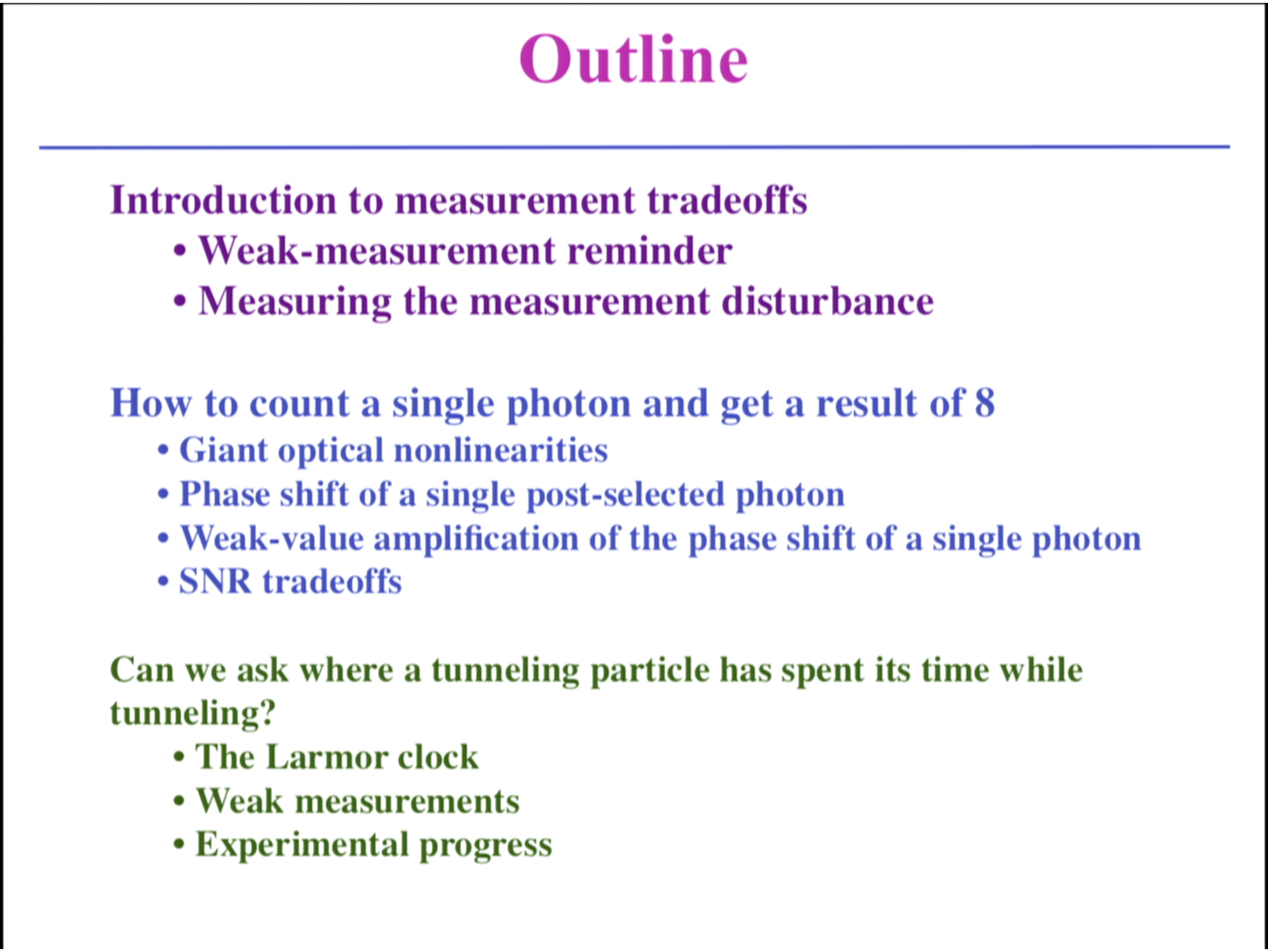
Title: Experimental measurement tradeoffs, from Heisenberg to Aharonov to quantum data compression

Date: Sep 23, 2016 12:00 PM

URL: http://pirsa.org/16090054

Abstract: Tradeoffs in measurement and information are among the central themes of quantum mechanics. I will try to summarize in this talk a few of our experiments related to modern views of these topics. In particular, I will try to give an example or two of the power of "weak measurements," both for fundamental physics and for possible precision metrology. One example will involve revisiting the question of Heisenberg's famous principle, and an interpretation which is widespread but has now been experimentally shown to be incorrect. Then I will also discuss our recent work on a "quantum data compression" protocol which would allow a small-scale quantum memory to store all the extractable information from a larger ensemble of identically prepared systems. Finally, I will talk about our experiment entangling two optical beams to demonstrate "weak-value amplification," and the ongoing controversy about when if ever this technique could be useful in practice.



Outline

Introduction to measurement tradeoffs

- Weak-measurement reminder
- Measuring the measurement disturbance

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
- SNR tradeoffs

Can we ask where a tunneling particle has spent its time while tunneling?

- The Larmor clock
- Weak measurements
- Experimental progress

DRAMATIS PERSONÆ

CQIQC

Toronto quantum optics & cold atoms group:

Photons: Hugo Ferretti Edwin Tham

Atoms: **Ramon Ramos** **David Spierings**

Atom-Photon Interfaces: **Josiah Sinclair** Shaun Pepper Alex Bruening

Theory: Aharon Brodutch

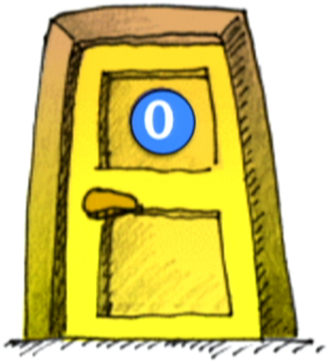
Some alums: **Matin Hallaji, Greg Dmochowski, Shreyas Potnis**, **Dylan Mahler**, **Amir Feizpour**, Alex Hayat, Ginelle Johnston, Xingxing Xing, **Lee Rozema**, Kevin Resch, Jeff Lundeen, Krister Shalm, Rob Adamson, Stefan Myrskog, Jalani Kanem, Ana Jofre, Arun Vellat Sadashivan, Chris Ellenor, Samansa 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...

25 years cifar
Canadian Institute for Advanced Research
NSERC CRSNG
NORTHROP GRUMMAN
Fetzer Franklin Fund Exploring Frontiers Breakthroughs Science

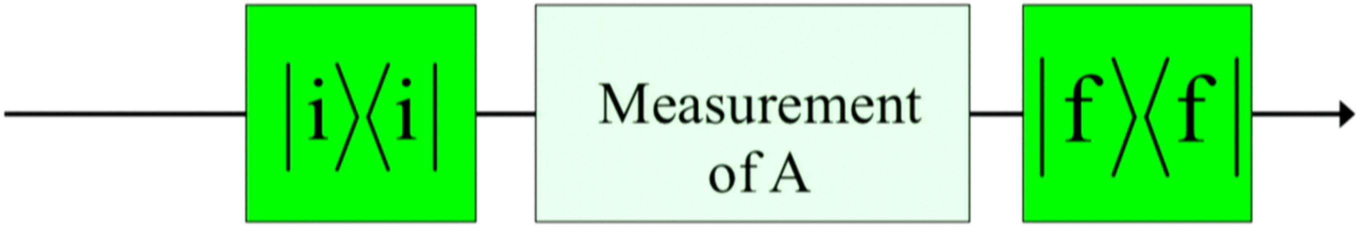
Quantum archaeology



Conditional measurements (Aharonov, Albert, and Vaidman)

AAV, PRL 60, 1351 ('88)

Prepare a particle in |i> …try to "measure" some observable A… *postselect* the particle to be in |f>



$|i\rangle\langle i|$

Measurement of A

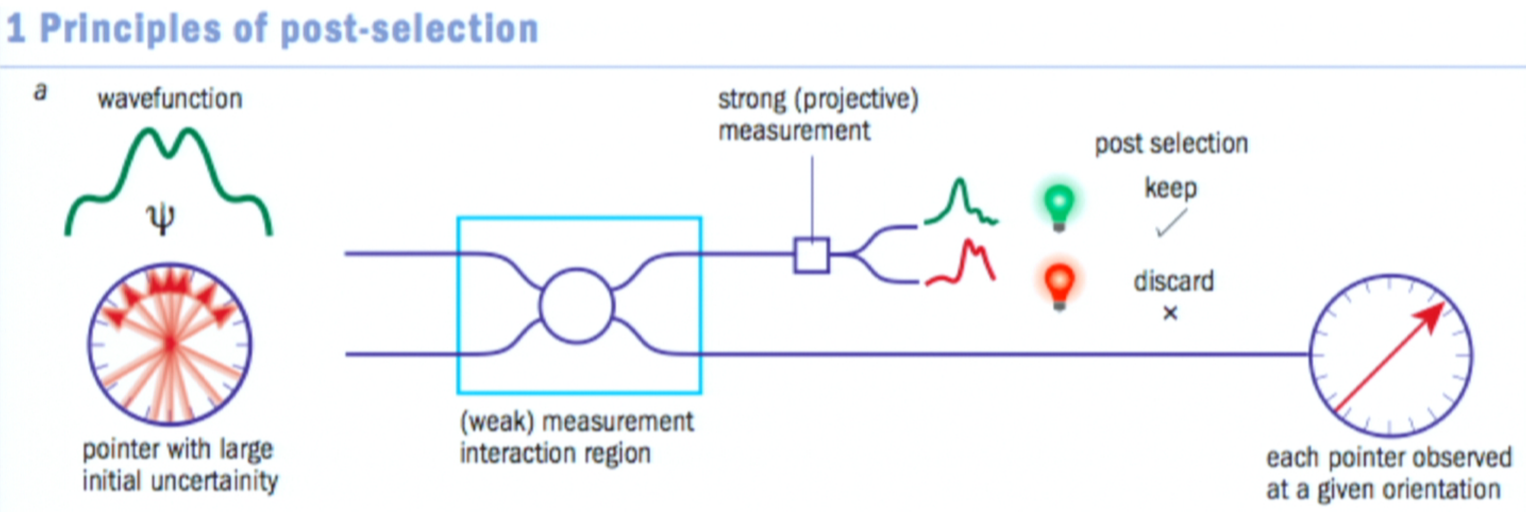
$|f\rangle\langle f|$

Does <A> depend more on i or f, or equally on both?
Clever answer: both, as Schrödinger time-reversible.
Conventional answer: i, because of collapse.

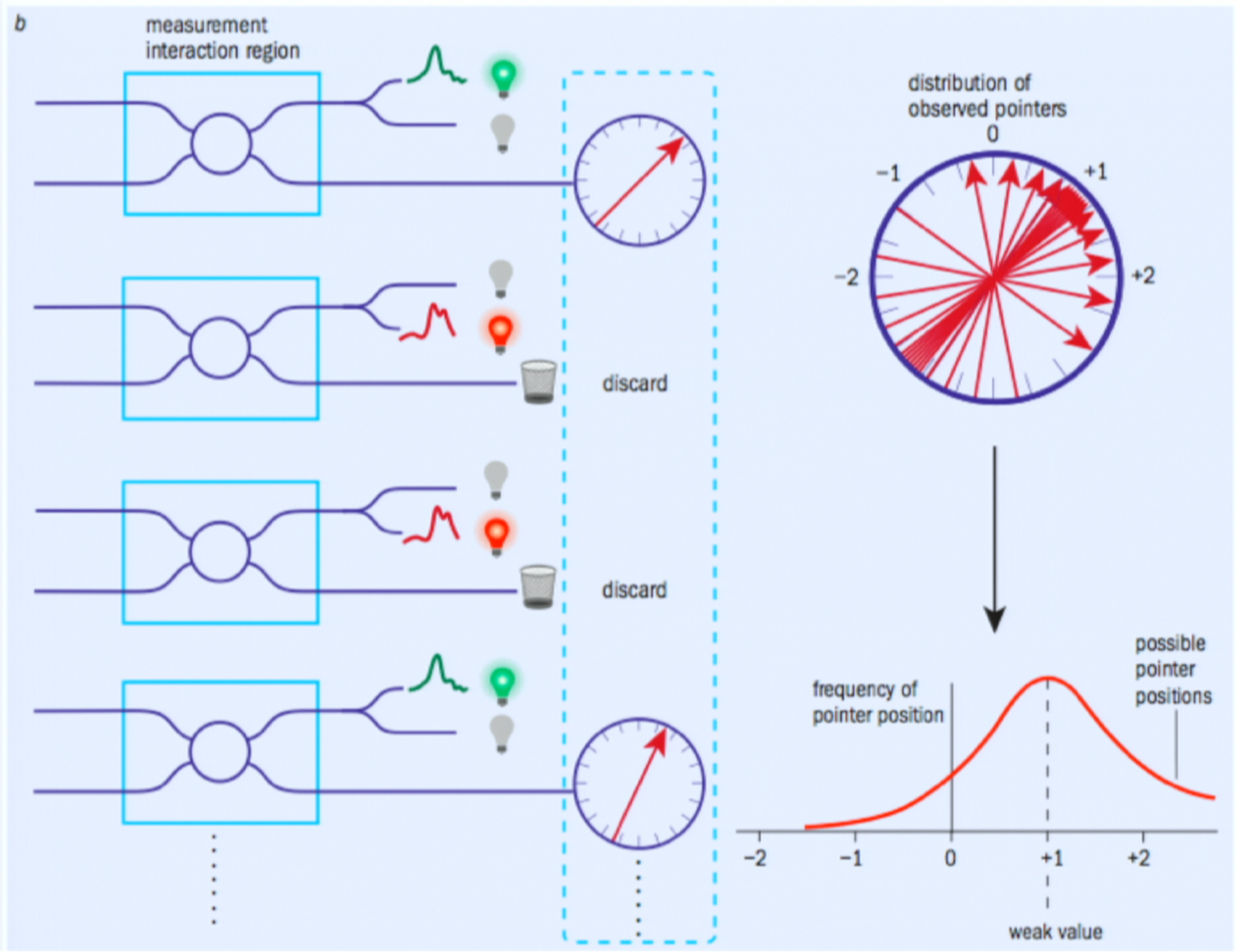
Reconciliation: measure A "weakly."
Poor resolution, but little disturbance.

