HQA Lecture 18

I. A brief history of diffraction

II. Walker diffraction

Light/electrons/walkers:

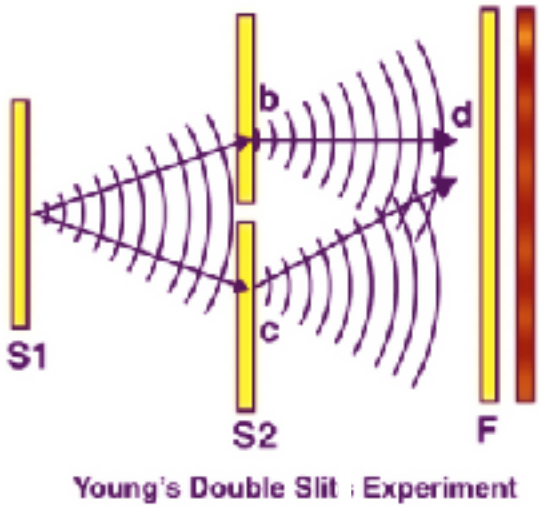
Waves or particles?

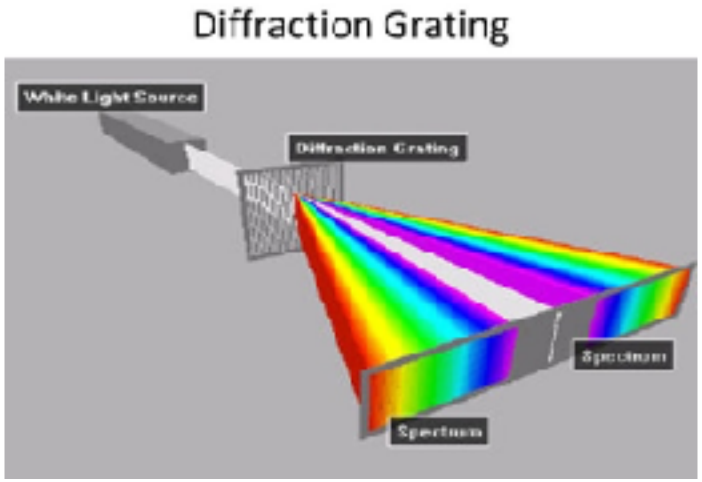
Both or neither?

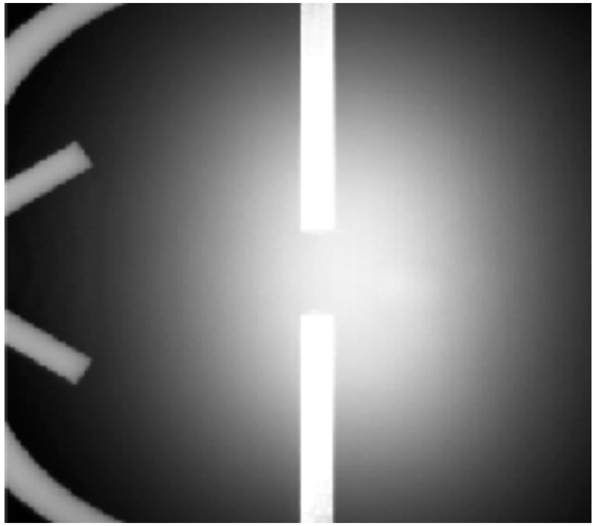
HQA4, Rio de Janeiro. June 2014

A brief history of diffraction

from the beginnings
to the bouncing droplets





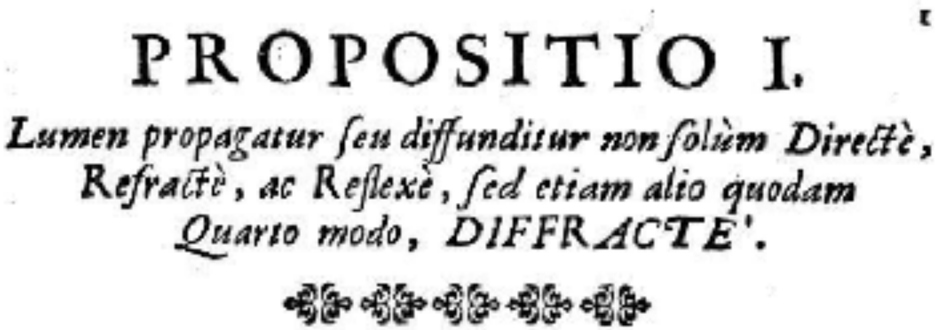


Giuseppe Pucci
Dan Harris
John Bush

UNIVERSITÀ DELLA CALABRIA

Waves

The **Diffraction of Light** was first studied by Friar **Francesco Maria Grimaldi** (1665) and reported in his treatise “De lumine”*


PROPOSITIO I.

Lumen propagatur seu diffunditur non solùm Directè, Refractè, ac Reflexè, sed etiam alio quodam Quarto modo, DIFFRACTE'.

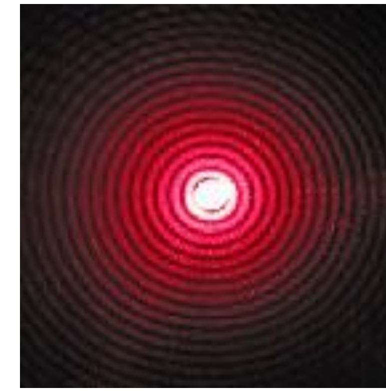
Diffraction comes from the Latin “diffractus”, meaning “broken” or “broken up”.

He associated light with the water of a river, and obstacles as rocks in the river responsible for wave generation. He thus considered light to be a wave and wrote an early version of what is now known as Huygens principle.

* Grimaldi Francesco Maria, Physico-mathesis de lumine coloribus et iride aliisque adnexis libri duo, 1665.

Sommerfeld’s Account of Grimaldi’s Work

``Grimaldi made careful observations of the shadows cast by opaque bodies. He found that the shadow boundary between light and dark was not sharply defined, and that a series of colored streaks or fringes appeared just outside and parallel to the shadow region. When observing the shadow of a thin rod, Grimaldi found colored fringes inside the shadow. Grimaldi realized that these fringes could not be explained by the known geometric laws of ray propagation, reflection and refraction. He used the Latin word diffraction to describe this new and surprising optical phenomenon. Grimaldi’s two-volume treatise ‘Physico-mathesis de lumine, coloribus, et iride’ was published posthumously in 1665. The first proposition of the first volume announced the discovery of diffraction in terms that are still used today: ‘Light is propagated or scattered not only directly and by reflection and refraction, but also in a certain other fourth mode, by diffraction’.”



He allowed a beam of sunlight to pass through a small aperture in a screen, and noticed that it was diffused in the form of a cone. The shadow of a body placed in the path of the beam was larger than that required by the rectilinear propagation of light. Careful observation also showed that the shadow was surrounded by coloured fringes, similar ones being seen within the edges, especially in the case of narrow objects. He showed that the effect could not be due to reflection or refraction, and concluded that the light was bent out of its course via refraction in passing the edges of bodies.

No, *particles*: Newton’s corpuscular theory

Newton (1704) developed a theory of light in terms of corpuscles, in opposition to Grimaldi's statement on the wave nature. He used the term *inflexion* (and not diffraction) to name a possible bending of corpuscle trajectories*.

“Light corpuscles generate waves in an Aethereal Medium, just like a stone thrown onto water generates waves. In addition, these corpuscles may be alternately accelerated and retarded by the waves.”

— Newton, Opticks, 1704.

Experiments gave results at odds with his theory. Although he was not able to explain diffraction, the simple way he described reflection and refraction phenomena gave his corpuscular theory favor over the wave theory.

Newton’s corpuscular description of light gained precedence over Grimaldi’s.

Waves again

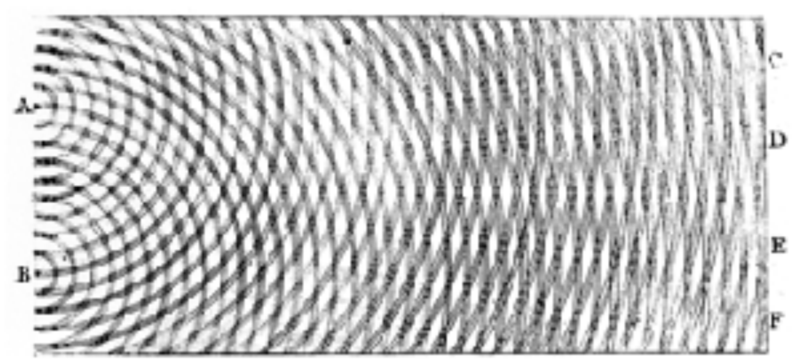
Huygens (1690) criticized Newton's theory because it was at odds with experimental observations and proposed Huygens' Principle*:

"every point on a wavefront acts as a source of a new wavefront, propagating radially outward."

Owing to the success of Newton's corpuscular theory, Huygens' ideas were not considered until the works of Young and Fresnel in the early 1800s.

Young (1804) improved upon Grimaldi's works to confirm Huygens theory, and performed the well-known double-slit experiment**.

— harshly criticized for opposing Newton, but eventually won over the scientific community with his ripple tank experiments



Young

Fresnel (1815) developed a formal theory that predicts the experimental results on diffraction. The theory was based on the Huygens principle and the theory of interference and established the wave nature of light***.

* Christian Huygens, Traité de la lumière, 1690.

** Thomas Young, 1804 The Bakerian lecture. Philosophical Transactions of the Royal Society of London 94 1-16.

*** Augustin-Jean Fresnel, Premier mémoire sur la diffraction de la lumière, 1815.

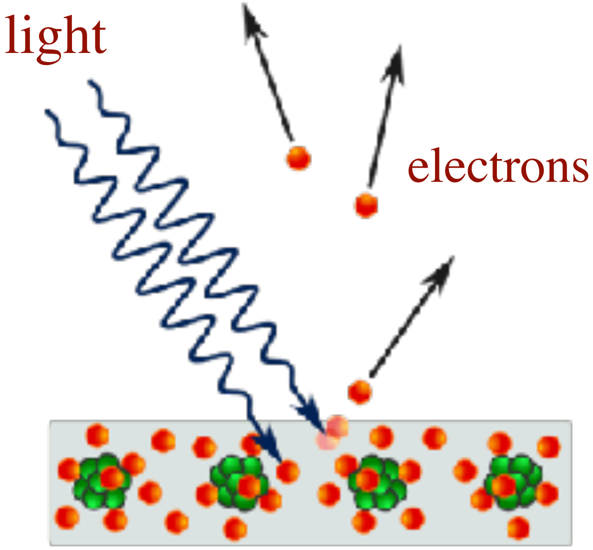
Particles, again

The wave nature of light was again questioned in the early 20th century by the works of Max Planck and Albert Einstein.

Planck stated that electromagnetic energy could be emitted with discrete values proportional to the frequency times the Planck constant *h*. He introduced the notion that electromagnetic energy could be exchanged via "quanta"*.

Note: Planck considered the quanta of light as a purely mathematical expedient without physical meaning.

Einstein (1905) demonstrated that the hypothesis of light quanta could rationalize the photoelectric effect, the emission of electrons from materials subjected to EM radiation (light)**.



* Planck, M. *Nobel Lecture* (1920).
** Einstein, A. *Annalen der Physik* 17 (6): 132–148 (1905).

J. J. Thomson suggested that a light diffraction experiment would have given a different diffraction pattern if performed with feeble light, where the intensity corresponds to a few light quanta. He presumably thought that diffraction was the result of interactions between quanta.

Reprinted from *Proc. Camb. Philos. Soc.*, **15** (1909), 114–115

Interference Fringes with Feeble Light

G. I. TAYLOR
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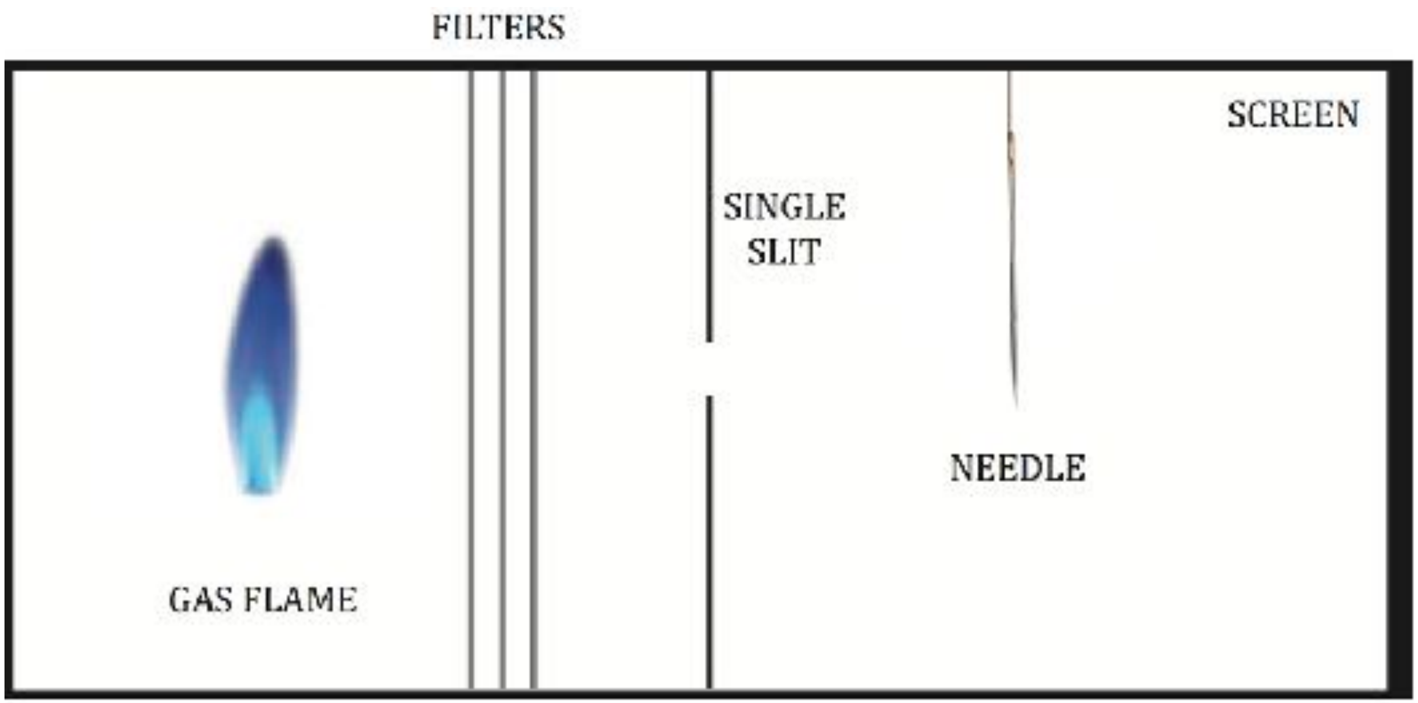
The phenomena of ionisation by light and by Röntgen rays have led to a theory according to which energy is distributed unevenly over the wave-front (J.J. Thomson, *Proc. Camb. Phil. Soc.* XIV. p.417, 1907). There are regions of maximum energy widely separated by large undisturbed areas. When the intensity of light is reduced these regions become more widely separated, but the amount of energy in any one of them does not change, that is, they are indivisible units.

Taylor’s experiment

The longest experiment lasted about 3 months, in which "*the amount of energy falling on the plate* [screen] *[…] was the same as that due to a standard candle burning at a distance slightly exceeding a mile.*"



Contrary to Thomson’s prediction, **Taylor observed the same diffraction pattern, independent of intensity**. He found that the wave nature of light does not depend on the amount of quanta, so inferred *that each quantum has an intrinsic wave nature*.

Taylor subsequently left `modern physics’ and became the most prominent fluid mechanician of his generation.

The modern treatment of the double slit experiment

Electron double slit diffraction experiments by Tonomura (1989)

The first single electron diffraction experiment with a double slit was first performed in … 2013

Controlled double-slit electron diffraction

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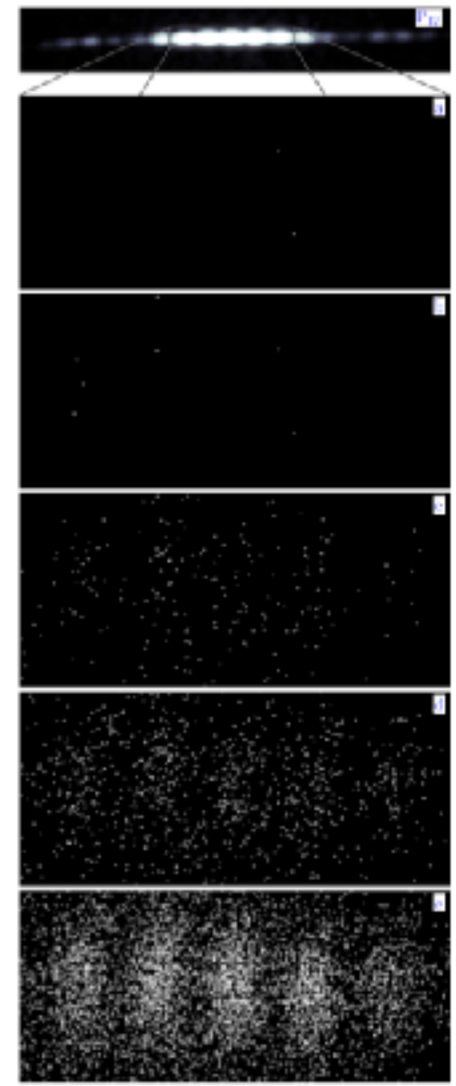
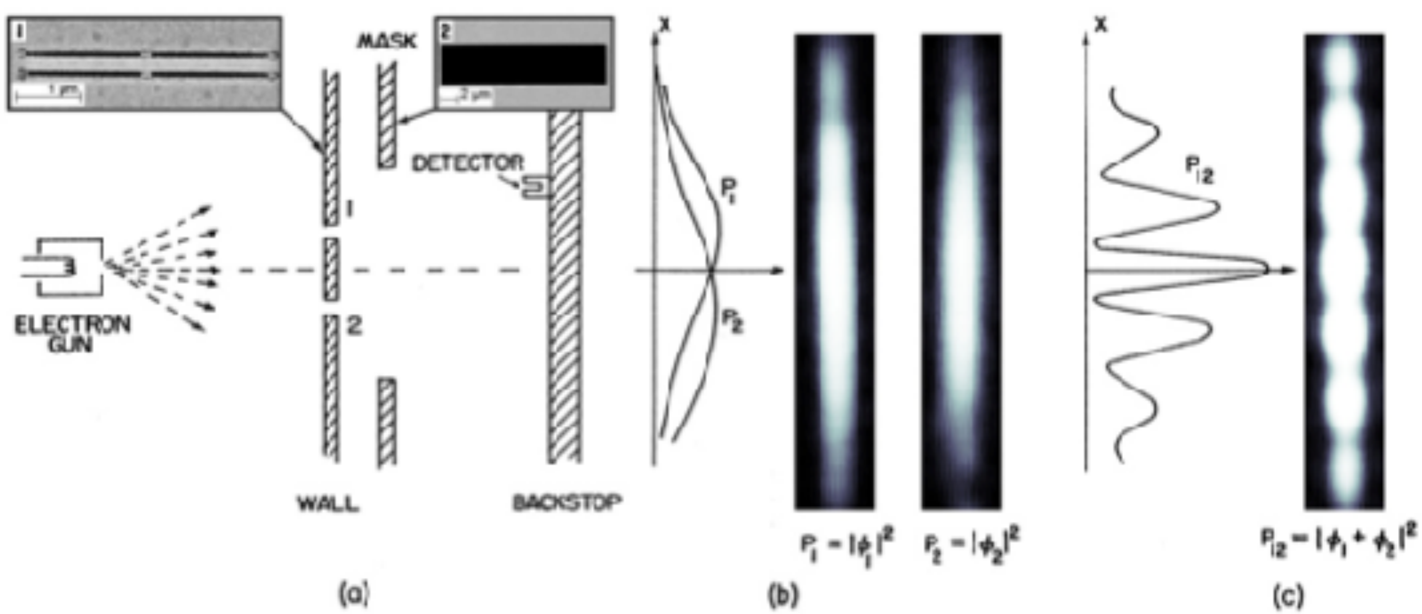
$$\lambda_{dB} = 50\,pm$$

$$width = 62\,nm$$

$$separation = 272\,nm$$

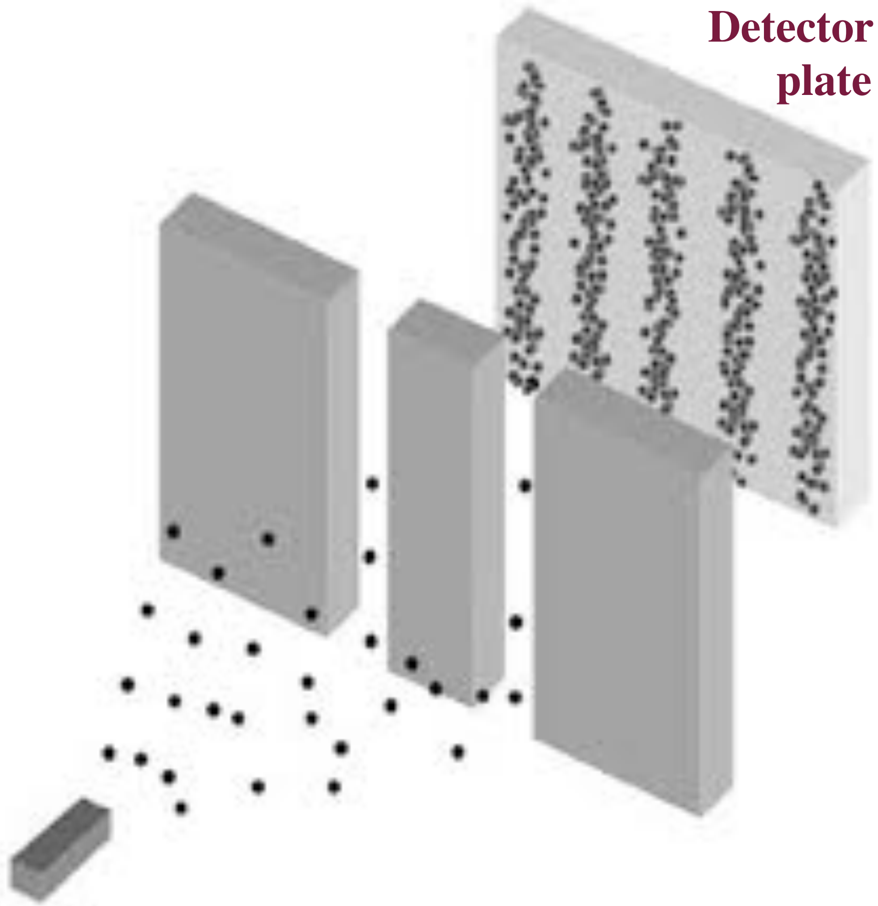
$$deepness = 100\,nm$$



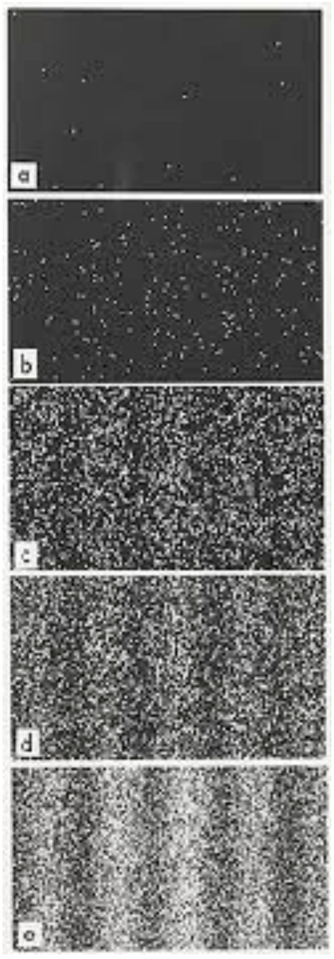


The double slit experiment: the central mystery of quantum theory

Is light a particle or a wave? And electrons?



Interference pattern



- interference pattern appears even when particles pass through one at a time
- interference pattern destroyed if you observe which slit particles pass through:

“ While the founding fathers agonized over the question `particle’ or `wave’, de Broglie in 1925 proposed the obvious answer `particle’ and `wave’…. This idea seems so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored”.

— John S. Bell

De Broglie (1920s)

- if light has both wave and particle natures, so too must matter
- proposed an association of a particle with an associated *matter wave*

Einstein-de Broglie relation:

$$mc^2 = \hbar\omega$$

De Broglie relation:

$$\mathbf{p} = \hbar\, \mathbf{k}$$

- a moving particle has an associated frequency and wavelength

→ **particles move in resonance with a guiding or `pilot' wave field**

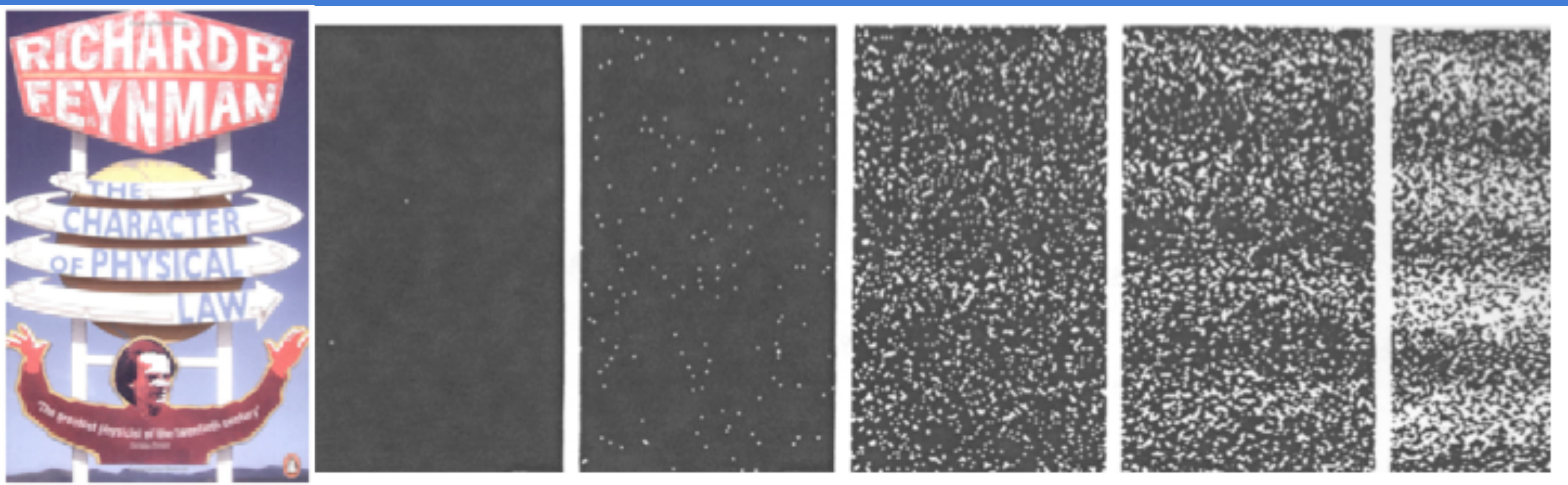
- predicted electron diffraction, the experimental confirmation of which by Davisson & Germer (1928) led to his Nobel Prize in 1929

``He has lifted a corner of the Great Veil."

