Probing "surreal"elements of quantum physics using weak measurements

Aephraim Steinberg, Dylan Mahler, Lee Rozema, Amir Feizpour, Matin Hallaji, Greg Dmochowski, Shreyas Potnis, Ramon Ramos, David Spierings
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Howard Wiseman
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Kevin Resch, Kent Fisher, Lydia Vermeyden

Centre for Q. Info. & Q. Control
Dept. of Physics, U. of Toronto

Emergent Quantum Mechanics
Vienna 2015
Fetzer Franklin Fund

"African Sonata" by Vladimir Kush

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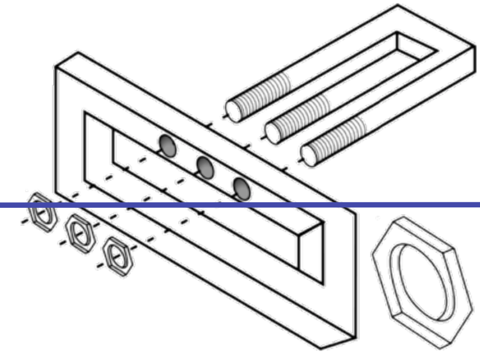
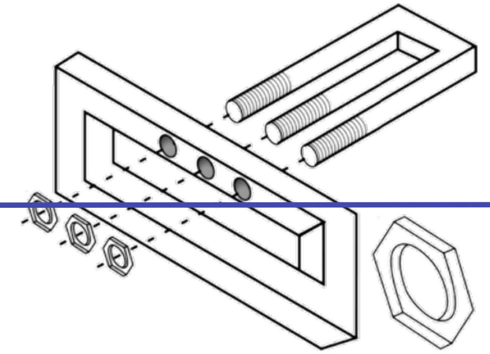
Perspective



Realism? Operationalism? Bohmianism?

Perspective



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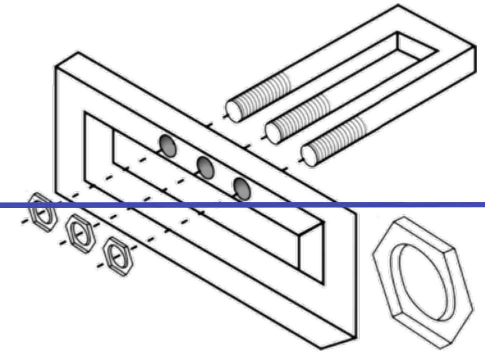
Agnosticism.

Perspective



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Howard Wiseman: "Consider a naive experimentalist, with no knowledge of QM. . ."

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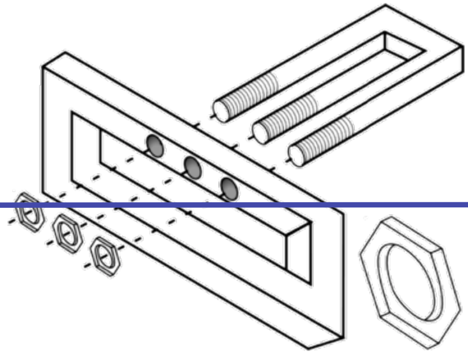

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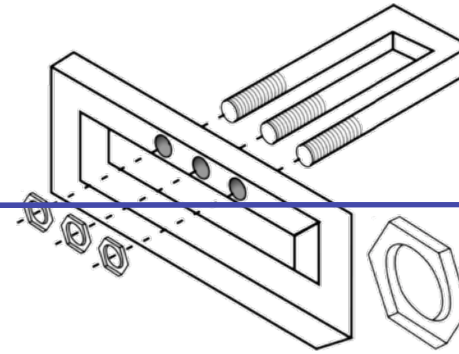

Realism? Operationalism? Bohmianism?

Agnosticism.

Howard Wiseman: "Consider a naive experimentalist, with no knowledge of QM. . ."

If there is some deeper reality underlying QM, what is revealed by weak measurements should tell us something about it – as Howard showed, this is true for Bohmian trajectories, in particular.

But I don't wish to think of our experiments as measuring Bohmian trajectories – they "naïvely" measure properties of quantum systems which I expect *any* underlying explanation to reproduce.

Outline

Nonlocal (surreal?) Bohm trajectories
- **Trajectories & how to measure them**
- ***Welcher Weg* detection & surrealistic trajectories**
- **Nonlocality of (Bohm) trajectories, & its observation**

How to count a single photon and get a result of 8
- **Giant optical nonlinearities**
- **Phase shift of a single post-selected photon**
- **Weak-value amplification of the phase shift of a single photon**
- **(Questions about SNR)**

Can we ask where a tunneling particle has spent its time while tunneling?
- **The Larmor clock**
- **Weak measurements**
- **Experimental progress**

DRAMATIS PERSONÆ

Toronto quantum optics & cold atoms group:

Photons: Hugo Ferretti Edwin Tham Isabella Huang (David Schmid)

Atoms: Shreyas Potnis Ramon Ramos David Spierings Sepehr Ebadi

Atom-Photon Interfaces: **Matin Hallaji Josiah Sinclair Greg Dmochowski**

Some alums: **Dylan Mahler, Amir Feizpour**, Alex Hayat, Ginelle Johnston, Xingxing Xing, **Lee Rozema**, Kevin Resch, Jeff Lundeen, Krister Shalm, Rob Adamson, Stefan Myrskog, Jalani Kanem, Ana Jofre, Arun Vellat Sadashivan, Chris Ellenor, Samansa Maneshi, Chris Paul, Reza Mir, Sacha Kocsis, Masoud Mohseni, Zachari Medendorp, Ardavan Darabi, Yasaman Soudagar, Boris Braverman, Sylvain Ravets, Nick Chisholm, Rockson Chang Chao Zhuang Max Touzel, Julian Schmidt, Xiaoxian Liu, Lee Liu, James Bateman, Zachary Vernon, Timur Rvachov,Luciano Cruz, Morgan Mitchell,...

Some helpful theorists:

Daniel James, Pete Turner, Robin Blume-Kohout, Chris Fuchs, Howard Wiseman, János Bergou, John Sipe, Paul Brumer, Michael Spanner...

CQIQC

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25 years cifar Canadian Institute for Advanced Research

NORTHROP GRUMMAN

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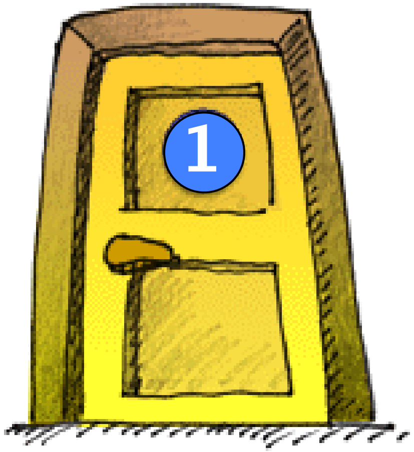
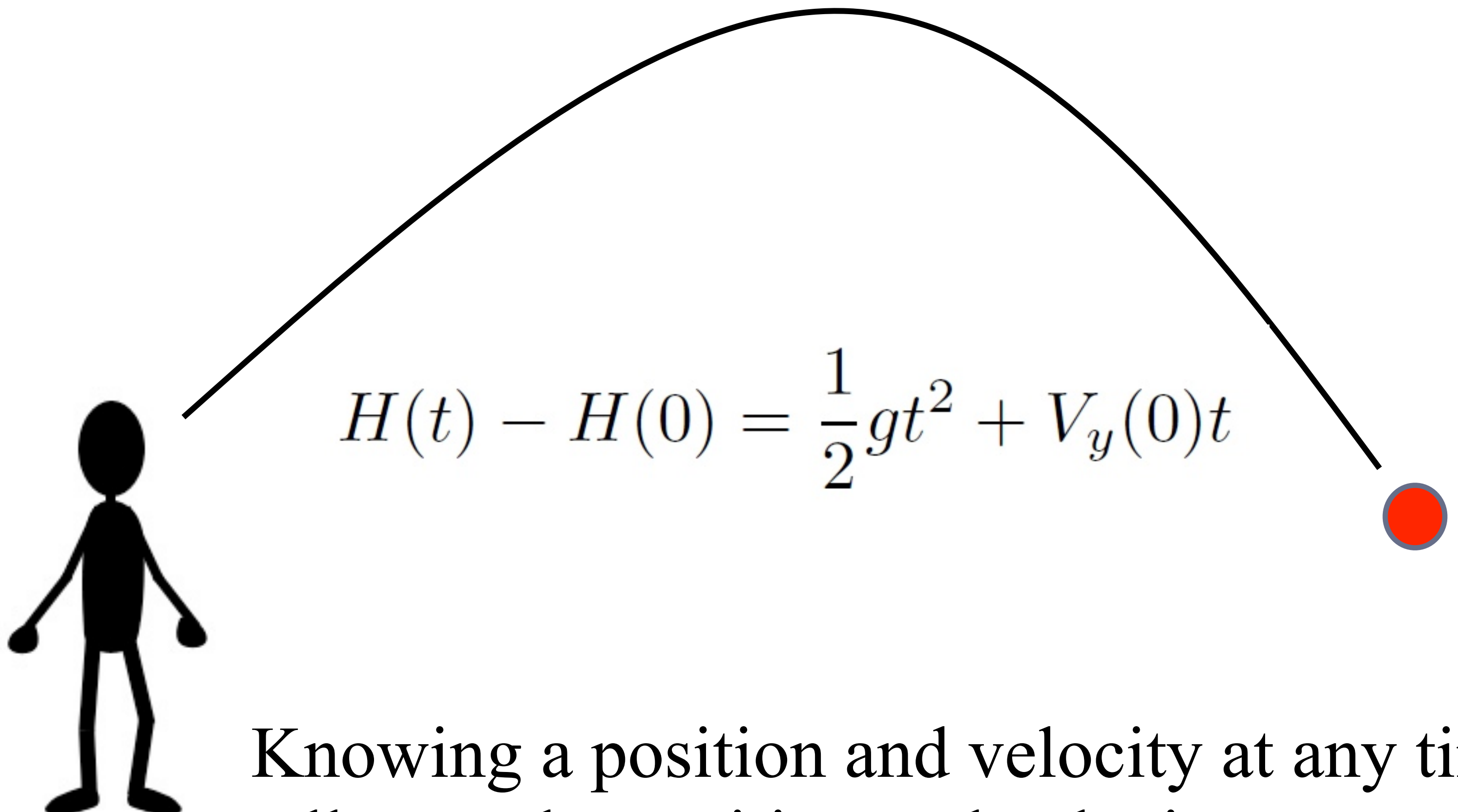


Surreal Bohm Trajectories

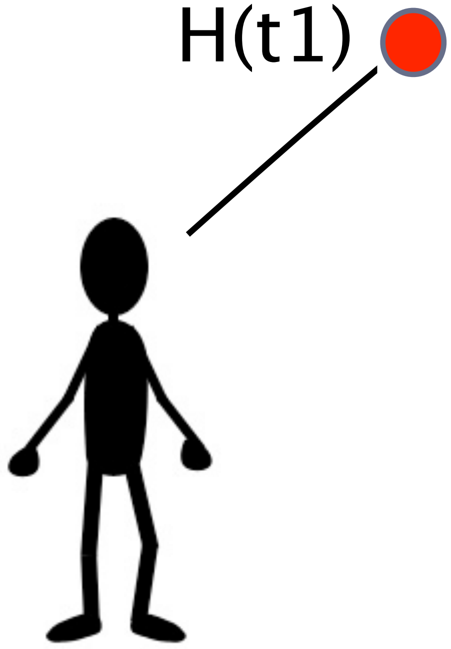
Classical Trajectories



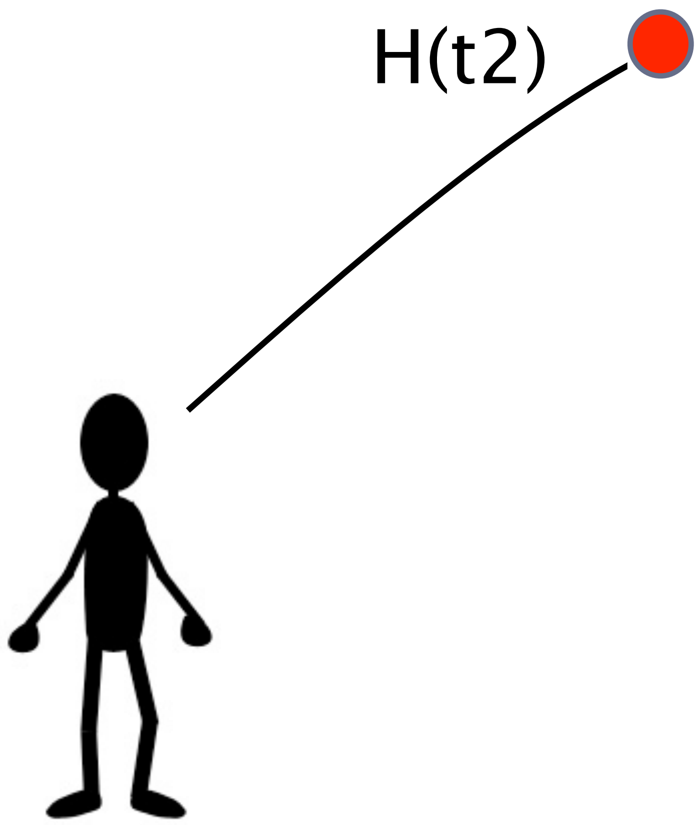
$$H(t) - H(0) = \frac{1}{2}gt^2 + V_y(0)t$$

Knowing a position and velocity at any time t tells you the position and velocity at any other time

Measuring the trajectory of a single particle



Measuring the trajectory of a single particle



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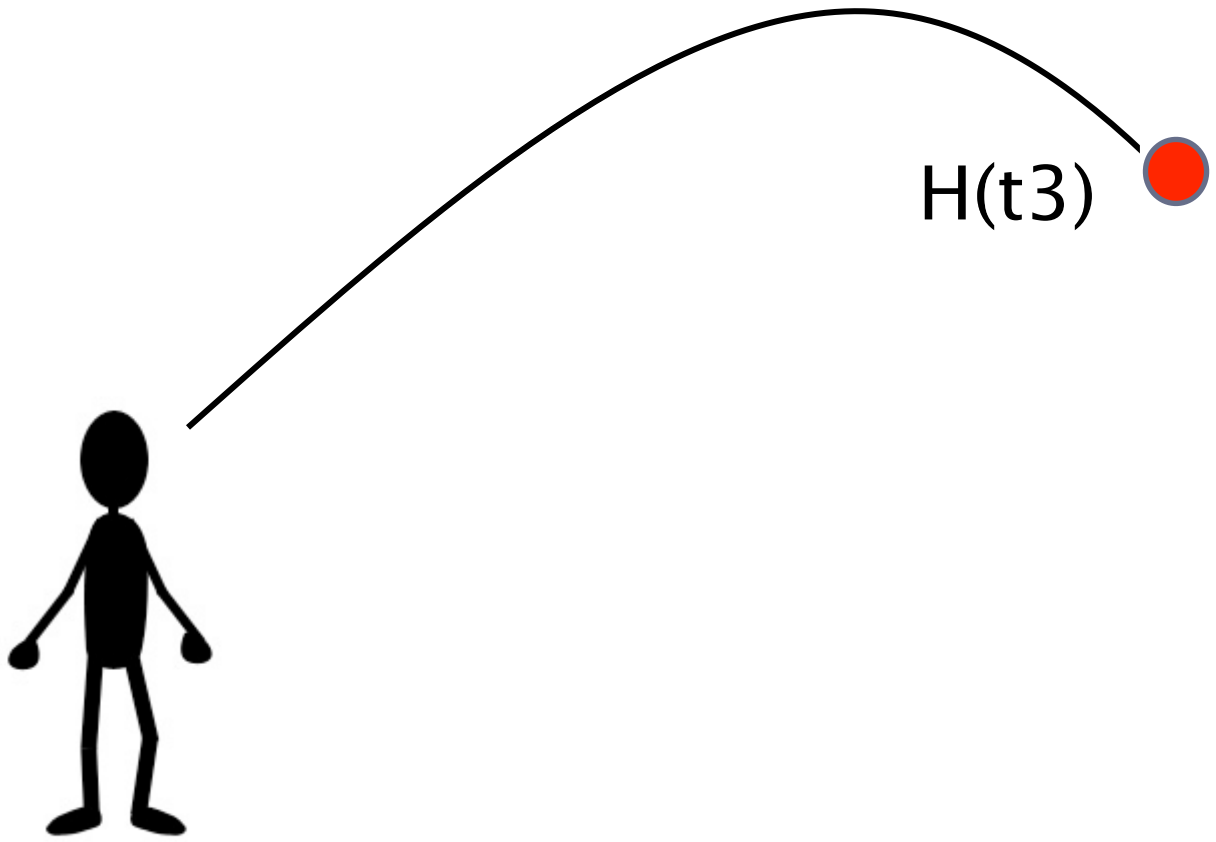

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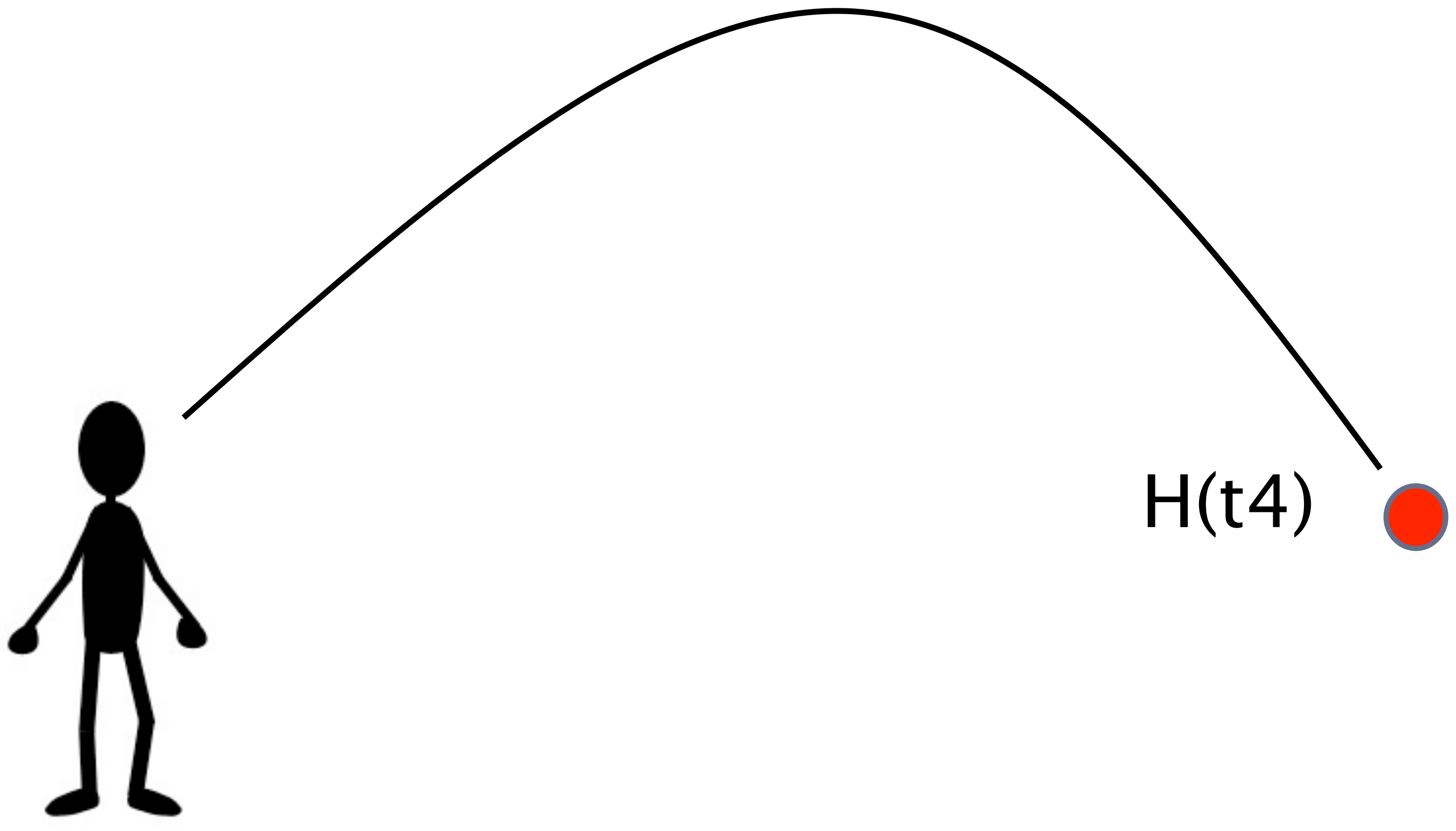
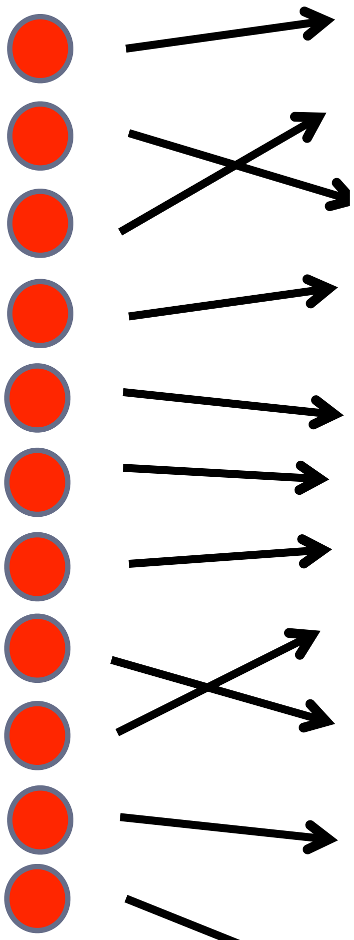


Measuring a set of "average trajectories" for an ensemble



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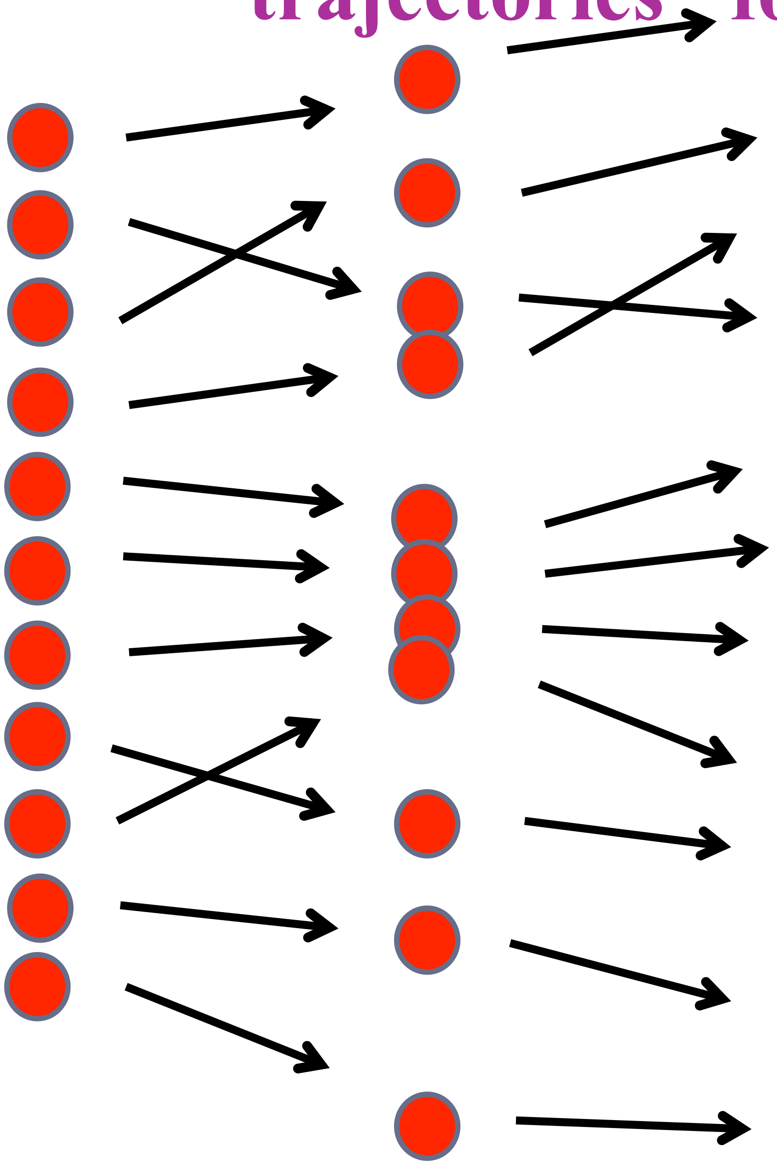

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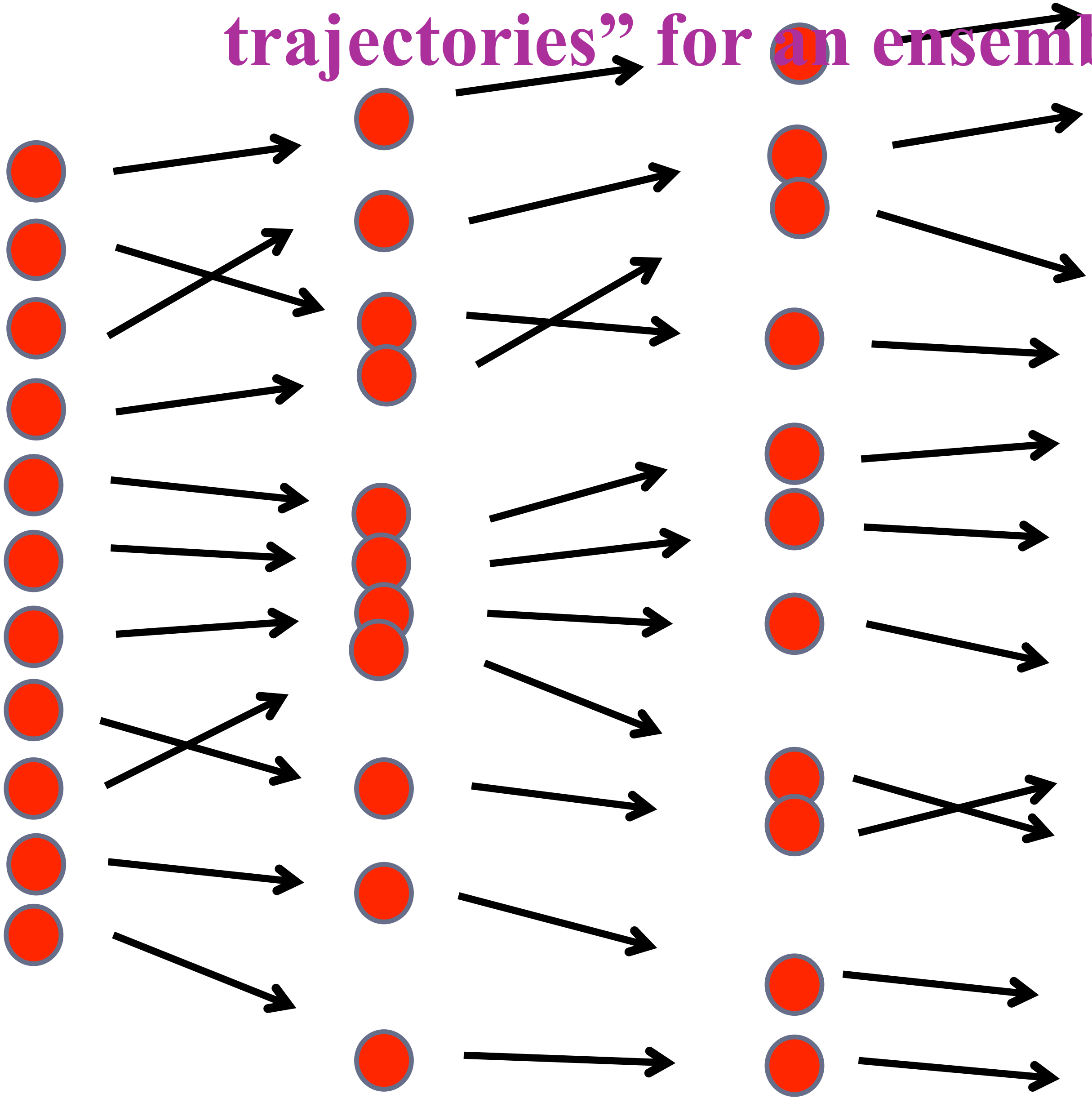

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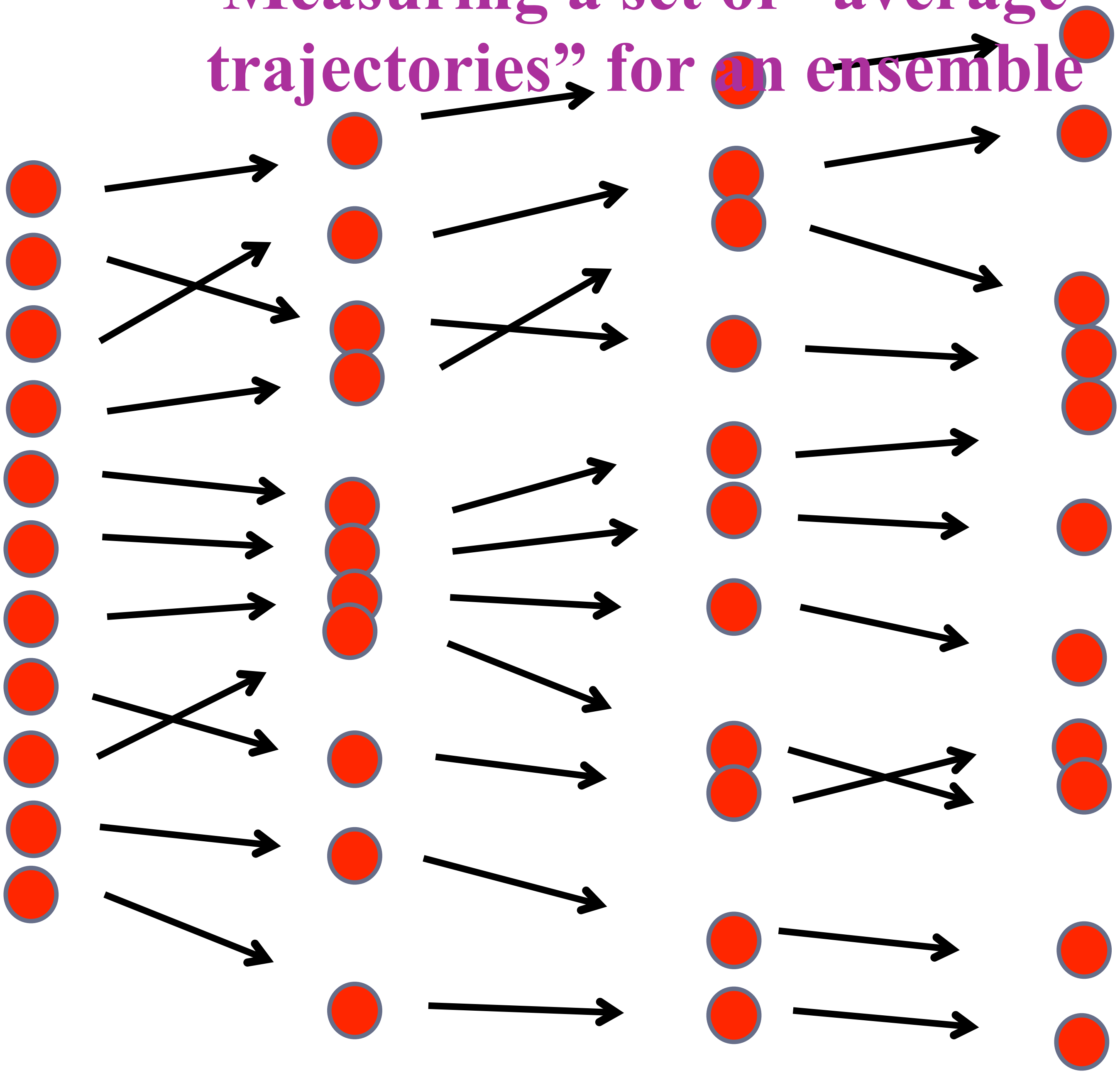

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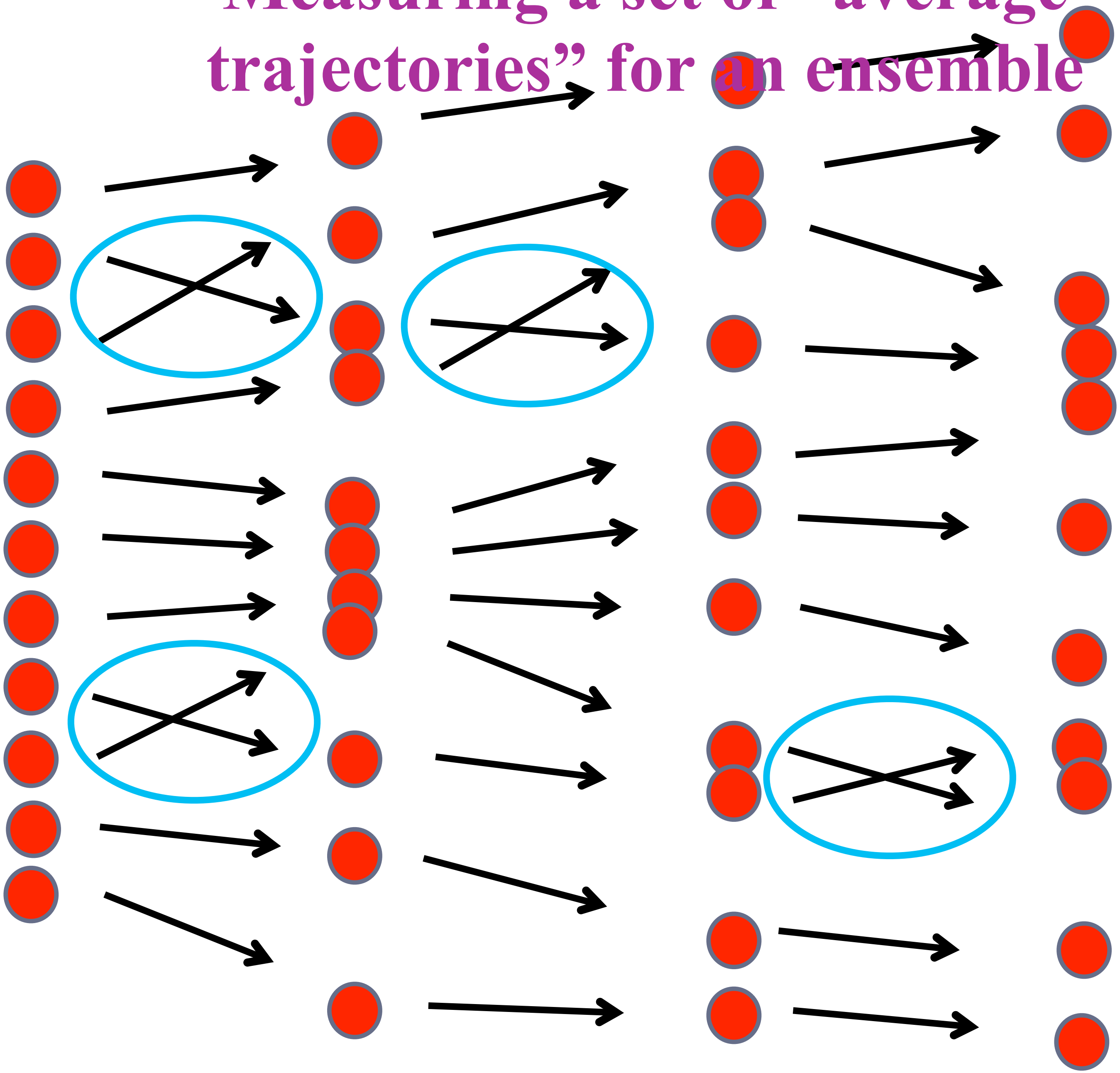