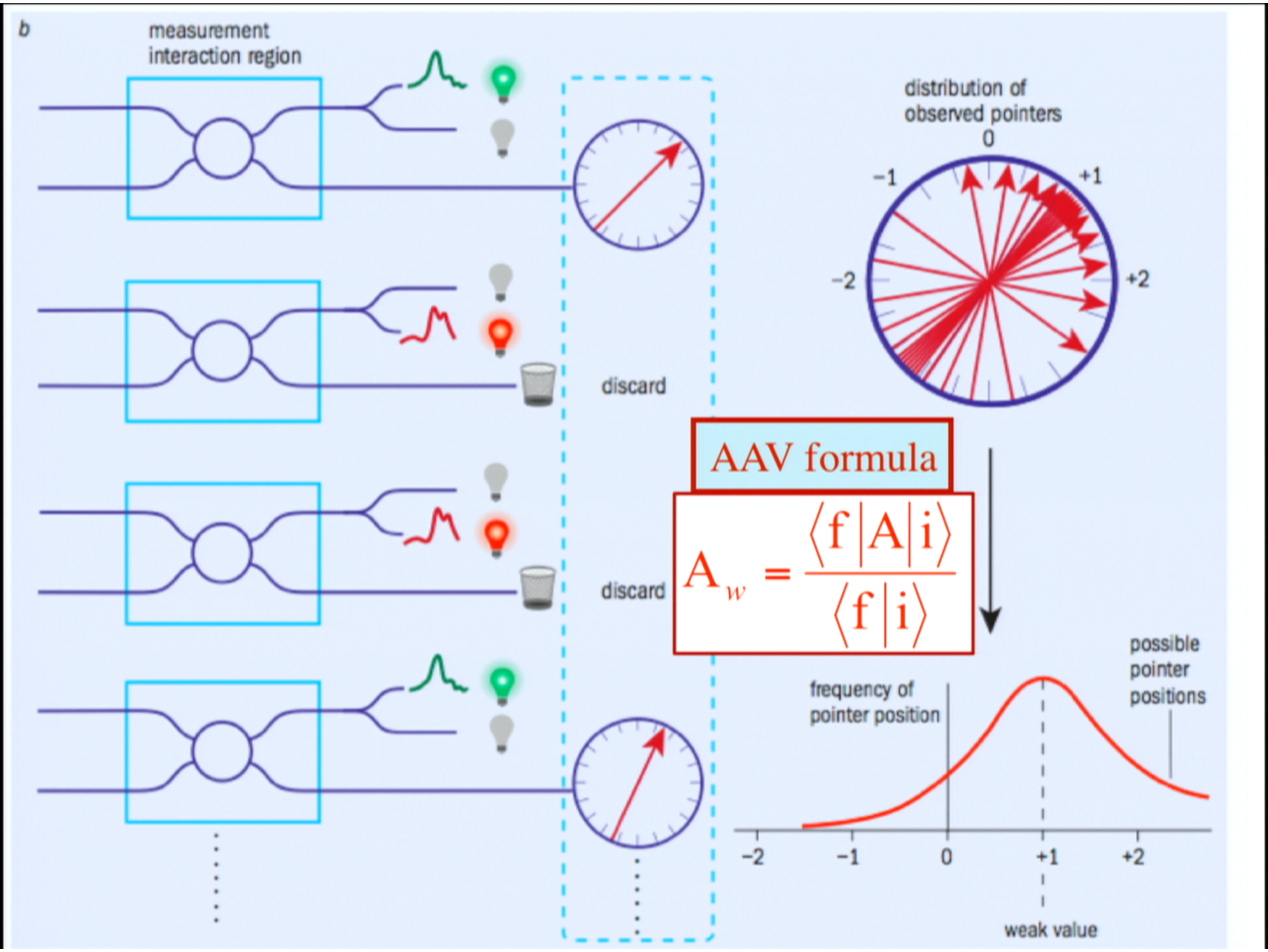
⇨ the "weak value"
(but how to determine?)

Operational effects of post-selecting on a particular final state



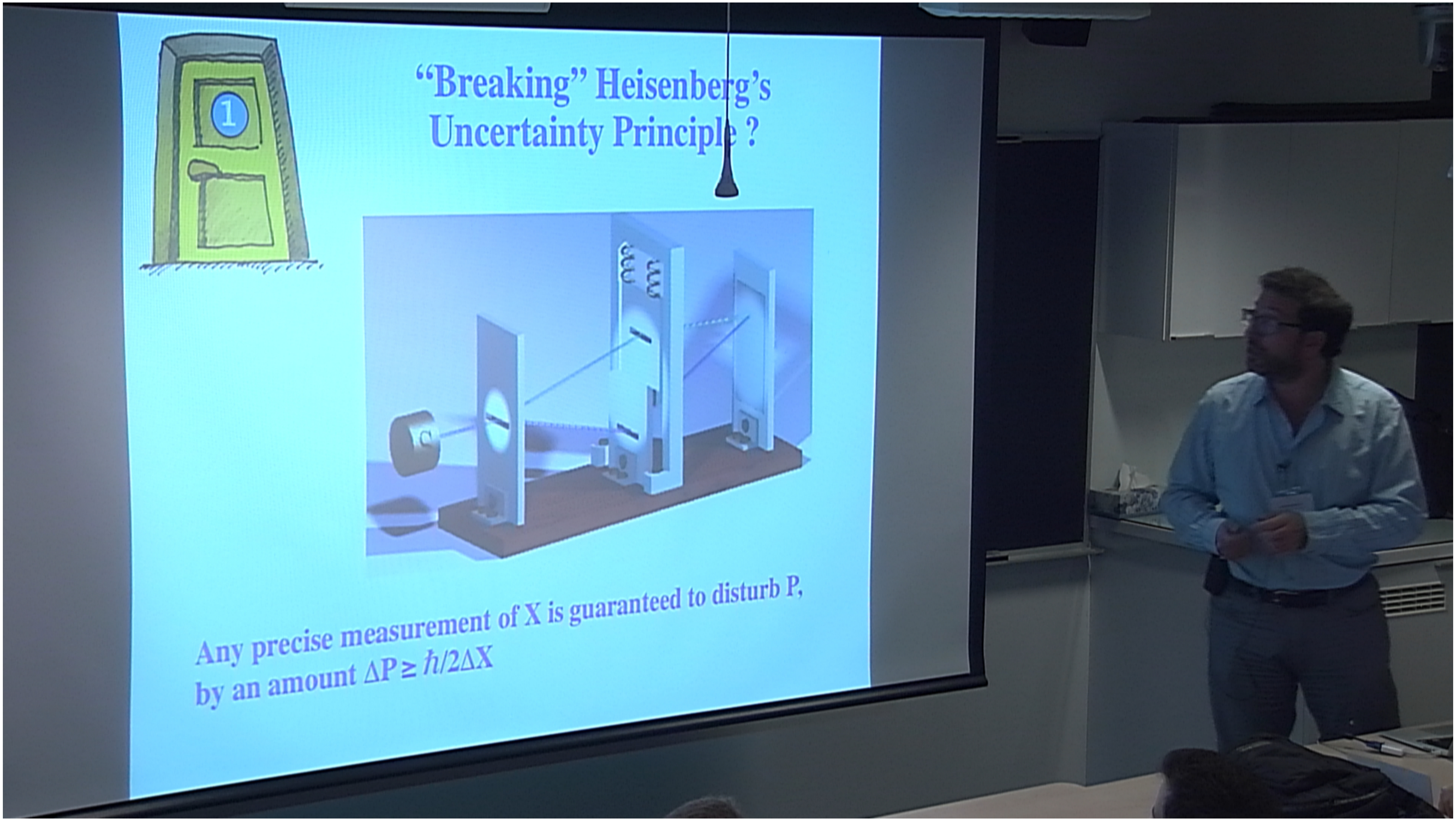
And now, even though each pointer position seems to be pretty random, if you make millions of measurements and build up statistics, you can figure out the average shift --


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



AAV formula

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



“Breaking” Heisenberg’s Uncertainty Principle ?

Any precise measurement of X is guaranteed to disturb P, by an amount $\Delta P \geq \hbar/2\Delta X$

"Any precise measurement of X is guaranteed to disturb P, by an amount $\Delta P \geq h/2\Delta X$"

What I've always taught my students:

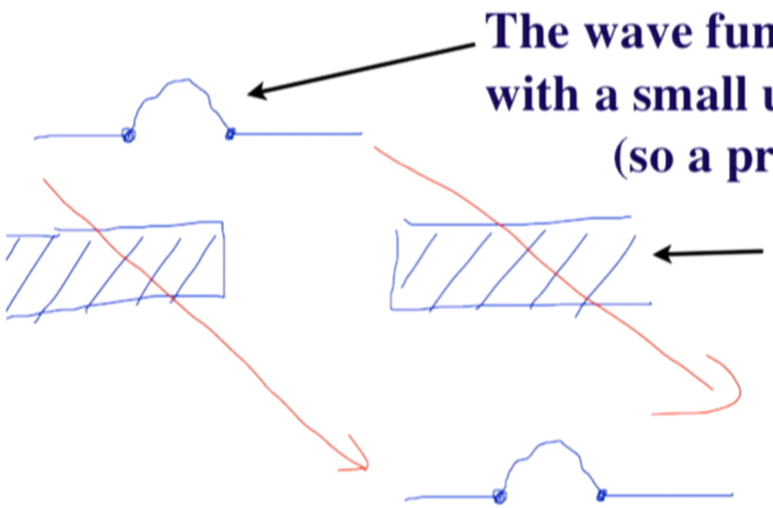
- This is true, but it puts a limit on measurement only.
- A much deeper statement puts a limit on *reality*:

"Any *state* in which X is *determined* precisely is guaranteed to have an *intrinsic* uncertainty in P, such that $\Delta P \geq h/2\Delta X$"

What I tell my students now:

Not only does the first version put a limit on measurement only, but it's also *wrong*!

Rotating-arm approximation for x & p...



The wave function of some particle, with a small uncertainty in position (so a pretty big one in momentum)

A slit – if the particle is transmitted, this constitutes a measurement that it was in the slit...

But if the slit is wider than the original wave function, the particle never even sees the walls; how could the particle be disturbed at all?

Ozawa's relation

Heisenberg's uncertainty principle
for *variances* is proved in every textbook,
and we take no issue with it:

$$\Delta(A)\Delta(B) \geq \langle[A,B]\rangle / 2$$

A similar relation for measurement precision
$\varepsilon(A)$ of the probe vs. disturbance to the
system $\eta(B)$ is, however, false:

$$\xcancel{\varepsilon(A)\eta(B) \geq \langle[A,B]\rangle / 2}$$

Ozawa, PRA 67, 042105 (2003):

$$\epsilon(A)\eta(B) + \epsilon(A)\Delta B + \eta(B)\Delta A \geq \frac{1}{2}\langle[A,B]\rangle$$

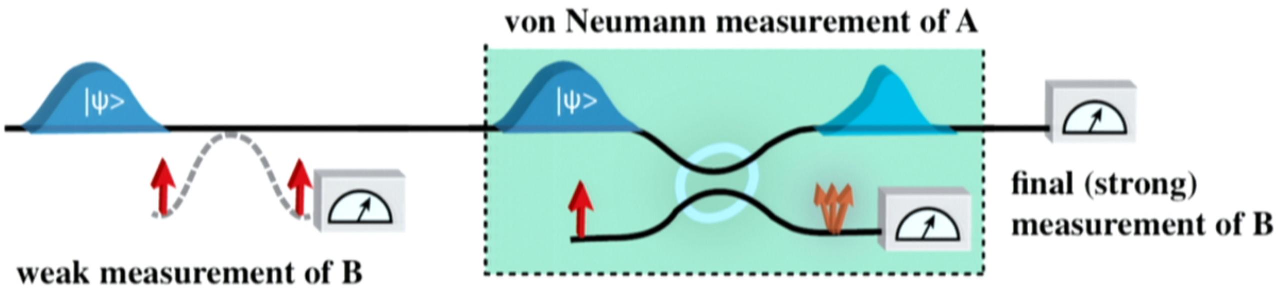
**But how can you measure the disturbance due to a measurement?
You would need to know B before and after the measurement –
but unless you're already in an eigenstate of B, this would change
the state (and the RHS of the inequality).**

Two clever approaches

(1)Don’t measure them directly, but extract them from a series of other measurements:
theory: Ozawa, Ann. Phys. 311, 350 (2004)
expt: Erhart *et al*., Nature Physics 8, 185 (2012)

(2) Use *weak measurement* to gently probe B before the disturbance, and compare the weak value with the post-selected value of B in order to tell how much the system was disturbed:
theory: Lund & Wiseman NJP 12, 093011 (2010)
expt: Rozema *et al*., PRL 109, 100404 (2012) *(this talk)*

Proposal Using Weak Measurements



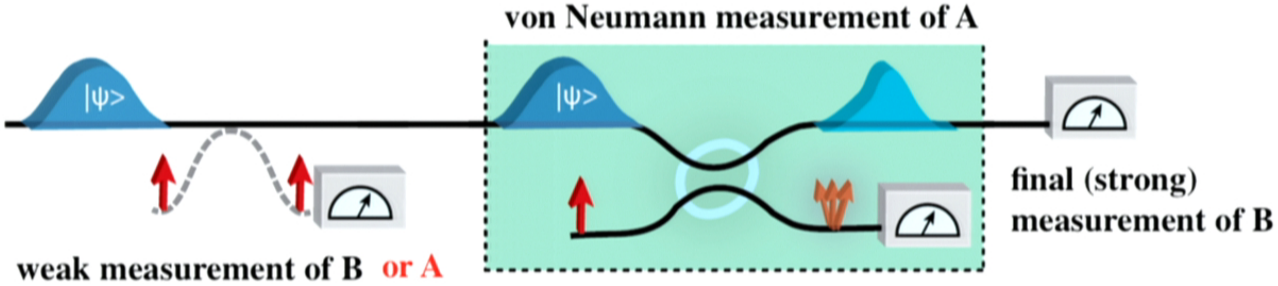
Consider a von Neumann measurement of A

- The system becomes entangled with probe, disturbing the system

- Define disturbance to B as the RMS difference between the value of B before and after the measurement

Lund & Wiseman, NJP 12, 093011 (2010)

Proposal Using Weak Measurements



von Neumann measurement of A

weak measurement of B or A

final (strong) measurement of B

Consider a von Neumann measurement of A

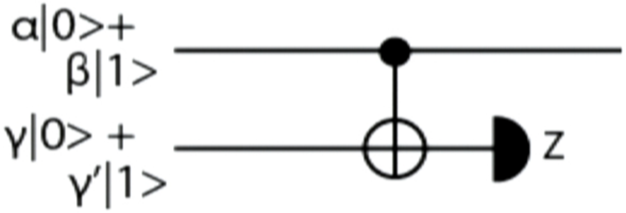
- The system becomes entangled with probe, disturbing the system

- Define disturbance to B as the RMS difference between the value of B before and after the measurement
- Define precision of A as the RMS difference between the value of A of the system before the measurement and the value of A on the probe

Lund & Wiseman, NJP 12, 093011 (2010)

Use a C-NOT gate as a variable-precision interaction

How do you control the strength of a C-NOT?



- **If $\gamma=1$: $\alpha |00> + \beta |11>$**
  - **Z_2 has complete information about Z_1**
- **If $\gamma=\gamma'$: $(\alpha|0> + \beta|1>) |+>$**
  - **Z_2 has no information about Z_1**

Setting the probe state sets the effective measurement strength

(cf. Pryde et al. PRL **94** 220405 (2005))

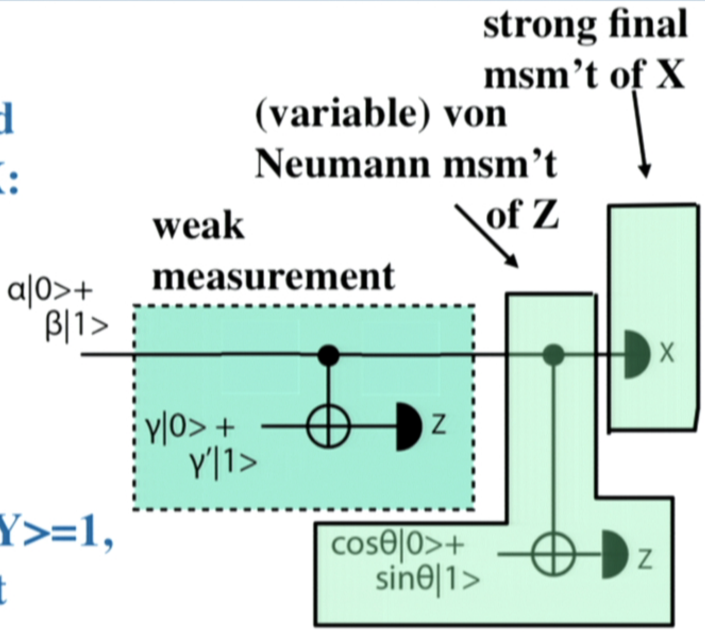
Quantum Circuit Implementation

Let us measure the precision of Z and the resulting disturbance caused to X:

-Heisenberg's inequality says:

$$\epsilon(Z) \times \eta(X) \geq \frac{1}{2}\langle [Z, X] \rangle = \frac{1}{2}\langle Y \rangle$$

