Wave-particle duality with naked eye

Emmanuel Fort

Institut Langevin, ESPCI ParisTech University Paris Diderot
CNRS UMR 7587, INSERM U979 "Wave Physics For Medicine"

Authors

Yves Couder
Antonin Eddi
Marc Miskin
Stéphane Perrard
Suzie Protière
Julien Moukhtar
Matthieu Labousse
Eric Sultan
Arezki Boudaoud

FAST (Orsay): Frédéric Moisy

MIT, USA: J. Bush's Group

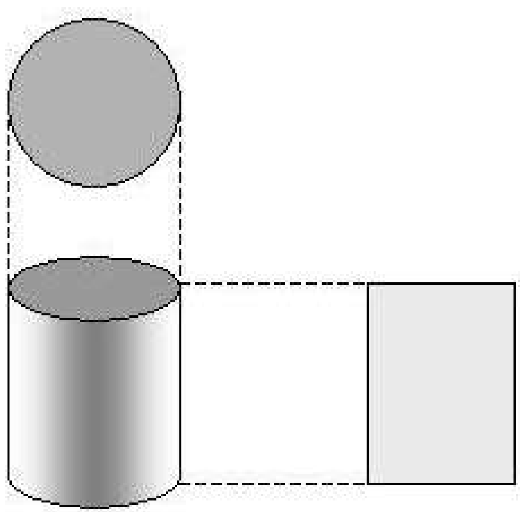
Outline of the presentation

- 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, inertial walkers

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

Coalescence of a drop deposited on the surface of the same fluid.

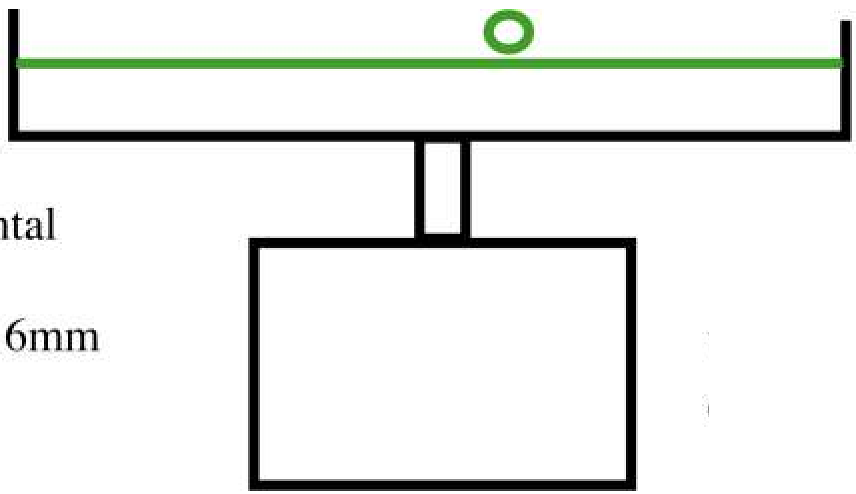
NON Coalescence of a drop deposited on the surface of the same

lasts approximately $\tau = 1/10$s

Fluids: Silicon oils with viscosities

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

Experimental cell 130x130x 6mm



Vertical acceleration

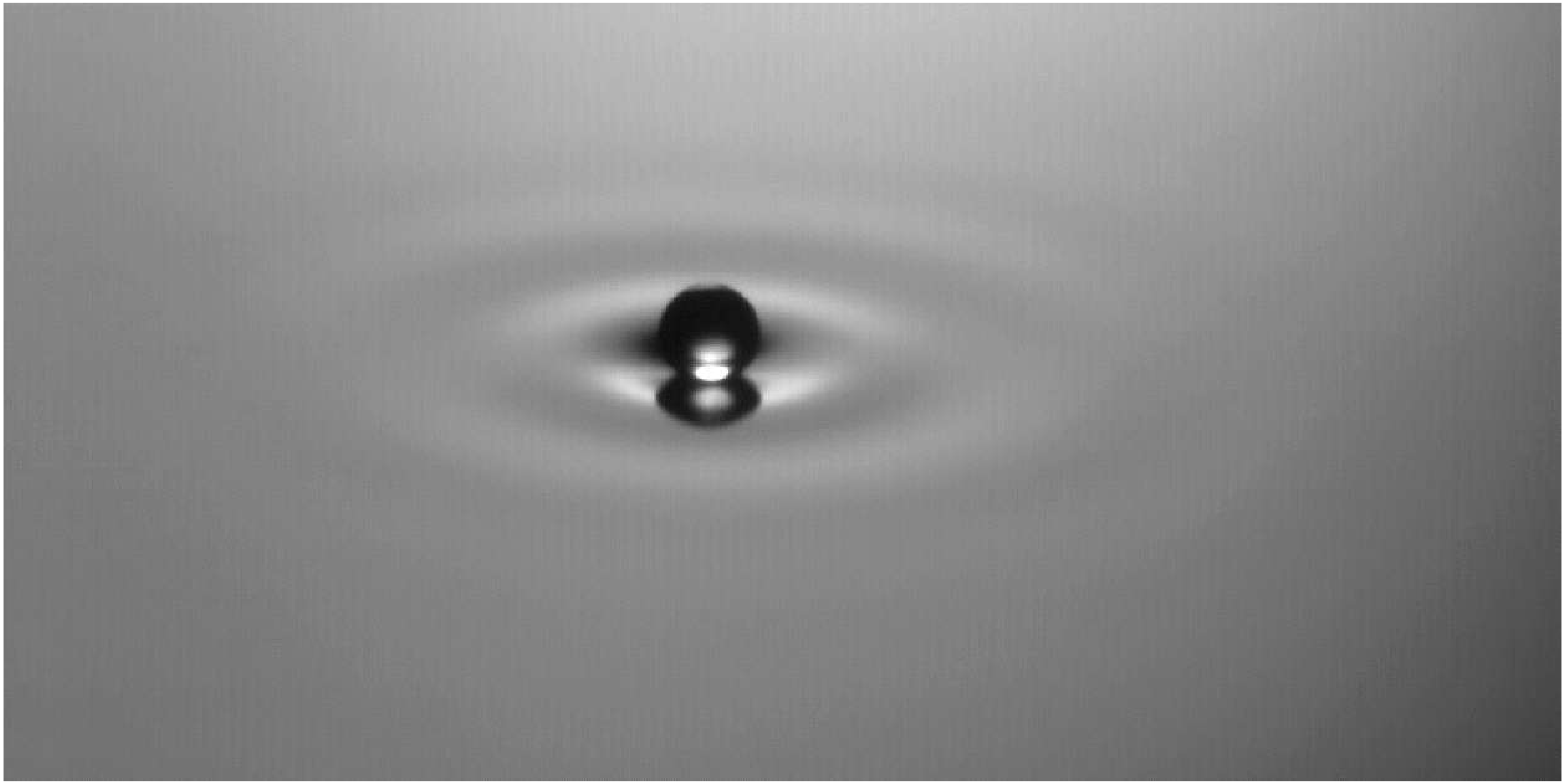
$$\gamma = \gamma_m \cos(\omega t)$$

with γ_m ranging from to 0 to 5g

Forcing frequency range:

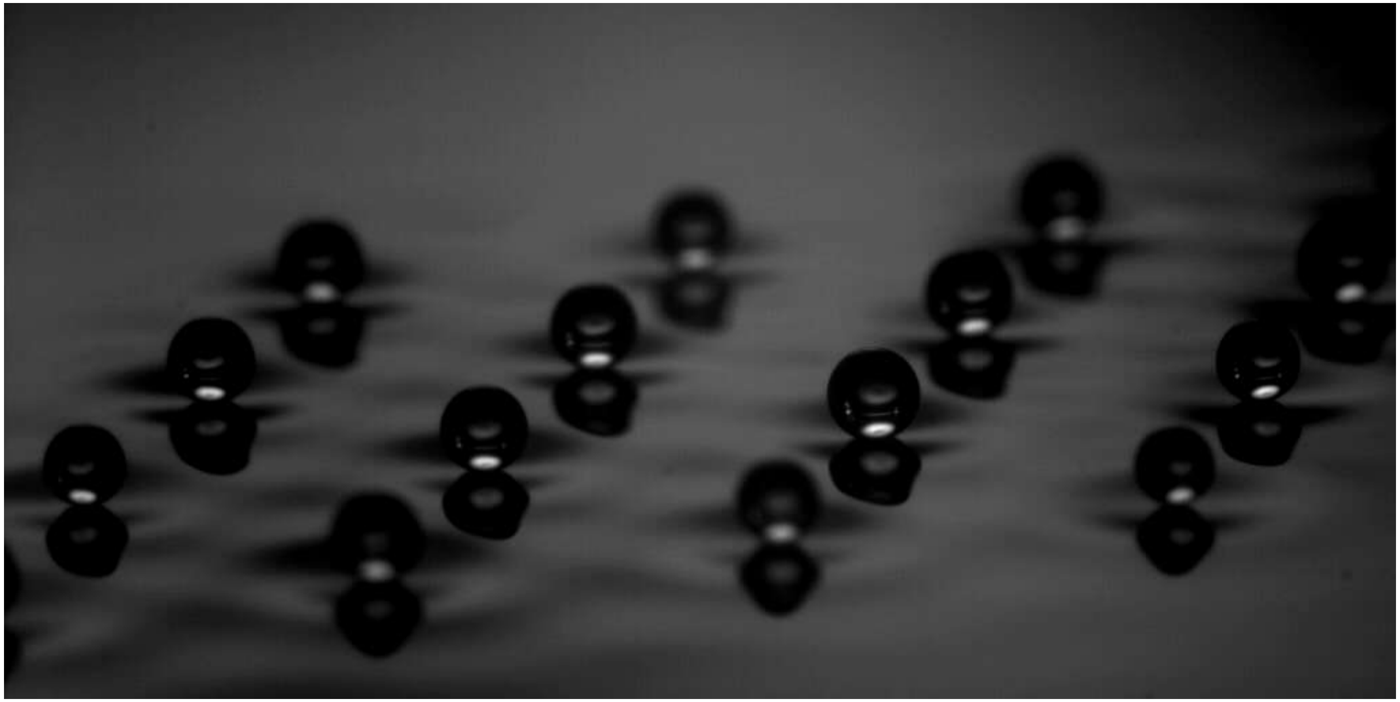
$$10 < \omega/2\pi < 300 \text{ Hz}$$

Bouncing droplet



Fast camera

Cristal of bouncing droplet



Phase diagram of the bouncing

Fixed parameters:

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

Phase diagram areas:

B : simple bouncing at the forcing frequency

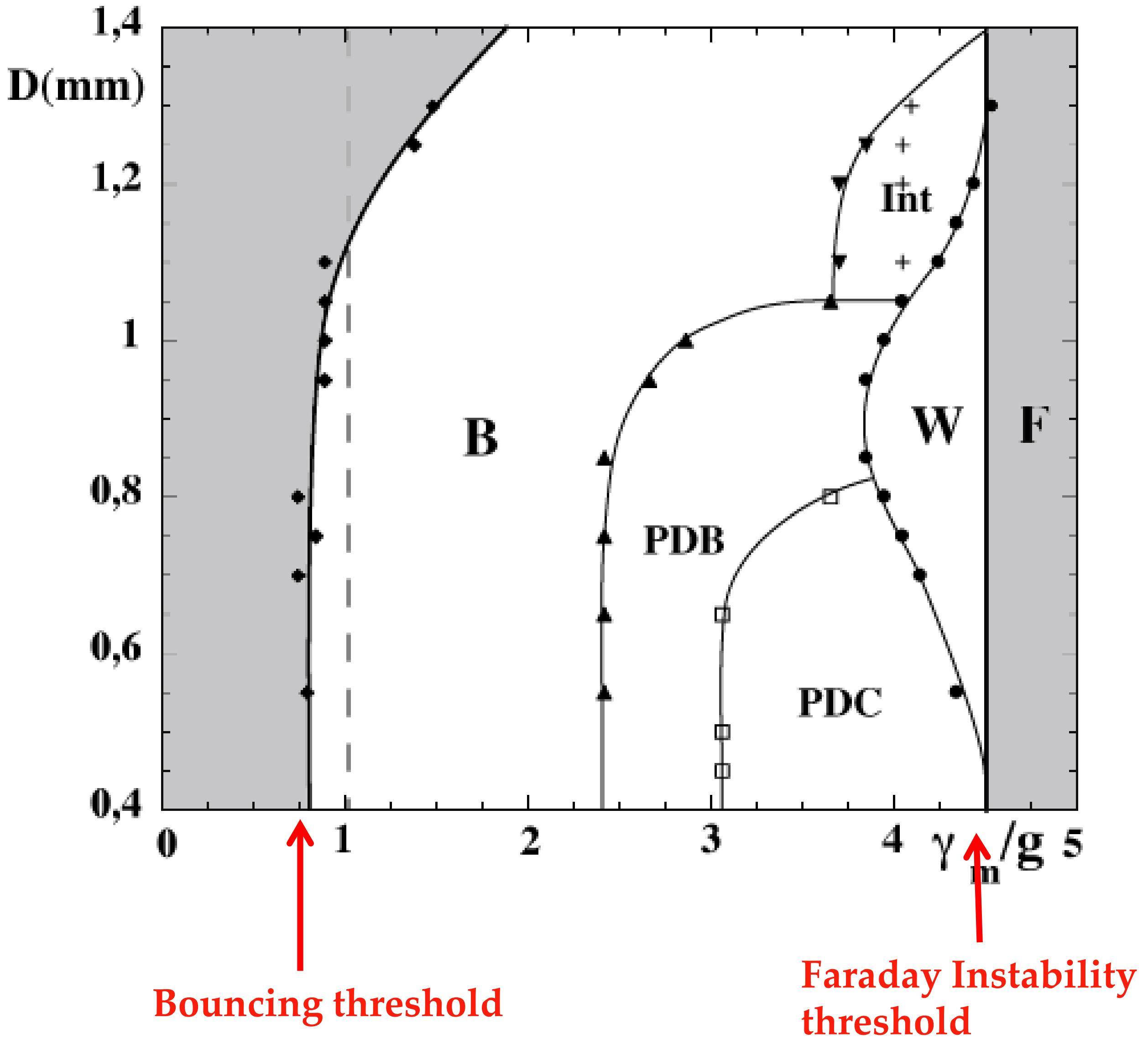
PDB : Period doubling

PDC: Chaos through a sequence of period doubling

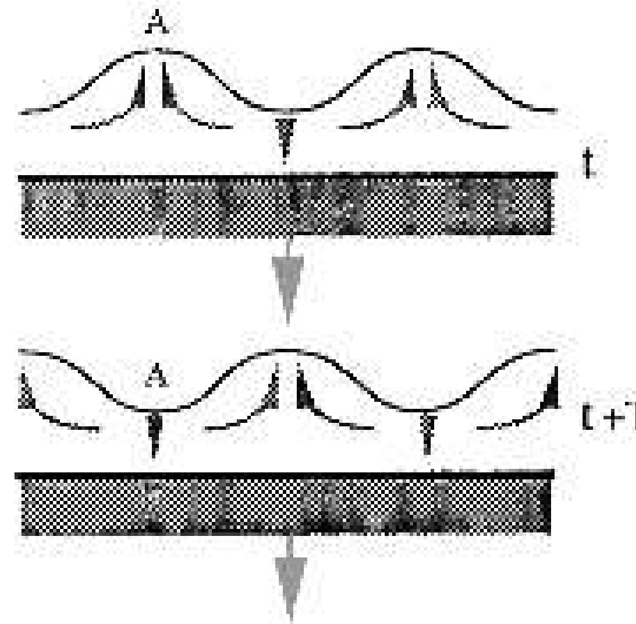
W : Walking

Int : Intermittent behavior

F : Faraday instability



Reminder: Faraday instability



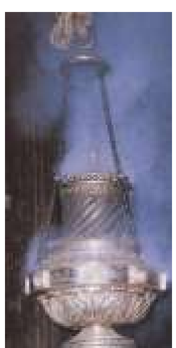
Occurs in a fluid submitted to a vertical acceleration

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

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

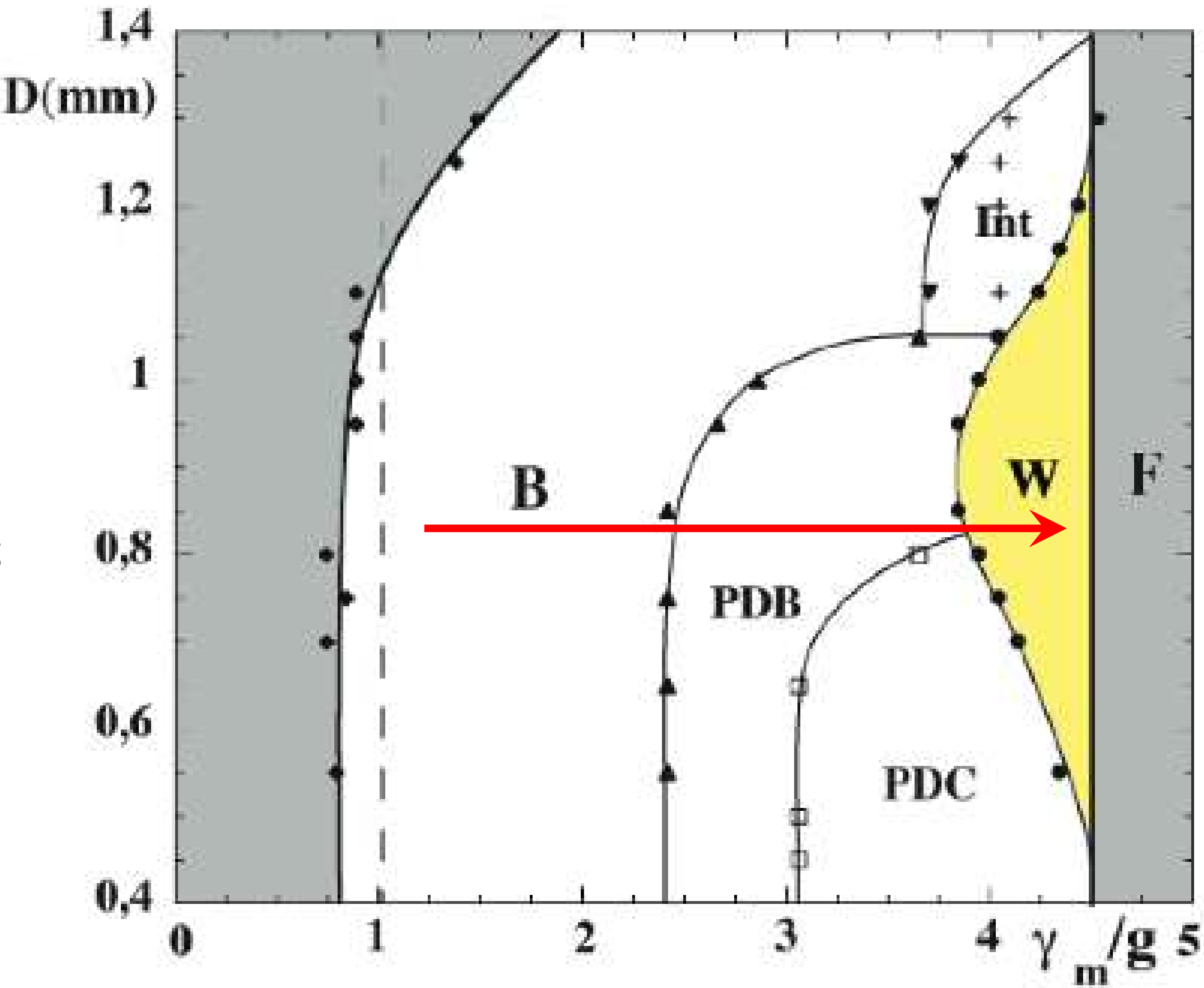
Parametric forcing of surface waves

Analogous to the para-metric forcing of a swing or a pendulum ***(example: botafumeiro)***



Phase diagram of the bouncing

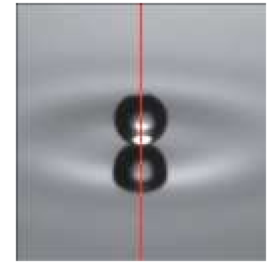
- B : simple bouncing at the forcing frequency
- PDB : Period doubling
- PDC: Chaos through a sequence of period doubling
- W : Walking
- Int : Intermittent behavior
- F : Faraday instability



Bouncing threshold

Faraday Instability threshold

Bouncing of intermediate drops



Spatio-temporal diagrams of the vertical motion

Size range: 0.6 < D < 1.1mm

γ_m=1.5g

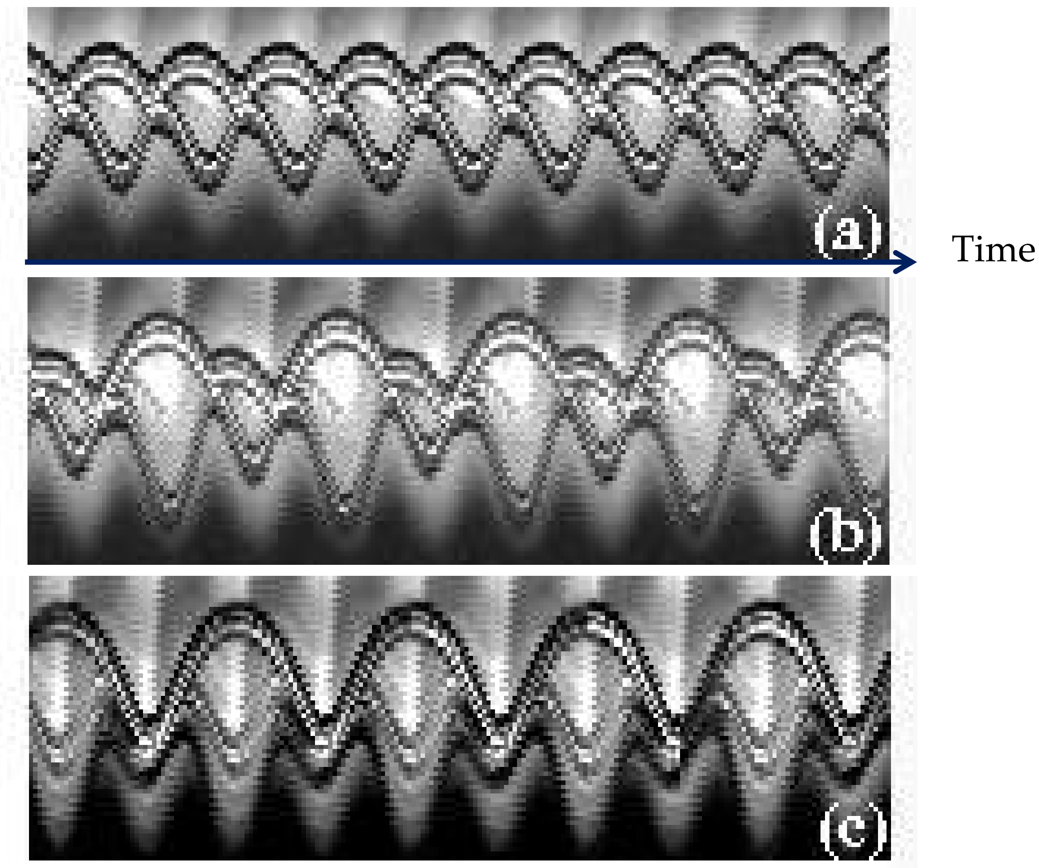
Bouncing at the forcing frequency

γ_m= 3g

Period doubling

γ_m= 4g

no chaos and complete period doubling



Just below the Faraday threshold, intermediate droplets

- undergo complete period doubling,

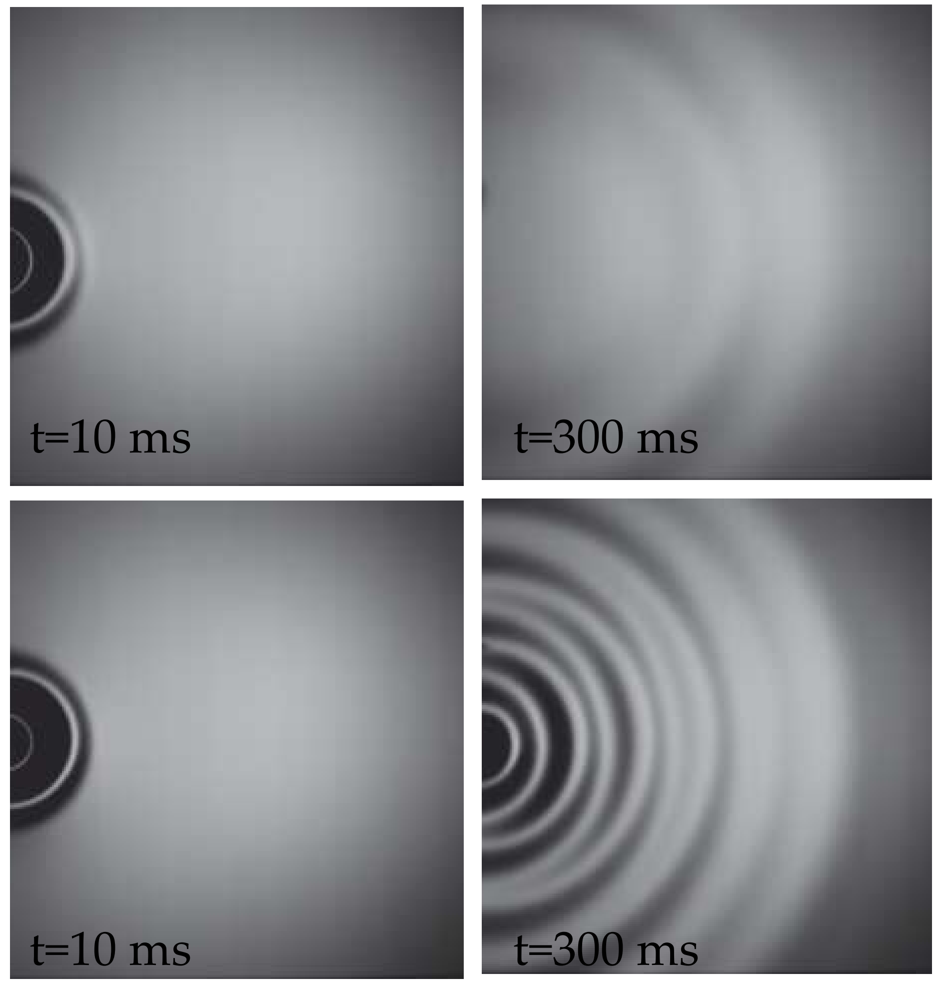
- bounce at Faraday period

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



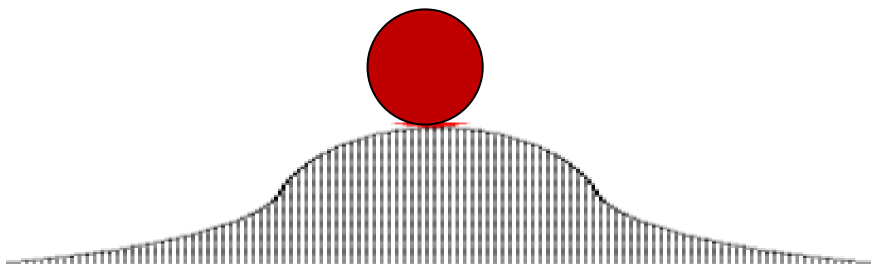
Near the Faraday threshold, the propagating capillary wave triggers stationary Faraday waves around the droplet

