Some final remarks on foundational issues…

The dangers of magical thinking and antirealism in QM

- its intrusion into other fields, the social sciences, the arts, the entire human intellectual process; *e.g.*

  ``*We have learned from quantum mechanics, from hard science, that there is no such thing as an objective reality, that we make our own reality…*"

- the Sokal Hoax and Mara Beller's response `*At whom are we laughing*'
- its damage to the credibility of scientists at a time that it is most needed

Could the Universe be a giant quantum computer?

Computational rules might describe the evolution of the cosmos better than the dynamical equations of physics – but only if they are given a quantum twist.

By David L. Chandler

ESSAY | 13 June 2023 | Correction 20 June 2023

Particle, wave, both or neither? The experiment that challenges all we know about reality

Thomas Young's double-slit experiment originally served to prove that light is a wave – but later quantum versions have made for a much fuzzier picture.

By Anil Ananthaswamy

SCIENCE

Quantum and *Consciousness* Often Mean *Nonsense*

Lots of things are mysterious. That doesn't mean they're connected.

Telegraph.co.uk

Parallel universe proof boosts time travel hopes

HARD SCIENCE — NOVEMBER 22, 2022

Brain experiment suggests that consciousness relies on quantum entanglement

Maybe the brain isn't "classical" after all.

Three interesting questions

Q1. How differently might quantum foundations have evolved had this fluid system been known to its founding fathers?

Q2. What are the chances that the quantum and fluid systems exhibit such similar behavior for completely different reasons?

Q3. What are the chances that, in 1930, mankind correctly surmised that the micro- and macroscopic worlds are philosophically distinct?

Closing thoughts on quantum philosophy

"The most important scientific revolutions all include, as their only common feature, the dethronement of human arrogance from one pedestal after another of previous convictions about our centrality in the cosmos."

— Stephen Jay Gould

Five anthropocentric follies

1. **Western religion:** man is created in the image of God
2. **Pre-Copernican Universe:** the Universe revolves around the Earth
3. **Ours is the only sun with planets:** first exoplanet confirmed in 1992
4. **Ours is the only planet with life:** not settled yet!
5. **Copenhagen Interpretation:** the act of human observation is central to evolution of the Universe

If you can’t beat `em…

The Many Many Worlds Interpretation

“Finally, as concerns my alignment vis-a-vis Quantum Interpretations, I remain steadfastly agnostic; however, if forced to choose, I would be inclined to back, by virtue of its inclusivity, the logical extension of the Many-Worlds Interpretation, the Many-Many-Worlds Interpretation, according to which each Quantum Interpretation is realized in some edition of the Multimultiverse, and there is even one world in which there is only one world, a world in which quantum statistics are underlaid by chaotic pilot-wave dynamics, there is no philosophical schism between large and small, and beables be.”

— JWMB, ARFM (2015)

Newton

`A man may imagine things that are false,
but he can only understand things that are true…'

Feynman

`No one understands quantum mechanics.'

John Bell

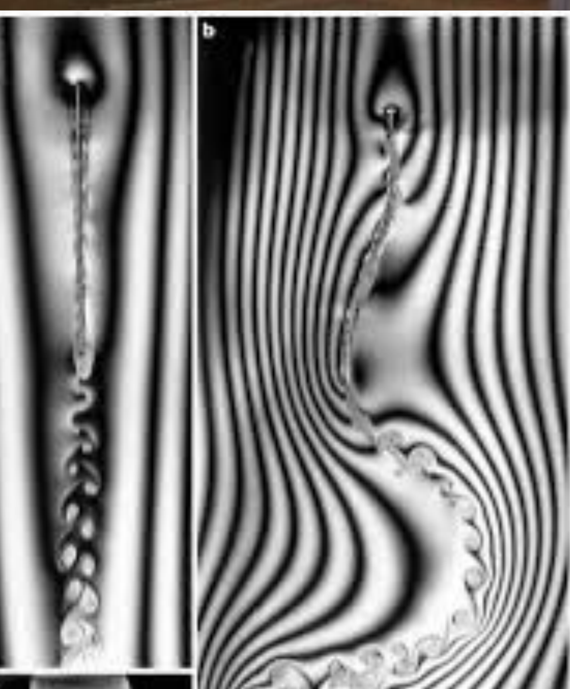
`` The deeper you dig into the quantum mysteries,
the more they fall apart in your hands.''

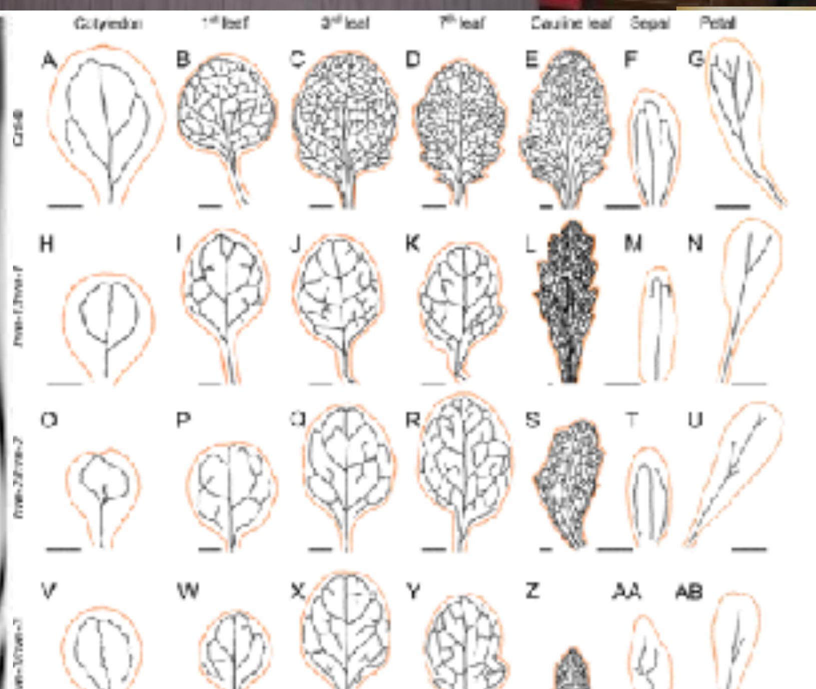
`I suspect that what will happen is that physicists will continue to buzz like flies against a closed window, then someone will open a door in the back of the room.'

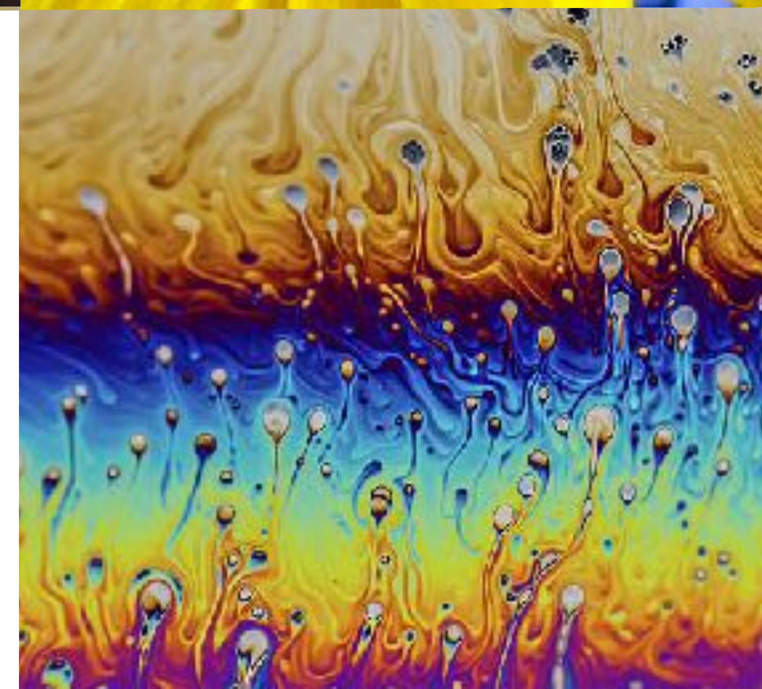
Lecture 4

The experiments of Yves Couder

Adventures in `theoretical mechanics'

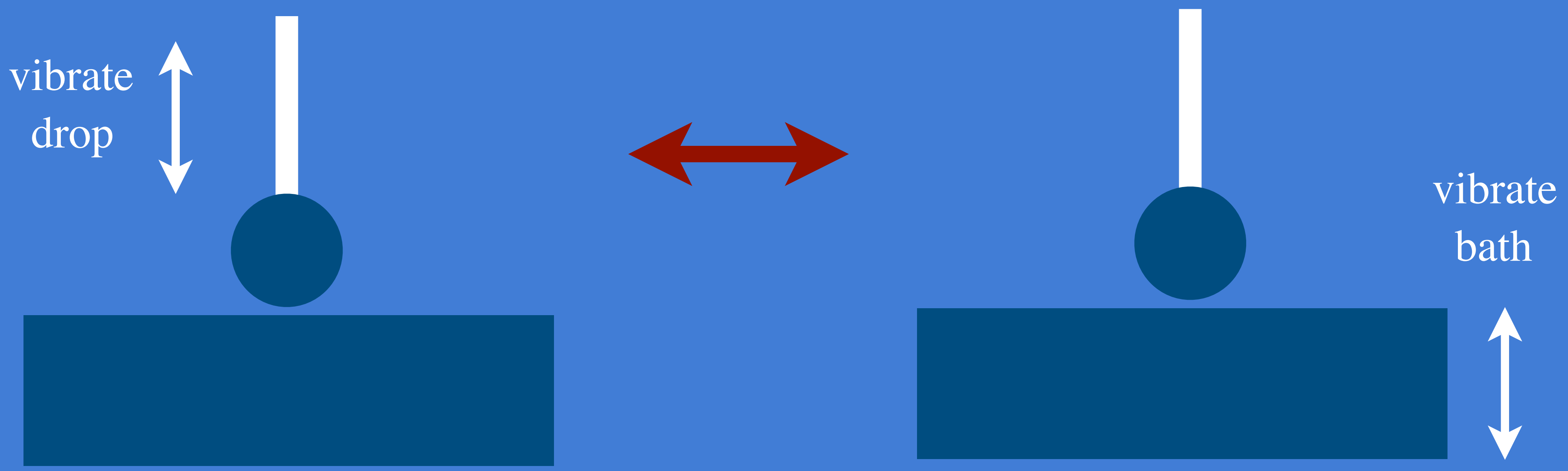






Accidental discovery in an undergraduate lab course

— Yves Couder and Emmanuel Fort



- motivated by an interest in non-coalescnce events
- vibration at certain amplitudes, frequencies was seen to preclude coalescence
- experimental control was facilitated by vibrating the bath rather than the needle
- the bath dislodged the droplet, which set the droplet walking across it

The Faraday system

Silicon oil + droplets

Diameter $\approx 0.8mm$

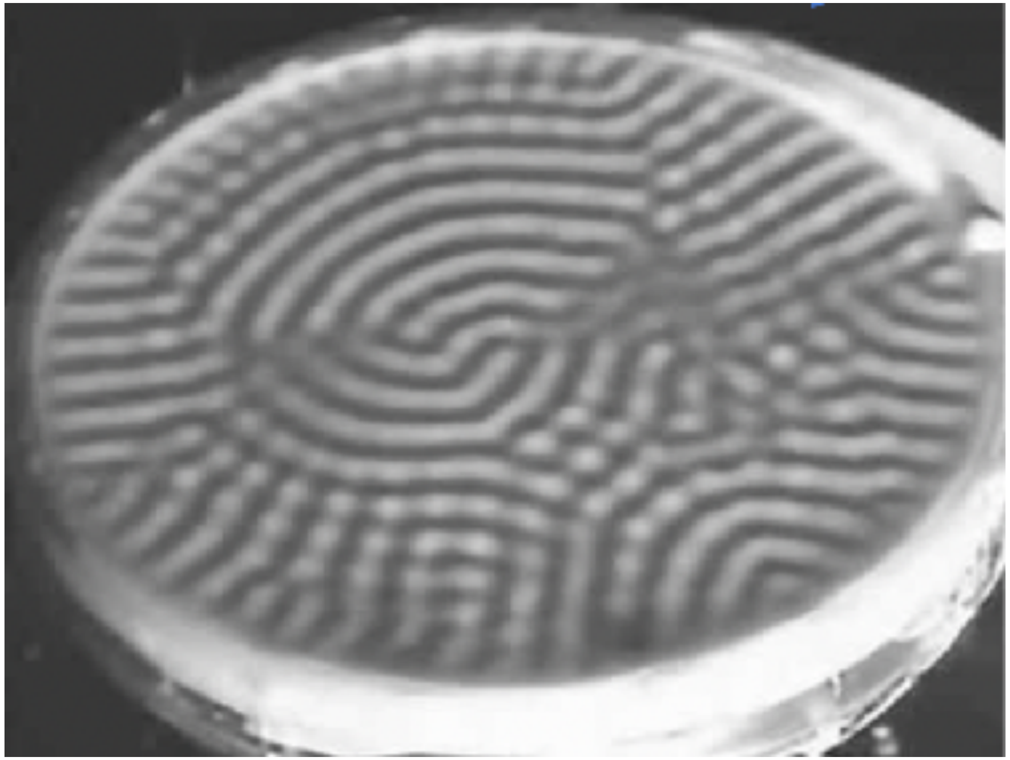
$$f \approx 80Hz$$

$$\ddot{z}(t) = \gamma \cos(2\pi f t)$$

$$z(t) = -A\cos(2\pi f t)$$

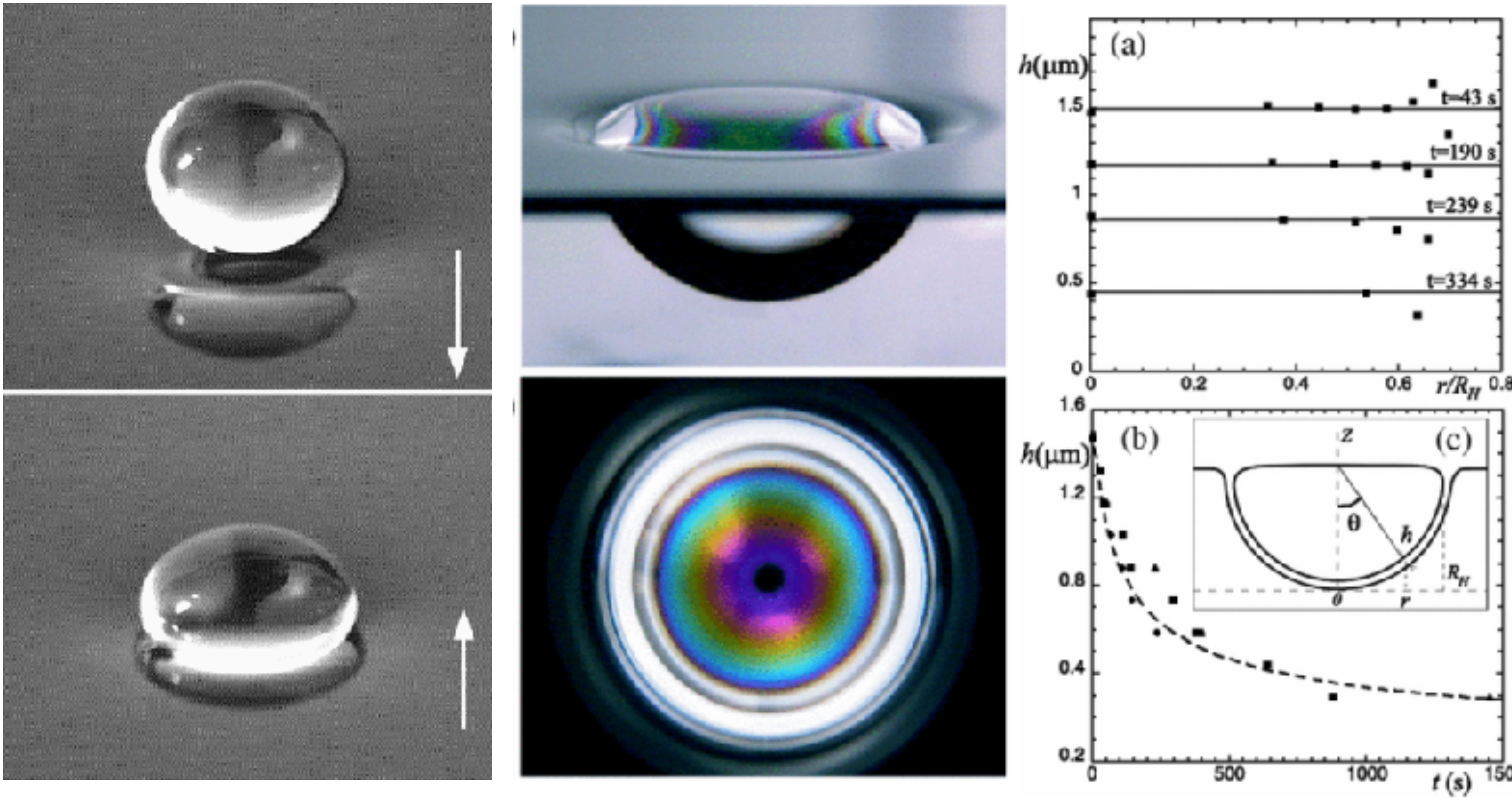
$$A = \frac{g}{4\pi^2 f^2}\frac{\gamma}{g} \approx 0.15mm$$

- beyond a critical vibrational acceleration, the bath surface destabilizes into a field of *subharmonic* Faraday waves



From Bouncing to Floating: Noncoalescence of Drops on a Fluid Bath

Y. Couder, E. Fort, C.-H. Gautier, and A. Boudaoud
Phys. Rev. Lett. **94**, 177801 – Published 5 May 2005

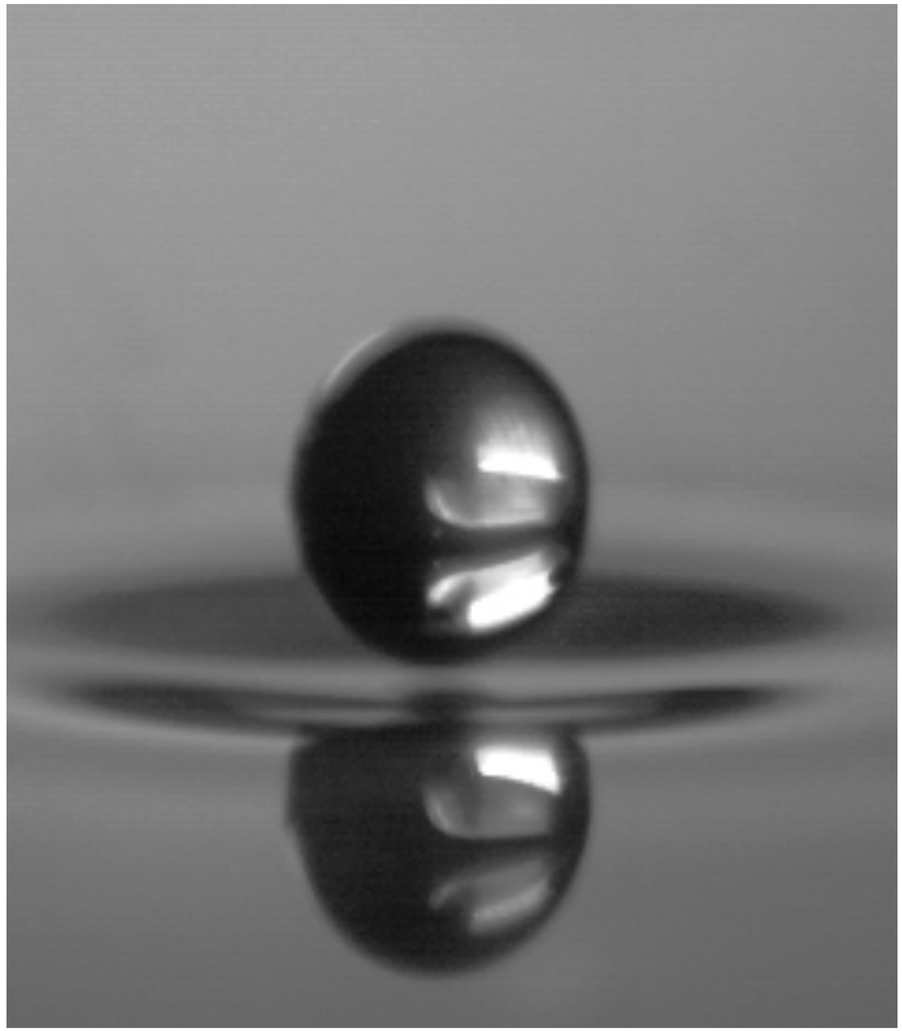


- can delay or eliminate coalescence via vibration of the bath

Noncoalescence on a vibrated fluid bath

Jearl Walker (1978)