We will see the largest violation for <Y>=1, which requires a Y eigenstate as input



strong final msm't of X

(variable) von Neumann msm't of Z

weak measurement

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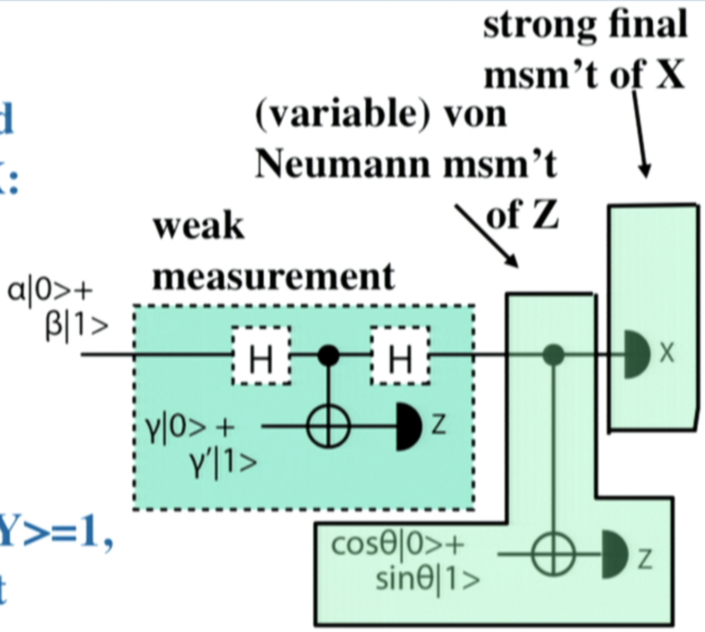


strong final msm't of X

(variable) von Neumann msm't of Z

weak measurement

We will see the largest violation for <Y>=1, which requires a Y eigenstate as input

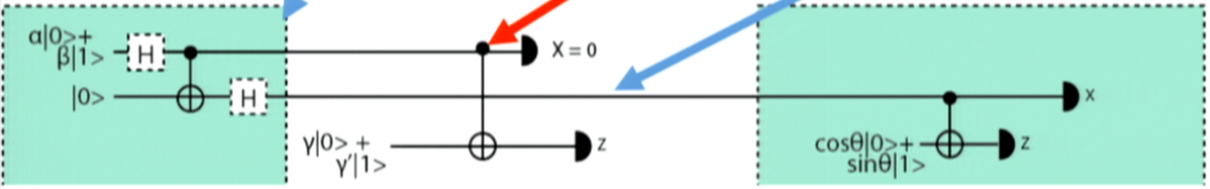
Do one experiment with H's in to measure disturbance of X, and one with H's out to measure precision of Z

Putting it all together

To implement consecutive C-NOT gates start with an entangled state

Do first C-NOT with qubit 1,

teleport state to qubit 2, leaving it free to control a second C-NOT



Entangled State Preparation

Weak Measurement and Post-Selection

von Neumann Measurement

Putting it all together

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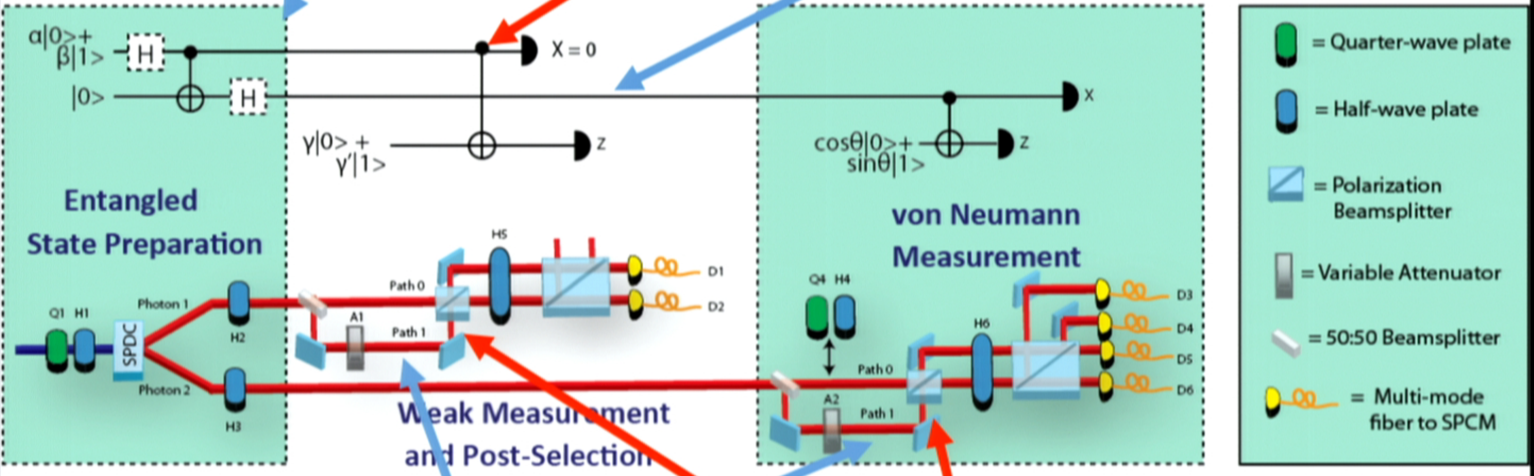
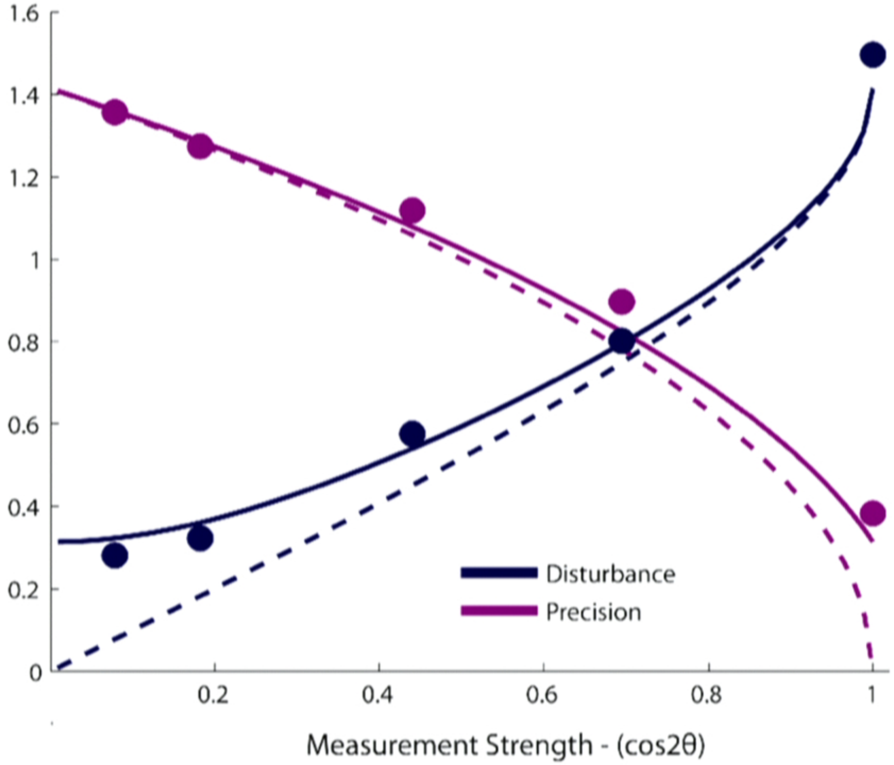


Probes are both path qubits
State set with variable attenuator

PBS's implement CNOTs
Polarization qubit controls the path qubit

Results – Disturbance & Precision

Fix the strength of the weak probe, vary the strength of the von Neumann measurement and observe the precision and disturbance



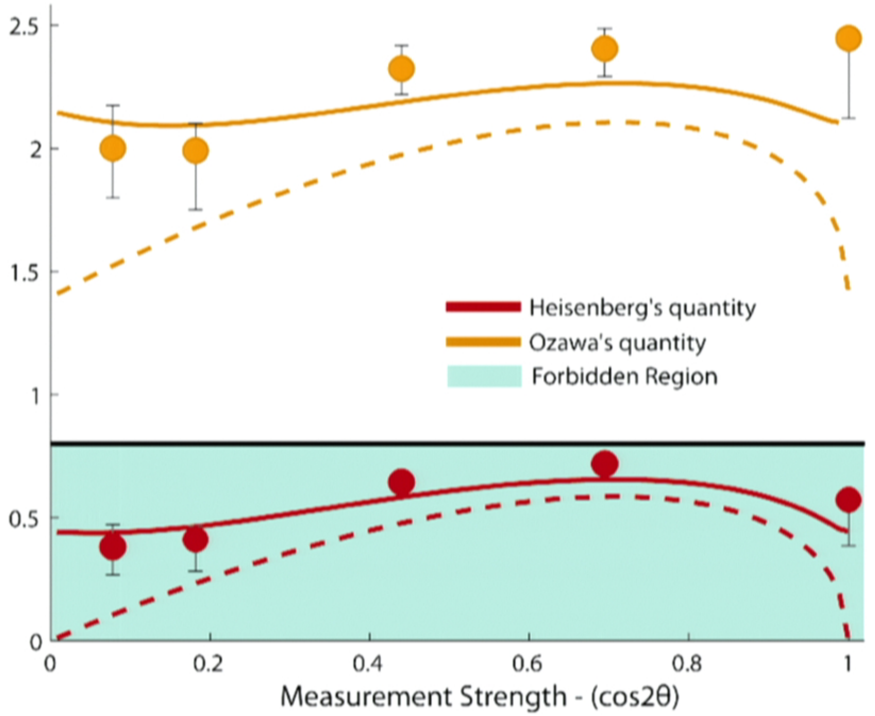
Dashed lines are theory, solid lines are simulations accounting only for imperfect entangled state preparation

Results – Ozawa & Heisenberg's Quantities

Rozema et al., PRL 109, 100404 (2012)

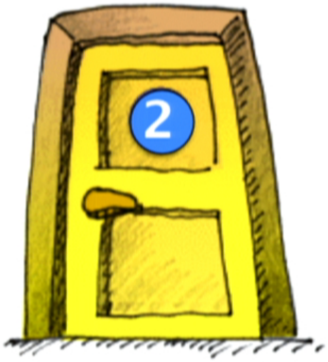
Forbidden region set by measuring of <Y> on the qubit after the weak measurement and teleportation

Dashed lines are theory, solid lines are simulations accounting only for imperfect entangled state preparation

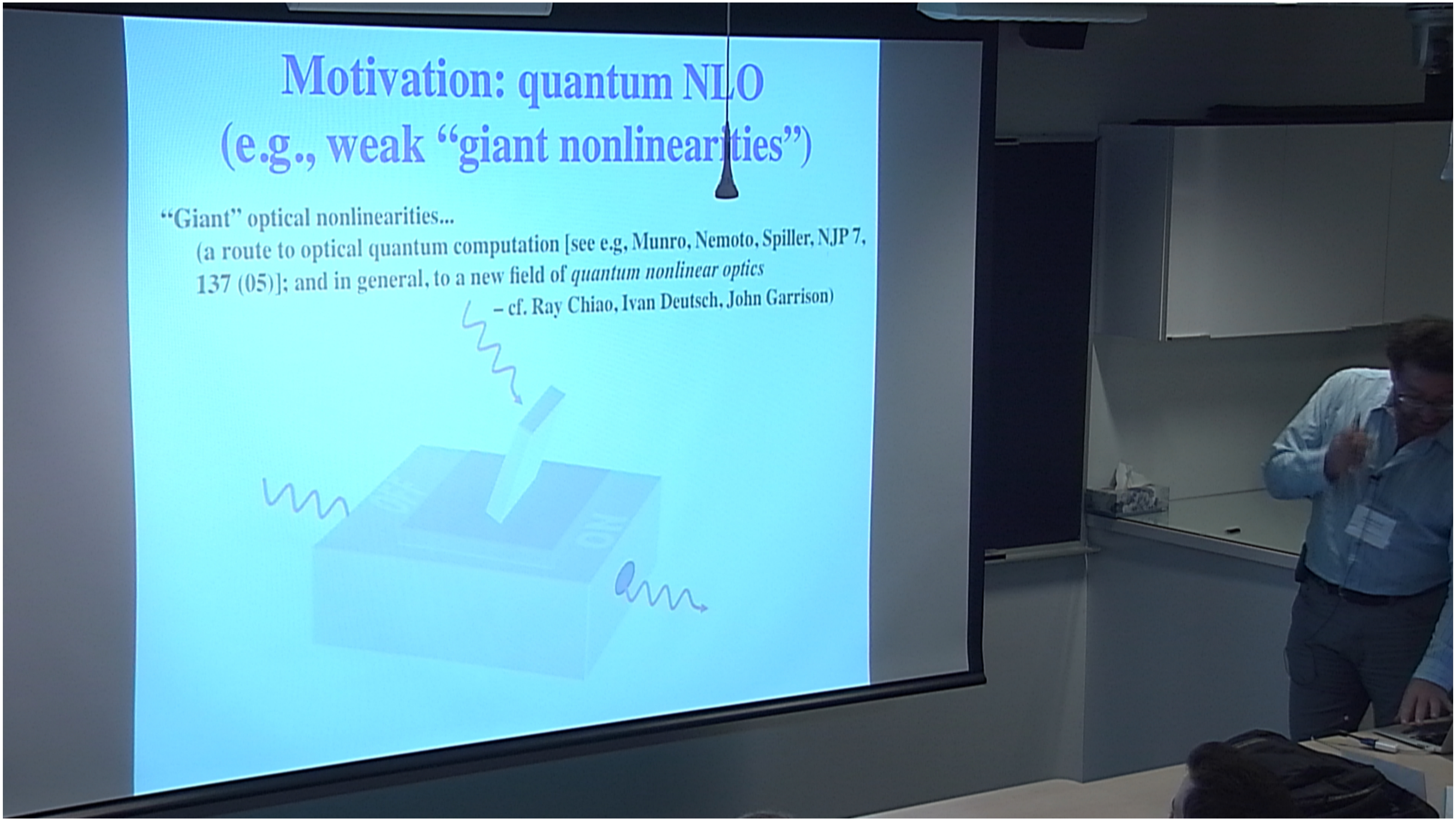


Heisenberg's relation is clearly violated $\varepsilon(A)\eta(B) \geq 1/2\langle[A,B]\rangle$

Ozawa's remains valid $\epsilon(A)\eta(B) + \epsilon(A)\Delta B + \eta(B)\Delta A \geq \frac{1}{2}\langle[A,B]\rangle$



How to count to 8 on a single photon



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)

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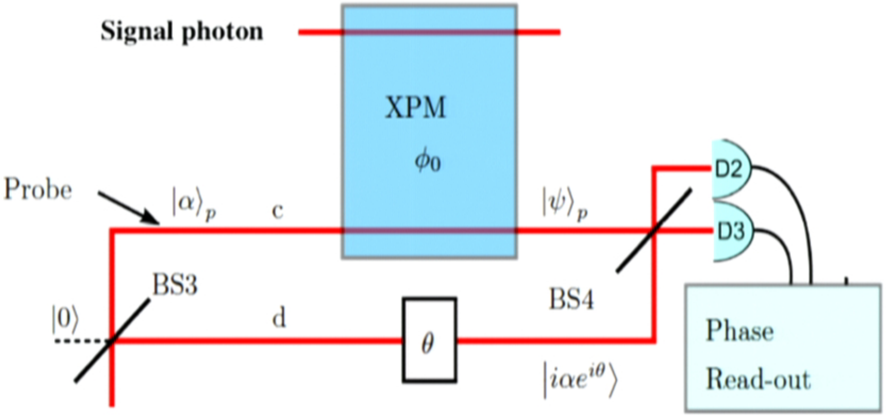
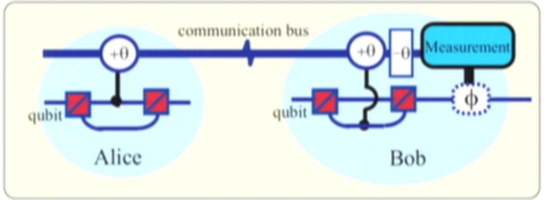
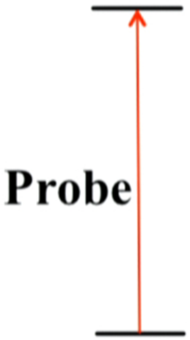


