

# Wave-particle duality with the naked eye

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# Outline of the presentation

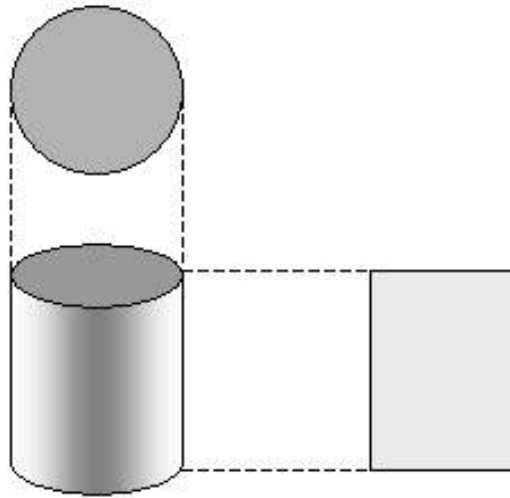
- Classic Wave-particle duality
  - A macroscopic object with memory driven wave-particle duality
  - Quantization Experiments: Orbits, Landau-like orbits
  - Statistical experiments: diffraction, interference, tunneling
  - Thought experiment: Inertial walkers
  - Work in progress: cavity, Anderson localization, central force

## Wave particle duality

**Wave-particle duality** is a central concept of quantum mechanics, this duality addresses the inability of classical concepts like "particle" and "wave" to fully describe the behavior of quantum-scale objects.

QM postulates that all particles exhibit both wave and particle properties.

Quantum theory works very well **but... no intuition!**



**Tentative illustration, does it help ?**

It is safe to say that nobody understands quantum mechanics.

*Richard Feynman.*

# Wave particle duality

Can any of the phenomena characteristic of the quantum wave-particle duality be observed in a non quantum system?

We were drawn into investigating this question by the, almost accidental, finding of a wave-particle association at macroscopic scale.

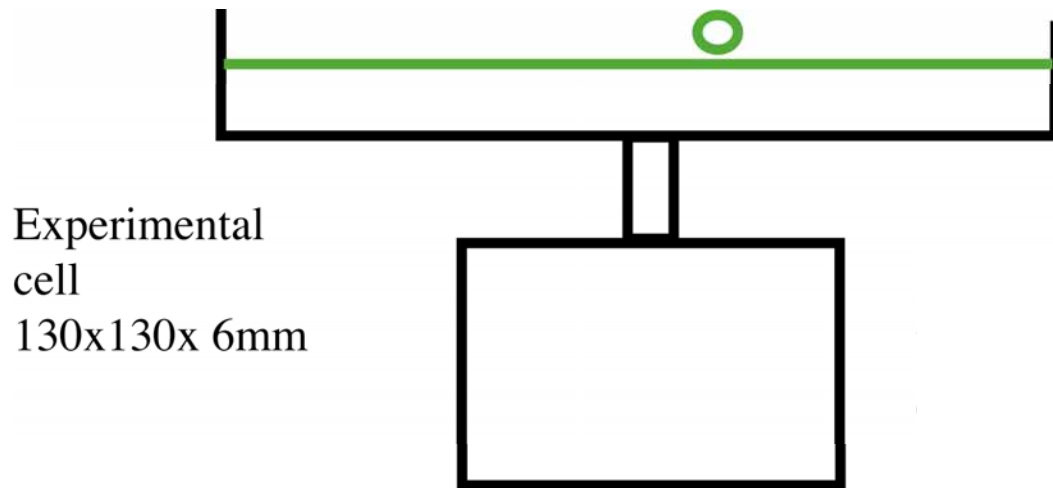
It all started during experimental projects for undergraduate students in their third year of university

# Basic experimental setup

~~Non-Condensate droplets deposited on the surface of the same fluid~~  
lasts approximately  $\tau=1/10$ s

Fluids: Silicon oils with viscosities

$$5 \cdot 10^{-3} \text{ Pa}\cdot\text{s} < \mu < 500 \cdot 10^{-3} \text{ Pa}\cdot\text{s}$$



Vertical acceleration

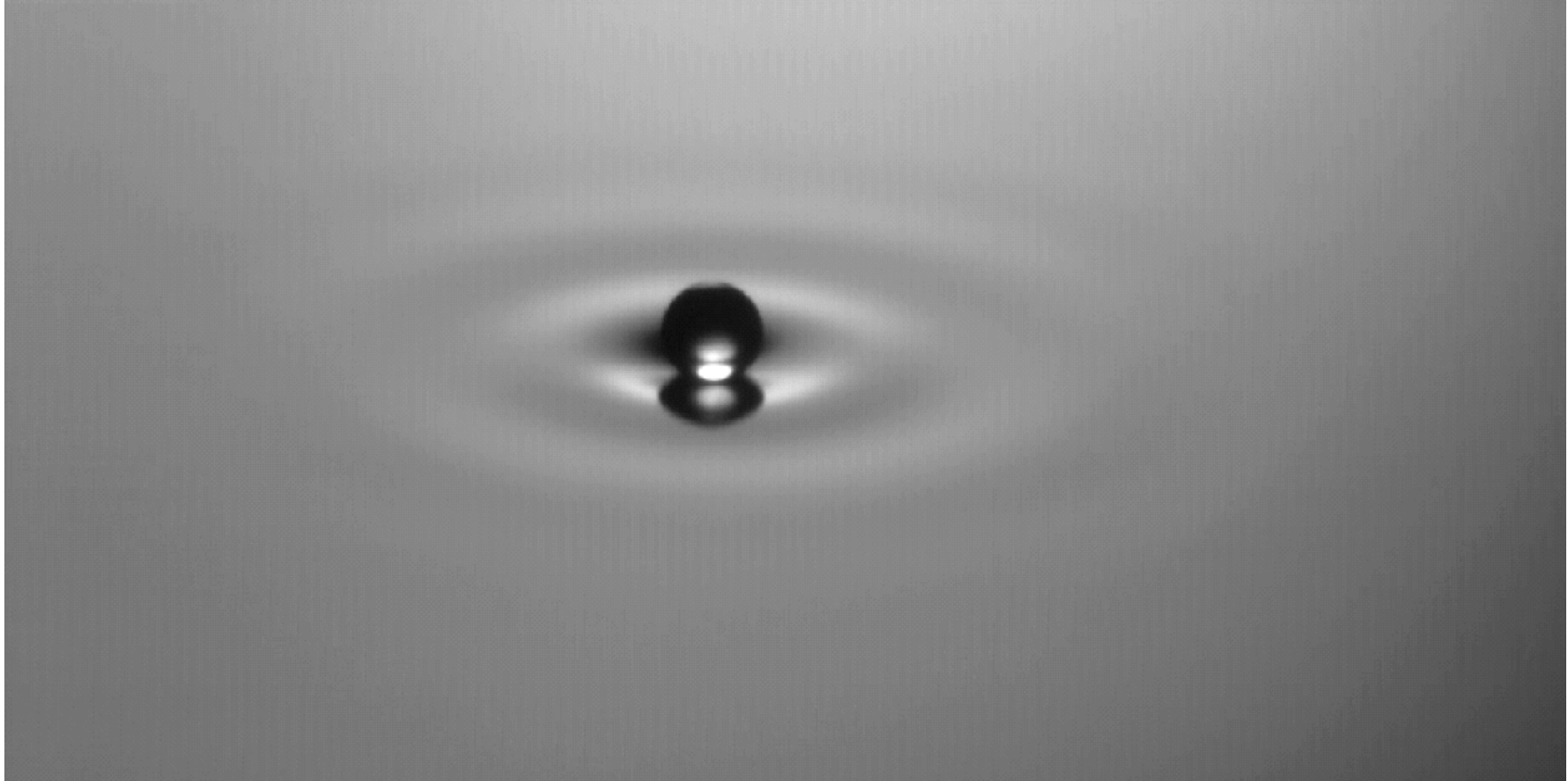
$$\gamma = \gamma_m \cos(\omega t)$$

with  $\gamma_m$  ranging from 0 to 5g

Forcing frequency range:

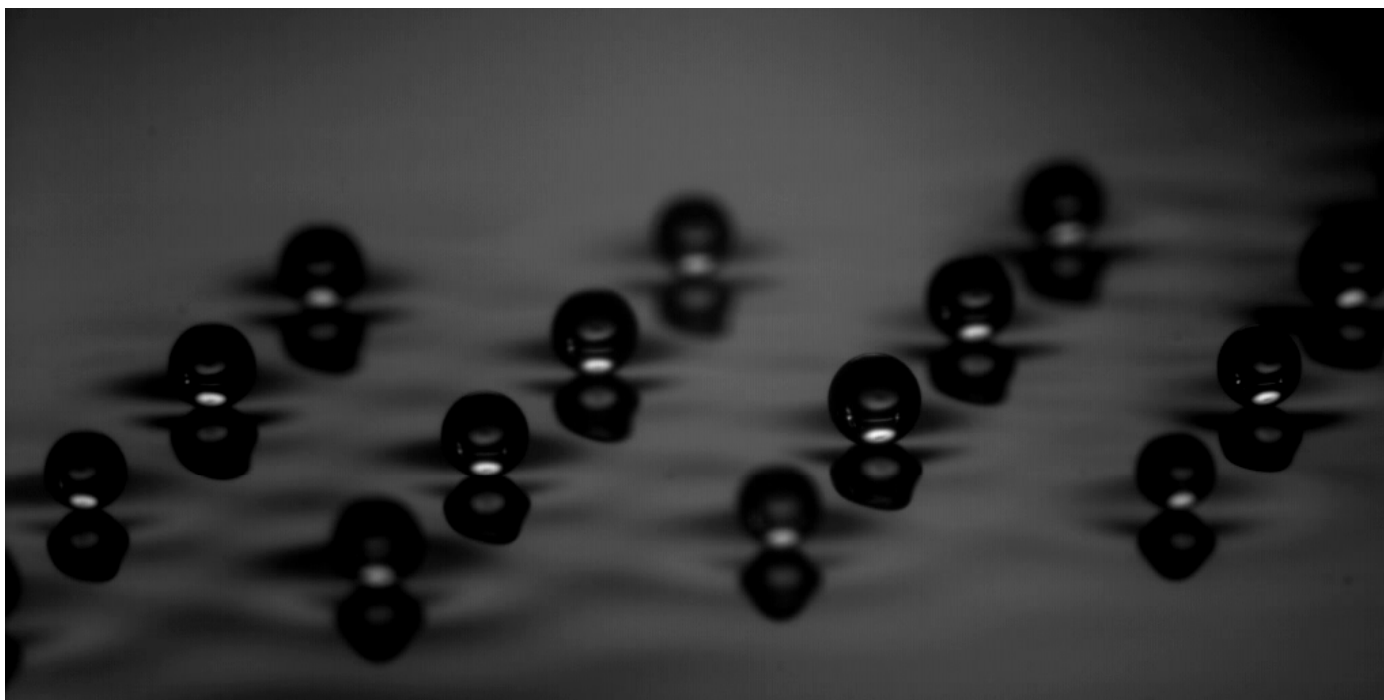
$$10 < \omega/2\pi < 300 \text{ Hz}$$

## Bouncing droplet



Fast camera

# Cristal of bouncing droplet





# Phase diagram of the bouncing

## Fixed parameters:

- Silicon oil
- Viscosity:  $\mu_L = 50 \cdot 10^{-3} \text{ Pa s}$
- Forcing frequency: 50 Hz

## Phase diagram areas:

B : simple bouncing at the forcing frequency

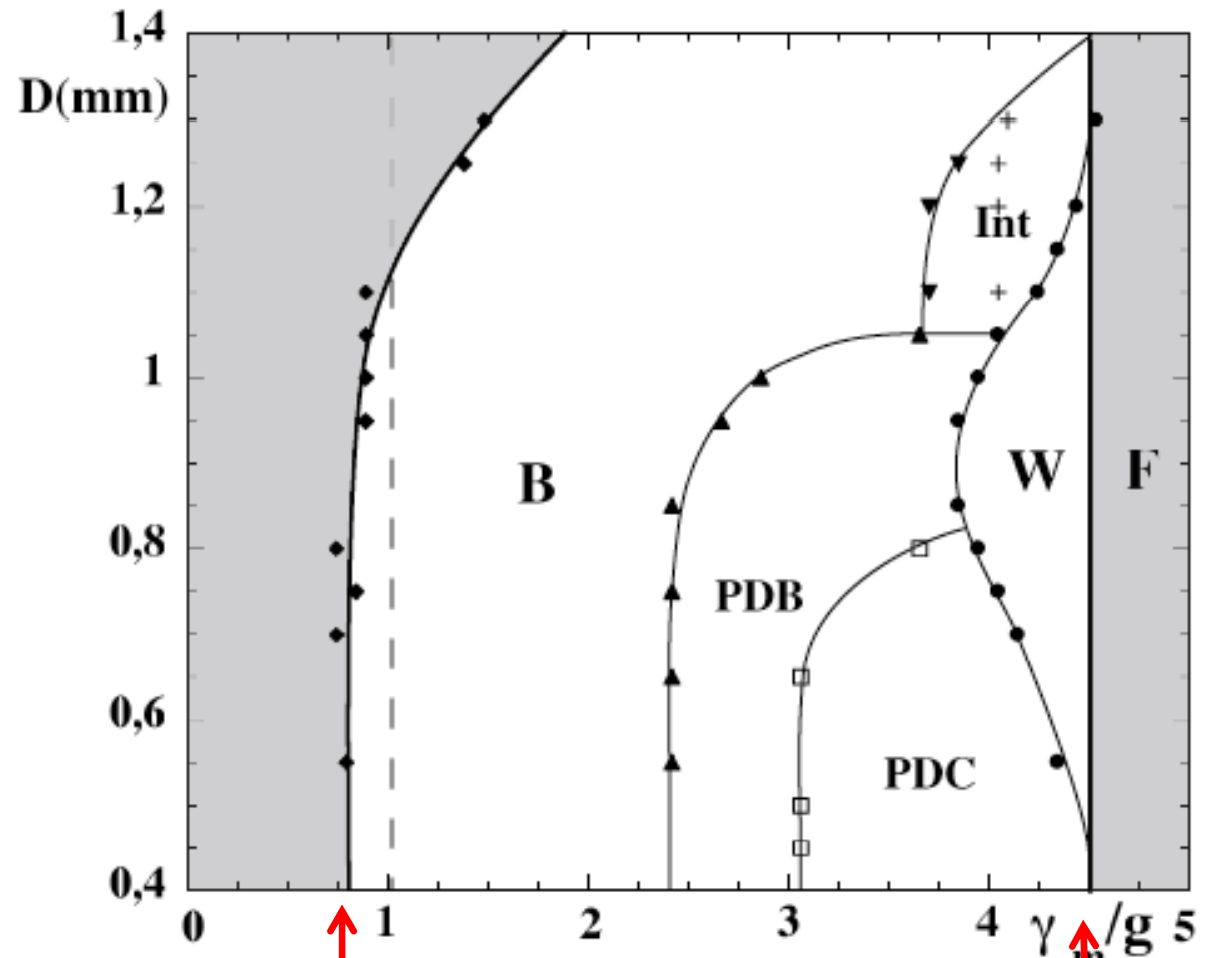
PDB : Period doubling

PDC: Chaos through a sequence of period doubling

W : Walking

Int : Intermittent behavior

F : Faraday instability



Bouncing threshold

Faraday Instability threshold

# Reminder: Faraday instability

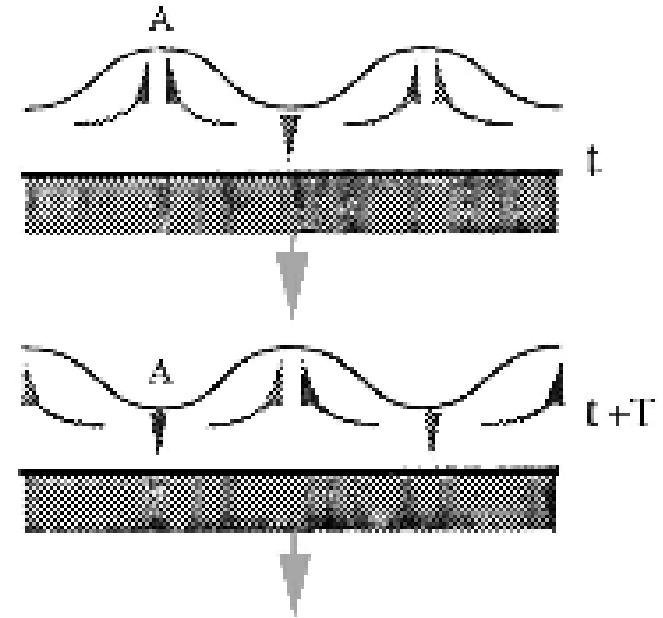
Occurs in a fluid submitted to a vertical acceleration

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

Over a threshold value  $\gamma_m^F$  of the excitation, there is **formation of standing surface waves with half the frequency of forcing**

