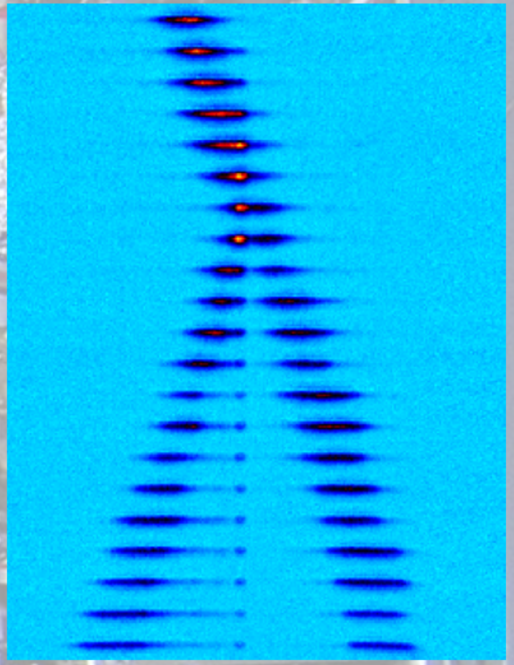
Measuring the time a tunneling atom spends in the forbidden region

Aephraim Steinberg,
Ramón Ramos, David Spierings,
and Isabelle Racicot
Centre for Q. Info. & Q. Control
Dept. of Physics, U. of Toronto



Quantum Measurement: Fundamentals, Twists, and Applications
ICTP Trieste, Apr-May 2019

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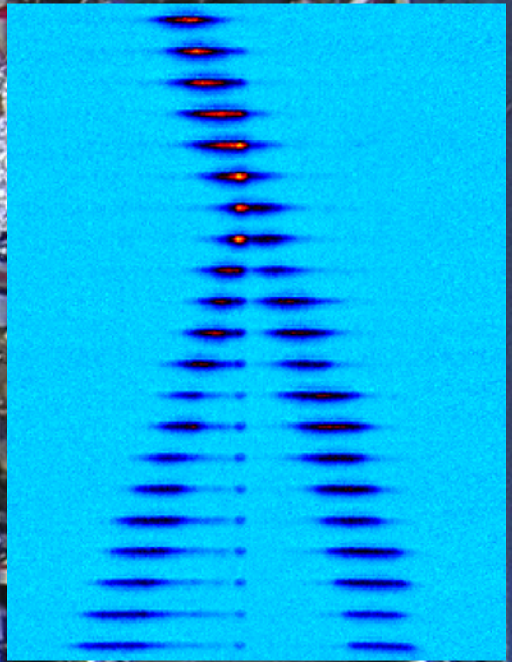

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The Team

Toronto quantum optics & cold atoms group:

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 at the moment, looking for an excellent postdoc!

CQIQC-VIII (Toronto, Aug 26 - 30, 2019)

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Conference on Quantum Information and Quantum Control VII

August 28 to September 1, 2017, University of Toronto

From CQIQC-VI (2015):

Plenary Talks:

Jeff Shapiro, Massachusetts Institute of Technology
Mark Thompson, University of Bristol

Confirmed Invited Speakers:

Itai Arad, National University of Singapore
Rainer Blatt, University of Innsbruck
Todd Brun, University of Southern California
Tommaso Calarco, Universität Ulm
Bob Coecke, Oxford University
Keiichi Edamatsu, Tohoku University
Jens Eisert, Freie Universität Berlin
Christopher A. Fuchs, University Massachusetts Boston
Ivette Fuentes, University of Vienna
Akira Furusawa, University of Tokyo
Jay M. Gambetta, IBM TJ Watson Lab USA
Rajibul Islam, Harvard University
Kurt Jacobs, University of Massachusetts
Ronnie Kosloff, Hebrew University of Jerusalem
Tony Leggett, University of Illinois at Urbana-Champaign
Daniel Lidar, University of Southern California
Masoud Mohseni, Google
Klaus Mølmer, Aarhus University
Bertrand Reulet, Université de Sherbrooke
Terry Rudolph, Imperial College, London
Irfan Siddiqi, University of California, Berkeley
Rob Spekkens, Perimeter Institute
Mike Thewalt, Simon Fraser University
Robert Whitney, CNRS Grenoble
Nathan Wiebe, Microsoft

Motivation: the tunneling time problem

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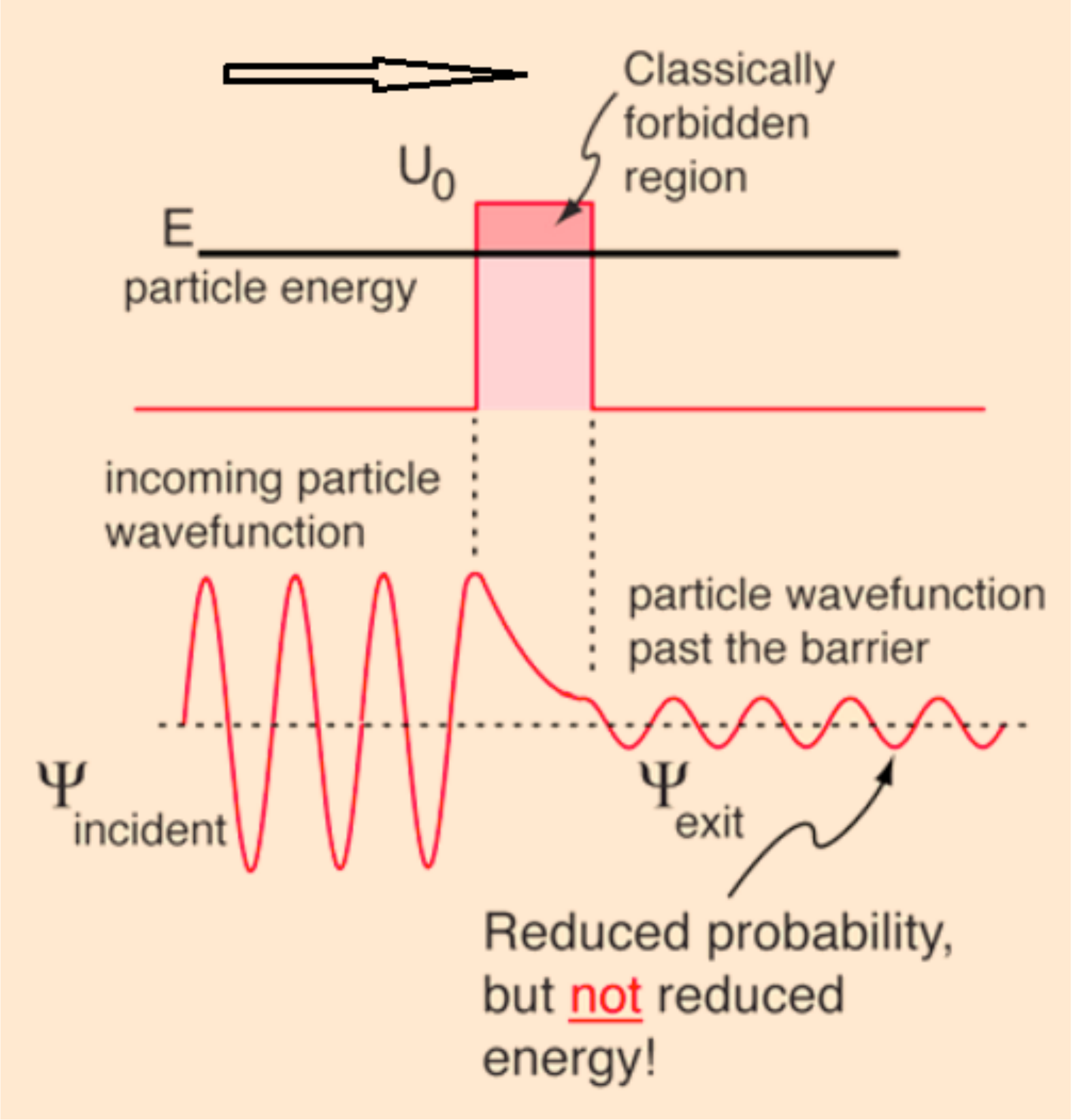


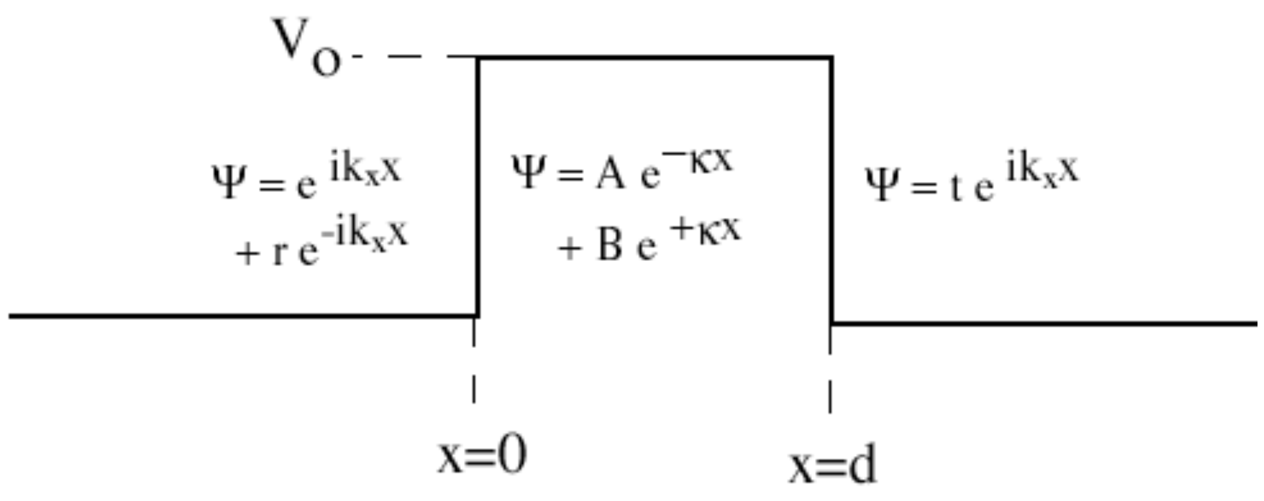
We all learn how to calculate the transmission *probability* . . .

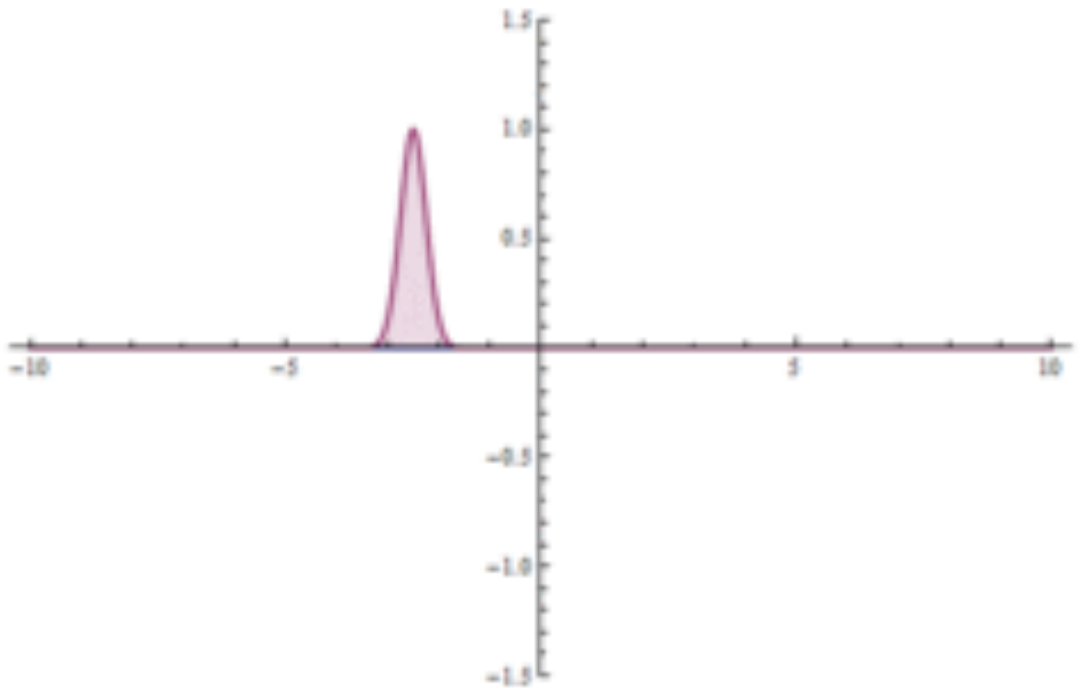
But *when* does a transmitted particle appear?

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



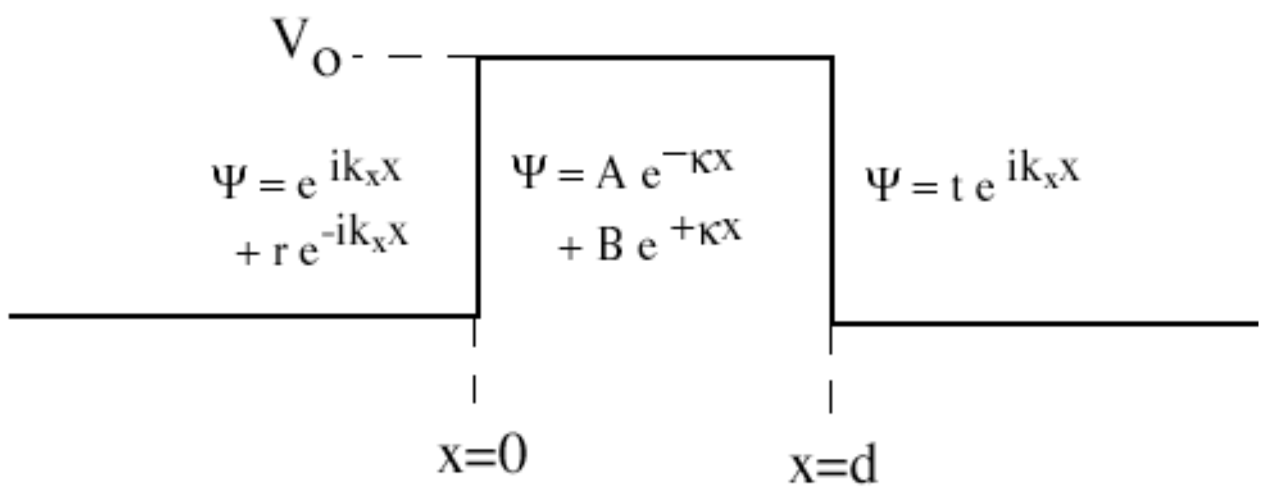


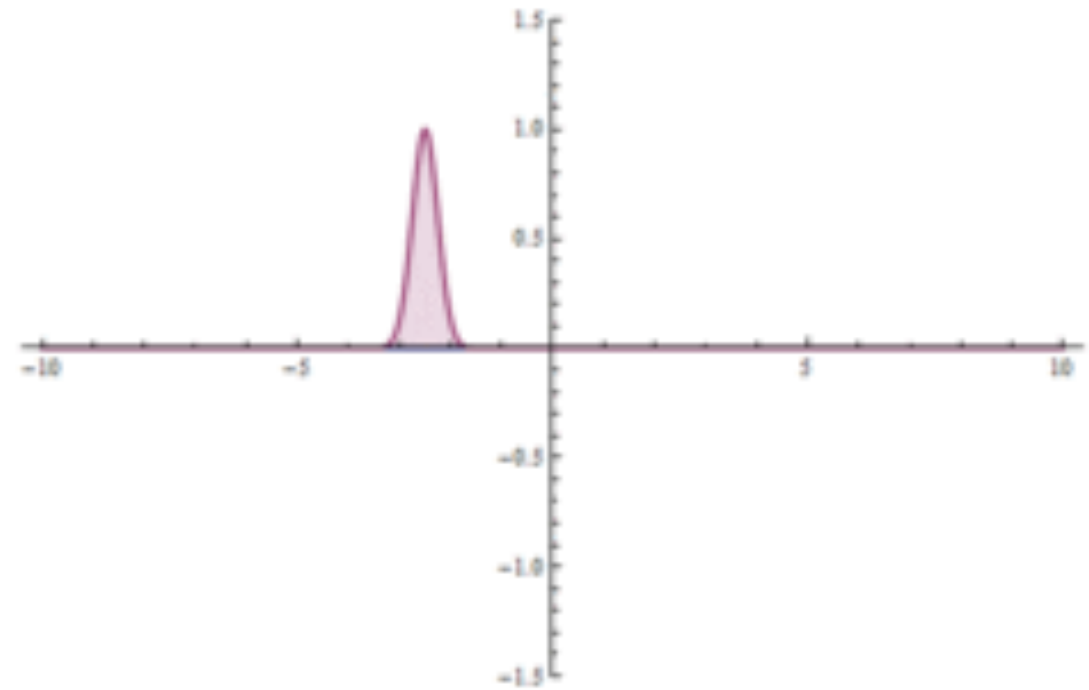
When does a wave packet peak appear?

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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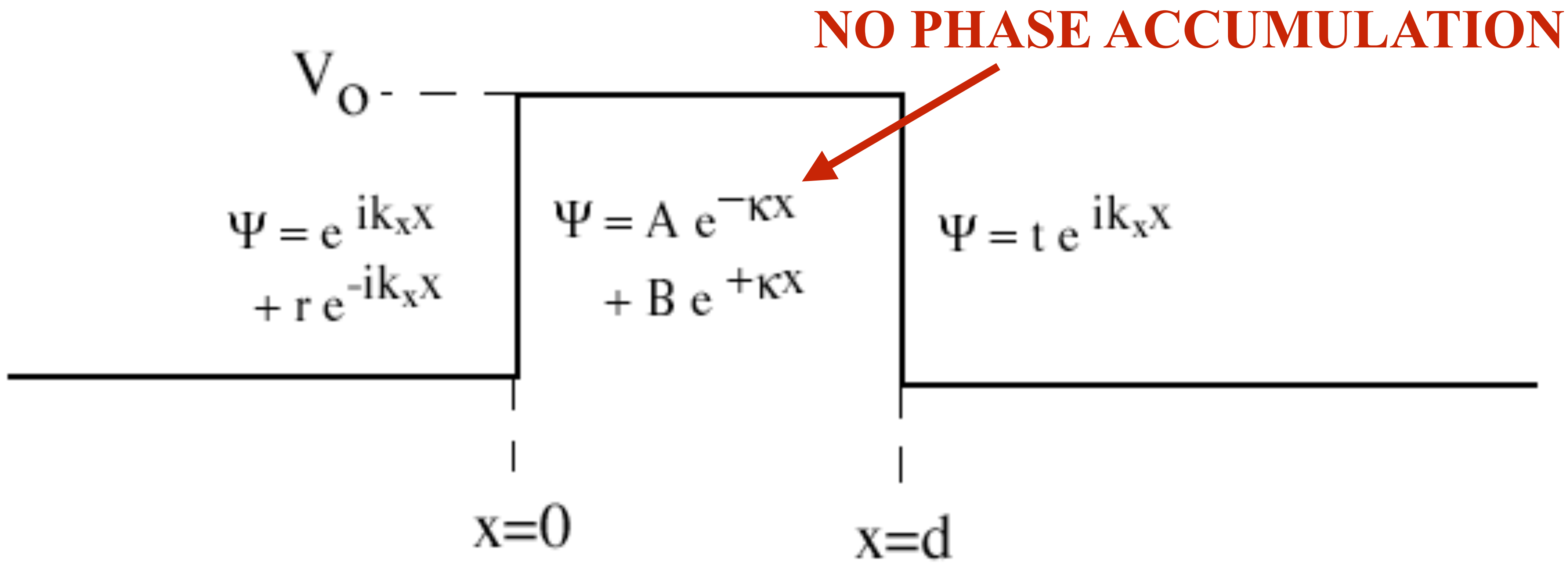


The time delay for a peak to appear becomes independent of the thickness of the barrier, at least for thick barriers…

t is independent of d... so, for large enough d, it can even be < d/c (this is also true with relativistic equations such as Dirac or Maxwell).

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)
…

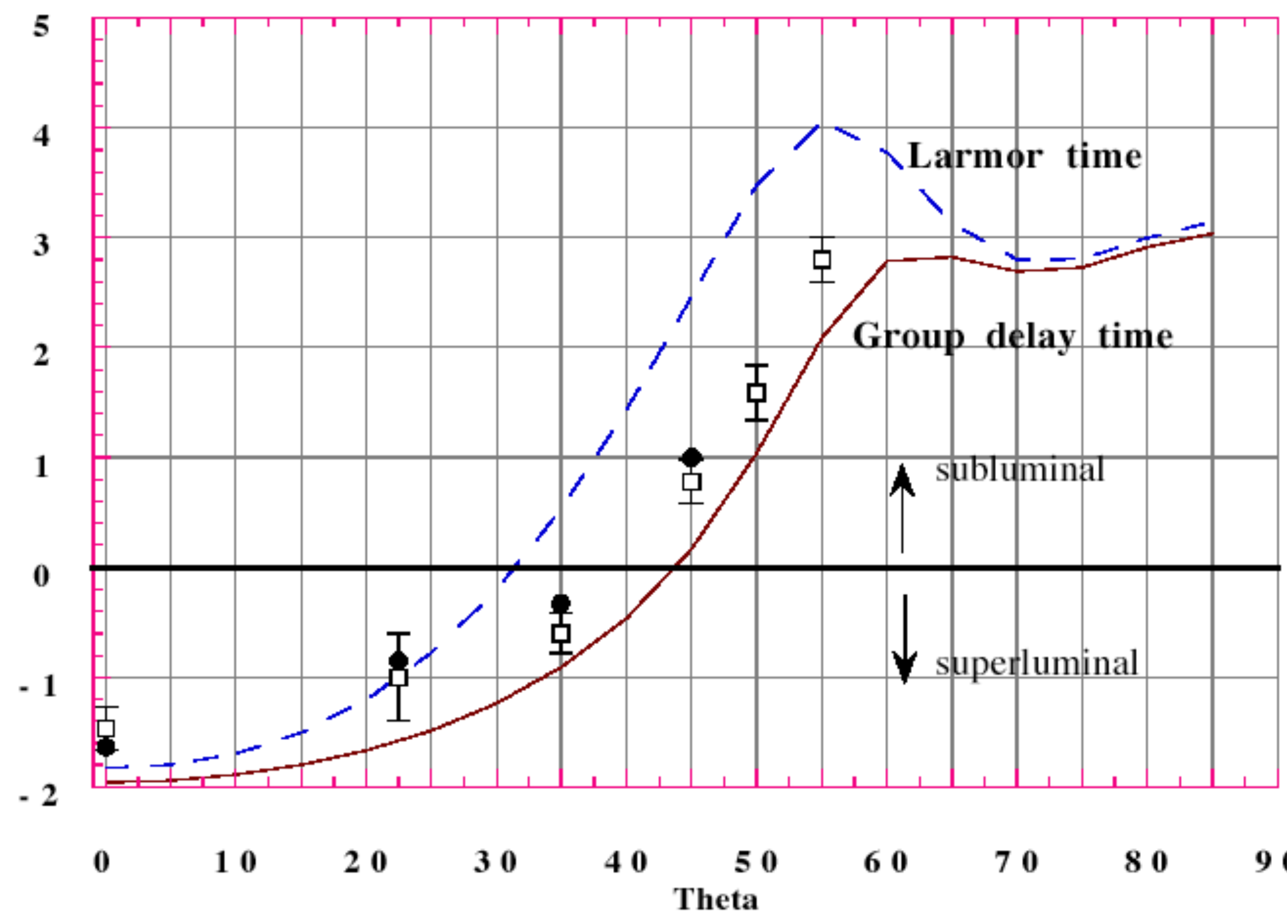
Group delay (arrival time)

The Wigner time (group delay) *has* been verified, in multiple experiments; it does indeed exhibit the Hartmann effect.

That is – it can be very small, even << d/c (but not zero).

Delay time (fs)
***relative* to 3.6fs**
vacuum propagation time

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

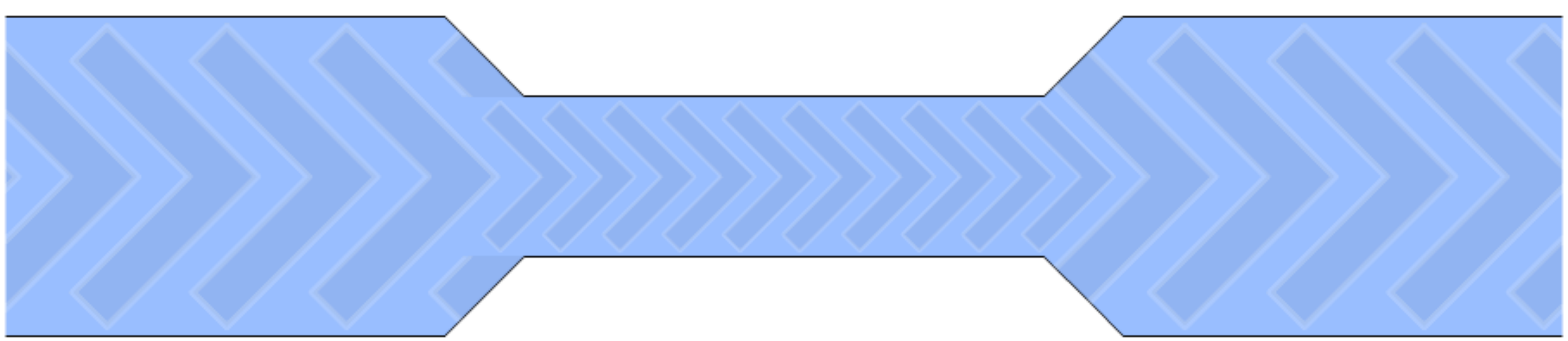


Barrier traversal time

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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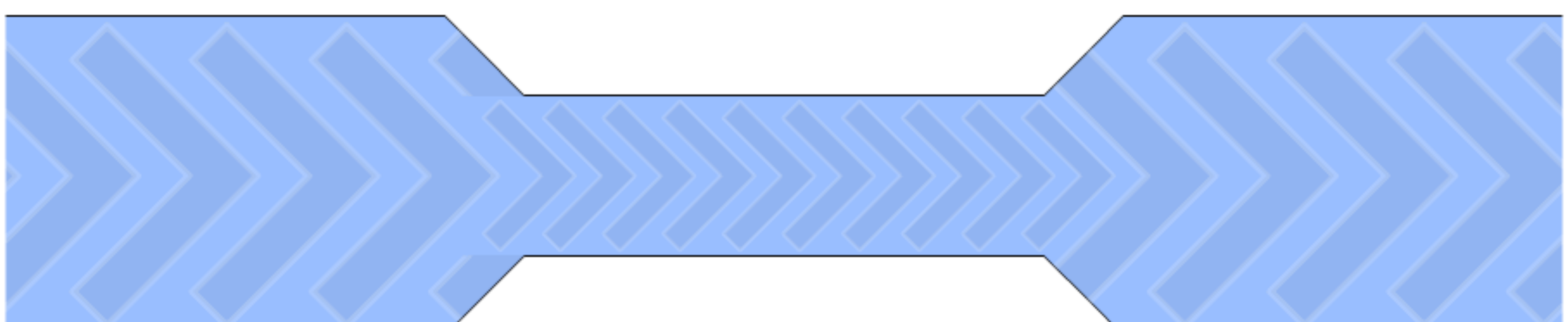