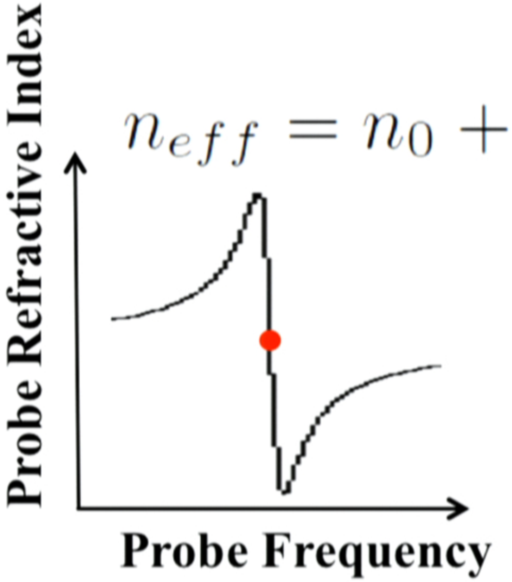


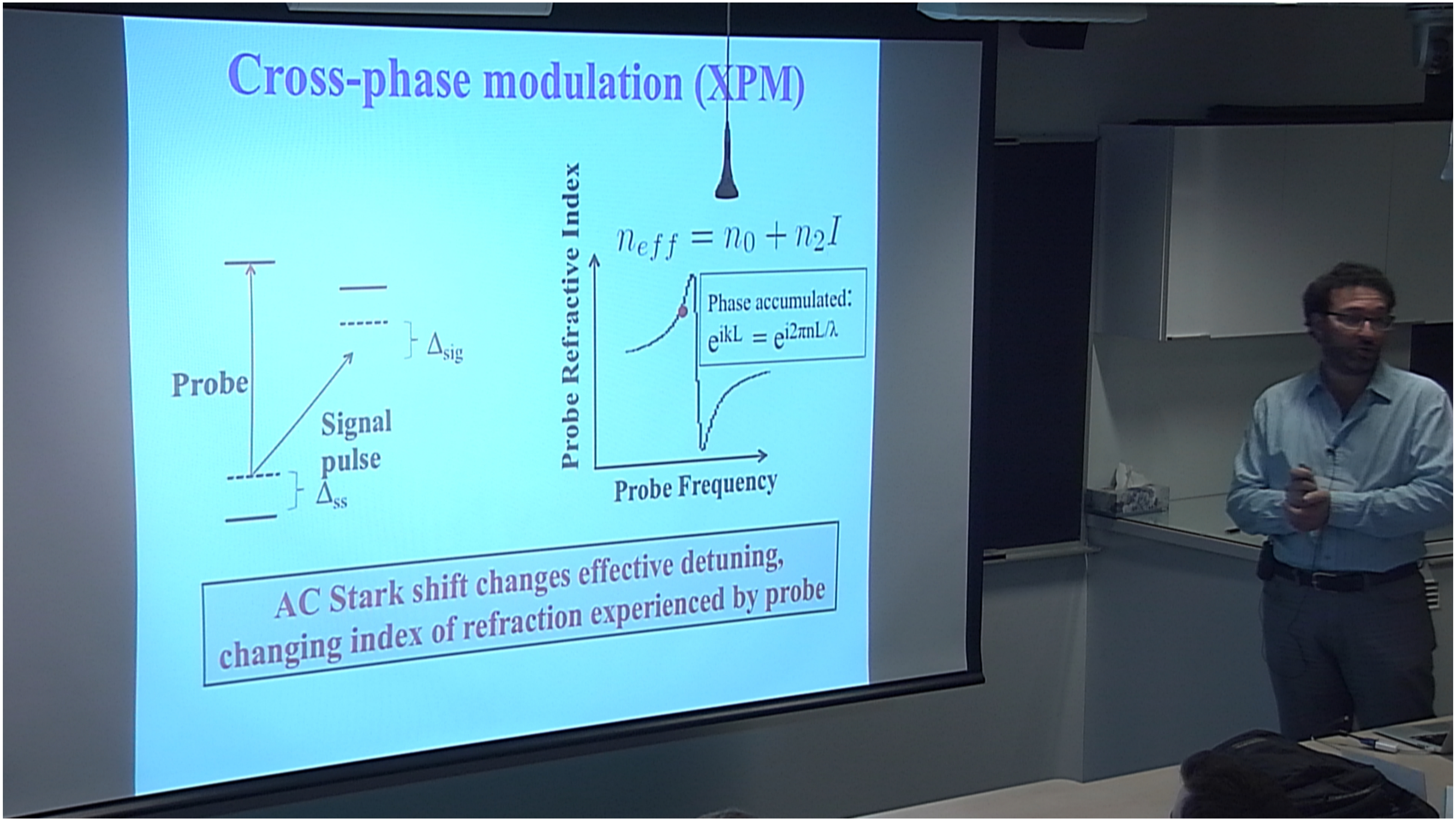
(Also of course, cf. “giant giant nonlinearities,”
e.g., Lukin & Vuletic with Rydberg atoms; Jeff Kimble *et al.* on nanophotonic approaches; Gaeta Rb in hollow-core fibres; et cetera)

Cross-phase modulation (XPM)



$$n_{eff} = n_0 + n_2 I$$





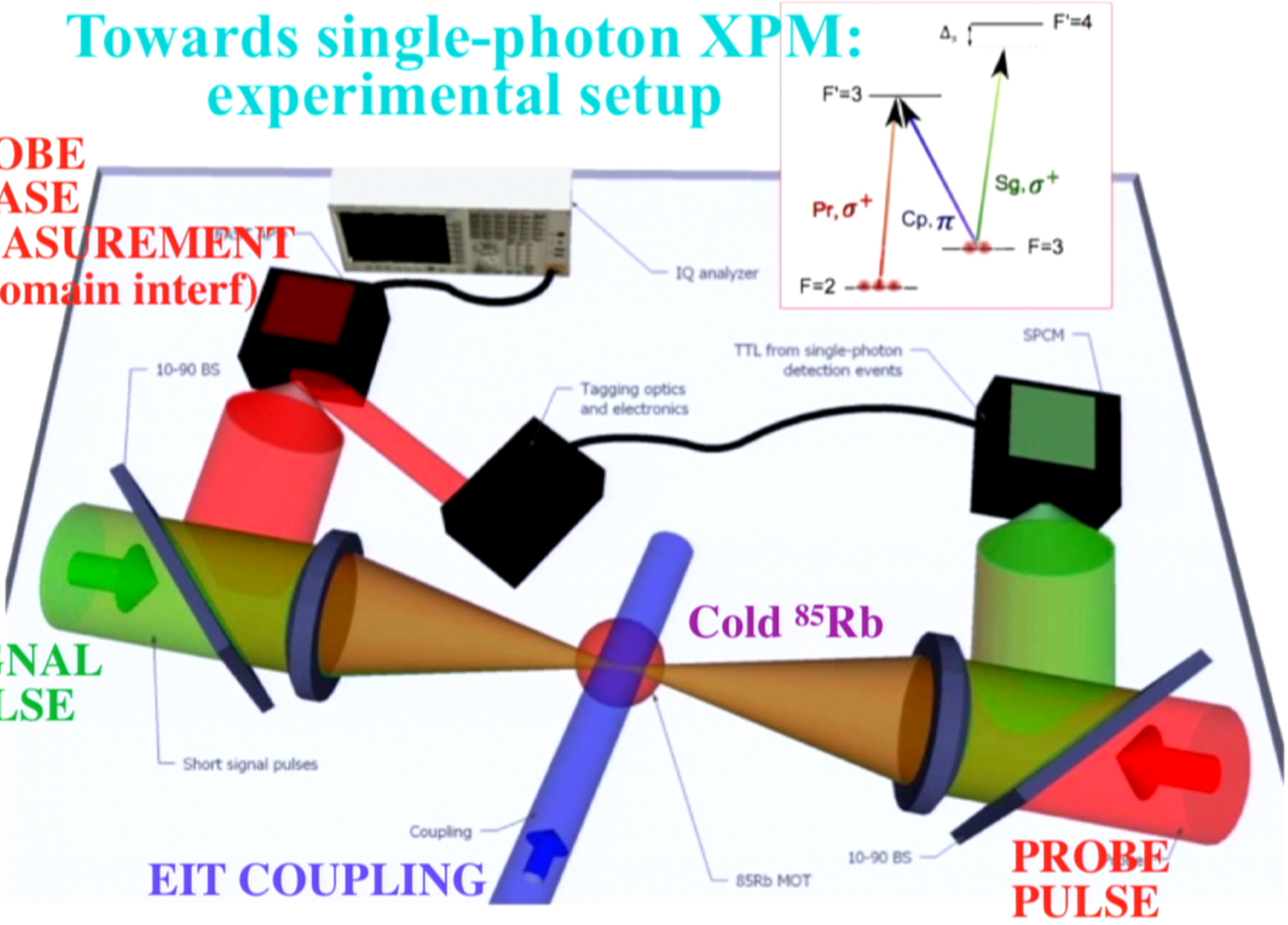
Cross-phase modulation (XPM)

$$n_{eff} = n_0 + n_2 I$$

Phase accumulated:
$e^{ikL} = e^{i2\pi nL/\lambda}$

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

Towards single-photon XPM: experimental setup



PROBE PHASE MEASUREMENT (f-domain interf)

SIGNAL PULSE

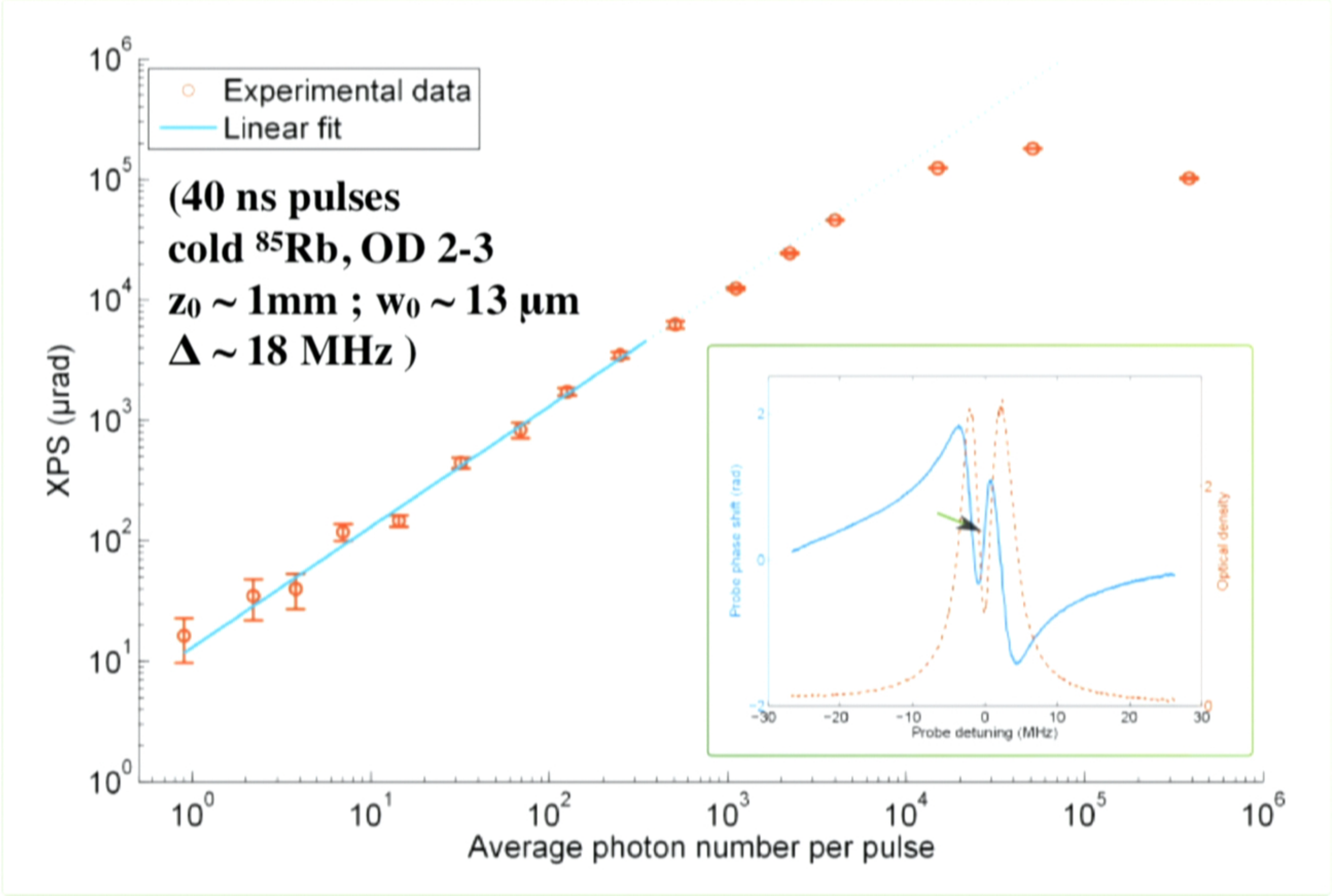
Cold ^{85}Rb

EIT COUPLING

PROBE PULSE

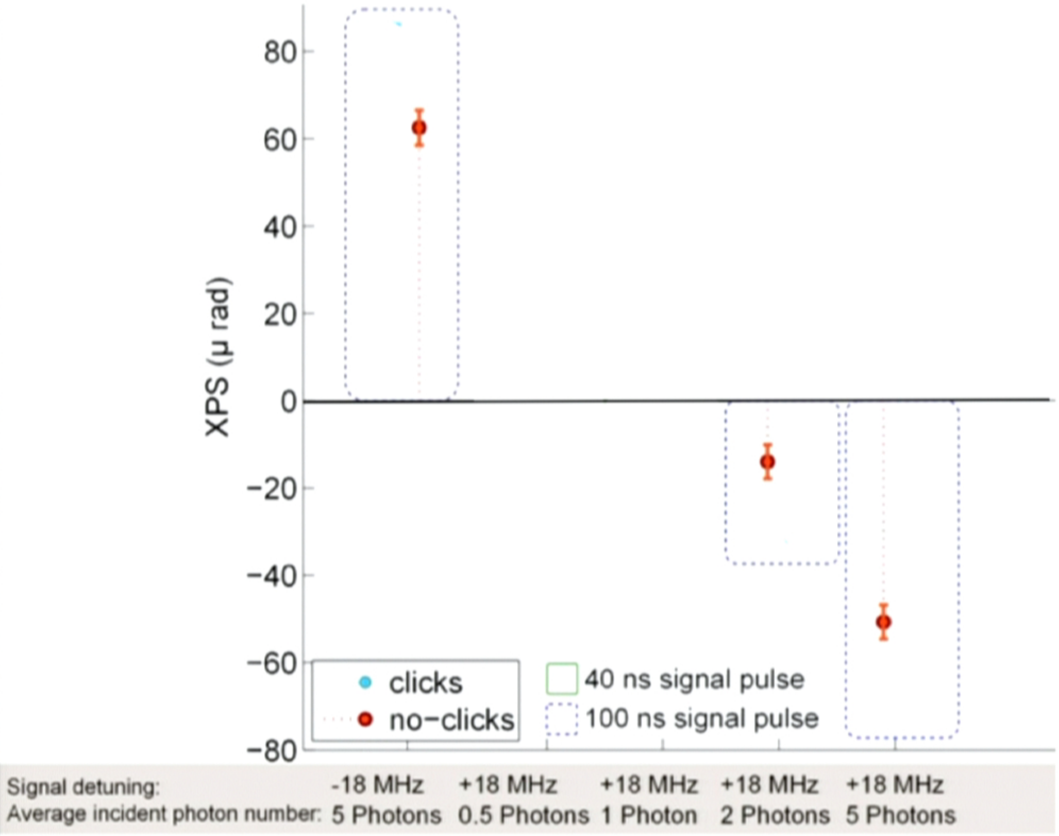
A. Feizpour et al., Nature Physics, DOI: 10.1038/nphys3433 (2015)