Walking instability

For intermediate droplets (0.6 < D < 1.1mm) near the Faraday threshold:

Period doubling & Local generator of almost sustained Faraday waves
= **Bouncing droplets are efficient local Faraday generator**

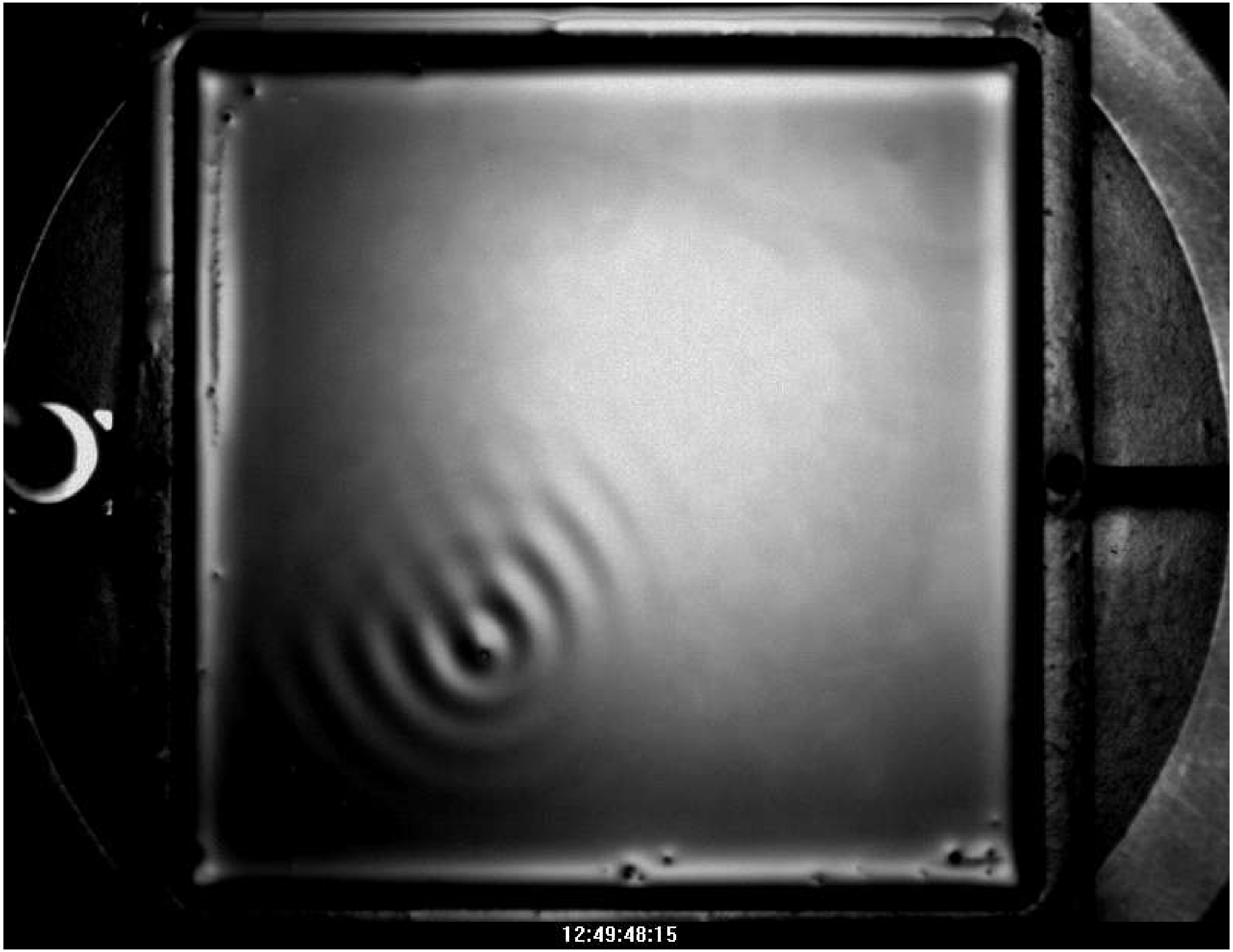
The droplet is at the top of a bump created by the accumulation of the previous bounces which have triggered a local Faraday instability.



It becomes instable…

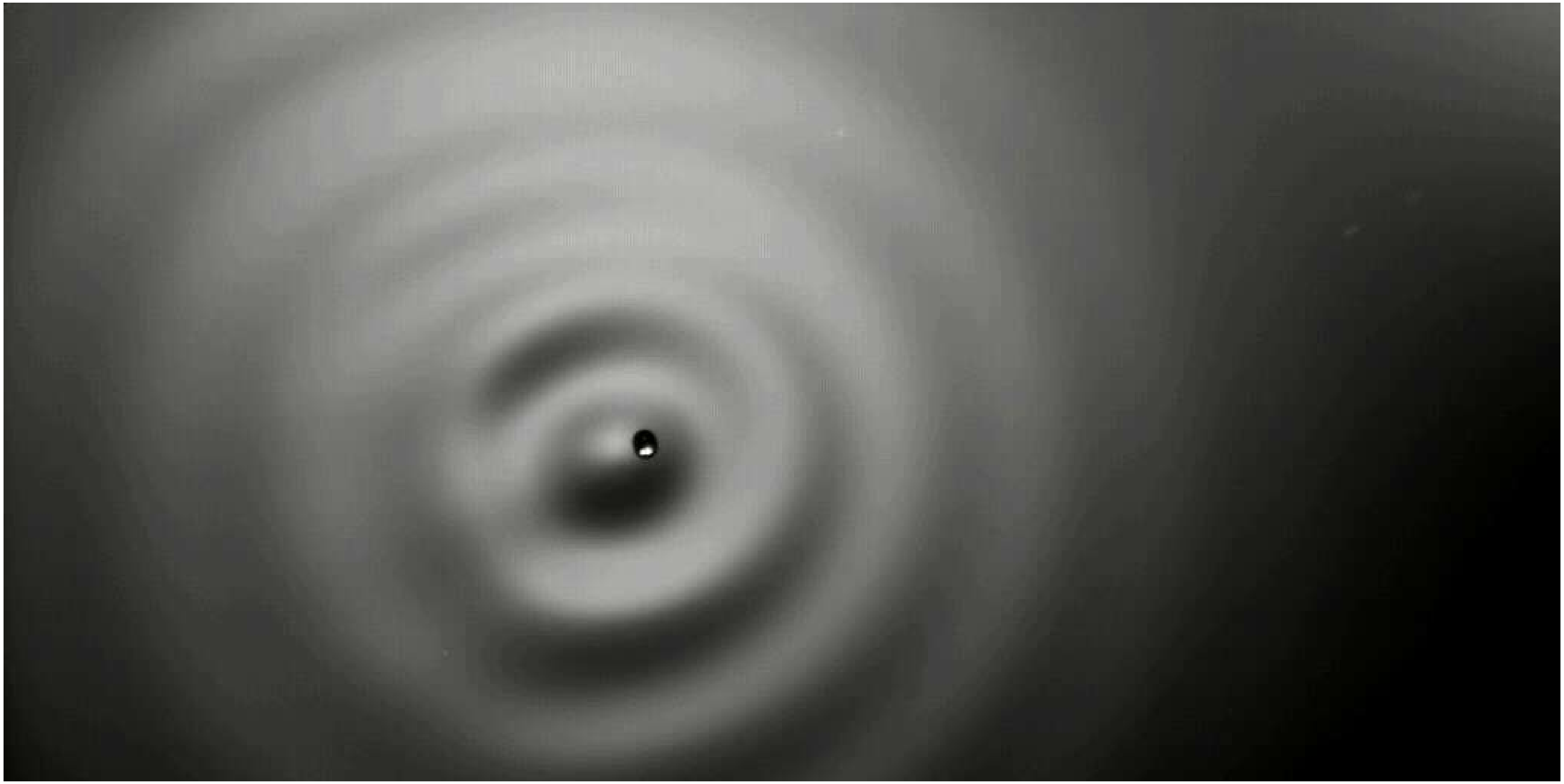
Above this "walking" threshold, droplets become **self-propelled,** "surfing" on their own wave.

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:

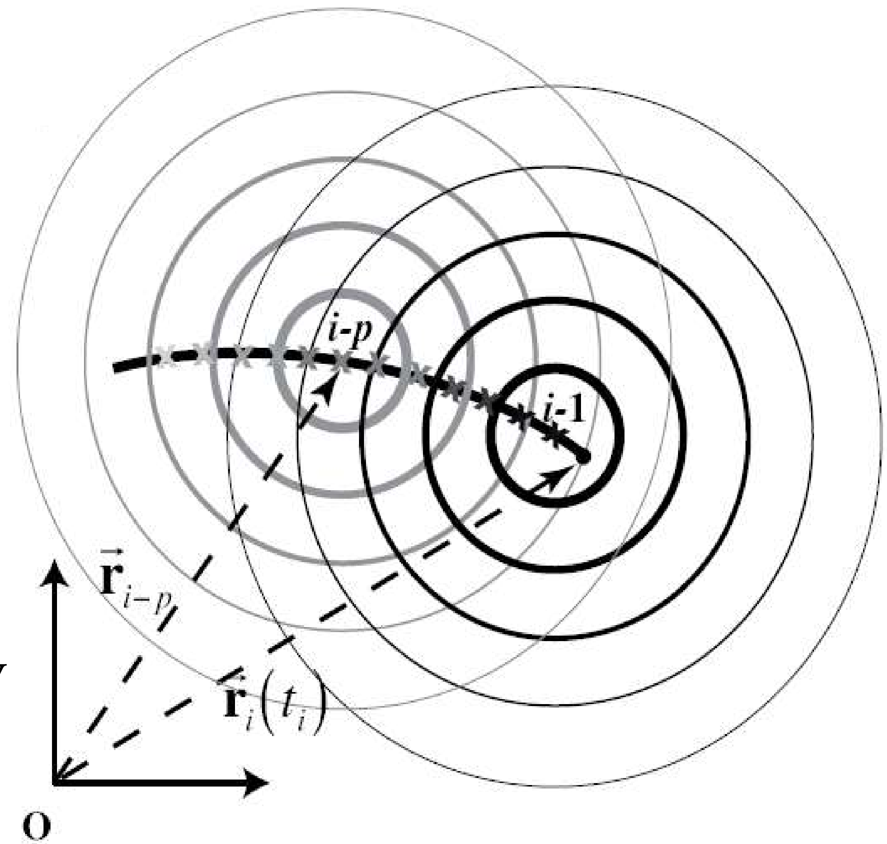
$$h(\vec{\mathrm{r}}, t_i) = \sum_{p=i-1}^{-\infty} \frac{A}{\left|\vec{\mathrm{r}}_i - \vec{\mathrm{r}}_p\right|^{1/2}} \exp-\left(\frac{t_i - t_p}{\tau}\right) \exp-\left(\frac{\left|\vec{\mathrm{r}} - \vec{\mathrm{r}}_p\right|}{\delta}\right) J_0\left(\frac{2\pi\left|\vec{\mathrm{r}} - \vec{\mathrm{r}}_p\right|}{\lambda_F}\right)$$

where $\vec{r}_p$ is the position of a previous impact

which occurred at time $t_p = t_i - (i - p)T_F$.

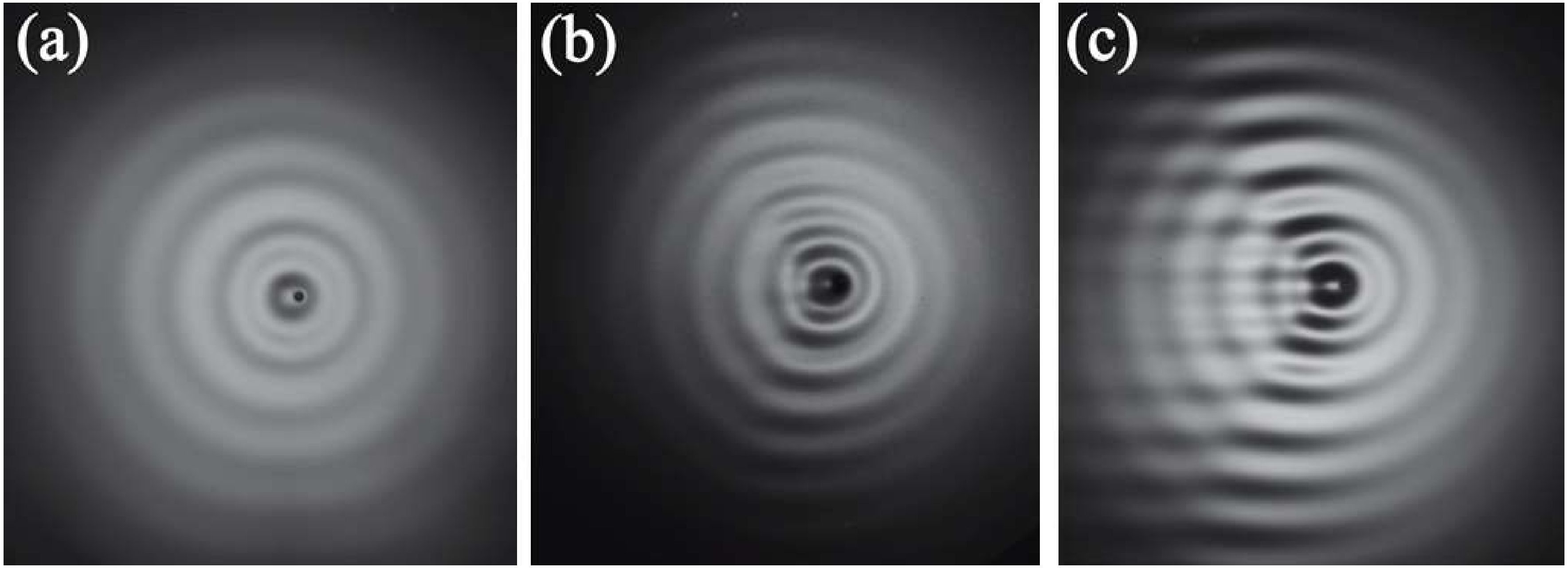
The spatial damping, δ: of travelling waves is fixed and related to the fluid viscosity.

The damping time, τ: 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 : $\tau \propto \left|\gamma_m - \gamma_m^F\right|^{-1}$
- The waves generated during the previous bounces along the trajectory form a ``**path-memory"** of the walker wavefield.
- A **memory parameter** M= τ/T_F is the number of bounces that contribute to the wave field .
-This parameter can be tuned easily by changing the excitation amplitude

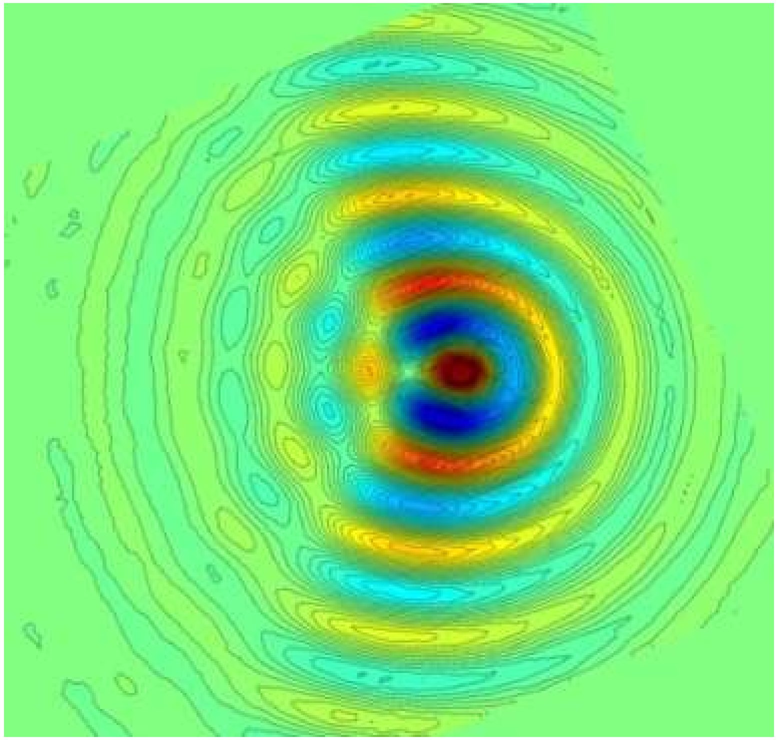


M=5 **M=10** **M=40**

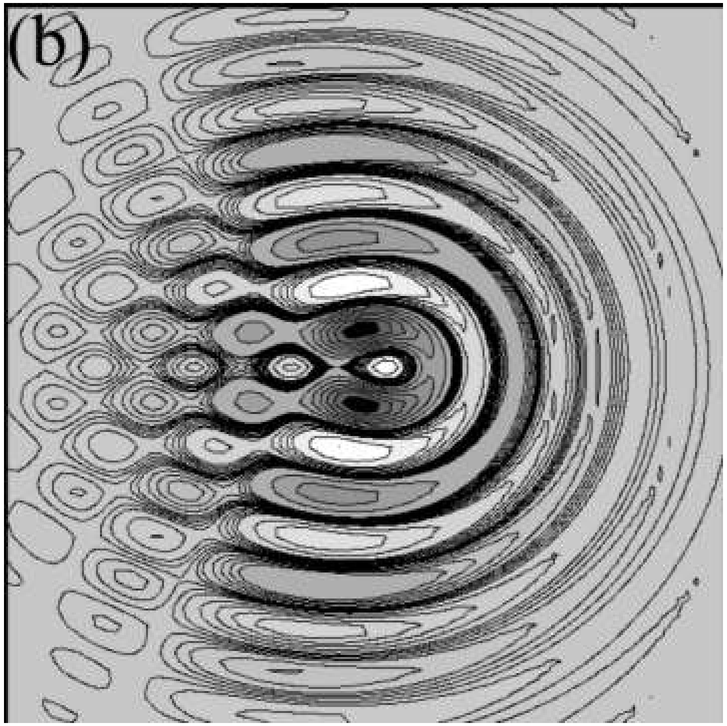
Results of the path-memory model

(1) The walking bifurcation is recovered

(2) A realistic structure of the wave field is obtained for a rectilinearly moving walker



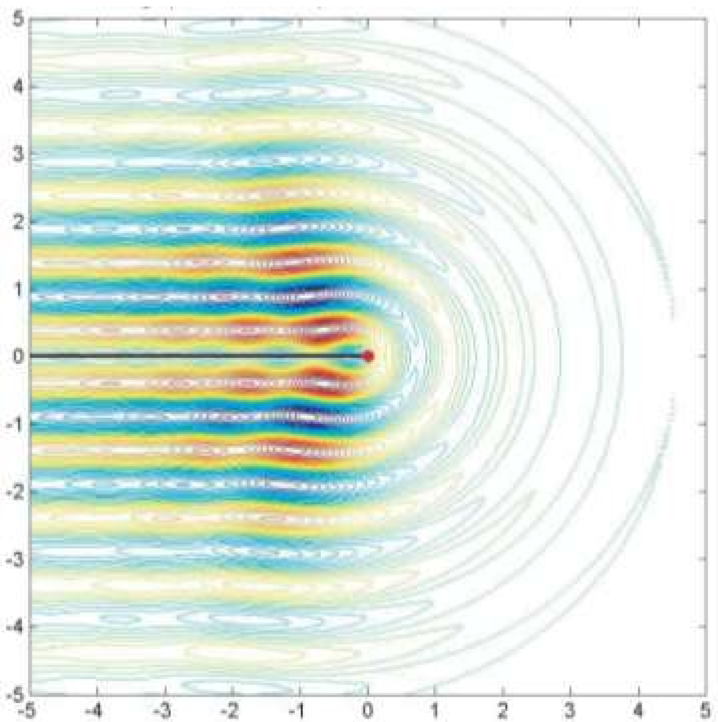
The measured field



Its simulation

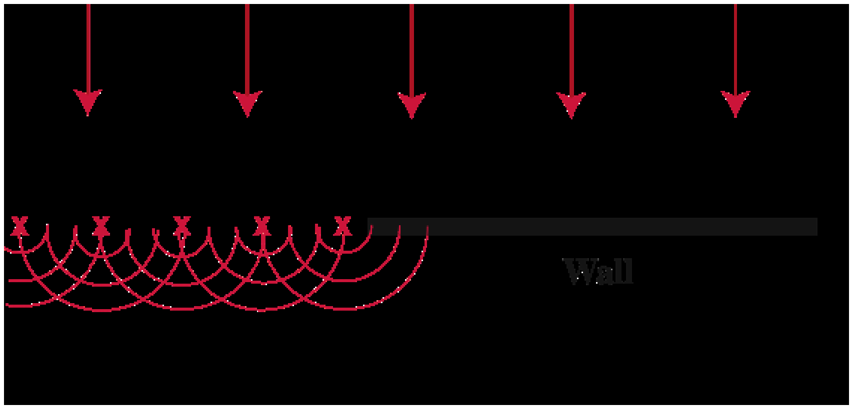
The wave field of a walker with a rectilinear trajectory

The structure of the wave field exhibits Fresnel interference fringes



Fresnel diffraction behind an edge

The equivalent of the wall is the region of the straight trajectory which has not yet been visited by the droplet



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 :

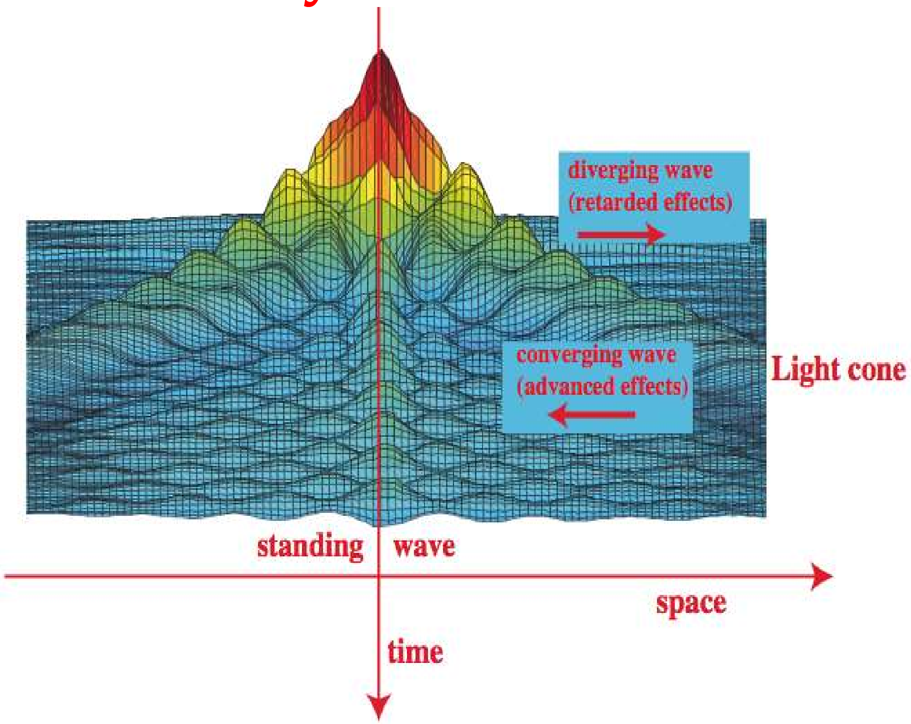
« But there there is also the convergent wave, the interpretation of ***which could raise interesting philosophical issues****, but that appears necessary to insure the stability of the material point »*

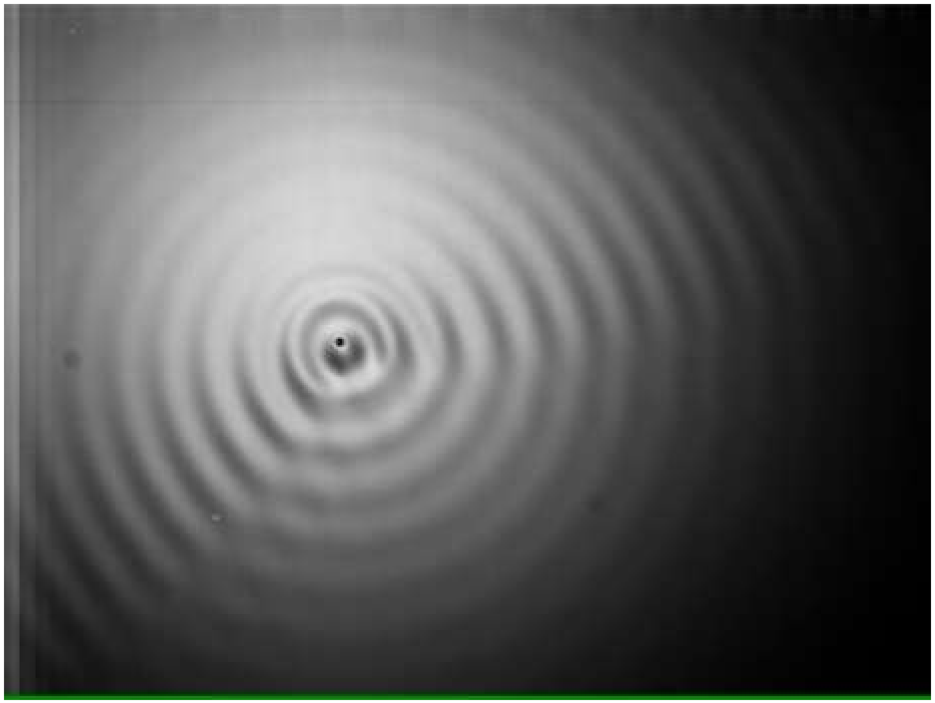
Memory & Soul (of a Walker)

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

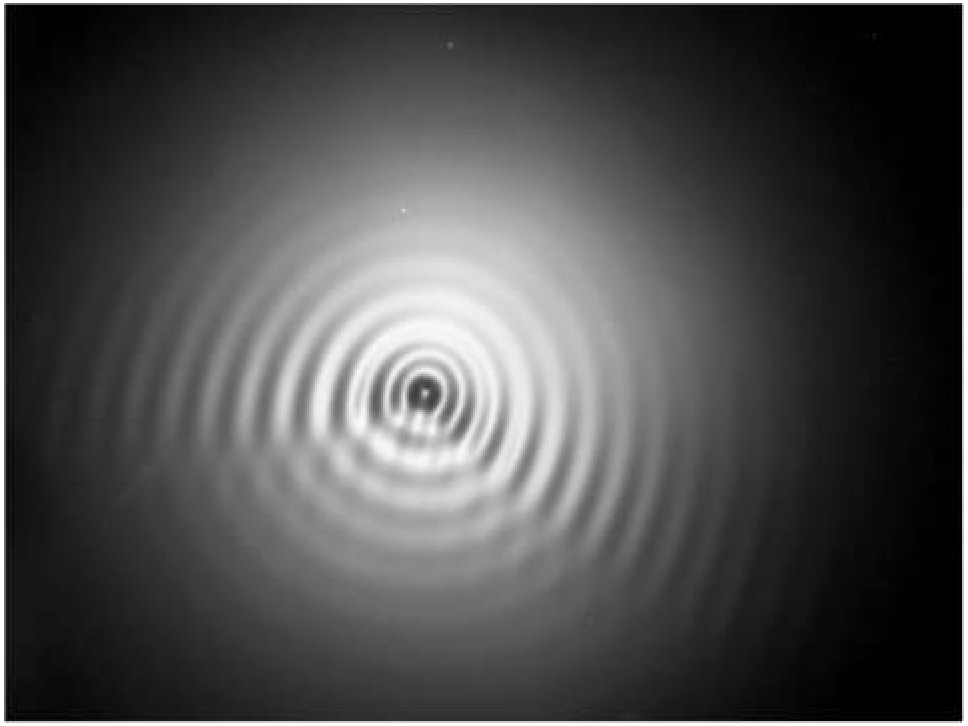
A walker is a "symbiotic" association of a particle with a wave:

If the particle vanishes, so does the wave

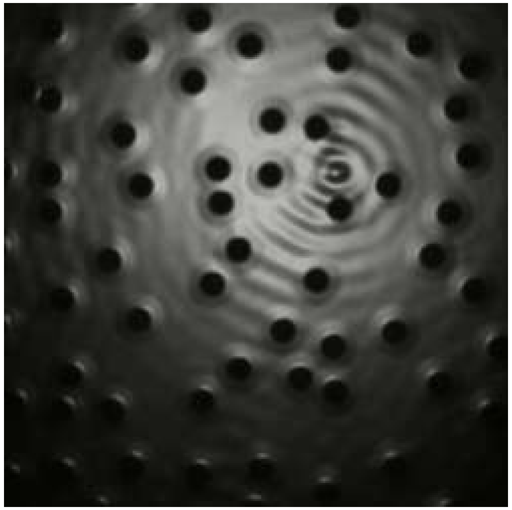
If the wave is damped, the droplet stops

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

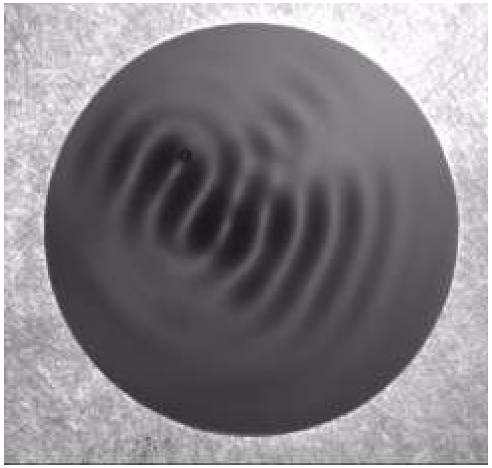
A walker is a non-quantum macroscopic dual object!



