Quantum Physics 1

2015-2016

Lecture of 9 September 2015 and later

Homework for week 3 of the course

Study: **Chapters 2 and 3,**
emphasis on sections 2.4, 3.1, 3.2, 3.6
and Eqs. [2.111]-[2.113] (Dirac delta function in Sec. 2.5,)
(2.1, 2.2, 2.3 was last week)

See **http://www.quantumdevices.nl/teaching/**

Problems:

To be made <u>before</u> the tutorial session
Chapter 2 - 2.18, 2.19, and 2.21
Chapter 3 - 3.1, 3.3, and 3.22

Previous lectures

QUANTUM MECHANICS

The essential differences between classical mechanic and quantum mechanics concerns:

1) The state of a physical system

2) The time evolution of a physical system

3) Making measurements on a physical system

& this in the form of 5 postulates

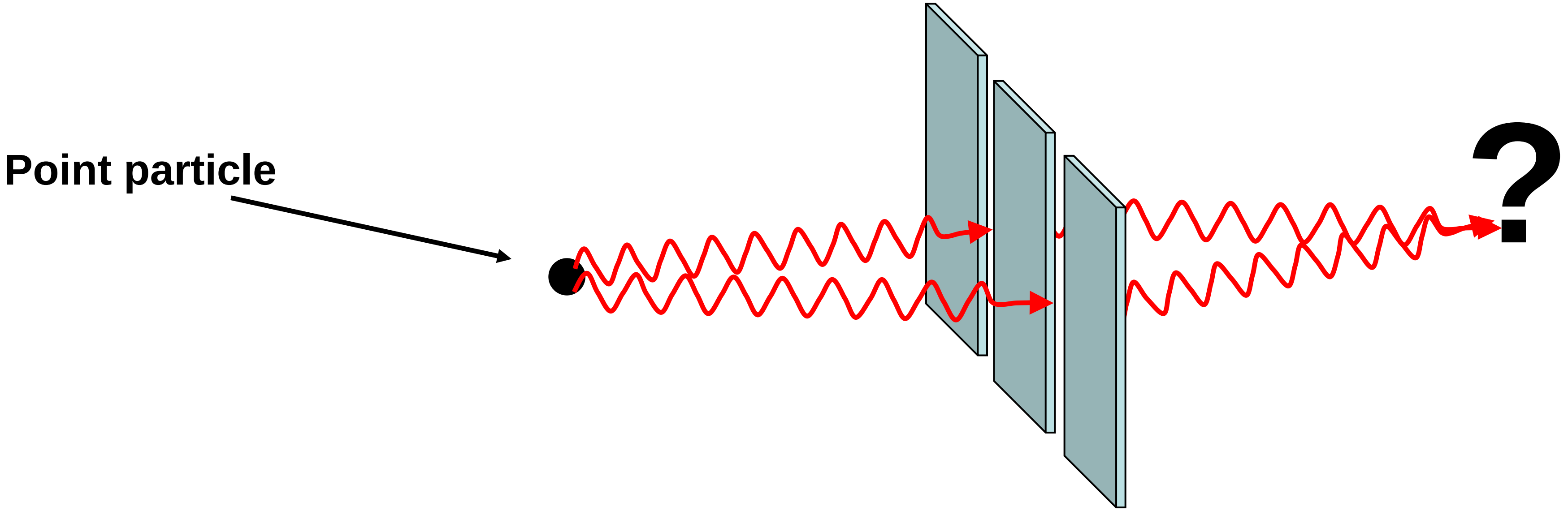
Previous lecture: a state is described by a wave function

Today:

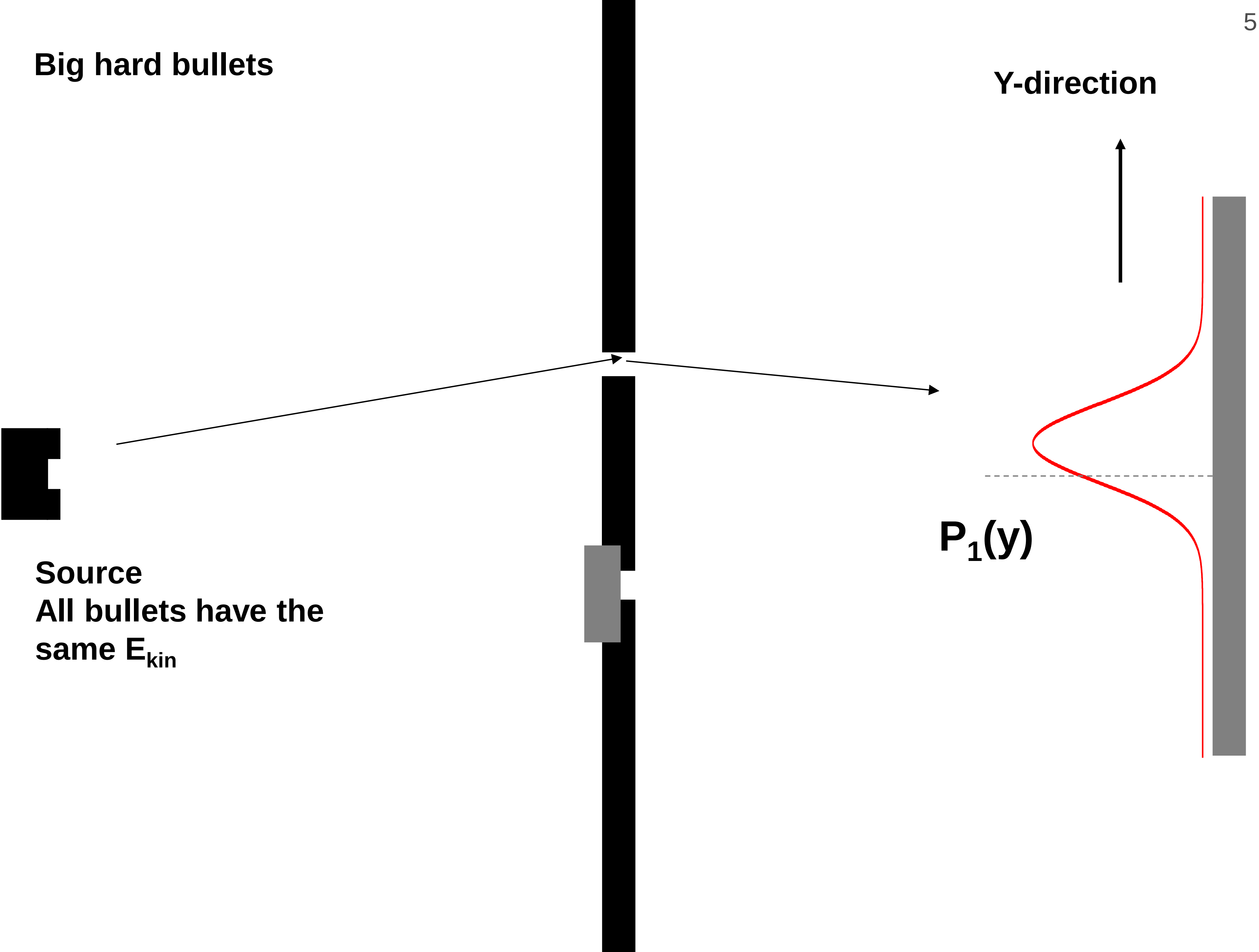
Quantum interference of wave functions

(lecture follows the extra study material from the Feynman Lectures - handout)

Double slit experiments.



