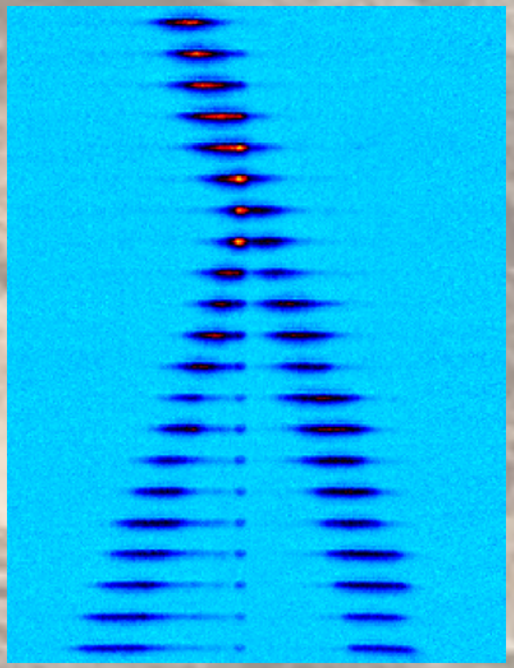
Learning about a quantum system's past from present observations: from tunneling times to pigeonholes

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



Causality in the Quantum World
Capri, Sep 2019

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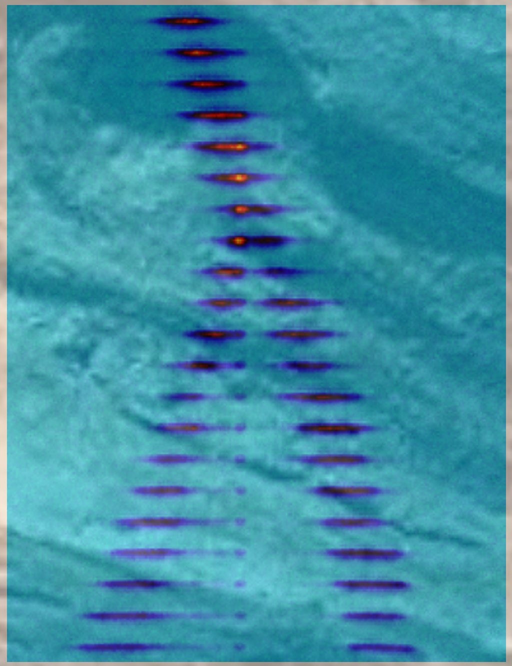

CQIQC

VELUT ARBOR ÆVO

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CQIQC

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Photons: Hugo Ferretti Edwin Tham
Noah Lupu-Gladstein Arthur Pang

BEC: **Ramón Ramos** **David Spierings**
Isabelle Racicot Joseph McGowan

Atom-Photon Interfaces:
Josiah Sinclair Daniela Angulo Murcillo Kyle Thompson

Post-doc(T): Aharon Brodutch **Post-doc(X):** Kent Bonsma-Fisher

Some past contributors: Alex Bruening, Shaun Pepper, Sepehr Ebadi, 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**, **Chris Ellenor**, Samansa Maneshi, **Mirco Siercke**, Chris Paul, Reza Mir, Sacha Kocsis, Masoud Mohseni, Zachari Medendorp, Fabian Torres-Ruiz, Ardavan Darabi, Yasaman Soudagar, Boris Braverman, Sylvain Ravets, **Rockson Chang**, Max Touzel, James Bateman, Luciano Cruz, Zachary Vernon, Timur Rvachov, Marcelo Martinelli, Morgan Mitchell,...

Some helpful theorists:
Stacey Jeffery, Barry Sanders, Mankei Tsang, Howard Wiseman, Pete Turner, Robin Blume-Kohout, Chris Fuchs, János Bergou, John Sipe, Daniel James, Paul Brumer, Michael Spanner...

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NOTE:
Always looking for excellent graduate students;
and probably still room for an excellent postdoc!

Perspective: quantum archaeology

Conventional wisdom:

in QM, one cannot look at present observations ("where did the photon hit the screen") and draw conclusions about the past ("what path did it take to get there?").

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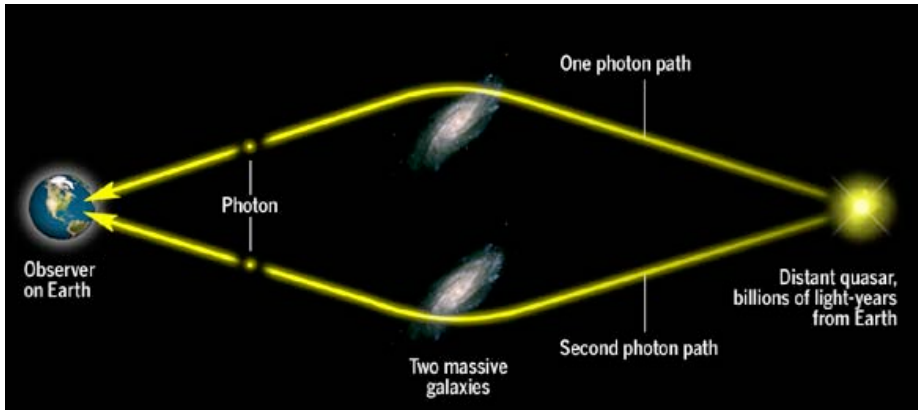

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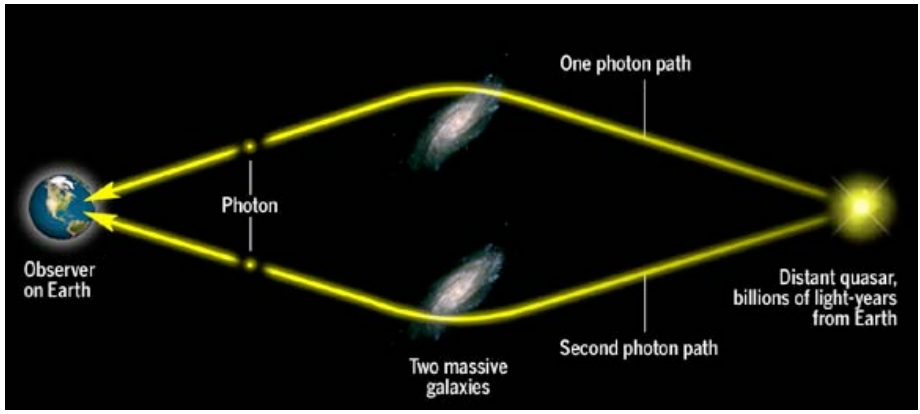

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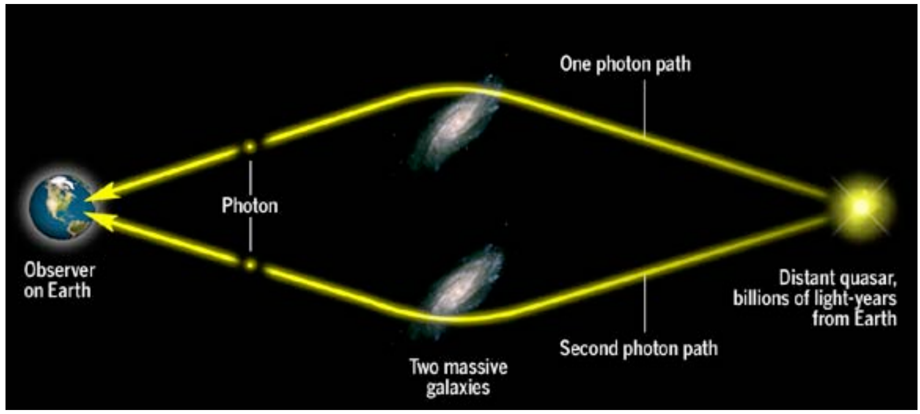

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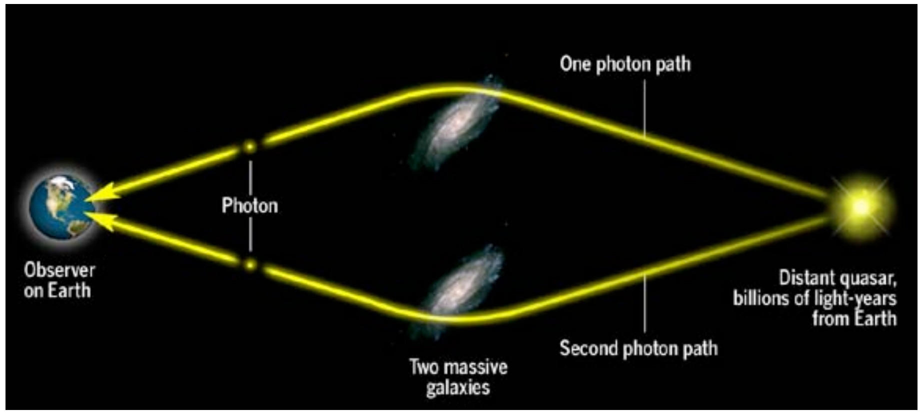


in CM, of course, one does this all the time:

True wisdom:

There *is* no classical world.
It was a quantum dinosaur which left that bone behind, and yet we reason about it. The question is merely where the limits on retrodiction lie, in a universe governed by QM.

01

Intro to tunneling times: what do we learn when a particle is transmitted?

02

LATEST RESULT…

EXPERIMENT: how much time does a particle spend in the "forbidden" region before being transmitted?

03

ONGOING WORK…

(a) How does observation *perturb* tunneling?

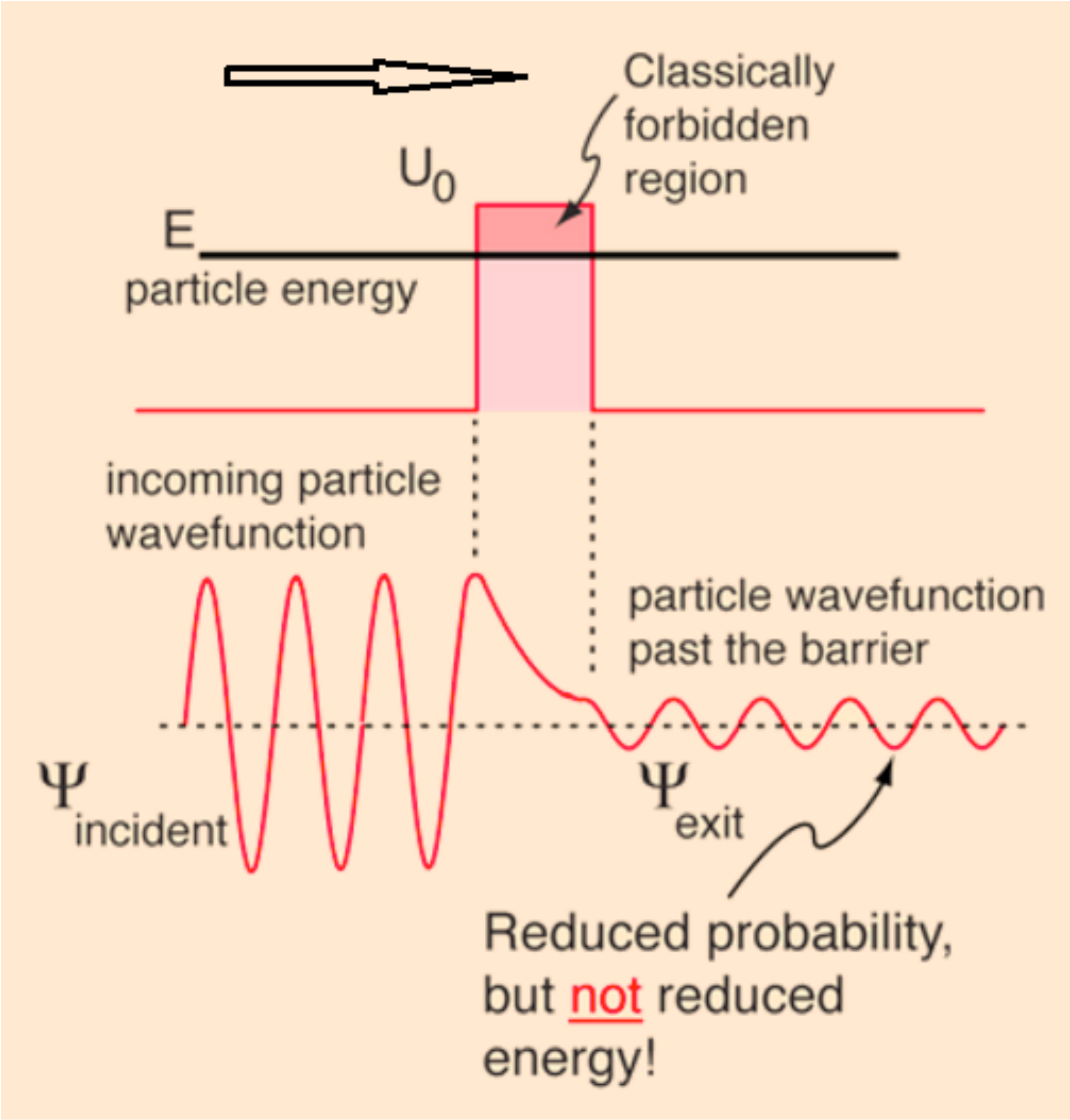
04

(b) Pigeonholes: Given a present observation, how much can we infer about the past? Are weak or strong measurements more reliable?

05

(c) Measuring the past effects of a post-selected photon… an open (?) question in NLO

Motivation: the tunneling time problem



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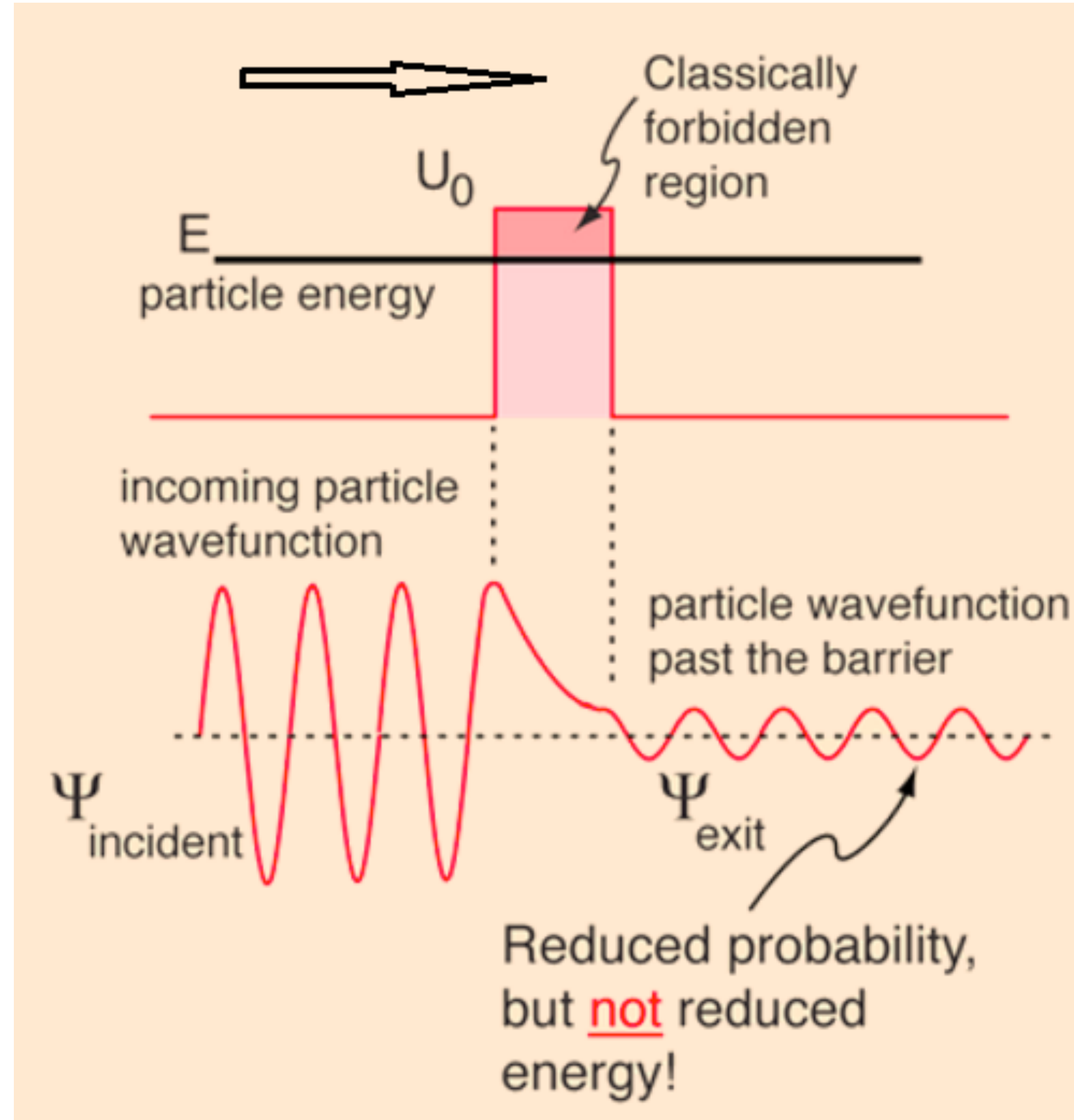


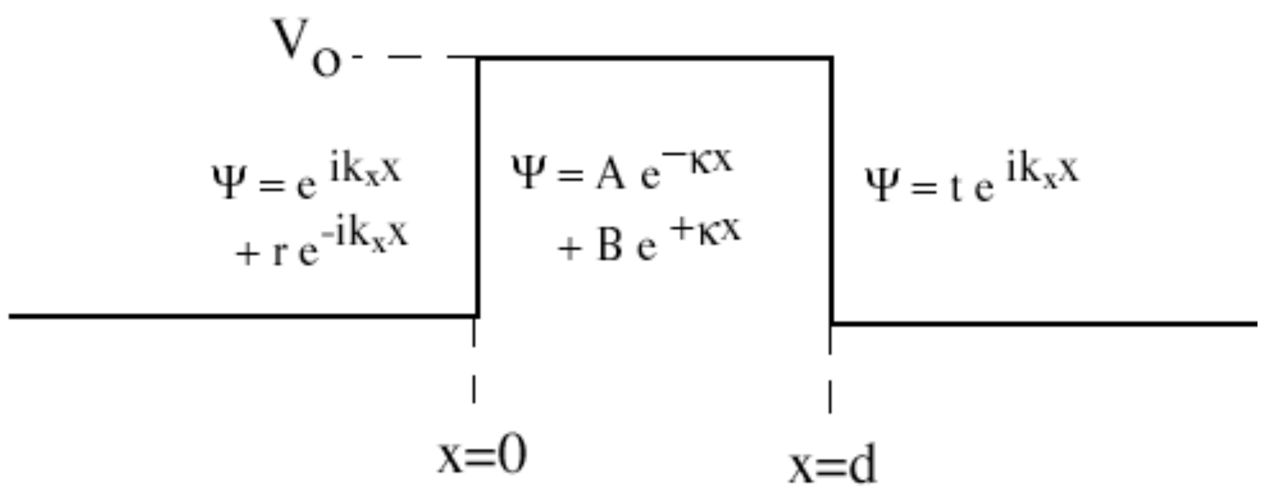
We all learn how to calculate the transmission *probability* . . .

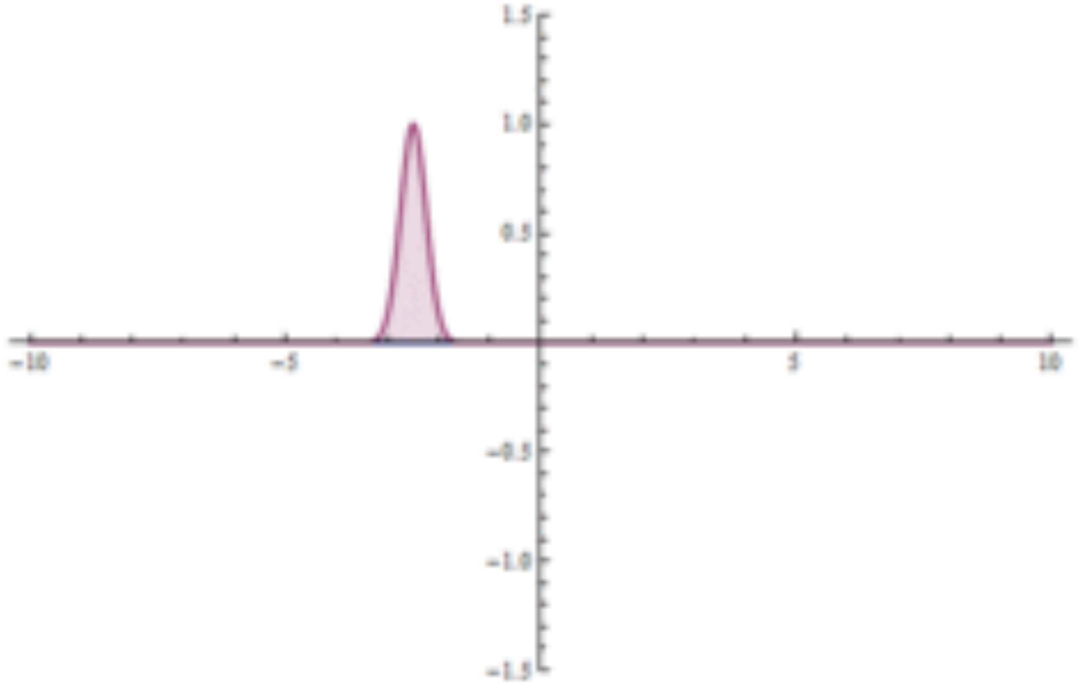
But *how long* does a particle take to get transmitted?

As the kinetic energy = E – V_0 gets smaller, v goes down and t goes up. But once E – V_0 goes *negative*, there is no classical solution:

$v_{semiclassical}$ becomes *imaginary?*

Back to basics: the rectangular barrier



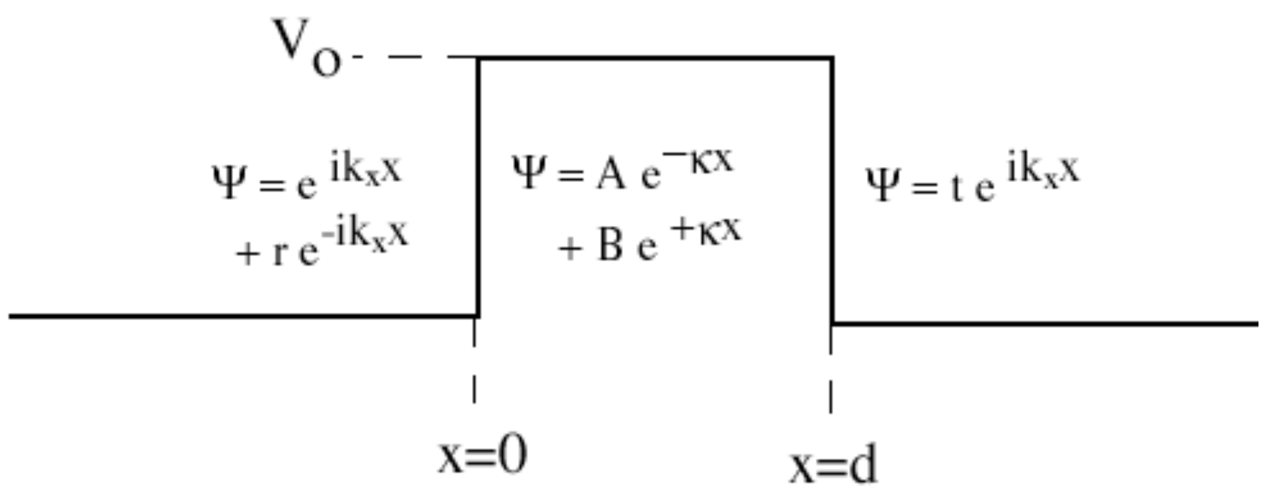


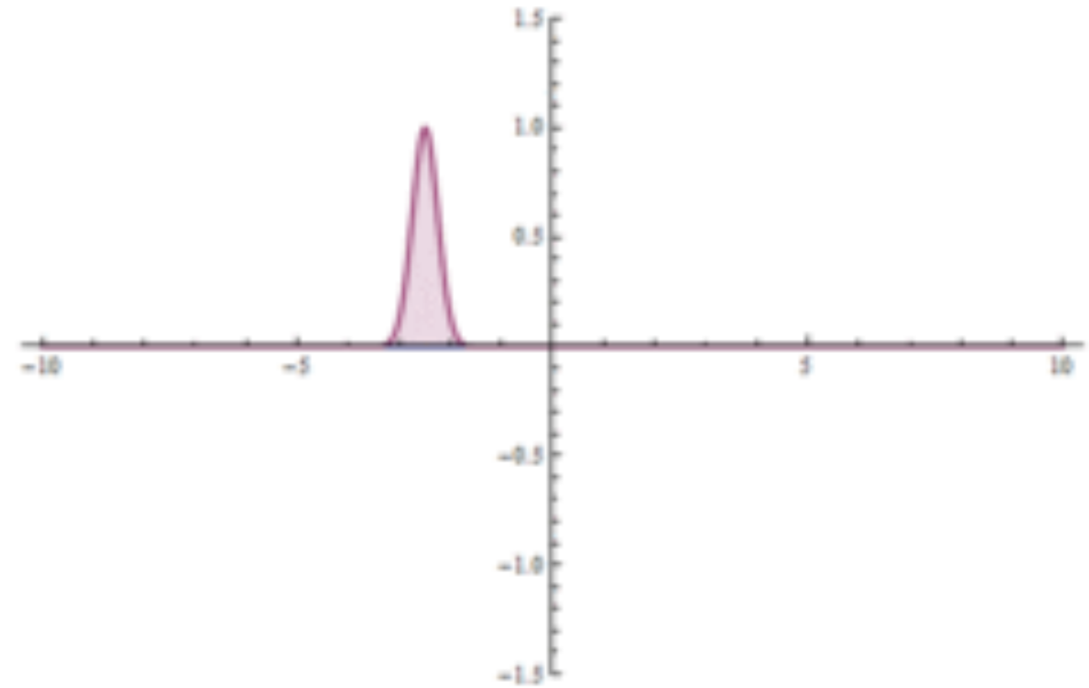
When does a wave packet peak appear?

The “obvious” stationary phase approach (“group velocity”) involves looking at how a wave accumulates phase as a function of position . . . but inside the barrier, the real exponentials don’t accumulate phase.

The time delay becomes independent of the thickness of the barrier…

Back to basics: the rectangular barrier





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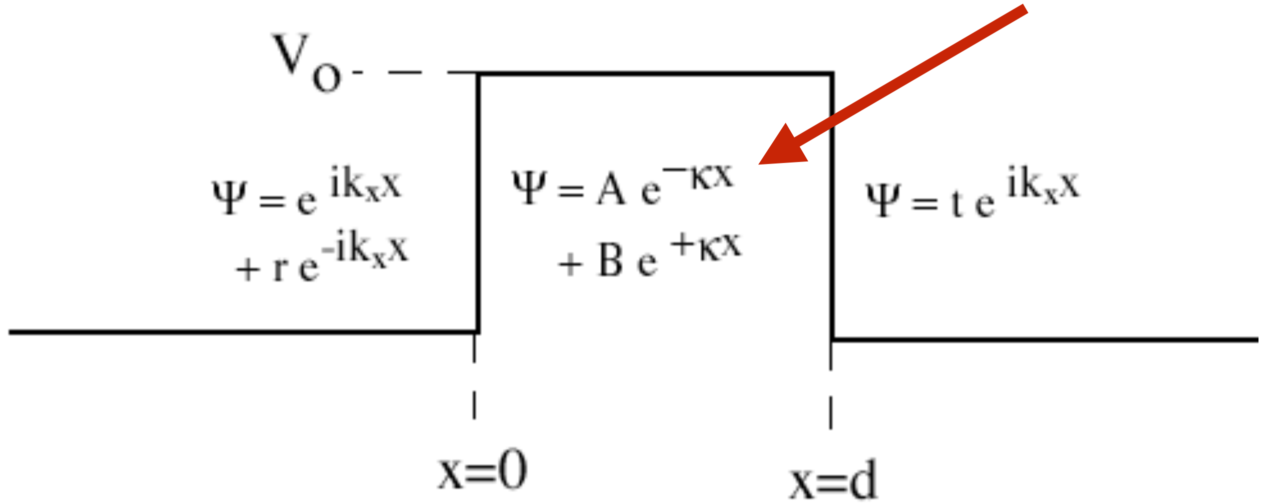

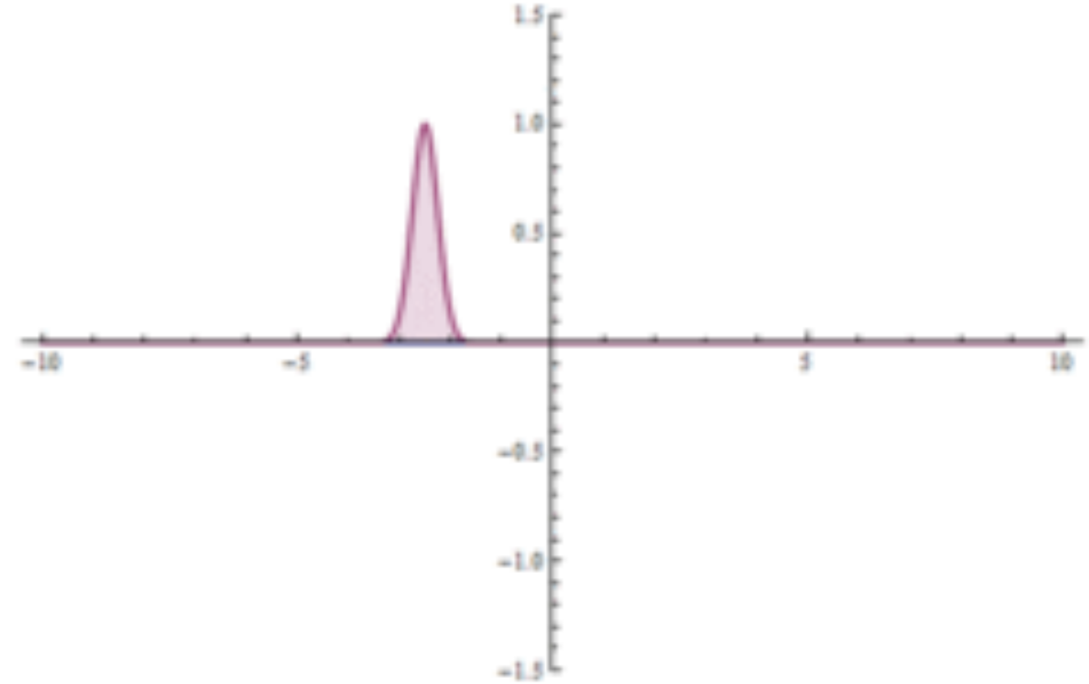

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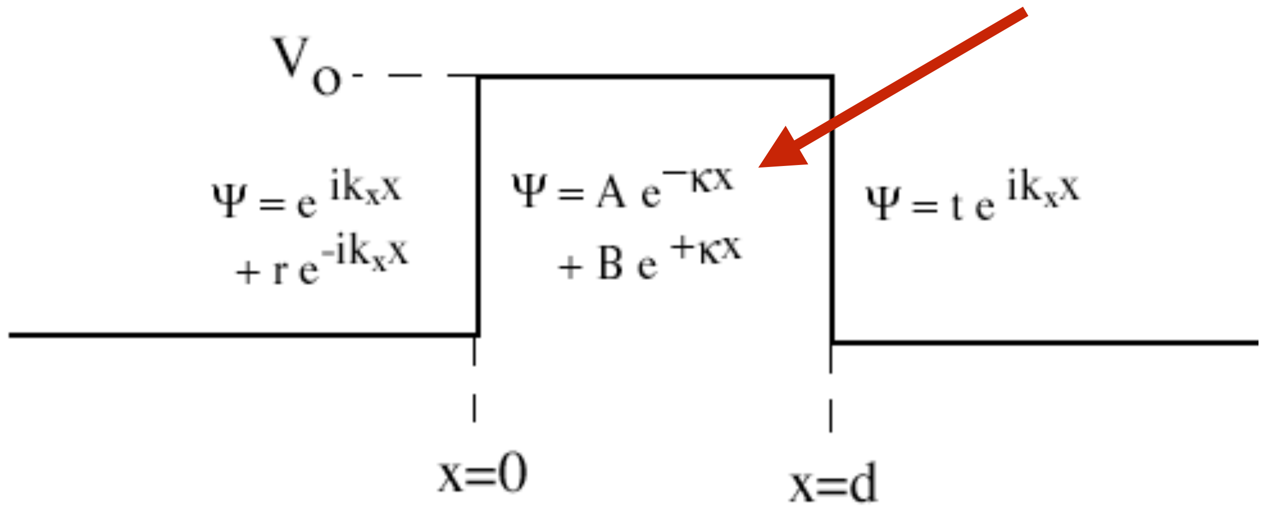

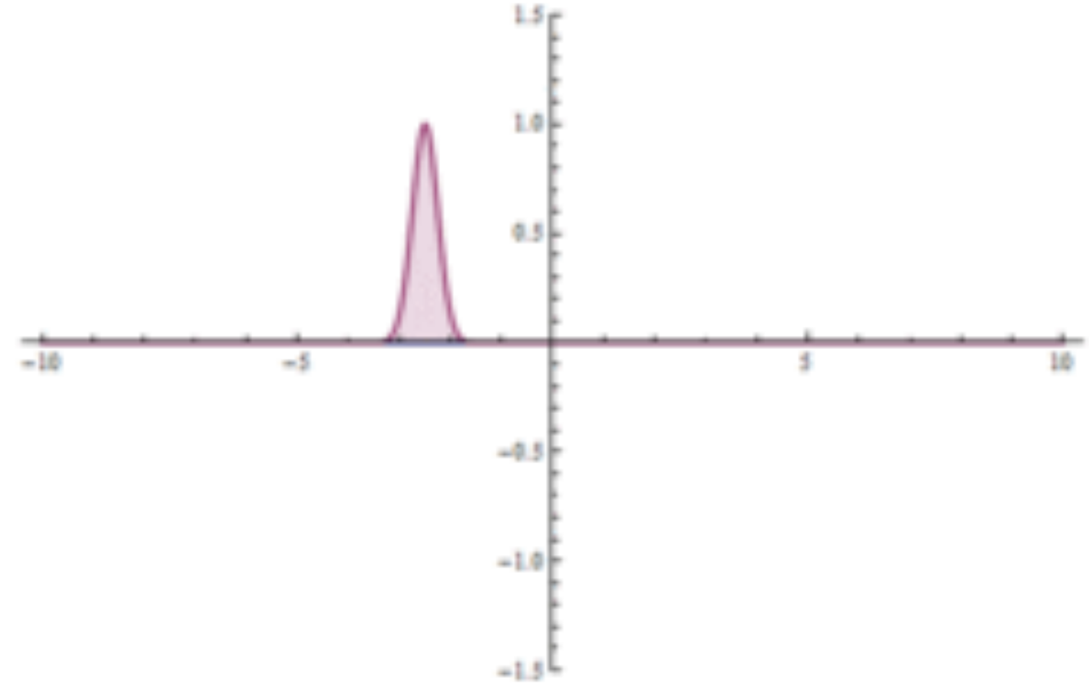

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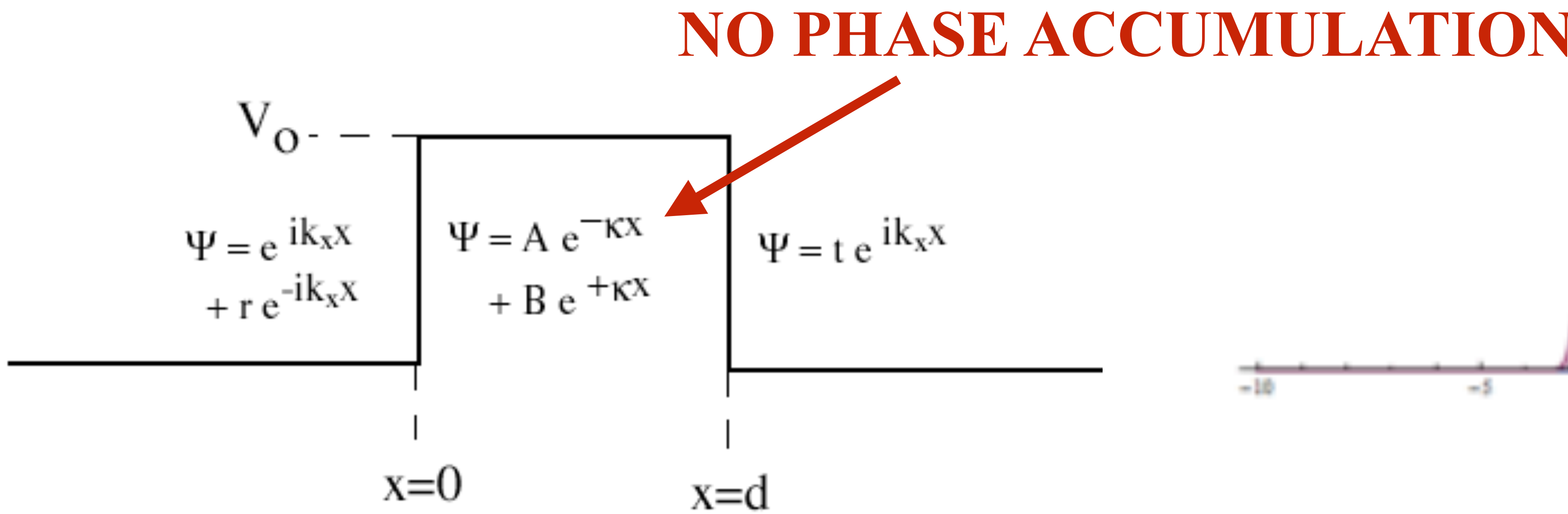

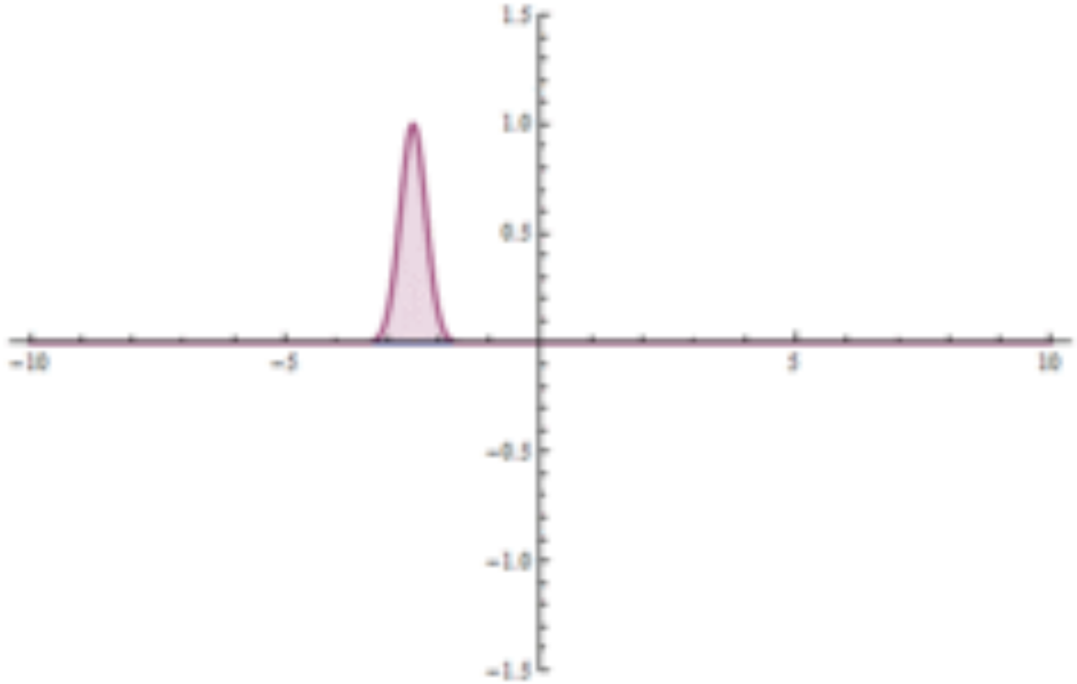

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L.A. MacColl, Phys Rev **40**, 621 (1932)
E.P. Wigner, Phys. Rev. **98**, 145 (1955)
T.E. Hartman, J. Appl. Phys. **33**, 3427 (1962)
• • •

AMS, P.G. Kwiat, R.Y. Chiao, PRL 71, 708 (1993)
and others

INTERACTION TIMES:

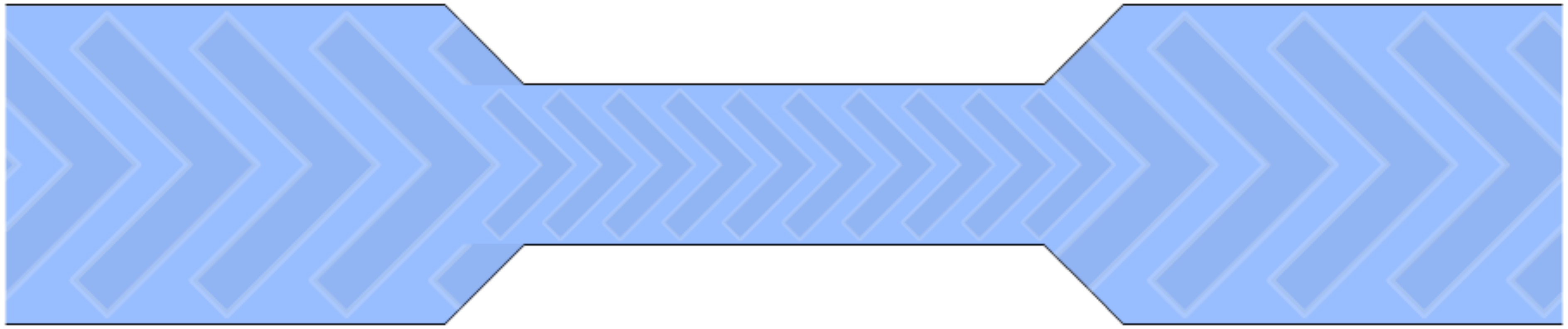
Büttiker & Landauer pioneered new approaches to the problem in the 1980s.

