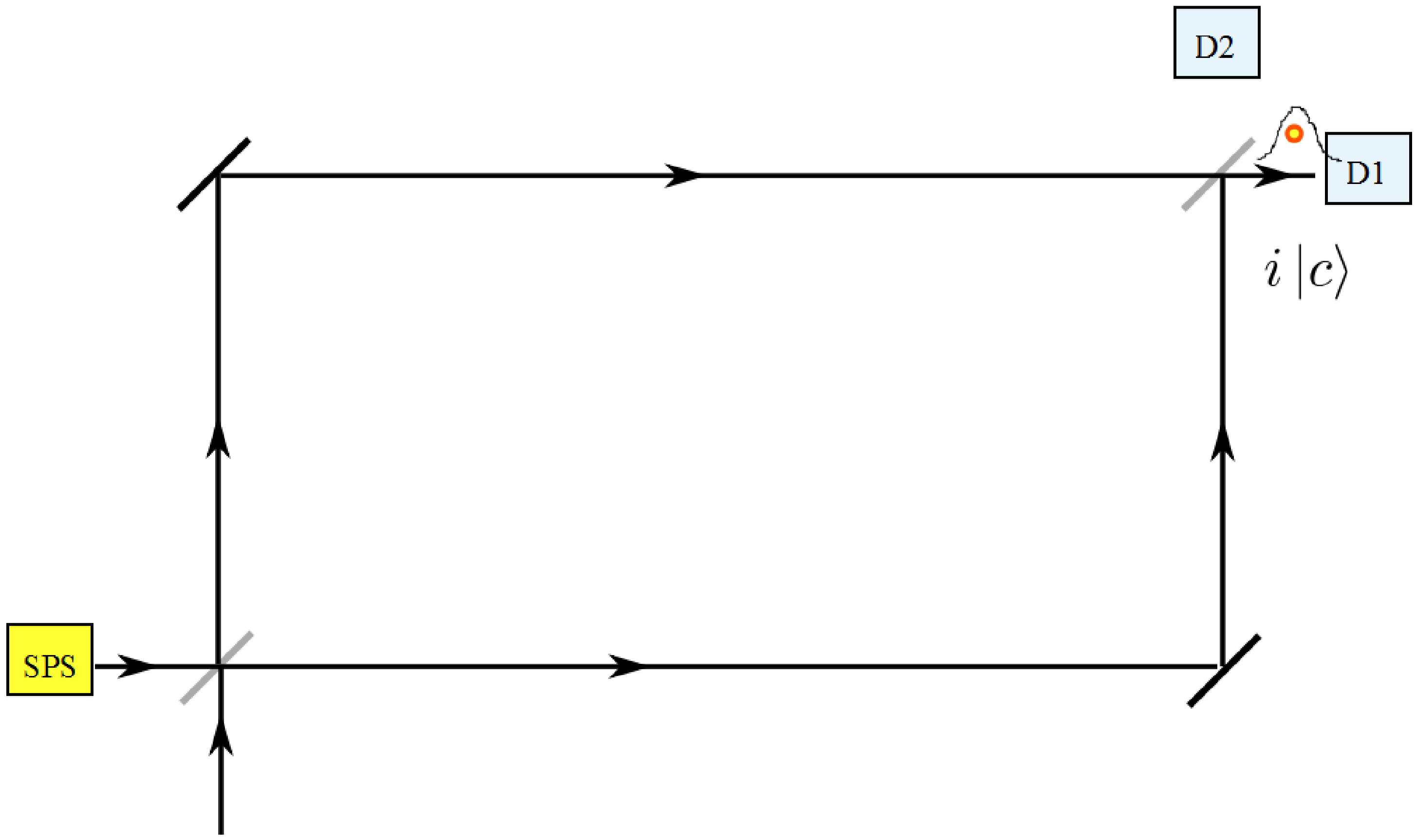
Splitting a particle



Superposition state

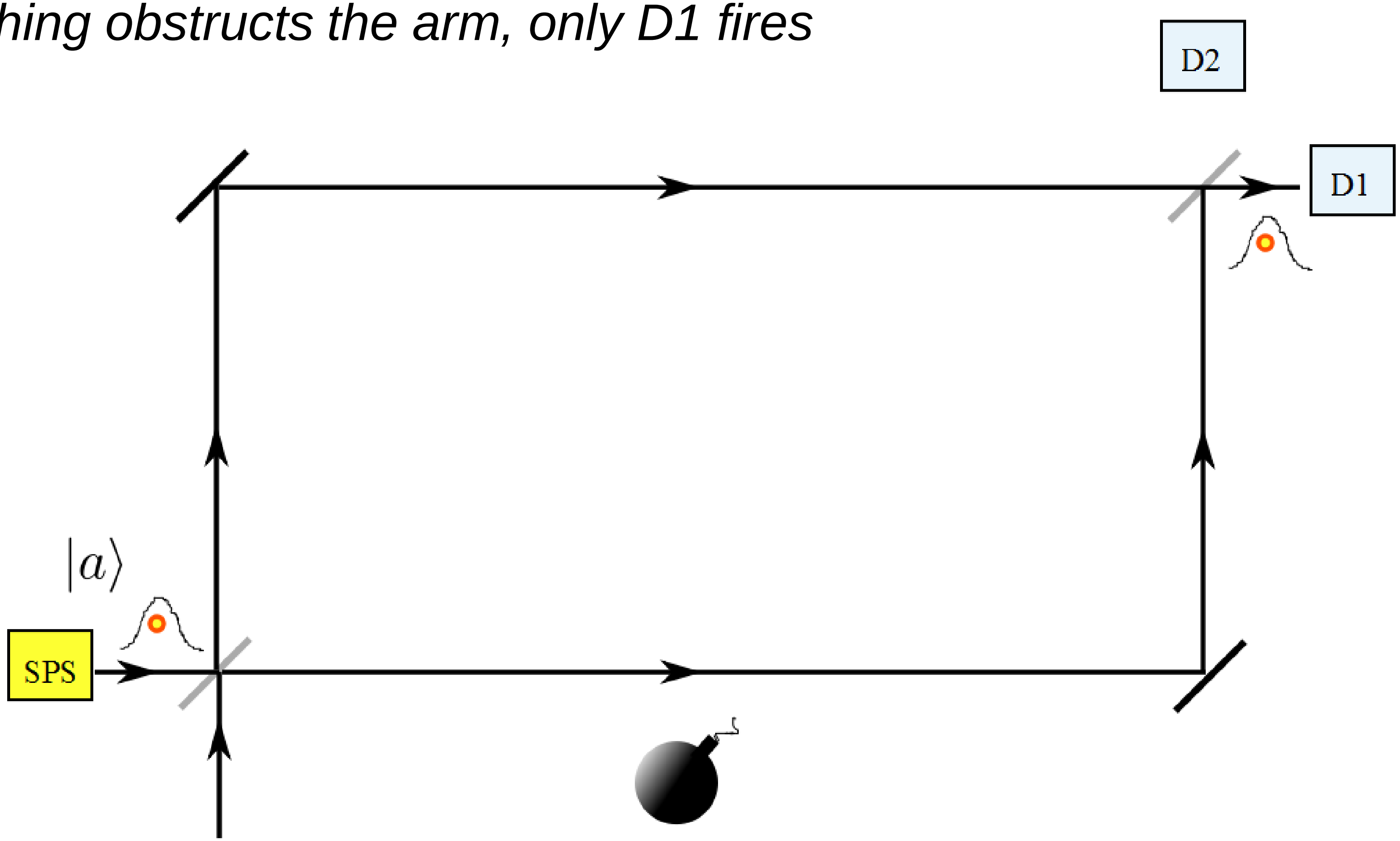


Quantum Interference



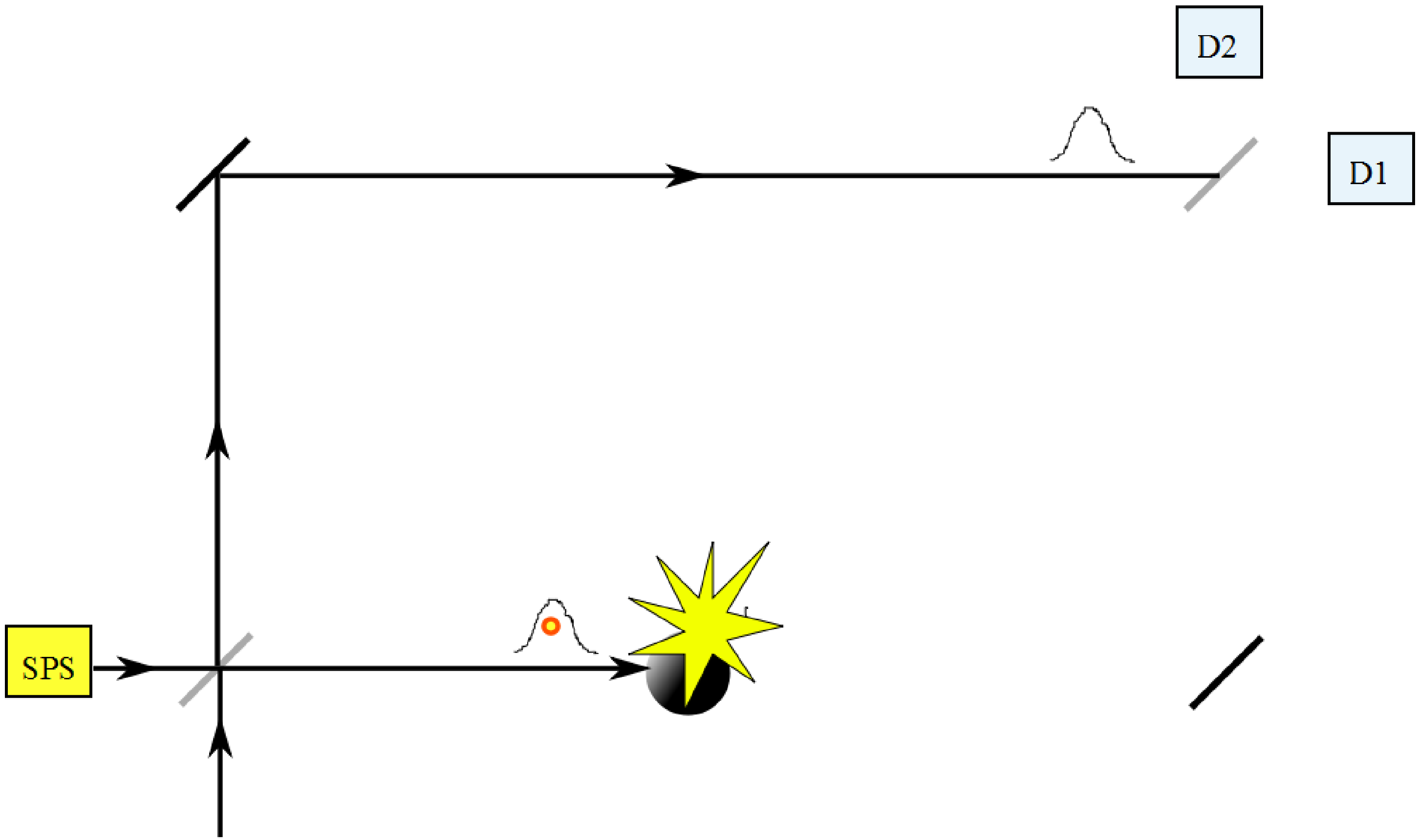
“Interaction Free Measurement”

- **“Quantum Mechanical Interaction-Free