Big hard bullets

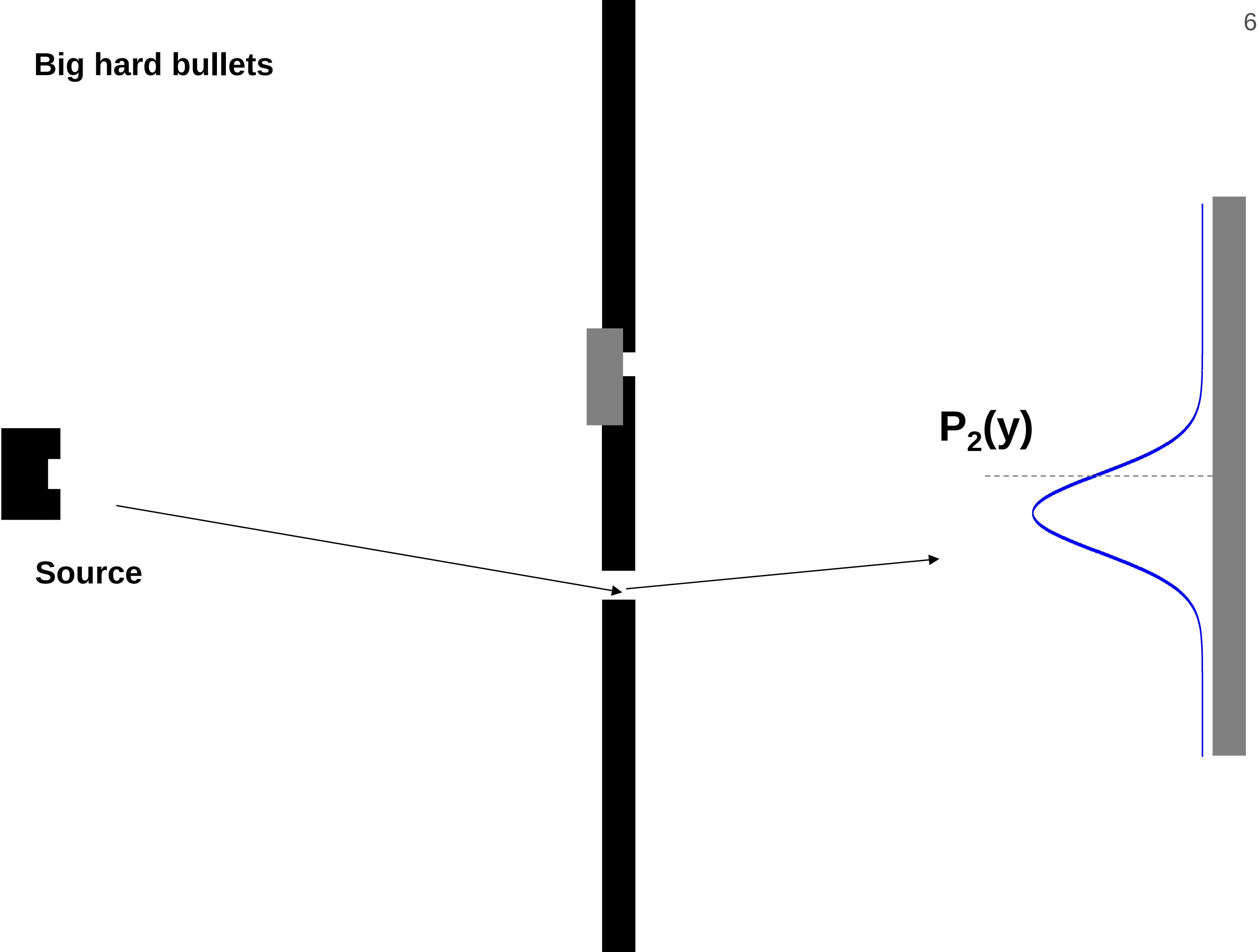


Y-direction

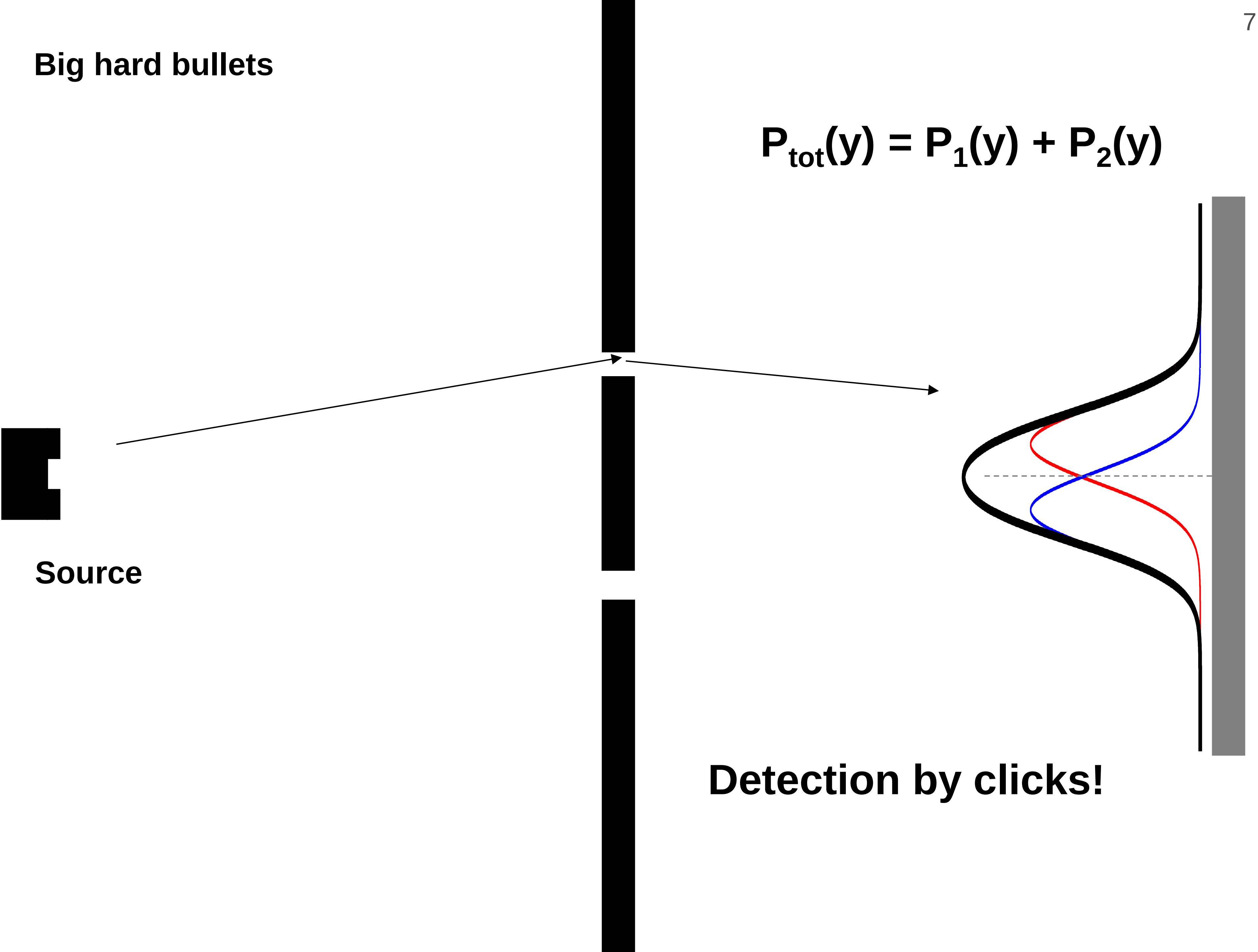
$P_1(y)$

Source
All bullets have the same E_{kin}

Big hard bullets



Big hard bullets

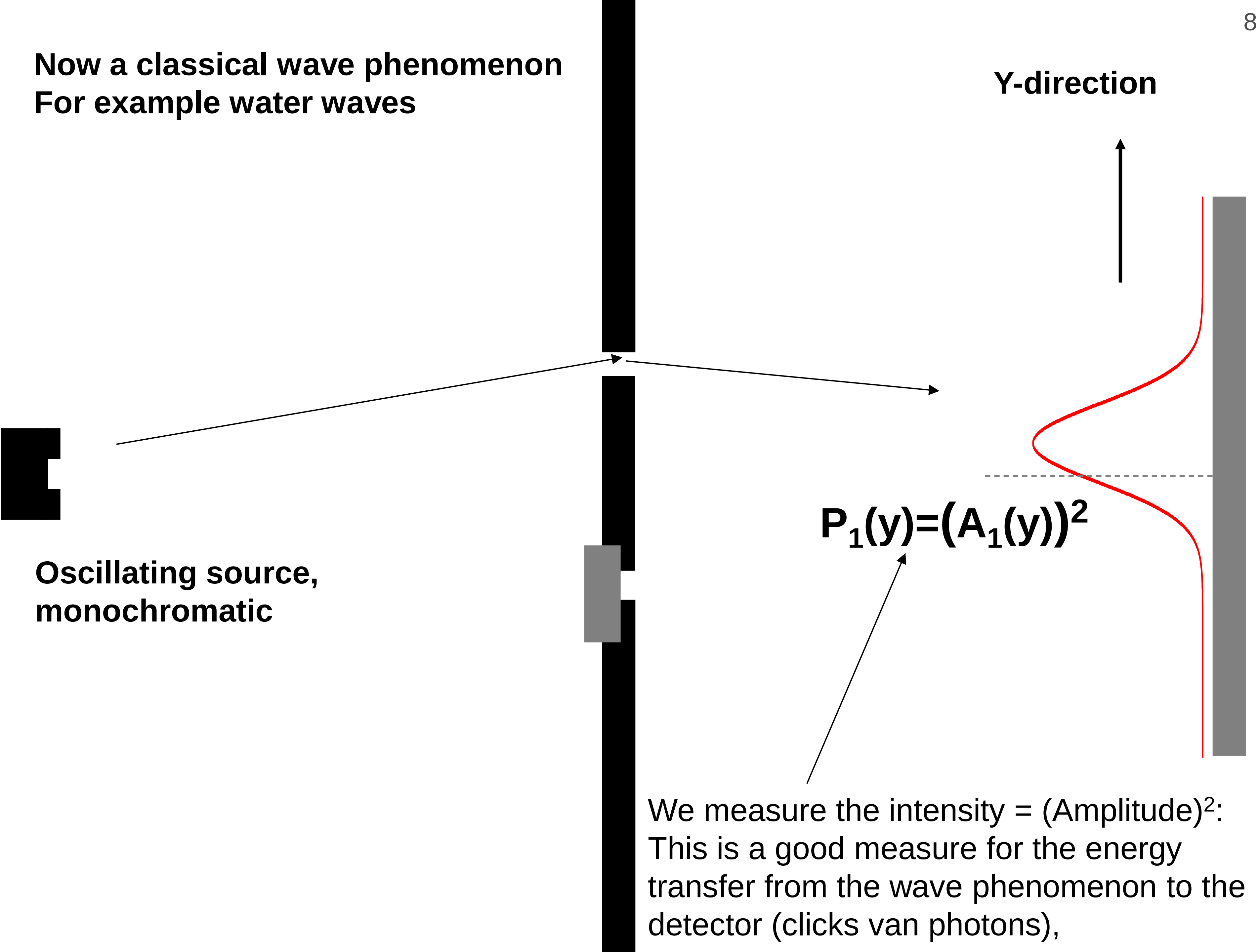


Source

$$P_{tot}(y) = P_1(y) + P_2(y)$$

Detection by clicks!

Now a classical wave phenomenon
For example water waves



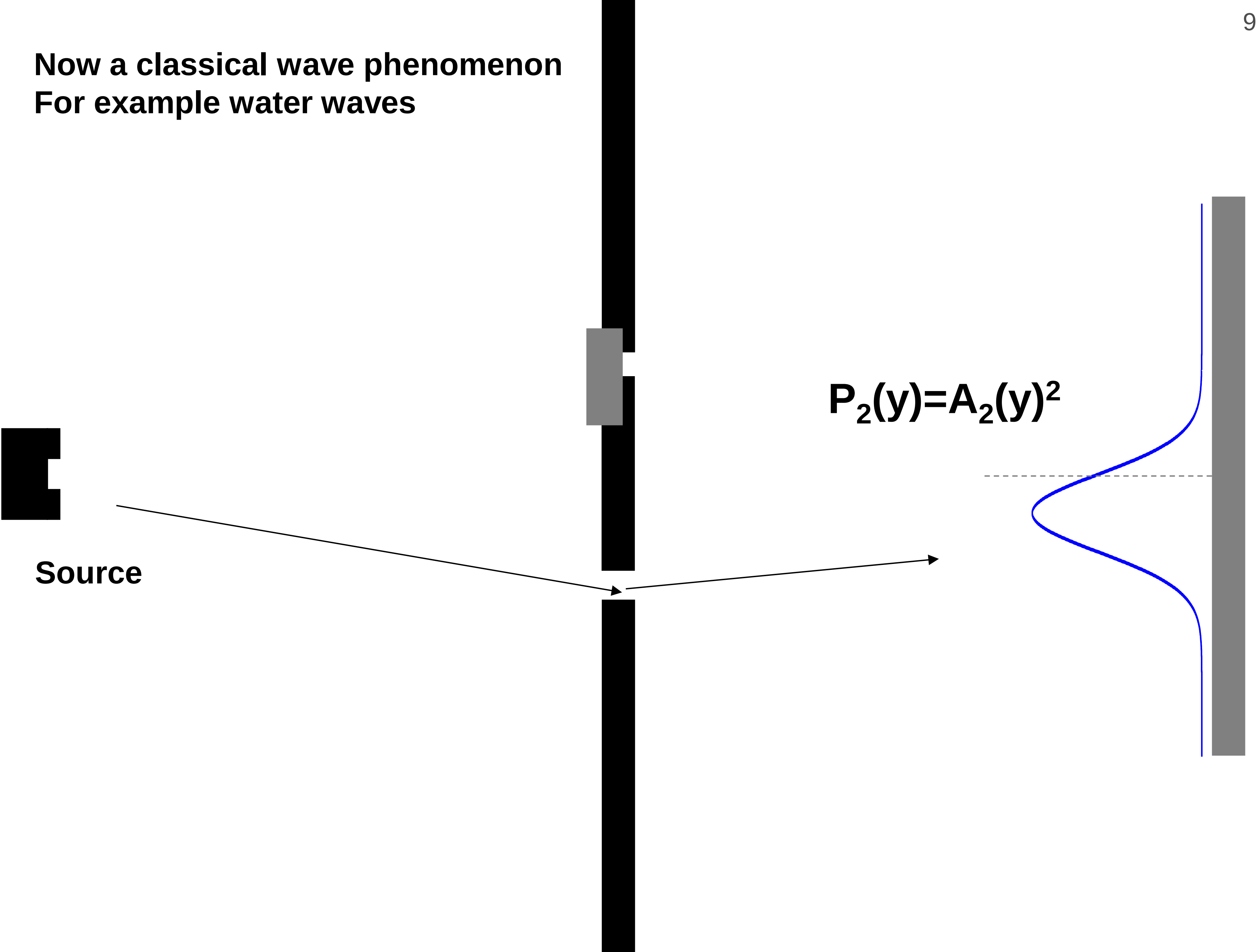
Y-direction

Oscillating source, monochromatic

$$P_1(y)=(A_1(y))^2$$

We measure the intensity = (Amplitude)^2:
This is a good measure for the energy transfer from the wave phenomenon to the detector (clicks van photons),