Barrier traversal time

Rolf Landauer

NATURE · VOL 341 · 19 OCTOBER 1989

CONSIDER a large box with a particle that can escape through a thin tube. The particle spends a long time bouncing around the box until it escapes and then a shorter time in the tube, while escaping. A similar distinction in timescale exists for quantum mechanical tunnelling out of a trap through a barrier, although this has received limited recognition. The time taken by the final escape event has now been measured in a subtle and definitive experiment by a group at Saclay[1].



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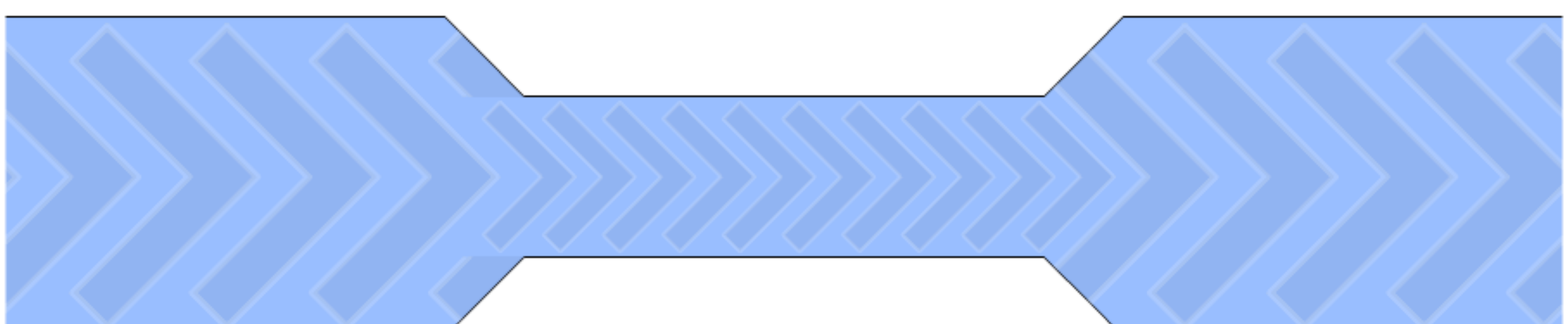

Characteristic time for macroscopic quantum tunneling

Estève *et al.* measured the timescale beyond which reflections no longer have a significant effect on the tunneling rate of a SQUID.

There is only a qualitative agreement with the data, as expected in view of the finiteness of temperature and friction. The continuous line is a best fit obtained from our full numerical theory using the parameter values listed in Table I and for $s = 0.9855$, the estimated value being $s = 0.9858 \pm 0.0005$. The corresponding passage time is $t_p = 78$ ps.

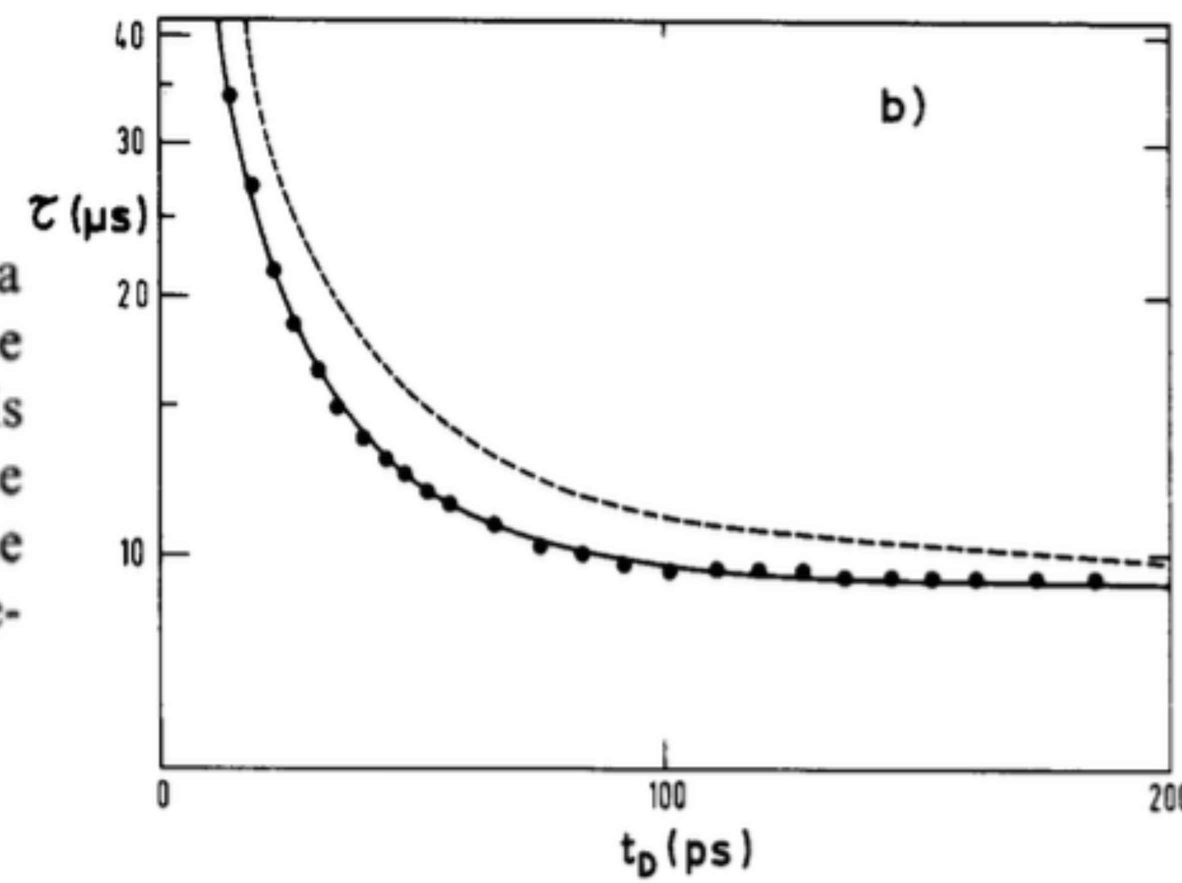

Fig. 5. Lifetime τ of the zero voltage state versus delay t_d at two temperatures (a) $T = 65$ mK and (b) $T = 18$ mK. Dashed line corresponds to the zero temperature perturbative expression (2). Full line is the prediction of a numerical calculation using theory developed in Ref. [8].

Esteve, D., Martinis, J. M., Urbina, C., Turlot, E., Devoret, M. H., Grabert, P. & Linkwitz, S. Physica Scr. T29, 121–124 (1989);

See also "Tunneling Times and Superluminality", R. Y. Chiao and AMS in Progress in Optics vol. XXXVII (1997) + ref's therein

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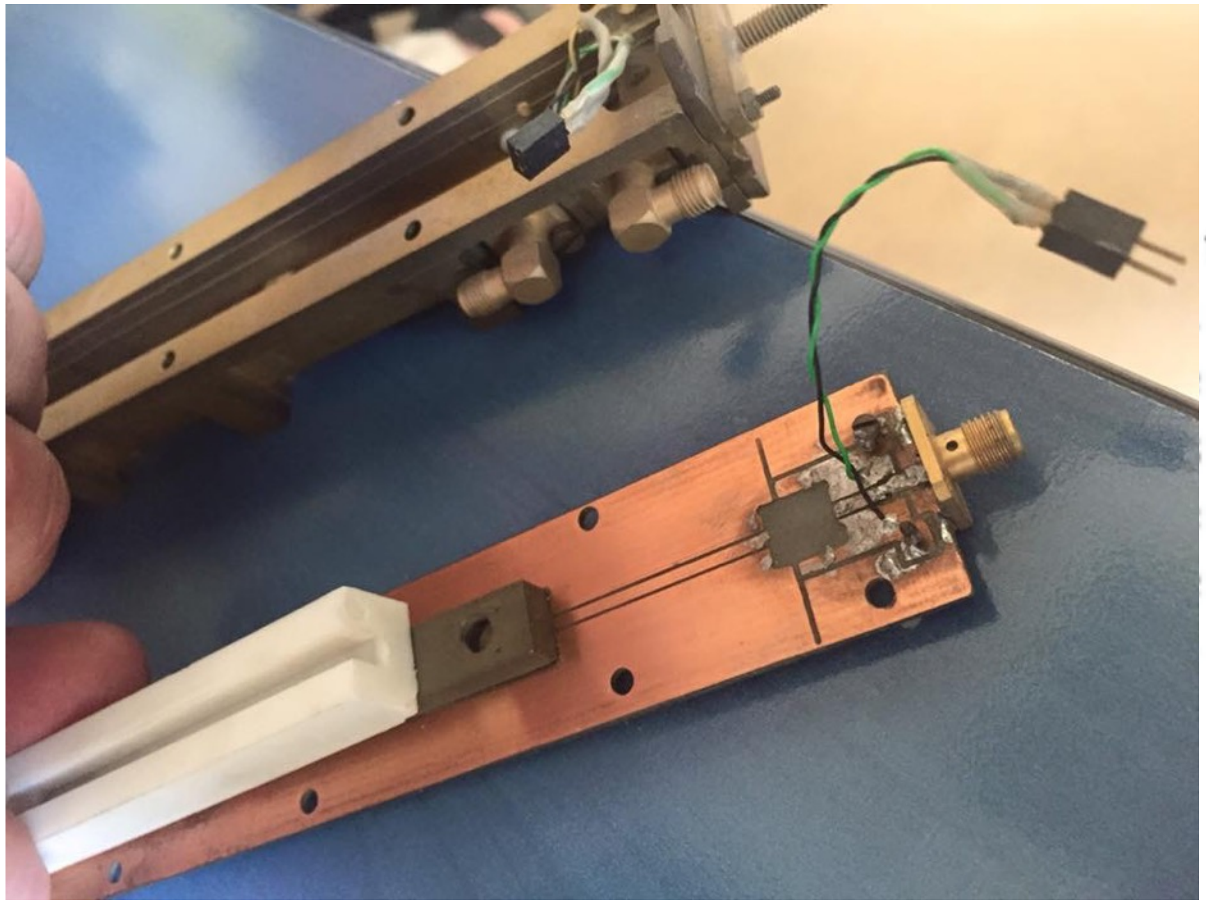

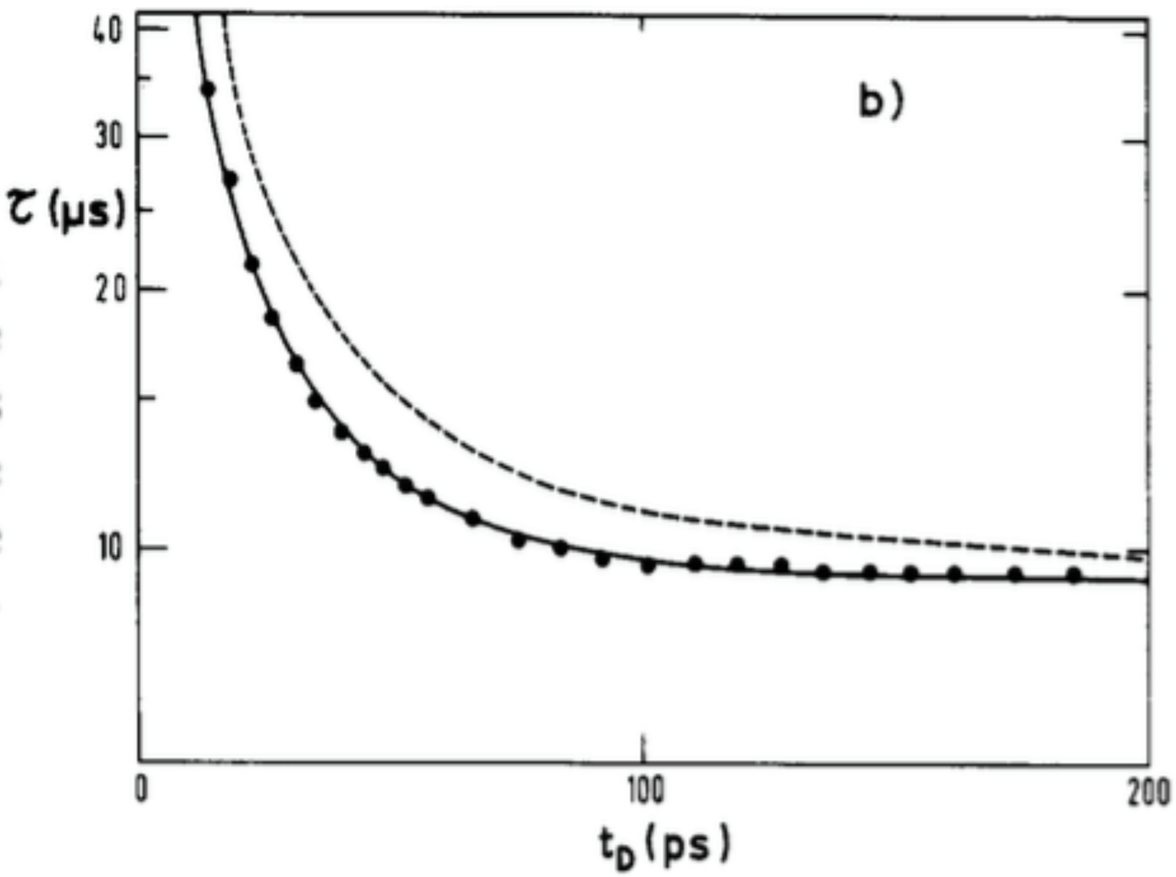

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Is this the end of the story?

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… apparently not …

Measuring tunneling time – physicists solve great mystery of the quantum world

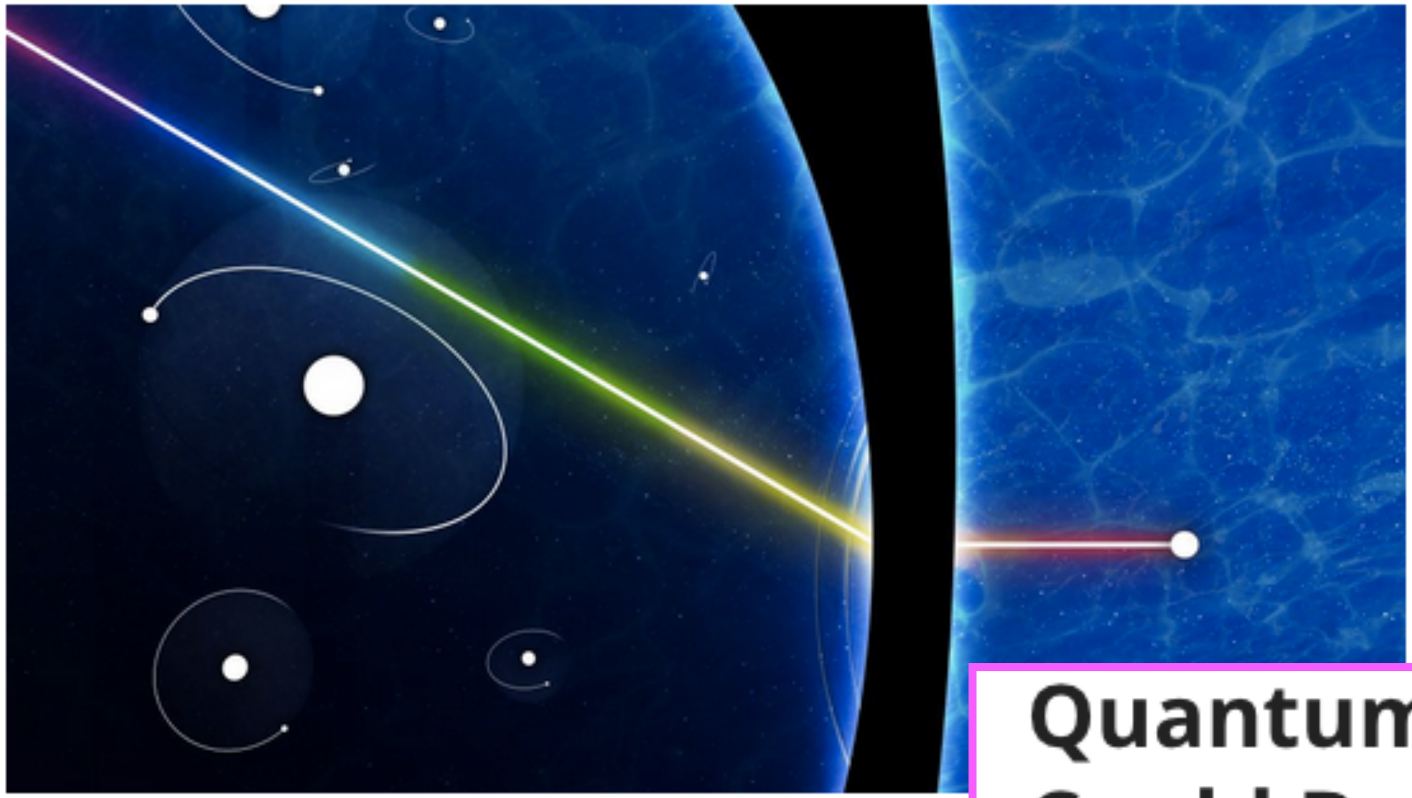


Image courtesy of Nature.

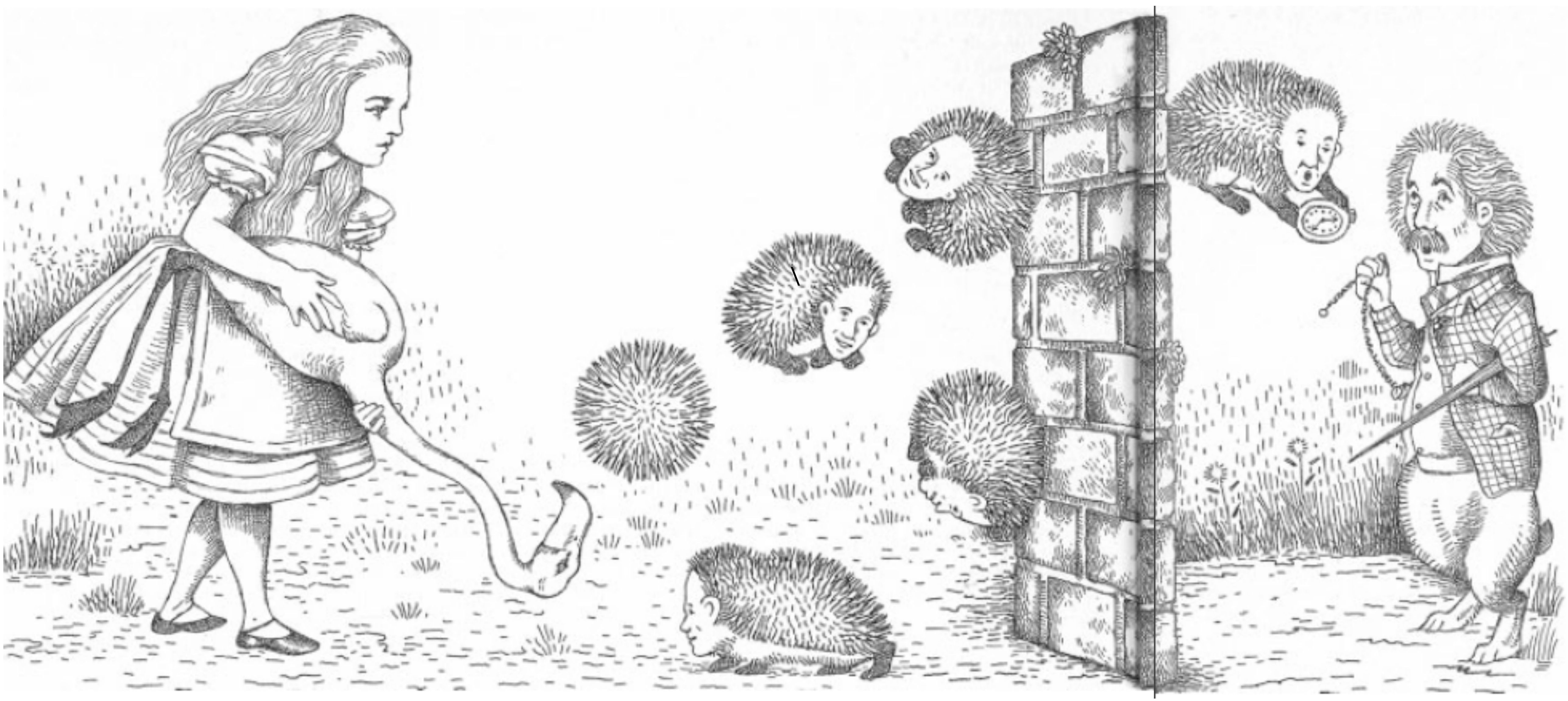
Sainadh, U. S. et al. Attosecond angular streaking and tunnelling time in atomic hydrogen. Nature 568, 75 (2019).

Quantum Tunneling Is So Quick It Could Be Instantaneous

An international research team led by Griffith University physicists has solved one of the great mysteries that has plagued scientists since the advent of quantum physics – measuring the time it takes for a particle to tunnel through a barrier.

How long has the transmitted particle *spent* in the barrier region?
(& may we say something different about it and about reflected particles?)

“Time is what a clock measures”…



(courtesy Scientific American, 1993)

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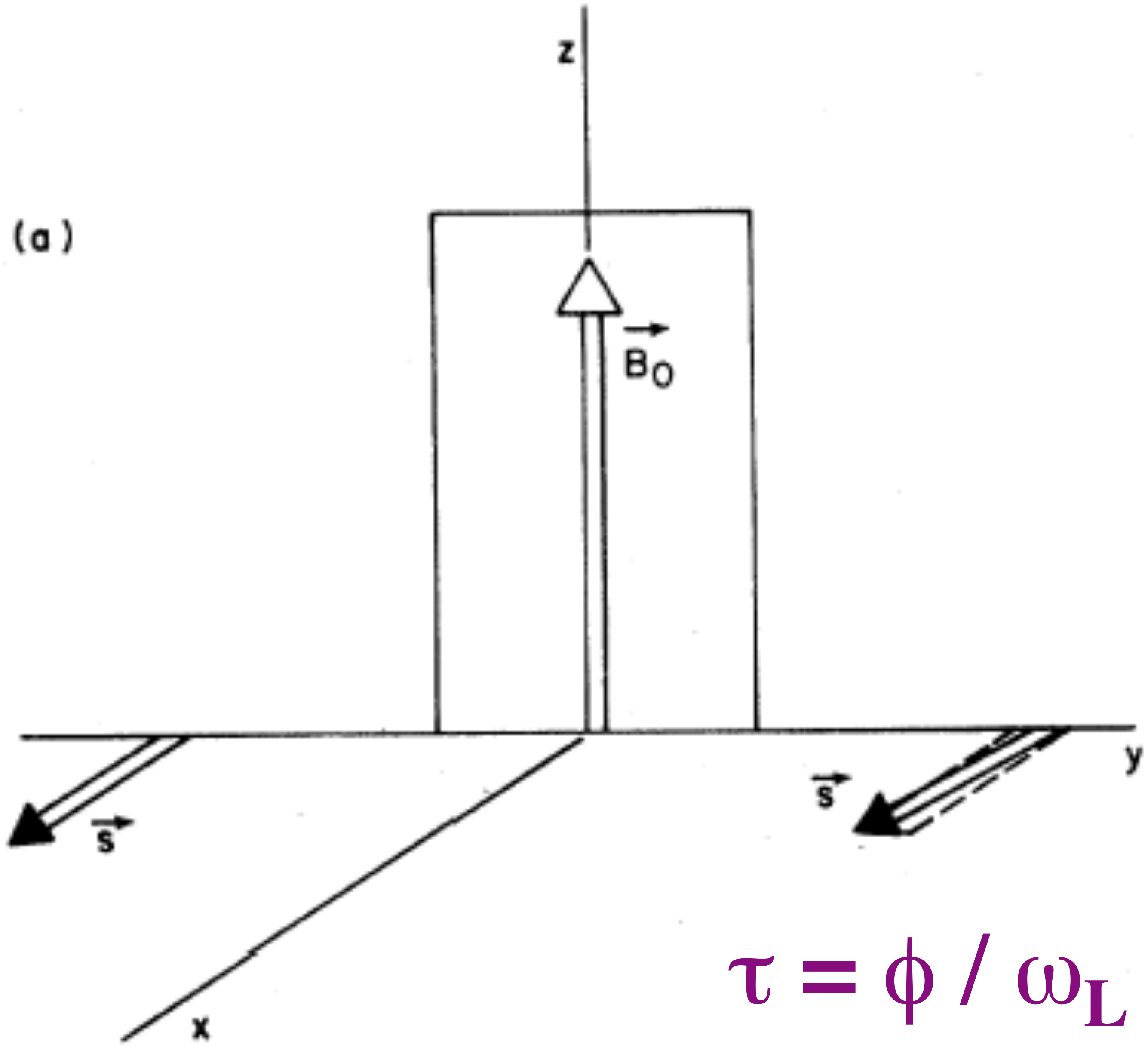
A nice clock: Baz & Rybachenko's "Larmor time"

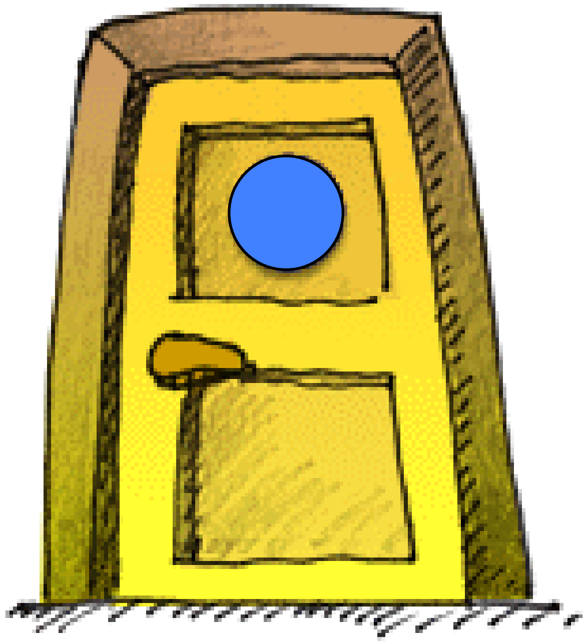


$$\tau = \phi / \omega_L$$

A.I. Baz', Sov. J. Nucl. Phys. **4**, 182 (1967)

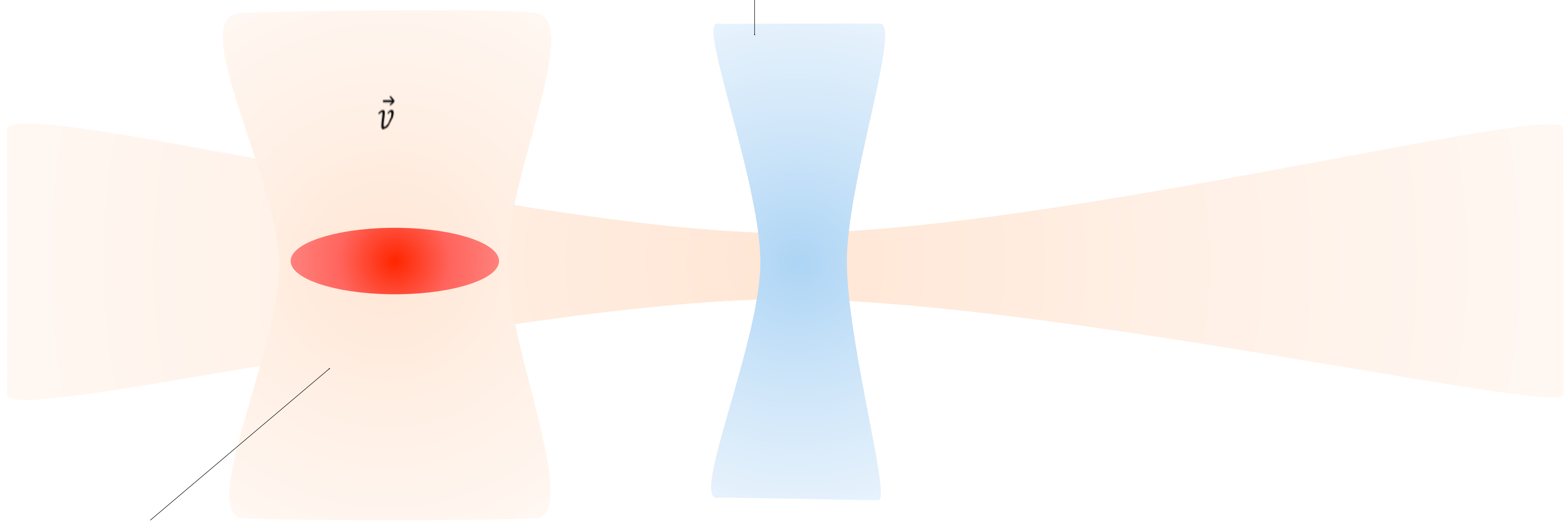
V.F. Rybachenko, Sov. J. Nucl. Phys. **5**, 635 (1967)

The experiment



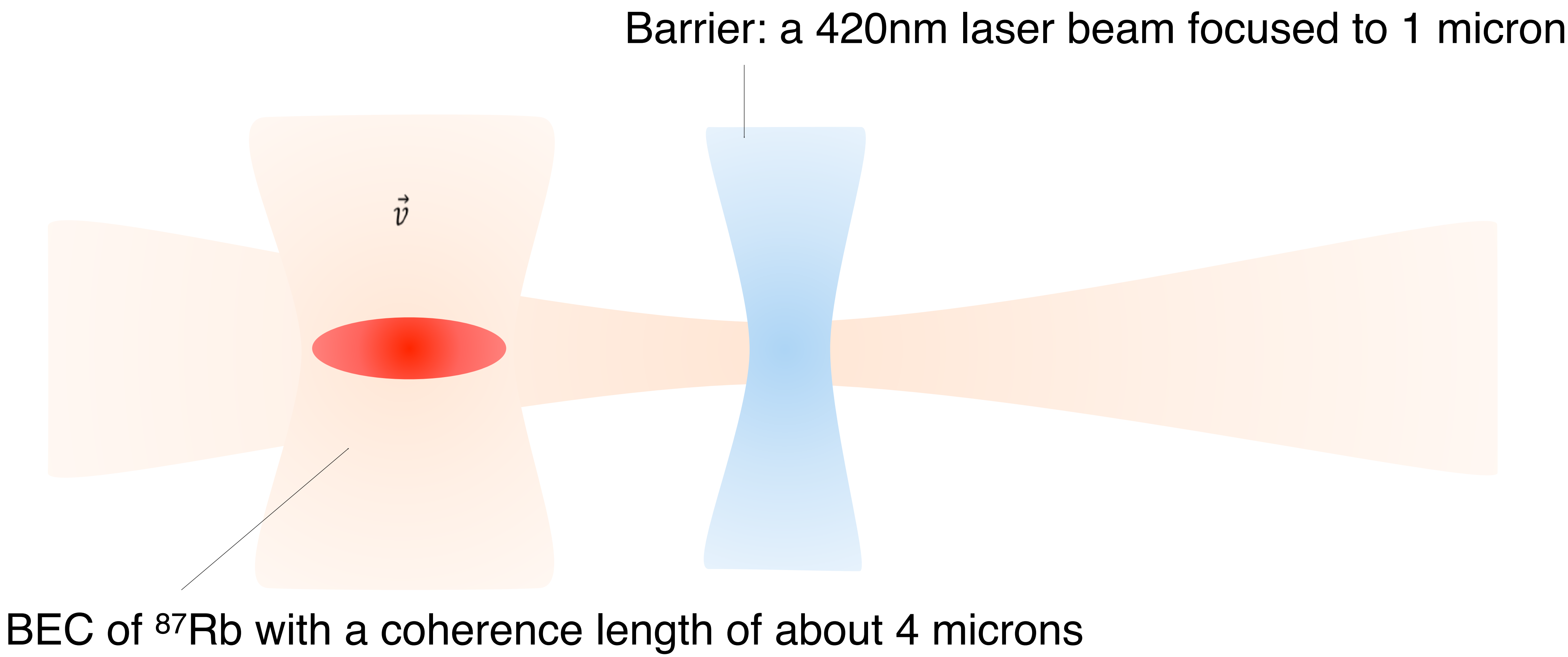
What is the tunnel barrier?

Barrier: a 420nm laser beam focused to 1 micron



BEC of ^{87}Rb with a coherence length of about 4 microns

What is the tunnel barrier?

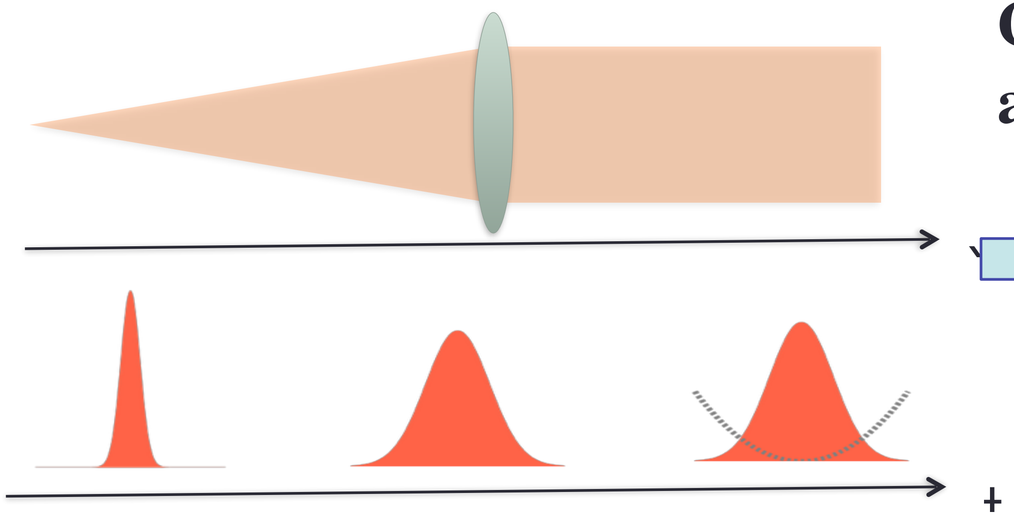


The blue-detuned beam acts like a repulsive potential for the atoms.

Barrier height of about 150 nK >> 1nK temperature of the atoms (corresponding to a critical incident velocity of about 4 mm/s).

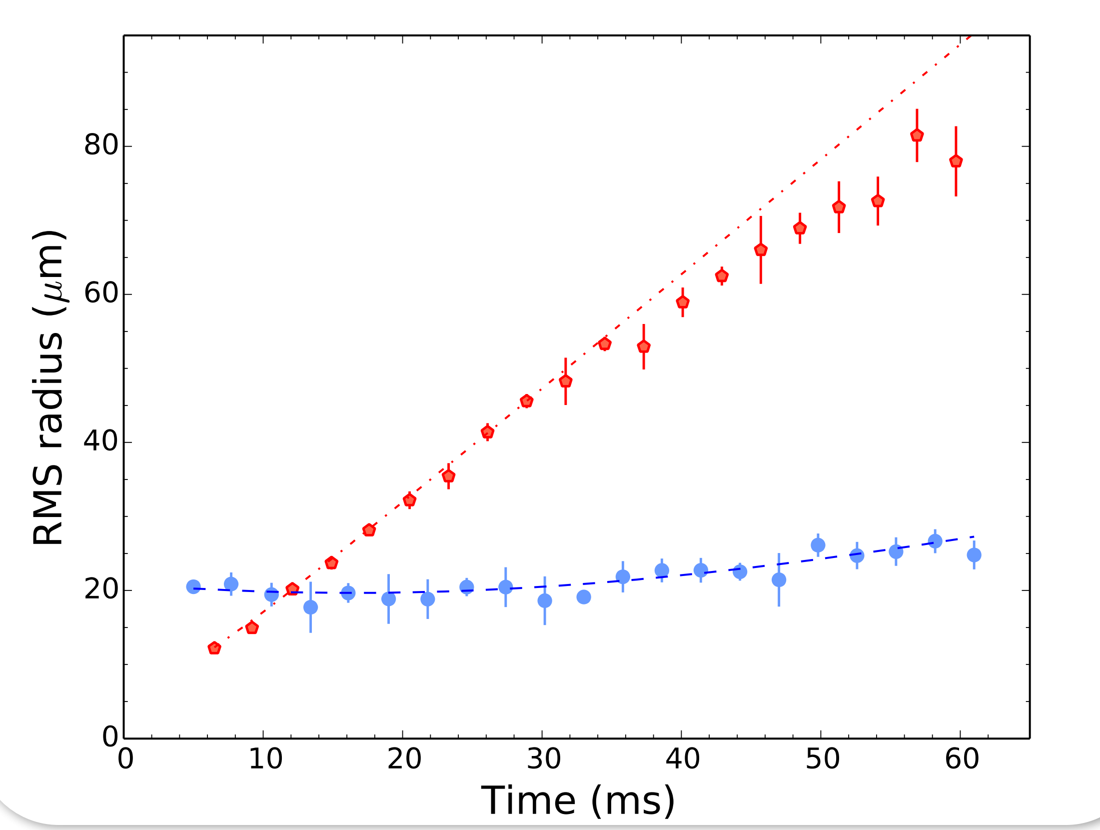
Start with BEC of ^{87}Rb atoms below 100nK.