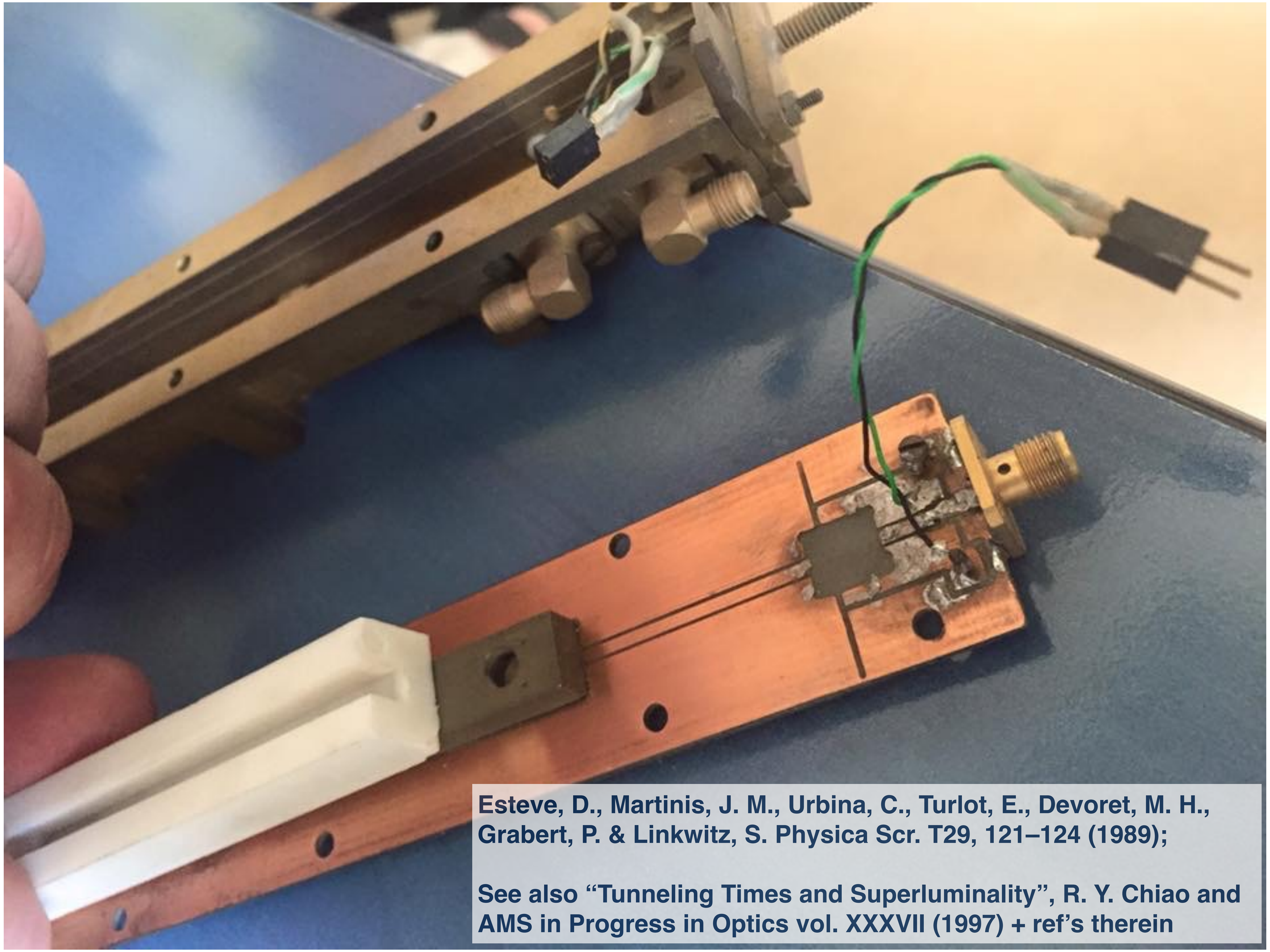

Esteve, D., Martinis, J. M., Urbina, C., Turlot, E., Devoret, M. H., Grabert, P. & Linkwitz, S. Physica Scr. T29, 121–124 (1989);

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

Characteristic time for macroscopic quantum tunneling

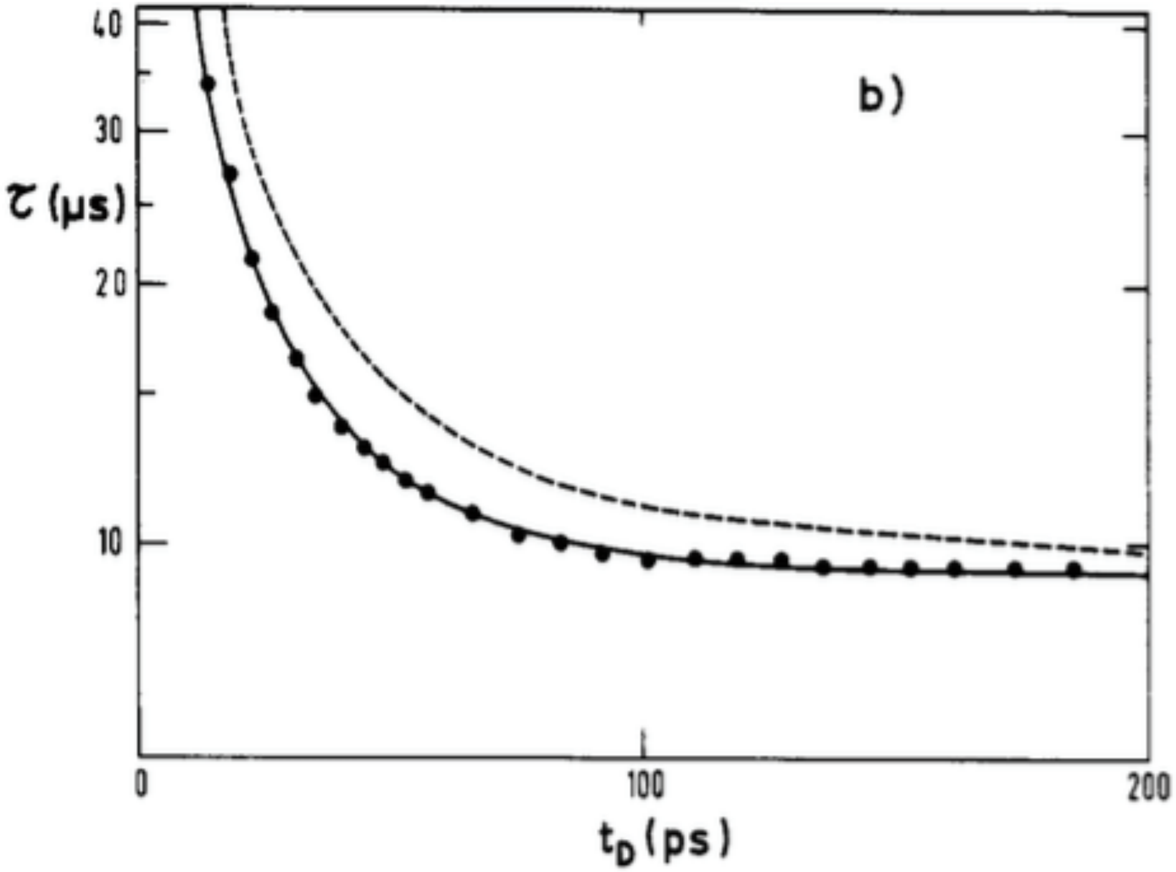

Fig. 5. Lifetime τ of the zero voltage state versus delay t_d at two temperatures (a) $T = 65$ mK and (b) $T = 18$ mK. Dashed line corresponds to the zero temperature perturbative expression (2). Full line is the prediction of a numerical calculation using theory developed in Ref. [8].

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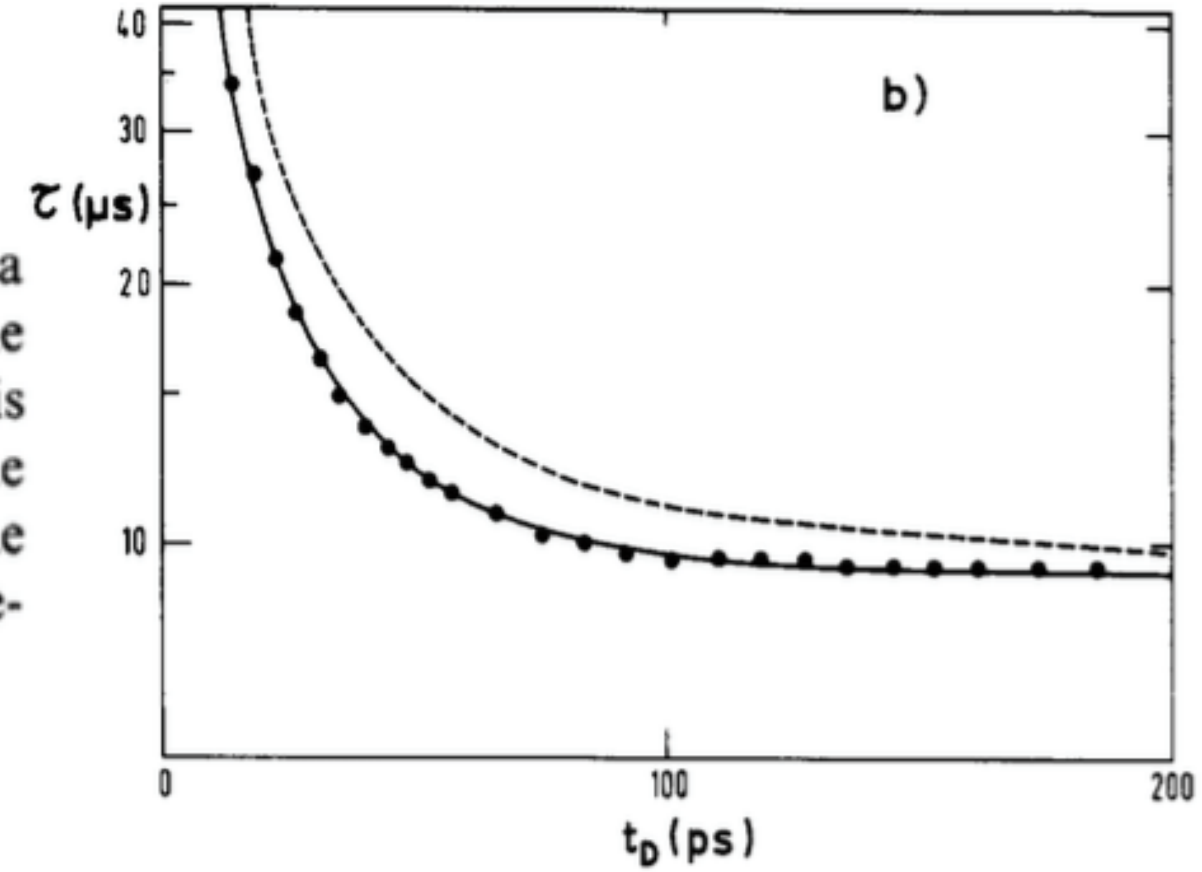
Characteristic time for macroscopic quantum tunneling

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.



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

Is this the end of the story?

… apparently not …

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

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

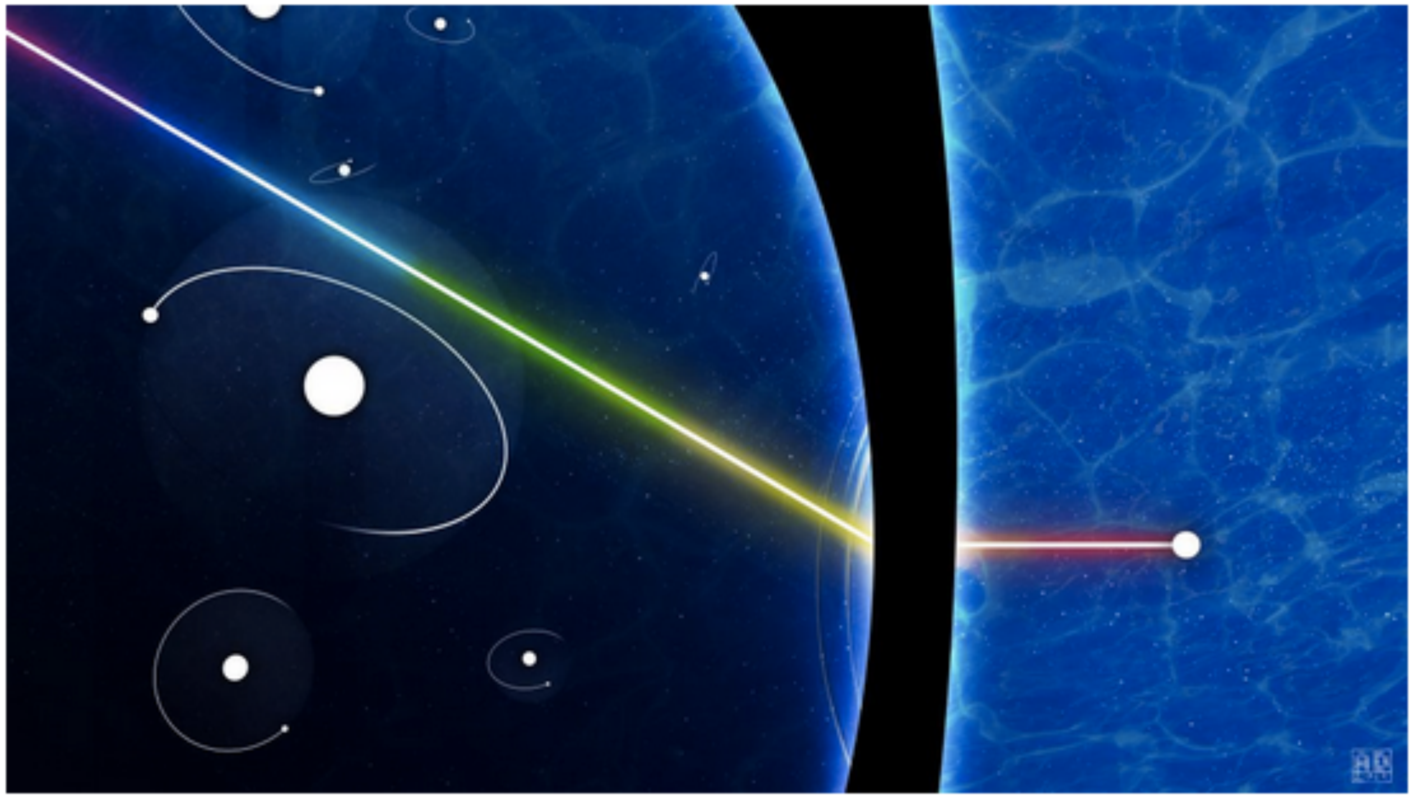
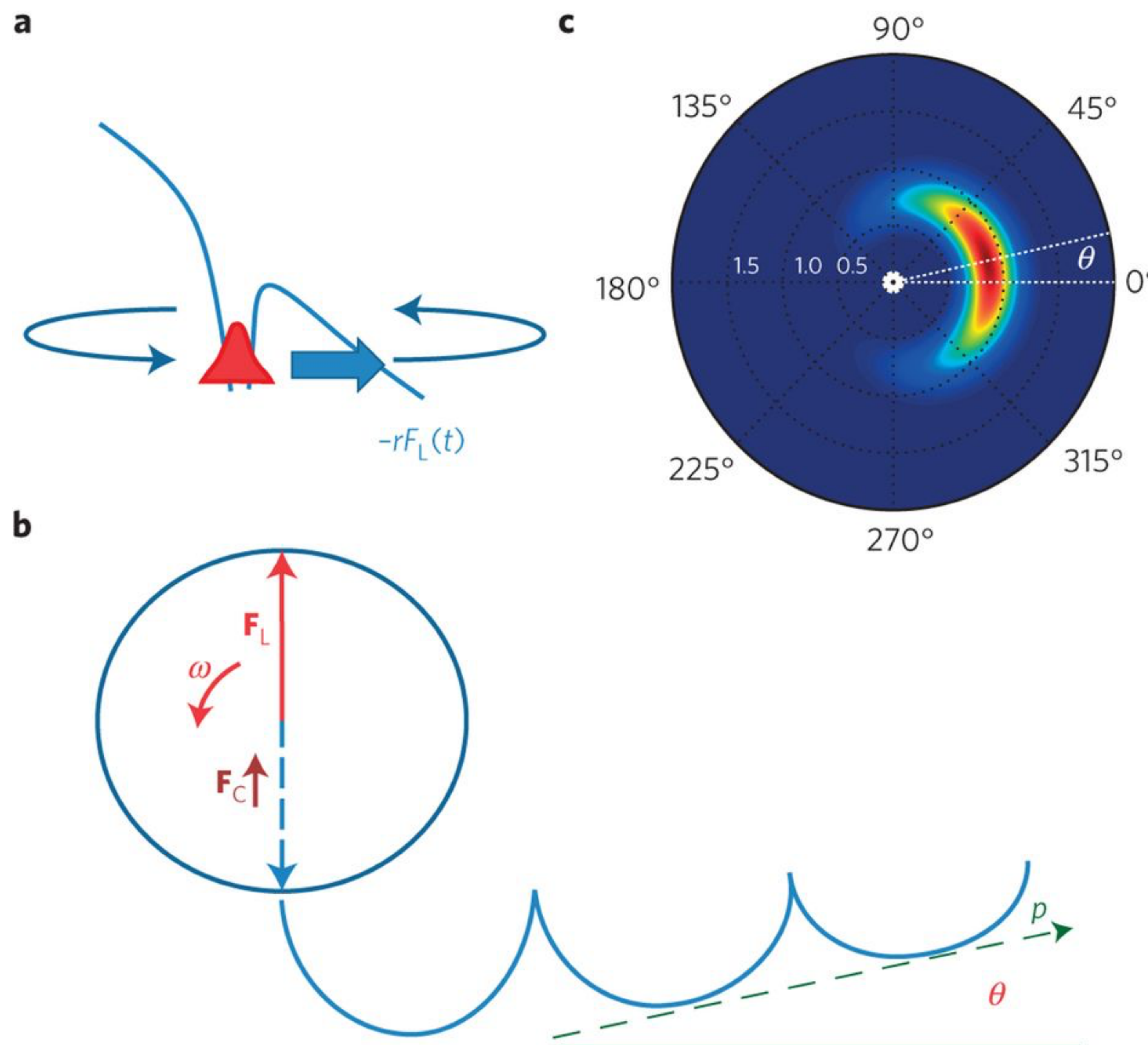


Image courtesy of Nature.

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.

Quantum Tunneling Is So Quick It Could Be Instantaneous

The Attoclock (Ursula Keller and others, 2008-present)



Eckle, P. et al. Attosecond ionization and tunneling delay time measurements in helium. Science 322, 1525–9 (2008).

Landsman, A. S. et al. Ultrafast resolution of tunneling delay time. Optica 1, 343 (2014).

Torlina, L. et al. Interpreting attoclock measurements of tunnelling times. Nat. Phys. 11, 503–508 (2015).

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

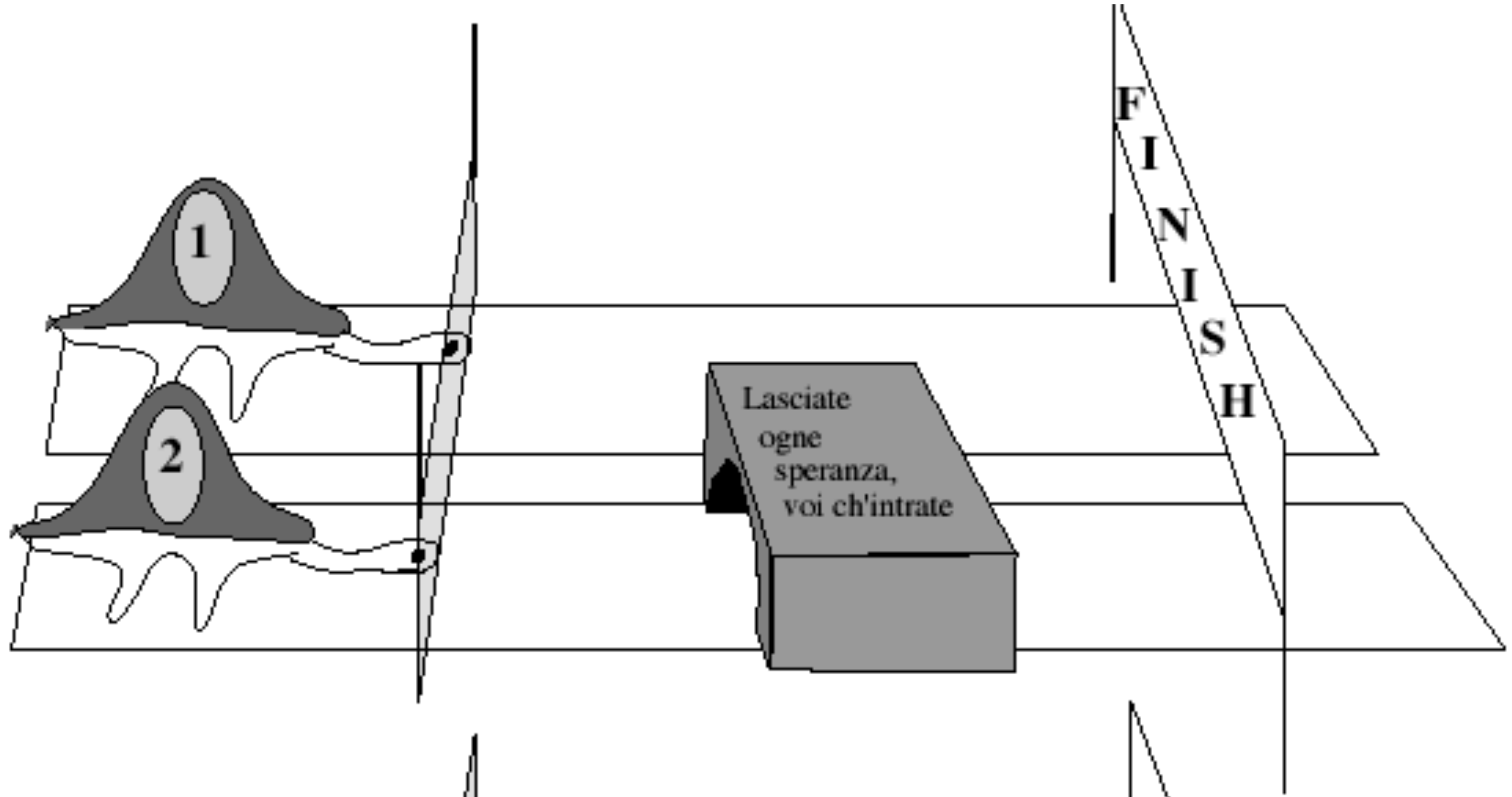
… ***et al.*** **…**

SEE ALSO ATOM TUNNELING IN AN OPTICAL LATTICE:

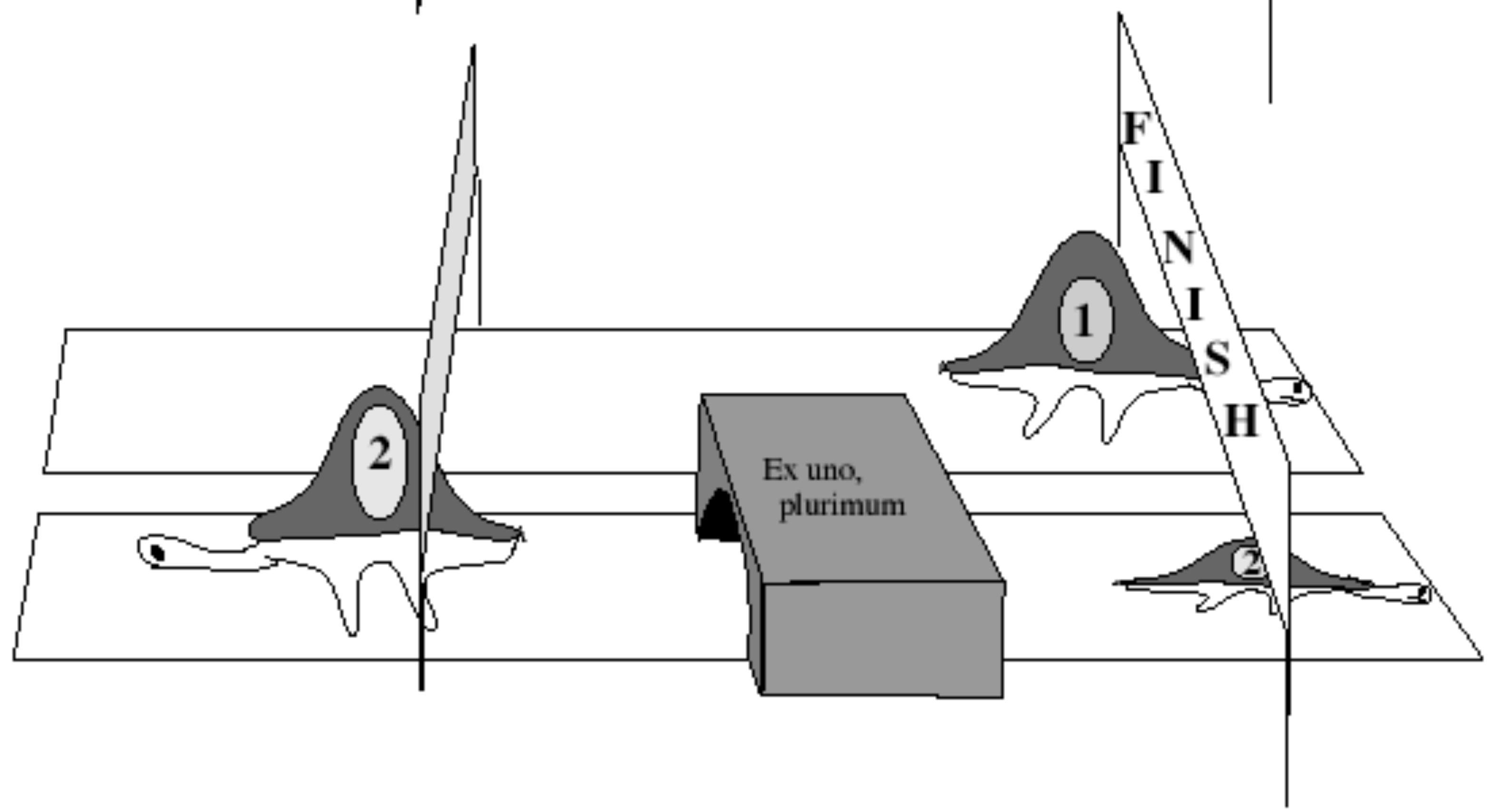
Fortun, A. et al. Direct Tunneling Delay Time Measurement in an Optical Lattice. Phys. Rev. Lett. 117, 010401 (2016).

(What does it measure?)

Does energy travel FTL?

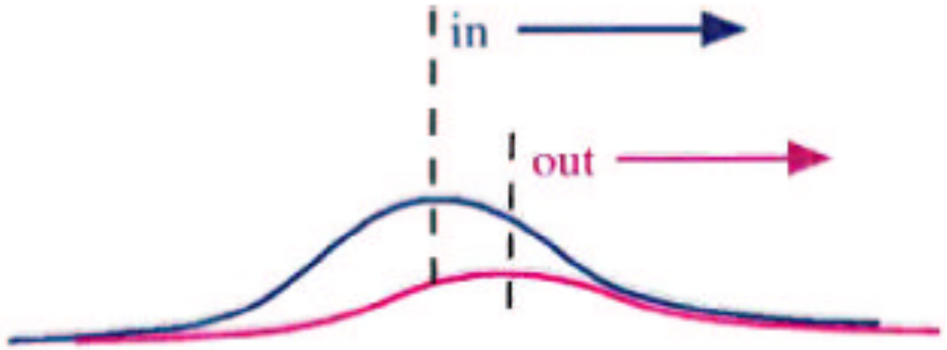


NO:



What about information?

also “NO!”



No energy need travel faster than *c*.

What about information, however?

The transmitted pulse is constructed causally out of the initial pulse. Although it *looks* as though it travelled >c, this is merely a result of a Taylor expansion.
A barrier is a very good analog computer.

What about information?