Now a classical wave phenomenon
For example water waves



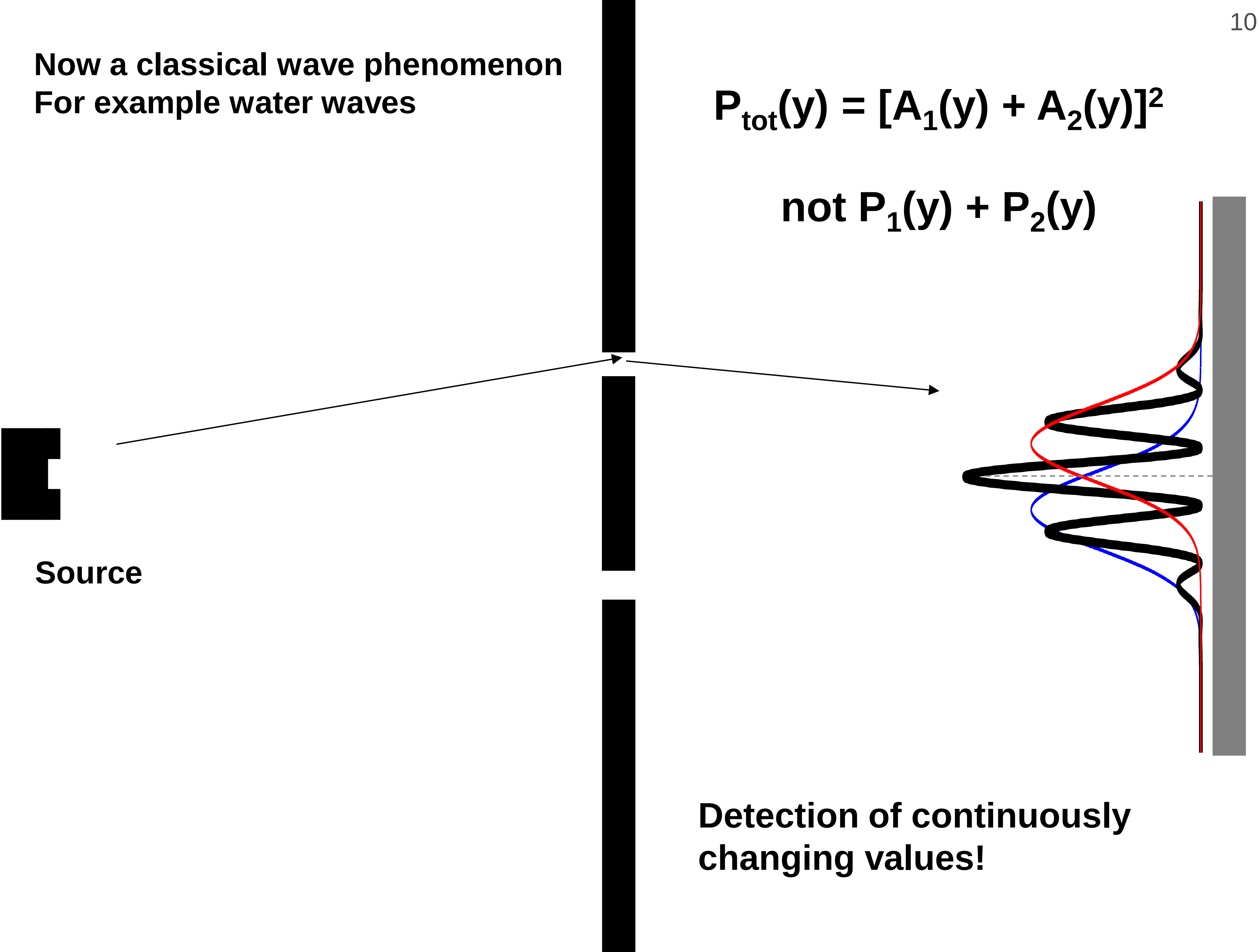
Source

$P_2(y)=A_2(y)^2$

Now a classical wave phenomenon
For example water waves

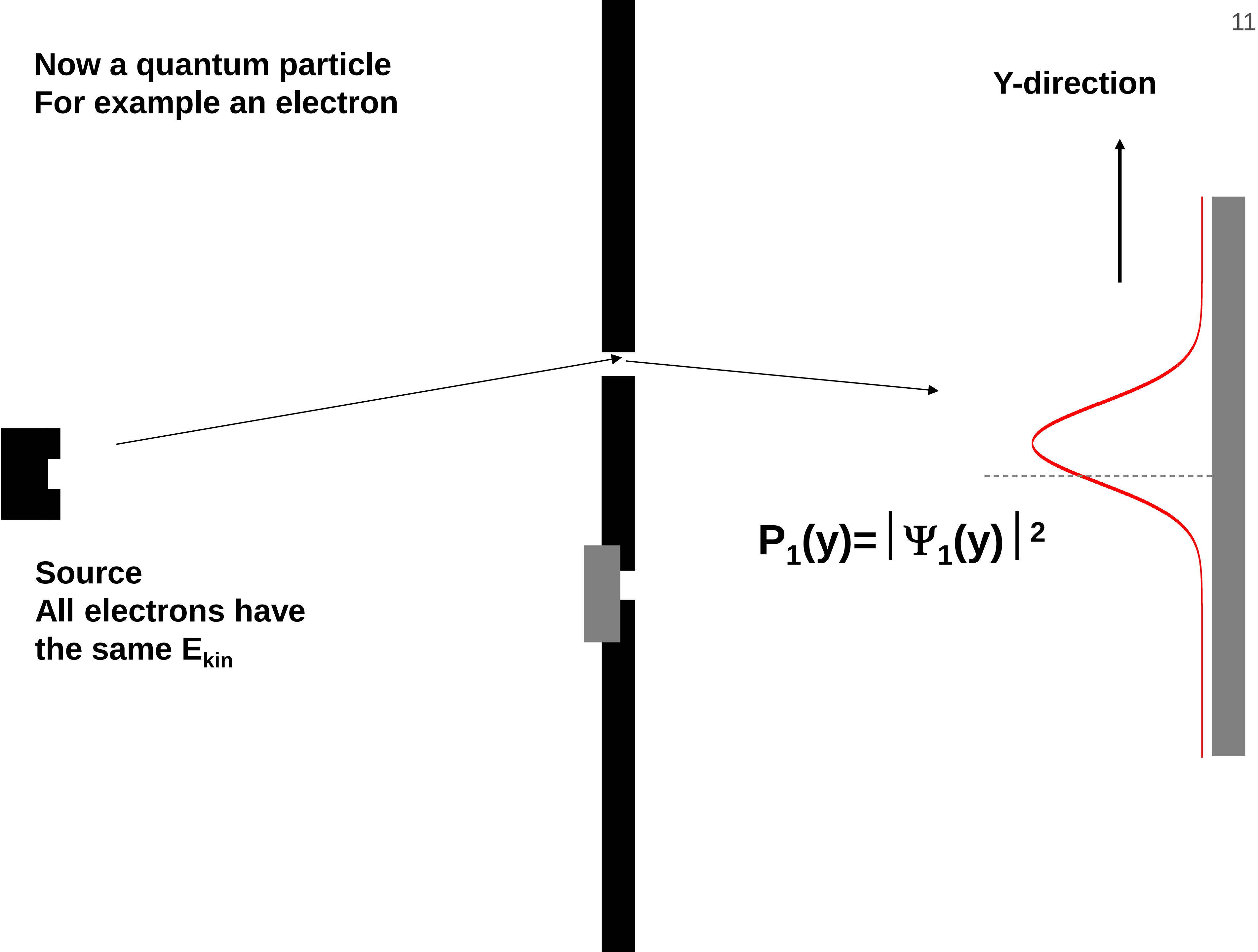
$$P_{tot}(y) = [A_1(y) + A_2(y)]^2$$

$$\text{not } P_1(y) + P_2(y)$$



Detection of continuously changing values!