— Einstein

Double slit experiment with electrons

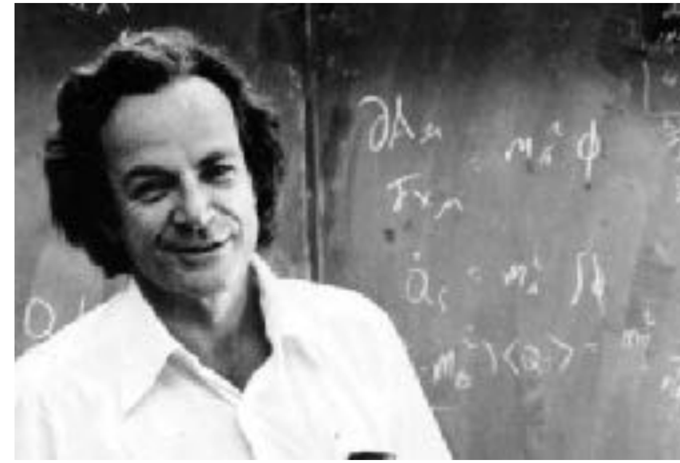
“ A phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.”



An interesting question

How differently might quantum foundations have evolved had this fluid system been known to its founding fathers?

Two comments by Richard P. Feynman…



"We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery. "*

“How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.”

…and one by John S. Bell

“De Broglie showed in detail how the motion of a particle, passing through just one of two holes in the screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, **that it is a great mystery to me that it was so generally ignored.**”

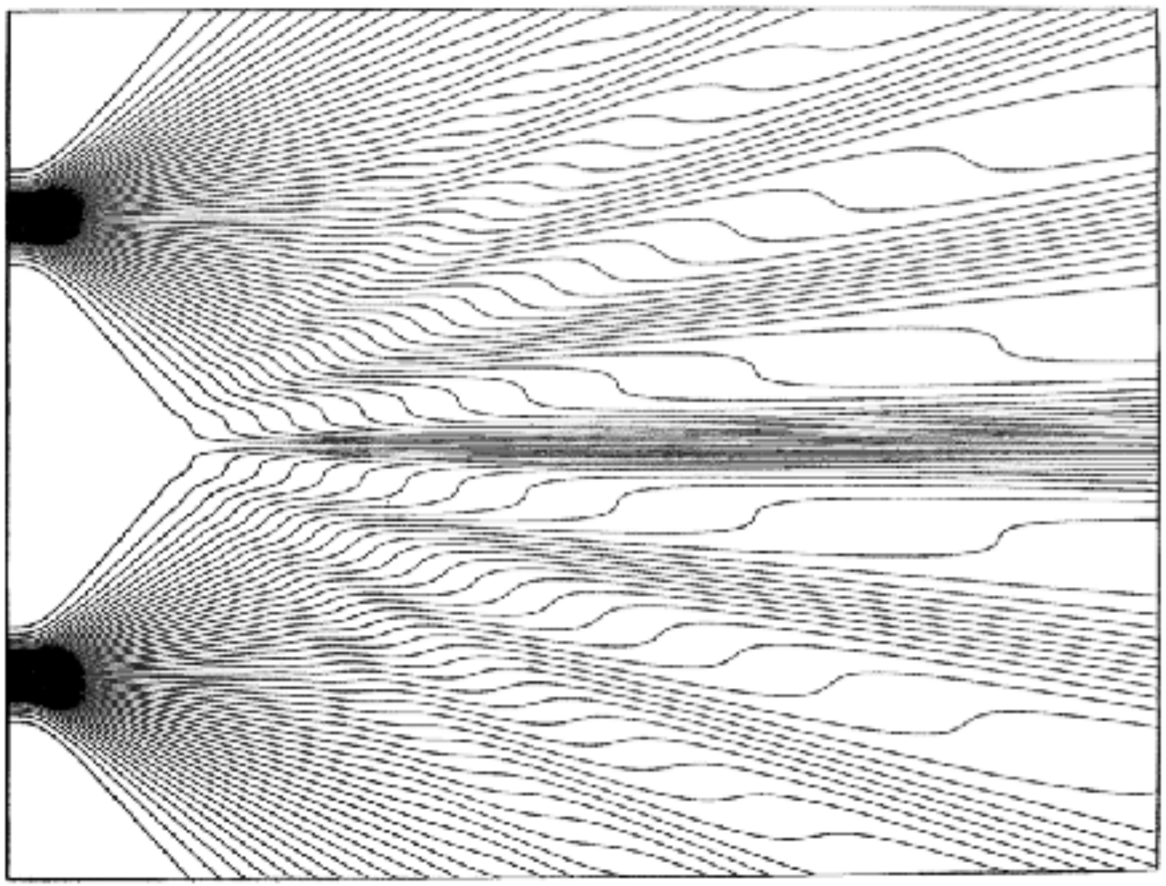
* Feynman R., Leighton R. B. and Sands M.L. 1965 *The Feynman Lectures on Physics: Quantum Mechanics* vol3. Chapter 1.

“Attempts have been made by de Broglie, David Bohm and others to construct theories based on hidden variables, but the theories are very complicated and contrived. For example, the electron would definitely have to go through only one slit in the two-slit experiment. To explain that interference occurs only when the other slit is open, it is necessary to postulate a special force on the electron which exists only when that slit is open. Such artificial additions make hidden variable theories unattractive, and there is little support for them among physicists.”

- Encyclopedia Britannica (2007)

Bohmian trajectories: Theoretical predictions

- trajectories deduced with a Gaussian distribution of initial position at each slit
- results consistent with standard predictions of quantum theory



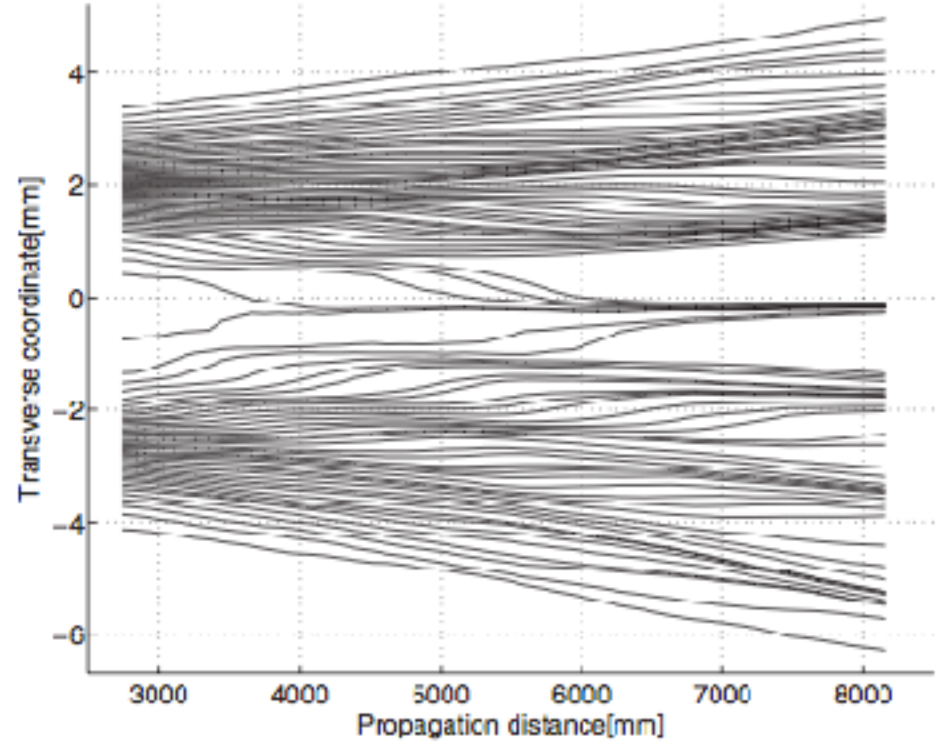
* Philippidis C., Bohm D., Kaye R. D. The Aharonov-Bohm effect and the Quantum Potential. *Il Nuovo Cimento* **71B**, 1:75-88 (1982).

Bohmian trajectories via weak measurement

3 JUNE 2011 VOL 332 SCIENCE

Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer

Sacha Kocsis,[1,2]* Boris Braverman,[1]* Sylvain Ravets,[3]* Martin J. Stevens,[4] Richard P. Mirin,[4] L. Krister Shalm,[1,5] Aephraim M. Steinberg[1]†



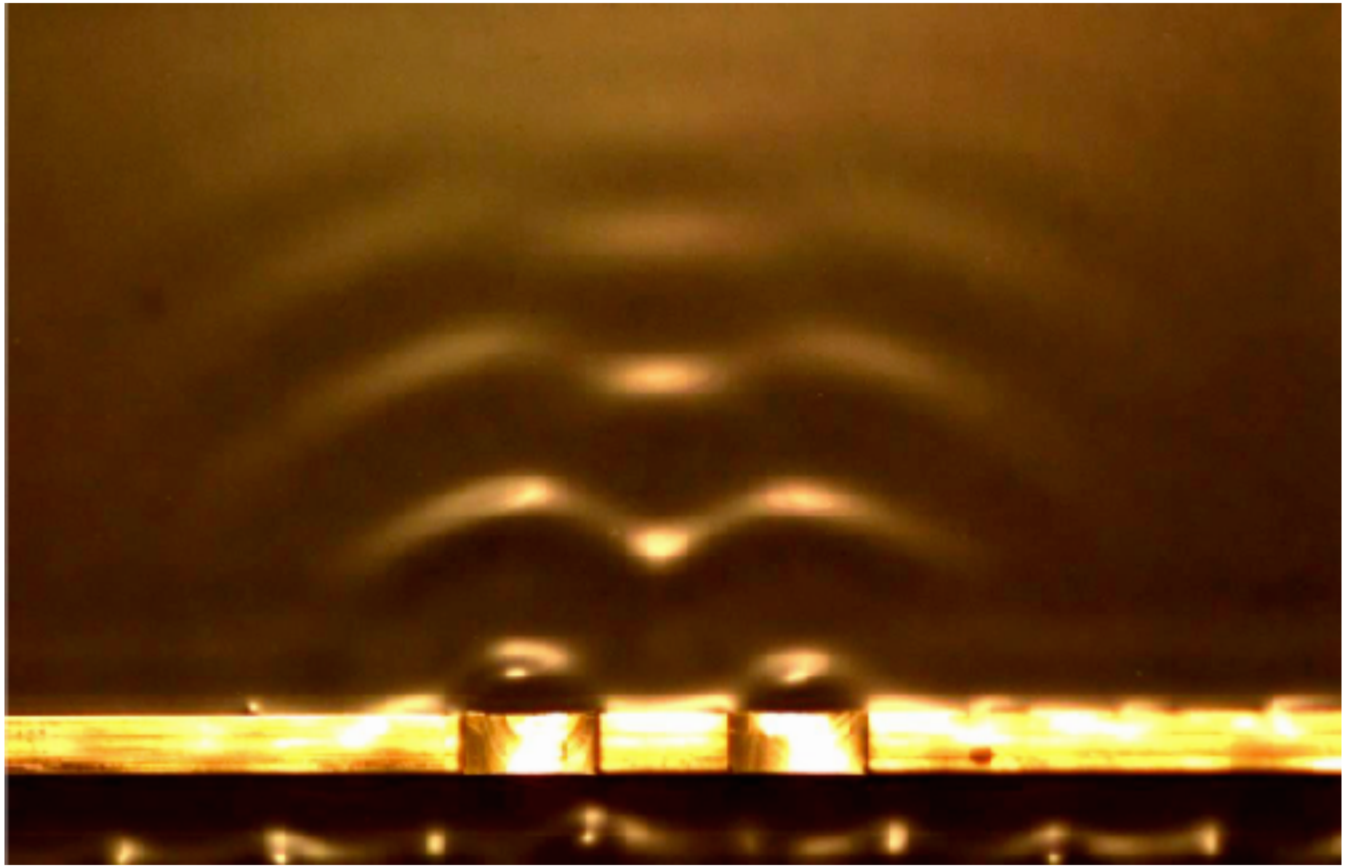
Published online 2 June 2011 | Nature | doi:10.1038/news.2011.344

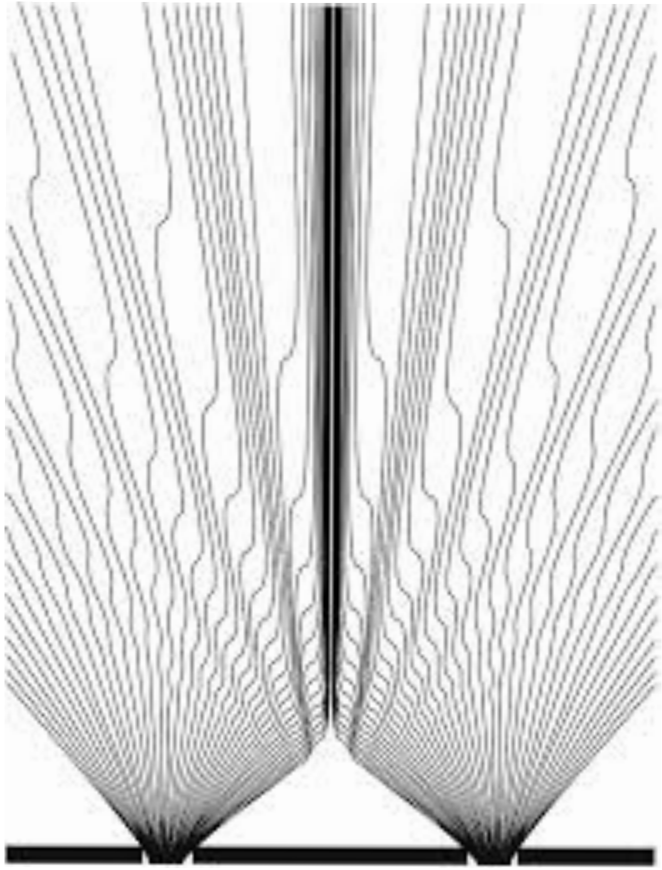
David Deutsch of the University of Oxford, UK, is not convinced that the experiment has told us anything new about how the universe works. He says that although "it's quite cool to see strange predictions verified", the results could have been obtained simply by "calculating them using a computer and the equations of quantum mechanics".

"Experiments are only relevant in science when they are crucial tests between at least two good explanatory theories," Deutsch says. "Here, there was only one, namely that the equations of quantum mechanics really do describe reality."

A more sensible objection

- how is the quantum potential generated in such systems?

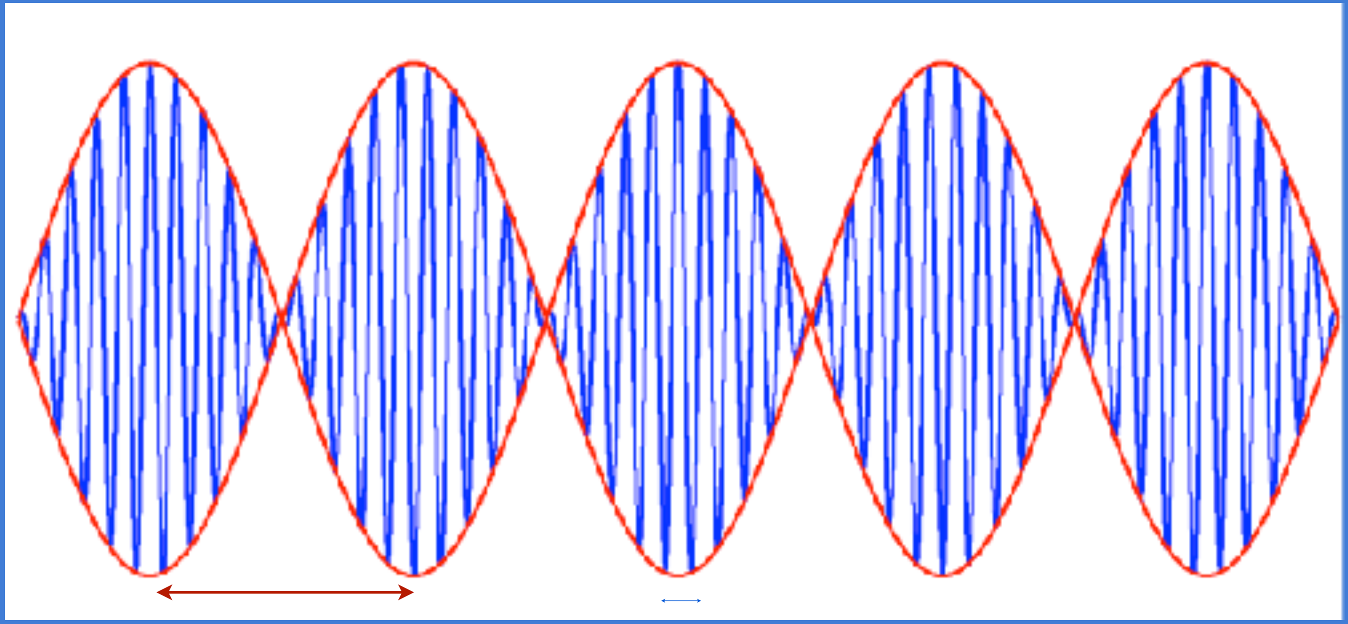




- does it rely on the successive release of particles over a short time scale?
- does it rely on the particles feeling the wakes of their forerunners?
- or does it simply represent a mean field as would influence the statistics?

The Quantum Pilot Wave (according to SED)

- EM wave generated by resonant interaction between particle ZTB and the vacuum fluctuations

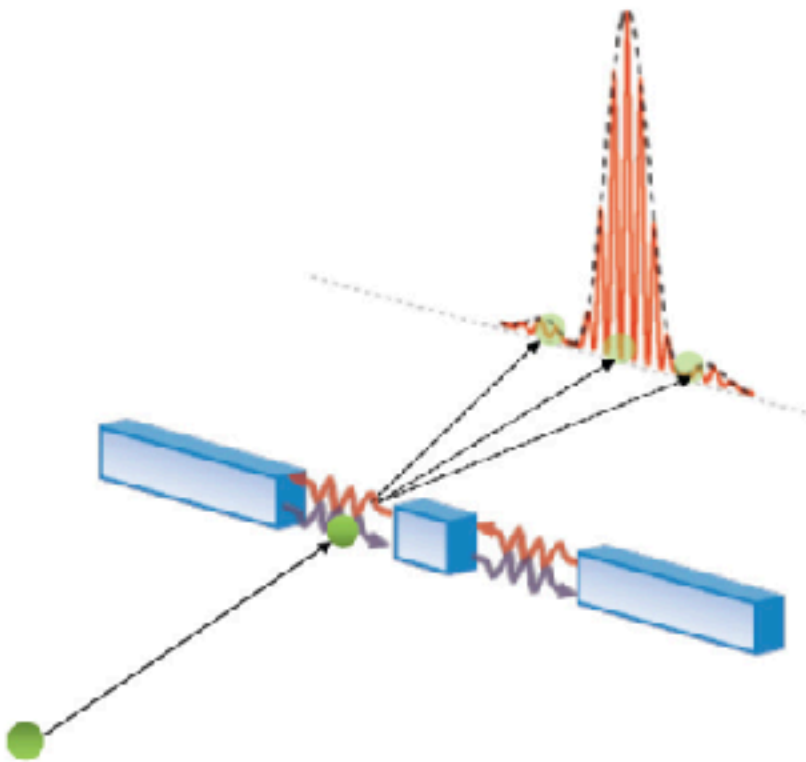


$$\lambda_B = \frac{h}{mv} \qquad \lambda_c = \frac{h}{m_o c}$$

"The de Broglie wave is the wave formed by the modulation of the Lorentz-transformed, Doppler-shifted superposition of the whole set of random, stationary EM waves with the Compton frequency with which the particle interacts."

- De la Pena & Cetto (Quantum Dice, 1997)

Stochastic Electrodynamics: Double Slit Electron Diffraction
from de la Pena and Cetto "The Emergent Quantum" (2014)



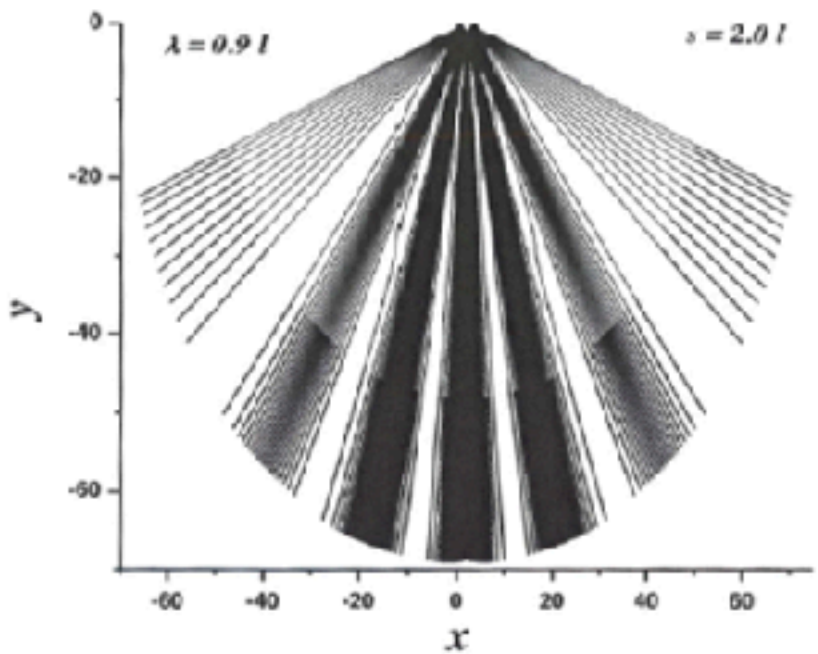
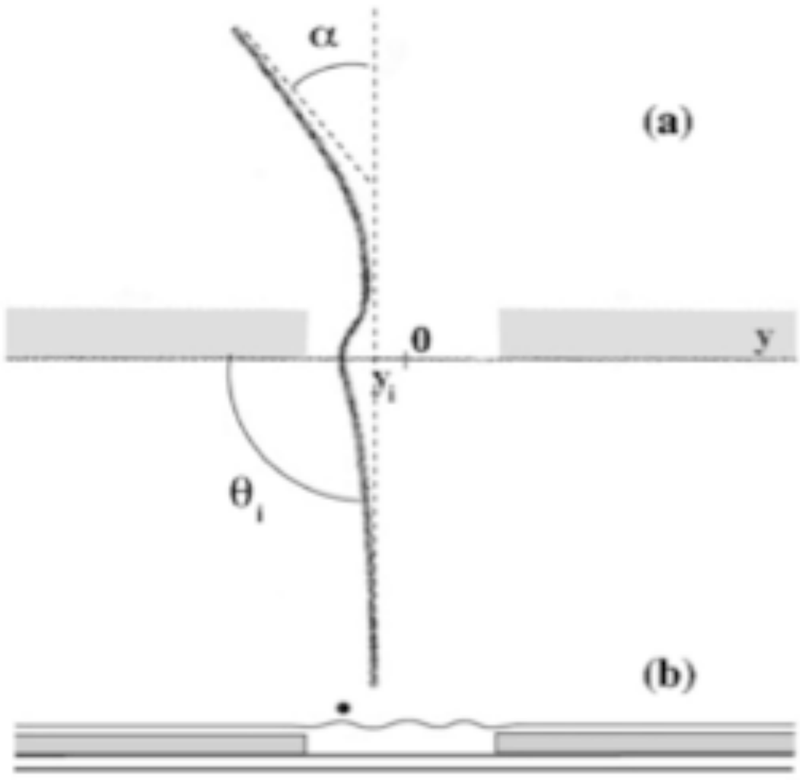


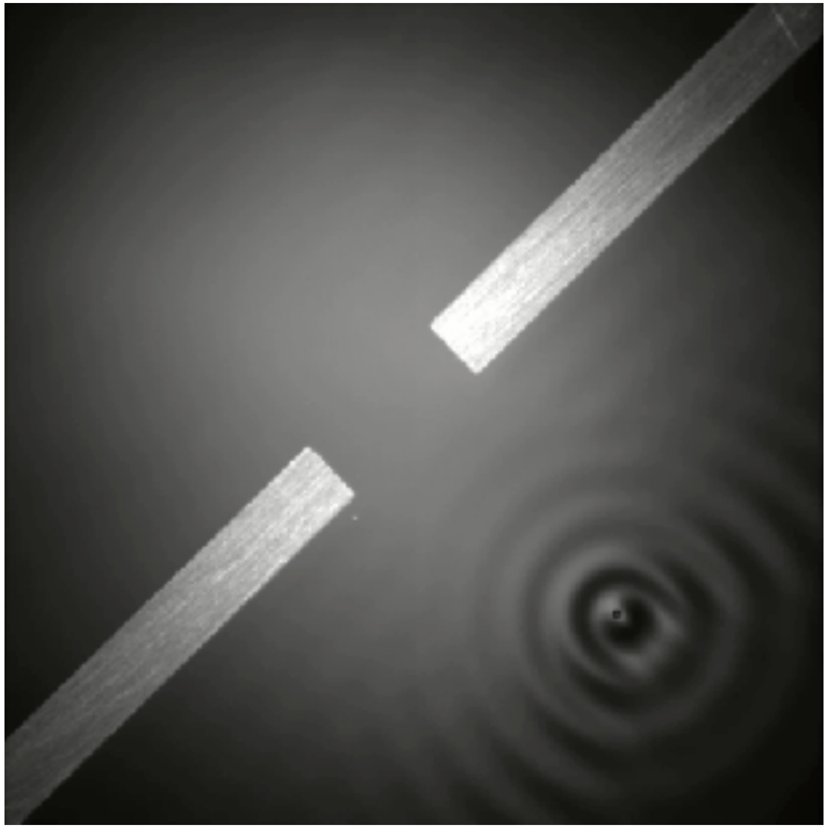
Fig. 9.2 Trajectories followed by electrons in a realistic simulation of a two-slit experiment. The particles are uniformly distributed in the beam behind the slits. The diffracted modes of the field have momentum p_B and the momentum of the particles is p, with $p = p_B$. Figure courtesy of J. Avendaño, adapted from Avendaño and de la Peña (2010)

Diffraction of walkers

(Couder & Fort 2006)

- the walkers are droplets piloted by their accompanying wave fields
- what happens when they pass through a slit?