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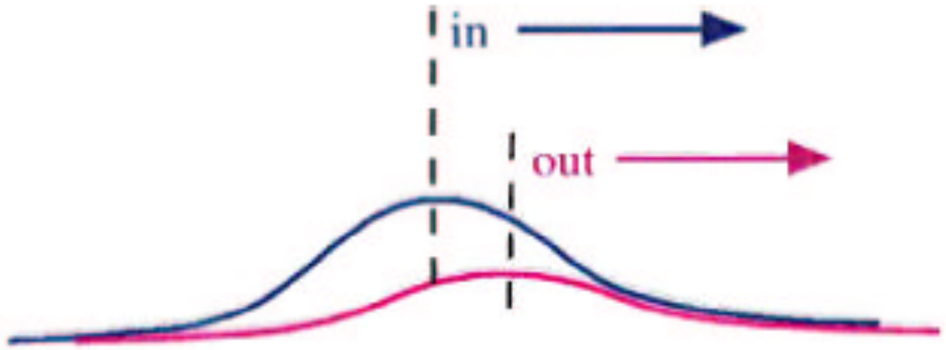

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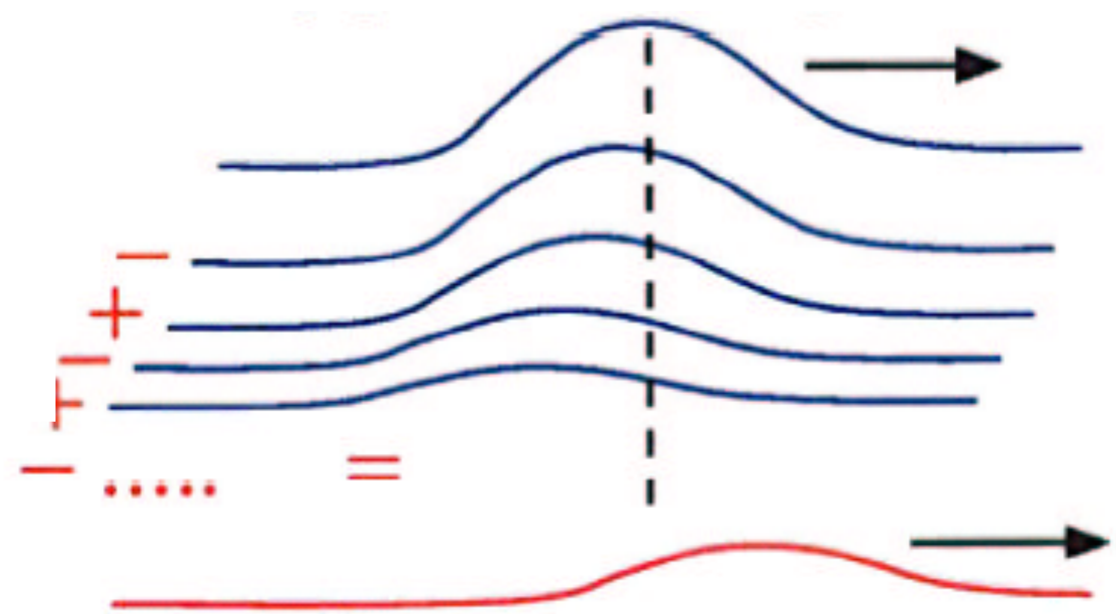
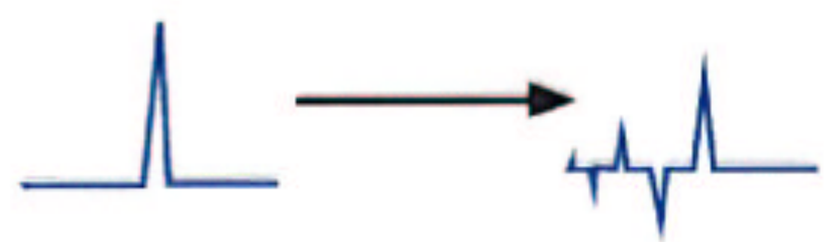
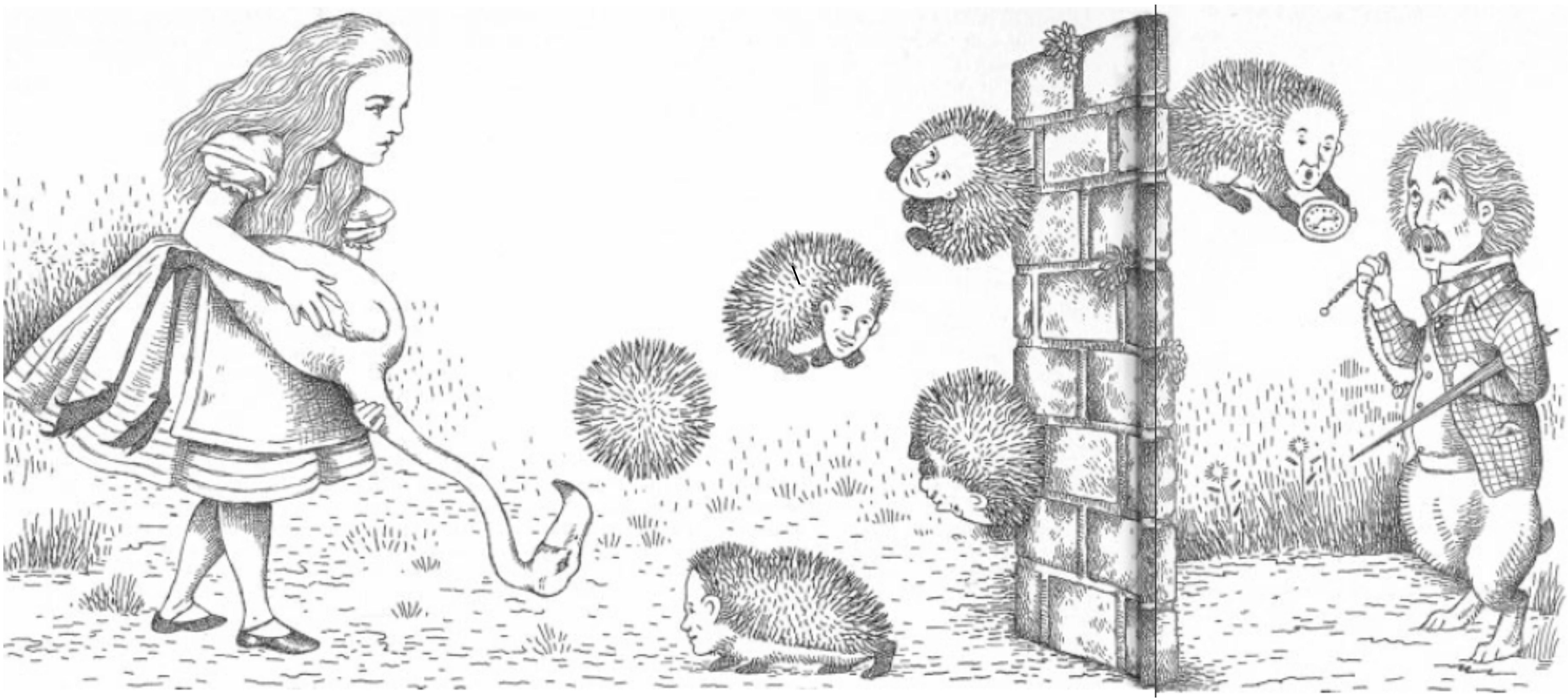


BUT: ***no*** **new** ***information propagates faster than c.***



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"…

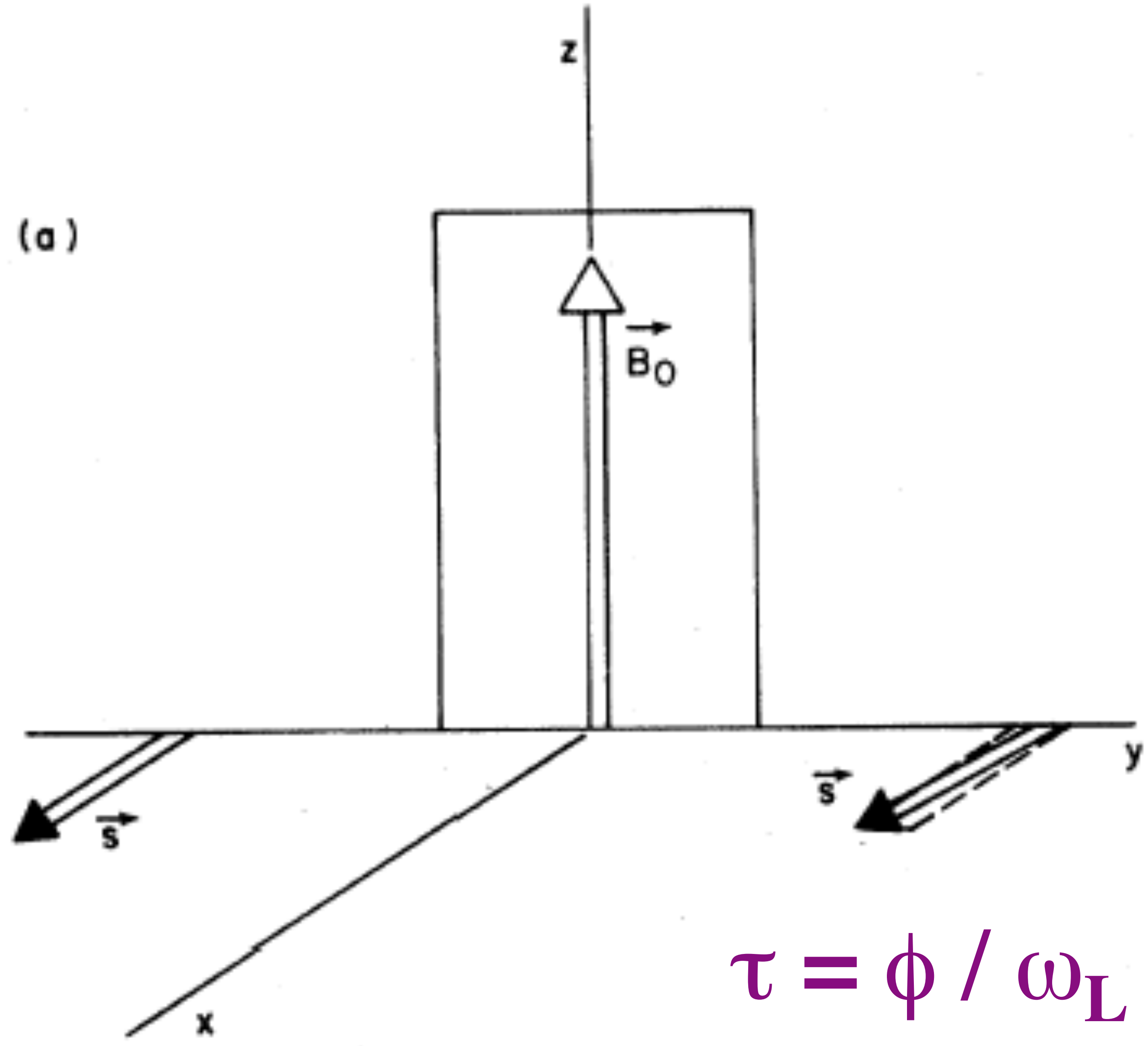


(courtesy Scientific American, 1993)

INTERACTION TIMES:

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

One example: Baz & Rybachenko's "Larmor time"

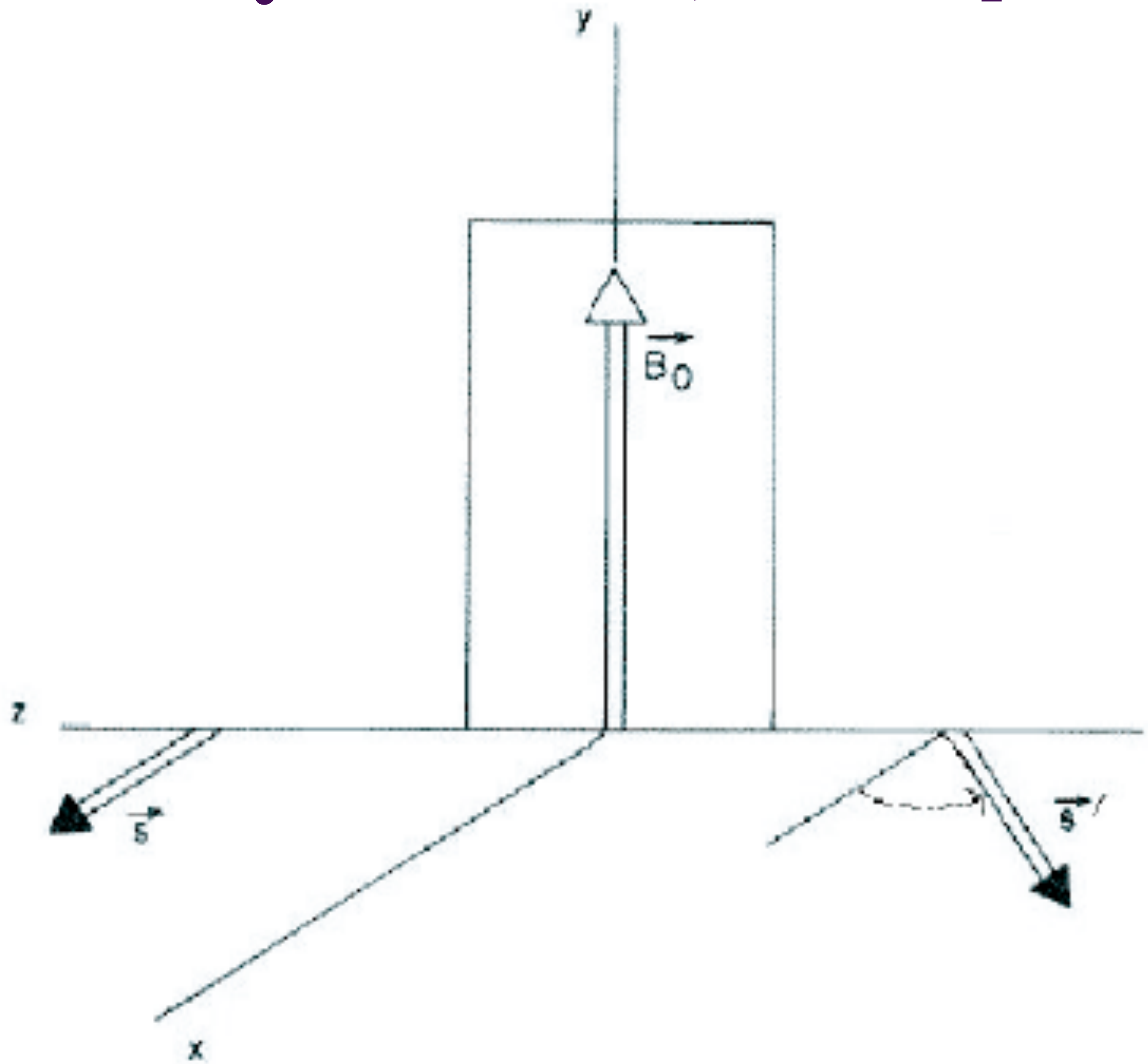


$$\tau = \phi / \omega_L$$

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

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

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



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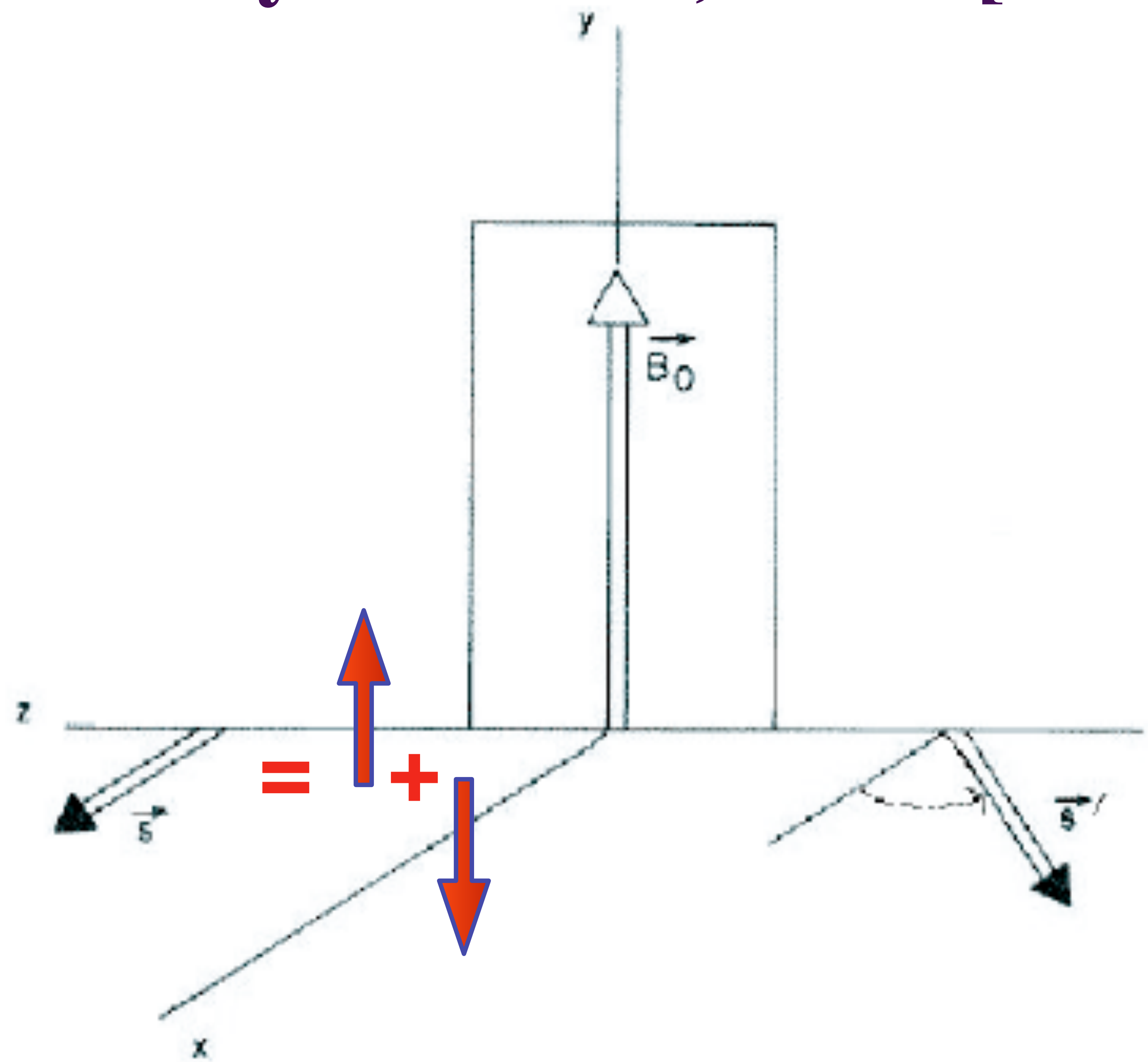

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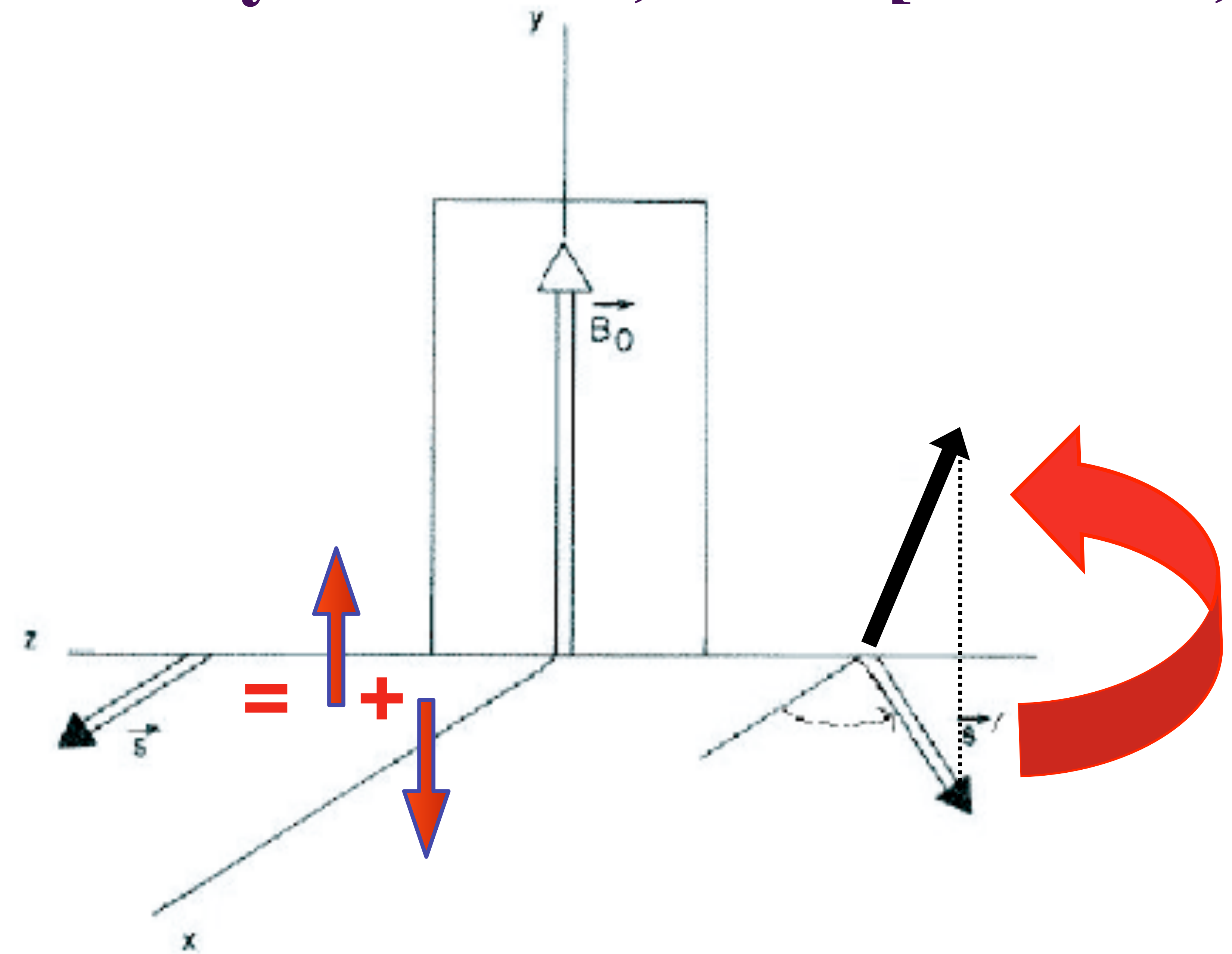

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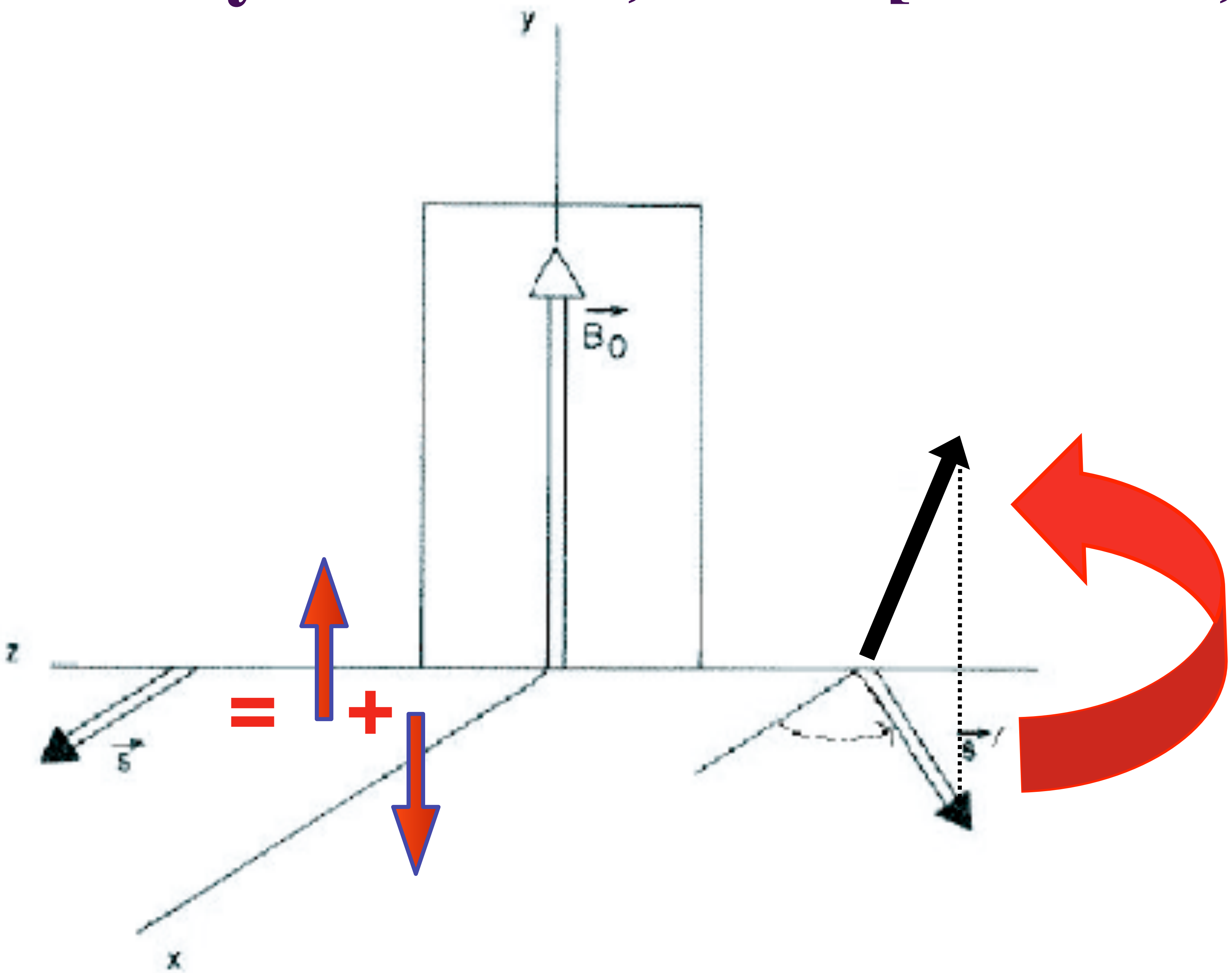


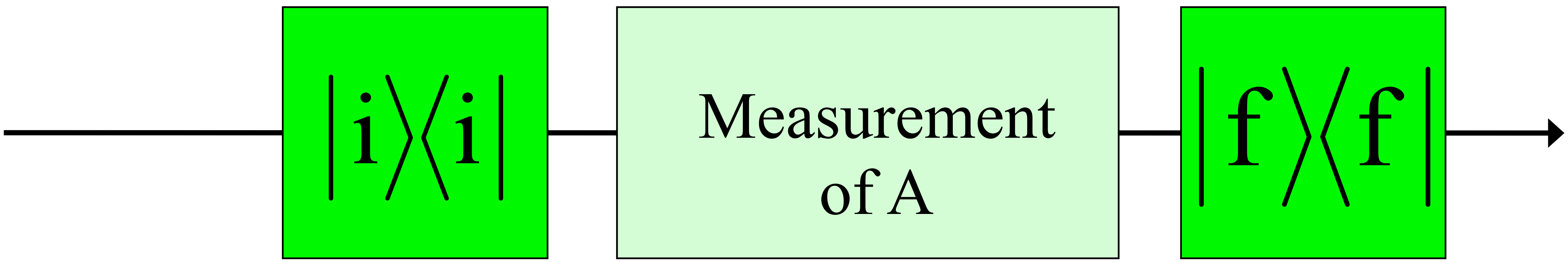
The presence of two components to the Larmor time mystified Büttiker; a Feynman-path approach led to complex times [Sokolovski + Baskin, PRA 36, 4604 (1987)], which mystified every one.

Connection to "weak measurement"

Conditional measurements (Aharonov, Albert, and Vaidman)

AAV, PRL 60, 1351 ('88)
[& viz. ABL, PRB 134, 1410 ('64)]

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

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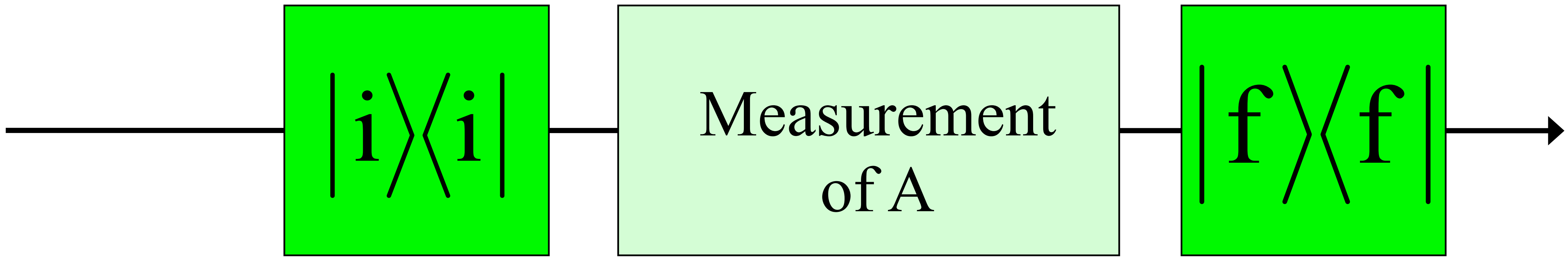