50cS Si oil



Forcing parameter

$$\Gamma = A(2\pi f)^2/g$$

f ~ 30 Hz

Amplitude A

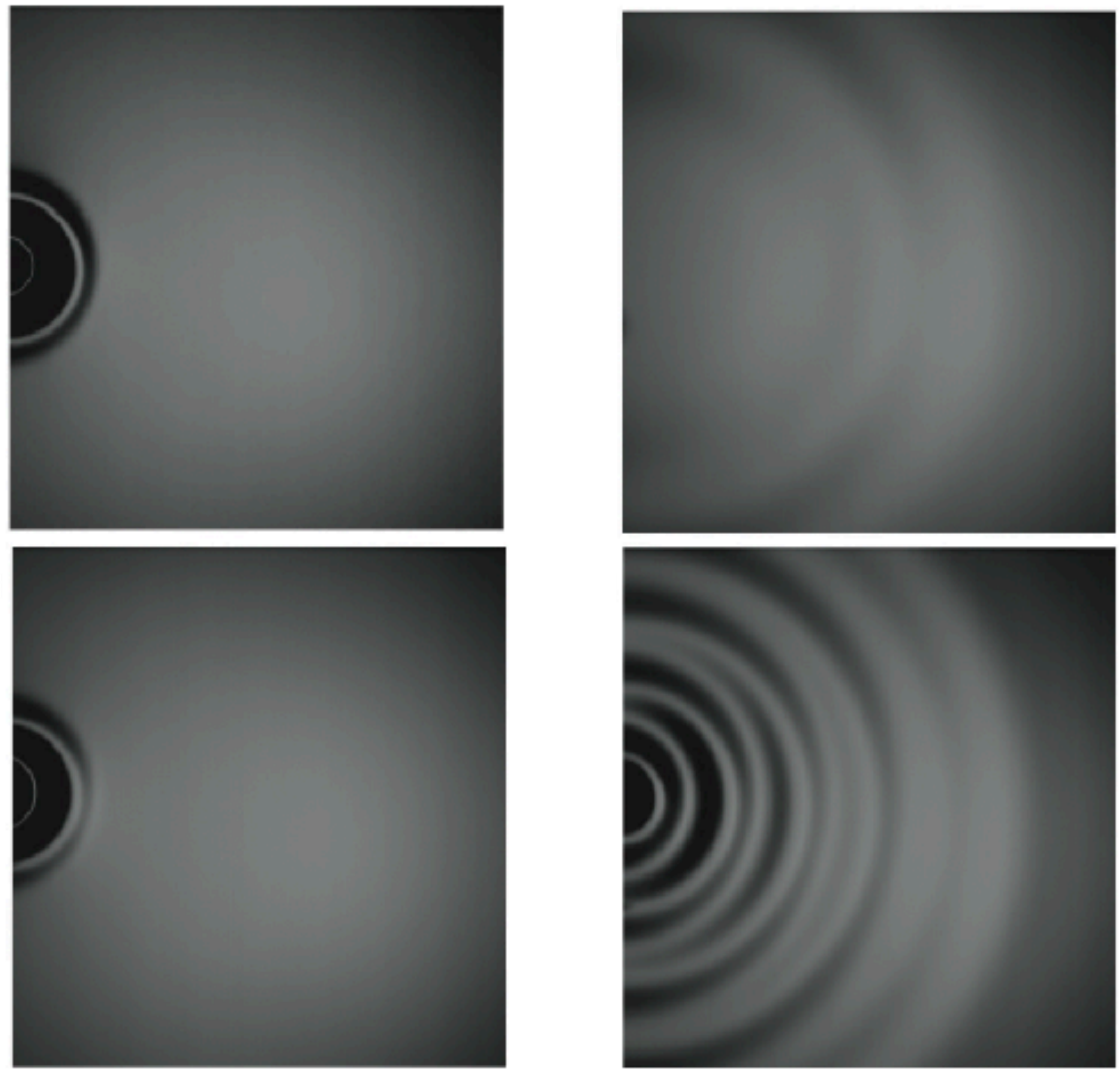
- drive system below the Faraday threshold
- air layer between drop and bath is dynamically sustained

The influence of vibration on surface waves

- vibration predisposes bath to monochromatic wave field with Faraday wavelength

Drop a sphere into a quiescent bath

Drop a sphere into a vibrating bath

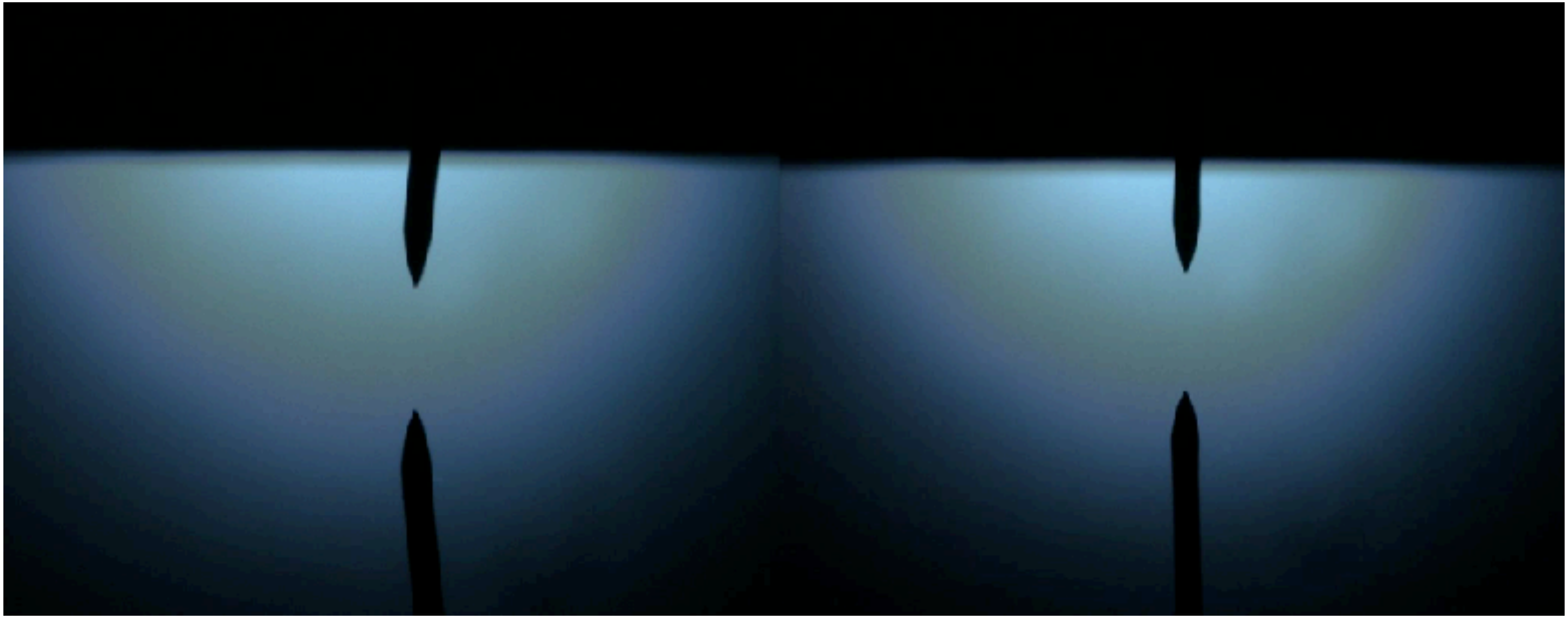


Disturbance of forced and unforced interfaces

- withdraw millimetric needle from interface

No forcing

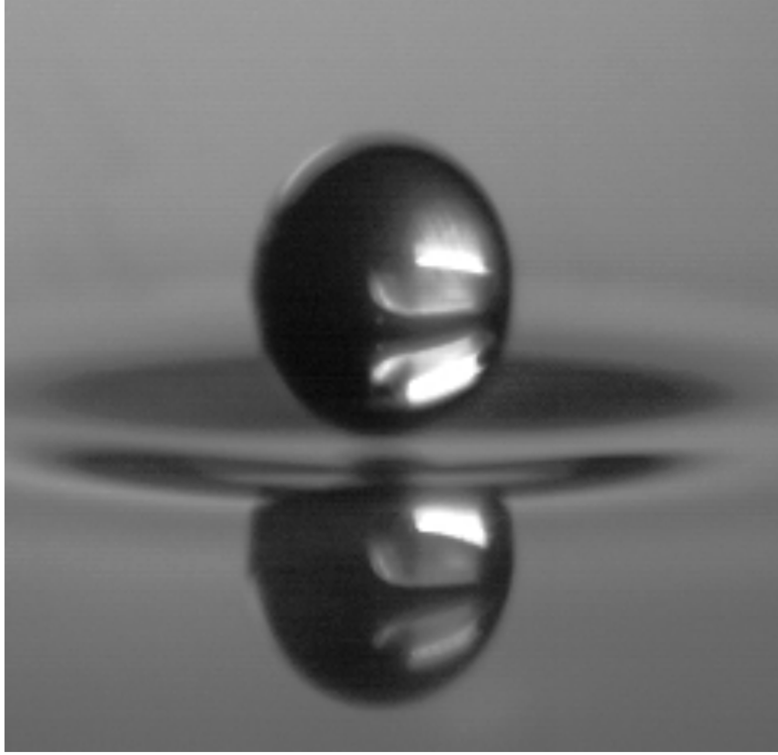
Vibrational forcing



- waves quickly disperse
- field of Faraday waves persist

- vibration predisposes bath to monochromatic wave field with Faraday wavelength

Bouncing to walking



- as vibrational acceleration is increased…

$$\Gamma = A(2\pi f)^2/g$$

- drop initially bounces as driving frequency
- eventually its bouncing period will double, and so match the subharmonic frequency of the system's Faraday waves
- such period-doubled bouncers excite a relatively robust monochromatic wave field with the Faraday wavelength
- one can consider the bath as a damped oscillator forced at resonance
- the vigorous wave field may then destabilize the period-doubled bouncer, which transforms into a walker

Note: the resonance between drop and wave is responsible for the robust monochromatic wave field and many of the emergent quantum features

Droplets walking on a vibrated fluid bath

Video courtesy of Yves Couder

- bouncing droplets interact with their own wave fields, walk
- walkers consist of both particle (droplet) and guiding wave

1149-041 Lisboa, Portugal
e-mail: ruiol@ispa.pt
†CCMar, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

1. Borg, B. *Comp. Biochem. Physiol. C* **109,** 219–245 (1994).
2. Oliveira, R. F. *Adv. Study Behav.* **34,** 165–239 (2004).
3. Wingfield, J. C., Hegner, R. E., Dufty, A. M. & Ball, G. F. *Am. Nat.* **136,** 829–846 (1990).
4. Rowland, W. J. *Environ. Biol. Fish.* **56,** 285–305 (1999).
5. Oliveira, R. F., Almada, V. C. & Canário, A. V. M. *Horm. Behav.* **30,** 2–12 (1996).
6. Martin, P. & Bateson, P. *Measuring Behaviour: An Introductory Guide* (Cambridge Univ. Press, Cambridge, 1993).
7. Hirschenhauser, K., Taborsky, M., Oliveira, T., Canário, A. V. M. & Oliveira, R. F. *Anim. Behav.* **68,** 741–750 (2004).
8. Oliveira, R. F., Lopes, M., Carneiro, L. A. & Canário, A. V. M. *Nature* **409,** 475 (2001).
9. Scott, A. P. & Sumpter, J. P. *Gen. Comp. Endocrinol.* **73,** 46–58 (1988).
10. Scott, A. P., Mackenzie, D. S. & Stacey, N. E. *Gen. Comp. Endocrinol.* **56,** 349–359 (1984).

Competing financial interests: declared none
doi:10.1038/437207a

DYNAMICAL PHENOMENA

Walking and orbiting droplets

Small drops can bounce indefinitely on a bath of the same liquid if the container is oscillated vertically at a sufficiently high acceleration[1]. Here we show that bouncing droplets can be made to 'walk' at constant horizontal velocity on the liquid surface by increasing this acceleration. This transition yields a new type of localized state[2–5] with particle–wave duality: surface capillary waves emanate from a bouncing drop, which self-propels by interaction with its own wave and becomes a walker. When two walkers come close, they interact through their waves and this 'collision' may cause the two walkers to orbit around each other[6–8].

The bouncer transition to walking is continuous and occurs when the vertical acceleration of the bath, γ_m, reaches a critical threshold, γ_m^c. Below γ_m^c, the drops bounce with no horizontal motion. Above γ_m^c, bouncing drops acquire a rectilinear motion along the surface of the bath (Fig. 1a–c). Their velocity V_w is constant (0–20 mm s^{-1}) and increases with γ_m.

Why do the drops start walking? This phenomenon occurs below, but near, the onset of the Faraday instability, a point at which the surface becomes spontaneously wavy. In this regime, the vertical motion of a drop becomes subharmonic, with a period that is double that of the forcing. As a result, it emits a damped Faraday wave. The drop undergoes successive identical parabolic jumps that are locked with its wave. Each jump brings the drop into collision with the side of the central bulge of the wave generated by the previous collision (Fig. 1a). This collision with an inclined surface generates a non-zero horizontal impulse, which can be translated as an equation for the drop's horizontal motion, averaged over a period π/ω_0 of the subharmonic vertical motion

$$m\,d^2x/dt^2 = a \sin\{(\pi k/\omega_0)\, dx/dt\} - b\, dx/dt \quad (1)$$

where m is the drop's mass, a is about 10^{-6} N, k is the wavenumber, and b is about 10^{-6} N m^{-1} s. The left-hand side of equation (1) represents the inertia of the drop; the first term on the right-hand side accounts for the effective force due to the inclined surface, and the second for viscous damping during the collision. Equation (1) predicts the observed continuous transition of the droplet from stationary to walking when $a > b\omega_0/(\pi k)$.

When walkers coexist in a cell, they inevitably collide. These 'collisions' do not involve any contact between the drops but only a deflection of their horizontal trajectories, when the wave generated by a drop affects the horizontal velocity of the other one. The main parameter characterizing this collision is d_c, the minimal distance of approach of the two drops; depending on the value of d_c, the walkers either attract or repel each other. Attraction leads to a twin-star-like orbiting motion of the drops (Fig. 1d, and see movie in supplementary information). The diameters of the orbits take discrete values d_n^{orb}, which self-adapt to the forcing frequency[9,10]. The orbital diameters are slightly smaller than an integer multiple of the Faraday wavelength (λ_F), or $d_n^{orb} = (n - \varepsilon)\lambda_F$ when the drops bounce in phase. They are $d_n^{orb\prime} = (n + 1/2 - \varepsilon)\lambda_F$ when the drops bounce in antiphase; the offset, $\varepsilon = 0.2 \pm 0.02$, is such that when a drop collides with the surface, it falls on the inward slope of the wave emitted by the other. This provides the centripetal force needed for the orbital motion. For other values of d_c, each drop falls on the outward slope of the wave of the other, which causes a repulsion.

We have shown that walkers can behave as billiard balls, undergo scattering collisions or form circular orbits, and can even display complex three-body motion (results not shown). The variety of these phenomena can be explained by interaction through waves and by generalizing equation (1) to two or more drops (the resulting equations yield the same quantification of orbits and numerical trajectories, which are very similar to the experimental collisions; S. P. *et al.*, manuscript in preparation). In this system, real particles experience the same non-local interaction as nonlinear waves.

Y. Couder*, S. Protière*, E. Fort†, A. Boudaoud‡
*Matières et Systèmes Complexes, and †Matériaux et Phénomènes Quantiques, Université Paris 7 Denis Diderot, 75005 Paris, France
‡Laboratoire de Physique Statistique, 24 rue Lhomond, 75231 Paris, France
e-mail: boudaoud@lps.ens.fr

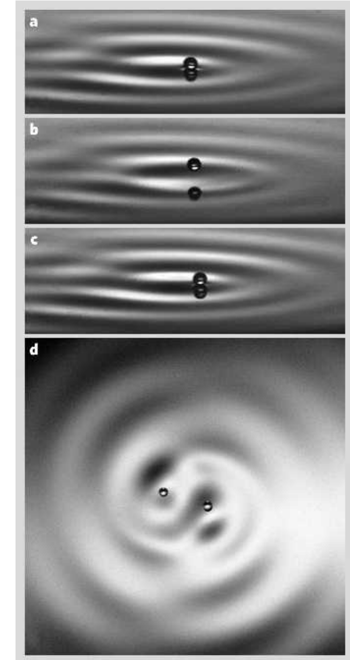


Figure 1 | Behaviour of silicon oil droplets on a bath of silicon oil when it is oscillated vertically. Experimental parameters: oil viscosity, 20×10^{-3} Pa s; forcing frequency, $\omega_0/2\pi = 80$ Hz, diameter of droplets $D \approx 0.65$ mm; forcing acceleration, $\gamma_m/g \approx 3.9$ (where g is the acceleration due to gravity). **a–c,** Photographs showing the motion of a single drop in interaction with its own localized Faraday wave on the liquid surface. The drop's motion is composed of a series of identical parabolic jumps, each jump bringing the drop into collision with the forward side of the central bulge of the wave generated by the previous collision. **d,** Photograph of two orbiting drops and associated waves. The horizontal motion is in a twin-star-like orbit of diameter $d_n = 5.8$ mm. (For movies, see supplementary information.)

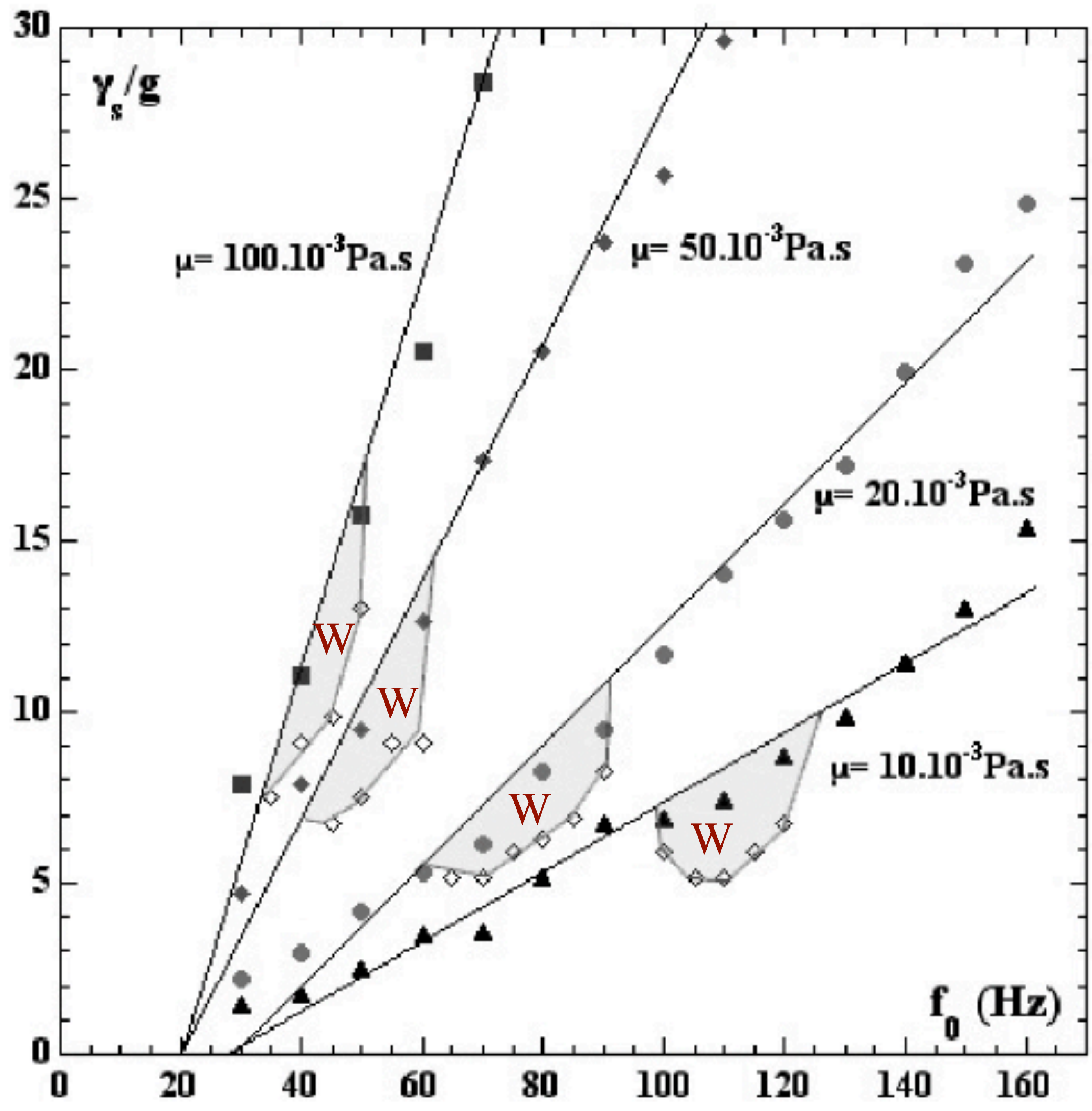
1. Couder, Y., Fort, E., Boudaoud, A. & Gautier, C. H. *Phys. Rev. Lett.* **94,** 177801 (2005).
2. Fauve, S. & Thual, O. *Phys. Rev. Lett.* **64,** 282–284 (1990).
3. Aranson, I. S., Gorshkov, K. A., Lomov, A. S. & Rabinovich, M. I. *Physica D* **43,** 435–453 (1990).
4. Lioubashevski, O., Arbell, H. & Fineberg, J. *Phys. Rev. Lett.* **76,** 3959–3962 (1996).
5. Umbanhowar, P. B., Melo, F. & Swinney, H. L. *Nature* **382,** 793–796 (1996).
6. Stegeman, G. I. & Segev, M. *Science* **286,** 1518–1523 (1999).
7. Moskalenko, A. S., Liehr, A. W. & Purwins, H. G. *Eur. Phys. Lett.* **63,** 361–367 (2003).
8. Liehr, A. W., Moskalenko, A. S., Astrov, Y. A., Bode, M. & Purwins, H. G. *Eur. Phys. J. B* **37,** 199–204 (2004).
9. Boudaoud, A., Couder, Y. & Ben Amar, M. *Eur. Phys. J. B* **9,** 159–165 (1999).
10. Boudaoud, A., Couder, Y. & Ben Amar, M. *Phys. Rev. Lett.* **82,** 3847–3851 (1999).