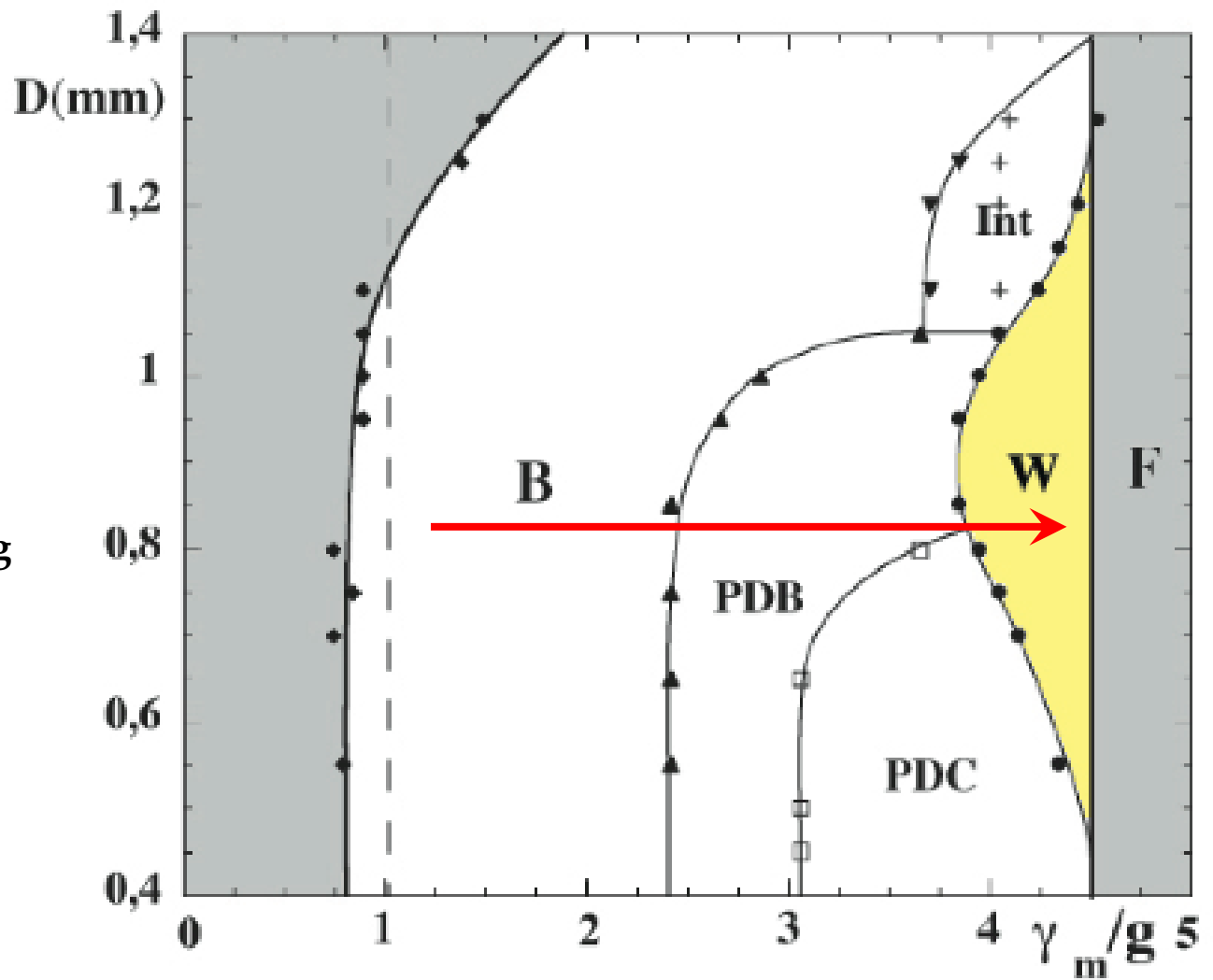
## Parametric forcing of surface waves

Analogous to the parametric forcing of a swing or a pendulum  
(*example: botafumeiro*)



# Phase diagram of the bouncing

- **B** : simple bouncing at the forcing frequency
- **PDB** : Period doubling
- **PDC**: Chaos through a sequence of period doubling
- **W** : Walking
- **Int** : Intermittent behavior
- **F** : Faraday instability



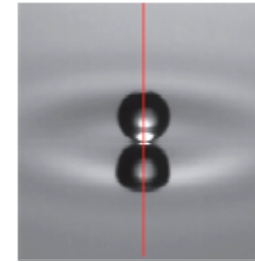
Bouncing threshold

Faraday Instability threshold

# Bouncing of intermediate drops

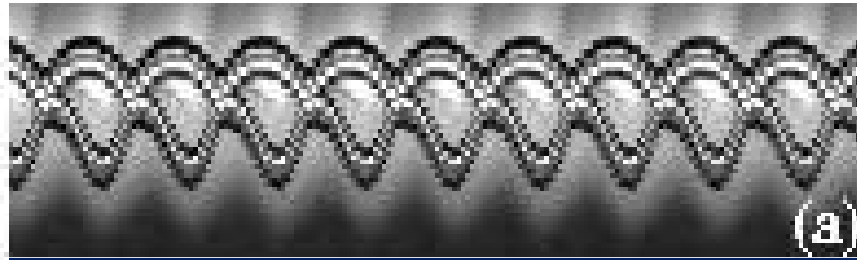
## Spatio-temporal diagrams of the vertical motion

Size range:  $0.6 < D < 1.1\text{mm}$



$$\gamma_m = 1.5g$$

Bouncing at the forcing frequency



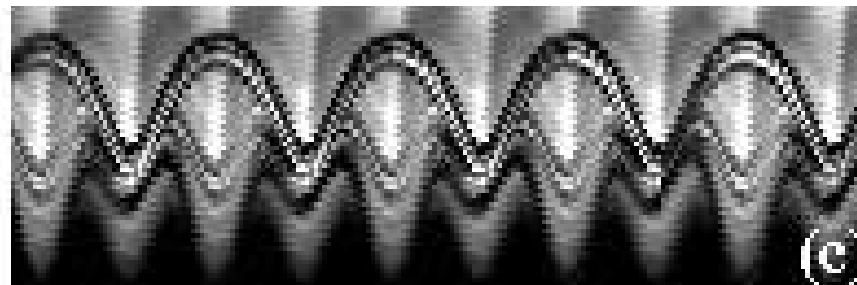
$$\gamma_m = 3g$$

Period doubling



$$\gamma_m = 4g$$

no chaos and complete period doubling



Time

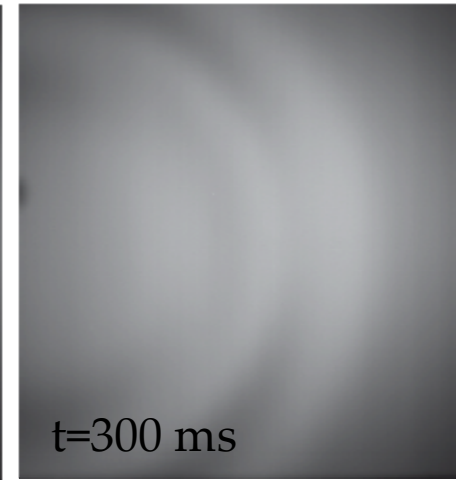
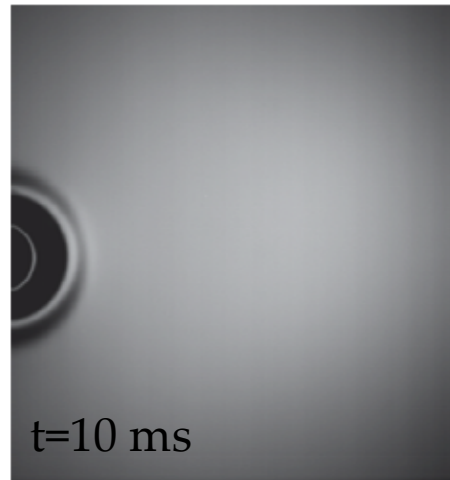
Just below the Faraday threshold, intermediate droplets


- undergo complete period doubling,
- bounce at Faraday period

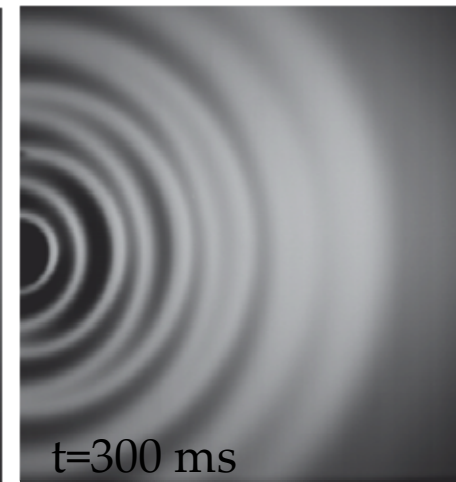
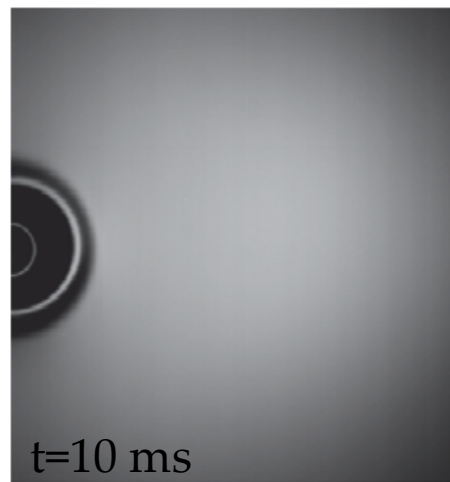
# Wavefield produced by a single collision

Experiment performed with a 2 mm steel ball

 Without periodic forcing

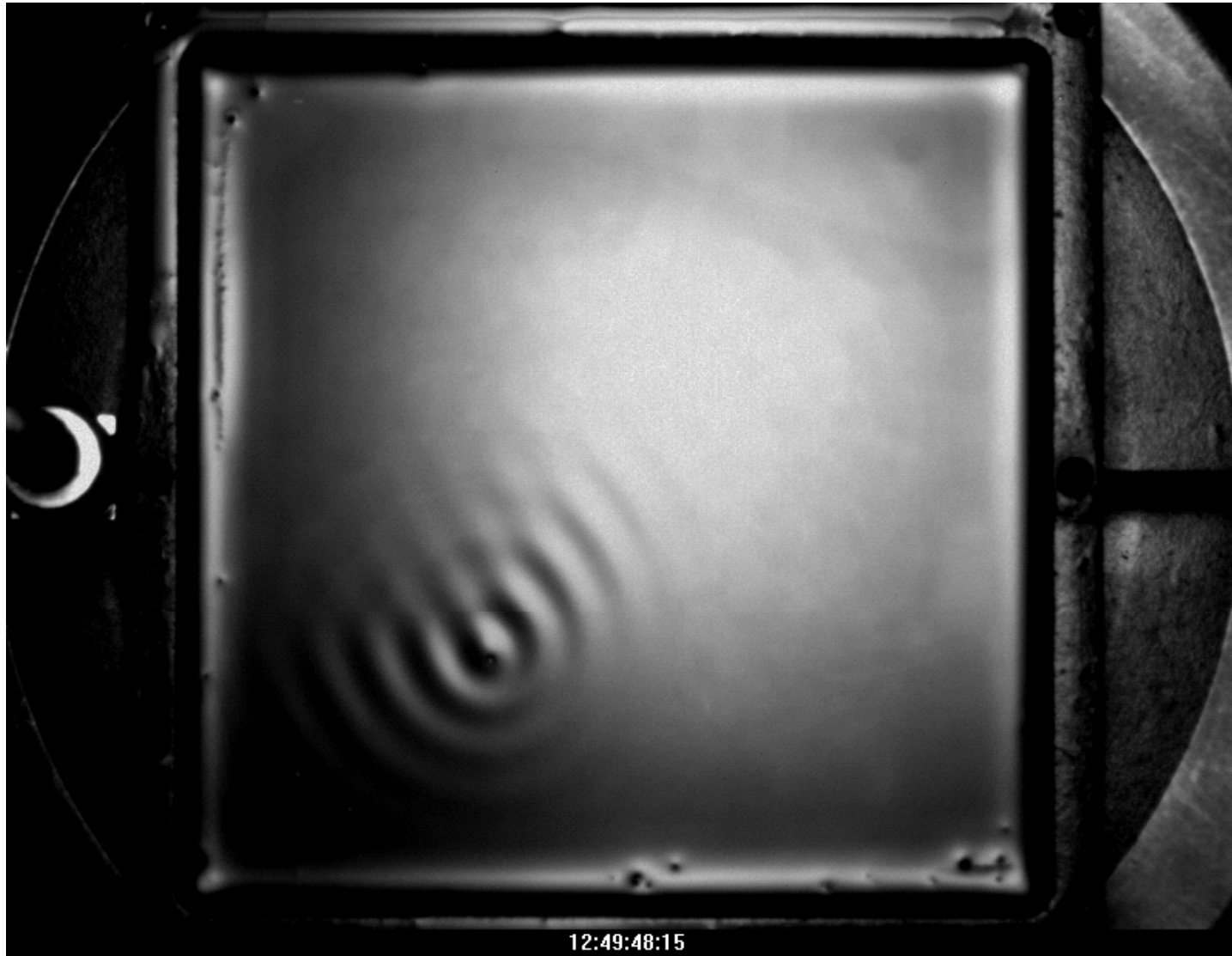


 With a periodic forcing near the Faraday instability threshold



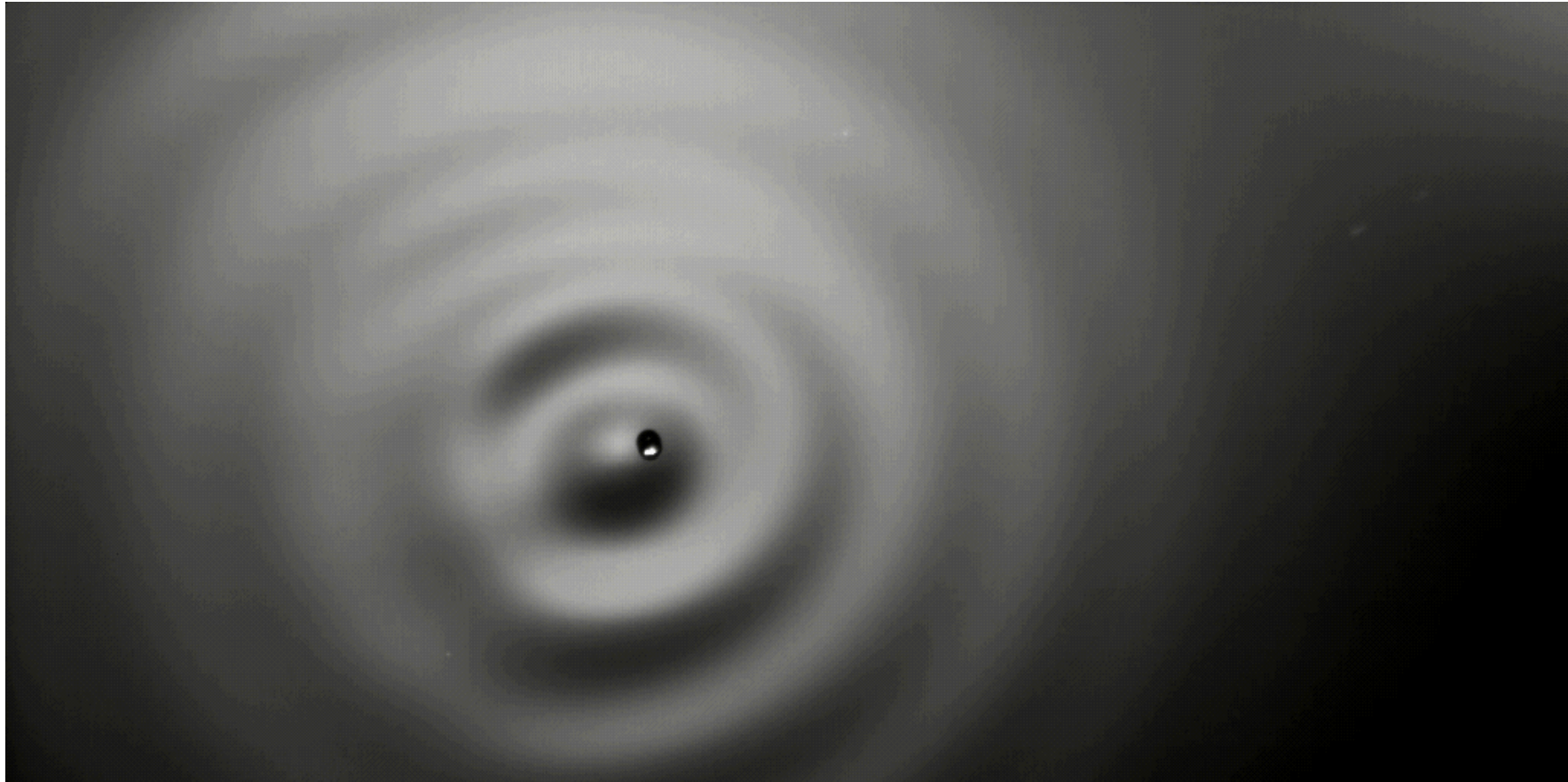
**Near the Faraday threshold, the propagating capillary wave triggers stationary Faraday waves around the droplet**

# A Walker in "strobe" mode



Real time movie, top view

## A Walker: oscillatory motion



Fast camera, top view

The droplet falls on the front side of the bump created by the previous bounces

It gives the droplet a « kick » at each bounce to maintain self propulsion

## The path-memory model

The relative surface height

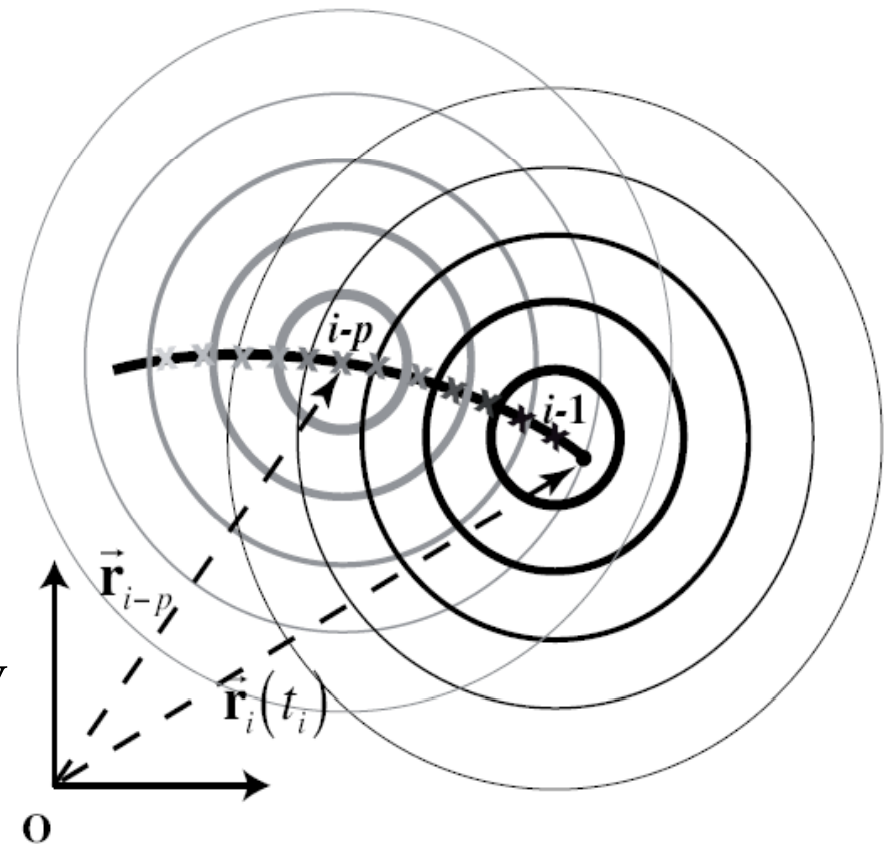
$h(\vec{r}, t_i)$  position  $\vec{r}$  and time  $t_i$  is given by:

$$h(\vec{r}, t_i) = \sum_{p=i-1}^{-\infty} \exp\left(-\frac{t_i - t_p}{\tau}\right) \exp\left(-\frac{|\vec{r} - \vec{r}_p|}{\delta}\right) J_0\left(\frac{2\pi|\vec{r} - \vec{r}_p|}{\lambda_F}\right)$$

where  $\vec{r}_p$  is the position of a previous impact which occurred at time  $t_p = t_i - (i - p)T_F$ .