To get wavelength > 1 micron, use delta-kick cooling:



Cool atoms as low as 900 pK

TIME-OF-FLIGHT TEMP. MEASUREMENT



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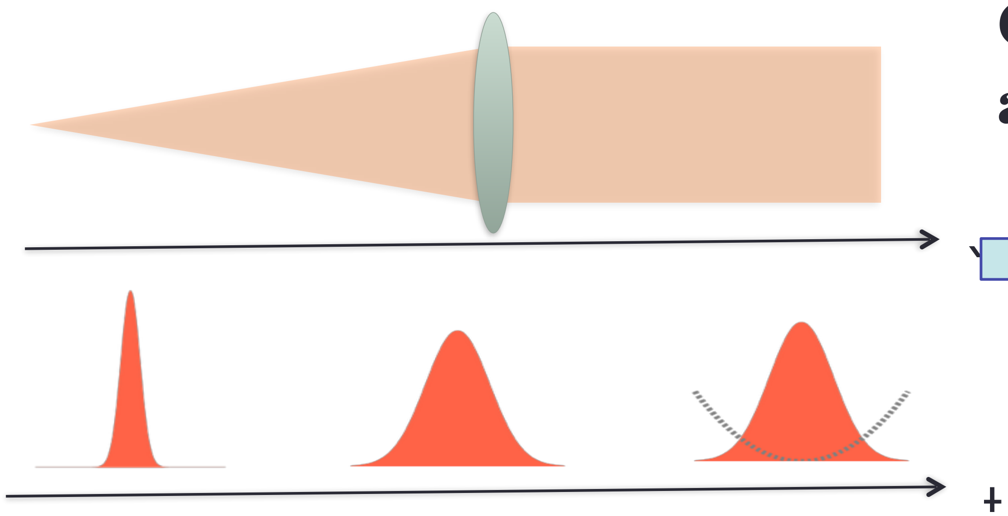

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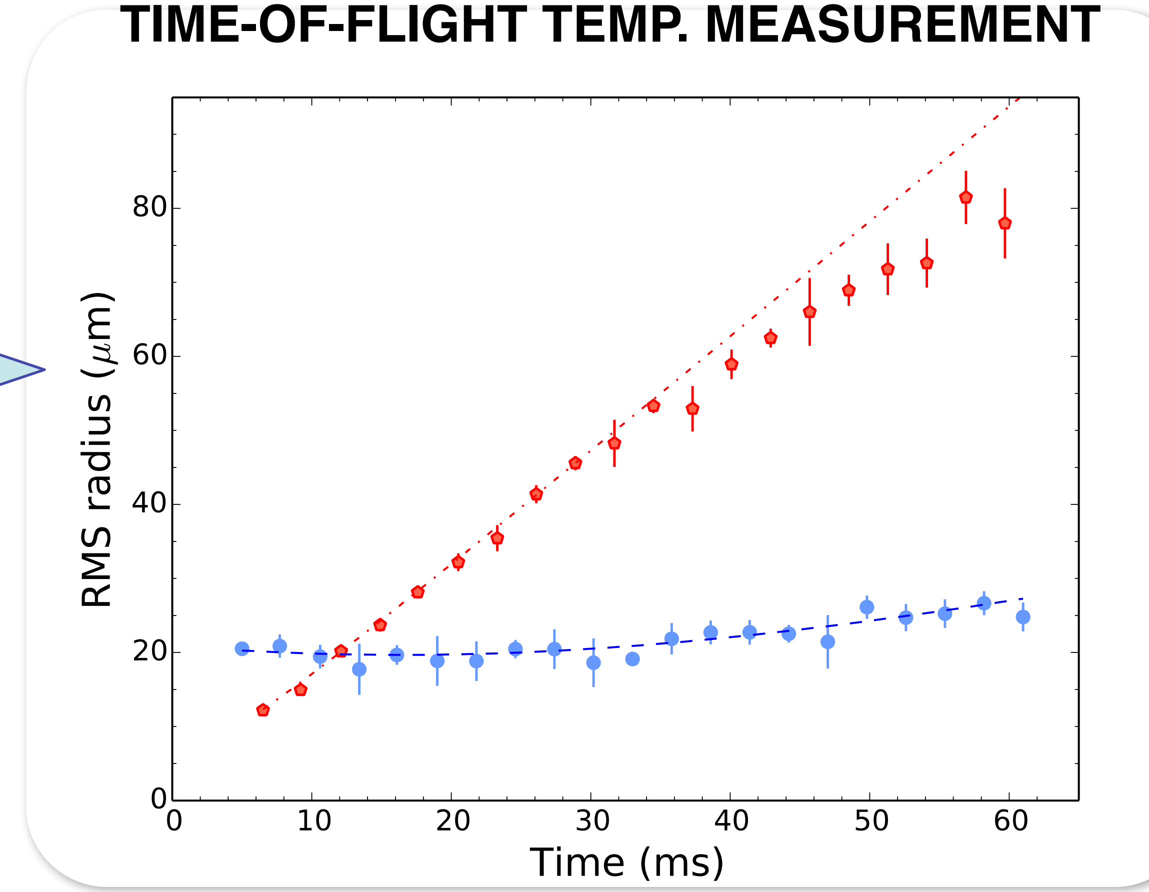
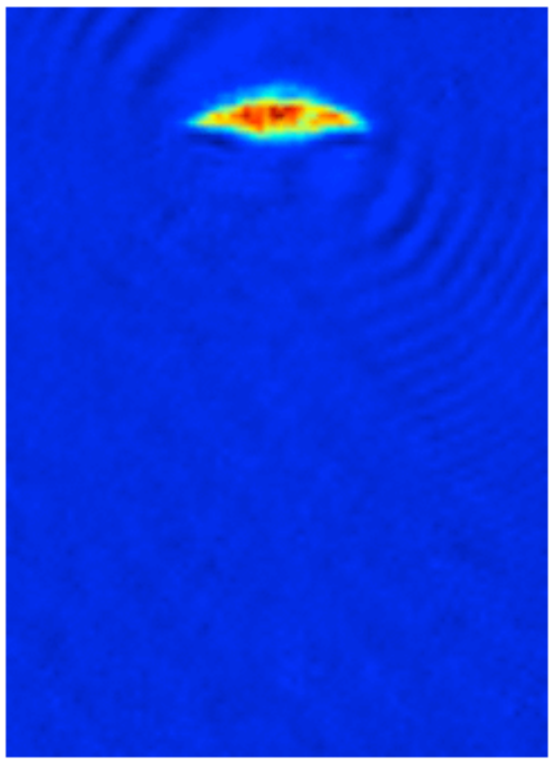
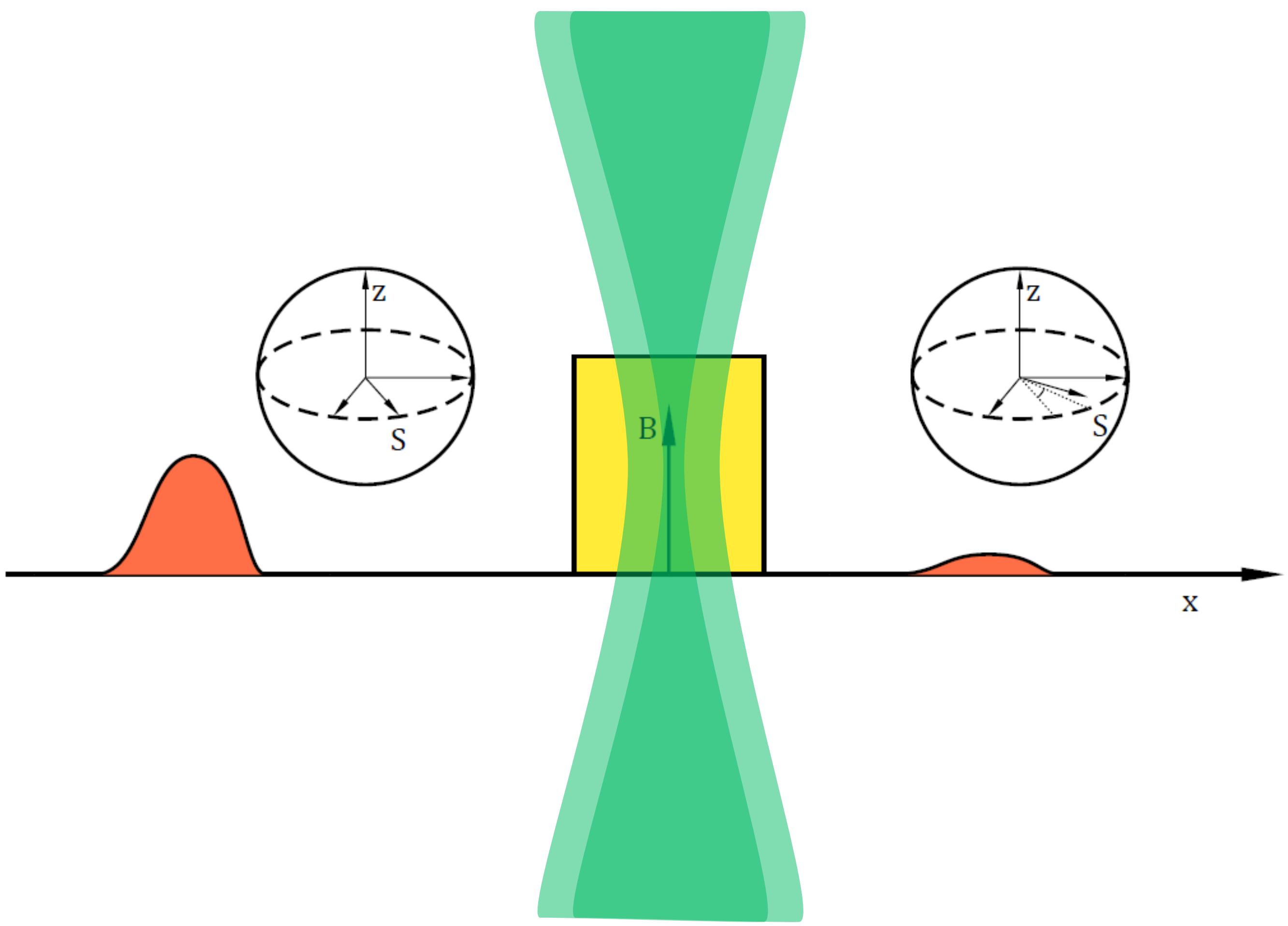


Then fire them (slowly) at a barrier made of a focussed blue-detuned laser beam:

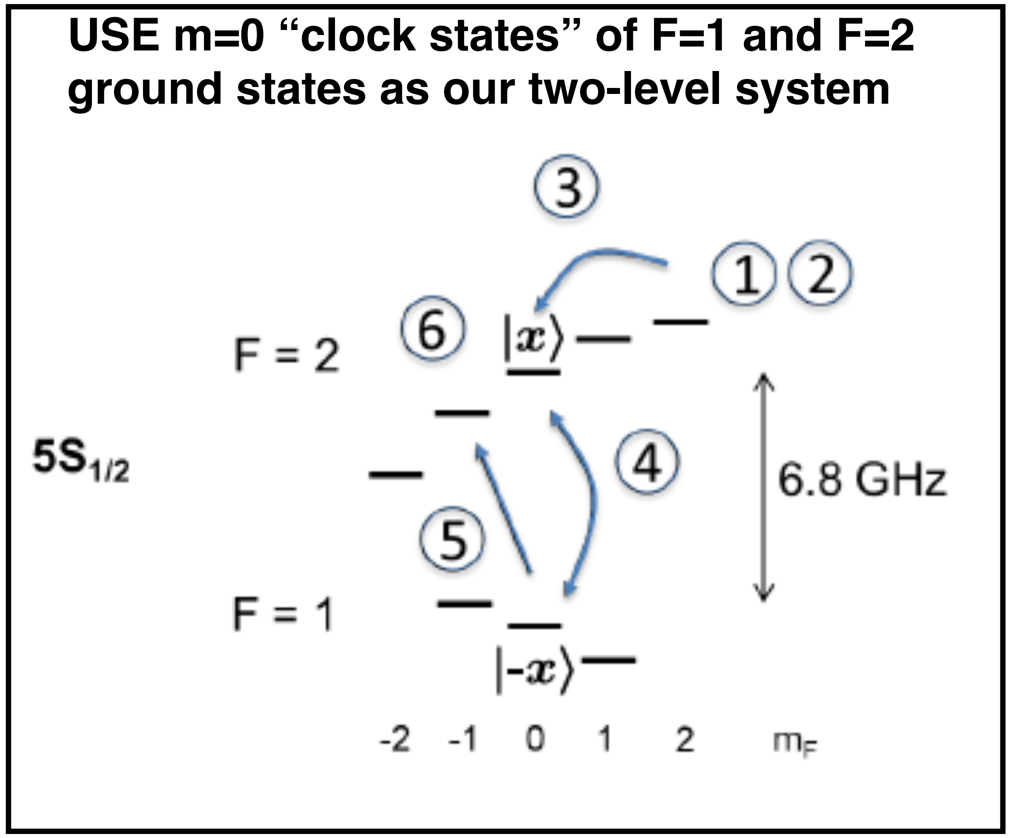


What is the probe?

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



Raman beams



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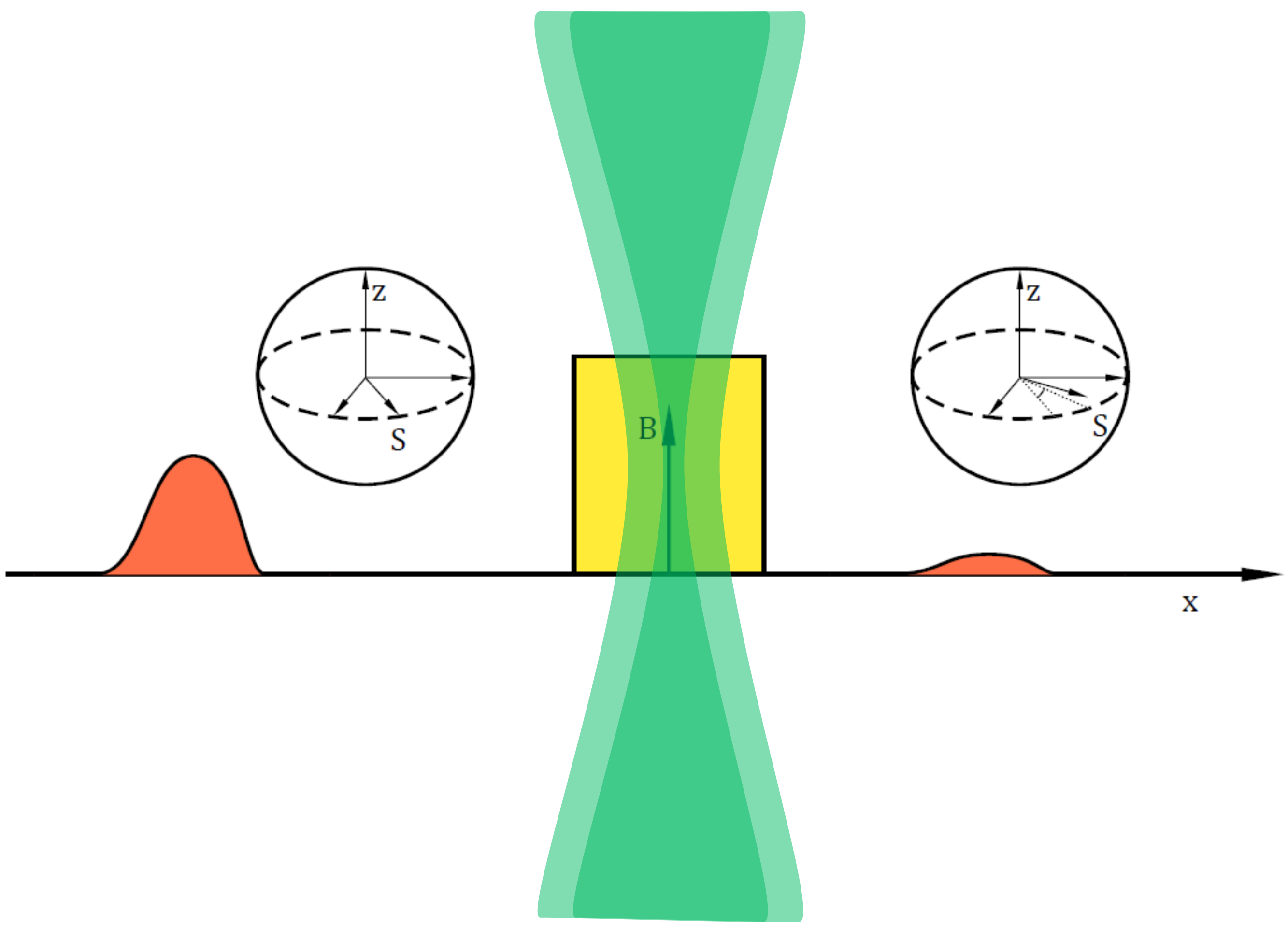
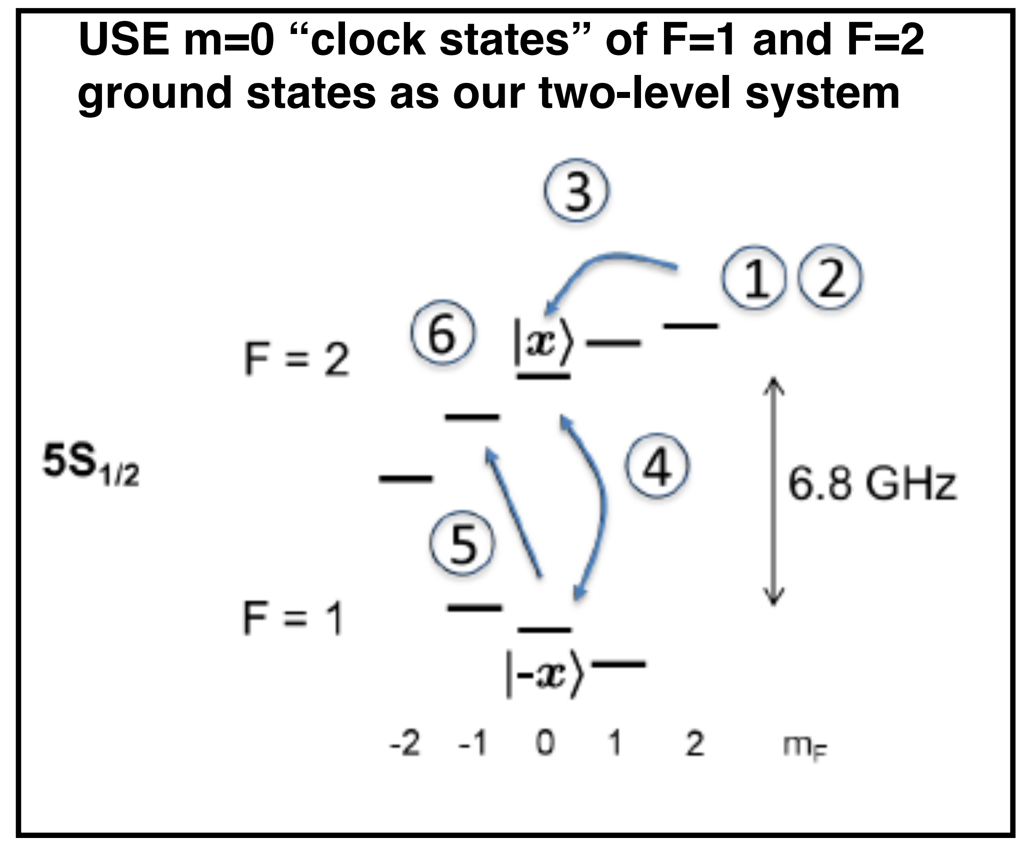
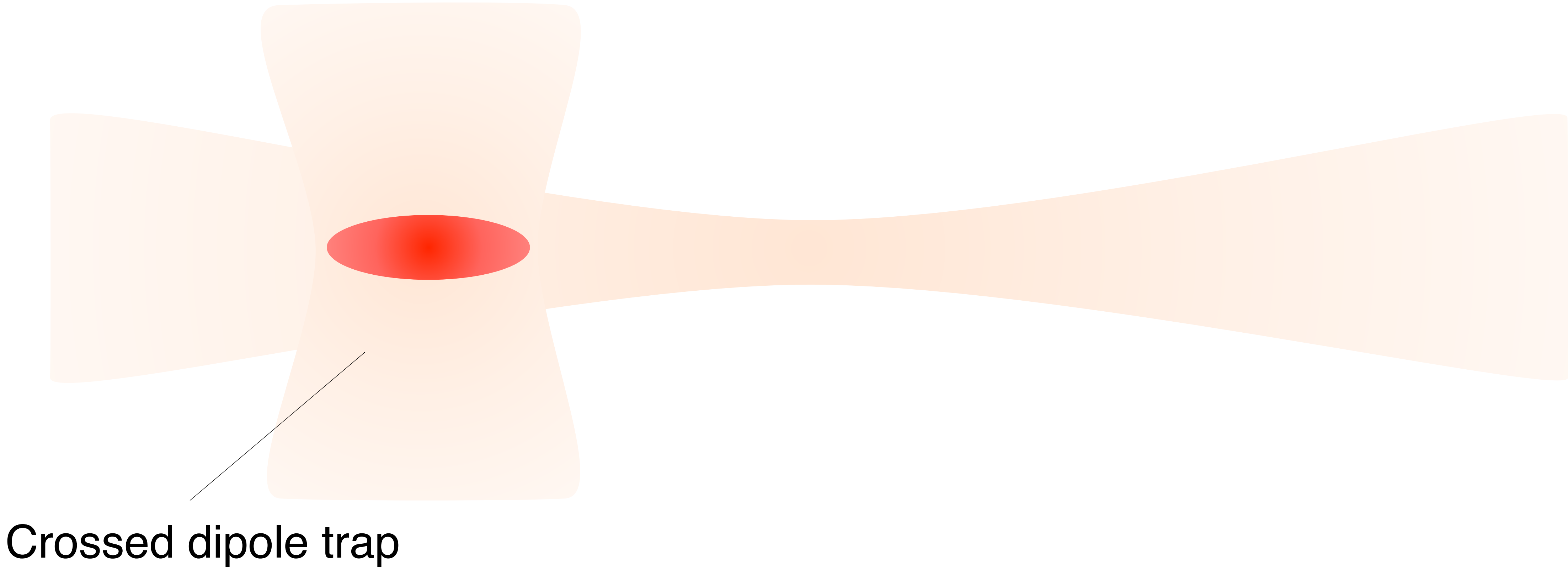




In practice: difficult enough to focus barrier to 1 micron, let alone to make probe even smaller!

For now, modulate barrier at 6.8 GHz to act as probe also.

Experimental sequence: idealized



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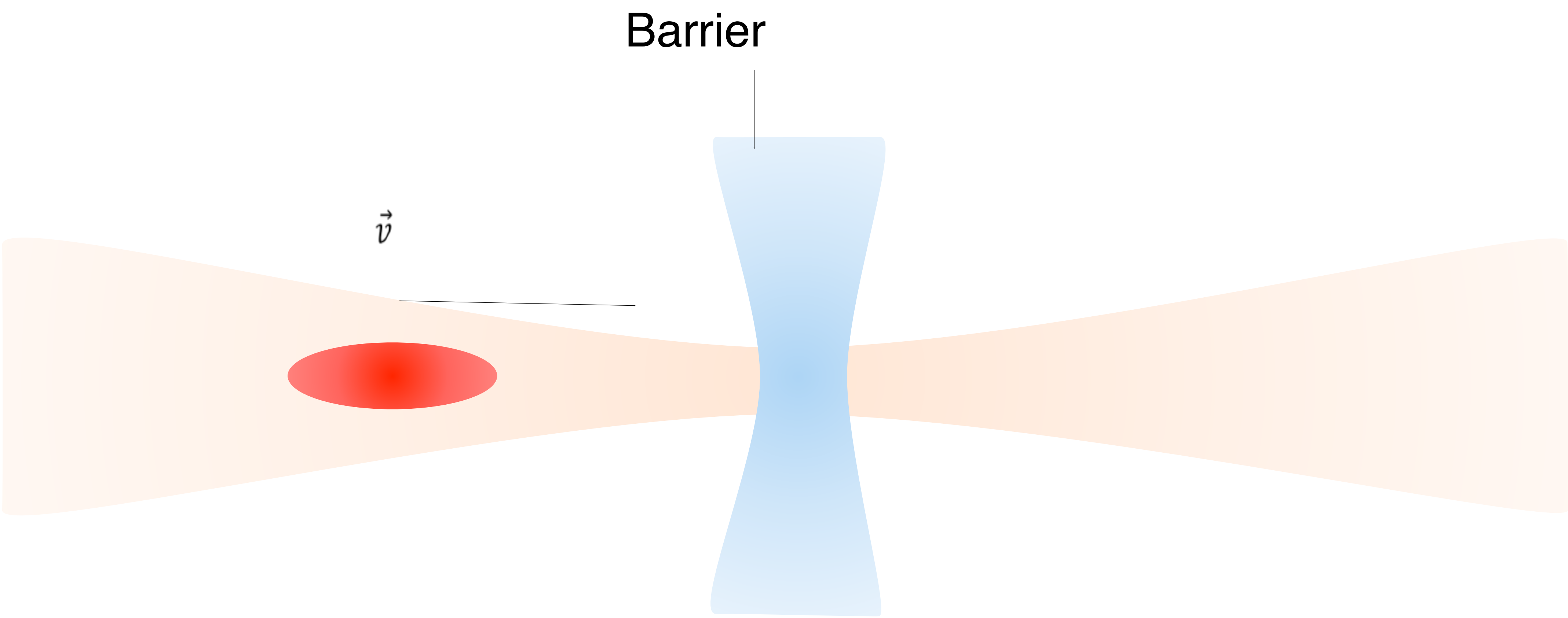

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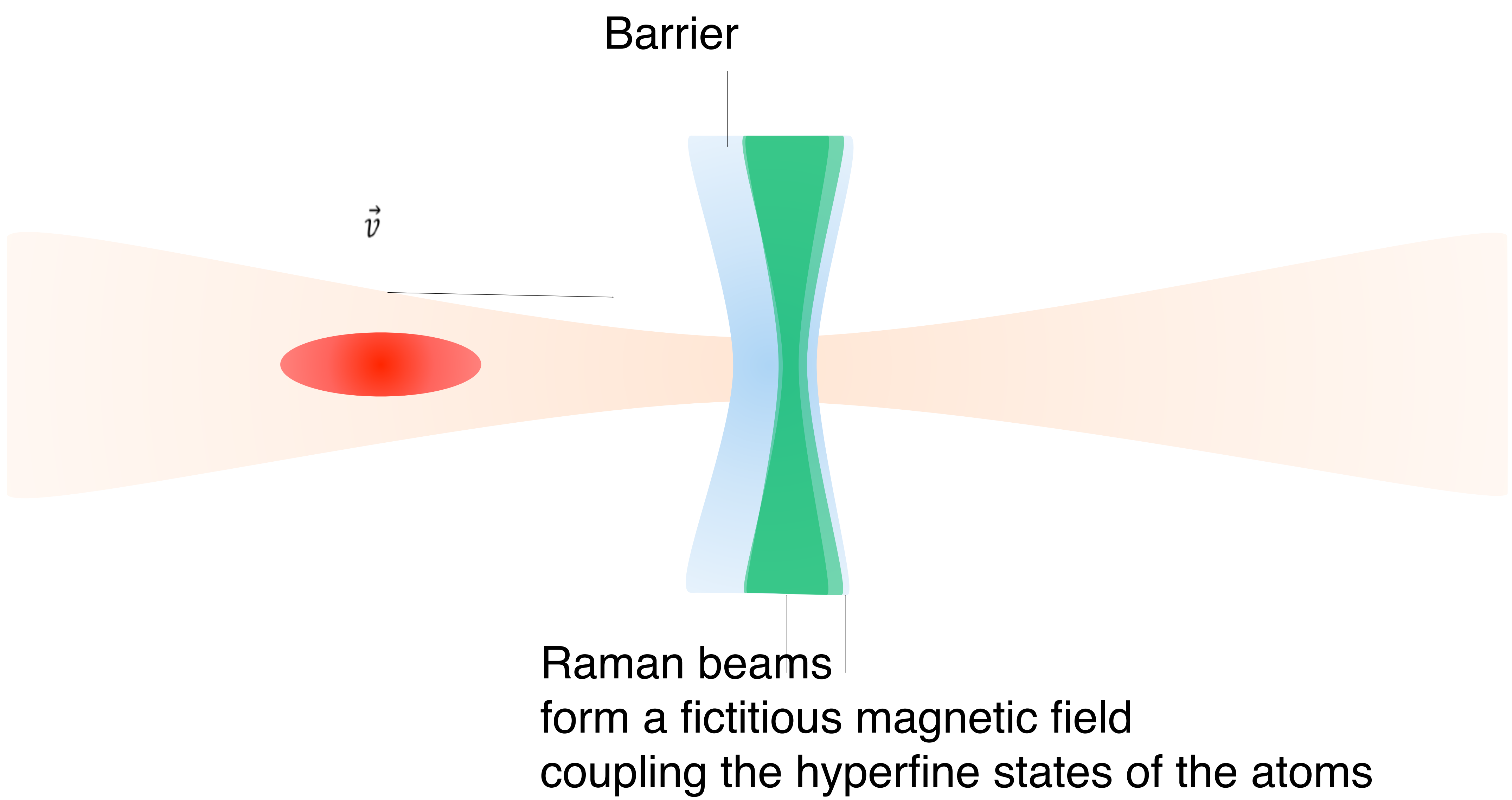

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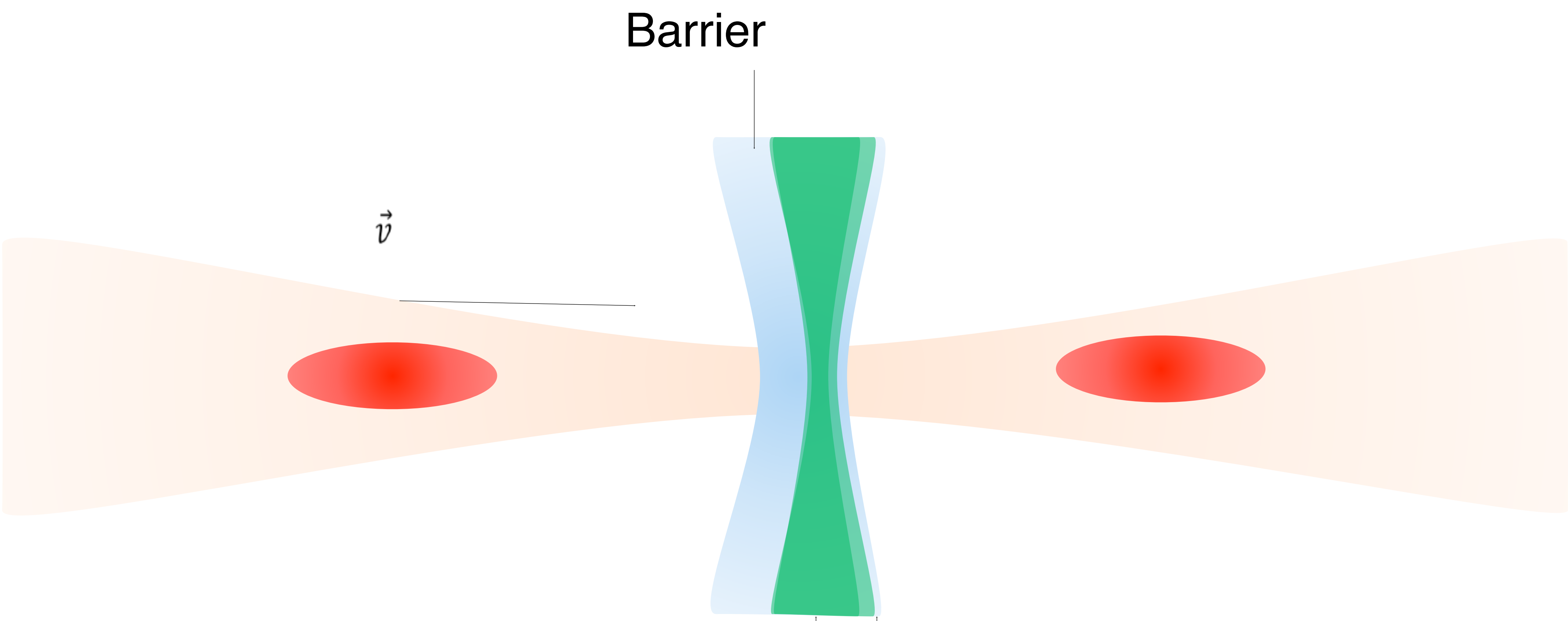
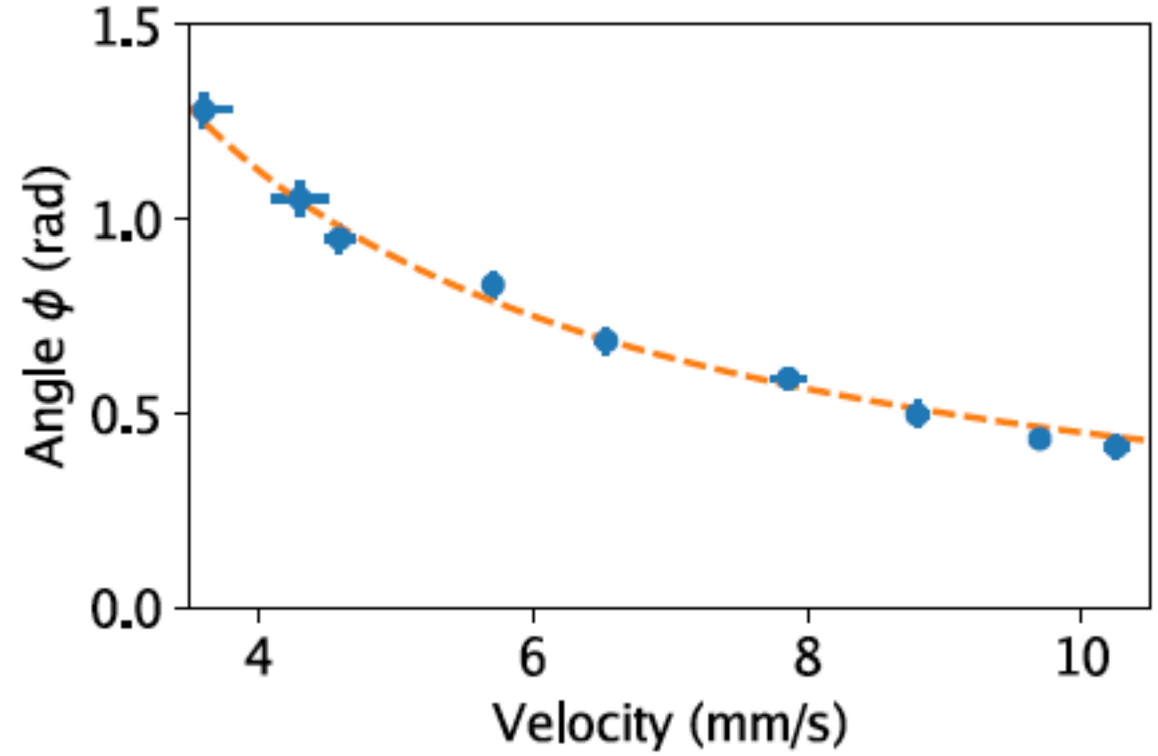
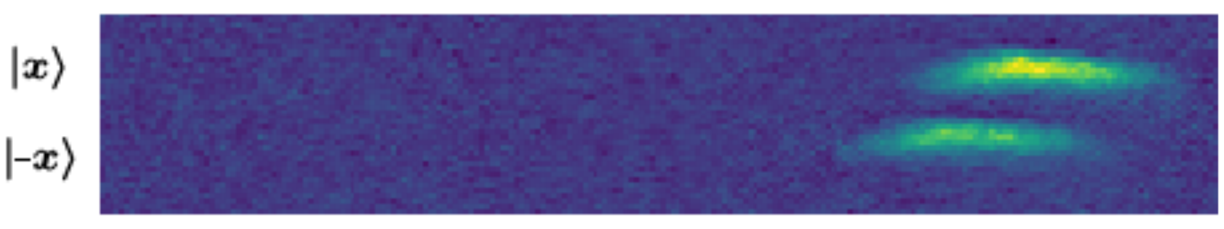


Raman beams
form a fictitious magnetic field
coupling the hyperfine states of the atoms

Calibrating the Larmor clock on a free wavepacket:



Stern-Gerlach measurement of precession:



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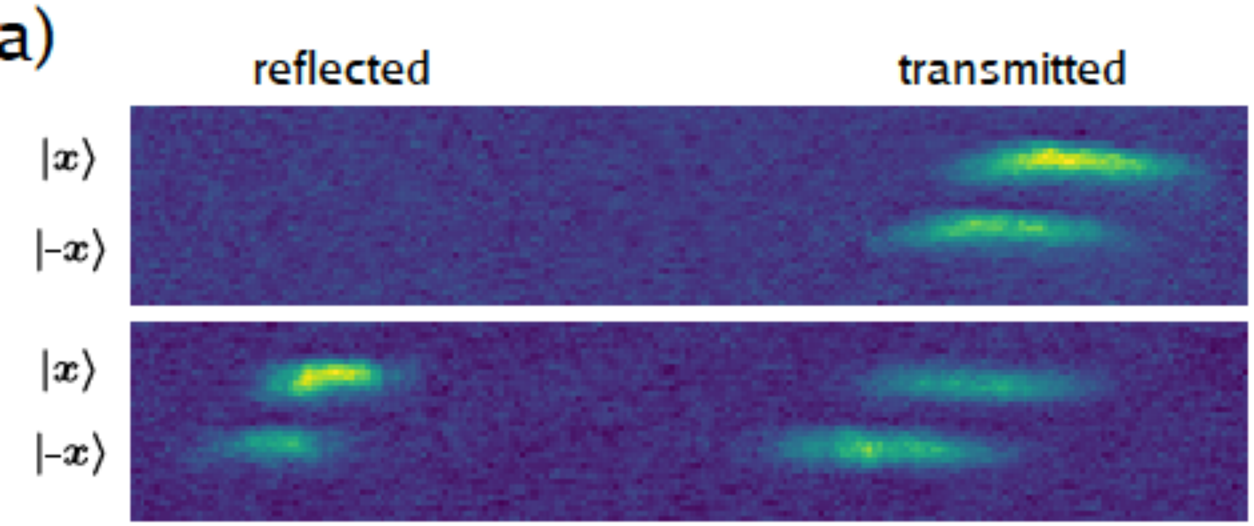
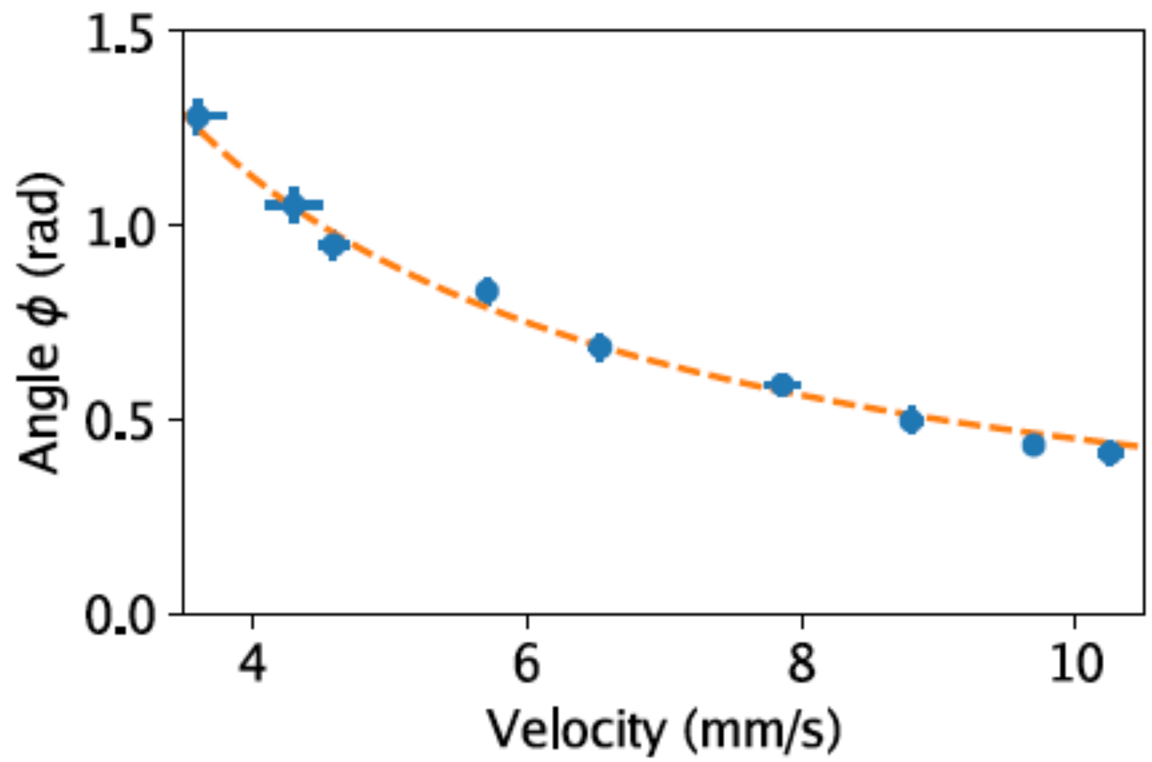
Raw images (no barrier; barrier close to E) :





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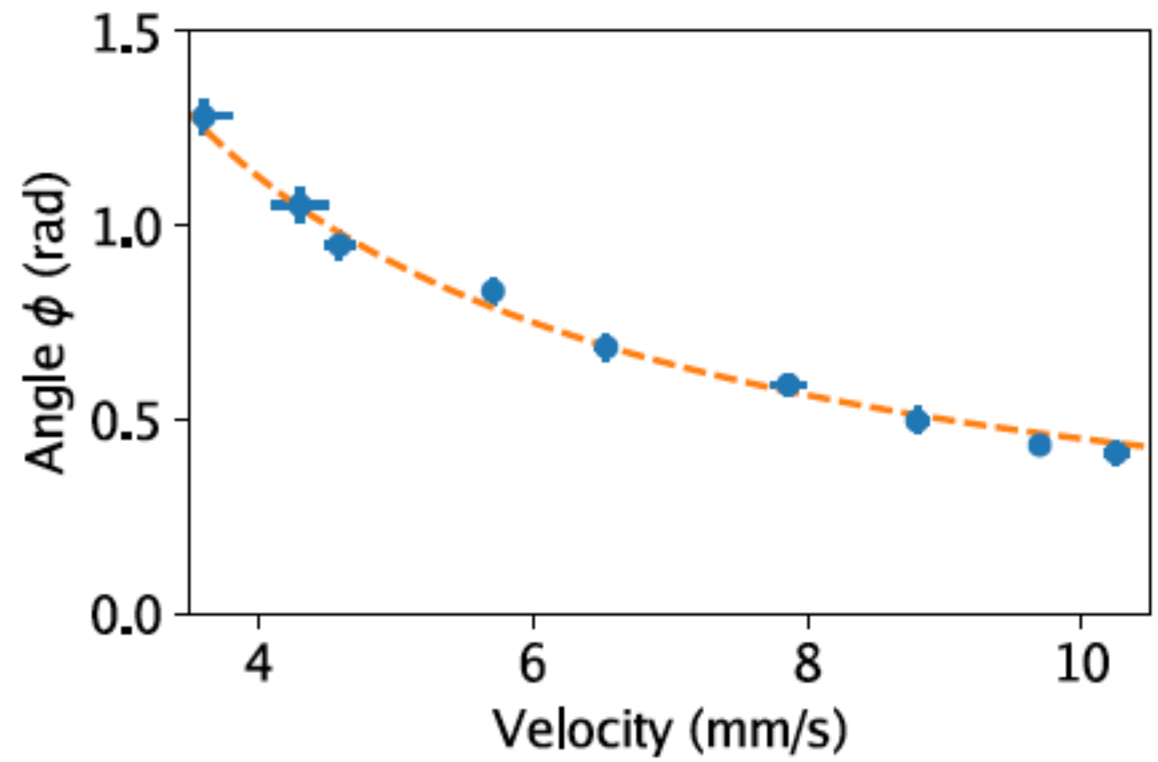

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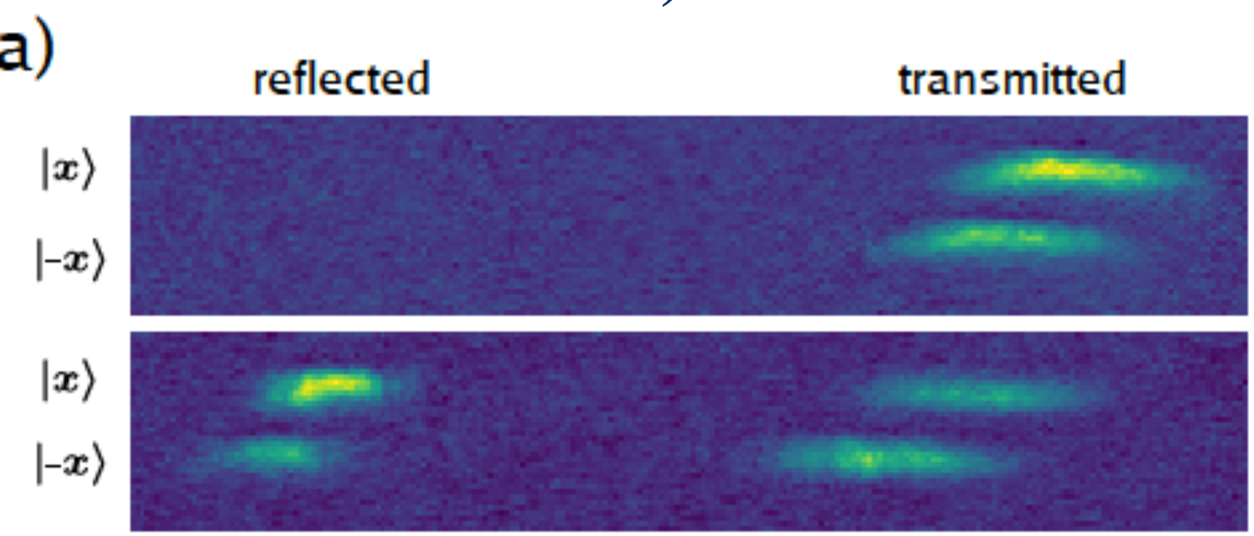
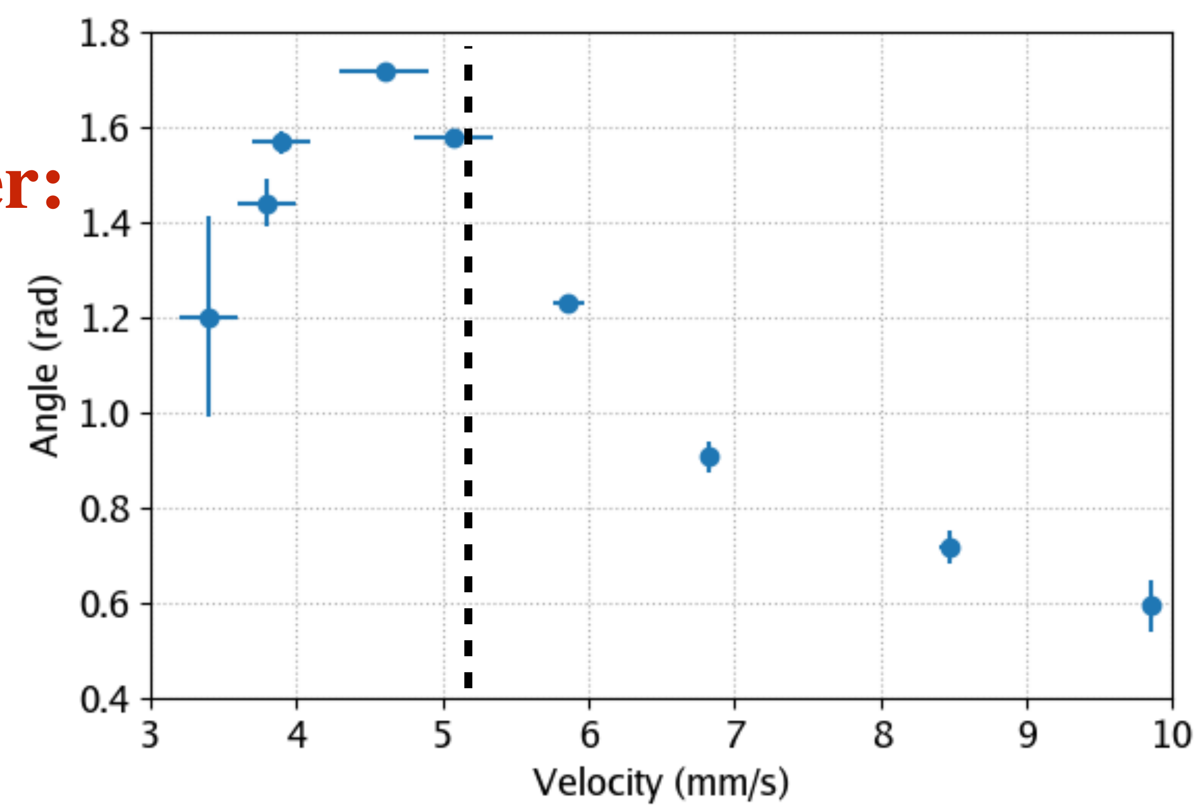
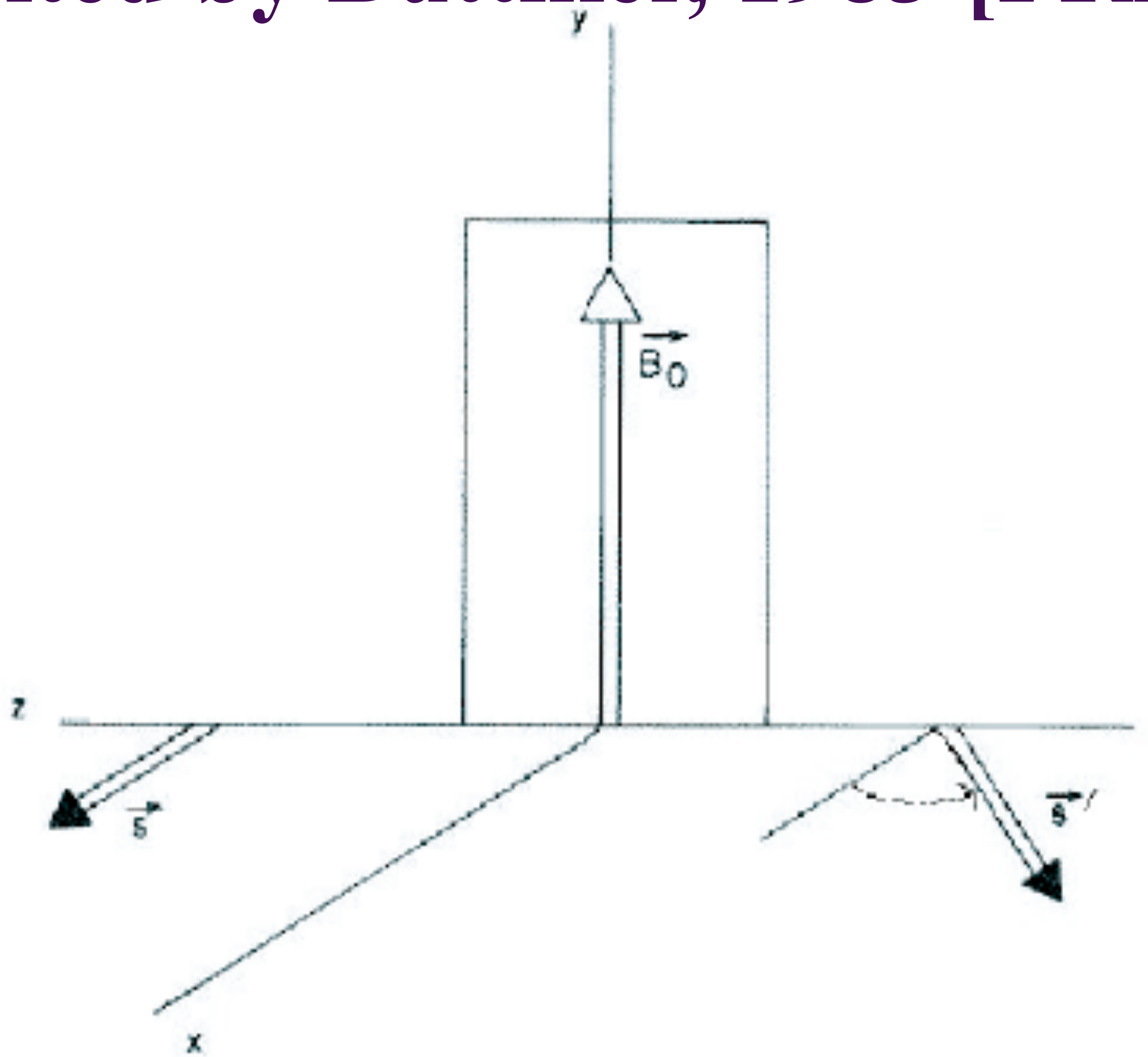


Early precession data with barrier:

(Take w/ grain of salt)



“Larmor Clock”
(as revisited by Büttiker, 1983 [PRB 27, 6178])



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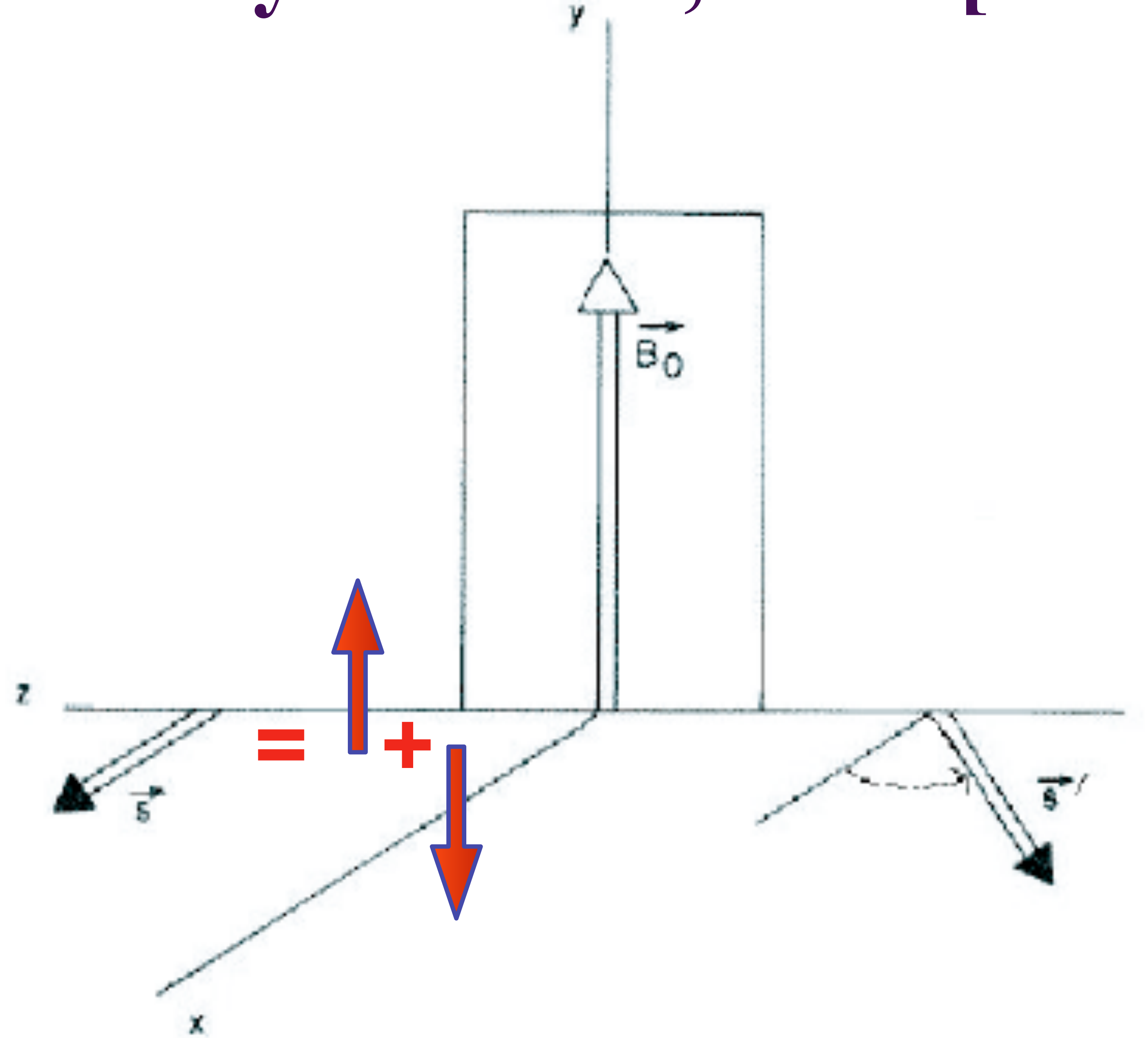

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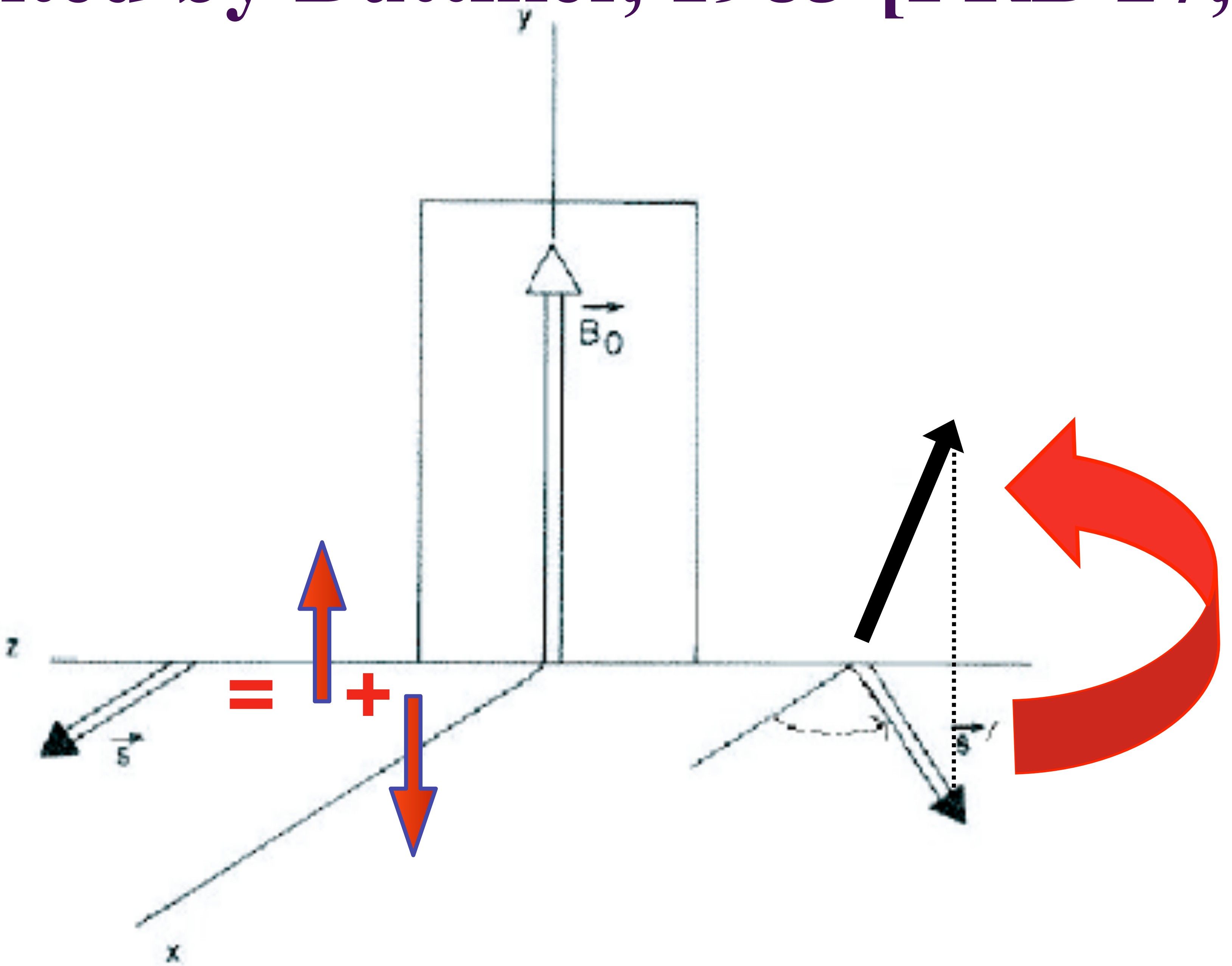

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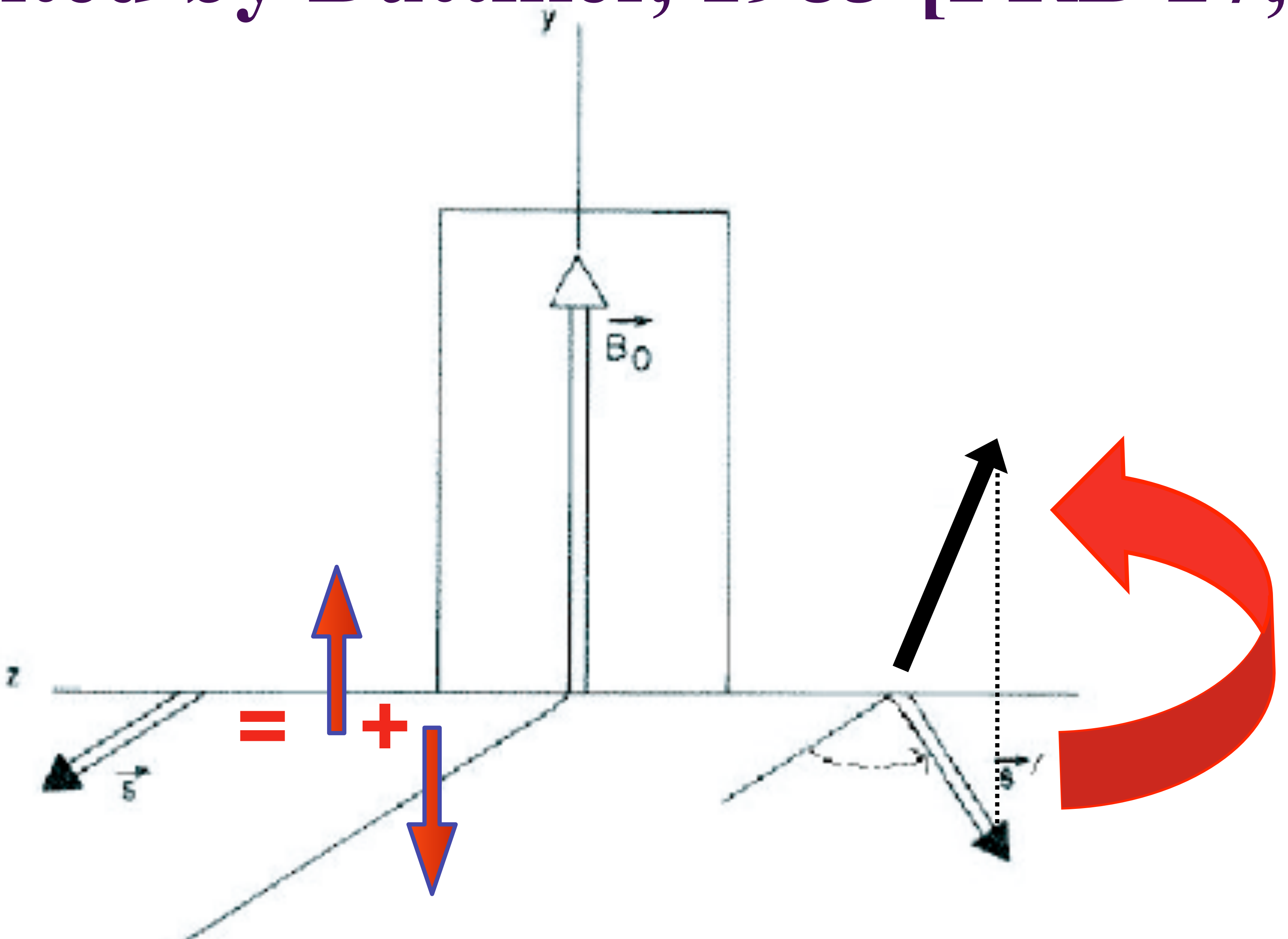

The presence of two components to the Larmor time mystified Büttiker; a Feynman-path approach led to complex times [Sokolovski + Baskin, PRA 36, 4604 (1987)], which mystified every one.

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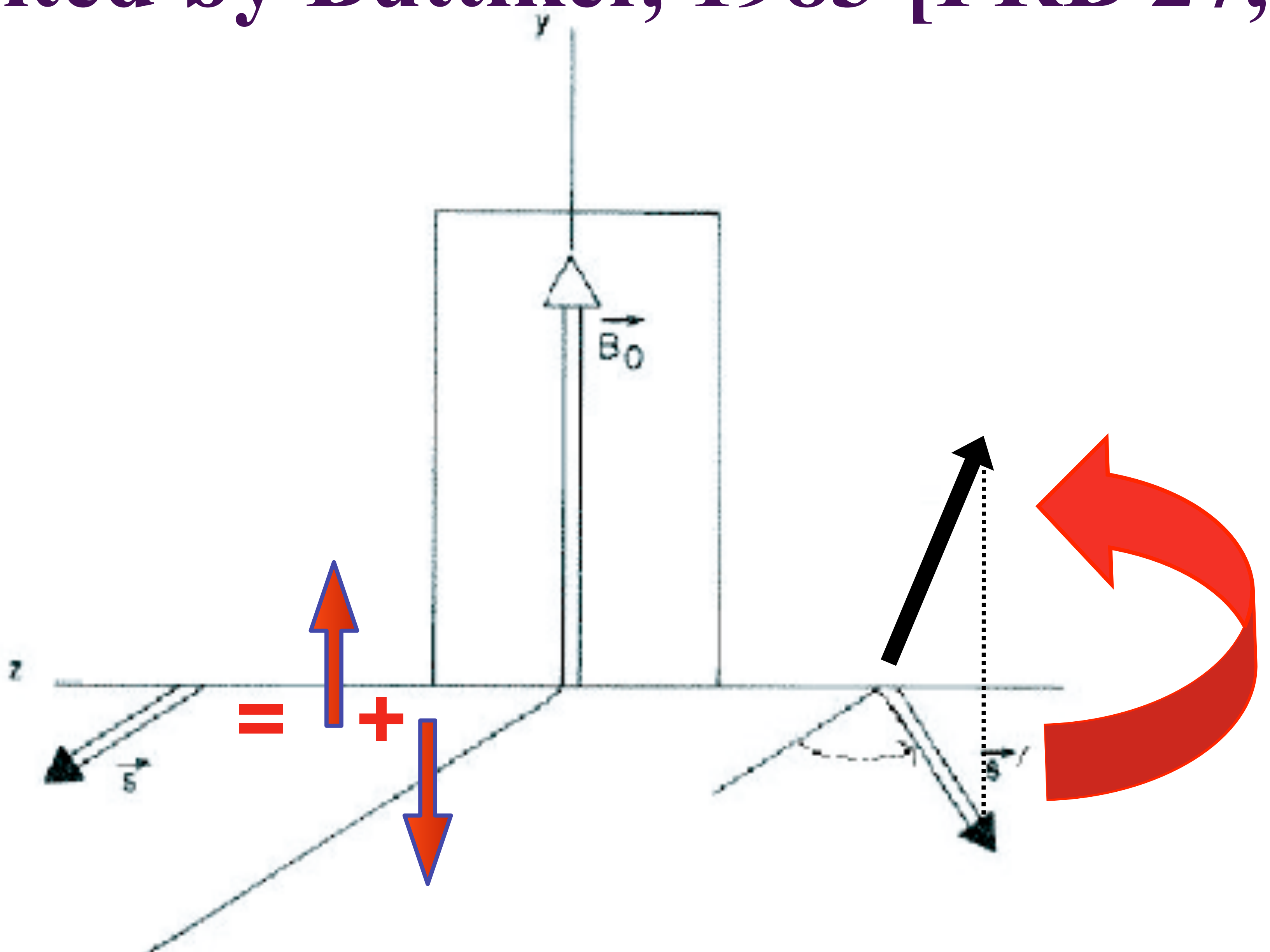
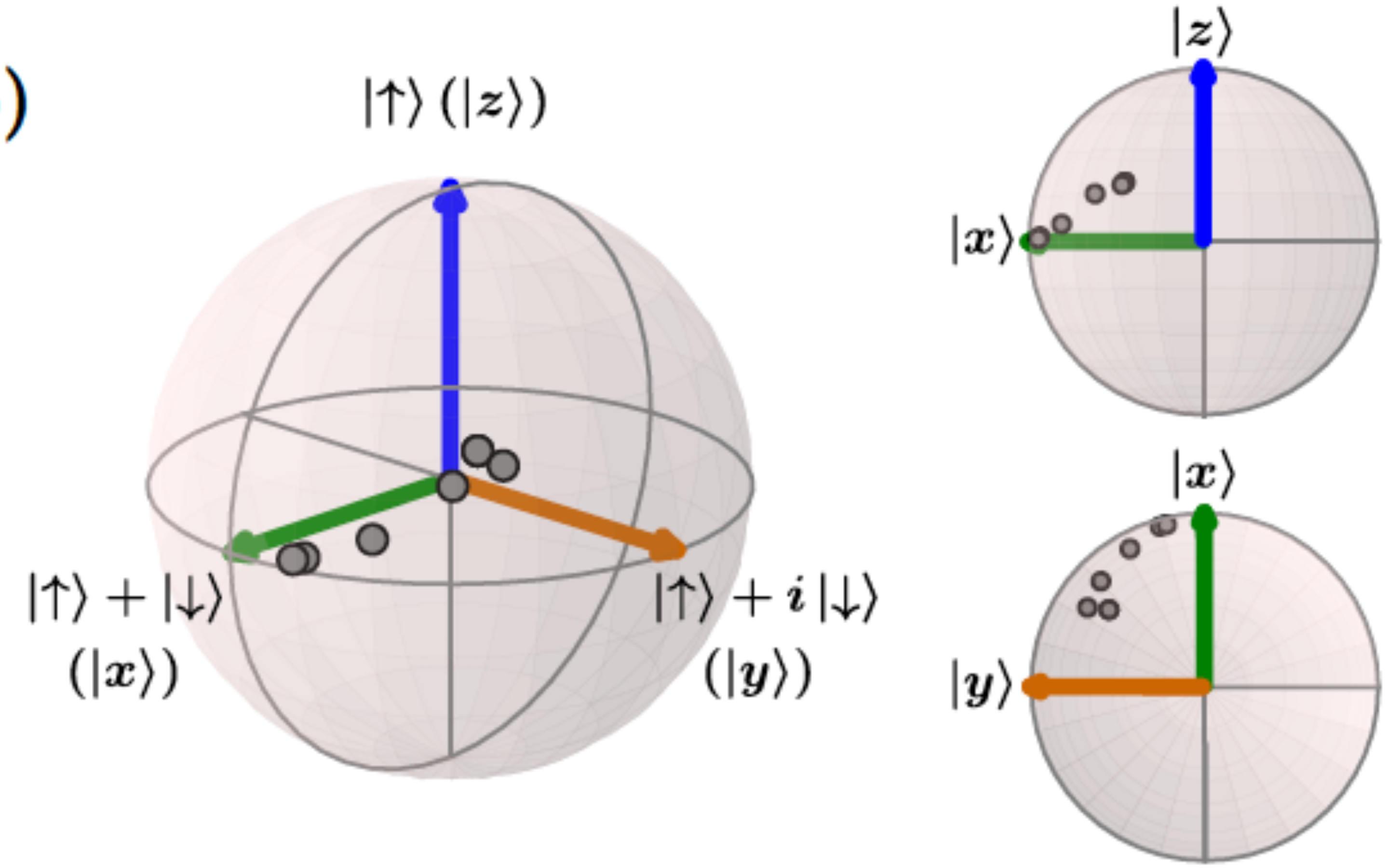


The presence of two components to the Larmor time mystified Büttiker; a Feynman-path approach led to complex times [Sokolovski + Baskin, PRA 36, 4604 (1987)], which mystified every one.

These can be unified by the “weak measurement” formalism of Aharonov, Albert, & Vaidman, in which a postselected (“weak”) value has a real part (the shift in a measurement pointer) and an imaginary part (related to the backaction).