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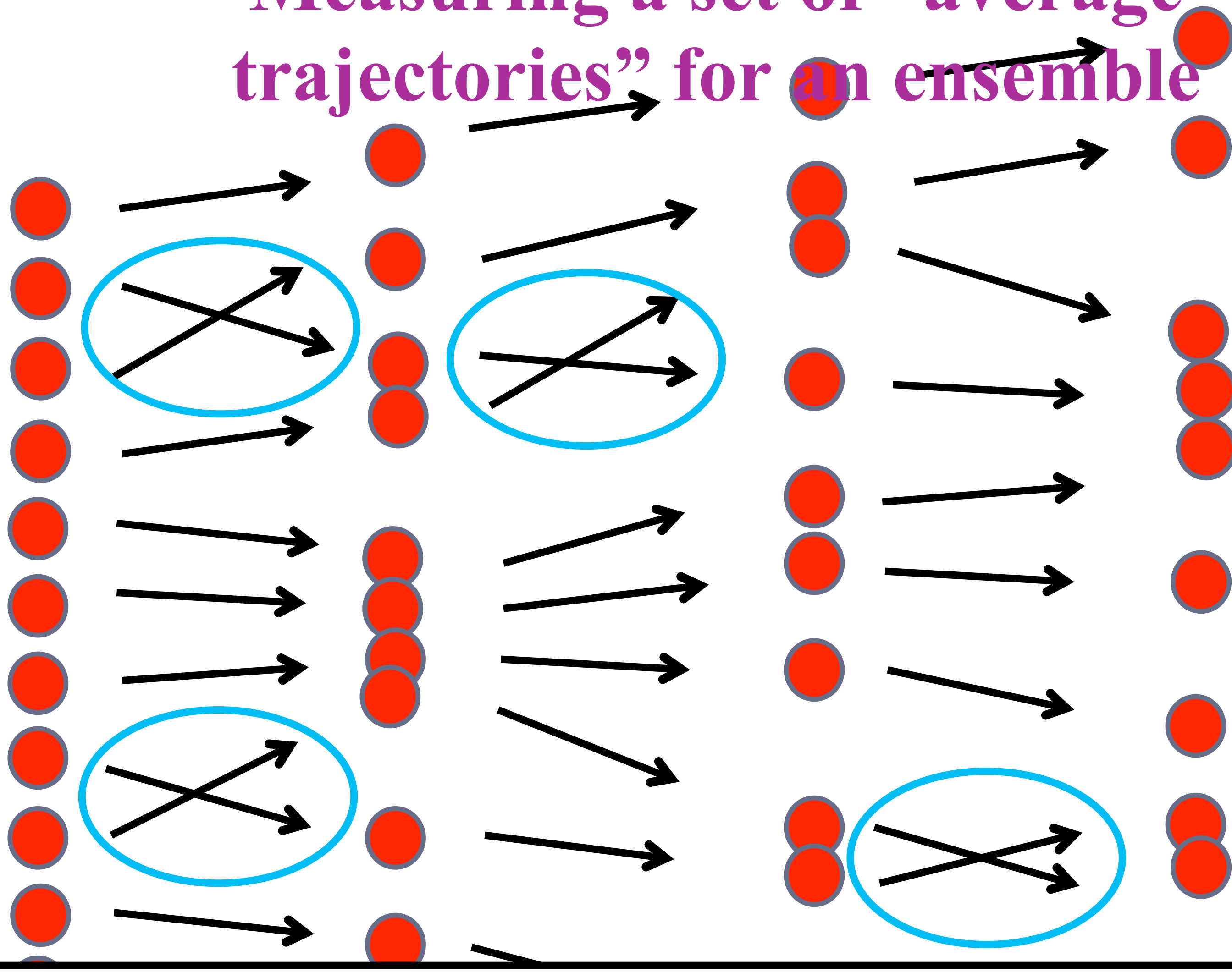

Crossings impossible in any setting where direction depends only on position
(Bohm / Hydrodynamics by mathematical structure;
our experiment by intrinsic design)
May still arise due to overly coarse-grained measurements

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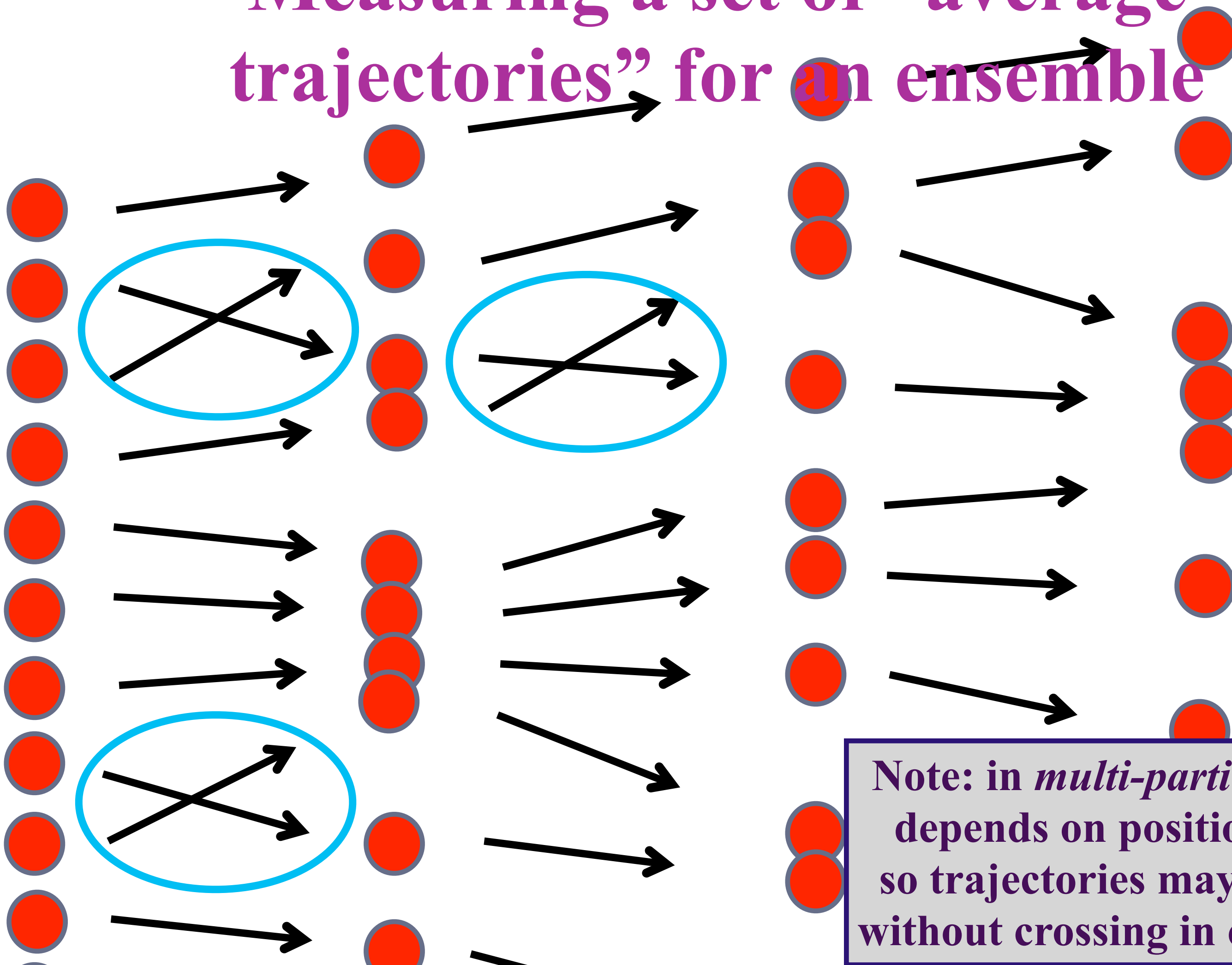

Note: in *multi-particle* Bohm, direction depends on positions of *all* particles, so trajectories may cross in real space without crossing in configuration space!

Crossings impossible in any setting where direction depends only on position
(Bohm / Hydrodynamics by mathematical structure;
our experiment by intrinsic design)
May still arise due to overly coarse-grained measurements

Grounding Bohmian mechanics in weak values and bayesianism

H M Wiseman
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New Journal of Physics **9** (2007) 165
Received 25 October 2006
Published 15 June 2007
Online at http://www.njp.org/
doi:10.1088/1367-2630/9/6/165

While the positions at different times do not commute, so can not be measured jointly with arbitrary precision, one can *weakly* measure $x(t)$ conditioned on a particular $x_f(t+dt)$, to find where the *average* particle that reached x_f was a time dt later. Repeating for all x_f – and at many times t – one can reconstruct *average* trajectories.

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OR: while we cannot jointly measure x(t) and p(t), we can *weakly* measure p(t) conditioned on a particular x(t), to find where the average particle at x is heading.

Again, by repeating for values of x and at many times, one can connect the dots.

Grounding Bohmian mechanics in weak values and bayesianism

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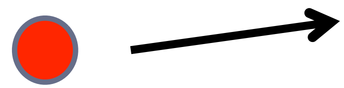
Again, by repeating for values of x and at many times, one can connect the dots.

Wiseman's result: this yields precisely the Bohm trajectories!

(Less dramatic reading: the weak value of p at x is the probability current at x)

Weak measurement



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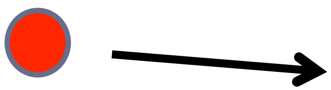
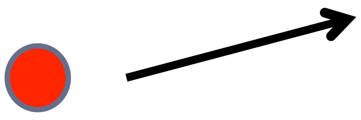
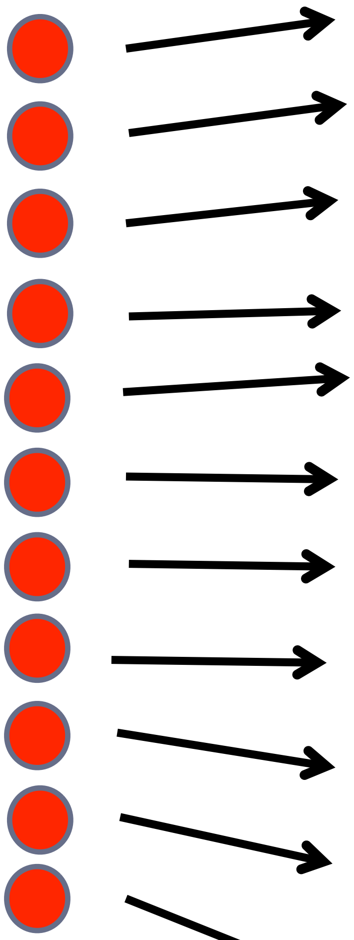


Weak measurement



On average…



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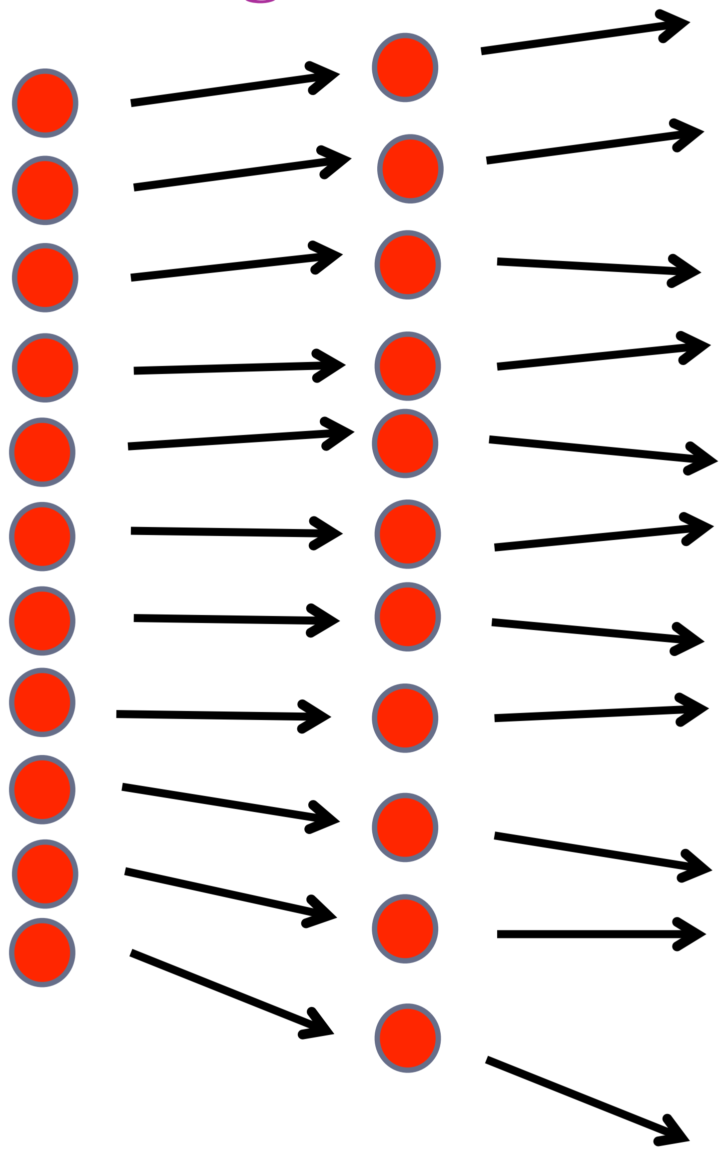

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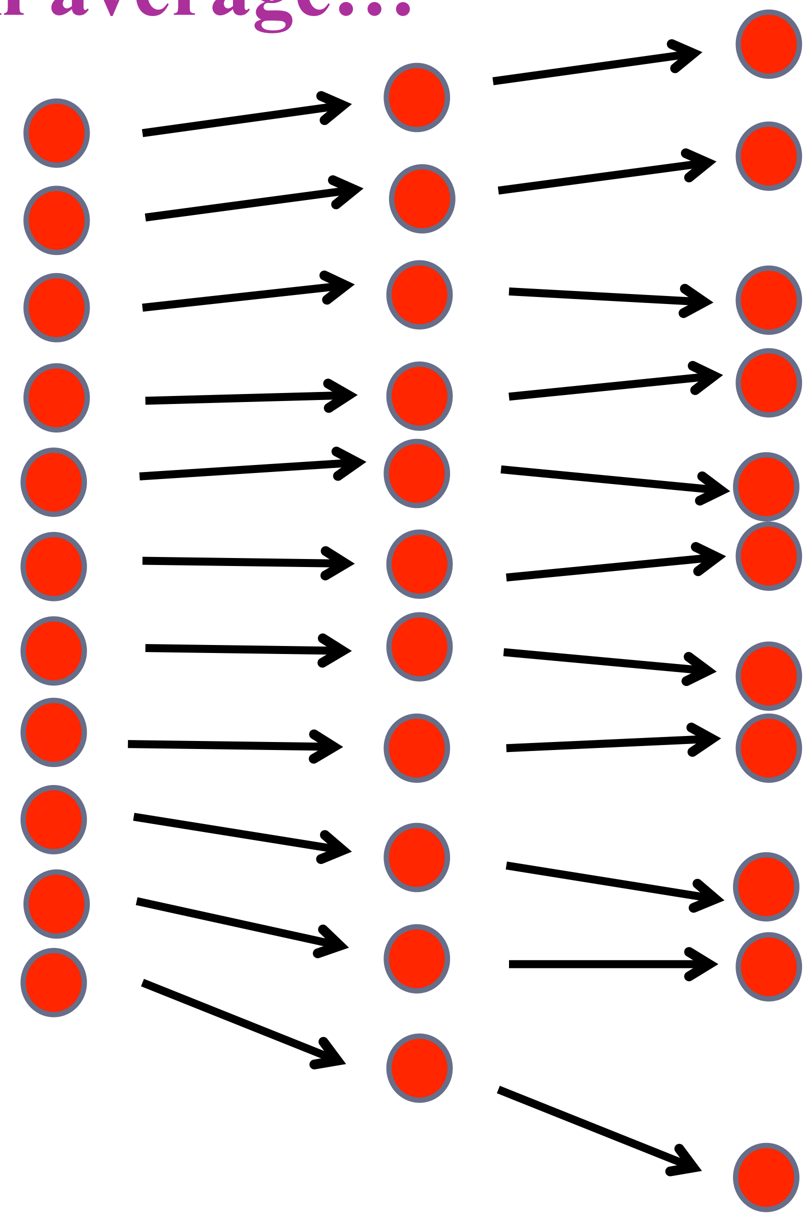


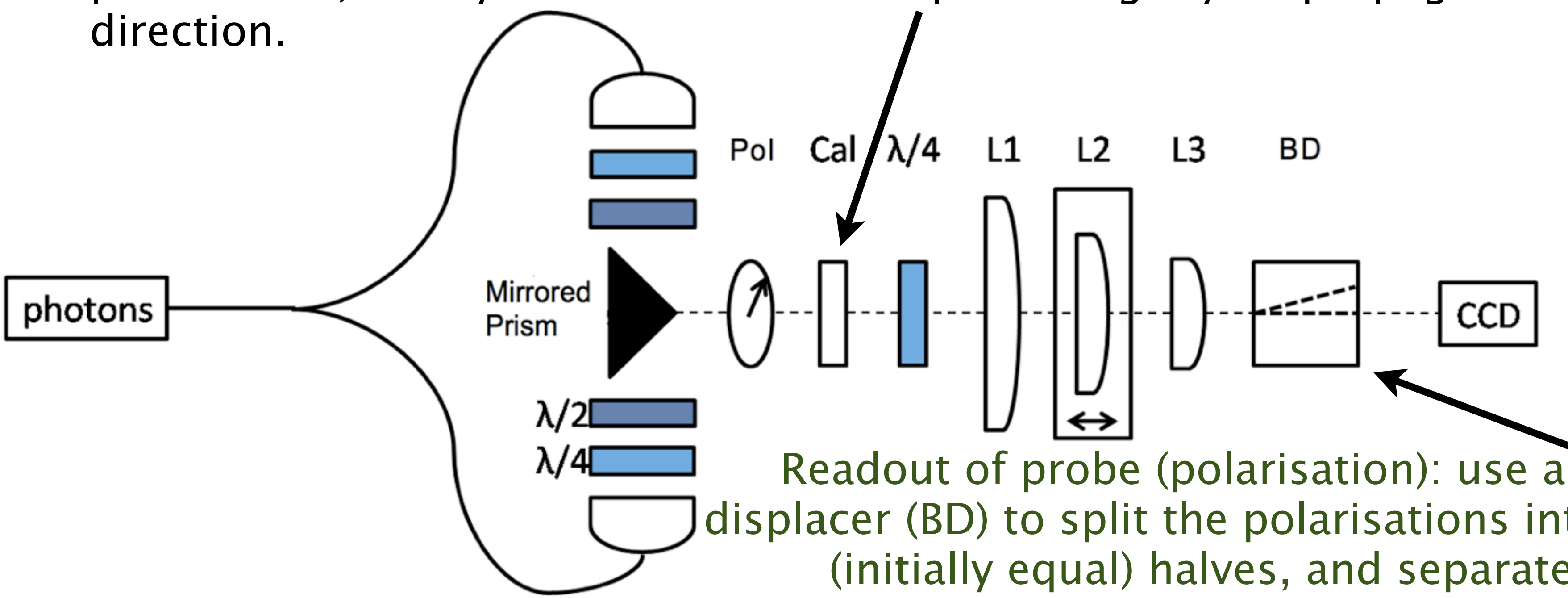
The weak-value double-slit apparatus

Some mapping...

Electrons -> single photons from a quantum dot
Time -> distance along propagation direction (z)
Position -> (horizontal) transverse position (x)
Momentum Px -> direction of photon propagation (|k| is fixed)

Pointer -> polarization of each propagating photon

Coupling of momentum Px to probe: a calcite crystal, which rotates the polarisation, but by an amount which depends slightly on propagation direction.



Readout of probe (polarisation): use a beam displacer (BD) to split the polarisations into two (initially equal) halves, and separate them vertically. Image both fringe patterns on the CCD.

Movies of some (not excellent) data

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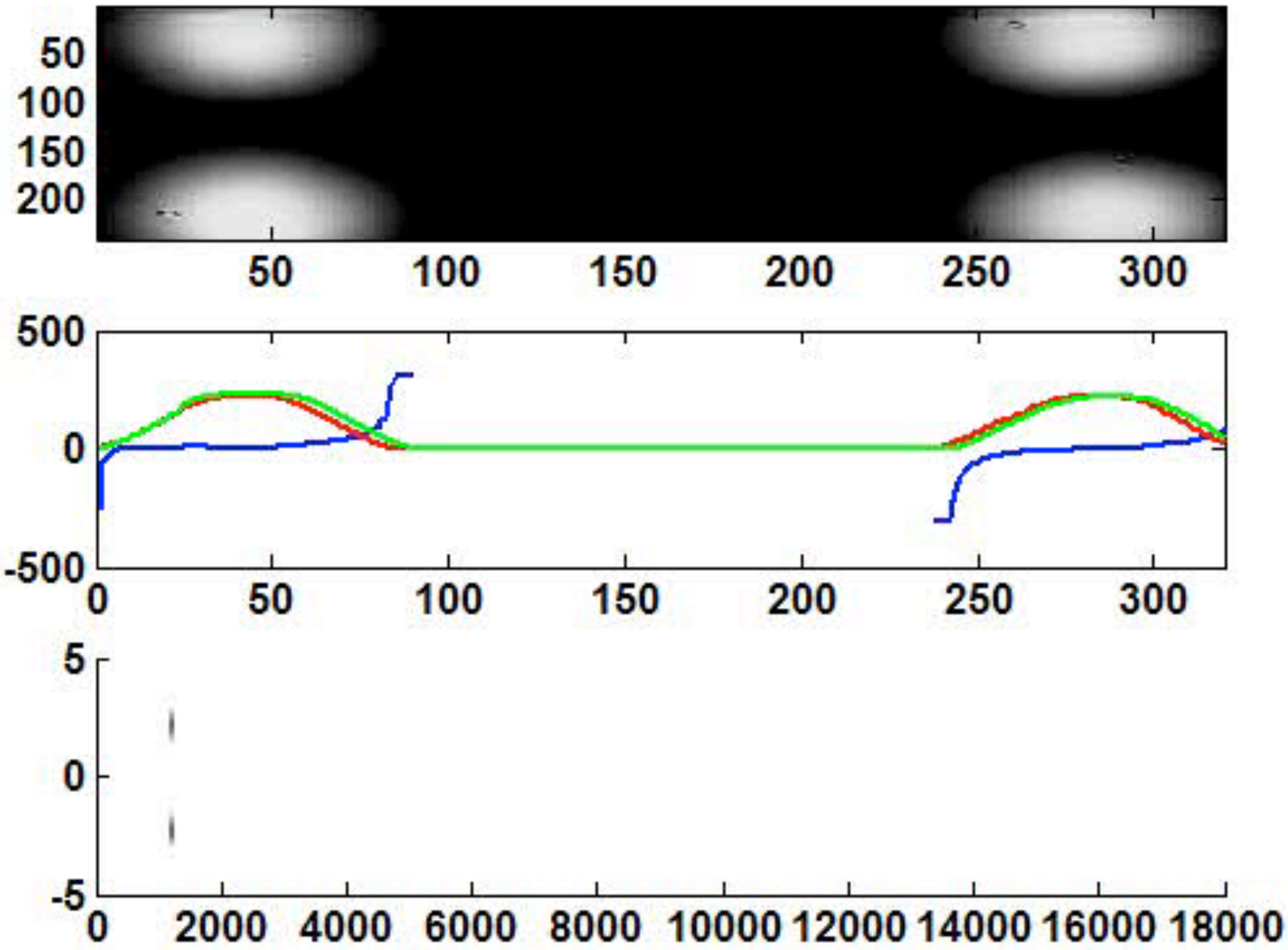
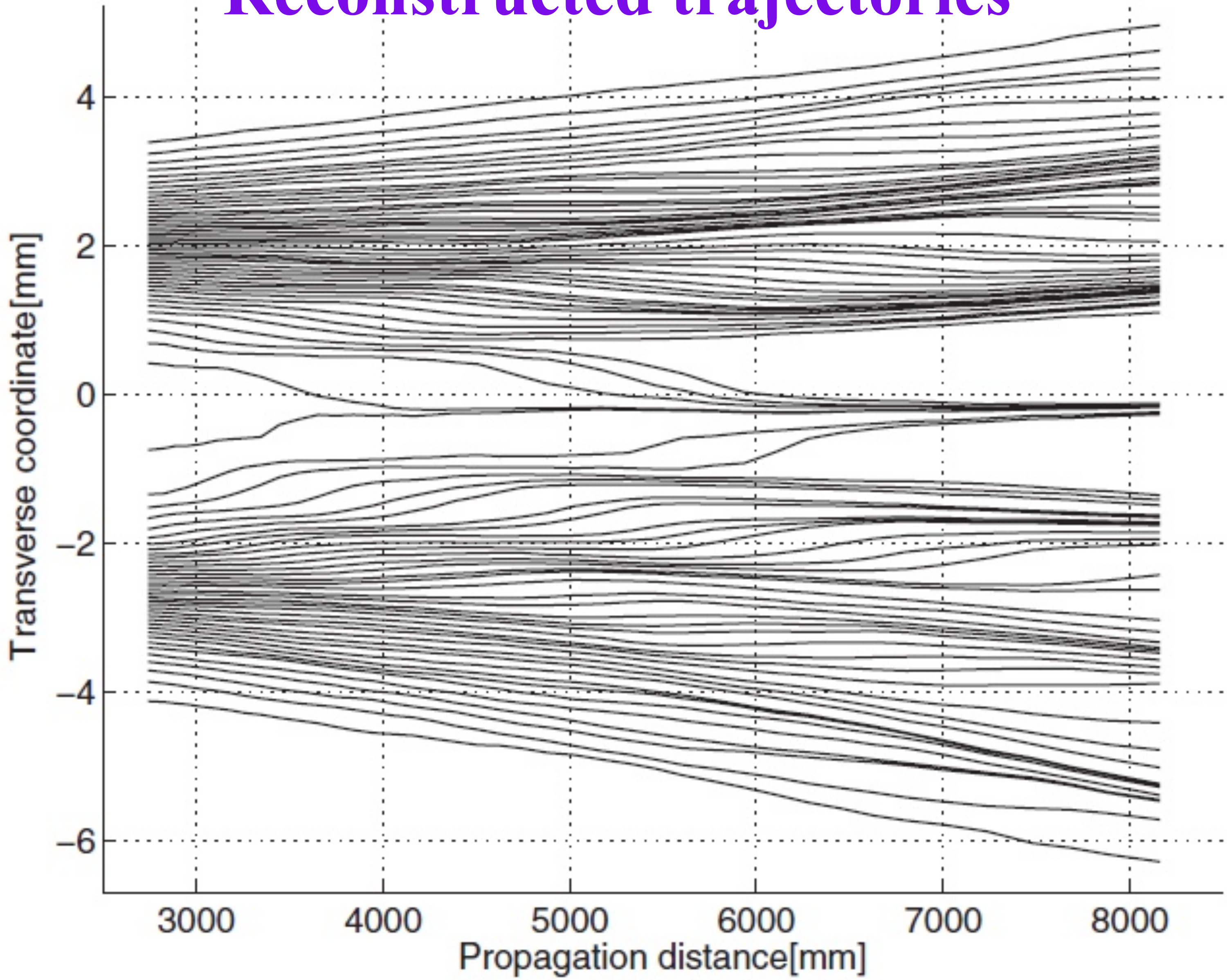


Reconstructed trajectories



[S. Kocsis, et al., Science 332, 1170 (2011).]

Matters get entangled...

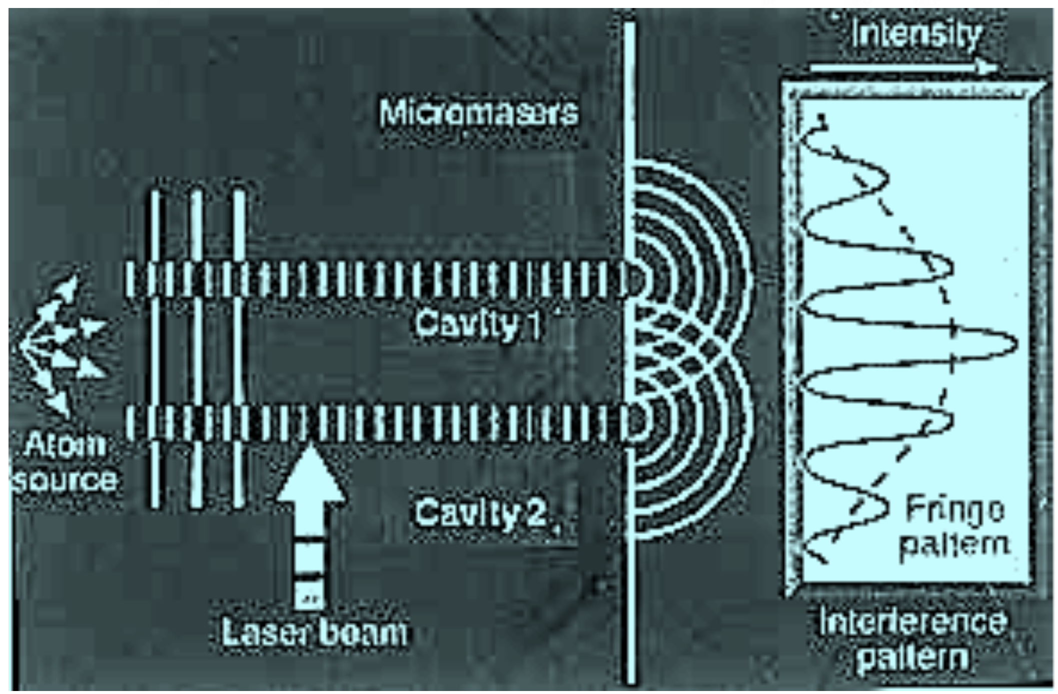
Surrealistic Bohm Trajectories

Berthold-Georg Englert[1,2], Marlan O. Scully[3], Georg Süssmann, and Herbert Walther[1,2]

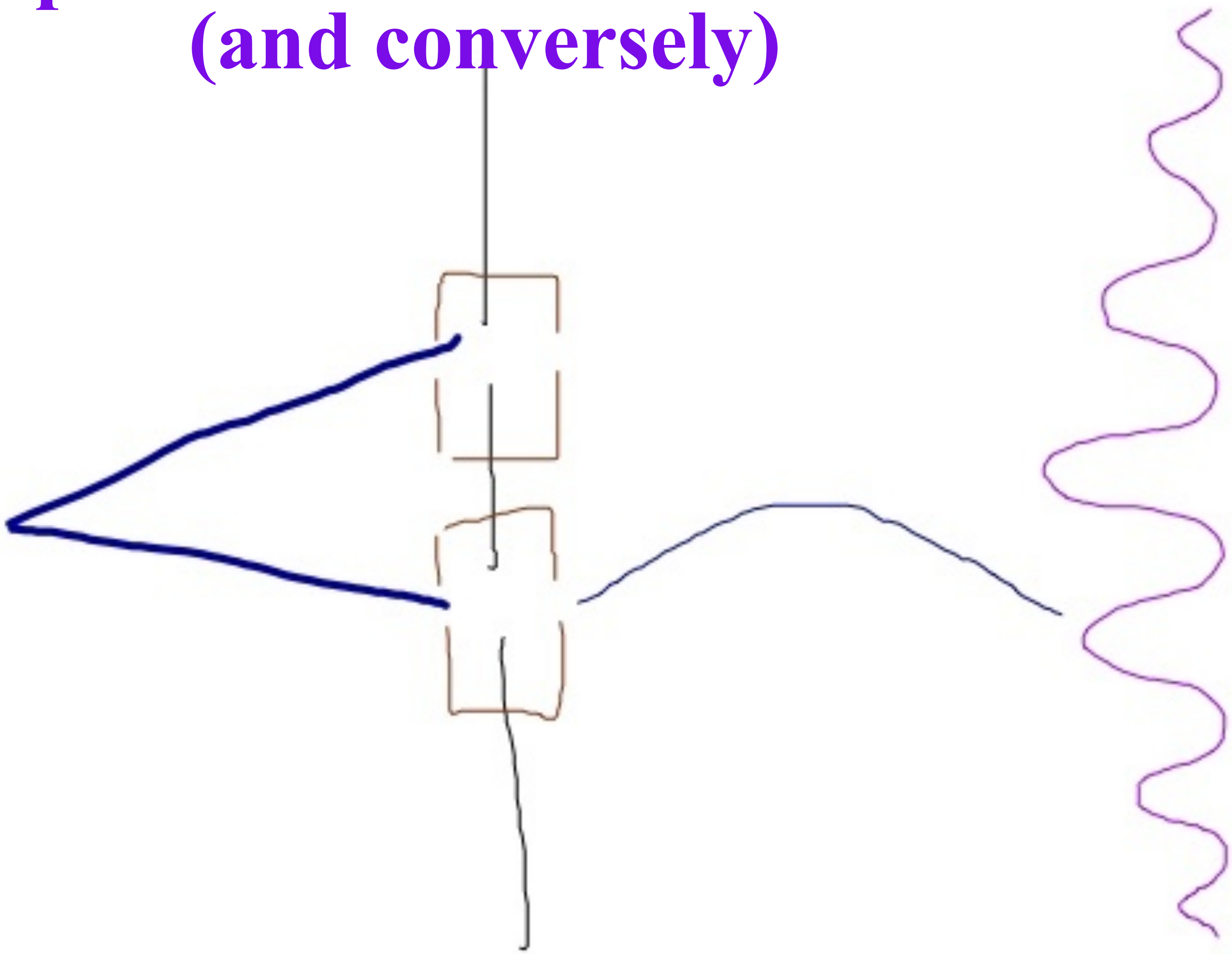
[1] Sektion Physik, Universität München, Am Coulombwall 1, D-8046 Garching, Germany
[2] Max-Planck-Institut für Quantenoptik, Ludwig-Prandtl-Straße 10, W-8046 Garching.
[3] Department of Physics, Texas A & M University, College Station, TX 77843-4242.