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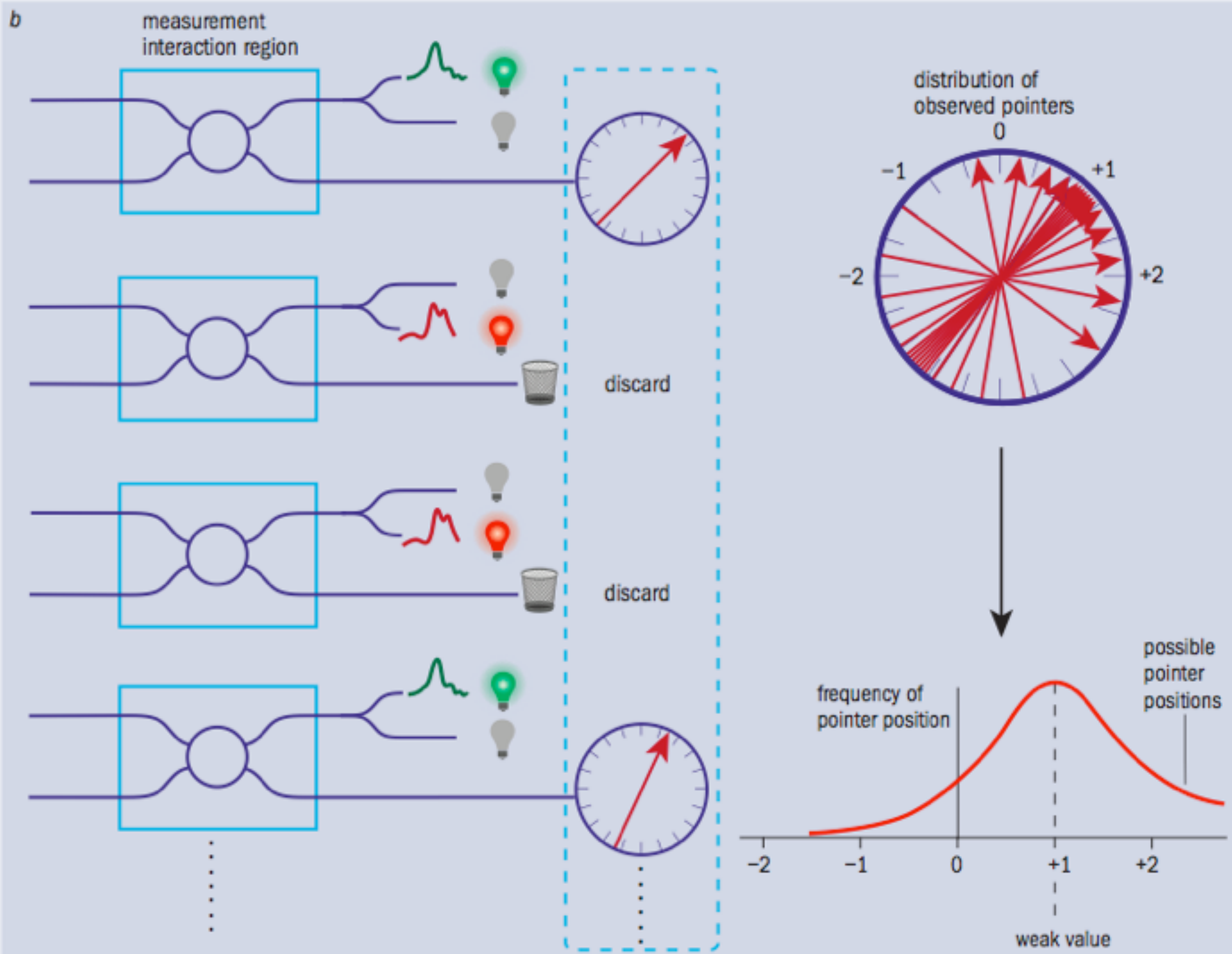
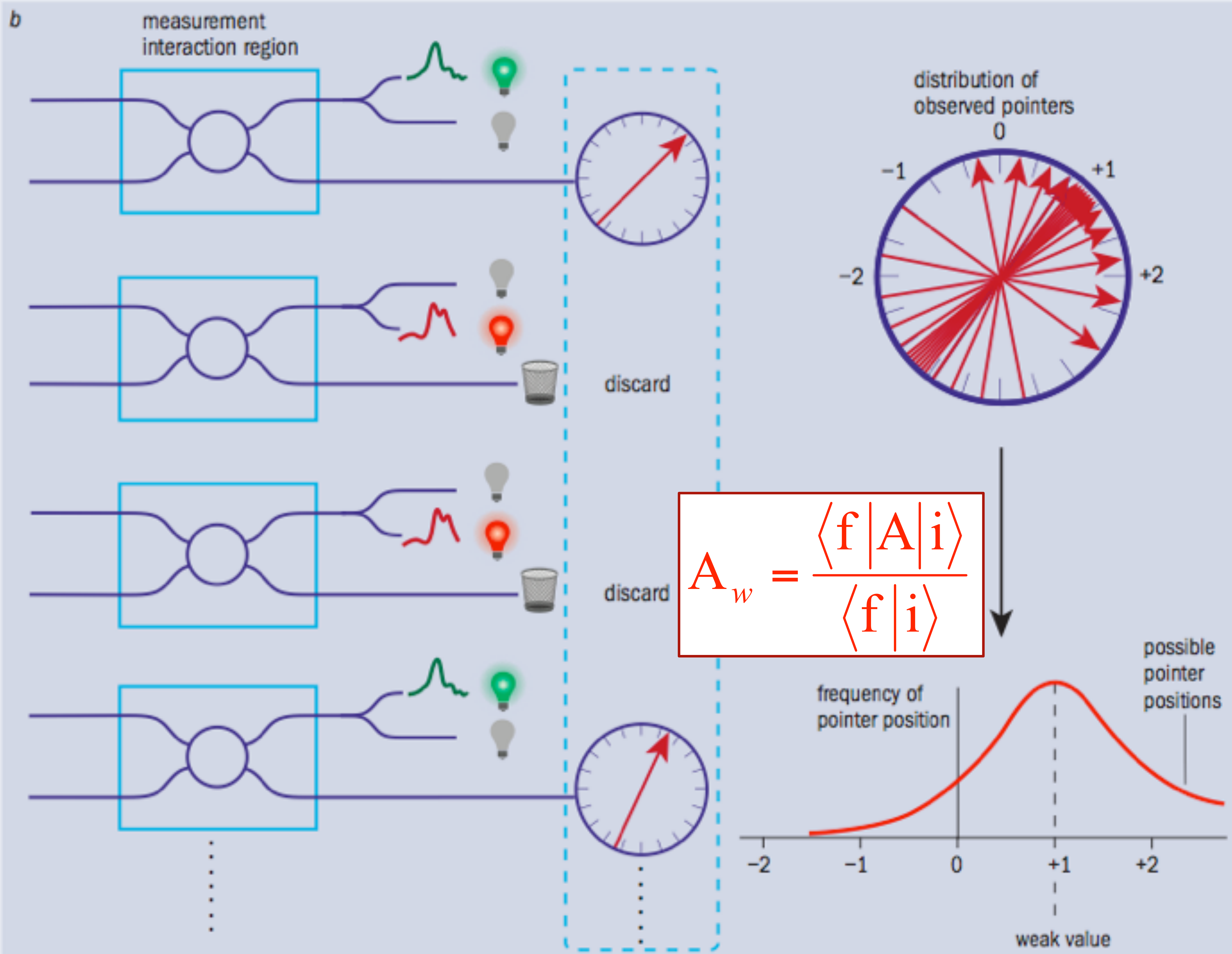
Reconciliation: measure A "weakly."
Poor resolution, but little disturbance.

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


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

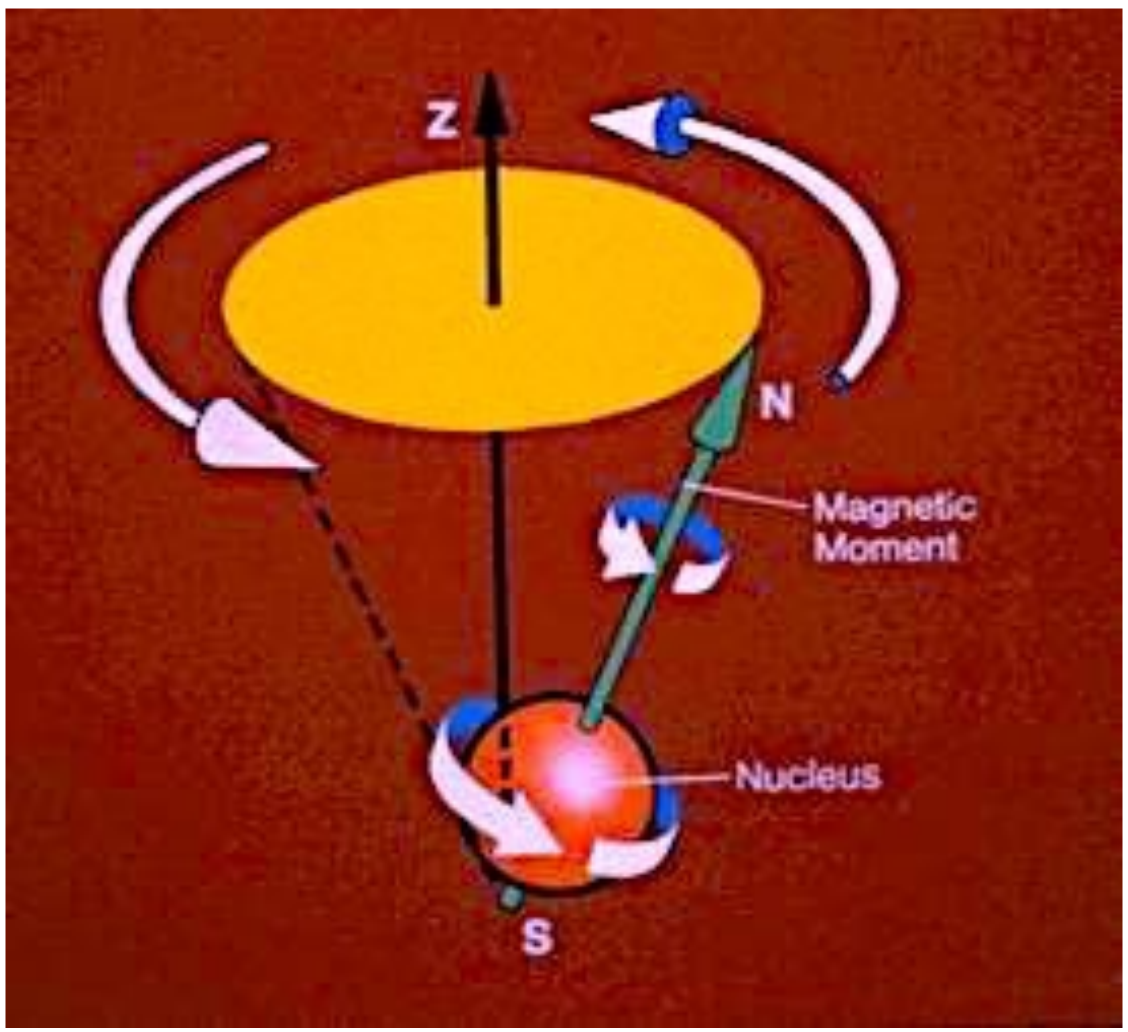


$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

Clock readout

"And then you measure the spin angle, in the B -> 0 limit, and that tells you the time."

Physicist: "oh, that sounds straightforward. Clever idea."



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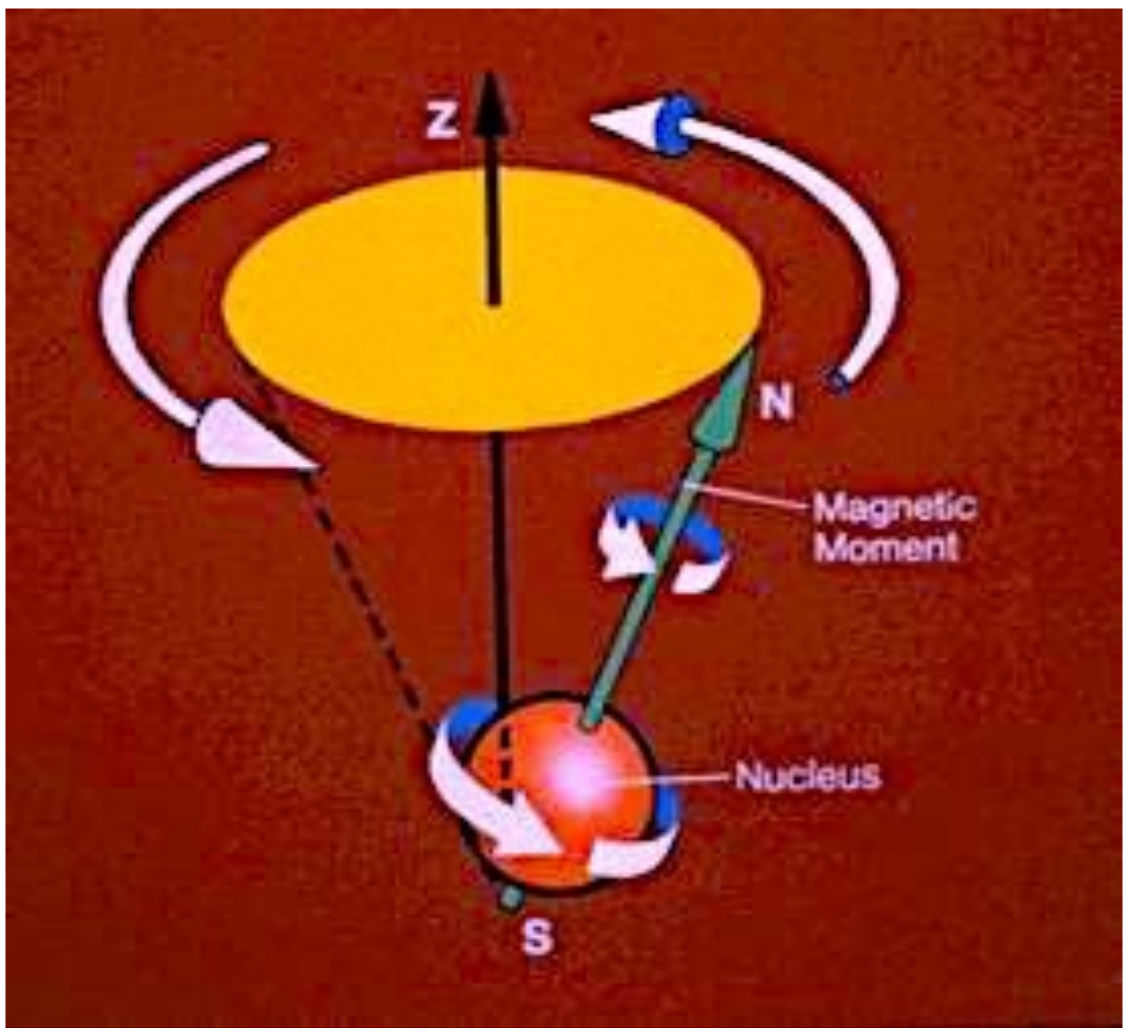

"With weak measurement, you repeat the experiment many times, and the peak of the pointer distribution tells you the value."

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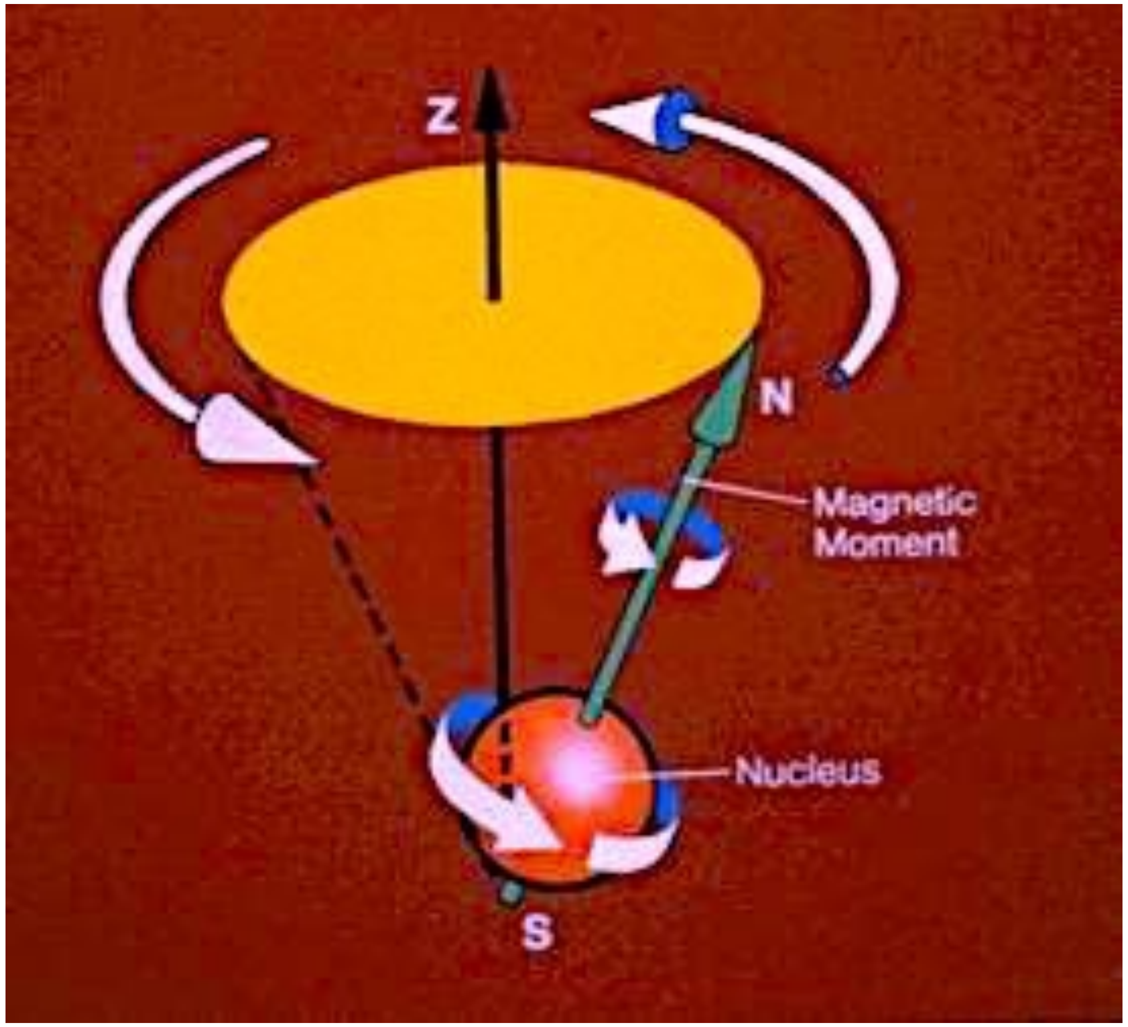
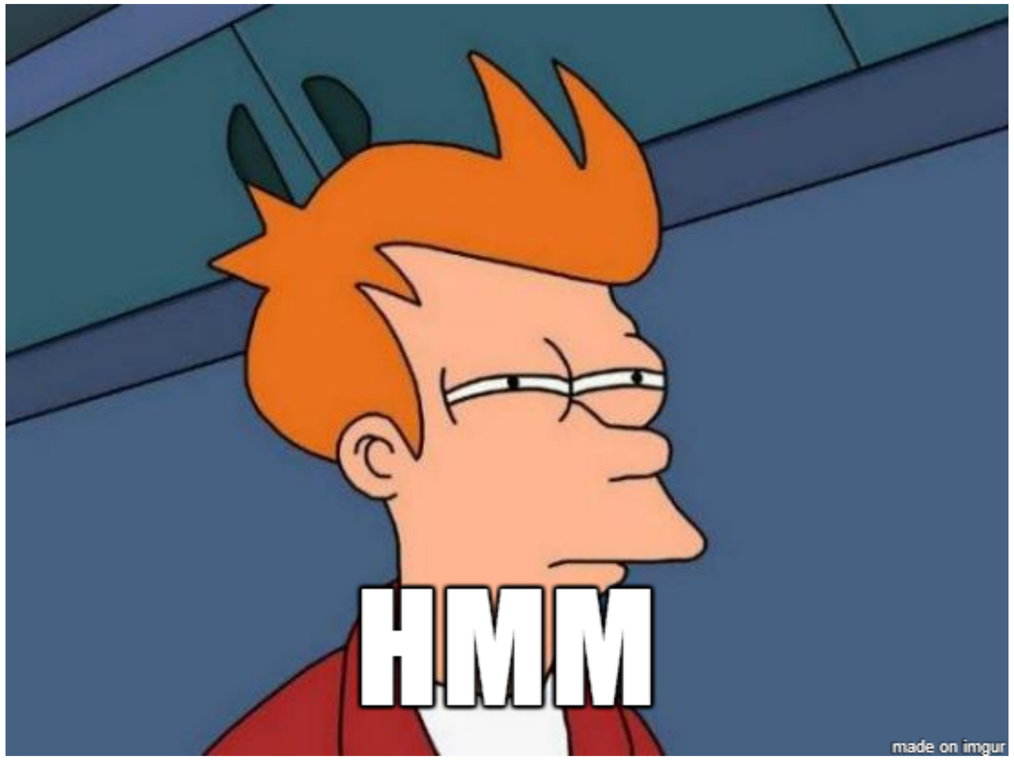
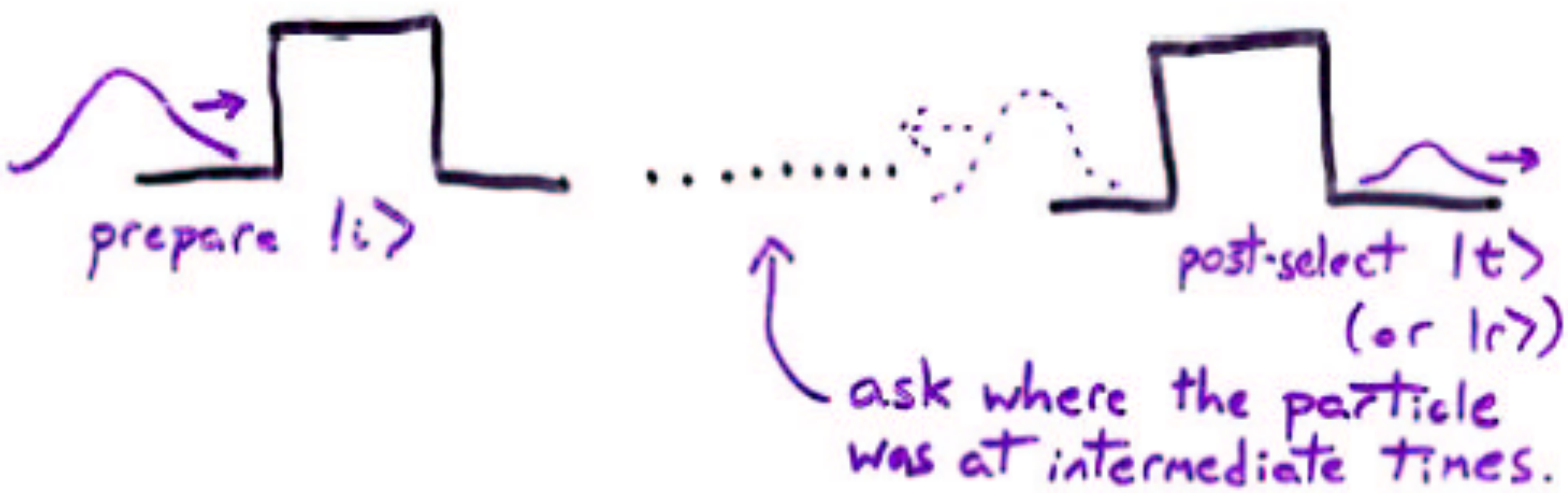


"With weak measurement, you repeat the experiment many times, and the peak of the pointer distribution tells you the value."

Same physicist: "oh, that's not really a *measurement*, because it has such a big uncertainty, and you have to average many trials to get any information."



Conditional probabilities: weak values



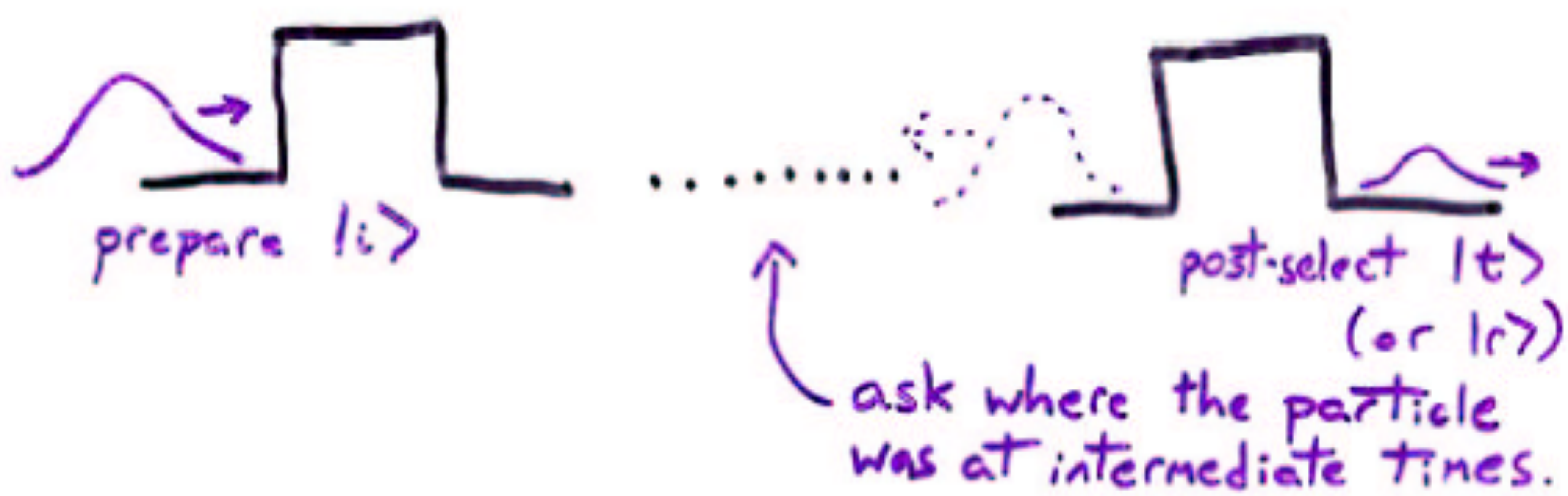
$$P(x) = |\Psi(x)|^2 = \langle\Psi|\underbrace{x\rangle\langle x|}_{\text{Proj}(x)}\Psi\rangle$$

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

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

AMS, PRL 74, 2405 (1995)

Conditional probabilities: weak values



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

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

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

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

AMS, PRL 74, 2405 (1995)

It turns out these *are* weak values, but which hadn't been invented yet. Their Real and Imaginary parts have an unambiguous interpretation.

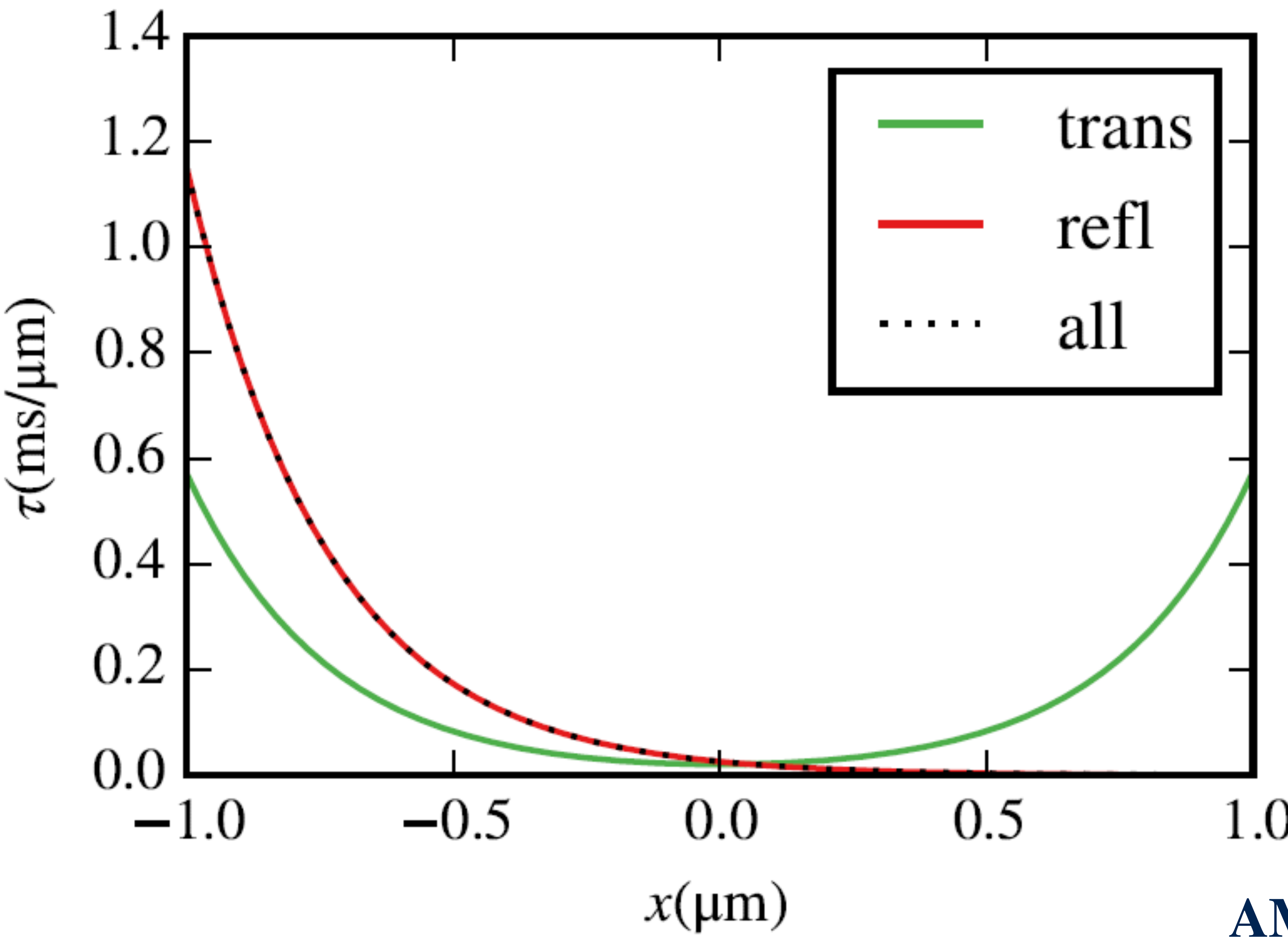
The real part describes the shift in the pointer position (e.g., precession about B)

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)

Where does a particle spend time inside the barrier?