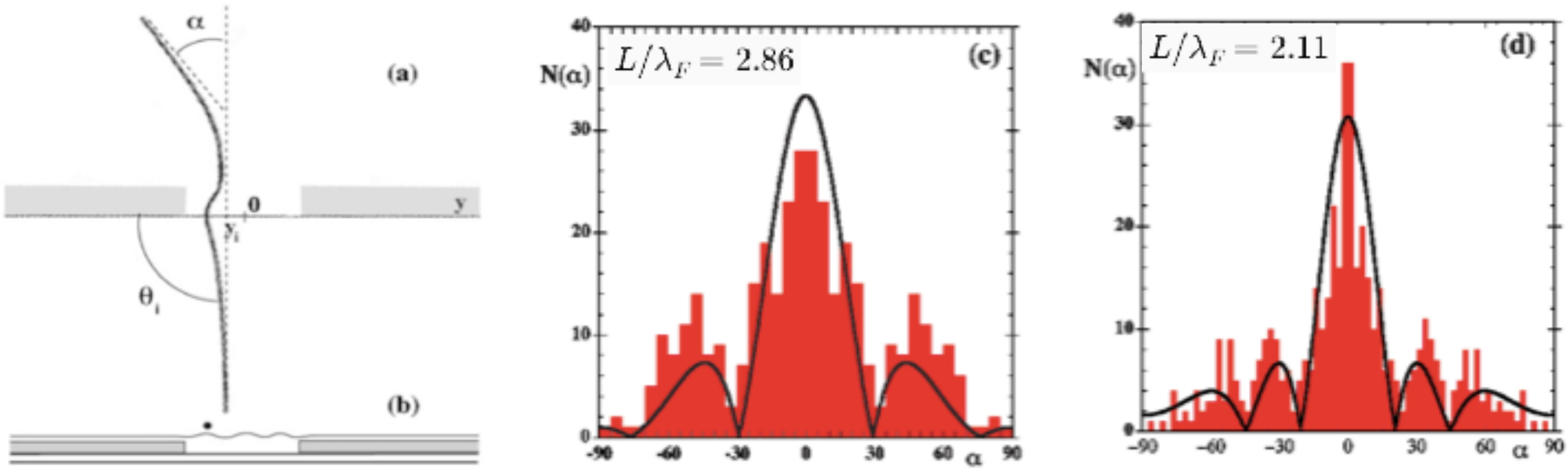




- far from threshold (weak waves), nothing interesting happens
- as threshold approached (strong waves), each drop is randomly deflected
- ..... and the statistics?

Diffraction of walkers: Single slit

(Couder & Fort 2006)



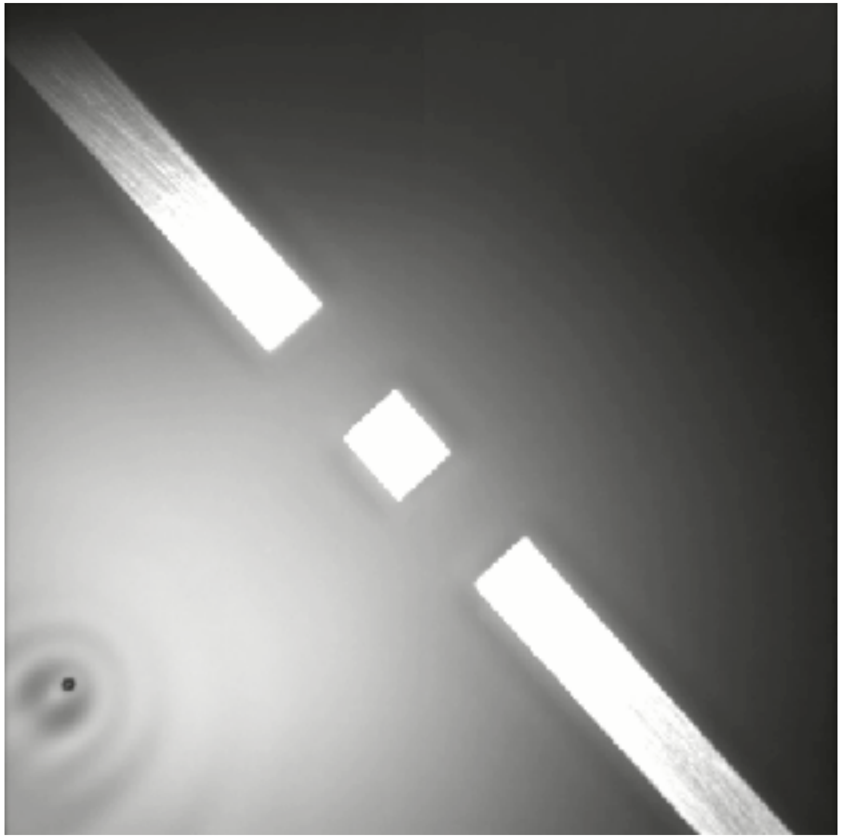
- distortion of waves passing through slit leads to particle diffraction
- data sets gathered from 125 trajectories from a single drop, symmetrized
- impact parameters uniformly distributed so as to best mimic a place wave

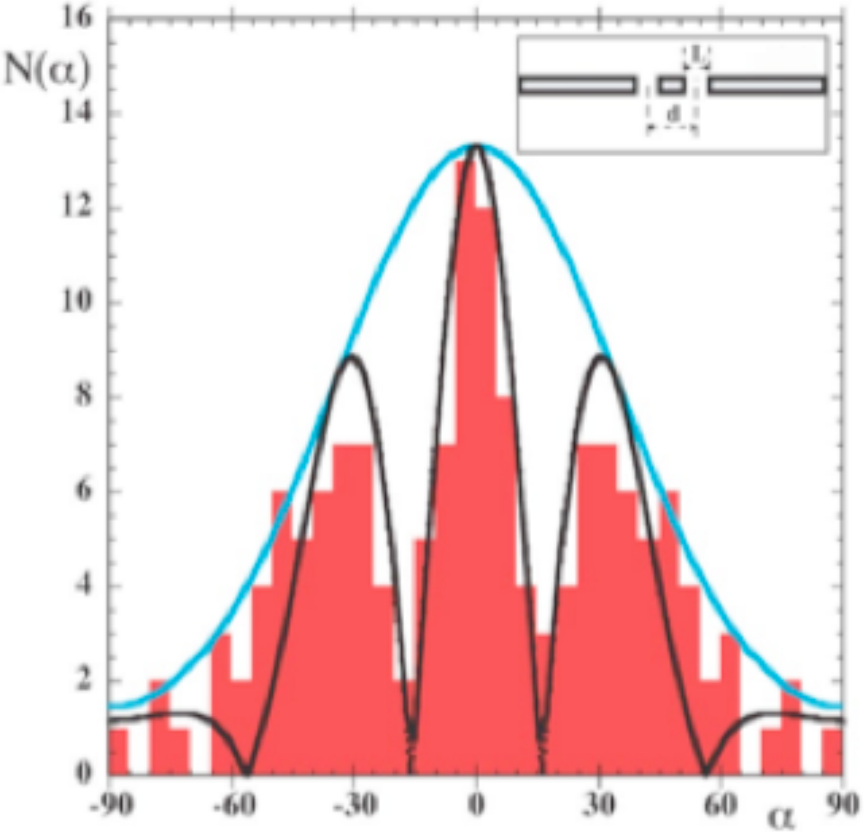
Data fit to Fraunhofer diffraction pattern: $f(\alpha) = A\left|\frac{\sin(\pi L \sin\alpha/\lambda_F)}{\pi L \sin\alpha/\lambda_F}\right|.$

valid for far field $X/L \gg L/\lambda_F$, which is *not* the case here

Double-slit experiment

Couder & Fort (2005)





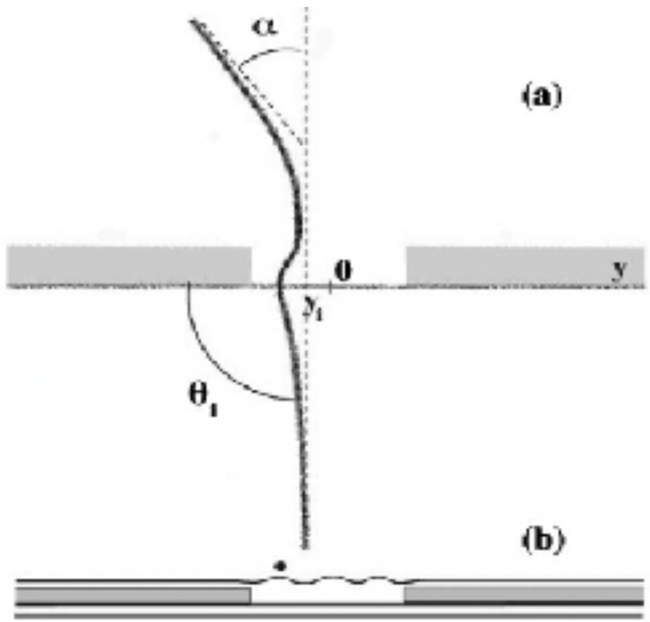
- data gathered from 75 trajectories from a single drop, symmetrized

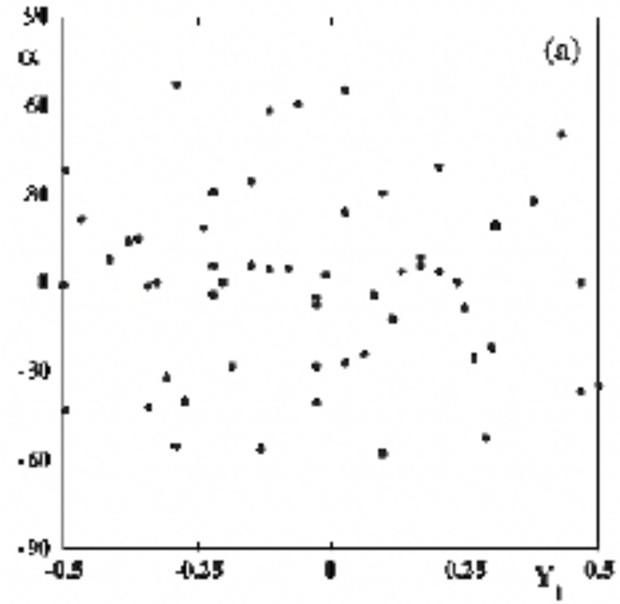
Fit to Fraunhofer diffraction pattern: $f(\alpha) = A\left|\frac{\sin(\pi L \sin\alpha/\lambda_F)}{\pi L \sin\alpha/\lambda_F}\cos(\pi d \sin\alpha/\lambda_F)\right|$

valid for far field $X/L \gg L/\lambda_F$, which is *not* the case here

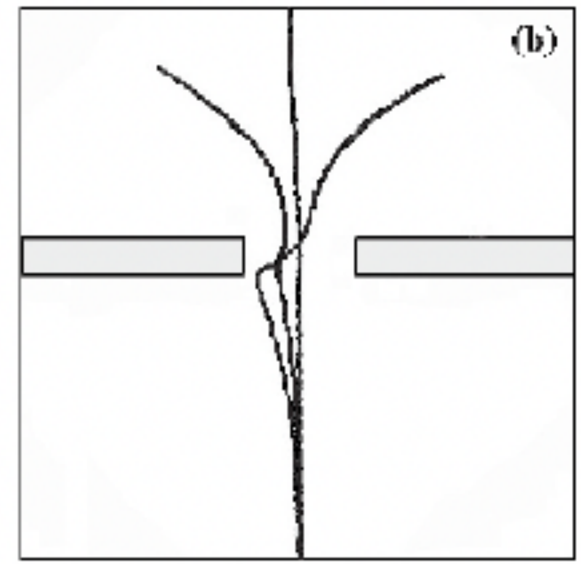
- run just below Faraday threshold to ensure extended pilot-wave
- particle passes though one slit, but its wave is influenced by both

Evidence of chaos in slit diffraction





Identical impact parameters



- no correlation between impact parameter and deflection angle
- evidence of chaos: extreme sensitivity to initial conditions

Experimental problems

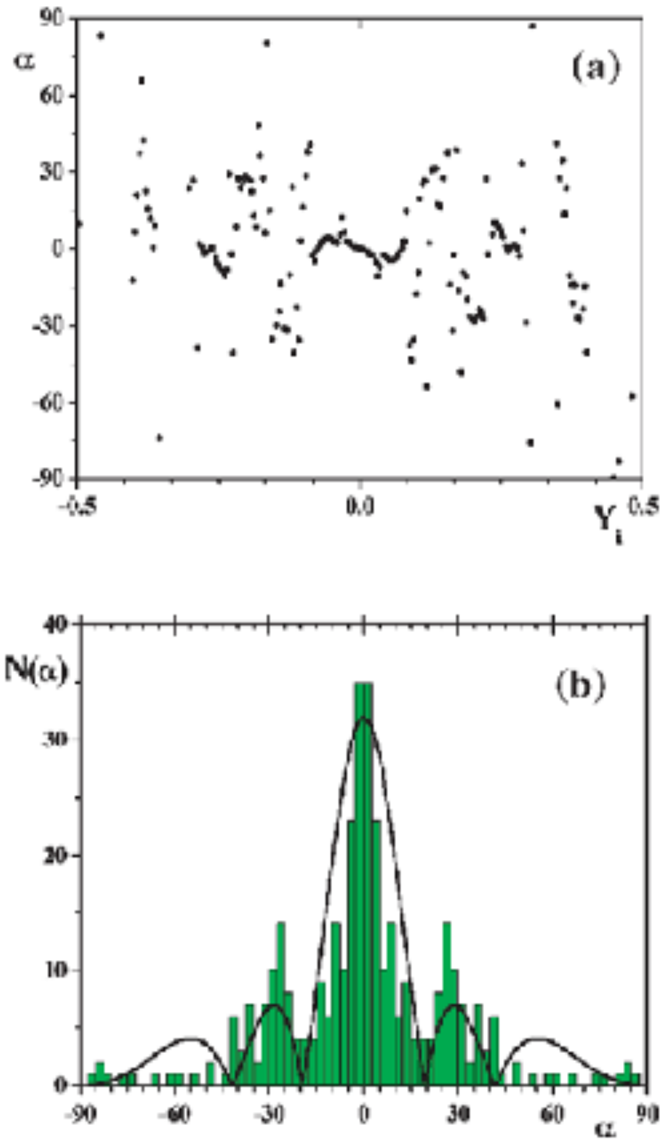
- all were performed in a single session with a single drop
- neither drop size nor vibrational acceleration were either reported or measured
- experiments performed without a lid, exposing experiments to ambient air currents

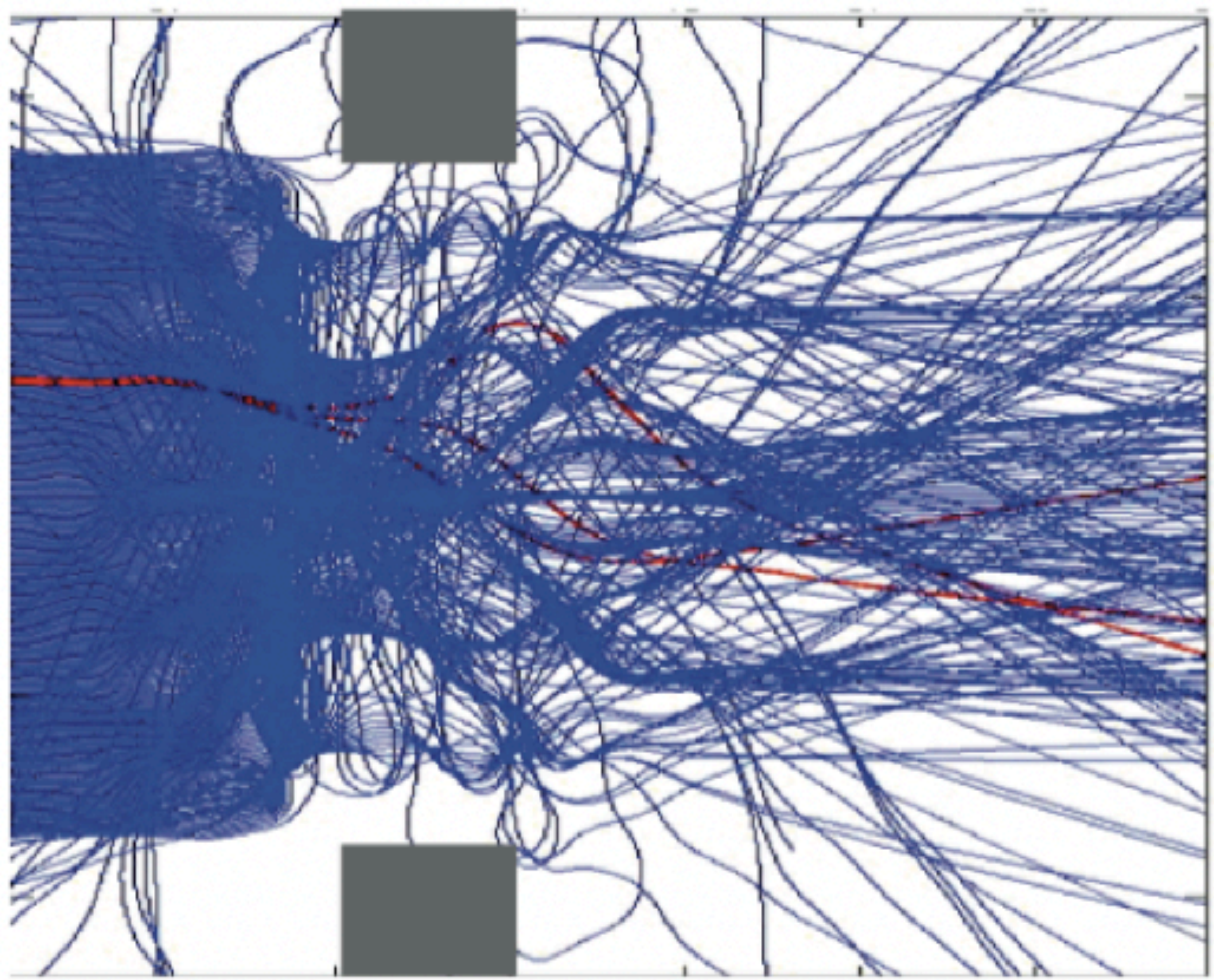
The path-memory model

$$m\frac{d\mathbf{r_i}}{dt} \propto \nabla\zeta(\mathbf{r_i}, \mathbf{t_i})$$

$$\boldsymbol{x}_{n+1} = \boldsymbol{x}_n + \boldsymbol{v}_{n+1}T_{\mathrm{F}},$$

$$\boldsymbol{v}_{n+1} = \mathrm{e}^{-Dt_s/m}\left(\boldsymbol{v}_n - |v_z|\boldsymbol{\nabla}\tilde{h}(\boldsymbol{x}_n, t_n)\right)$$



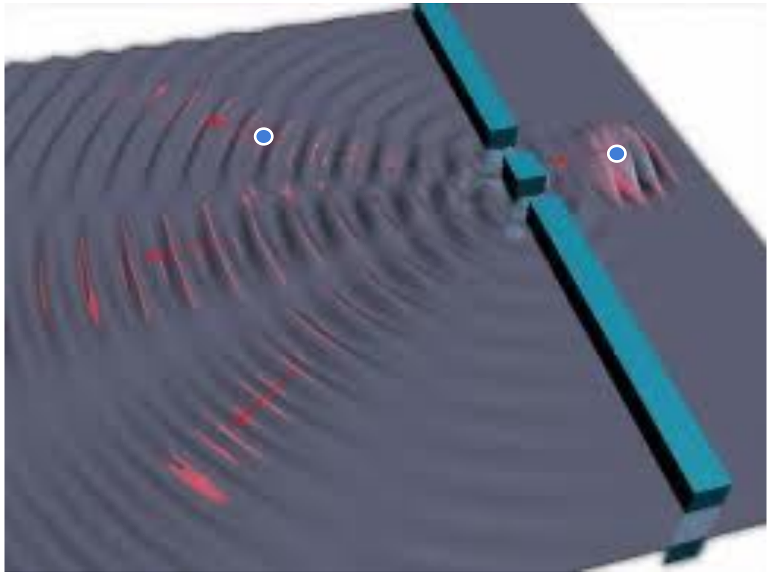


What is the mystery of single-particle diffraction in QM?

- interference persists even when electrons pass through one at a time
- interference disappears if you observe through which slit the electron passes

Note

- there is no mystery if one ascribes to pilot-wave theory
- the pilot waves pass through both slits, guide the particle



And in the bouncing droplet experiments?

- there is no measurement problem: observation is not intrusive
- however, one can envision a measurement technique so heavy-handed as to destroy the interference pattern

e.g. "observe" droplets via collision with incident stream of droplets

Comment on

Y. Couder and E. Fort:

Single-Particle Diffraction and Interference at a Macroscopic Scale

Phys. Rev. Lett. 97, 154101 (2006).

Anders Andersen[1], Jacob Madsen[1], Christian Reichelt[1], Sonja Rosenlund Ahl[1], Benny Lautrup[2], Clive Ellegaard[3], Mogens T. Levinsen[3], and Tomas Bohr[1]

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[2]*Niels Bohr International Academy, The Niels Bohr Institute*

[3]*The Niels Bohr Institute, University of Copenhagen, Denmark*

Note: no experimental results are reported.

"We have tried to reproduce their results experimentally with our own **double slit** set-up, but without success. "

PHYSICAL REVIEW E **92**, 013006 (2015)

Double-slit experiment with single wave-driven particles and its relation to quantum mechanics

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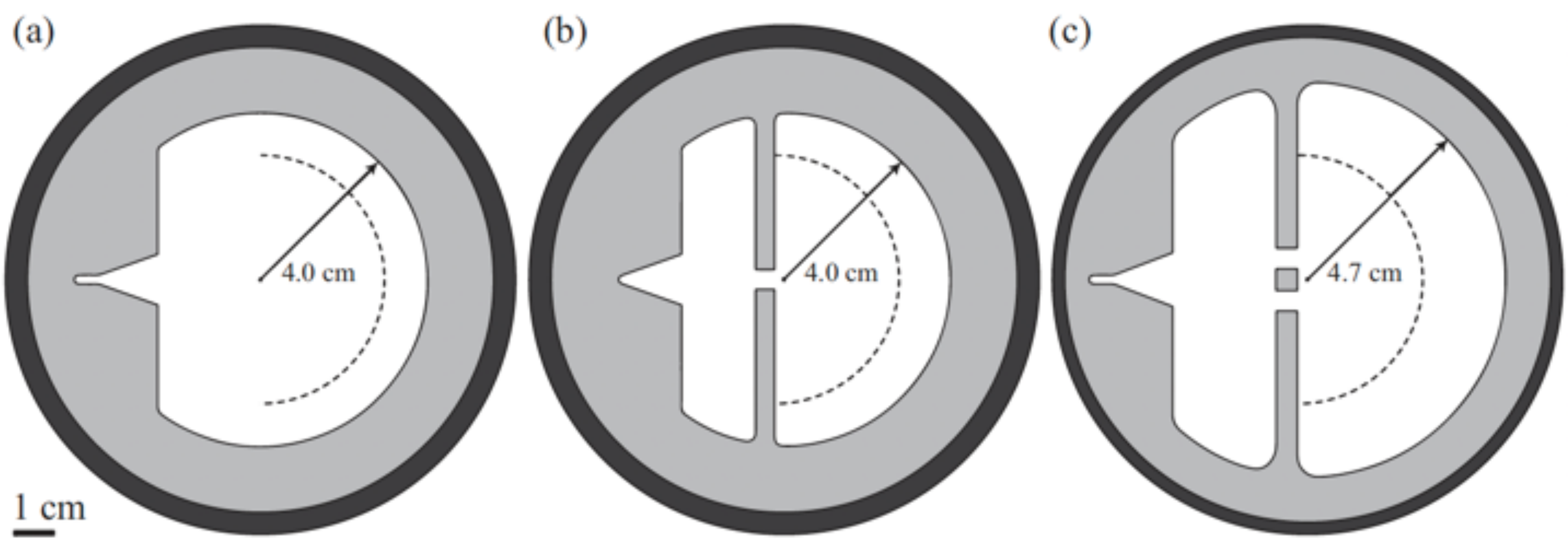
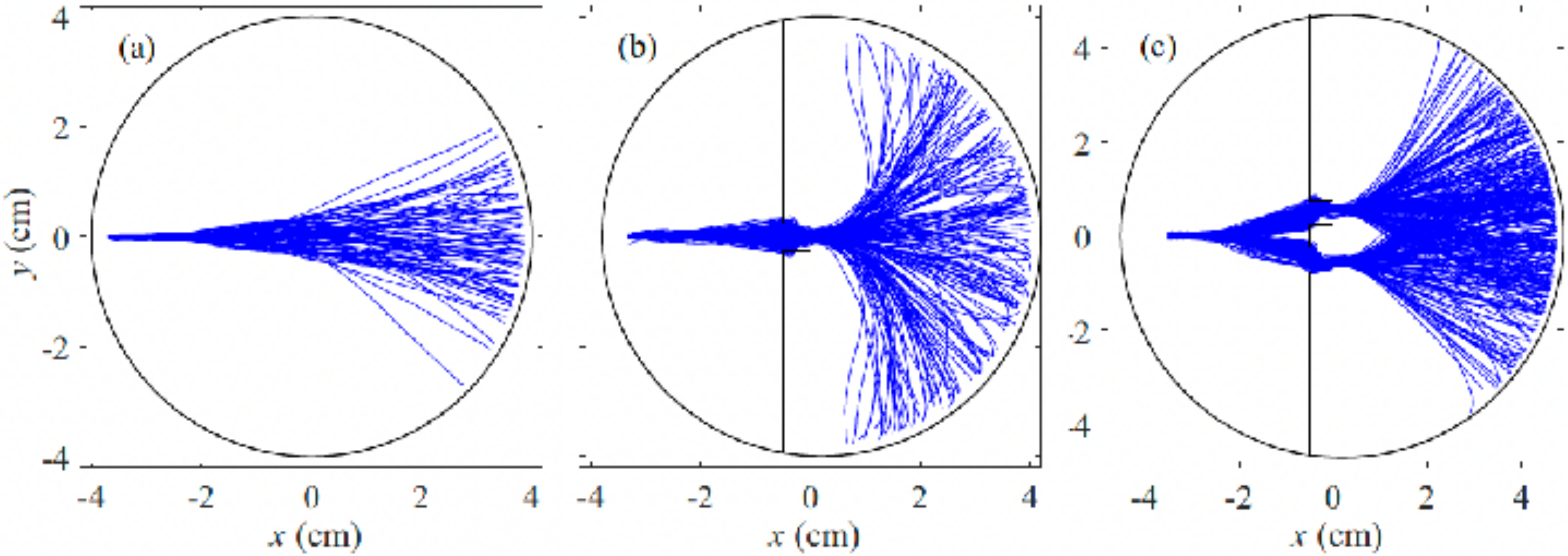
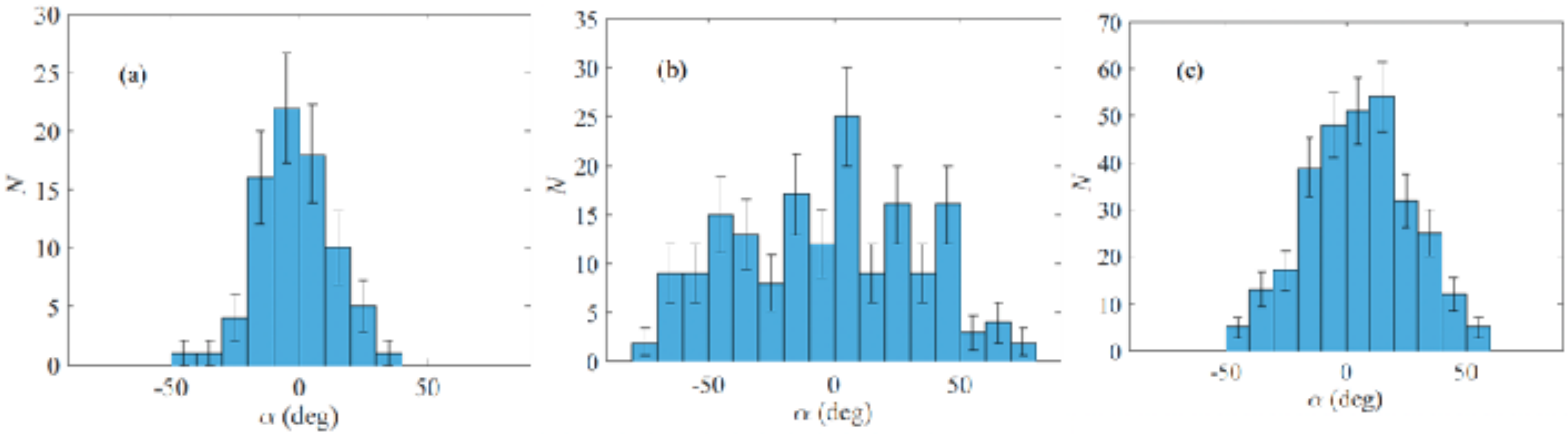