Z. Naturforsch. **47 a**, 1175–1186 (1992); received September 22, 1992

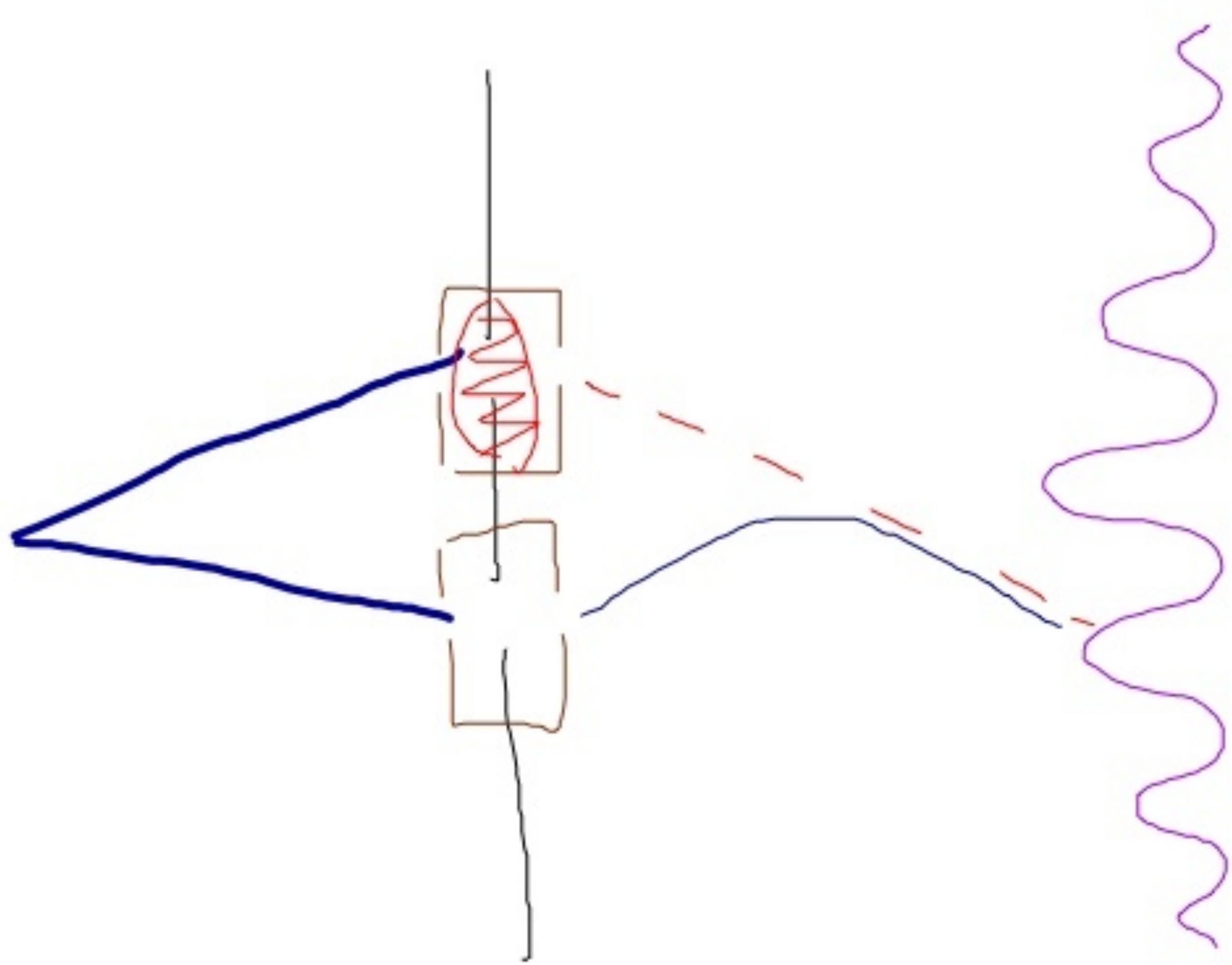
A study of interferometers with one-bit which-way detectors demonstrates that the trajectories, which David Bohm invented in his attempt at a *realistic* interpretation of quantum mechanics, are in fact *surrealistic*, because they may be macroscopically at variance with the observed track of the particle. We consider a two-slit interferometer and an incomplete Stern-Gerlach interferometer, and propose an experimentum crucis based on the latter.



Bohmian trajectories cannot cross: every particle which reaches the lower half of the interference pattern must come from the lower slit (and conversely)



Yet sometimes the upper which-path detector will fire even though the particle lands on the bottom



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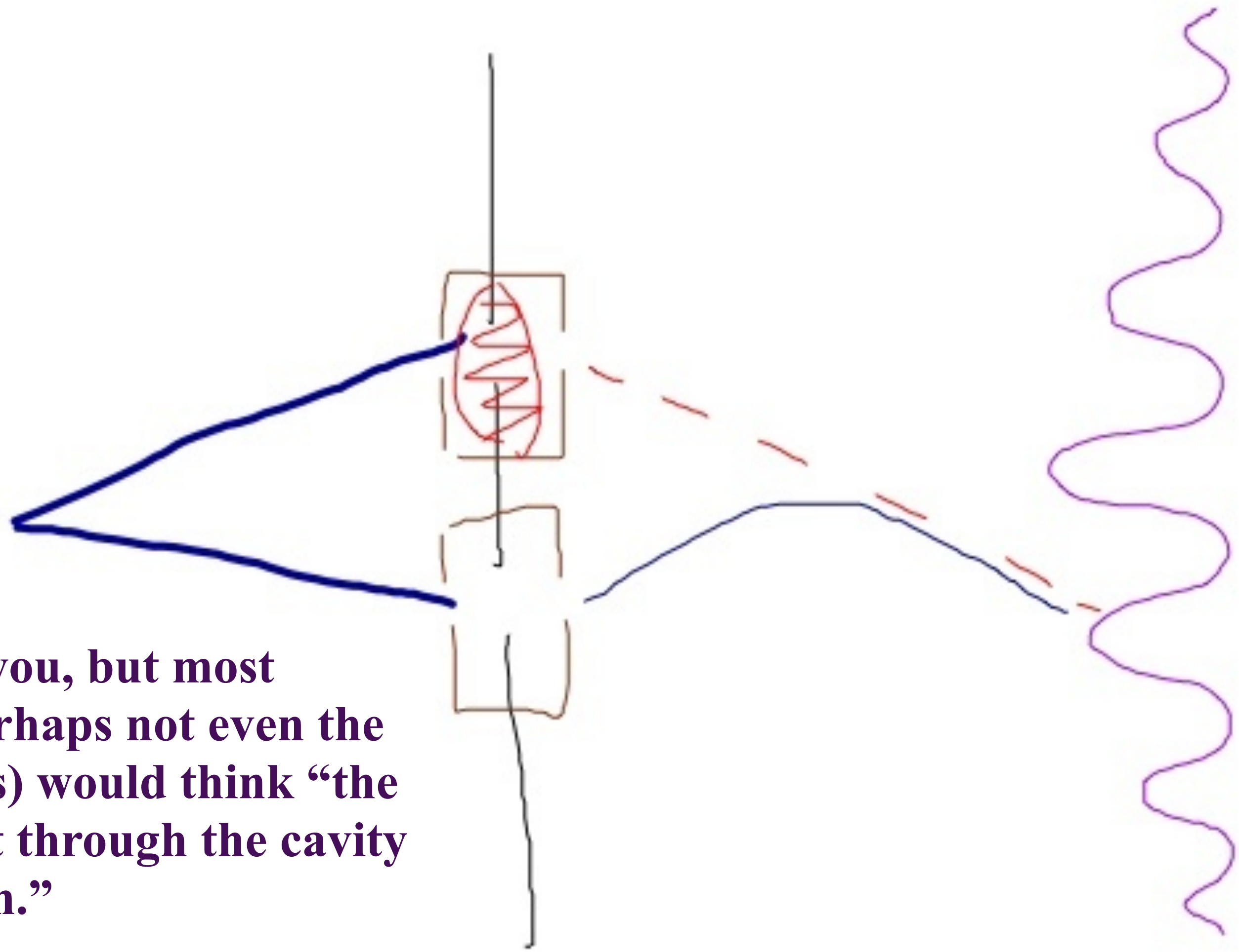

I don't know about you, but most experimentalists (perhaps not even the most naïve among us) would think "the particle 'really' went through the cavity which has the photon."

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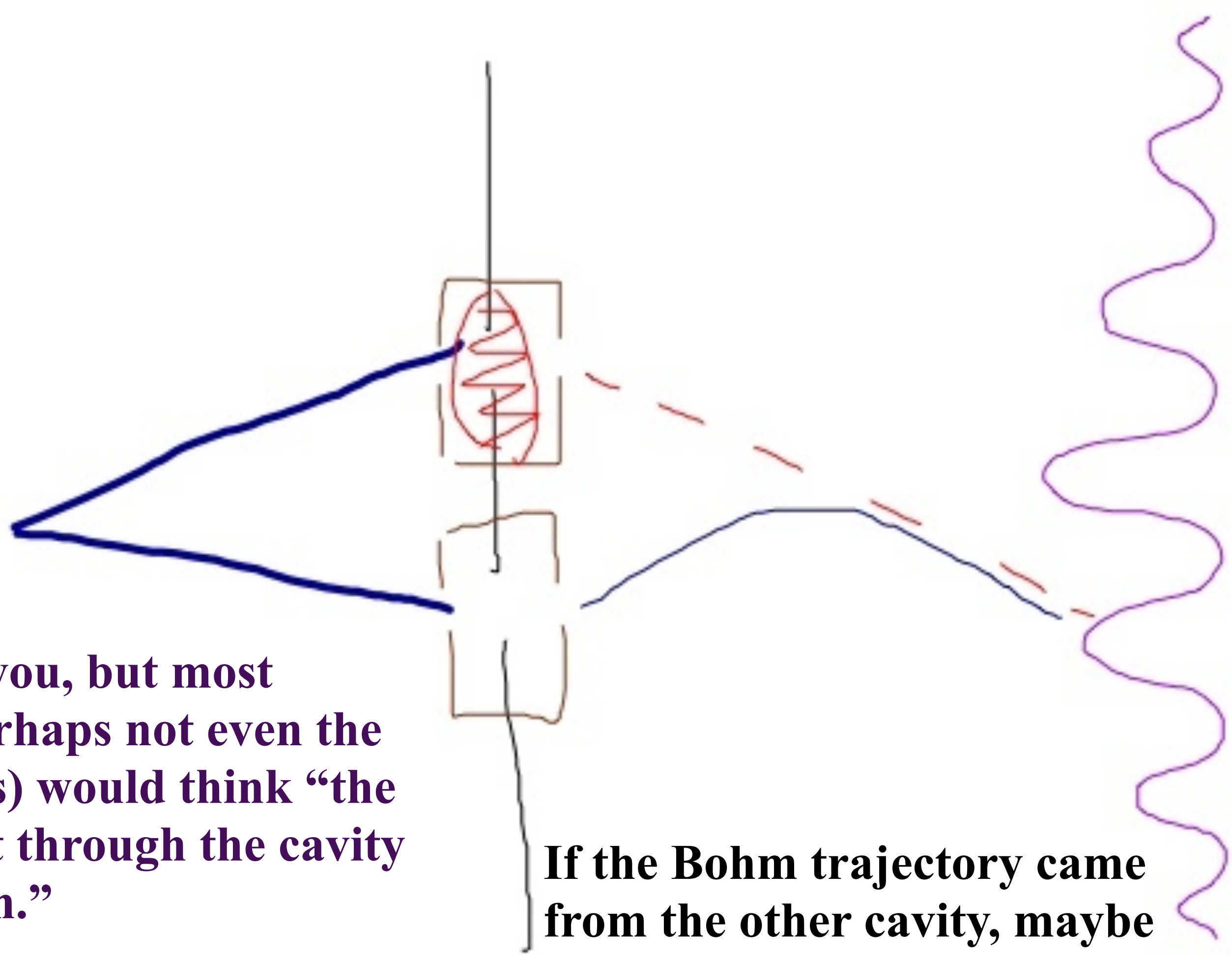
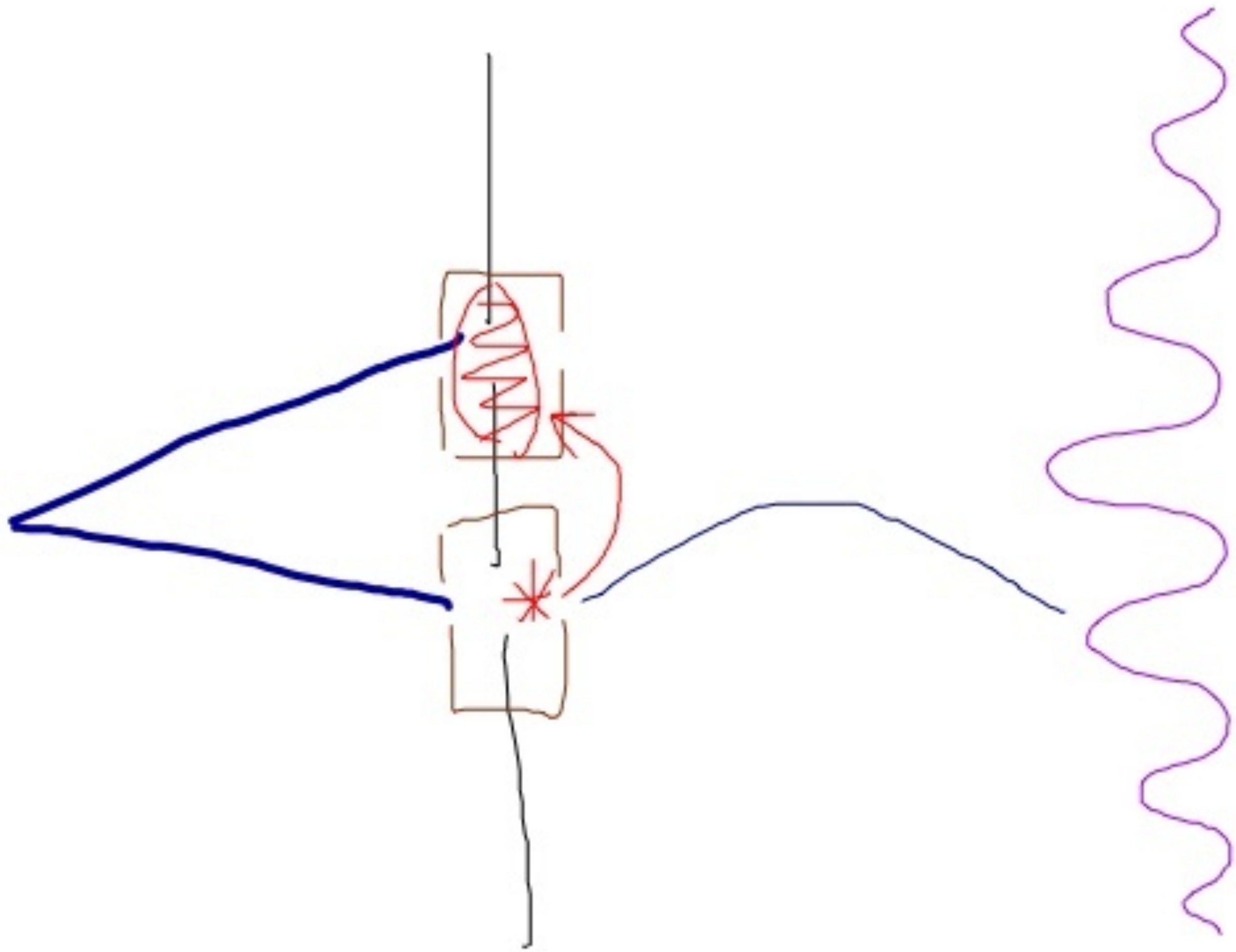


I don't know about you, but most experimentalists (perhaps not even the most naïve among us) would think "the particle 'really' went through the cavity which has the photon."

If the Bohm trajectory came from the other cavity, maybe it is not telling us about reality, but is "surreal."

BUT: 2-particle Bohmian mechanics is nonlocal.



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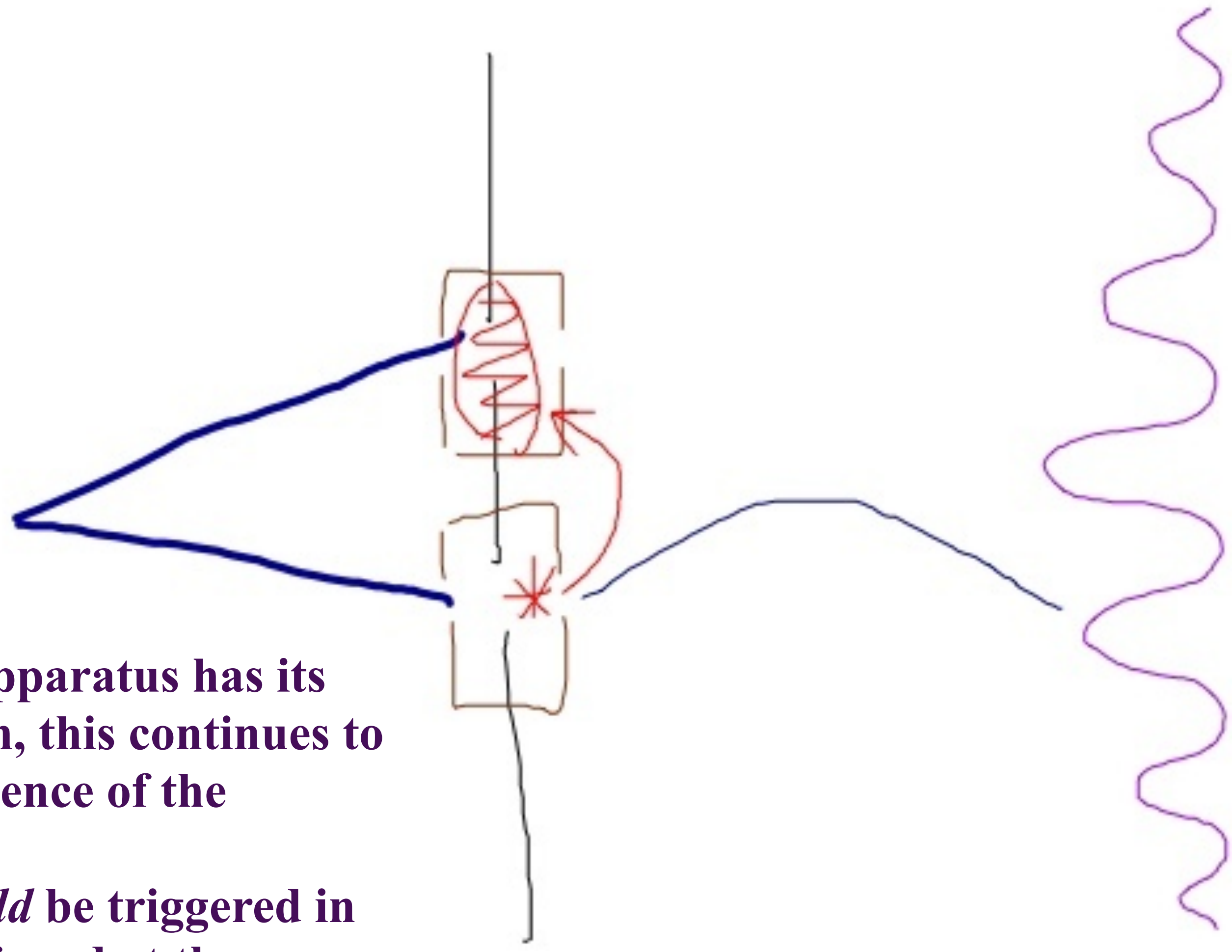

If the measurement apparatus has its own Bohmian position, this continues to evolve under the influence of the interfering particle.
The WW particle *could* be triggered in the lower slit, but be found at the upper slit at later times.

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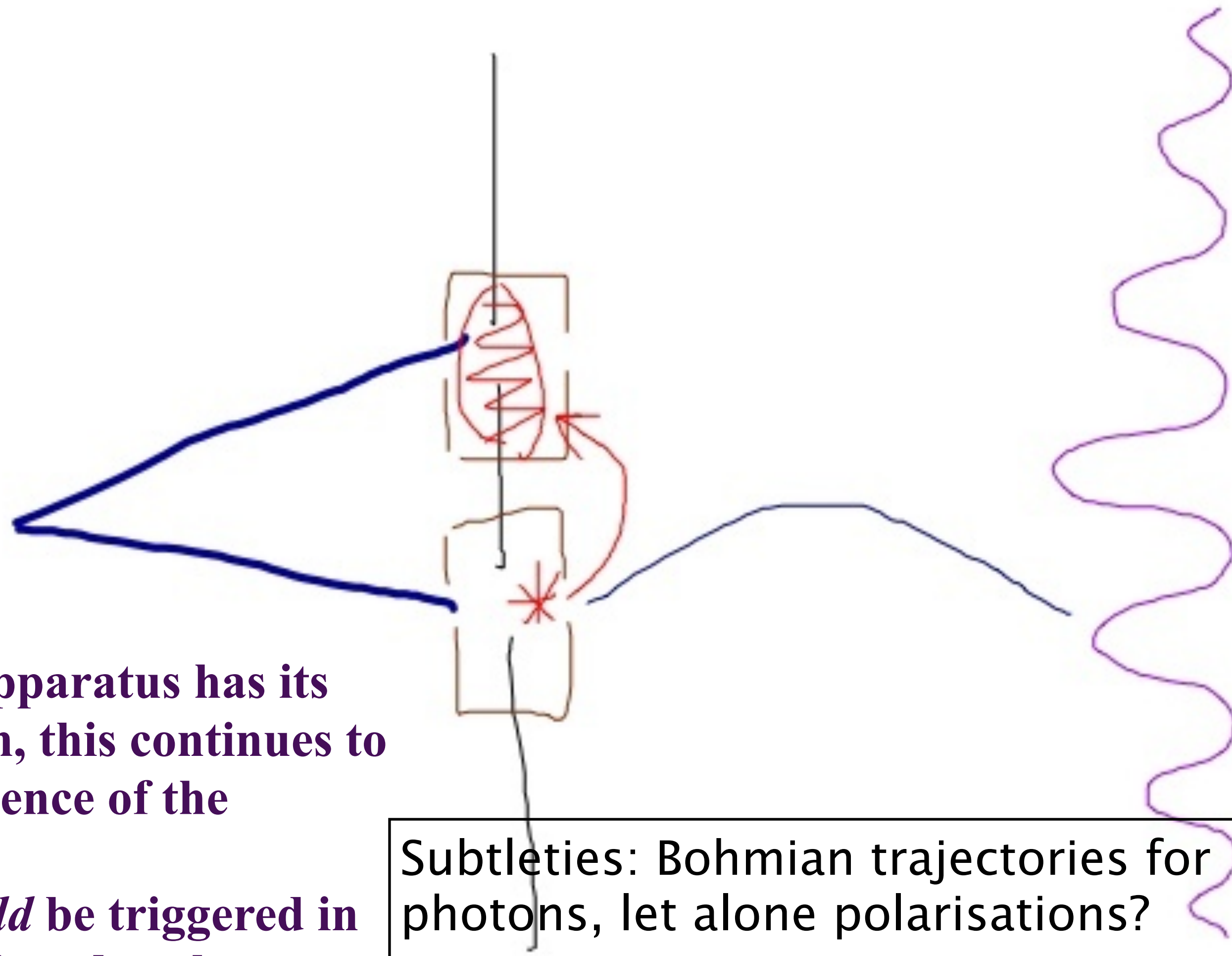

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Subtleties: Bohmian trajectories for photons, let alone polarisations?

Excuse: I'm just the naïve experimentalist. In the end, these experiments are about QM, not specifically Bohmian ...

MUCH literature & debate on this.

(Here I refer only to the papers directly relevant to the experiment we actually did, not a representative list)

Physica Scripta. Vol. T76, 41–46, 1998

Do Bohm Trajectorie
Picture of Particle M

Marlan O. Scully

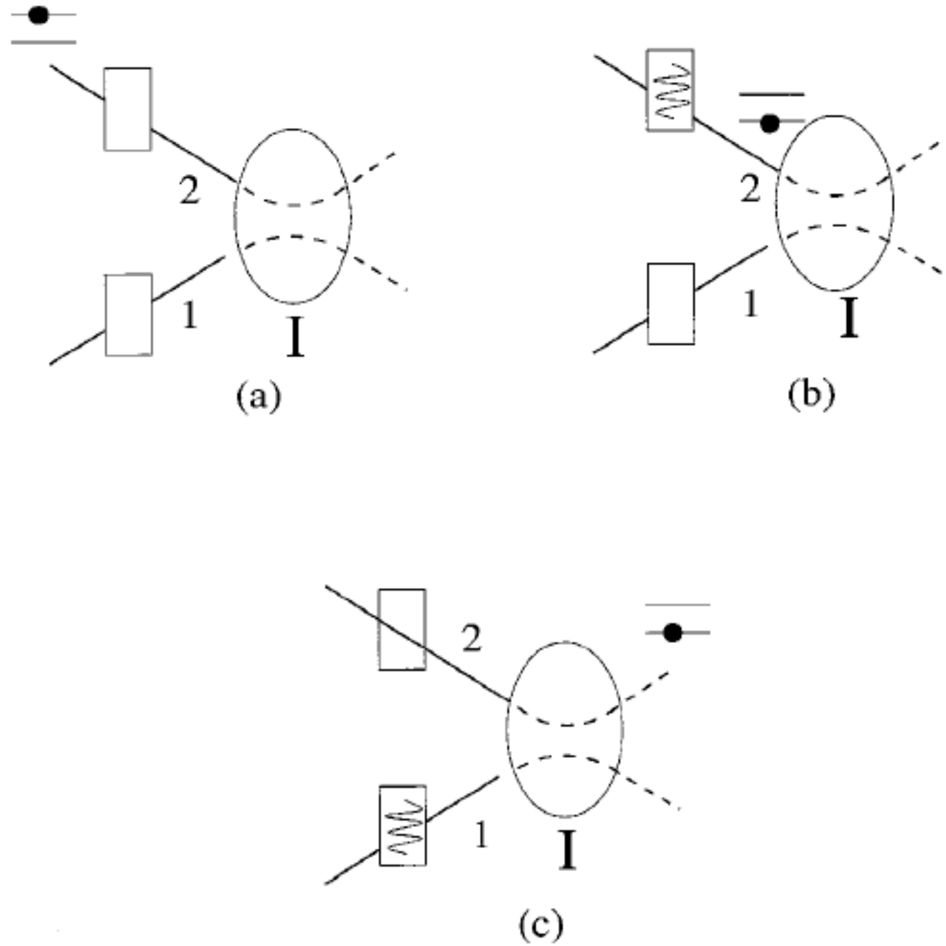

Fig. 4. Illustration of DHS nonlocality. (a) Excited atom approaching a cavity. (b) Excited atom having passed through the cavity leaves a WW photon. (c) Exiting region I, the photon is transferred to cavity one. The net result is that the photon is dynamically transferred from cavity 2 to 1 via the nonlocal interaction associated with the atom passing through region I.

MUCH literature & debate on this.

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Quantum Trajectories, Real, Surreal or an Approximation to a Deeper Process?

B. J. Hiley, R. E. Callaghan and O. J. E. Maroney.

$$\mathbf{p}_a = \nabla_{\mathbf{r}_a} S(\mathbf{r}_a, \mathbf{r}_b, t) \qquad \text{and} \qquad \mathbf{p}_b = \nabla_{\mathbf{r}_b} S(\mathbf{r}_a, \mathbf{r}_{b,t}) \tag{31}$$

This means that as the atom moves along its trajectory in the region of interference, I, the particle in the box also moves, showing that this particle is still coupled to the atom even though they are separated in space. This would then also account for why the probability

MUCH literature & debate on this.

(Here I refer only to the papers directly relevant to the experiment we actually did, not a representative list)

Braverman & Simon, Phys. Rev. Lett. 110, 060406 (2013)

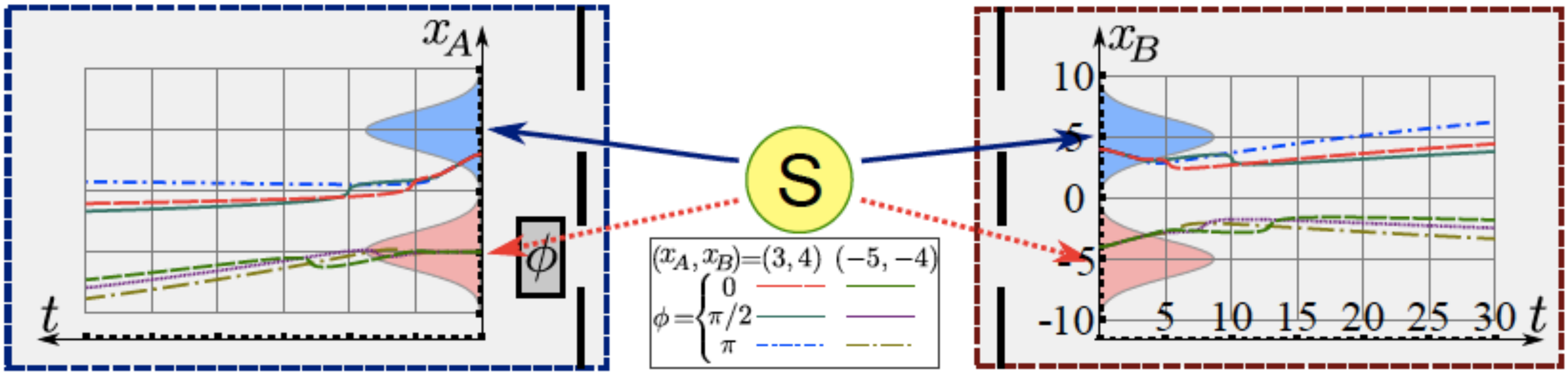
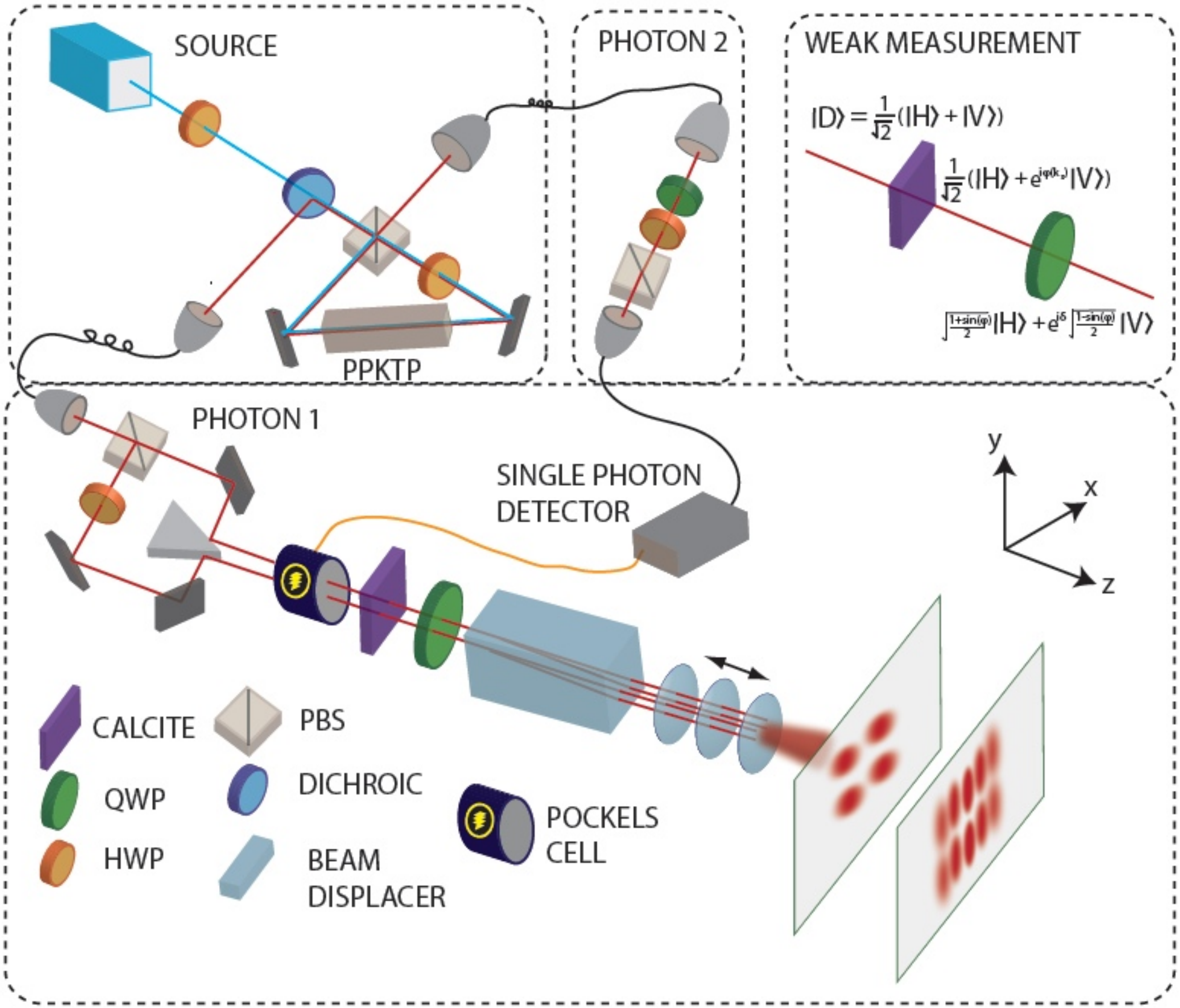
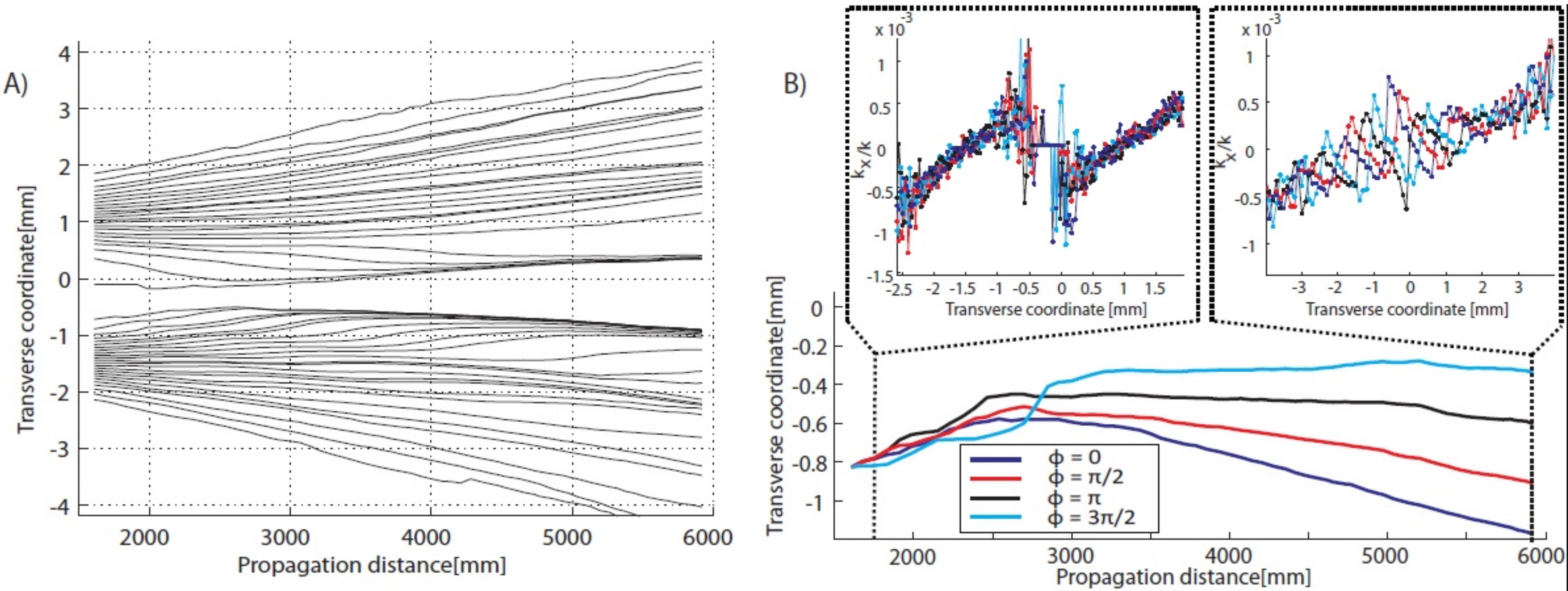


FIG. 1: Conceptual structure of the proposed experiment and calculated Bohmian trajectories. A source produces a pair of path-entangled photons such that either both photons go through the upper slits on each side or both photons go through the lower slits, see Eq. (5). A phase shift ϕ is introduced behind the slit on the left, creating the state of Eq. (6). The resulting Bohmian trajectories for photons A and B are shown for two possible starting positions, corresponding to the Bohmian particles passing through the upper or lower slits respectively, and for different values of the phase shift. One can see that the trajectory of photon B depends on ϕ, even though the phase shift is applied to photon A. This shows the highly non-local (signaling) character of Bohmian mechanics.