Measurements,” A.C. Elitzur, L.Vaidman,** *Foundations of Physics, Vol. 23, No. 7, 1993.*
- *If nothing obstructs the arm, only D1 fires*



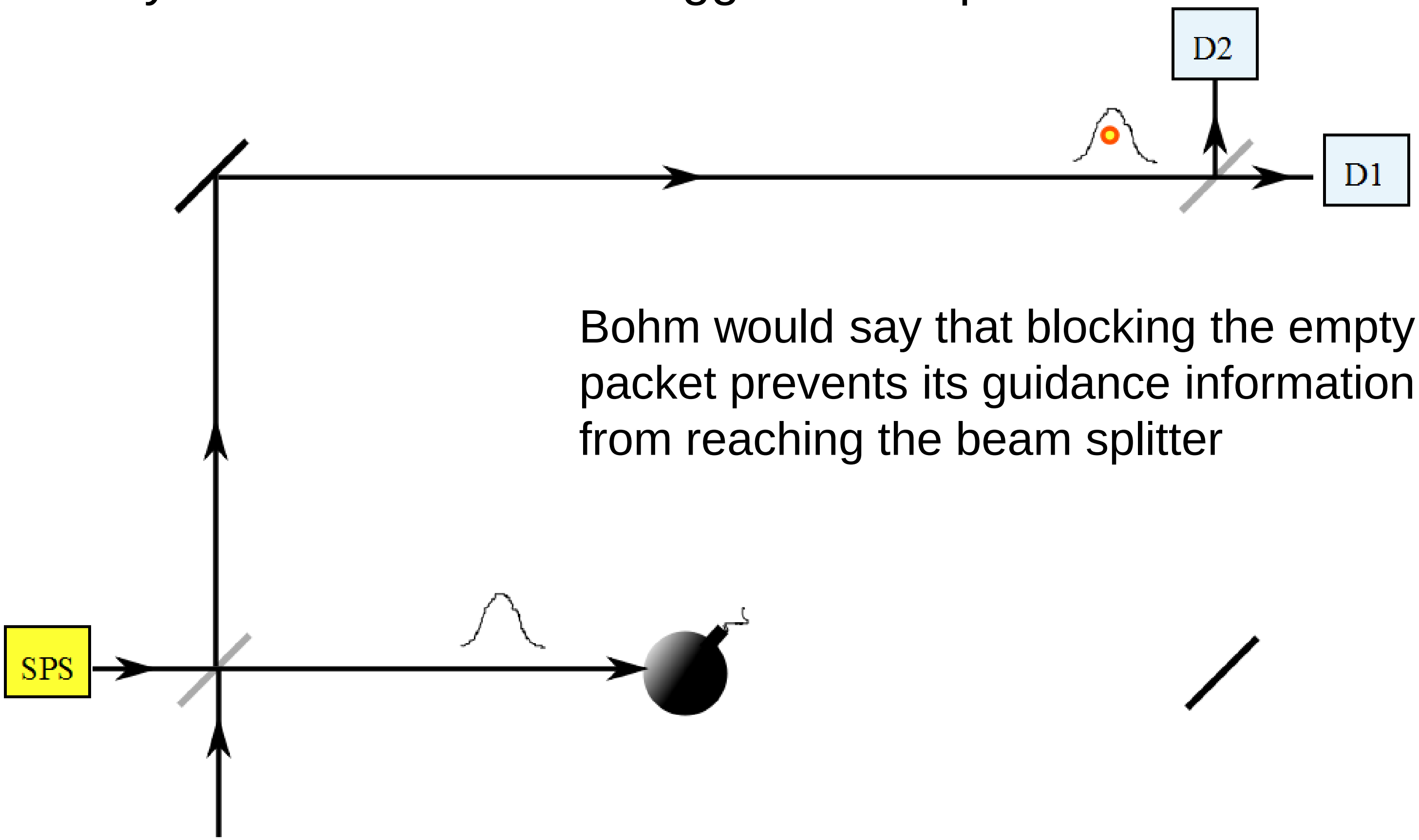
Interaction Free Measurement

- If device is present, Probability = ½ that the device will be triggered.