Supplementary information accompanies this communication on *Nature*'s website.
Competing financial interests: declared none
doi:10.1038/437208a

BRIEF COMMUNICATIONS ARISING online
▸ **www.nature.com/bca** see *Nature* contents.

$$m\,d^2x/dt^2 = a \sin\{(\pi k/\omega_0)\, dx/dt\} - b\, dx/dt$$

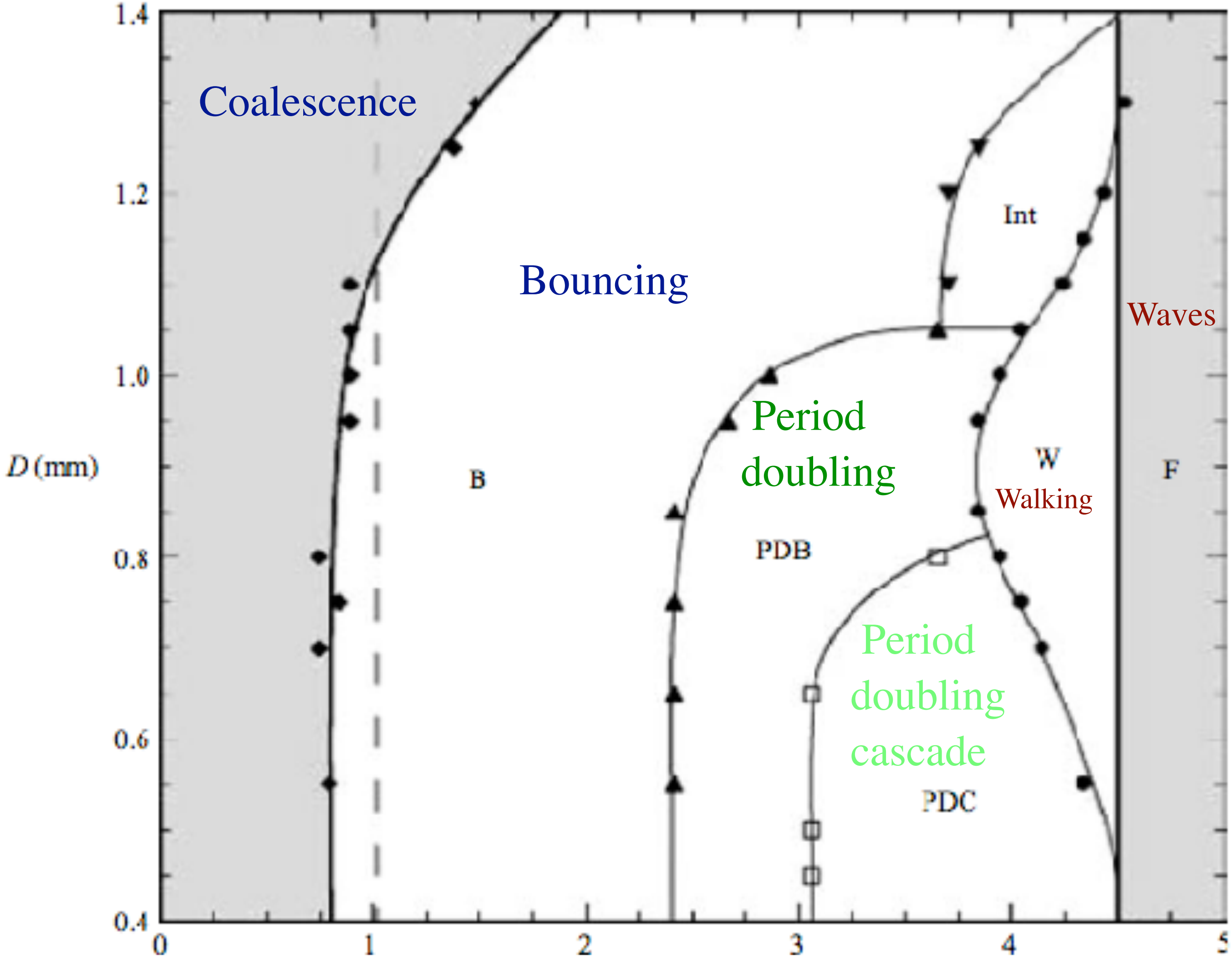
The elusive walkers



$f = 50Hz$

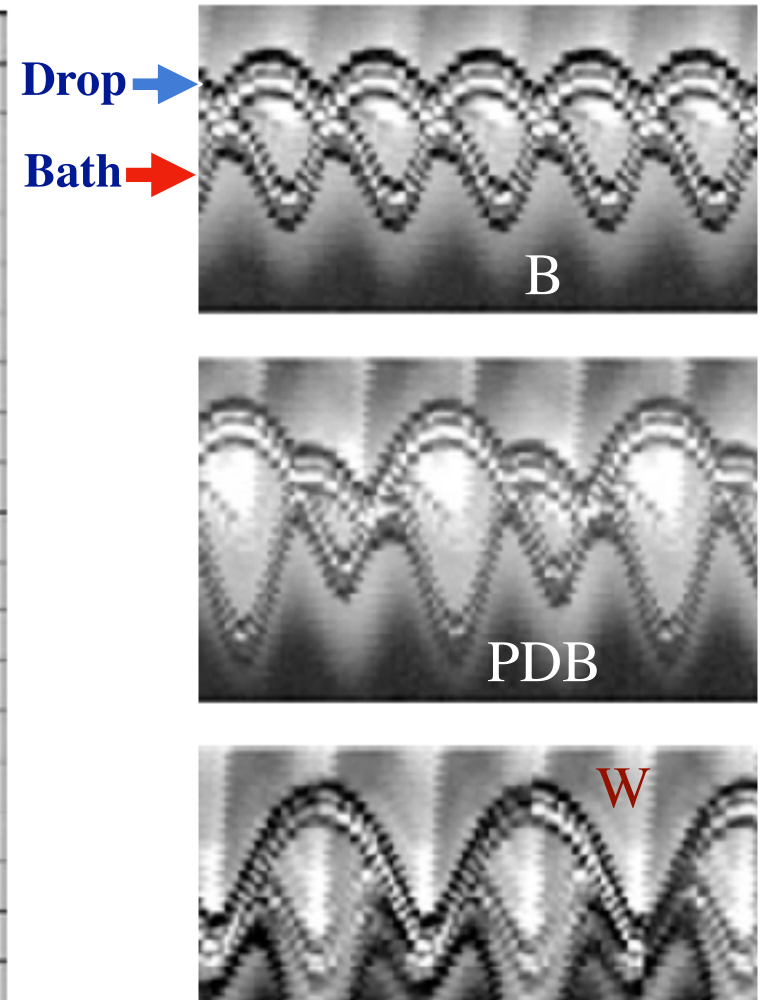
$\nu = 50cSt$

Couder's phase diagram



$$\Gamma = A(2\pi f)^2/g$$

Kymograph of vertical drop-bath dynamics

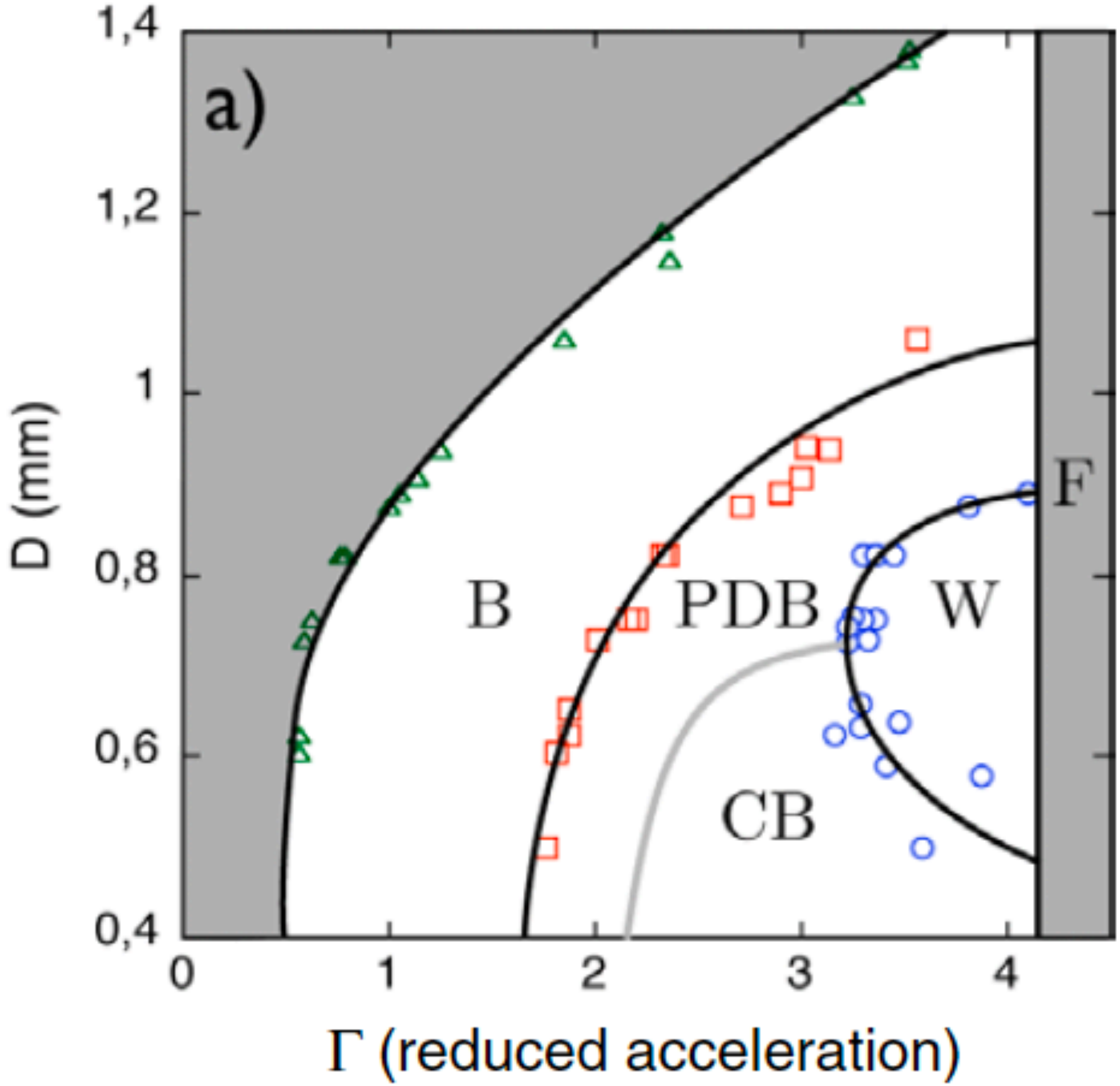


- prior to walking, the droplet achieves resonance with its subharmonic Faraday waves