Extending our original average-trajectories experiment to handle (polarisation-)entangled pairs



Experimental results

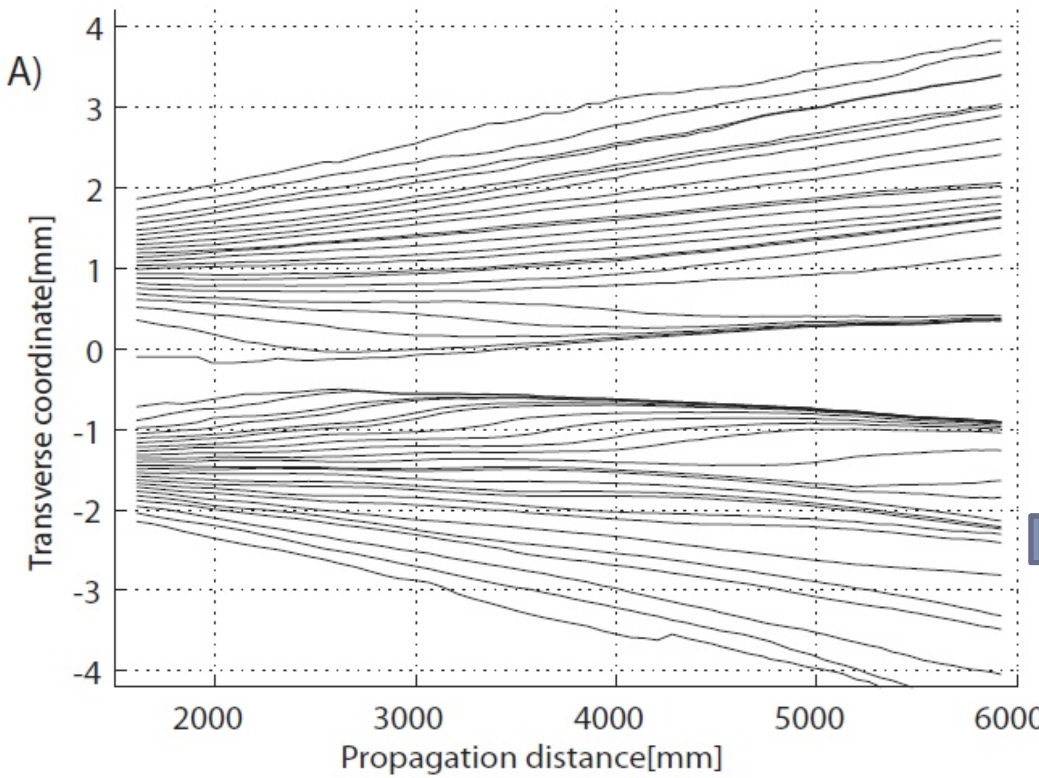


Trajectories of photon 1 when photon 2 is detected with a certain phase (in an equal superposition of "upper slit" and "lower slit" – à la Quantum Eraser).

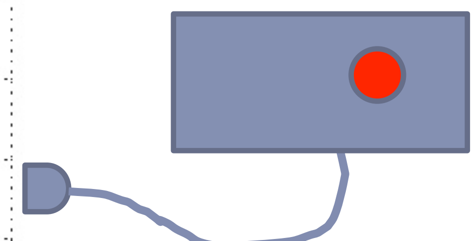
Different phases for detection of photon 2 lead to different trajectories for photon 1!

Surrealism in Bohmian Mechanics

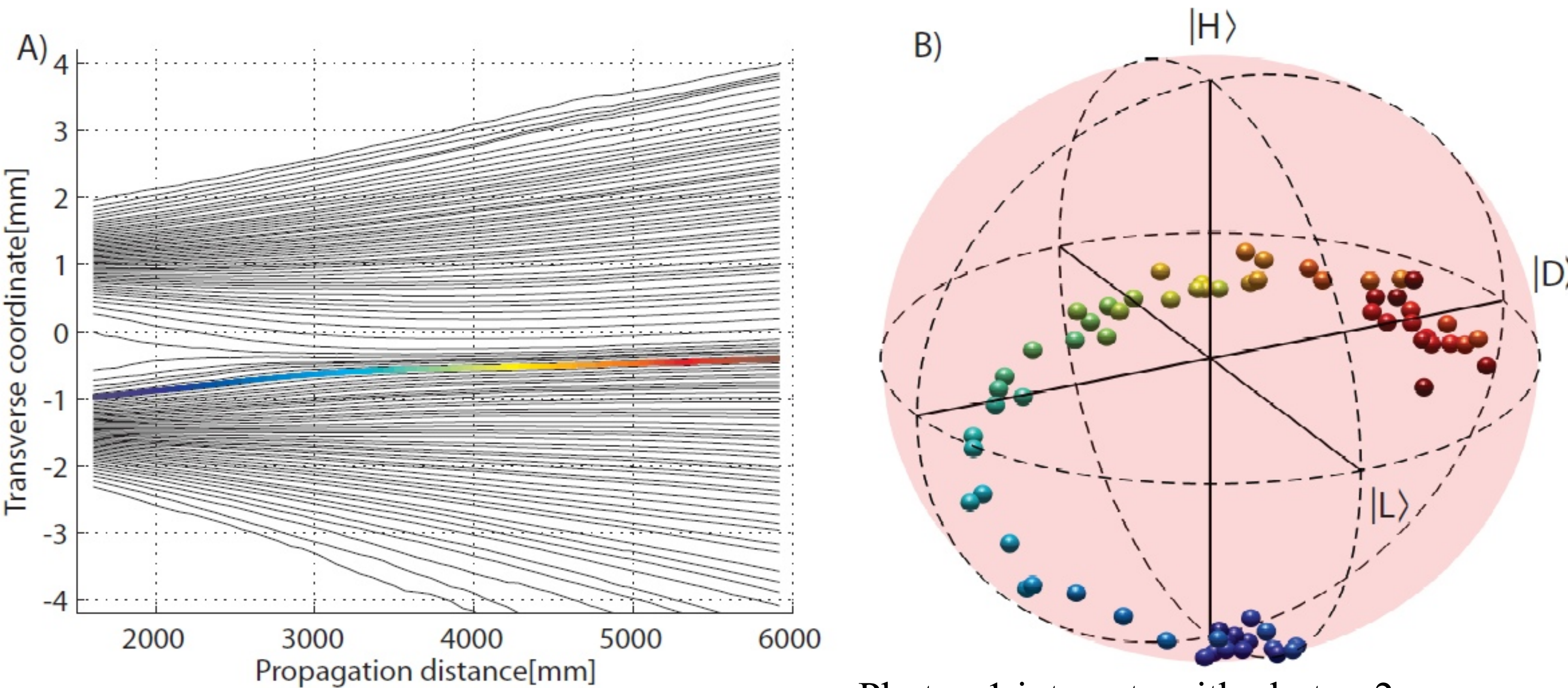
Follow our photon along one of the measured trajectories, and at each point, measure the polarisation of the other photon (the WW detector)...



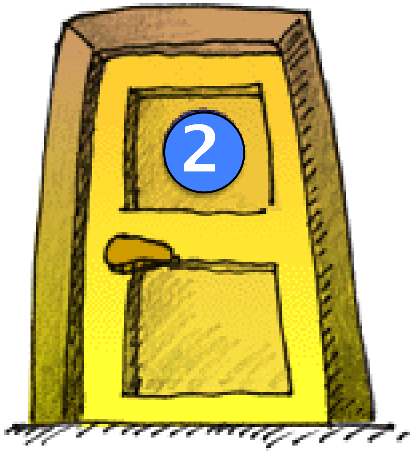
Bohmian mechanics says: when detector clicks, particle came from bottom slit!



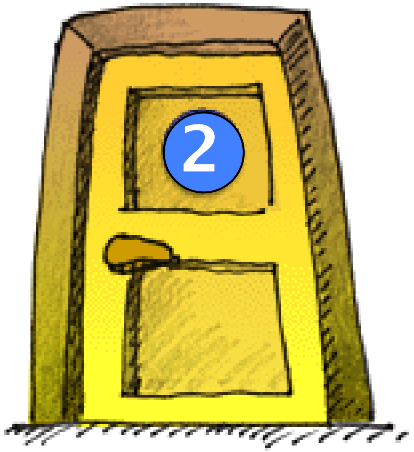
The WW device's reading *evolves* as the other photon moves along its trajectory



Photon 1 interacts with photon 2 (nonlocally!) to change the outcome of the WWM



How to count to 8 on a single photon



How to count to 8 on a single photon

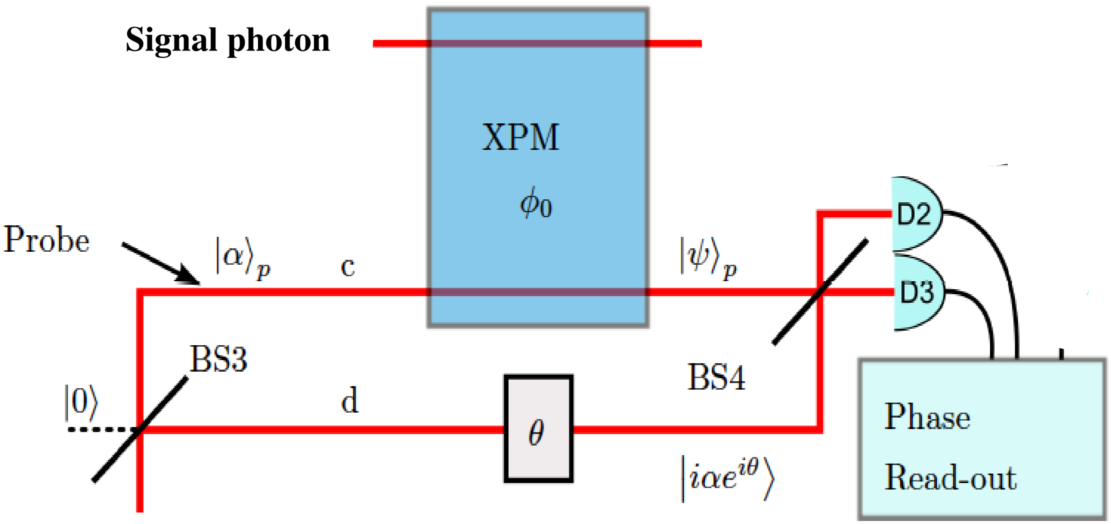
Background:

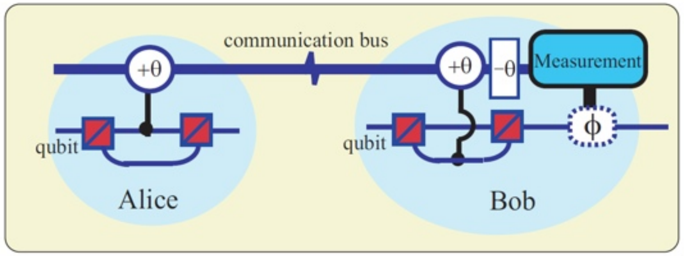
Quantum non-demolition measurements
via weak (/giant) optical nonlinearities

Motivation: quantum NLO (e.g., weak “giant nonlinearities”)

“Giant” optical nonlinearities...

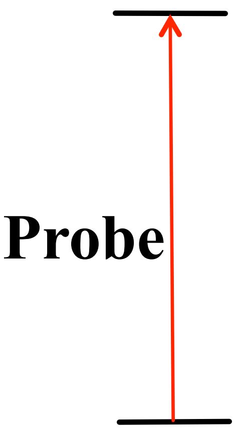
(a route to optical quantum computation [see e.g, Munro, Nemoto, Spiller, NJP 7, 137 (05)]; and in general, to a new field of *quantum nonlinear optics*
– cf. Ray Chiao, Ivan Deutsch, John Garrison)

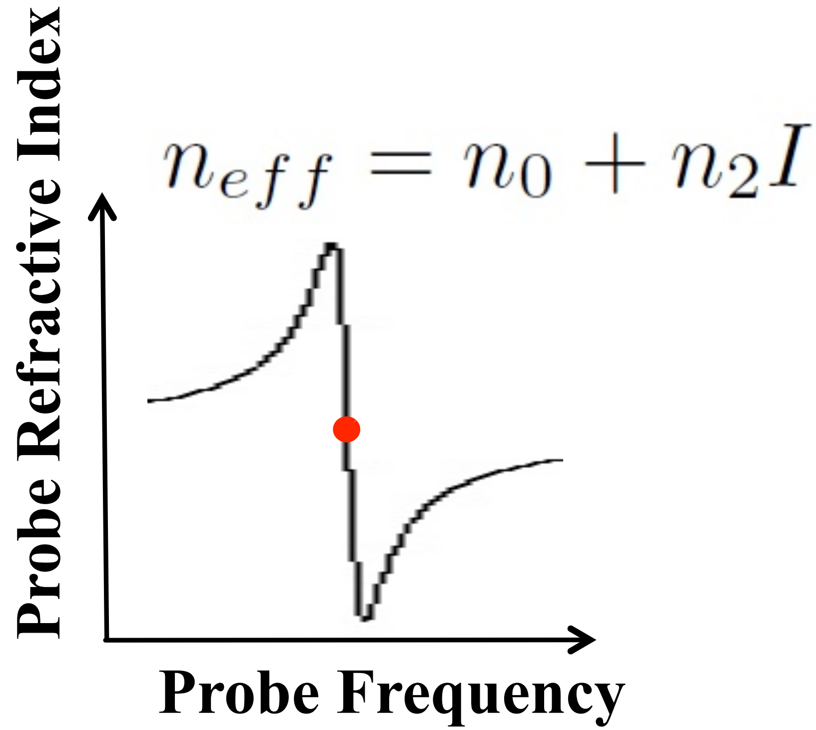




(Also of course, cf. “giant giant nonlinearities,”
e.g., Lukin & Vuletic with Rydberg atoms; Jeff Kimble *et al.* on nanophotonic approaches;
Gaeta Rb in hollow-core fibres; et cetera)

Cross-phase modulation (XPM)





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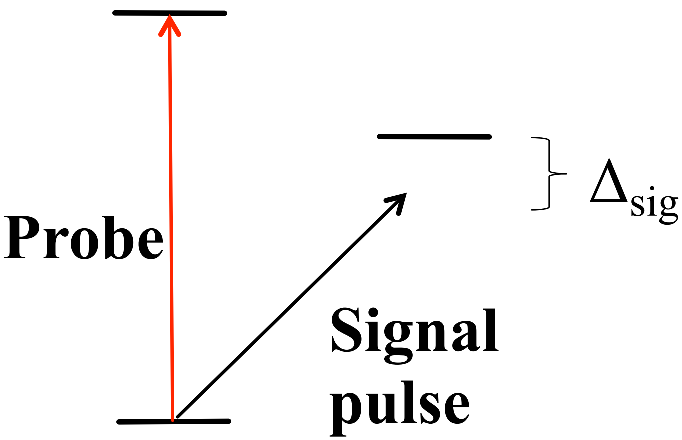

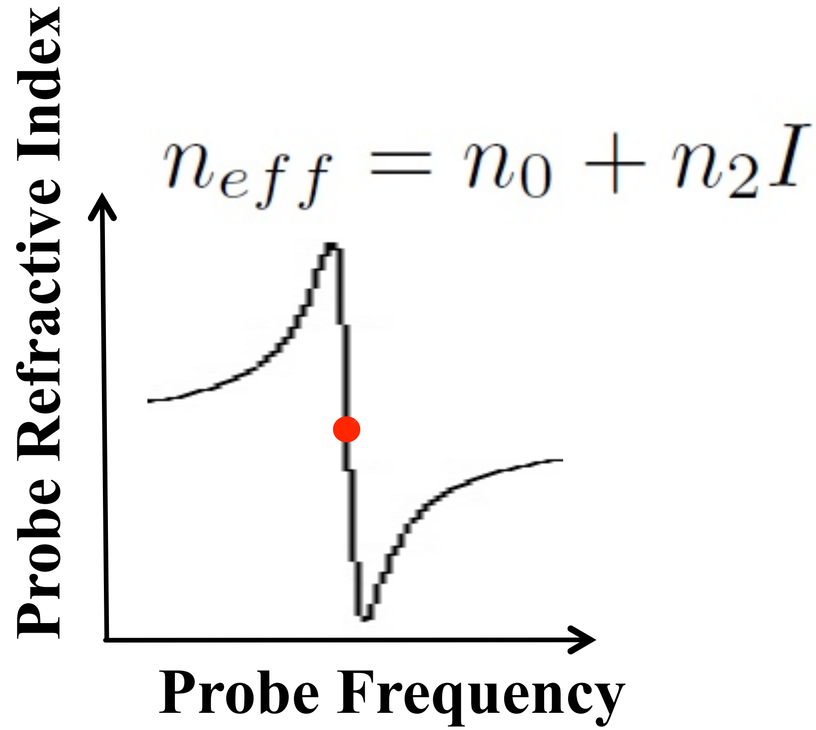

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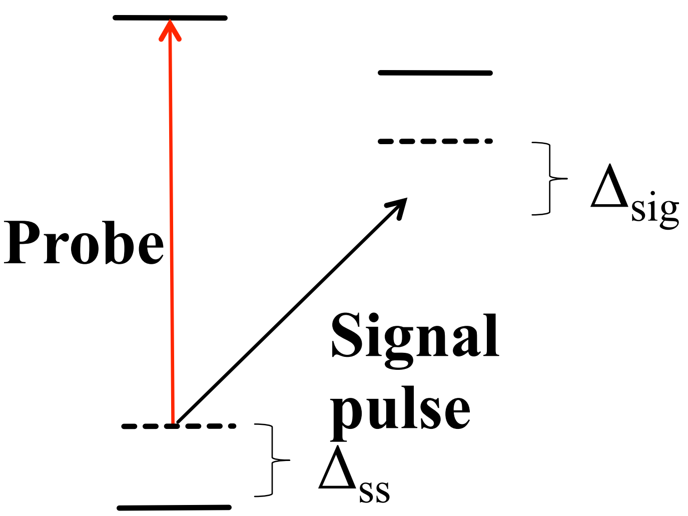

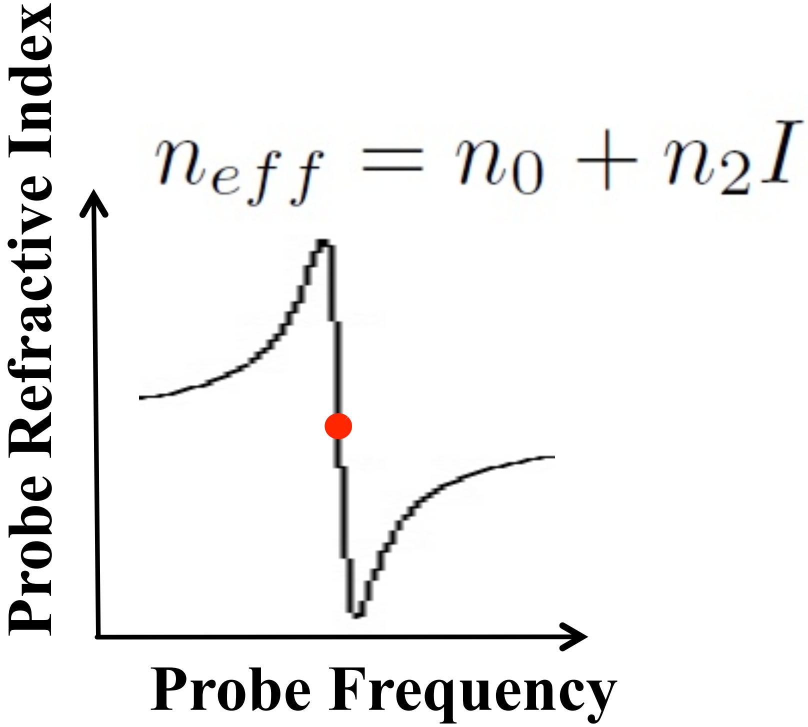

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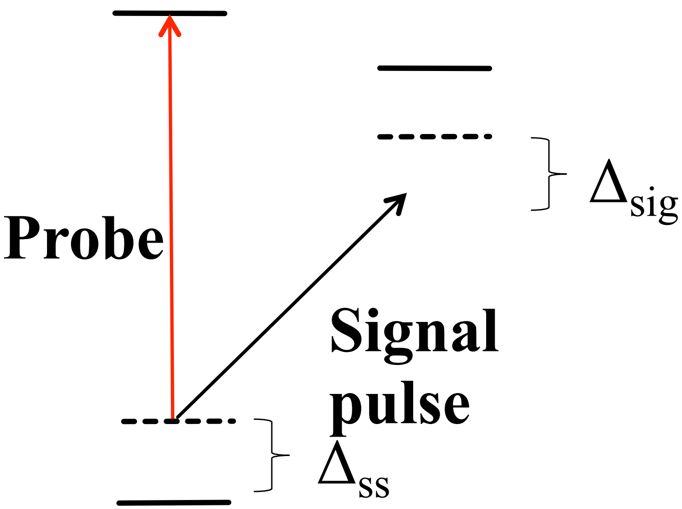

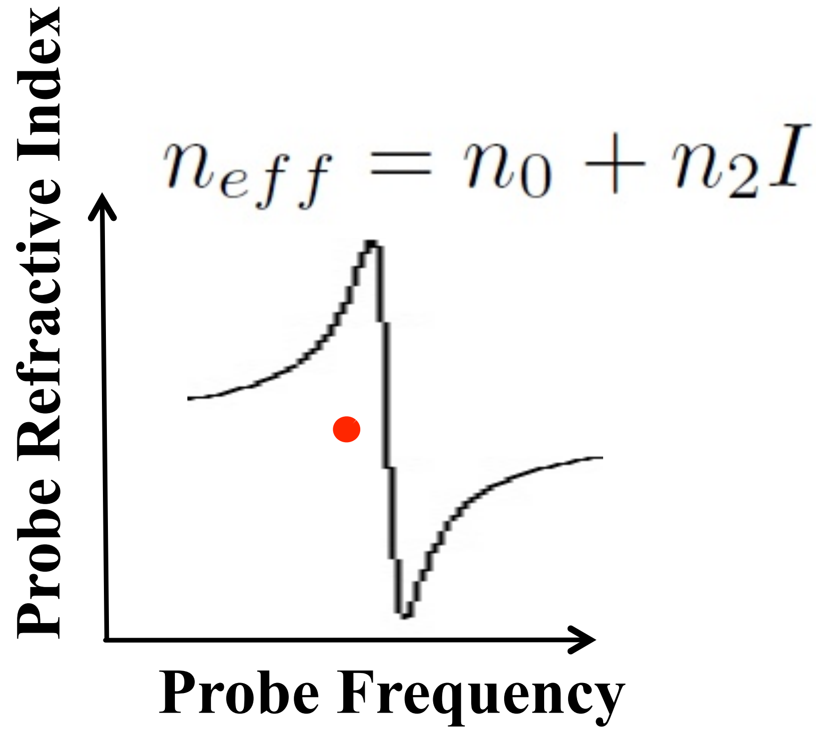

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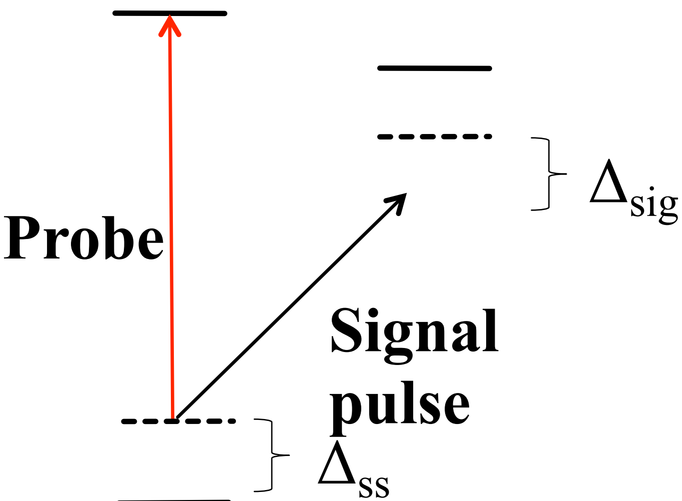

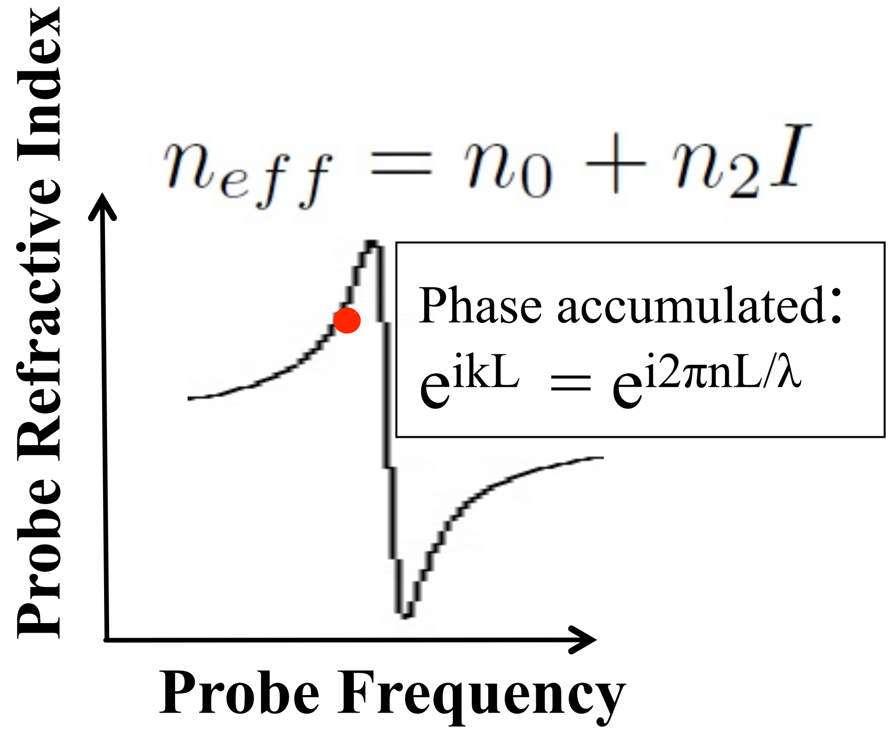

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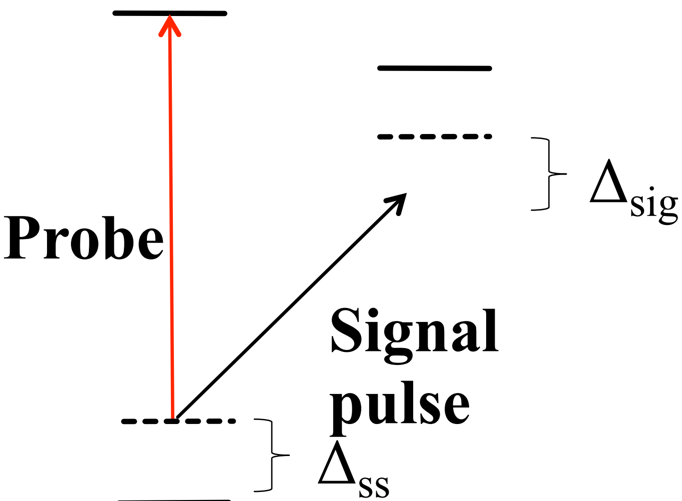
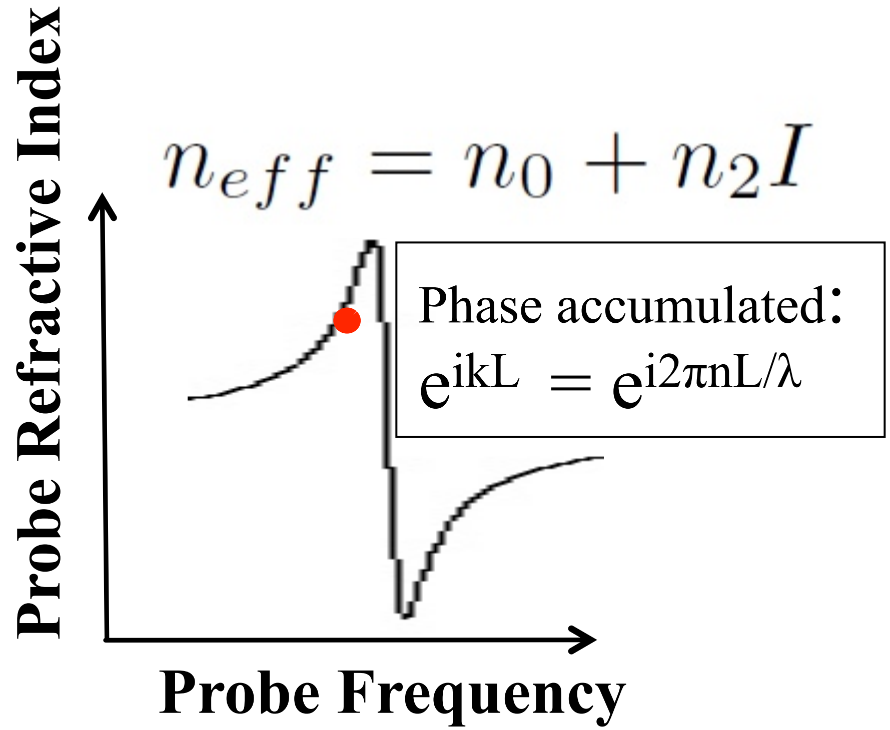
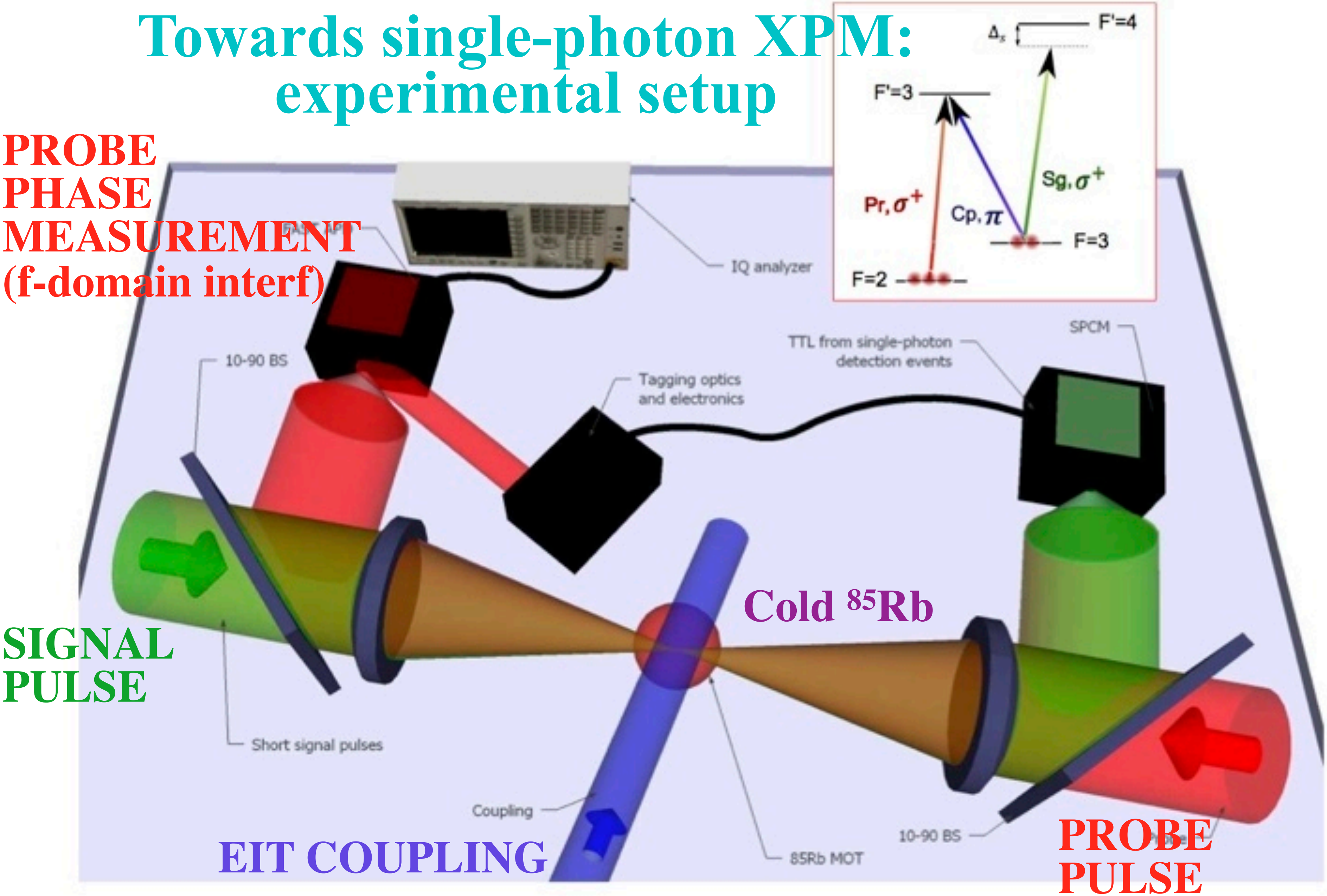