Now a quantum particle
For example an electron

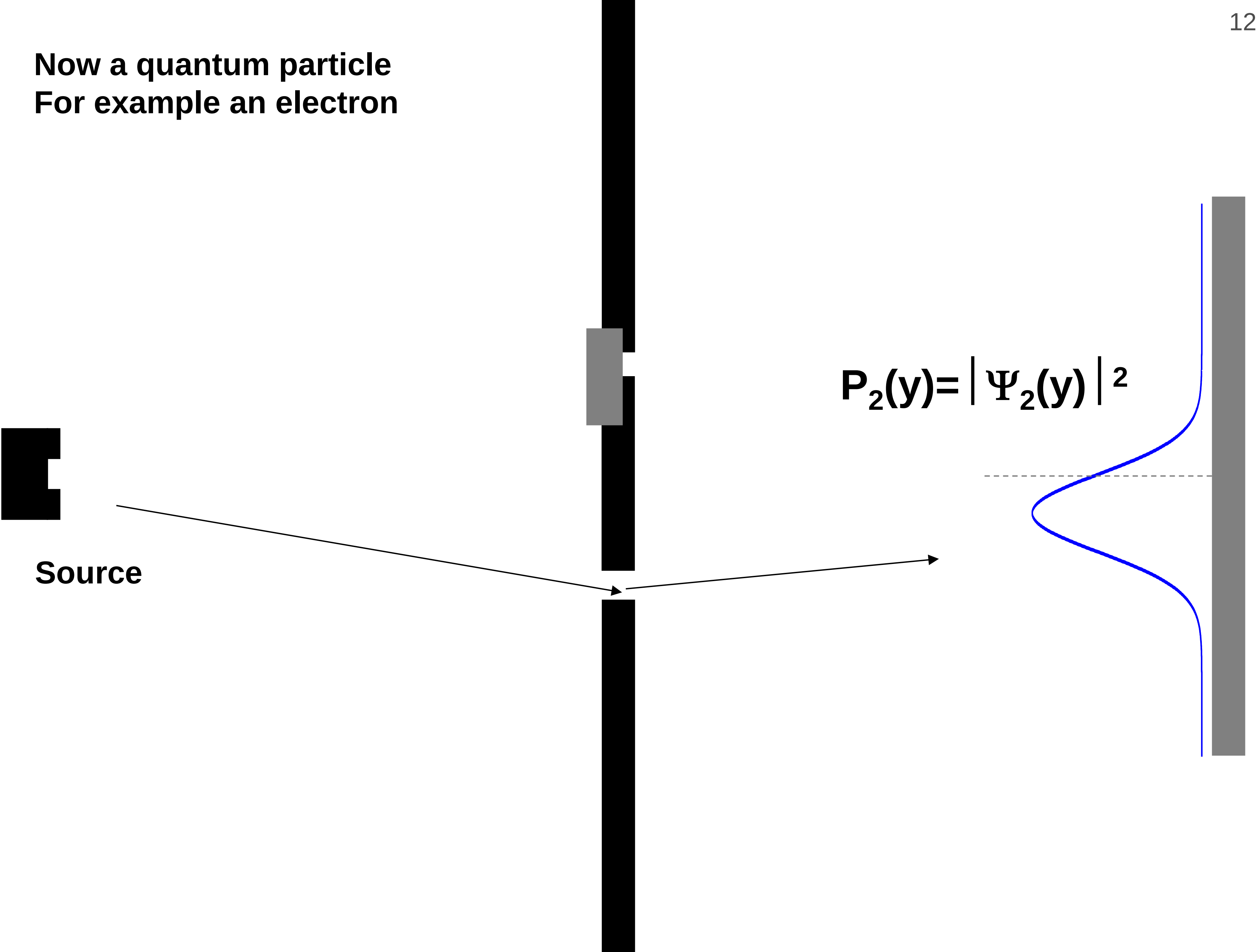


Y-direction

$P_1(y)=|\Psi_1(y)|^2$

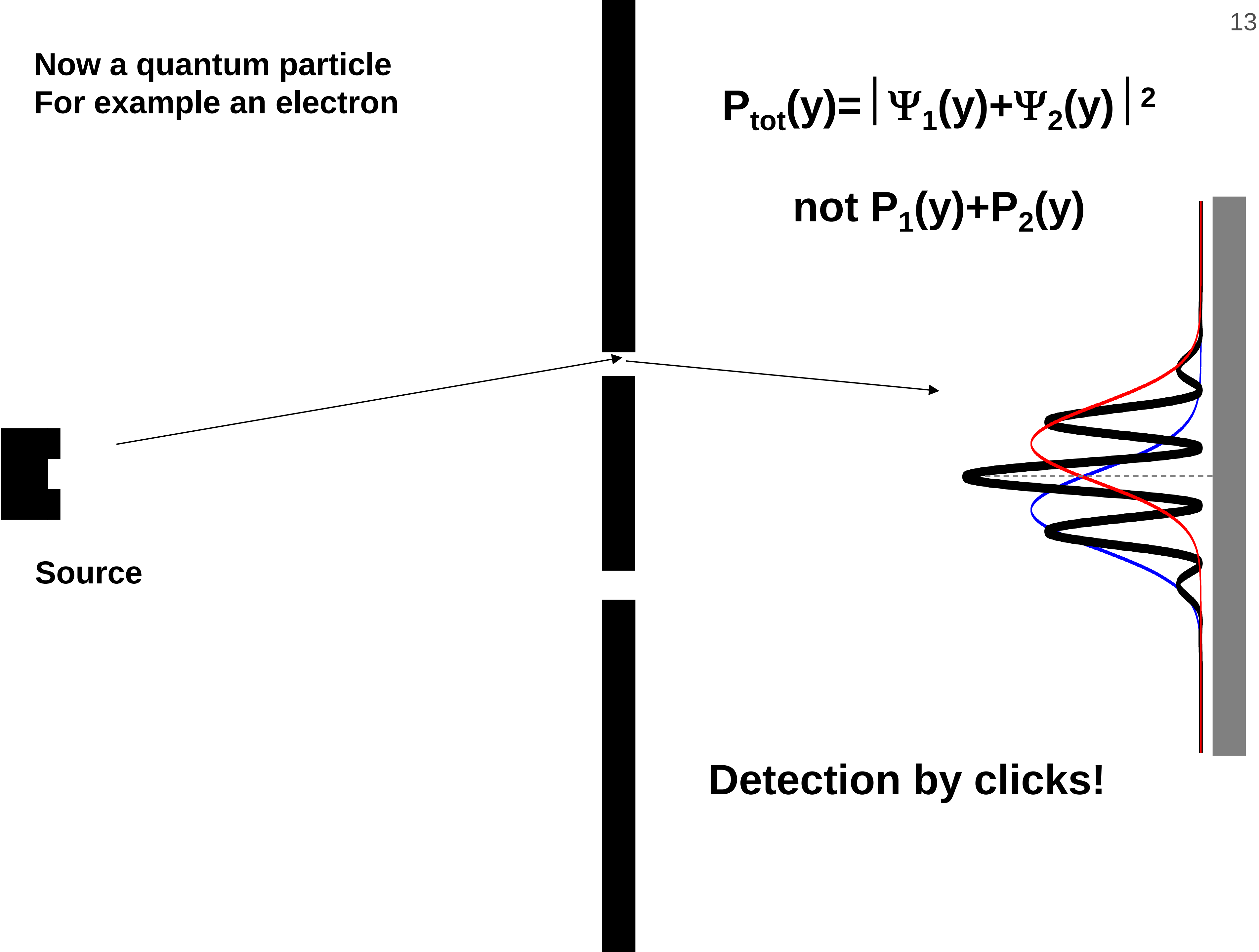
Source
All electrons have
the same E_{kin}

Now a quantum particle
For example an electron



$P_2(y) = |\Psi_2(y)|^2$

Now a quantum particle
For example an electron



$$P_{tot}(y)=|\Psi_1(y)+\Psi_2(y)|^2$$

not $P_1(y)+P_2(y)$

Detection by clicks!

Conclusion:

Quantum particle move as a wave, but are detected as a small hard bullet, by click that indicate integer chunks, *quanta*.

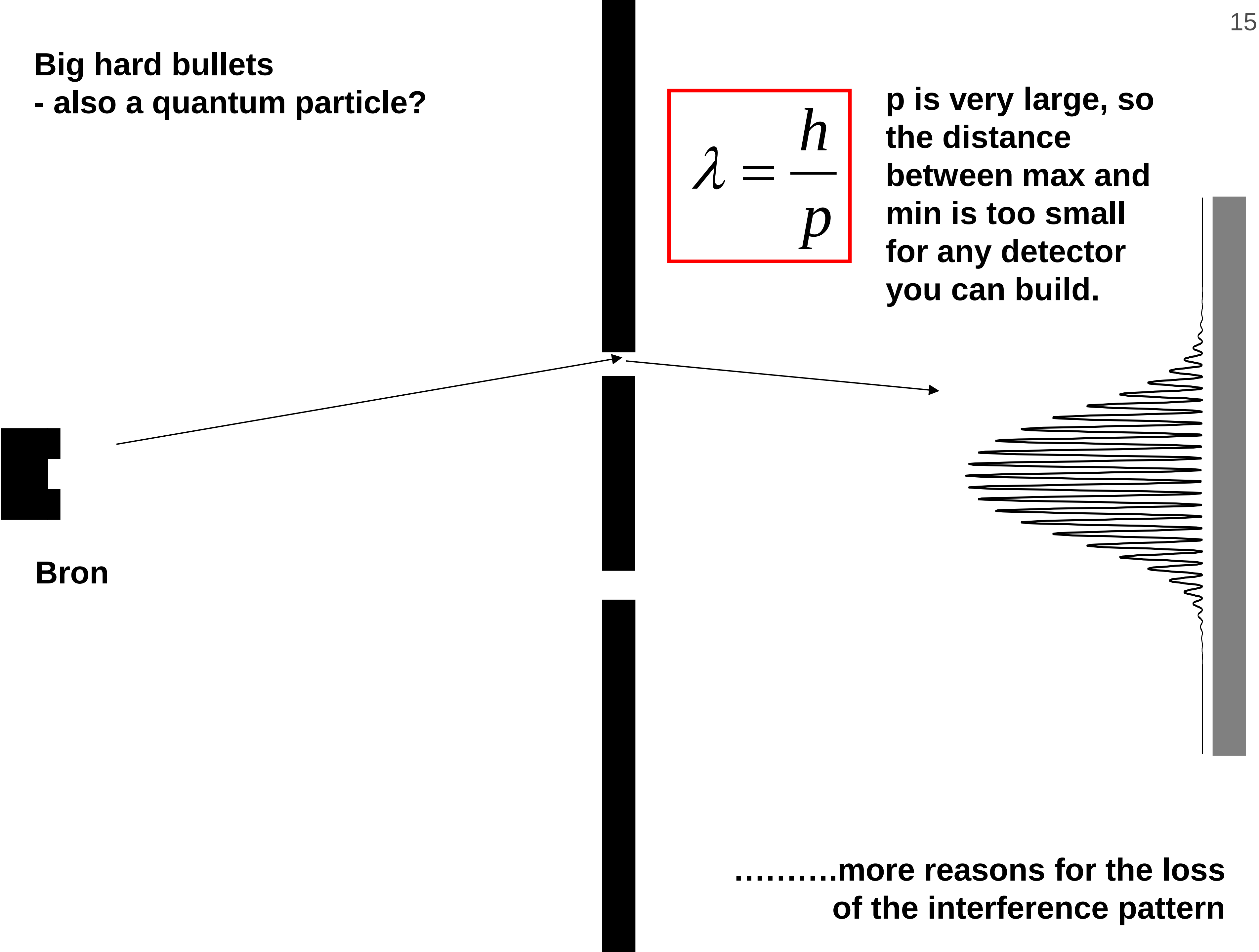
How long is the wavelenght?

De Broglie

$$\boxed{\lambda = \frac{h}{p}}$$

for photons, electrons,
….and all moving masses!

Big hard bullets
- also a quantum particle?

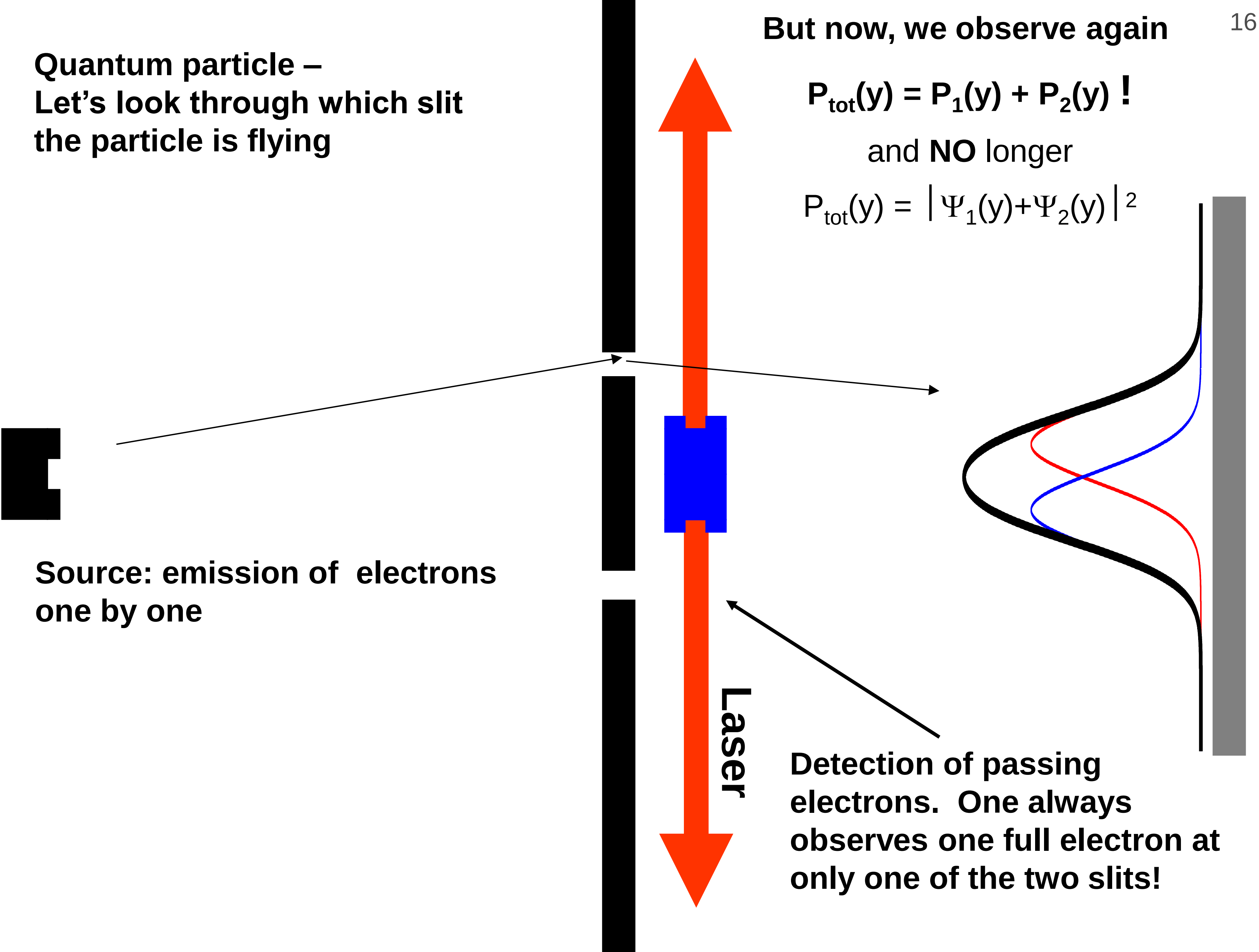


$$\lambda = \frac{h}{p}$$

p is very large, so the distance between max and min is too small for any detector you can build.

……….more reasons for the loss of the interference pattern

Quantum particle –
Let's look through which slit the particle is flying



But now, we observe again

$$P_{tot}(y) = P_1(y) + P_2(y)\ !$$

and **NO** longer

$$P_{tot}(y) = |\Psi_1(y)+\Psi_2(y)|^2$$

Source: emission of electrons one by one

Detection of passing electrons. One always observes one full electron at only one of the two slits!