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

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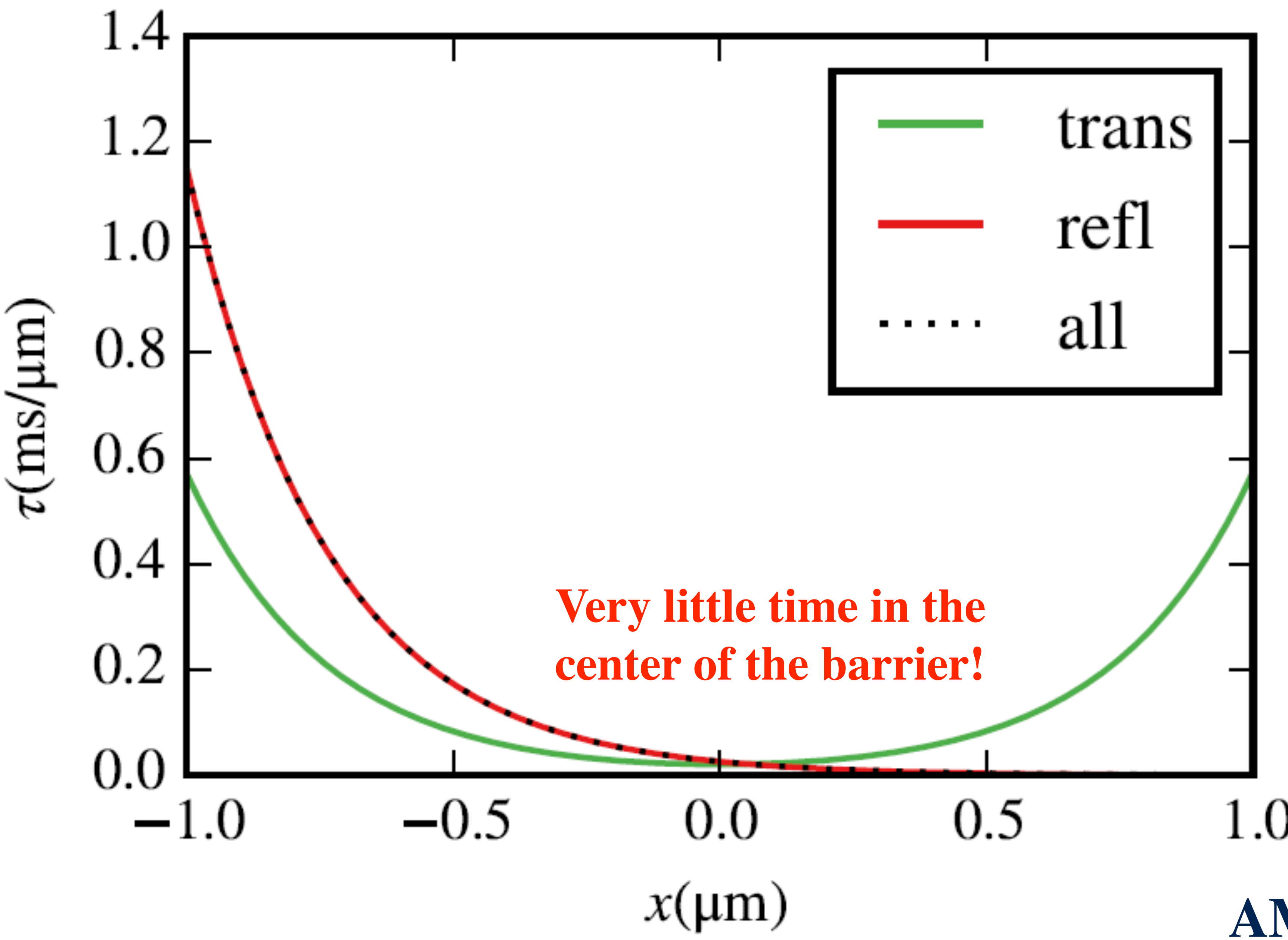

AMS, PRL 74, 2405 (1995)
AMS, PRA 52, 32 (1995)

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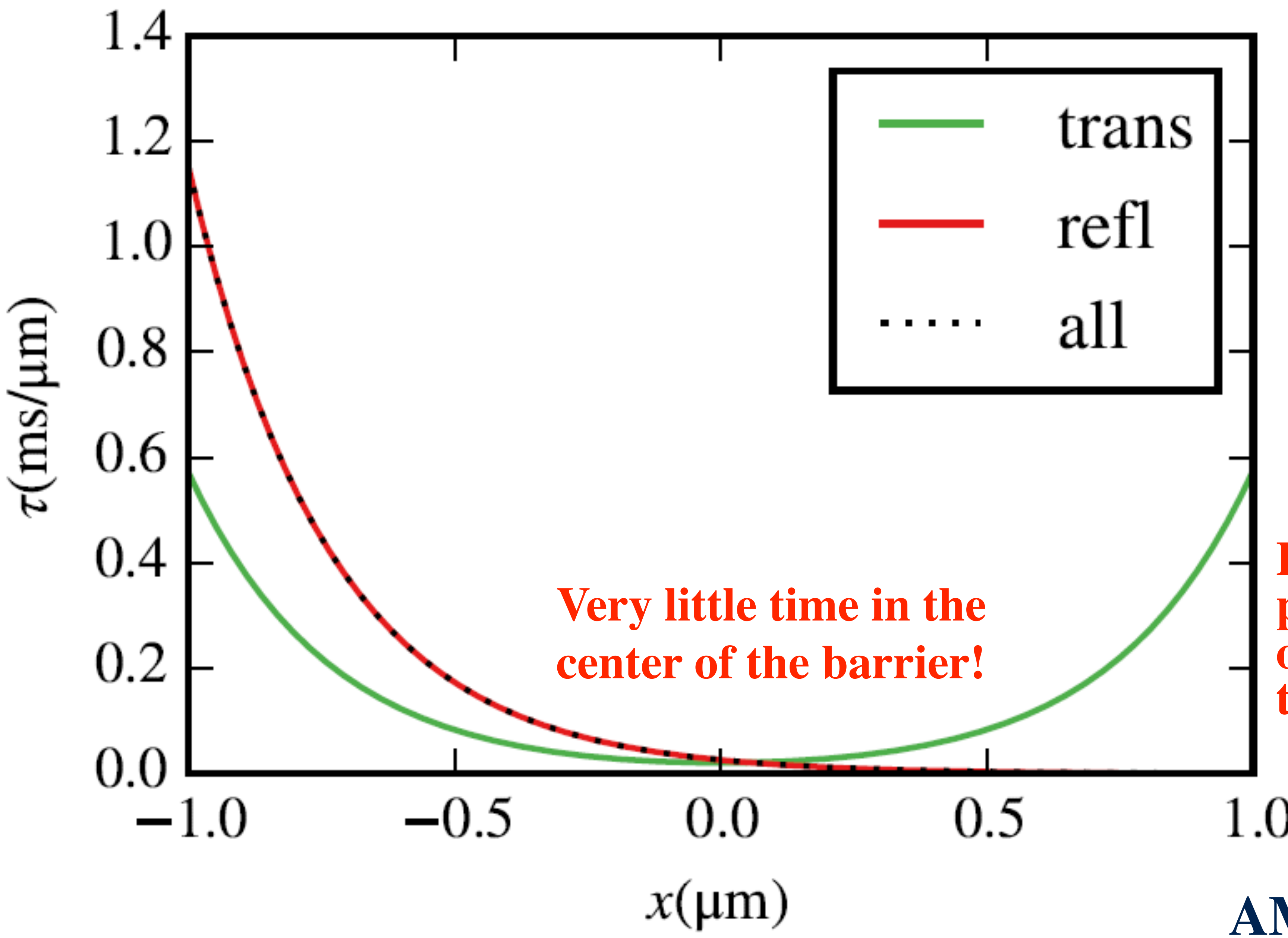
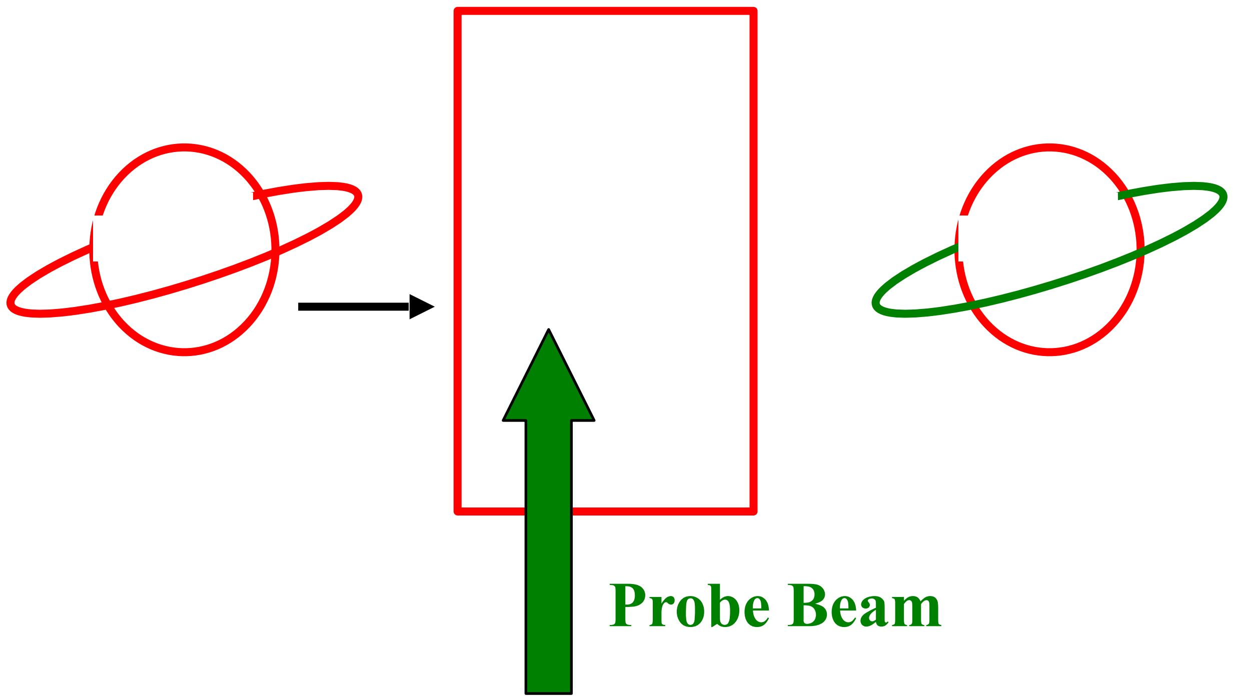


But – unlike the reflected particles – the transmitted ones "see" the region near the exit!

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

How To Measure This?

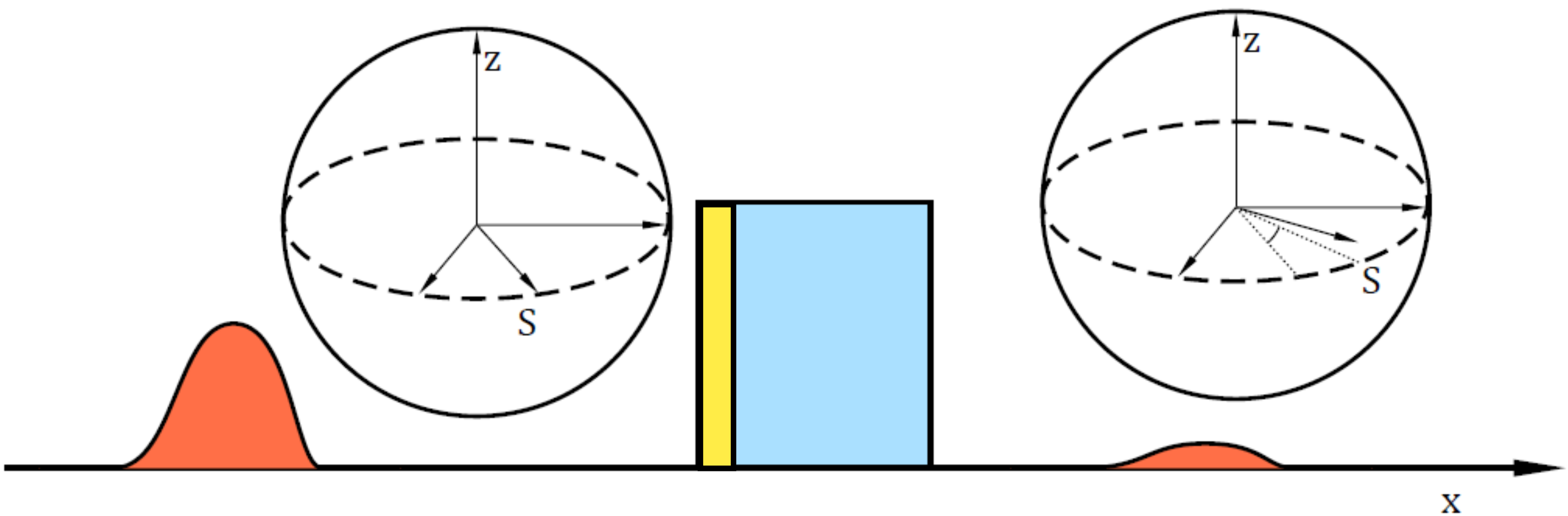
Any interaction localized to the barrier region will do – in fact, the Larmor time turns out to be a special case.



Once atoms can tunnel through micron-scale barriers, we can superpose similar-sized probe beams to use the atoms' internal degrees of freedom as a "clock."

E.g., stimulated Raman coupling of hyperfine/Zeeman levels.

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



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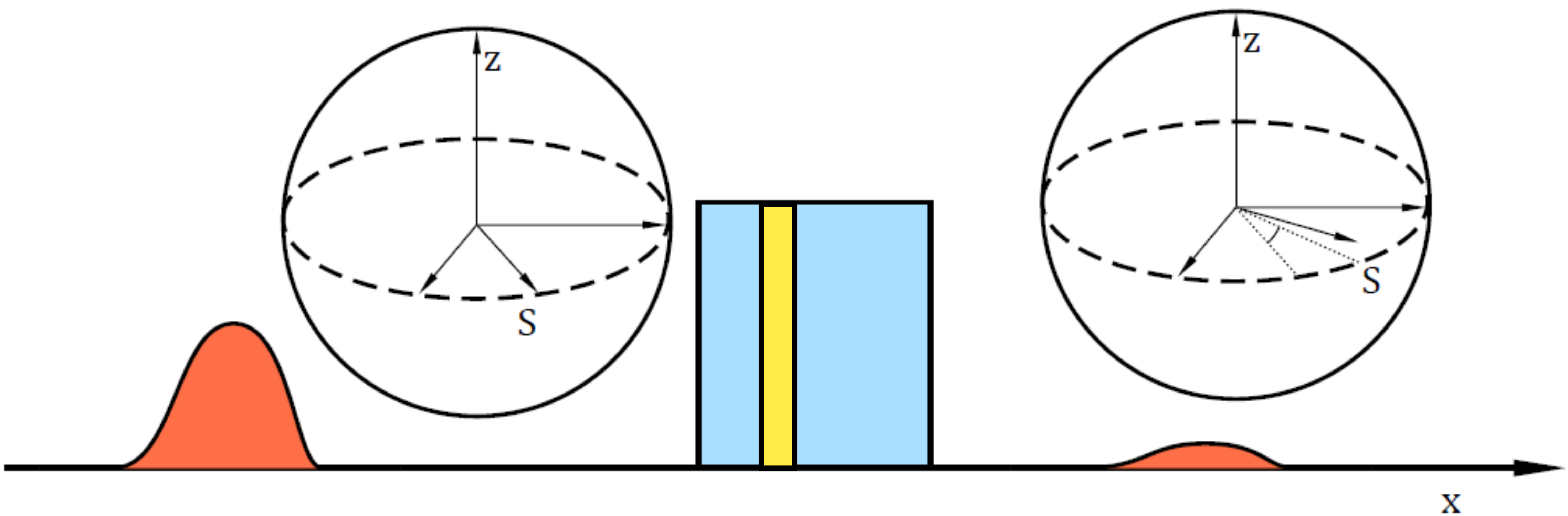

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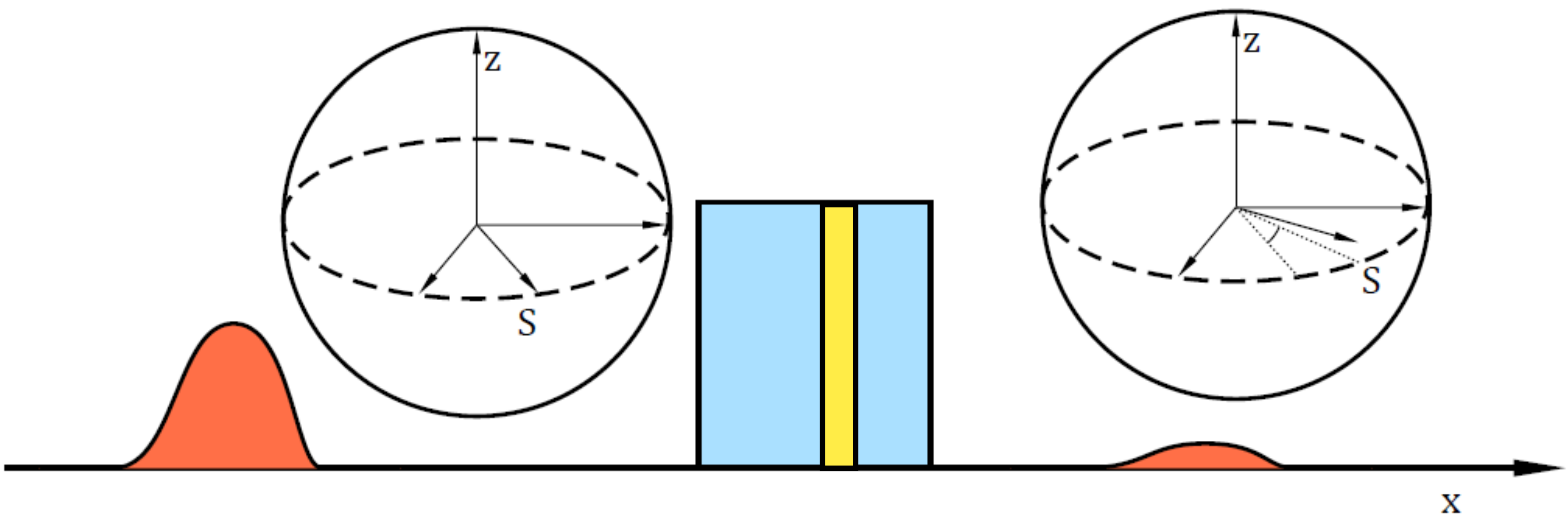

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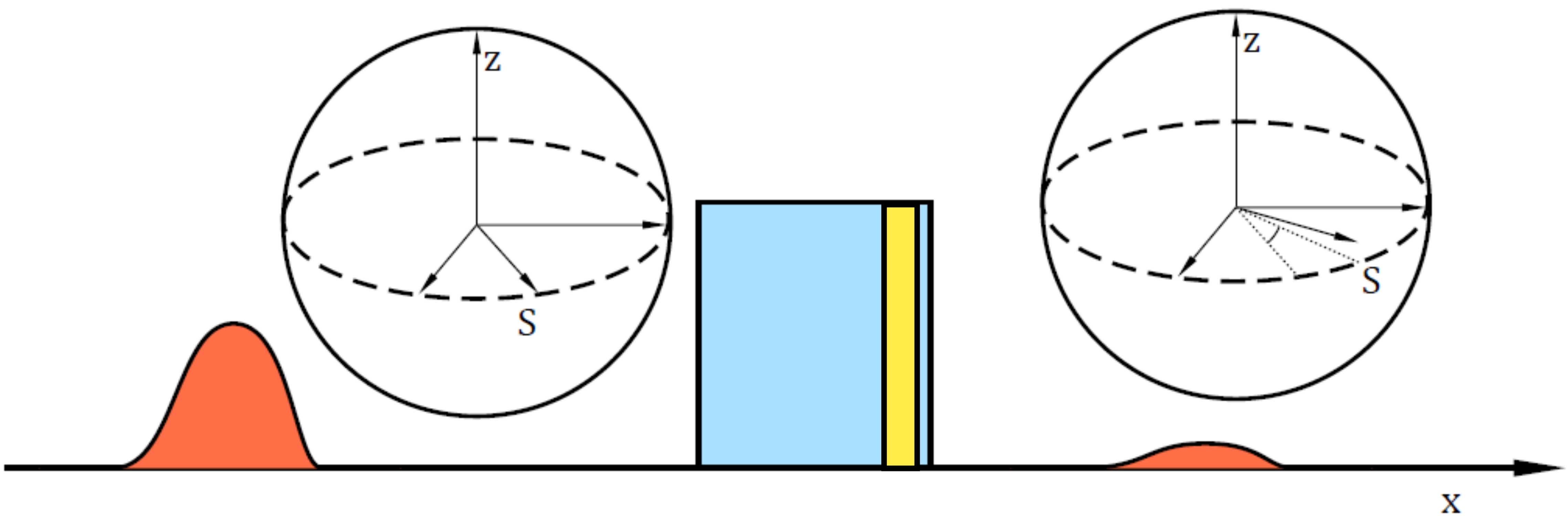
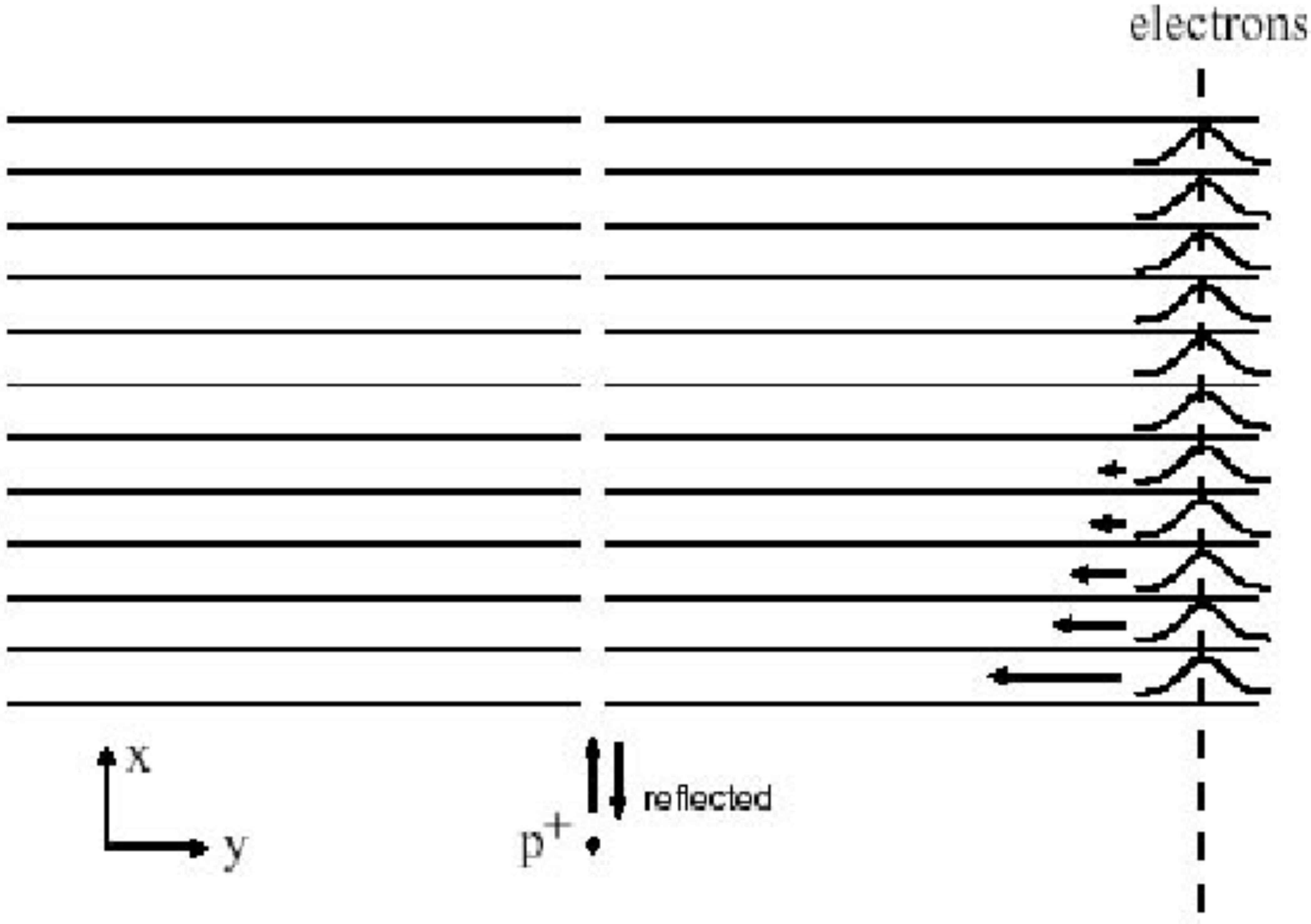
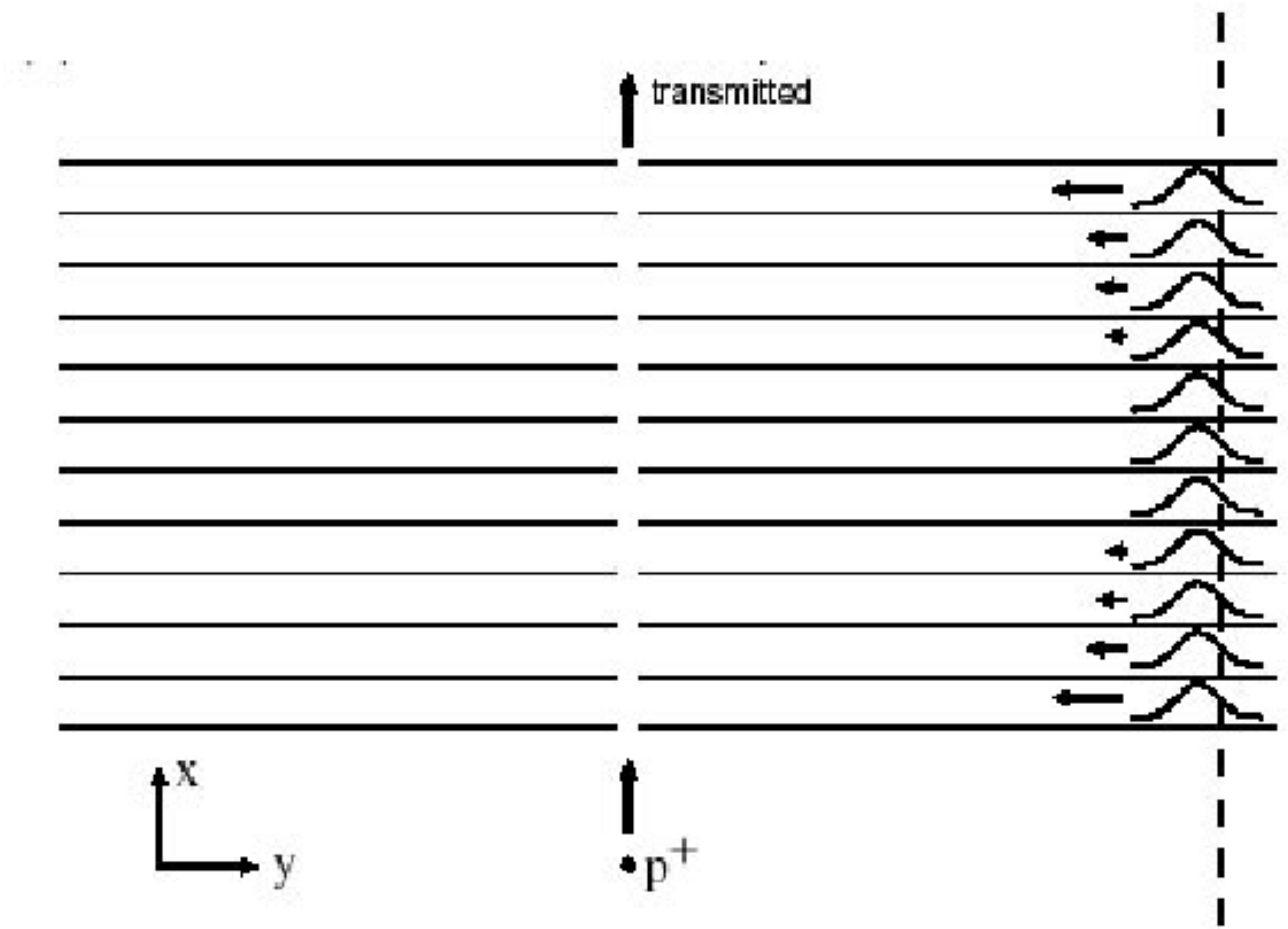


What would this really mean?

a Gedankenexperiment...