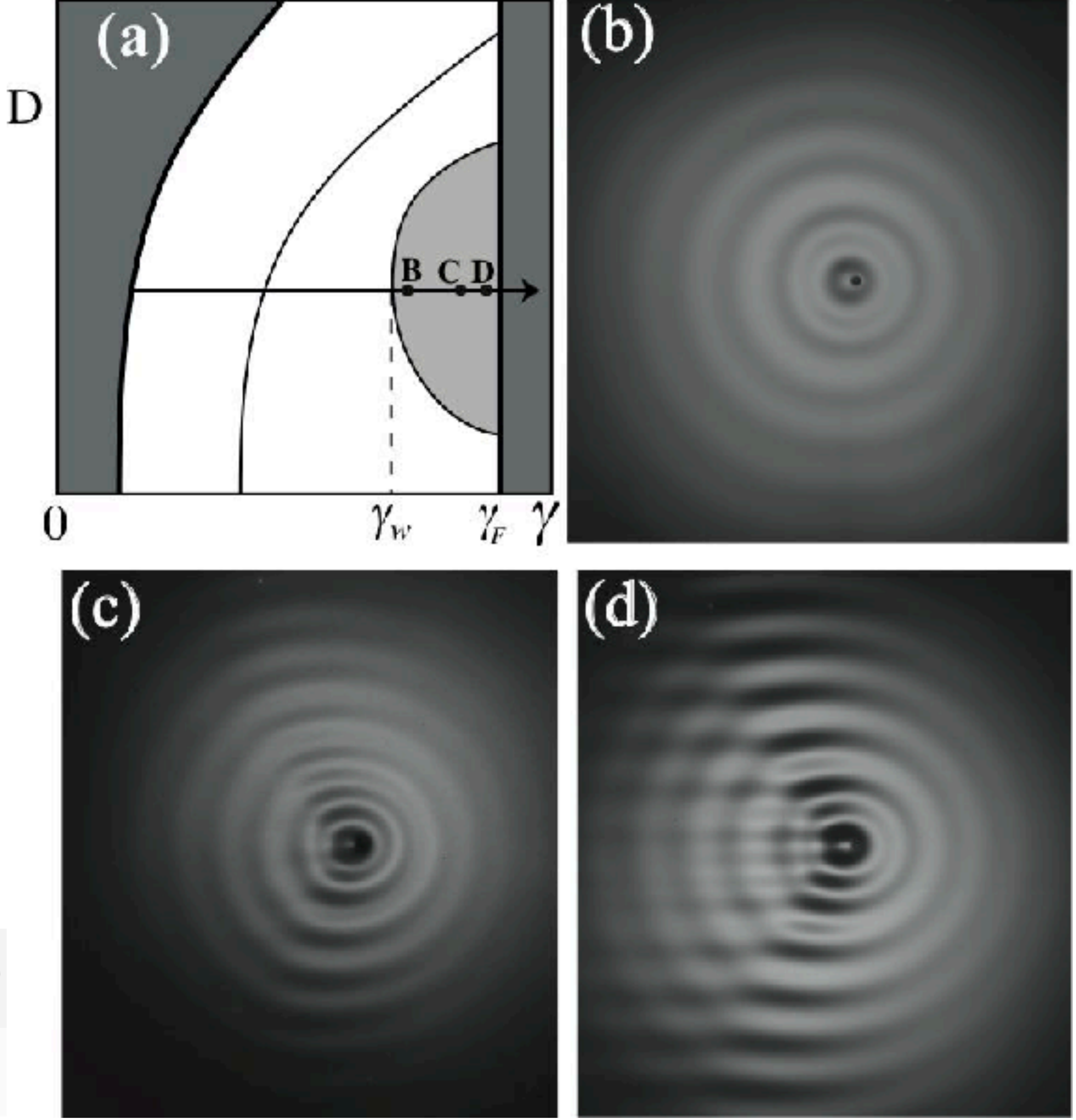
Couder's phase diagram

$f = 80Hz$

$\nu = 20cS$



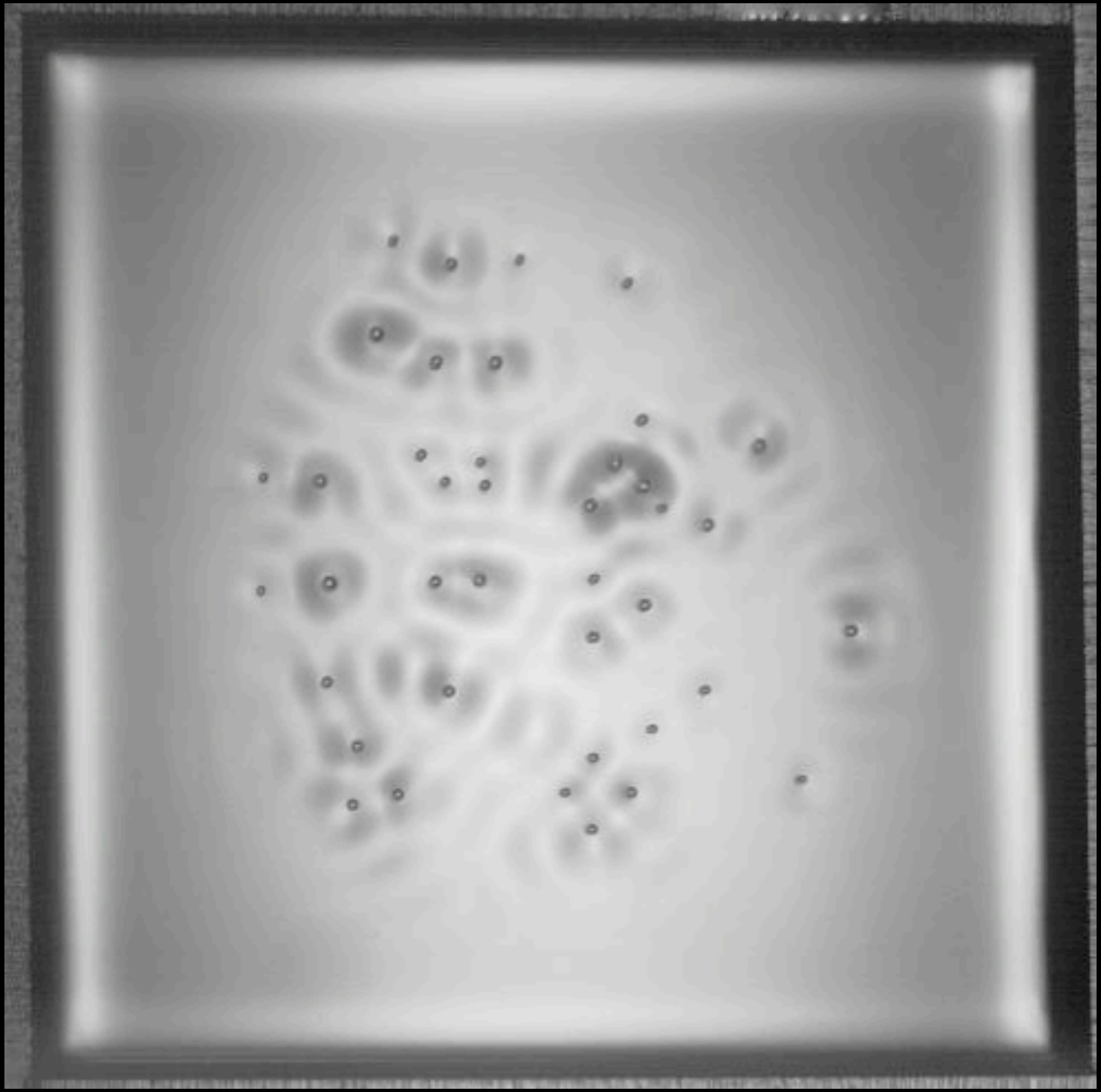
Evolution of the wave field



$f = 80Hz$

$\nu = 20cS$

The interaction of many walkers

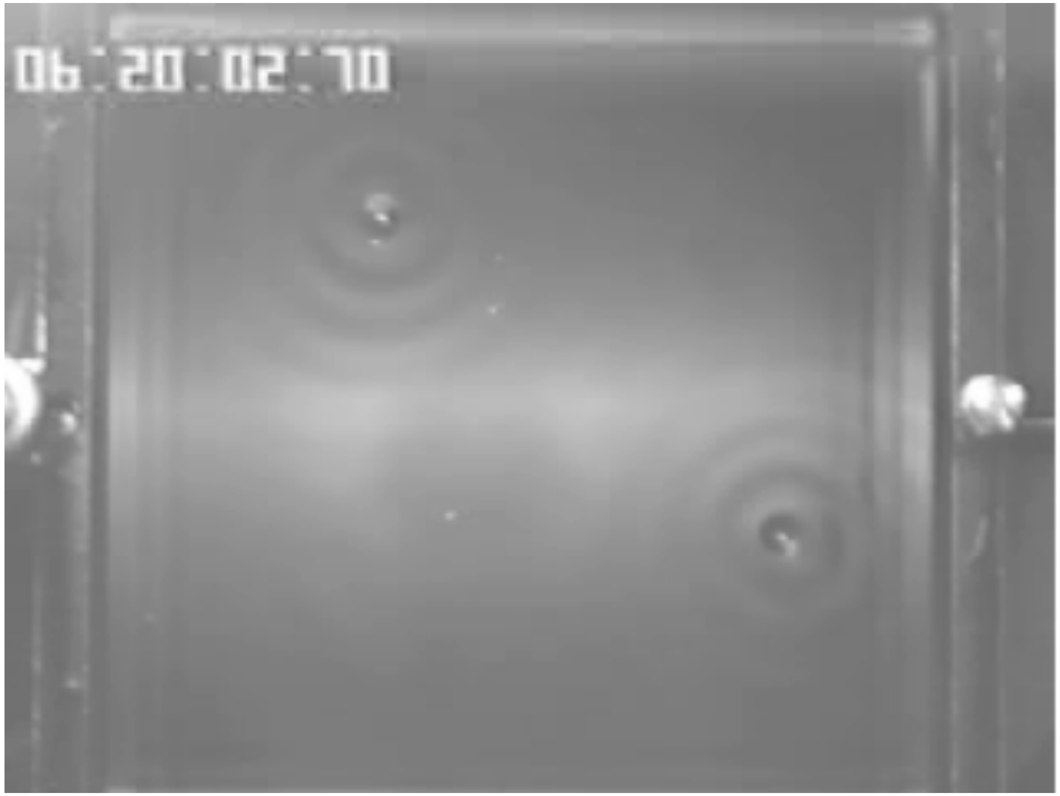


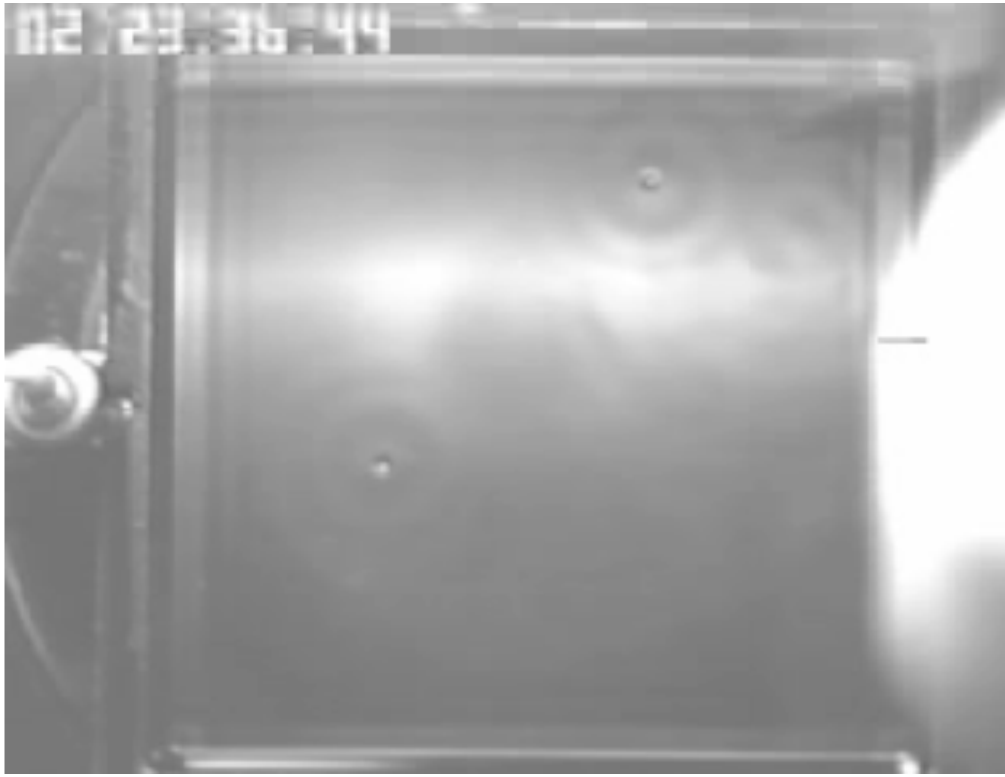
Video courtesy of Tristan Gilet

- walkers interact, scatter, promenade, lock into orbits, merge

Droplets walking on a vibrated fluid bath

- a pair of walkers interact: either scattering or locking into orbit



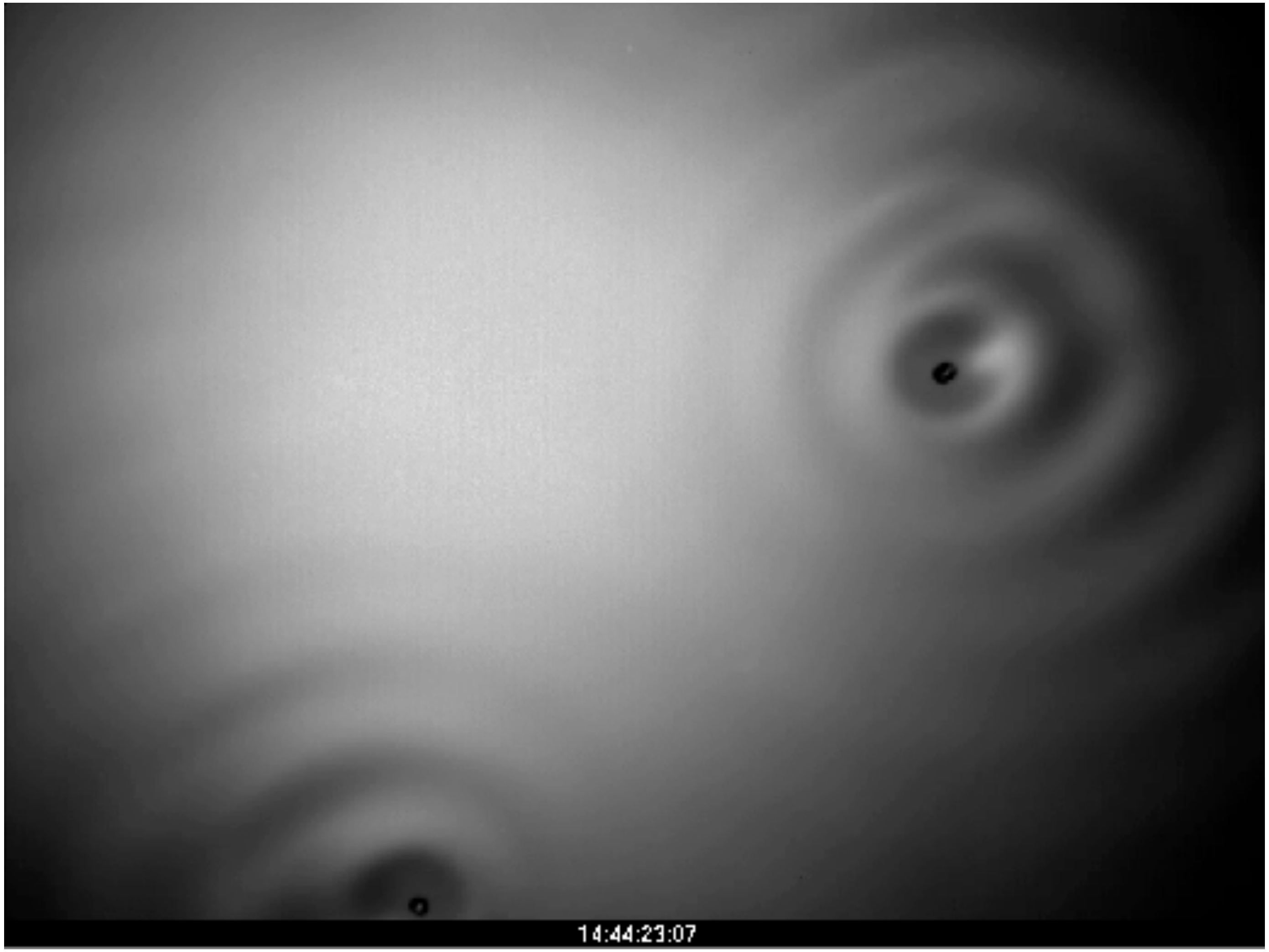


Videos courtesy of Yves Couder

Bouncing phase effects

- recall that there is a critical memory (vibrational acceleration) above which drops are period-doubled relative to the vibrational forcing
- period-doubled bouncers bounce subharmonically w.r.t. the driving, and so are in resonance with the bath's most unstable Faraday wave modes
- prior to period-doubling, the wave field is relatively weak and incoherent, quickly disperses
- beyond period-doubling, the wave field is more pronounced, coherent, quasi monochromatic with the Faraday wavelength
- period-doubled bouncers may be either in- or out-of-phase w.r.t. the driving, and so w.r.t. each other
- period-doubled bouncers have long-range influences on each other, the form of which depends on whether they are in-phase or out-of-phase.

Quantized orbits of identical droplets



In-phase orbiters:

$$d_n^{\mathrm{orb}} = (n - \varepsilon)\lambda_{\mathrm{F}}$$

Out-of-phase orbiters:

$$d_n^{\mathrm{orb}} = (n + 1/2 - \varepsilon)\lambda_{\mathrm{F}}$$

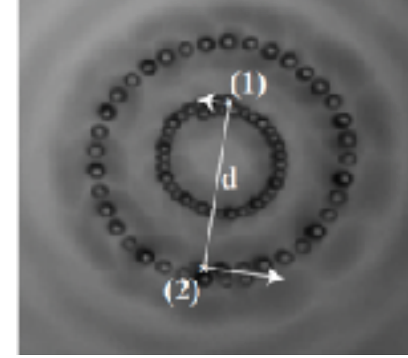
- orbital quantization reflects influence of the shared pilot-wave field
- drops orbit on radii for which the wave force is radially inward
- larger radii become prevalent as the memory is increased progressively
- circular orbits may destabilize into wobbling states

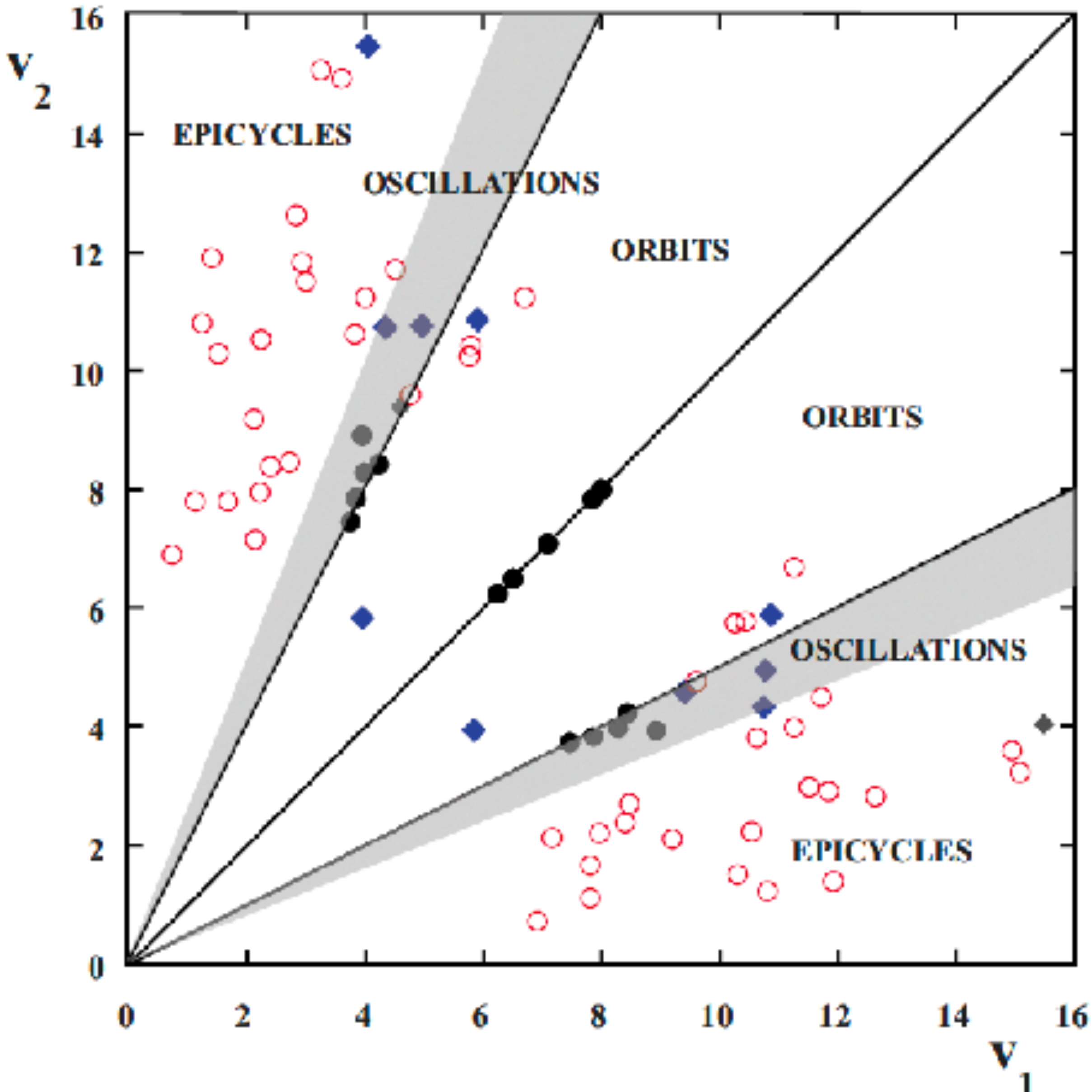
Orbiting unequal pairs

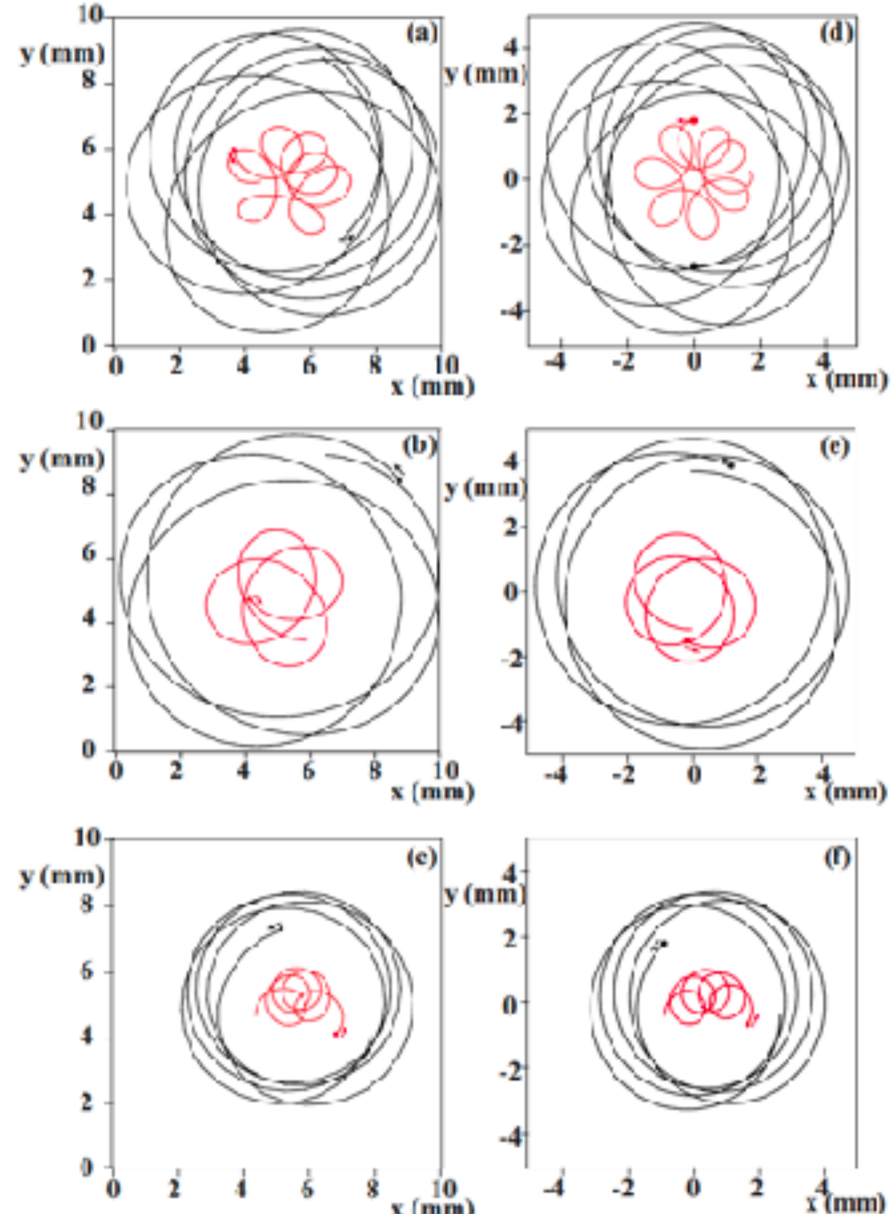
PHYSICAL REVIEW E 78, 036204 (2008)

Exotic orbits of two interacting wave sources

S. Protière, S. Bohn, and Y. Couder
Laboratoire Matière et Systèmes Complexes, UMR 7057 CNRS and Université Paris 7-Denis Diderot, Bâtiment Condorcet, Case 7056, 75205 Paris Cedex 13, France



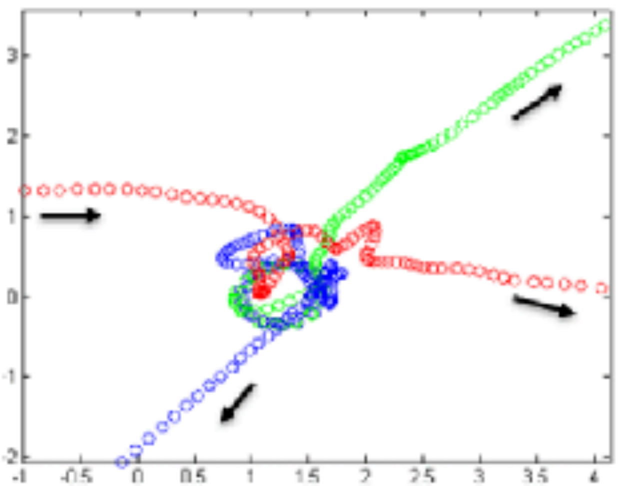




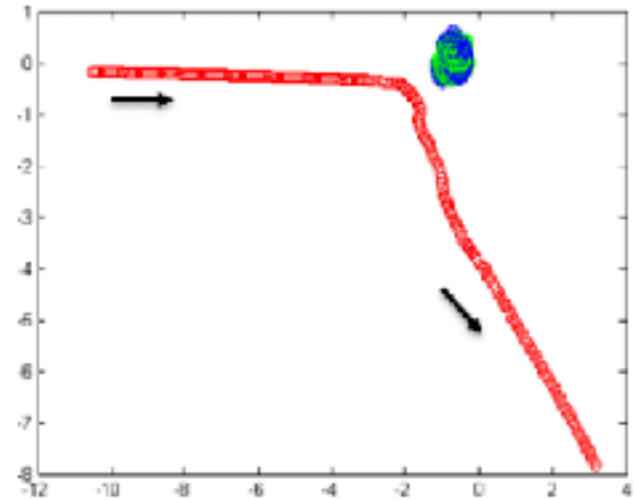
Droplets walking on a vibrated fluid bath

Slide: Yves Couder

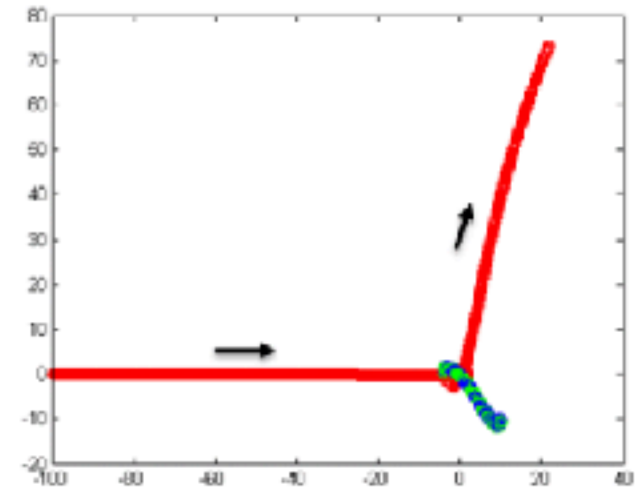
Wave particle duality in multiple bouncing fluid droplets, "Feynman diagrams" to calculate scattering statistics?