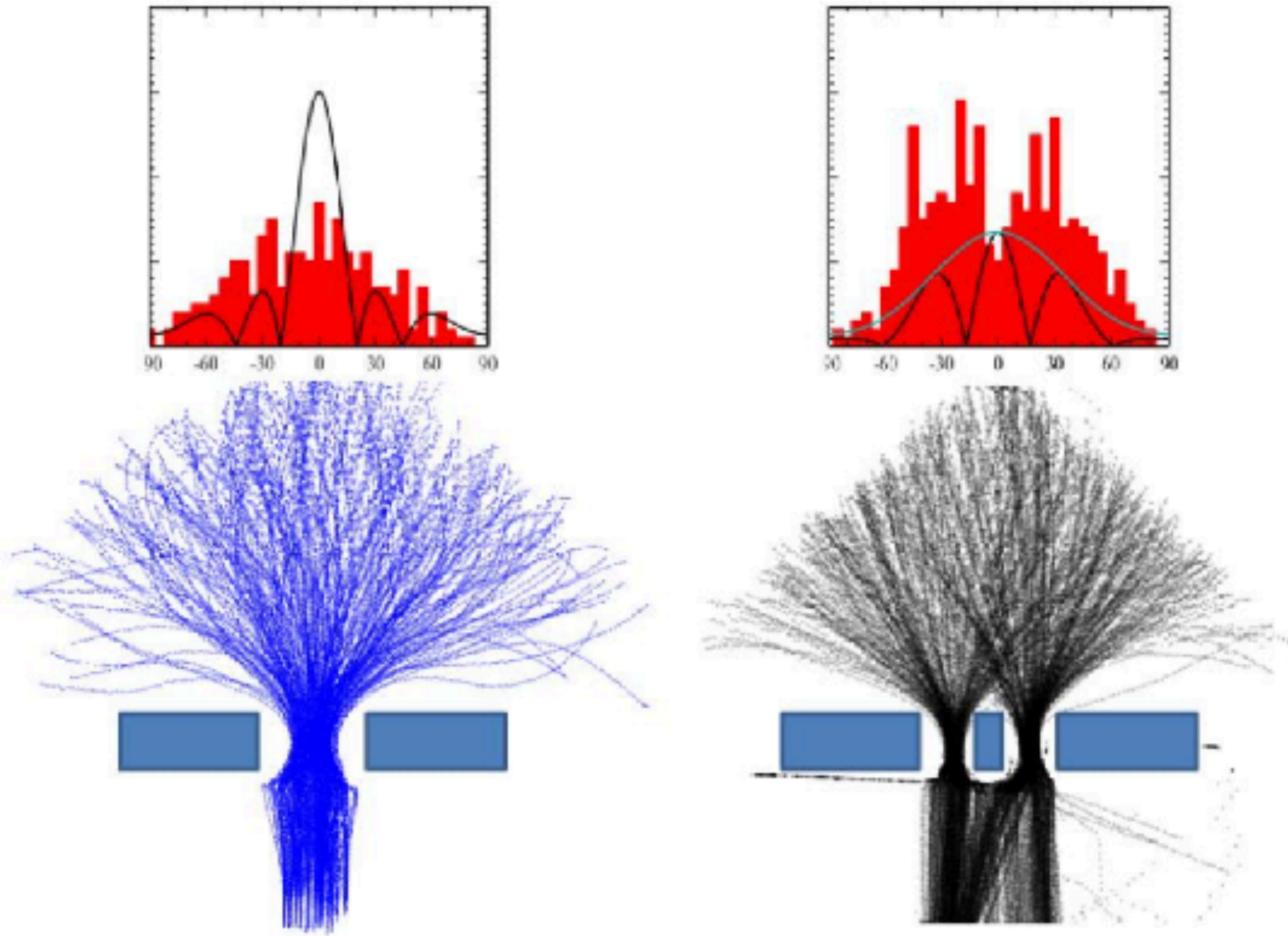
- domain too small; absence of straight trajectories suggest influence of air currents
- specious arguments suggesting influence of second slit is negligible
- sound arguments concerning sparse statistics in experiments of Couder & Fort

Momentum exchange in the electron double-slit experiment

Batelaan, H., Jones, E., Huang, W. C. W., & Bach, R. (2016).

EmQM15: Emergent Quantum Mechanics 2015 IOP Publishing
Journal of Physics: Conference Series 701 (2016) 012007 doi:10.1088/1742-6596/701/1/012007

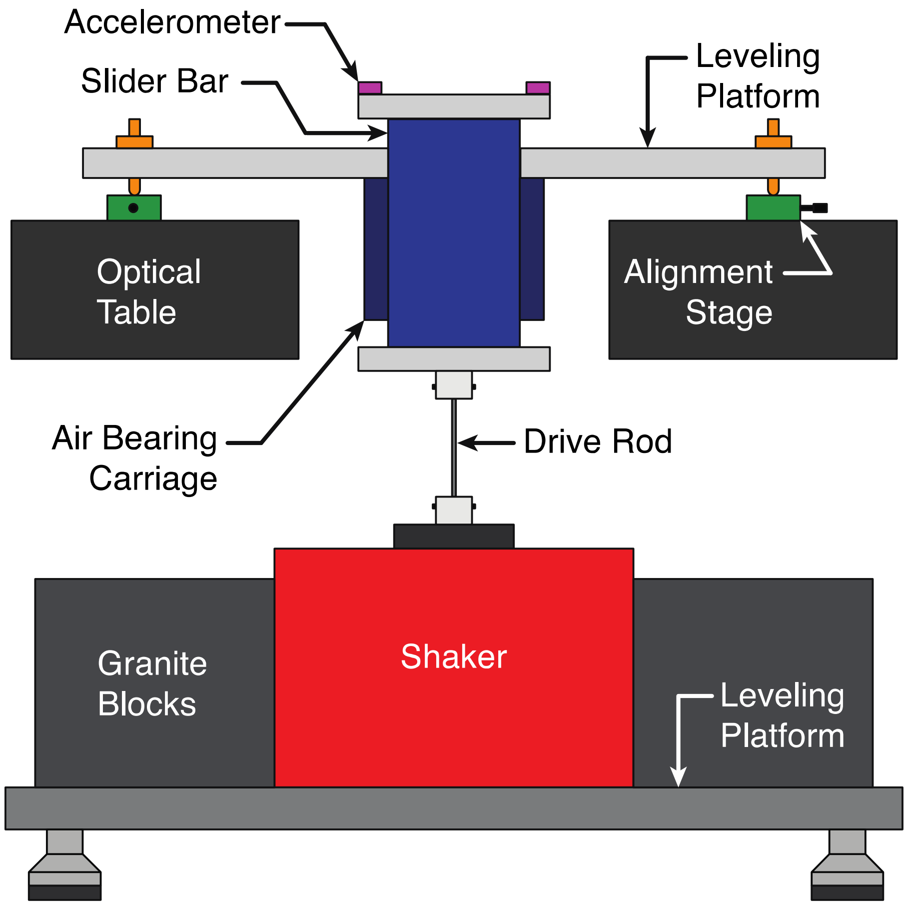
No straight trajectories

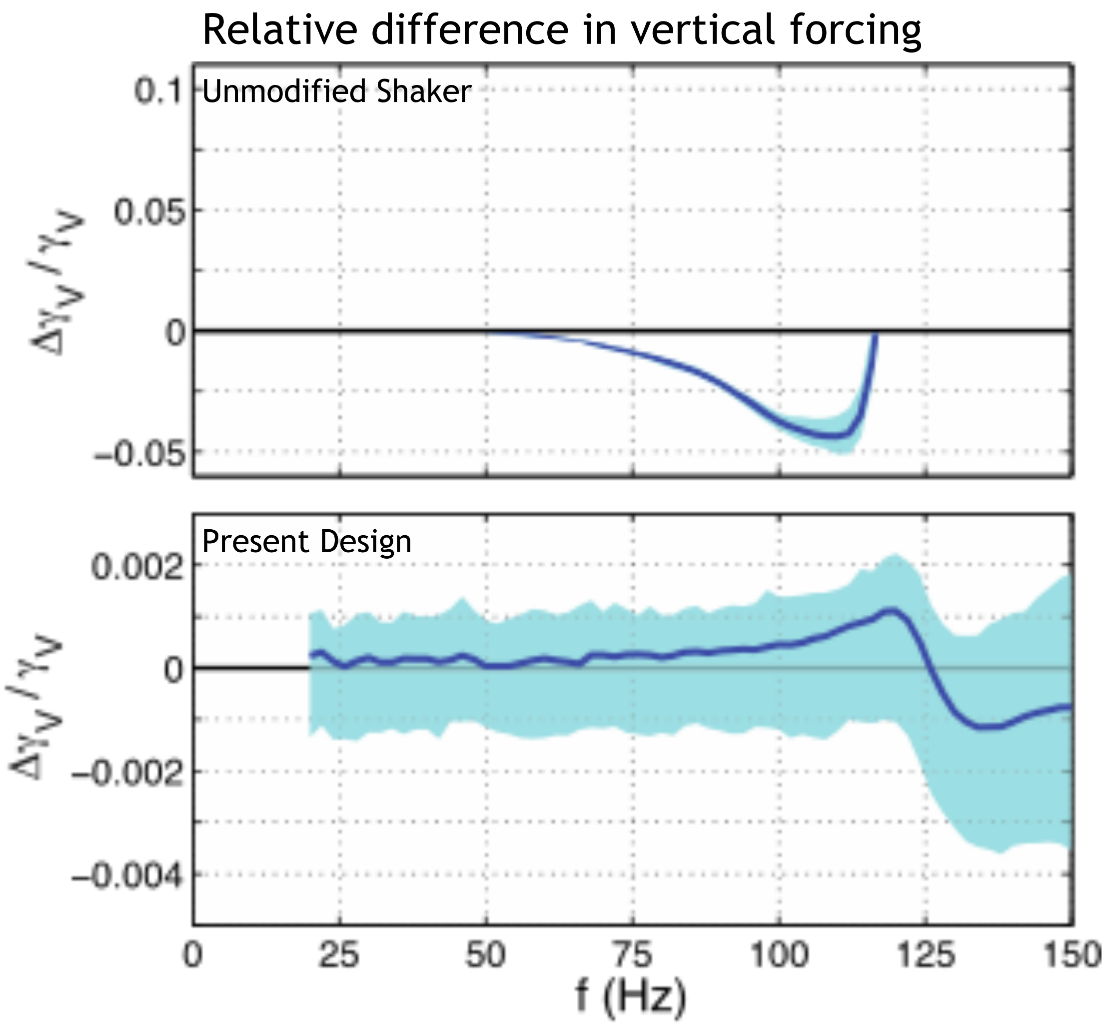


Experimental refinements of Dan Harris

Uniaxial Vibration Generation

$$a(t) = \gamma \cos(\omega t)$$

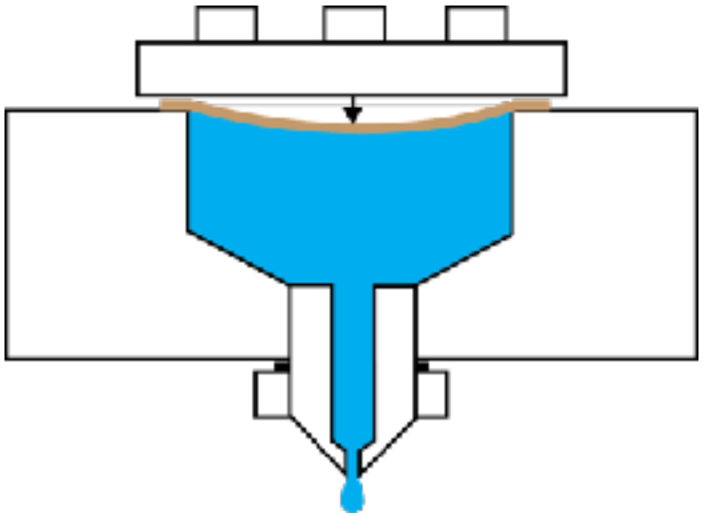




- standard electromagnetic shakers are plagued with resonances which can lead to significant non-axial motion of payload
- shaker guided by air-bearing provides uniform vibration to within **0.1%** in measured vertical acceleration

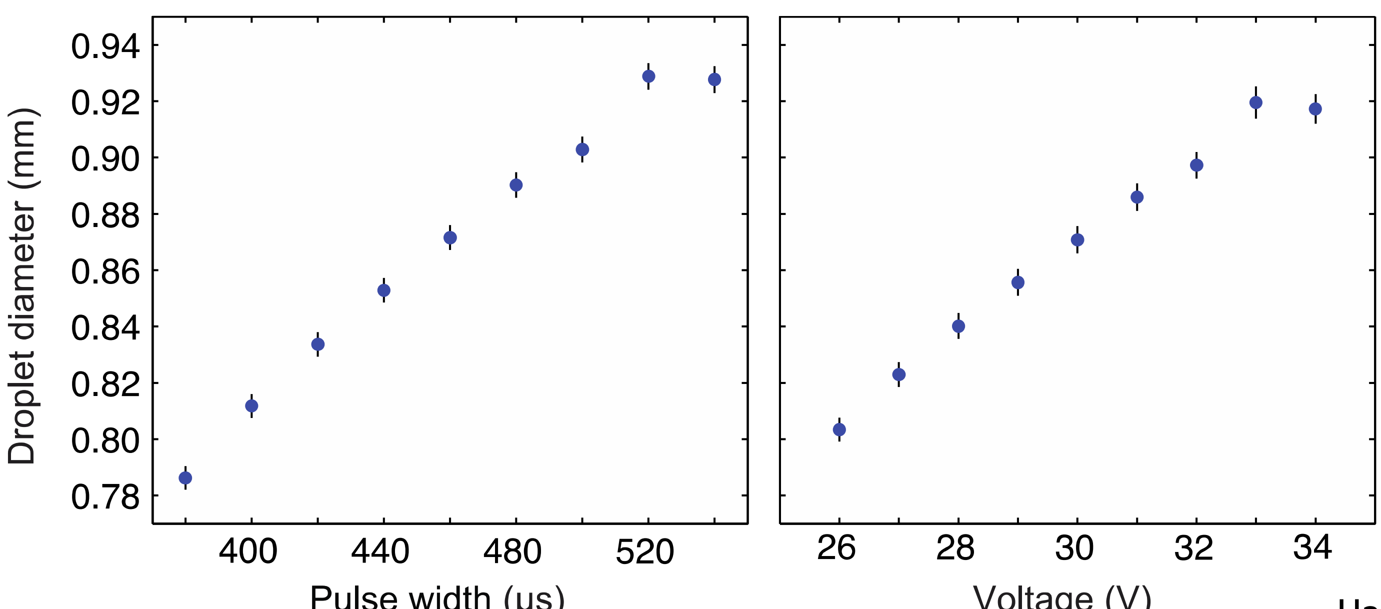
Harris & Bush, *JSV* (2015)

Piezoelectric Droplet Generator



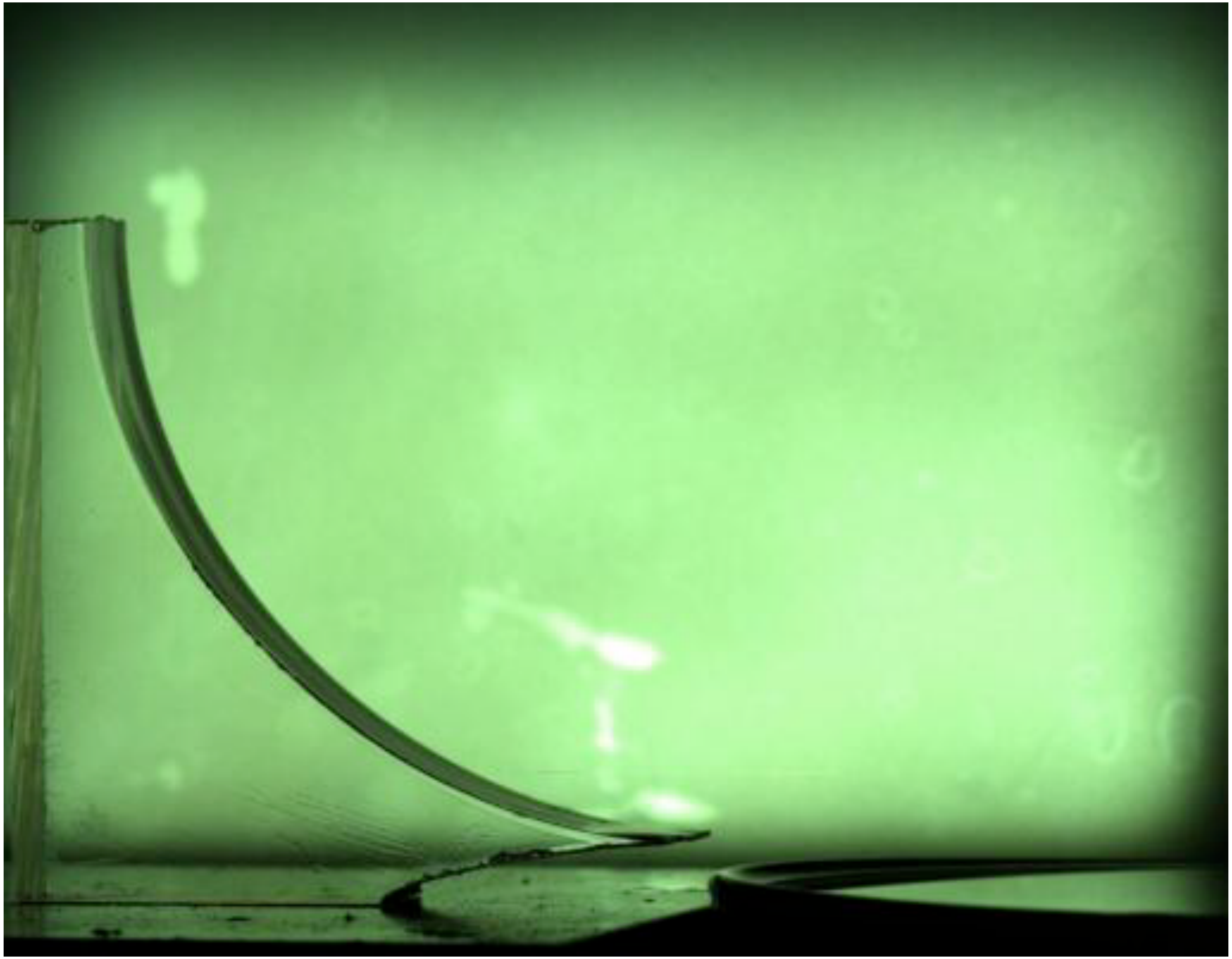
- simple droplet-on-demand generator with variation of droplet diameter **less than 1%** between experiments

- by varying the parameters of the electrical pulse, different droplet sizes can be achieved with the same nozzle



Harris, Liu & Bush, *Exp. Fluids* (2015)

Droplet Slide



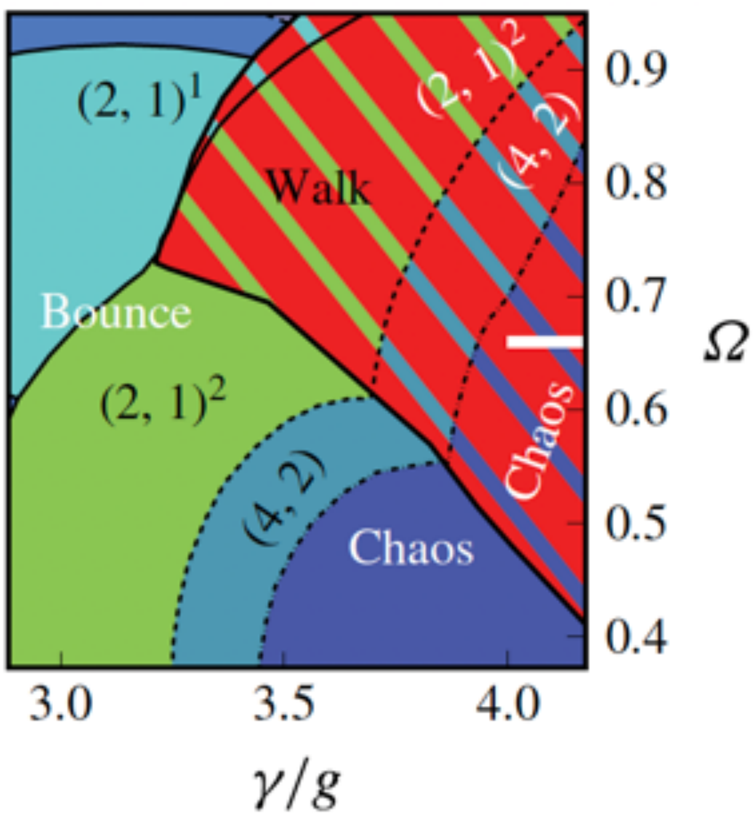
- droplet is deposited gently onto the surface of the bath by sliding it down a wetted surface