**The spatial damping,  $\delta$ :** of travelling waves is fixed and related to the fluid viscosity.

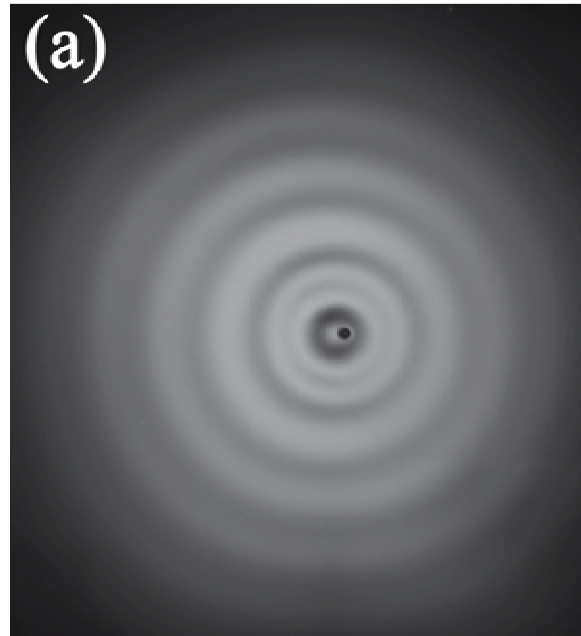
**The damping time,  $\tau$ :** the path memory parameter, is tunable, being determined by the distance to the Faraday instability threshold.



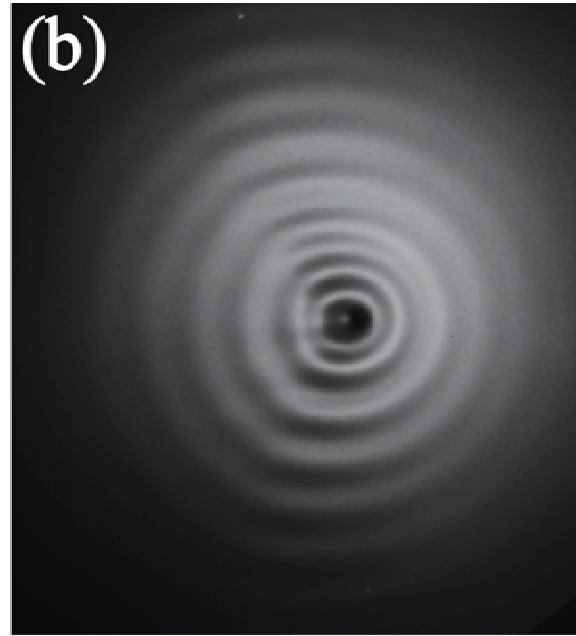


## The path memory concept

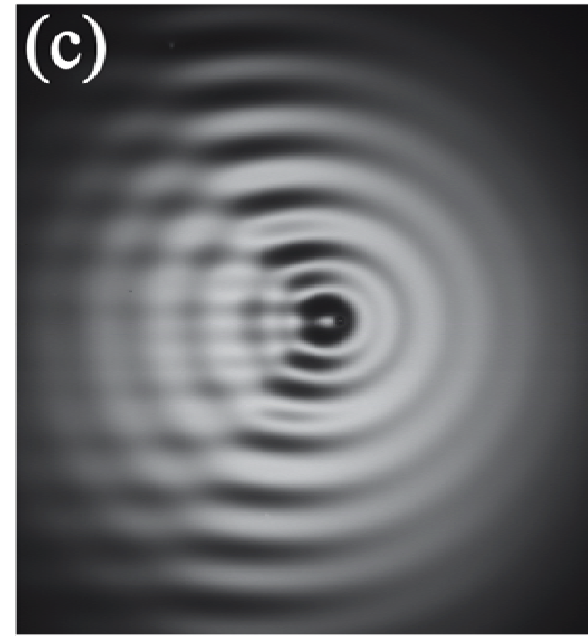
- At each bounce, a circular localized mode of standing waves is generated
- The localized Faraday instability is damped on a typical time :  $\tau \propto |\gamma_m - \gamma_m^F|^{-1}$
- The waves generated during the previous bounces along the trajectory form a ``path-memory'' of the walker wavefield.
- A **memory parameter**  $M = \tau/T_F$  is the number of bounces that contribute to the wave field .
- This parameter can be tuned easily by changing the excitation amplitude



**M=5**



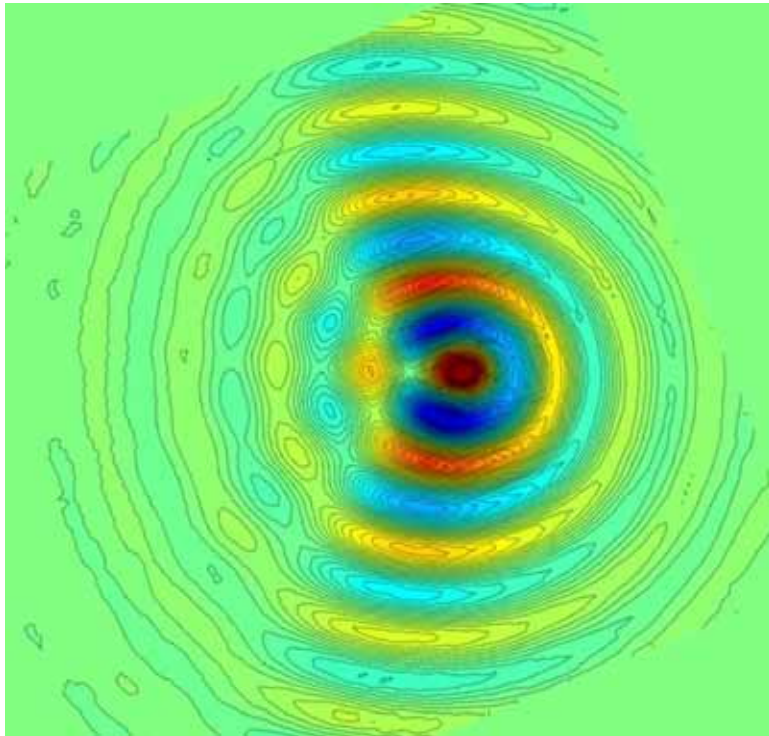
**M=10**



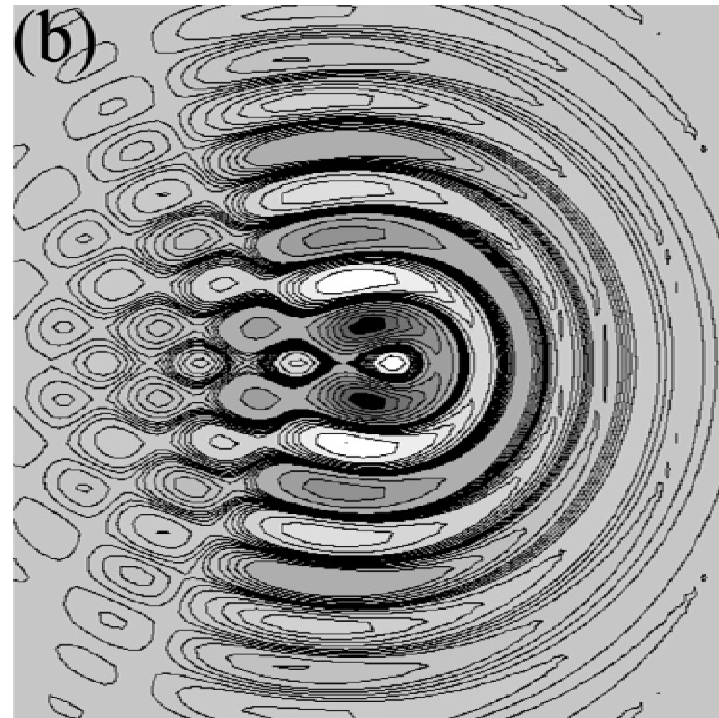
**M=40**

## Results of the path-memory model

- (1) The walking bifurcation is recovered
- (2) A realistic structure of the wave field is obtained for a rectilinearly moving walker



*The measured field*



*Its simulation*

# The pre-Schrödinger de Broglie model (1926)

de Broglie assumes that there are well defined particles that he considers as point sources or singularities.

This material point has an internal oscillation (*zitterbewegung*) and emitting in the surrounding medium a wave of frequency :

$$\nu_0 = \frac{1}{h} m_0 c^2$$

The particle is surrounded by a stationary spherical wave, the superposition of a divergent and a convergent wave.

$$\varphi(r_0, t_0) = \frac{A}{2r_0} \left\{ \cos \left[ 2\pi\nu_0 \left( t_0 - \frac{r_0}{c} \right) + c_1 \right] + \cos \left[ 2\pi\nu_0 \left( t_0 + \frac{r_0}{c} \right) + c_2 \right] \right\}$$

**Non causal!**

de Broglie writes :

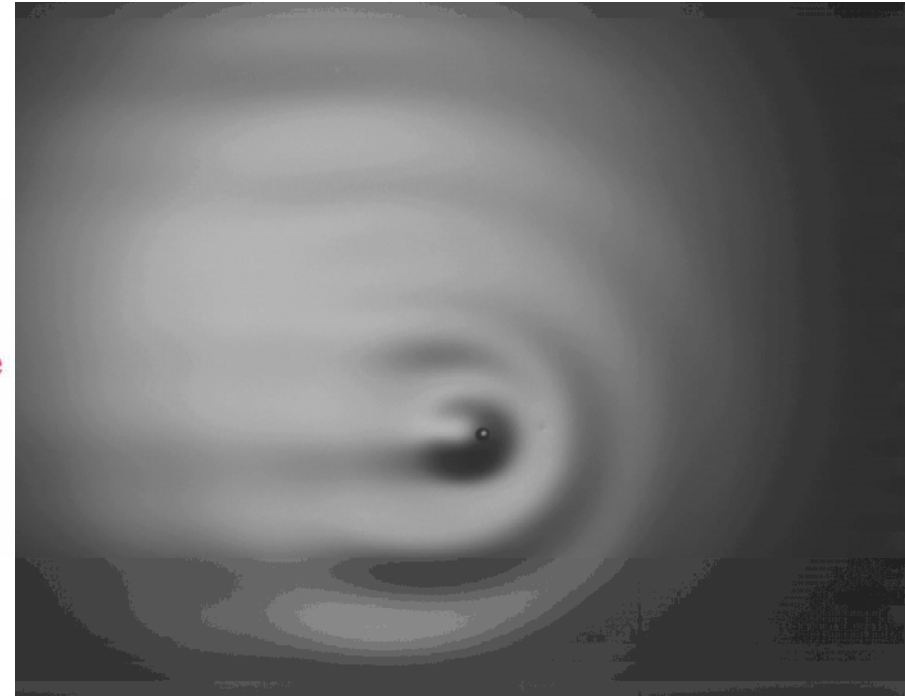
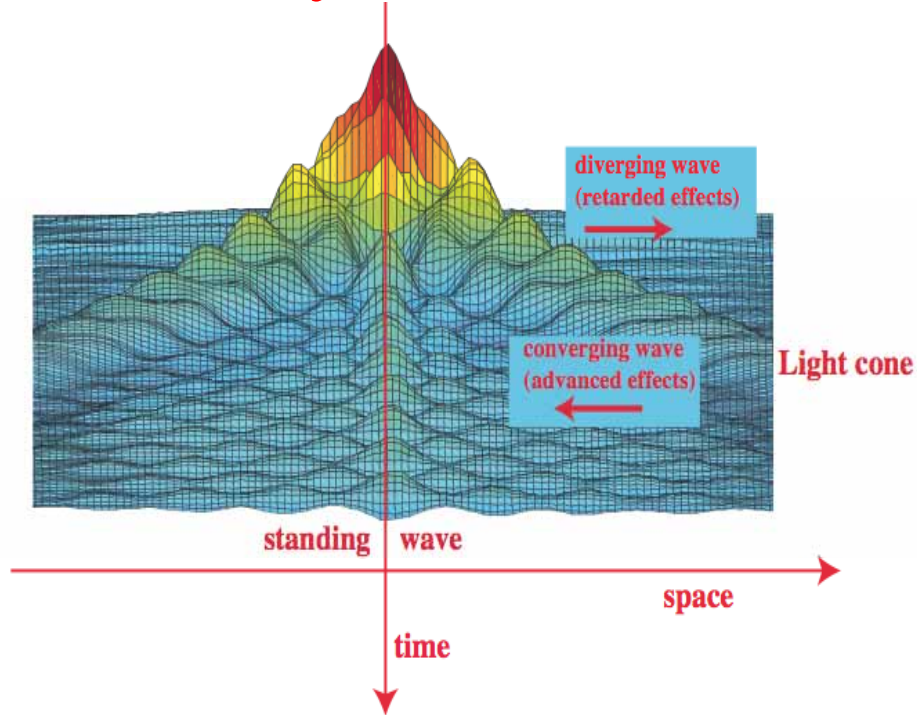
*« But there is also the convergent wave, the interpretation of which could raise interesting philosophical issues, but that appears necessary to ensure the stability of the material point »*

# Memory & Soul (of a Walker)

In path-memory dynamics, convergent waves are retro-propagating waves triggered by the propagation of the divergent wavefront.

Advanced waves are coming from the future of the past.

**Causality is restored!**



Top view, fast camera

## A “classic” dual object

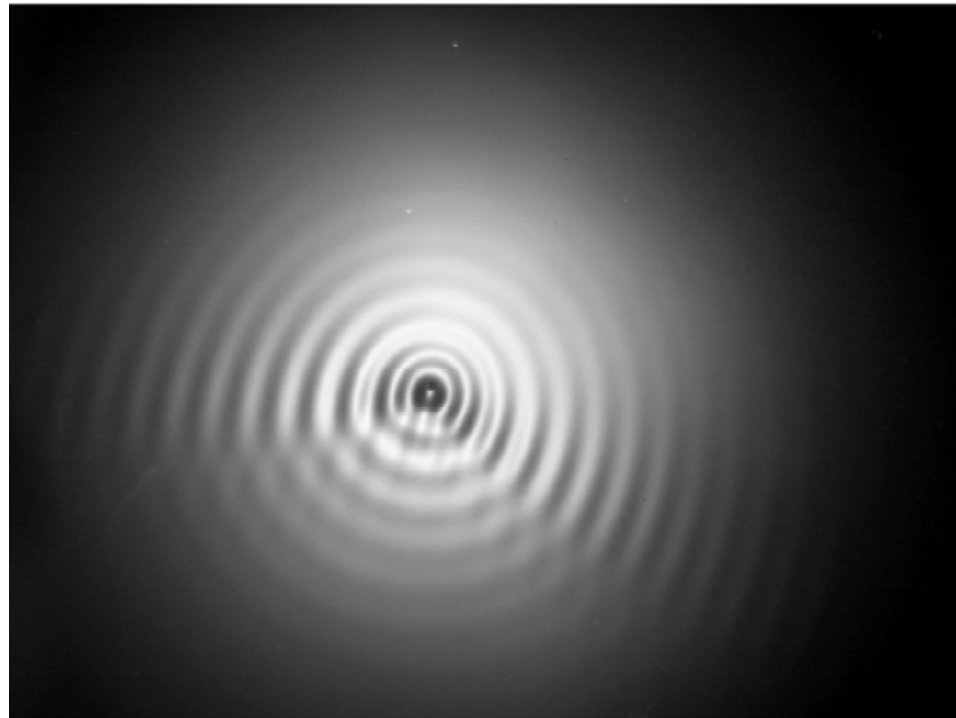
A walker is a “symbiotic” association of a particle with a wave:

If the particle vanishes, so does the wave

If the wave is damped, the droplet stops

The dynamics of the discrete object is driven by the wave that it produces along its trajectory

**A walker is a non-quantum macroscopic dual object!**



# Quantum-like Experiments

## Quantization experiments

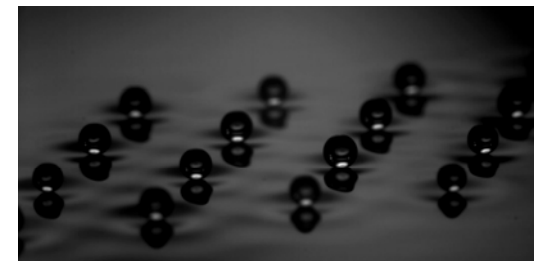
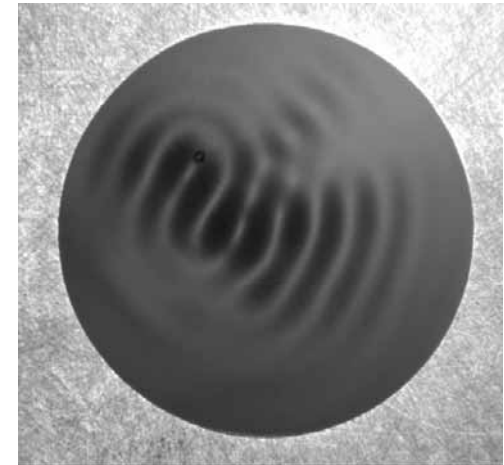
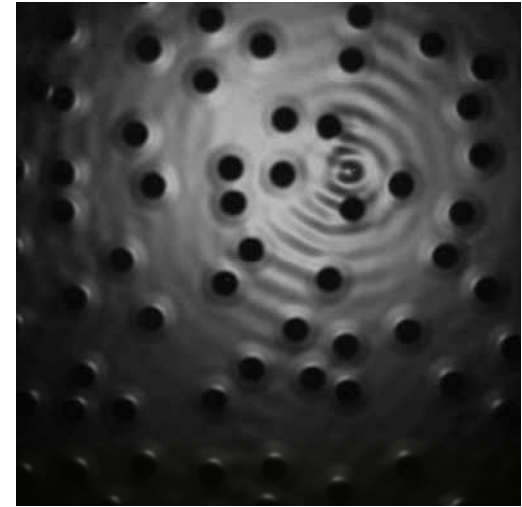
- Interacting walkers
- Landau-like quantization
- Zeeman-like experiments
- Cristal and Phonons modes