Towards Interaction Free Measurement

- Probability = ½ that the device will not be triggered by the photon.
- Probability = ¼ that device not triggered and particle detected at D2

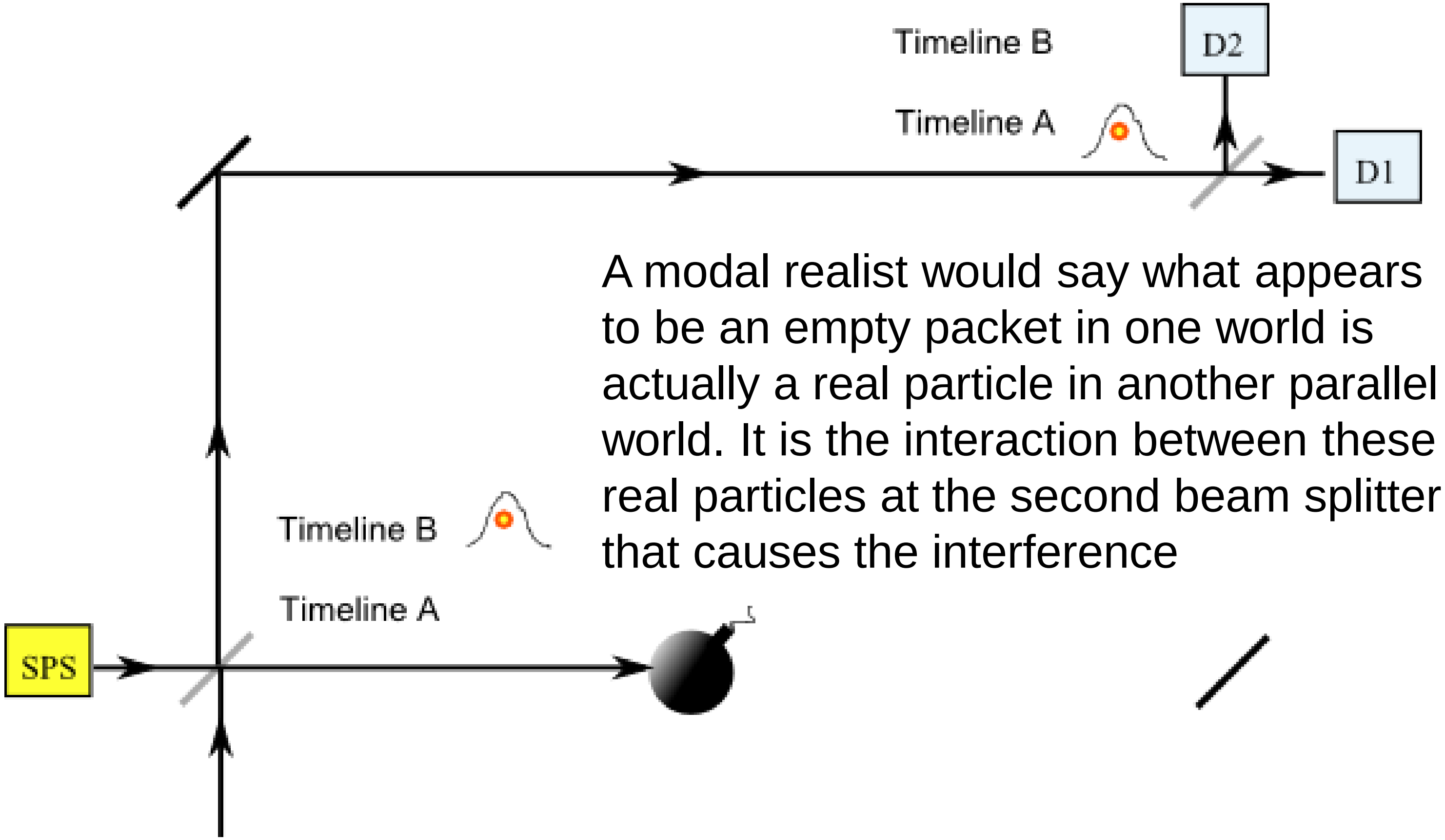


Bohm would say that blocking the empty packet prevents its guidance information from reaching the beam splitter

One quarter of the time, we get an interaction free measurement

MR view on IFM interference

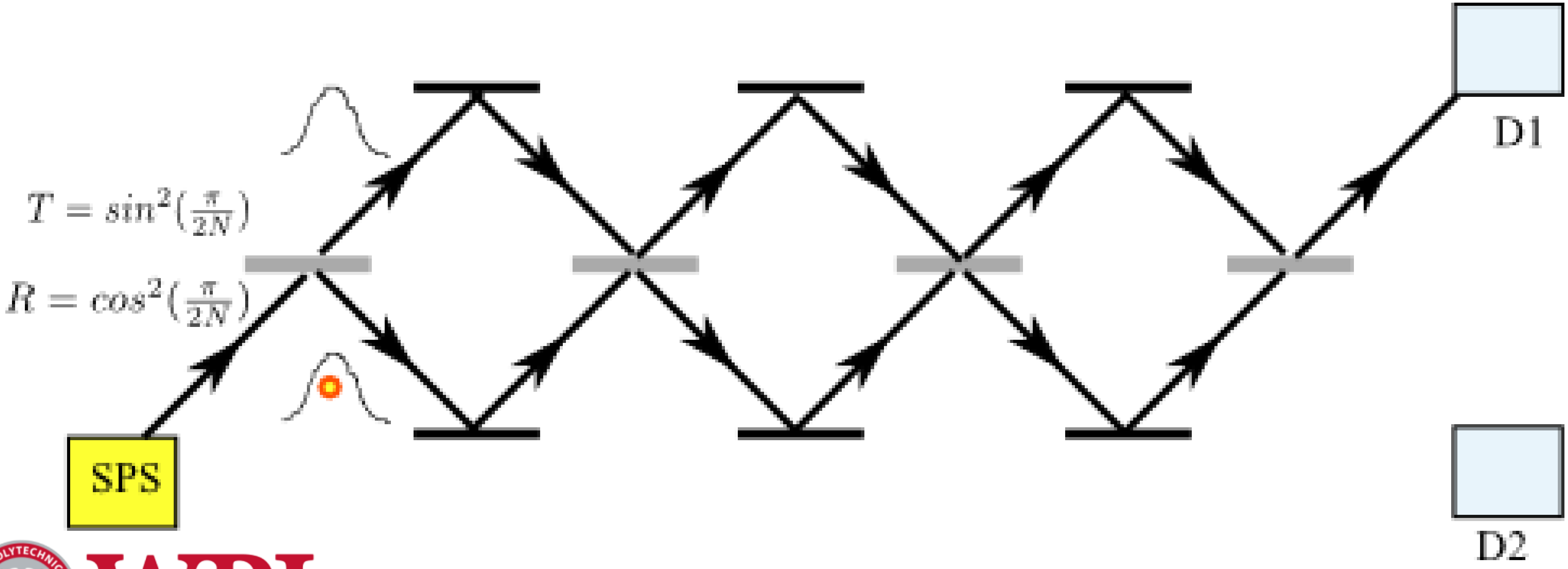
- Probability = ½ that the device will not be triggered by the photon.
- Probability = ¼ that device not triggered and particle detected at D2



A modal realist would say what appears to be an empty packet in one world is actually a real particle in another parallel world. It is the interaction between these real particles at the second beam splitter that causes the interference