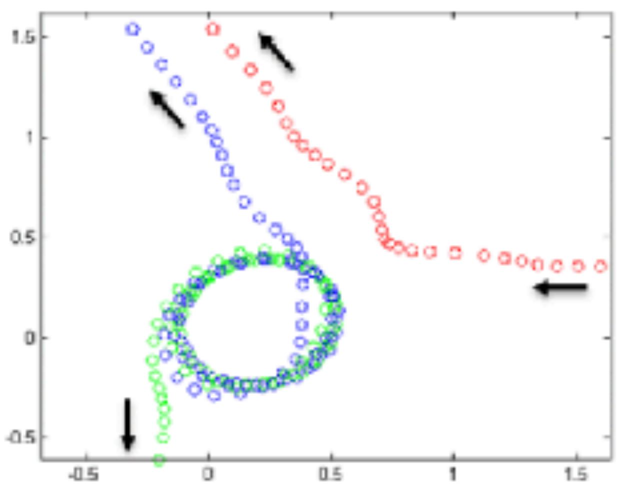
(a) Droplets in different directions



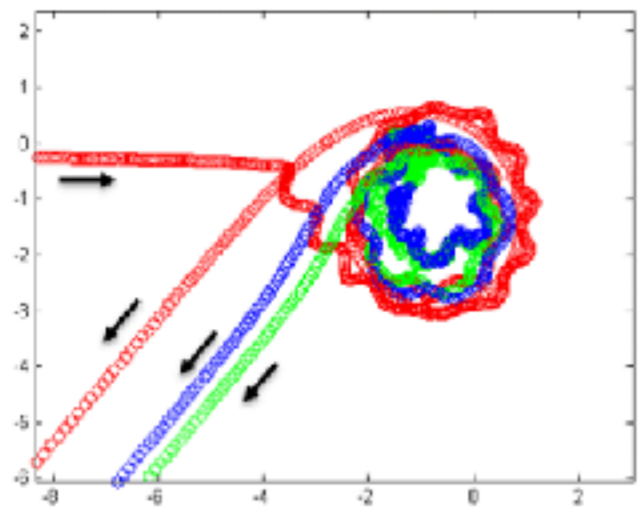
(b) Scattering



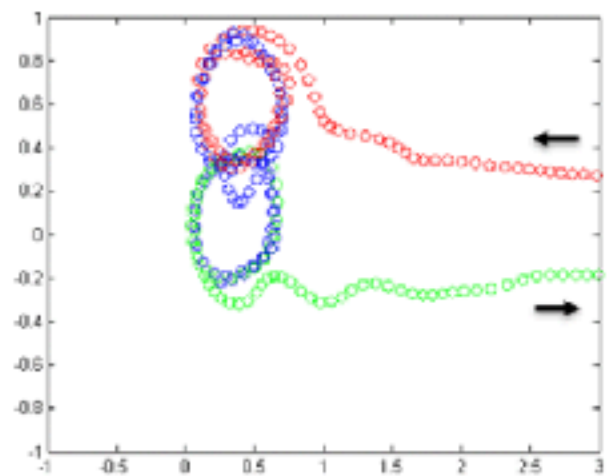
(c) Slingshot



(d) Two parallel walkers

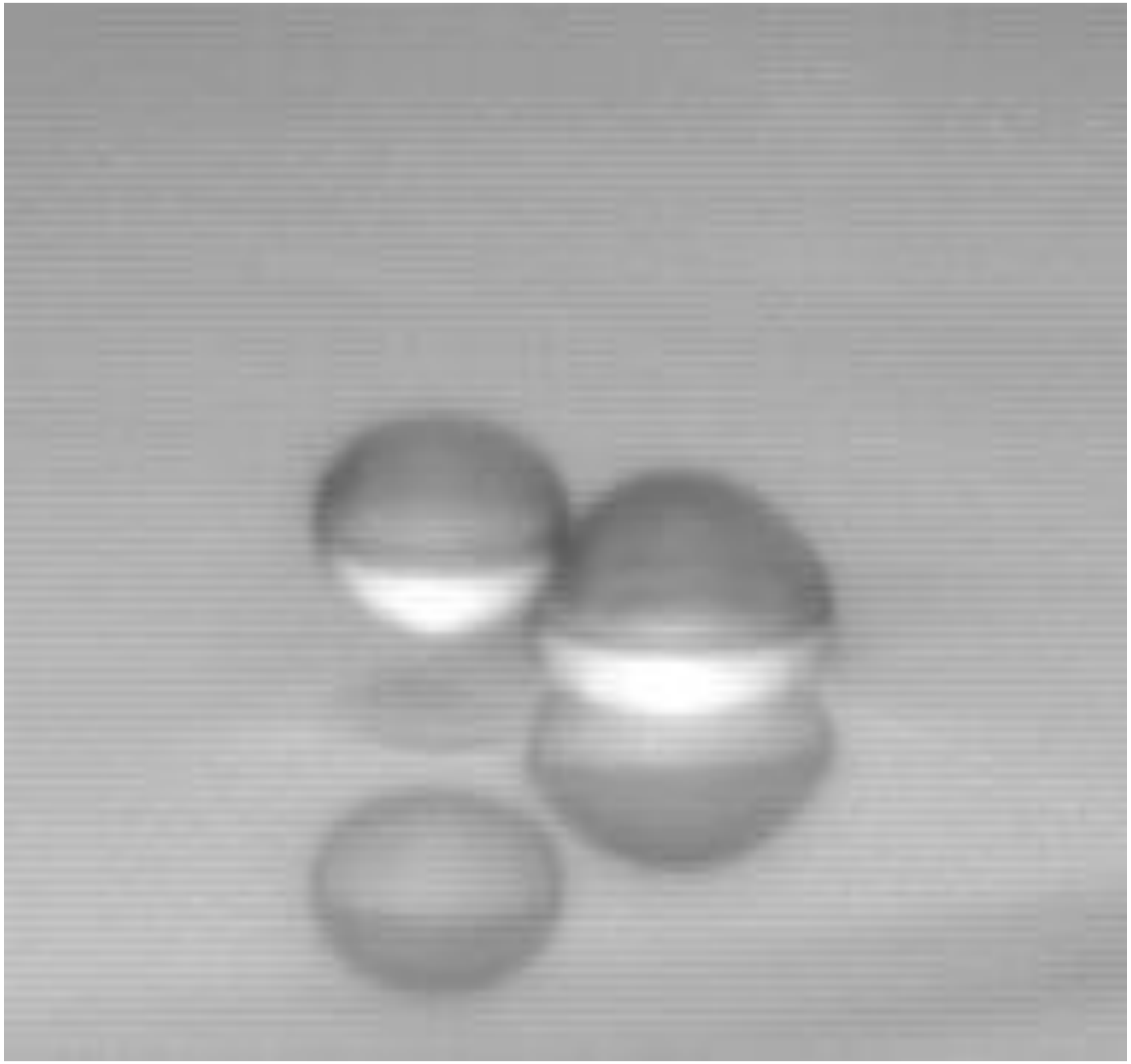


(e) Three parallel walkers



(f) Switching orbits

The interaction of two bouncers: merger followed by partial coalescence



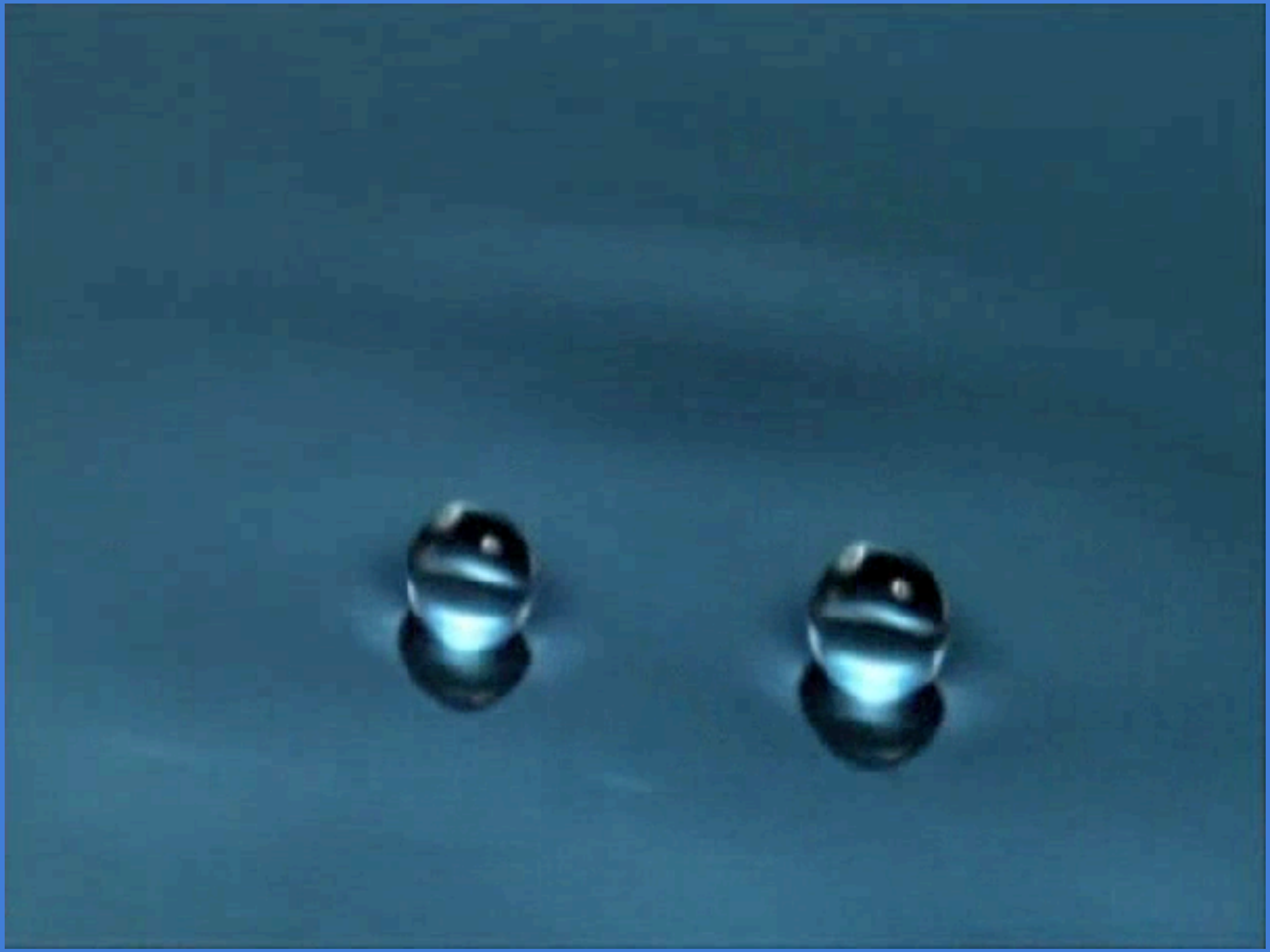
- a means of sorting droplets according to size

T. Gilet

Phase effects

- a pair of droplets lock into phase, interact through their wave fields

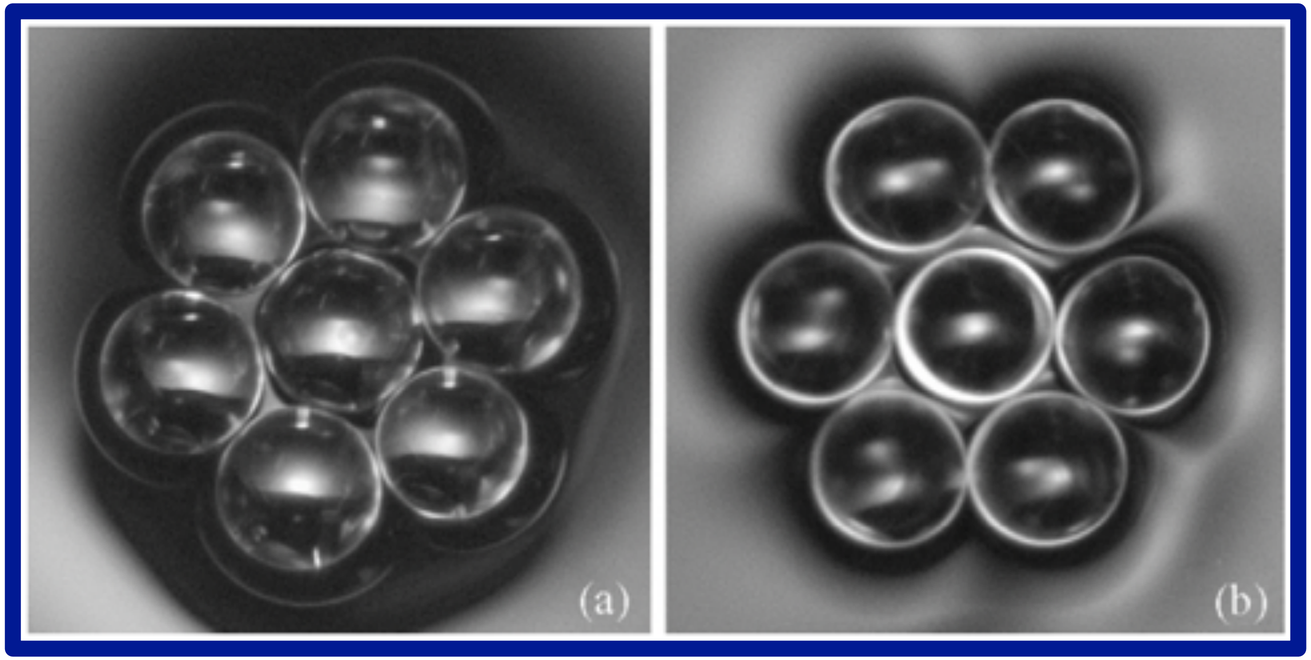
30cS
Si oil



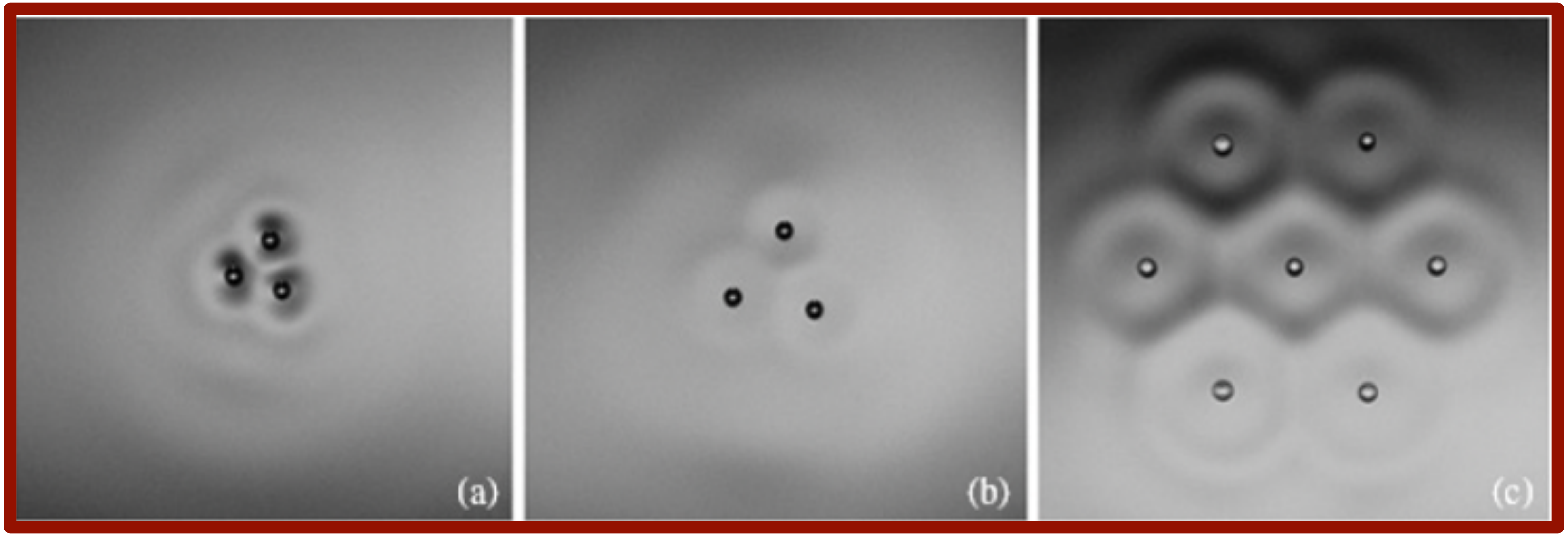
f ~ 40 Hz

Bouncing droplet crystals

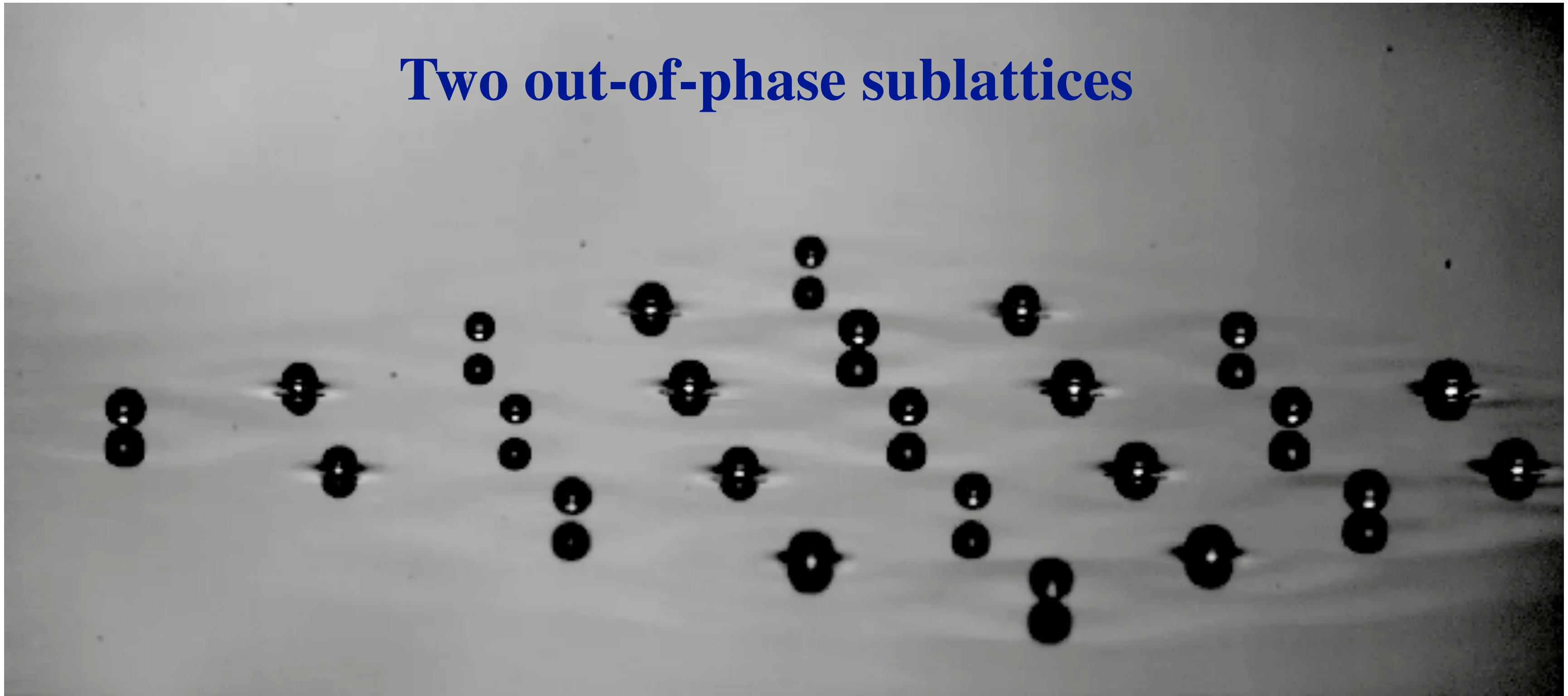
Crystals before period doubling



Crystals after period doubling

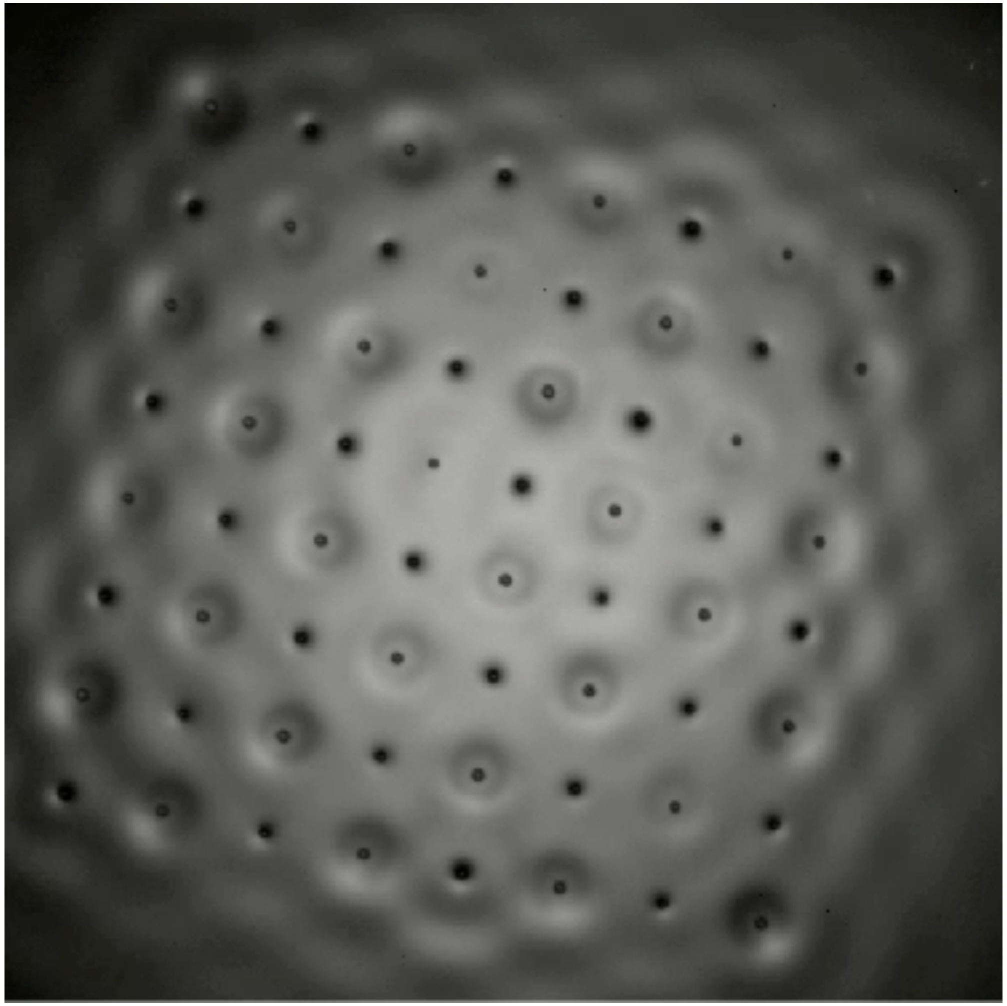


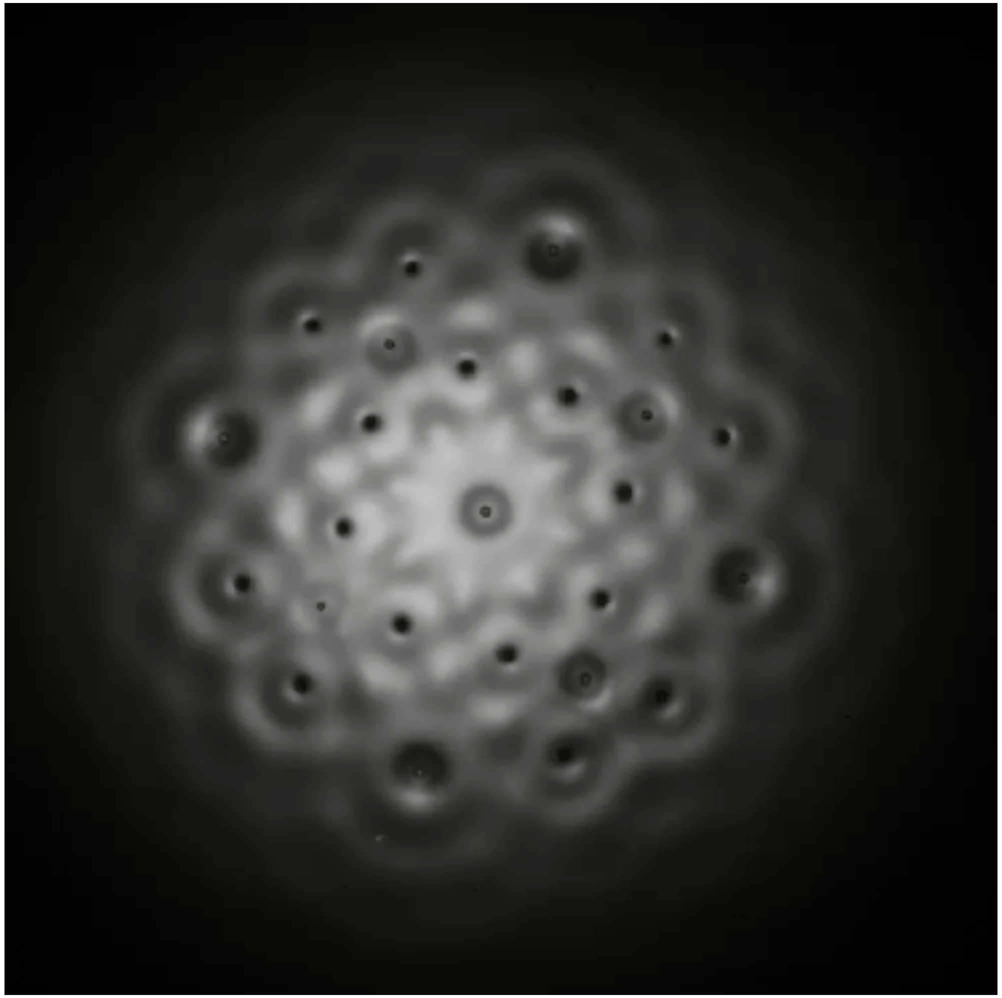
Bouncing droplet lattices



Bouncing droplet crystals

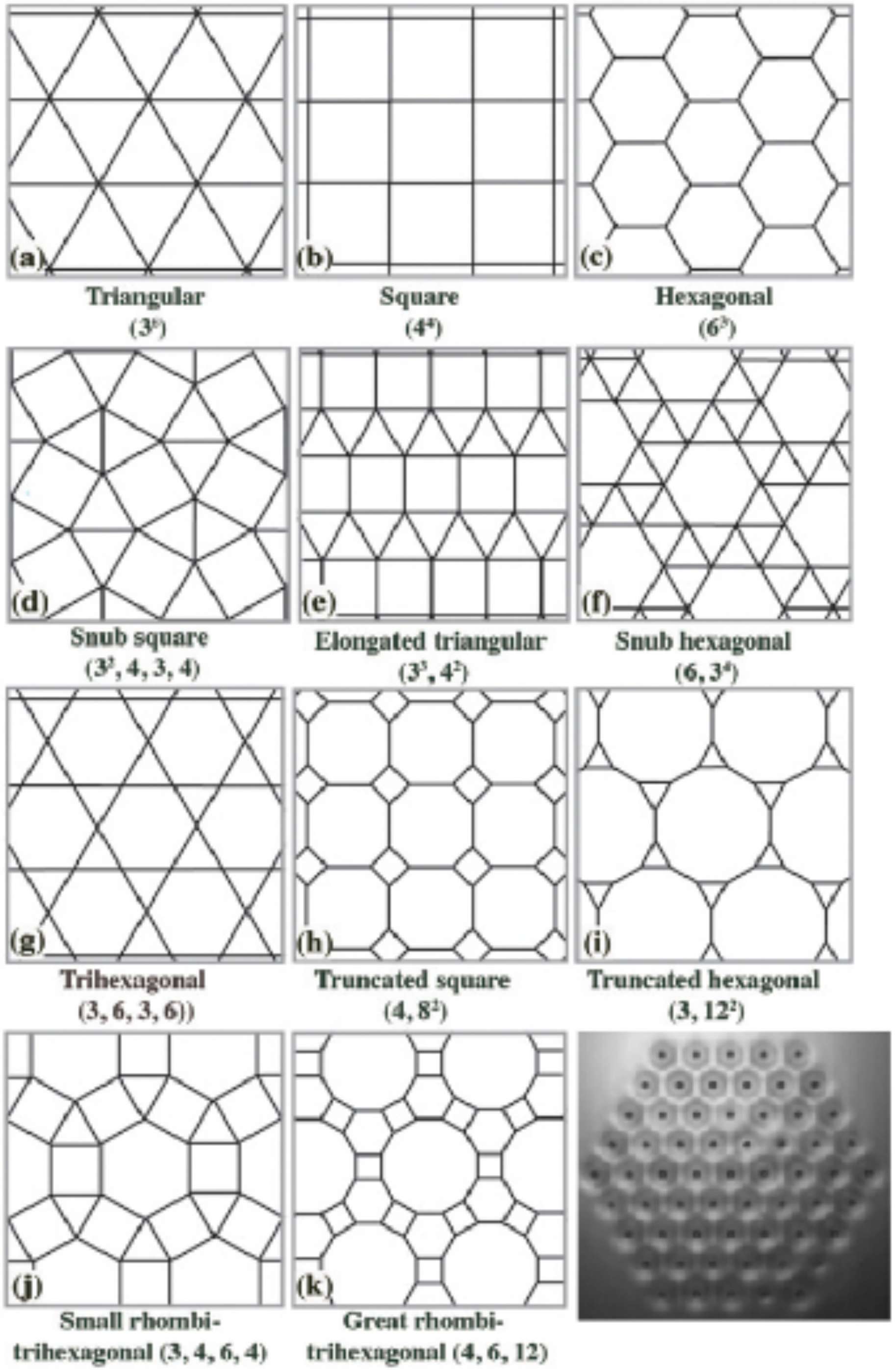
- exploited possible phase difference to obtain more elaborate crystals