## Statistical experiments:

- Single particle diffraction and interferences
- Tunneling effect

## Ongoing research

- Anderson-like localization
- Cavity
- Central force

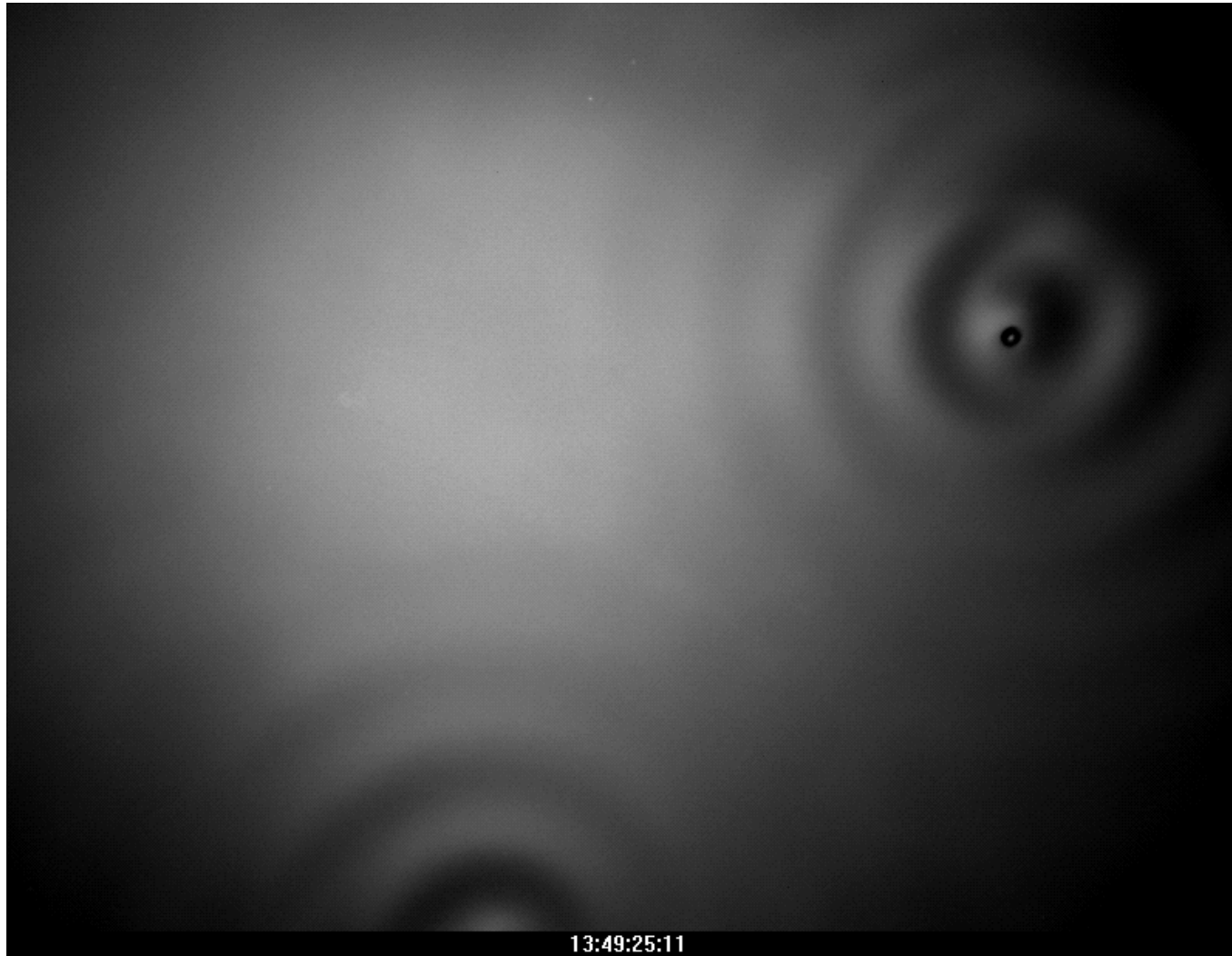


## Quantization experiments

- Interacting walkers

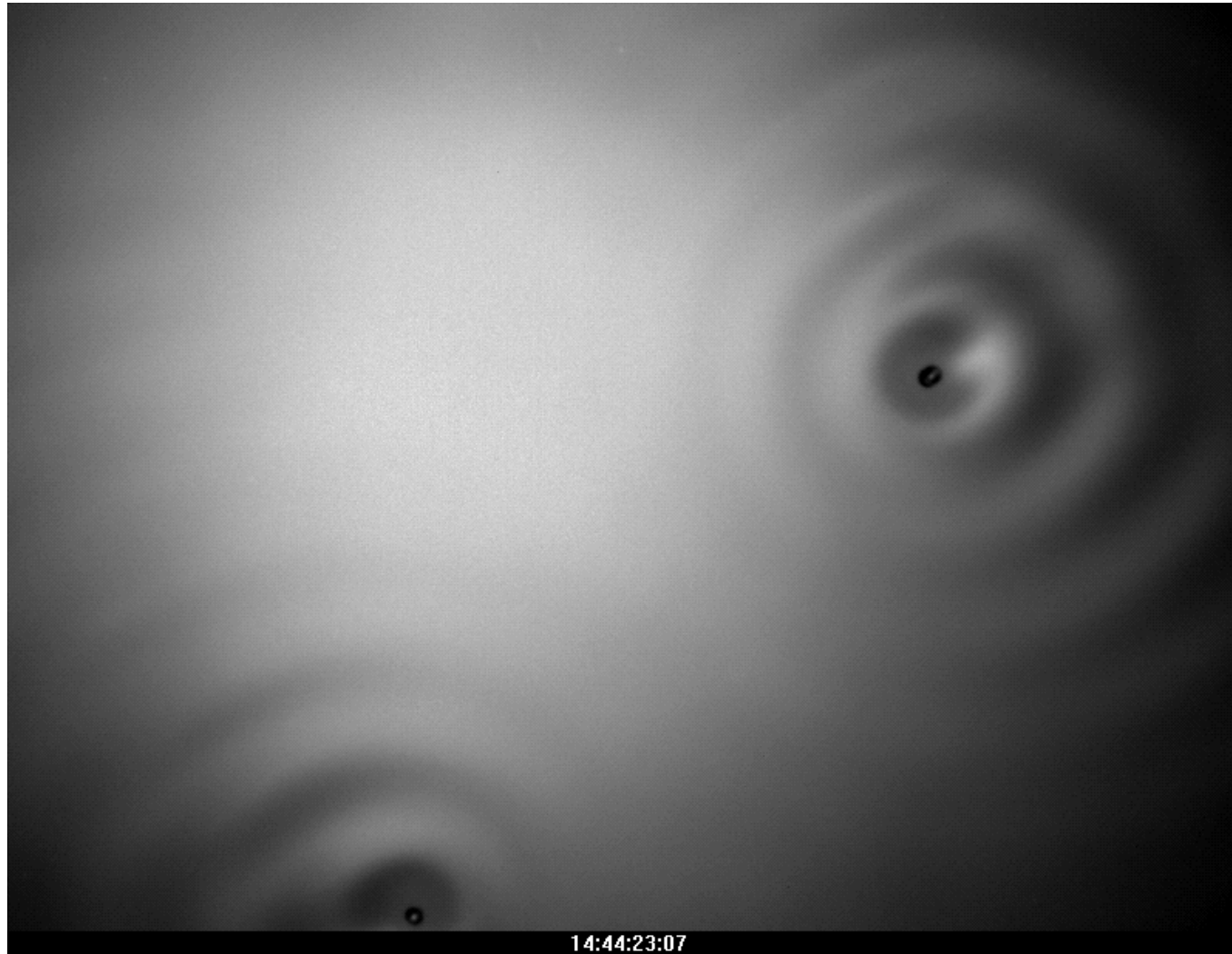
Couder Y. *et al.*, *Nature* **437**, 208. (2005)

## Collision of walkers





## Collision of walkers



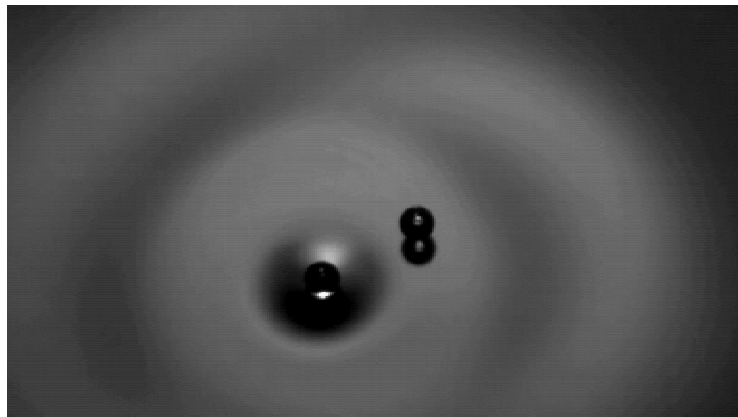
# Quantization of the orbits

## Images of the smallest 4 orbits

Diameters of the orbits:

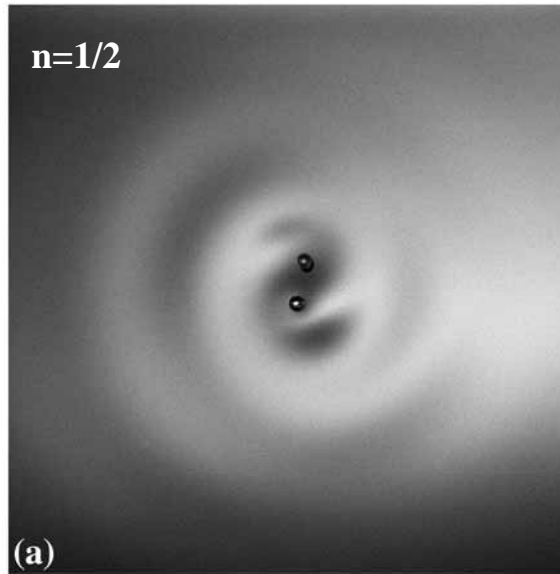
$$d = (n + \epsilon) \lambda_{\text{Far}}$$

- in phase:  $n > 0$  integer
- out of phase:  $n$  half-integer

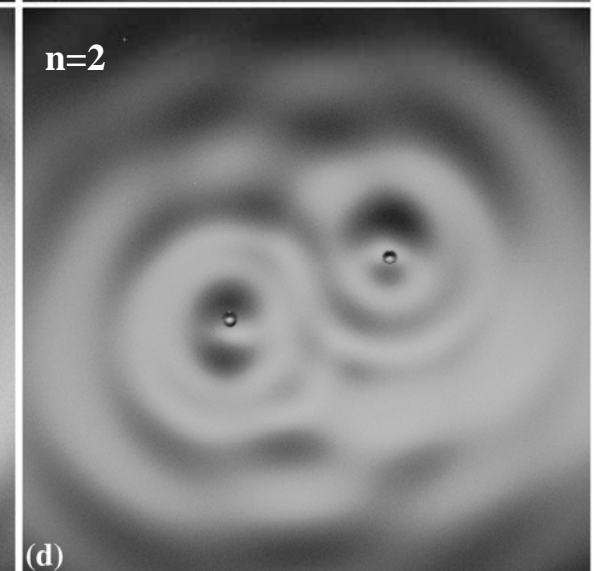
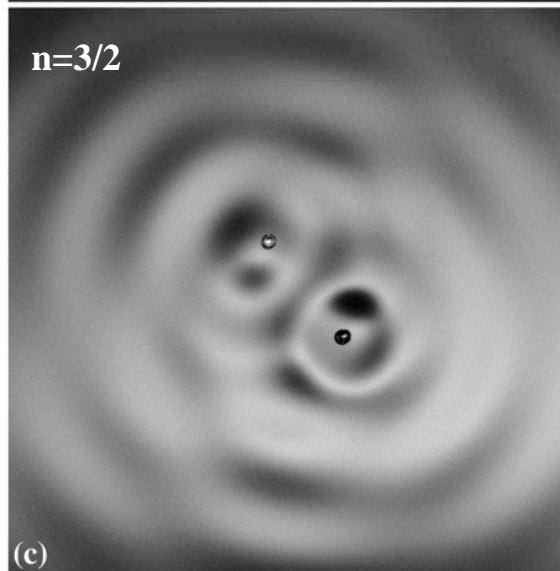
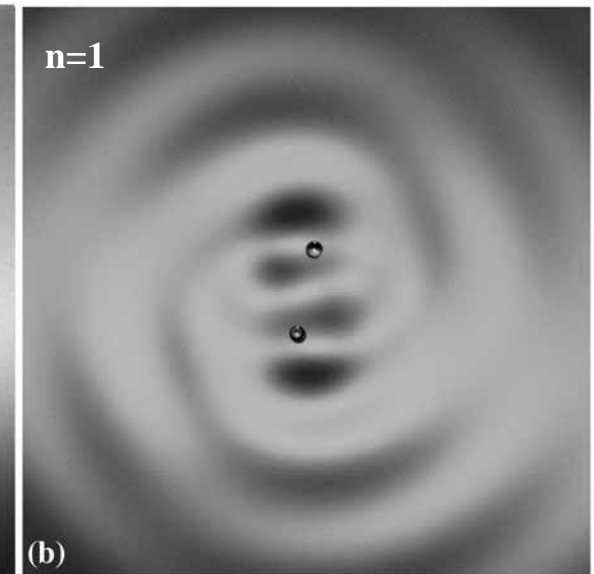


Smallest orbit ( $n=1/2$ )

## Out of phase droplets



## In phase droplets



## Quantization experiments

- Landau-like quantization

Fort E., *et al.*, *PNAS* **107**, 17515 (2010).

# Landau quantization

**Quantization of the orbital motion** with magnetic field

When submitted to a constant magnetic field,

- the energy of the electron becomes quantized (Landau levels):

$$E_n = (n + 1/2)\hbar\omega_c \quad \text{where } \omega_c = qB/m.$$

- the possible modes becomes discrete due to the quantization of the angular momentum quantization in a magnetic field

**Bohr Sommerfeld imposes:**  $\oint (\mathbf{p} - e\mathbf{A}) \cdot d\mathbf{l} = (n + \gamma)h$

(where  $\gamma = 1/2$  in the semi-classical approach)

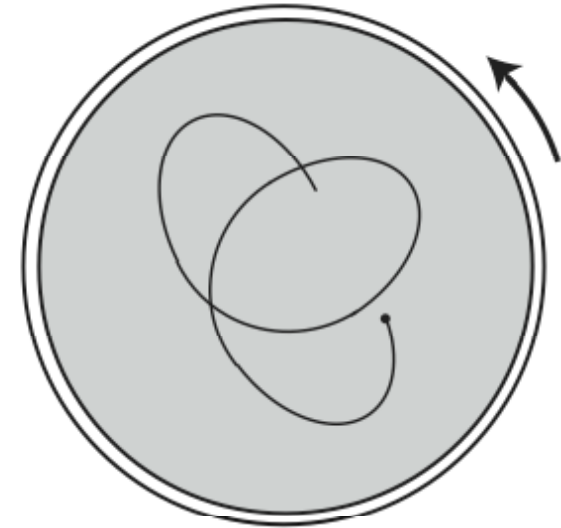
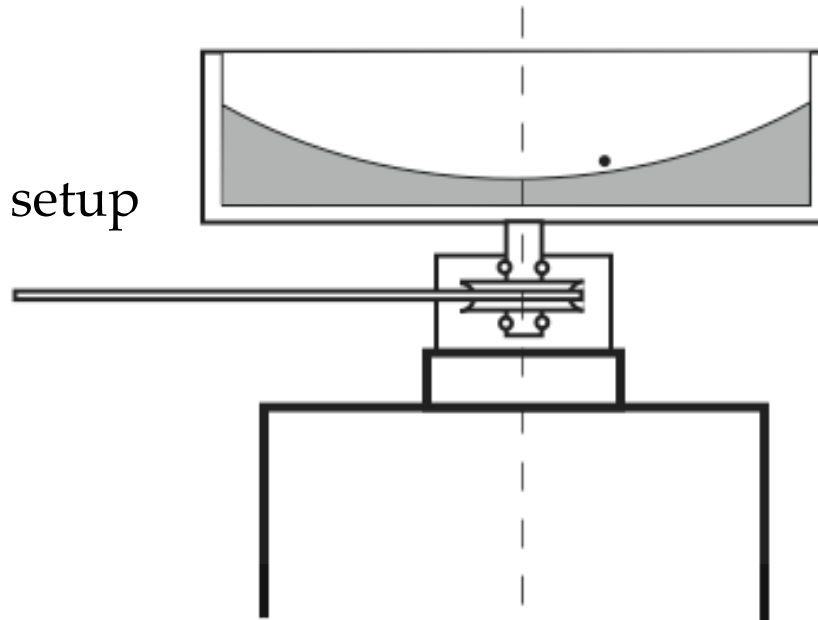
The **Larmor radius** takes discrete values:  $\rho_L^n = \frac{1}{\sqrt{\pi}} \sqrt{\frac{h}{qB} \left( n + \frac{1}{2} \right)}$