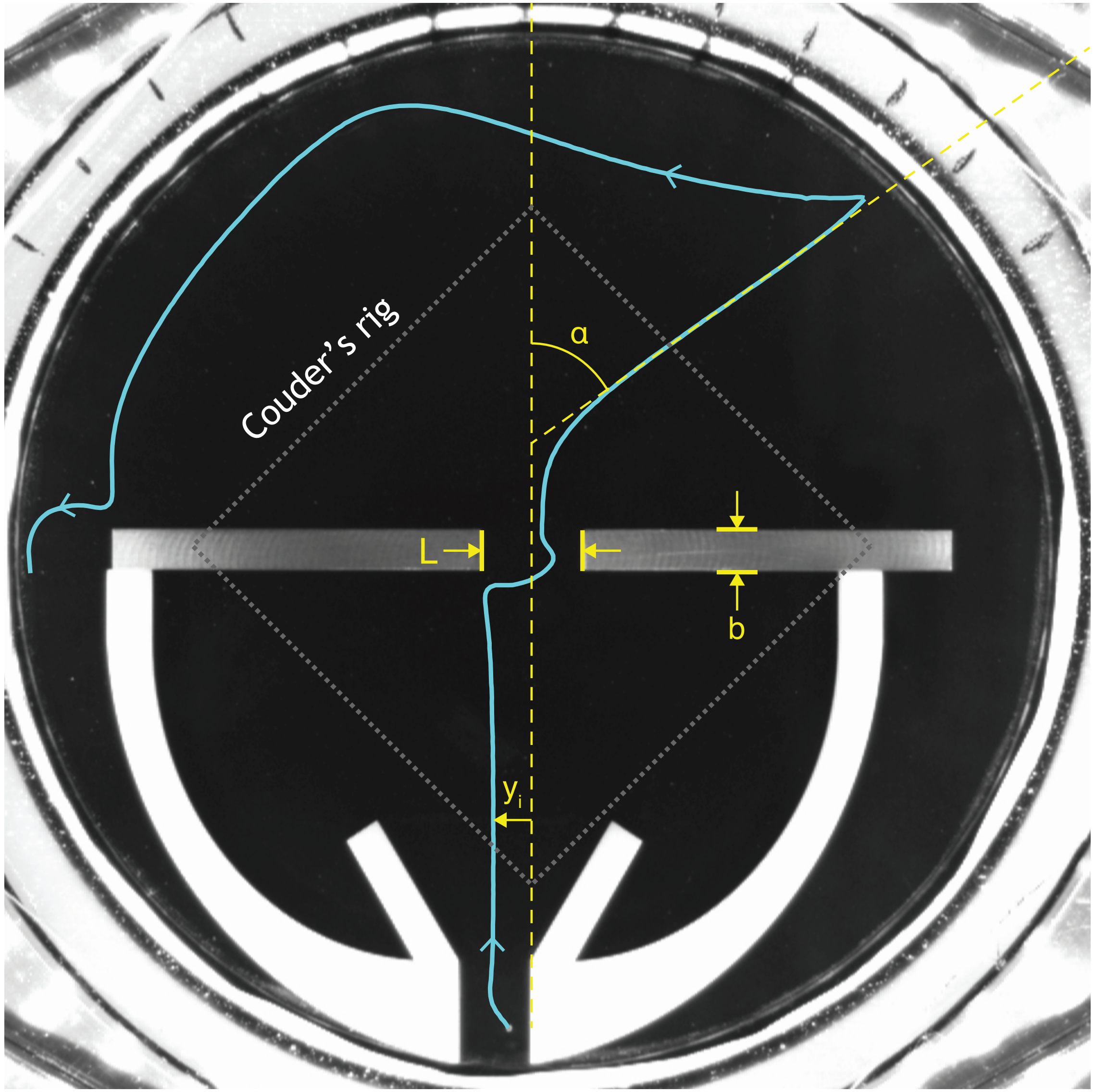
Differences with Couder & Fort's setup

A. Increased bath size: minimize outer boundary effects

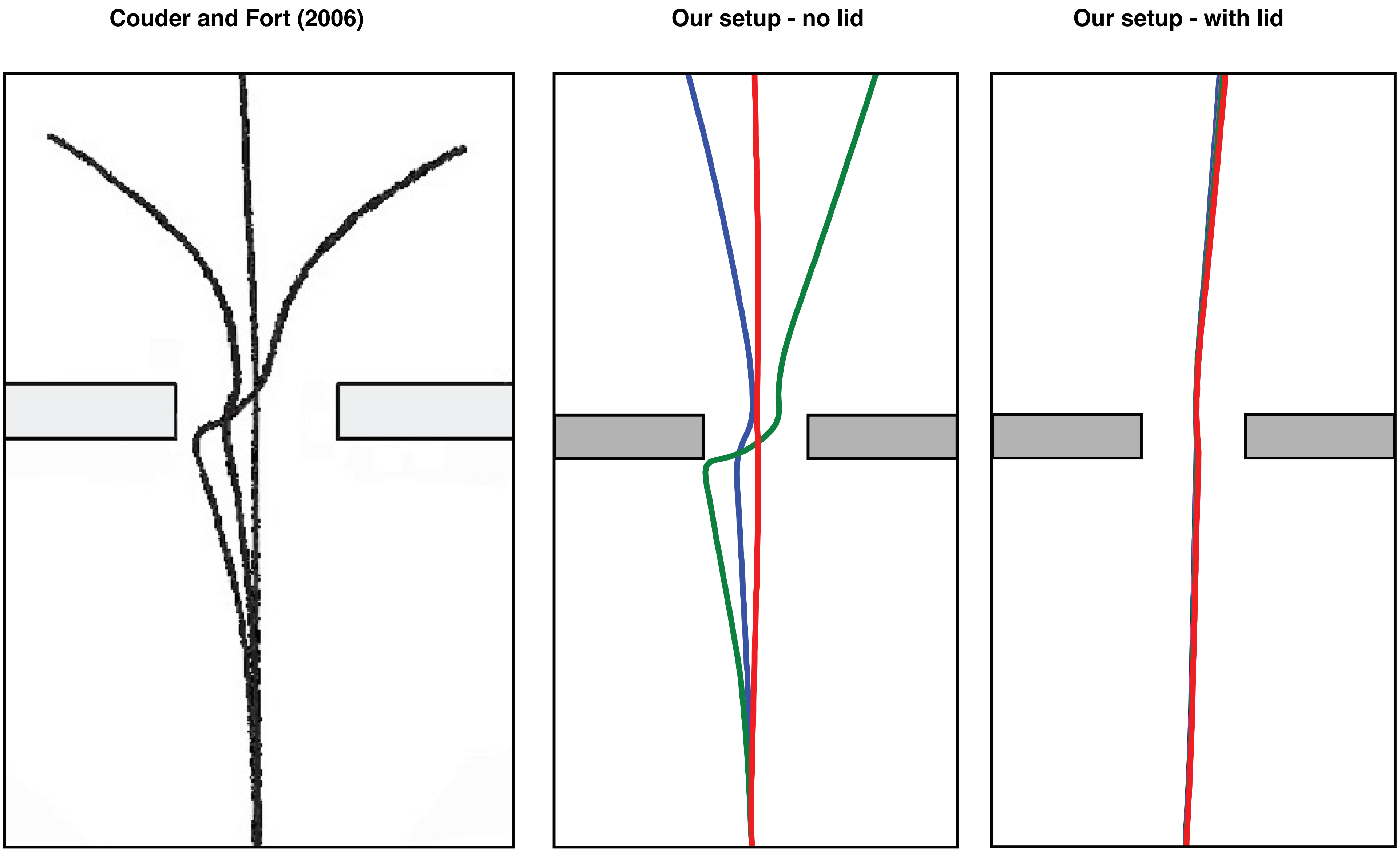
B. Reproducible: reported drop size, memory

C. Eliminated influence of air currents





Differences with Couder & Fort's setup



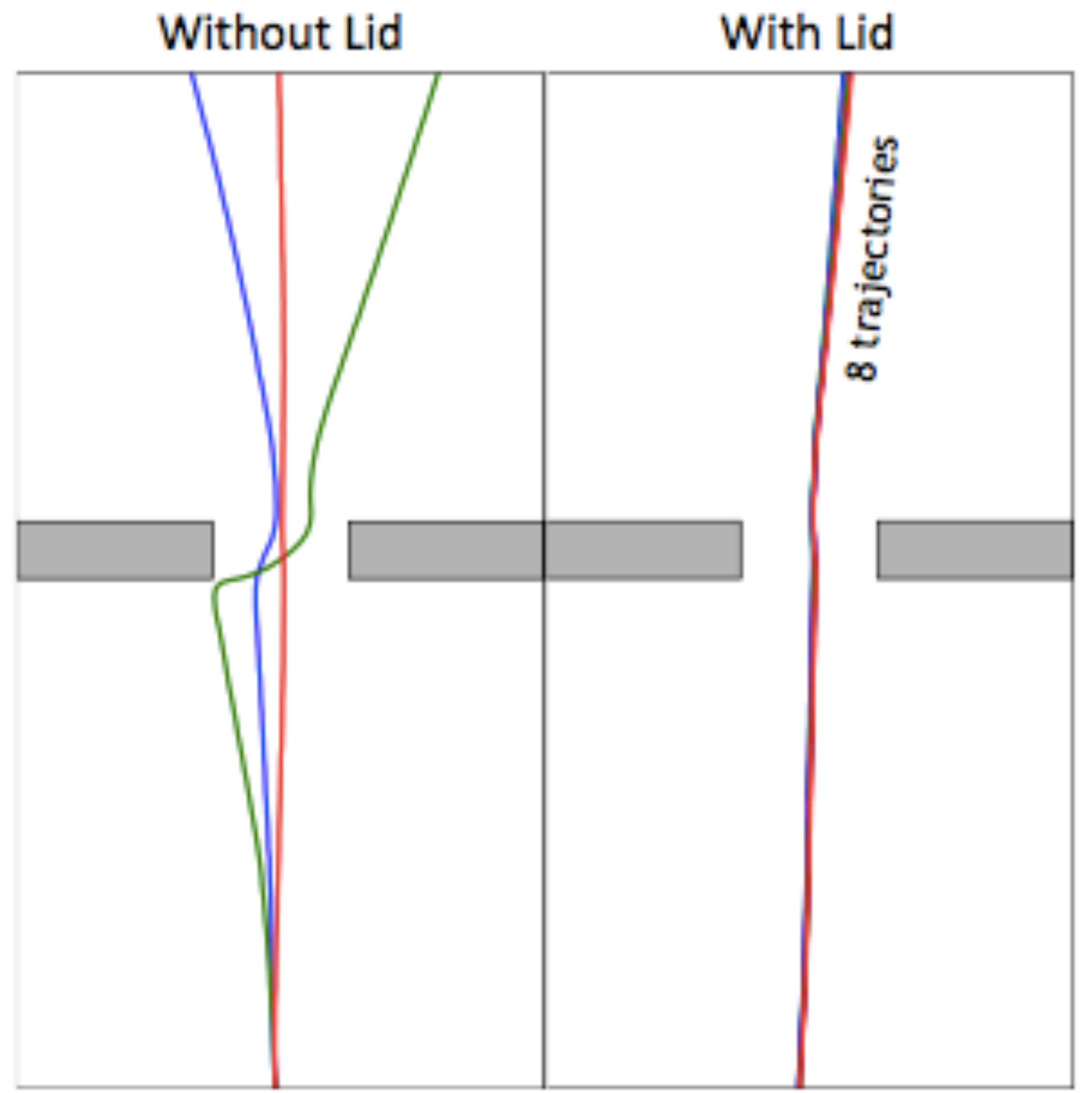
Influence of ambient air currents

- Qualitatively different trajectories arise when experiment is isolated from air currents

- **Key point:** Droplets walk in a straight line in the absence of external perturbations (barriers, air currents, irregular vibration)

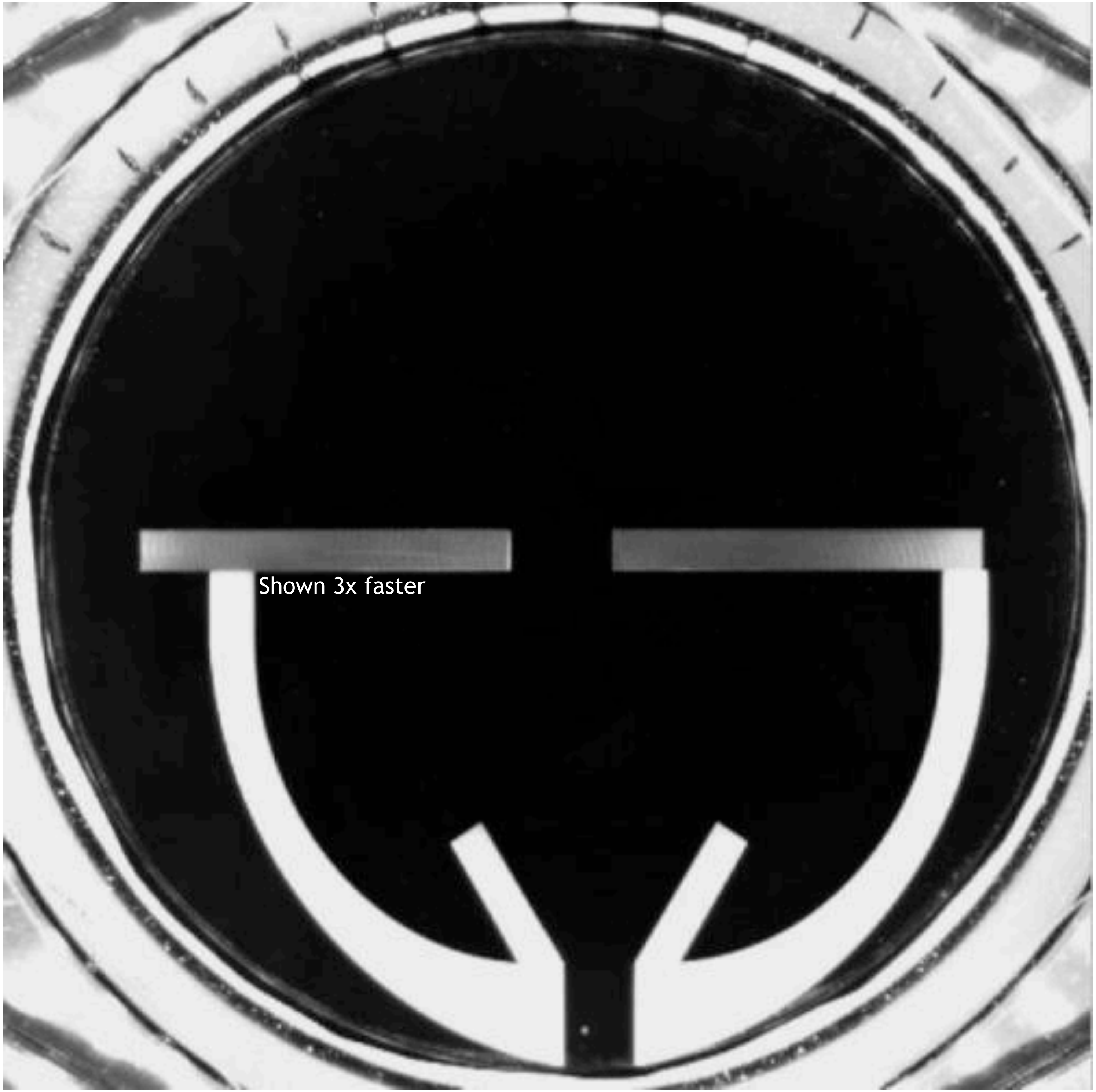
- Oza, Rosales, and Bush (2013) demonstrated that walking droplets are neutrally stable to lateral perturbations

$u_o = 12 \text{ mm/s}, \ \gamma/\gamma_F = 0.95$



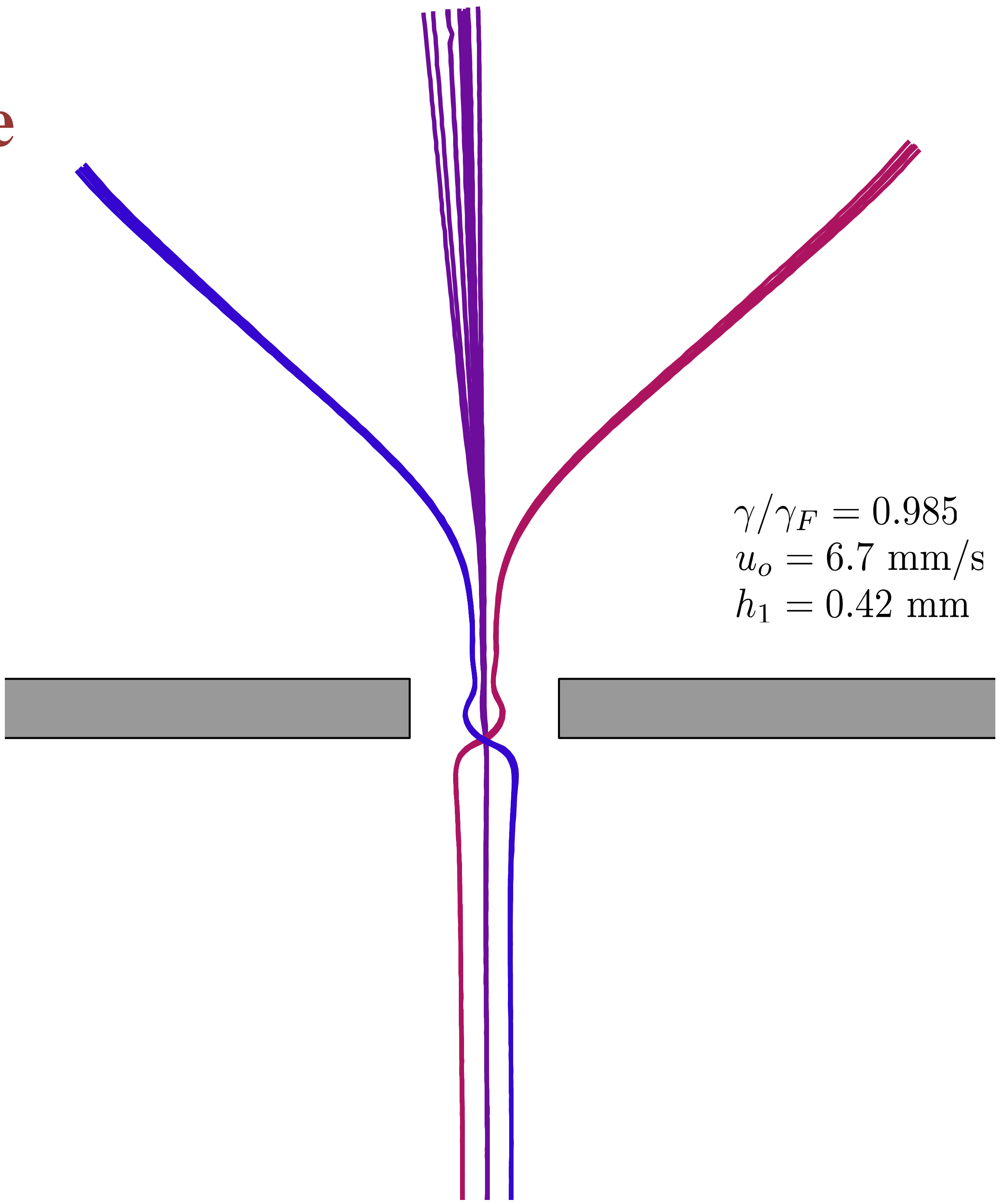
Launcher

- necessitated by lid
- continuous passages of slit without manual intervention
- insures normal incidence to slit
- allows for variation of impact parameter

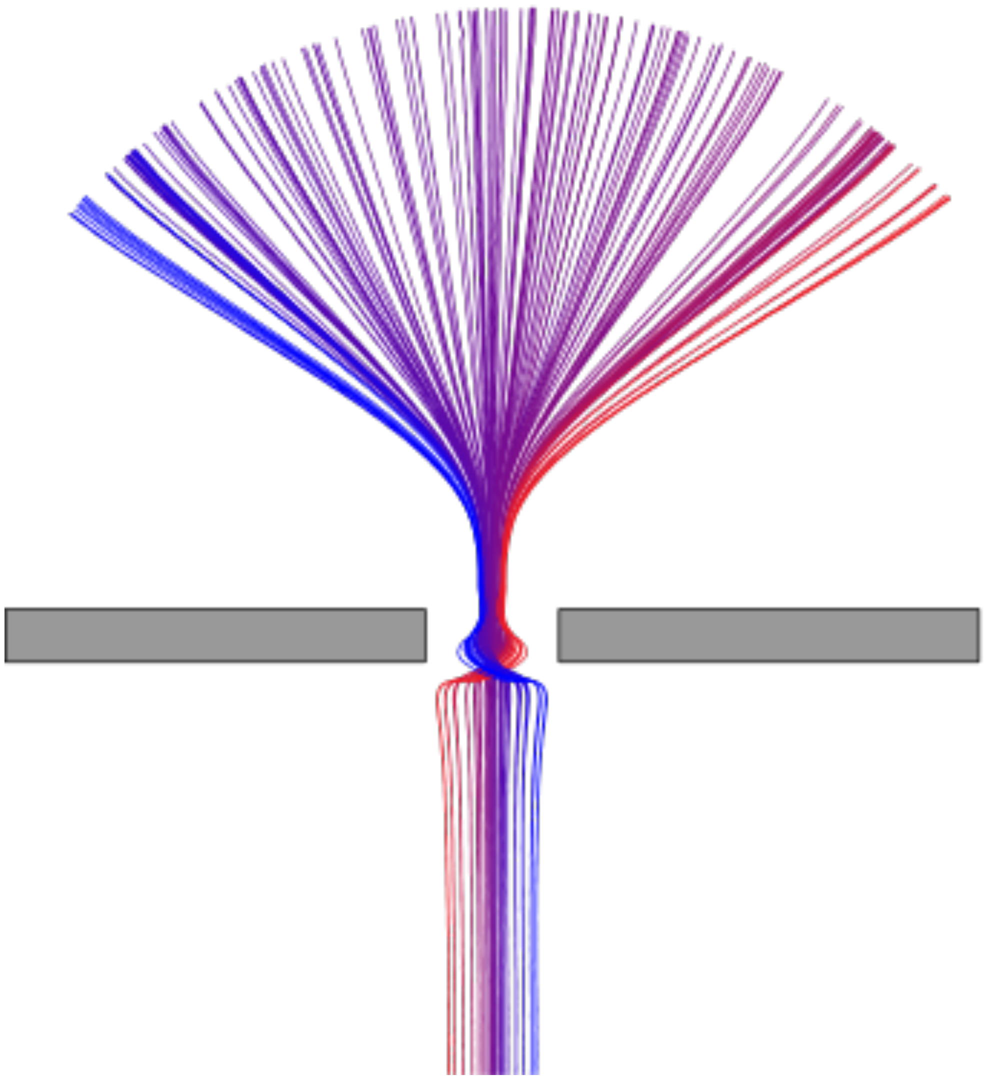


Non-chaotic Regime

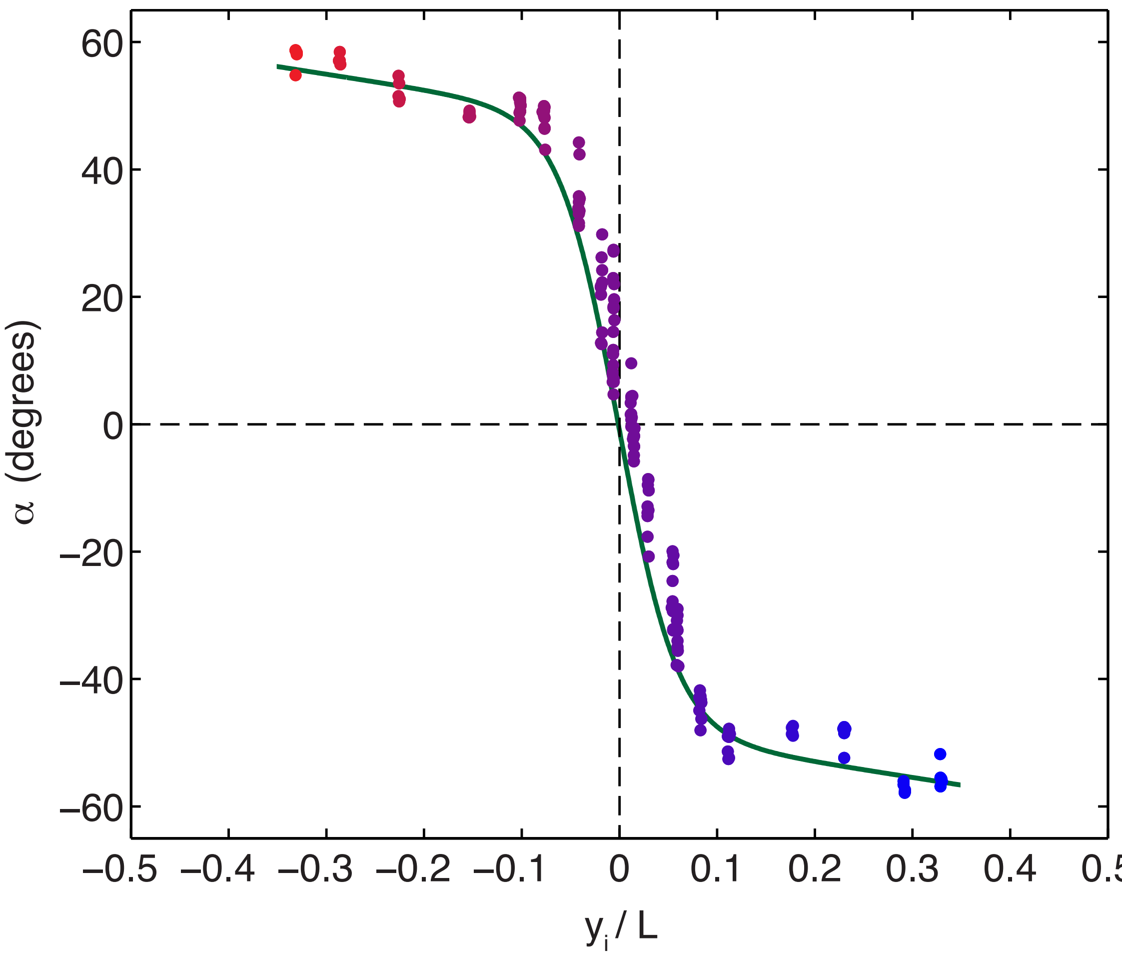
- the droplet is deviated due to spatial confinement of its pilot wave field
- a well-defined deflection angle exists for each impact parameter (three shown here)



Non-chaotic Regime: Impact Parameter Sweep



$$\gamma/\gamma_F = 0.985$$

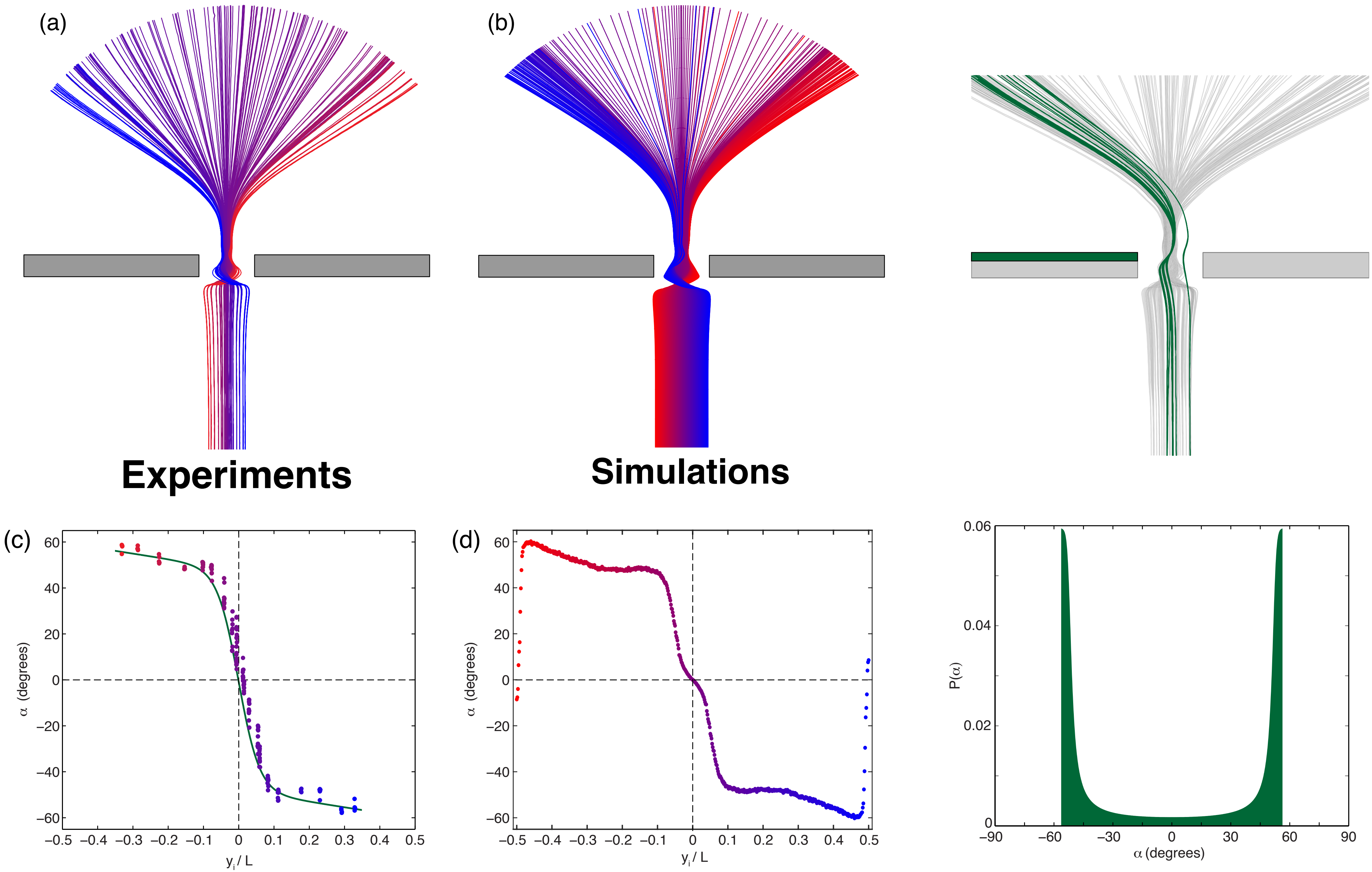


- **diffraction angle is uniquely prescribed by impact parameter**
- this regime would be difficult to observe without isolation from ambient air currents and precise control of impact parameter