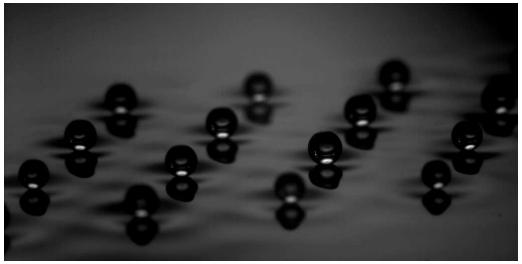
Quantum-like Experiments



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



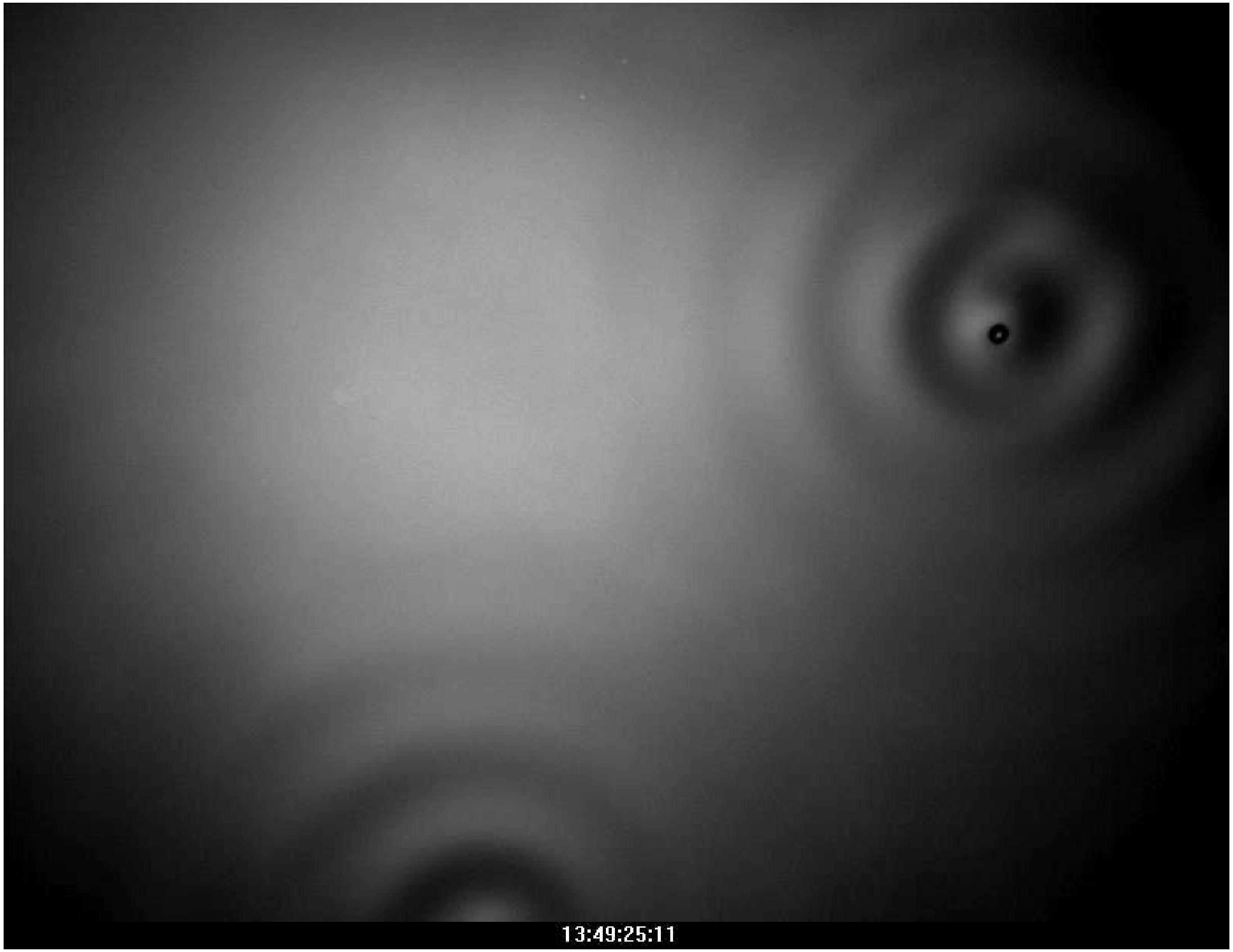
Statistical experiments:
- Single particle diffraction and interferences
- Tunneling effect
- *Anderson-like localization*
- *Cavity*
- *Central force*



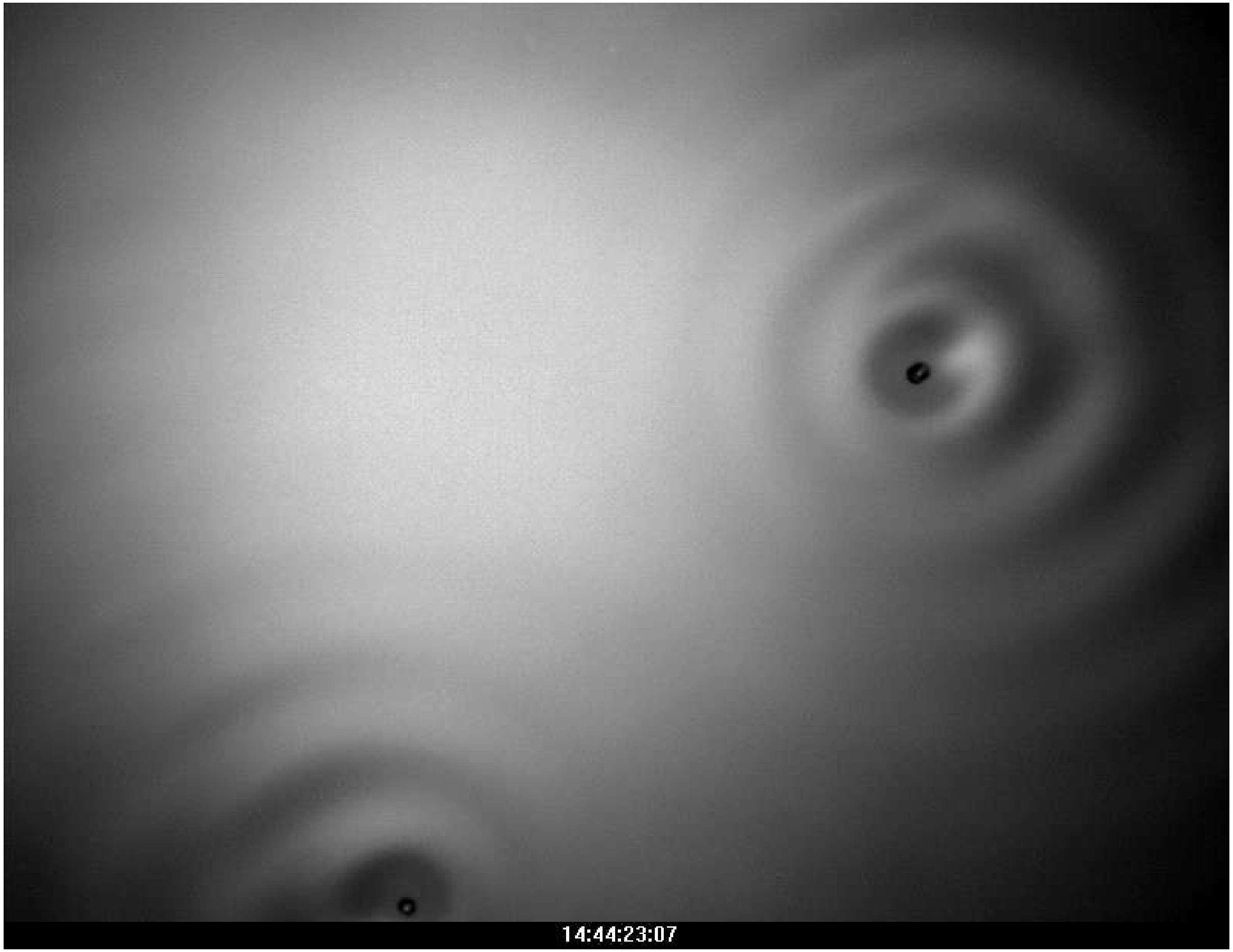
Quantization experiments
- Interacting walkers

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

Collision of walkers



Collision of walkers



Quantization of the orbits

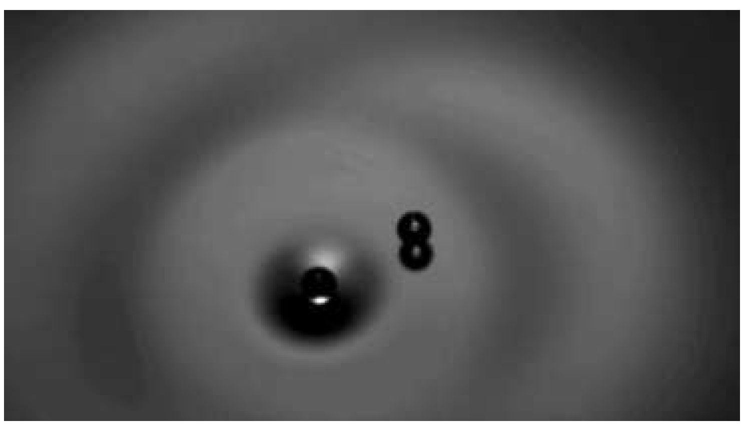
Out of phase droplets **In phase droplets**

Images of the smallest 4 orbits

Diameters of the orbits:

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

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



Smallest orbit (n=1/2)

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)

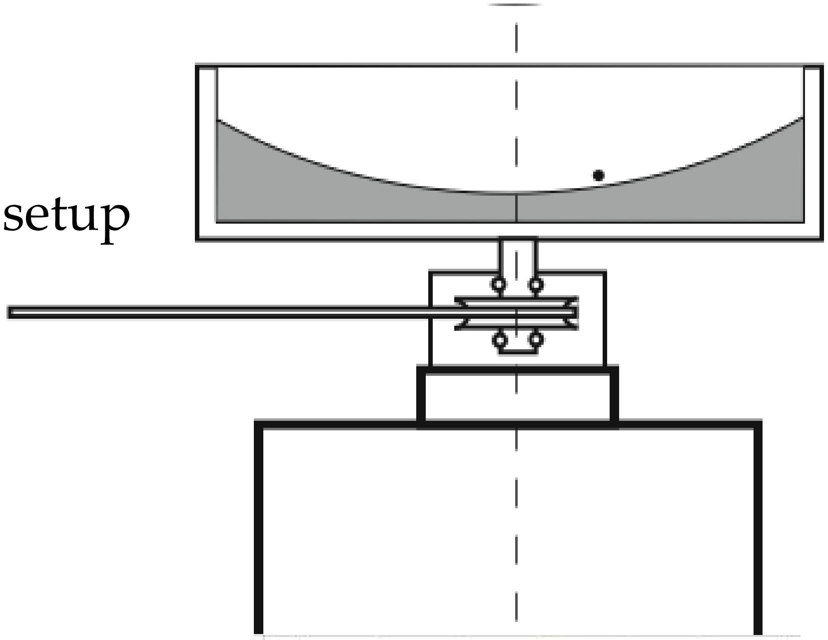
The **Larmor radius** takes discrete values: $\rho_L^n = \frac{1}{\sqrt{\pi}}\sqrt{\frac{h}{qB}\left(n + \frac{1}{2}\right)}$

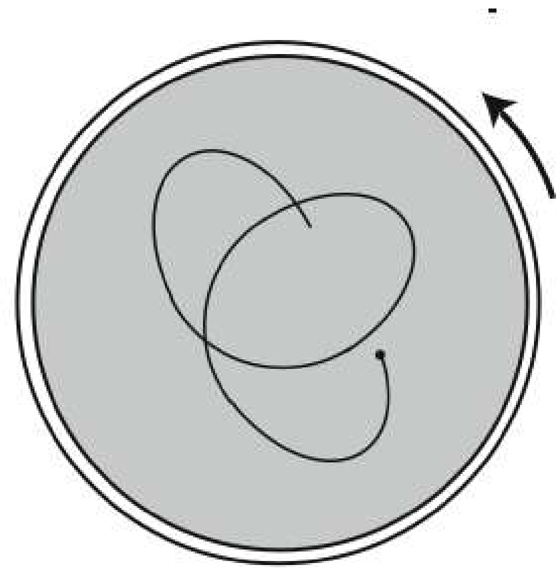
Analogy: magnetic field and rotating frame

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

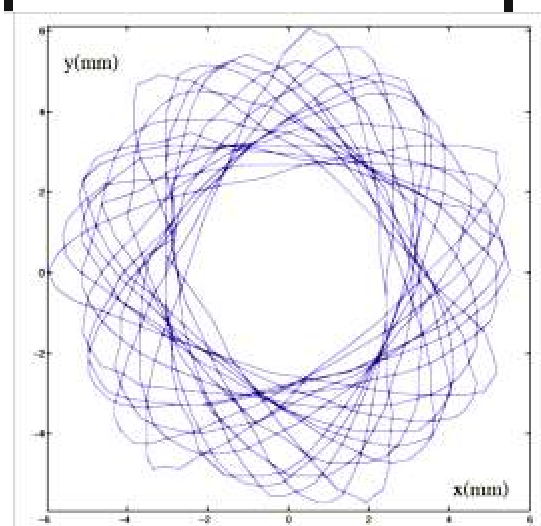
The rotating Faraday experiment

Experimental setup

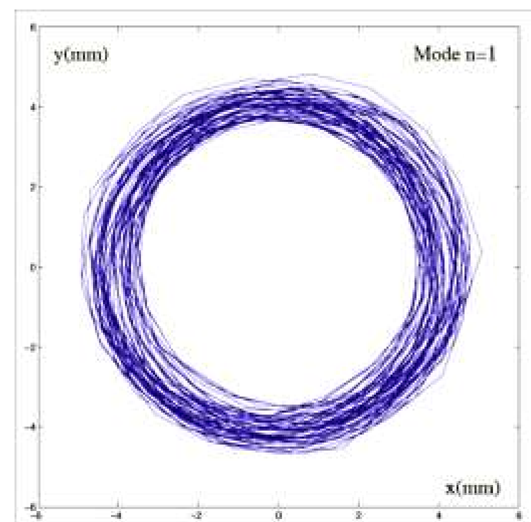




Measured trajectories



Trajectory in the laboratory frame of reference

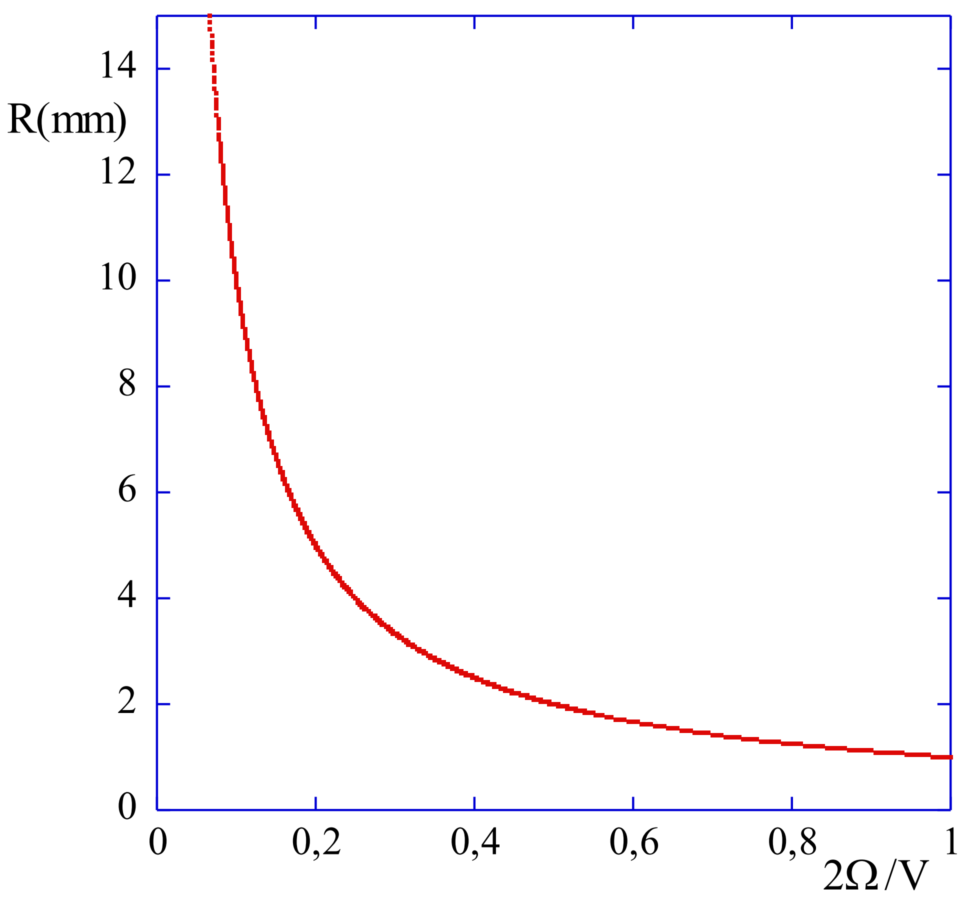


Trajectory in the rotating frame of reference

Classical radius of the orbits

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

$$R=V/2\Omega$$



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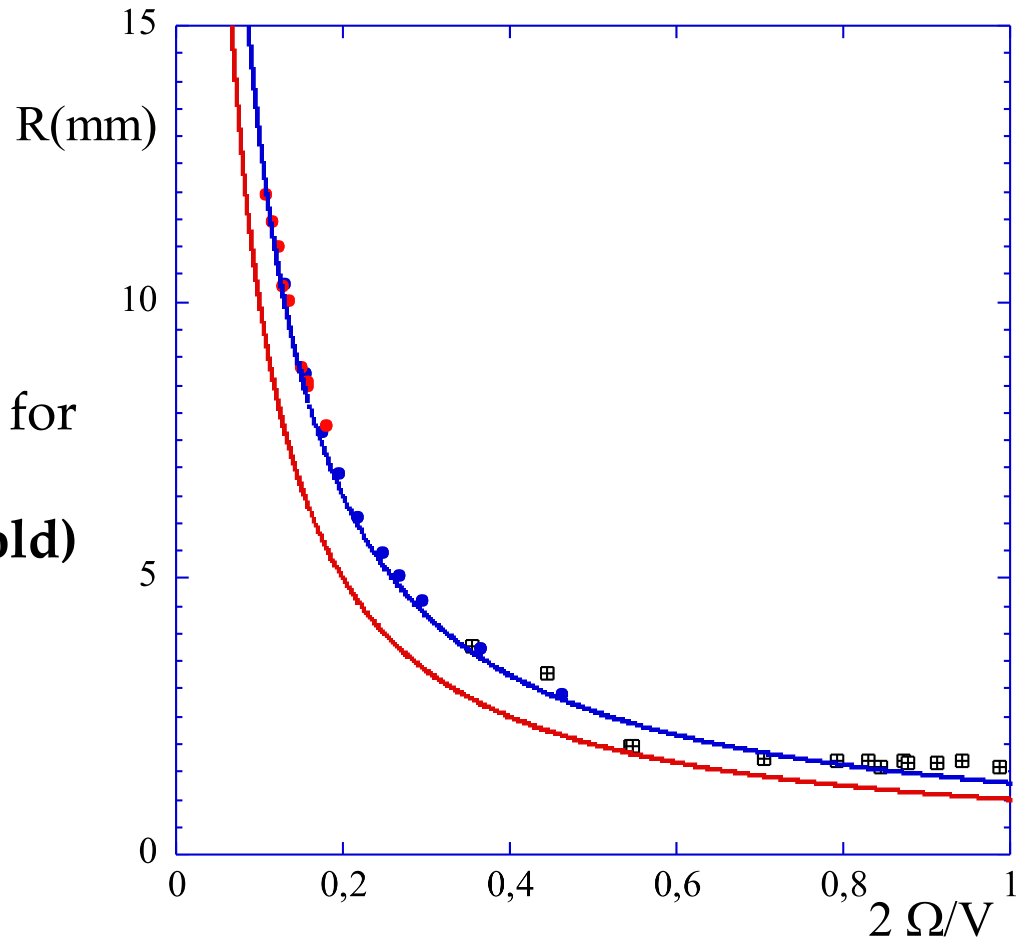


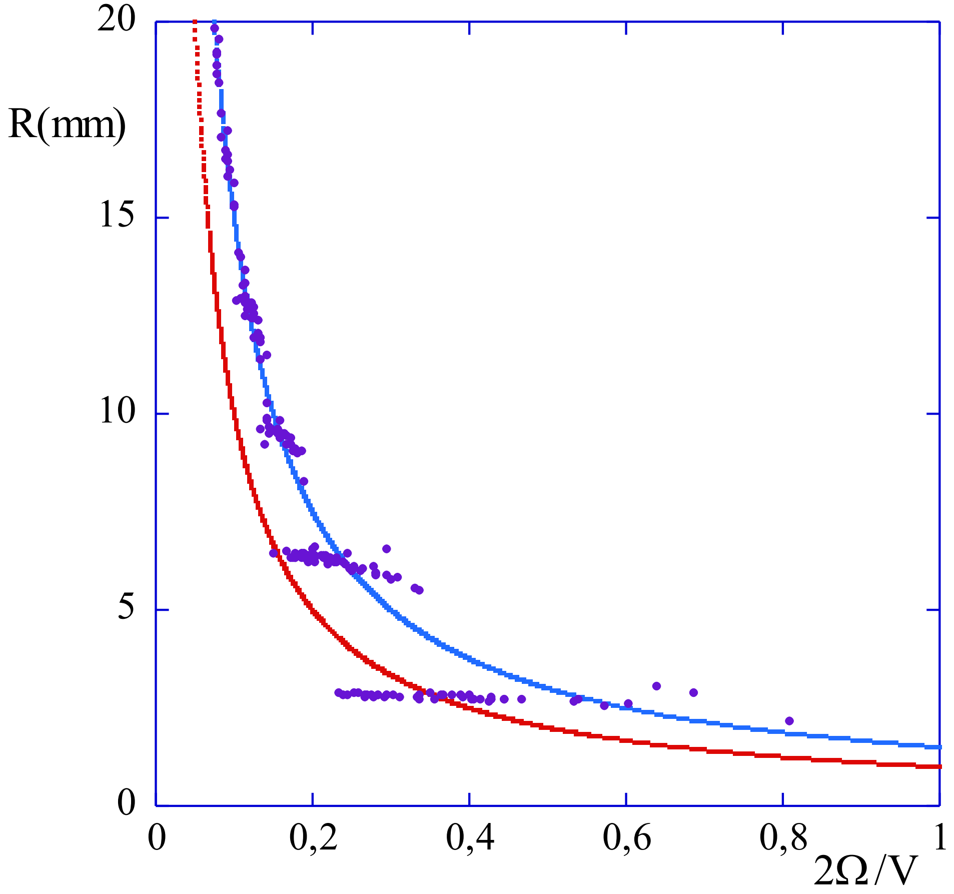
Measured radius of the orbits for walkers **with short memory (far from the Faraday threshold)**

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

$R=a\ (V/2\Omega)$ 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)**



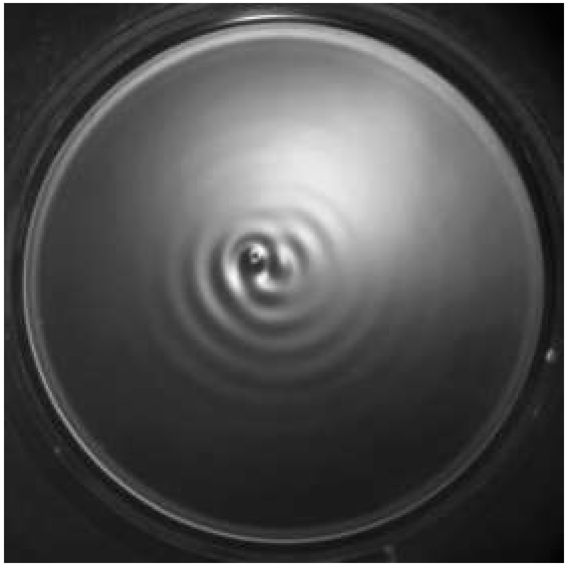
Near the Faraday instability threshold, the radius of the orbit evolves by discrete jumps when W is increased