# Analogy: magnetic field and rotating frame

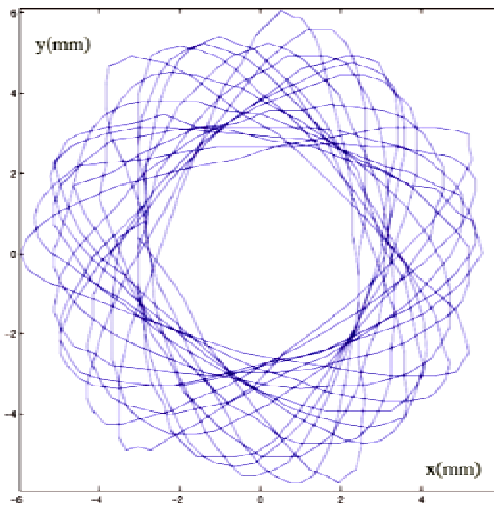
<p>In a magnetic field <math>\mathbf{B}</math></p> $\vec{F} = q(\vec{V} \wedge \vec{B})$ <p>Orbital motion</p>	<p>On a surface rotating with angular velocity <math>\Omega</math></p> $\vec{F}_c = -2m(\vec{V} \wedge \vec{\Omega})$ <p>Orbital motion in the rotating frame</p>
<p>Larmor angular velocity</p> $\omega_L = qB/m$	<p>Orbital motion angular velocity</p> $2\Omega$
<p>Orbit radius</p> $\rho_L = V/\omega_L$	<p>Orbit radius</p> $R = V/2\Omega$

# The rotating Faraday experiment

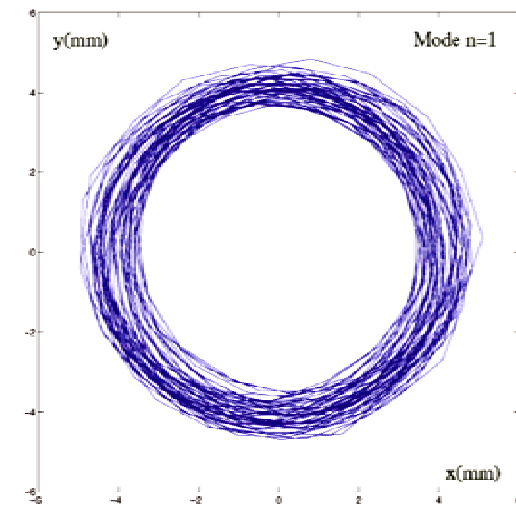
Experimental setup



Measured trajectories



Trajectory in the laboratory  
frame of reference

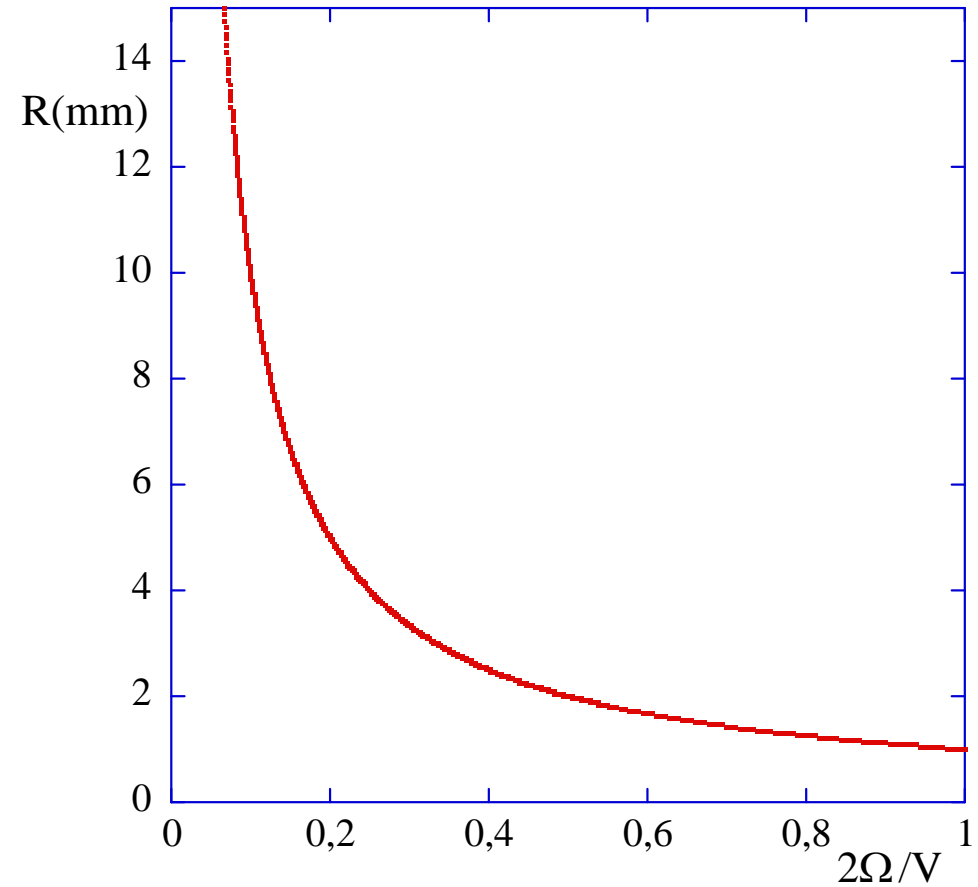


Trajectory in the rotating  
frame of reference

# Classical radius of the orbits

The classical radius of the orbit observed in the rotating frame and due to **Coriolis effect** should be:

$$R = V/2\Omega$$



# Classical radius of the orbits

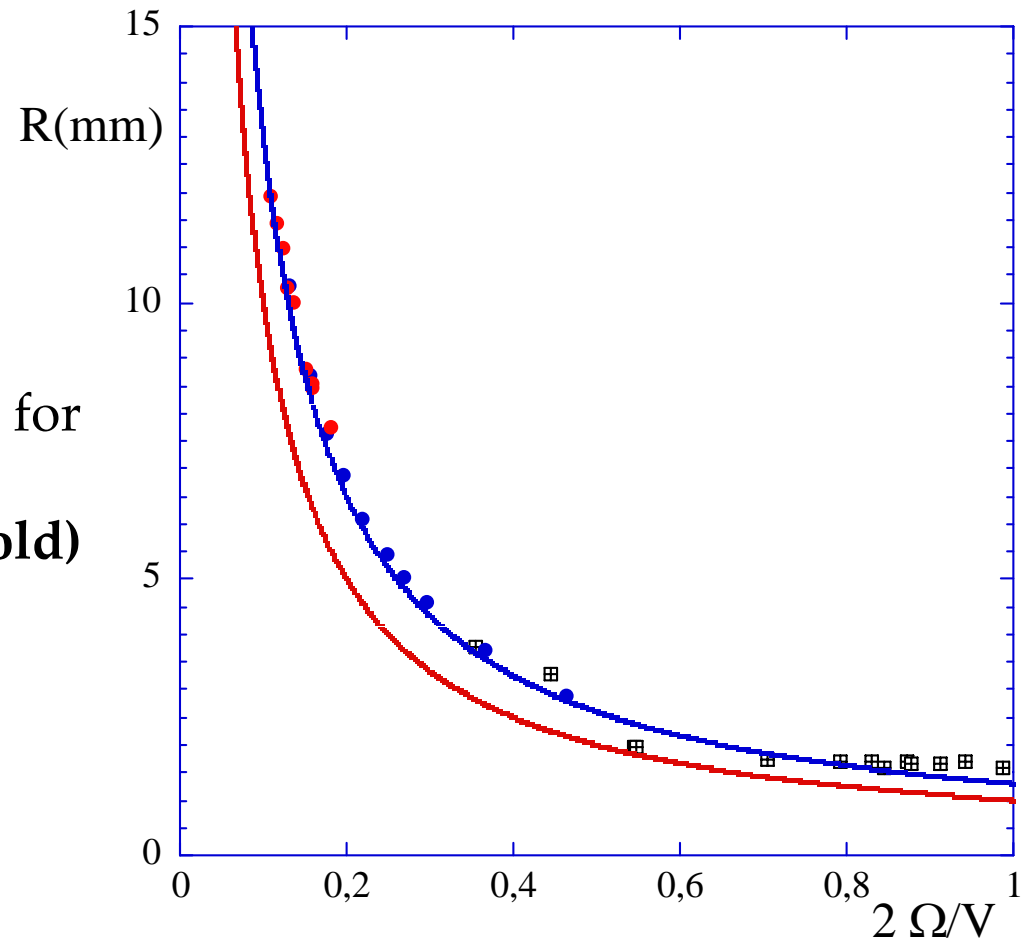
The classical radius of the orbit observed in the rotating frame and due to **Coriolis effect** should be:

$$R = V/2\Omega$$

Measured radius of the orbits for walkers **with short memory (far from the Faraday threshold)**

The radius of the orbit observed in the rotating frame has a classical dependance, but slightly shifted

$$R = a (V/2\Omega) \quad \text{with } a=1.3$$



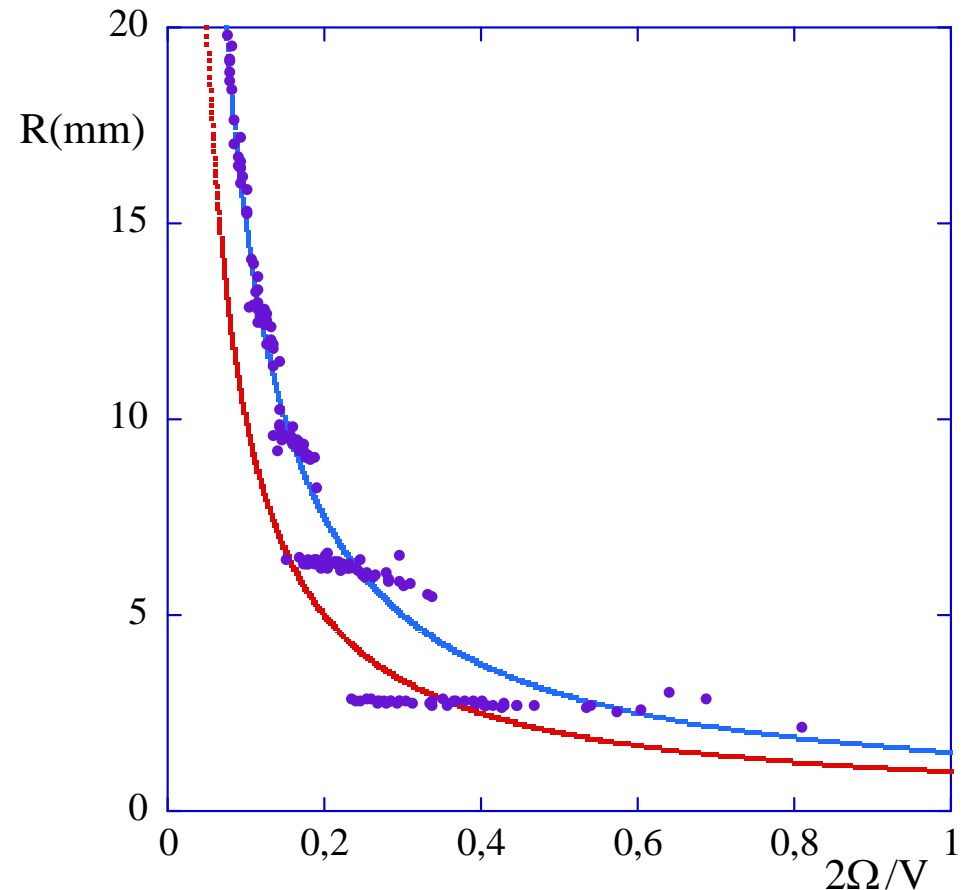


## ...Less-Classical radius of the orbits with path-memory

Measured radius of the orbits for walkers **with long memory** (near the Faraday threshold)

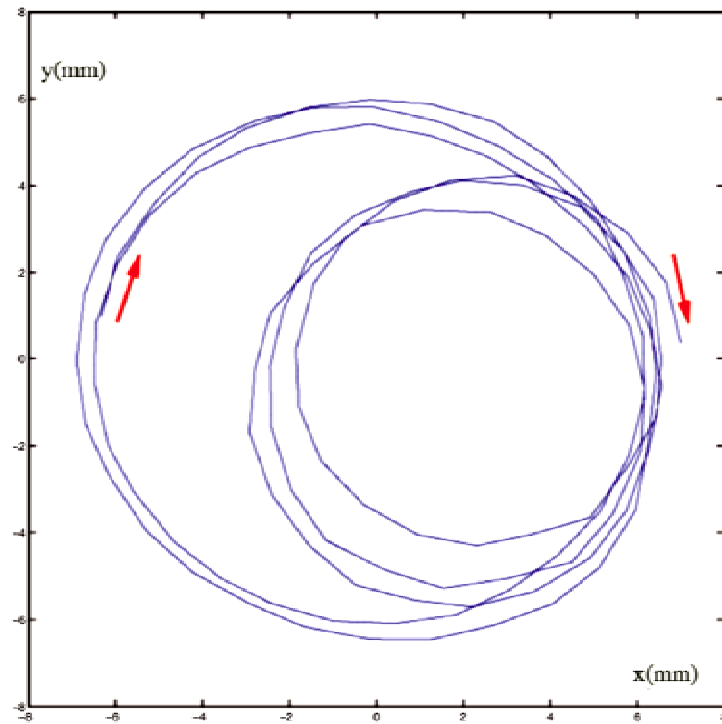
Near the Faraday instability threshold, the radius of the orbit evolves by discrete jumps when  $W$  is increased

**Quantization appears in the orbits with path-memory**



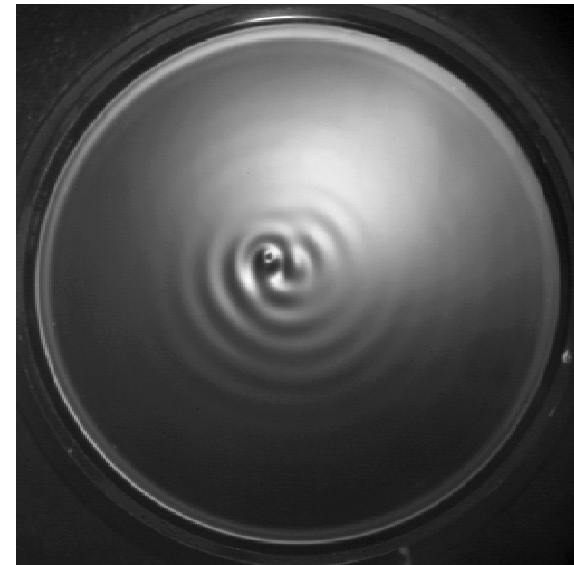
# Transition between two discrete orbits