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

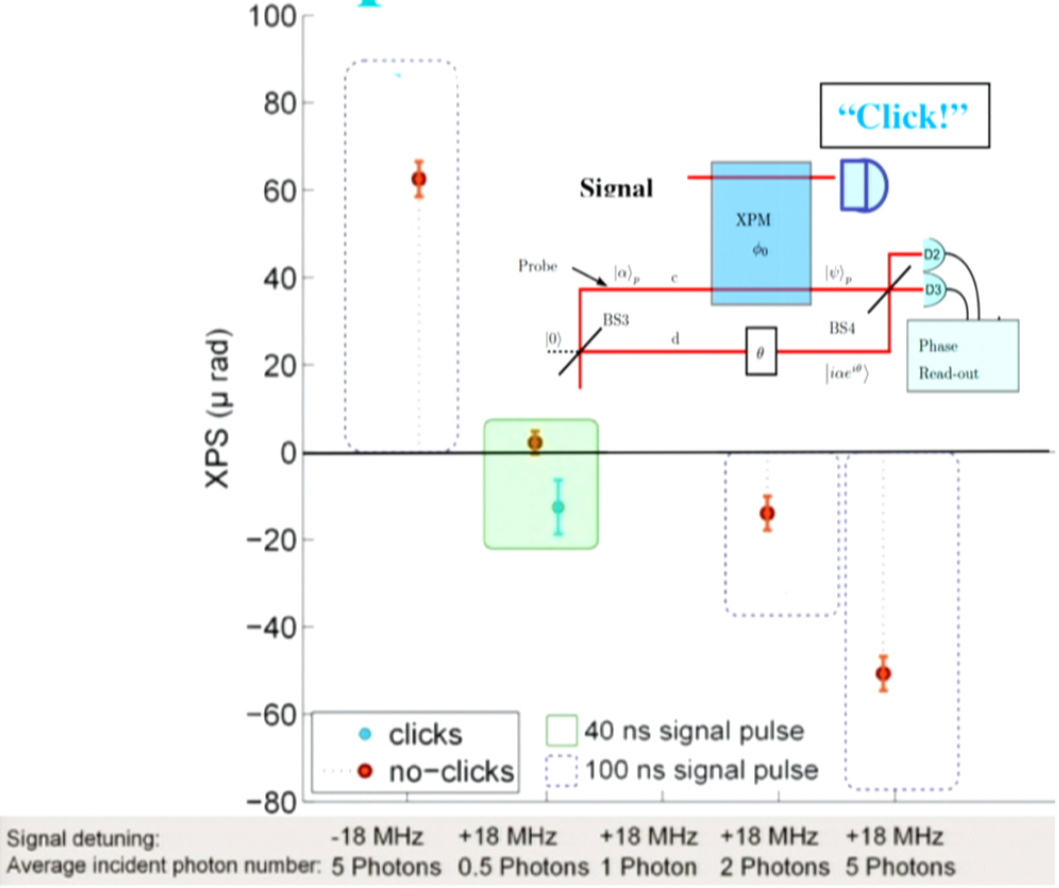


(40 ns pulses
cold ^{85}Rb, OD 2-3
$z_0 \sim 1$mm ; $w_0 \sim 13$ µm
$\Delta \sim 18$ MHz)

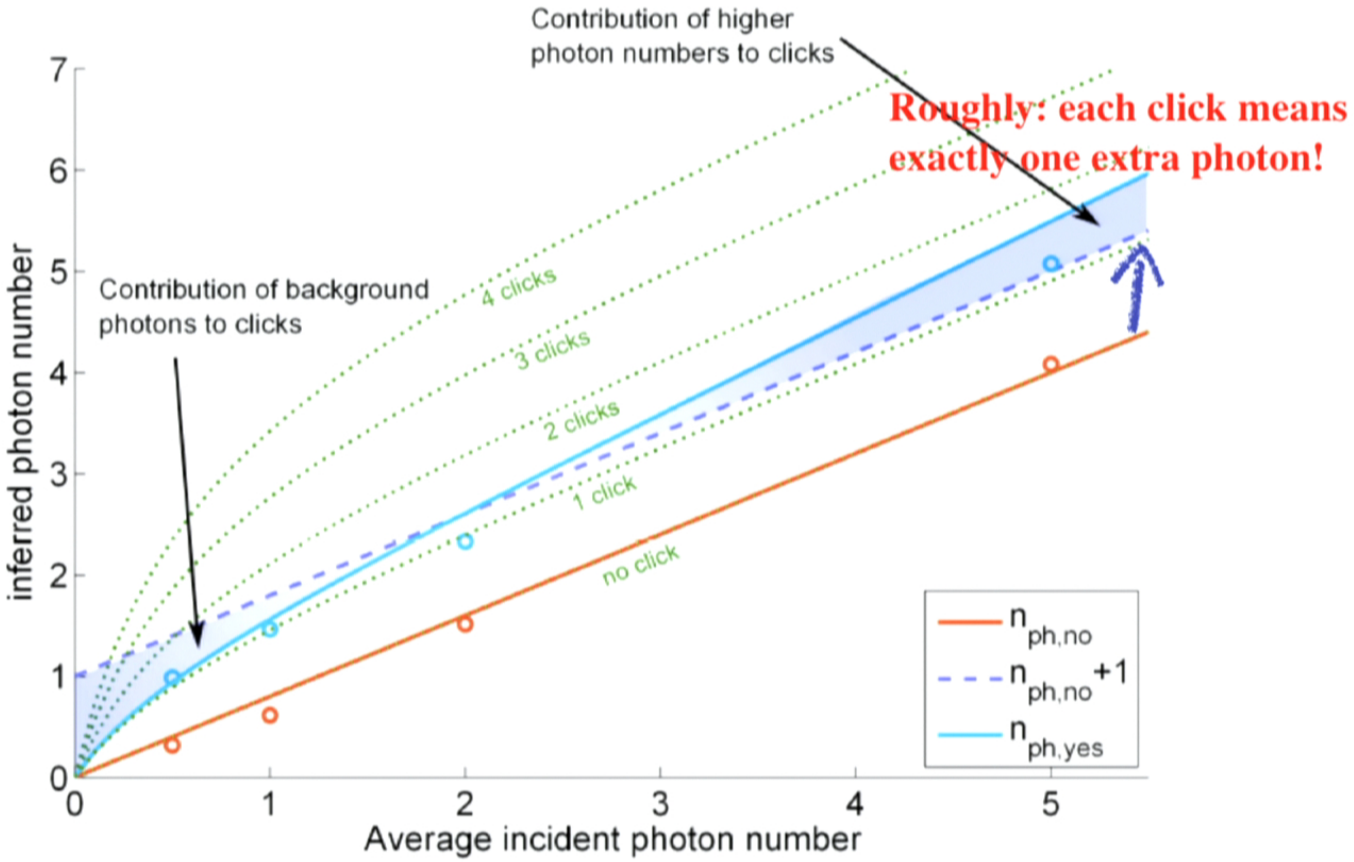
Non-linear phase shift due to single photons



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



Post-selected single photons

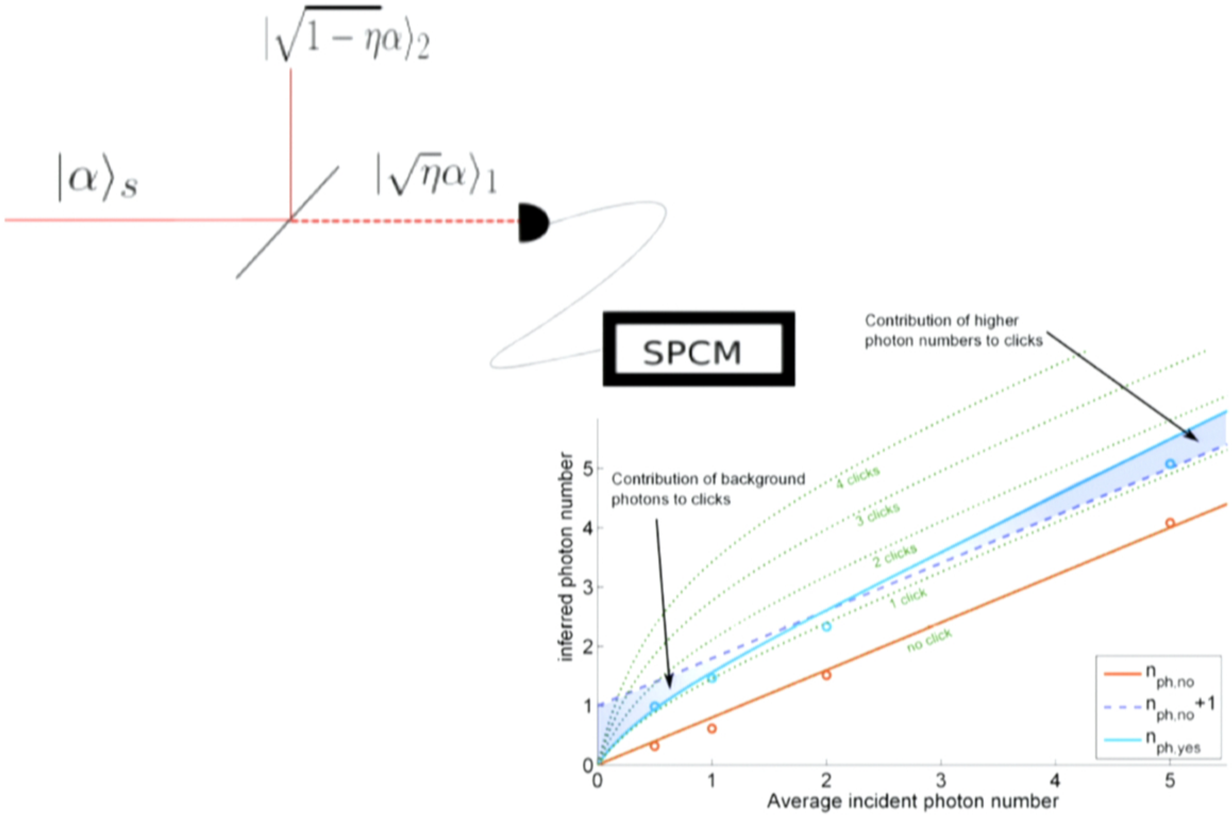


Contribution of higher photon numbers to clicks

Contribution of background photons to clicks

Roughly: each click means exactly one extra photon!

Post-selected single photons



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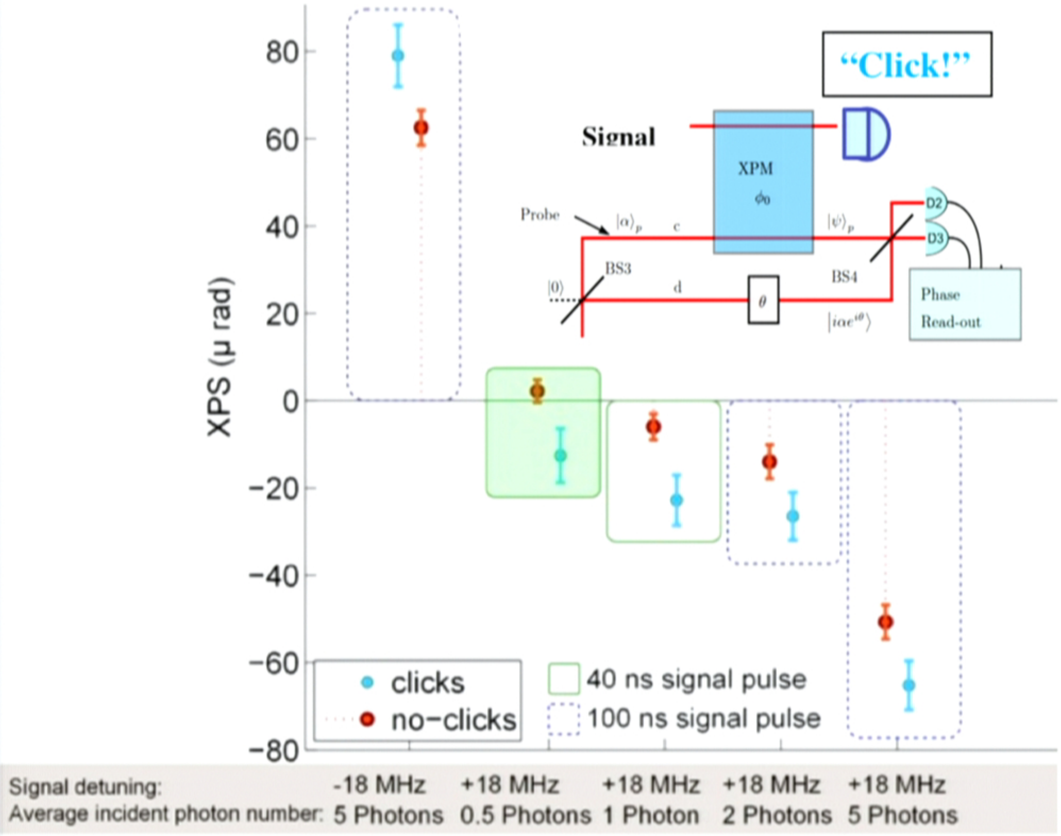
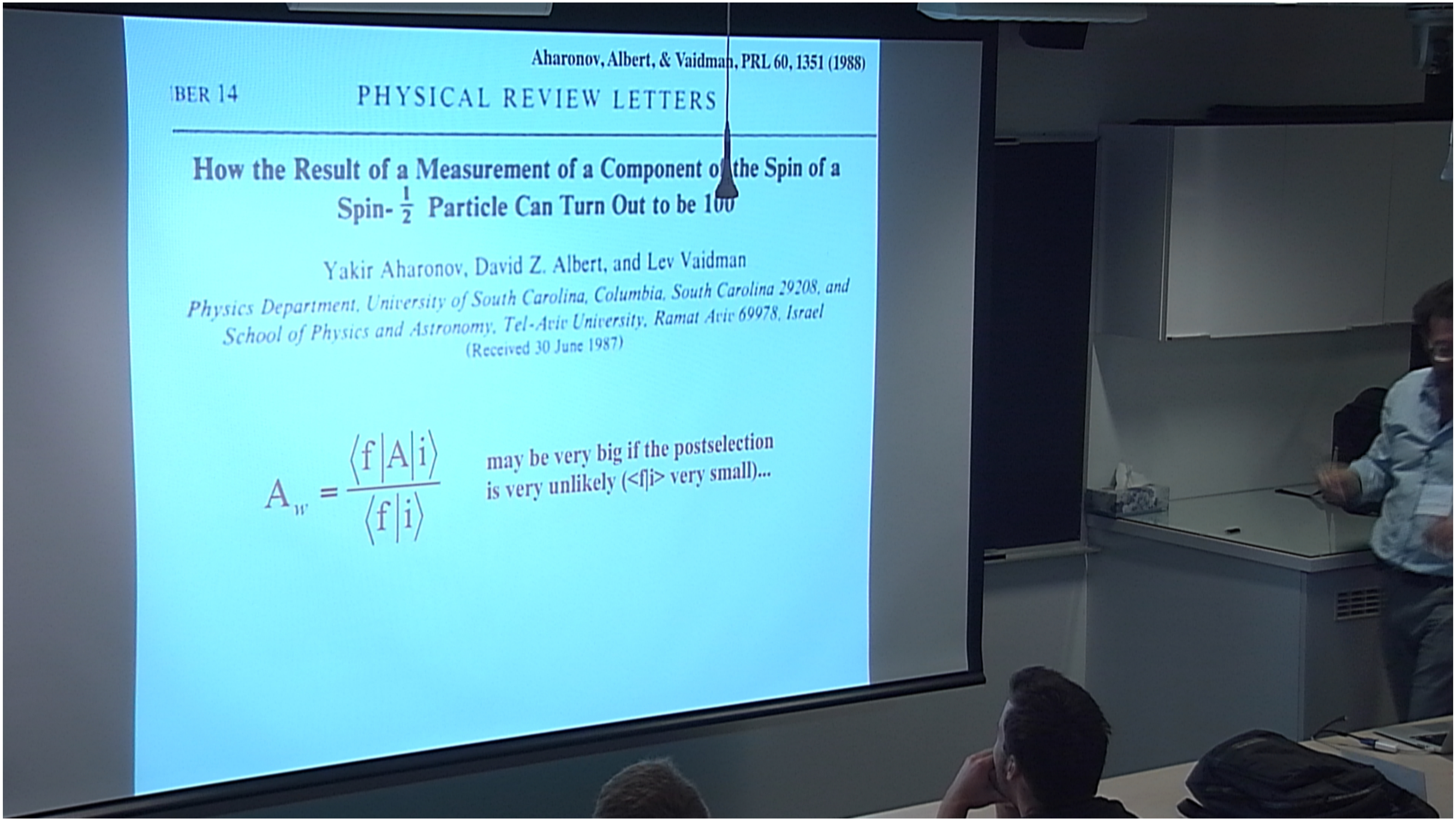
Non-linear phase shift due to single photons