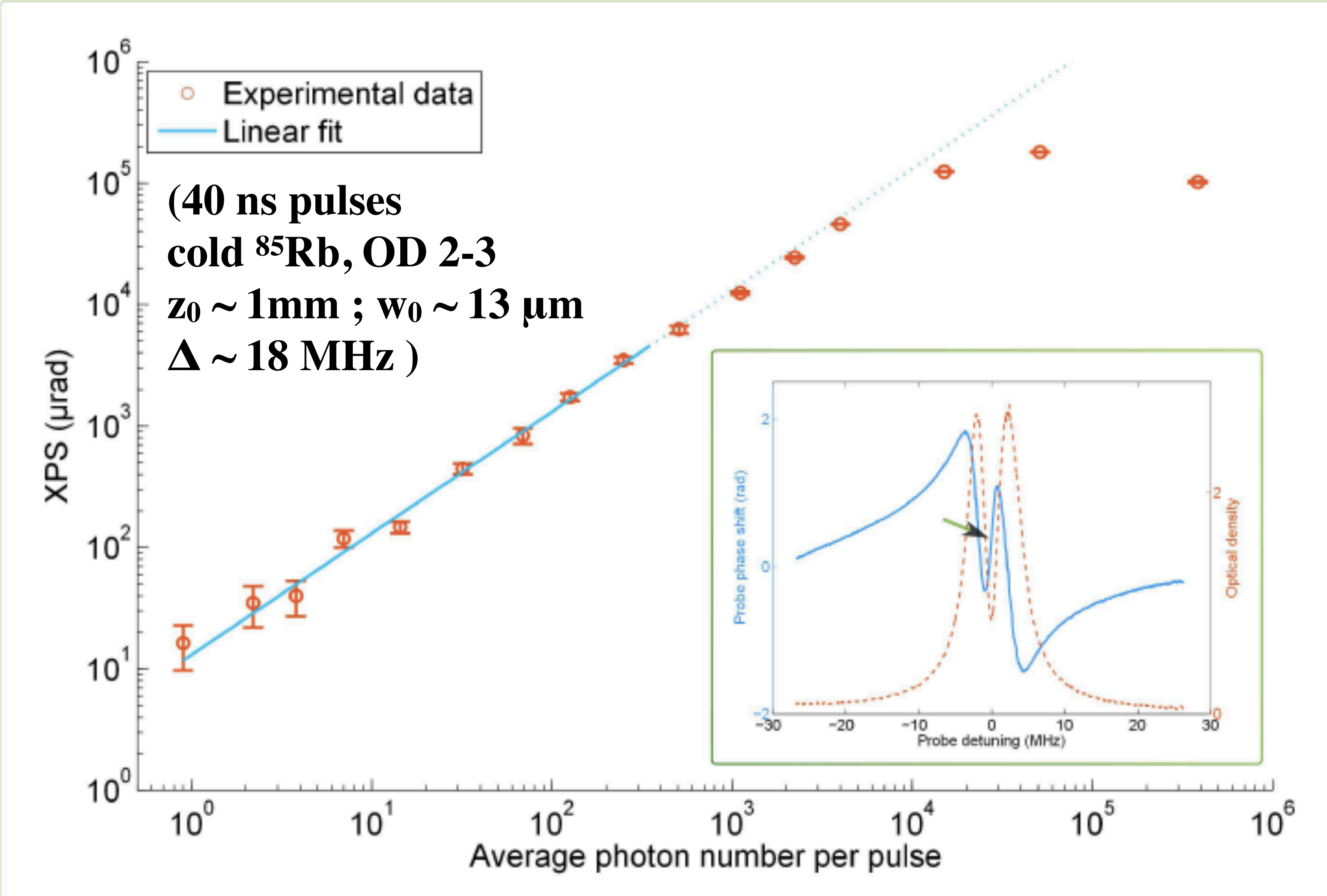
AC Stark shift changes effective detuning, changing index of refraction experienced by probe

Towards single-photon XPM: experimental setup

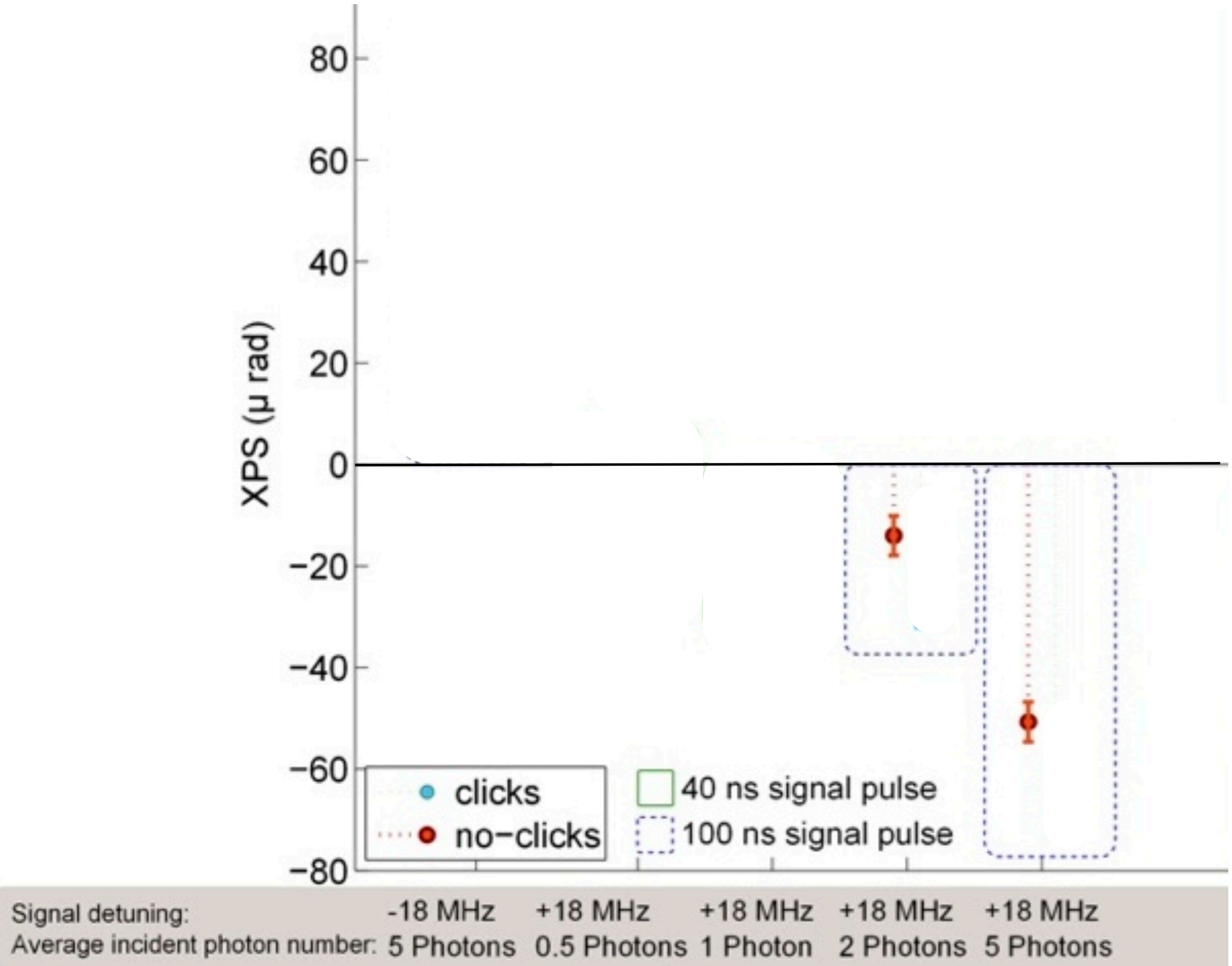


A. Feizpour et al., Nature Physics, DOI: 10.1038/nphys3433 (2015)

Measurement of cross phase shift, down to signal pulses with <n> = 1



Non-linear phase shift due to single photons



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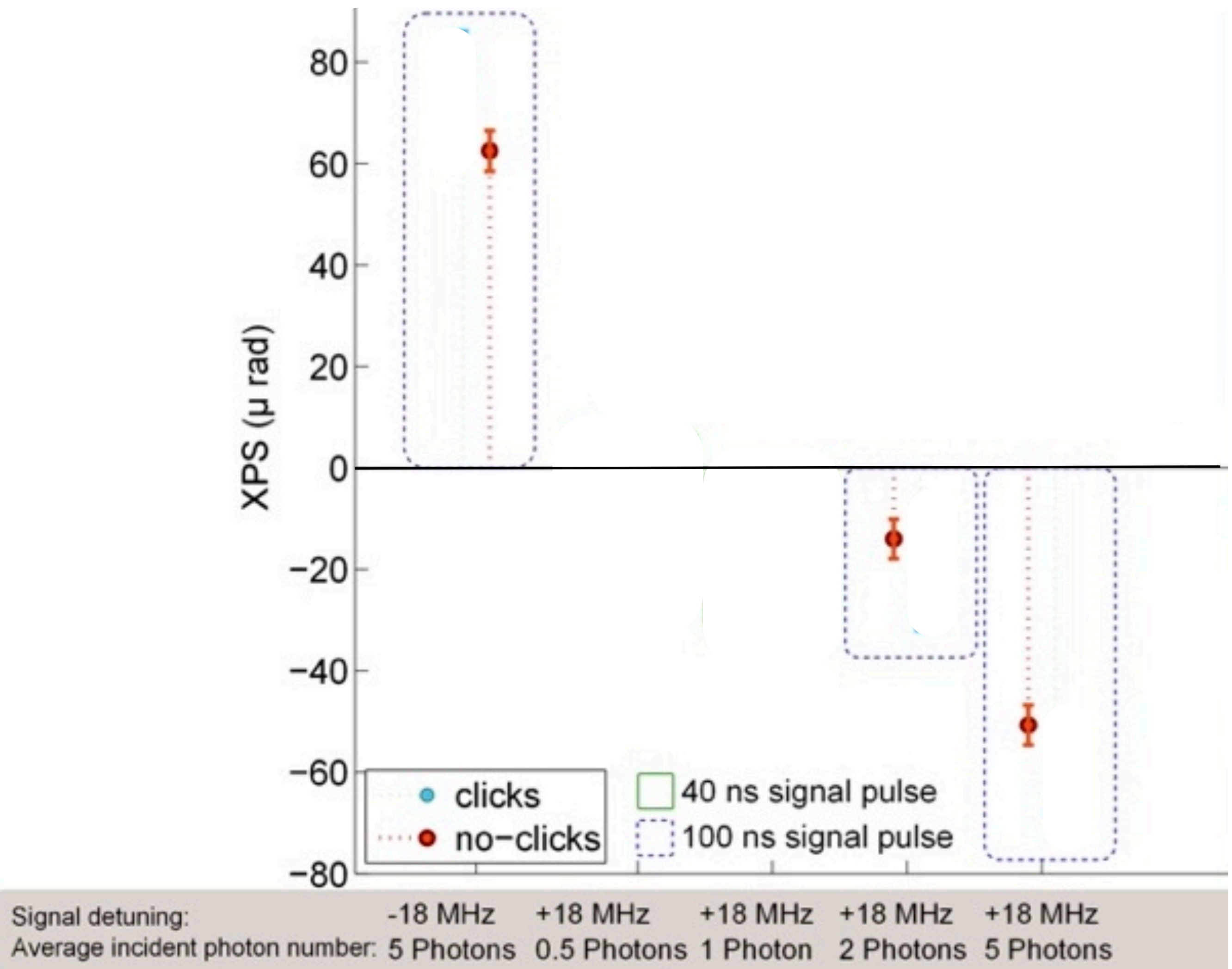
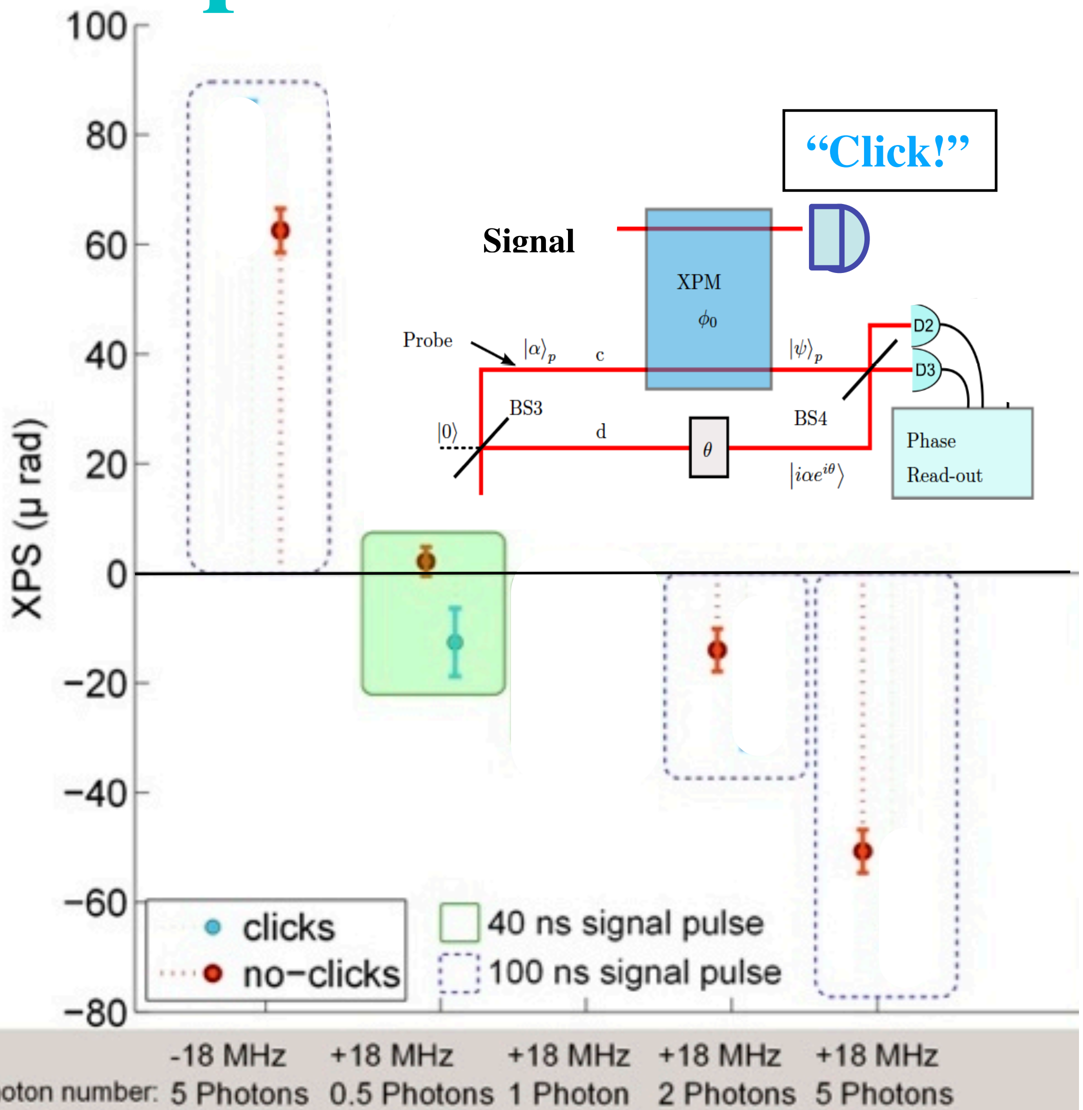


Non-linear phase shift due to a single post-selected photon



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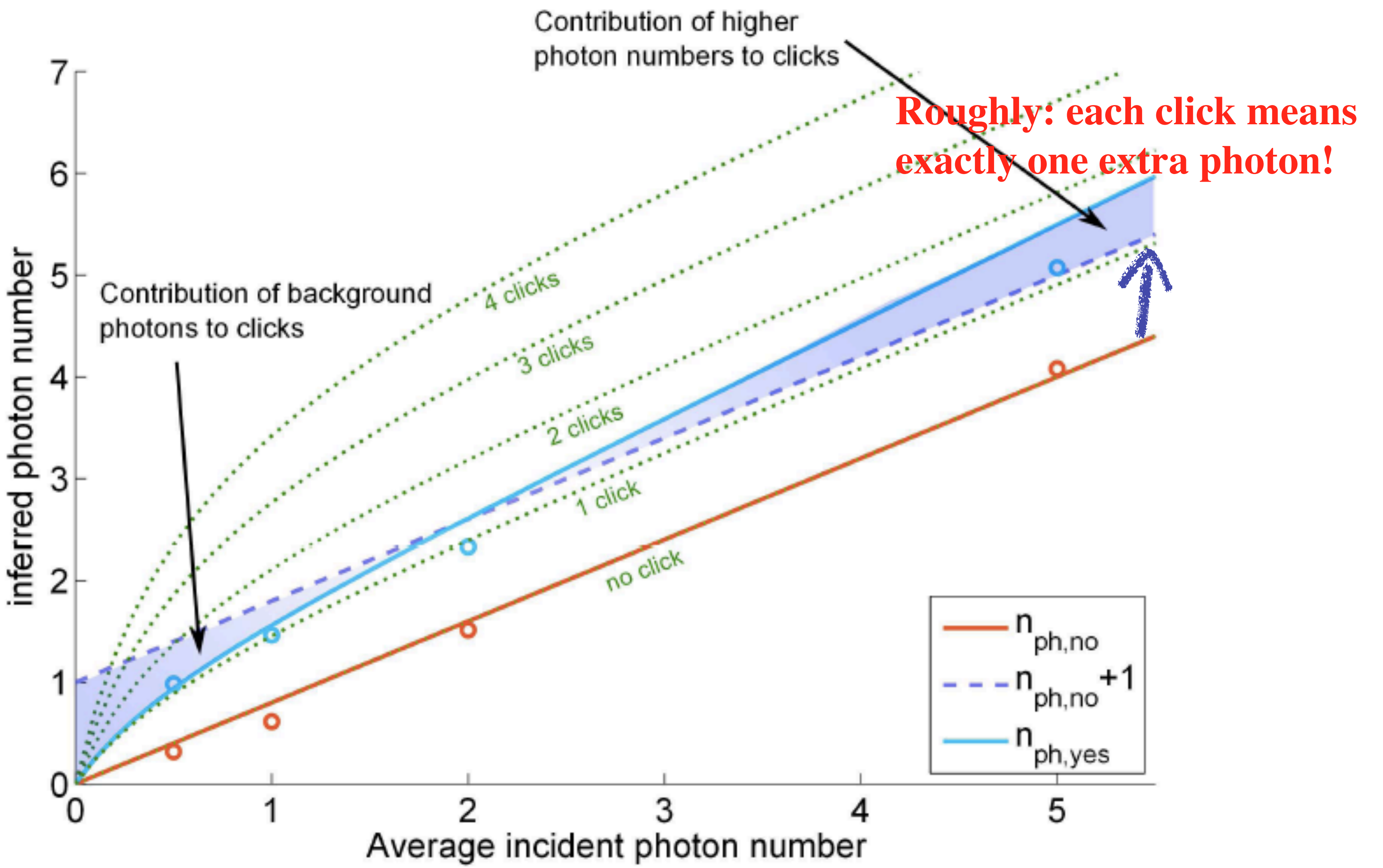

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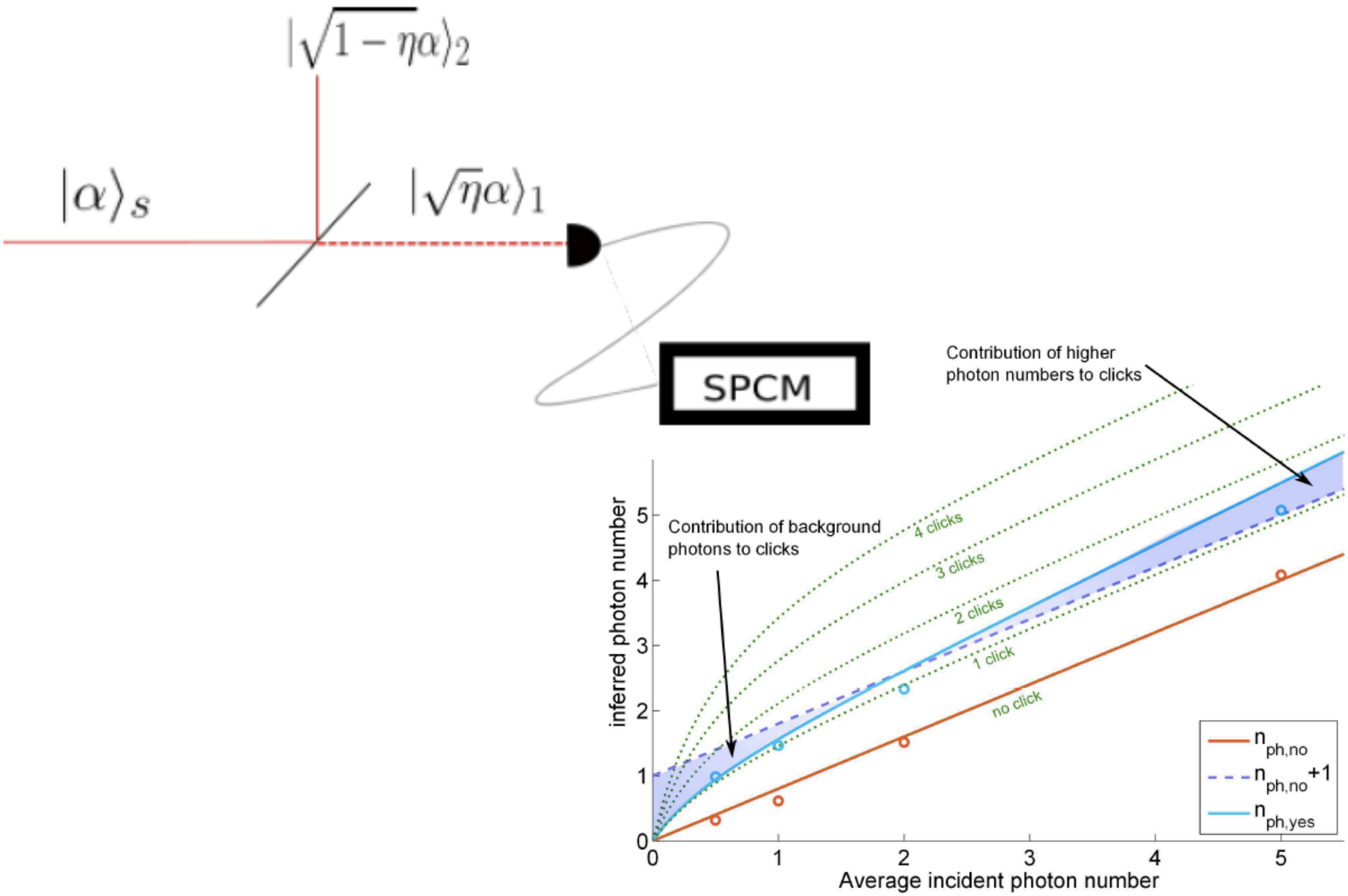

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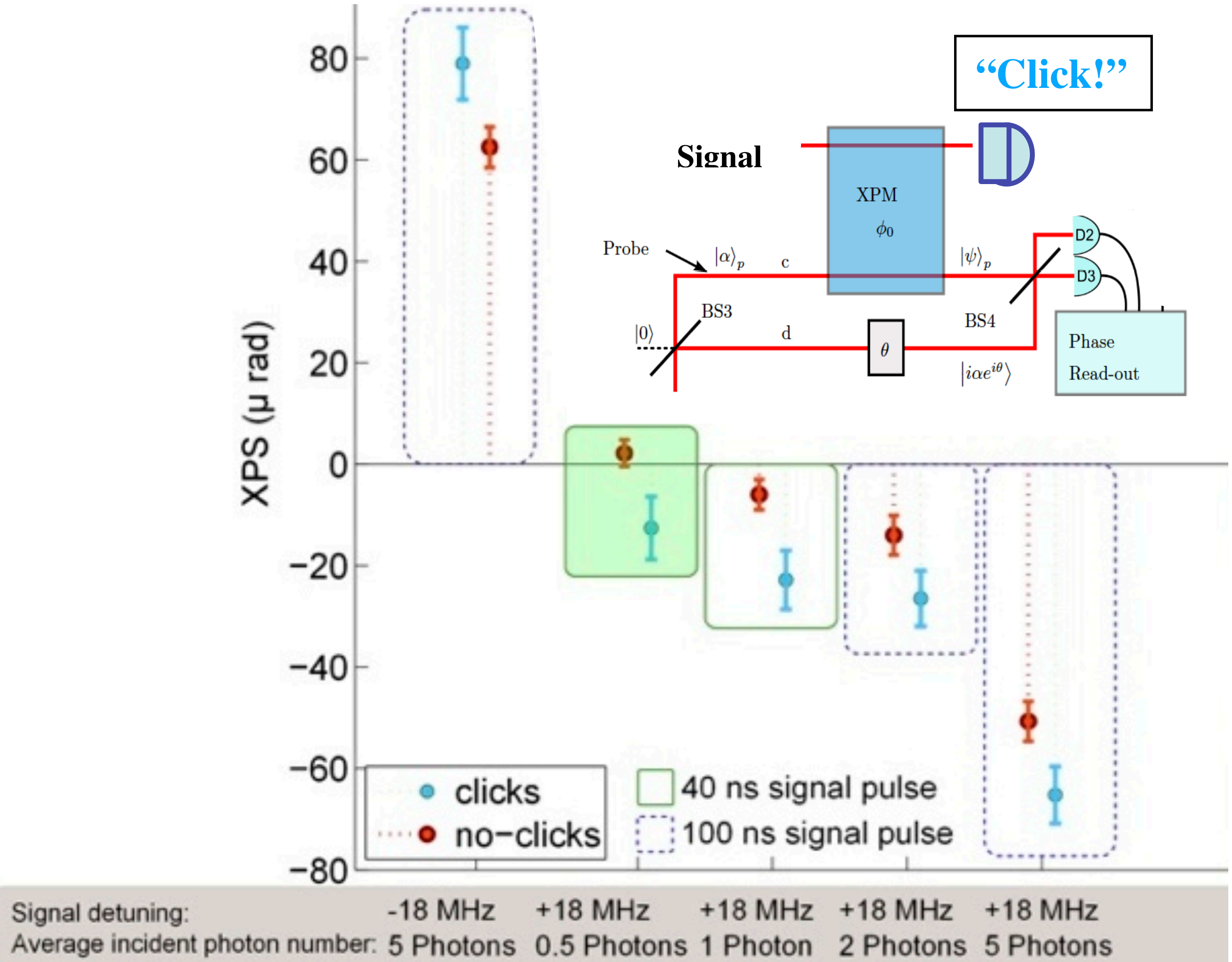

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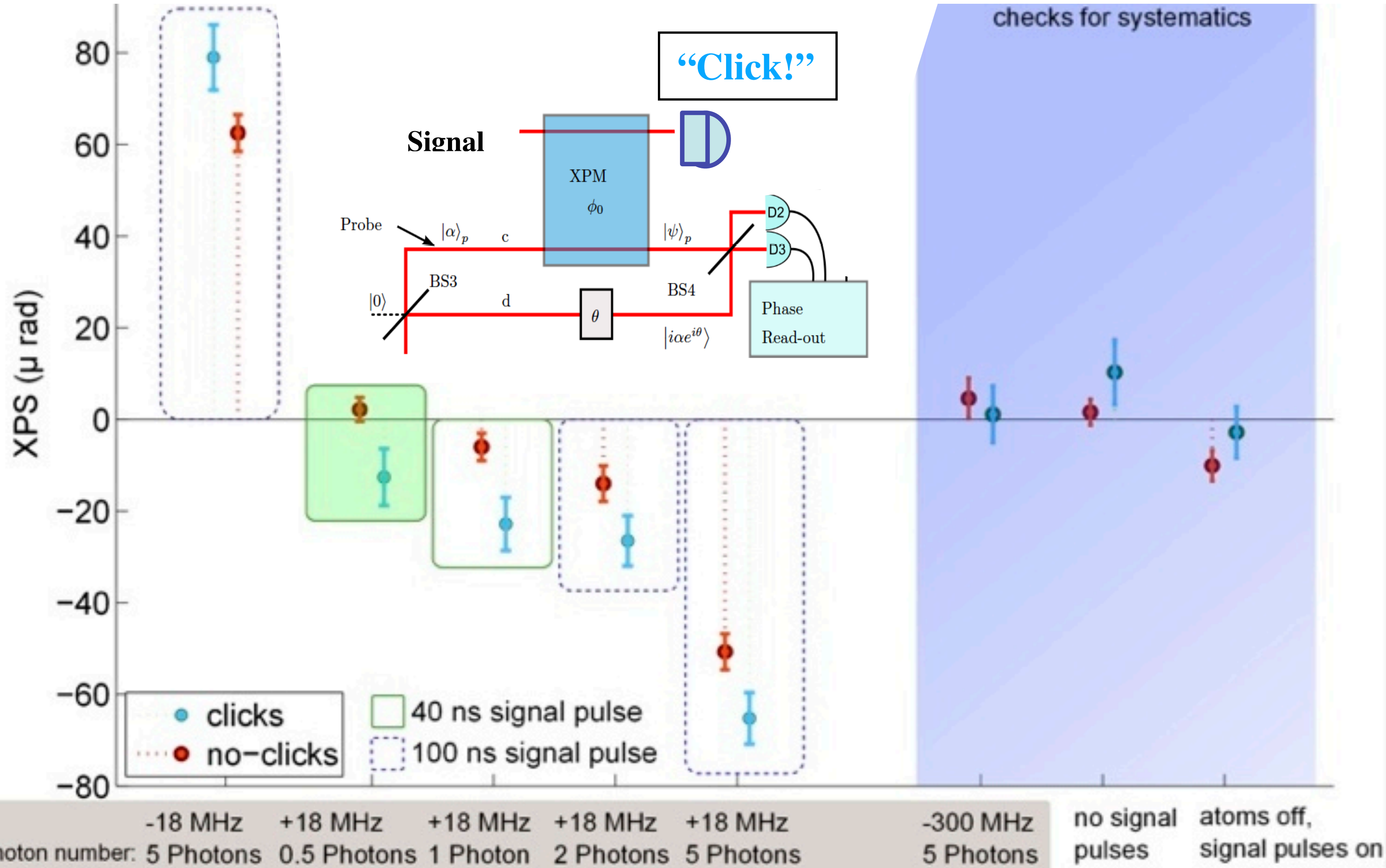

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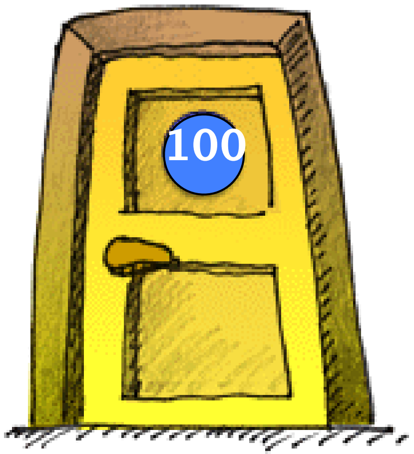
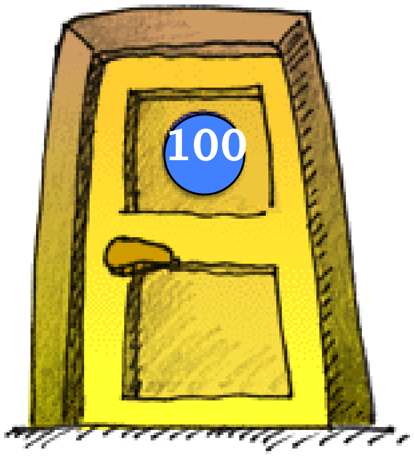


Can a single photon have the effect of 100 photons?