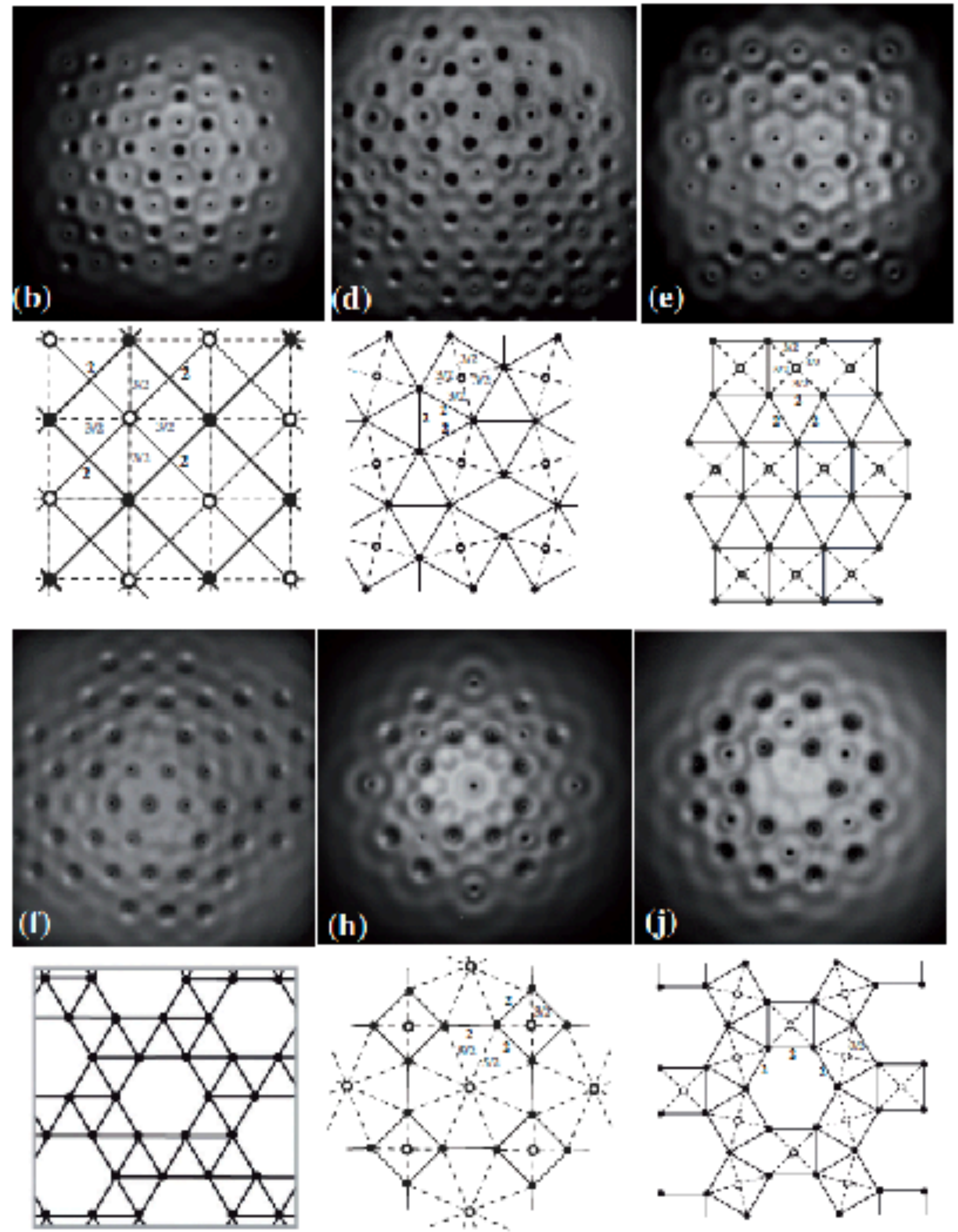




Archimedean Tilings generated by bouncing drops

Eddi, Decelle, Fort & Couder (2009)

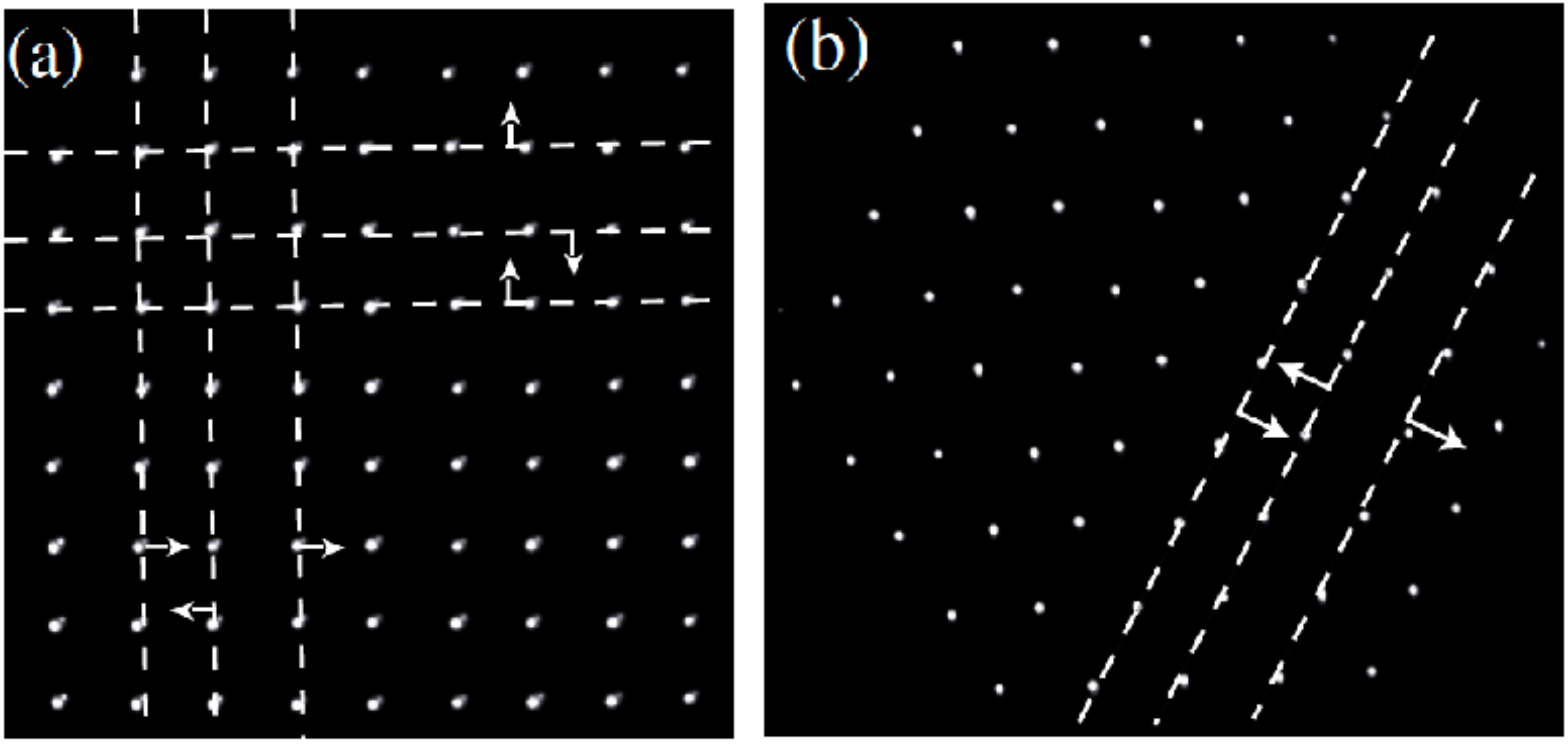




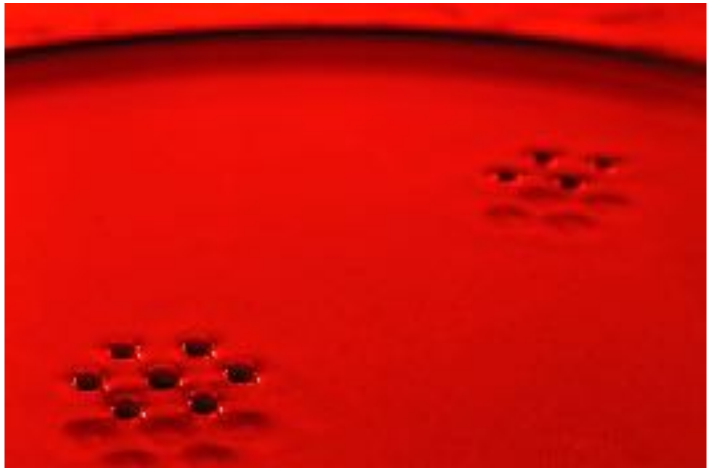
Analog phonons in bouncing crystal lattices

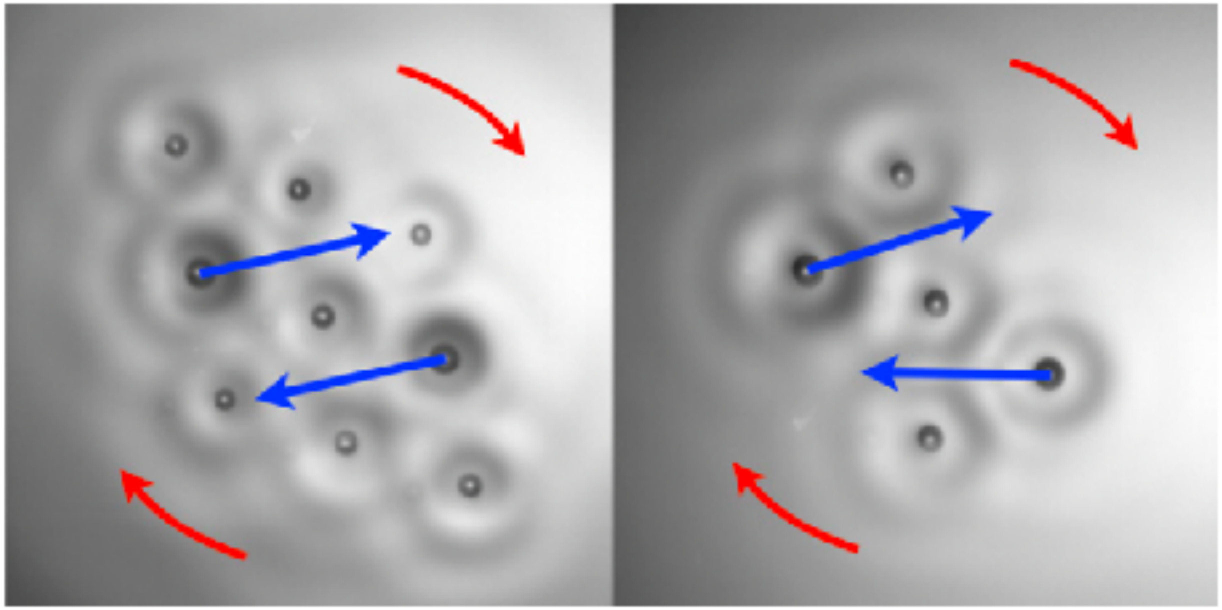
Eddi et al. (2014)

- as memory increases, stable lattices develop vibrational modes akin to phonons
- oscillations may take several forms, according to lattice geometry, drop size
- beyond a critical memory, lattice melts, disintegrates into a disordered form



Orbiting and drifting rafts





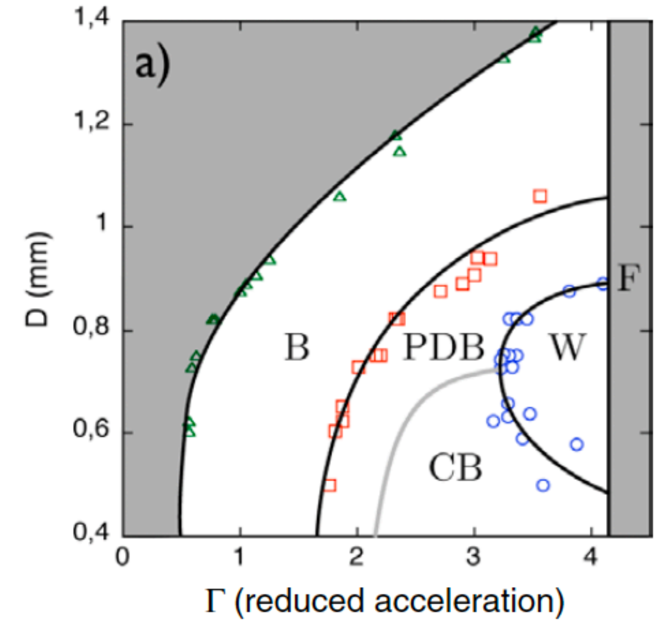
- lattices may be stationary, or spin at a steady rate owing to asymmetry of wave field

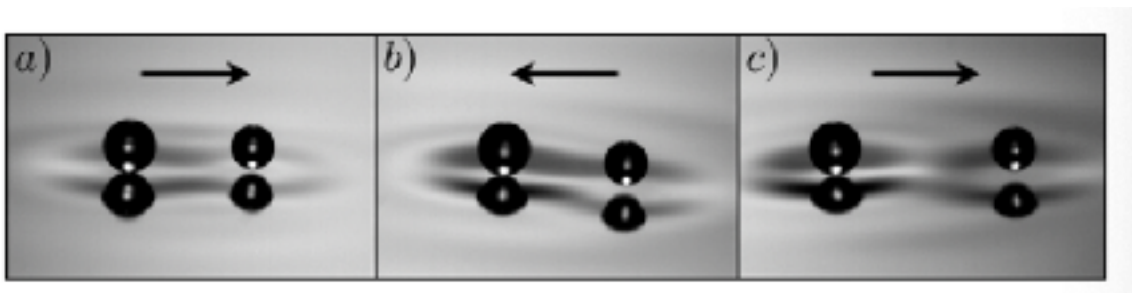
(Eddi et al. 2009)

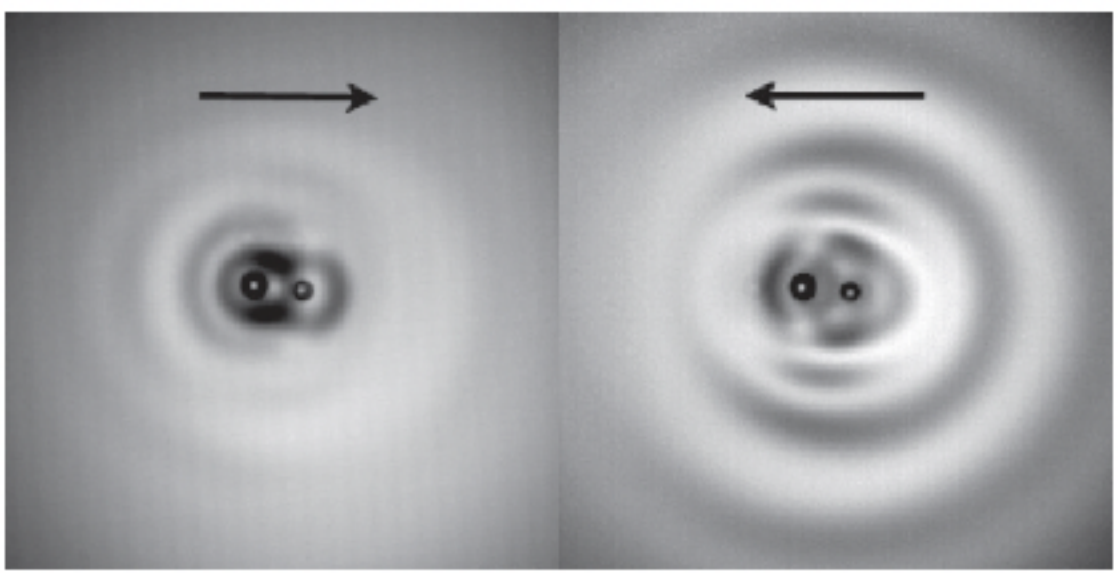
Ratcheting unequal pairs

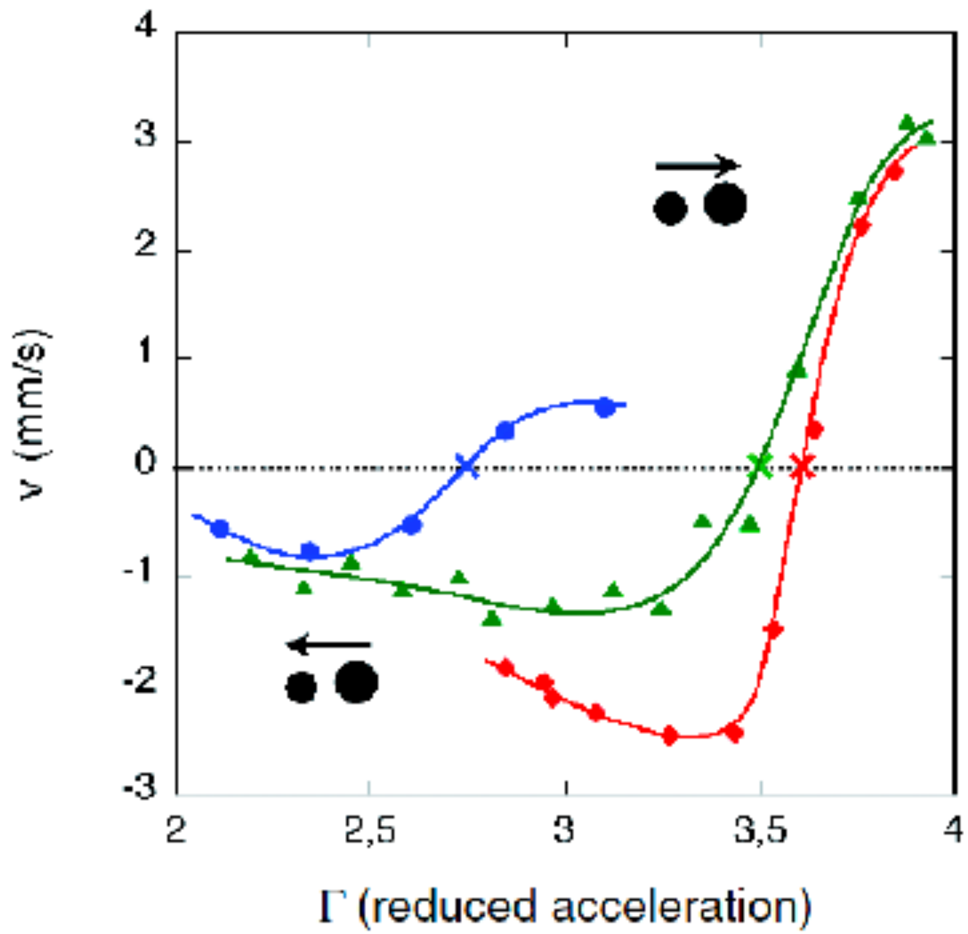
Eddi et al. (2009)

- wave interaction leads to propulsion via ratcheting
- direction of motion depends on amplitude of forcing
- relation to optical ratchets?