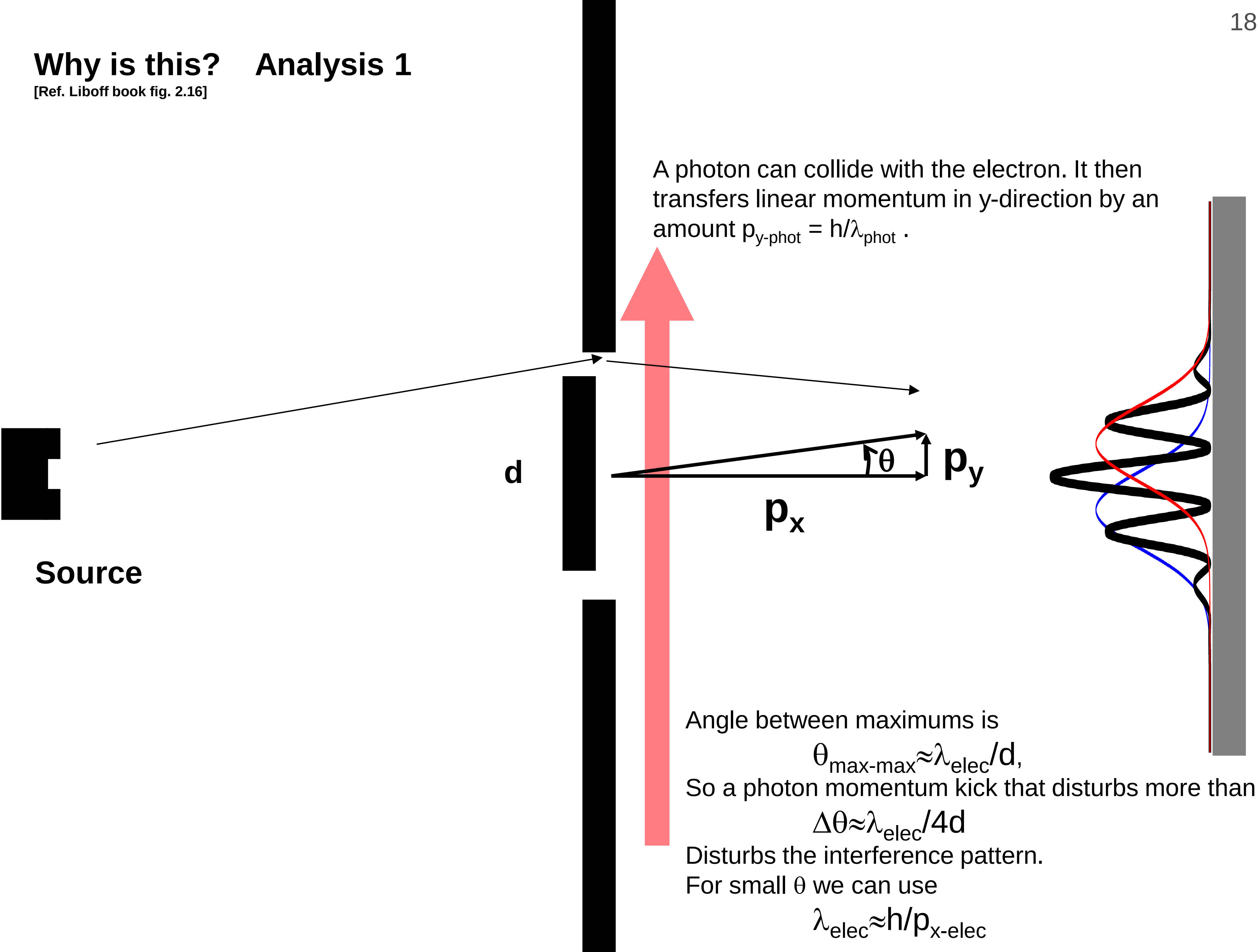
Conclusion:

Determining through which slit the electron is flying and observing the interference patterns cannot happen at the same time!

Why is this?

Why is this? Analysis 1

[Ref. Liboff book fig. 2.16]



A photon can collide with the electron. It then transfers linear momentum in y-direction by an amount $p_{y\text{-phot}} = h/\lambda_{phot}$.

Angle between maximums is

$$\theta_{max\text{-}max} \approx \lambda_{elec}/d,$$

So a photon momentum kick that disturbs more than

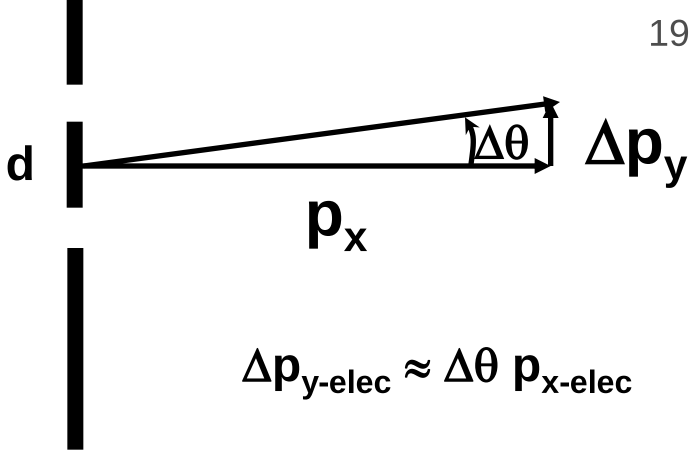
$$\Delta\theta \approx \lambda_{elec}/4d$$

Disturbs the interference pattern.

For small θ we can use

$$\lambda_{elec} \approx h/p_{x\text{-elec}}$$

Analysis 1 continued



$\Delta p_{y\text{-elec}} \approx \Delta\theta\, p_{x\text{-elec}}$

The angle between maximums is

$\theta_{\text{max-max}} \approx \lambda_{\text{elec}}/d$,

so a photon momentum kick that disturbs θ more than

$\Delta\theta \approx \lambda_{\text{elec}}/4d$

disturbs the interference pattern very strongly.

For small θ we can use

$\lambda_{\text{elec}} \approx h/p_{x\text{-elec}}$

Preventing a $p_{y\text{-elec}}$ disturbance has as requirement

$\Delta p_{y\text{-elec}} \approx \Delta\theta\, p_{x\text{-elec}} < (\lambda_{\text{elec}}/4d) \cdot p_{x\text{-elec}} \approx (h/p_{x\text{-elec}})\cdot(1/4d) \cdot p_{x\text{-elec}} = h/4d$

Sufficient resolution for determining the position of the electron requires

$\Delta y_{\text{elec}} < d/4$.

The product of these two requirements together gives

$\Delta p_{y\text{-elec}}\, \Delta y_{\text{elec}} << (h/4d)(d/4) = h/16$.

Heisenberg, however, states that this is impossible!

Nature ALWAYS requires that $\Delta p_{y\text{-elec}}\, \Delta y_{\text{elec}} > \hbar/2 \approx h/12$

What is this? – Analysis 2 (Feynman Lectures, handout of this week)

Having sufficient position resolution for determining the position of the electron near the slit requires

$$\Delta y < d/4.$$

This can only be done with a photon that has a wavelength that is not too large,

$$\lambda_{phot} < d/4.$$

Therefore, the momentum kick of the photon is at least

$$\Delta p_{y\text{-}elec} = h/\lambda_{phot} > 4h/d.$$

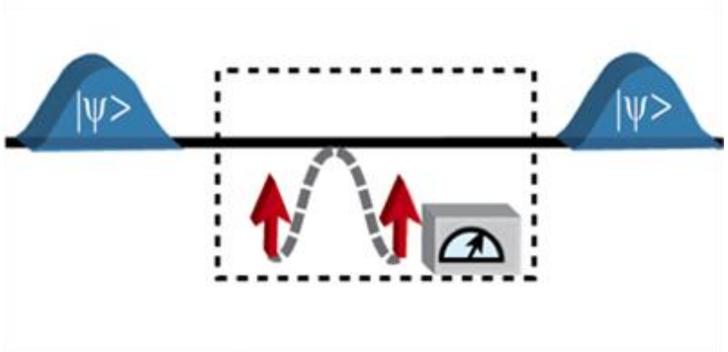
This is more than the $\Delta p_{y\text{-}elec}$ that gives the limit above which the interference pattern will be disturbed (see previous slide).

Recent research

We are still learning quantum physics…

Phys. Rev. Lett. 2012 on a series of weak measurements

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.109.100404
Phys. Rev. Lett. **109**, 100404 (2012)



The Certainty of Uncertainty

When first taking quantum mechanics courses, students learn about Heisenberg's uncertainty principle, which is often presented as a statement about the intrinsic uncertainty that a quantum system must possess. Yet Heisenberg originally formulated his principle in terms of the "observer effect": a relationship between the precision of a measurement and the disturbance it creates, as when a photon measures an electron's position. Although the former version is rigorously proven, the latter is less general and—as recently shown—mathematically incorrect. In a paper in *Physical Review Letters*, Lee Rozema and colleagues at the University of Toronto, Canada, experimentally demonstrate that a measurement can in fact violate Heisenberg's original precision-disturbance relationship.

If the observer affects the observed, how can one even make such a measurement of the disturbance of a measurement? Rozema *et al.* use a procedure called "weak" quantum measurement: if one can probe a quantum system by means of a vanishingly small interaction, information about the initial state can be squeezed out with little or no disturbance. The authors use this approach to characterize the precision and disturbance of a measurement of the polarizations of entangled photons. By comparing the initial and final states, they find that the disturbance induced by the measurement is less than Heisenberg's precision-disturbance relation would require.

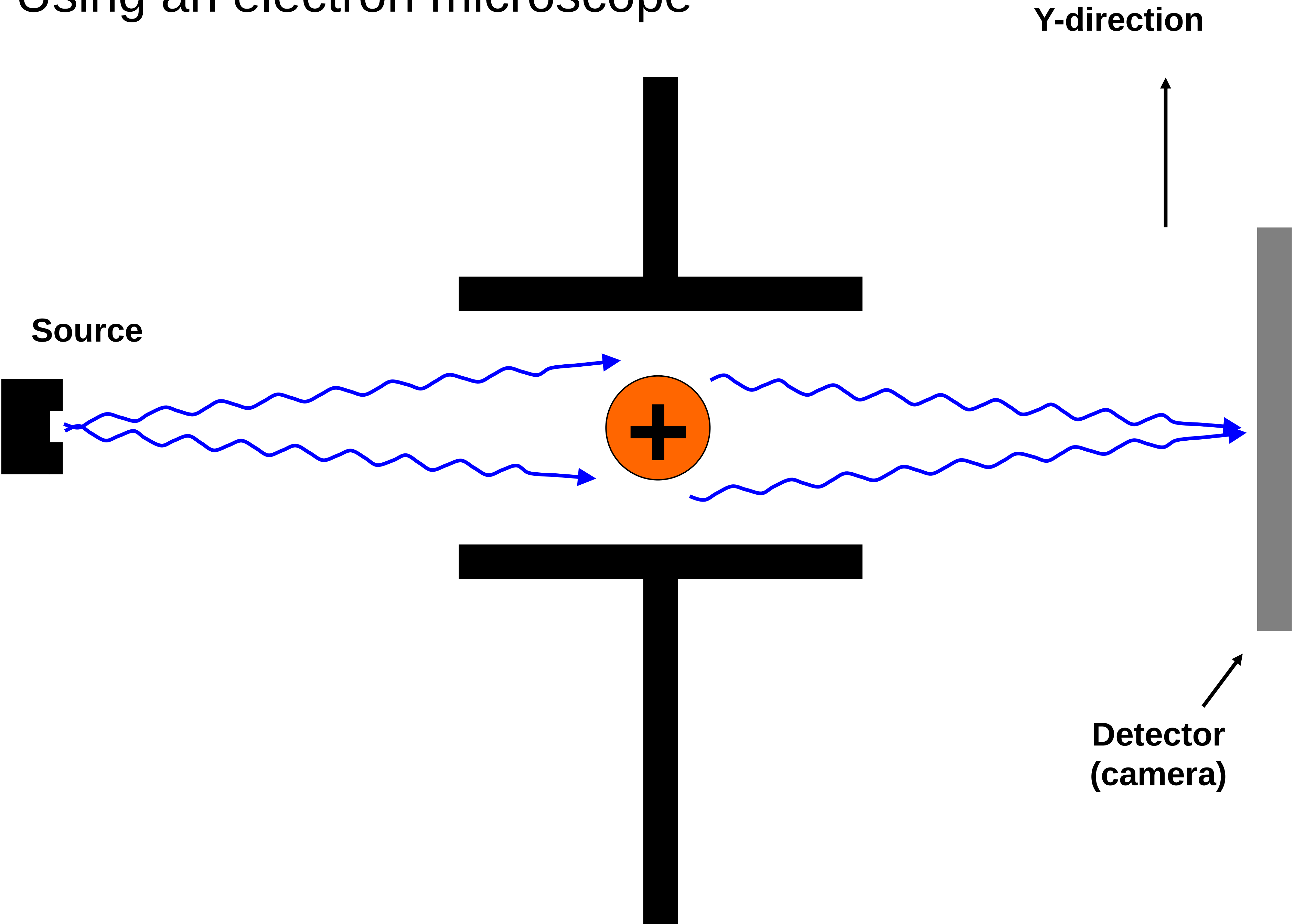
While the measurements by Rozema *et al.* leave untouched Heisenberg's principle regarding inherent quantum uncertainty, they expose the pitfalls of its application to measurements' precision. These results not only provide a demonstration of the degree of precision achievable in weak-measurement techniques, but they also help explore the very foundations of quantum mechanics. – *David Voss*