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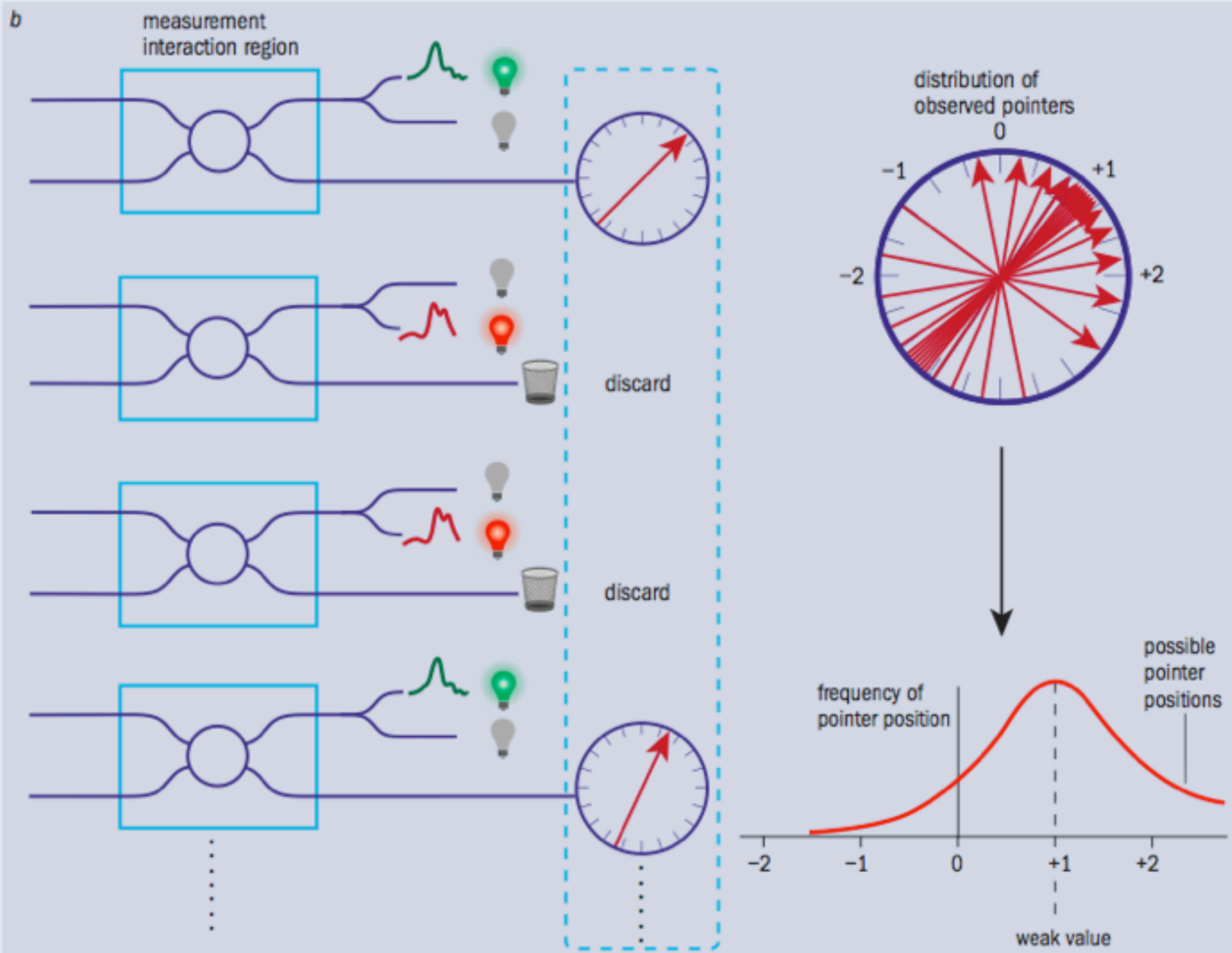
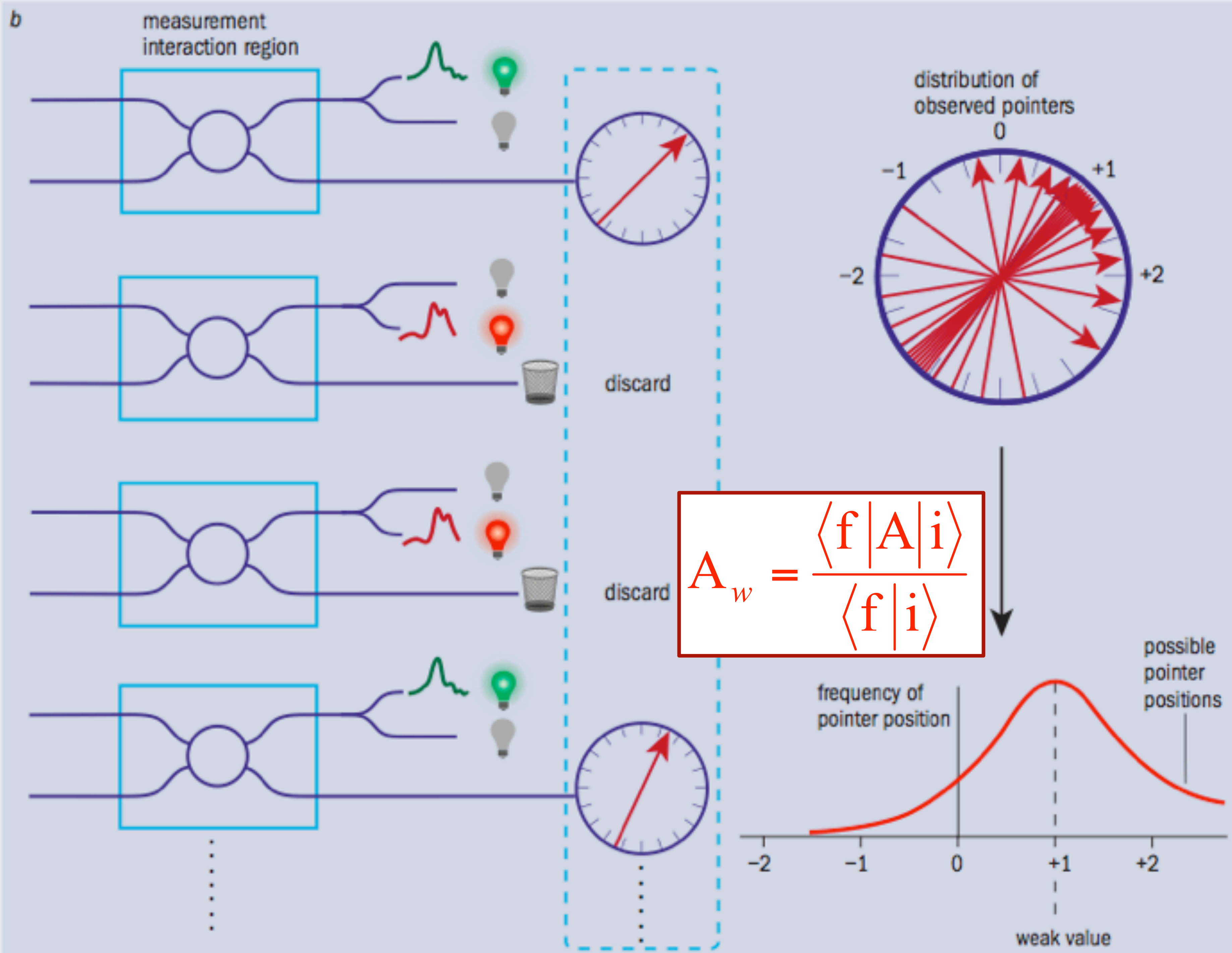

b
measurement interaction region
discard
discard
distribution of observed pointers
0
−1
+1
−2
+2
frequency of pointer position
possible pointer positions
−2
−1
0
+1
+2
weak value



$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

Aharonov, Albert, & Vaidman, PRL 60, 1351 (1988)

IBER 14 PHYSICAL REVIEW LETTERS

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

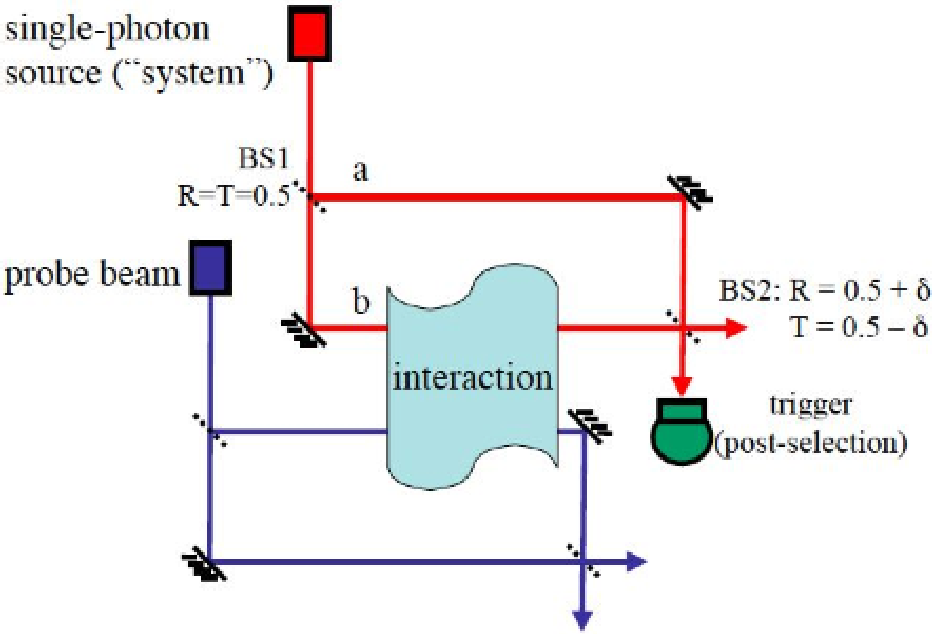
Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel

(Received 30 June 1987)

$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

may be very big if the postselection is very unlikely (<f|i> very small)...

How the result of the measurement of the number of 1 photon can be 100



<u>Weak Measurement Amplification of Single-Photon Nonlinearity</u>,
Amir Feizpour, Xingxing Xing, and Aephraim M. Steinberg
Phys Rev Lett 107, 133603 (2011)

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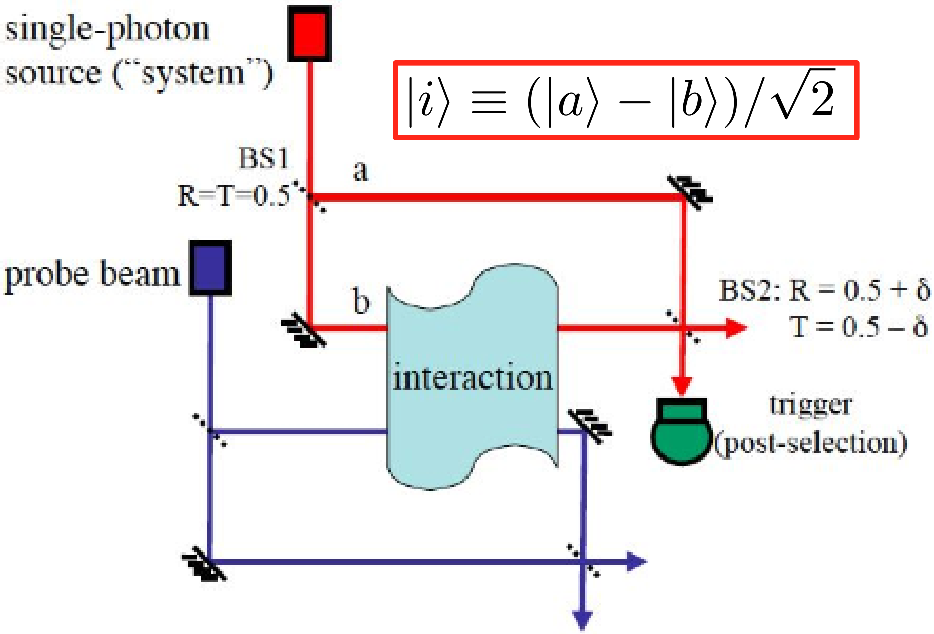

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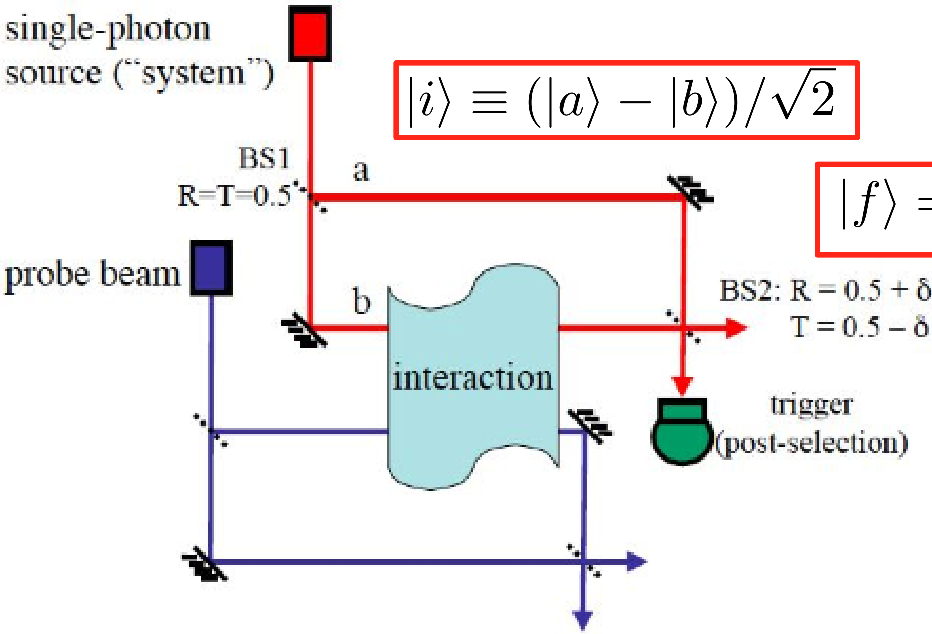

$$|i\rangle \equiv (|a\rangle - |b\rangle)/\sqrt{2}$$

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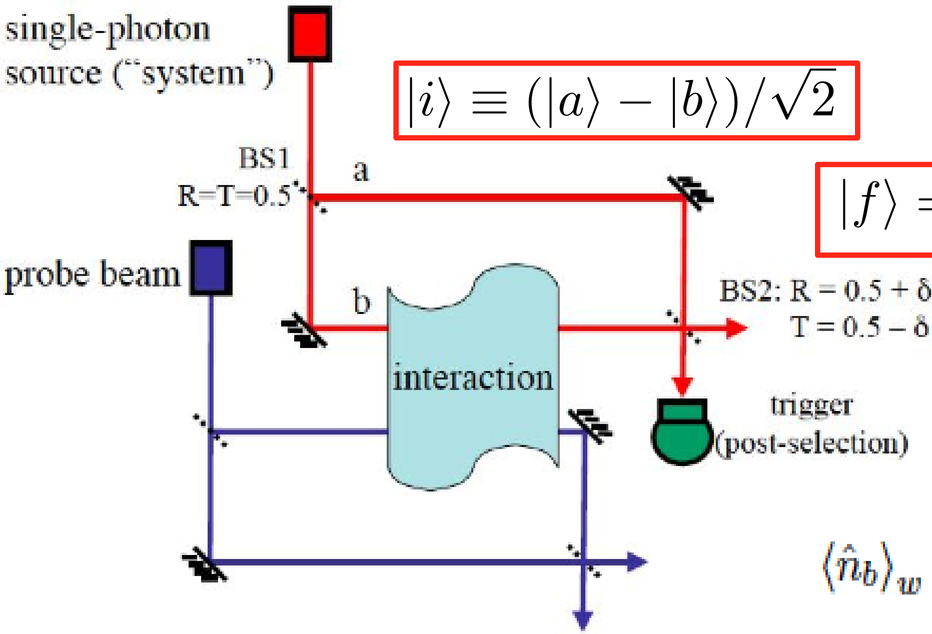

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$$\langle \hat{n}_b \rangle_w = \frac{\langle f|\,\hat{n}_b\,|i\rangle}{\langle f|\,i\rangle} = \frac{t/\sqrt{2}}{(t-r)/\sqrt{2}} = \frac{(1+\delta)/2}{\delta} \simeq \frac{1}{2\delta}\,.$$

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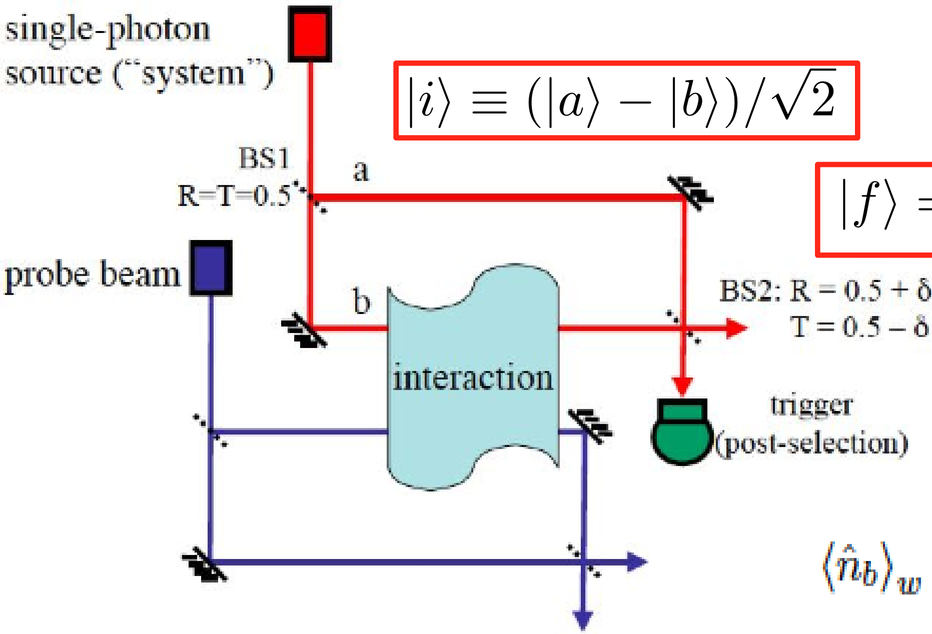

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$\langle n \rangle_w$ may be >> 1.

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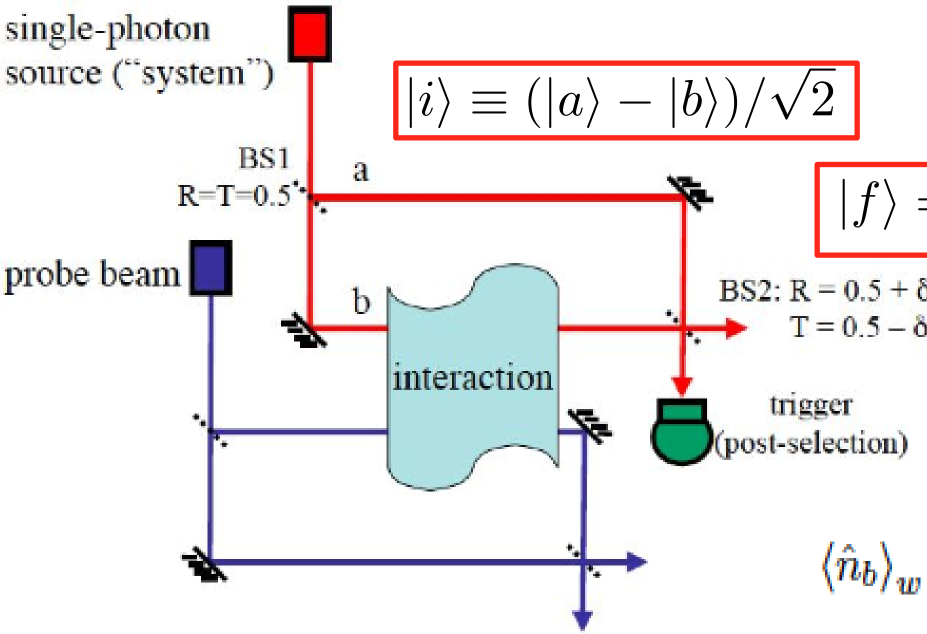

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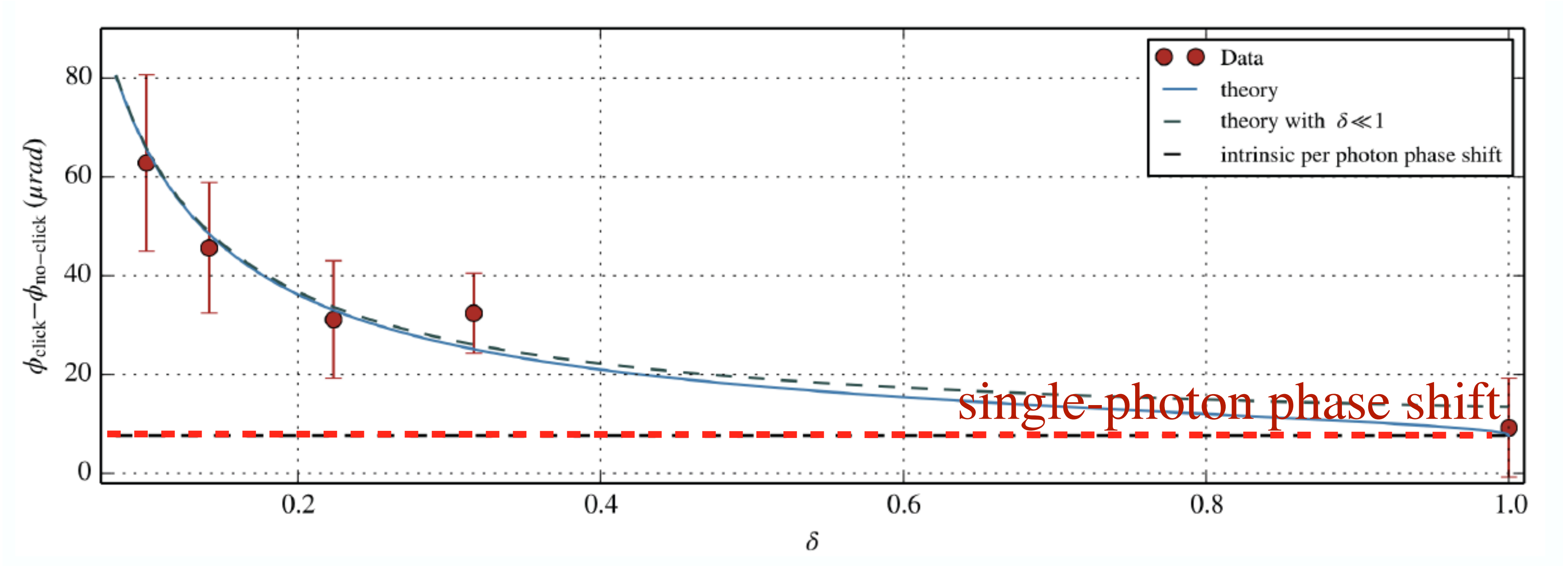
When the post-selection succeeds, the phase shift on the probe may be much larger than the phase shift due to a single photon -- *even though there only ever* is *at most one signal photon*!

$\langle n \rangle_w$ may be >> 1.

<u>Weak Measurement Amplification of Single-Photon Nonlinearity</u>, Amir Feizpour, Xingxing Xing, and Aephraim M. Steinberg Phys Rev Lett 107, 133603 (2011)

The phase shift due to an appropriately post-selected photon



Is weak measurement good for anything *practical*?

"Weak value amplification" has been proposed as a way to enhance the signals of small effects (like our nonlinearity...?):

Hosten & Kwiat, Science 319, 5864 (08); and, more quantitatively --

Selected for a Viewpoint in *Physics*

RL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA

(Received 12 January 2009; published 27 April 2009)

We report on the use of an interferometric weak value technique to amplify very small transverse deflections of an optical beam. By entangling the beam's transverse degrees of freedom with the which-path states of a Sagnac interferometer, it is possible to realize an optical amplifier for polarization independent deflections. The theory for the interferometric weak value amplification method is presented along with the experimental results, which are in good agreement. Of particular interest, we measured the angular deflection of a mirror down to 400 ± 200 frad and the linear travel of a piezo actuator down to 14 ± 7 fm.

DOI: 10.1103/PhysRevLett.102.173601 PACS numbers: 42.50.Xa, 03.65.Ta, 06.30.Bp, 07.60.Ly

Short story

Weak value ~ 1 / <f|i>

Success probability ~ $|\langle f|i\rangle|^2$

Pointer shift gets 10 times bigger,

as data rate gets 100 times smaller; noise 10 times bigger too.

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IF --- **the noise is "statistical," as opposed to "technical."**

Early conjectures: something like pixel size in a detector array is insurmountable. Use WVA to make shift > pixel size ("technical")
Truth: you can still fit the center of a distribution to better than the pixel size, and $1/N^{1/2}$ still applies in principle.

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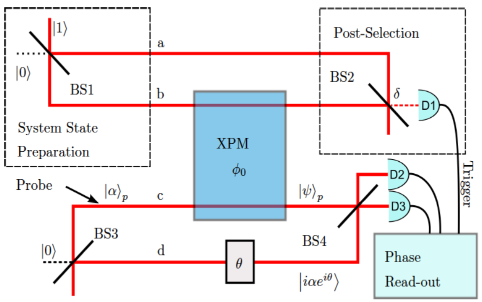
BUT: noise only drops as $1/N^{1/2}$ because of the random walk, i.e., the fact that the noise on different data points is uncorrelated. Adding more data points within a noise correlation time *does not* let you keep averaging the noise away; better to post-select, and get a bigger signal.

One (of many) perspective(s) on the signal-to-noise issues… "technical noise"

NOTE: some language issues?
To most theorists, "postselection" means "throwing something out"; to some experimentalists, it means "doing a measurement on the system at all" (and perhaps choice of basis)

A. Feizpour et al., Phys. Rev. Lett. 107, 133603 (2011) + experiment & theory in progress



WE CONTEND WVA IS USEFUL IN THE FOLLOWING SITUATIONS:

(1) limited by detector saturation

(2) most bins "empty" anyway

(3) noise correlation time > time between photons

(IN THIS REGIME, IT IS BETTER THAN STRAIGHT AVERAGING, YET STRICTLY SUB-OPTIMAL. IT IS RELATED TO THE BETTER – AND BETTER-KNOWN – "LOCK-IN" TECHNIQUE, BUT POTENTIALLY MORE "ECONOMICAL")

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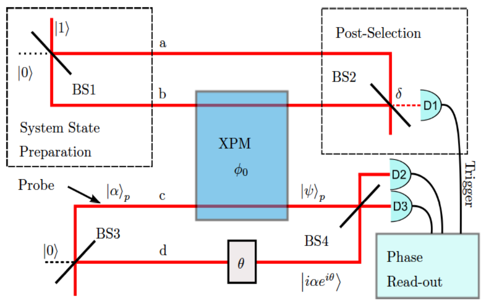

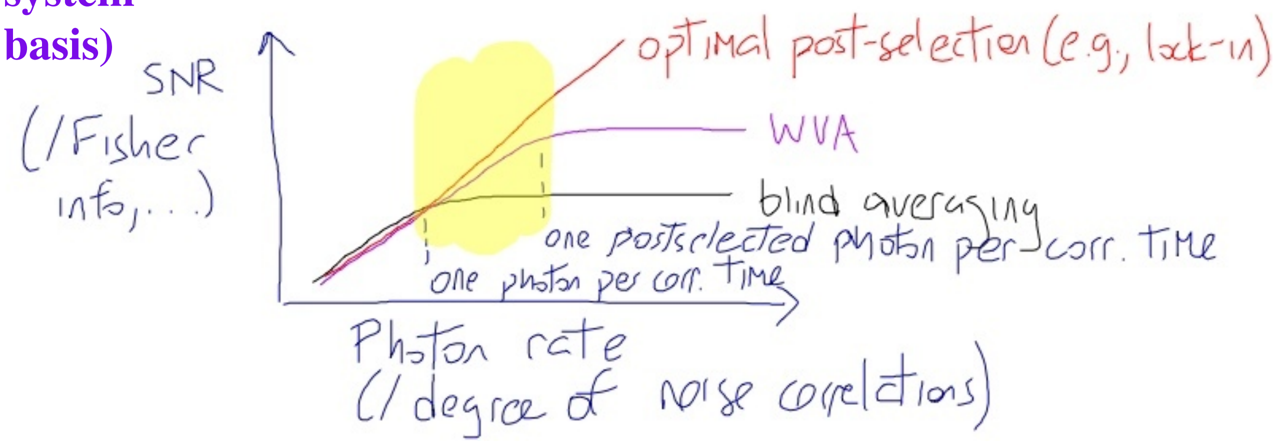

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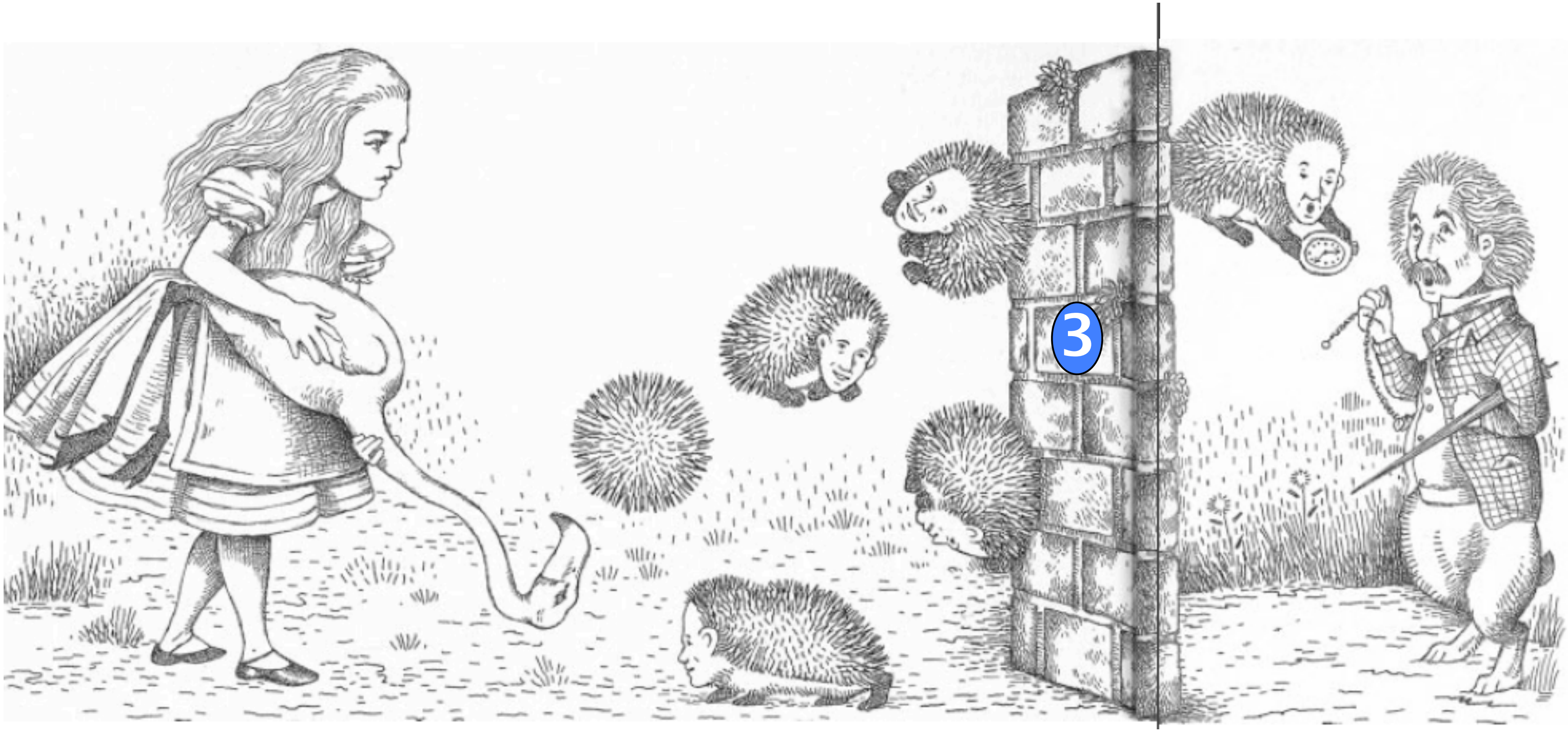
Watching a particle in a region it's "forbidden" to be in



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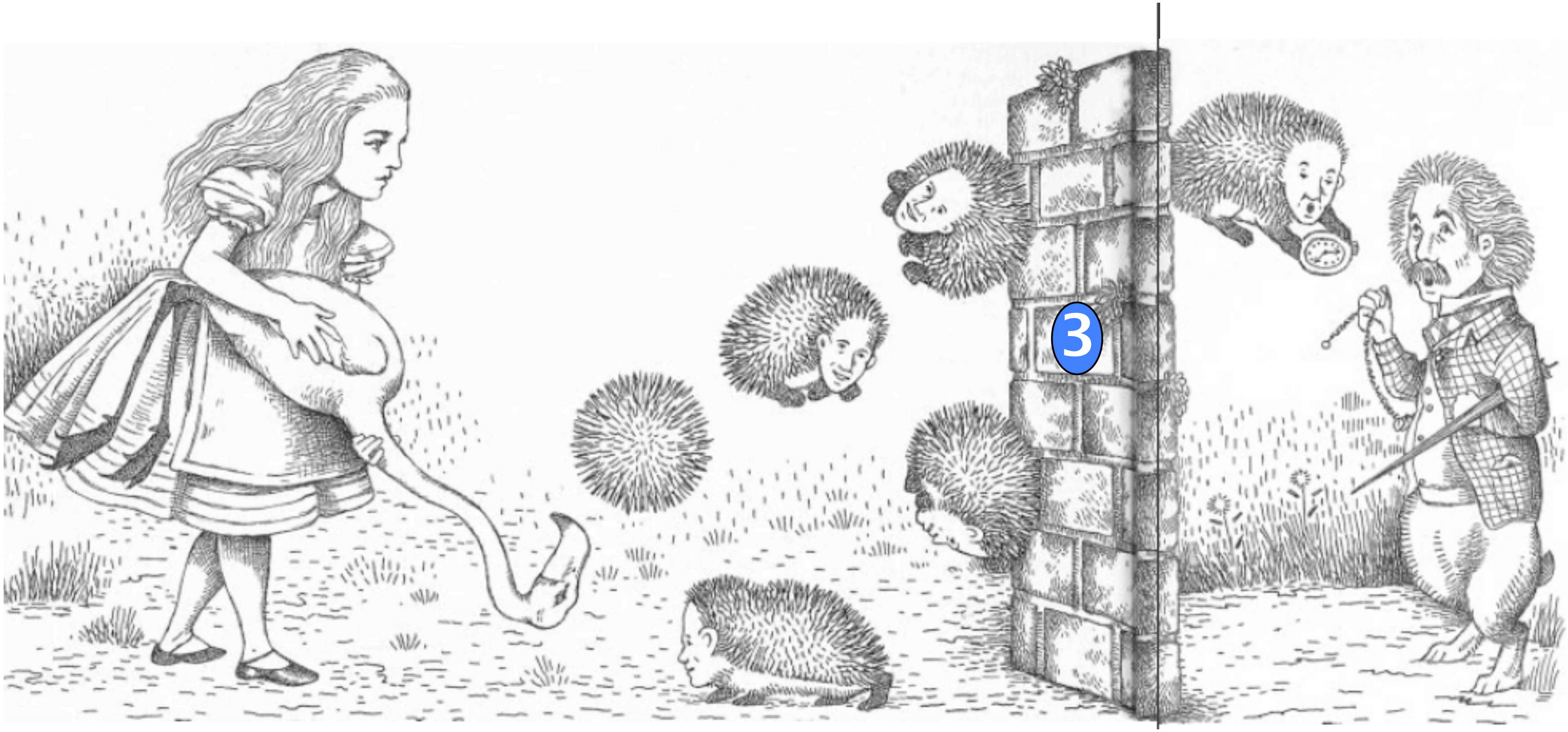
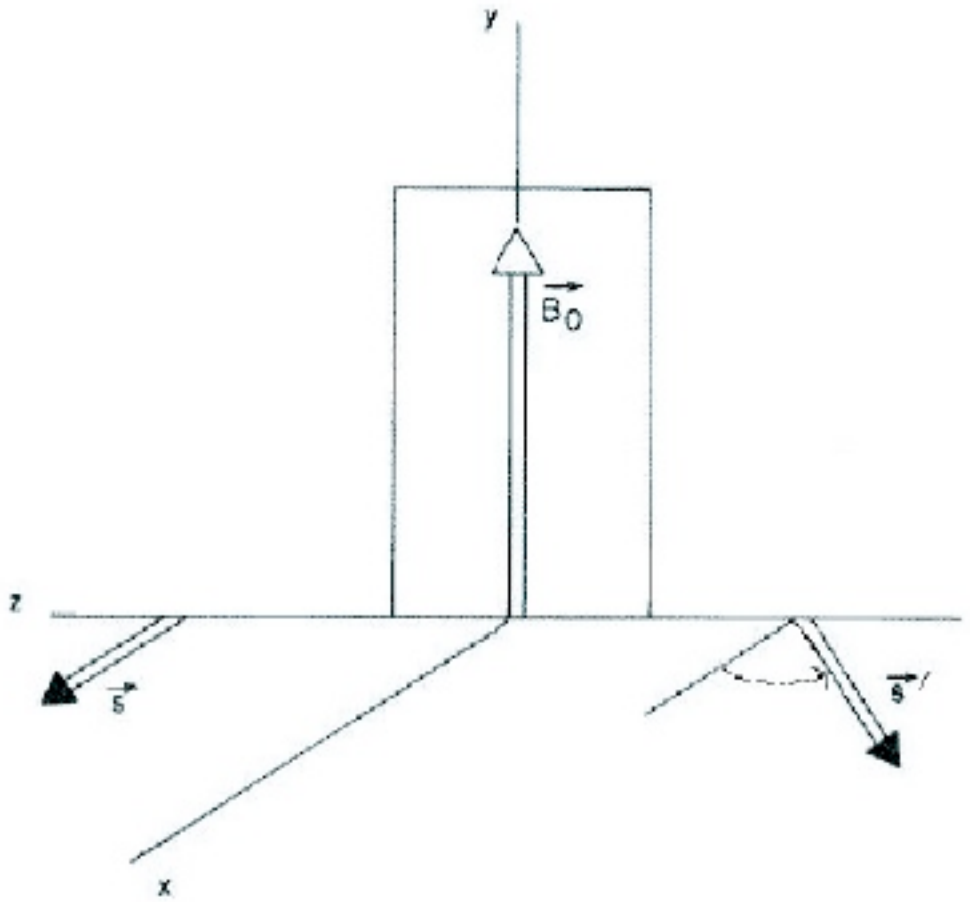


How long has the transmitted particle spent in the region?
Need a clock...