How to measure the out-of-plane ("imaginary") part?
Do full tomography on spin:

b)



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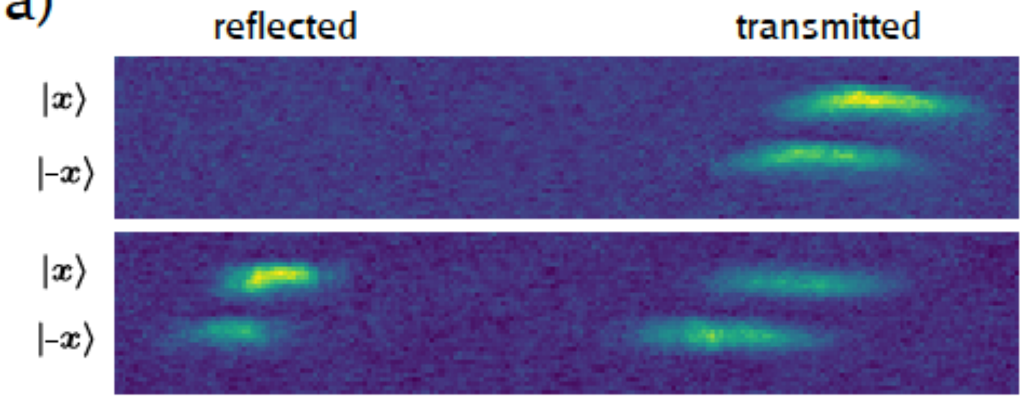
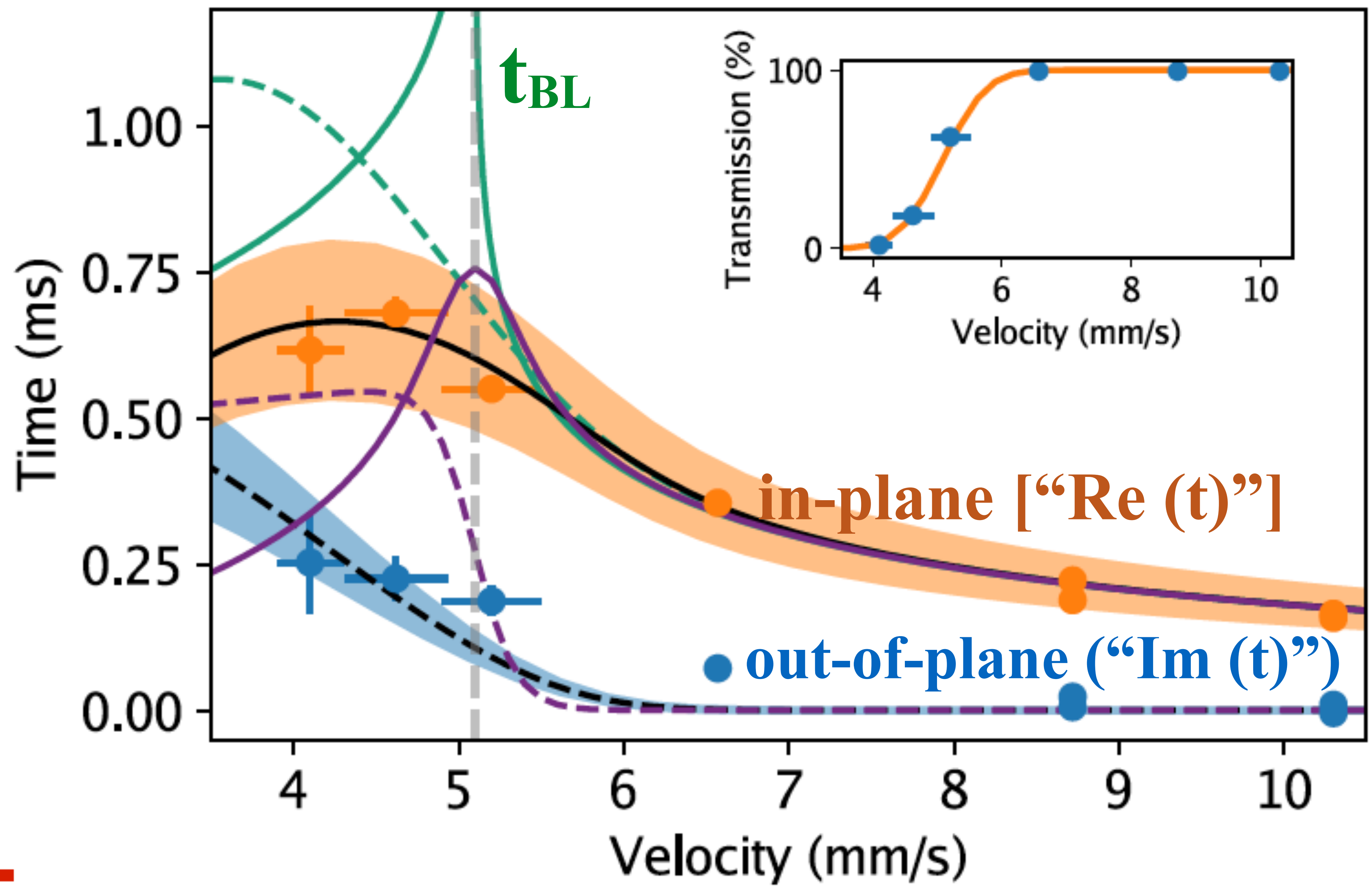
a)



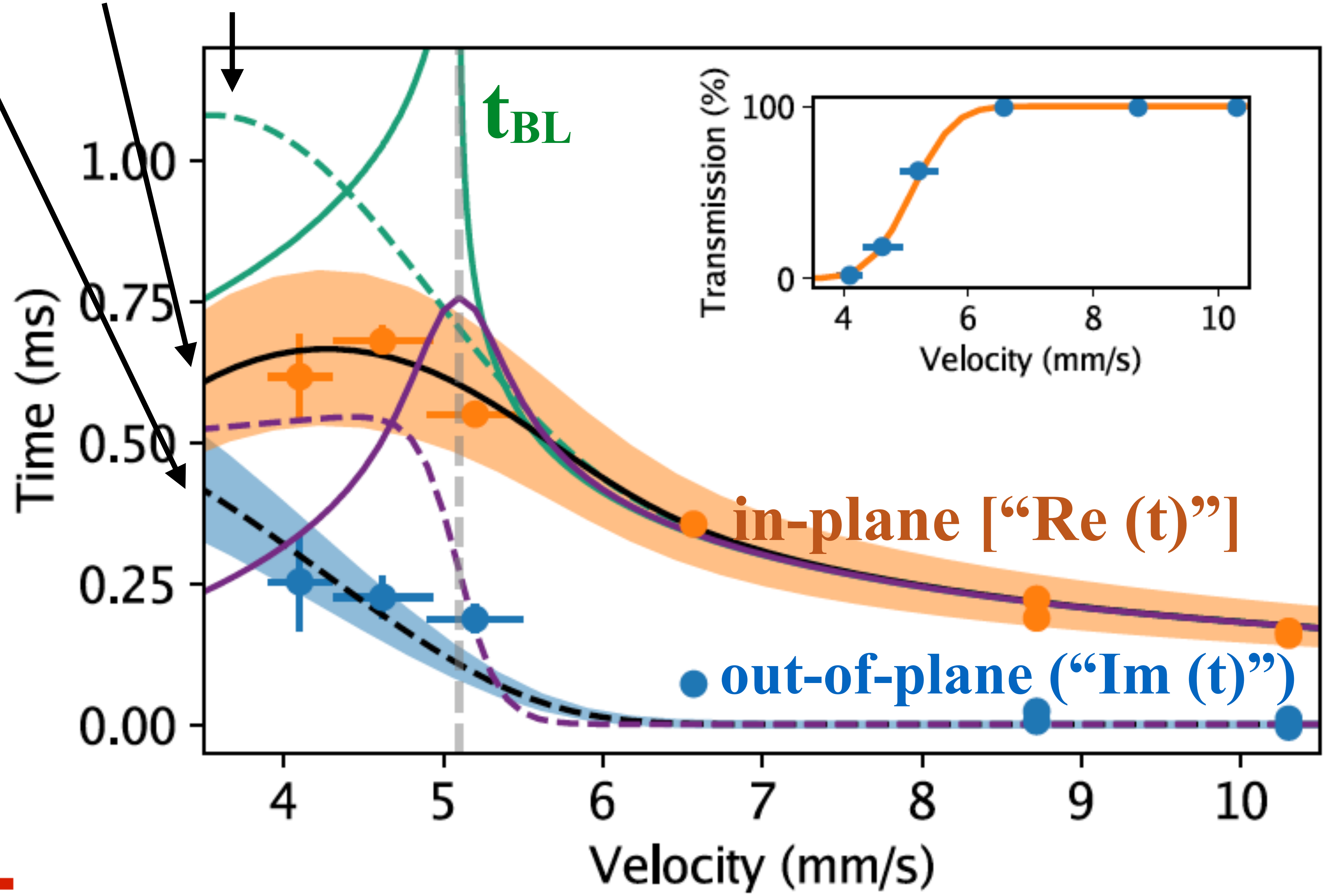
The results



t_{BL}
Time (ms)
1.00
0.75
0.50
0.25
0.00
4
5
6
7
8
9
10
Velocity (mm/s)
Transmission (%)
100
0
4
6
8
10
Velocity (mm/s)
in-plane ["Re (t)"]
out-of-plane ("Im (t)")

The results

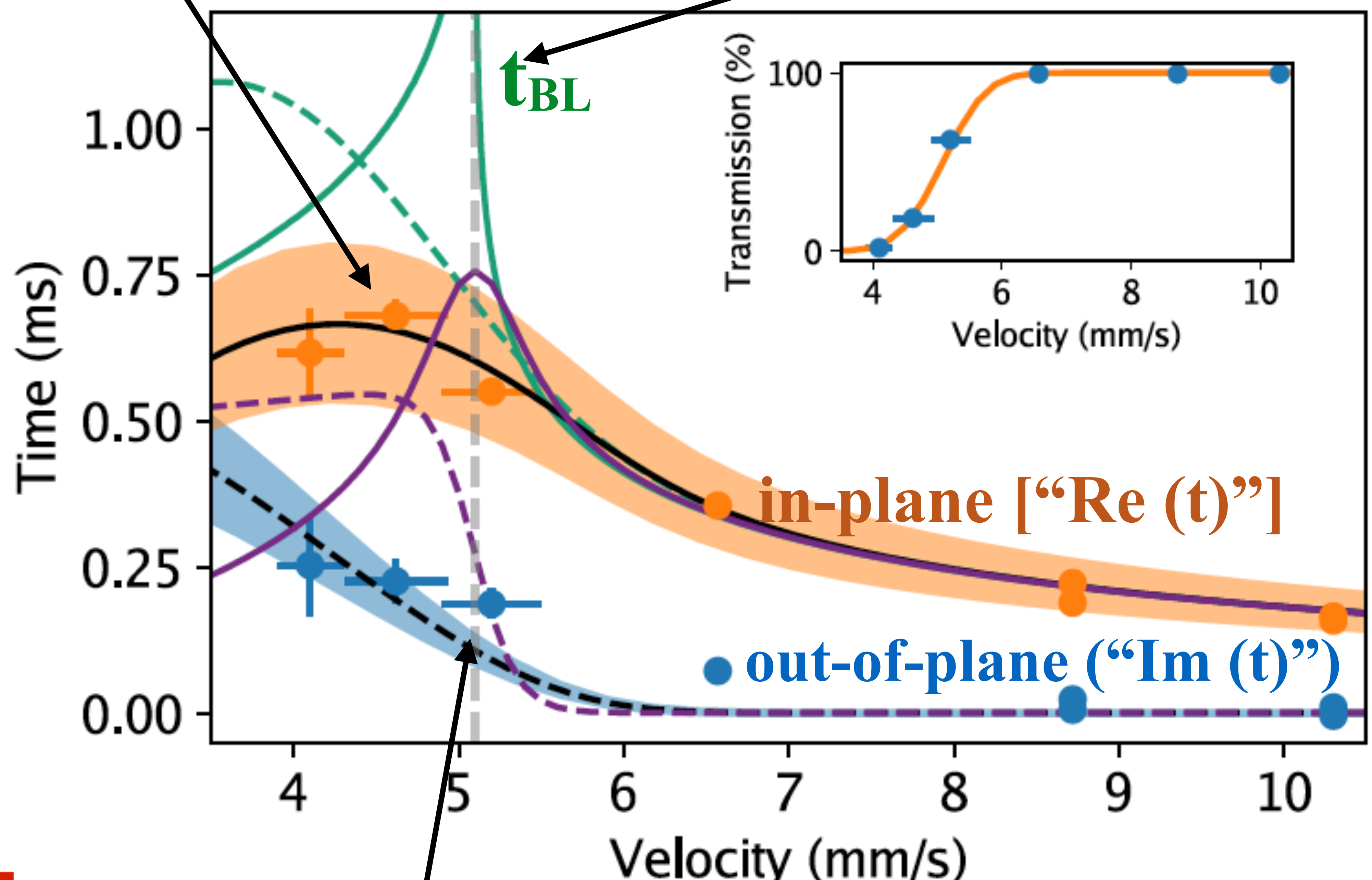
(Curves shifted/"smeared" due to preferential transmission of higher energies)



The results

"Real part" grows as v drops to top of barrier; but reaches a peak and should fall again.

Divergence of "semiclassical time" of course inconsistent with experimental results



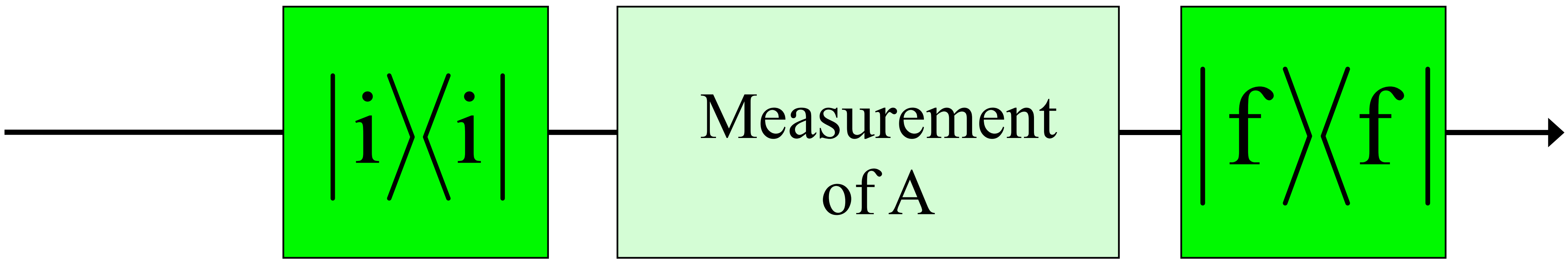
"Imaginary part" (back-action) becomes important in quantum regime

Complex times and connection to "weak measurement"

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>**



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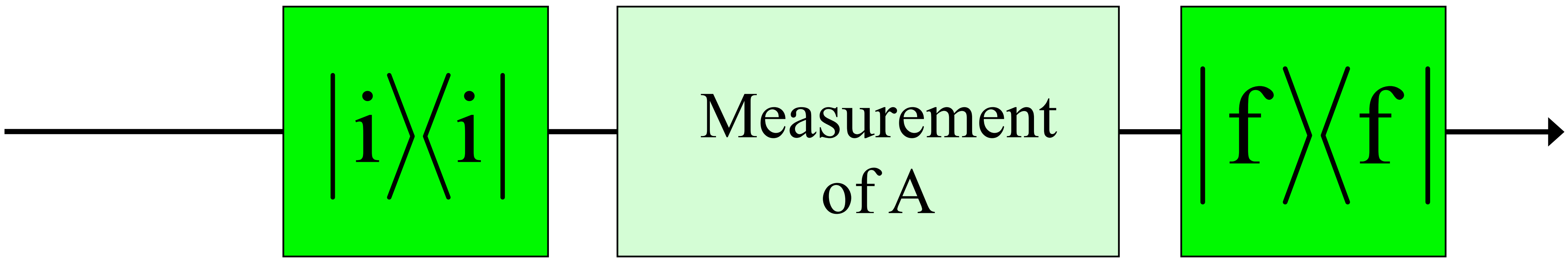
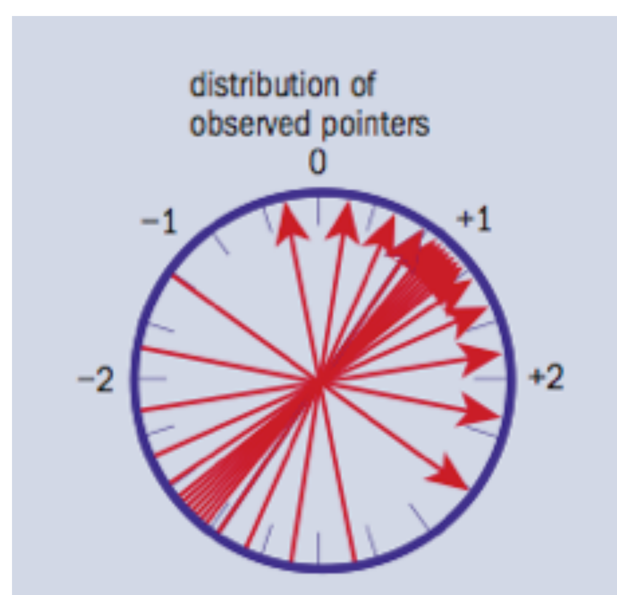


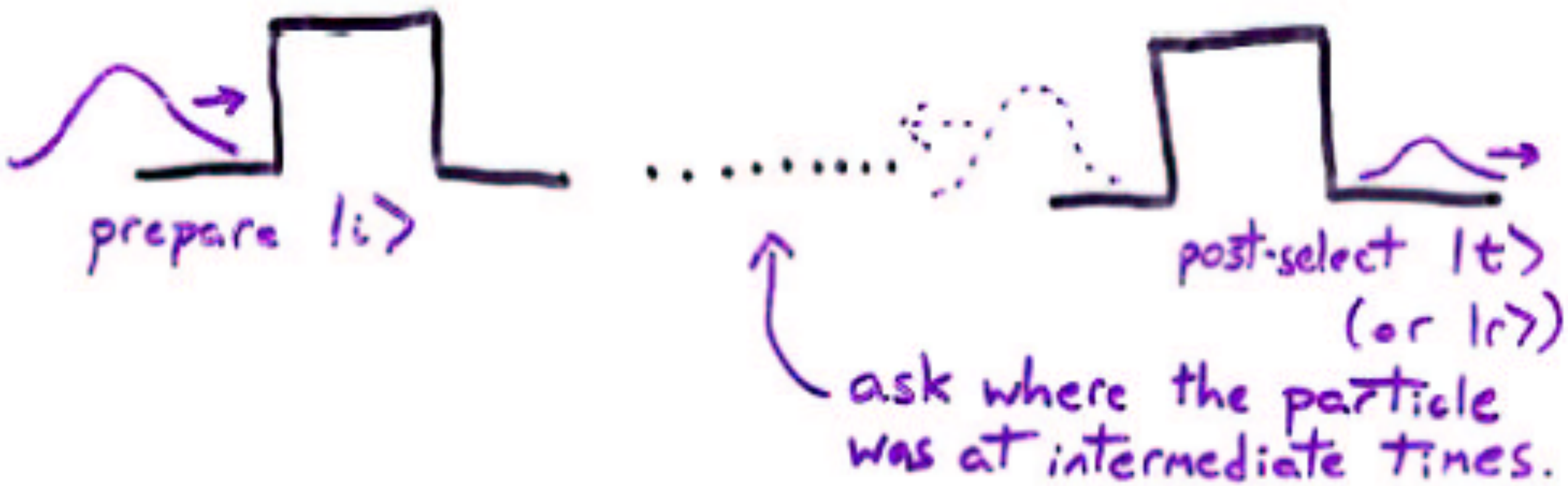
Measure A "weakly."
Poor resolution, but little disturbance.

the "weak value"



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

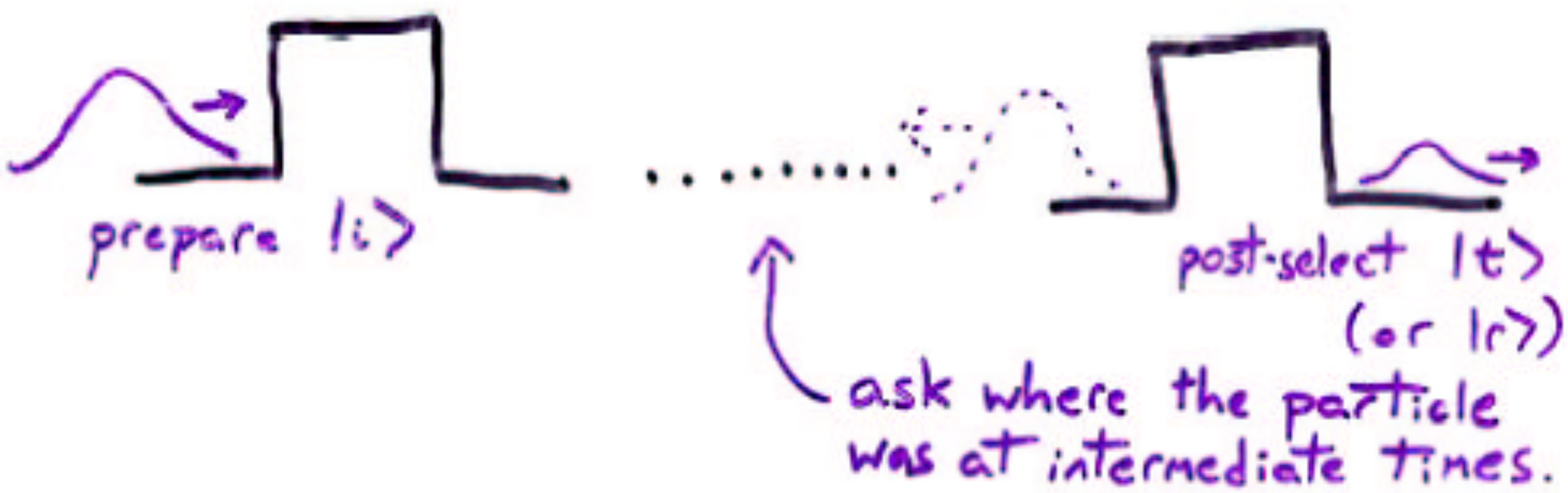
Conditional probabilities: weak values



$$P(x) = |\psi(x)|^2 = \langle\psi\underbrace{|x\rangle\langle x|}_{\mathrm{Proj}(x)}\psi\rangle$$

AMS, PRL 74, 2405 (1995)

Conditional probabilities: weak values



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$$P(\, x \mid \text{trans}\,) = [\, \langle \Psi_{TR} | x \rangle \langle x | \Psi_{IN} \rangle \,] \,/\, [\langle \Psi_{TR} | \Psi_{IN} \rangle]$$

$$P(\, x \mid \text{refl}\,) = [\, \langle \Psi_{RE} | x \rangle \langle x | \Psi_{IN} \rangle \,] \,/\, [\langle \Psi_{RE} | \Psi_{IN} \rangle]$$

AMS, PRL 74, 2405 (1995)

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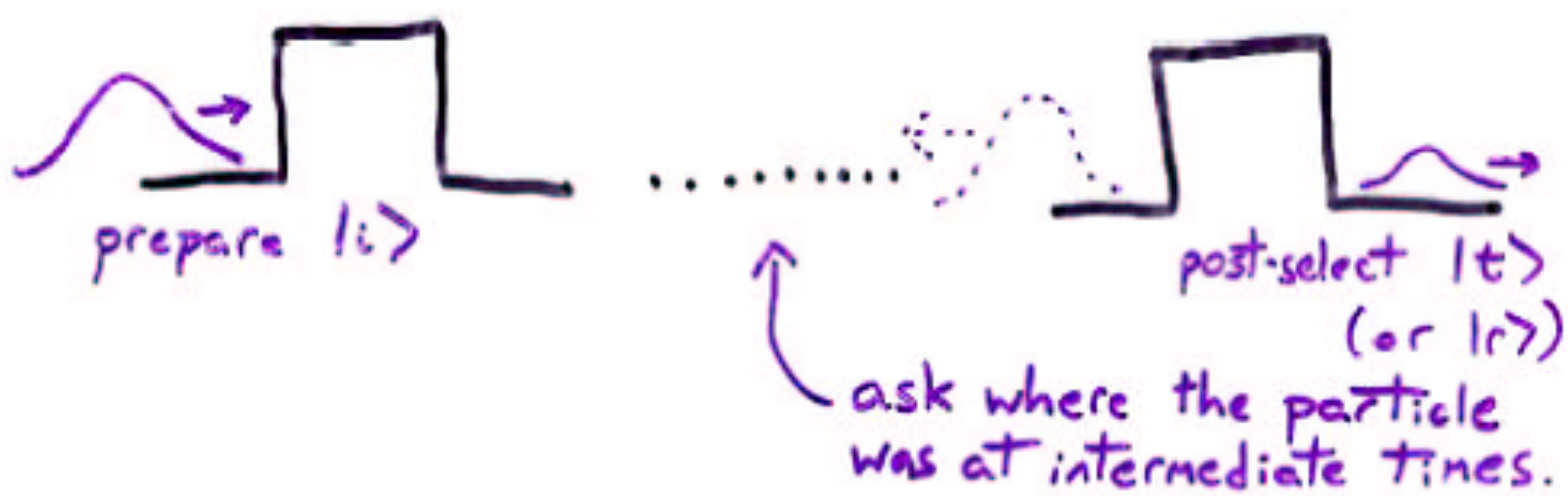

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$$P(x,t|trans) = \frac{1}{T}\psi_t^*(x,t)\psi_i(x,t) = |\psi_i(x,t)|^2 + \frac{R}{T}\psi_i^*(-x,t)\psi_i(x,t)$$
$$P(x,t|refl) = \frac{1}{R}\psi_r^*(x,t)\psi_i(x,t) = |\psi_i(x,t)|^2 + \frac{T}{R}\psi_i^*(-x,t)\psi_i(x,t)\ .$$

AMS, PRL 74, 2405 (1995)

It turns out the Larmor times *are* these weak values, though the latter hadn't been invented yet.

Their Real and Imaginary parts have an unambiguous interpretation.

The real part describes the shift in the pointer position (e.g., precession about B)

But consider a quantum-mechanical stopwatch.

$$\psi(x) \sim e^{-(x-t)^2/4\sigma^2}$$

some inevitable uncertainty

t complex $\Rightarrow \psi \sim e^{-(x - \mathrm{Re}\, t)^2/4\sigma^2}\, e^{ix\, \mathrm{Im}\, t/2\sigma^2}\, e^{\cdots}$

hand shifts by $\mathrm{Re}\, t$

picks up momentum of $\hbar\, \mathrm{Im}\, t/2\sigma^2$

normalization

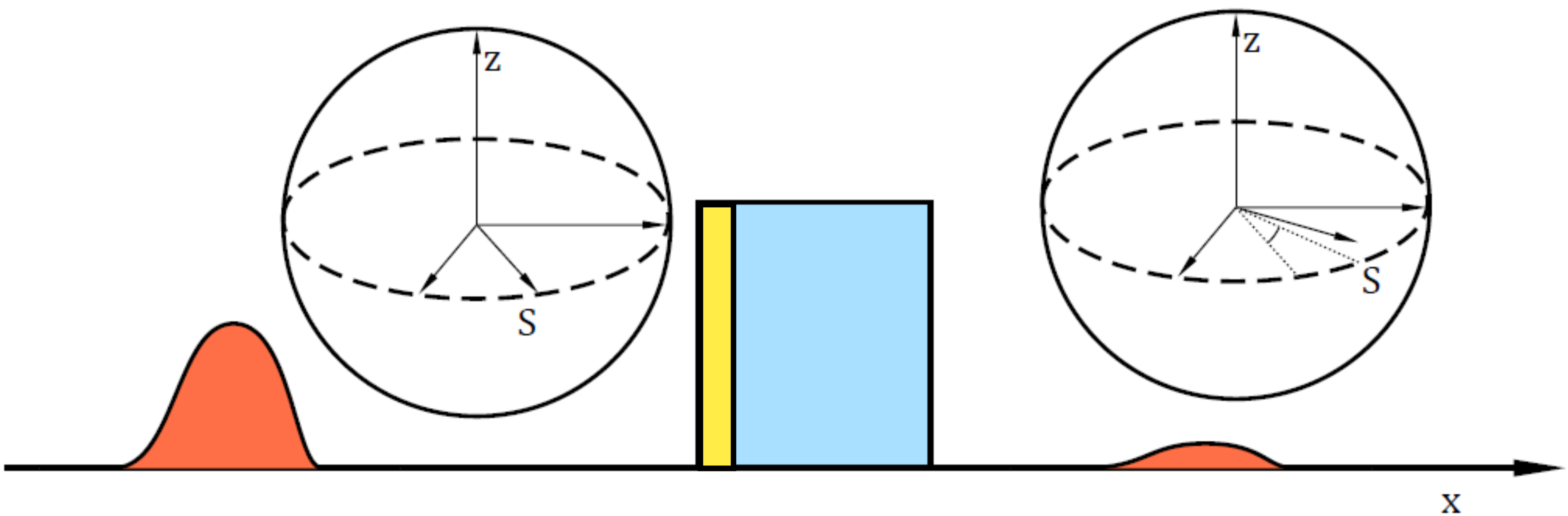
The imaginary part describes the *back-action* on the particle (effect on the conjugate variable, here *alignment* with B)

The latter vanishes with the weakness of the measurement, while the former remains constant.

AMS, PRA 52, 32 (1995)

Ongoing experiments asking what a system was doing before you opened the door

Even better will be: *Local* "Larmor Clock" – how much time spent in any given region?



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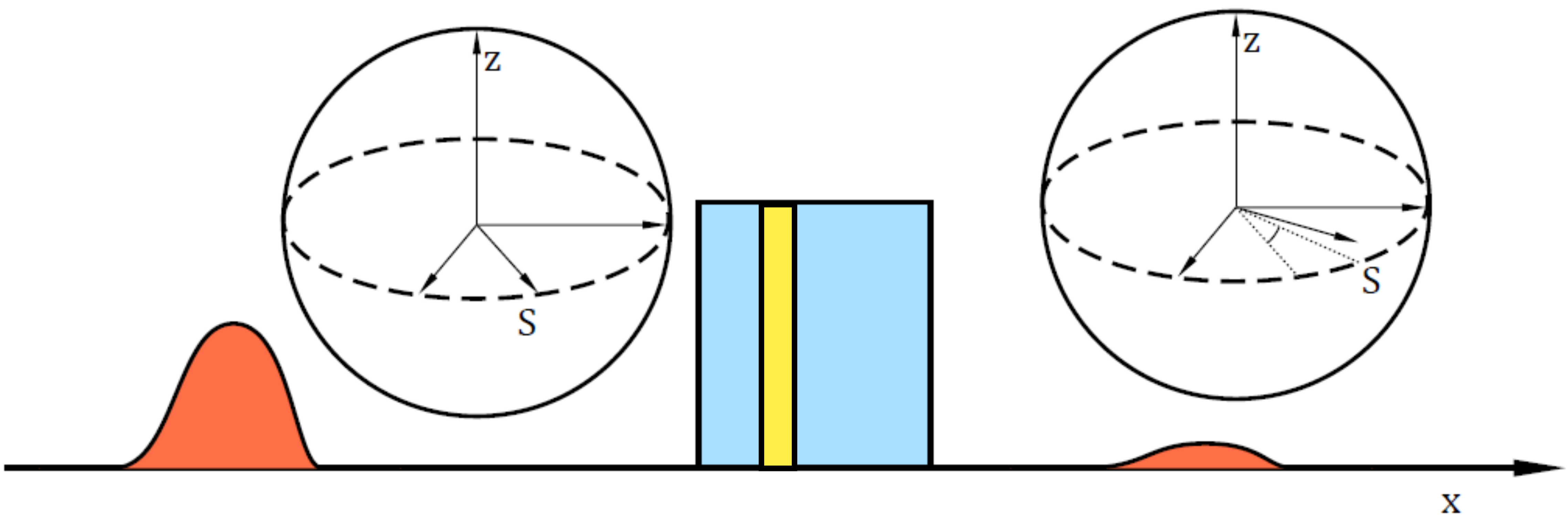

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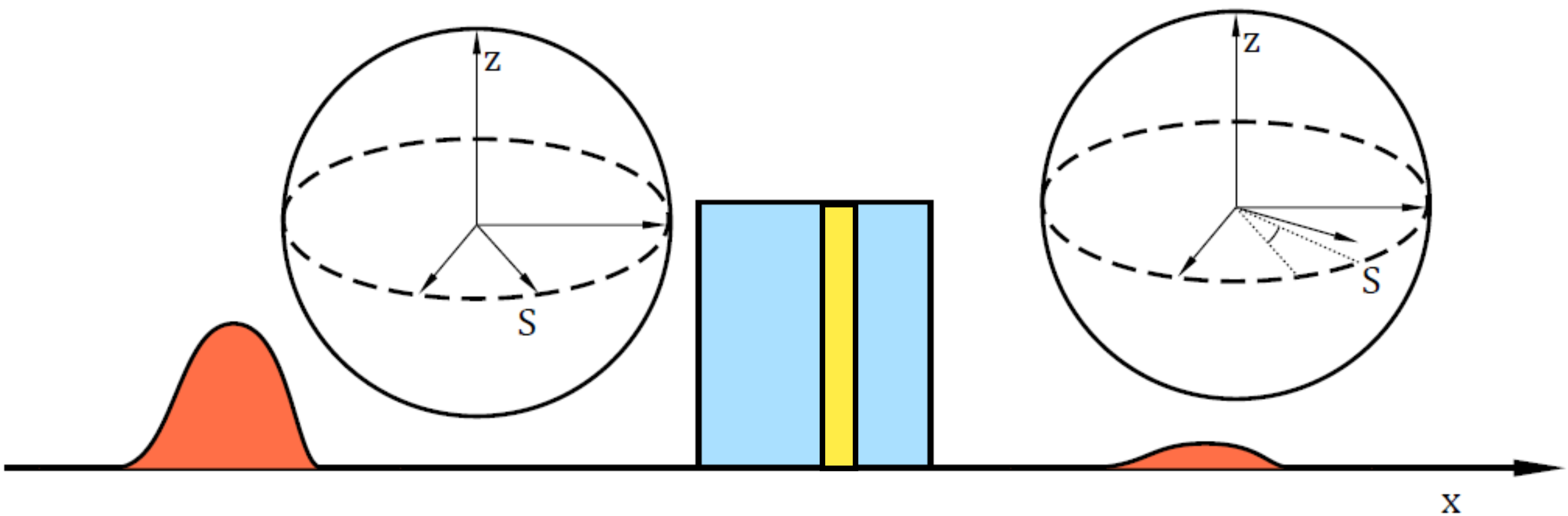

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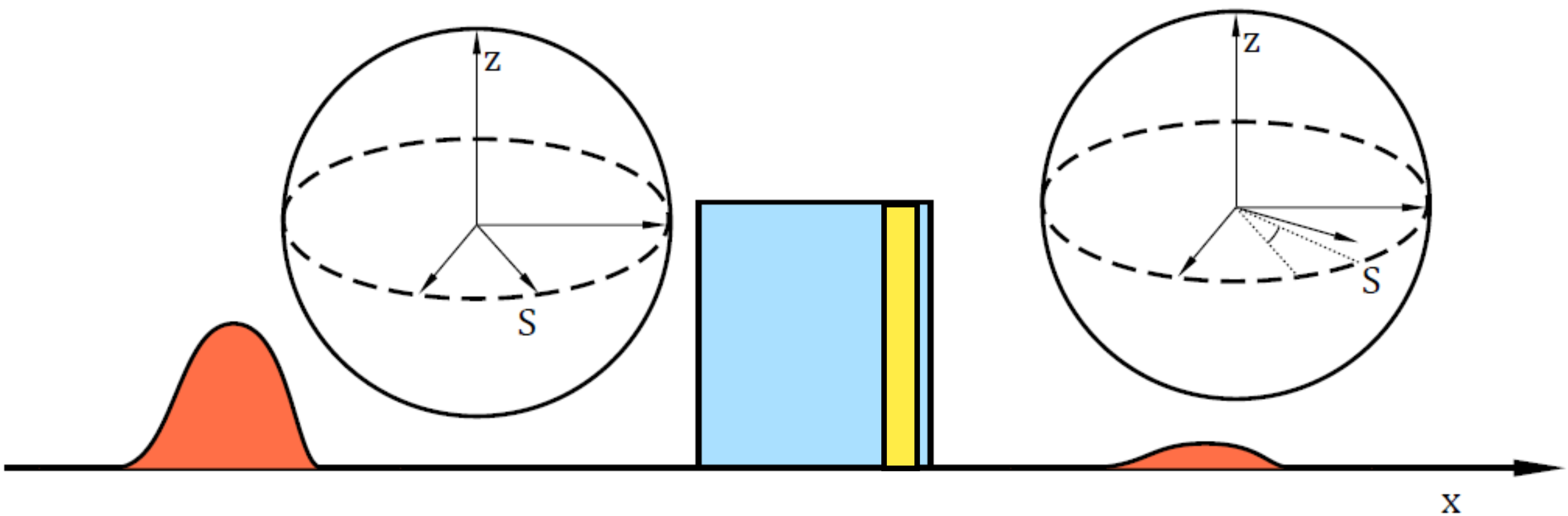
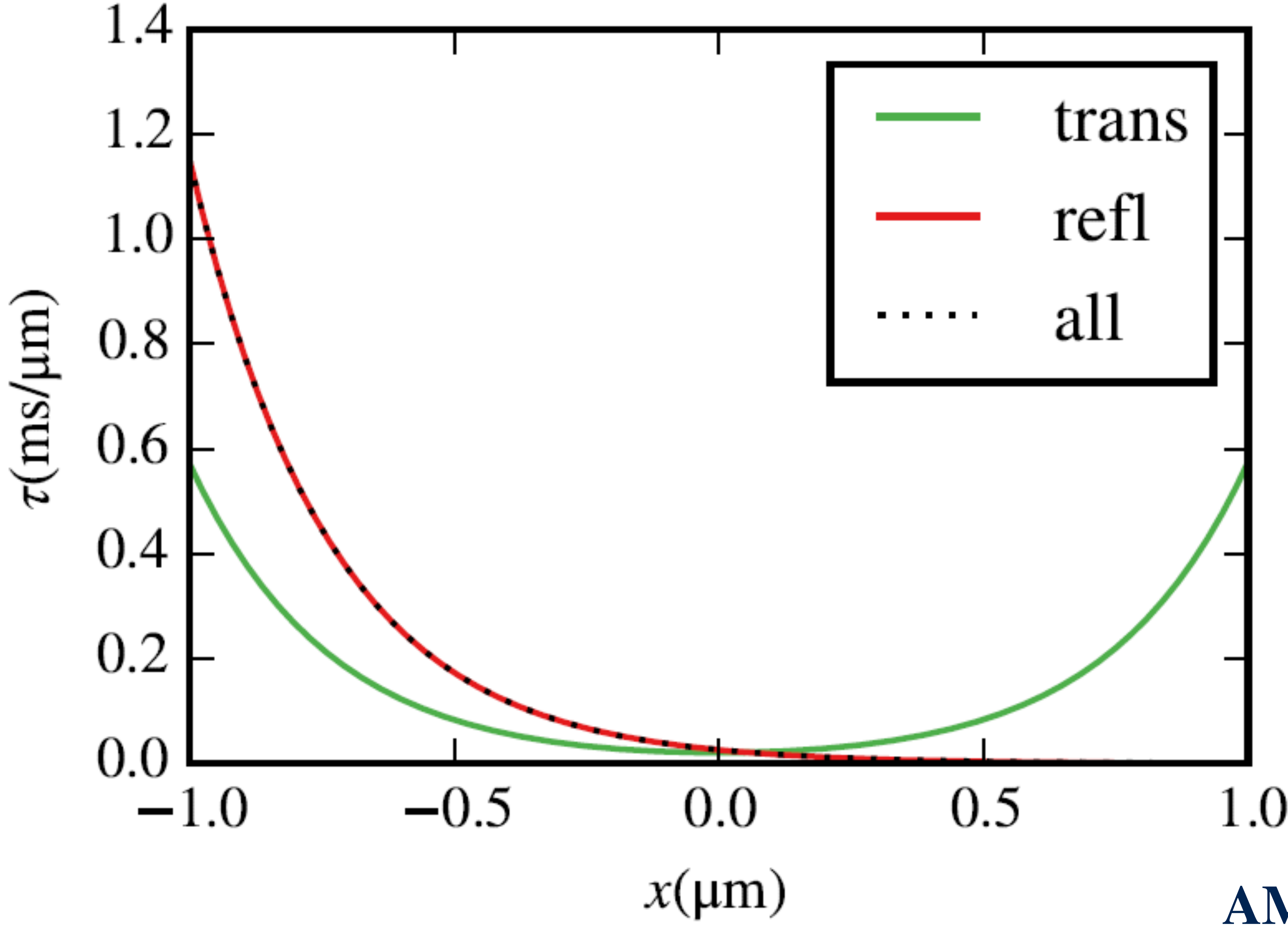


Predictions for a future experiment



AMS, PRL 74, 2405 (1995)
AMS, PRA 52, 32 (1995)

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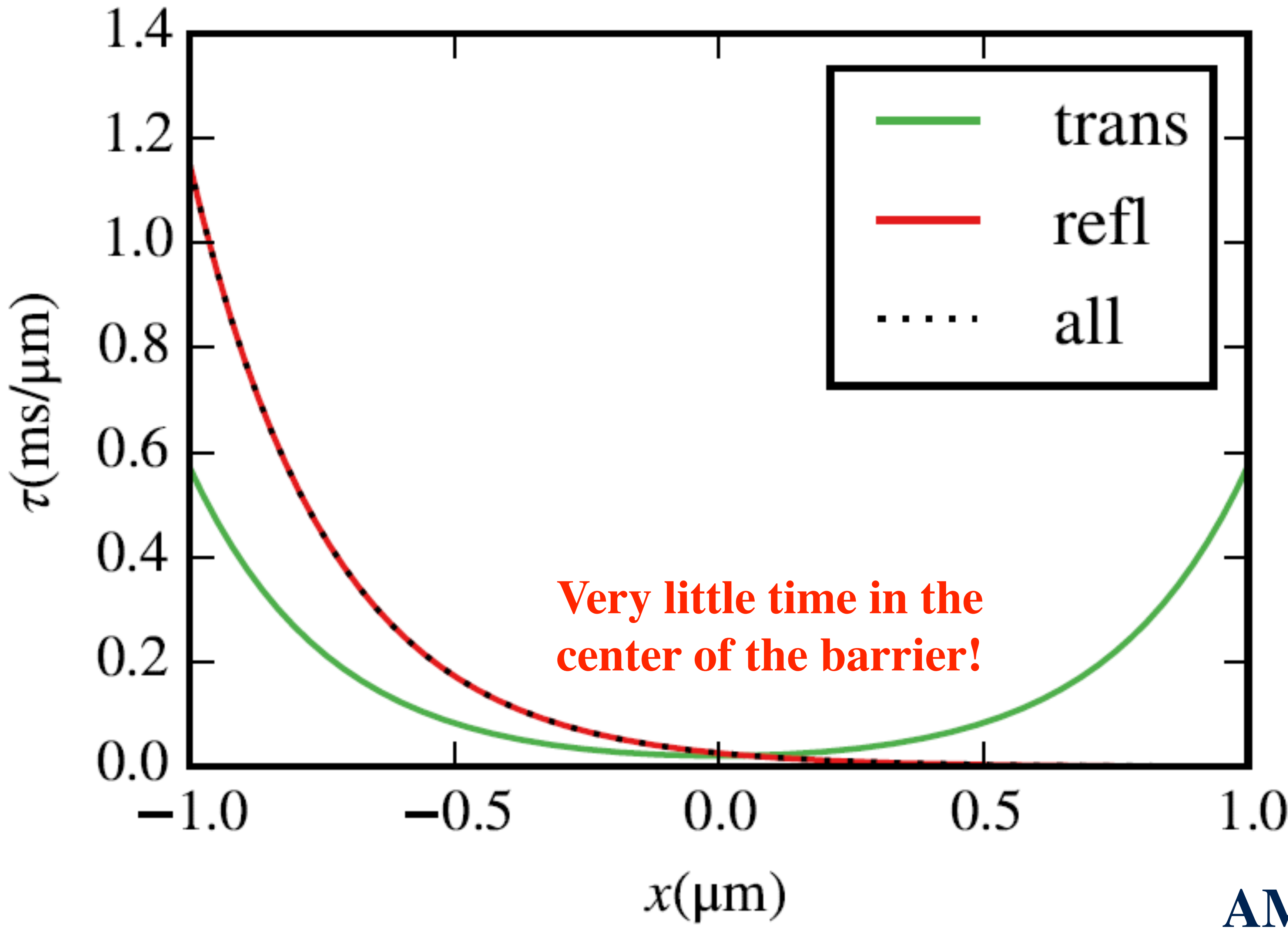
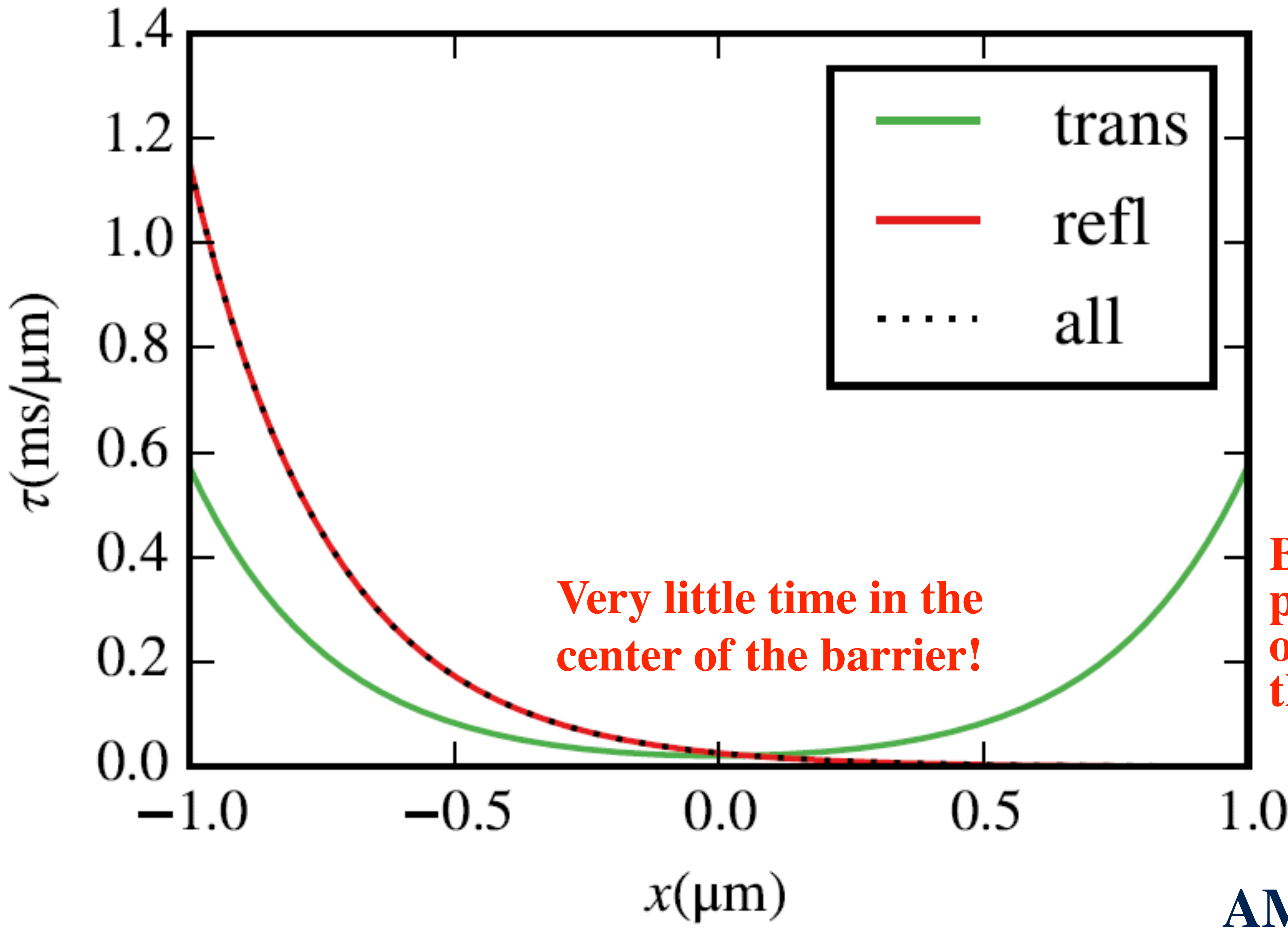


AMS, PRL 74, 2405 (1995)
AMS, PRA 52, 32 (1995)

Predictions for a future experiment



Very little time in the center of the barrier!