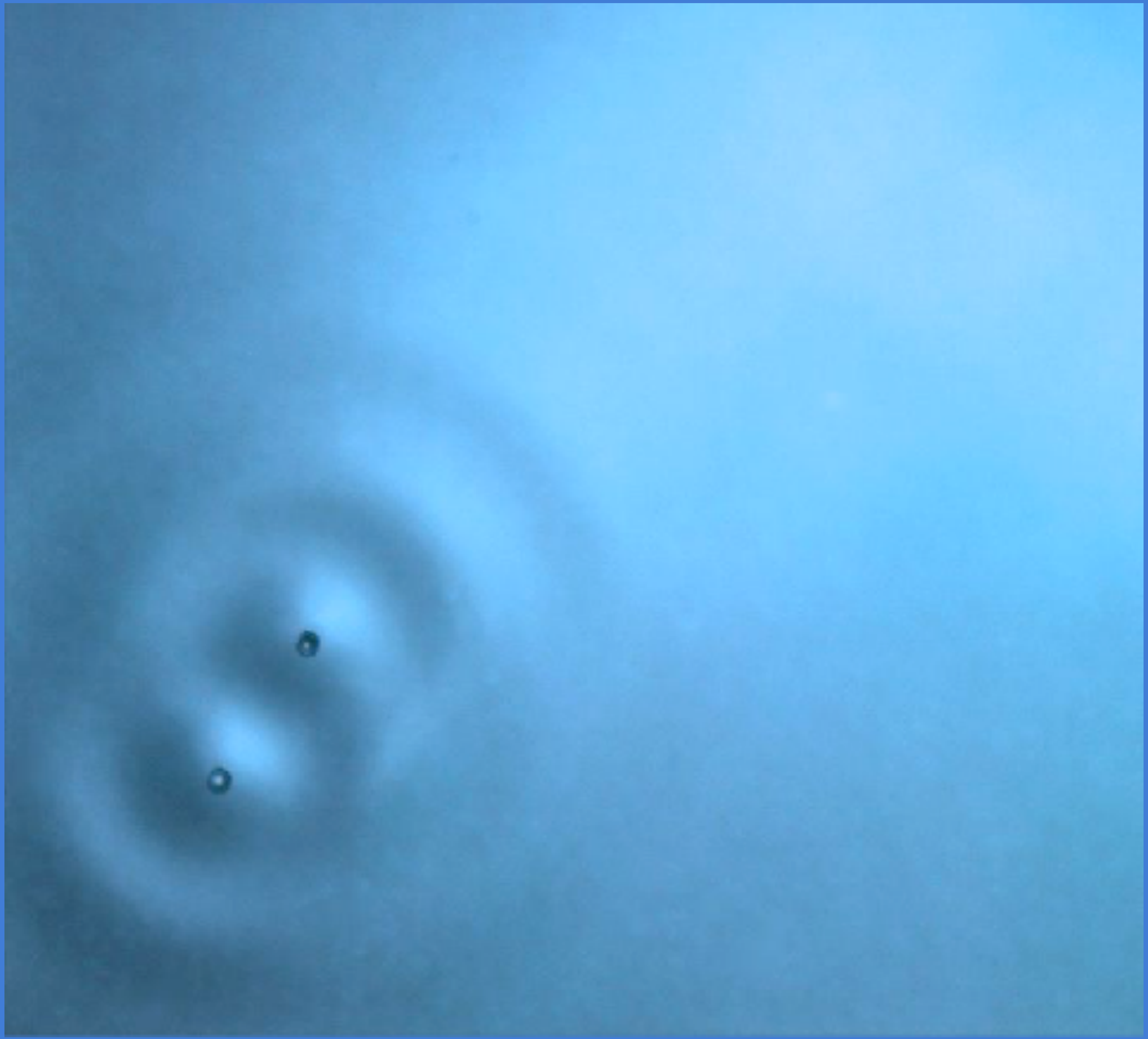








The promenade mode

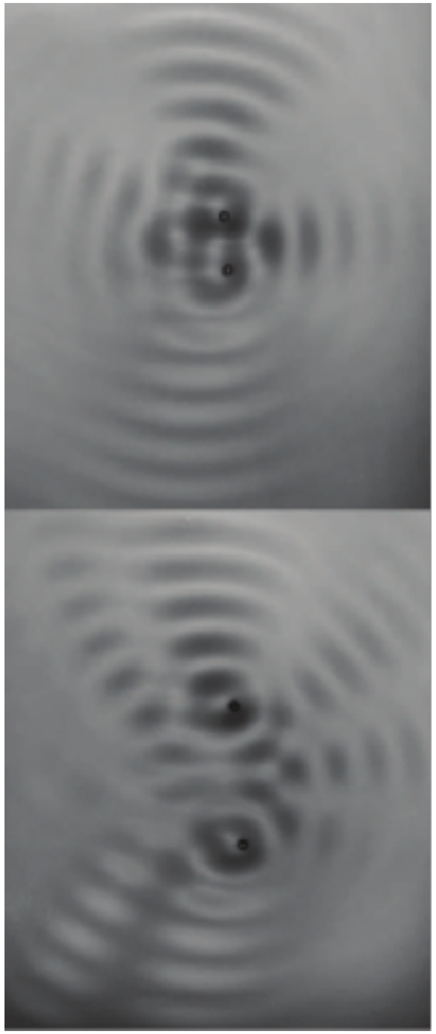


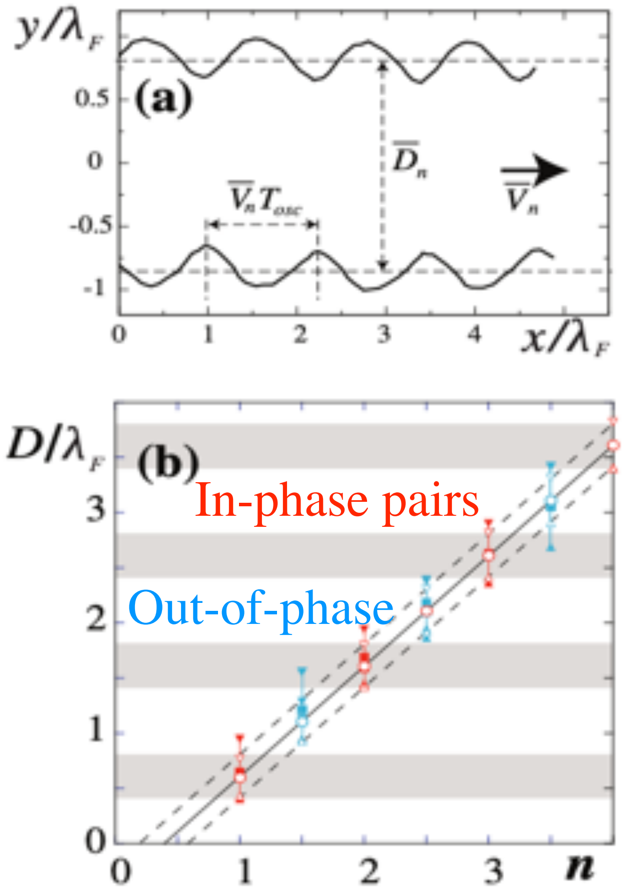
20cS Si oil,
50 Hz

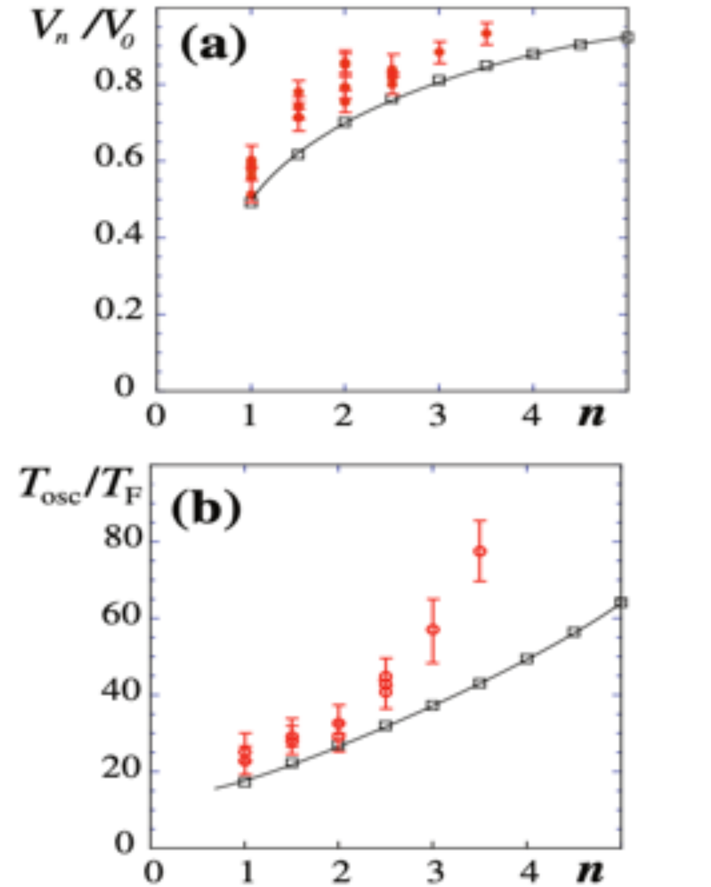
- a pair of walking droplets coupled through their wave fields

The promenade mode

Borghesi et al. (2015)







- droplet pairs promenade together, the distance between them quantized by the wave field according to:

$$\overline{D}_n = (n - \epsilon_0)\lambda_F.$$

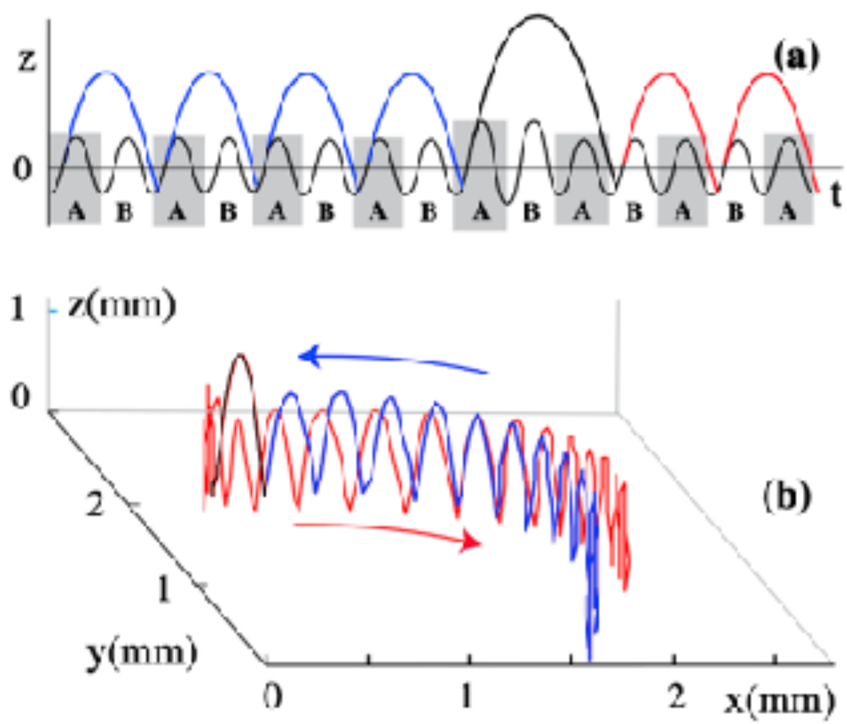
- n is integer for in-phase walkers, half-integer for out-of-phase walkers

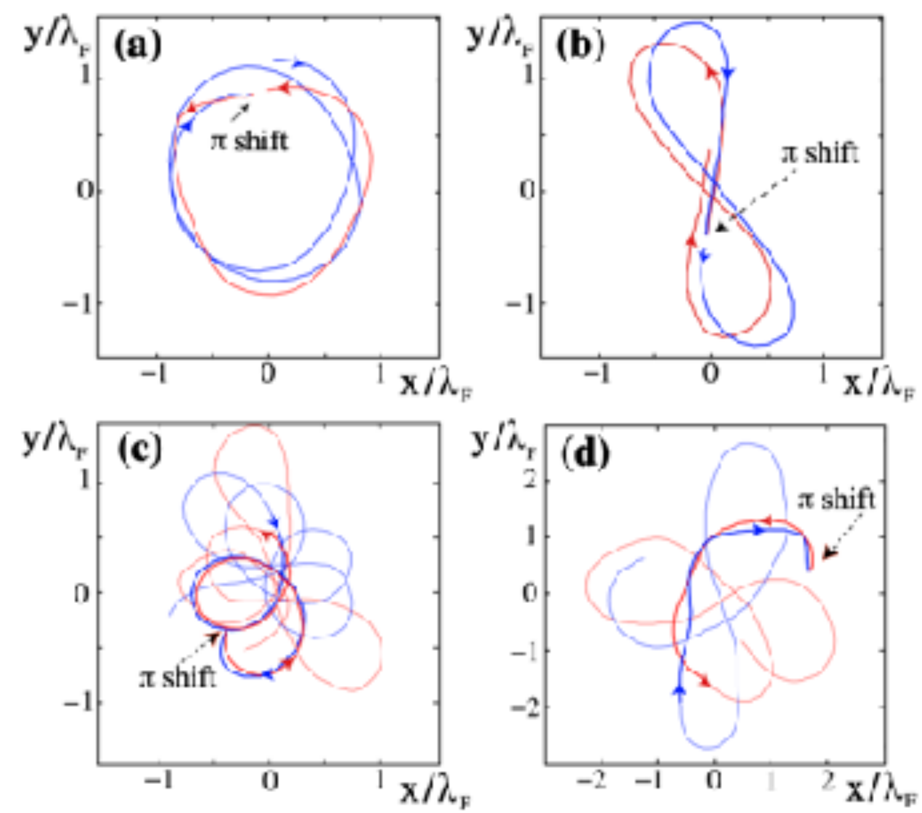
Wave-Based Turing Machine: Time Reversal and Information Erasing

S. Perrard, E. Fort, and Y. Couder

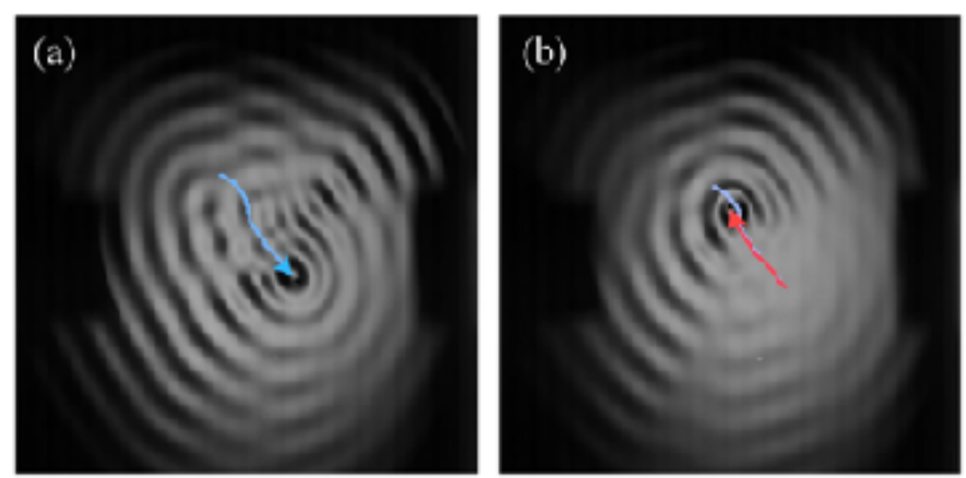
Phys. Rev. Lett. **117**, 094502 – Published 26 August 2016

Time-reversal in bouncing drops





- reverse bouncing phase reverses pilot wave
- drop retraces its steps for a time comparable to the memory time



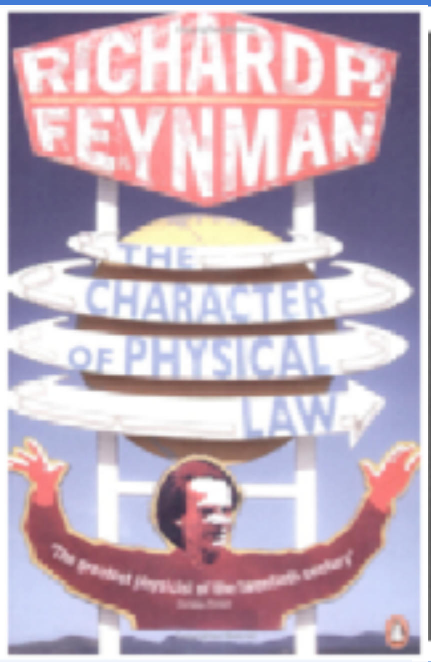
HALF TIME

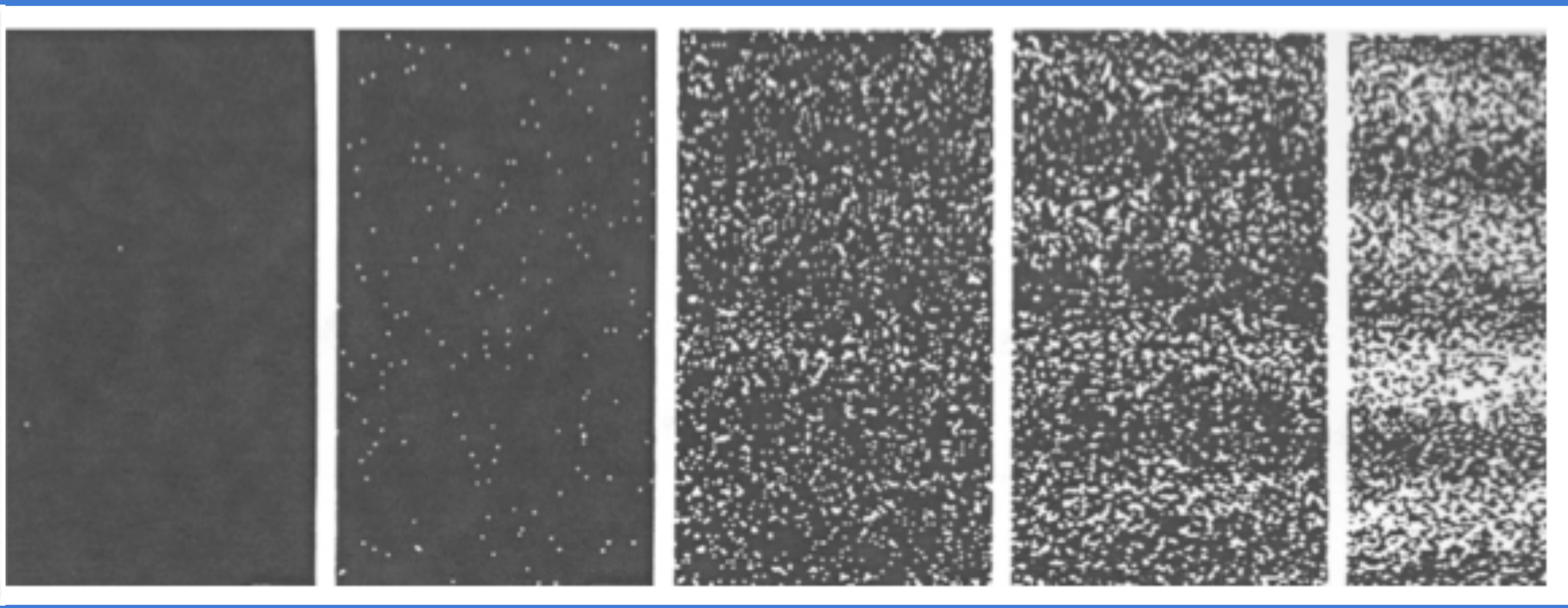
``The most beautiful experiment in the history of physics”

Electron double-slit diffraction experiments of Tonomura (1989)

Double slit experiment with electrons

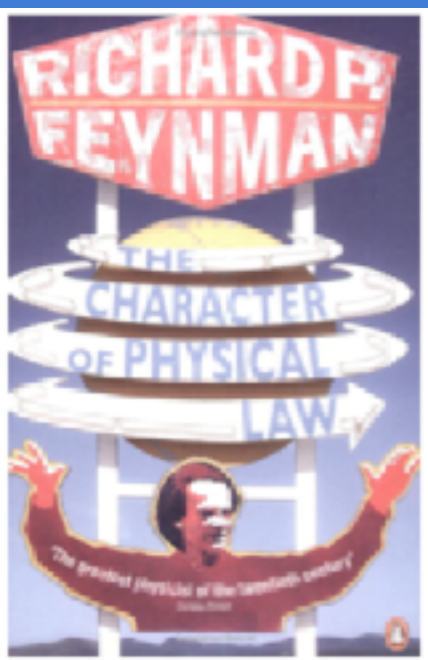
“ A phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.”

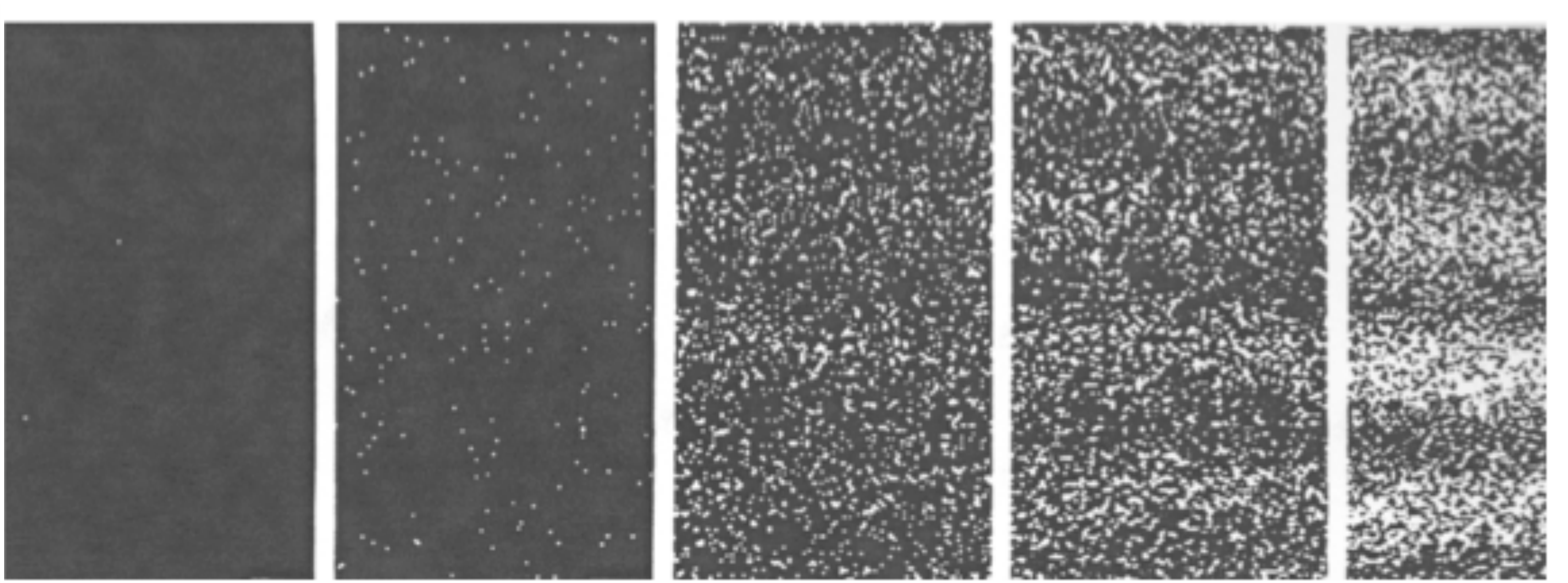




Double slit experiment with electrons

" 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."