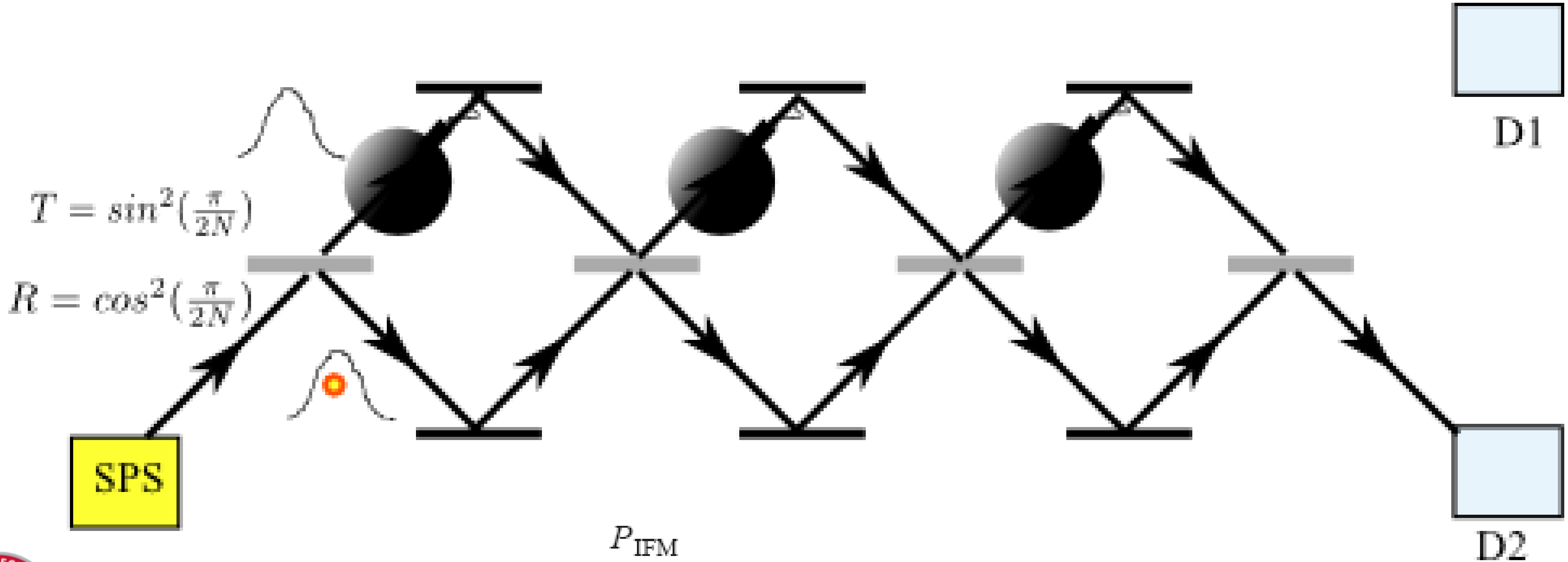
Asymptotically Perfect IFM detection!

- "**Interaction-free measurement**," P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, pp. 4763–4766, 1995.
  - Chain of beam splitters with given reflectivity and transmission coefficients, R,T.



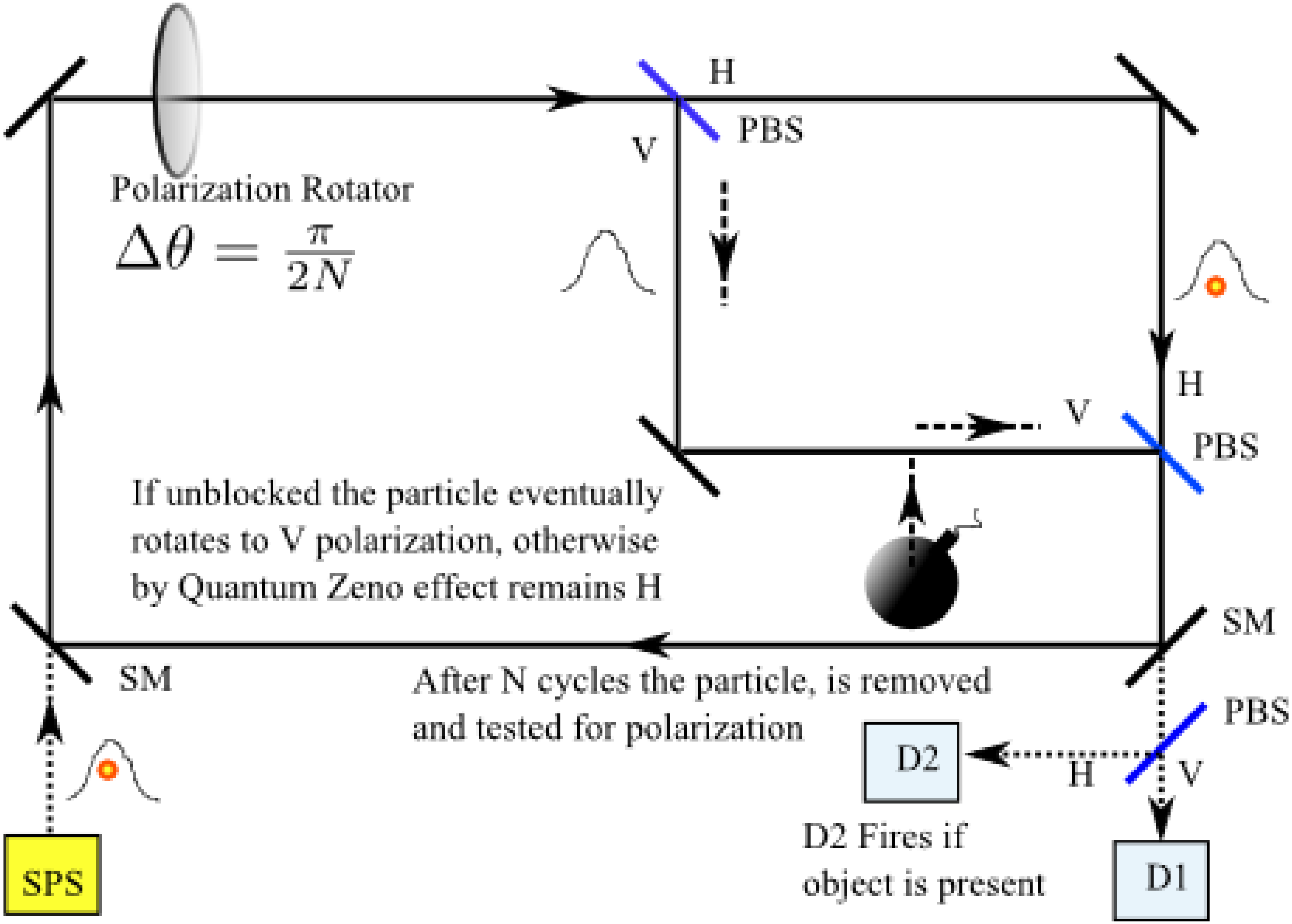
In the limit, perfect IFM measurement

- Upper path directed past bomb repeatedly
- $P_{IFM} = [\cos^2(\pi/2N)]^N \rightarrow 1 - \pi^2/4N$
  - As $N \rightarrow \infty$, the probability of triggering the bomb $\rightarrow 0$, detection $\rightarrow 1$