Quantization appears in the orbits with path-memory

Transition between two discrete orbits

A transition from the orbit n=2 to n=1 when Ω is increased

n=2



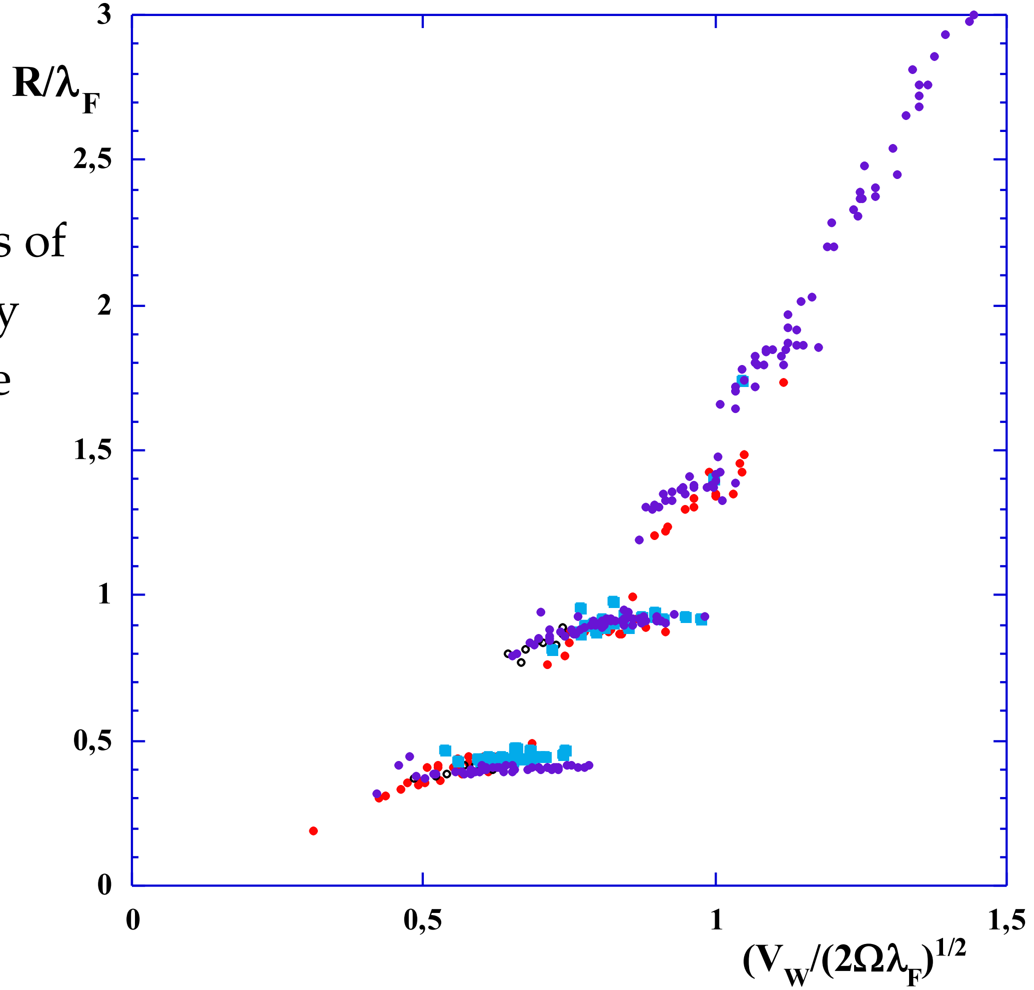
n=1

Trajectory in the rotating
frame of reference

Dimensionless radius of the orbits

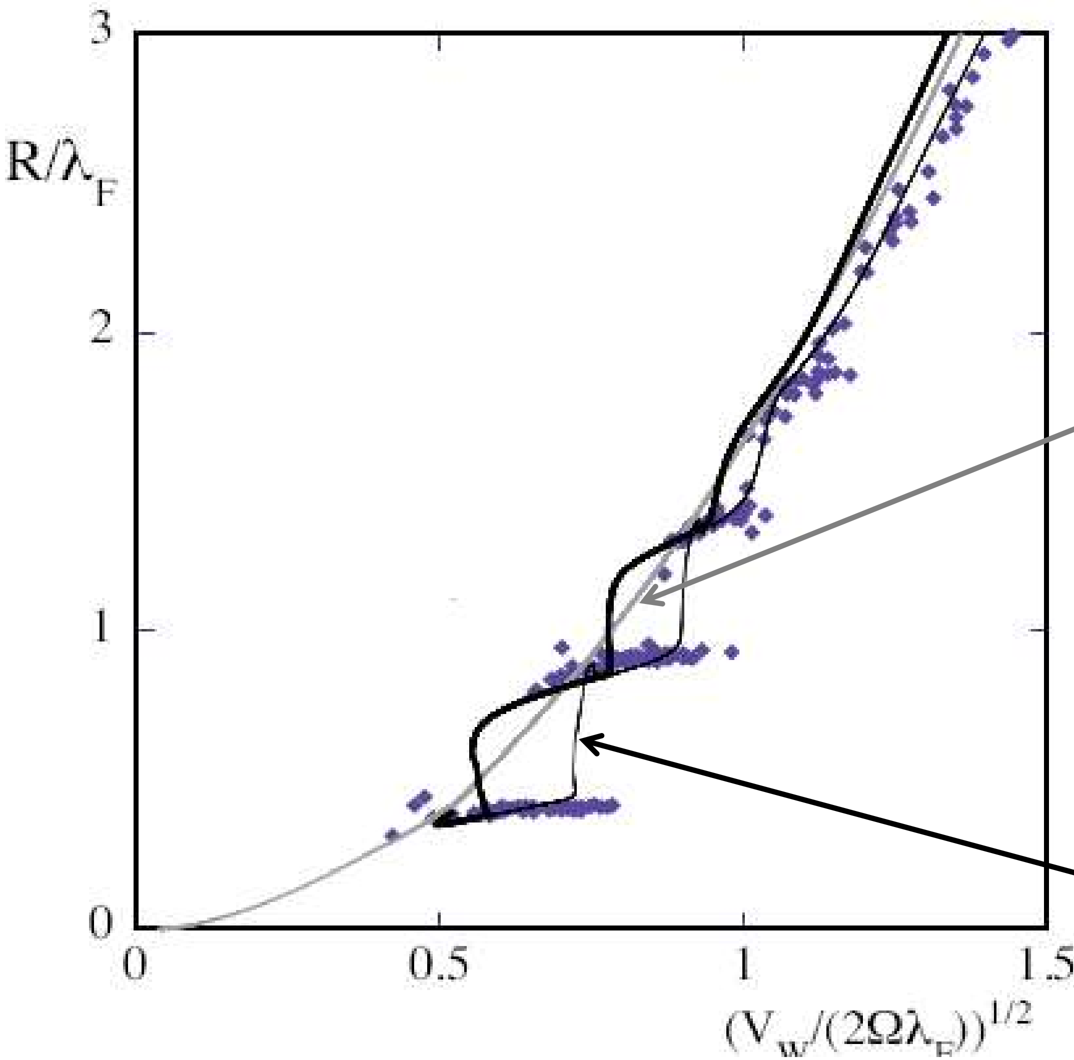
The radii of the orbits obtained at various frequencies and for walkers of various velocities are all **rescaled** by expressing: R/λ_F as a function of the non dimensionnal parameter:

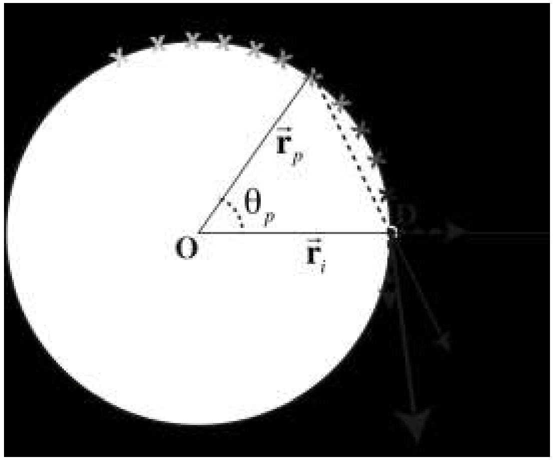
$$\sqrt{\frac{V_W}{2\Omega\lambda_F}}$$



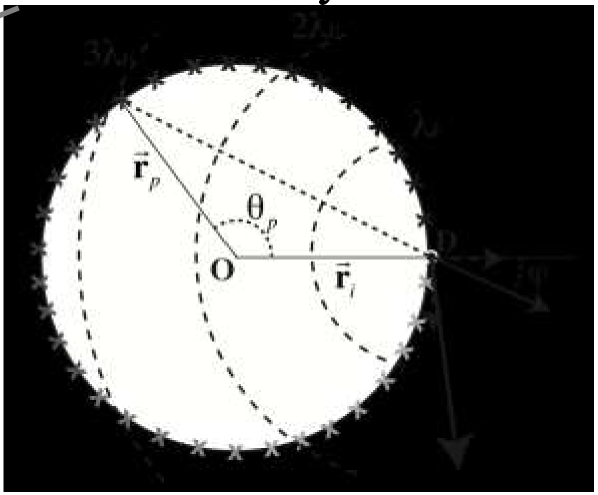
Path-memory dynamics for a circular orbits

Simulations with Path-memory model





Short memory



Long memory

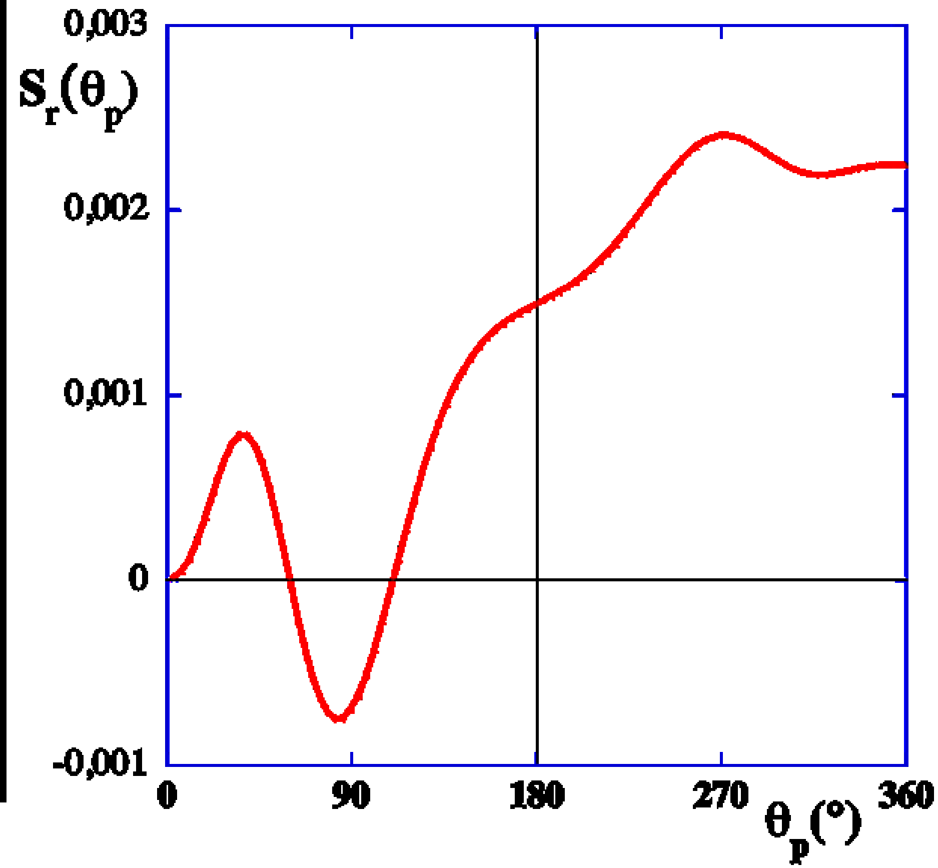
Waves associated with the sources diametrically opposed to the droplet modulate the radial force with a spatial period equal to the Faraday wavelength.

Virtual memory droplet model

Radial slope S_r at the point of bouncing generates an additional centripetal (or centrifugal) force.

2Ω

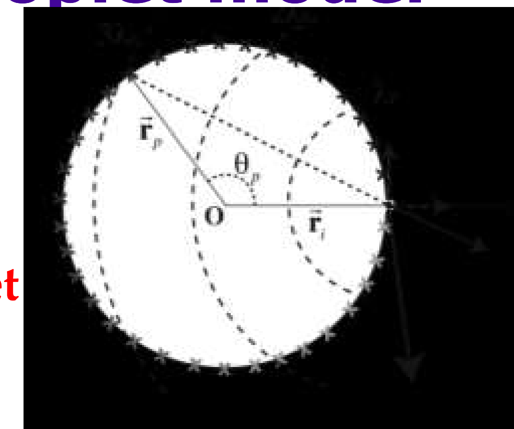
Cumulated radial slope around the orbit

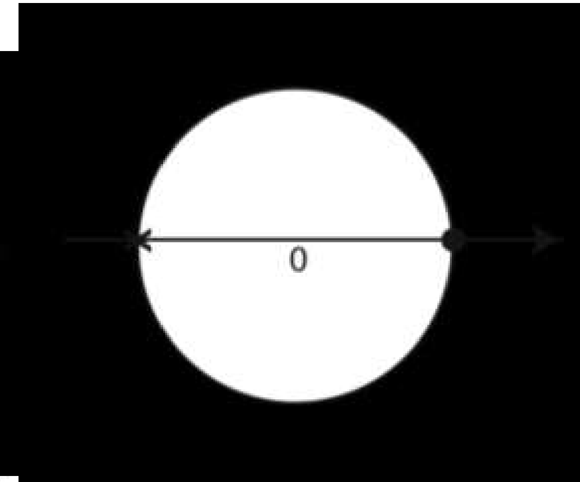


π geometric phase

Virtual memory droplet model

The evolution of the orbits diameters can be recovered assuming that only one source diametrically opposed to the droplet generates the additional force



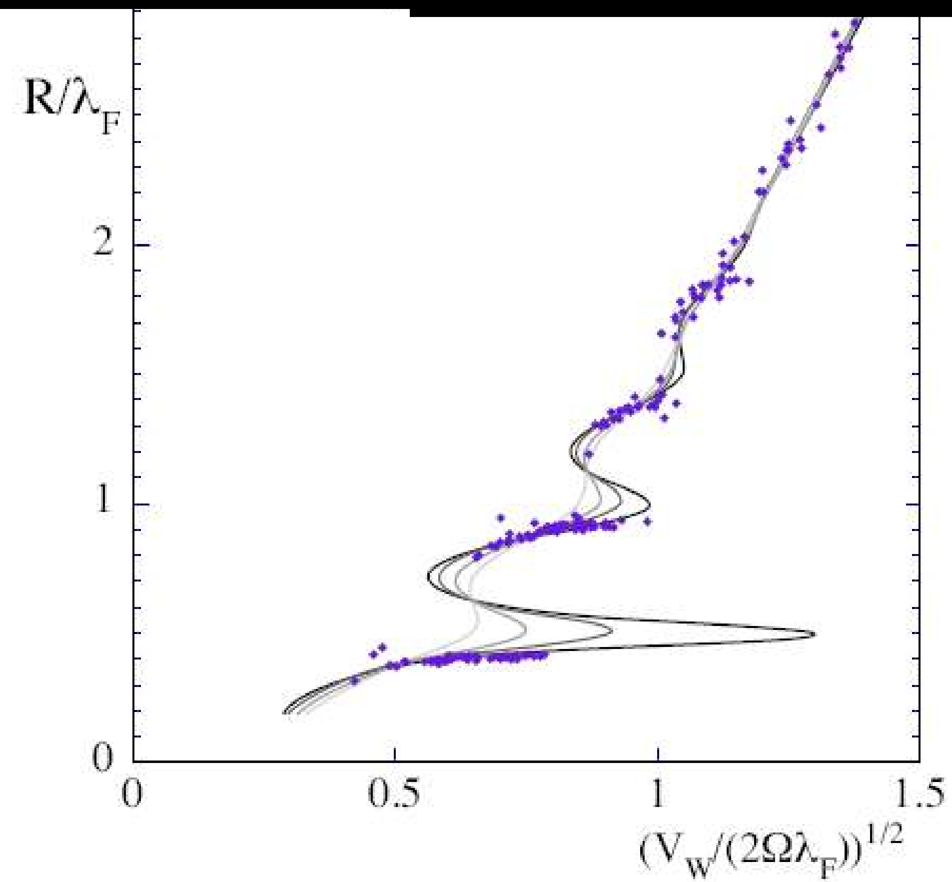


Newton's law: radial component

$$\frac{mV_W^2}{R} = -2\frac{m}{a}\Omega V_W + A\sin\left(2\pi\frac{2R}{\lambda_F} + \phi\right)$$

with $$A = A_0 e^{-\frac{r}{\delta}} e^{-\frac{t}{\tau}}$$

A_0 is the only parameter
τ is changed from short to long memory



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:

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

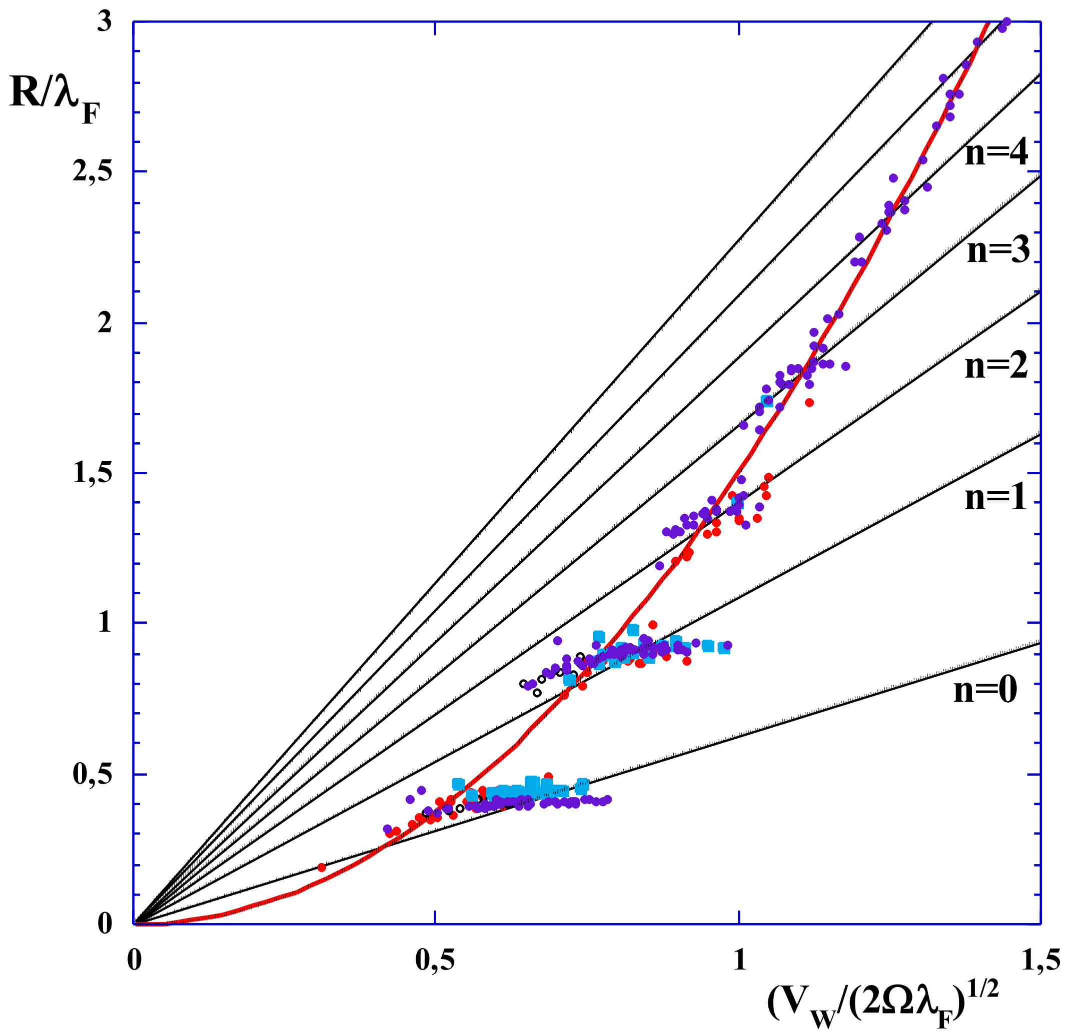
$$\lambda_{dB} \Leftrightarrow \lambda_F$$

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

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

We find

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



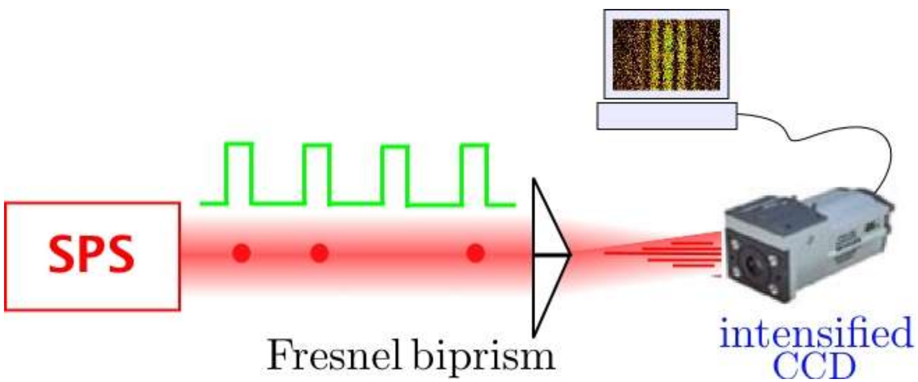
Diameter quantization: 2 R = n λ_F

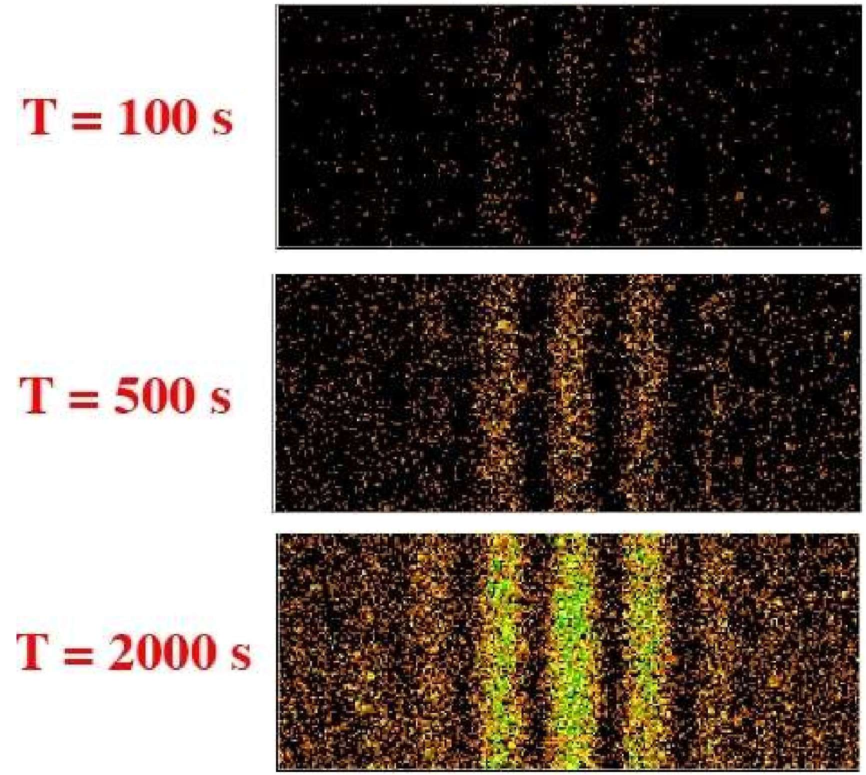
Statistical experiments:

- Single particle diffraction and interferences

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

Single particle interference





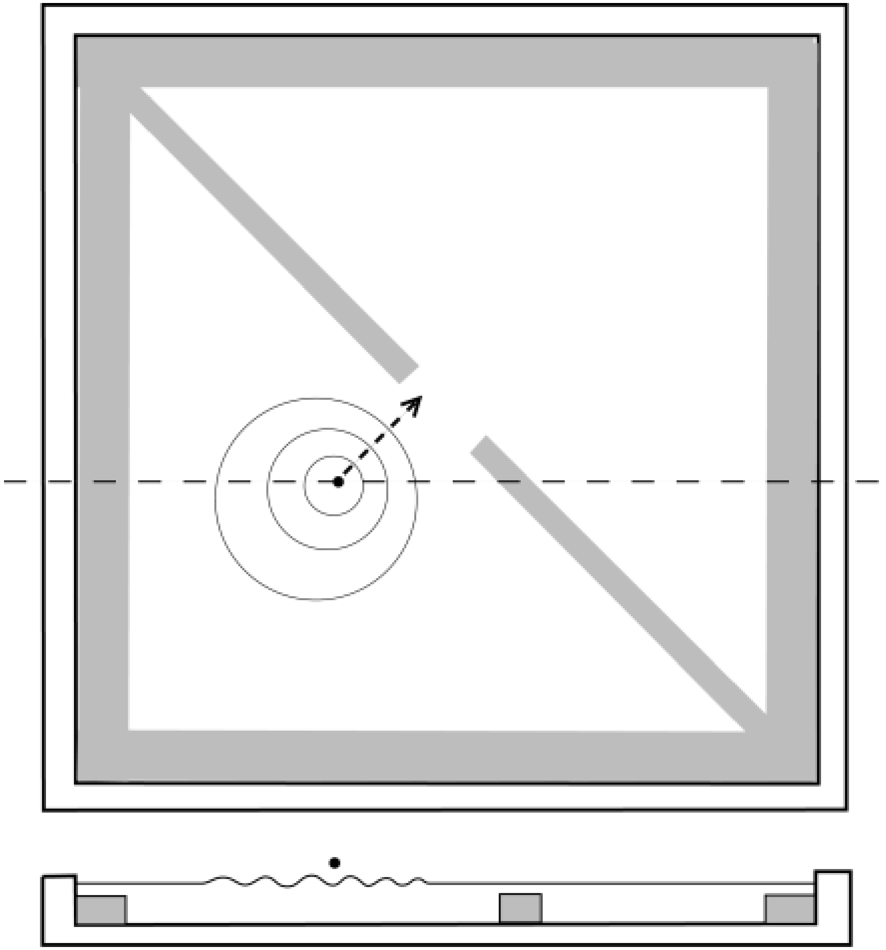
R. Feynman's, Lectures on Physics,
Quantum Mechanics, (First chapter!)