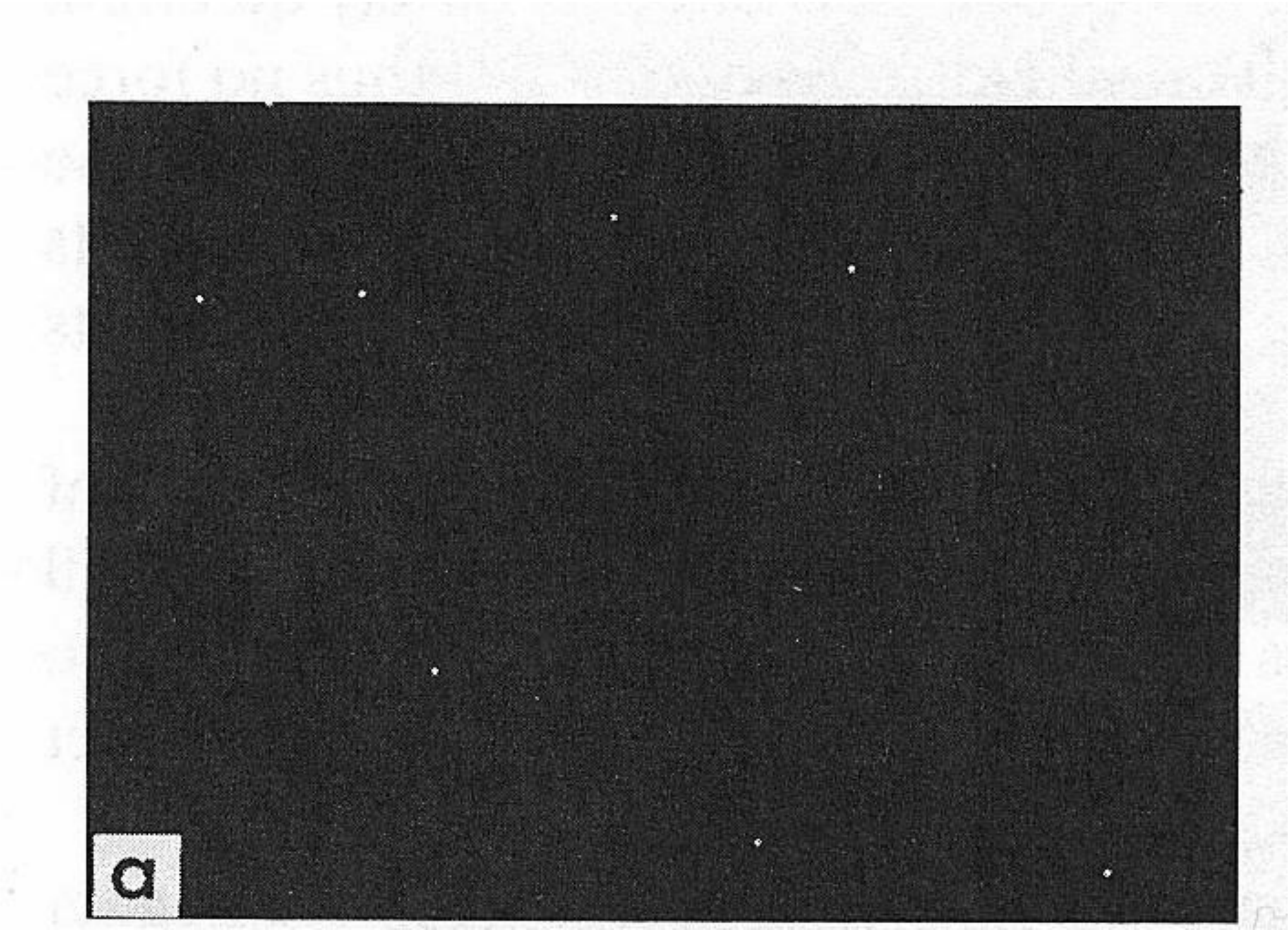
PRL **109,** 100404 (2012) PHYSICAL REVIEW LETTERS week ending 7 SEPTEMBER 2012

Violation of Heisenberg's Measurement-Disturbance Relationship by Weak Measurements

Lee A. Rozema, Ardavan Darabi, Dylan H. Mahler, Alex Hayat, Yasaman Soudagar, and Aephraim M. Steinberg

Using an electron microscope





Y-direction ⟶

Source: A. Tonomura, *Annals of the New York Academy of Sciences* **755**, p. 227 (1995).

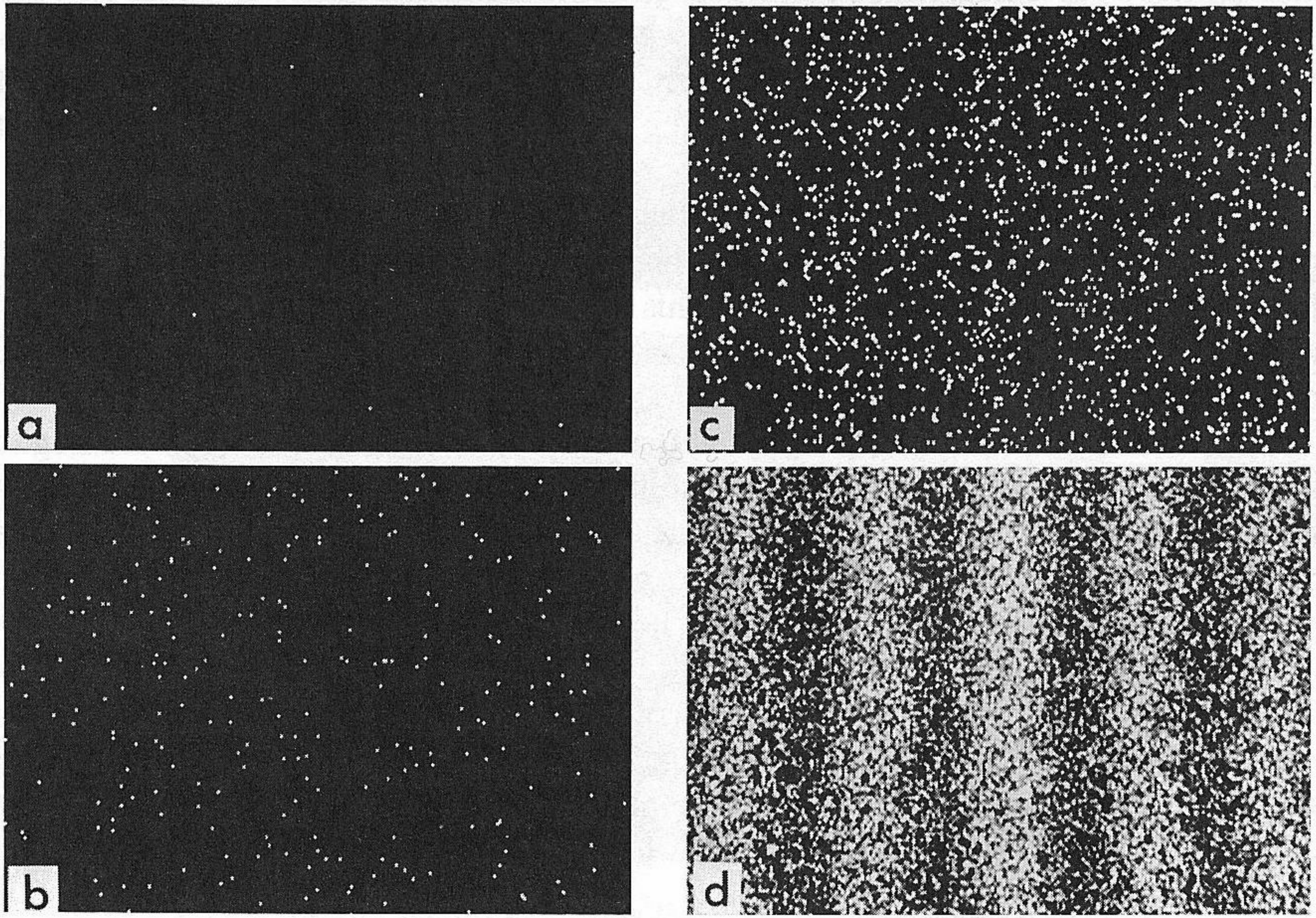


FIGURE 2. Single-electron buildup of the electron interference pattern: (a) $N = 8$, (b) $N = 100$, (c) $N = 3000$, and (d) $N = 100{,}000$.

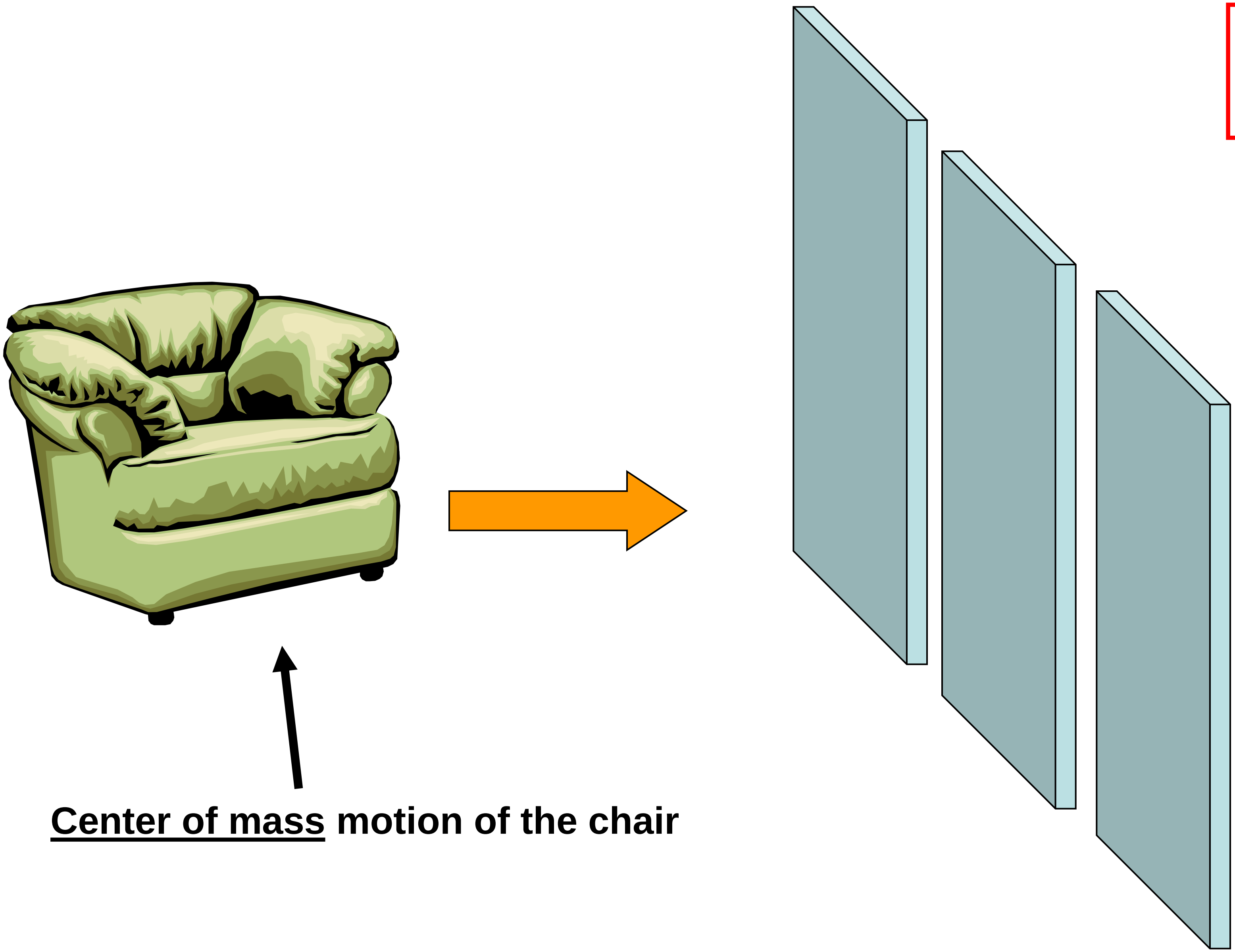
Conclusion:

A quantum particle interferes with itself. For the case here it does not concern interference between the waves of two different particles.

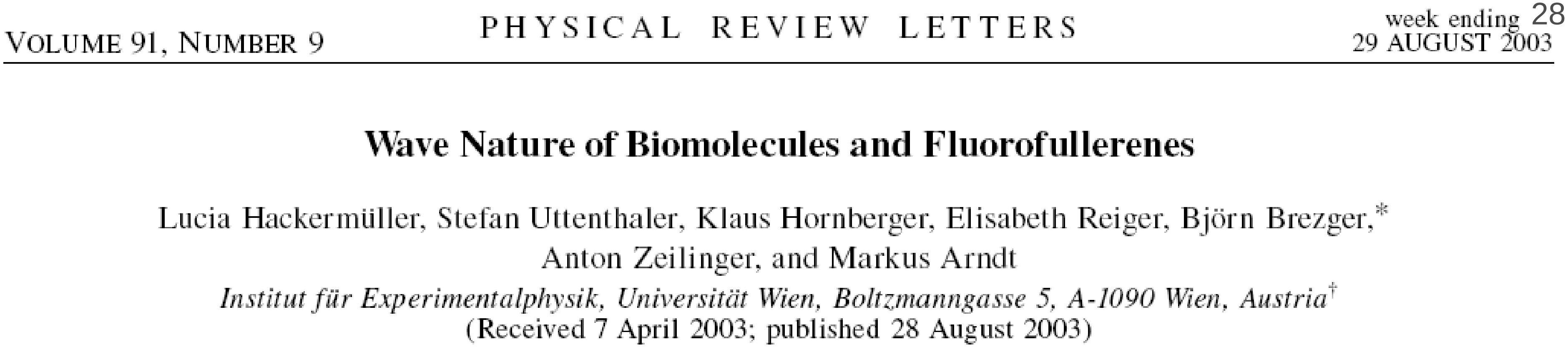
When you measure the position of a particle whose y-position is described by a wave function that is a very wide wave front in y-direction, the measurement outcome gives a very specific y-value.

Can we show double-slit quantum interference with chairs?

$$\lambda = \frac{h}{p}$$



Center of mass motion of the chair

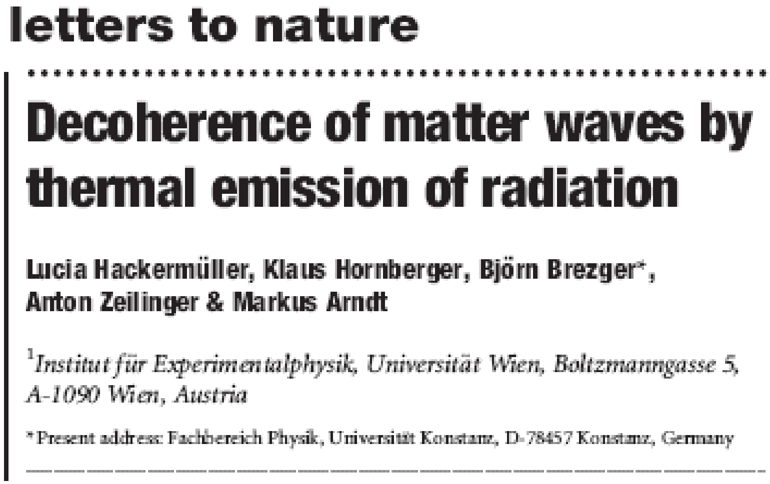


VOLUME 91, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2003

Wave Nature of Biomolecules and Fluorofullerenes

Lucia Hackermüller, Stefan Uttenthaler, Klaus Hornberger, Elisabeth Reiger, Björn Brezger,*
Anton Zeilinger, and Markus Arndt
Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria†

(Received 7 April 2003; published 28 August 2003)



letters to nature

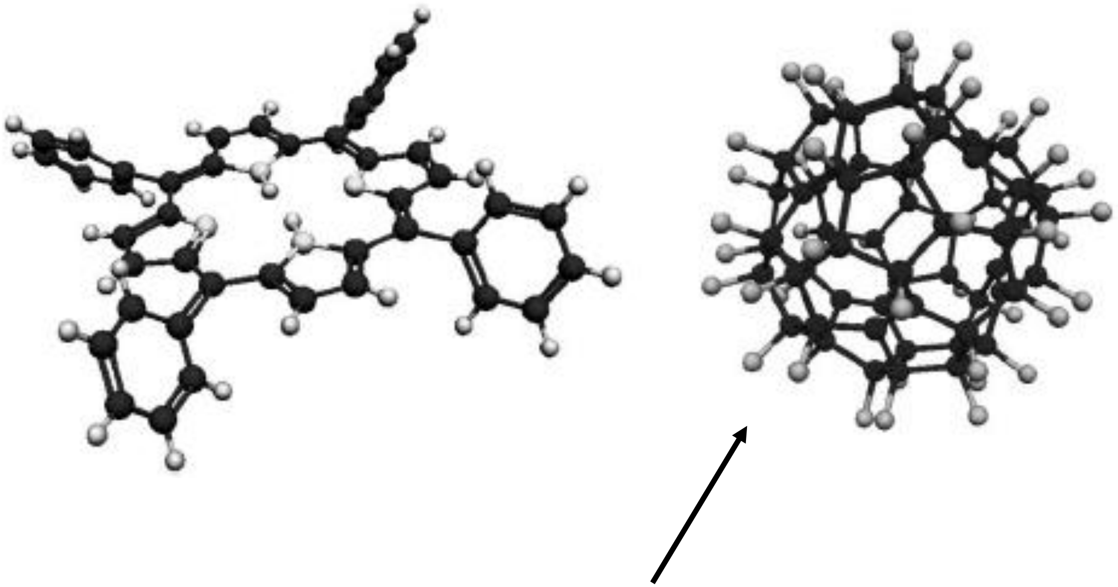
Decoherence of matter waves by thermal emission of radiation

Lucia Hackermüller, Klaus Hornberger, Björn Brezger*, Anton Zeilinger & Markus Arndt

[1]*Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria*

* Present address: Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany

Nature **427**, 711 (Feb. 2004)



1632 atomic mass units

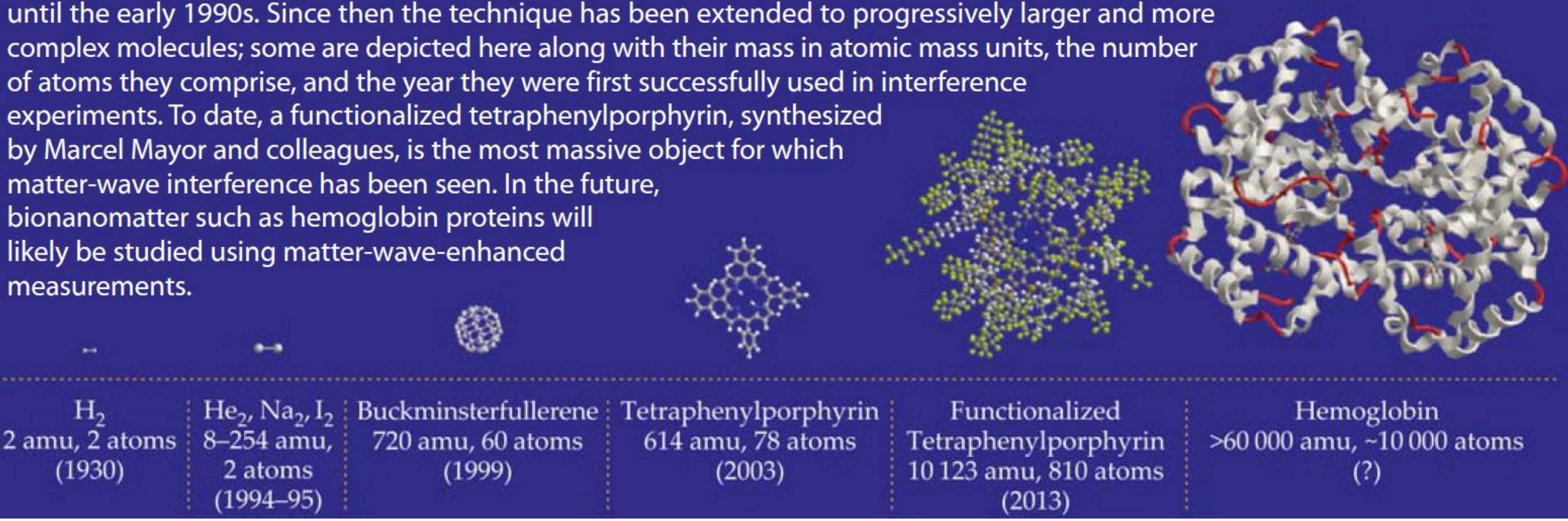
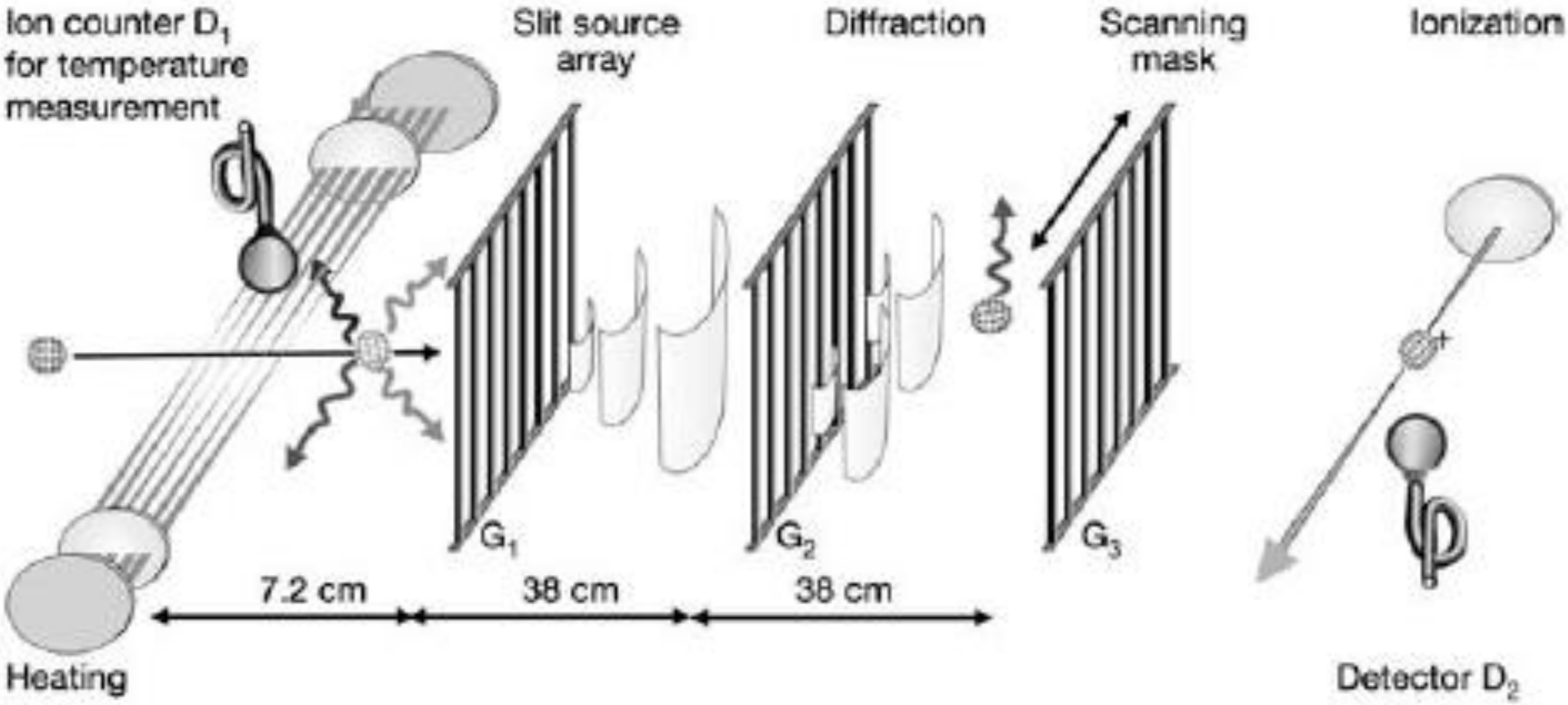