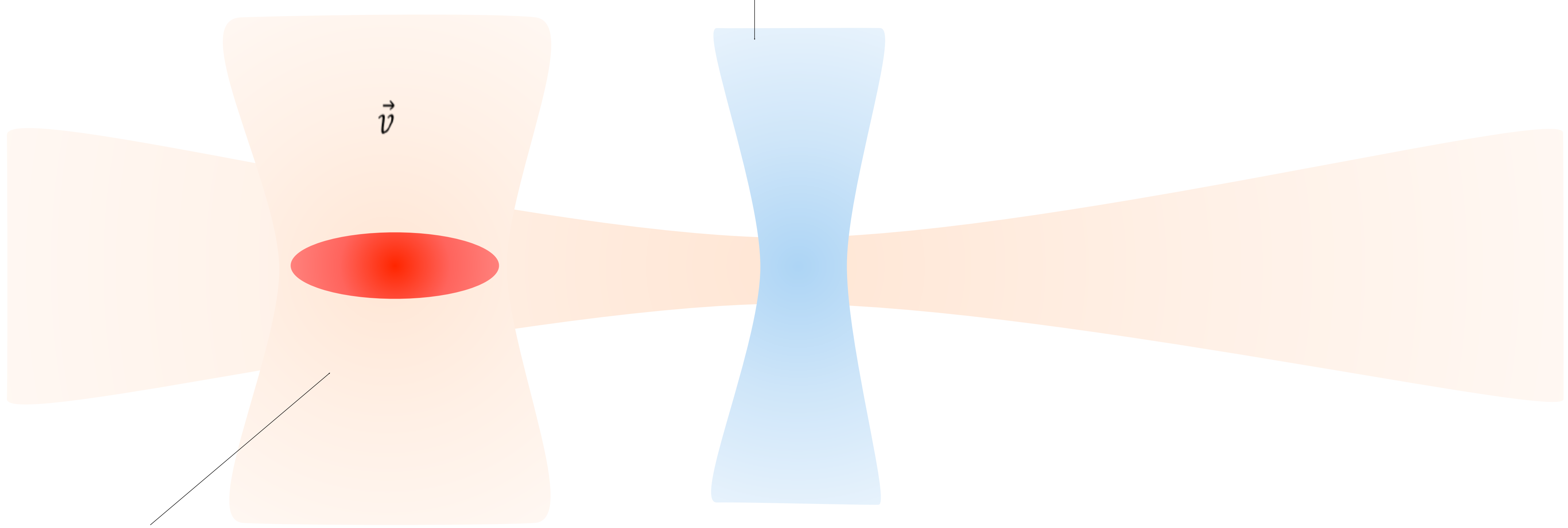
...the flip side



AMS, PRA 52, 32 (1995)

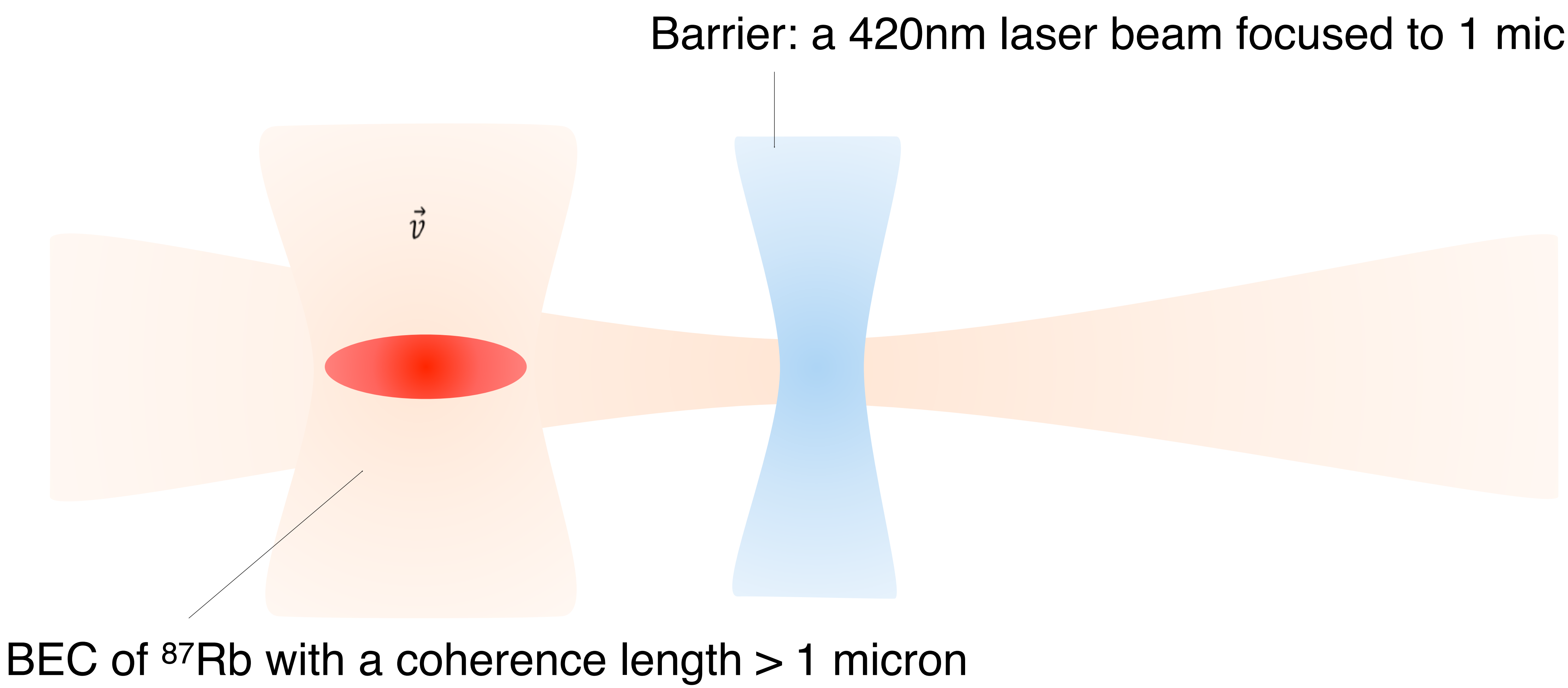
What is the tunnel barrier?

Barrier: a 420nm laser beam focused to 1 micron



BEC of ^{87}Rb with a coherence length > 1 micron

What is the tunnel barrier?

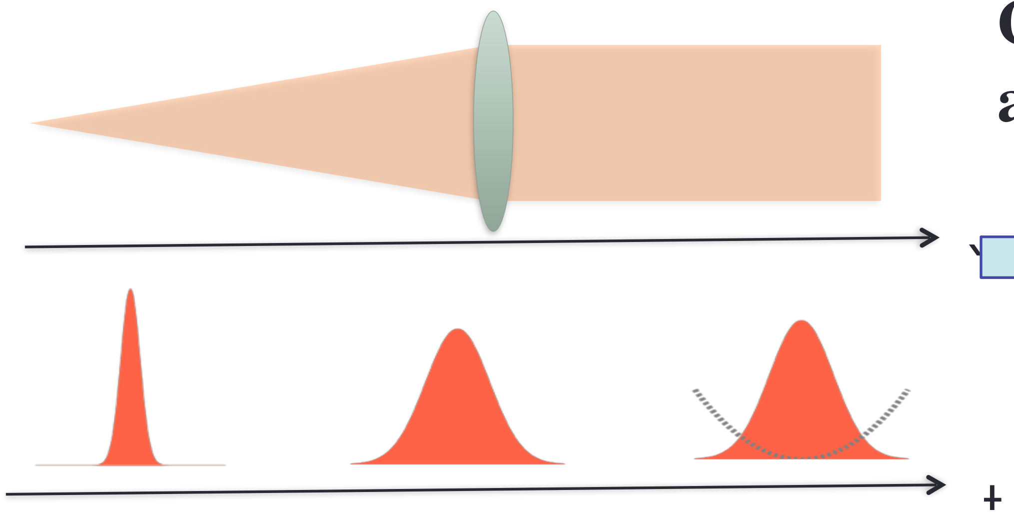


The blue-detuned beam acts like a repulsive potential for the atoms.

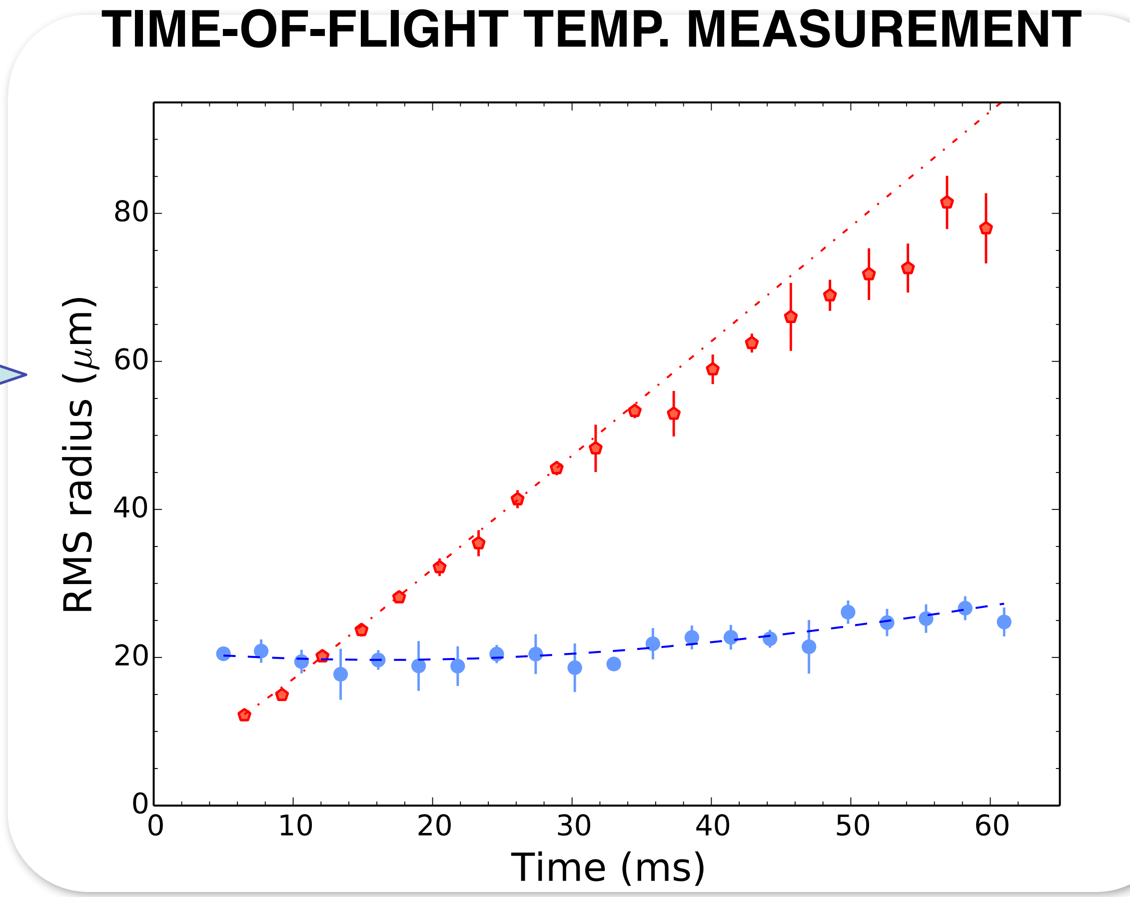
Barrier height of about 150 nK >> 1nK temperature of the atoms (corresponding to a critical incident velocity of about 4 mm/s).

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



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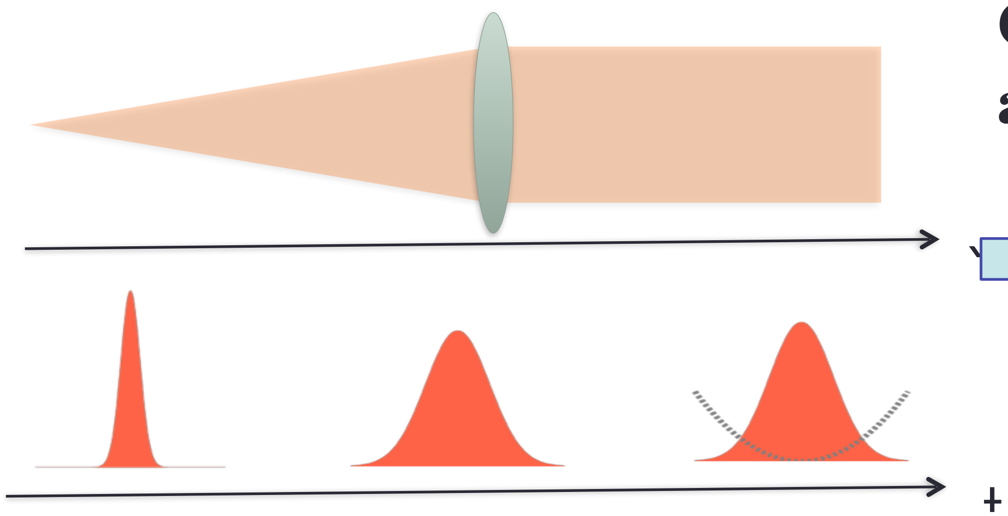

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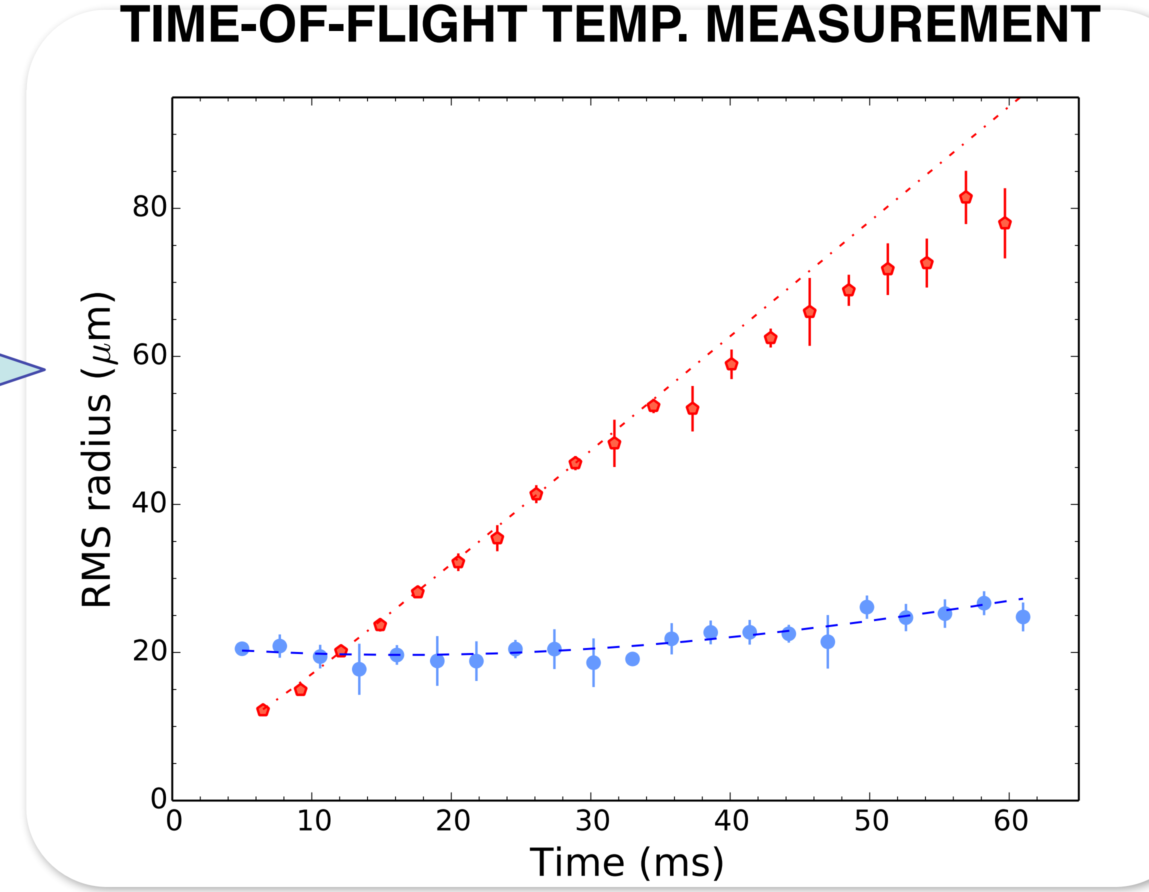
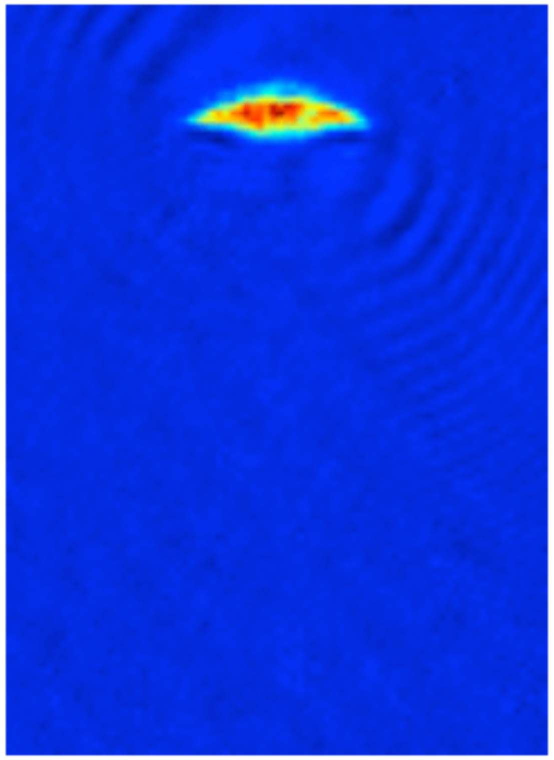
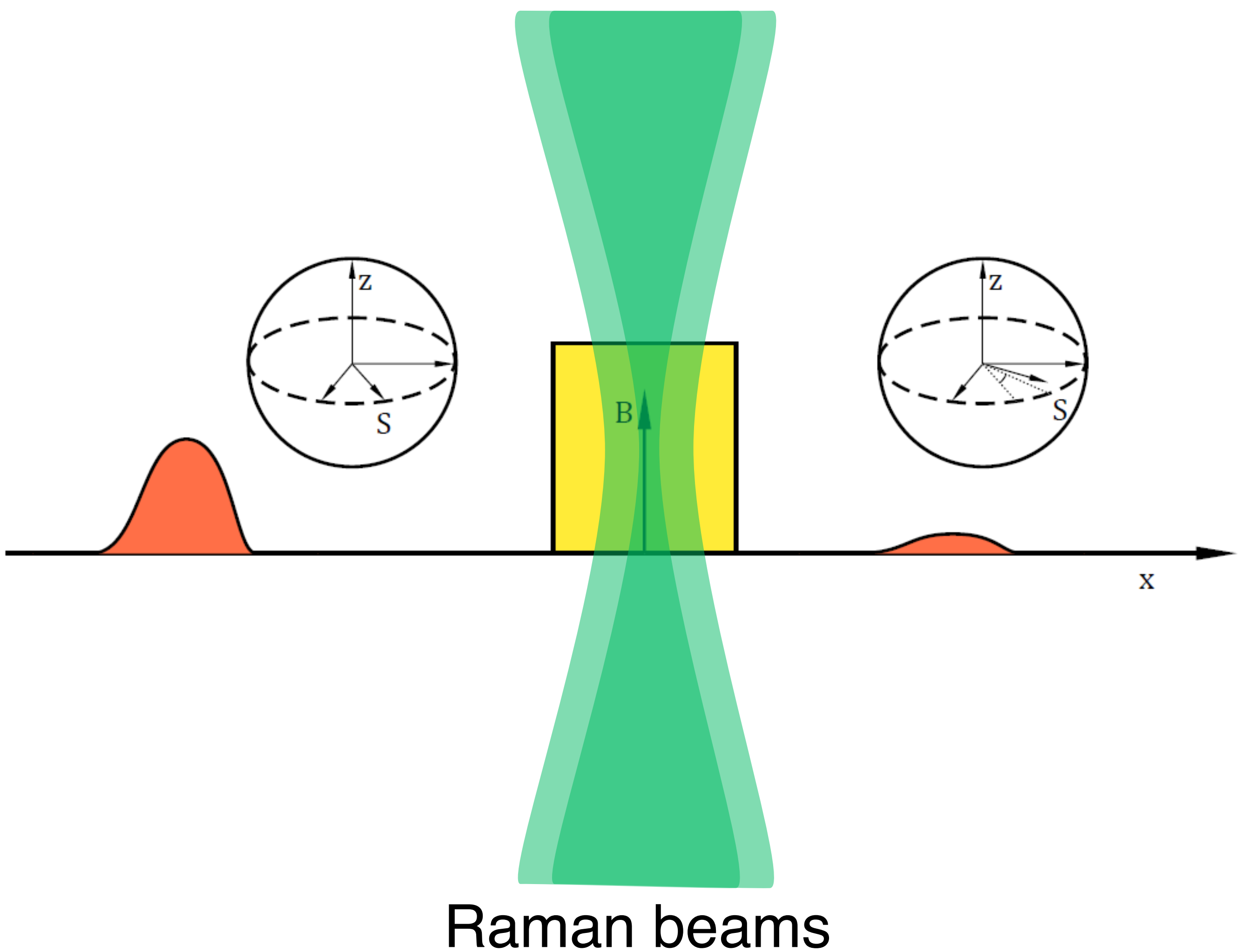


Then fire them (slowly) at a barrier made of a focussed blue-detuned laser beam:



What is the probe?

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



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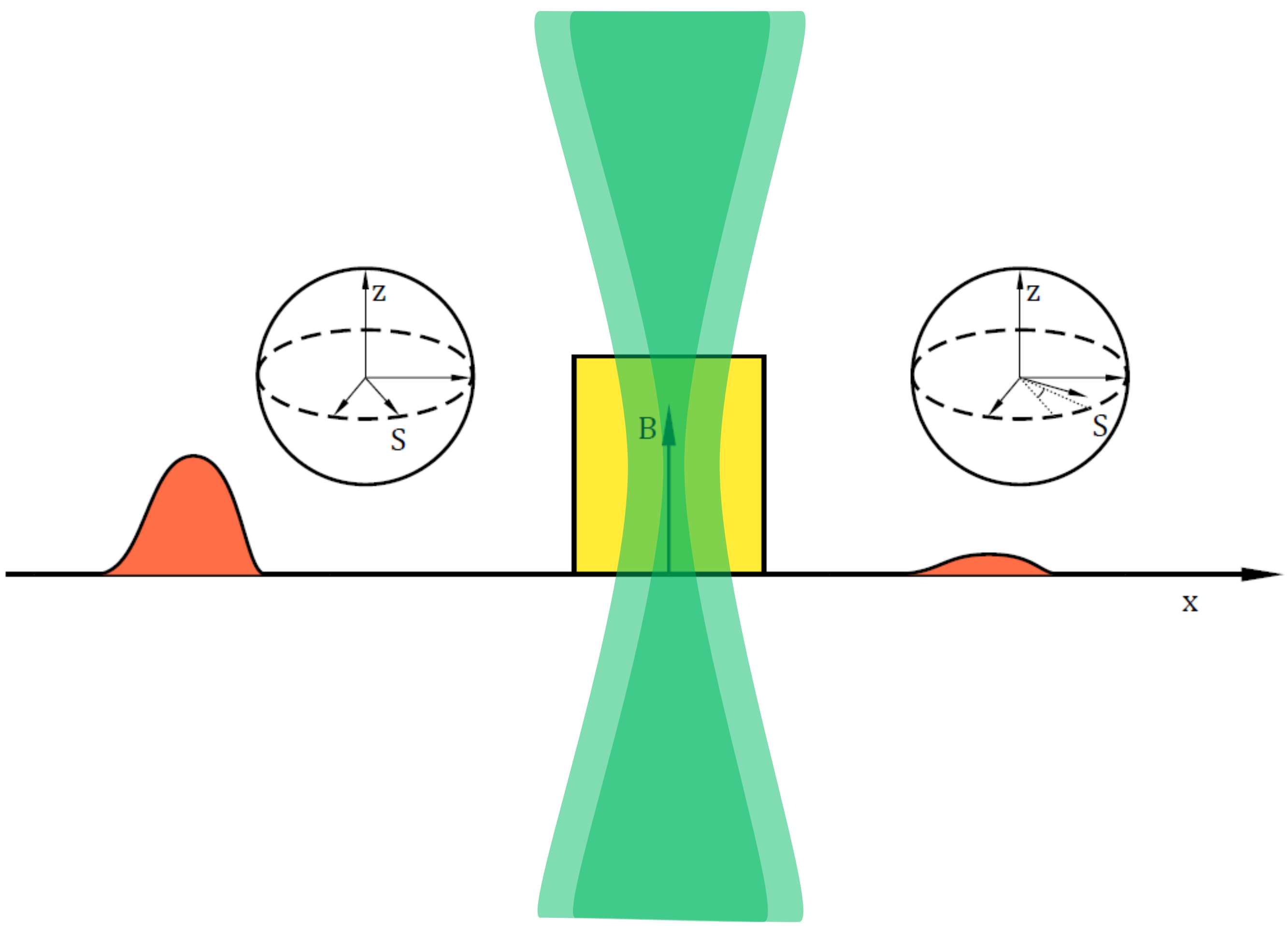
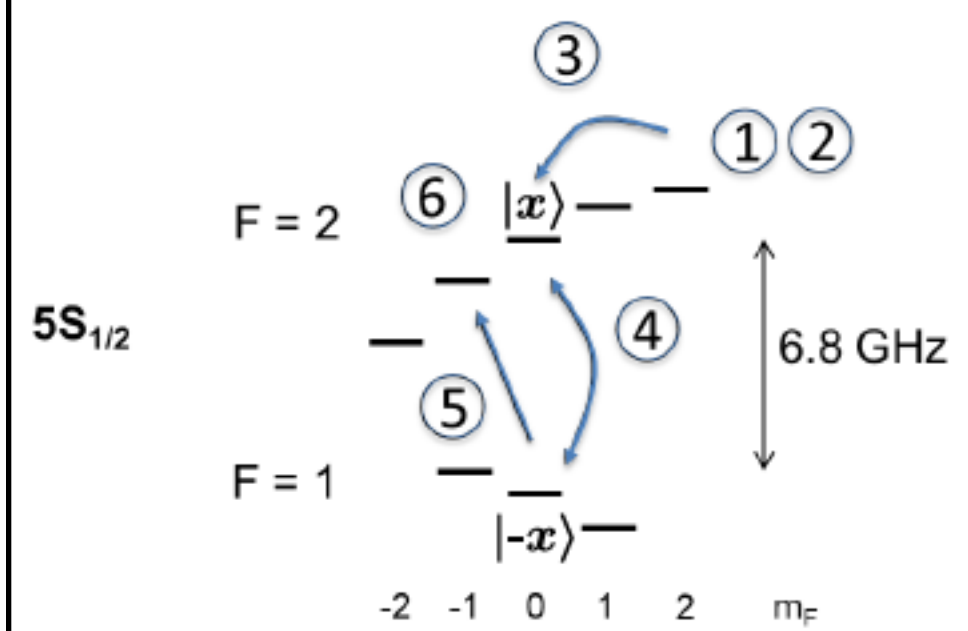


Raman beams

USE m=0 “clock states” of F=1 and F=2 ground states as our two-level system



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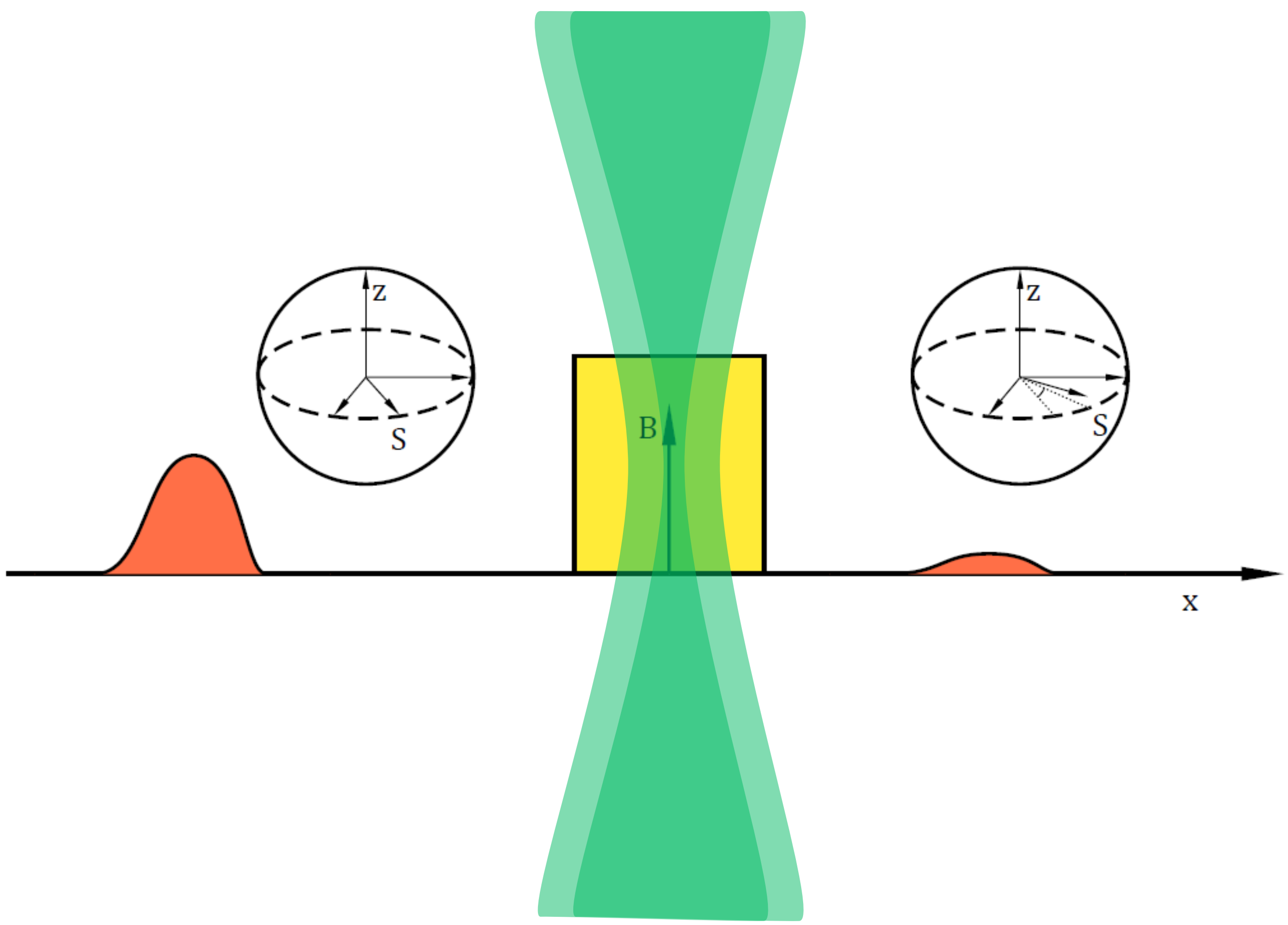
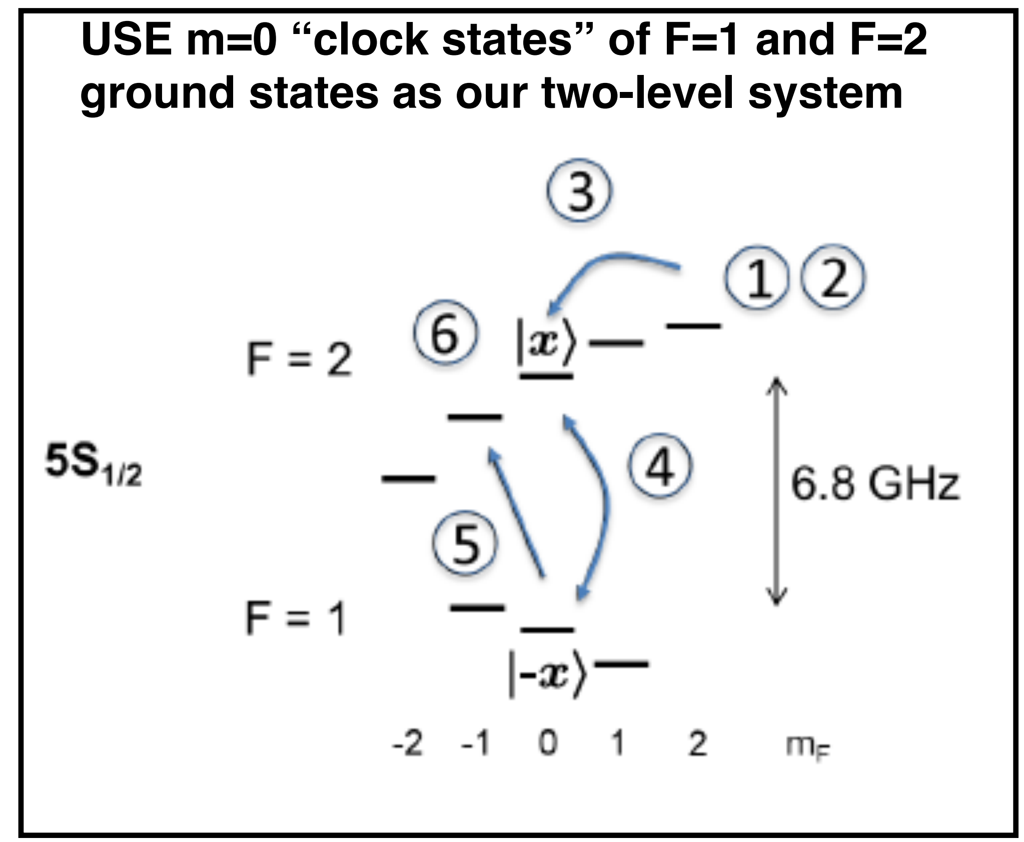