Experimentally confirmed

Folded Experimental Realization

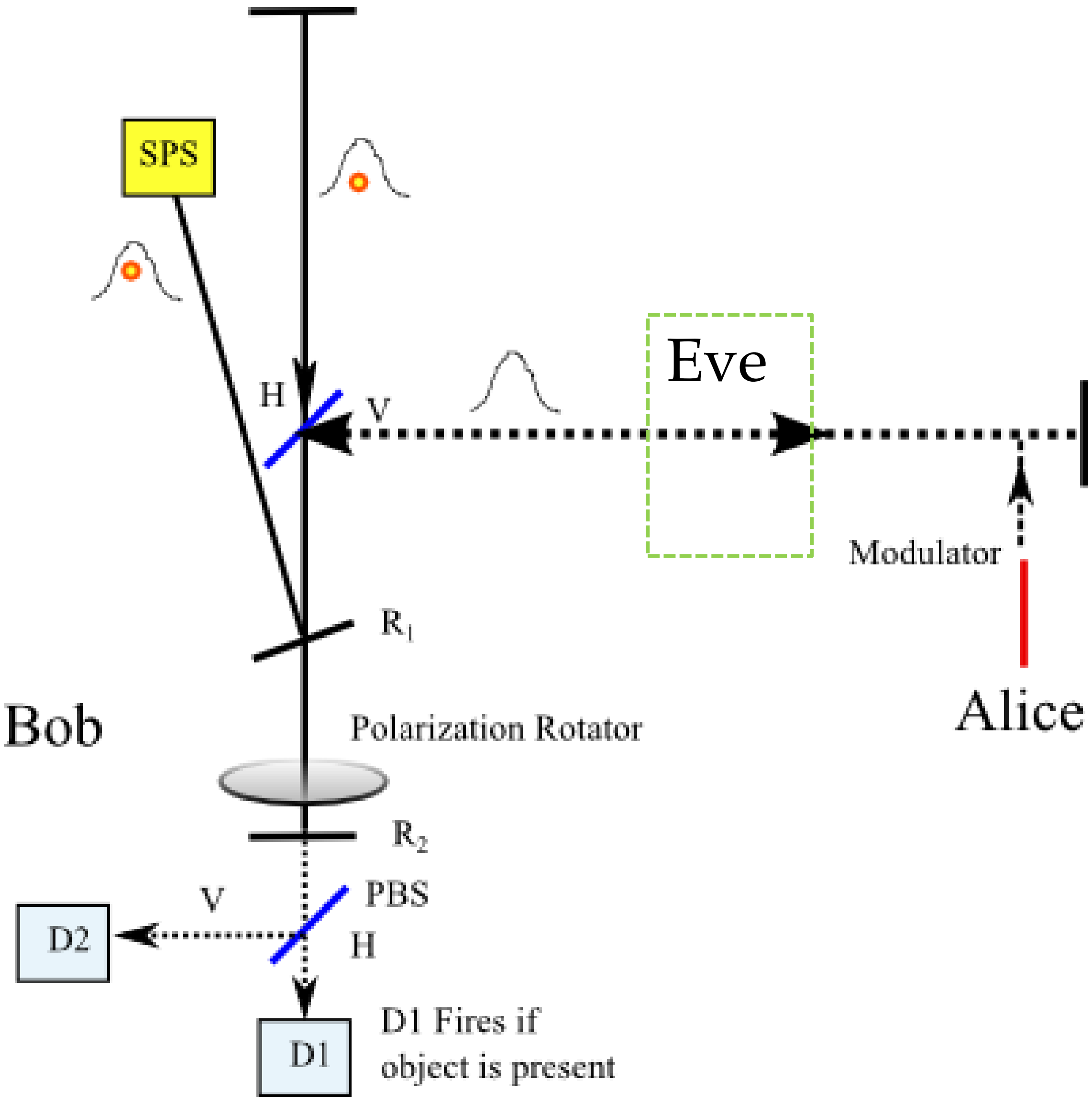


IFM Applications

- Radiation-less imaging and imaging of delicate objects (e.g. ultra-cold Bose-Einstein condensates)
  - Proposed in Kwiat et al.'s "Quantum Seeing in the Dark (Sci. Amer. Nov. 1996)
  - Demonstrated by White, Nairz and Kwiat in "Interaction-free imaging" (Phys. Rev. Vol. 58, No. 1, July 1998)
- A communications system for which IFM provides perfect security?

Perfectly Secure Communications

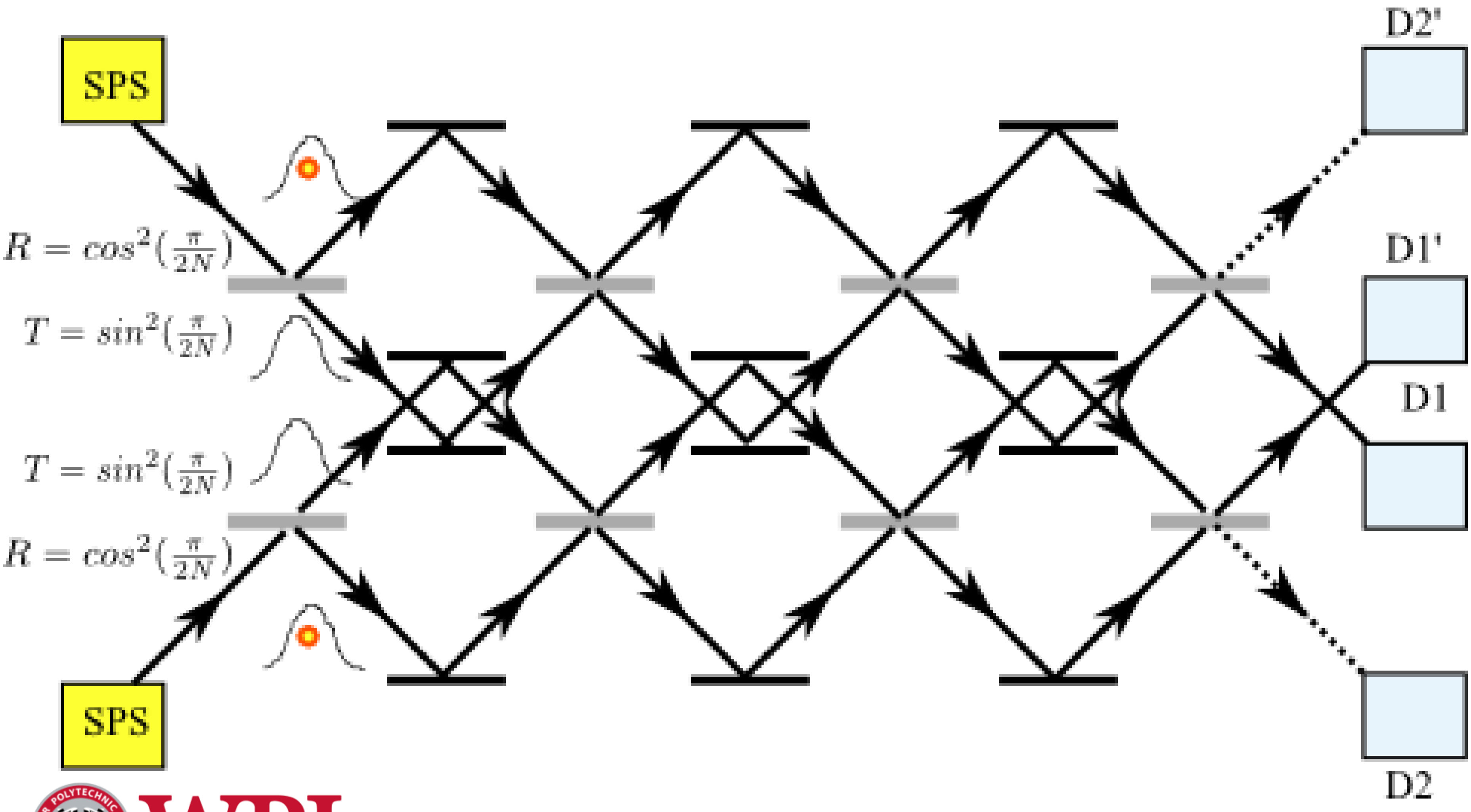
- Restructured IFM
- Bidirectional empty-packet channel
- Alice transmits by modulating empty beam
- D2 reads modulation
- D1 fires on ‘attenuation’ (half of the time)
- Beam, hence message, is unreadable by eavesdropper



Taking Model Realism too seriously?

- As off base as it seems, consider the empty packet as a real packet moving behind the curtain of the reality's stage.
- Then a second actor using the same path, behind the curtain, would bump the first.
- That is, two apparent ghosts (in the view of the audience) would bump into each other and disrupt the play.

Do quantum ghost packets bump?