“Larmor Clock” (Baz’; Rybachenko; Büttiker 1983)



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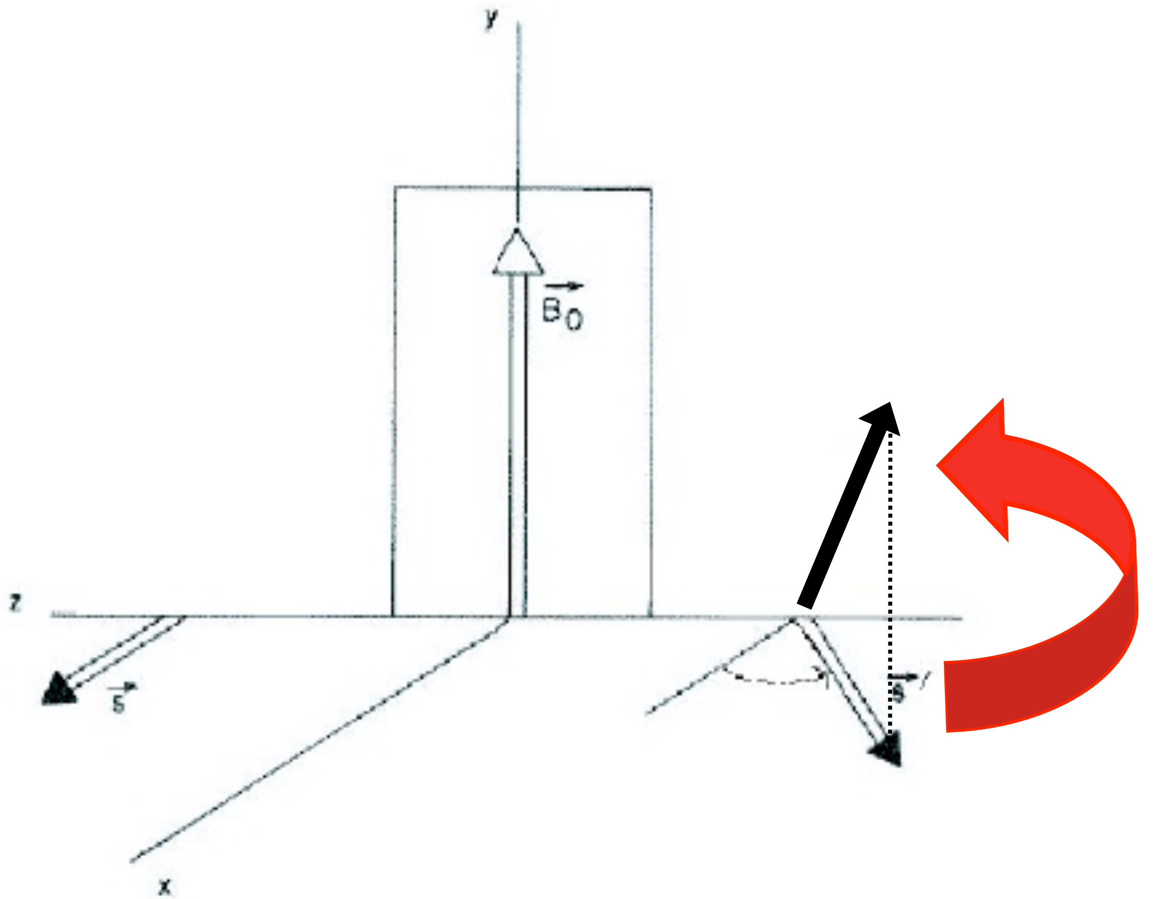
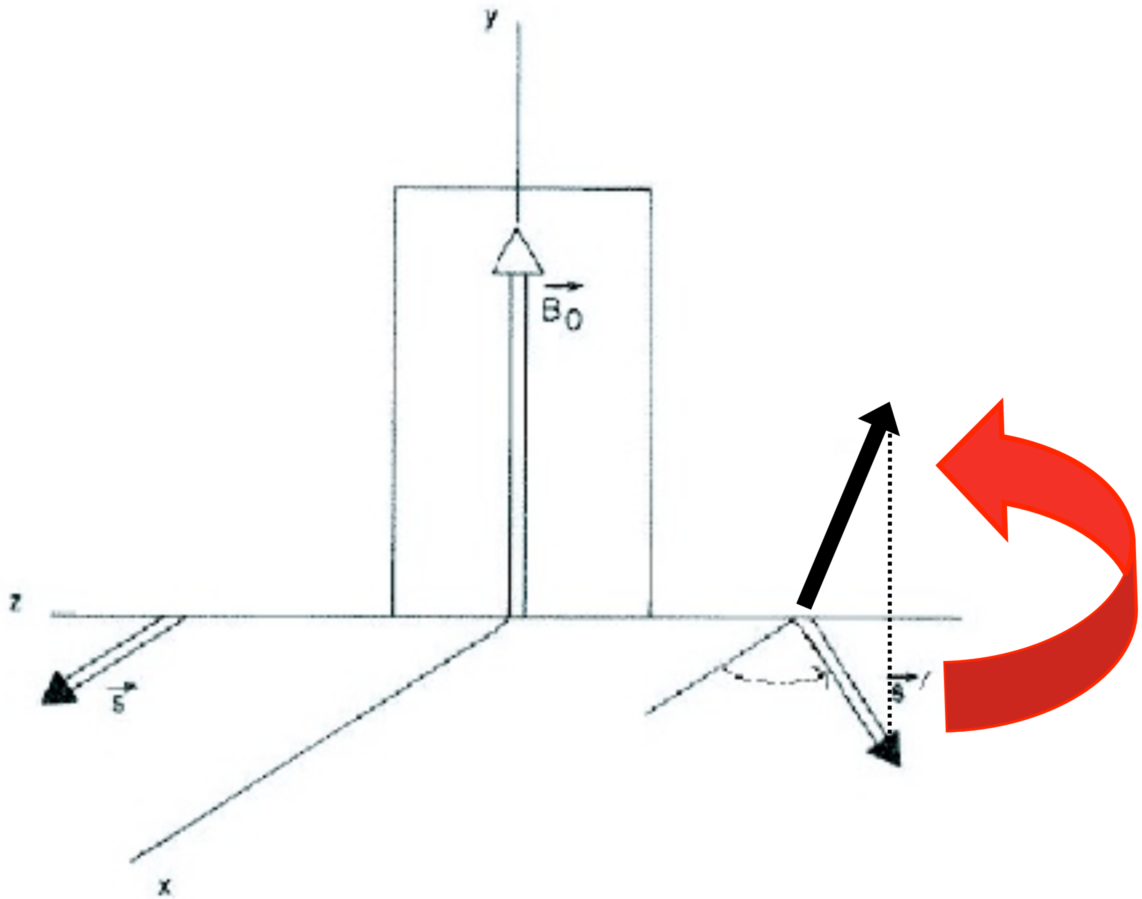
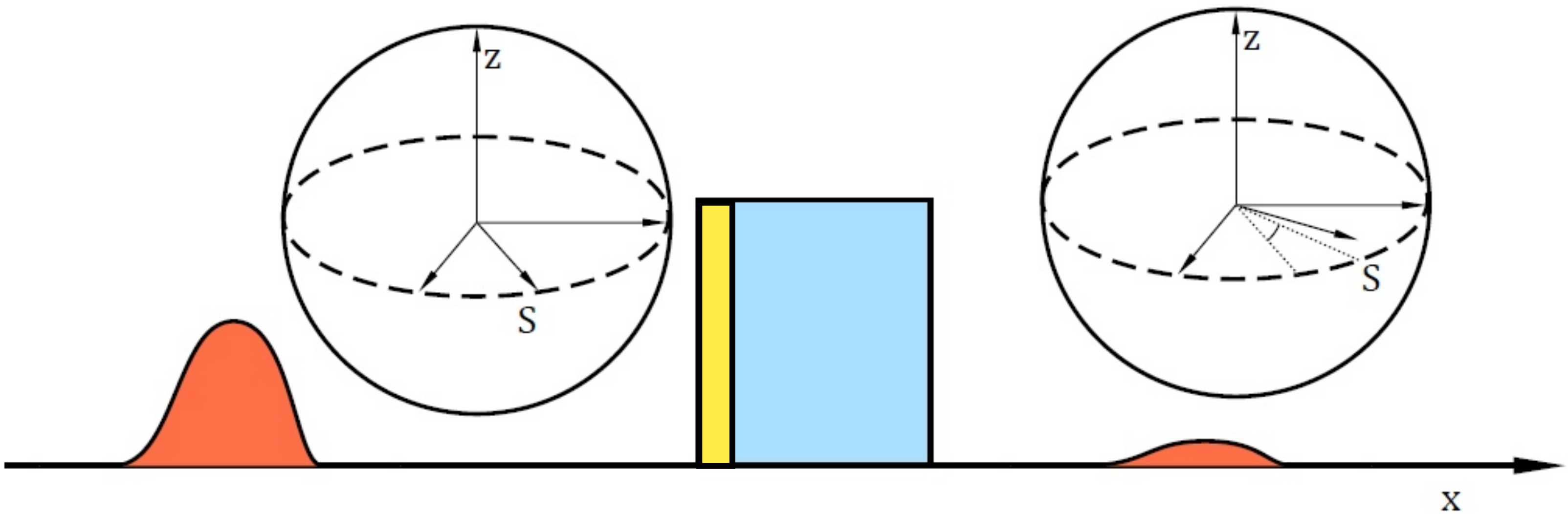


“Larmor Clock”
(Baz’; Rybachenko; Büttiker 1983)



Two components mystified Büttiker;
Feynman approach led to complex times, which mystified every one;
It turns out these are weak values, whose Real and Imaginary parts are easily interpreted – but which hadn’t been invented yet.

Local "Larmor Clock" – how much time spent in any given region?



- $\tau = \theta_{\text{rot}}/\omega_l$
  - In plane rotation measures the tunneling time
  - Spin aligns along z axis; back-action of the measurement.

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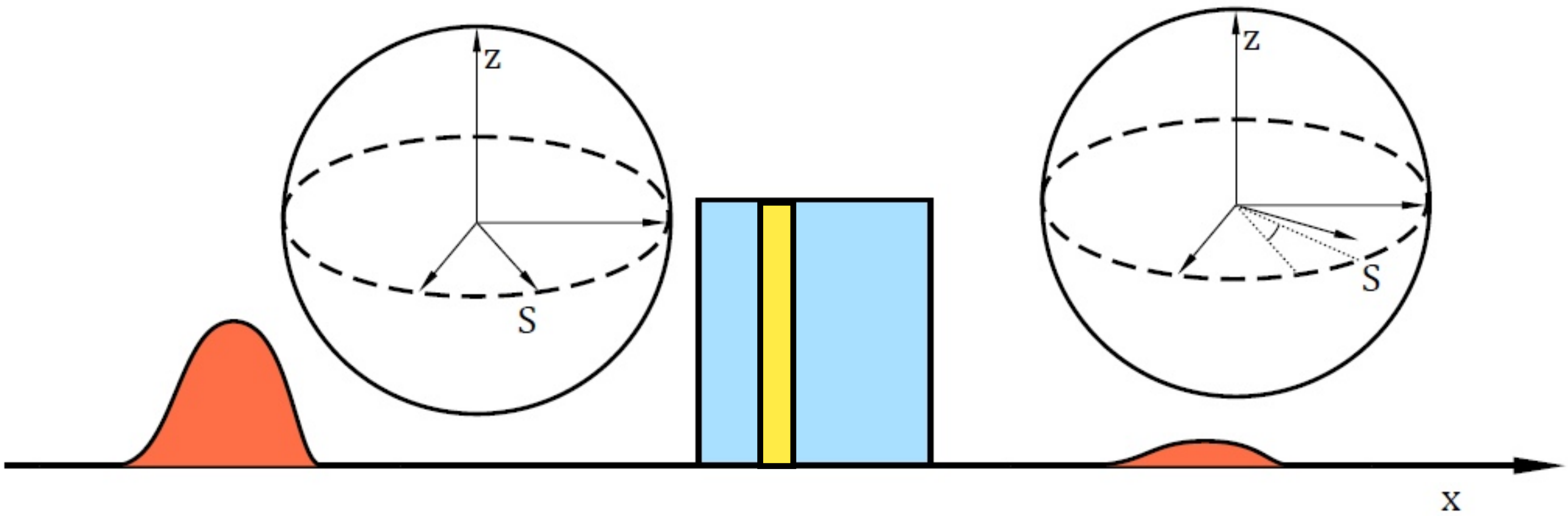

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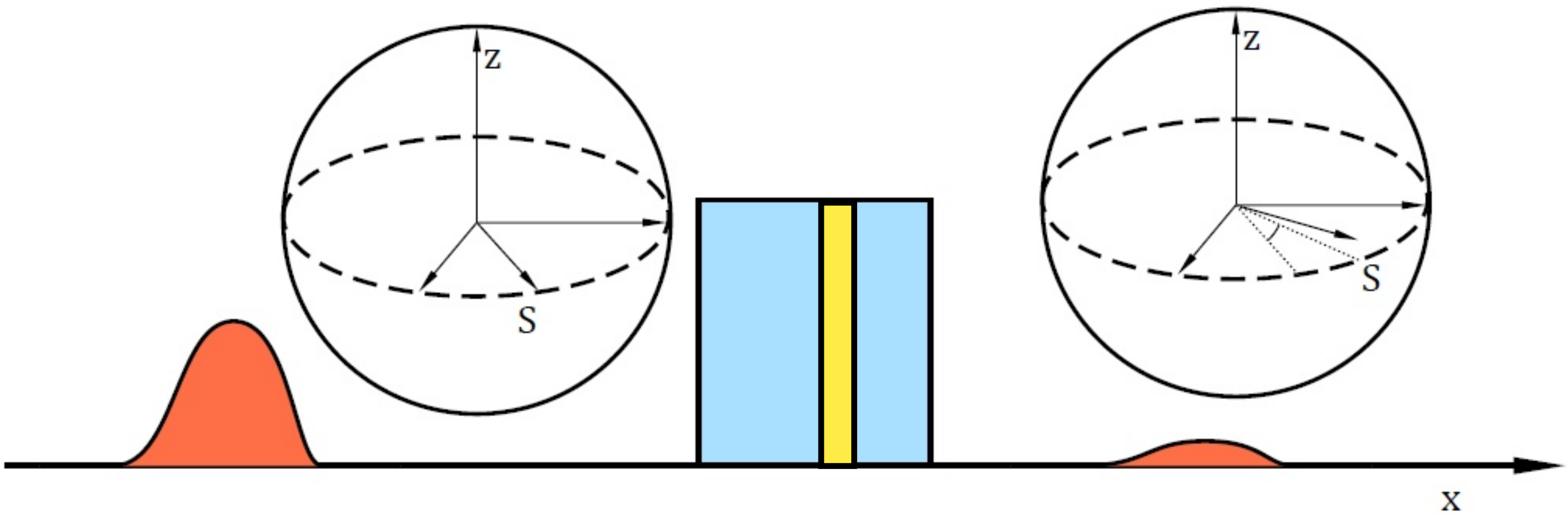

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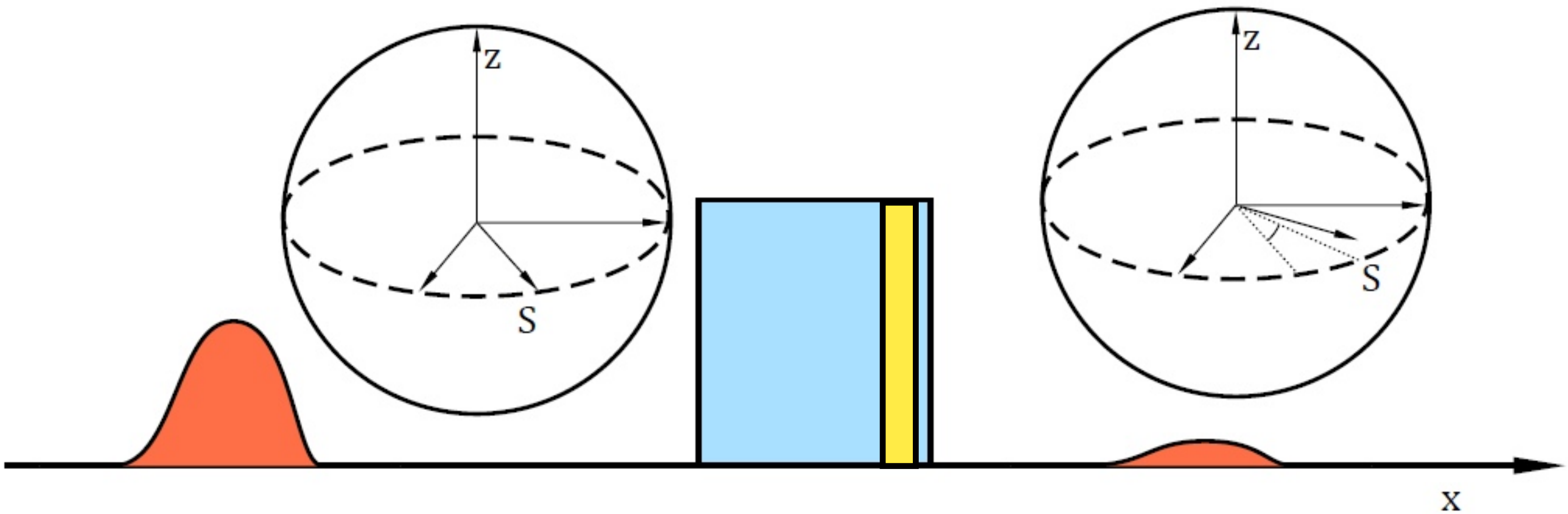

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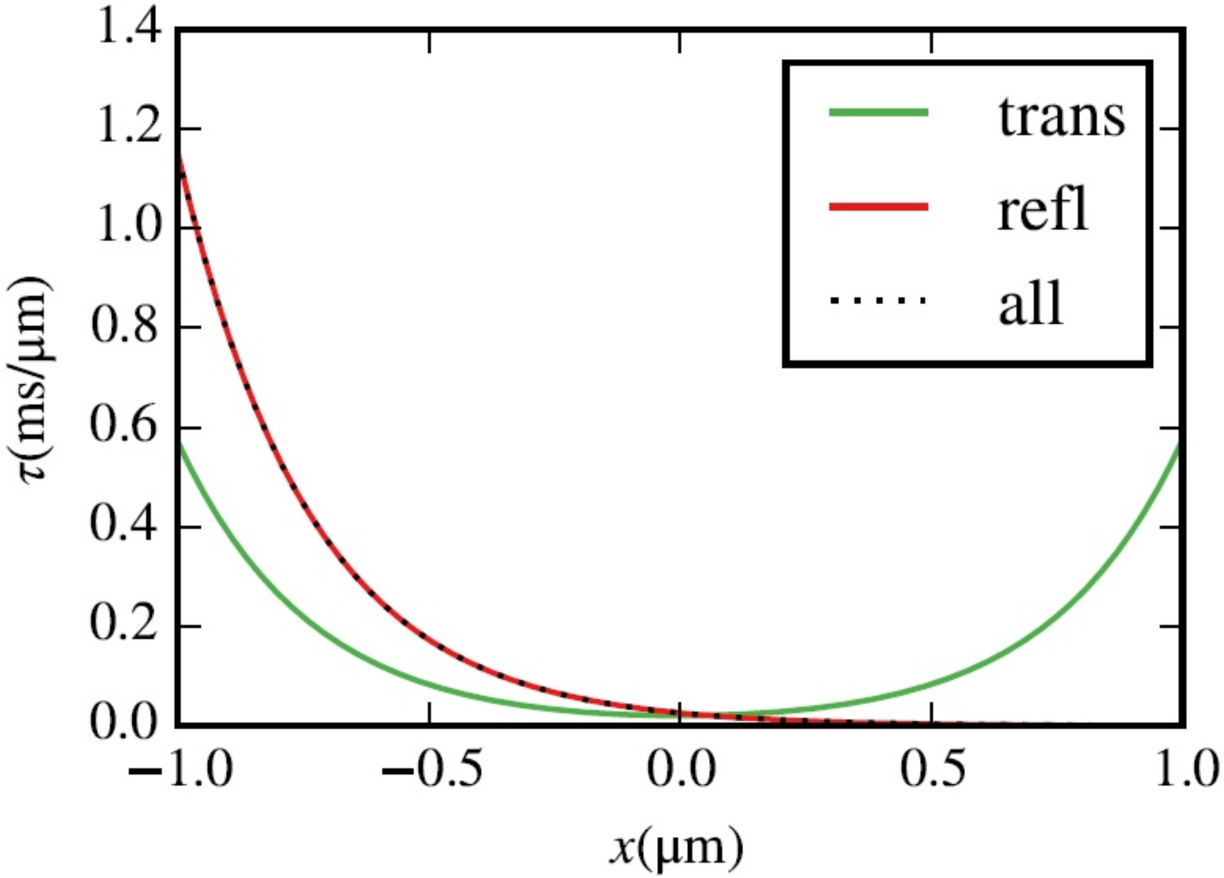
Where does a particle spend time inside the barrier?



AMS, Phys. Rev. Lett., *74*(13), 2405–2409, *Phys. Rev. A*, *52*(1), 32–42.

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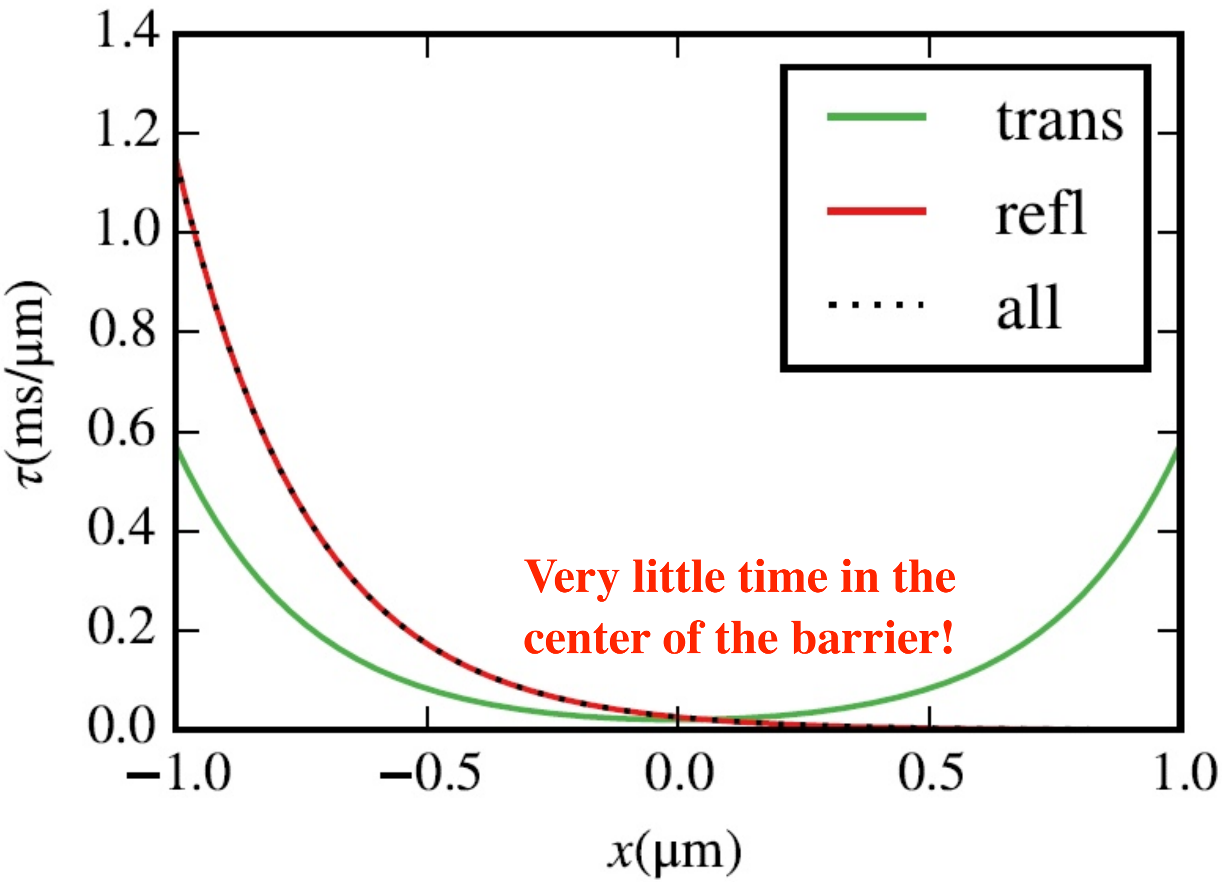

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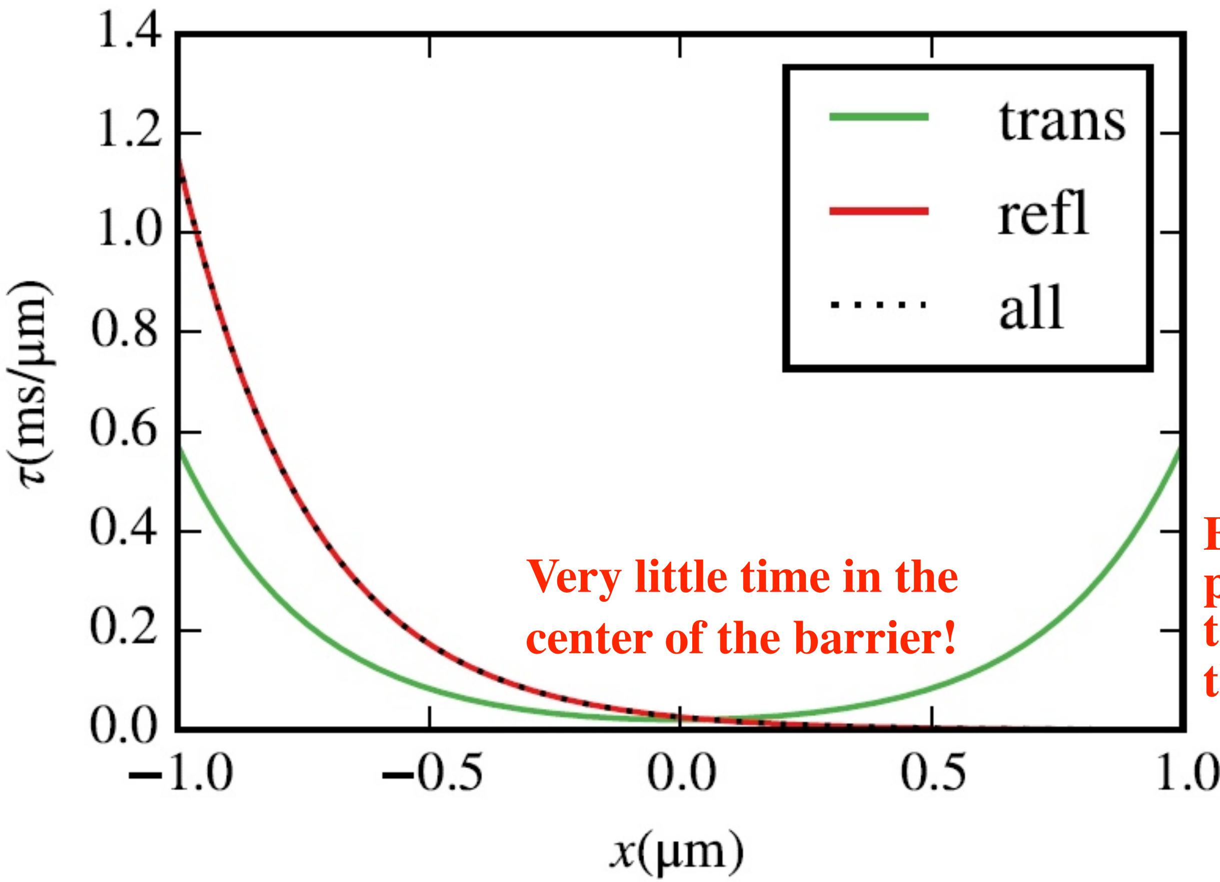
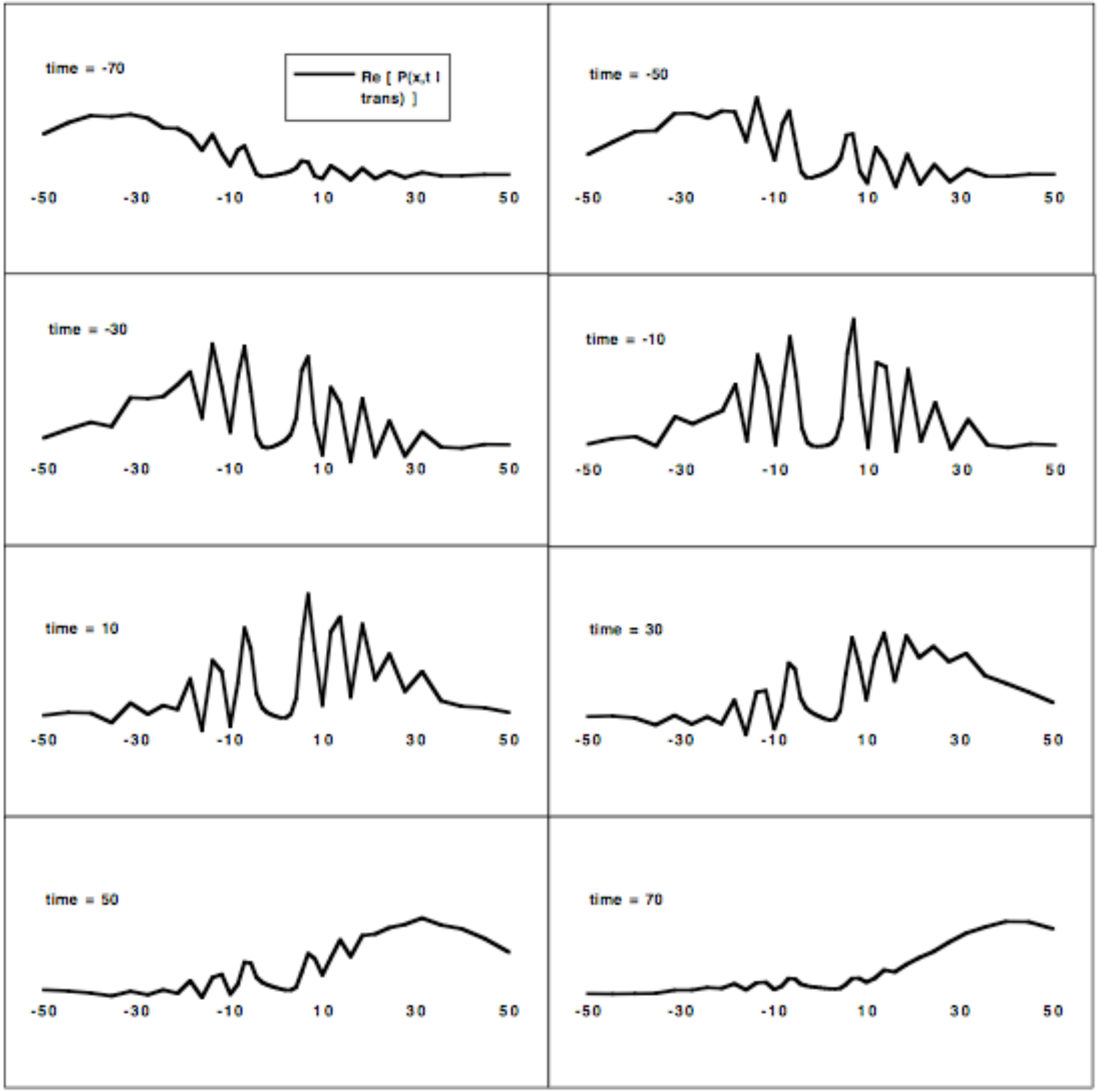


Very little time in the center of the barrier!