« … In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examin 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=1mm (h_0=4mm 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:

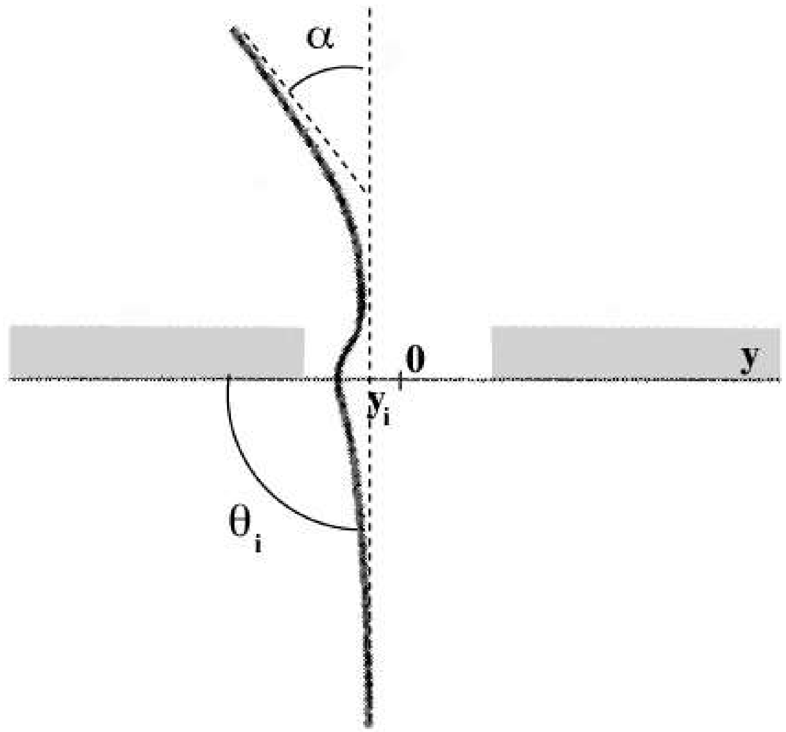
L : the width of the slit,

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

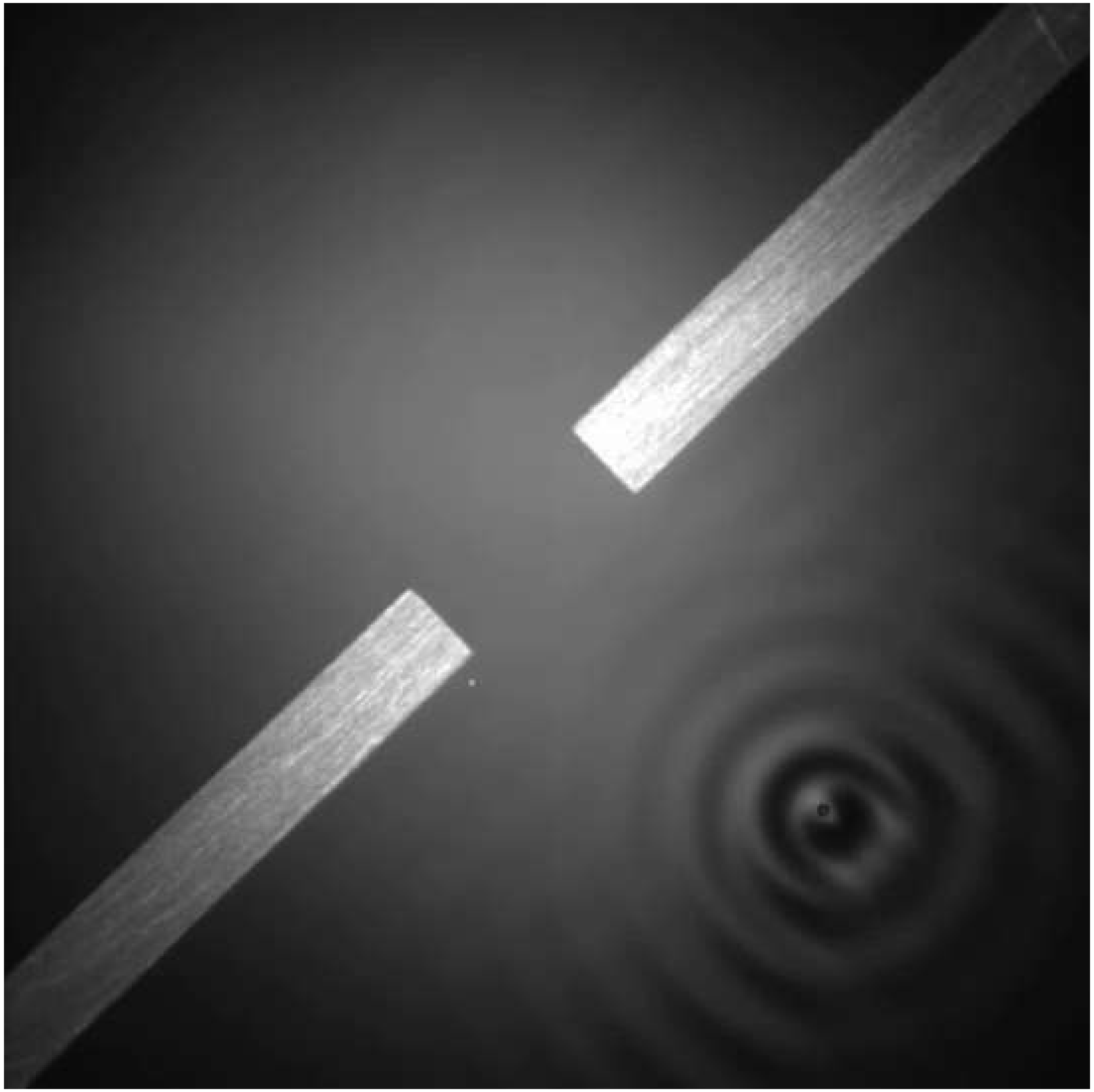
a : the angle of deviation

$Y_i = y_i/L$: the impact parameter

(With $-0.5 < Y_i < 0.5$)



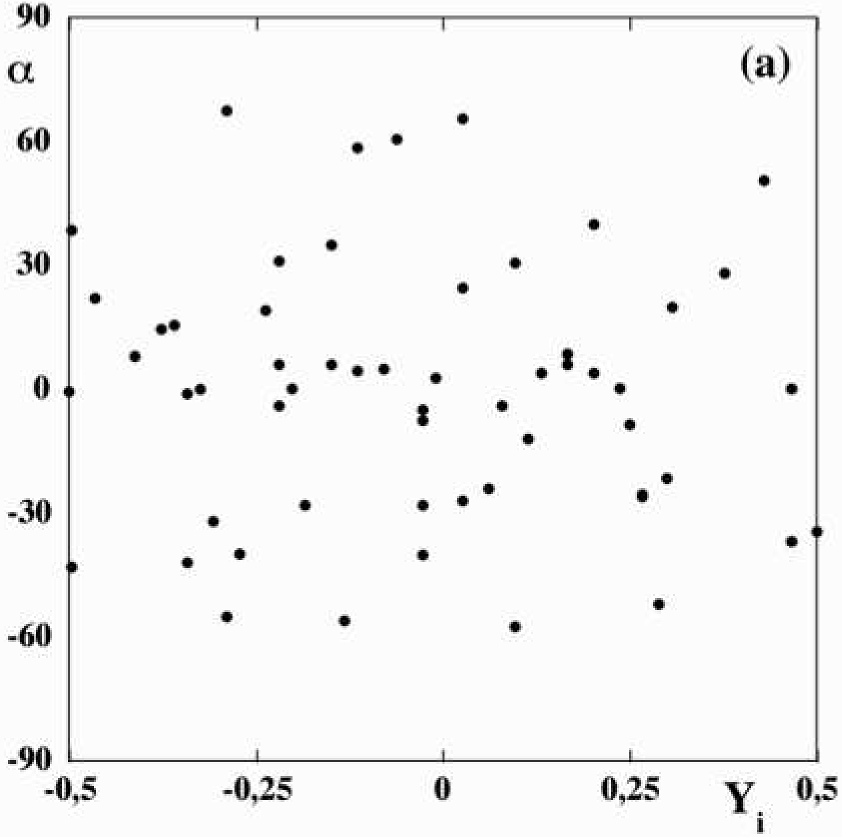
A single "diffracting" droplet



Deviation angle α *vs* the impact parameter Y_i ?

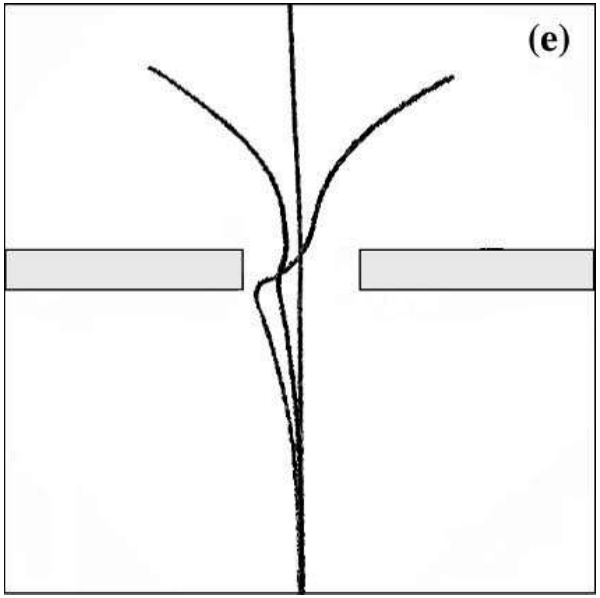
The measured deviation in experiments performed with the same walker, the same angle of incidence, but various impact parameters

L/λ_F=3.1 (L=14.7mm and λ_F= 4.75 mm).



Impact parameter

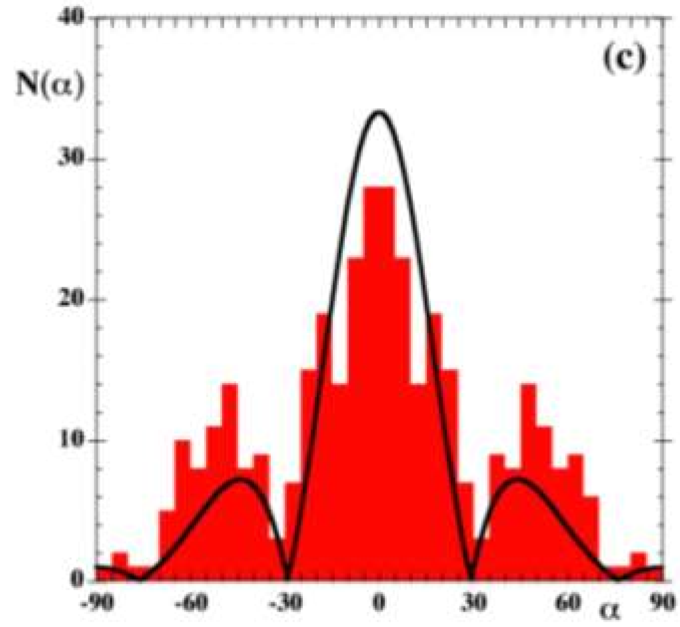
Three independent trajectories with the same initial conditions (within experimental accuracy)



Diffraction histograms

$\omega/2\pi$= 50Hz,

L/λ_F=2.11 (L=14.7mm and λ_F= 6.95 mm).

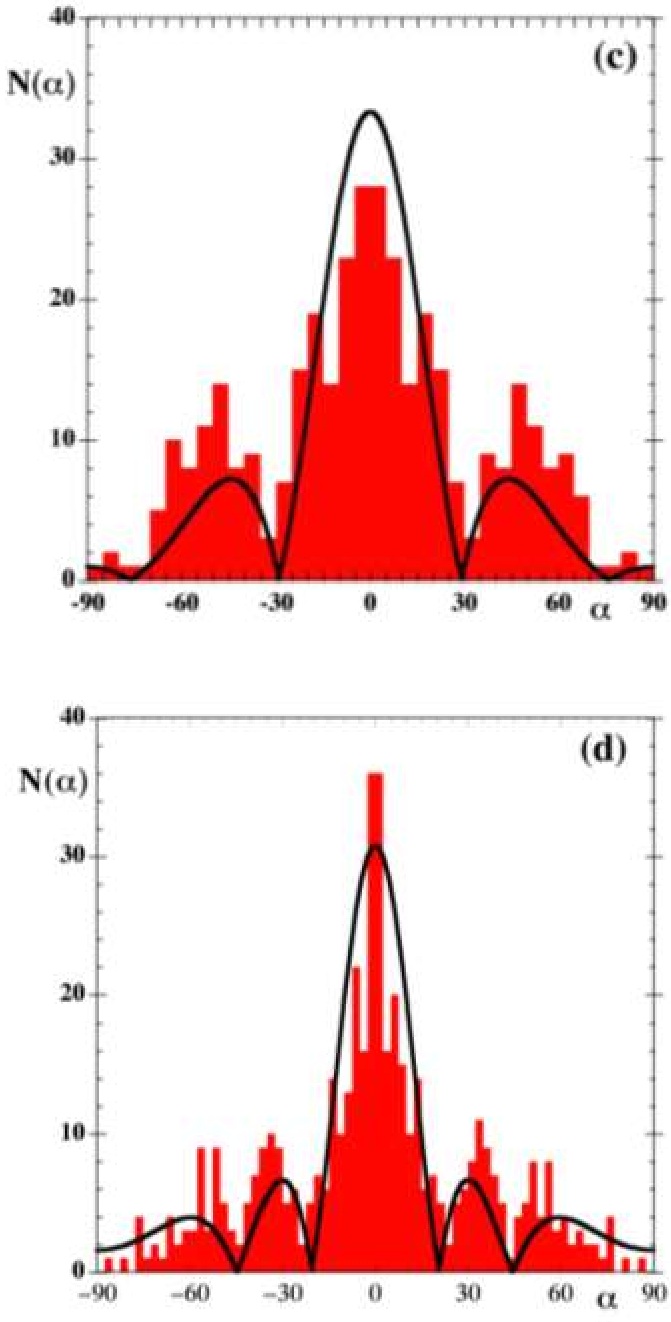


The curve is the modulus of the amplitude of diffraction of a plane wave with L/λ_F =1.96.

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

Diffraction histograms

ω/2π= 50Hz,
L/λ_F=2.11 (L=14.7mm and λ_F= 6.95 mm).



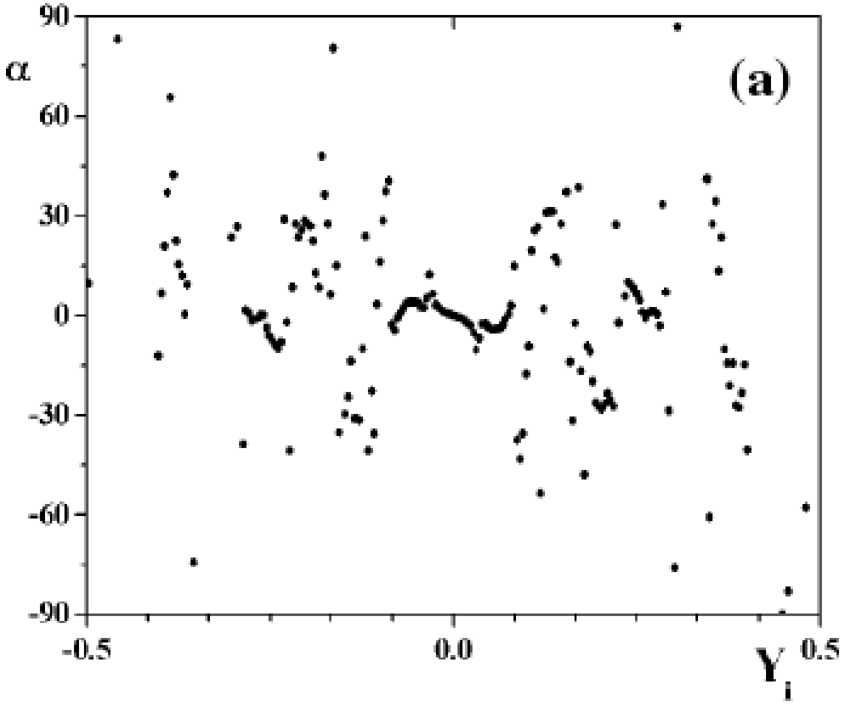
The curve is the modulus of the amplitude of diffraction of a plane wave with L/λ_F =1.96.

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

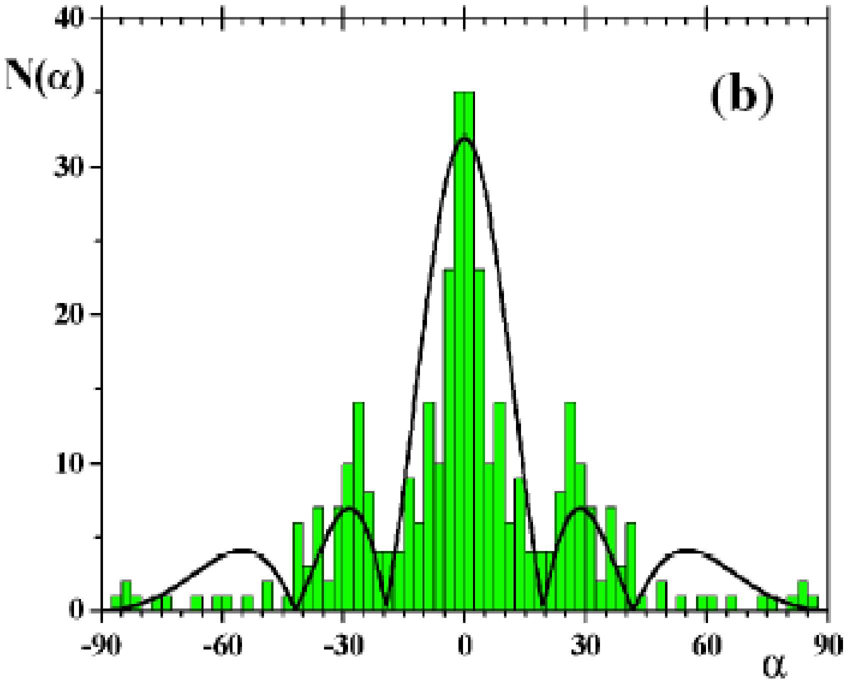
Same with ω/2π= 80Hz ,
L/λ_F=3.1 (L=14.7mm and λ_F= 4.75 mm).

Diffraction with path-memory model

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



Deviation
vs normalized impact parameter

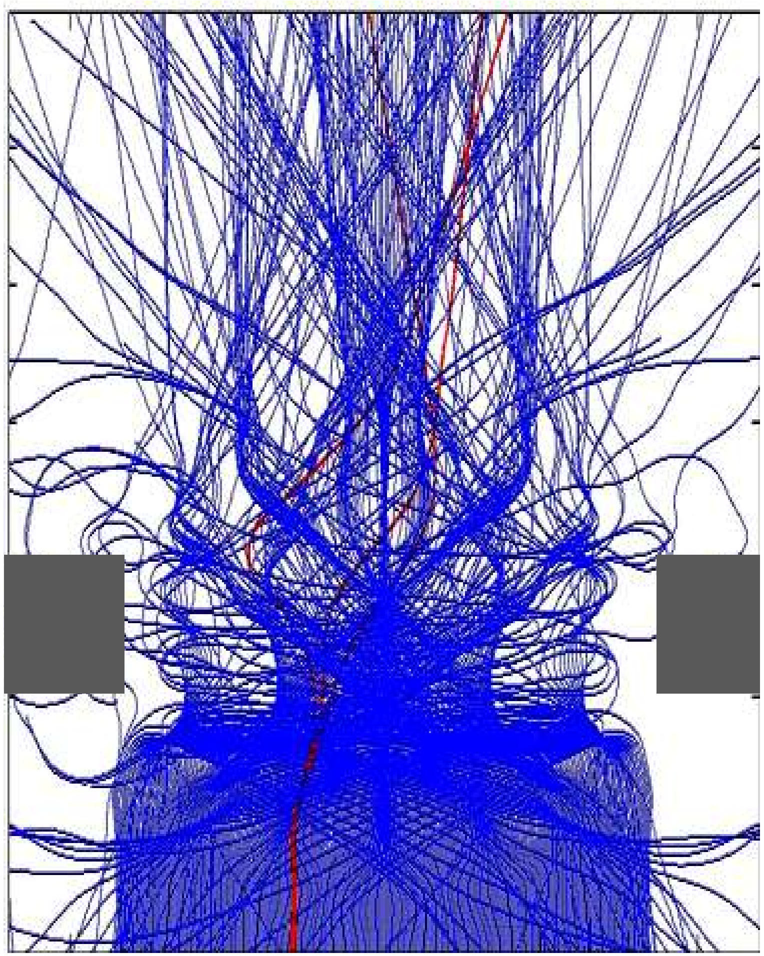


Deviation histogram

Diffraction with path-memory model

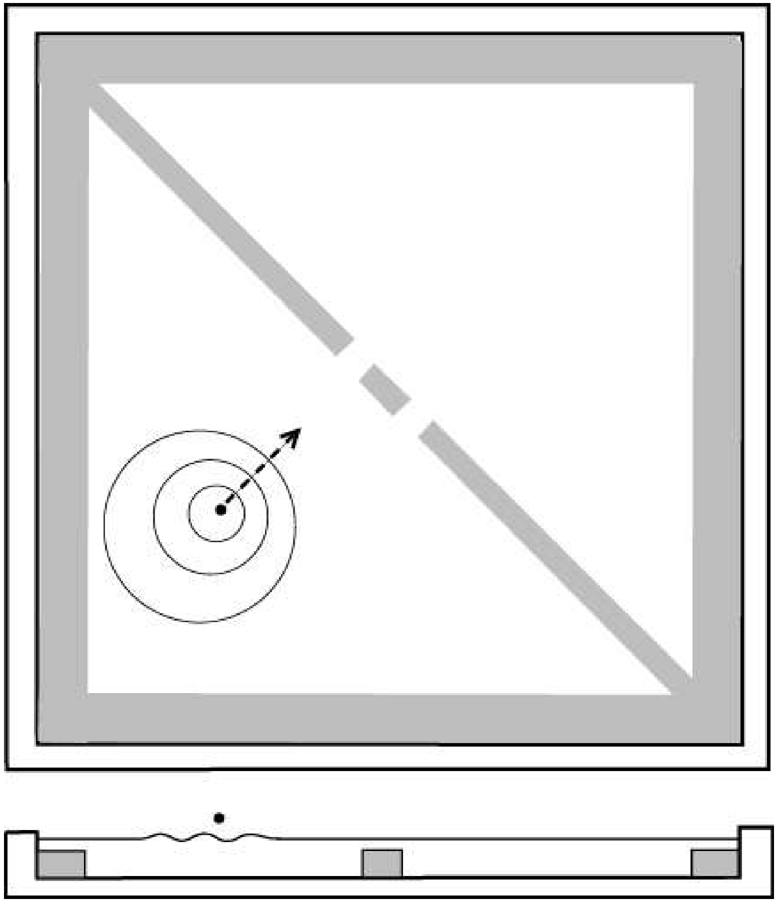
Trajectories

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



Three independent trajectories with impact factor within λ_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.

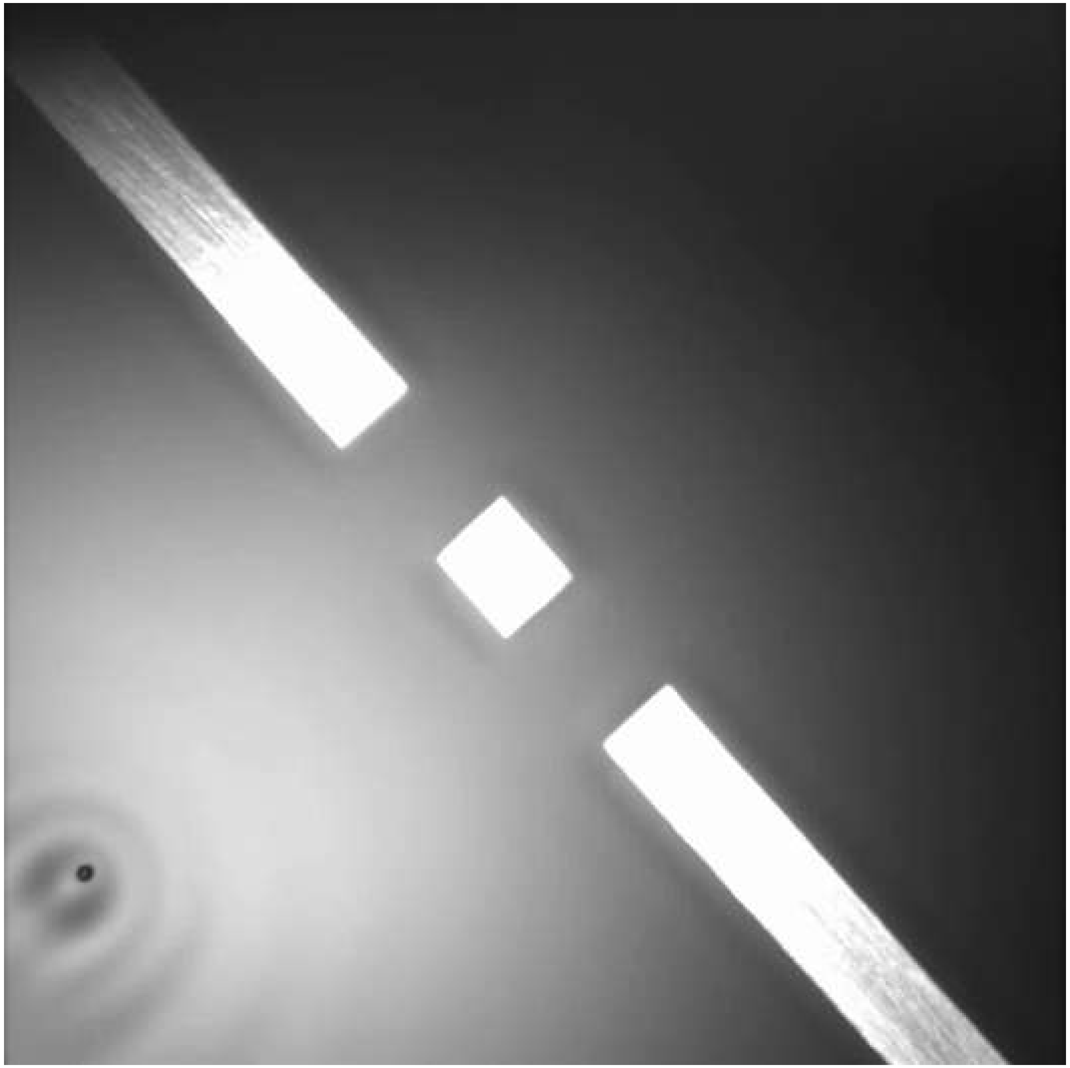
Before making any exposures it was necessary to find out what proportion of the light was cut off by these screens. A plate was exposed to direct gas light for a certain time. The gas flame was then shaded by the various screens that were to be used, and other plates of the same kind were exposed till 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 blackness 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 5×10^{-6} ergs per sec, and the amount of energy per cubic centimetre of this radiation is 1.6×10^{-16} ergs.