‘Low’ memory case

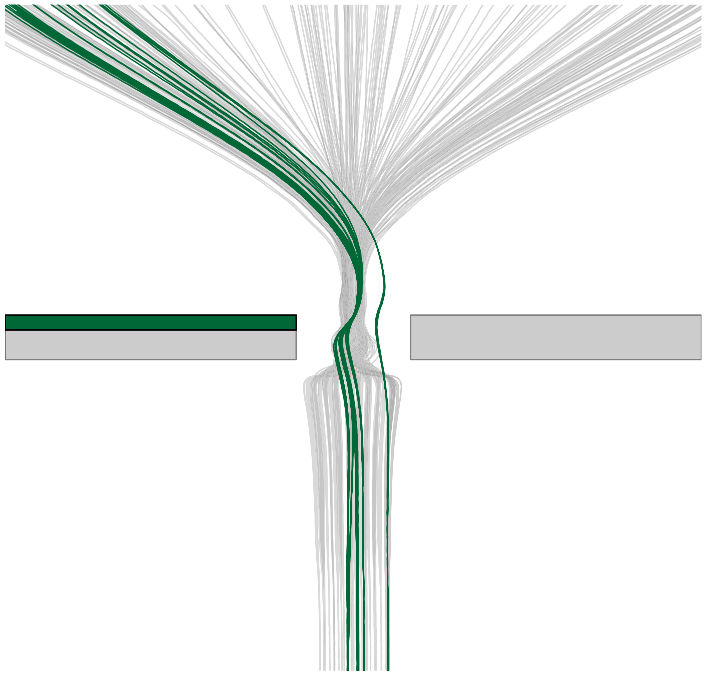
$\gamma/\gamma_F = 0.985$

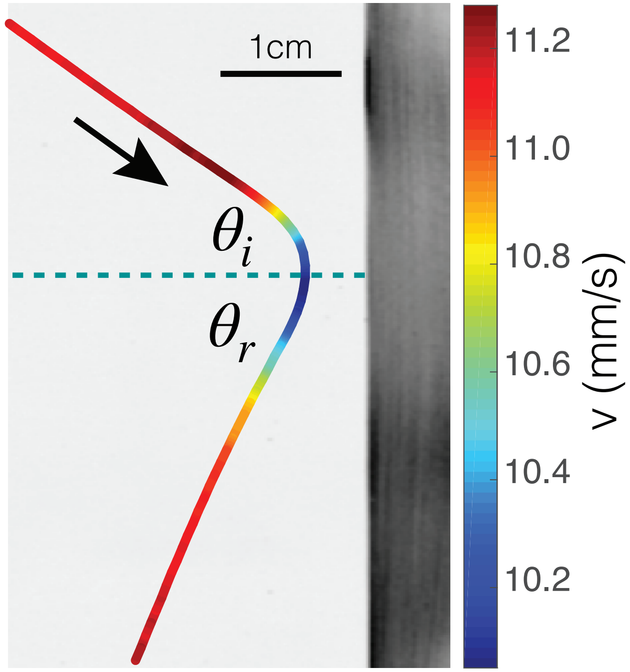
- deflection angle uniquely prescribed by impact parameter

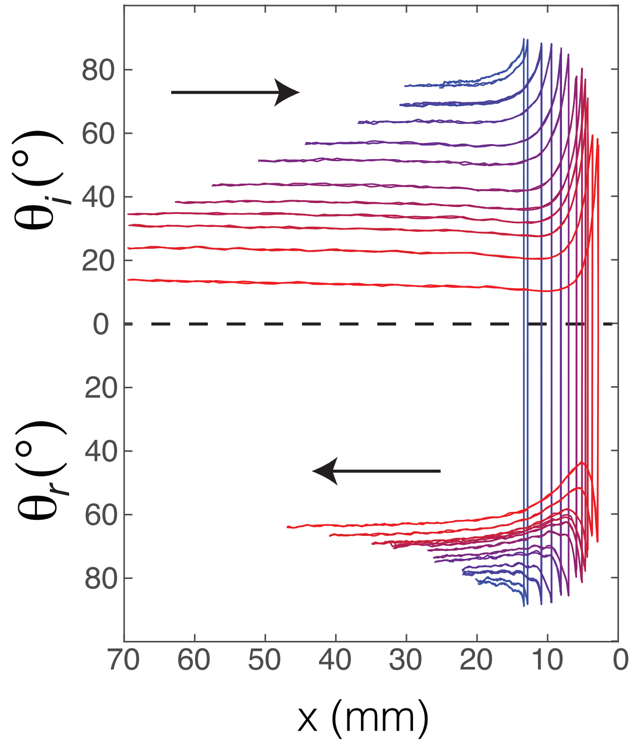


Statistics are dominated by a preferred angle

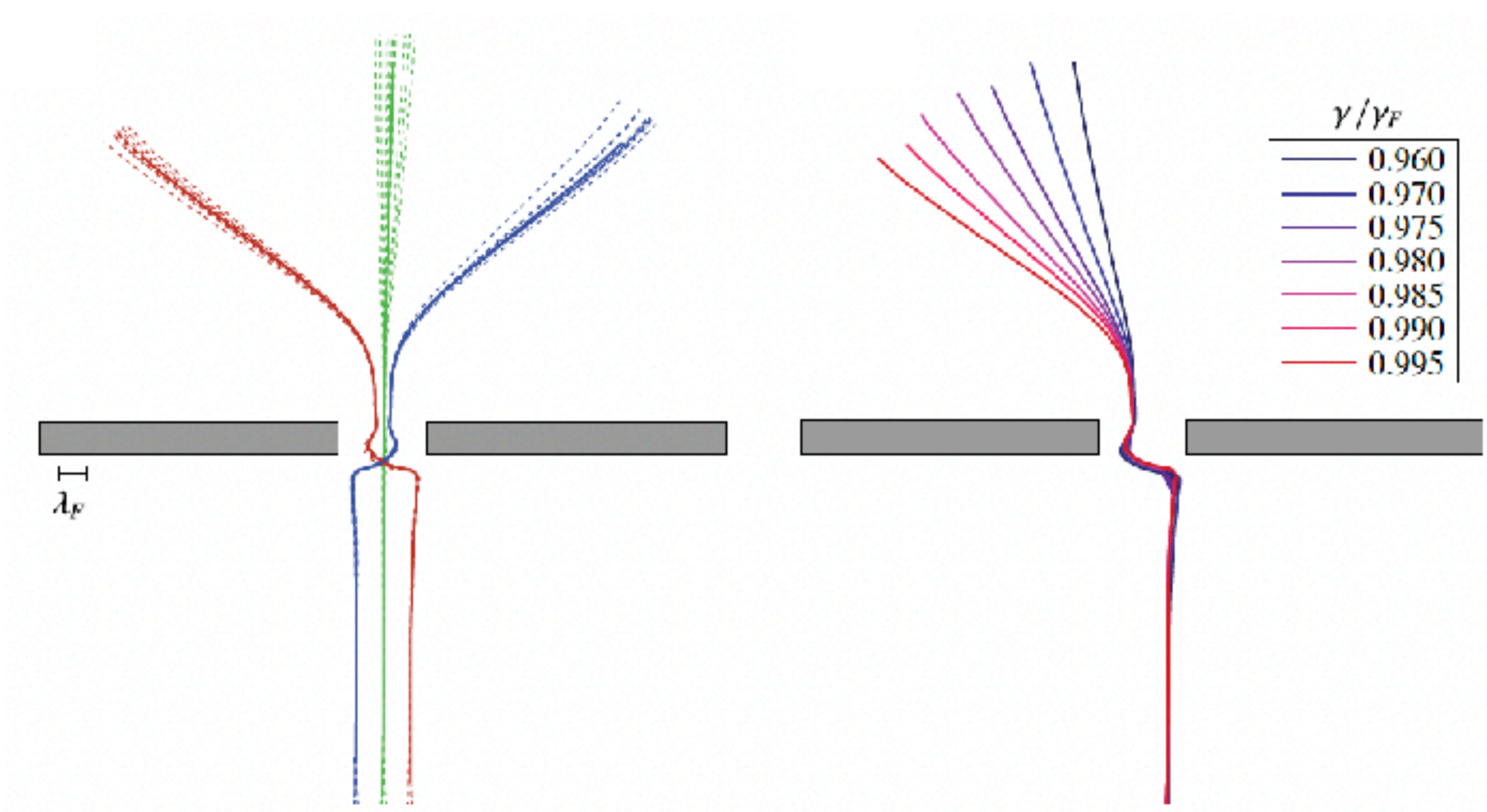
- a comparable preferred angle also exists for a walker passing a **single edge** or for **reflection** from a planar barrier







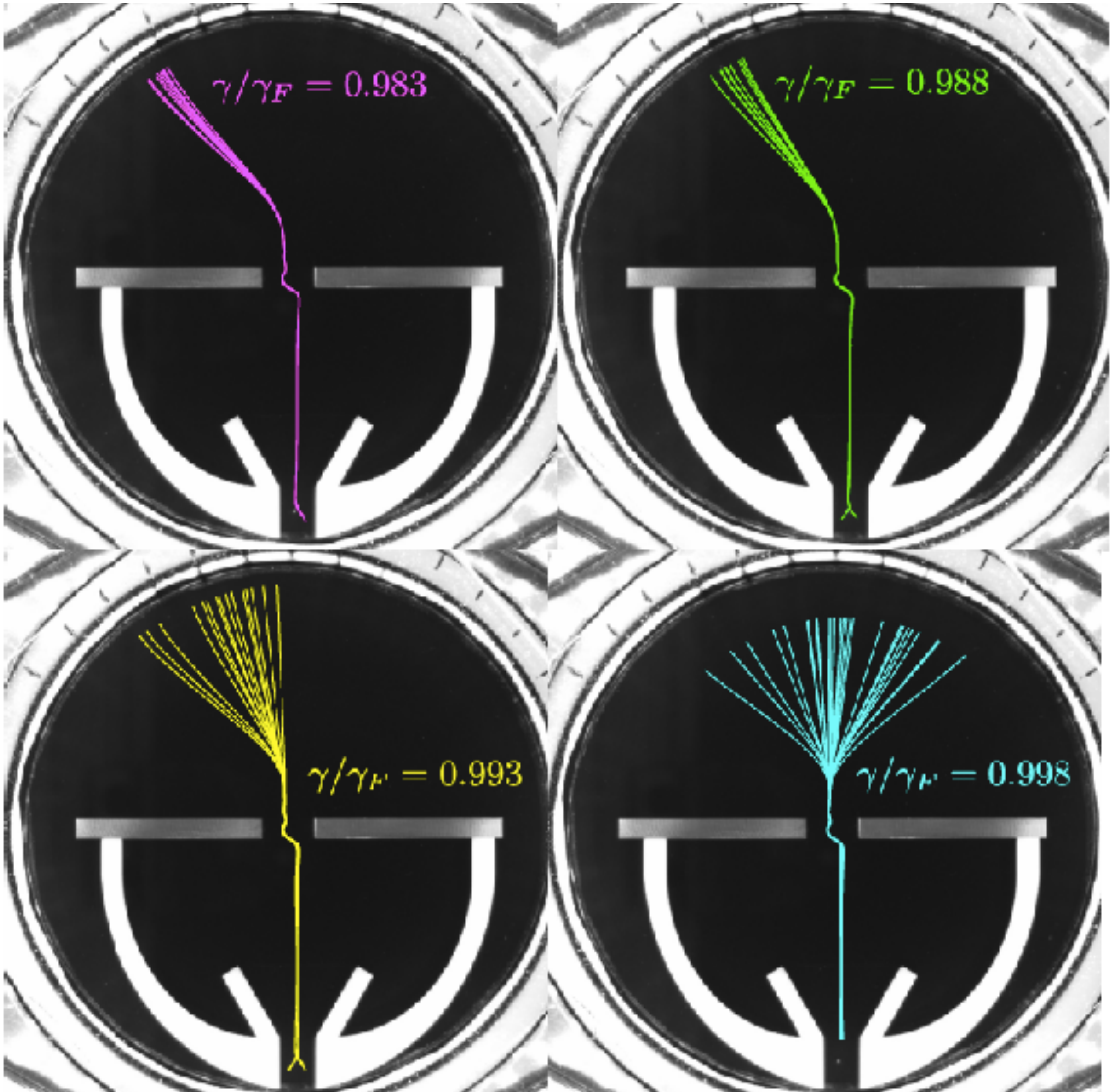
Dependence on impact parameter and memory



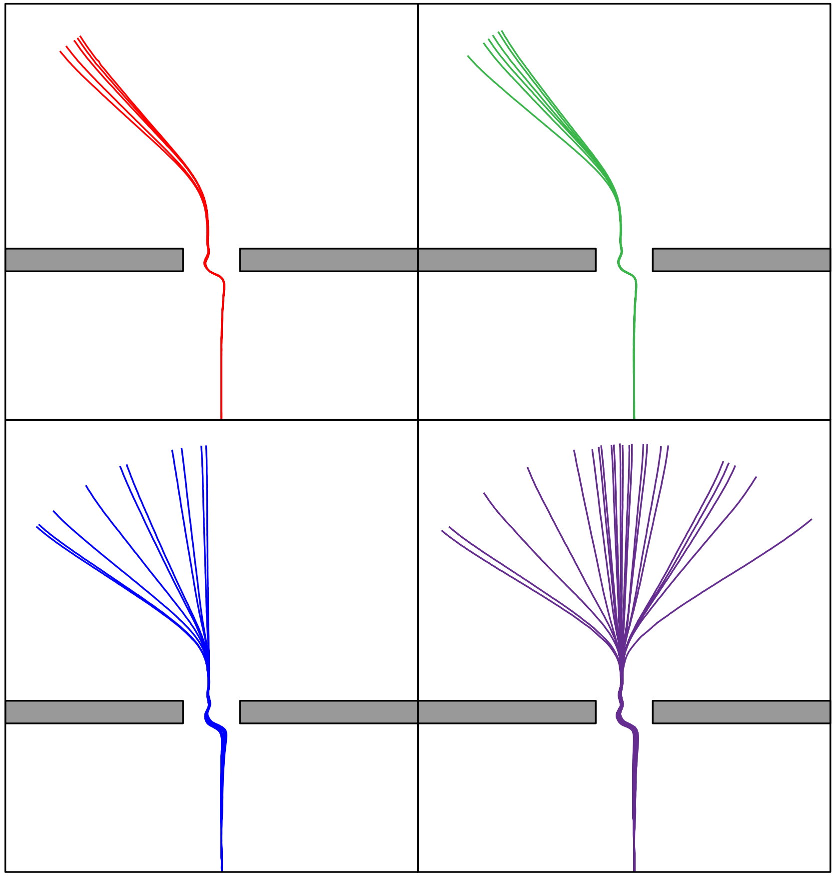
Influence of memory

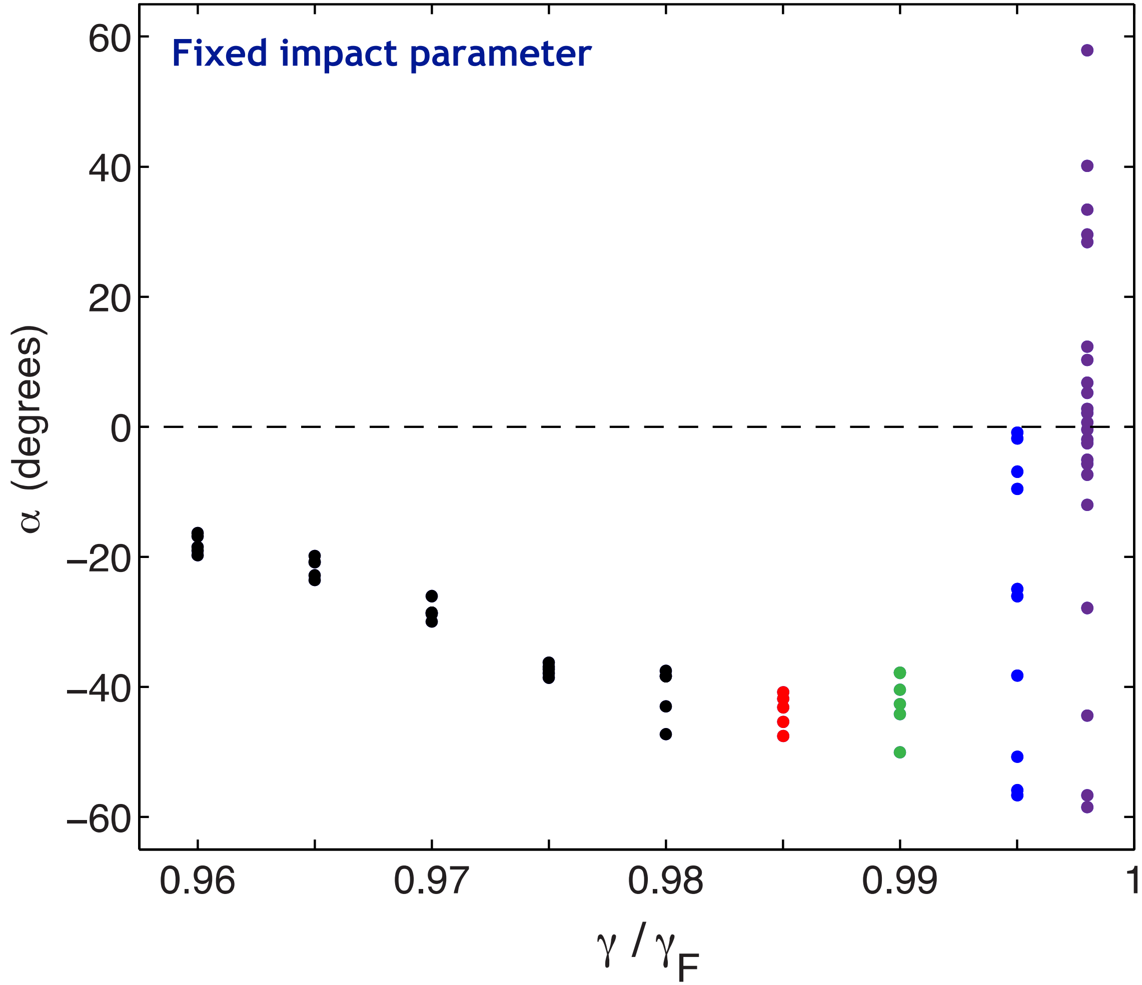
$u_o = 6.8$ mm/s
$h_1 = 0.6$ mm

Fix Impact Parameter



Transition to chaos with fixed impact parameter

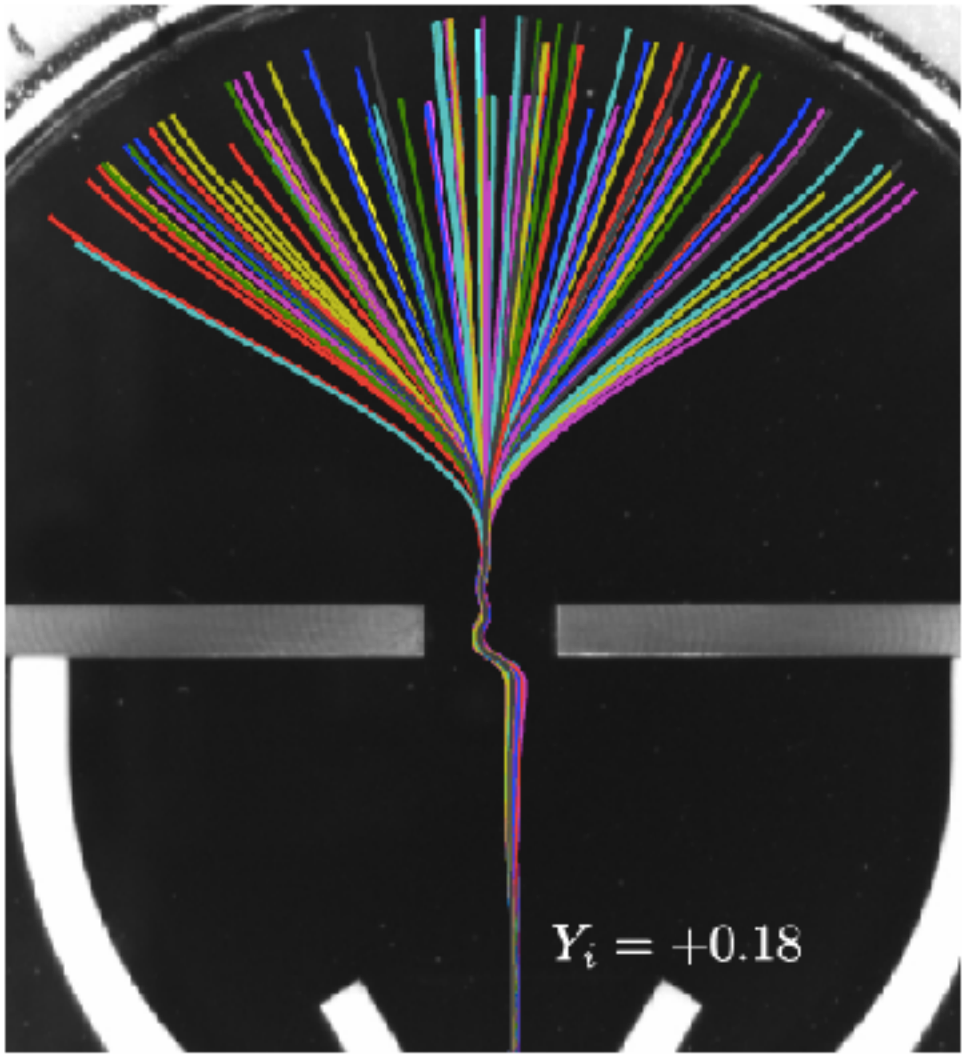




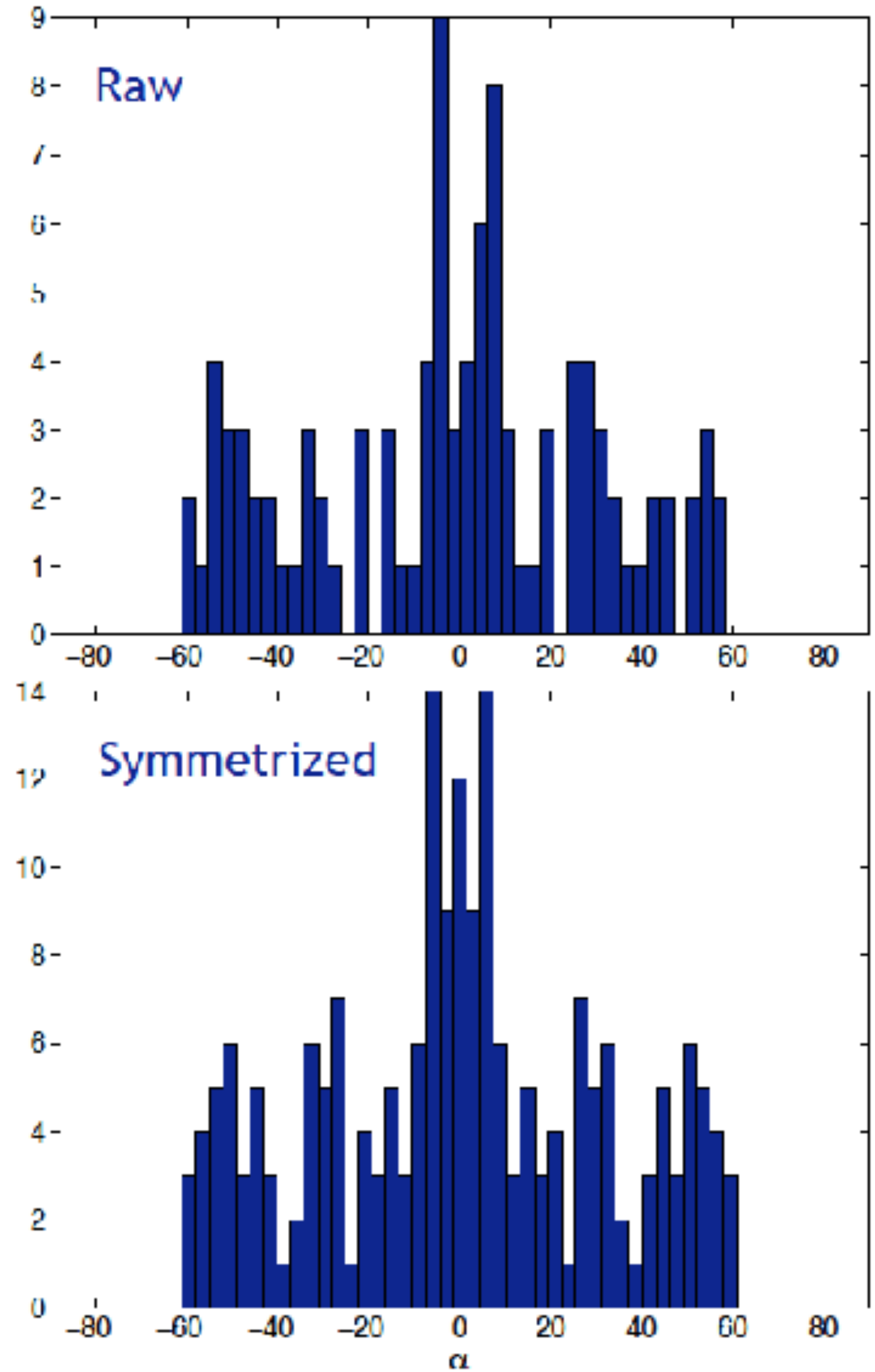
- at very high memory, a wide range of angles becomes accessible for fixed impact parameter
- divergence of trajectories appears **after** passing through slit
- **deflection angle no longer set by impact parameter at high memory**