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



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

BER 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

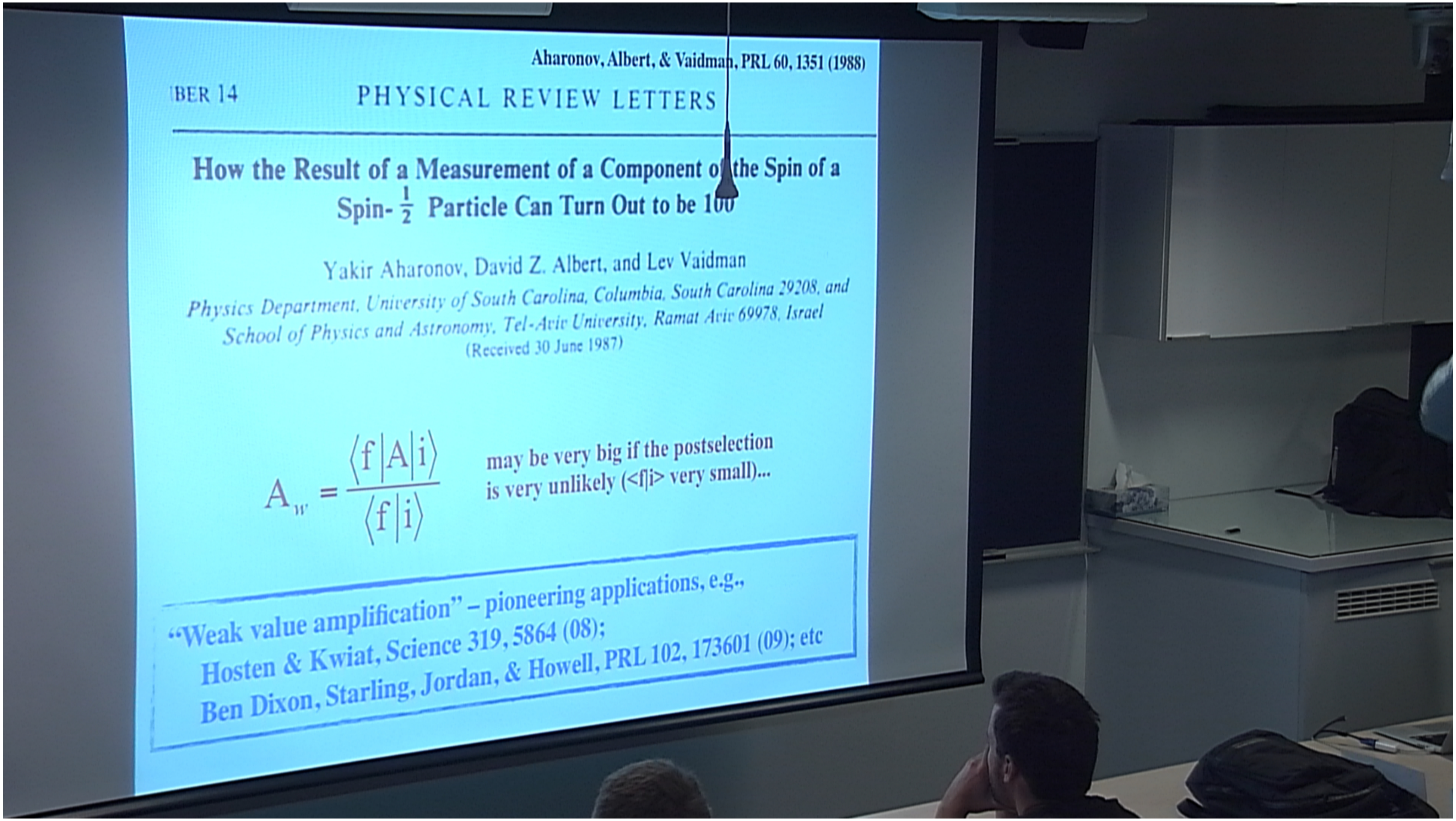
Yakir Aharonov, David Z. Albert, and Lev Vaidman

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)...



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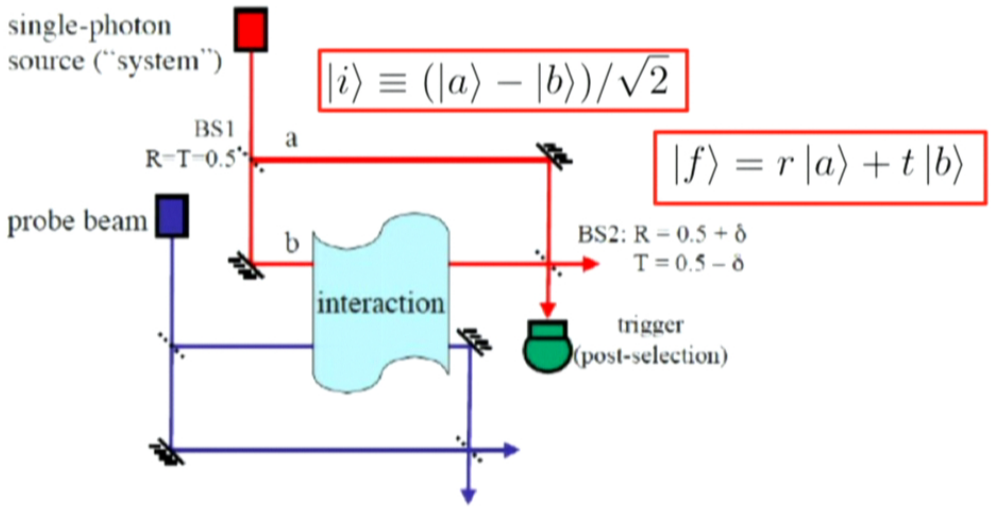
"Weak value amplification" – pioneering applications, e.g.,
Hosten & Kwiat, Science 319, 5864 (08);
Ben Dixon, Starling, Jordan, & Howell, PRL 102, 173601 (09); etc

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

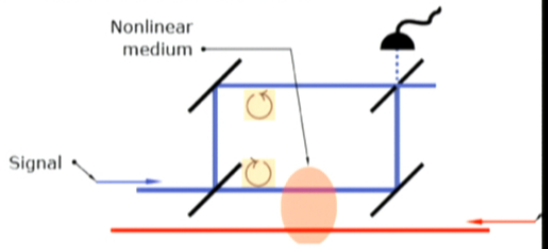


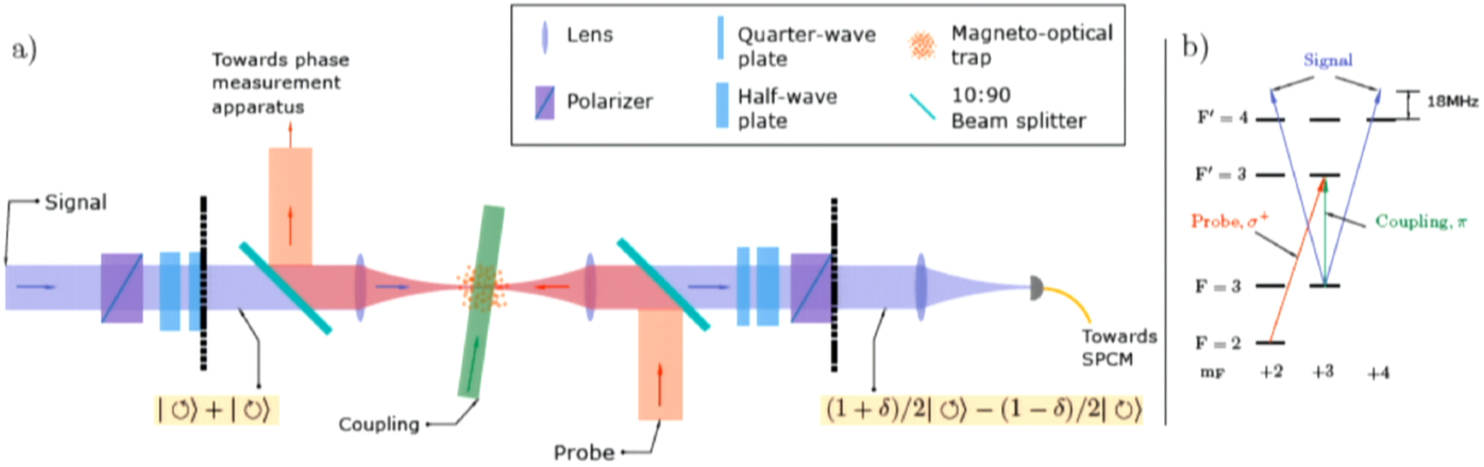
$$|i\rangle \equiv (|a\rangle - |b\rangle)/\sqrt{2}$$

$$|f\rangle = r\,|a\rangle + t\,|b\rangle$$

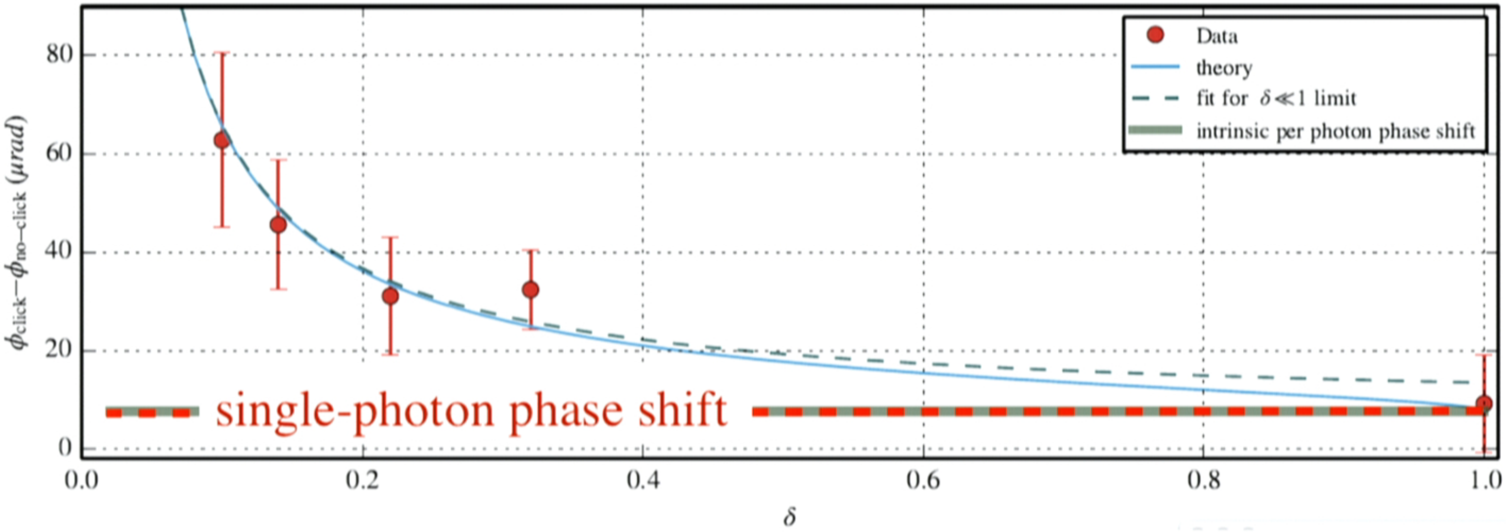
<u>Weak Measurement Amplification of Single-Photon Nonlinearity</u>,
Amir Feizpour, Xingxing Xing, and Aephraim M. Steinberg
Phys Rev Lett 107, 133603 (2011)

Polarisation interferometer





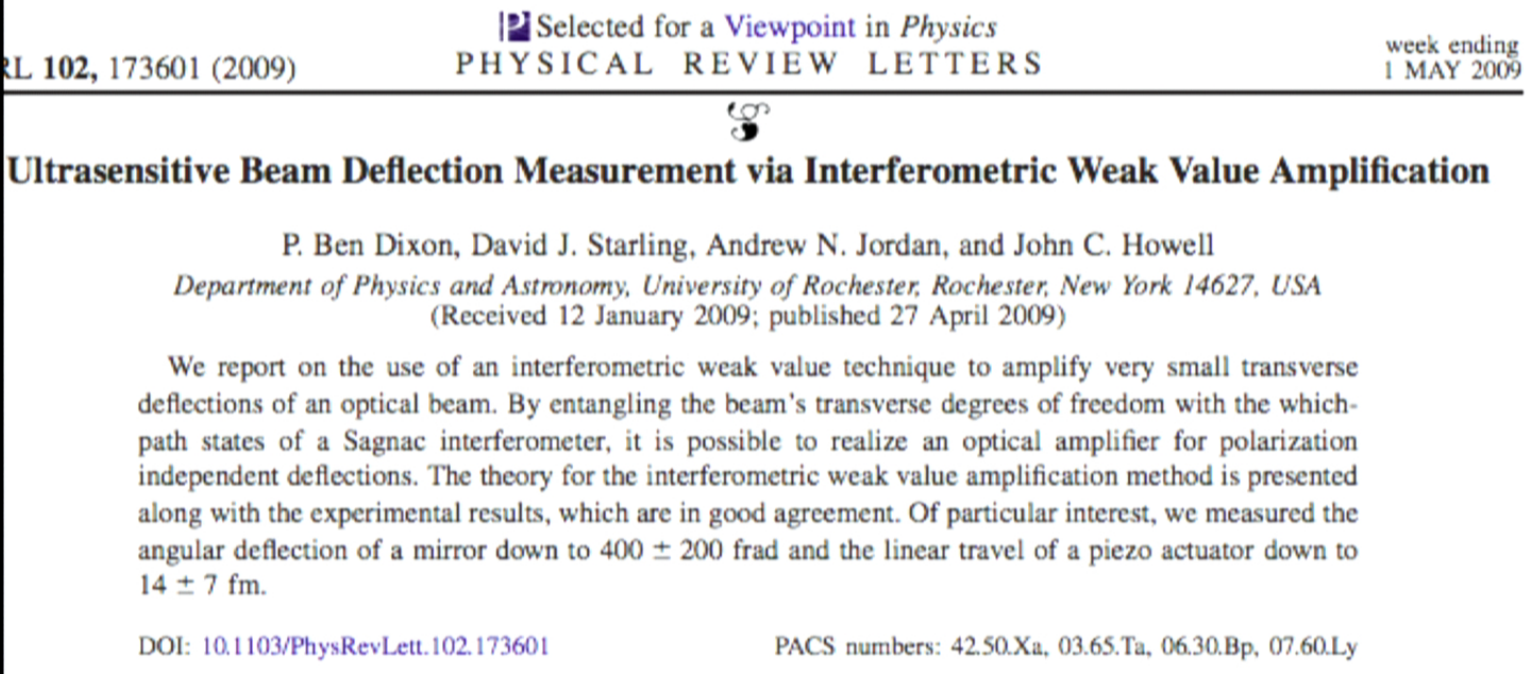
The phase shift due to an appropriately post-selected photon



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

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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.