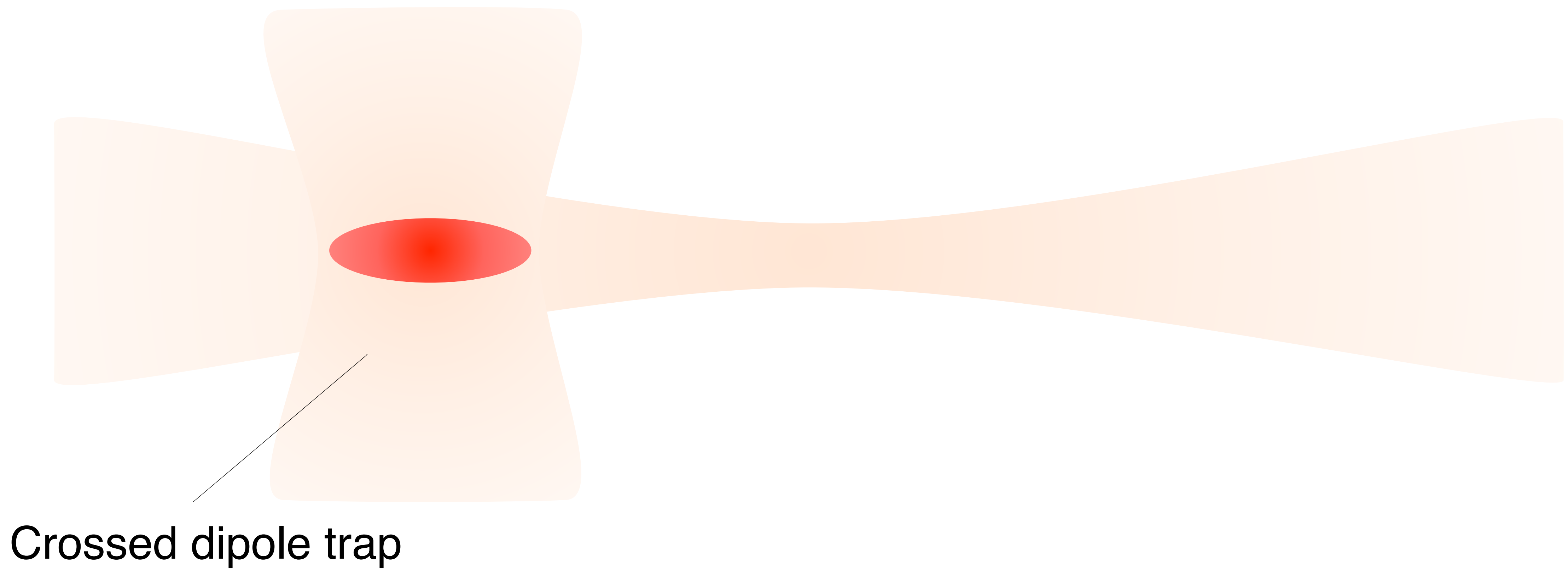
Raman beams



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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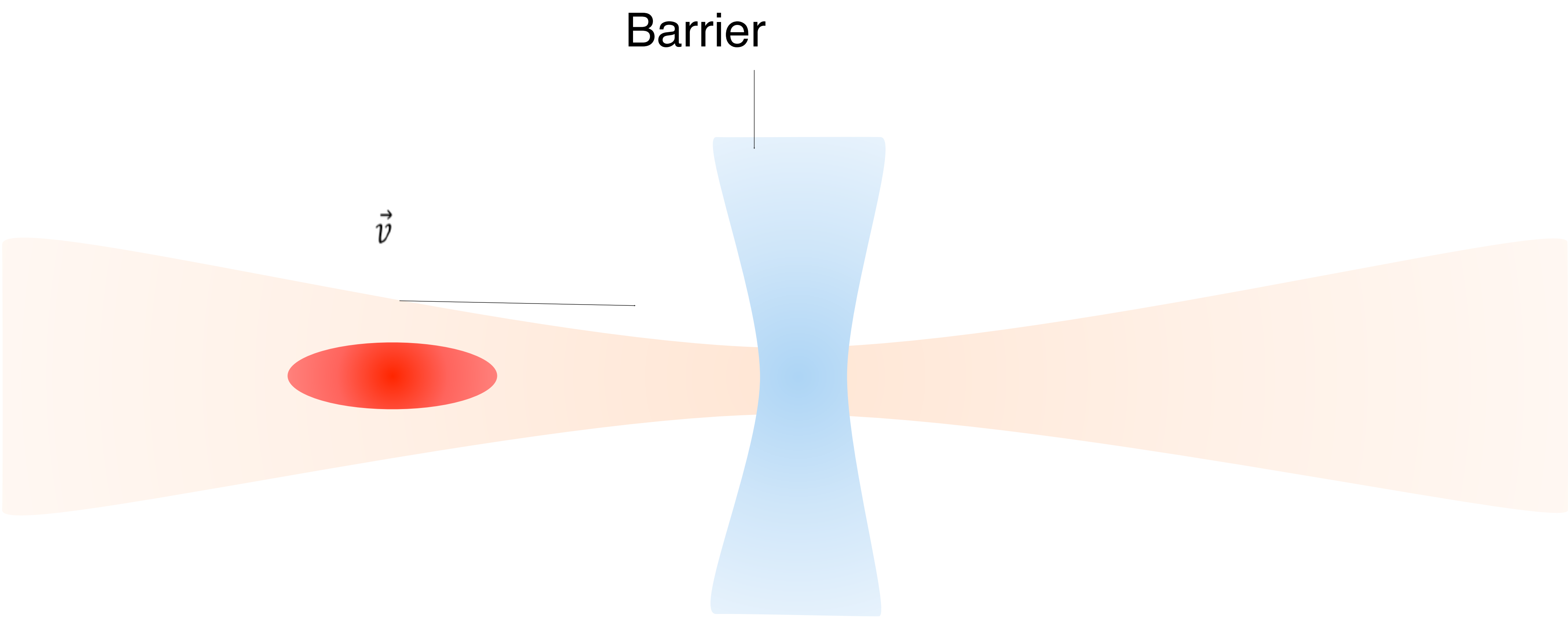

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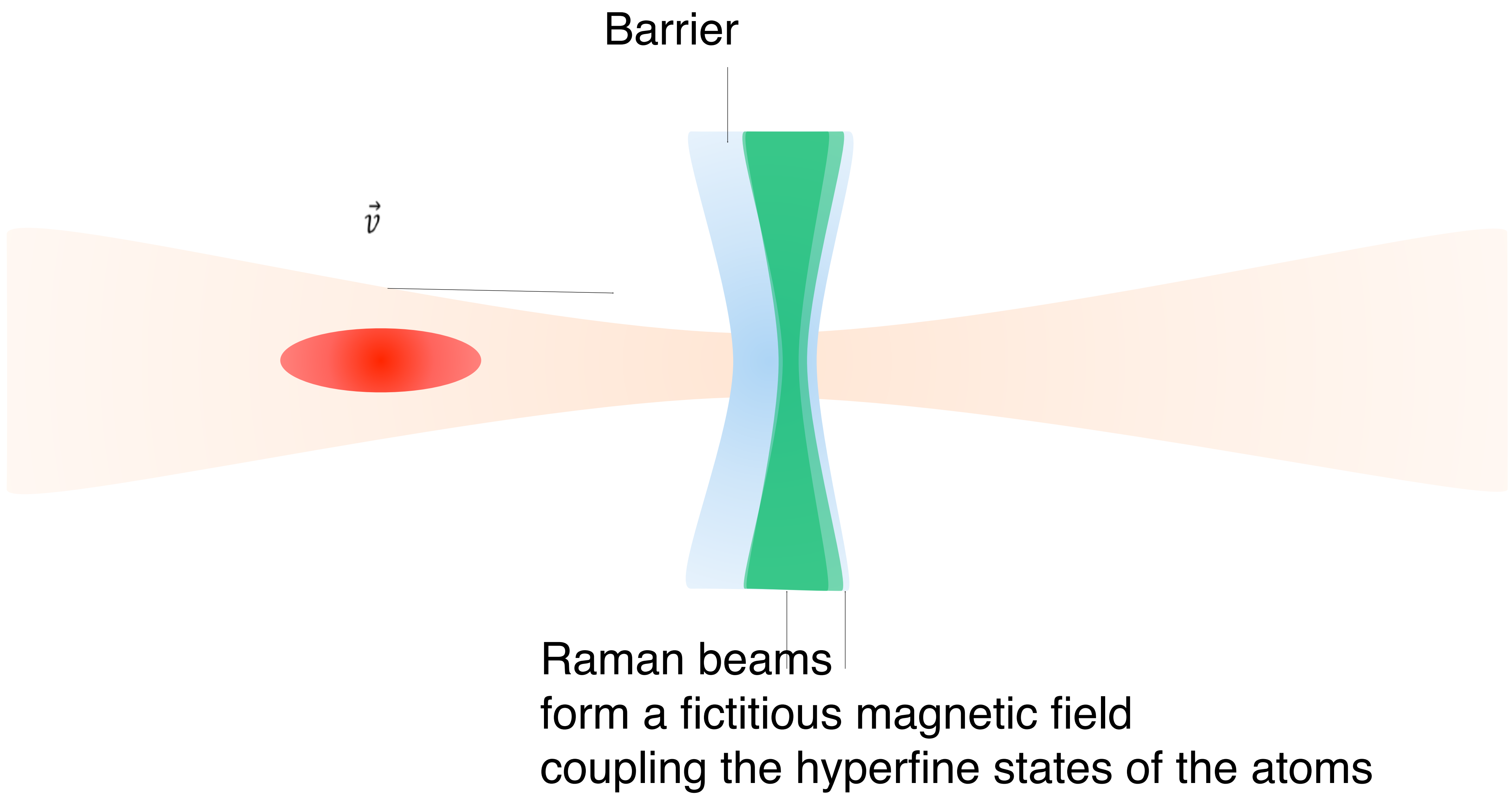

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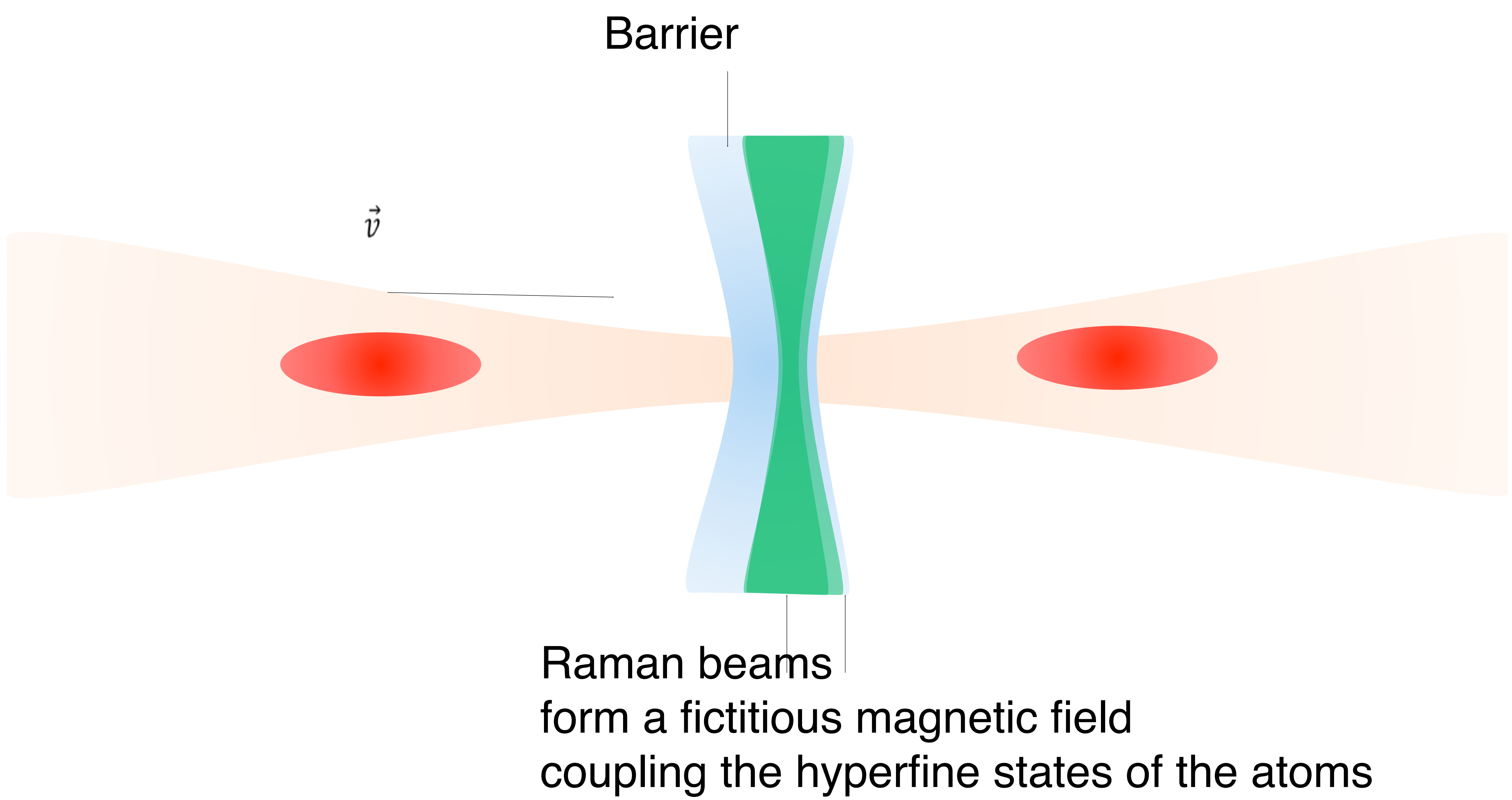

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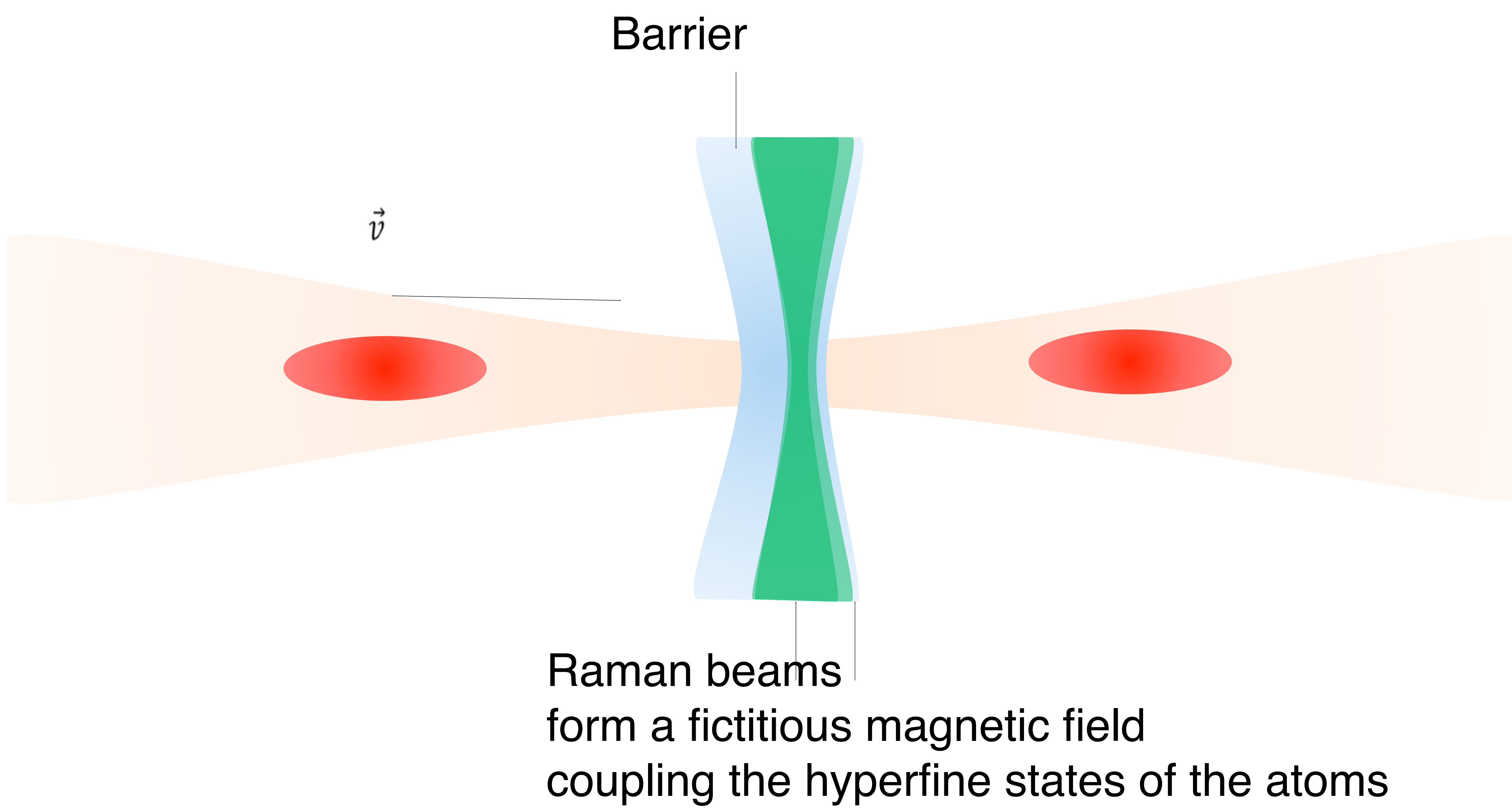

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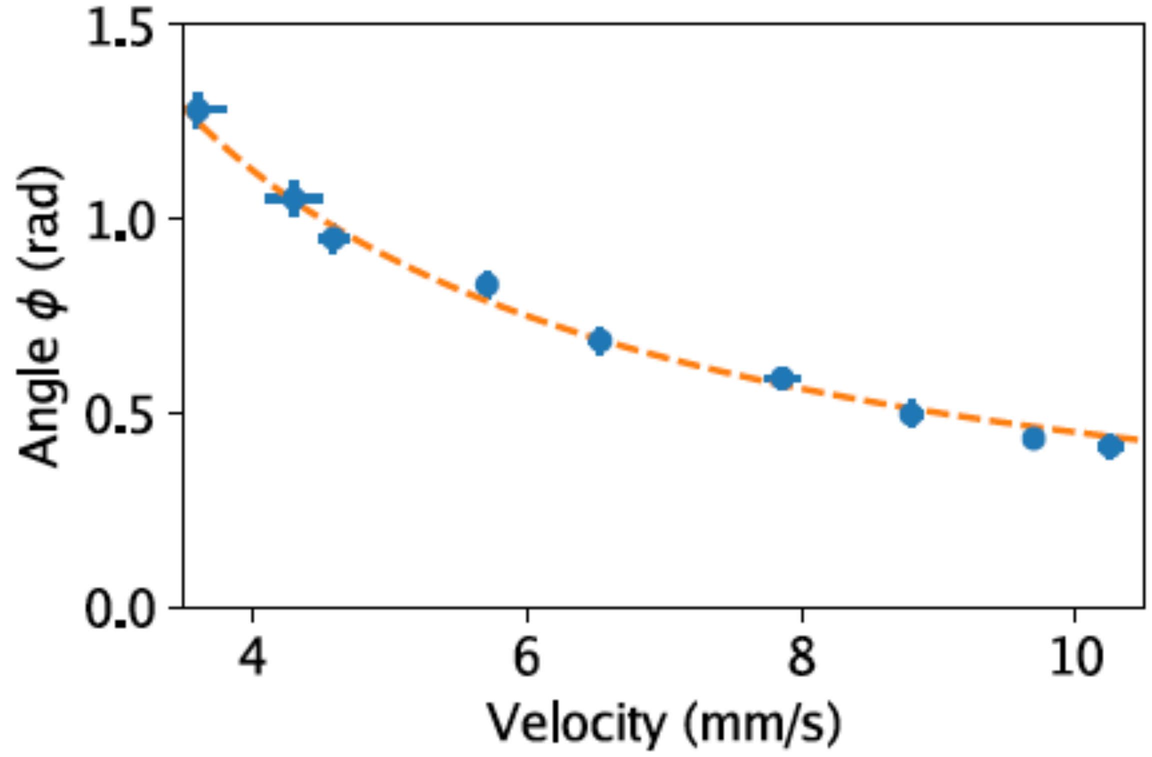
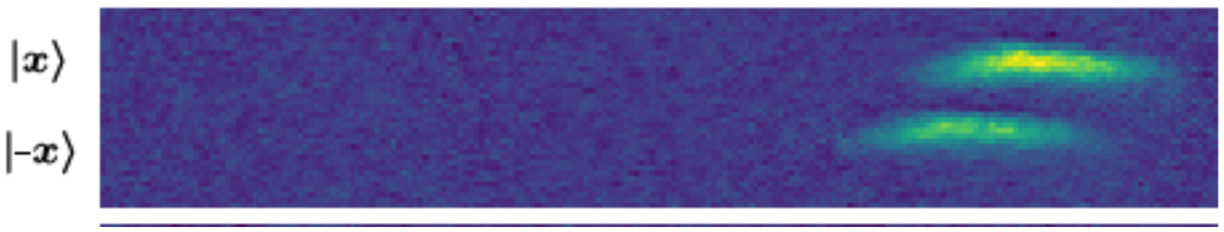
Calibrating the Larmor clock on a free wavepacket:



Stern-Gerlach measurement of precession:



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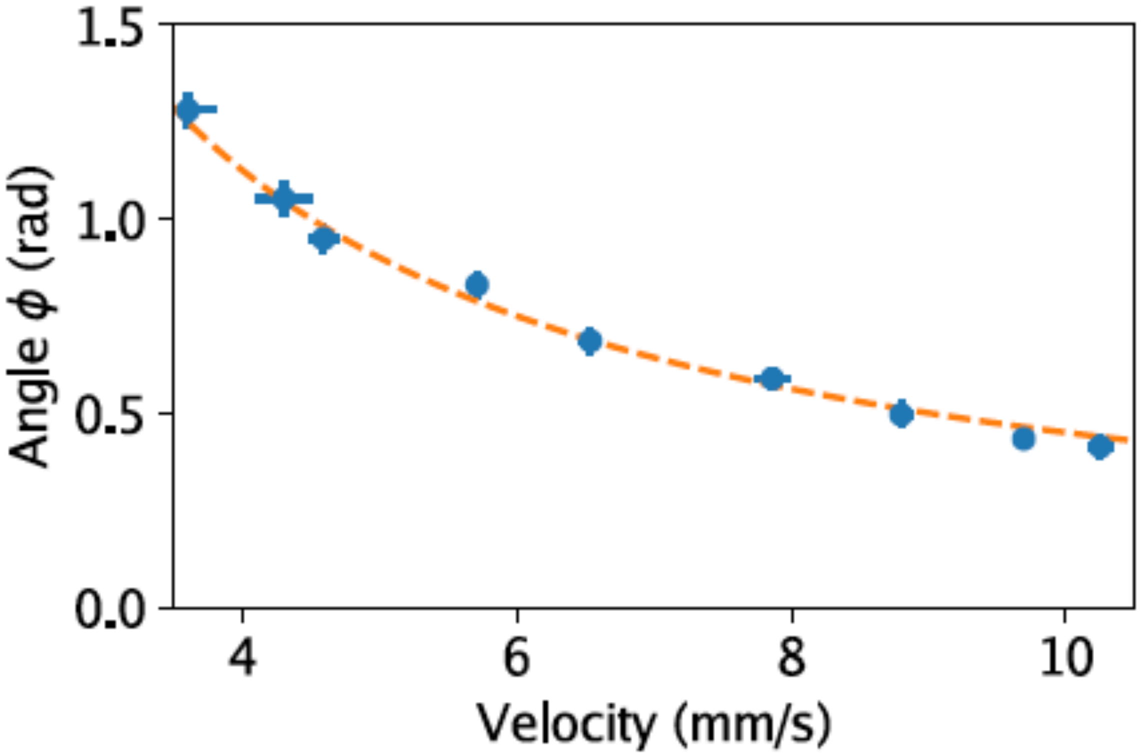
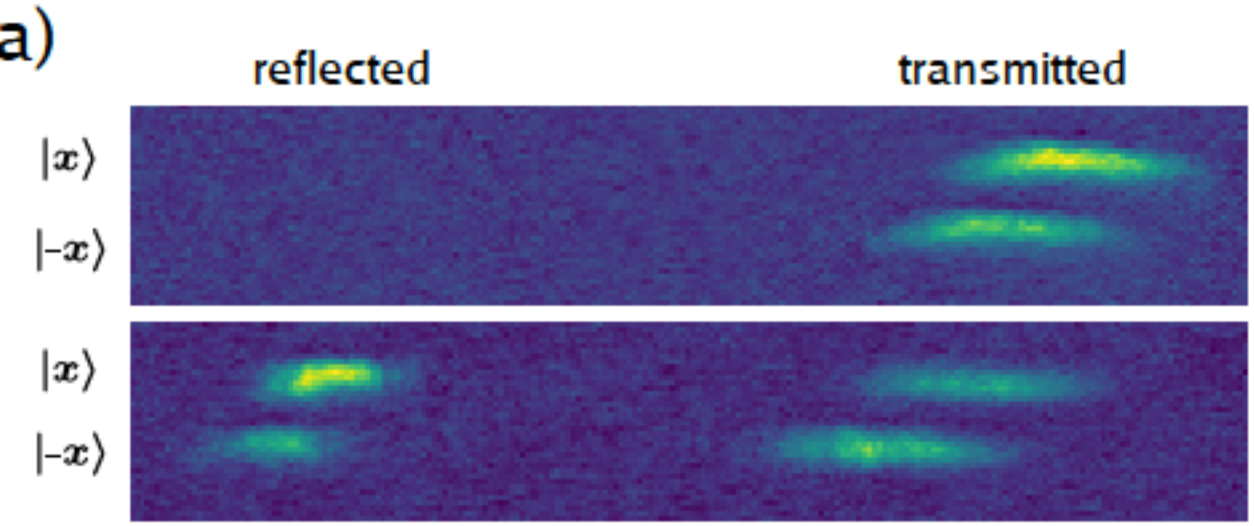


Raw images (no barrier; barrier close to E) :