A transition from the orbit  $n=2$  to  $n=1$  when  $\Omega$  is increased

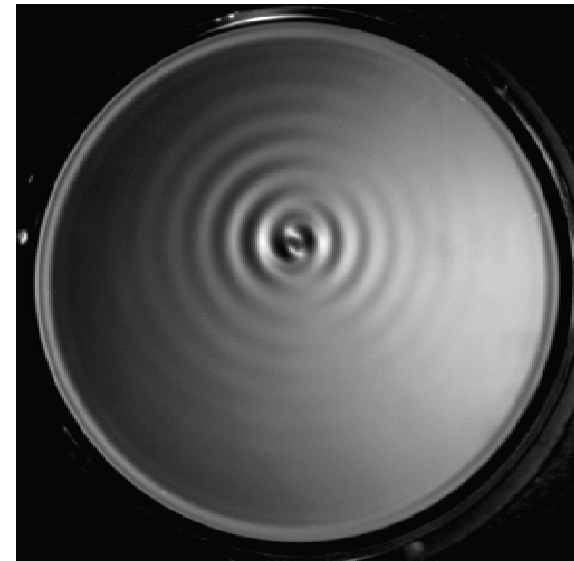


Trajectory in the rotating frame of reference

$n=2$



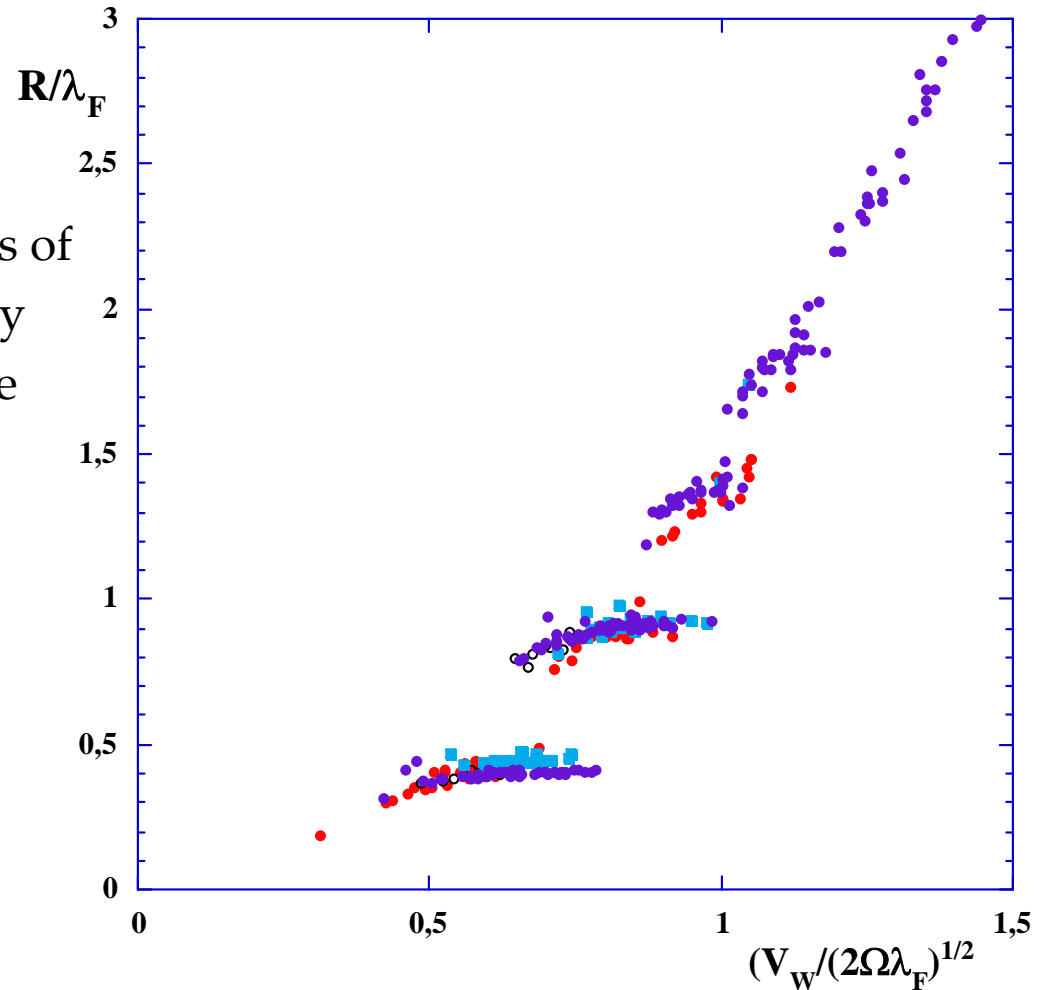
$n=1$



# Dimensionless radius of the orbits

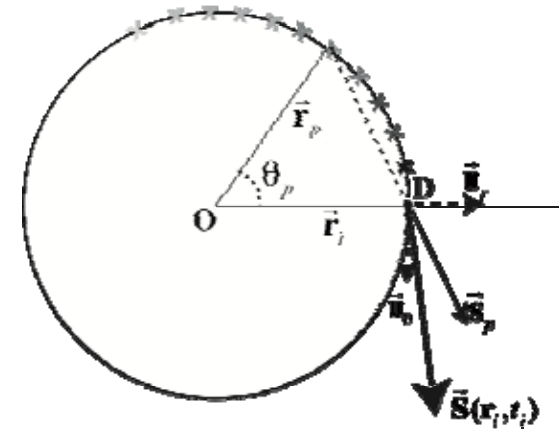
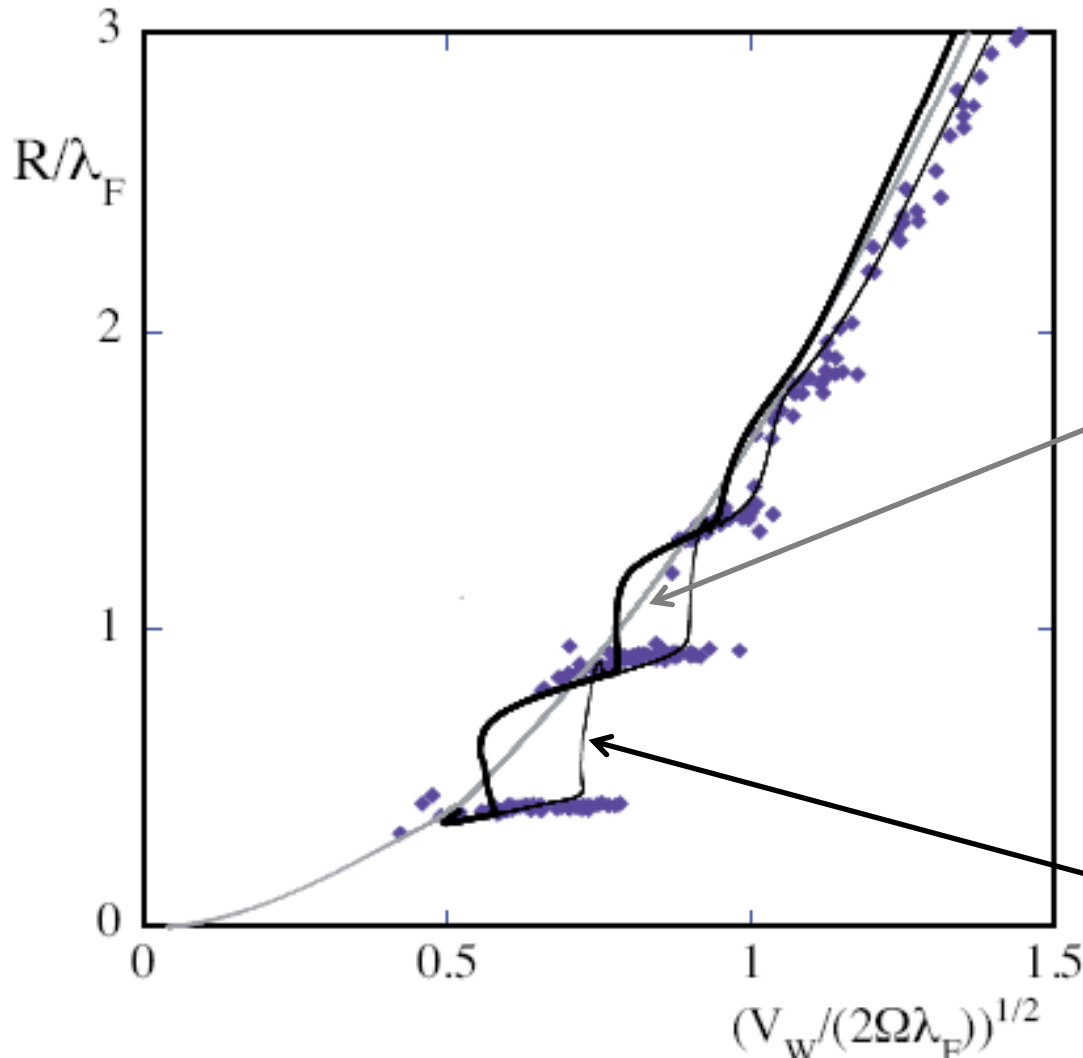
The radii of the orbits obtained at various frequencies and for walkers of various velocities are all **rescaled** by expressing:  $R/\lambda_F$  as a function of the non dimensionnall parameter:

$$\sqrt{\frac{V_w}{2\Omega\lambda_F}}$$

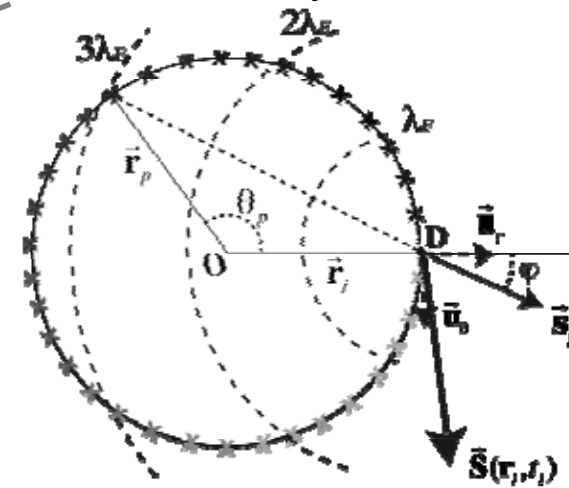


# Path-memory dynamics for a circular orbits

Simulations with Path-memory model



Short memory



Long memory

Waves associated with the sources diametrically opposed to the droplet modulate the radial force with a spatial period equal to the Faraday wavelength.

# Quantum analogy

## Larmor radius

$$\frac{\rho_n}{\lambda_{dB}} = \sqrt{1/\pi} \sqrt{\left(n + \frac{1}{2}\right) \frac{m}{qB} \frac{V}{\lambda_{dB}}}$$

The analogy suggests:

$$\frac{m}{qB} \Leftrightarrow \frac{1}{2\Omega}$$

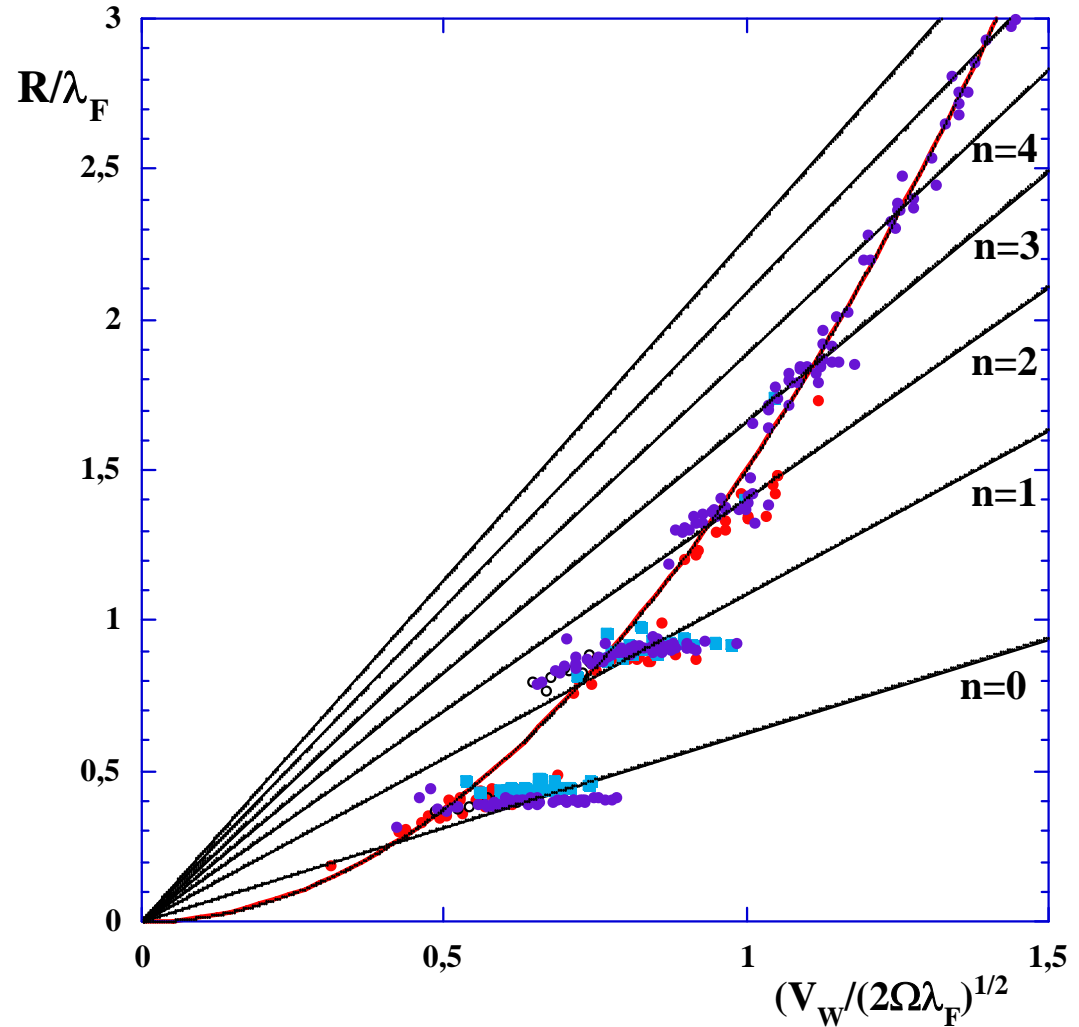
$$\lambda_{dB} \Leftrightarrow \lambda_F$$

$$\frac{R_n}{\lambda_F} = \sqrt{1/\pi} \sqrt{\left(n + \frac{1}{2}\right) \frac{1}{2\Omega} \frac{V_W}{\lambda_F}}$$

$$\sqrt{1/\pi} = 0.564$$

We find

$$\frac{R_n}{\lambda_F} = 0.89 \sqrt{\left(n + \frac{1}{2}\right) \frac{V_W}{2\Omega \lambda_F}}$$



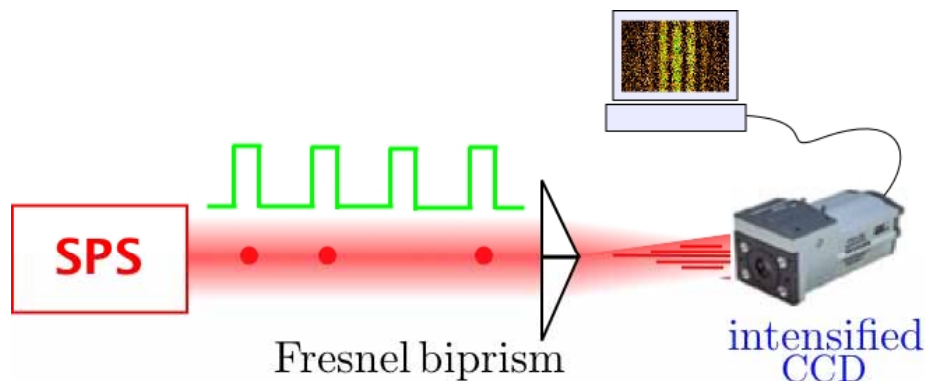
Diameter quantization:  $2 R = n \lambda_F$

## **Statistical experiments:**

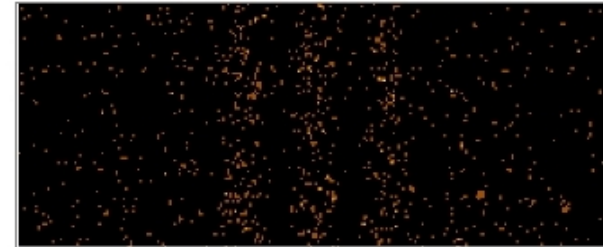
- Single particle diffraction and interferences

Couder Y. & Fort E, *Phys. Rev. Lett.* **97**, 15101, (2006)

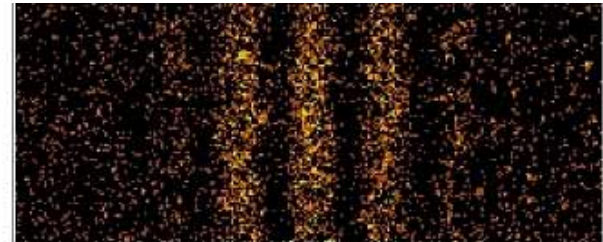
# Single particle interference



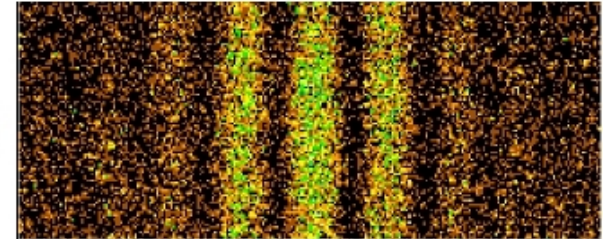
**T = 100 s**



**T = 500 s**



**T = 2000 s**



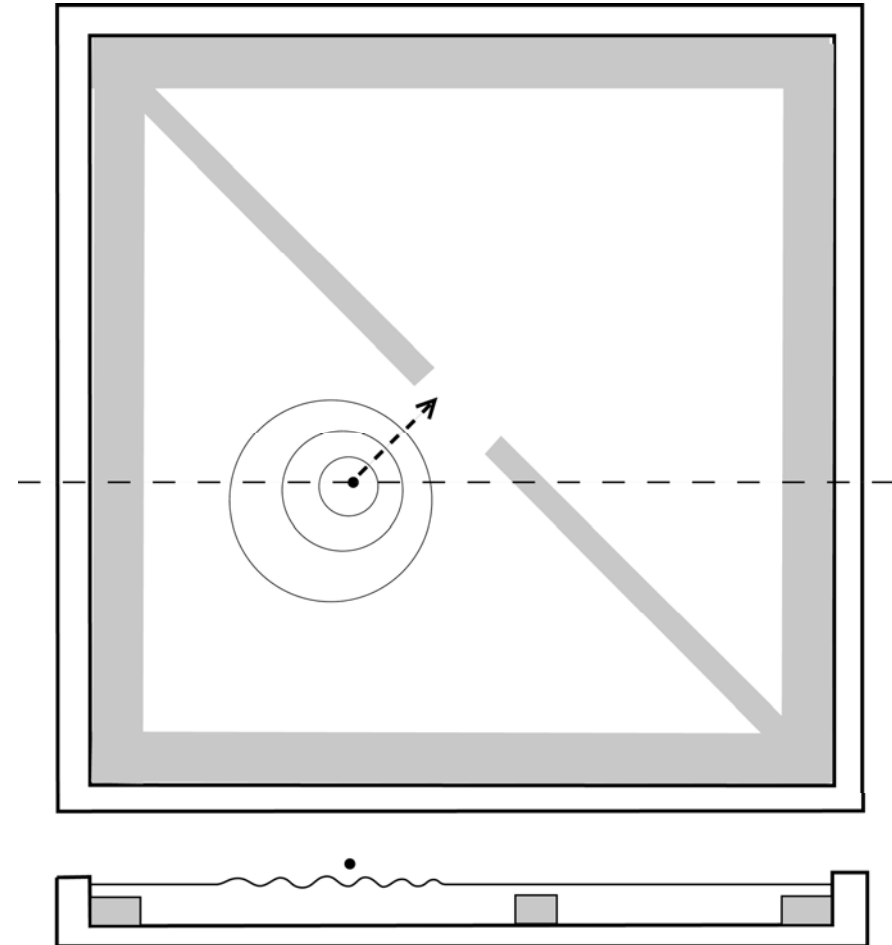
R. Feynman's, Lectures on Physics,  
Quantum Mechanics, (First chapter!)