Statistical behavior in chaotic regime

$\gamma/\gamma_F = 0.998$

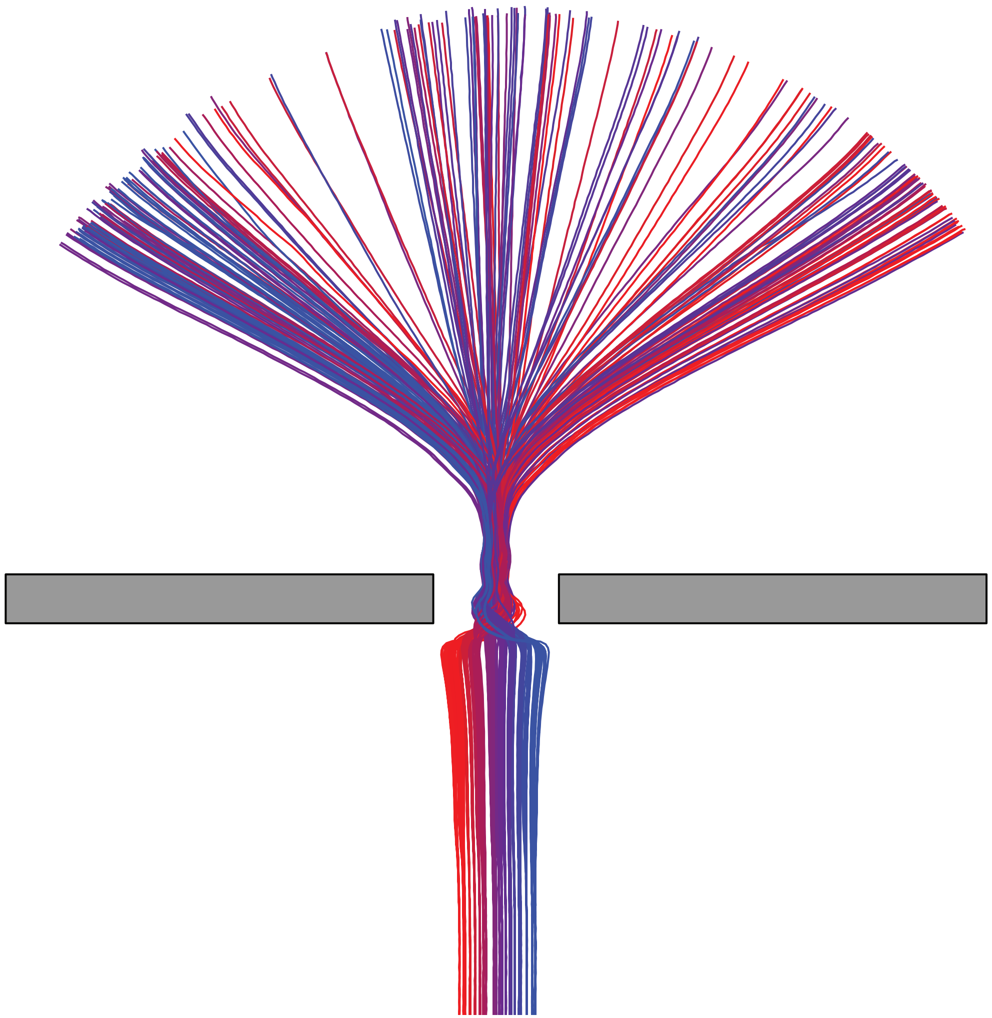


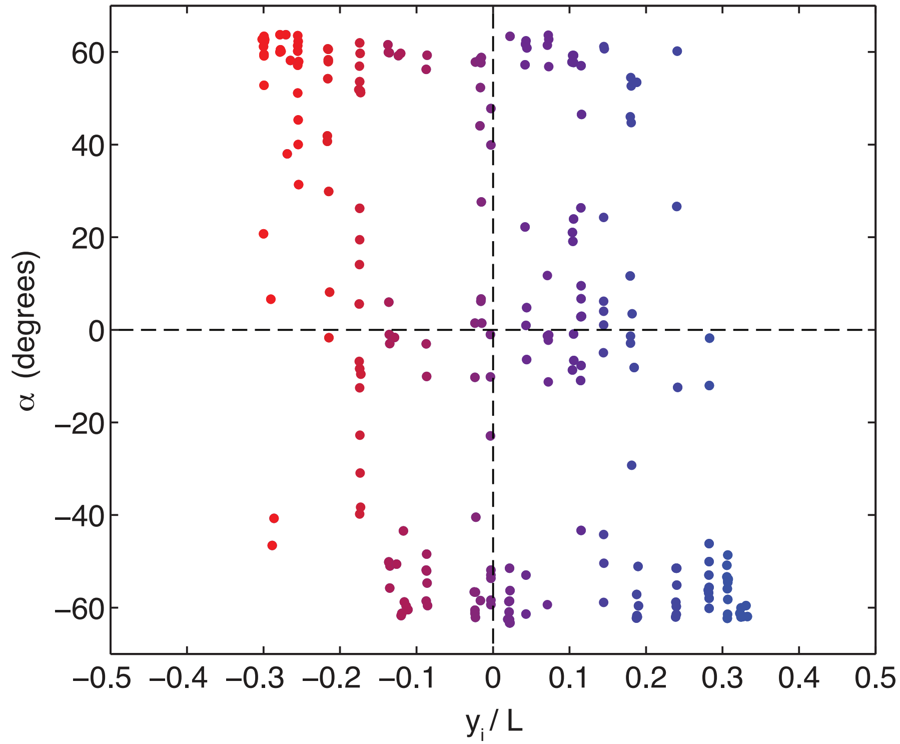
101 trajectories,
same impact parameter

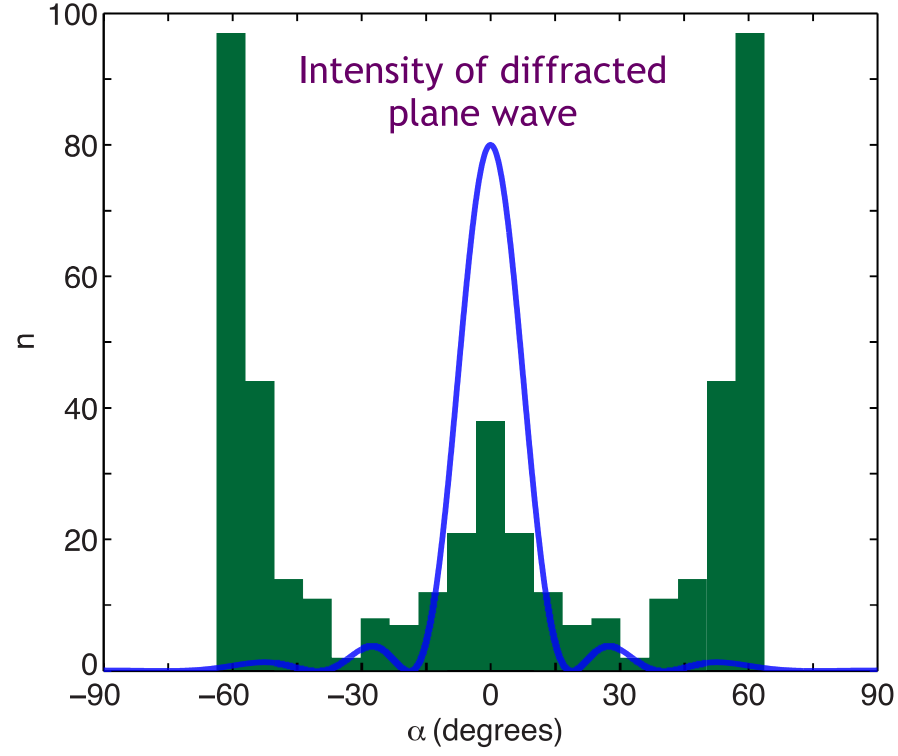


'High' memory case

$\gamma/\gamma_F = 0.998$



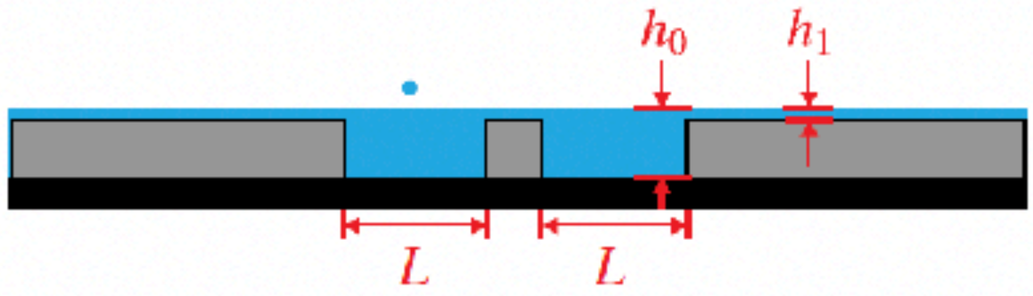


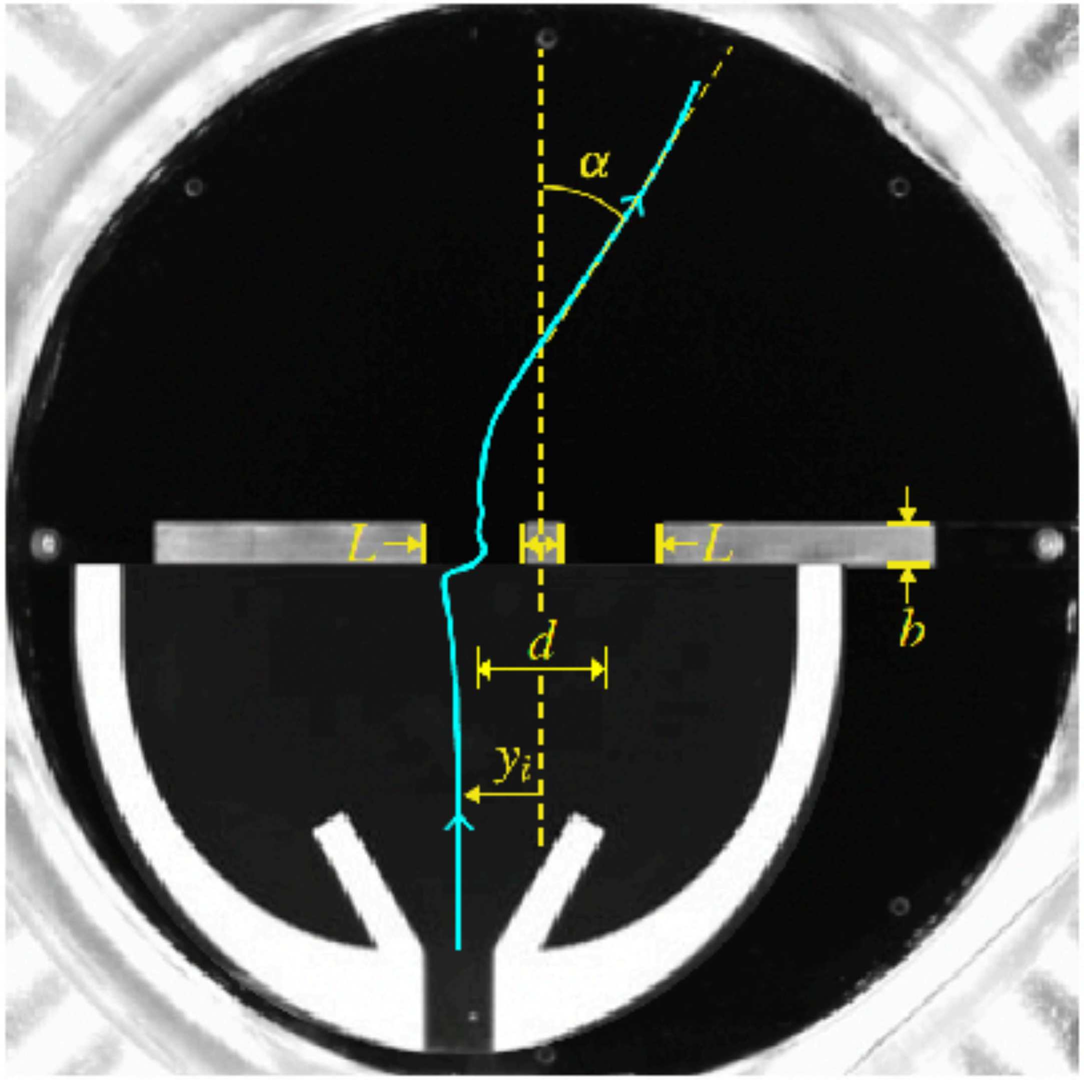


- **deflection angle not set by impact parameter**
- achieved in chaotic walking regime
- statistics do not ressemble Fraunhofer pattern