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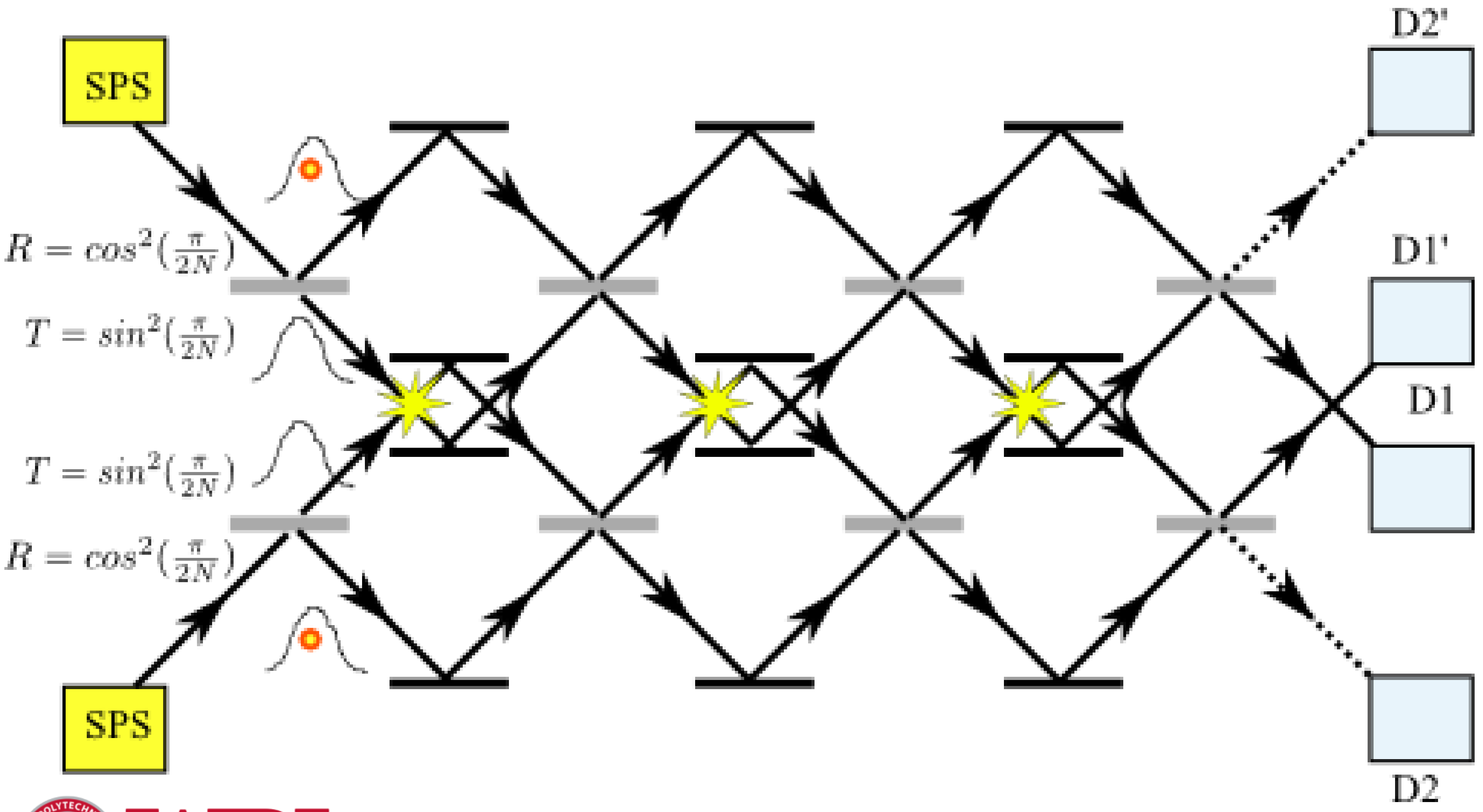
Billiards in a parallel world!



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Is it true?

- We don’t understand QM, but we know how to compute it!
- Still a very messy problem!
  - Express all components of the system in terms of the annihilation and creation operators of quantum particles
  - To obtain general solution allowing parameter optimization, conduct analysis symbolically
  - Find limit solution for infinite beam splitter stages and infinitesimal reflection probability

An exercise in Linear System Theory

- To obtain the limit of an infinite number of stages and R→1, exploit linearity of Quantum Theory
  - Equivalent to a discrete time Linear System with given initial conditions evaluated at a given time step k, $x[k]=A^k x[0]$ where A is the state transition matrix for one step
  - $A^k = Q\,\Lambda^k\,Q^{-1}$

$$\Lambda = \mathrm{diag}\begin{bmatrix} \frac{9R^2}{2} - 4R + \frac{1}{2} + \frac{\sqrt{81R^4 - 144R^3 + 78R^2 - 16R + 1}}{2} \\ \frac{9R^2}{2} - 4R + \frac{1}{2} - \frac{\sqrt{81R^4 - 144R^3 + 78R^2 - 16R + 1}}{2} \\ 0 \\ 1 \end{bmatrix}$$

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Modal matrix of eigenvectors

- Q =

$$\left[\frac{2(-1+3R)^2\left(\frac{9R^2}{2}-4R+\frac{1}{2}+\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)}{\left(\frac{5}{2}+\frac{27R^2}{2}-12R+\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)\left(\frac{3R^2}{2}-2R+\frac{1}{2}+\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},\ \frac{2(-1+3R)^2\left(\frac{9R^2}{2}-4R+\frac{1}{2}-\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)}{\left(\frac{5}{2}+\frac{27R^2}{2}-12R-\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)\left(\frac{3R^2}{2}-2R+\frac{1}{2}-\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},0,0\right]$$

$$\left[\frac{-I\left(\frac{9R^2}{2}-4R+\frac{1}{2}+\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)(-1+3R)}{\sqrt{R}\sqrt{1-R}\left(\frac{5}{2}+\frac{27R^2}{2}-12R+\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},\ \frac{-I\left(\frac{9R^2}{2}-4R+\frac{1}{2}-\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)(-1+3R)}{\sqrt{R}\sqrt{1-R}\left(\frac{5}{2}+\frac{27R^2}{2}-12R-\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},0,-1\right]$$

$$\left[\frac{-I\left(\frac{9R^2}{2}-4R+\frac{1}{2}+\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)(-1+3R)}{\sqrt{R}\sqrt{1-R}\left(\frac{5}{2}+\frac{27R^2}{2}-12R+\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},\ \frac{-I\left(\frac{9R^2}{2}-4R+\frac{1}{2}-\frac{\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)(-1+3R)}{\sqrt{R}\sqrt{1-R}\left(\frac{5}{2}+\frac{27R^2}{2}-12R-\frac{3\sqrt{81R^4-144R^3+78R^2-16R+1}}{2}\right)},0,1\right]$$

$$[1,1,1,0]$$

By well chosen changes of variables it was possible to obtain a closed form solution for the limit case: $\lim_{k\to\infty} Q\,\Lambda^k\,Q^{-1}x[0]$

Analytic Solution for outcomes

Probability of outcomes:
“Eve detected and bit intercepted”
“Eve detected but bit not intercepted”
“Eve not detected and bit intercepted”
“Eve not detected and bit not intercepted – annihilation’

$$\begin{bmatrix} \cos\left(\frac{\pi\sqrt{2}}{2}\right)^2 \\ \frac{1}{2}\sin\left(\frac{\pi\sqrt{2}}{2}\right)^2 \\ \frac{1}{2}\sin\left(\frac{\pi\sqrt{2}}{2}\right)^2 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.3668723290 \\ 0.3165638356 \\ 0.3165638356 \\ 0. \end{bmatrix}$$

Totaling P=1
Hence none annihilated on collision

Heavy leak, but highly detectable

- For each bit transmitted while Eve is trying to eavesdrop:
  - Prob. of Eve being detected is: 0.683
  - Prob. of Eve reading the bit is: 0.683

- After attempting to read k bits the probability of detecting the exploit is

$$P_d = 1 - \left[\frac{sin^2\left(\frac{\pi\sqrt{(2)}}{2}\right)}{2} \right]^k = 1 - 0.31656^k$$

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Trade off information for stealth?

- So far, eavesdropper and communications system are identical
- Can Eve go stealthier with more ghostly probe beam?
- Test simplest variation
  - Vary R near its optimal infinitesimal IFM value identically at all Eve's beam splitters
  - Study effect of her detectability (stealth)
  - Study effect on information leakage