Figure 5. Matter-wave diffraction started in 1930 with diatomic particles, but it didn't gain momentum until the early 1990s. Since then the technique has been extended to progressively larger and more complex molecules; some are depicted here along with their mass in atomic mass units, the number of atoms they comprise, and the year they were first successfully used in interference experiments. To date, a functionalized tetraphenylporphyrin, synthesized by Marcel Mayor and colleagues, is the most massive object for which matter-wave interference has been seen. In the future, bionanomatter such as hemoglobin proteins will likely be studied using matter-wave-enhanced measurements.

Reference
(very accessible publication, available on course website):

Physics Today, Volume **67**(Issue 5), page 30 (May 2014).


Ion counter D_1 for temperature measurement
Slit source array
Diffraction
Scanning mask
Ionization
G_1
G_2
G_3
7.2 cm
38 cm
38 cm
Heating
Detector D_2

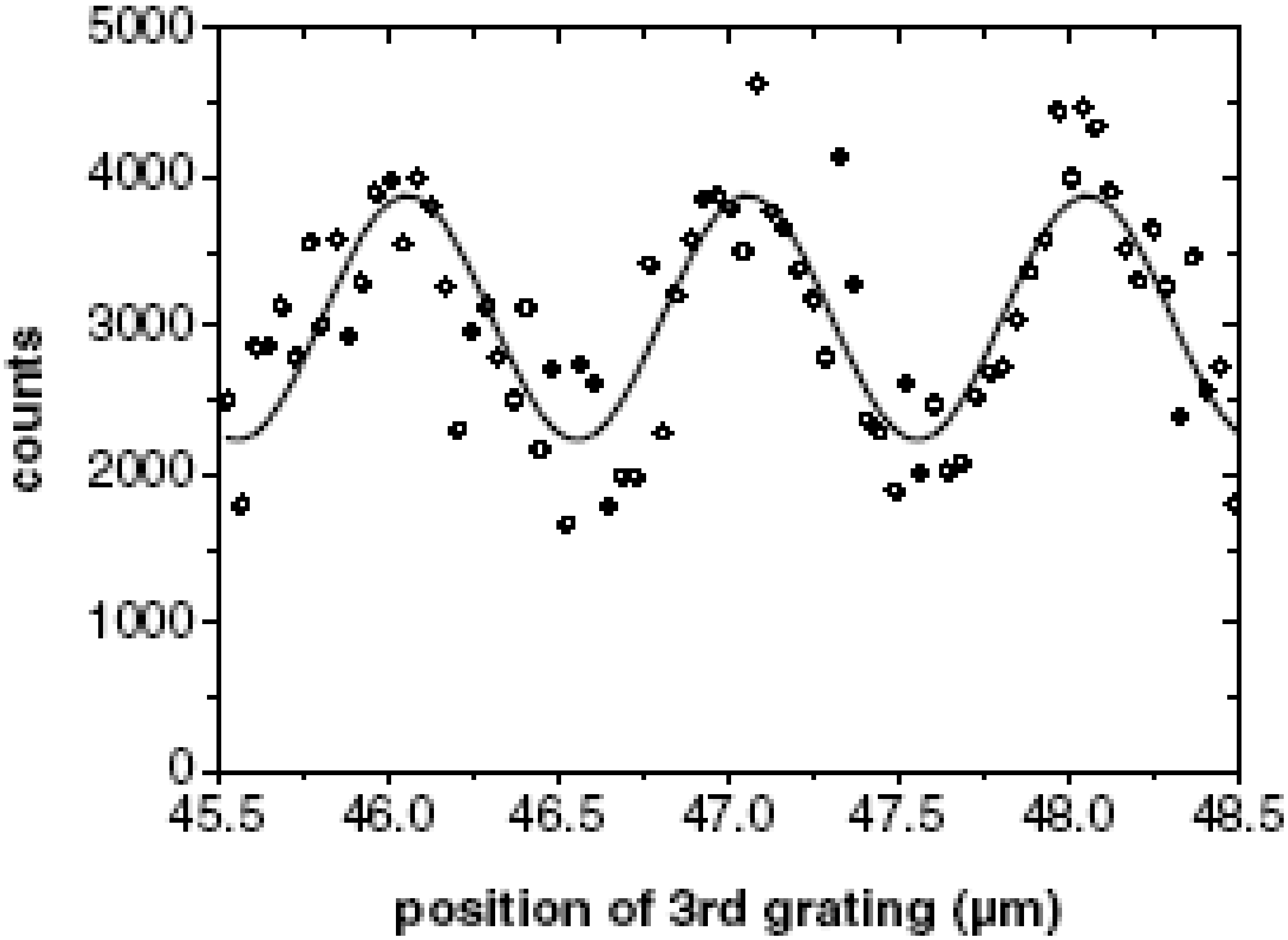
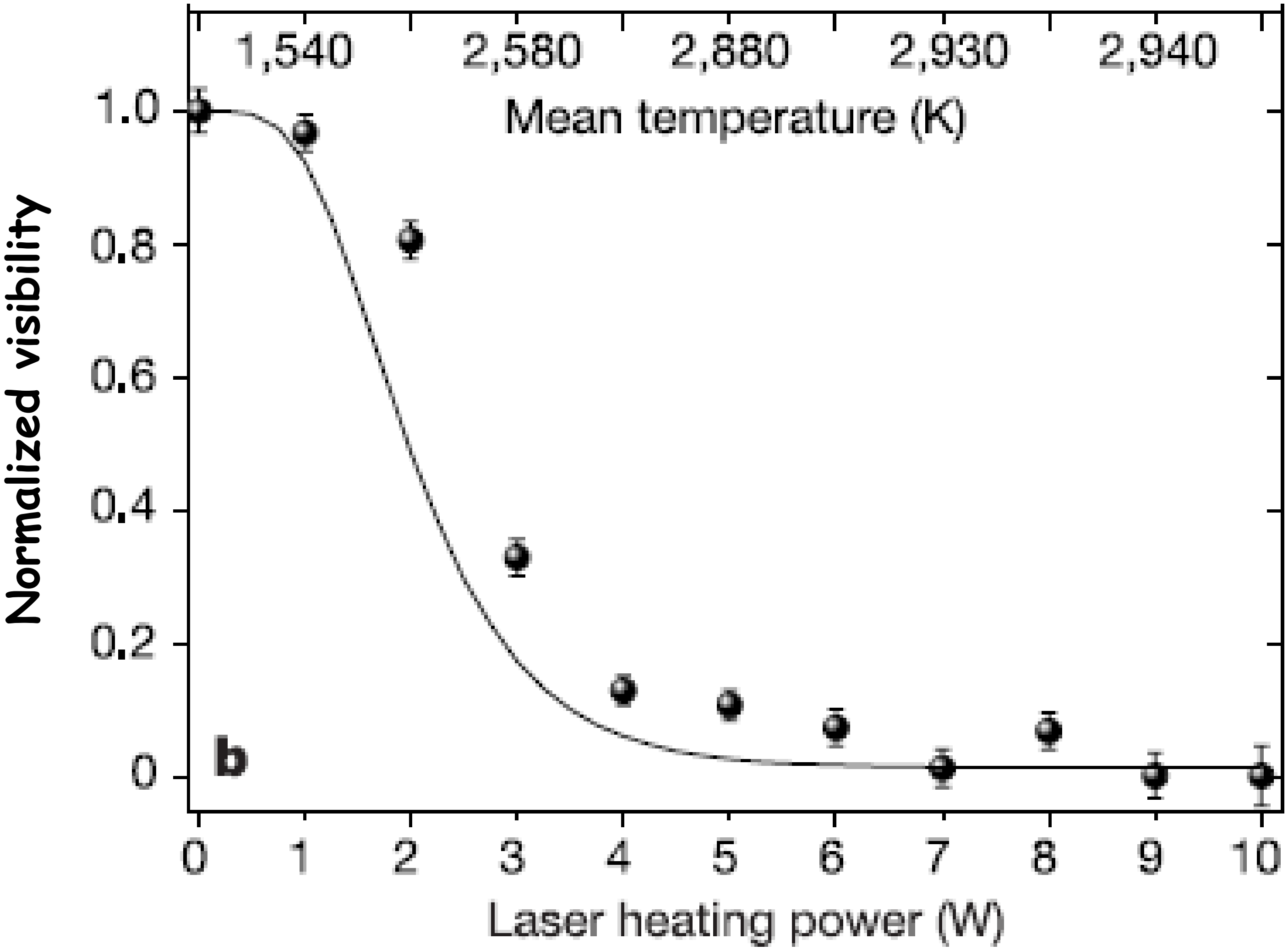


FIG. 4. Quantum interference fringes of $C_{60}F_{48}$. The beam has a mean velocity of $v_m = 105\,\mathrm{m/s}$ and a velocity spread (FWHM) of $\Delta v/v_m = 20\%$.


1,540
2,580
2,880
2,930
2,940
Mean temperature (K)
Normalized visibility
1.0
0.8
0.6
0.4
0.2
0
b
0
1
2
3
4
5
6
7
8
9
10
Laser heating power (W)

Why does the interference pattern go away when the temperature of the molecules is made higher?

The particle emits black-body radiation, and this can be used for observing along which trajectory the particle is flying:
(when T goes up, λ shorter, position information get more precise).

Its is not needed that we (human beings) are around for really making a measurement of this black-body radiation.

If there is something in the universe (anything!) that changes in a way that it contains information about which trajectory the particle was taking, the interference pattern will go way.

Summary:

1. The positions of both particles and photons are described by a wave function.
2. Such a wave function can interfere with itself.
3. (Lack of) quantum interference is still a topic of hot research.

Youtube rules: Good summary by Dr. Quantum,

see http://www.youtube.com/watch?v=DfPeprQ7oGc

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