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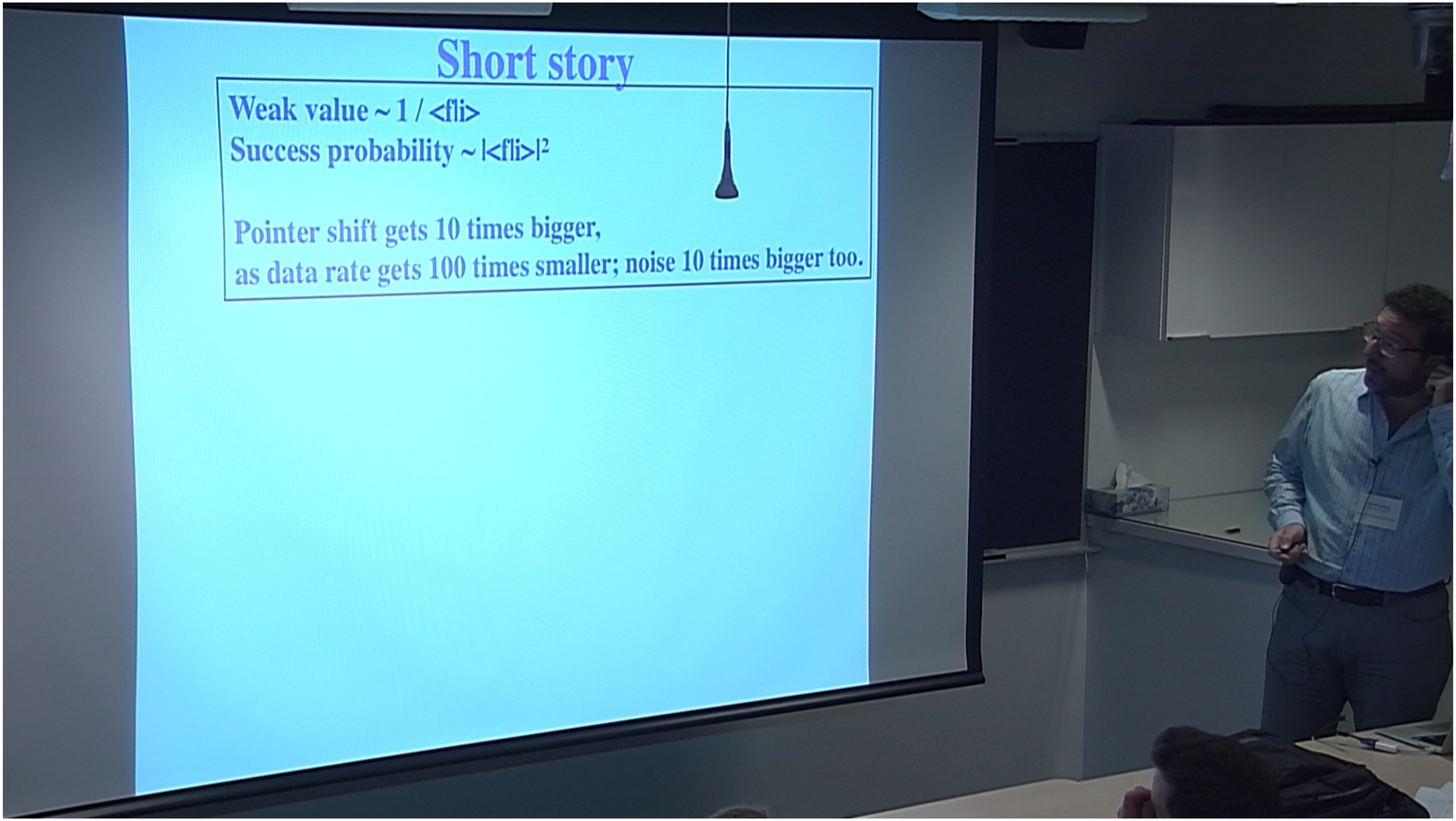


Short story

Weak value ~ 1 / <f|i>

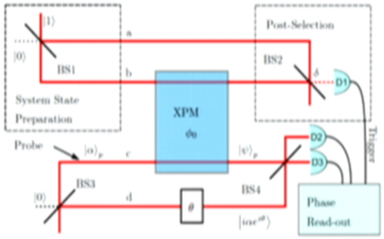
Success probability ~ |<f|i>|²

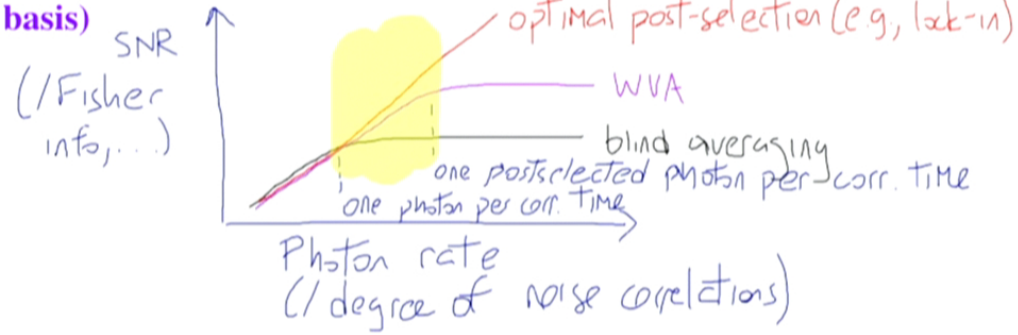
Pointer shift gets 10 times bigger,
as data rate gets 100 times smaller; noise 10 times bigger too.

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 to appear...





WE CONTEND WVA IS USEFUL IN THE FOLLOWING SITUATIONS:

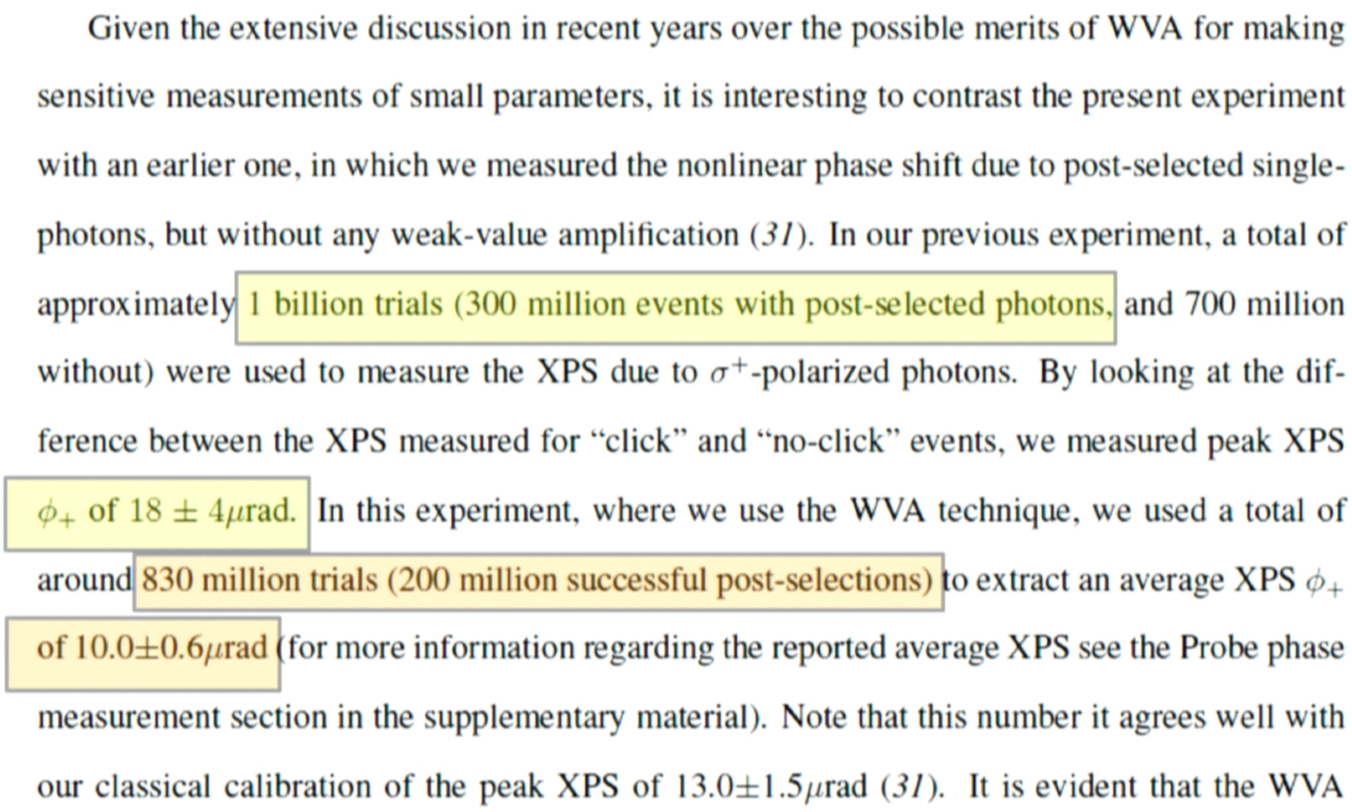
(1) limited by detector saturation

(2) most bins "empty" anyway

(3) noise correlation time > time between photons

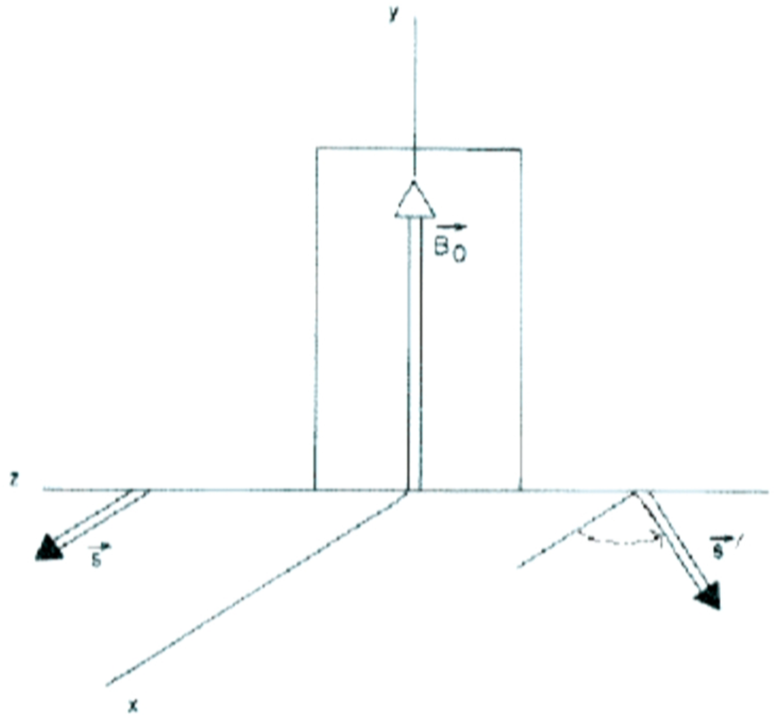
(IN THIS REGIME, IT IS BETTER THAN STRAIGHT AVERAGING, YET STRICTLY SUB-OPTIMAL. IT IS RELATED TO THE BETTER – AND BETTER-KNOWN – "LOCK-IN" TECHNIQUE, BUT POTENTIALLY MORE "ECONOMICAL")

One unexpected advantage



Given the extensive discussion in recent years over the possible merits of WVA for making sensitive measurements of small parameters, it is interesting to contrast the present experiment with an earlier one, in which we measured the nonlinear phase shift due to post-selected single-photons, but without any weak-value amplification (*31*). In our previous experiment, a total of approximately 1 billion trials (300 million events with post-selected photons, and 700 million without) were used to measure the XPS due to σ^+-polarized photons. By looking at the difference between the XPS measured for "click" and "no-click" events, we measured peak XPS ϕ_+ of $18 \pm 4\mu$rad. In this experiment, where we use the WVA technique, we used a total of around 830 million trials (200 million successful post-selections) to extract an average XPS ϕ_+ of $10.0 \pm 0.6\mu$rad (for more information regarding the reported average XPS see the Probe phase measurement section in the supplementary material). Note that this number it agrees well with our classical calibration of the peak XPS of $13.0 \pm 1.5\mu$rad (*31*). It is evident that the WVA

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



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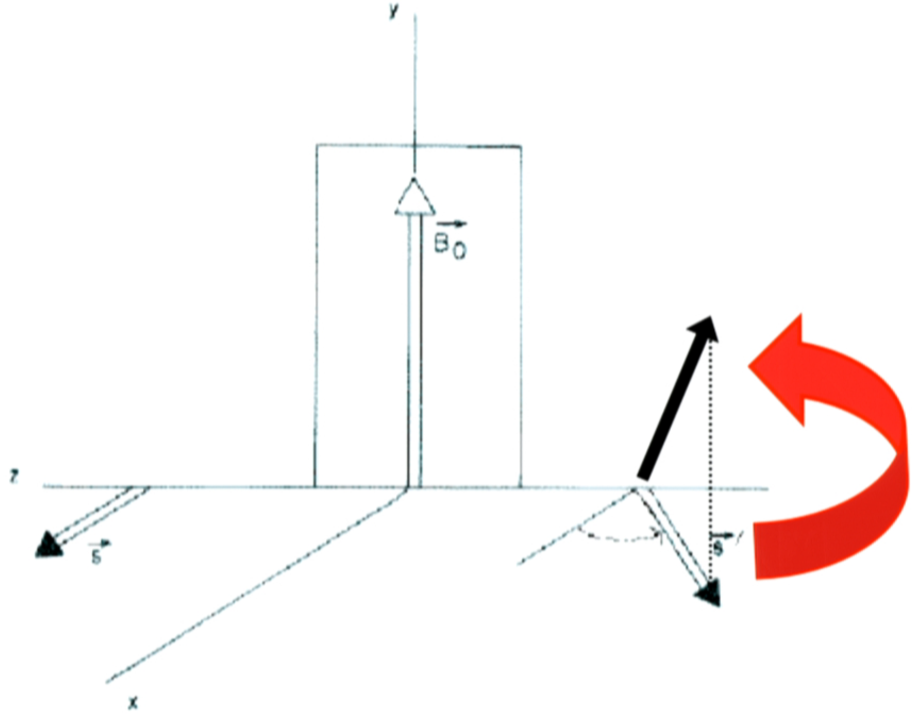

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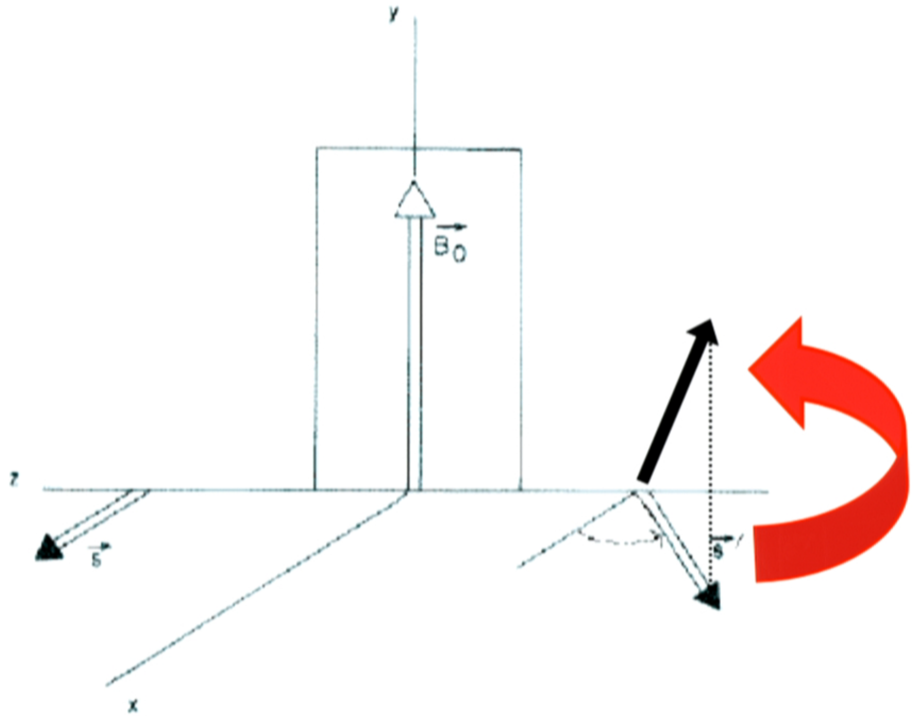
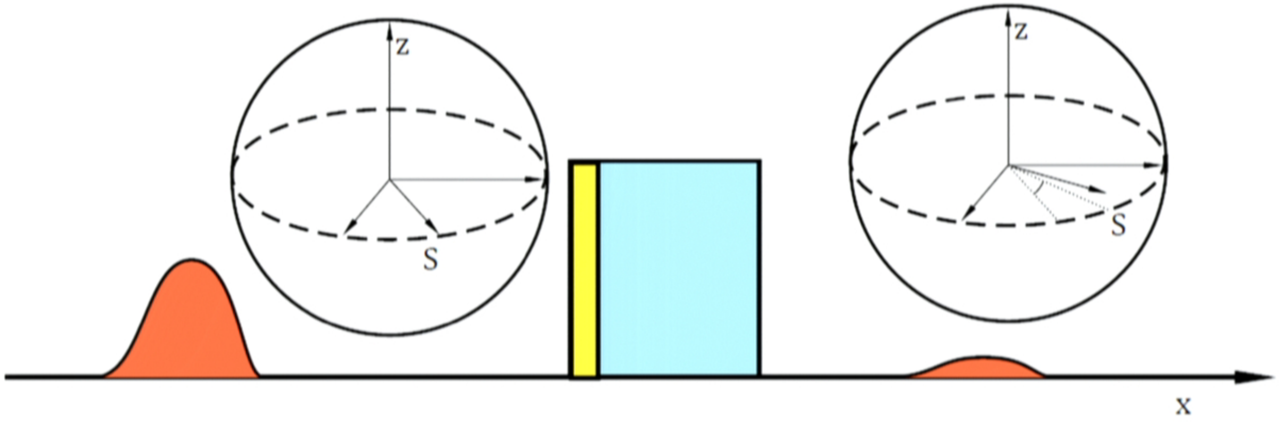