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

AMS, PRL 74, 2405 (1995)
AMS, PRA 52, 32 (1995)

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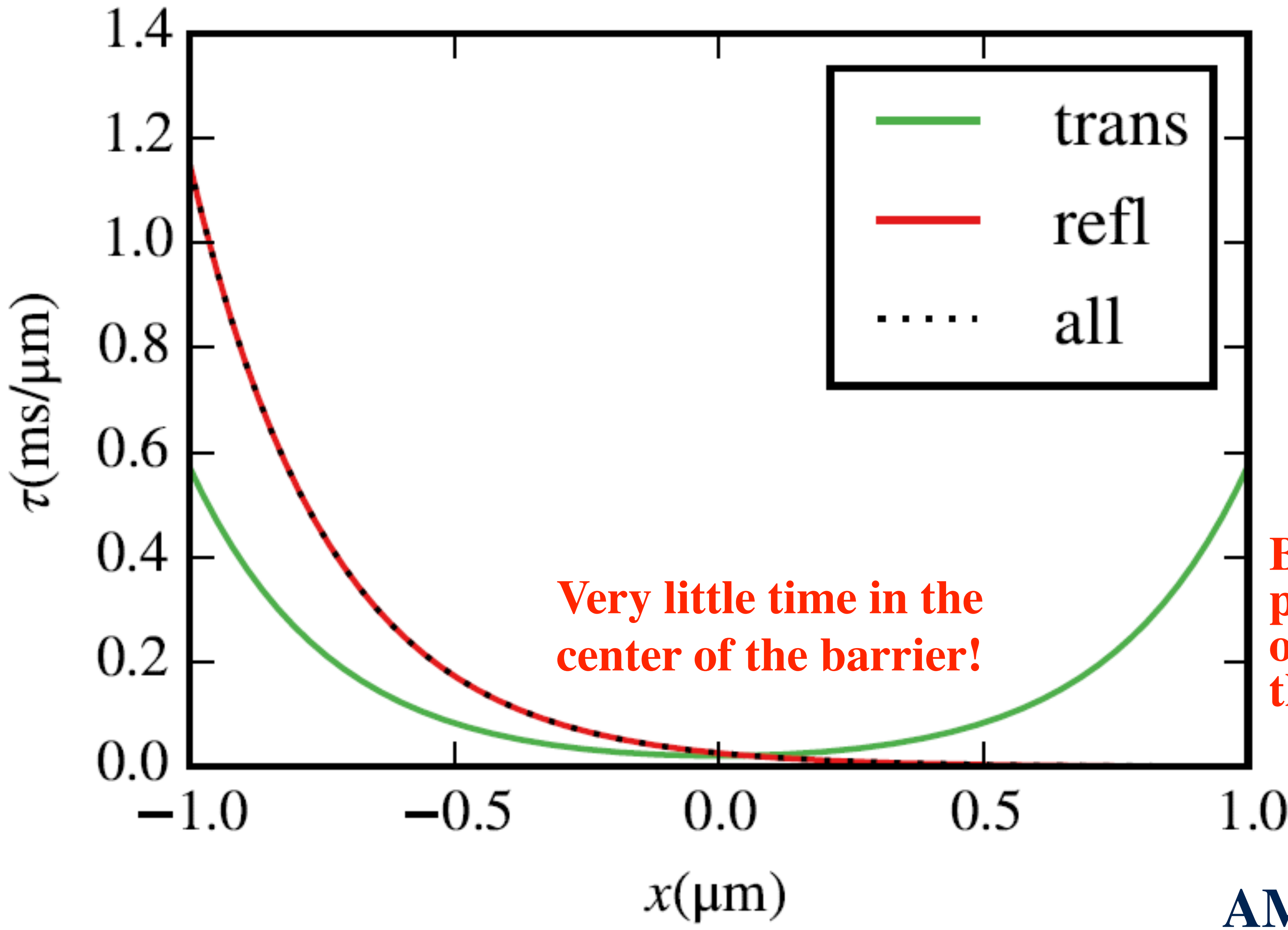

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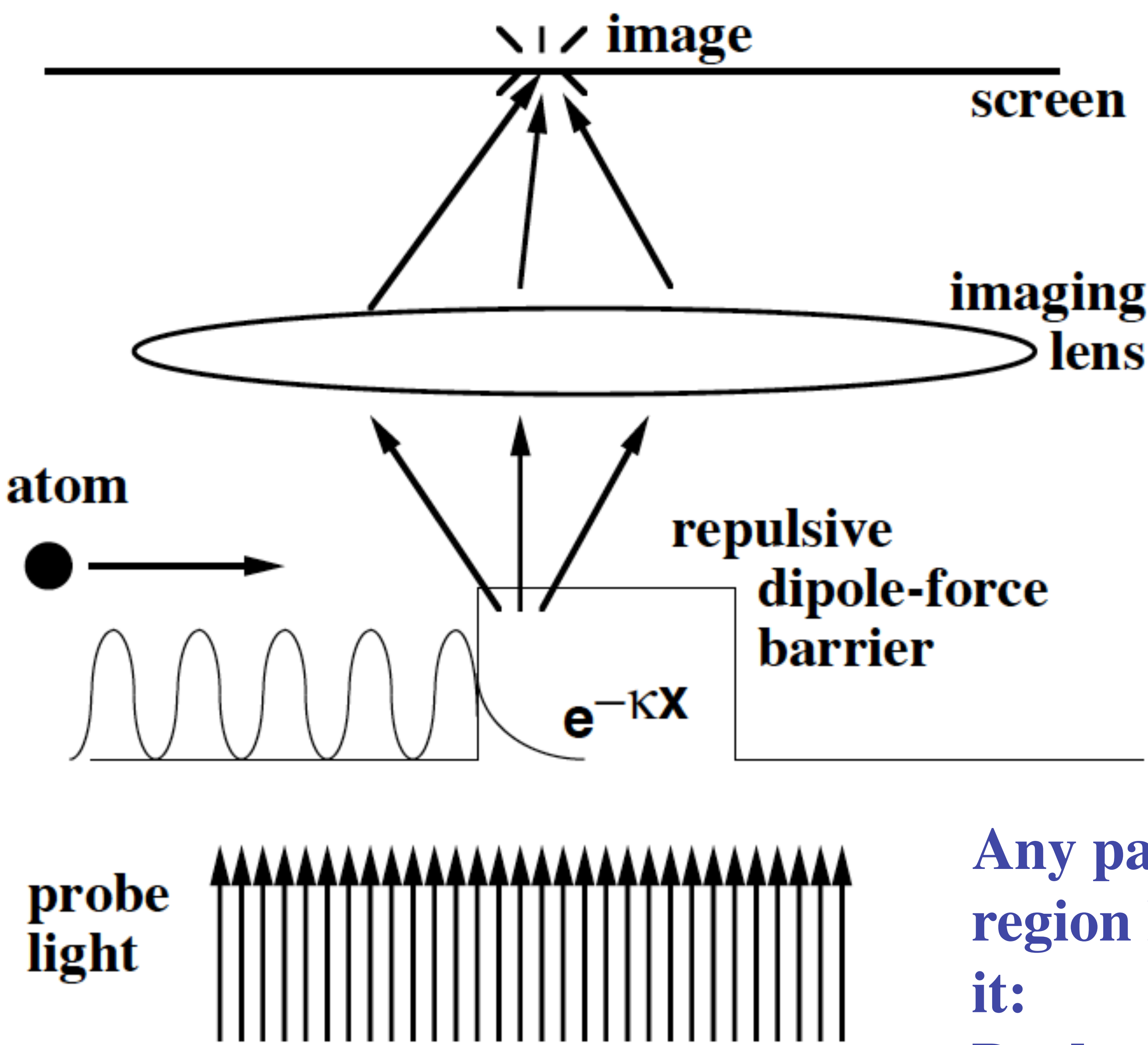
AMS, PRL 74, 2405 (1995)
AMS, PRA 52, 32 (1995)

CAVEAT: this is for the *real* part of the time; the imaginary part is instead essentially constant across the whole barrier (but nearly 0 for the transmitted atoms) – this reflects the fact that tunneling *probability* is, à la WKB, equally sensitive to a perturbation anywhere along the barrier.

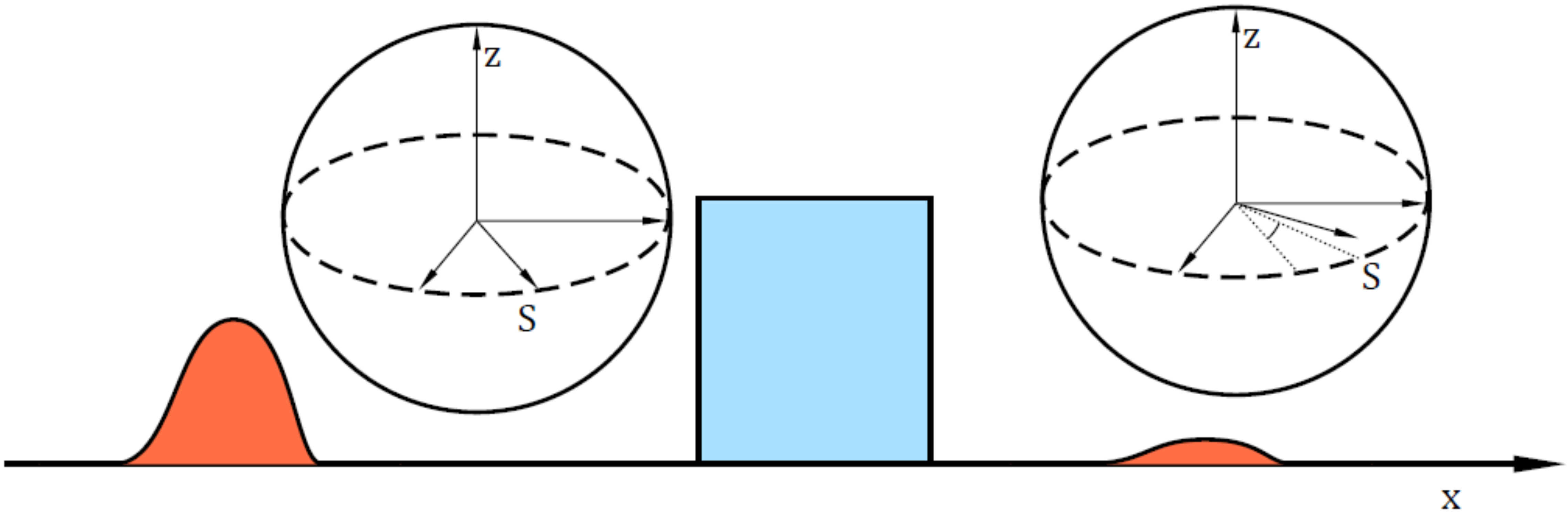
What if you made a strong measurement?



(Viz. AMS, quant-ph/9904098)

Any particle localized to the barrier region has enough energy to traverse it:
By dephasing different positions, an observation creates real momentum components even under the barrier.

Would a strong Larmor rotation at the entrance to the barrier yield enhanced transmission?



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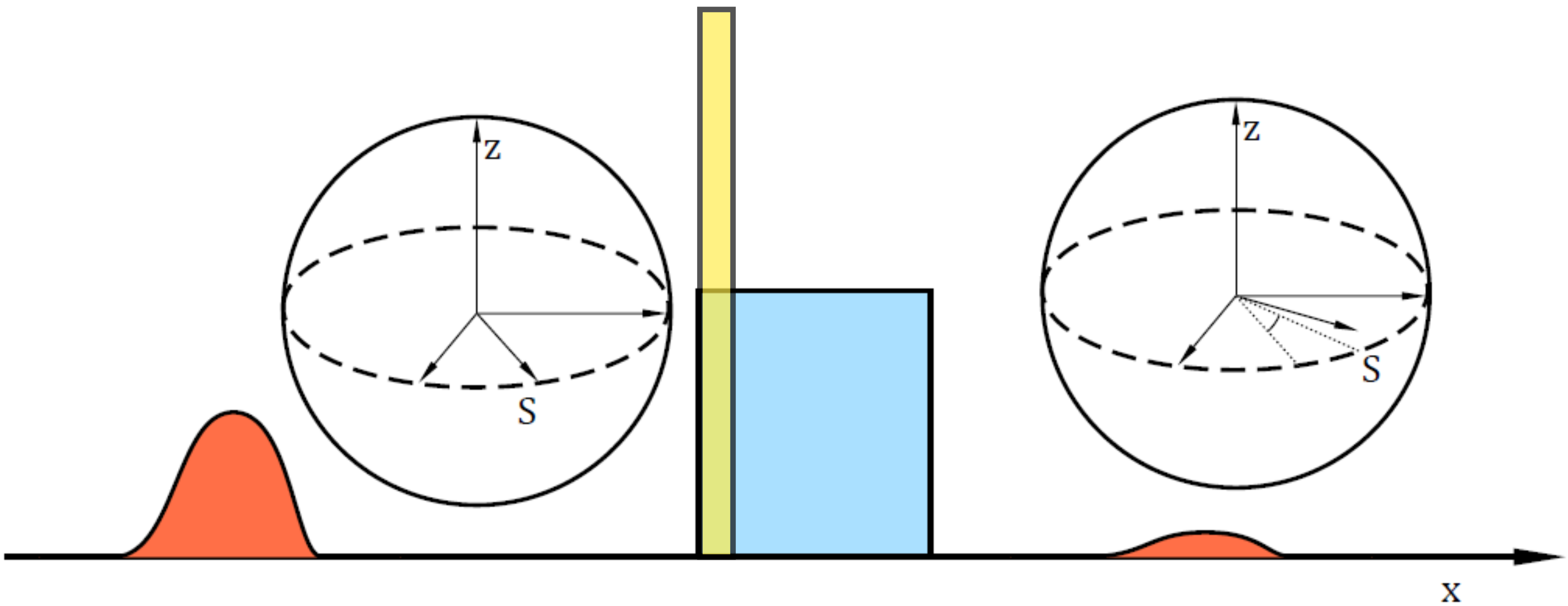
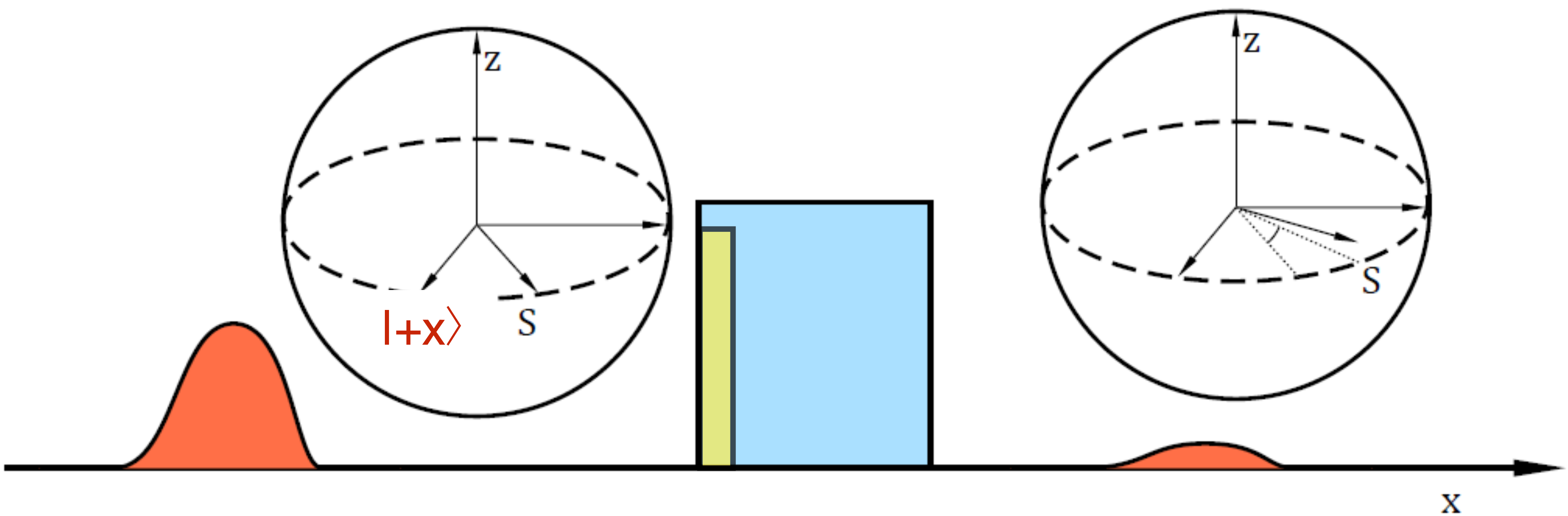


Would a *weak* Larmor rotation work just as well, if you *postselect* on |-x>?



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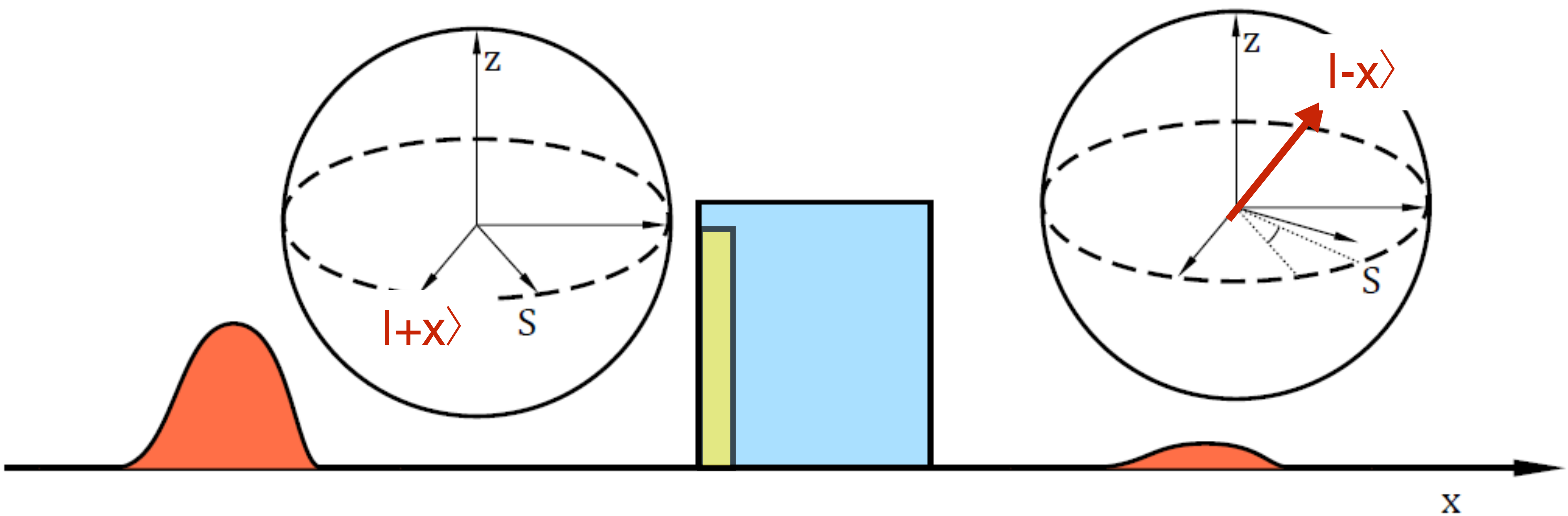

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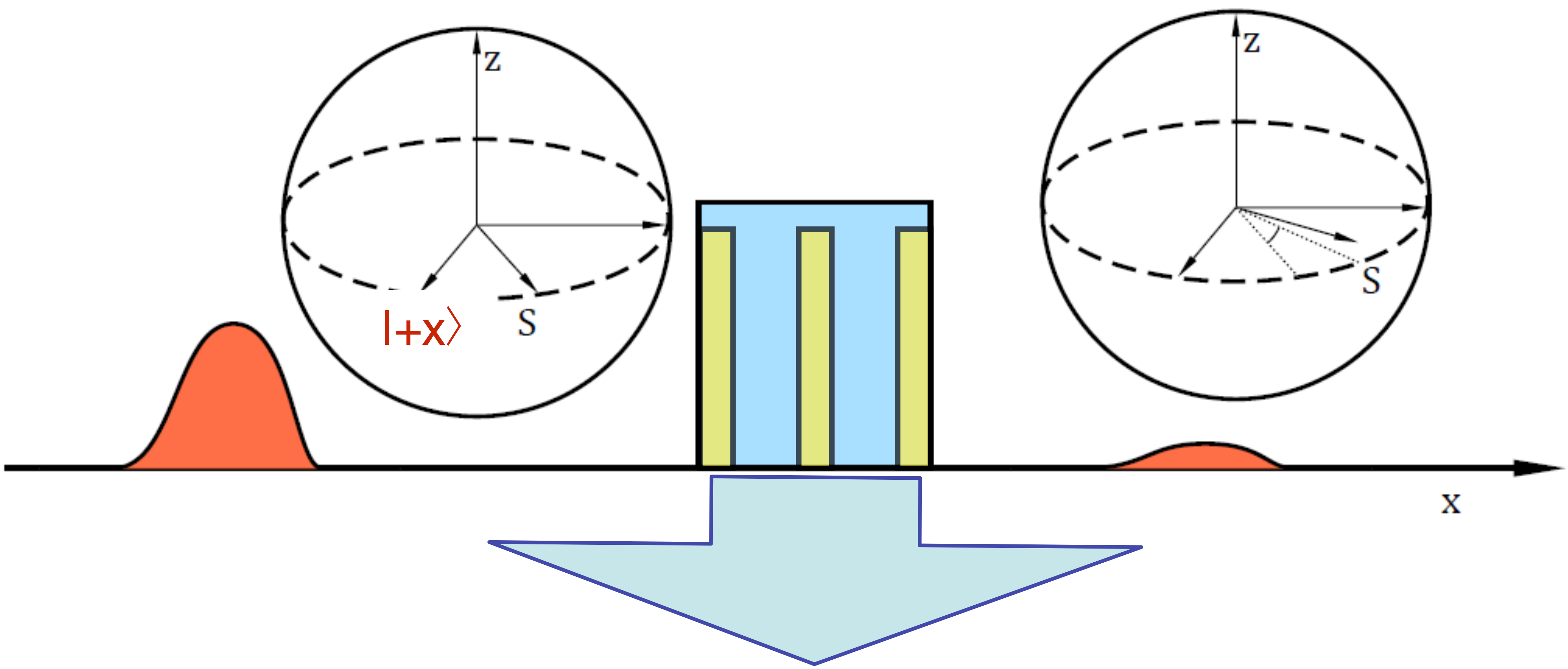

How should the ratio of t and r (for -x) depend on this position?

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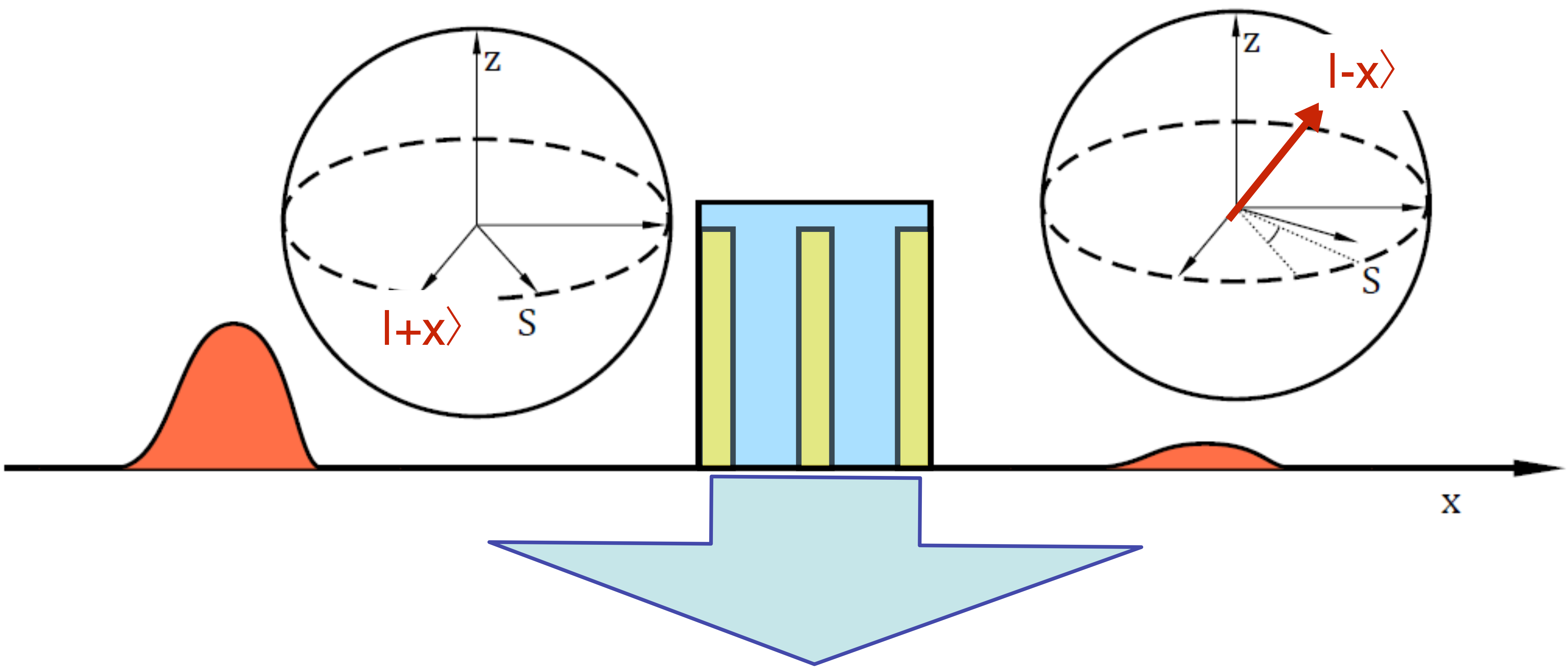

How should the ratio of t and r (for -x) depend on this position?

Still at the conjecture stage…

• **Conceptual view:**

The atom can never reach $|{-x}\rangle$ without going through the probe; postselection in $|{-x}\rangle$ thus constitutes a measurement: once found there (*even* on the left side of a thick barrier), transmission should be about as likely as reflection: P(trans | spin flip) ~ 50%

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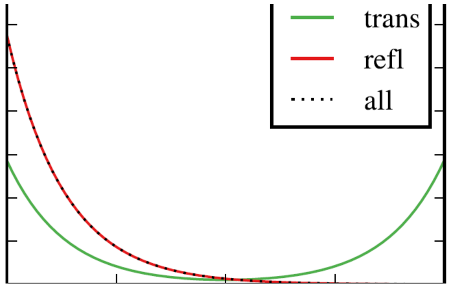
- **First guess:**

  Based on old calculations of $|{+y}\rangle$ projections (Re τ), P(trans)/P(refl) grows exponentially as you traverse the barrier; maybe this doesn't "count" as a "collapse"?



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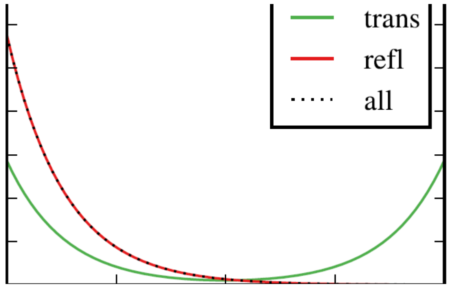
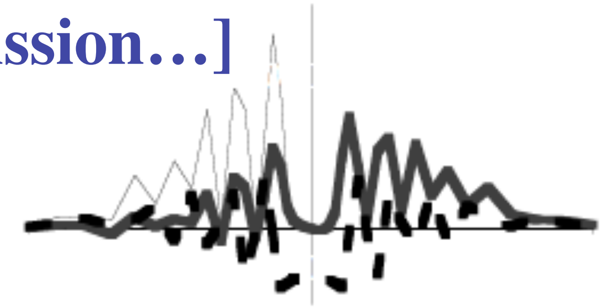


• **More careful thought:**

Recalling |+z〉 projections (Im τ), P(trans)/P(refl) is flat – maybe the projection *does* enhance transmission. [In fact, Im τ is *much* larger for transmission…]

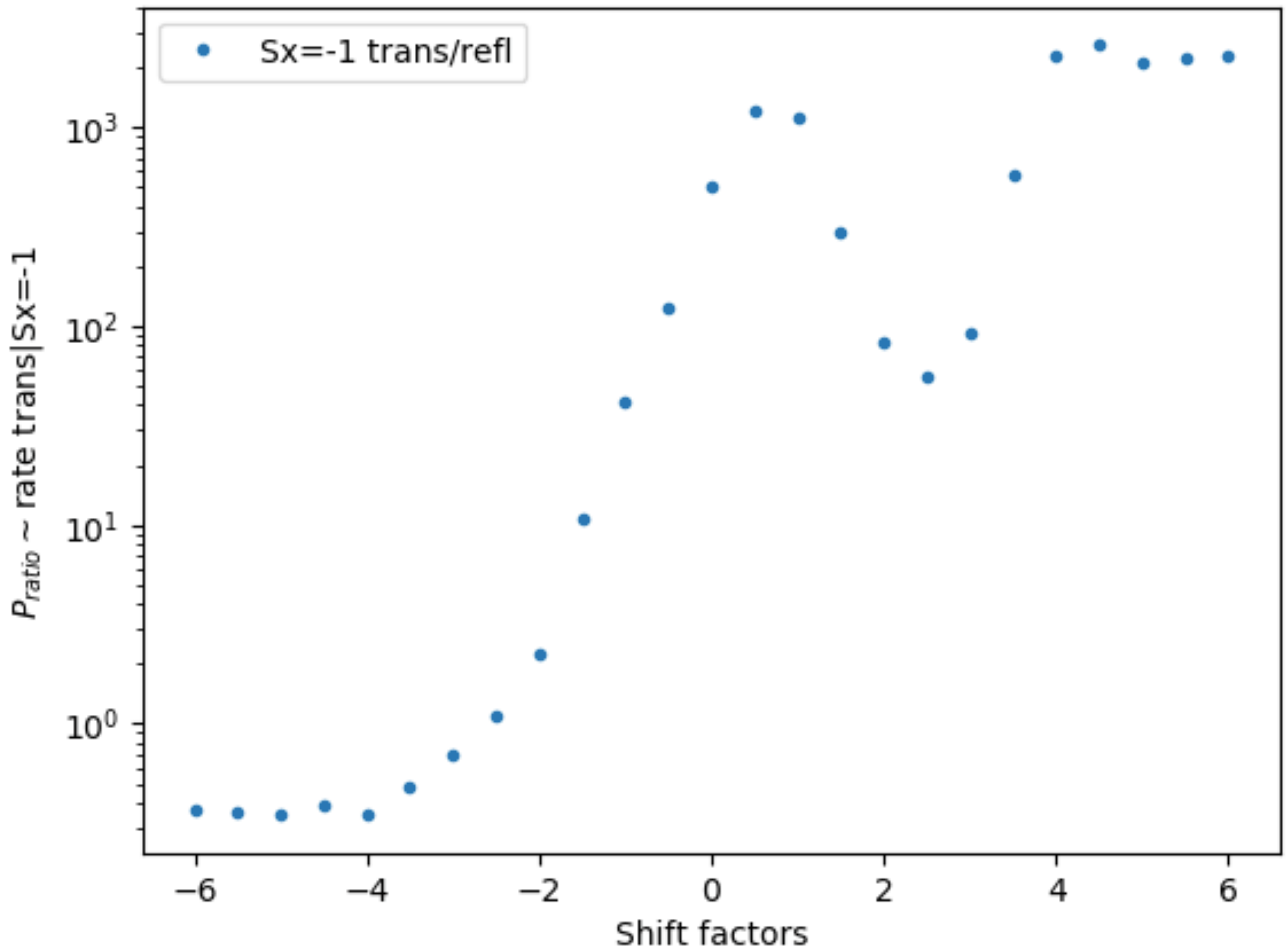


Still at the conjecture stage…

- Conceptual

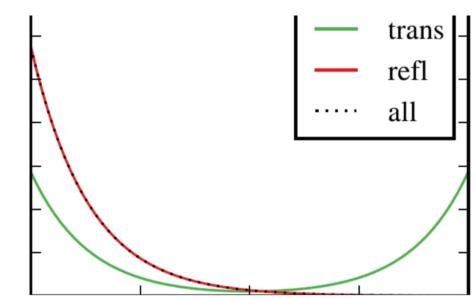
  The ato[…] […]stselection in |-x⟩
  thus con[…] […]side of a thick
  barrier) […]ns | spin flip) ~ 50%

The plot above this in the note shows the individual conditional probabilities. The velocity was such that overall transmission was ~4% when the probe was outside the barrier. Here is that plot on a log scale. I believe that between the -2,2 shifted regions the probe is inside the barrier, and outside beyond those shifts.



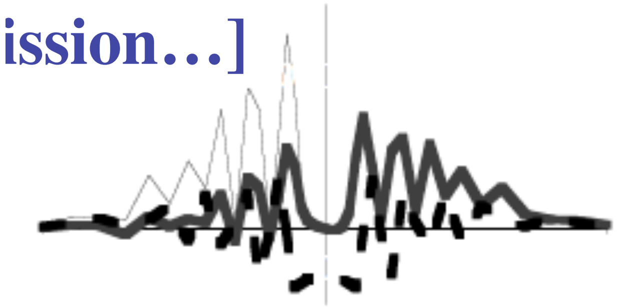
- First guess:

  Based on […] grows exponentially
  as you tr[…] […]se"?