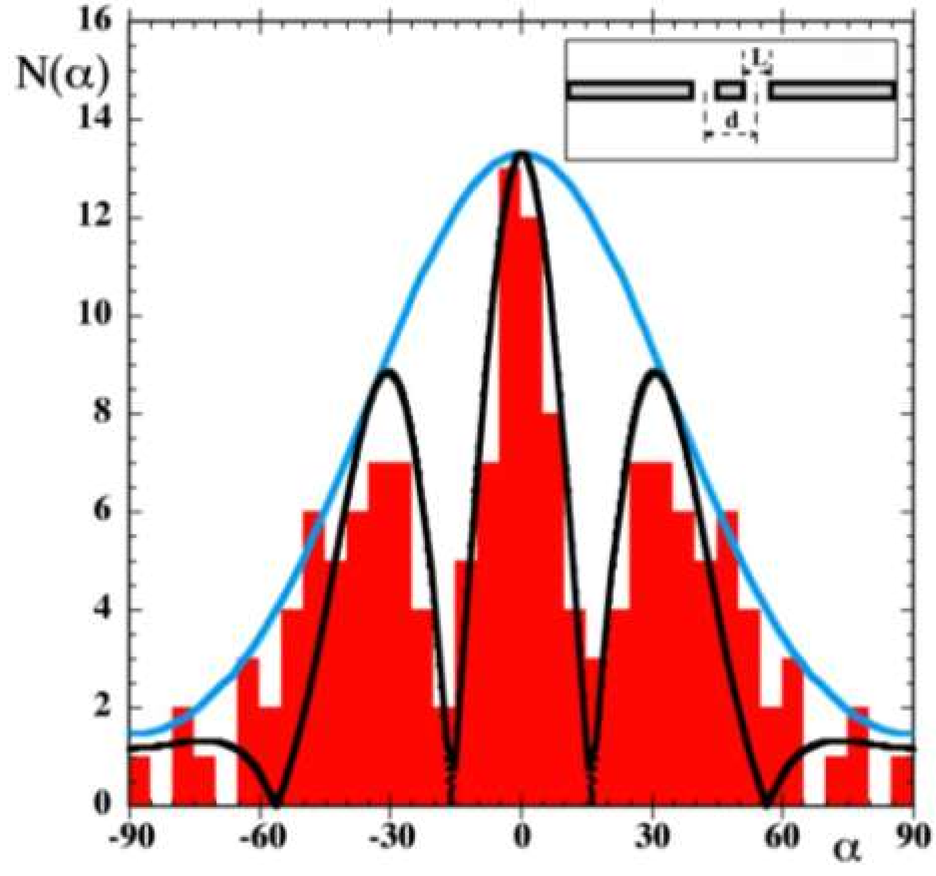
According to Sir J.J. Thomson this value sets an upper limit to the amount of energy contained in one of the indivisible units mentioned above.

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/λ_F= 0.9 and d/λ_F=1.7.

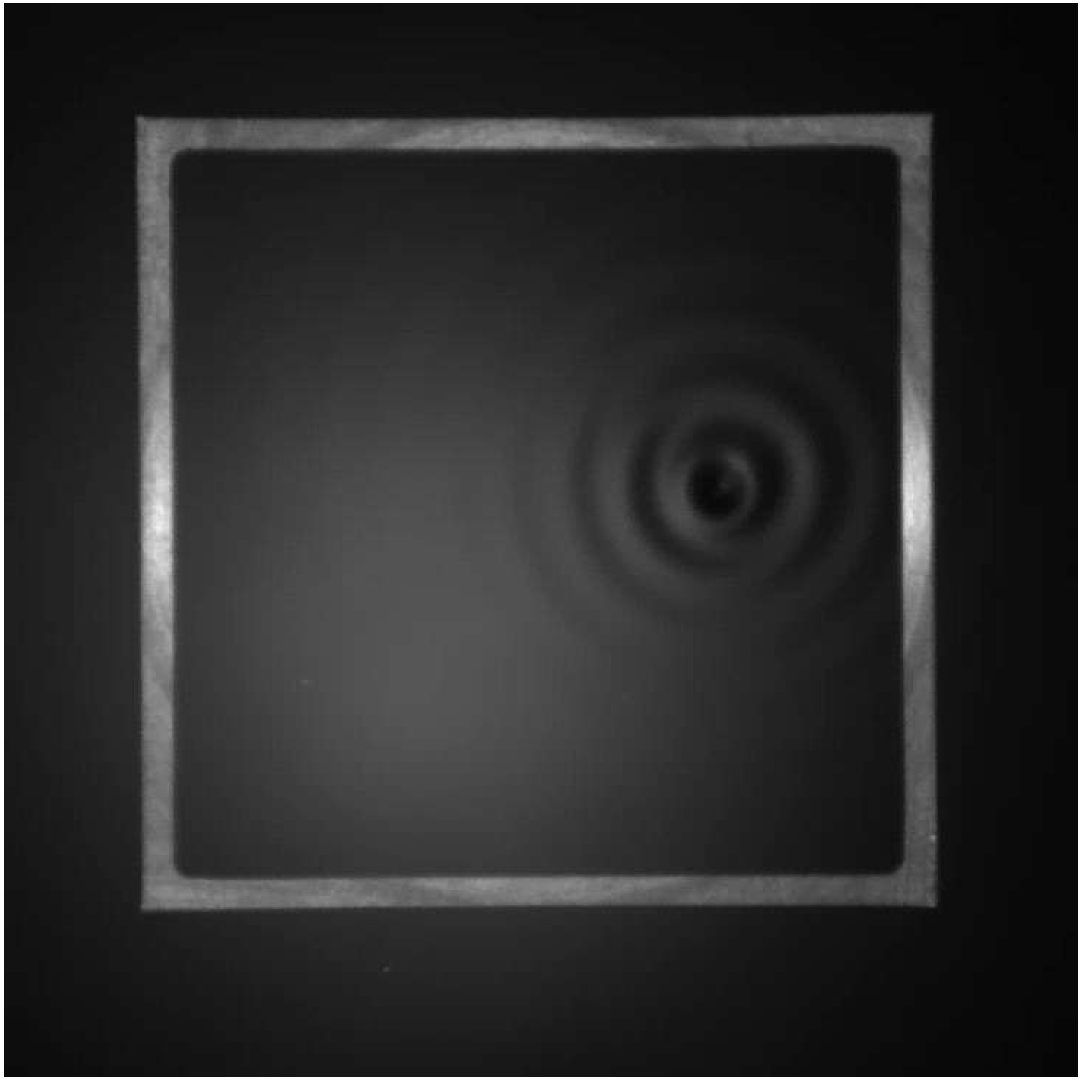
$$f(\alpha) = A\left|\frac{\sin(\pi L \sin\alpha/\lambda_F)}{\pi L \sin\alpha/\lambda_F}\cos(\pi d \sin\alpha/\lambda_F)\right|$$

Statistical experiments:

- Tunneling effect

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

Tunneling effet



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

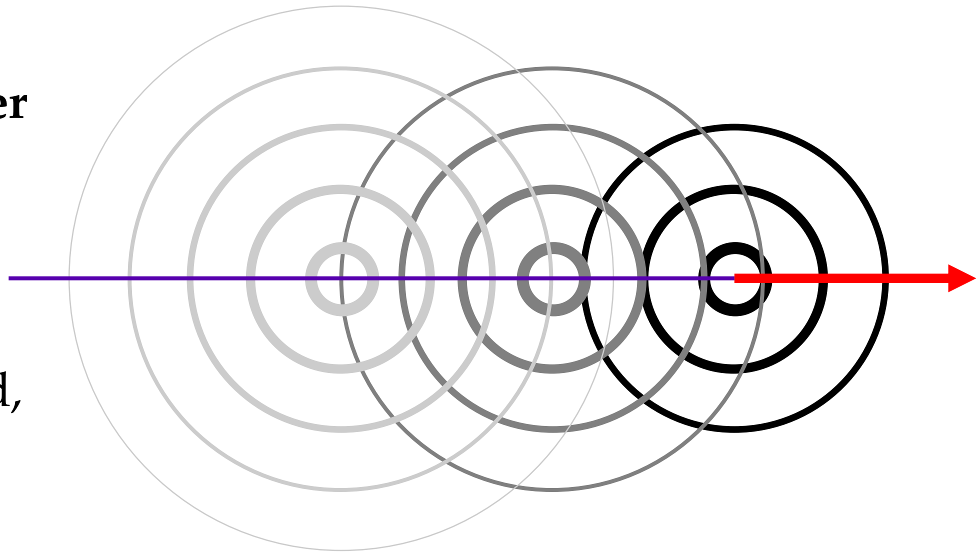
A thought experiment (simulations):

From hydrodynamic walkers to Inertial walkers

Inertial walkers

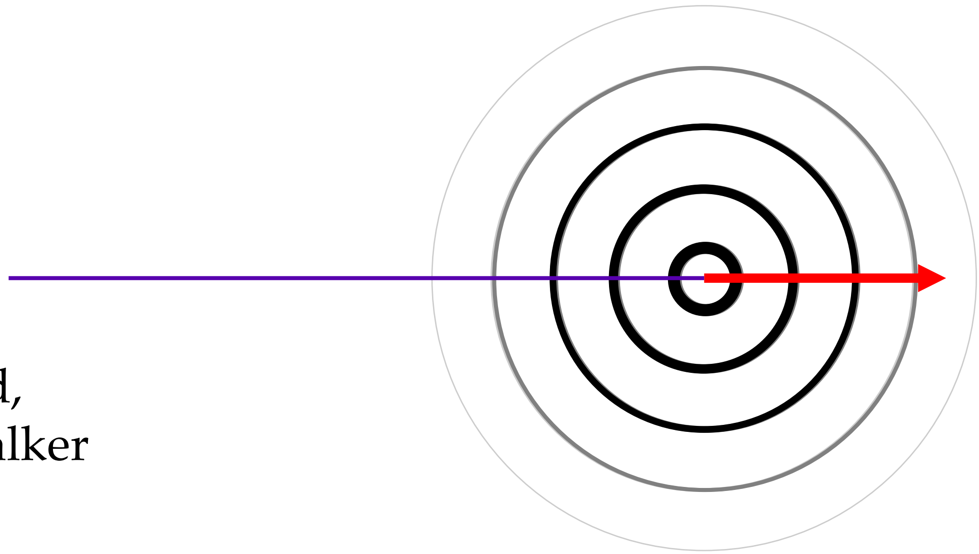
Hydrodynamics experimental walker
Secondary sources are fixed
in the lab frame
No Galilean invariance

If the walker moves at constant speed,
Memory creates a wake

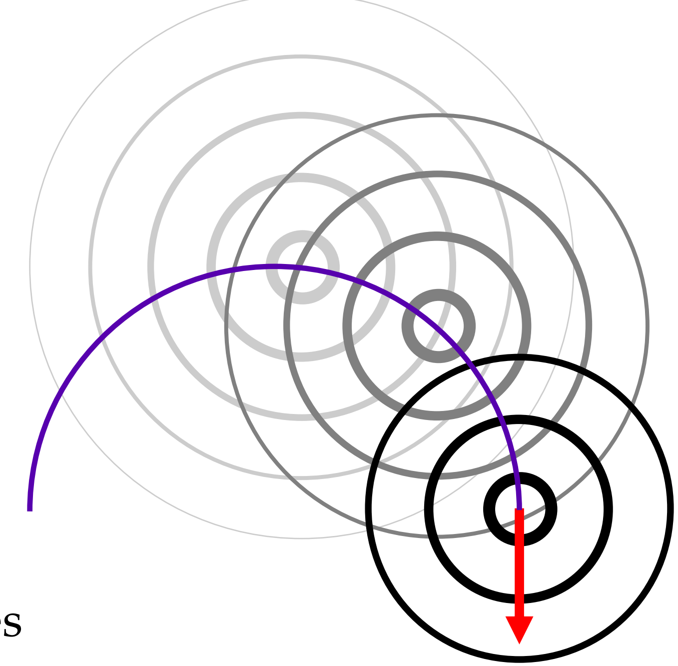


Inertial walker
Secondary sources are fixed
in the inertial frame of reference
Galilean invariance

If the walker moves at constant speed,
all the sources are centered on the walker
Slope is zero but no viscosity!

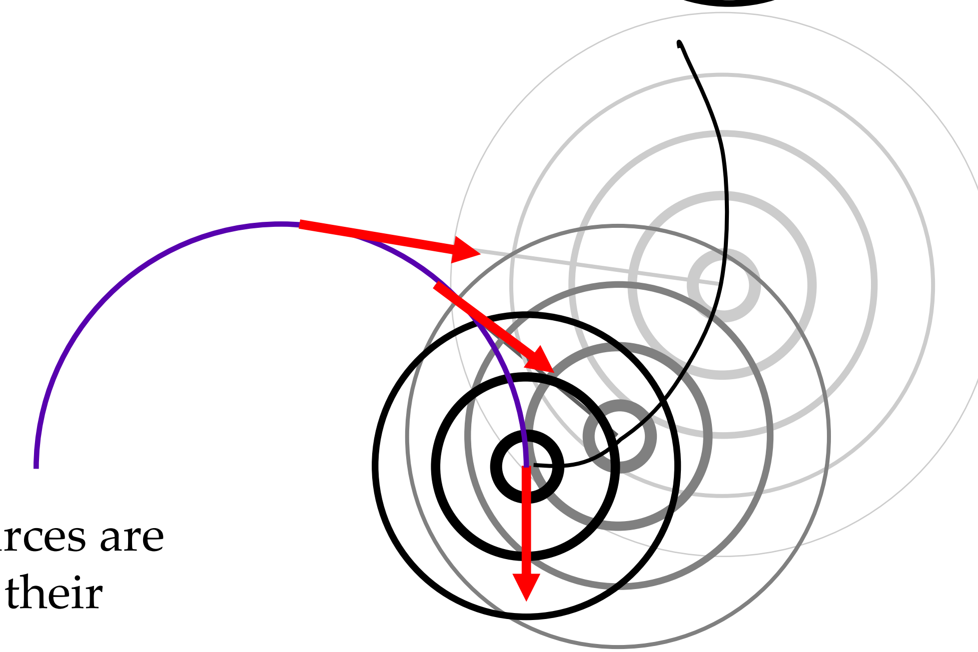


Inertial walkers



Hydrodynamics experimental walker
Secondary sources are fixed
in the lab frame
No Galilean invariance

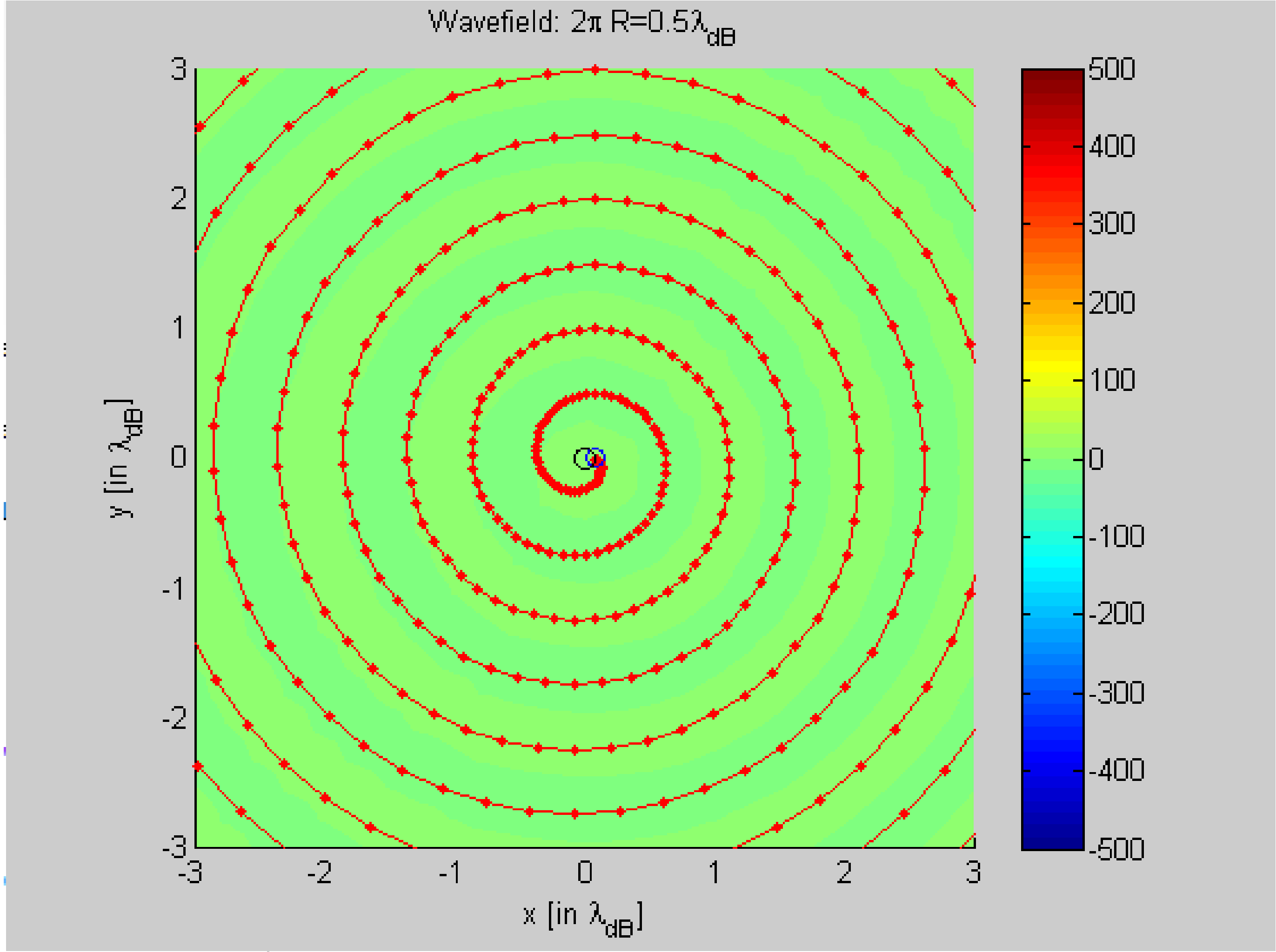
If the walker accelerates, the secondary sources stays along the trajectory



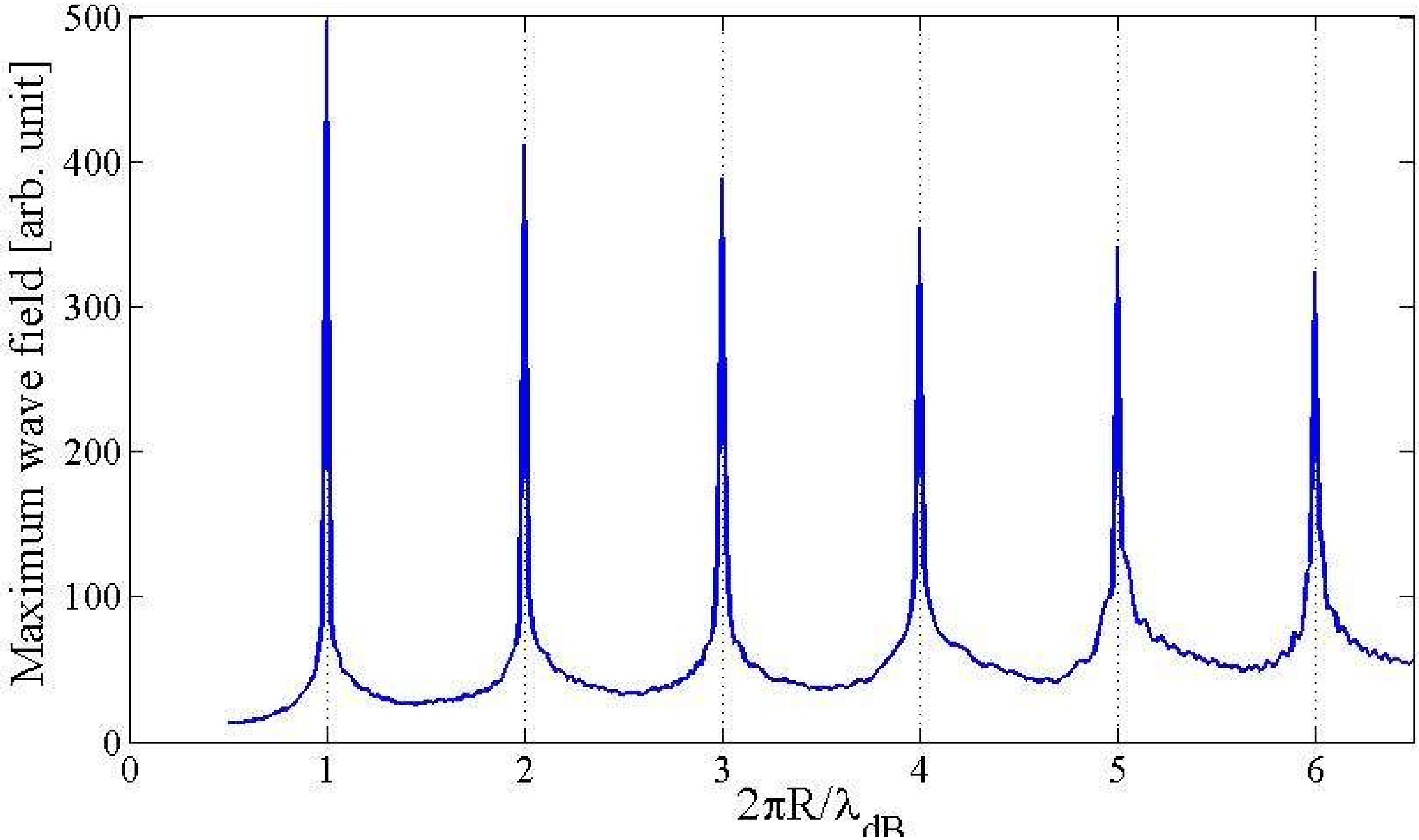
Inertial walker
Secondary sources are fixed
in the inertial frame of reference
Galilean invariance

If the walker accelerates, inertial sources are emitted tangentially and move with their inertial velocity

Inertial walkers in circular motion: Wave field for increasing radius



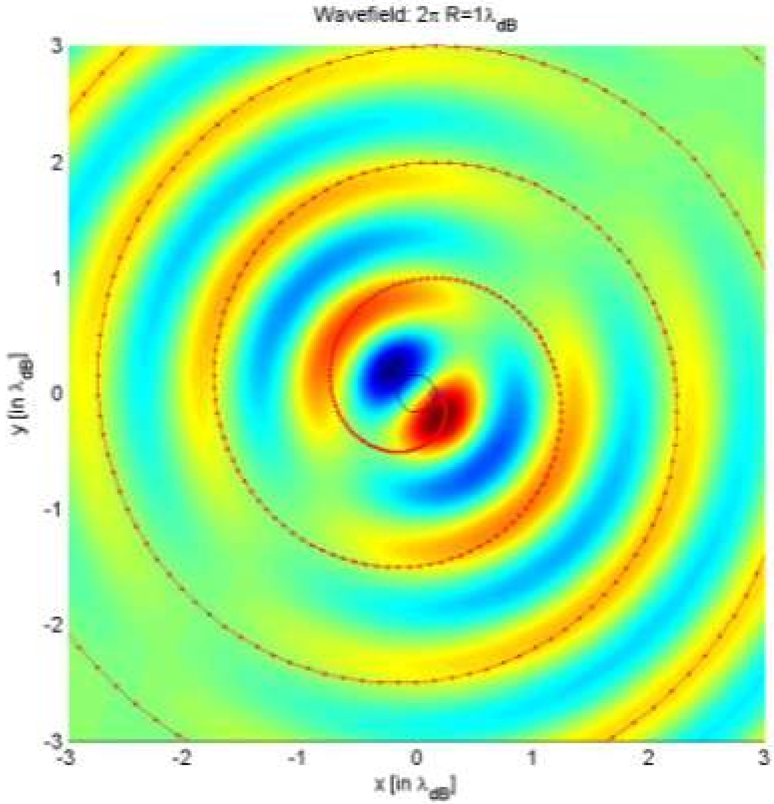
Inertial walkers in circular motion: Resonances in open space