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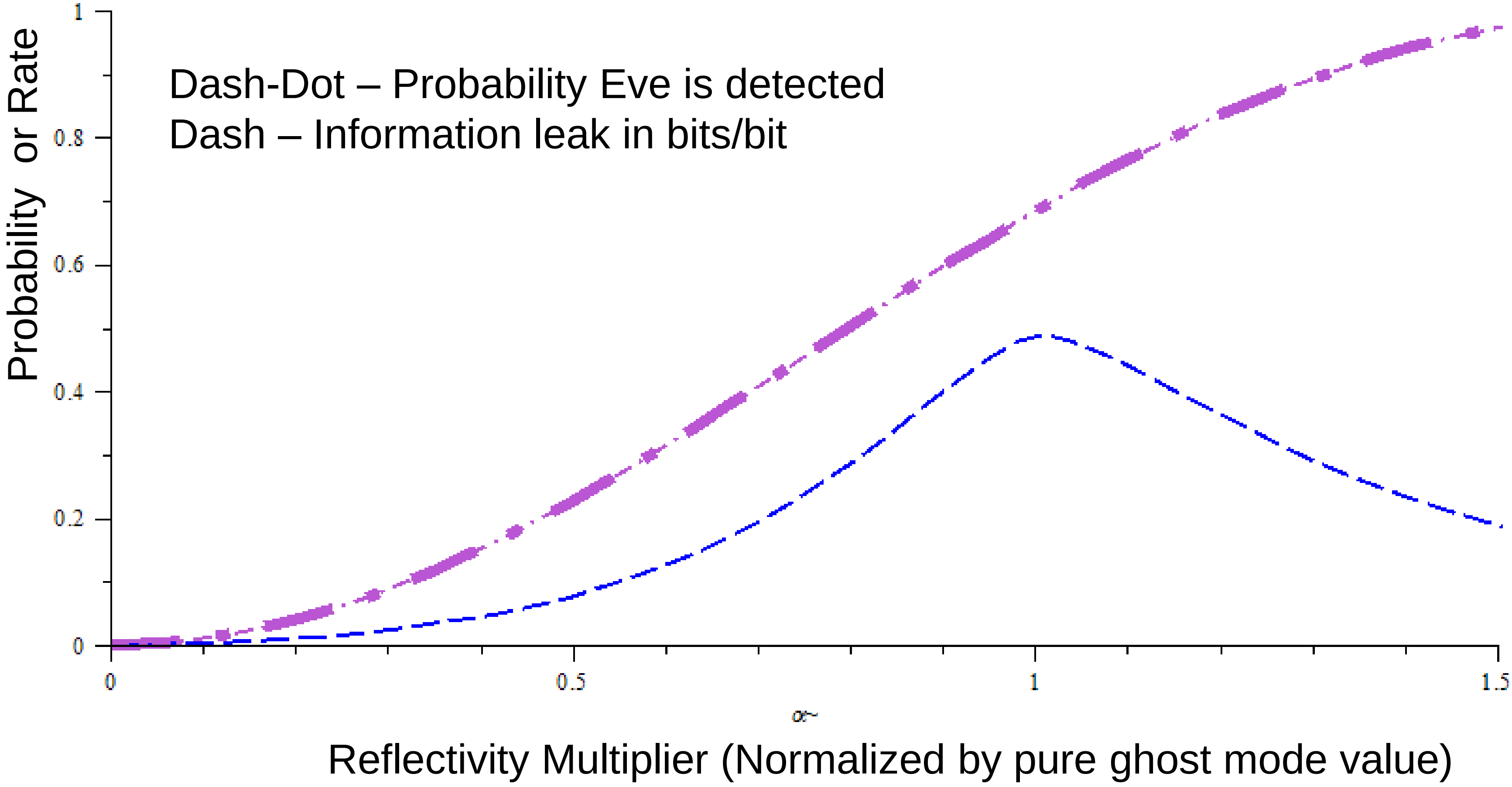
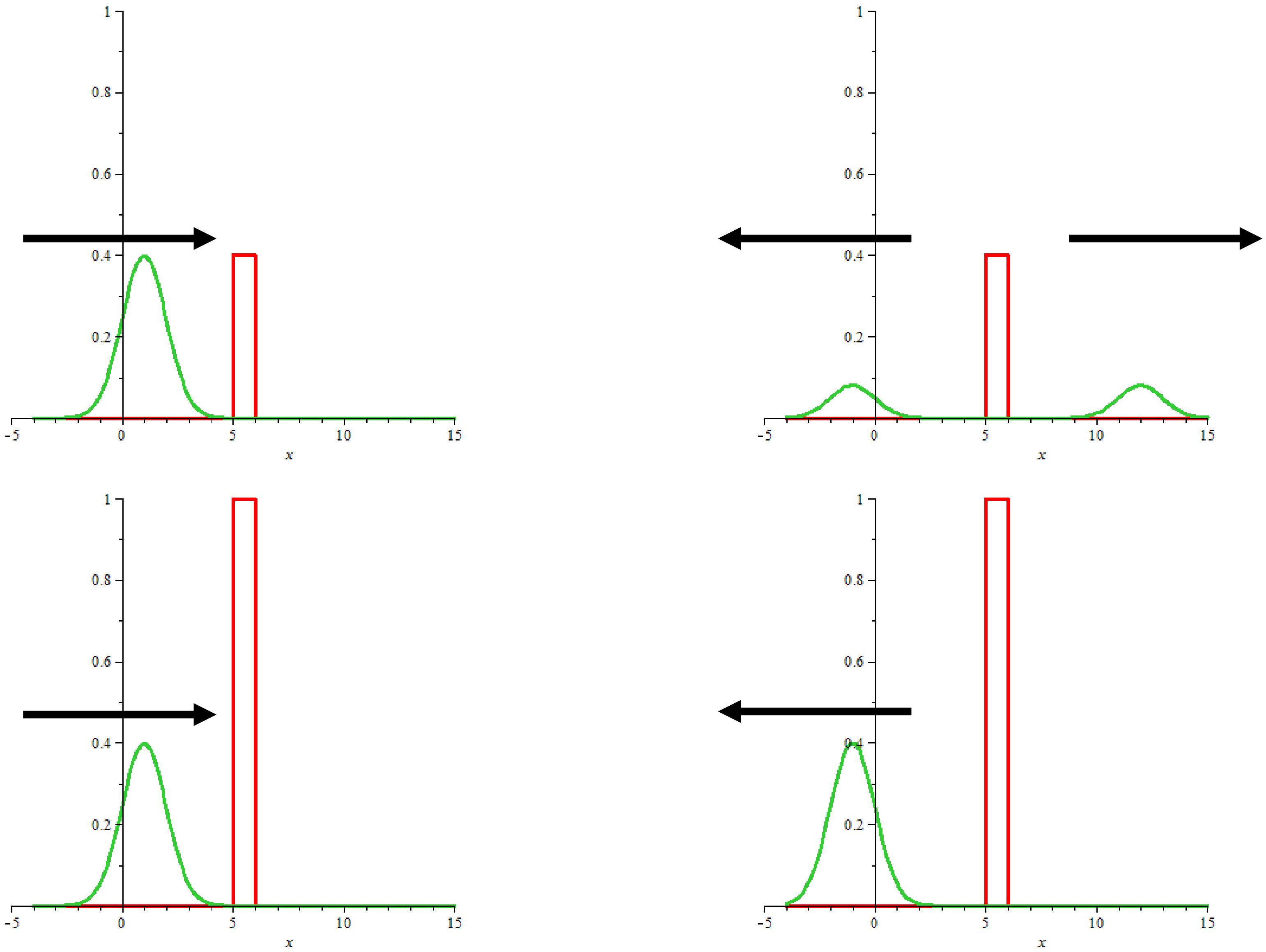
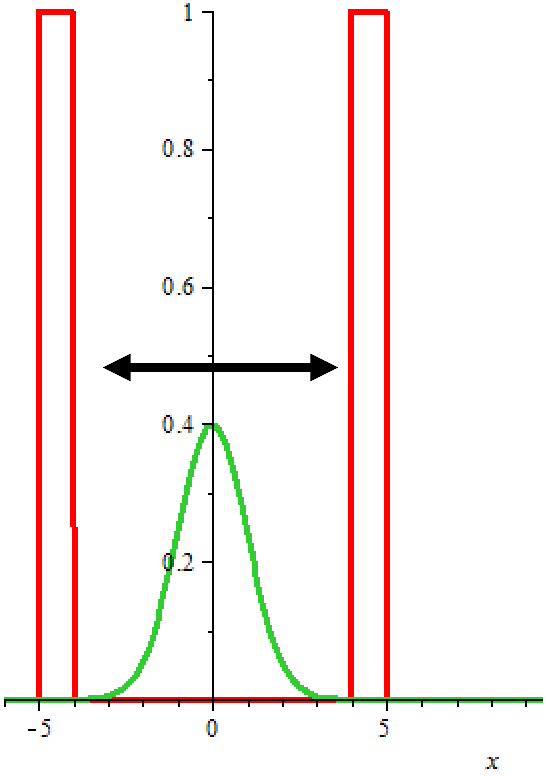
Performance of leak channel