- More carefu[…]

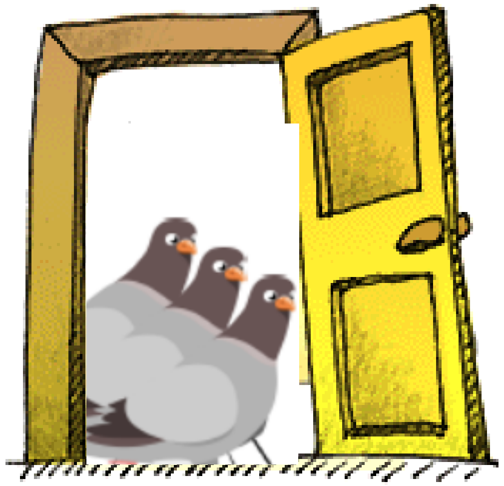
  Recallin[…] […] projection
  does enh[…] […]ission…]



- First actual calculations:

  Don't seem to support these ideas, but then again, we don't really understand them yet…

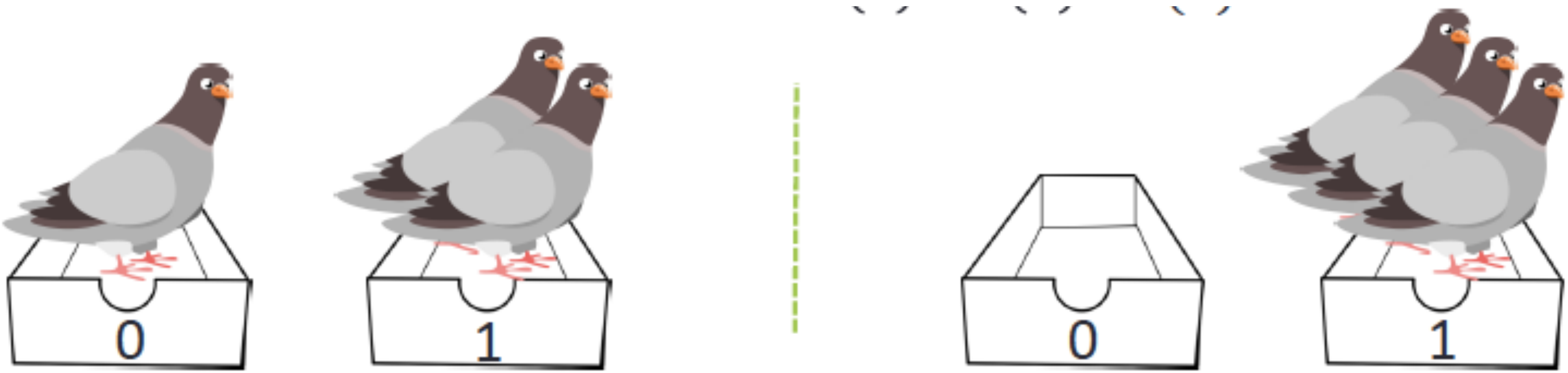
The pigeonhole-principle "paradox"



Giorni di piccione e giorni di statua

Aharonov *et al.,* PNAS vol. 113 no. 3 532-535 (2016)

When three pigeons are placed in two boxes, at least two of the pigeons must be in the same box.



Giorni di piccione e giorni di statua

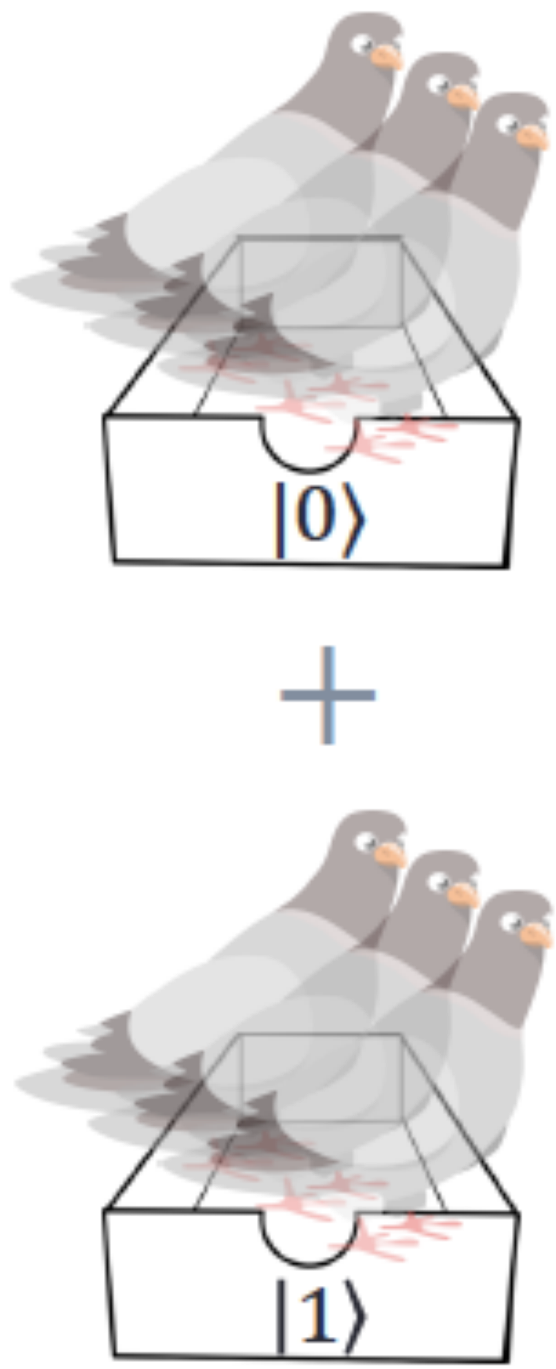
Aharonov *et al.,* PNAS vol. 113 no. 3 532-535 (2016)
[see also Vaidman for different formulations…]

Prepare 3 pigeons independently in:

$$|\psi\rangle = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes 3}$$

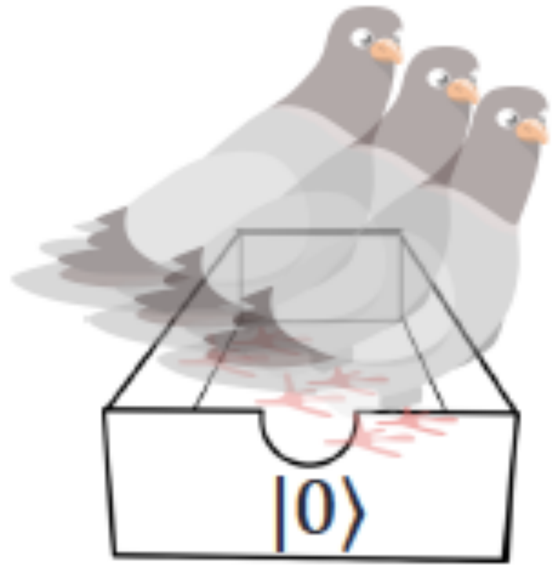
Post-select them independently in:

$$|\phi\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)^{\otimes 3}$$



Giorni di piccione
e giorni di statua

Aharonov *et al.,* PNAS vol. 113 no. 3 532-535 (2016)
[see also Vaidman for different formulations…]



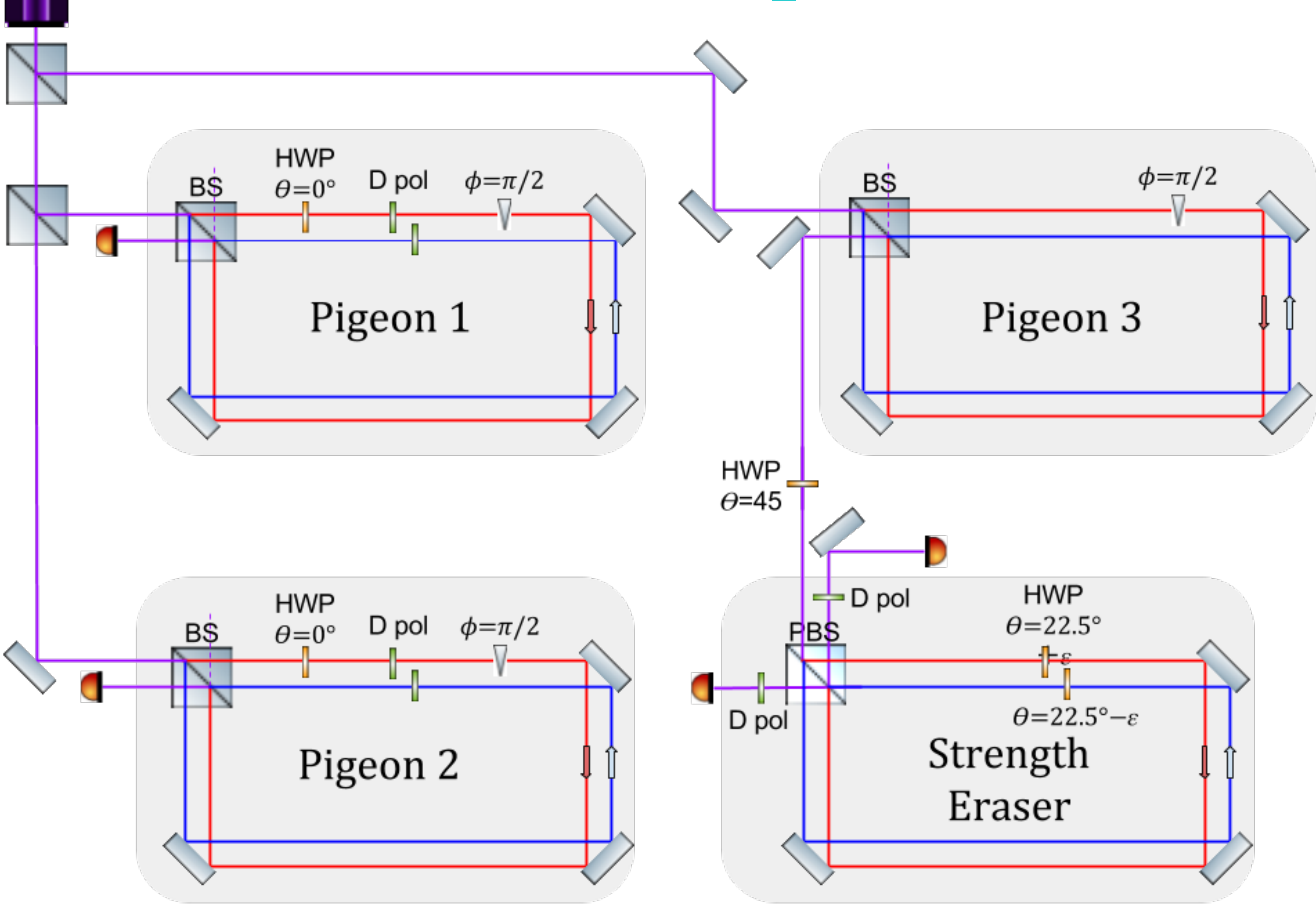
Prepare 3 pigeons independently in: $$|\psi\rangle = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes 3}$$

+

Post-select them independently in: $$|\phi\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)^{\otimes 3}$$

No two pigeons are ever found to have been "in the same box,"
***if* that is the only thing you measure**
(either strongly or weakly).

Underway: variable-strength measurements to probe transition



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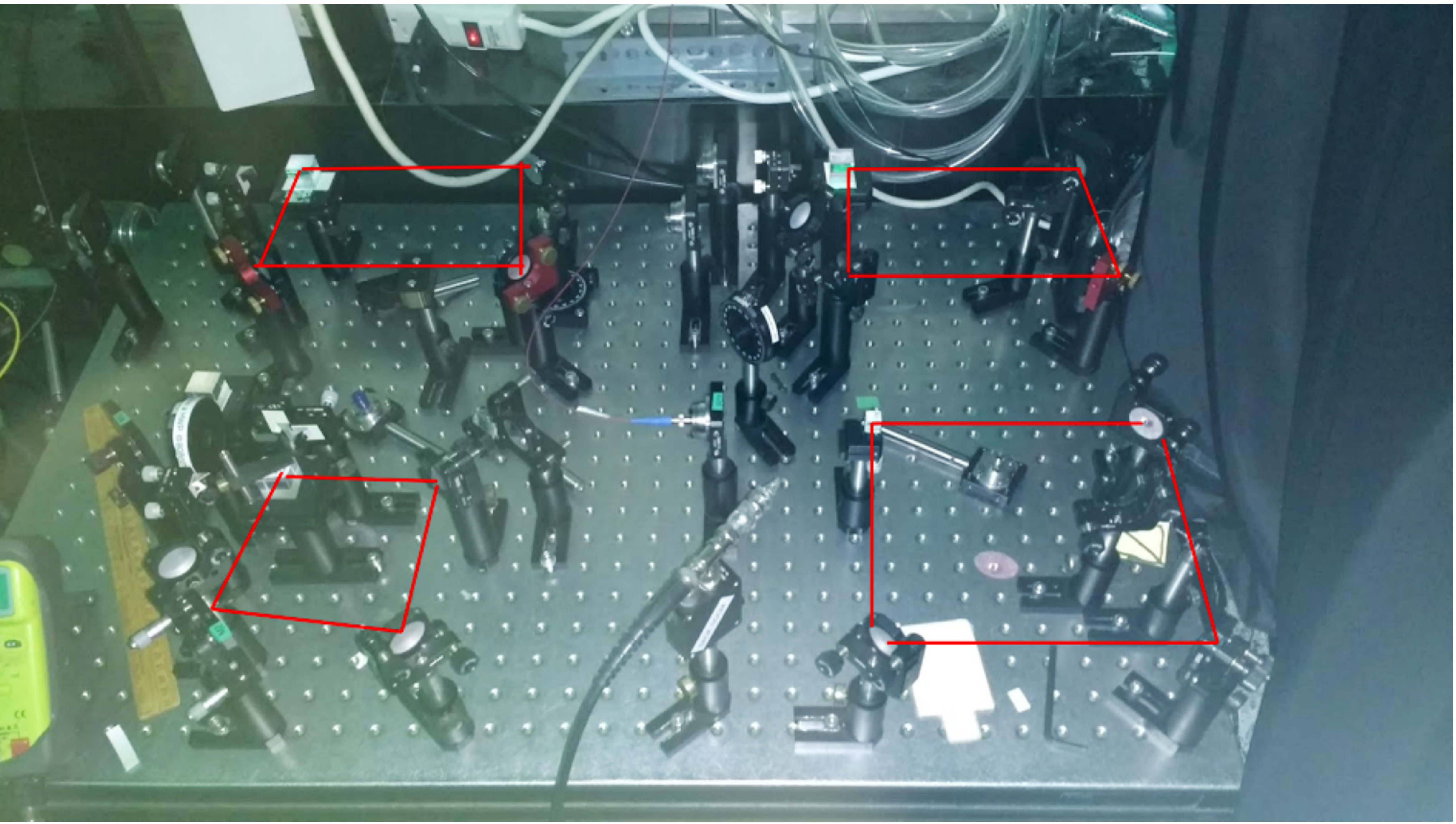
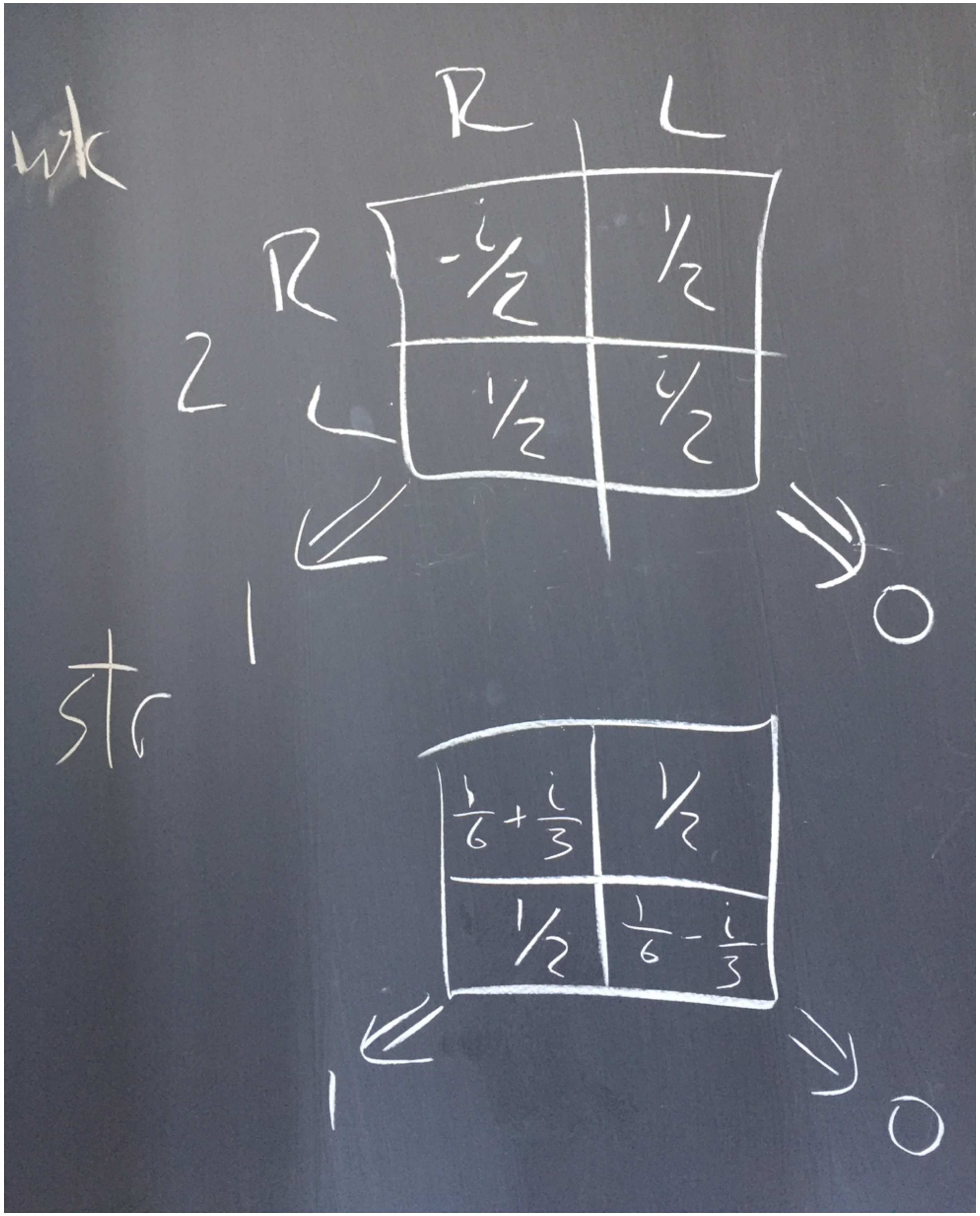


Which better describe the post-seelcted reality, weak or strong measurements?



THE STORY WE'D EXPECTED TO TELL:

For strong measurements, context matters;
P(both in L or both in R) (=0!)
≠ P(both in L)+P(both in R)

For weak measurements, context does not matter;
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But for weak measurements, these P's may be negative or even complex!

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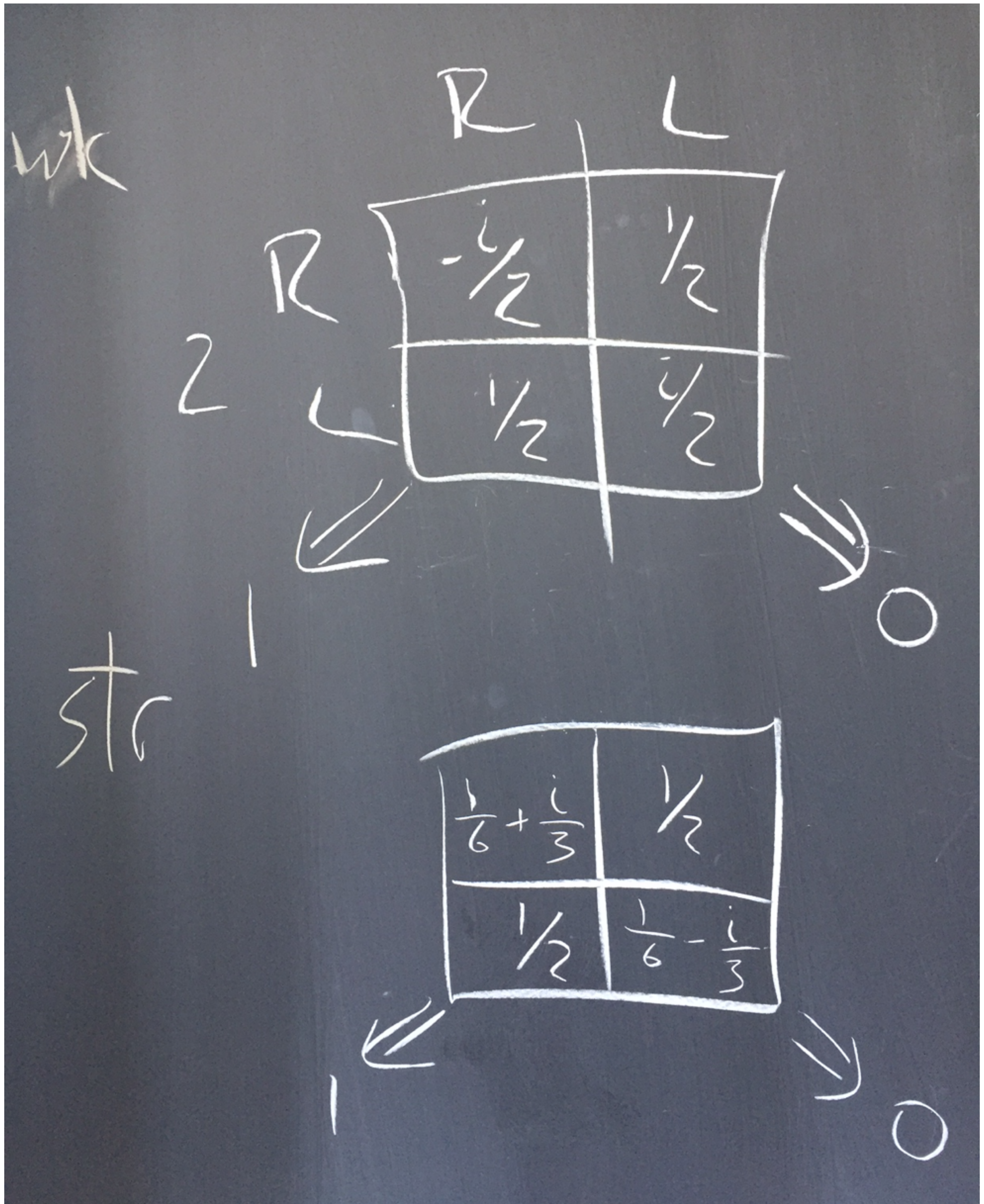

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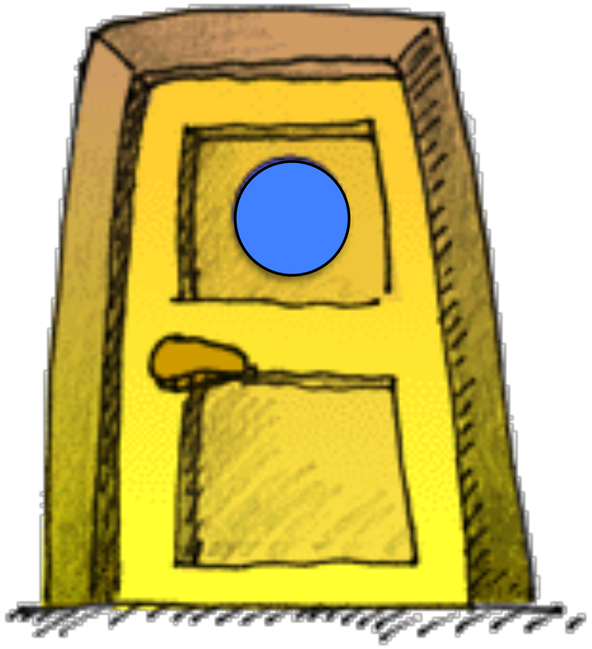
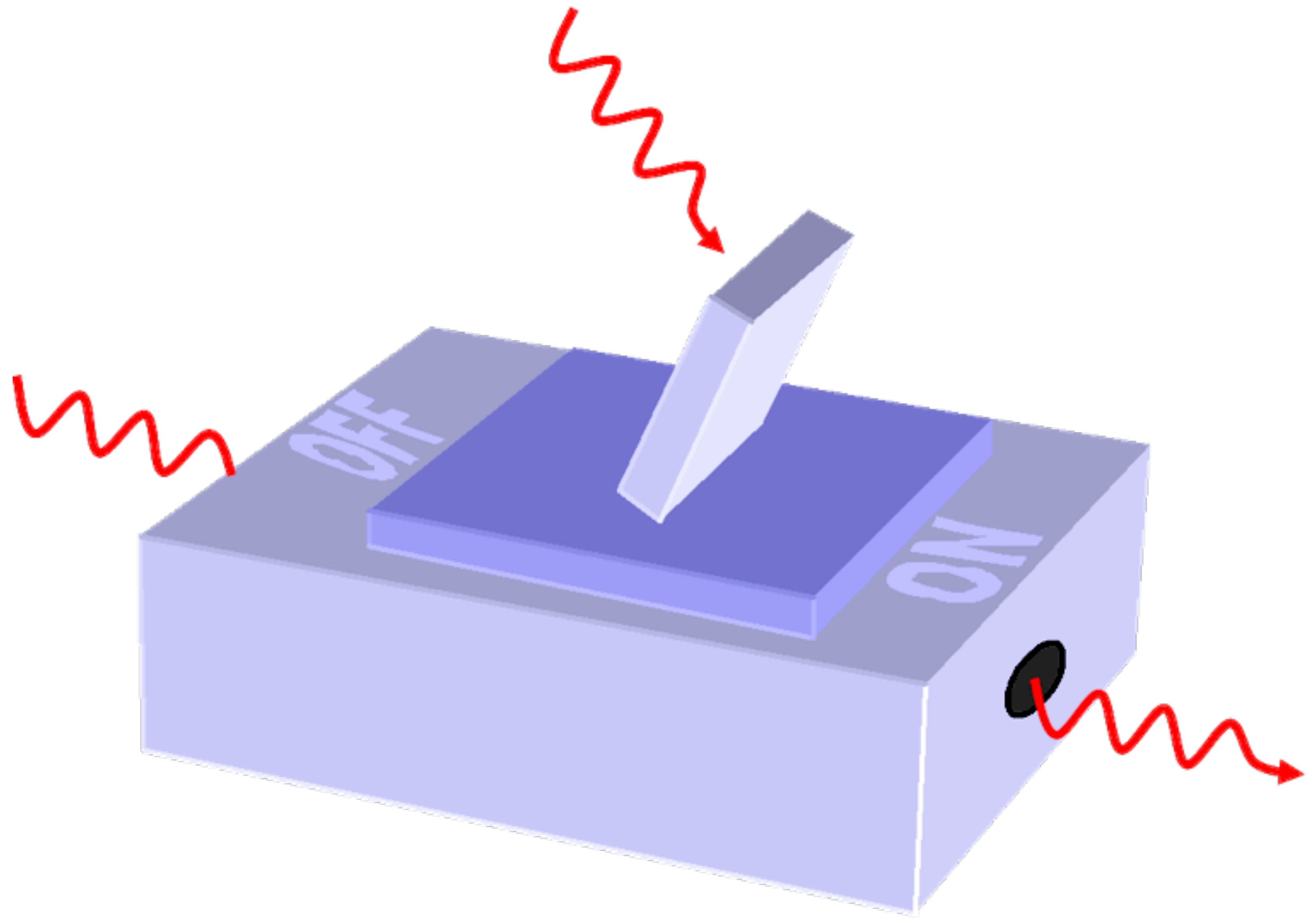
New twist:
By a consistent definition (effect on the probe momentum), strong measurements *also* have imaginary parts!

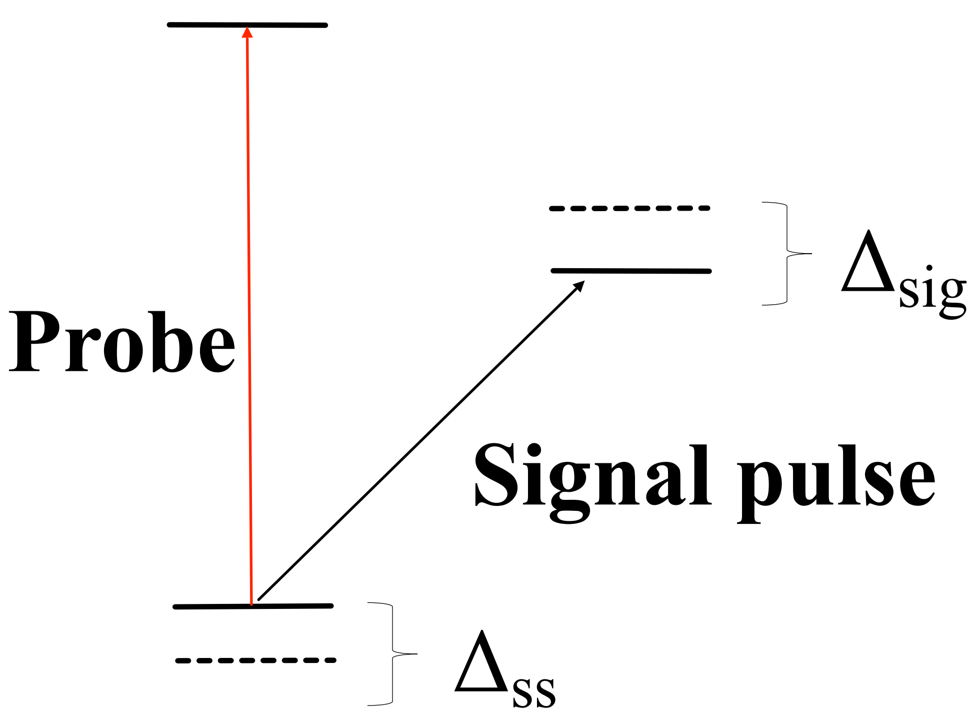
What was a photon doing before it was detected?

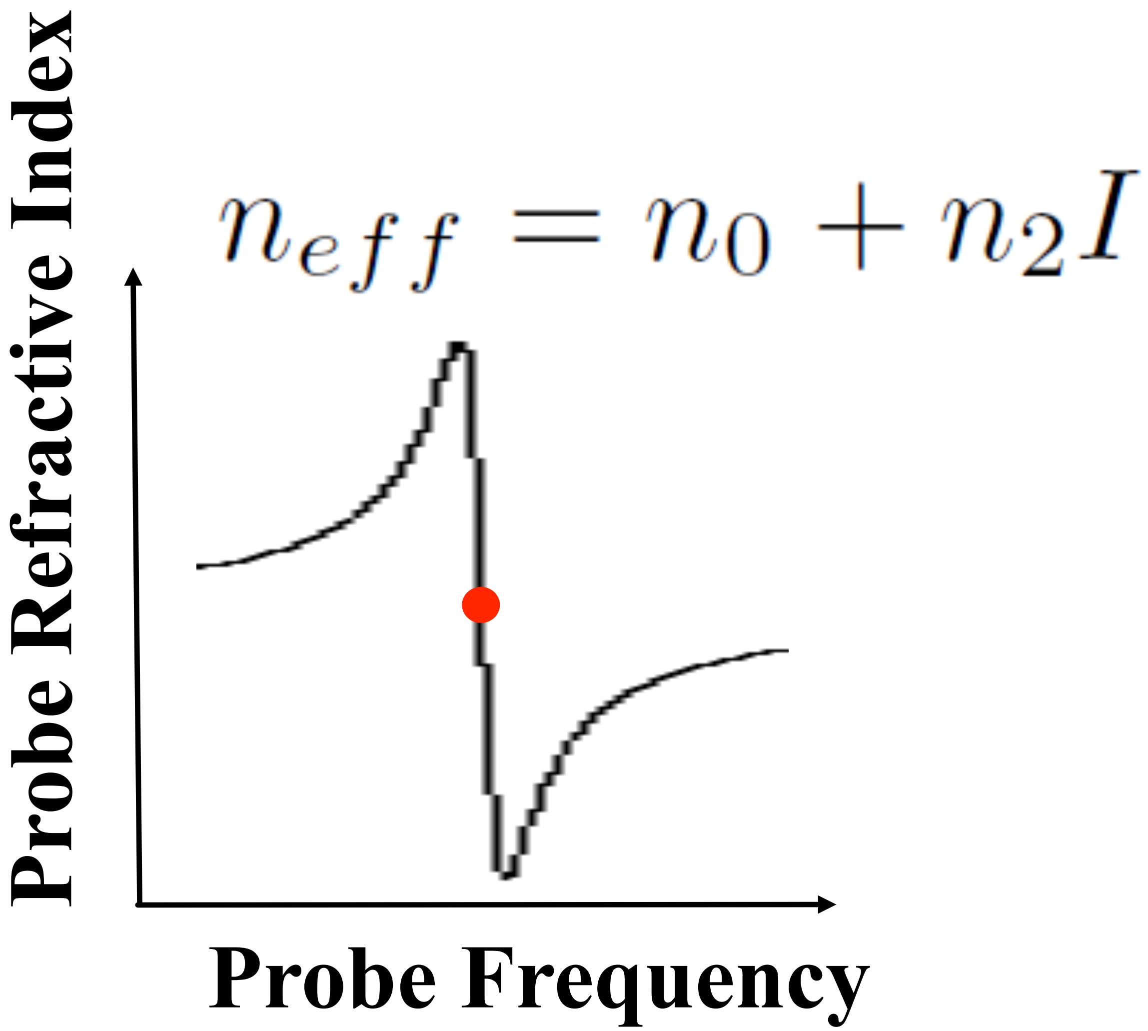


Original motivation: strongly interacting photons (quantum logic gates / QKD / …)



Cross-phase modulation (XPM)





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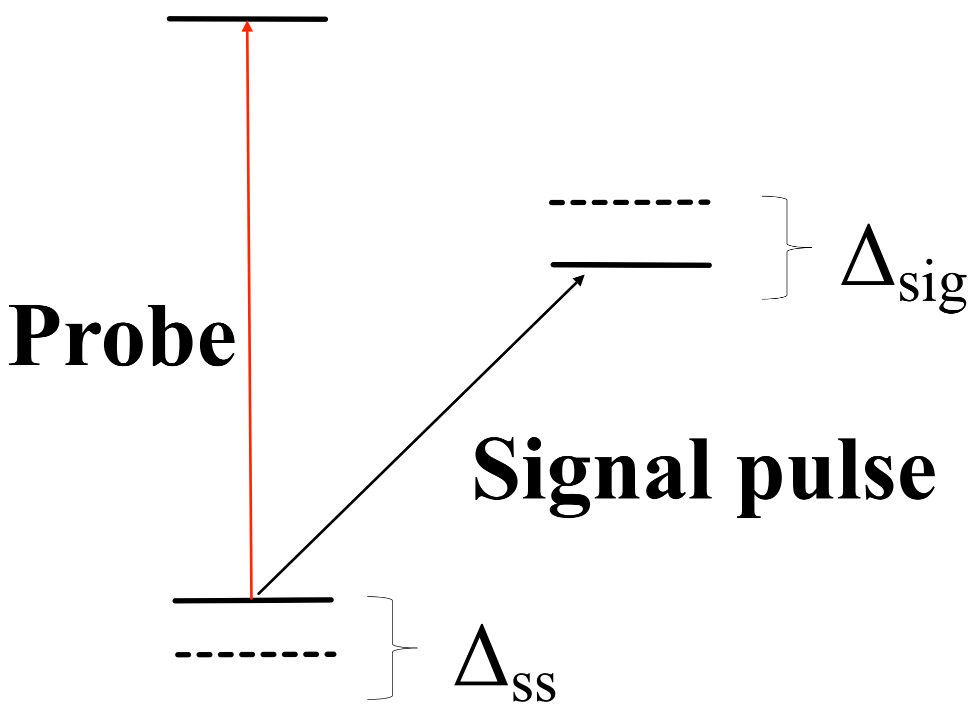

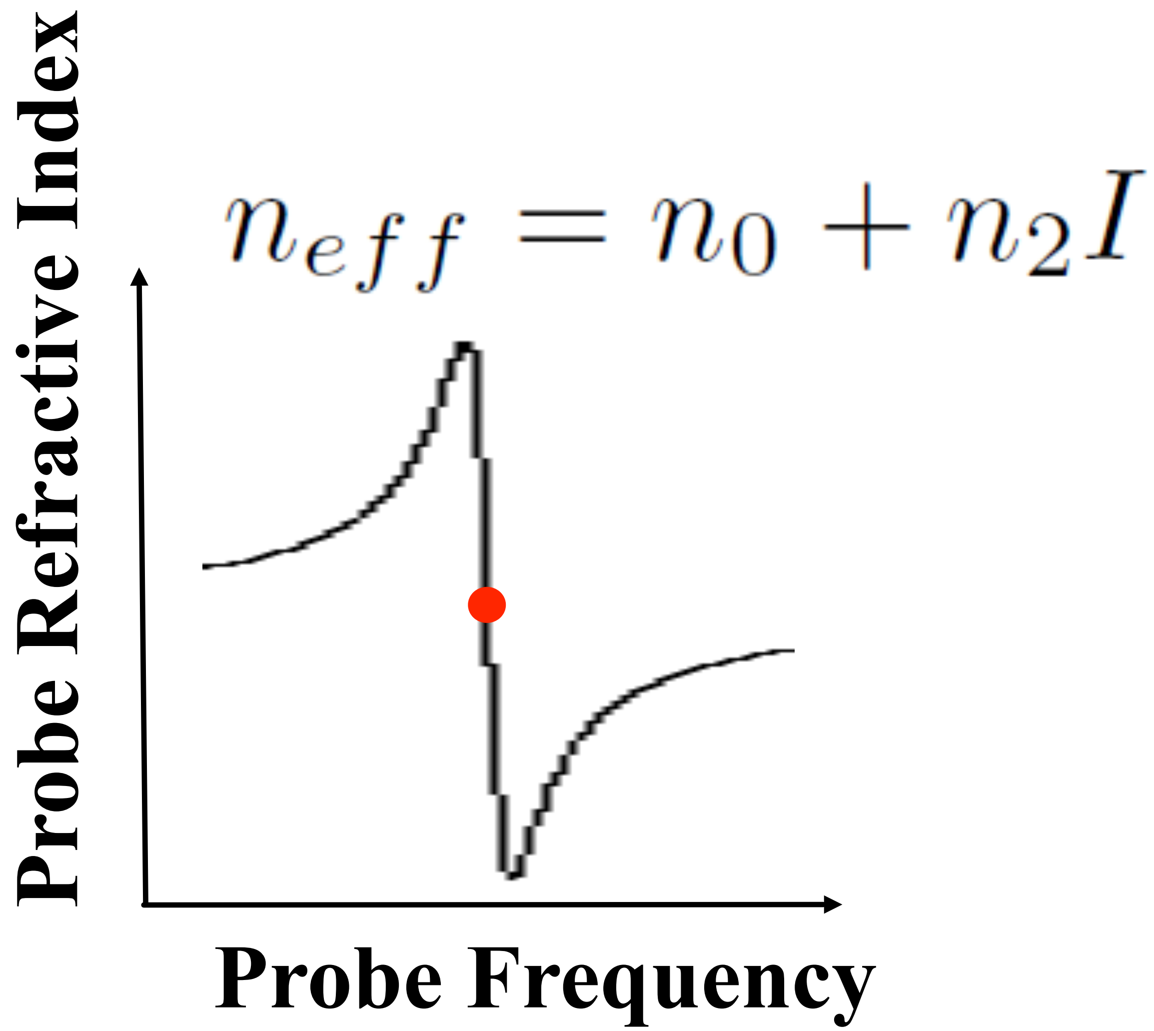

AC Stark shift changes effective detuning, changing index of refraction experienced by probe