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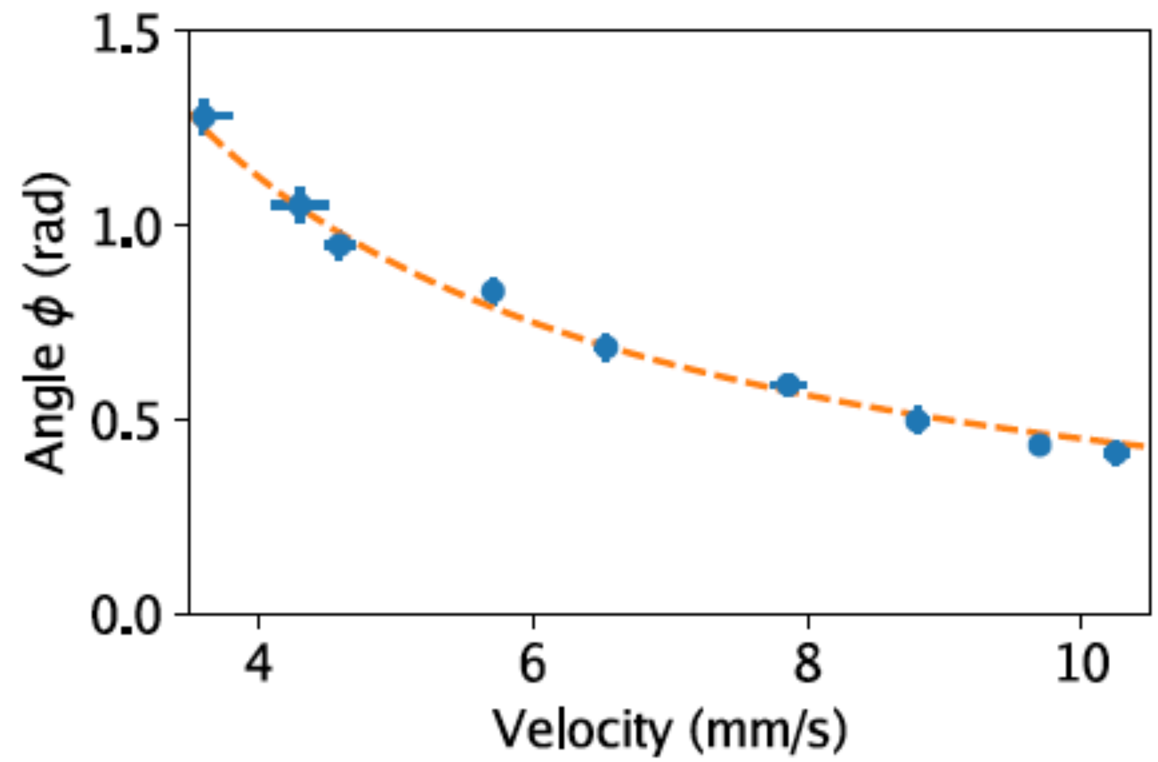

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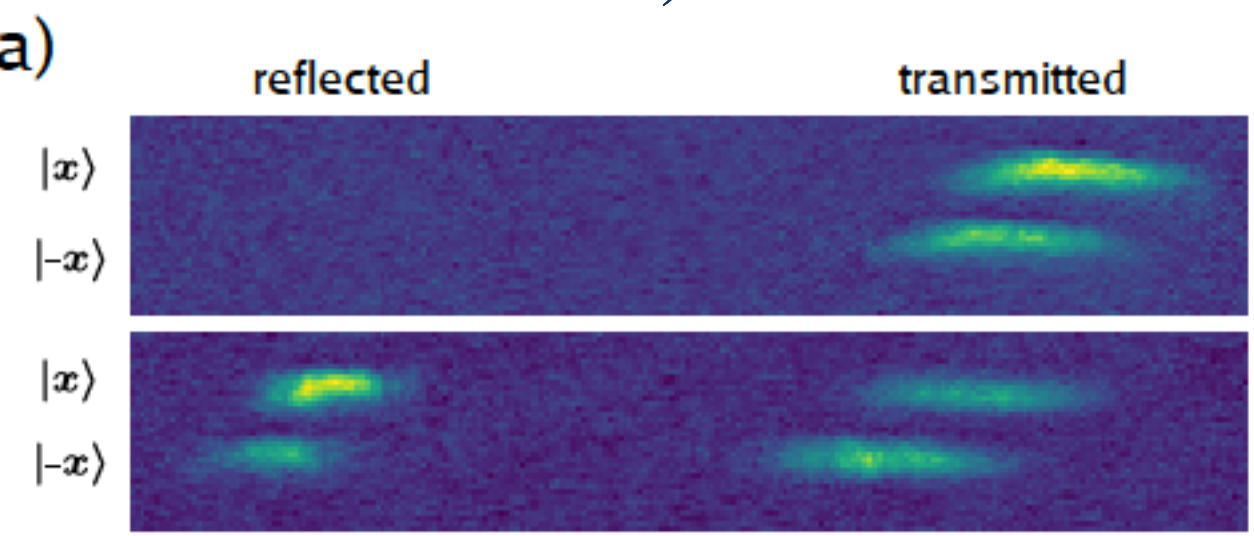
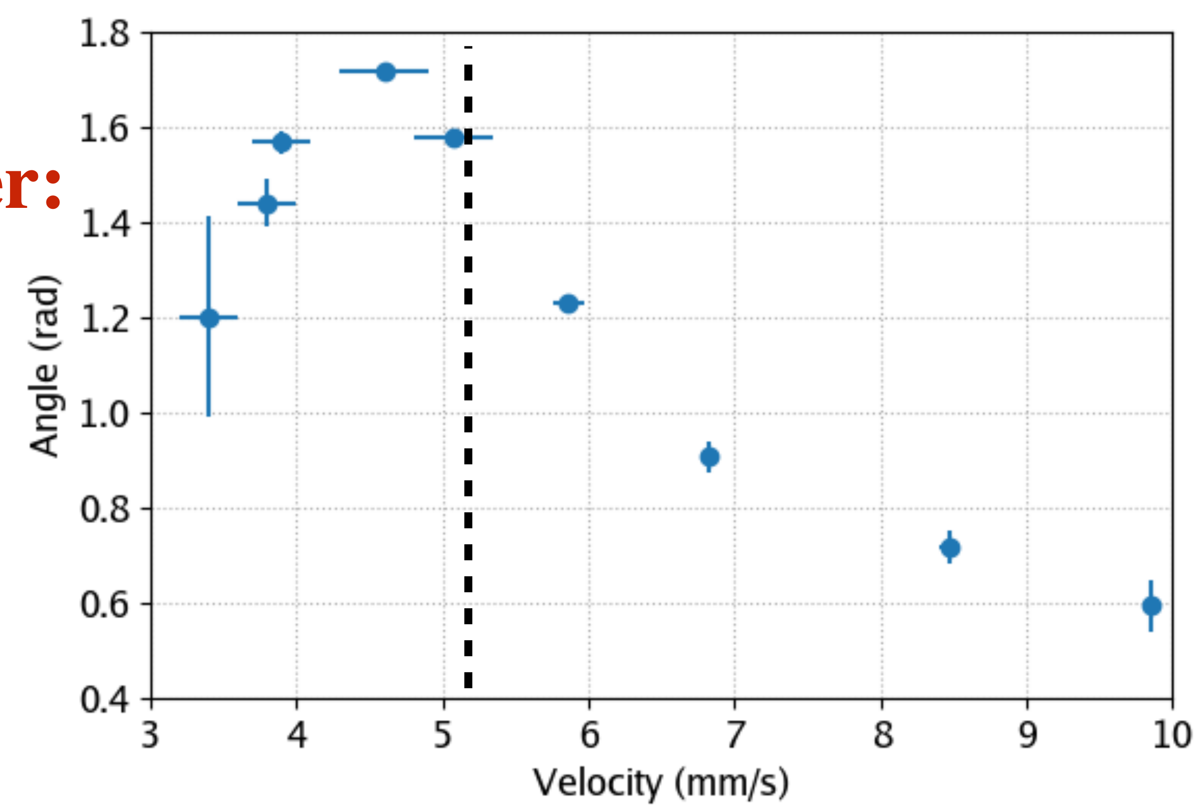


Early precession data with barrier:

(Take w/ grain of salt)



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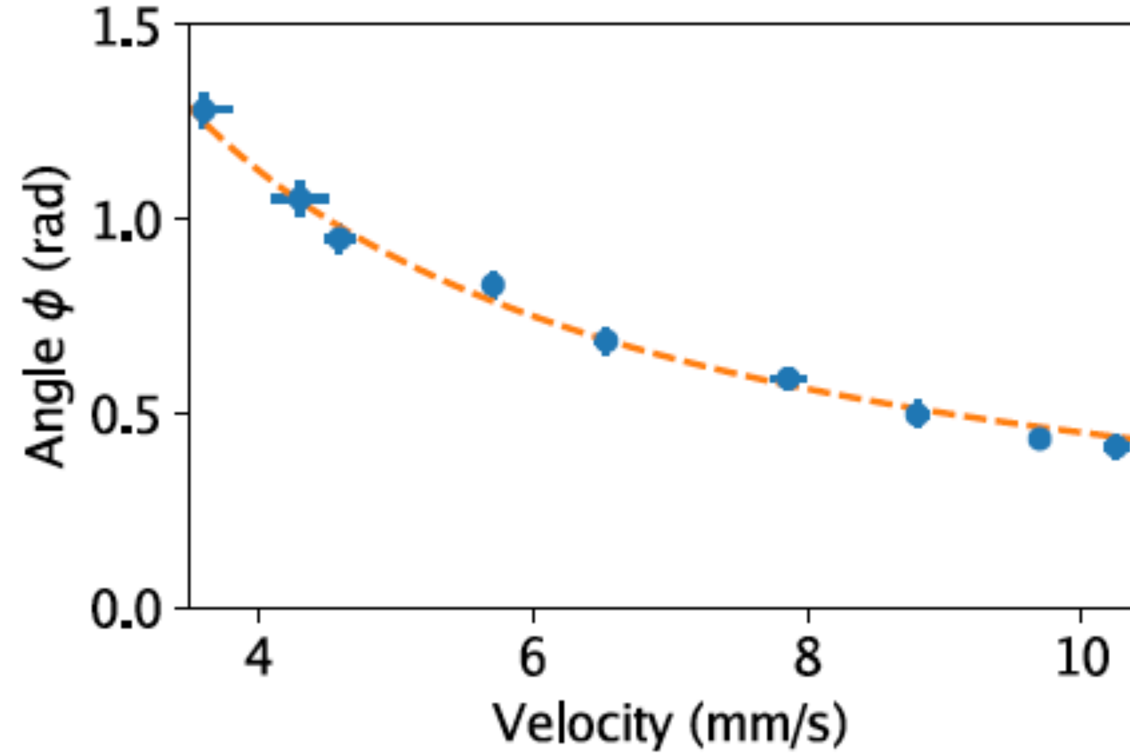

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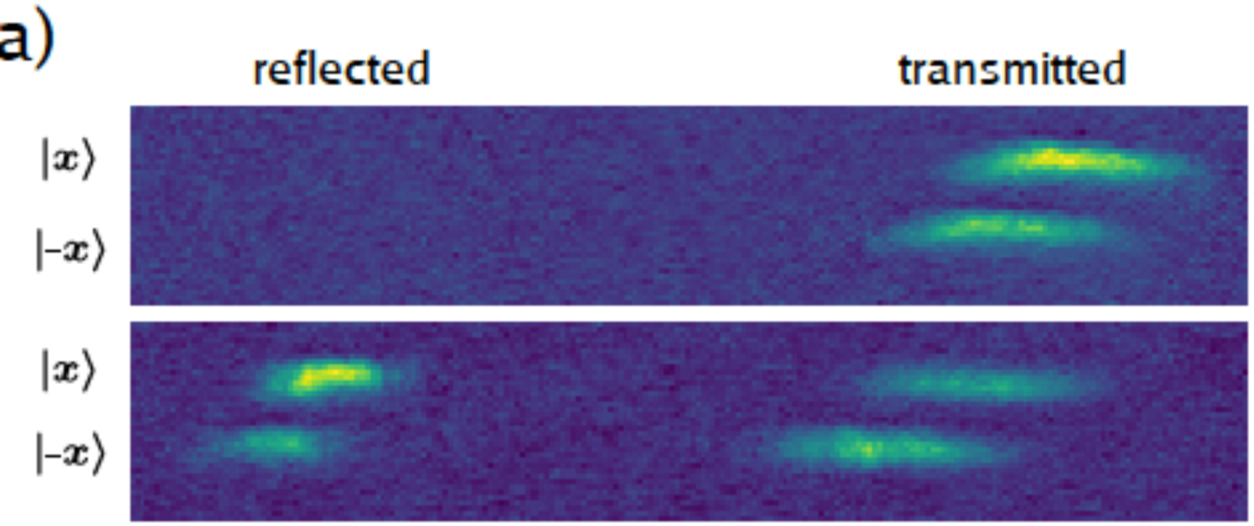
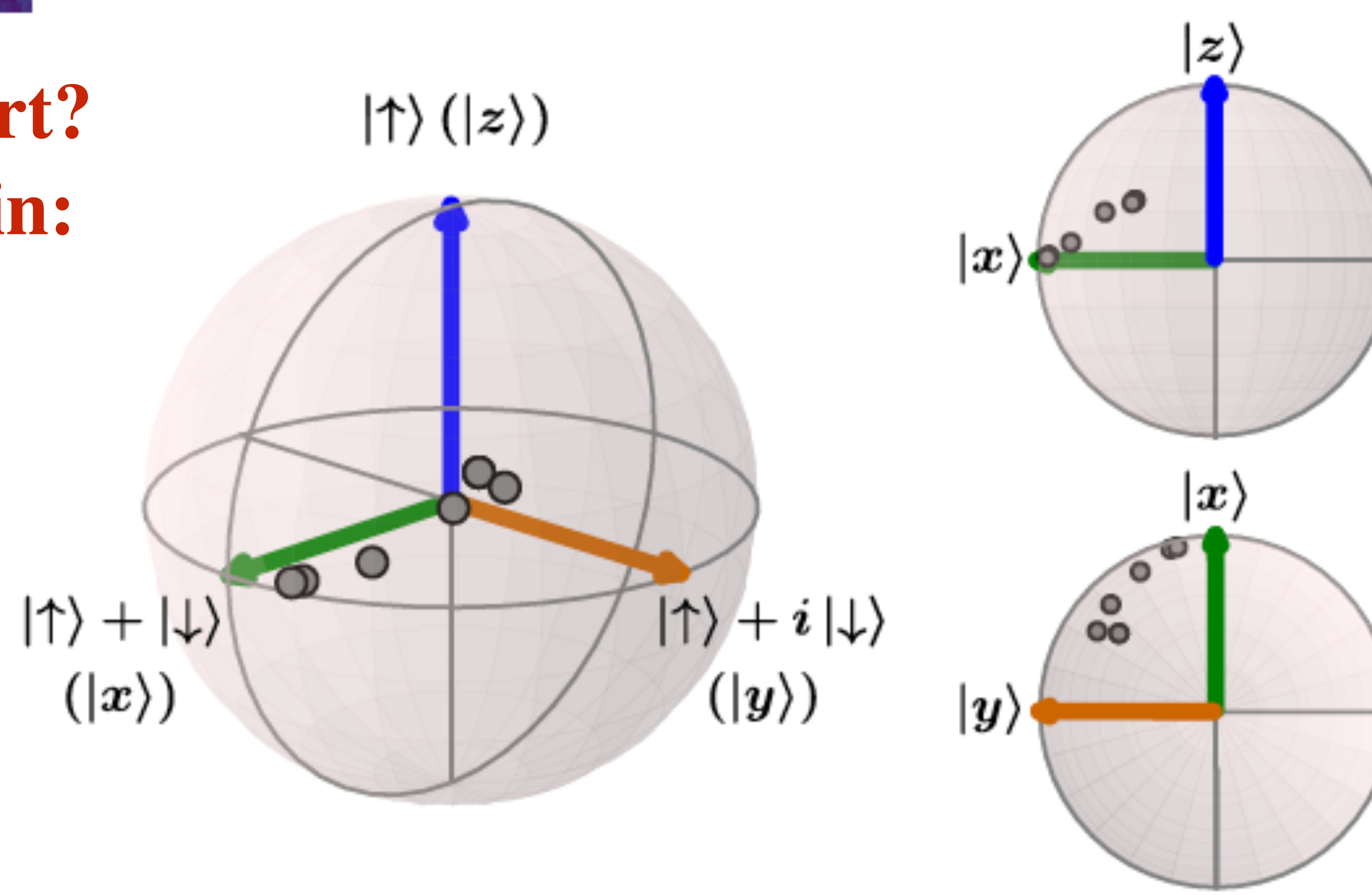
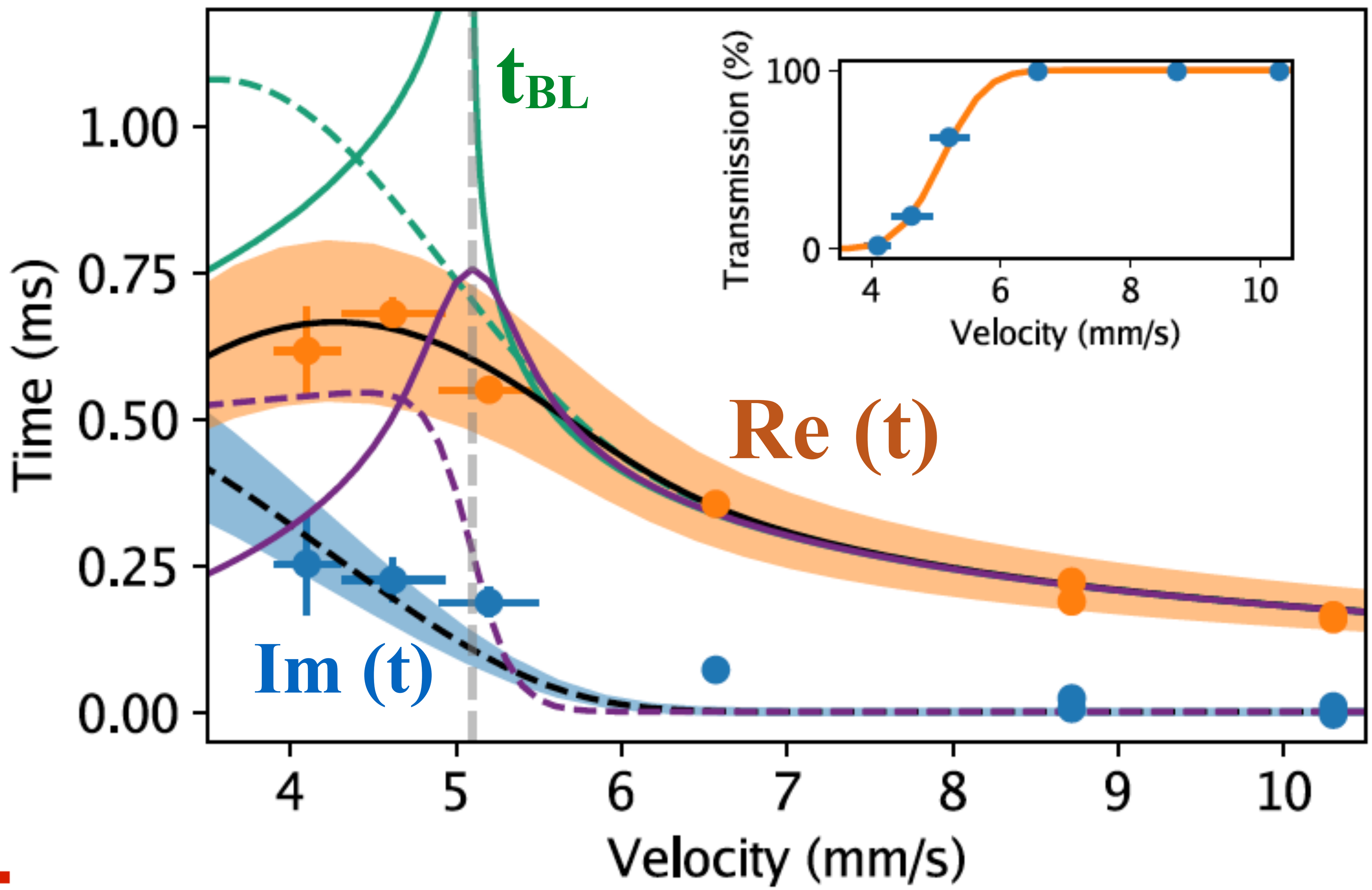


What of the imaginary part? Do full tomography on spin:



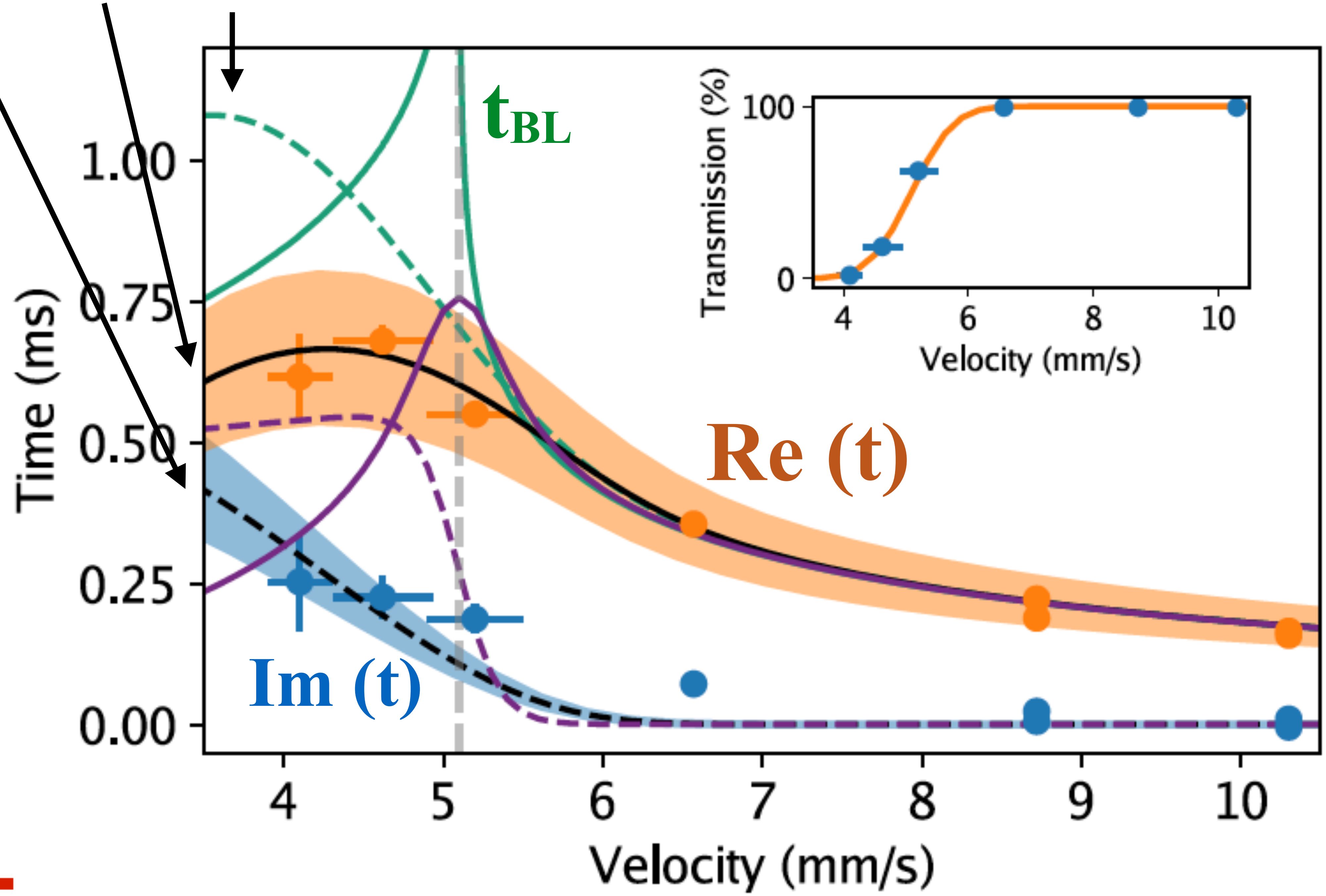
The results



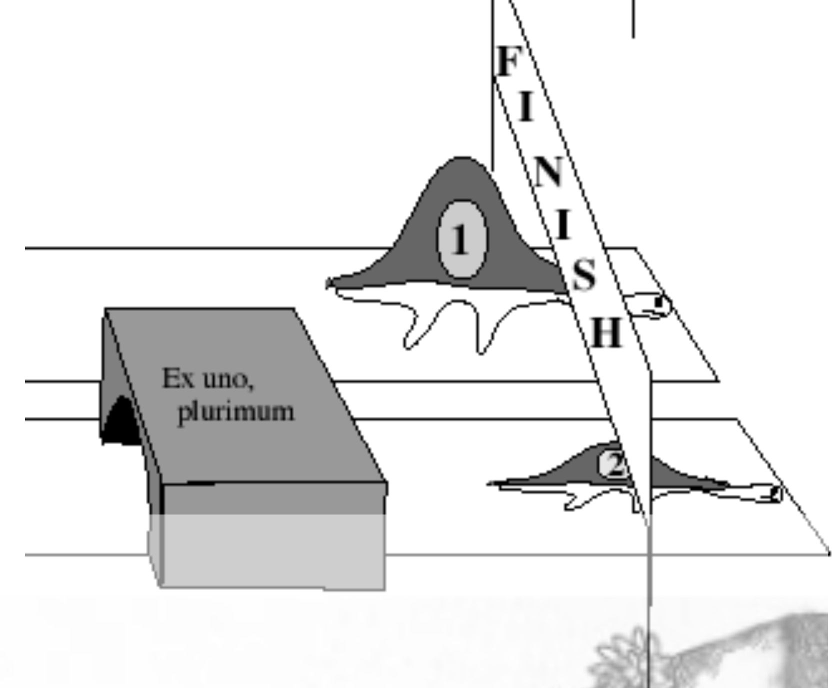
t_{BL}
Re (t)
Im (t)
Time (ms)
1.00
0.75
0.50
0.25
0.00
4
5
6
7
8
9
10
Velocity (mm/s)
Transmission (%)
100
0
4
6
8
10
Velocity (mm/s)

The results

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



Conclusion

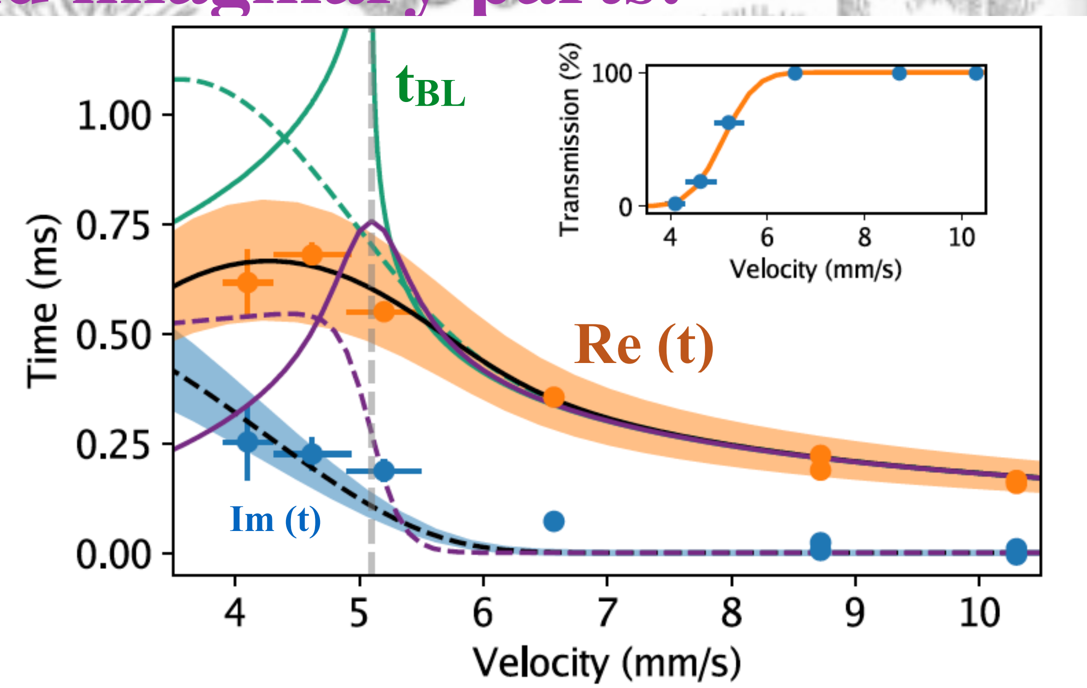


We have measured both components of the Larmor/weak tunneling time –
the real part to be approx. 0.6 ms
for our 1.3-micron barrier.

Good agreement with theory; not with the semiclassical time.

Starting to see that tunneling is faster than free propagation.

Clear, distinct physical *meanings* to real and imaginary parts.



CIQC

What remains to be done?

- Lower temperatures, lower energies, better data
- Probe reflected atoms as well
- Probe *subregions* of the barrier – demonstrate that reflected and transmitted atoms have different "histories"

- Add interactions/dissipation and study effect on tunneling times
- Study different sorts of barriers (e.g., double-barrier "cavities")

- Probe qualitative differences between Im t and Re t by varying measurement strength and/or squeezing probe

- Study how *strong* measurements should modify tunneling dynamics.

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