Potential barriers as beam splitters

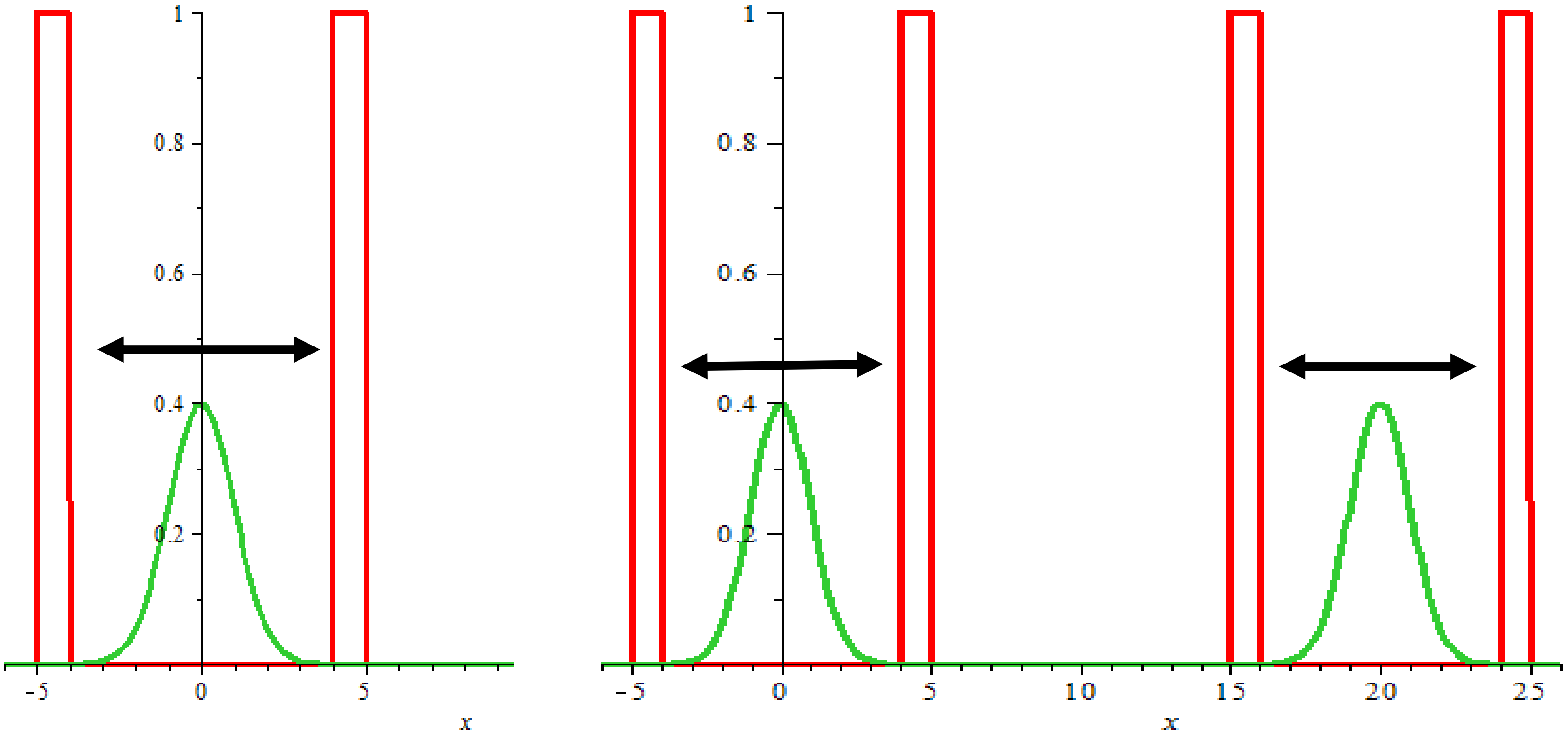


Qubit containers



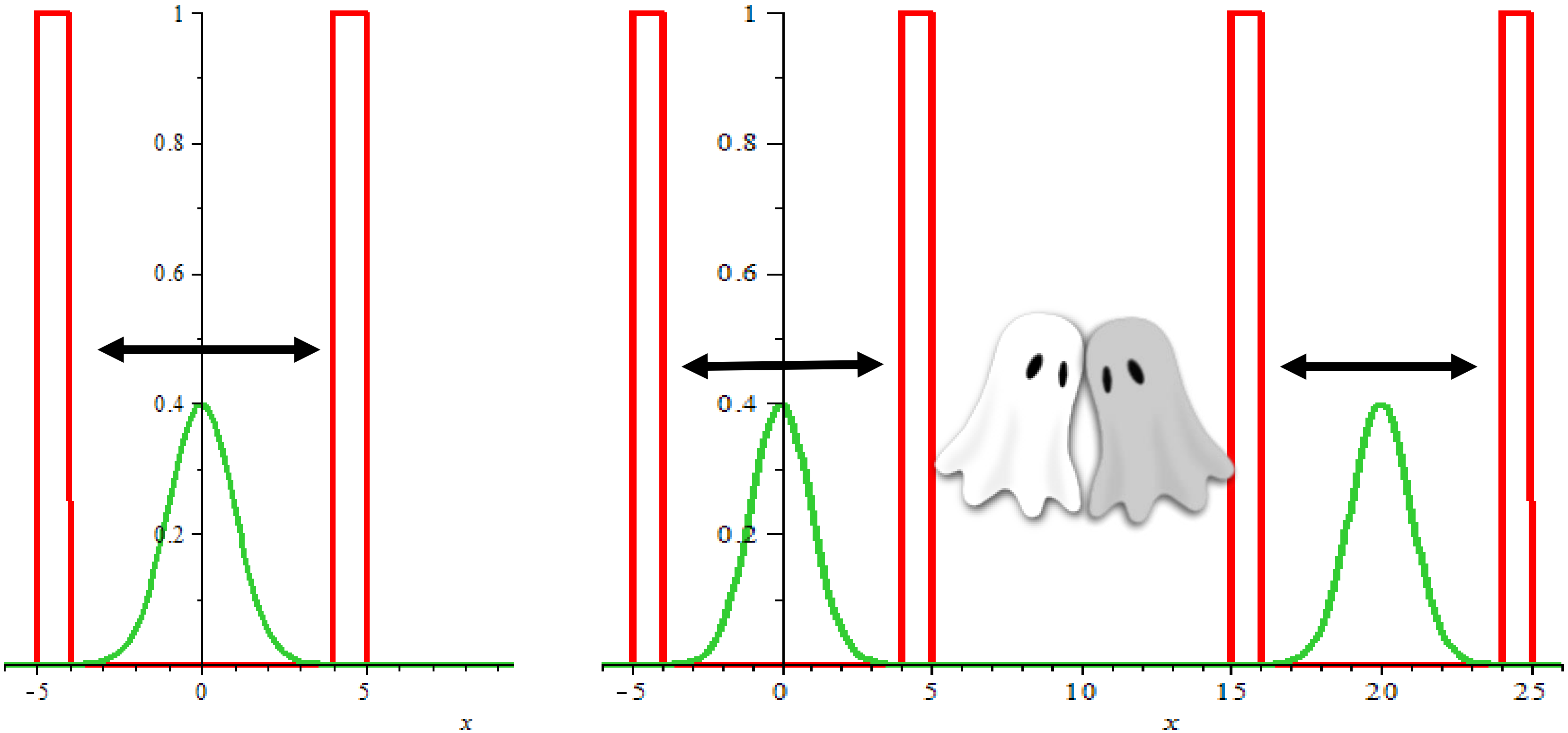
- Potential barriers as qubit container walls

Qubit containers



- Potential barriers as qubit container walls

Qubit containers



- Potential barriers as qubit container walls
- A hidden strong defect of physical realizations!

Conclusion

- IFM allows "real" objects to be probed without detection of the probe
- Object Free Interaction (OFI) is possible using a similarly "particle free" ghost probe beam
  - A "perfectly secure" communications system can be attacked by a quantum adversary.
- Simple parameterized probe scheme demonstrates stealth/leakage tradeoff
  - Might allow further optimization
- Empty packet ghosts have very real implications
  - Threatens operation of complex "confined" quantum systems such as quantum computers

Old Scottish Prayer

From ghoulies and ghosties

And long-leggedy beasties

And things that go bump in the night,

Good Lord, deliver us!

- Cornish Litany, author unknown, circa 1500AD