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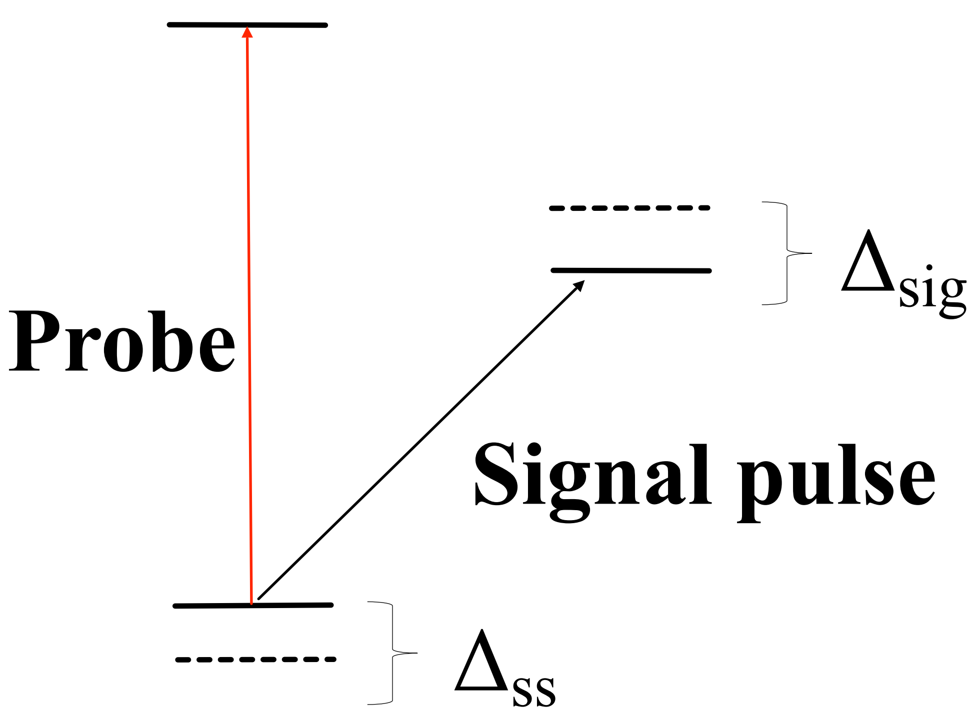

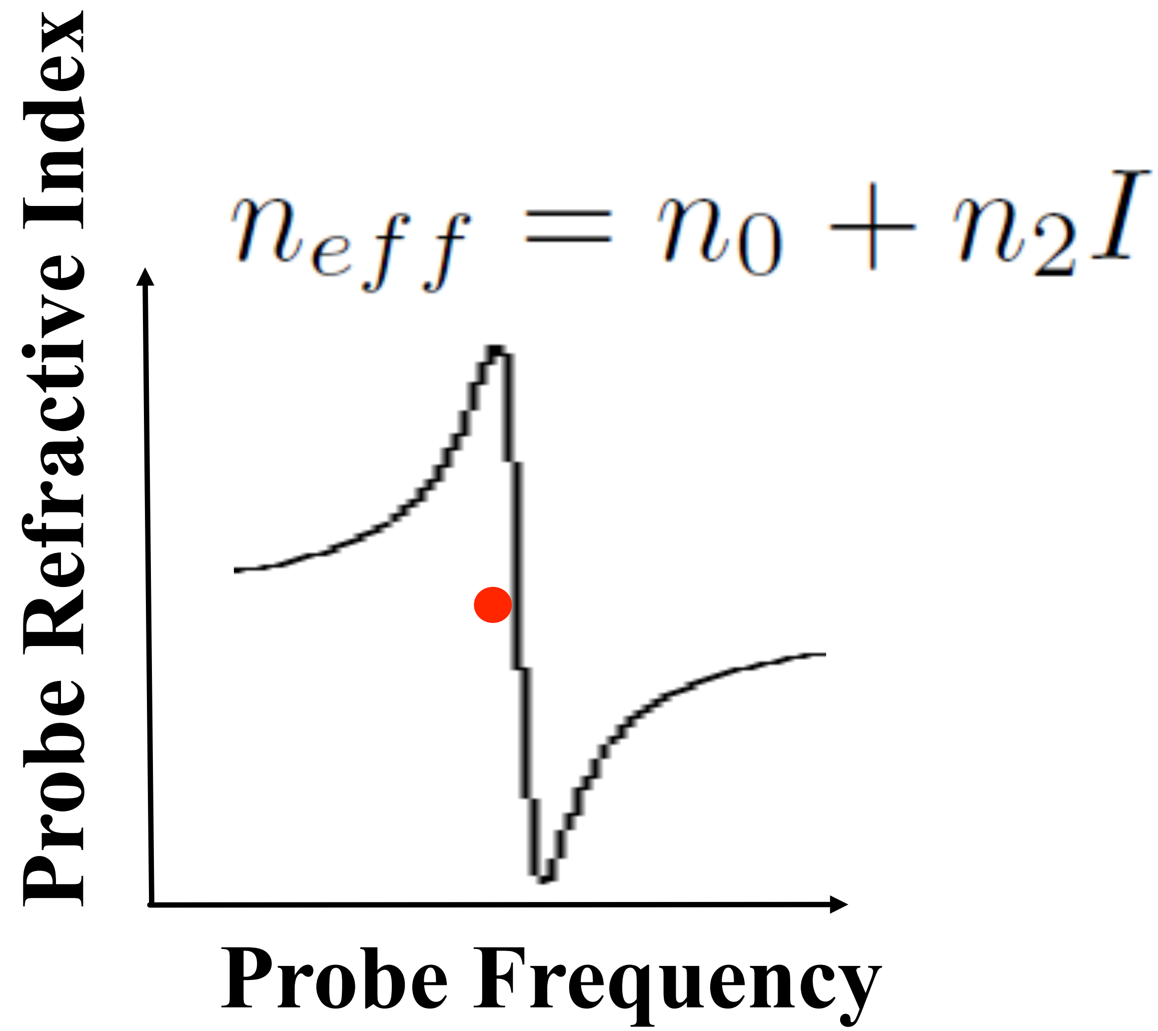

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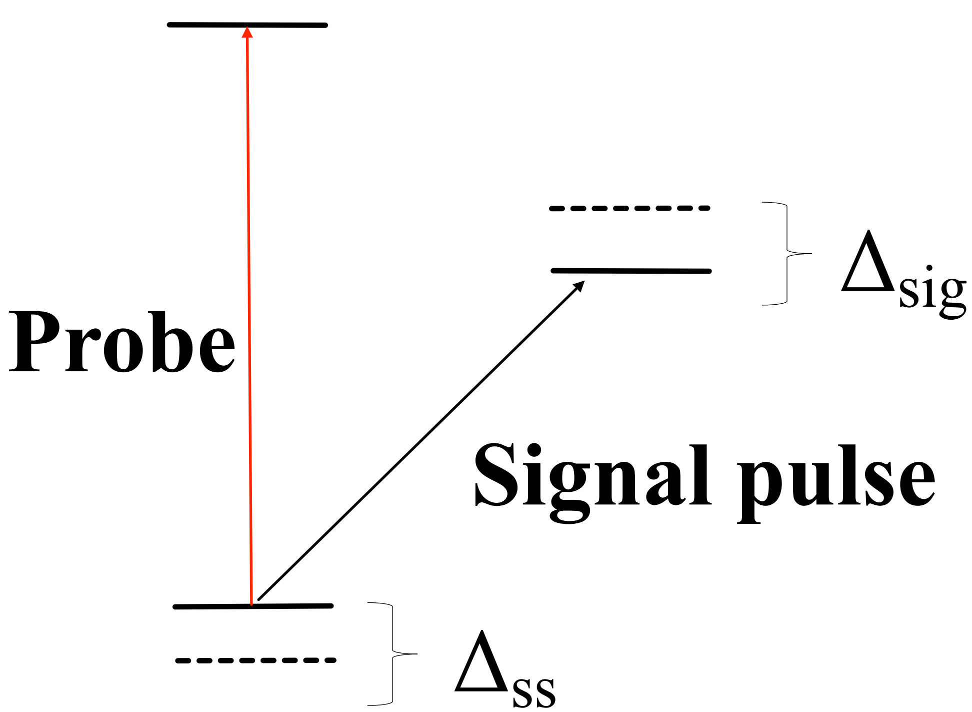

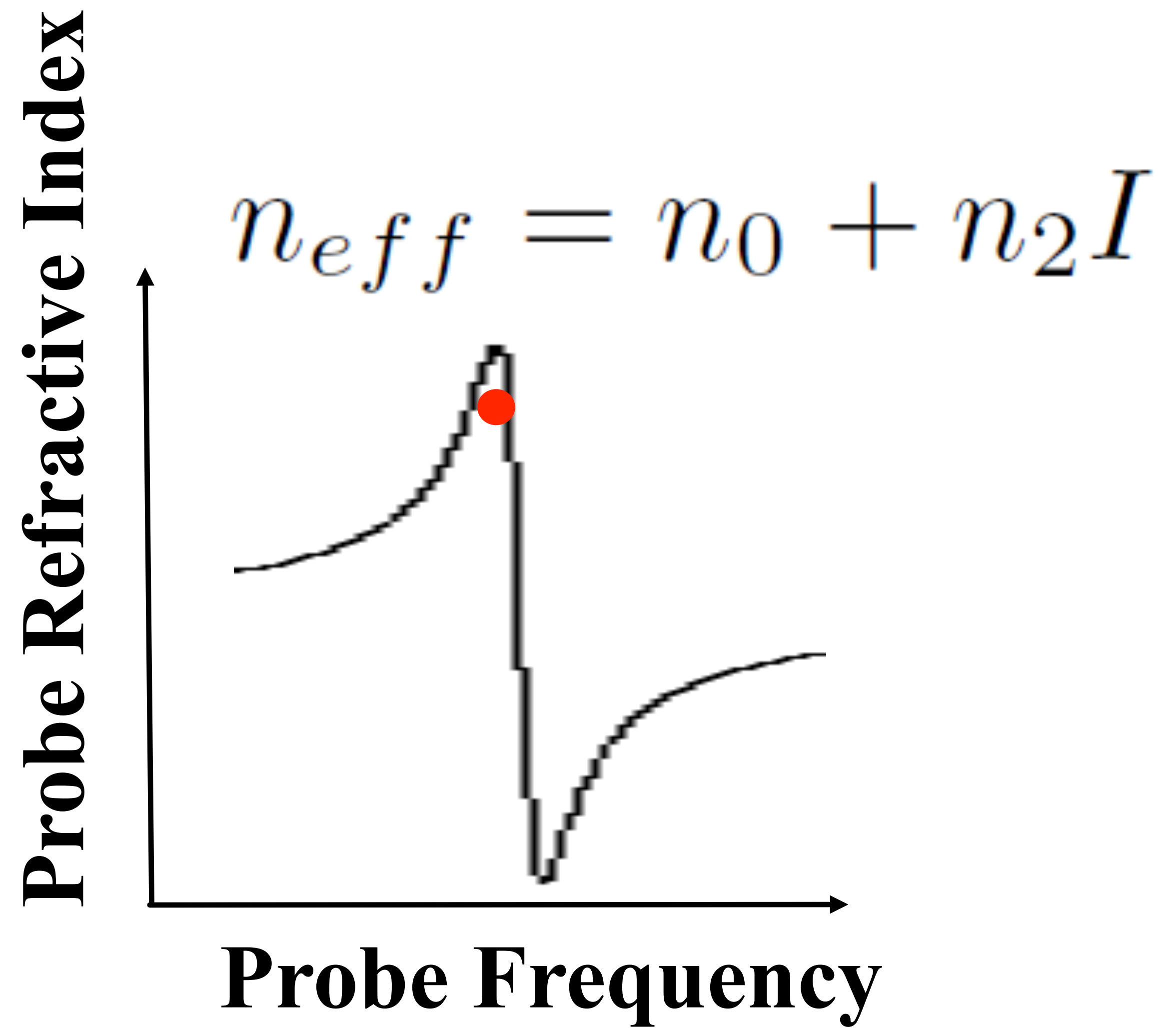

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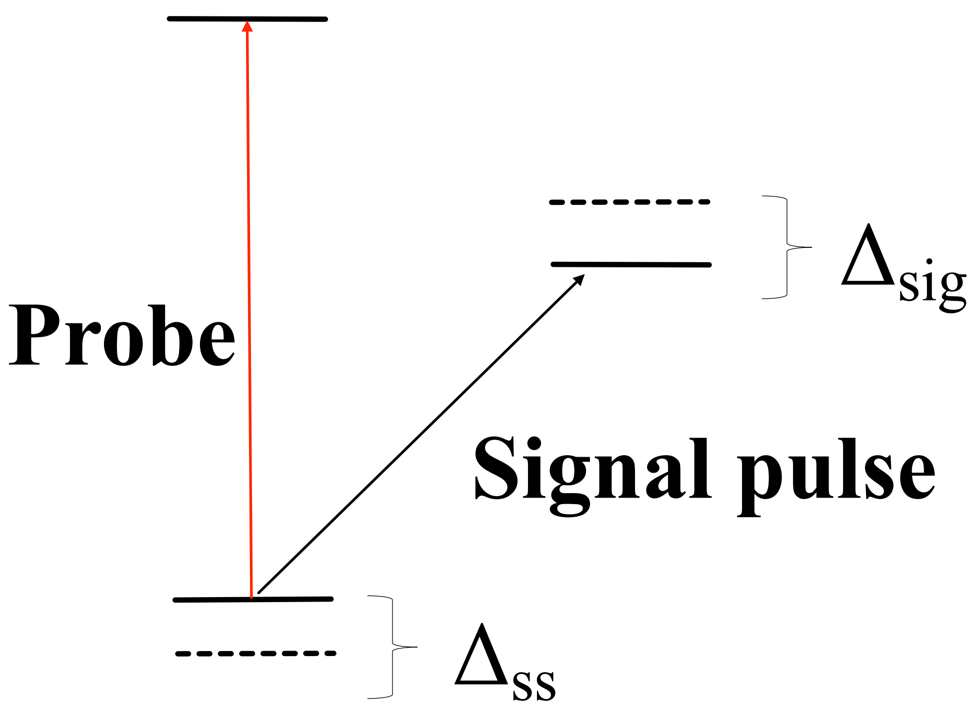

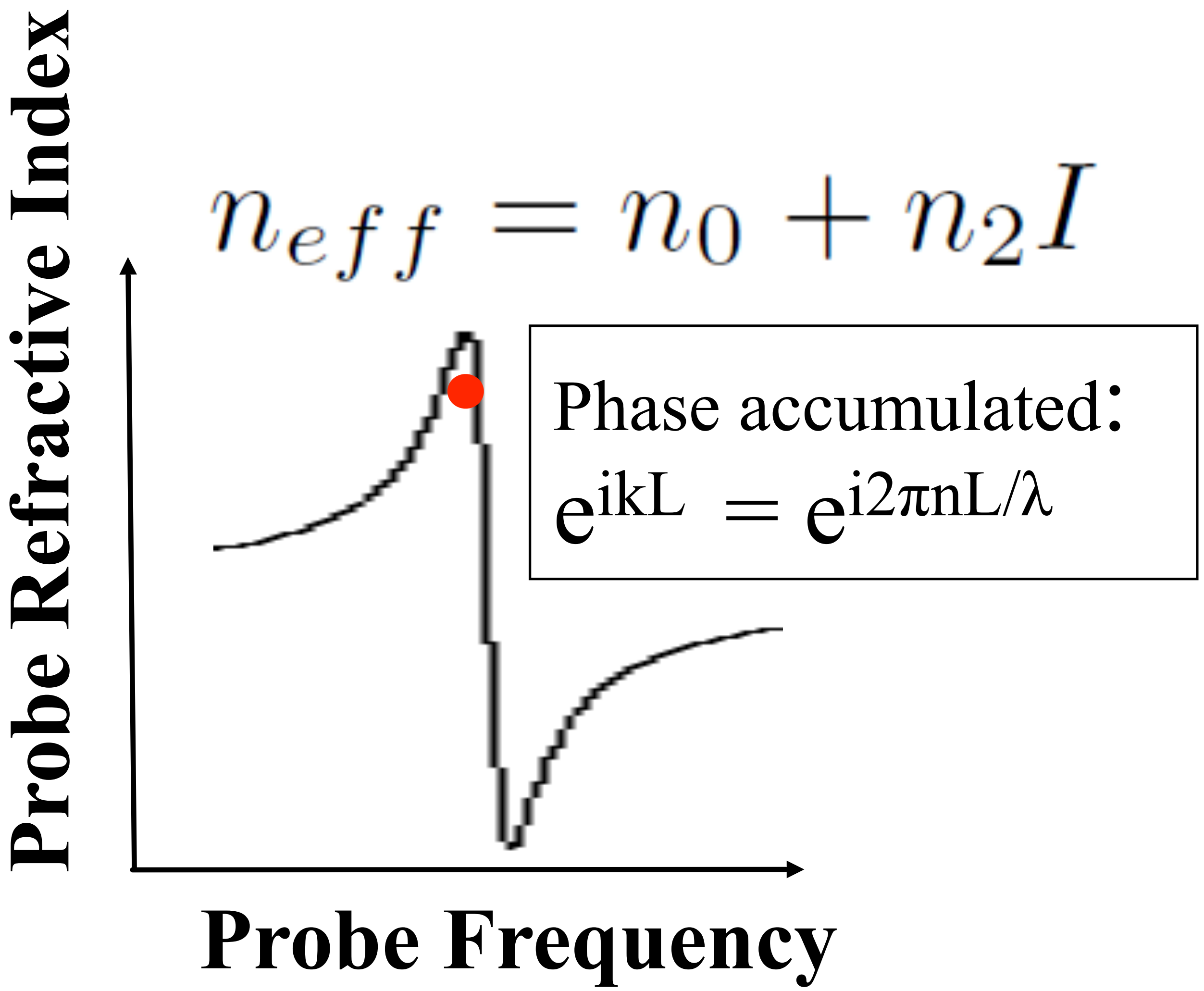

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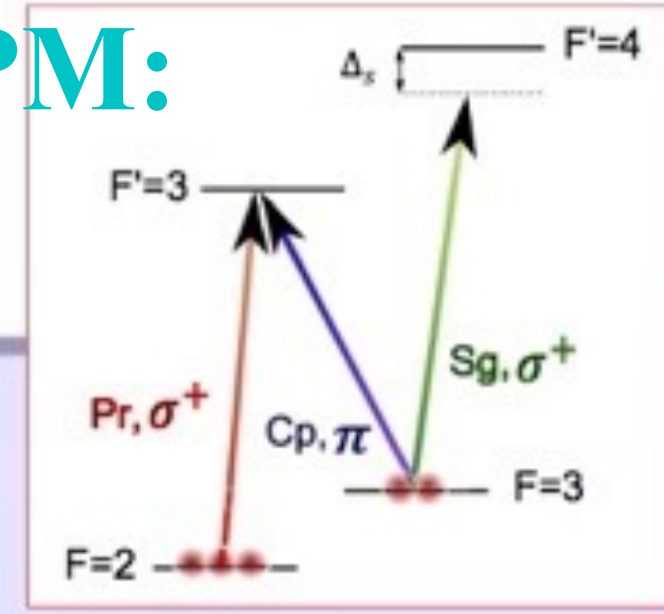
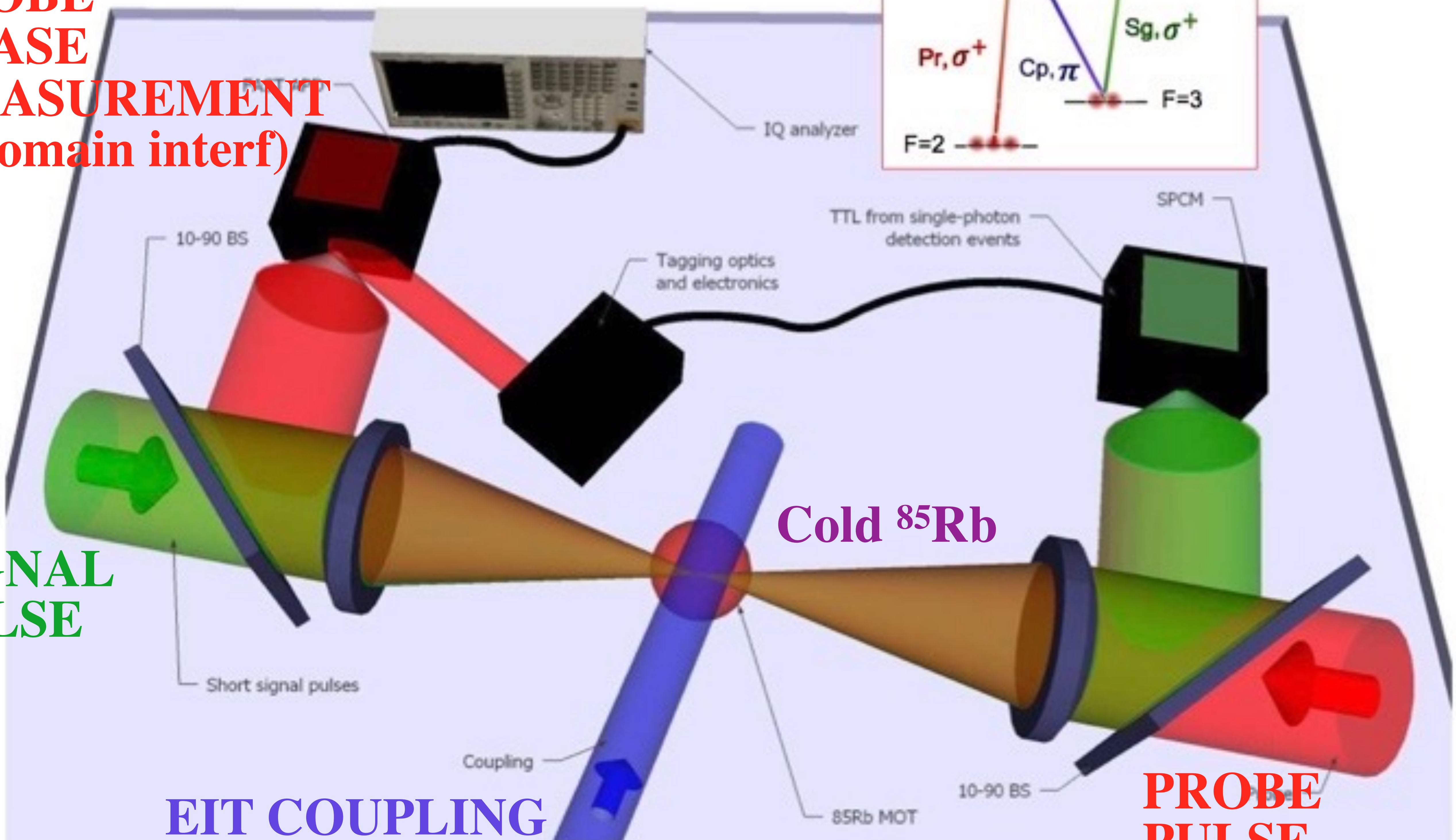
Towards single-photon XPM: experimental setup



PROBE PHASE MEASUREMENT (f-domain interf)



Cold ^{85}Rb

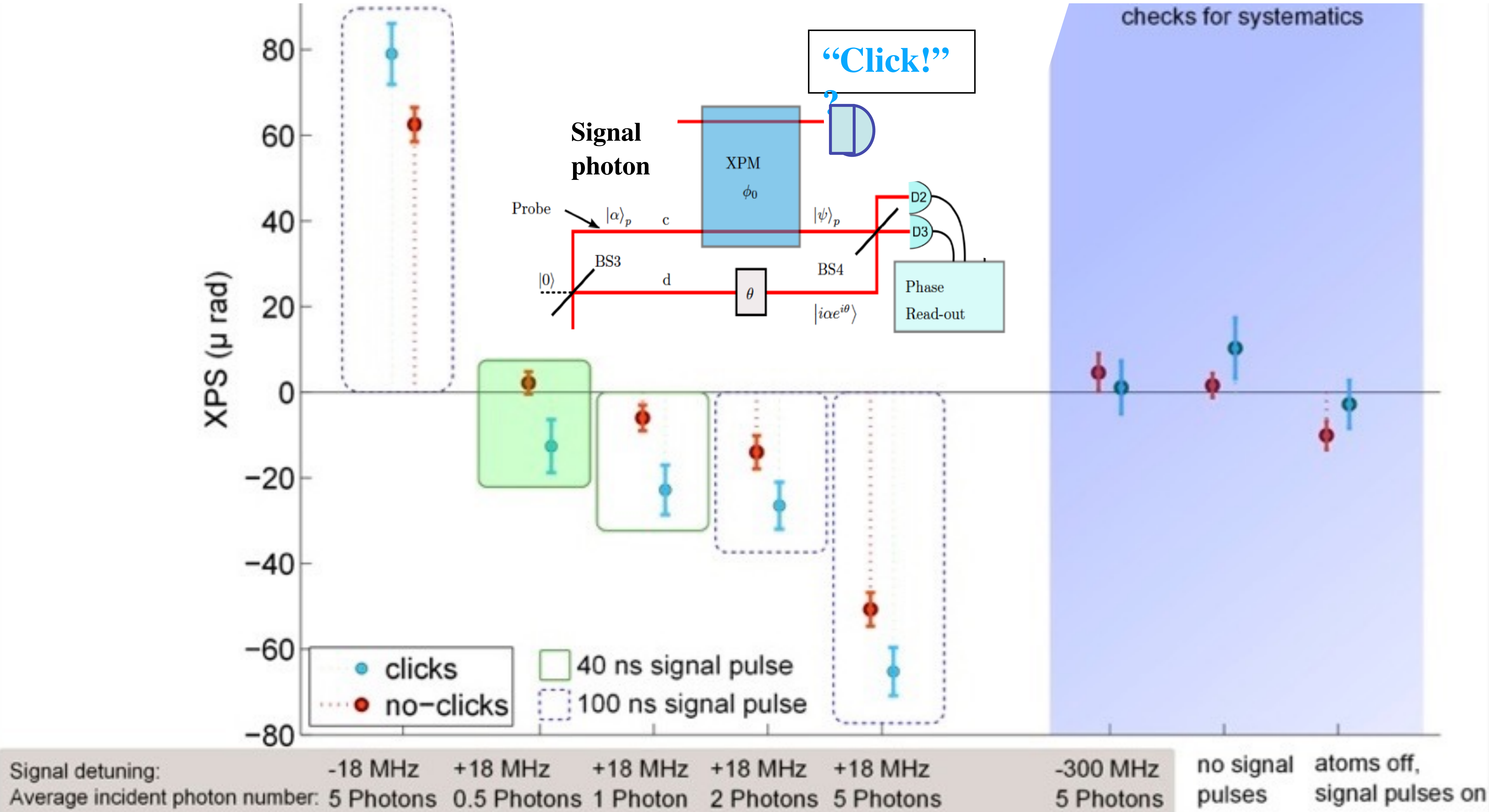
SIGNAL PULSE

EIT COUPLING

PROBE PULSE

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

Non-linear phase shift due to single photons



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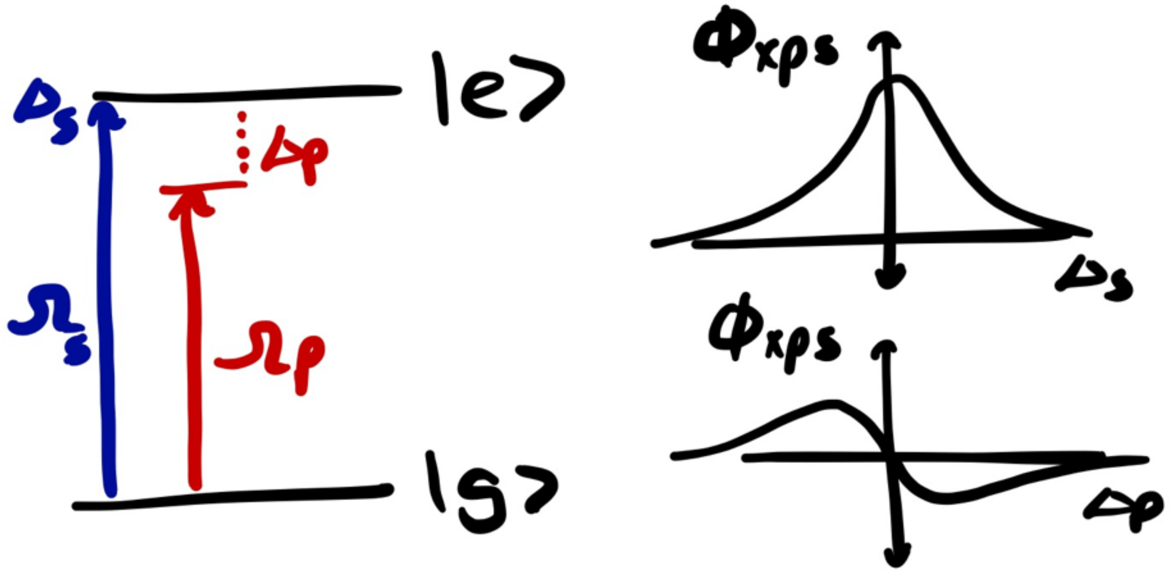
Are absorptive nonlinearities different from dispersive ones?

Another path to a cross-phase shift is to let the signal beam *saturate* the atom, modifying the phase shift seen by a probe.



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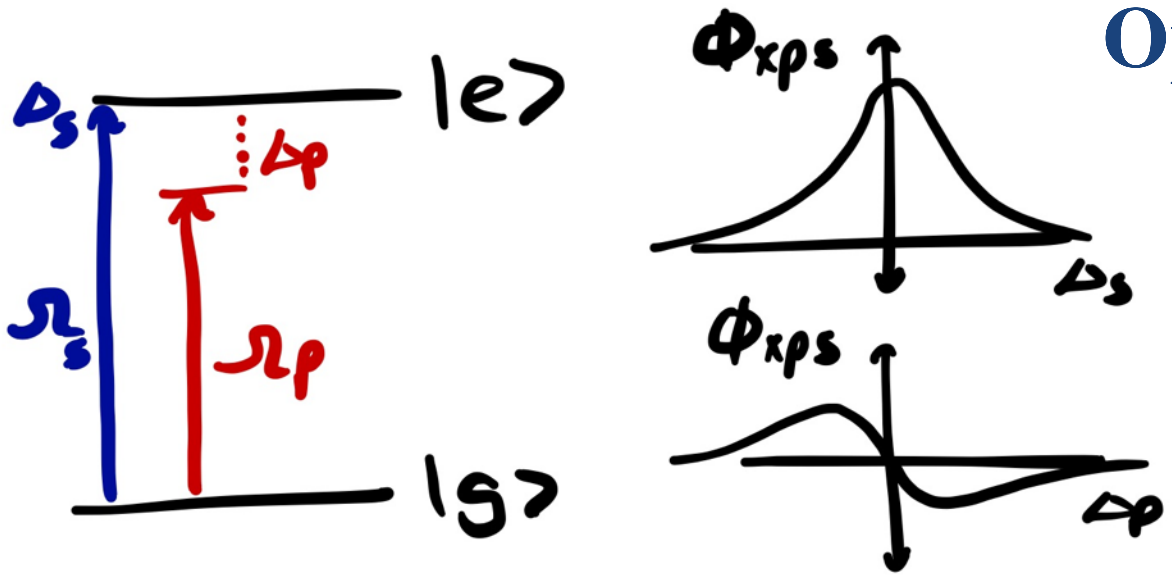
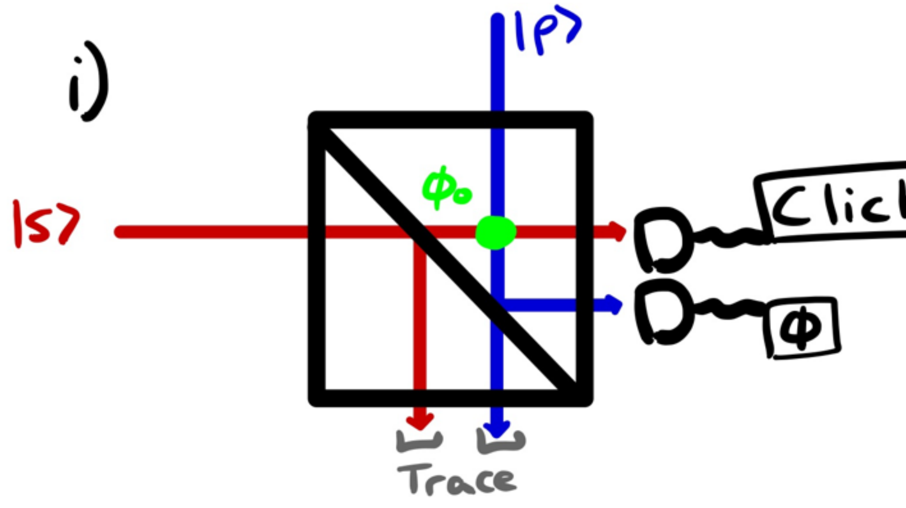


Open question – how to model this loss?



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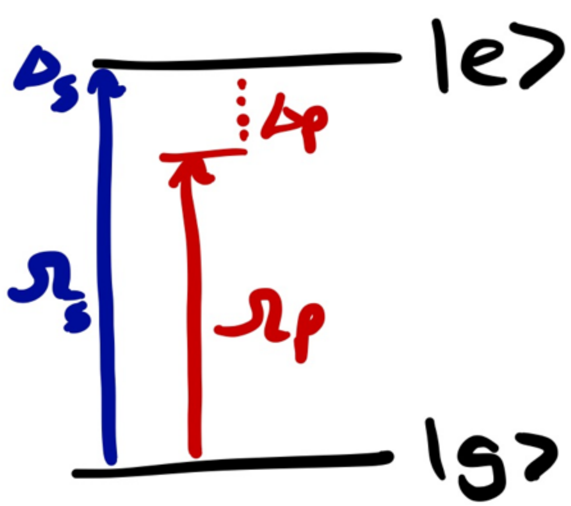

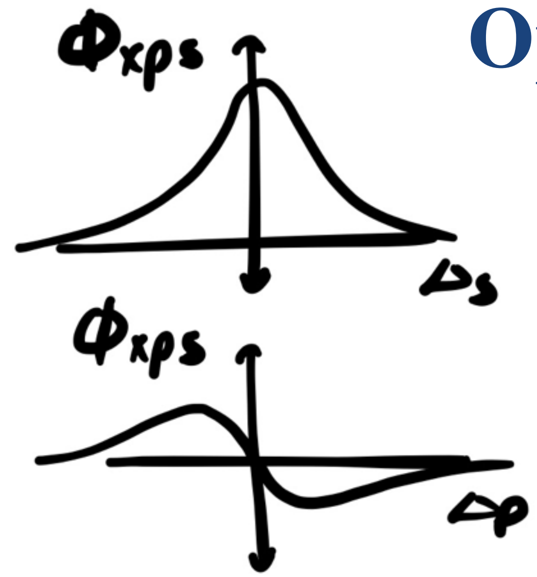

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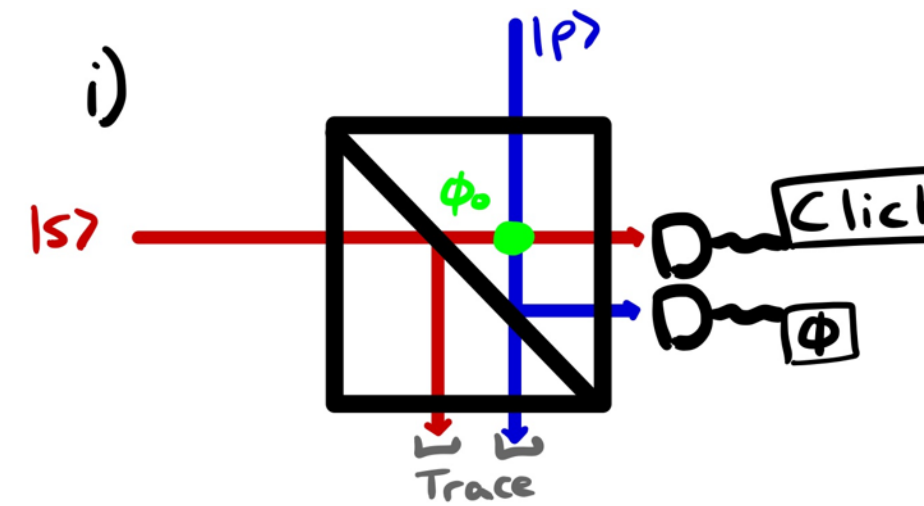
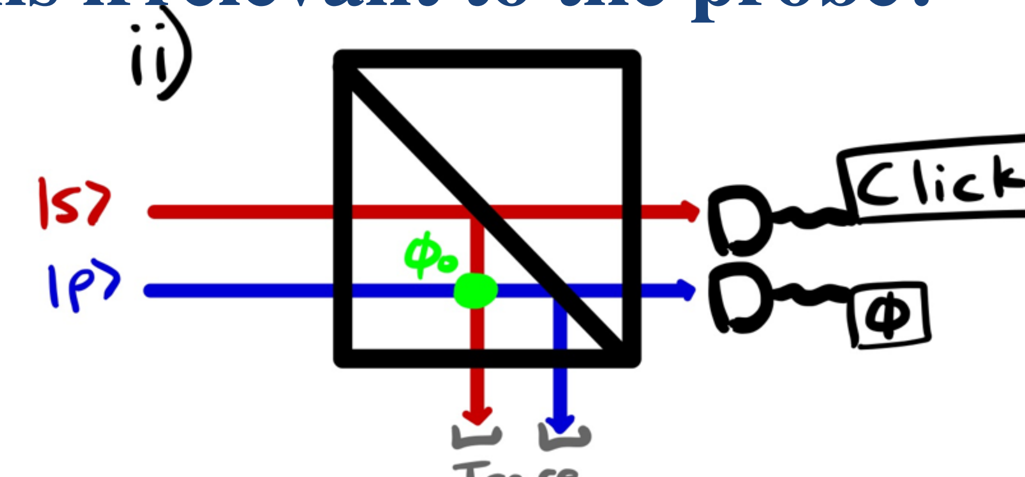
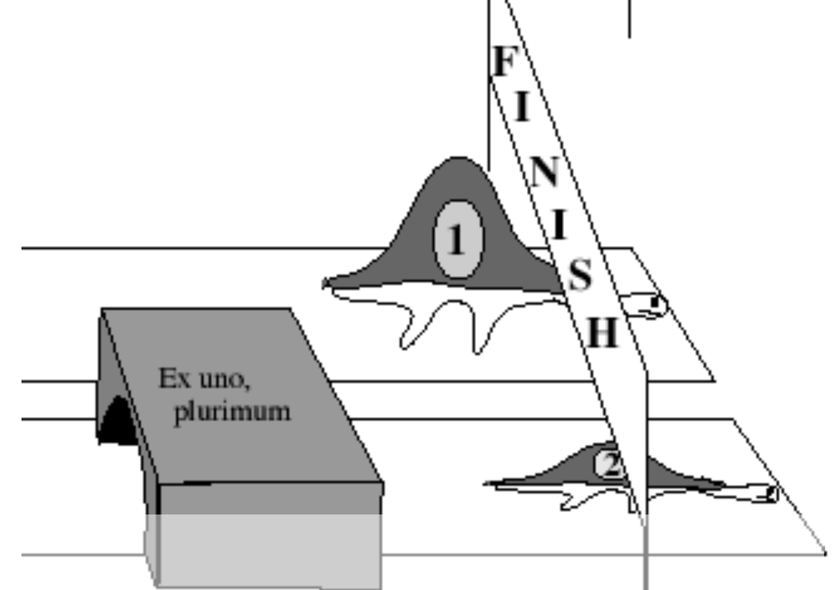


Or, since the signal *must* be absorbed in order to saturate the atom, are the transmitted photons irrelevant to the probe?



Conclusion



We have measured both components of the Larmor/weak tunneling time – the real part to be approx. 0.6 ms for our 1.3-micron barrier.

Clear, distinct physical *meanings* to real and imaginary parts.
Soon to measure transmission & reflection in different regions.

Open q's:

- **do spin-flipped particles become far more likely to get transmitted?**
- **what is the significance of "imaginary" parts of weak/strong values?**
- **is it absorbed or transmitted photons which have useful NL effects?**