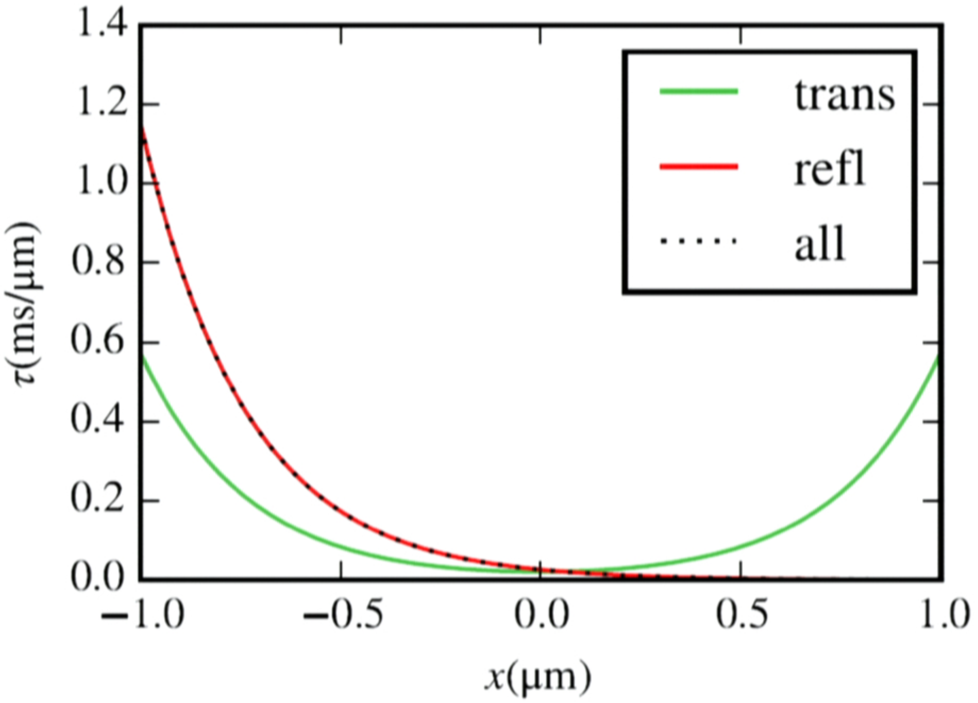
Two components mystified Büttiker;
Feynman approach led to complex times, which mystified every one;
It turns out these are weak values, whose Real and Imaginary parts are easily interpreted – but which hadn’t been invented yet.

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



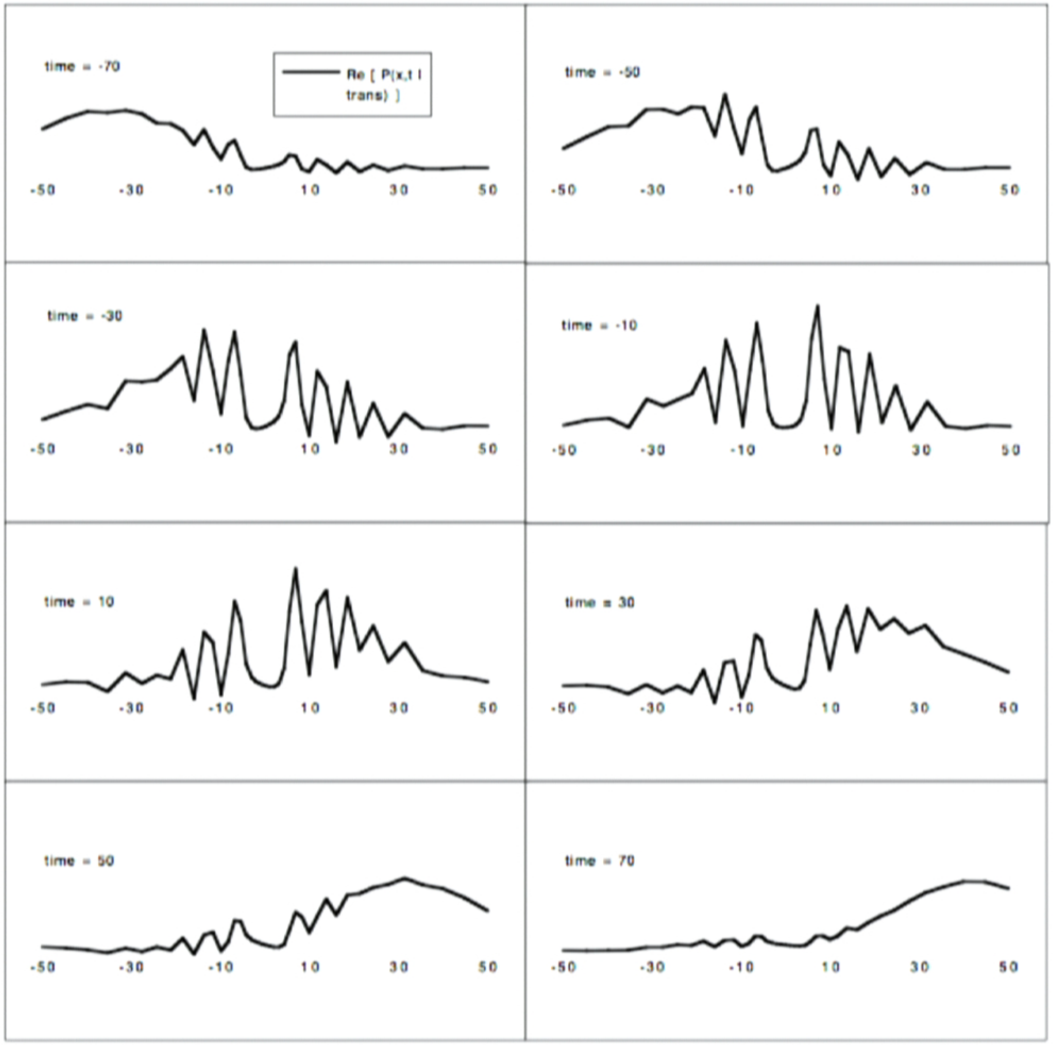
- $\tau = \theta_{\text{rot}}/\omega_l$
  - In plane rotation measures the tunneling time
  - Spin aligns along z axis; back-action of the measurement.

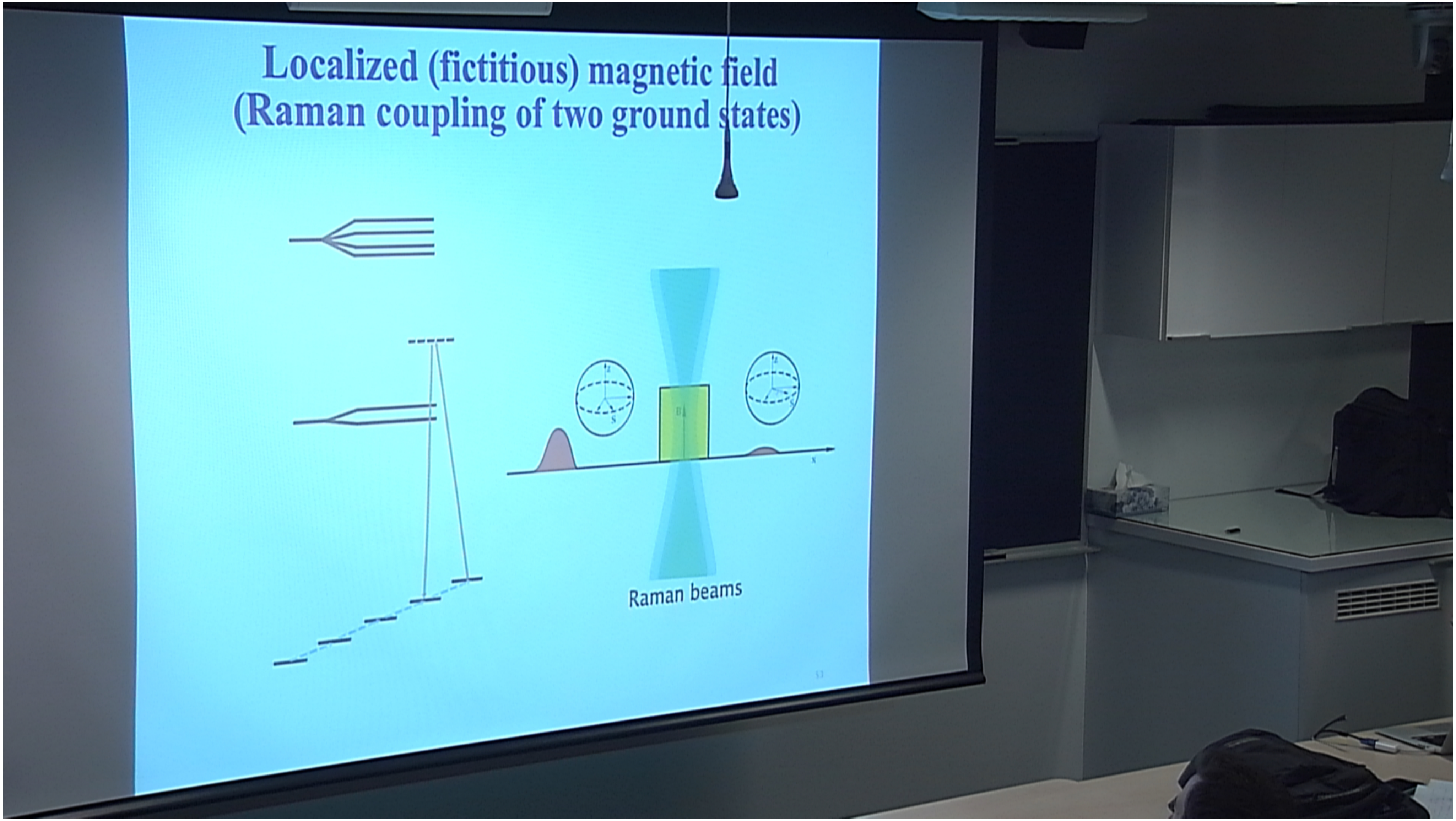
Where does a particle spend time inside the barrier?



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

Conditional-probability "movie" of tunneling

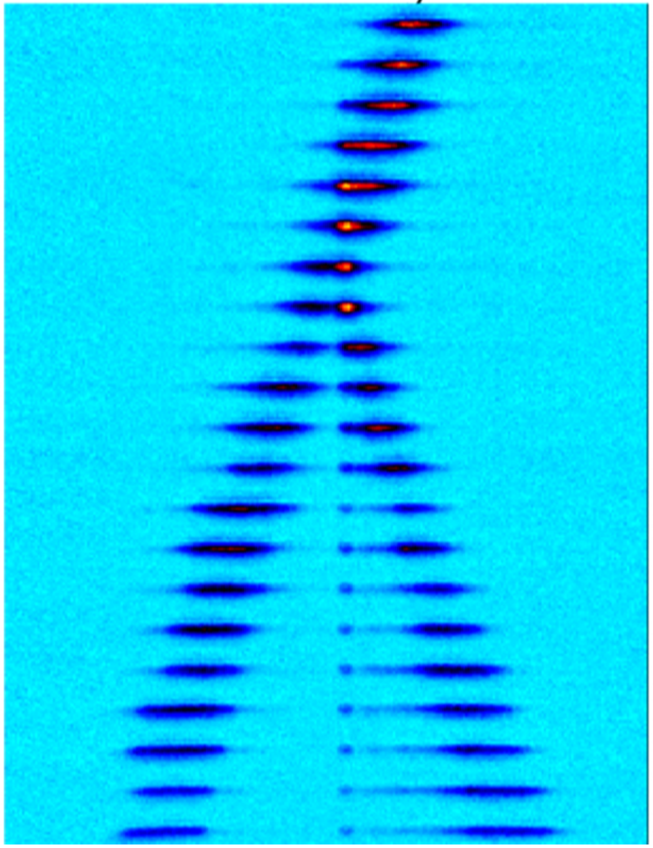




Localized (fictitious) magnetic field (Raman coupling of two ground states)

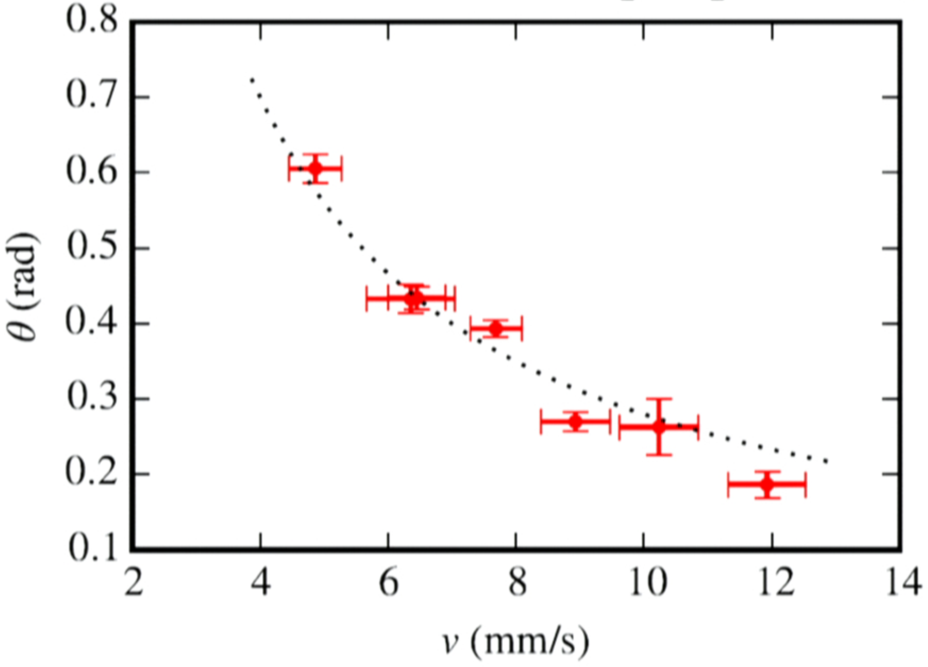
Raman beams

Preliminary evidence of tunneling through a *double* barrier (Fabry-Perot cavity for atoms)



Calibration of Larmor clock for free propagation

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



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

Summary

- In the past, we've used weak measurements to study Hardy's Paradox, momentum-disturbance relations, welcher Weg measurements, Bohmian trajectories & "surrealism," et cetera...

- 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