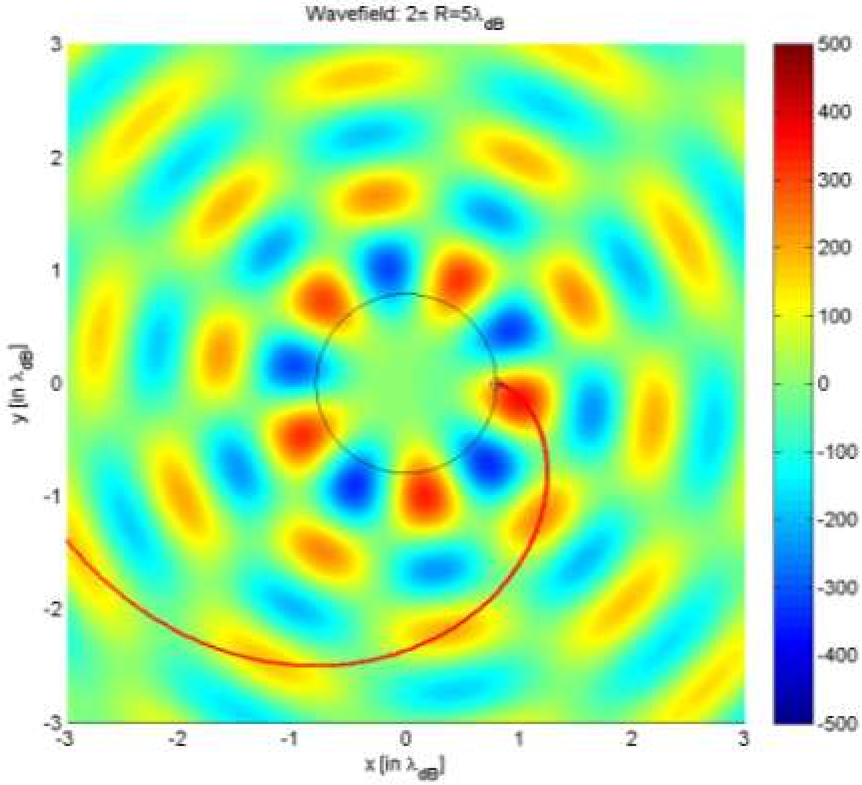


Resonances without cavity: signature of eigenmode of the trajectory

Bohr-Sommerfeld condition: $2\pi R = n \lambda$

Inertial walkers in circular motion: resonant modes

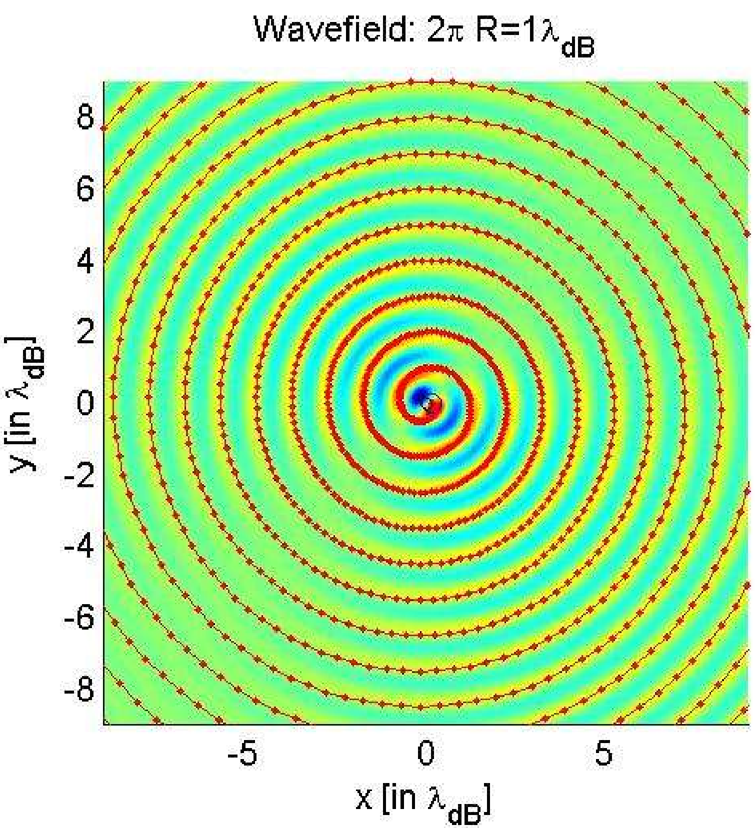


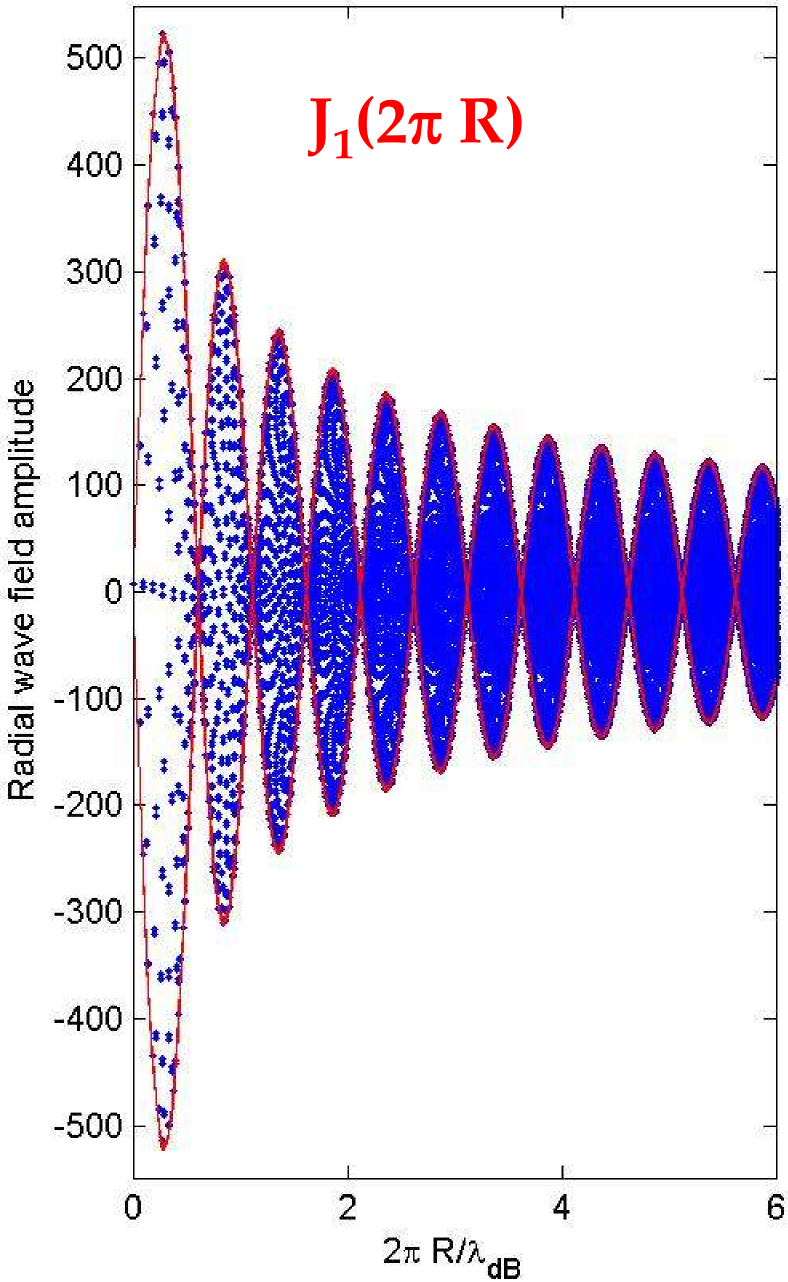


n=1 n=5

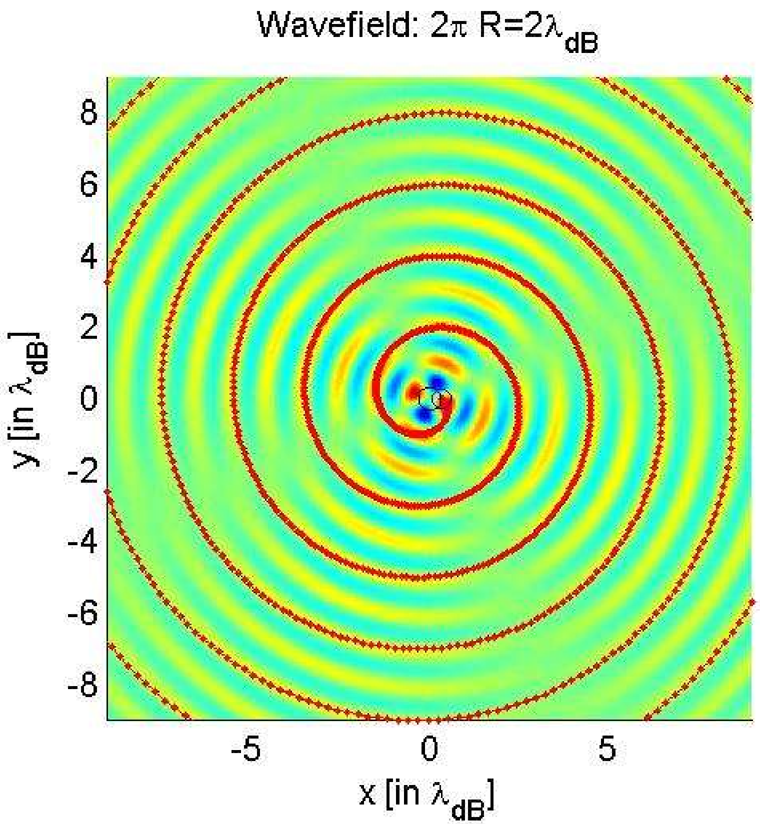
Bessel modes of first kind and order *n*

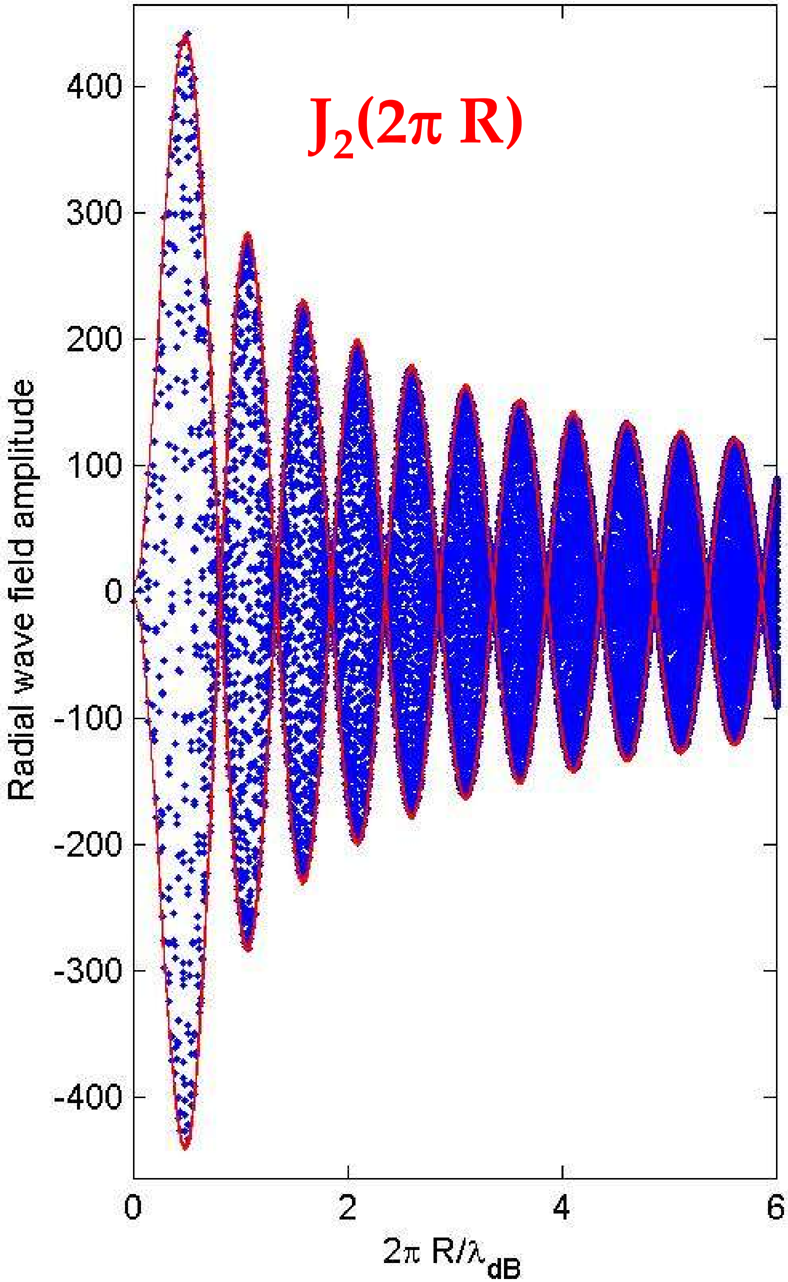
Inertial walkers in circular motion: Radial profile



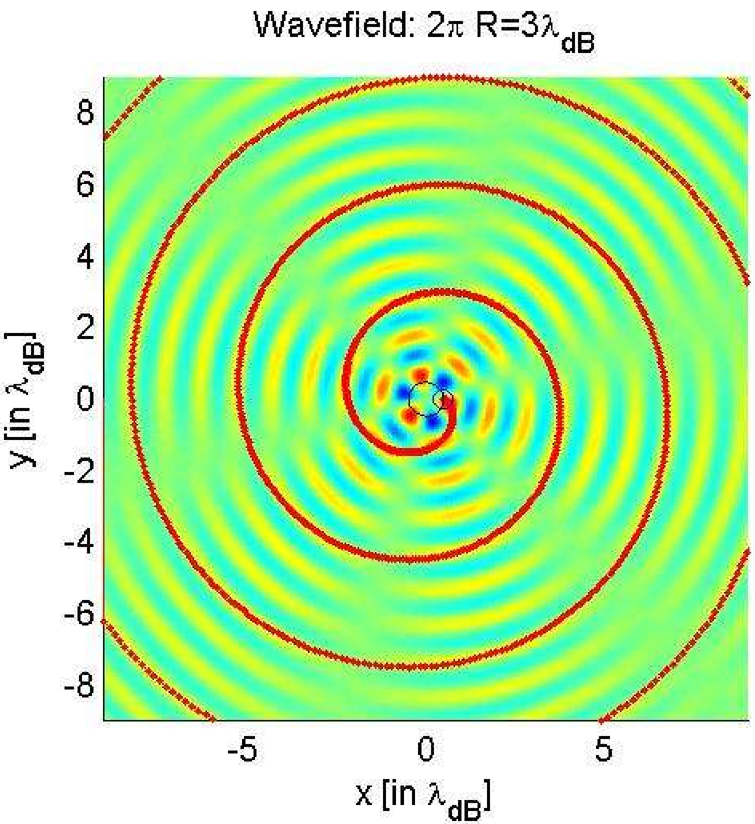


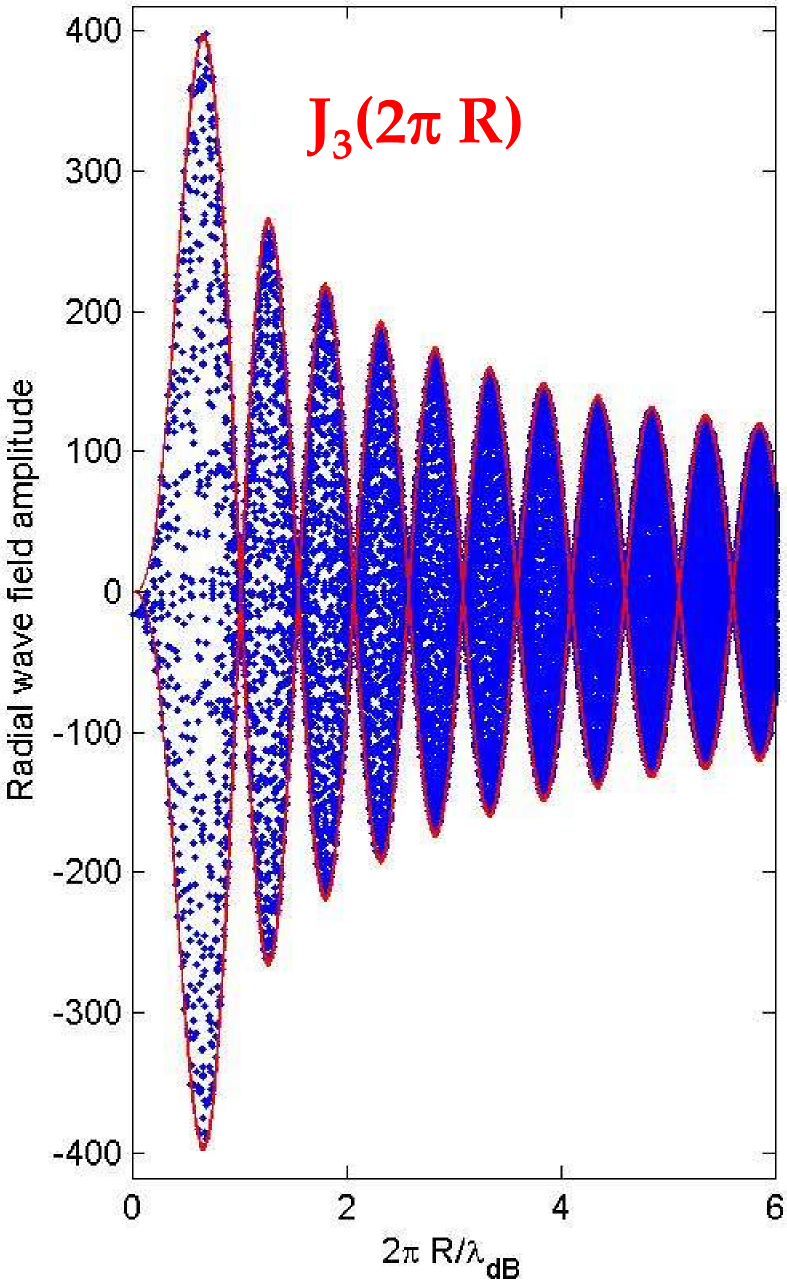
Inertial walkers in circular motion: Radial profile



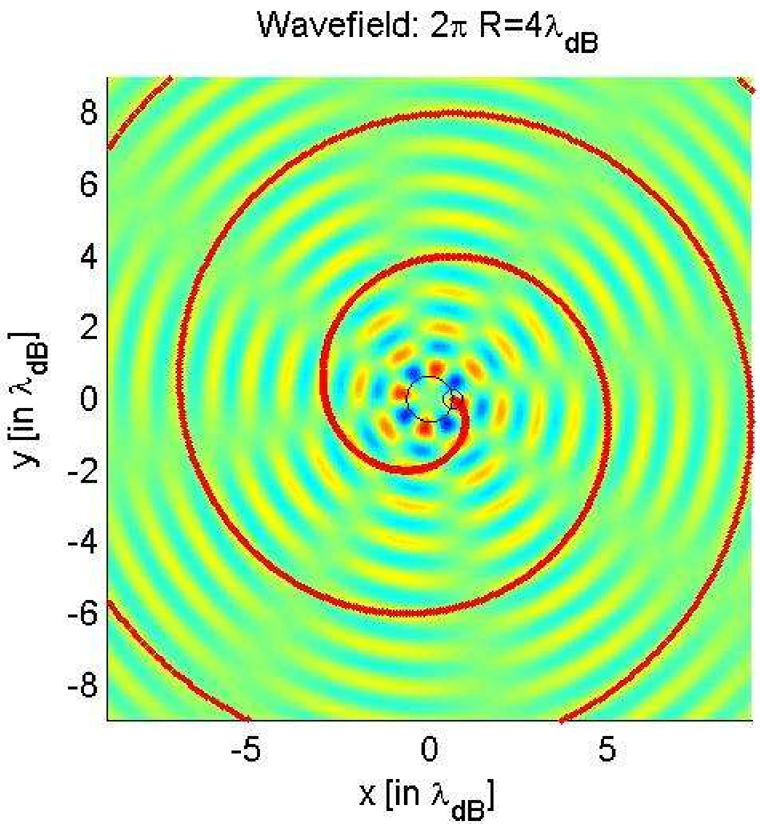


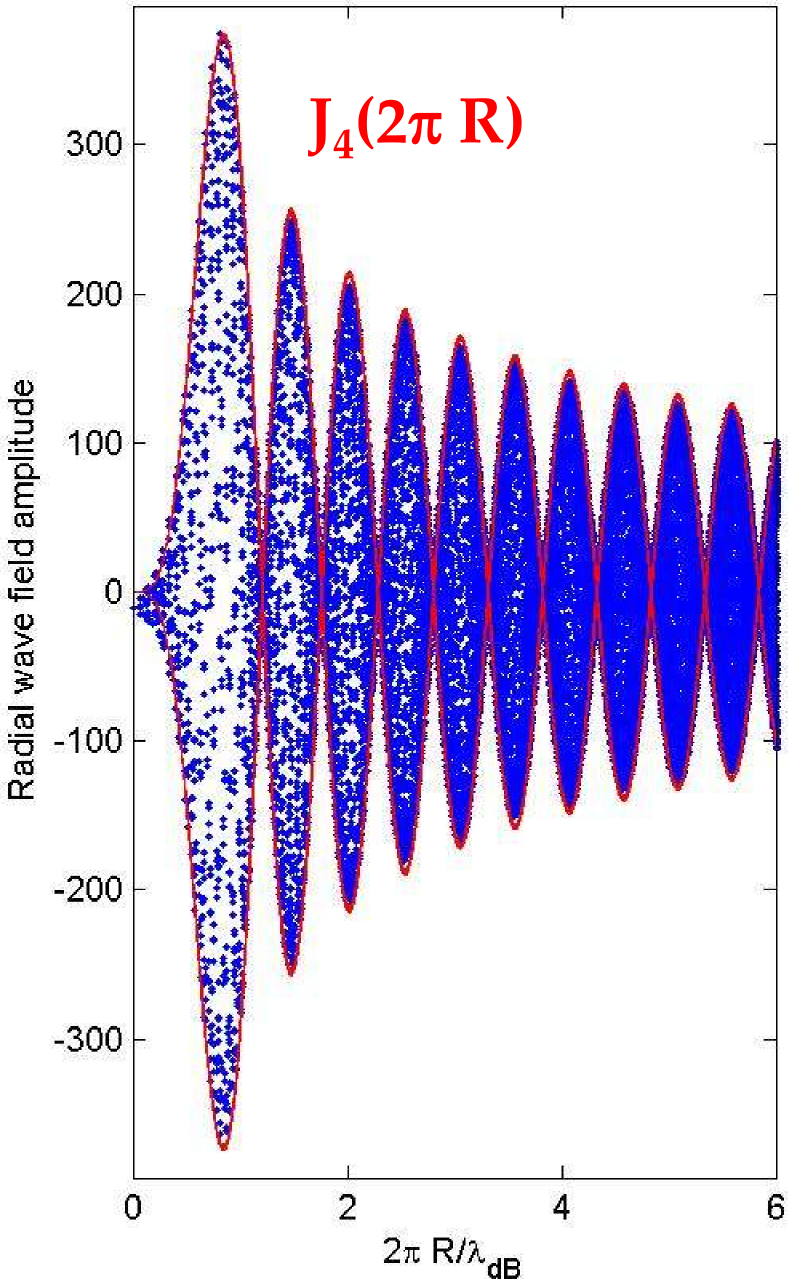
Inertial walkers in circular motion: Radial profile



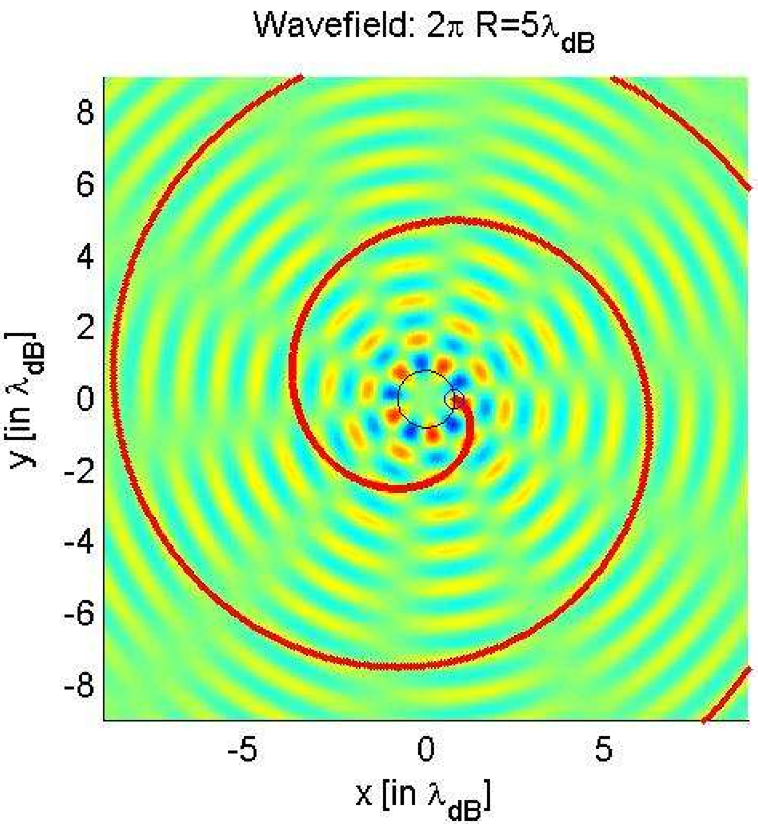


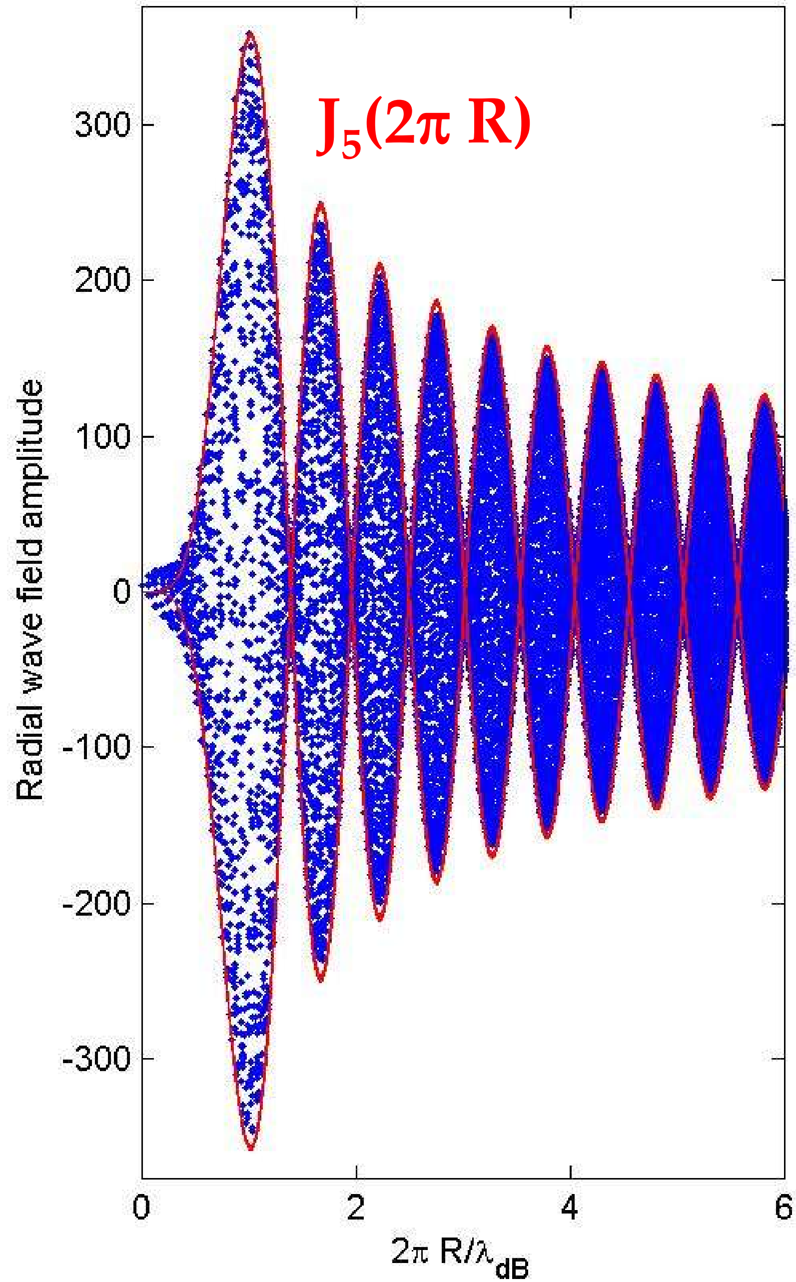
Inertial walkers in circular motion: Radial profile