« ... In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way and which is at the heart of quantum mechanics. In reality it contains the only mystery. We cannot make the mystery go away by explaining how it works. We will just tell you how it works.... »

# The experimental setup for diffraction and interference experiments

In the grey regions the fluid layer thickness is reduced to  $h_1=1\text{mm}$  ( $h_0=4\text{mm}$  elsewhere)

**In these regions the Faraday threshold being shifted, the walkers do not propagate**



Cross section



# Measurements on the droplet's trajectory

The relevant parameters:

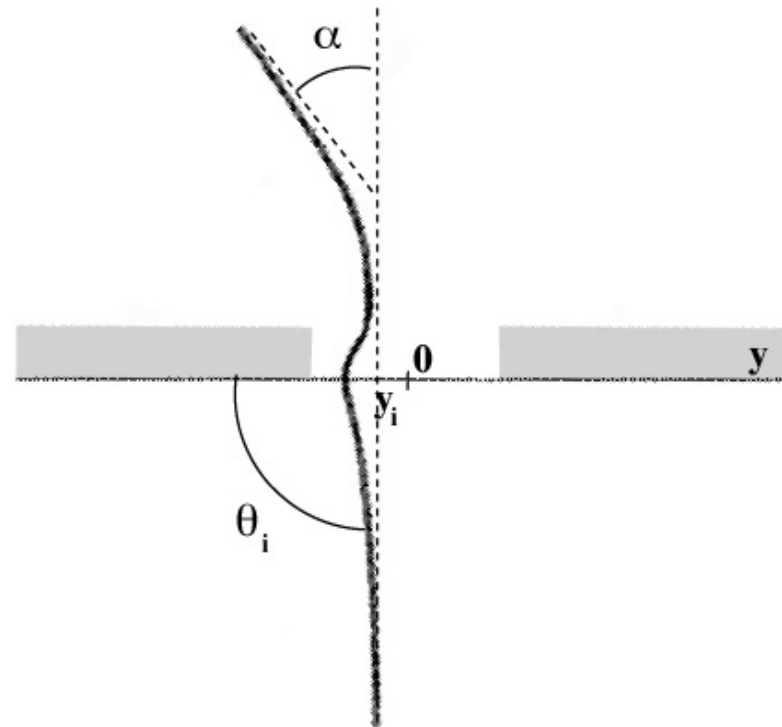
$L$  : the width of the slit,

$q_i$  : angle of incidence (chosen  $\theta_i = \pi/2$ )

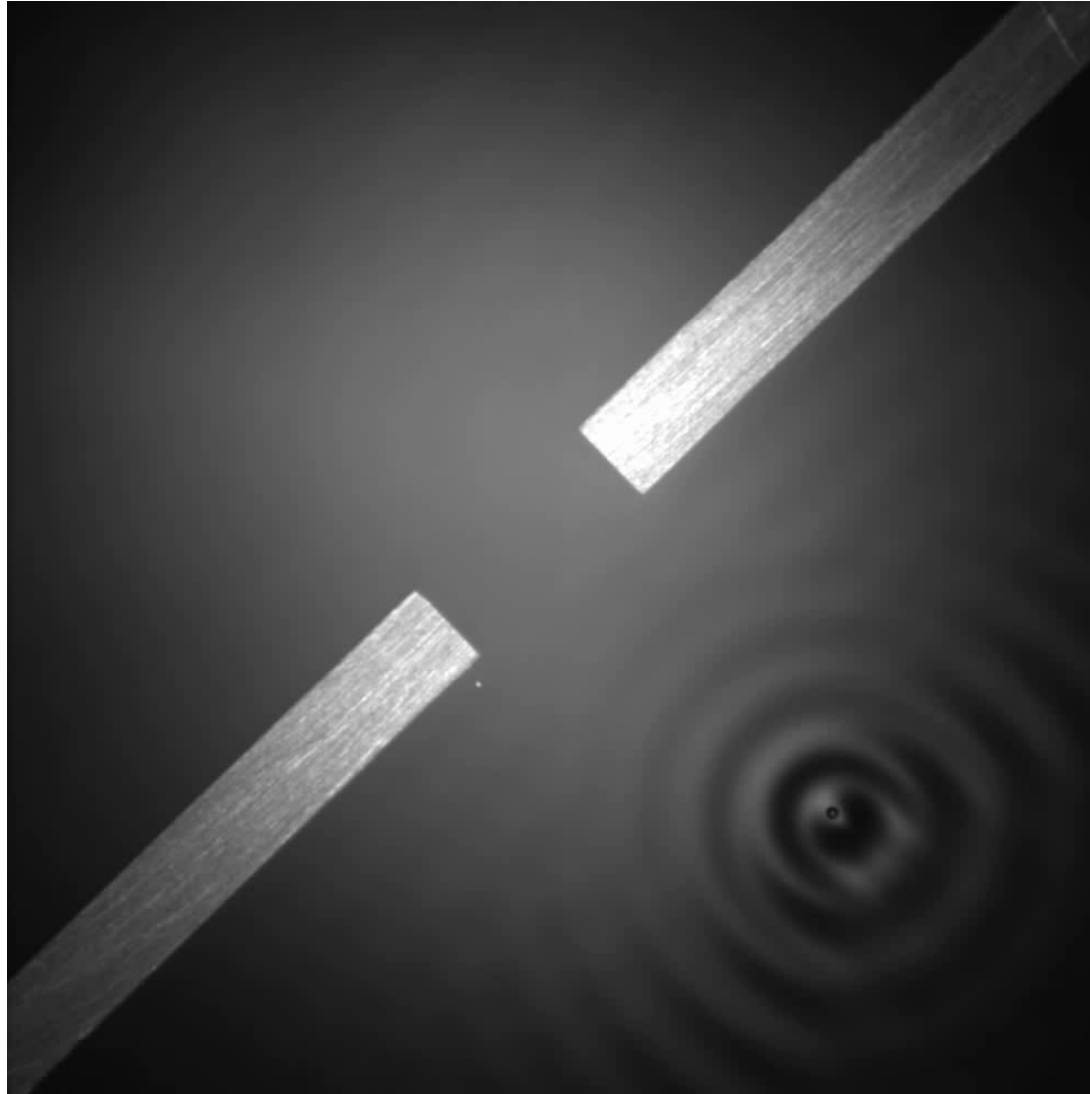
$a$  : the angle of deviation

$Y_i = y_i/L$  : the impact parameter

(With  $-0.5 < Y_i < 0.5$ )



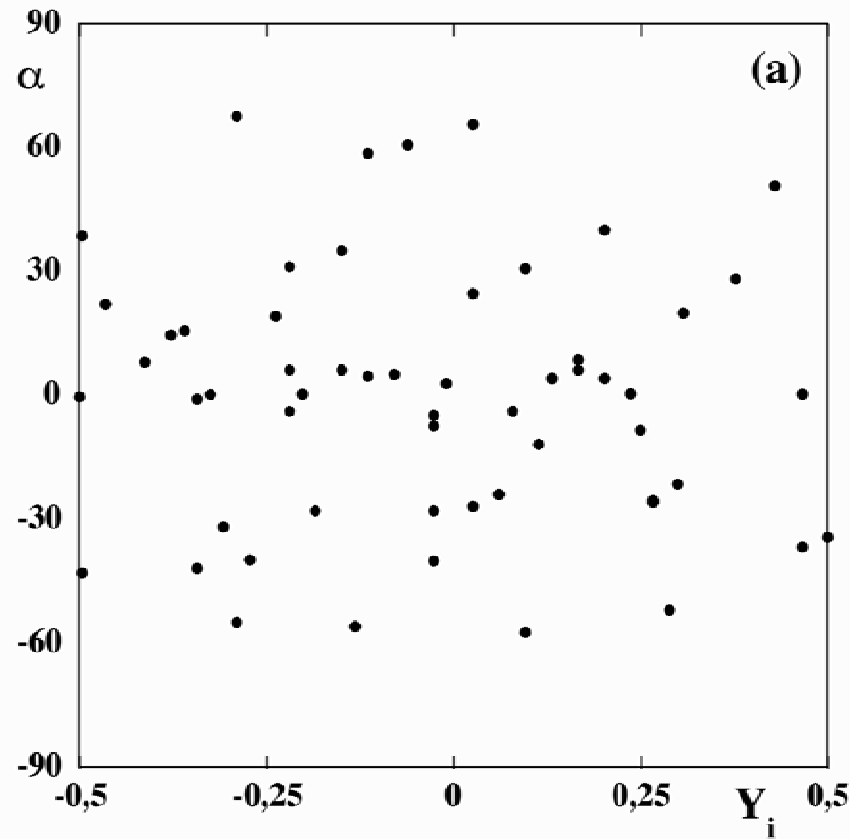
## A single “diffracting” droplet



# Deviation angle $\alpha$ vs the impact parameter $Y_i$ ?

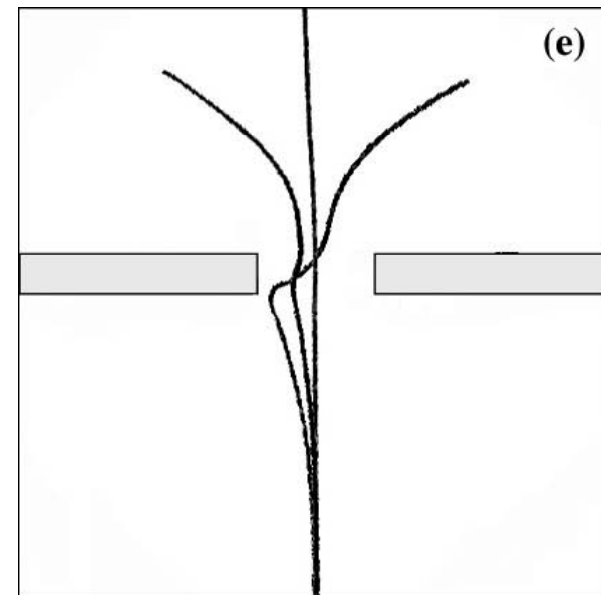
*The measured deviation in experiments performed with the same walker, the same angle of incidence, but various impact parameters*

$L/\lambda_F=3.1$  ( $L=14.7\text{mm}$  and  $\lambda_F=4.75\text{ mm}$ ).



Impact parameter

Three independent trajectories with the same initial conditions (within experimental accuracy)

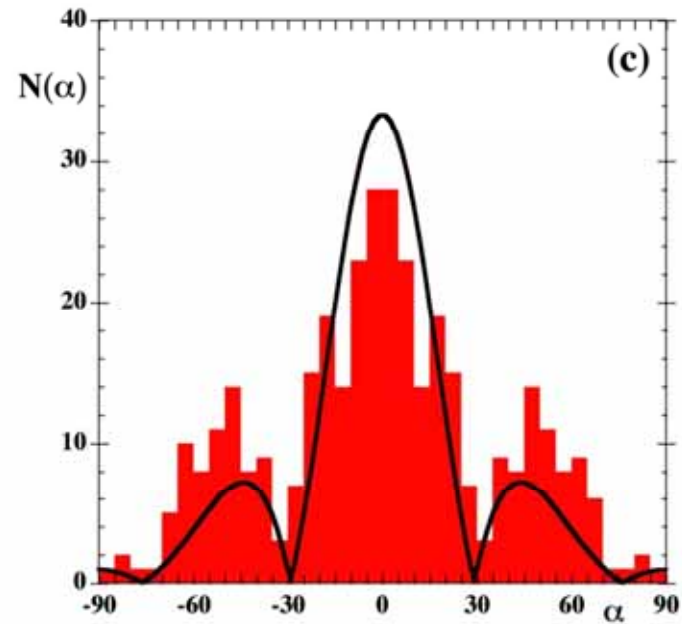


# Diffraction histograms

$\omega/2\pi = 50\text{Hz}$ ,  
 $L/\lambda_F = 2.11$  ( $L=14.7\text{mm}$  and  $\lambda_F=6.95\text{mm}$ ).

The curve is the modulus of the amplitude of diffraction of a plane wave with  $L/\lambda_F = 1.96$ .

$$f(\alpha) = A \left| \frac{\sin(\pi L \sin \alpha / \lambda_F)}{\pi L \sin \alpha / \lambda_F} \right|$$



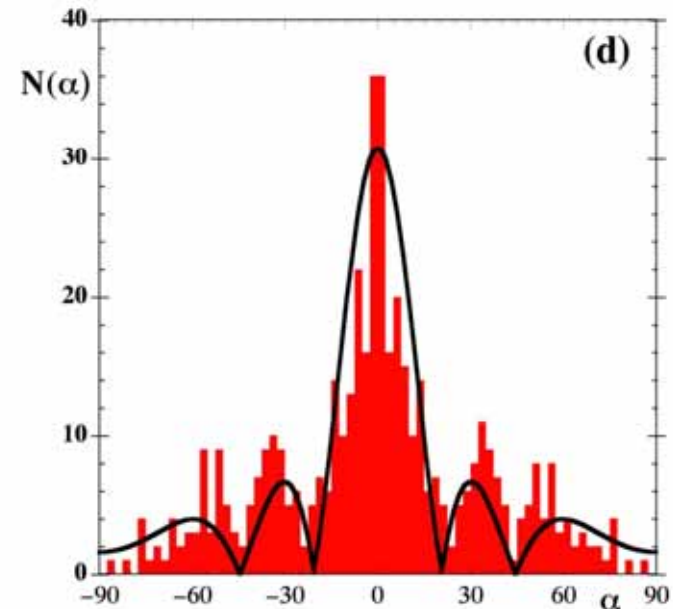
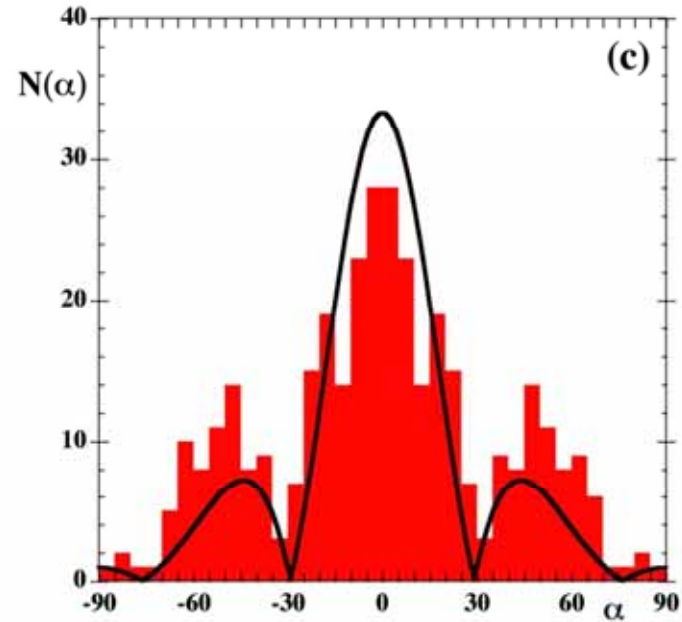
# Diffraction histograms

$\omega/2\pi = 50\text{Hz}$ ,  
 $L/\lambda_F = 2.11$  ( $L=14.7\text{mm}$  and  $\lambda_F = 6.95\text{ mm}$ ).

The curve is the modulus of the amplitude of diffraction of a plane wave with  $L/\lambda_F = 1.96$ .

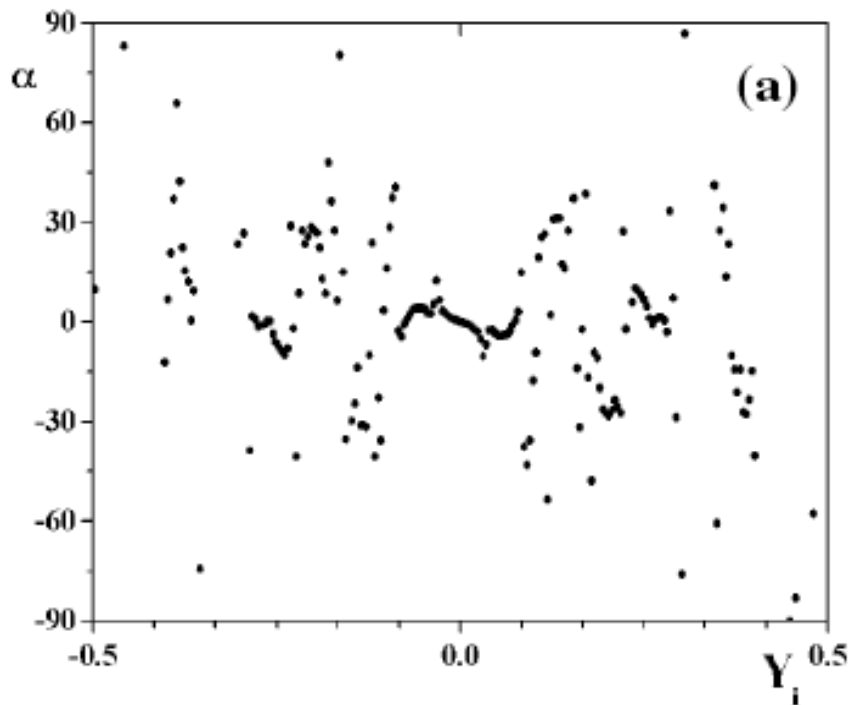
$$f(\alpha) = A \left| \frac{\sin(\pi L \sin \alpha / \lambda_F)}{\pi L \sin \alpha / \lambda_F} \right|$$

Same with  $\omega/2\pi = 80\text{Hz}$  ,  
 $L/\lambda_F = 3.1$  ( $L=14.7\text{mm}$  and  $\lambda_F = 4.75\text{ mm}$ ).