But – unlike the reflected particles – the transmitted ones "see" the region near the exit!

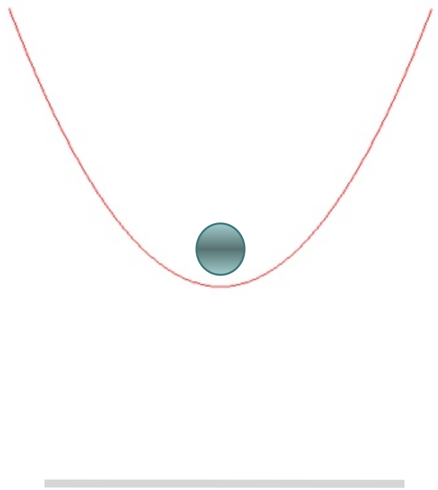
AMS, Phys. Rev. Lett., *74*(13), 2405–2409, *Phys. Rev. A*, *52*(1), 32–42.

Conditional-probability “movie” of tunneling



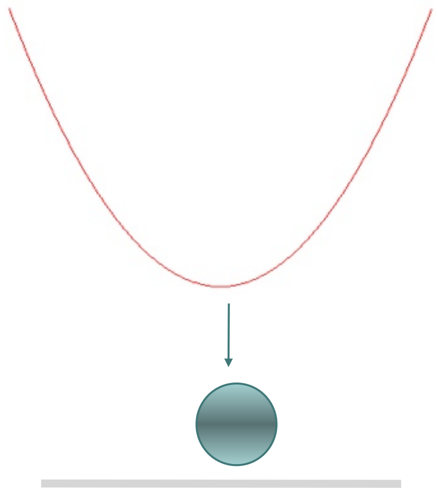
One possible experimental sequence

- BEC in magnetic trap



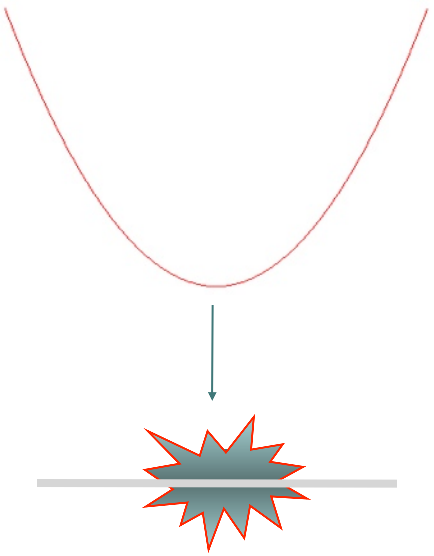
One possible experimental sequence

- BEC in magnetic trap
- Turn off trap, free expansion of condensate for 5 ms



One possible experimental sequence

- BEC in magnetic trap
- Turn off trap, free expansion of condensate for 5 ms
- Interaction with barrier



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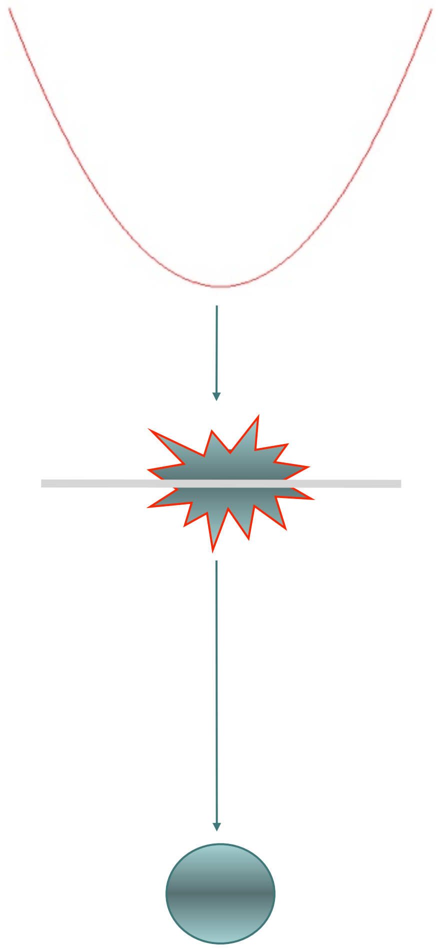
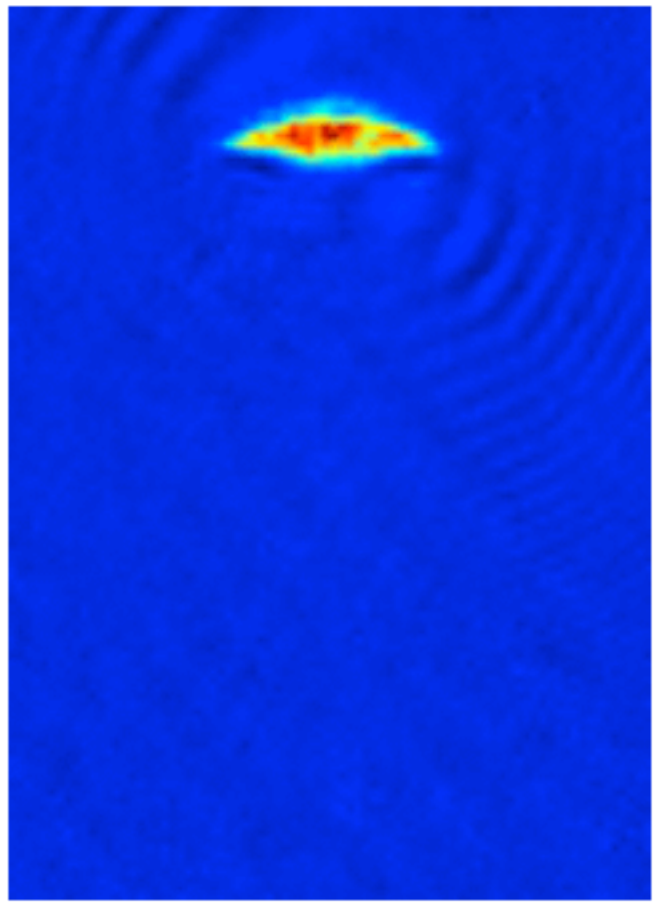
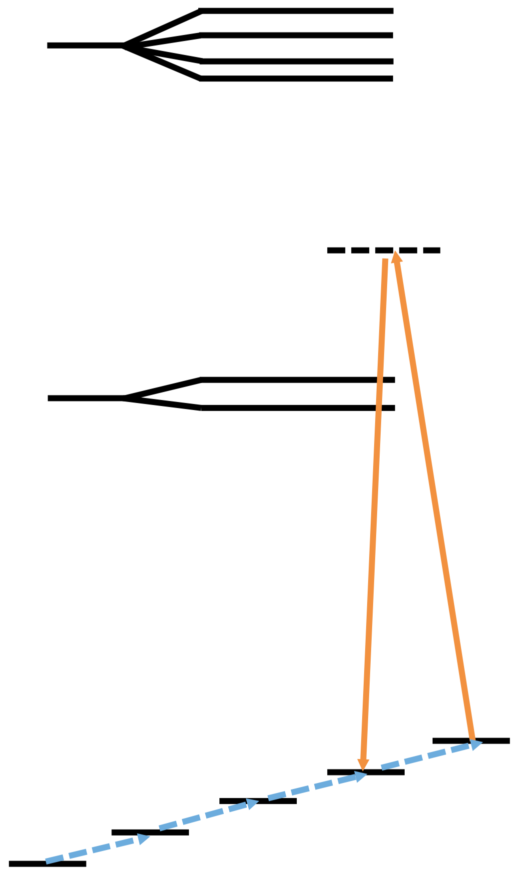
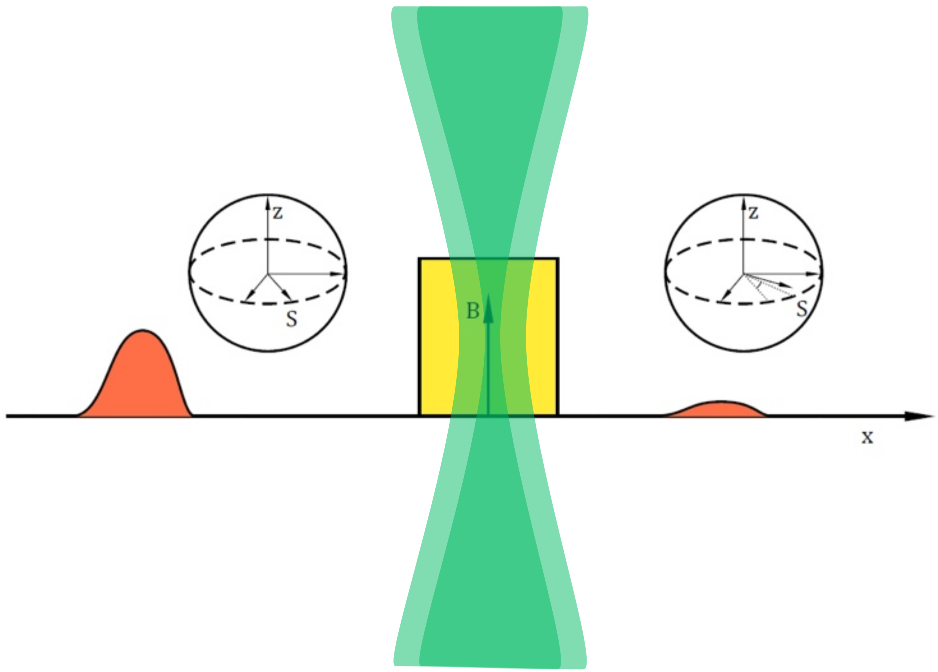


Atoms spilling *around* an optical "ReST" trap

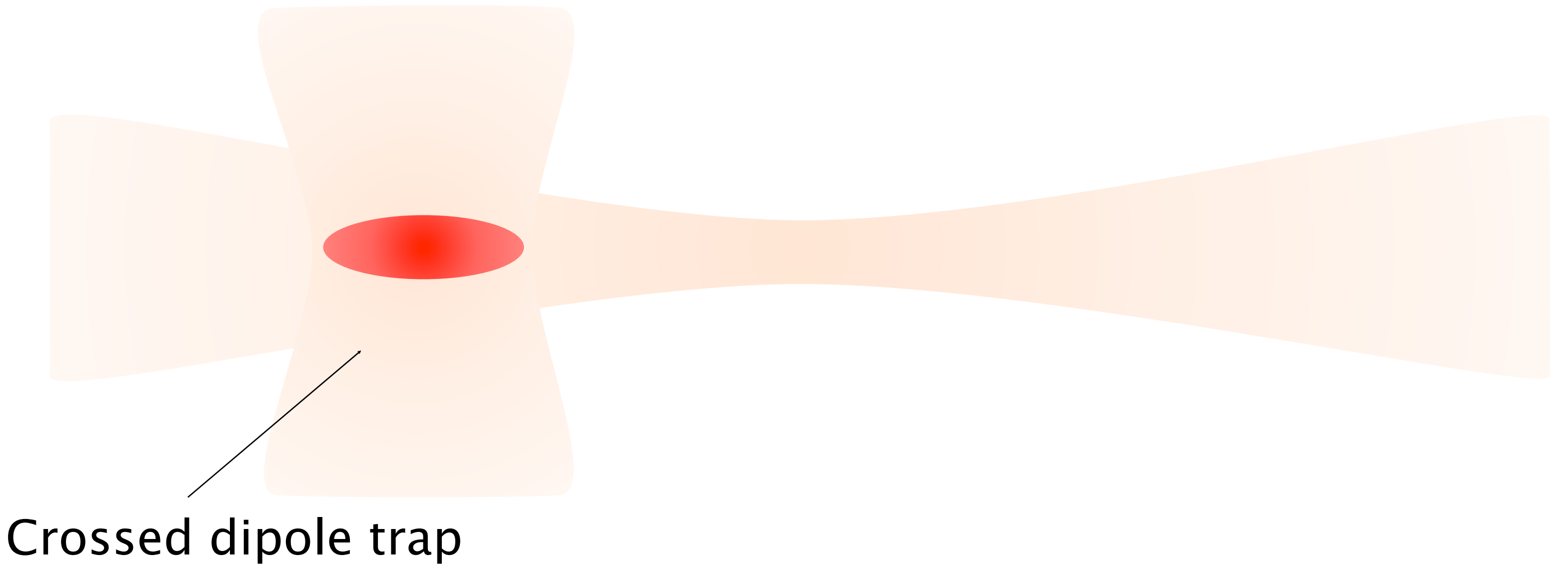


Localized (fictitious) magnetic field (Raman coupling of two ground states)





Experimental sequence: current plan



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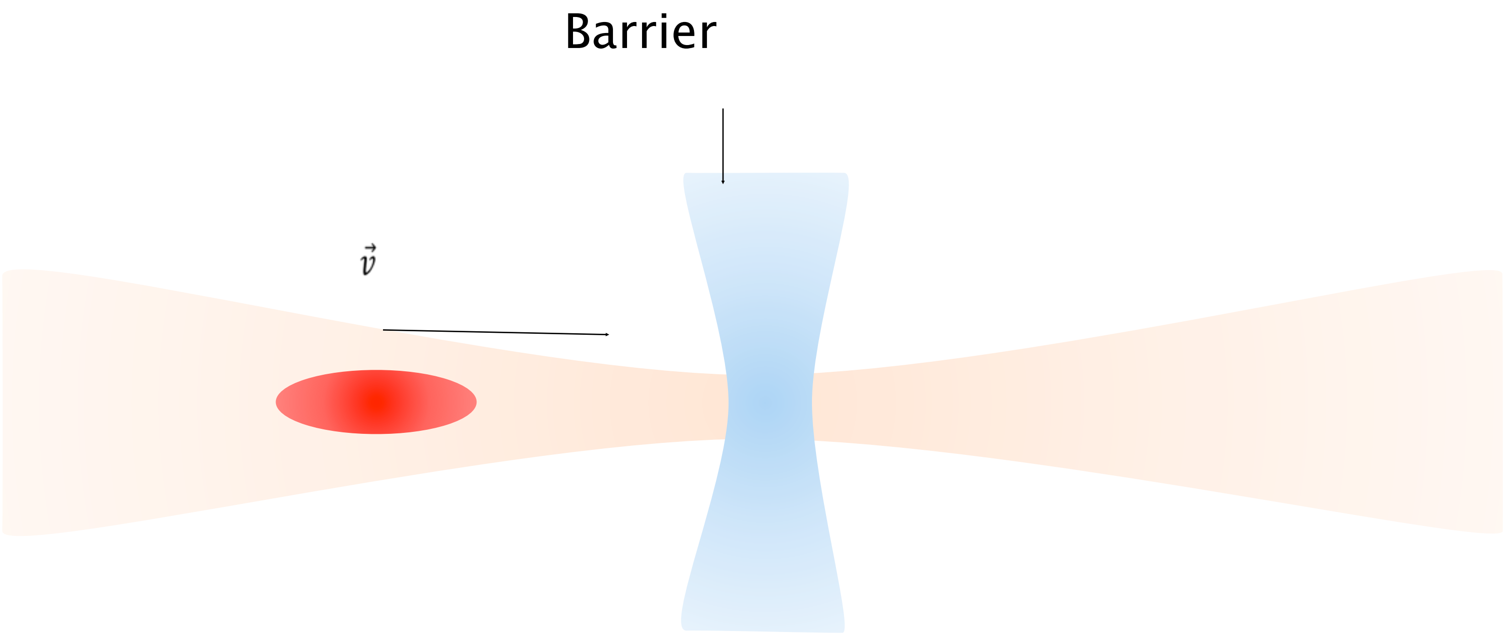

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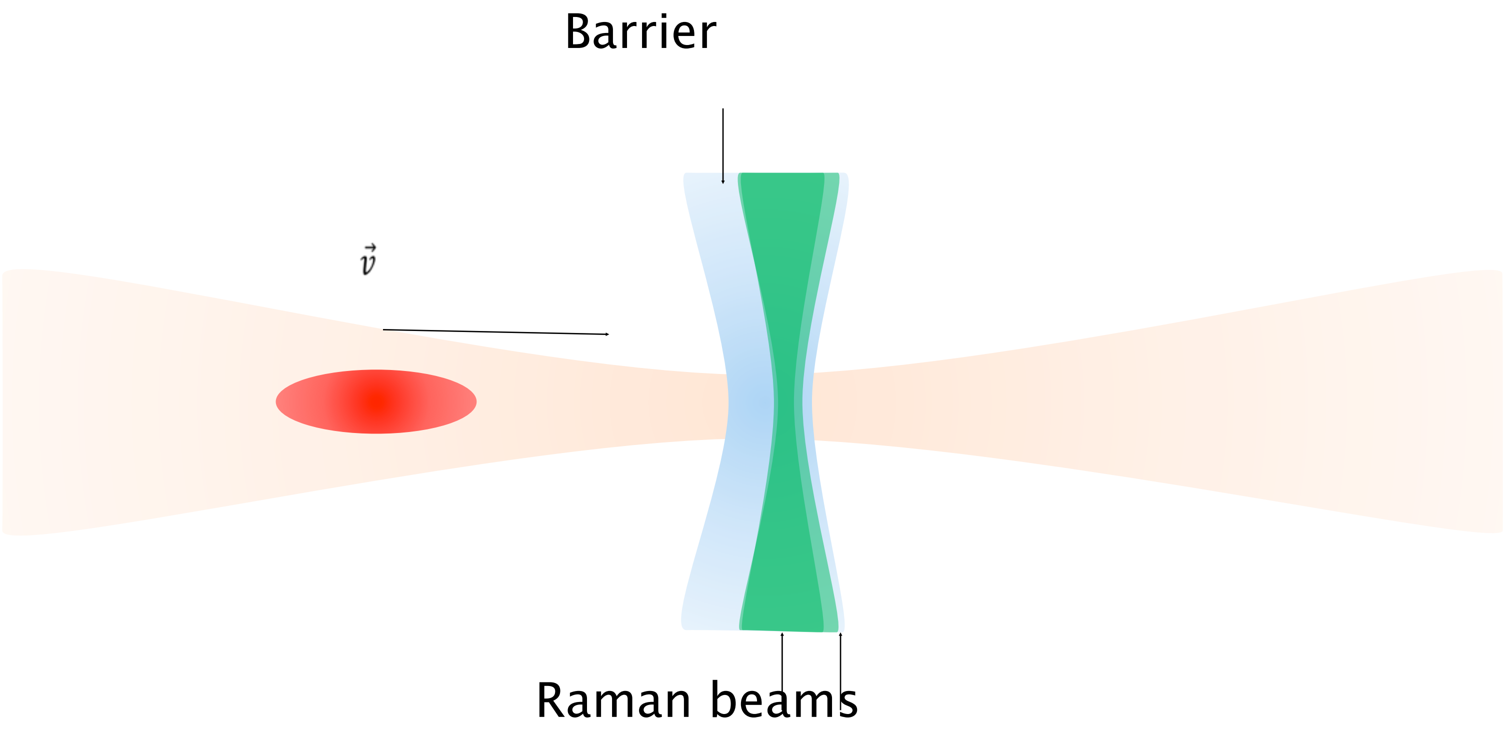

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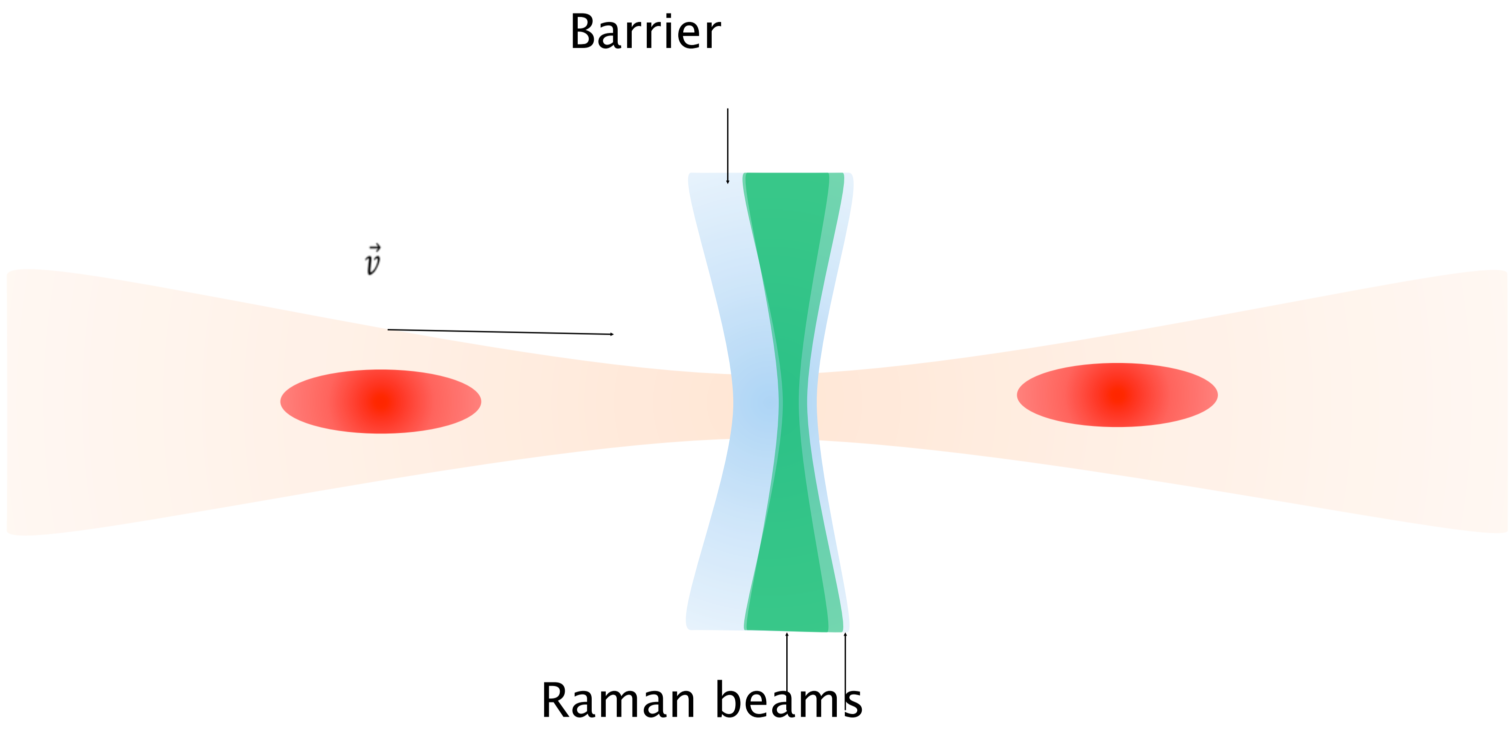
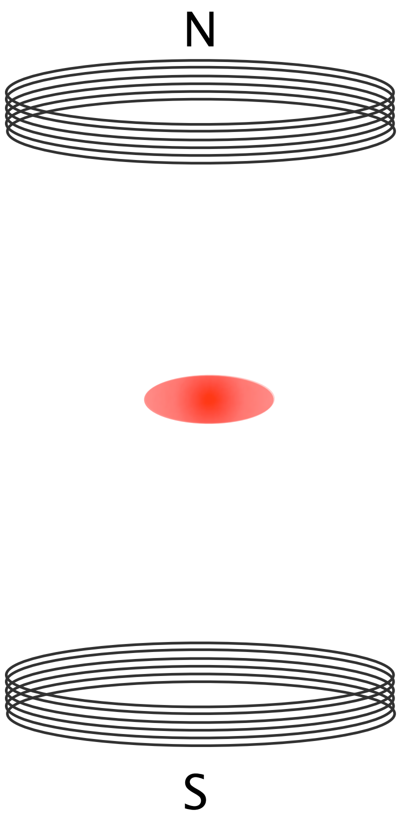
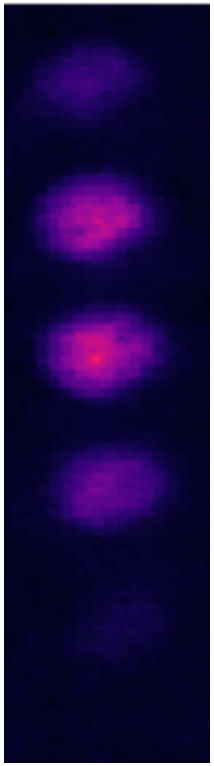


Stern-Gerlach measurement





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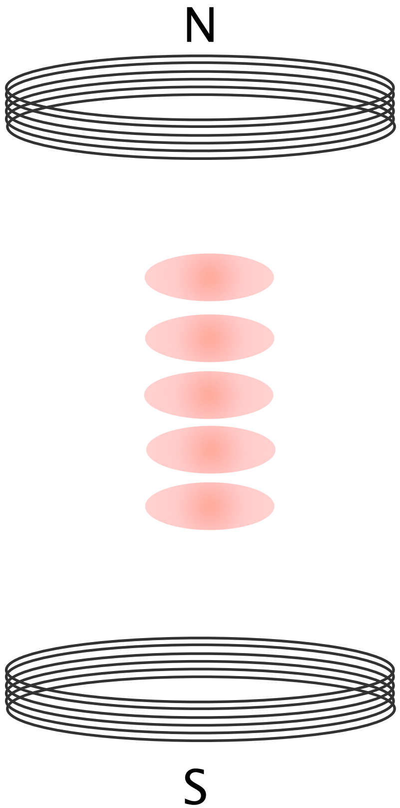
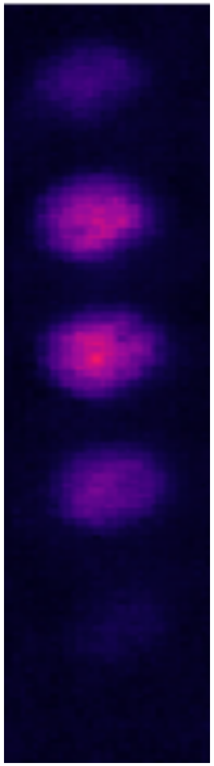
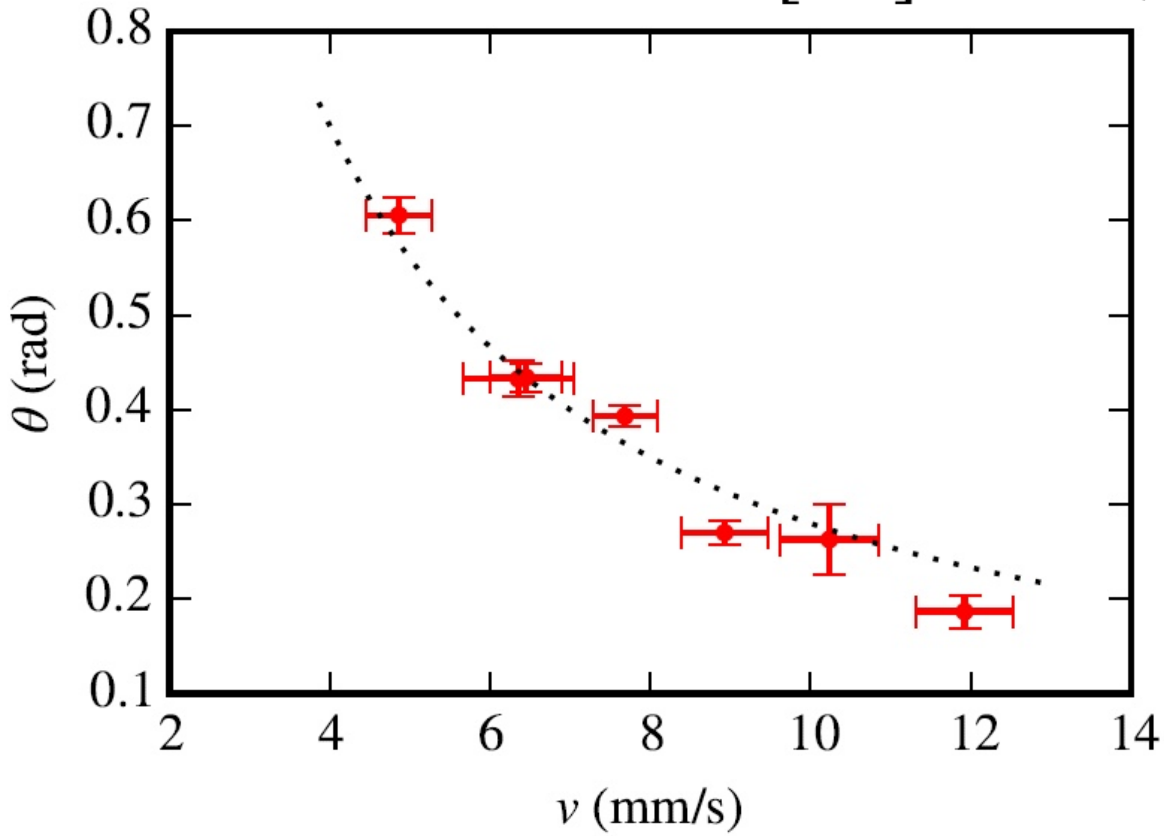




Calibration of Larmor clock for free propagation

$$\tau[\mathrm{ms}] = 1.9(2) \times \theta[\mathrm{rad}]$$



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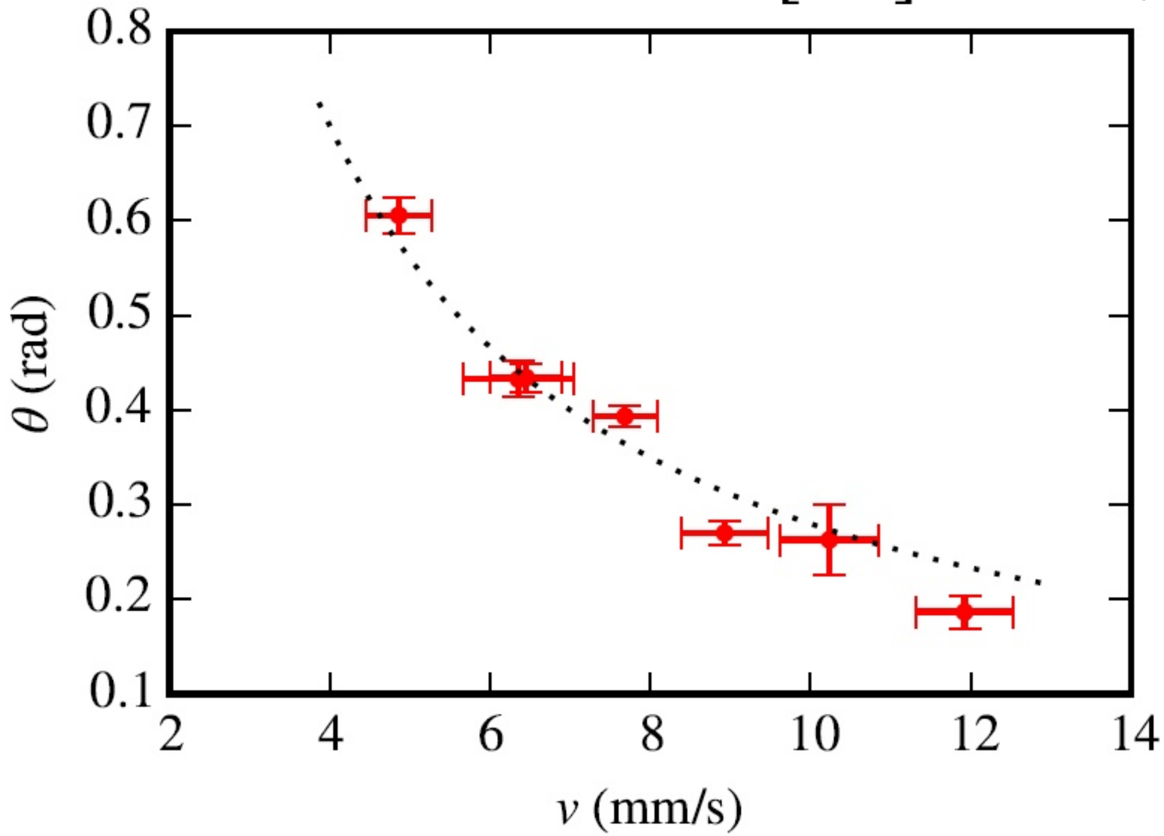

(A [very low-precision] confirmation that : t = L / v !)

Summary

If there is some deeper reality underlying QM, what is revealed (to us naïve experimentalists) by weak measurements should presumably tell us something about it.

- **We were able to use weak measurements on entangled photons to study the nonlocality of experimentally observed trajectories, and the relation to “surreal”ism.**

- **We were able to generate a “big” (10^{-5} rad) per-photon nonlinear phase shift, and measure it – and confirm that properly post-selected photons may have an amplified effect on the probe, as per the weak value.**

- **After talking about it for 20 years, we are getting close to being able to probe atoms while they tunnel through an optical barrier, using weak measurement to ask “where they were” before being transmitted**