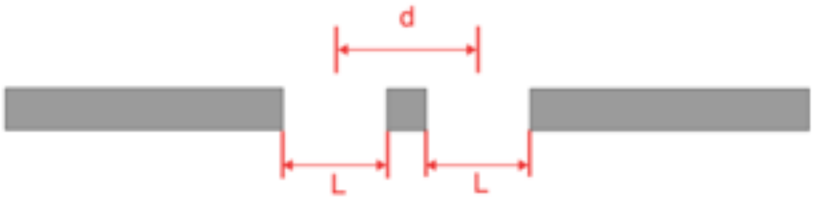
Double-slit experiment

$\gamma/\gamma_F = 0.998$



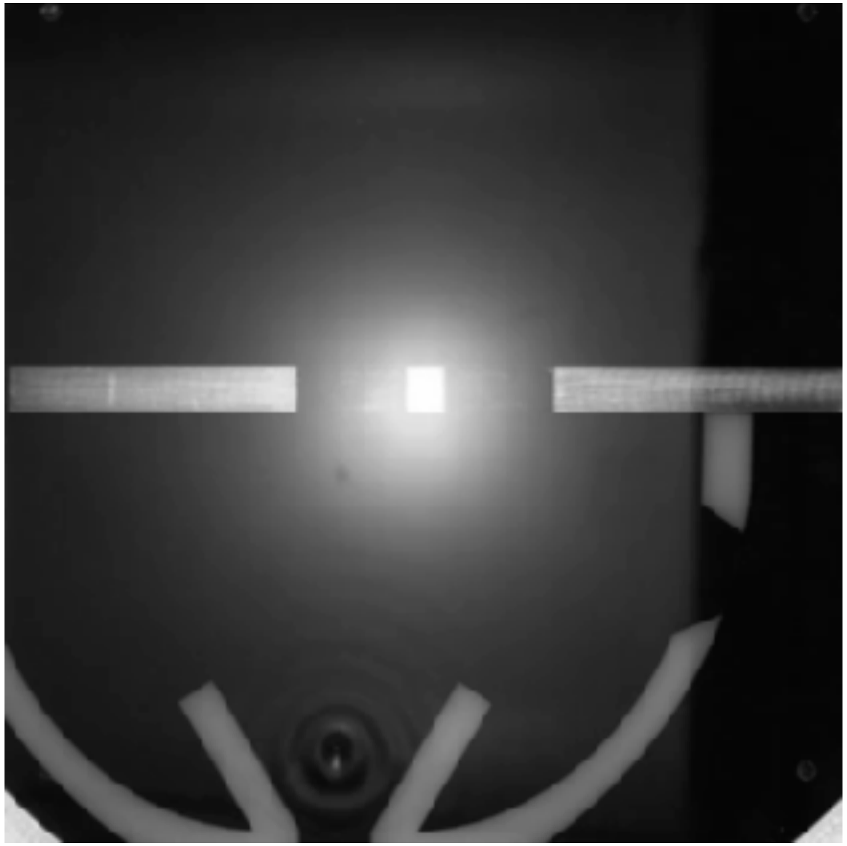


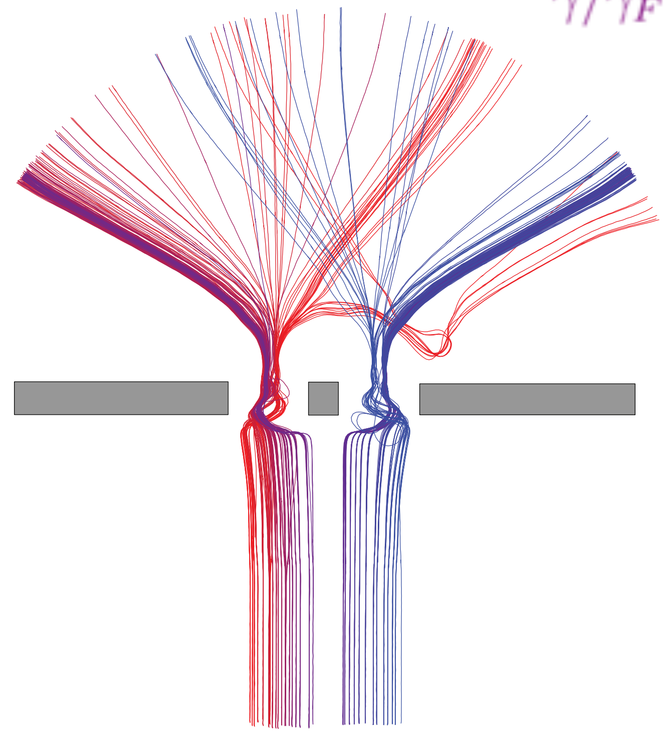
Double-slit experiment

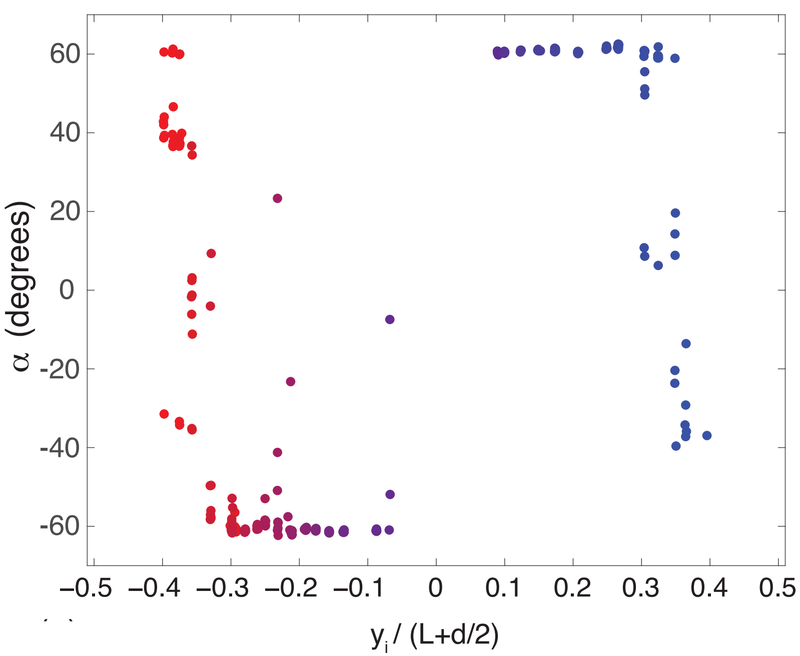


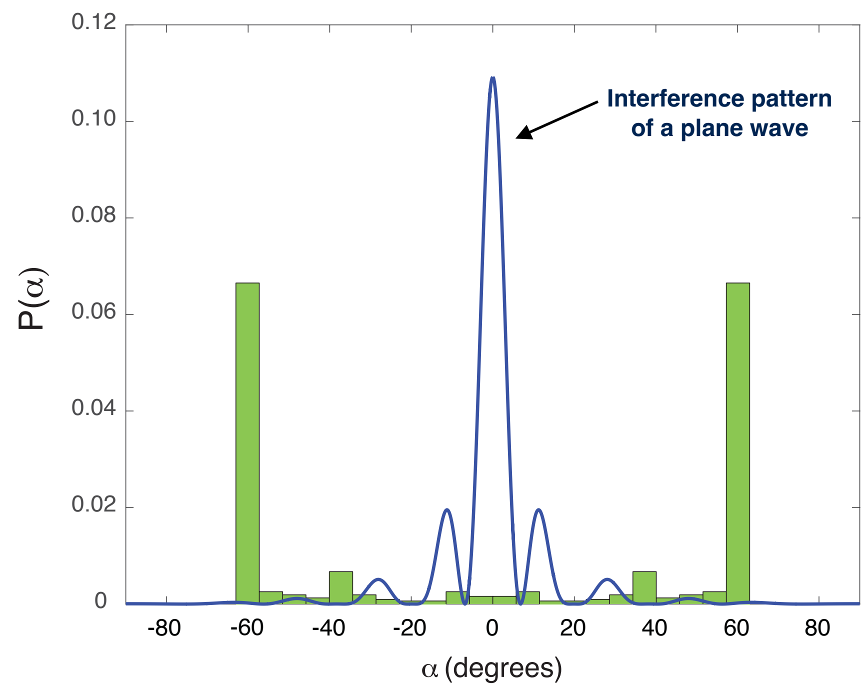
$\gamma/\gamma_F = 0.998$

Double-slit experiment

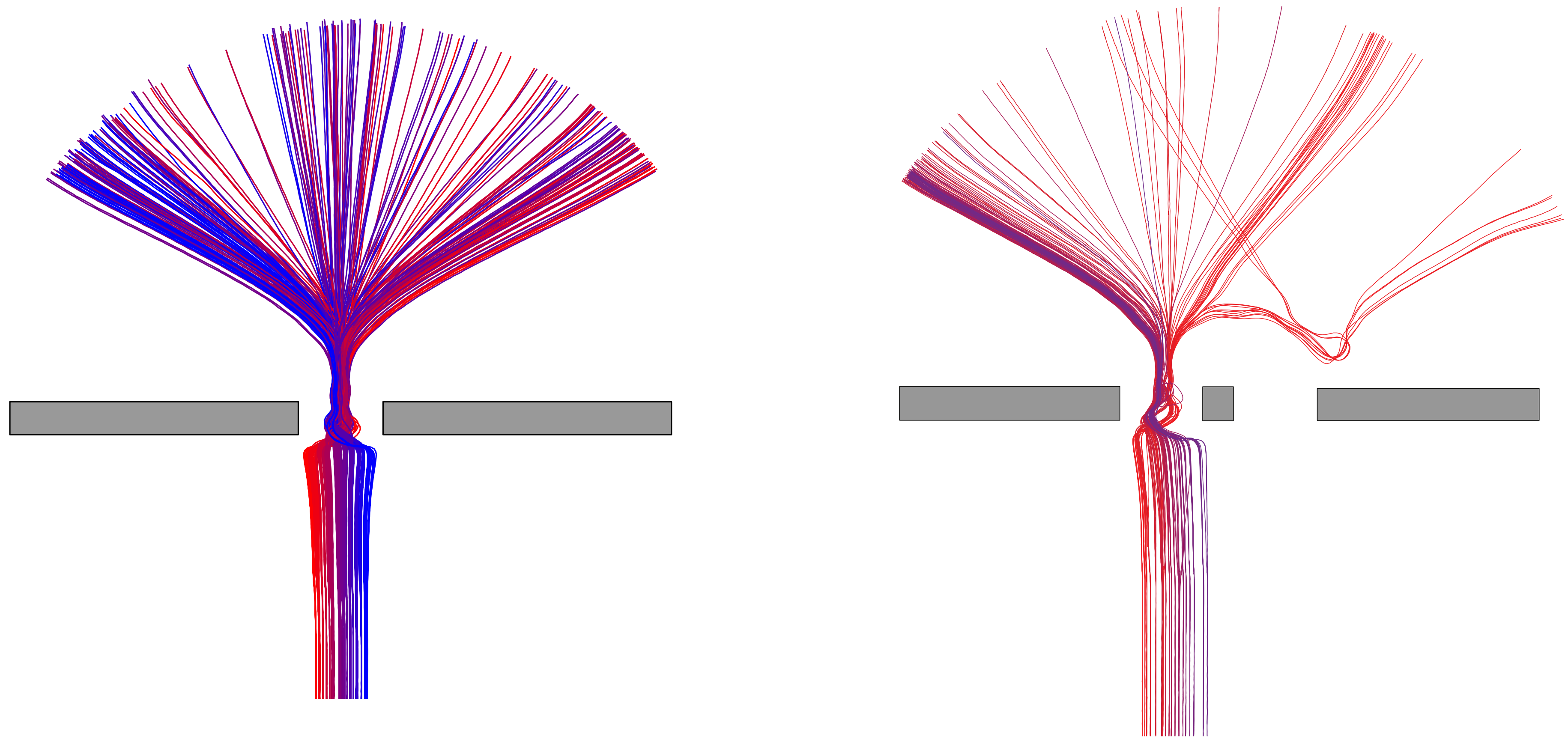






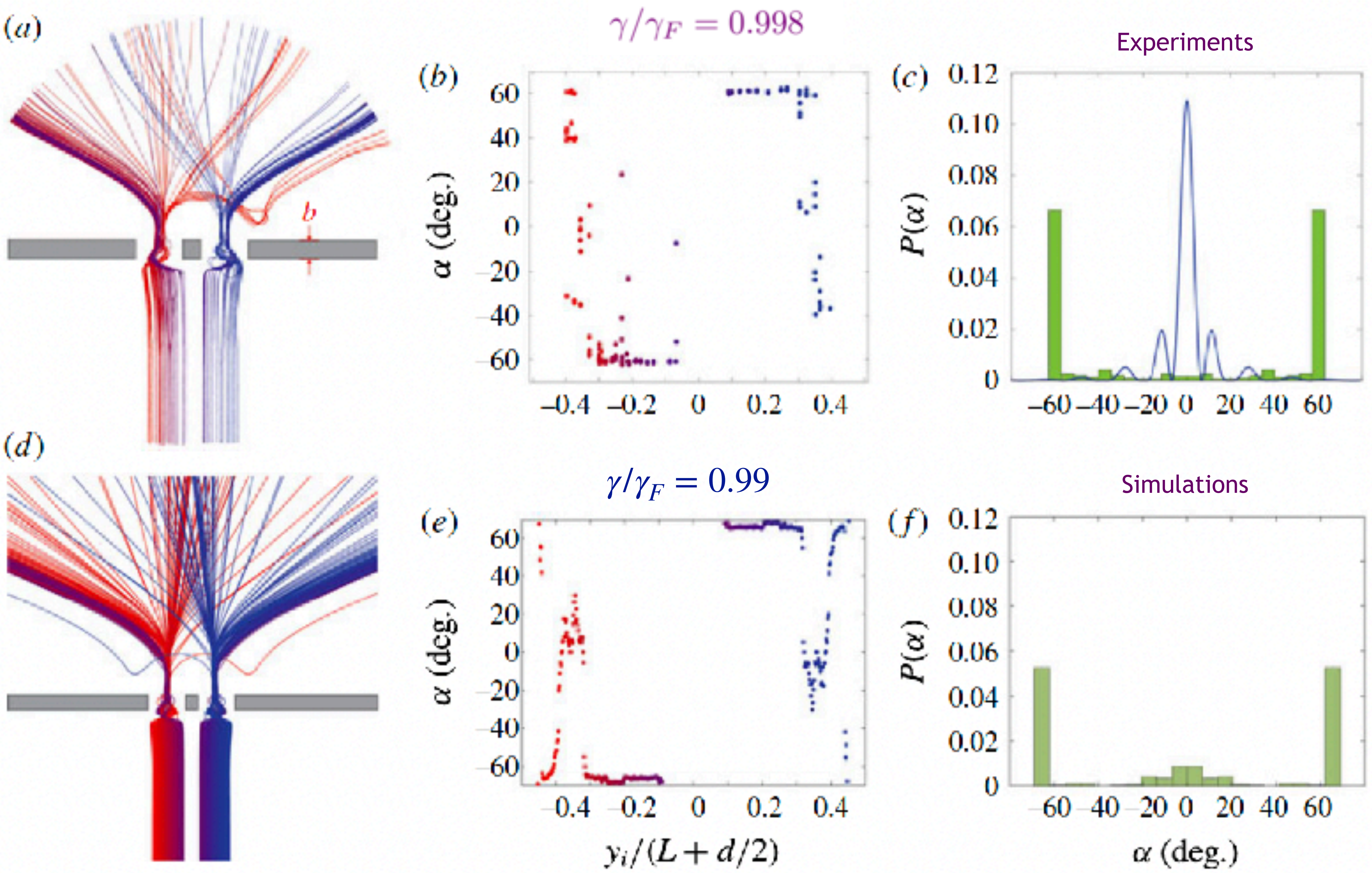


Influence of the second slit on the walker's motion



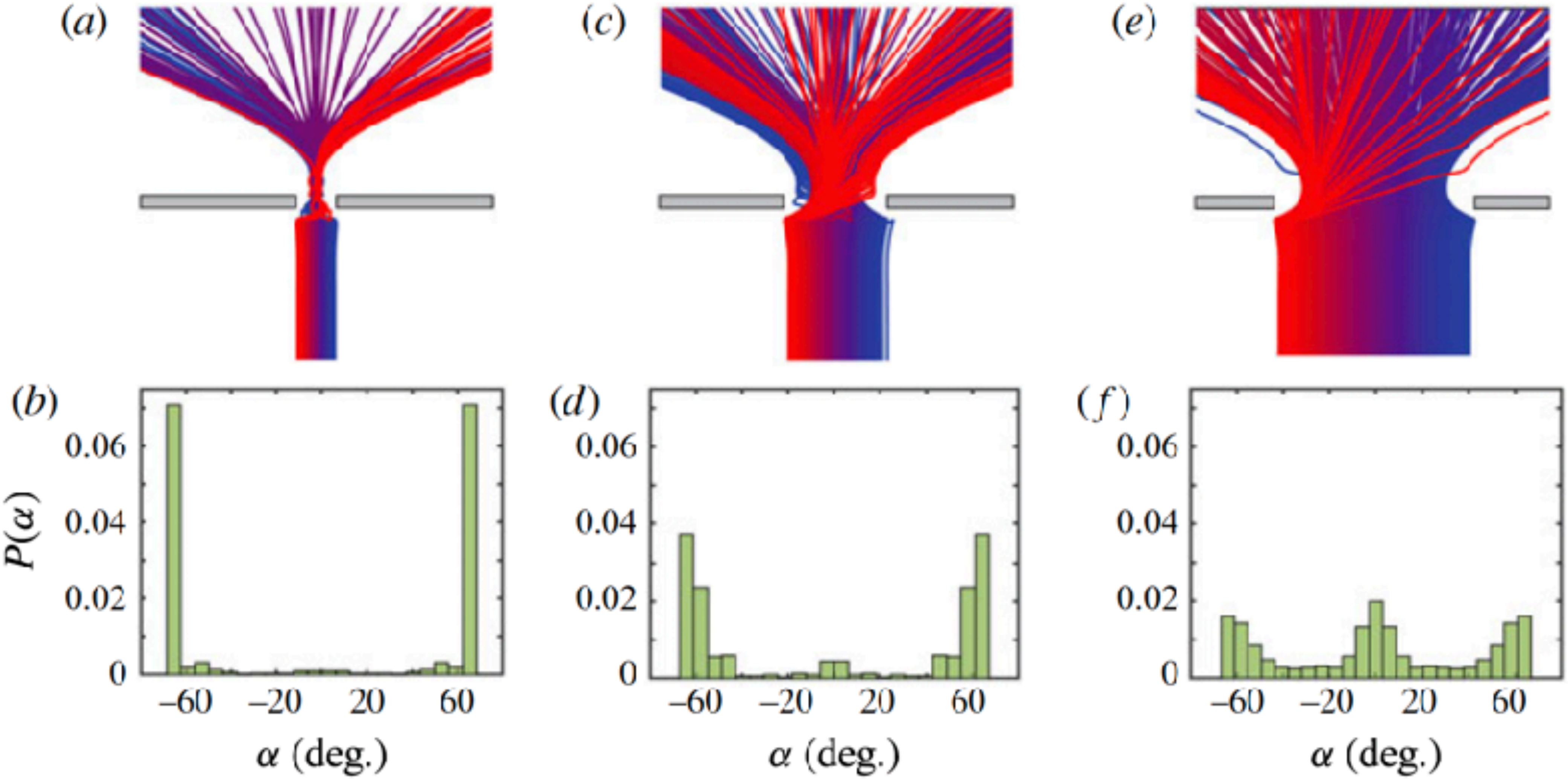
- diffraction patterns different for single- and double-slit arrangements
- walkers feel both slits by virtue of their spatial delocalization
- at odds with scaling arguments of Tomas Bohr
- consistent with physical picture proposed by de Broglie in the 1920s
- our results were confirmed by the most careful study of walker done to date, by Ellegaard & Levinsen (2020)

Double-slit diffraction: Experiments vs. Simulations



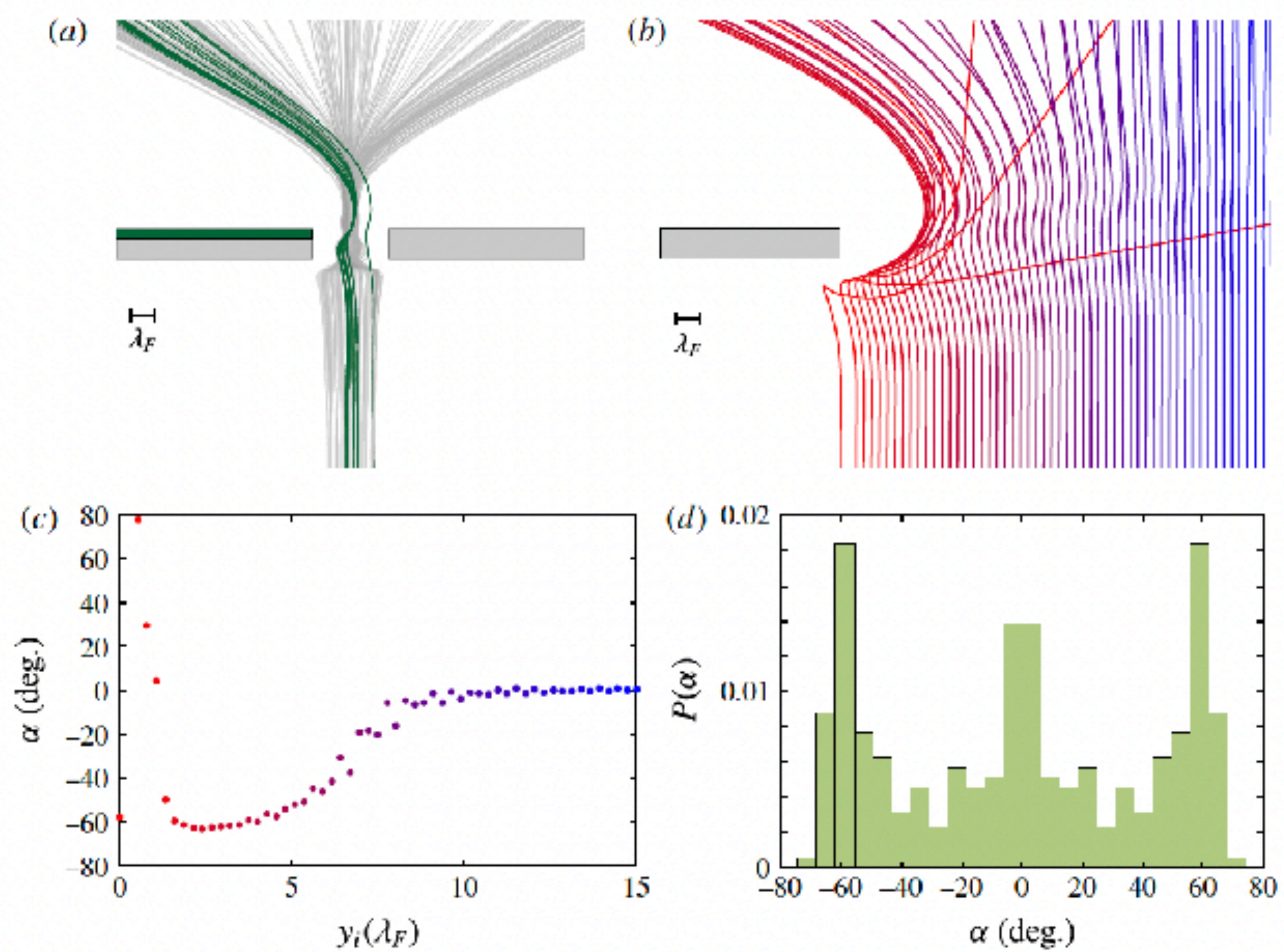
Simulations of double-slit experiment

$\gamma/\gamma_F = 0.99$



- relative magnitudes of central and side peaks prescribed by slit width

Simulations of diffraction past an edge



- magnitude of central peak set by range of impact parameters explored

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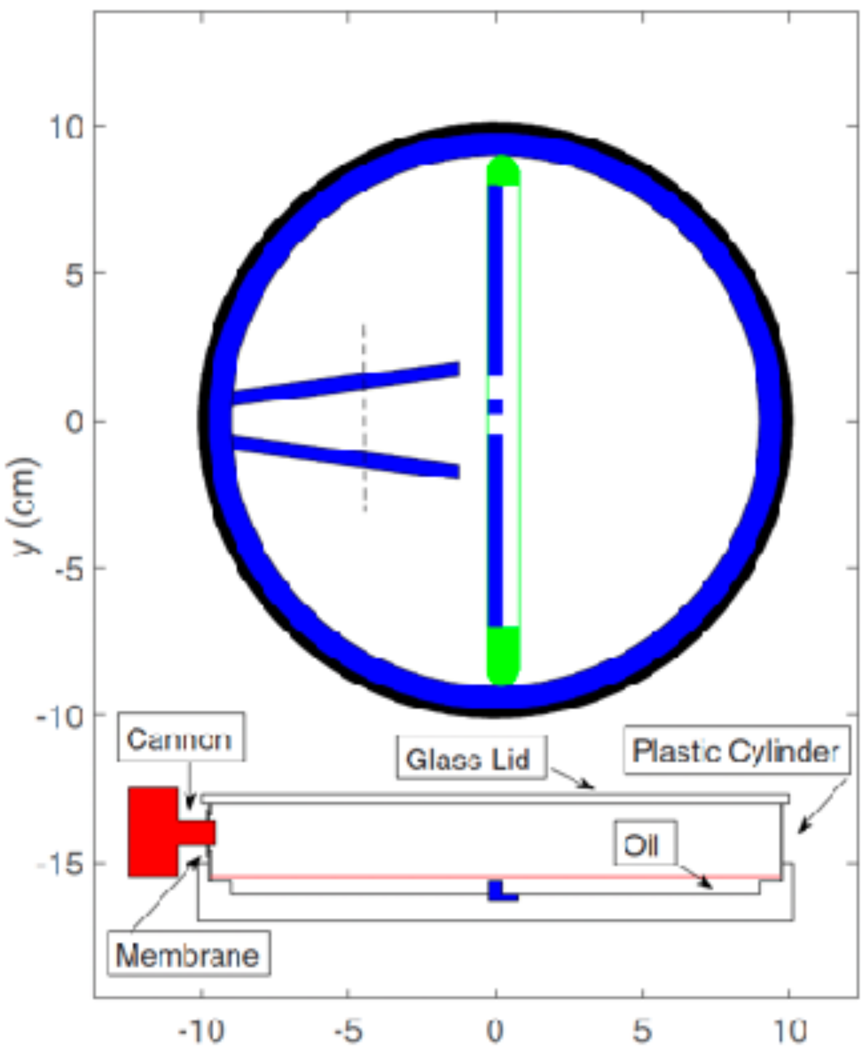
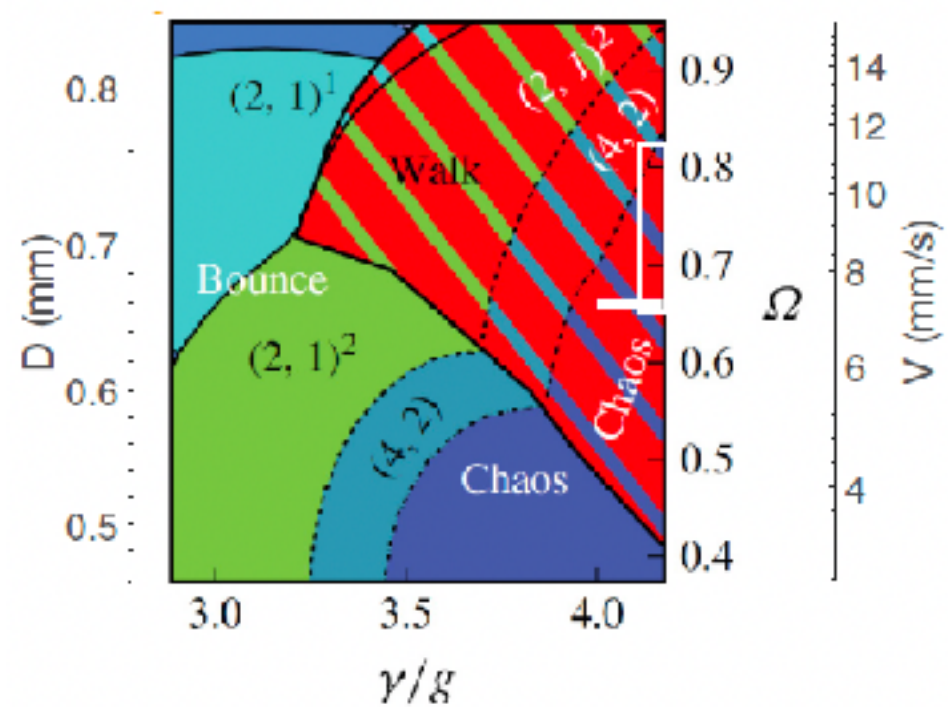
Interaction of wave-driven particles with slit structures

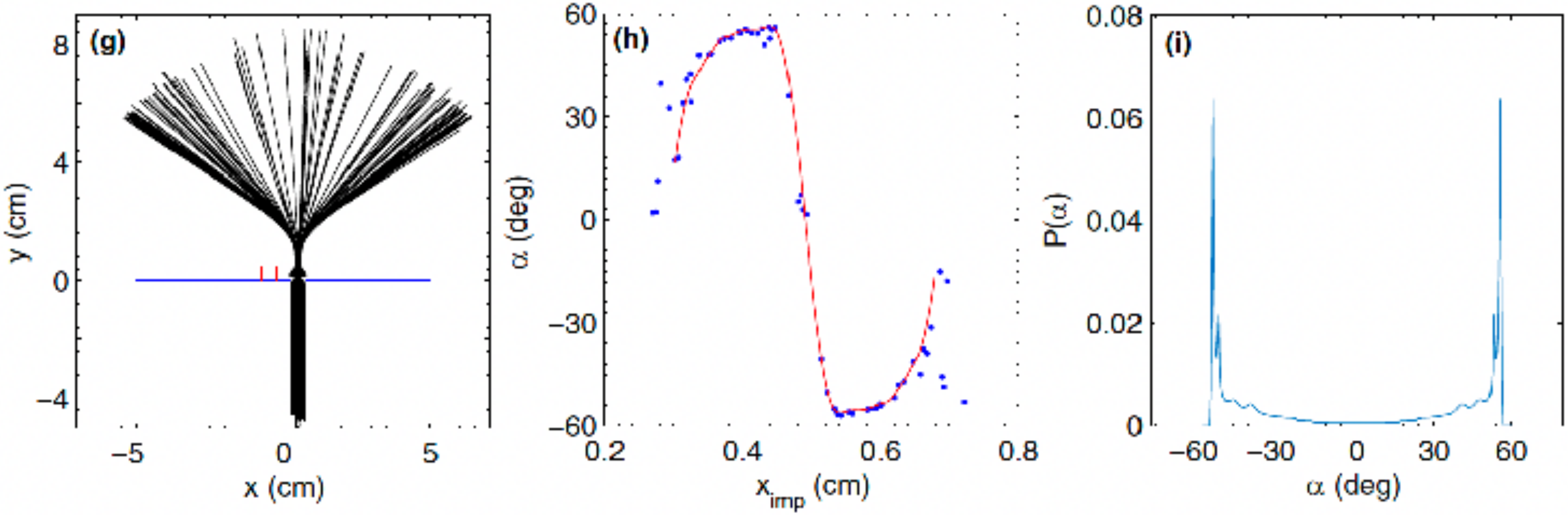
Clive Ellegaard and Mogens T. Levinsen
Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

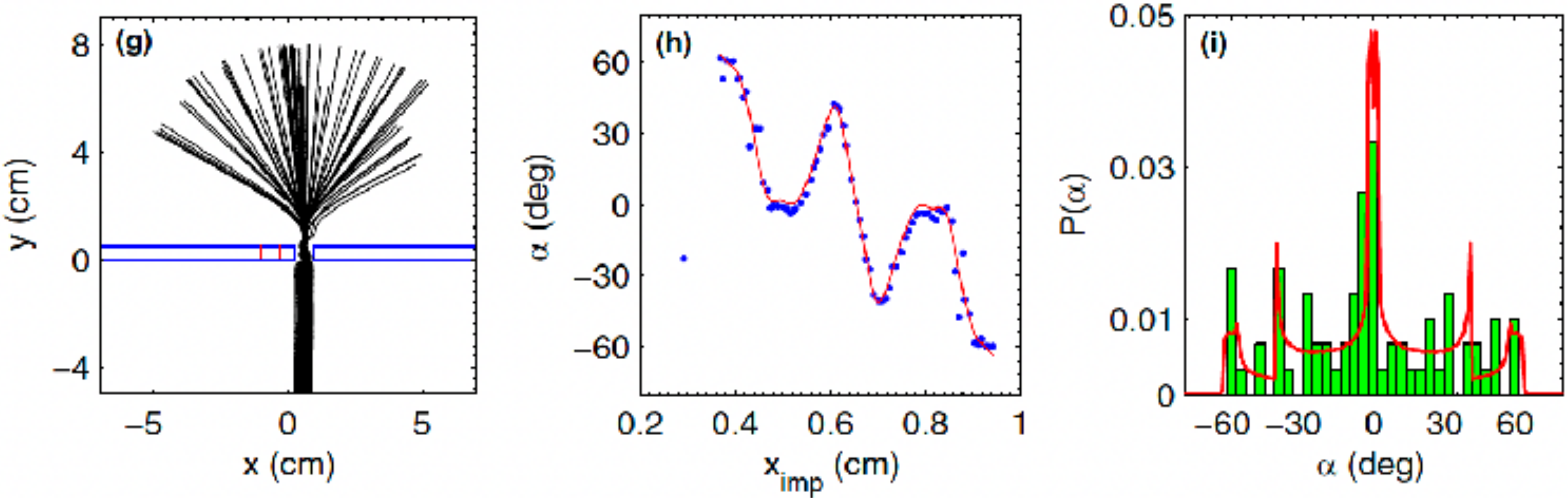
- the most exhaustive, careful experiments done to date are consistent with our results





- thermal control eliminated drifting Me


(g)
y (cm)
x (cm)
8
4
0
−4
−5
0
5
(h)
α (deg)
x_imp (cm)
60
30
0
−30
−60
0.2
0.4
0.6
0.8
(i)
P(α)
α (deg)
0.08
0.06
0.04
0.02
0
−60
−30
0
30
60


(g)
y (cm)
x (cm)
8
4
0
−4
−5
0
5
(h)
α (deg)
x_imp (cm)
60
30
0
−30
−60
0.2
0.4
0.6
0.8
1
(i)
P(α)
α (deg)
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0.03
0.01
0
−60
−30
0
30
60

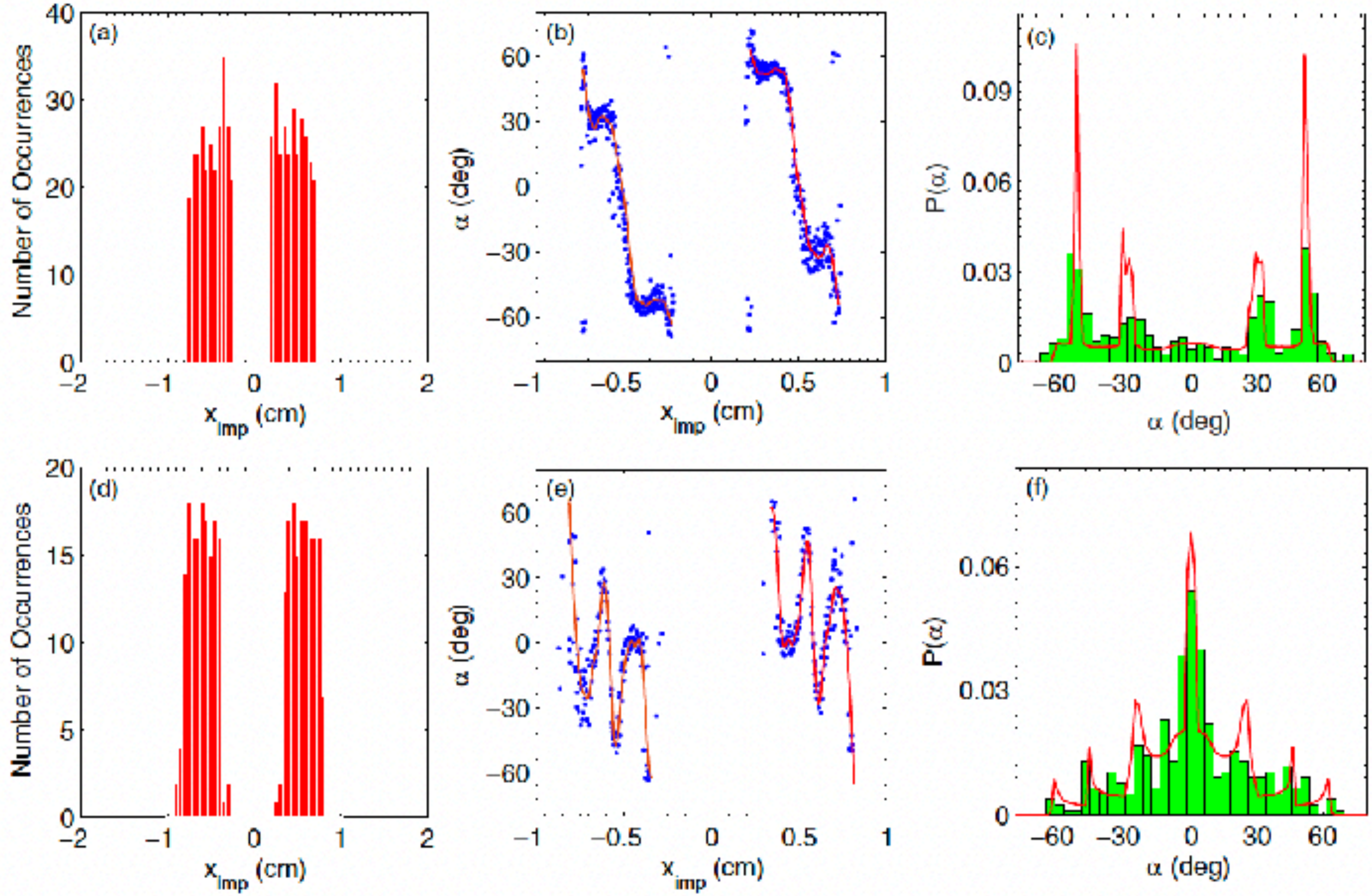

FIG. 16. Statistics of double-slit experiment. Distribution of impact parameters x_{imp} over double-slit (a) 5 mm slit, 557 tracks; (d) 7.5 mm slit, 331 tracks. (b), (e) Corresponding α versus x_{imp} (···) with fit ( ). (c), (f) $P(\alpha)$ ( ) from fit, normalized histogram showing experimental distribution of α. 5 mm slit: $v_{imp} = 11.1$ mm/s, $\gamma/\gamma_F = 0.999$, $h_1 = 0.71$ mm. 7.5 mm slit: $v_{imp} = 9.3$ mm/s, $\gamma/\gamma_F = 0.997$, $h_1 = 0.63$ mm.

Summary

- walking droplets exhibit single-particle diffraction when they interact with obstacles, slits, edges
- illustrates the physical picture for electron diffraction proposed by de Broglie, SED
- demonstrates how double-slit experiment may be rationalized with a *local* theory
- the emergent diffraction pattern is wave-like, but differs from that arising in QM

SO WHAT?

- one expects the pilot wave, wave interference patterns to be different in the two systems
- qualitative similarity is sufficient to obviate the need to deny philosophical similarity, and so be obliged to appeal to QM magic
- quantitative similarity will be approached with Dave's HQFT

QUANTUM PHYSICS

Famous Experiment Dooms Alternative to Quantum Weirdness

Oil droplets guided by "pilot waves" have failed to reproduce the results of the quantum double-slit experiment, crushing a century-old dream that there exists a single, concrete reality.

QUANTUM PHYSICS

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Oil droplets guided by "pilot waves" have failed to reproduce the results of the quantum double-slit experiment, crushing a century-old dream that there exists a single, concrete reality.

``Never interrupt your enemy when he is making a mistake."

— Napoleon