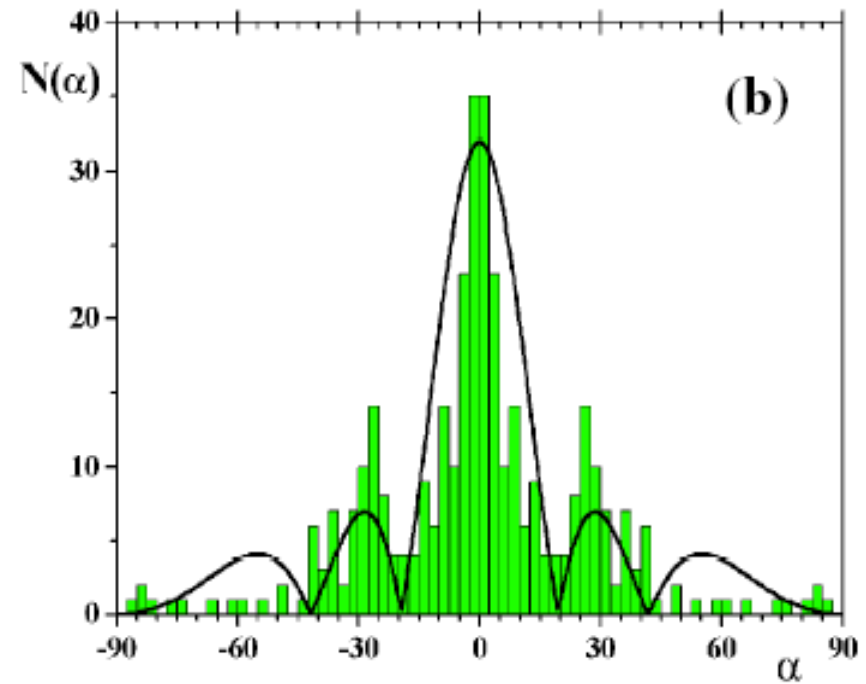


# Diffraction with path-memory model

Numerical simulations of the diffraction through a slit with  $L/\lambda_F=3$



Deviation  
*vs* normalized impact parameter

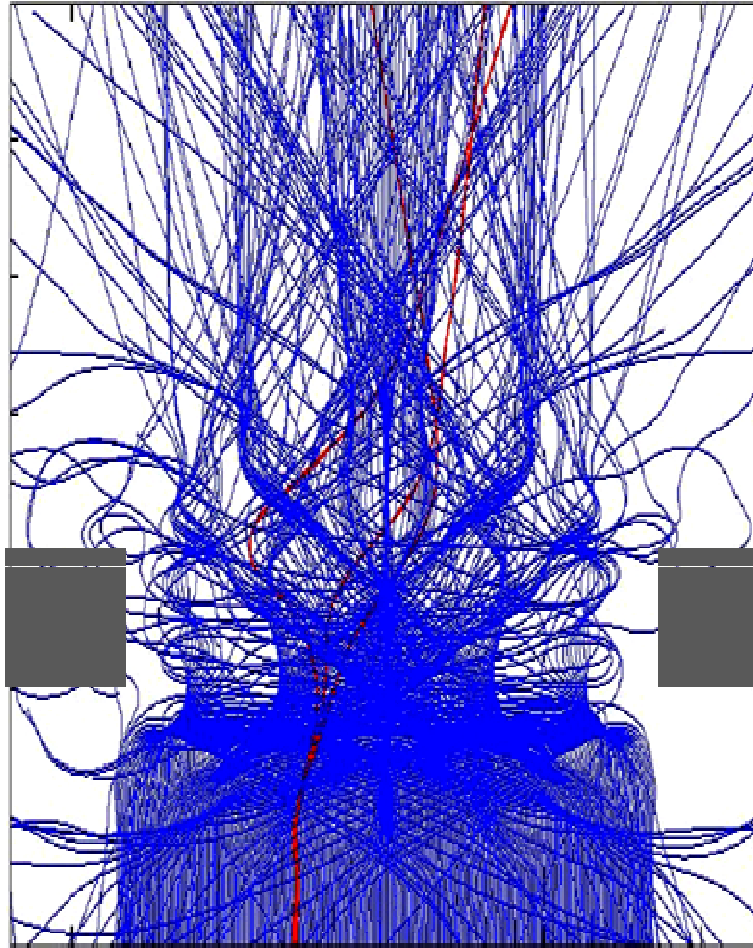


Deviation histogram

# Diffraction with path-memory model

## Trajectories

Numerical simulations of the diffraction through a slit with  $L/\lambda_F=3$

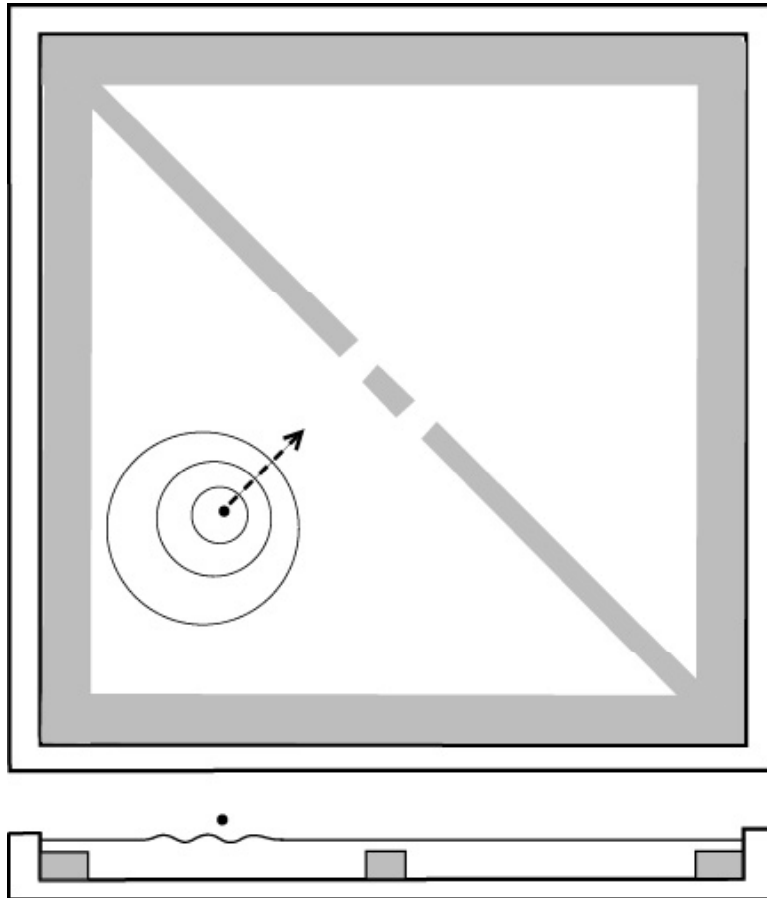


Three independent trajectories with impact factor within  $\lambda_F/50$

# Young's two slits experiment with walkers

## Interference Fringes with feeble light

G.I. Taylor, *Proc. Camb. Phil. Soc.*, 15, 114-115, (1909)



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.

So far all the evidence brought forward in support of the theory has been of an indirect nature; for all ordinary optical phenomena are average effects, and are therefore incapable of differentiating between the usual electromagnetic theory and the modification of it that we are considering. Sir J.J. Thomson however suggested that if the intensity of light in a diffraction pattern were so greatly reduced that only a few of these indivisible units of energy should occur on a Huygens zone at once the ordinary phenomena of diffraction would be modified. Photographs were taken of the shadow of a needle, the source of light being a narrow slit placed in front of a gas flame. The intensity of the light was reduced by means of smoked glass screens.

Before making any exposures it was necessary to find out what proportion of the light was cut off by these screens. A plate was exposed to direct gas light for a certain time. The gas flame was then shaded by the various screens that were to be used, and other plates of the same kind were exposed till they came out as black as the first plate on being completely developed. The times of exposure necessary to produce this result were taken as inversely proportional to the intensities. Experiments made to test the truth of this assumption shewed it to be true if the light was not very feeble.

Five diffraction photographs were then taken, the first with direct light and the others with the various screens inserted between the gas flame and the slit. The time of exposure for the first photograph was obtained by trial, a certain standard of blackness being attained by the plate when fully developed. The remaining times of exposure were taken from the first in the inverse ratio of the corresponding intensities. The longest time was 2000 hours or about 3 months. In no case was there any diminution in the sharpness of the pattern although the plates did not all reach the standard black-

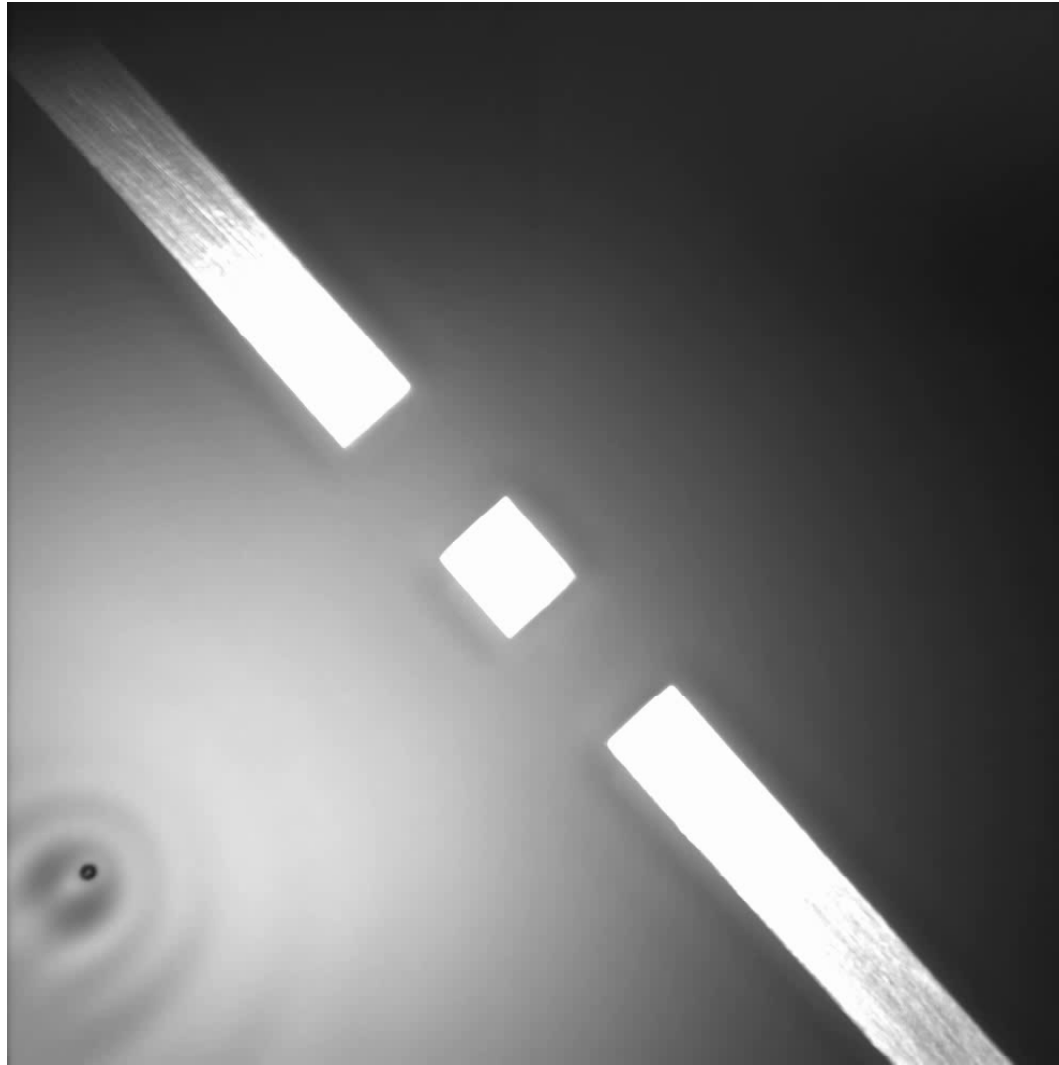
ness of the first photograph.

In order to get some idea of the energy of the light falling on the plates in these experiments a plate of the same kind was exposed at a distance of two metres from a standard candle till complete development brought it up to the standard of blackness. Ten seconds sufficed for this. A simple calculation will shew that the amount of energy falling on the plate during the longest exposure was the same as that due to a standard candle burning at a distance slightly exceeding a mile. Taking the value given by Drude for the energy in the visible part of the spectrum of a standard candle, the amount of energy falling on 1 square centimetre of the plate is  $5 \times 10^{-6}$  ergs per sec. and the amount of energy per cubic centimetre of this radiation is  $1.6 \times 10^{-16}$  ergs.

According to Sir J.J. Thomson this value sets an upper limit to the amount of energy contained in one of the indivisible units mentioned above.

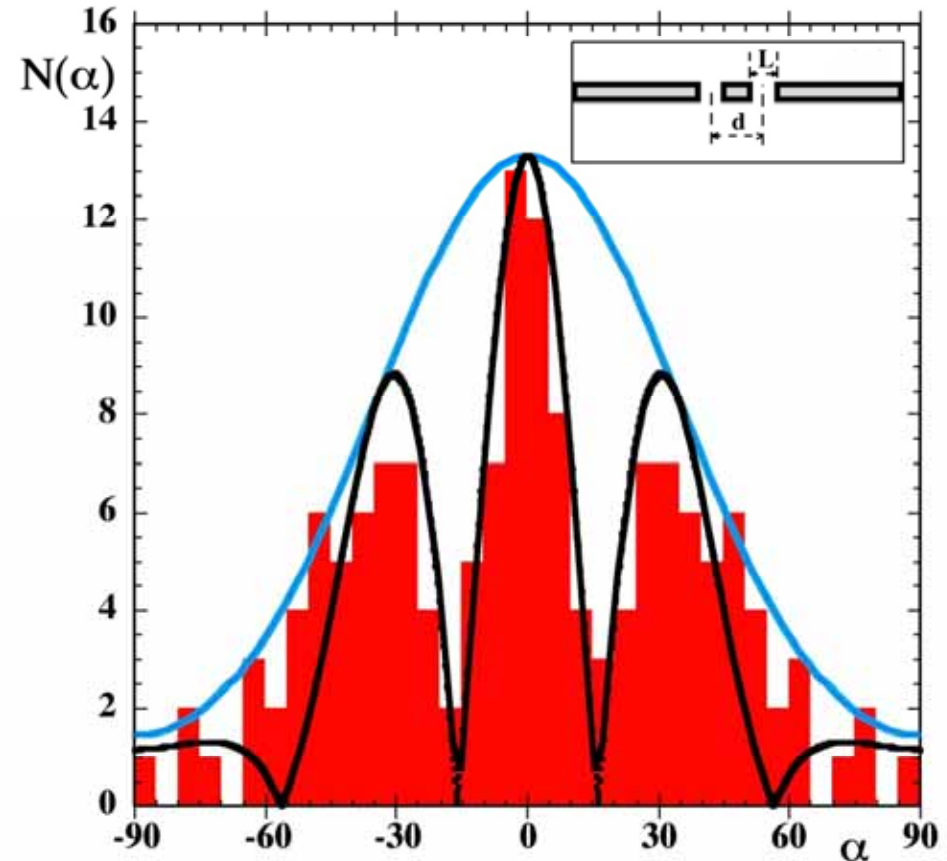


## Young's two slits experiment with walkers



# Young's two slits experiment with walkers

Deviation histogram with 75 realizations



The curve is the modulus of the amplitude of the interference of a plane wave through two slits with  $L/\lambda_F = 0.9$  and  $d/\lambda_F = 1.7$ .

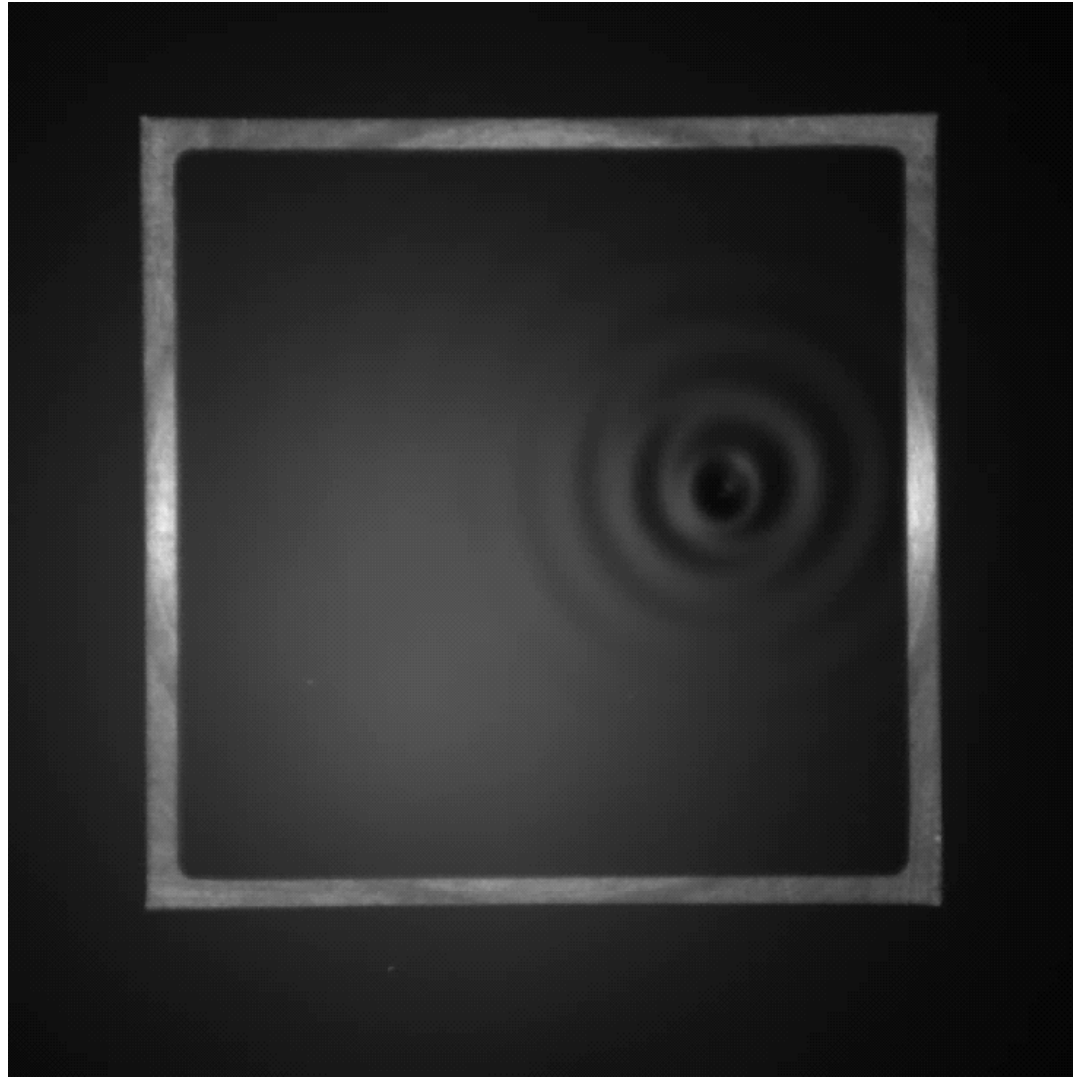
$$f(\alpha) = A \left| \frac{\sin(\pi L \sin \alpha / \lambda_F)}{\pi L \sin \alpha / \lambda_F} \cos(\pi d \sin \alpha / \lambda_F) \right|$$

## Statistical experiments:

- Tunneling effect

Eddi A, *et al. Phys. Rev. Lett.* **102**, 240401, (2009)

## Tunneling effect



The walker is confined in a square cavity with thin immersed walls

# Returning to our experiment

**Its main drawbacks: it is very far from quantum mechanics**

- Macroscopic scale : no relation with Planck constant.
- The system is dissipative and sustained by external forcing.
- This forcing imposes a fixed frequency
- The waves live on a material medium: there is an “ether”.

**Its main advantages: it is very far from quantum mechanics**

- At quantum scale the Planck limitation imposes itself to all phenomena. It is not possible to do a non-intrusive measurement.
- The observation with light is non intrusive so that the undisturbed trajectory of the particle and the wave can be observed directly.

**As a conclusion...**

**All the observed quantum like properties are linked with what we have called the “**wave mediated path memory dynamics**”.**

**This dynamics generates a new type of **space and time non locality**.**

**For this reason, we believe the debate on **hidden variables** is not closed**