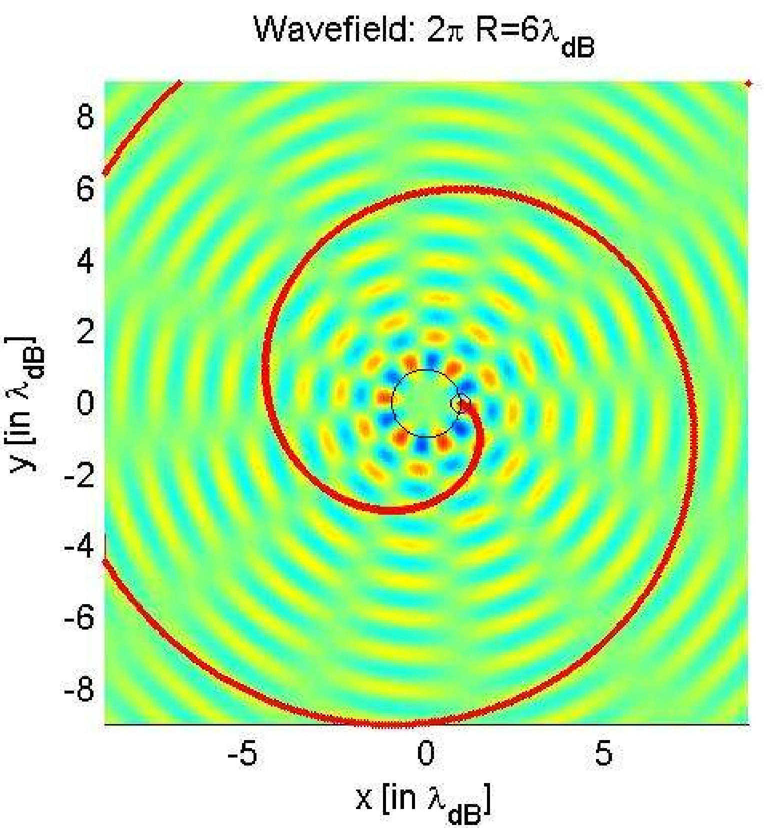


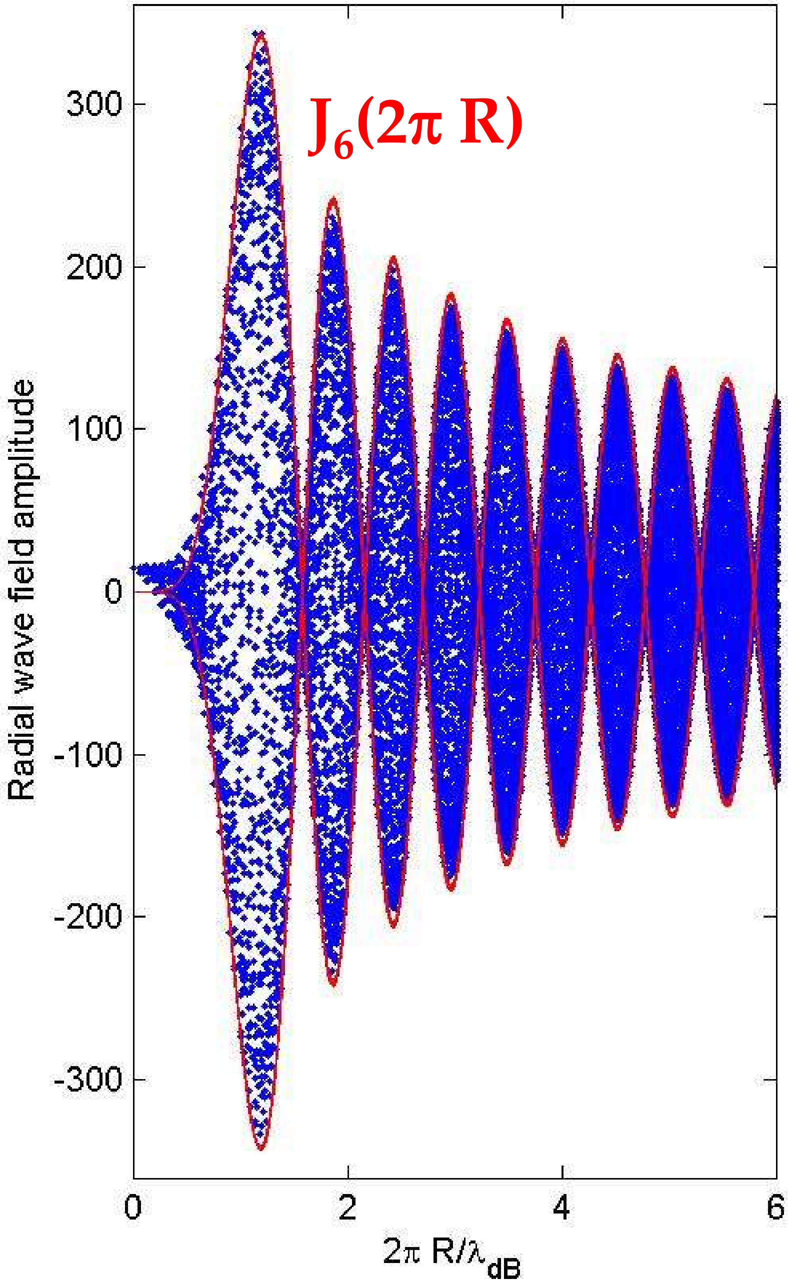
Inertial walkers in circular motion: Radial profile



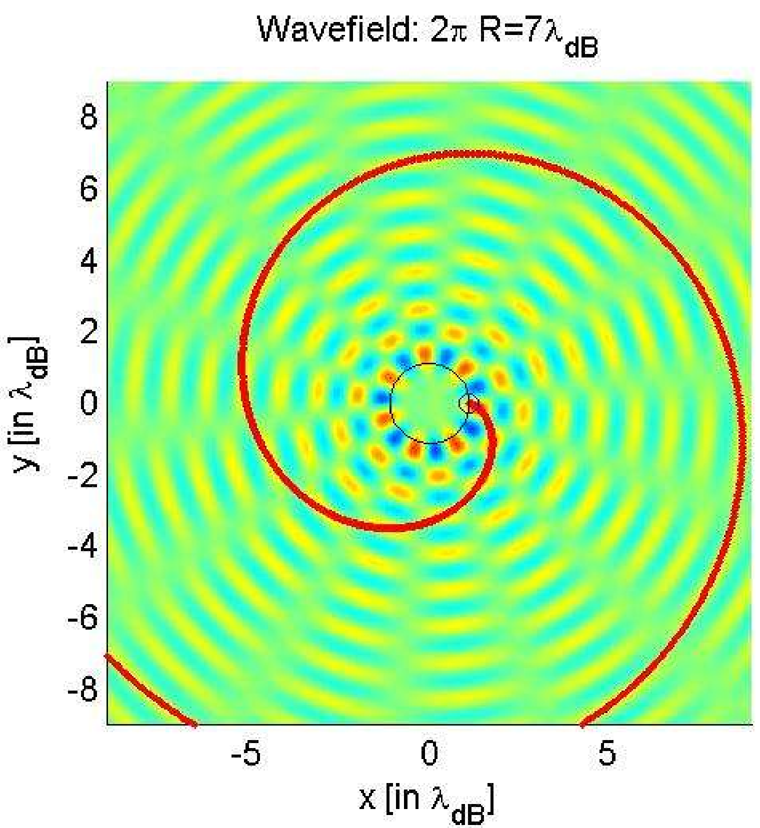


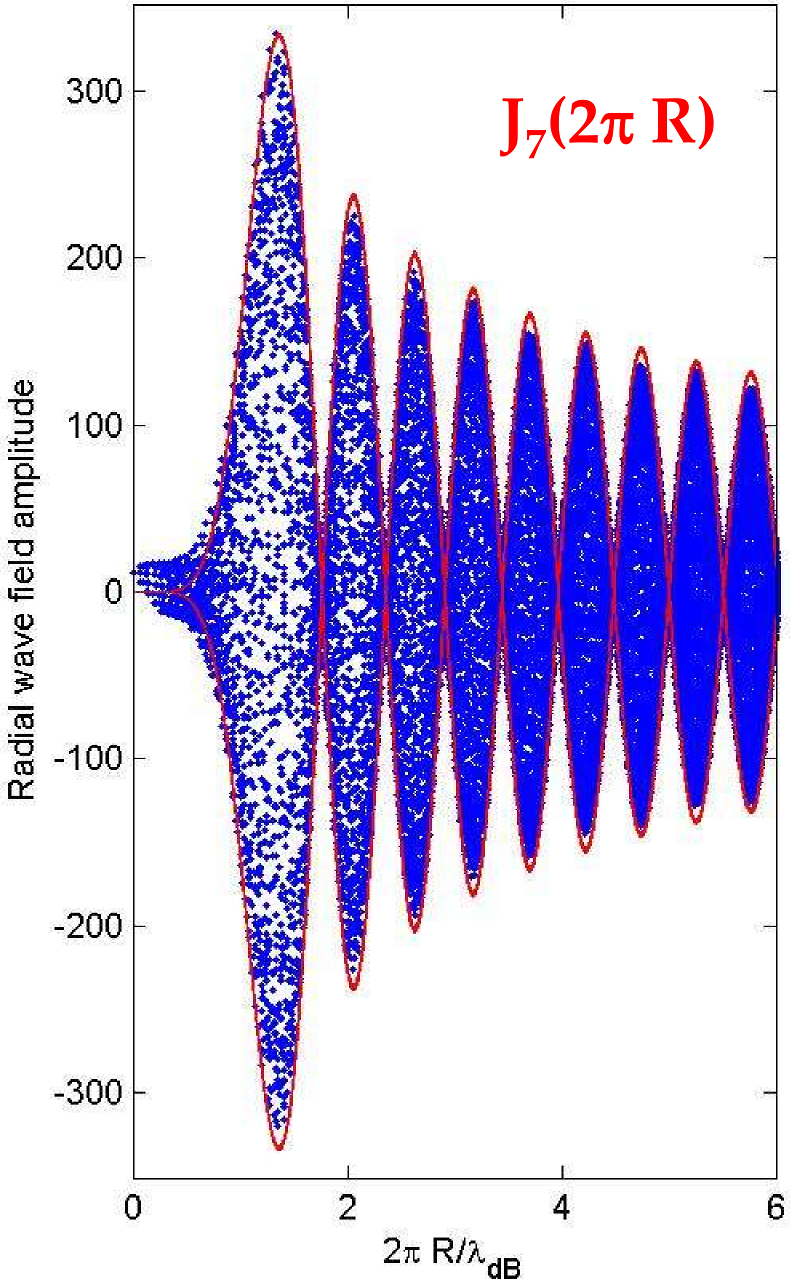
Inertial walkers in circular motion: Radial profile



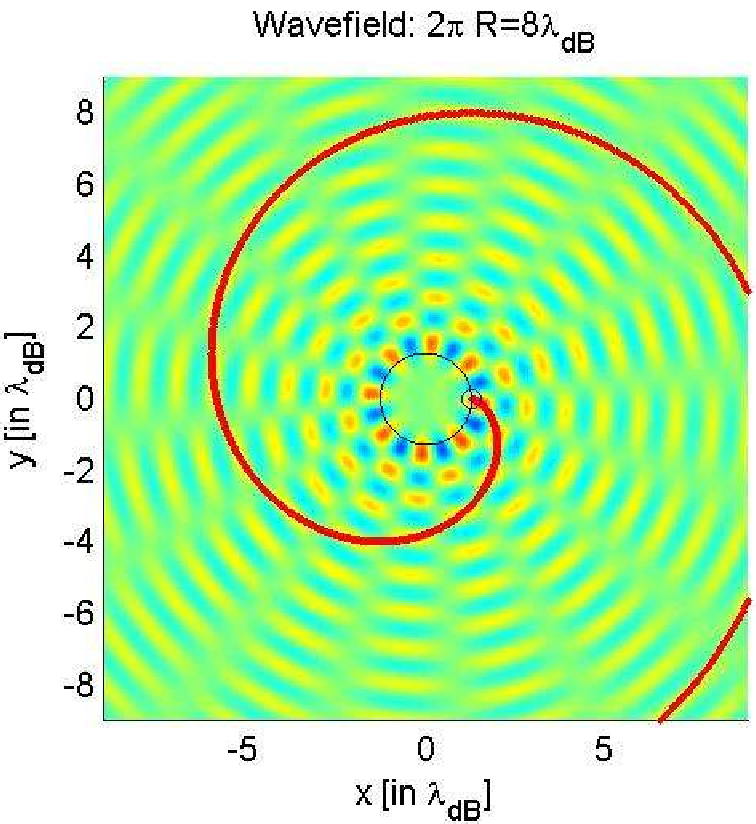


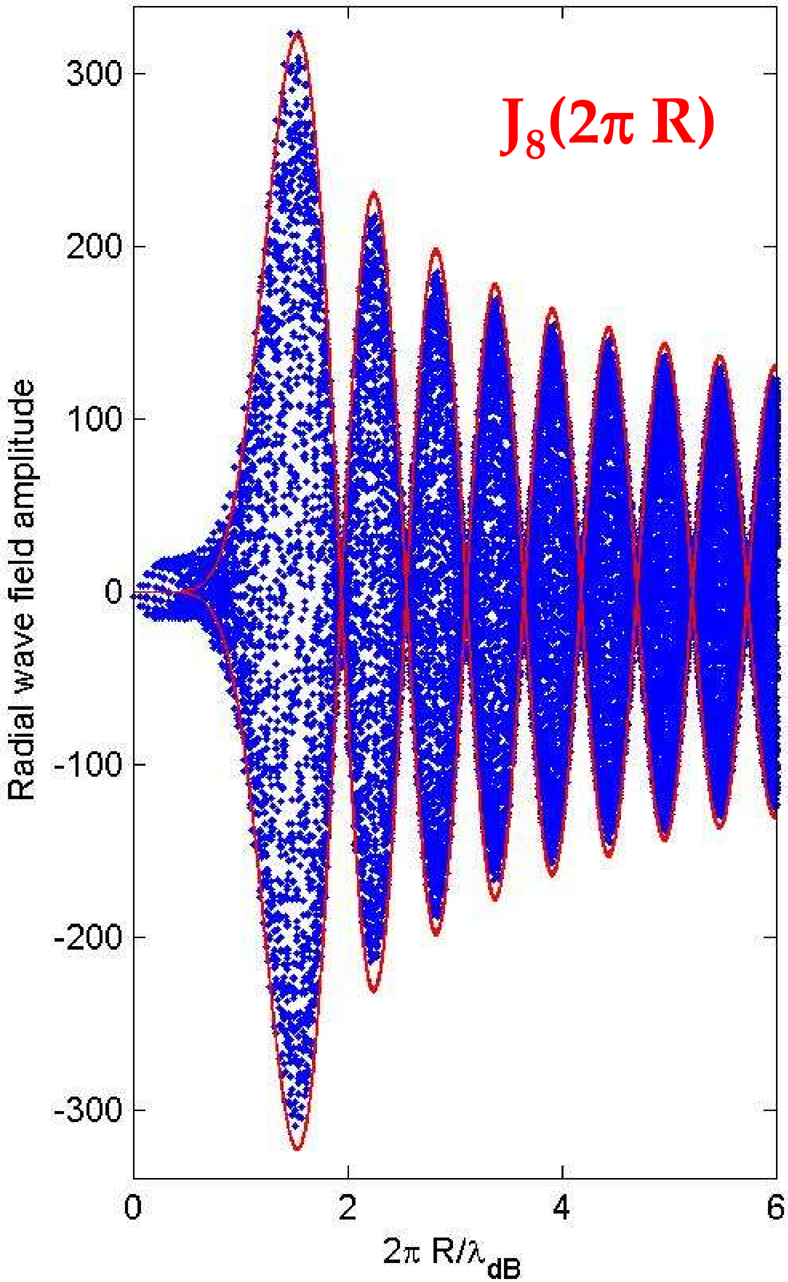
Inertial walkers in circular motion: Radial profile



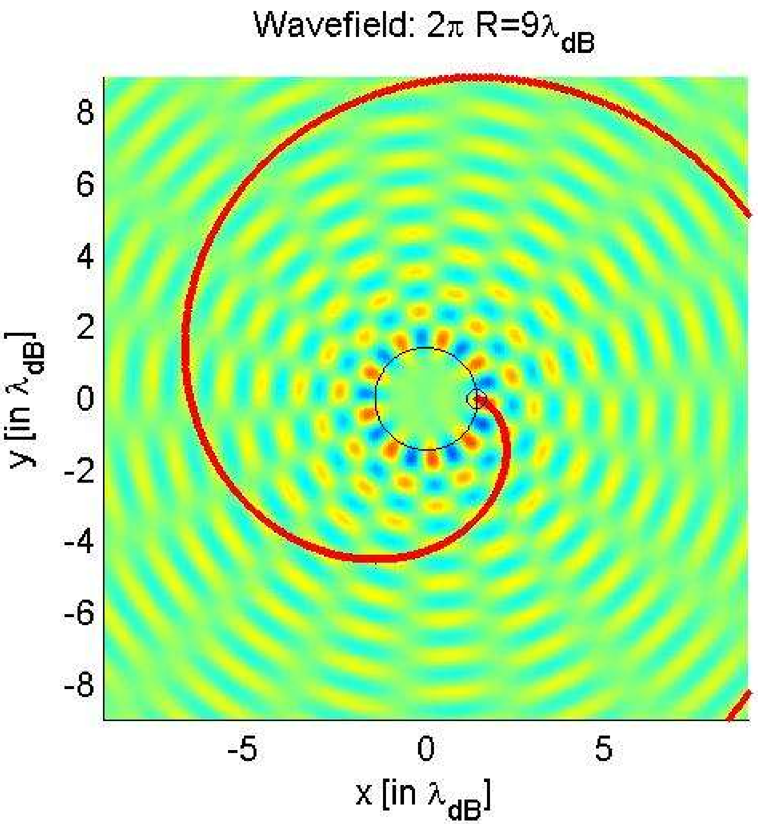


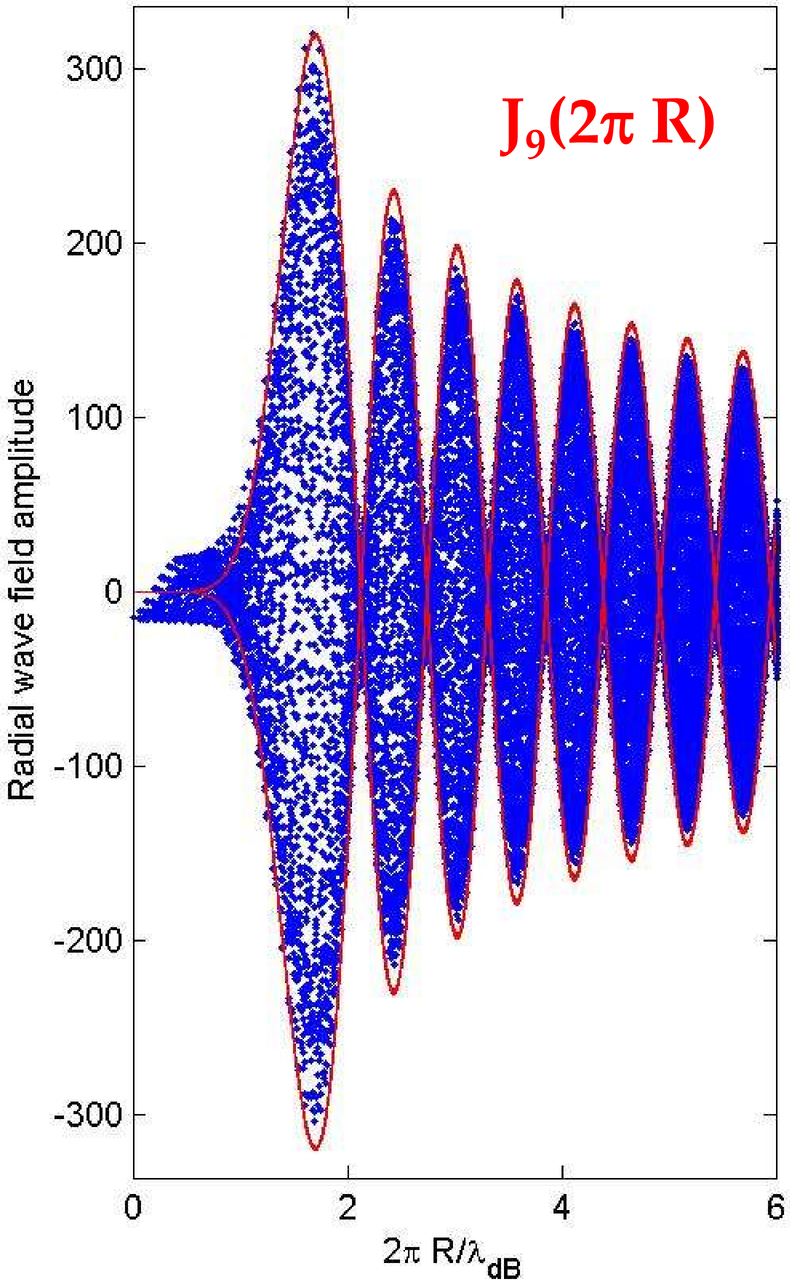
Inertial walkers in circular motion: Radial profile



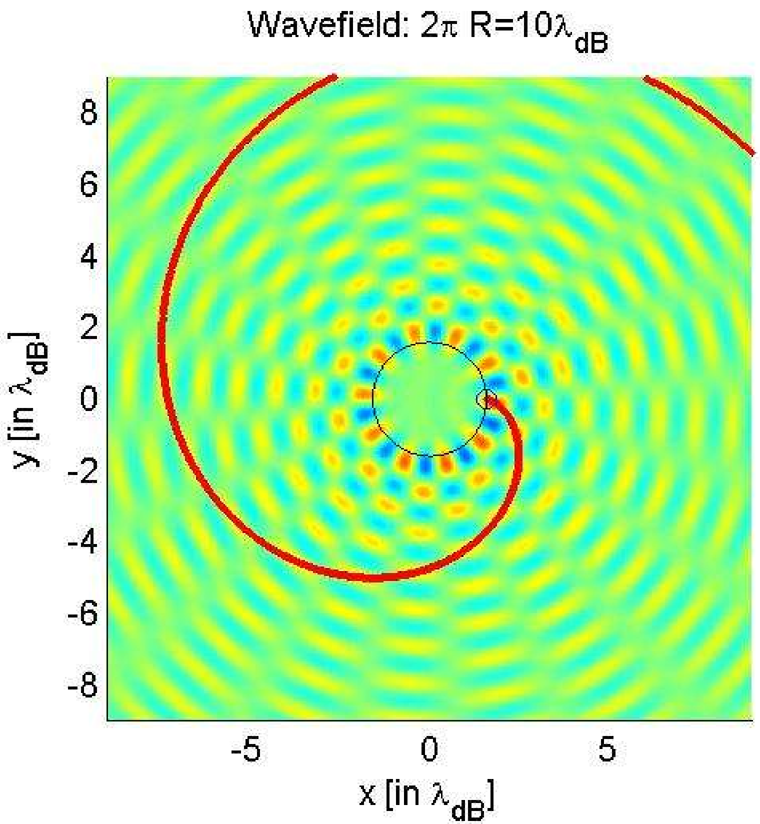


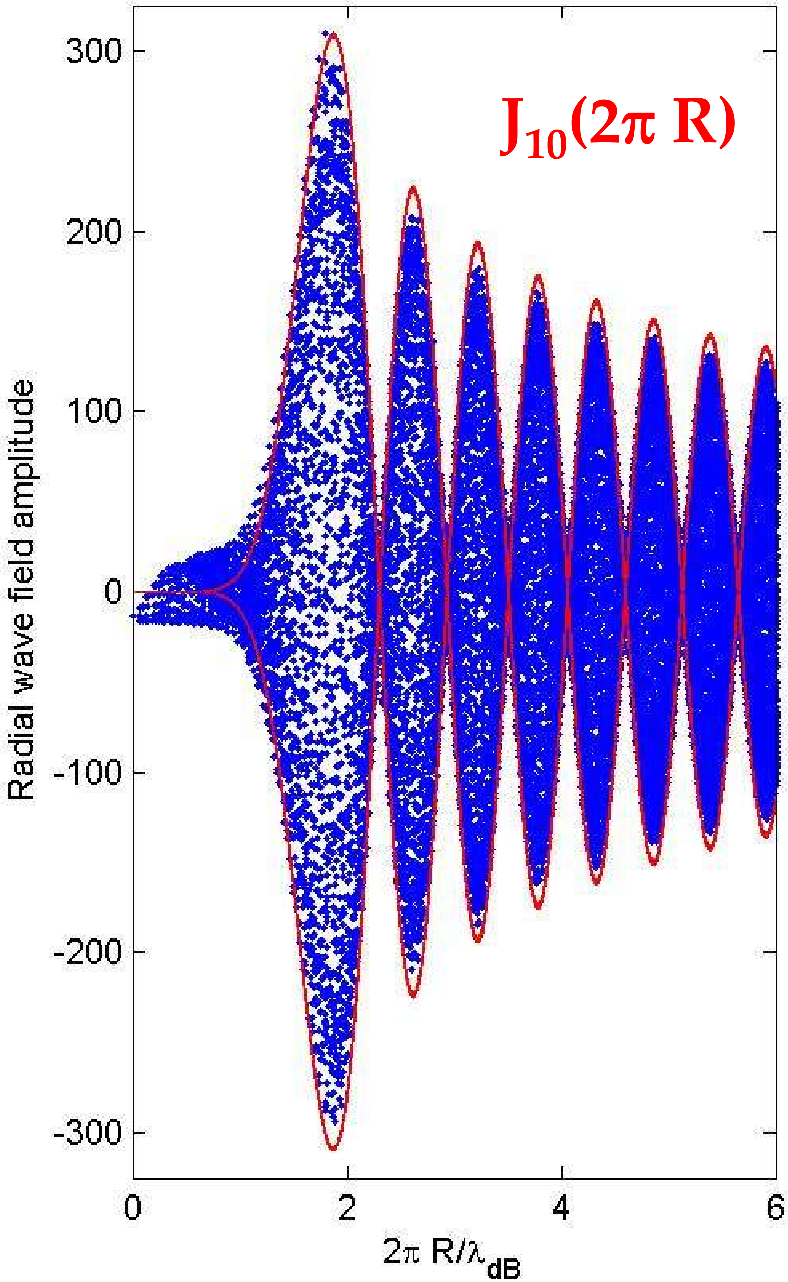
Inertial walkers in circular motion: Radial profile





Inertial walkers in circular motion: Radial profile





Inertial walkers: strange properties

Bohr atomic model

To explain the atomic emission/absorption ray, Bohr-postulated:

1. There exist special circular electronic orbits for which the laws of electrodynamics do not apply (no radiation)
2. These orbits satisfy the Bohr-Sommerfeld relation (quantized angular momentum)

1. Bessel beams are **non radiating (no divergent) electromagnetic** beams, (the energy flux is azimutal)
i.e. the trajectories that satisfy Bohr-Sommerfeld relation are non radiating
2. Resonances at Bohr-Sommerfeld conditions emerge from the geometry

Another singular property:

Fourier transforms of circles with azimuthal phase shift $2\pi l$ are Bessel functions of order l

Thus, the trajectories create a wave field that is their Fourier transform,

The 2 dual spaces coexist in the same space!

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