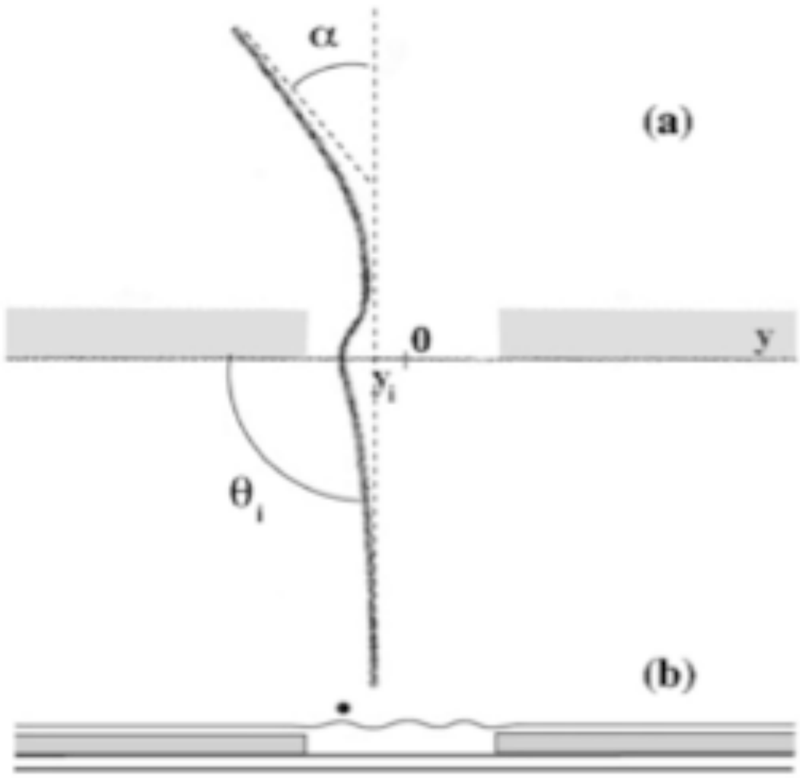
" While the founding fathers agonized over the question `particle' or `wave', de Broglie in 1925 proposed the obvious answer `particle' and `wave'.... This idea seems so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it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

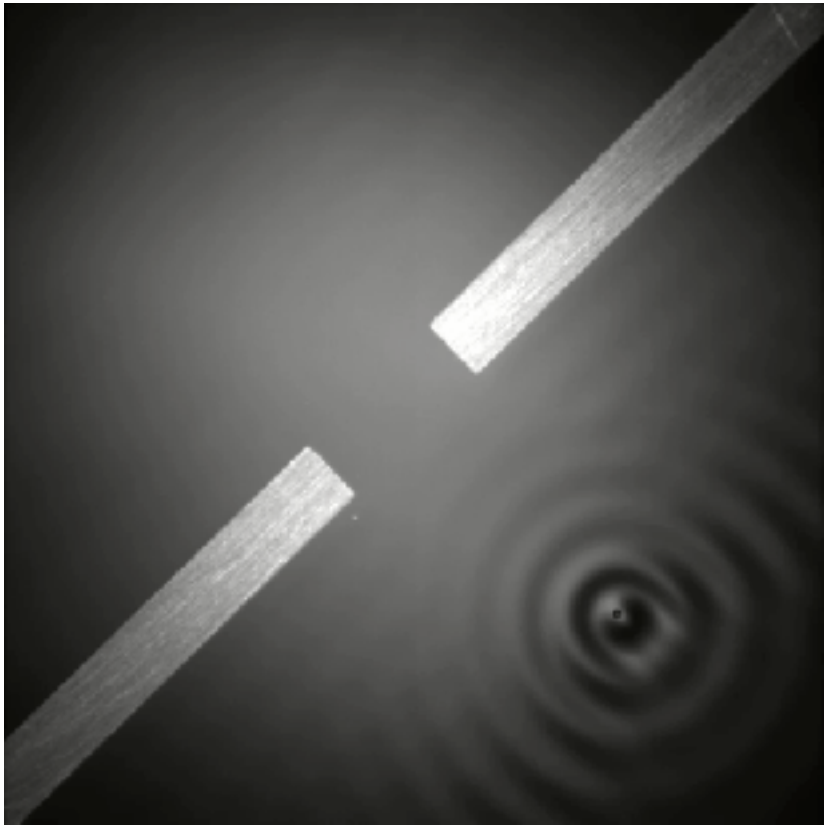
- John S. Bell

Diffraction of walkers

(Couder & Fort 2006)

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

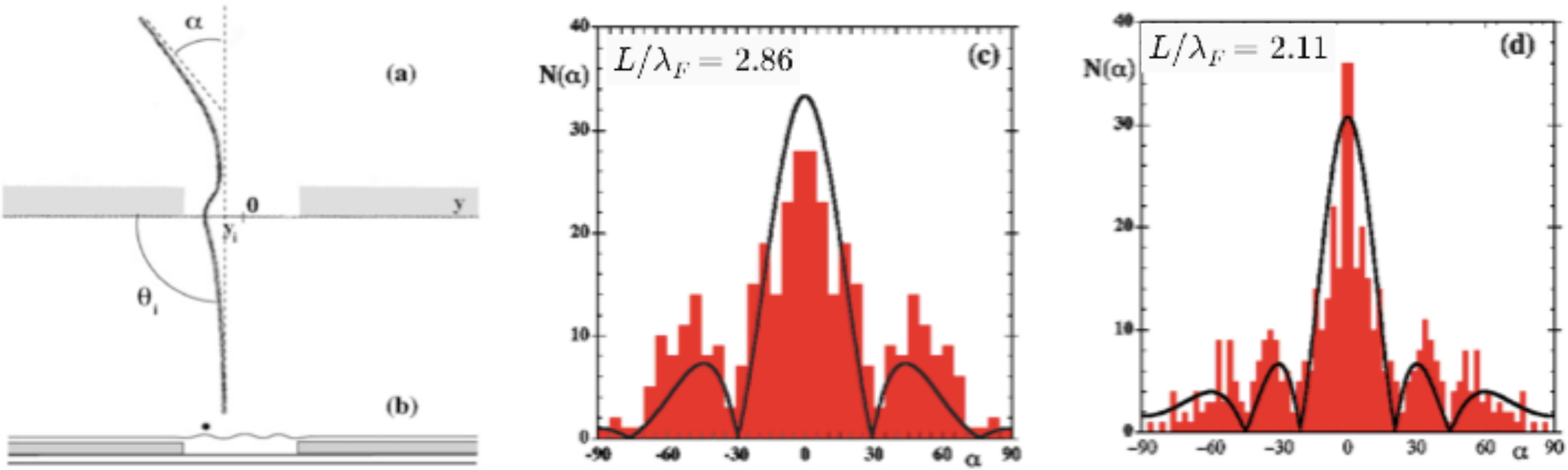




- far from threshold (weak waves), nothing interesting happens
- as threshold approached (strong waves), each drop is randomly deflected
- ..... and the statistics?

Diffraction of walkers: Single slit

(Couder & Fort 2006)



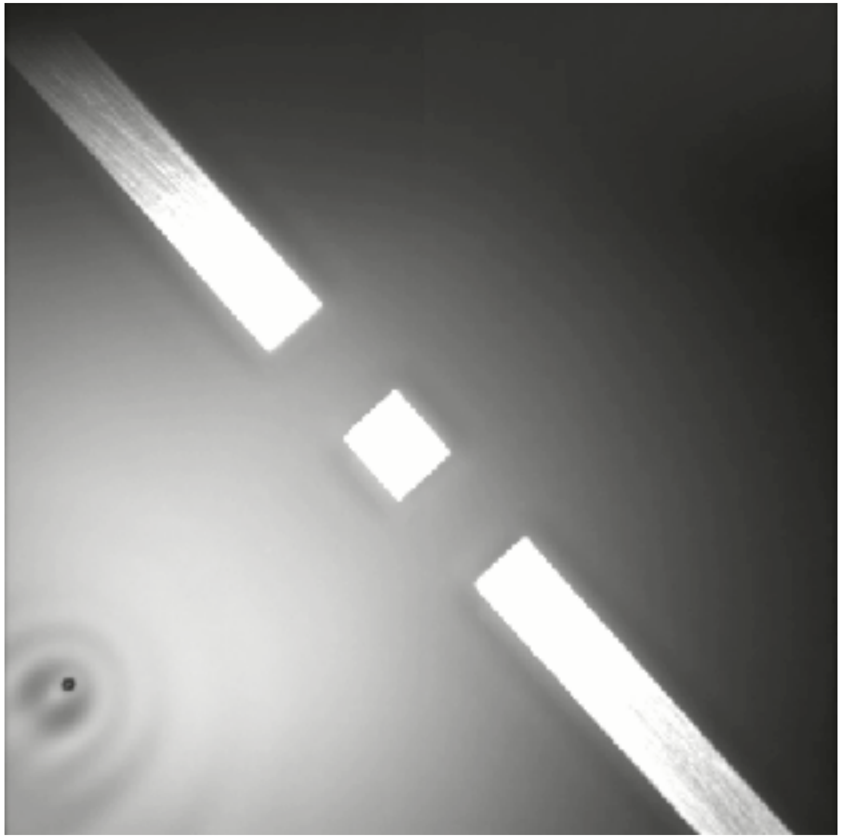
- distortion of waves passing through slit leads to particle diffraction
- data sets gathered from 125 trajectories from a single drop, symmetrized
- impact parameters uniformly distributed so as to best mimic a place wave

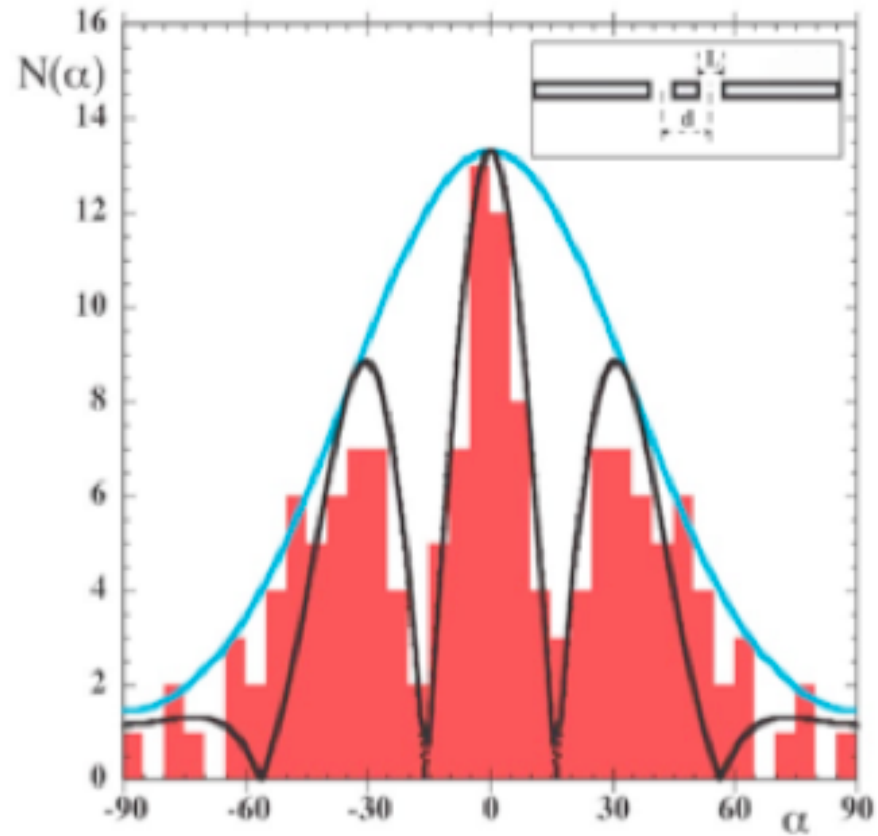
Data fit to Fraunhofer diffraction pattern: $$f(\alpha) = A\left|\frac{\sin(\pi L \sin\alpha/\lambda_F)}{\pi L \sin\alpha/\lambda_F}\right|.$$

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

Double-slit experiment

Couder & Fort (2005)





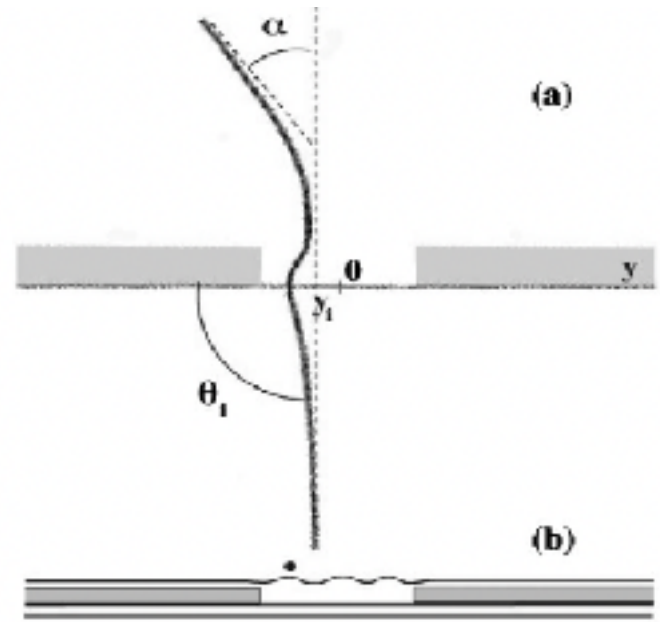
- data gathered from 75 trajectories from a single drop, symmetrized

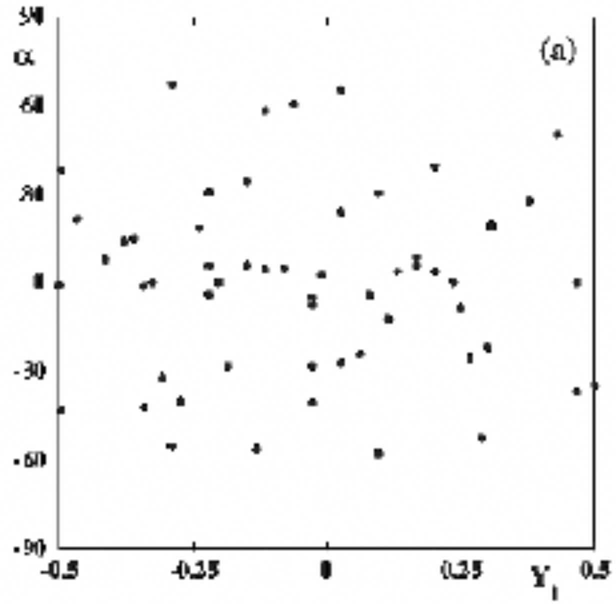
Fit to Fraunhofer diffraction pattern: $f(\alpha) = A \left| \frac{\sin(\pi L \sin\alpha / \lambda_F)}{\pi L \sin\alpha / \lambda_F} \cos(\pi d \sin\alpha / \lambda_F) \right|$

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

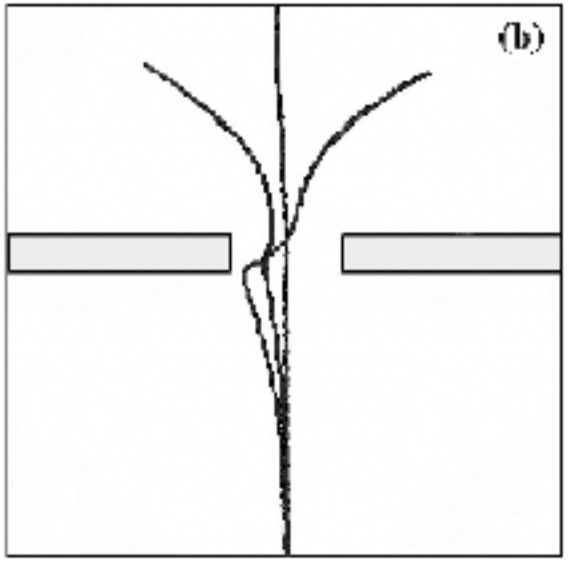
- run just below Faraday threshold to ensure extended pilot-wave
- particle passes though one slit, but its wave is influenced by both

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

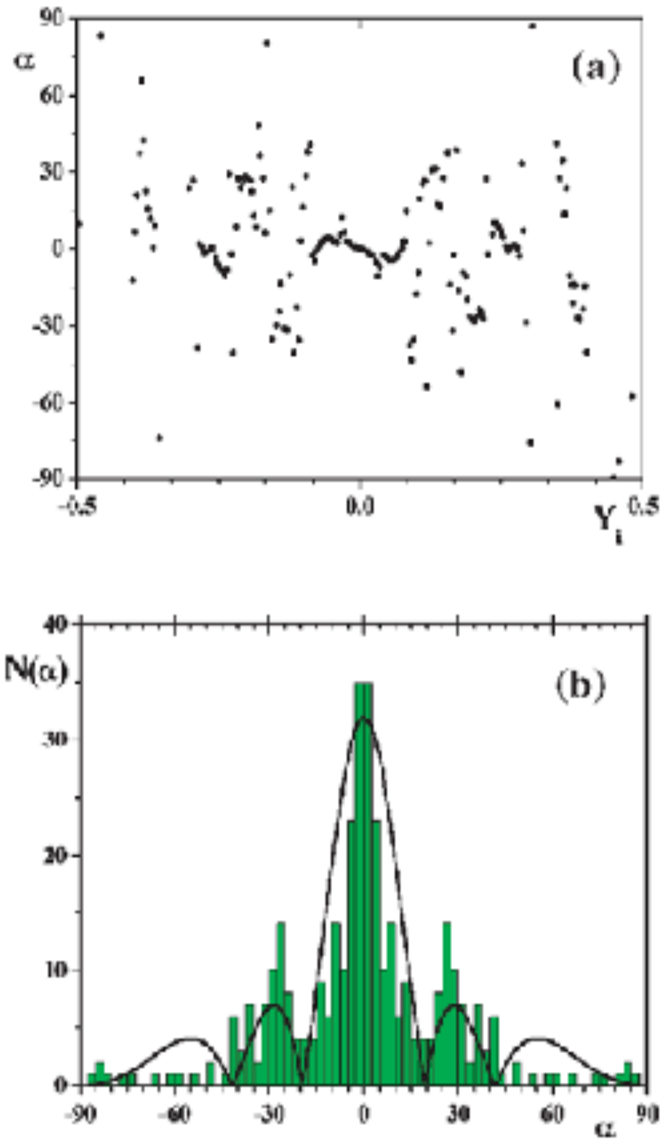
- all were performed in a single session with a single drop
- neither drop size nor vibrational acceleration were either reported or measured
- experiments performed without a lid, exposing experiments to ambient air currents

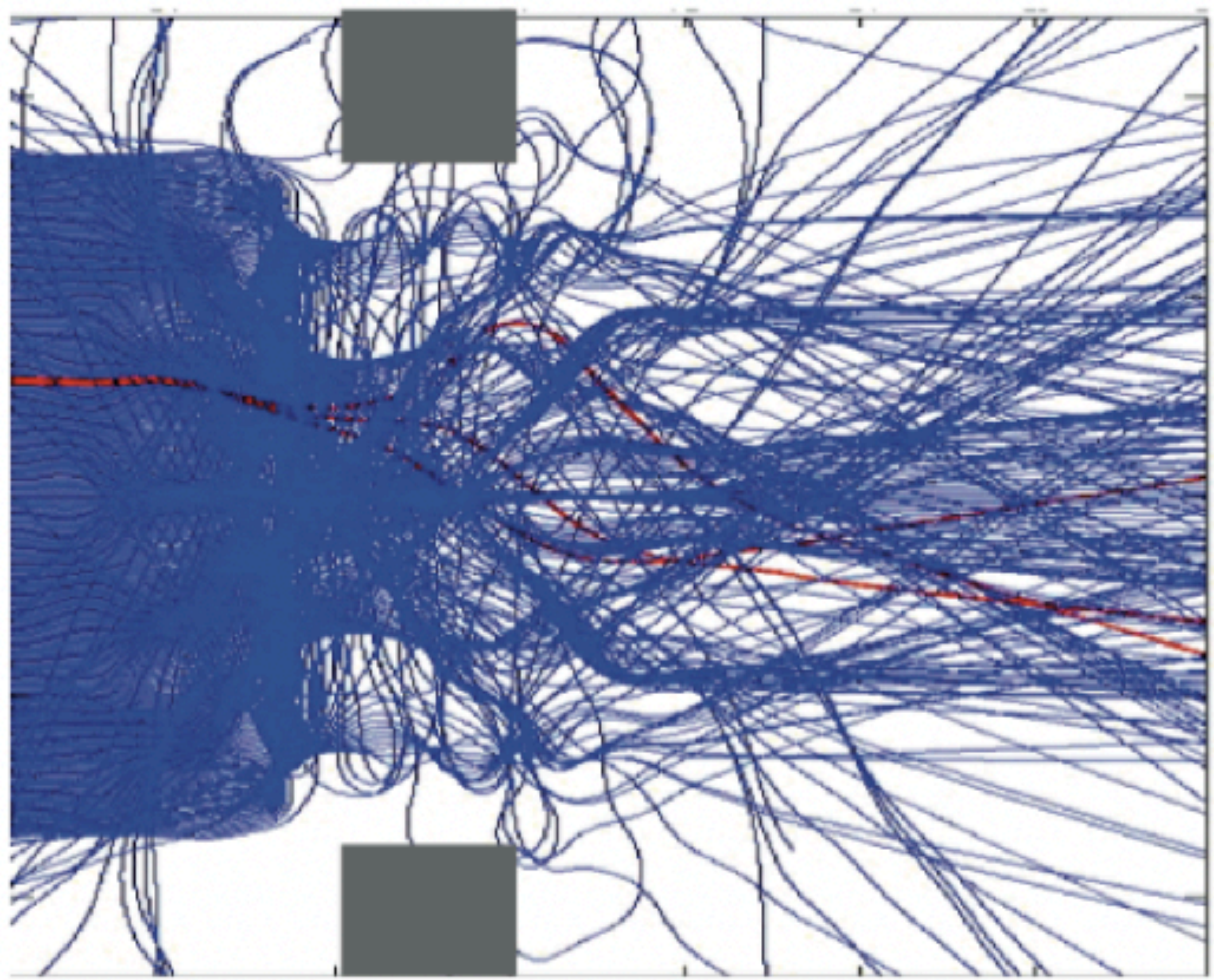
The path-memory model

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

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

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





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, interfere, guide the particle

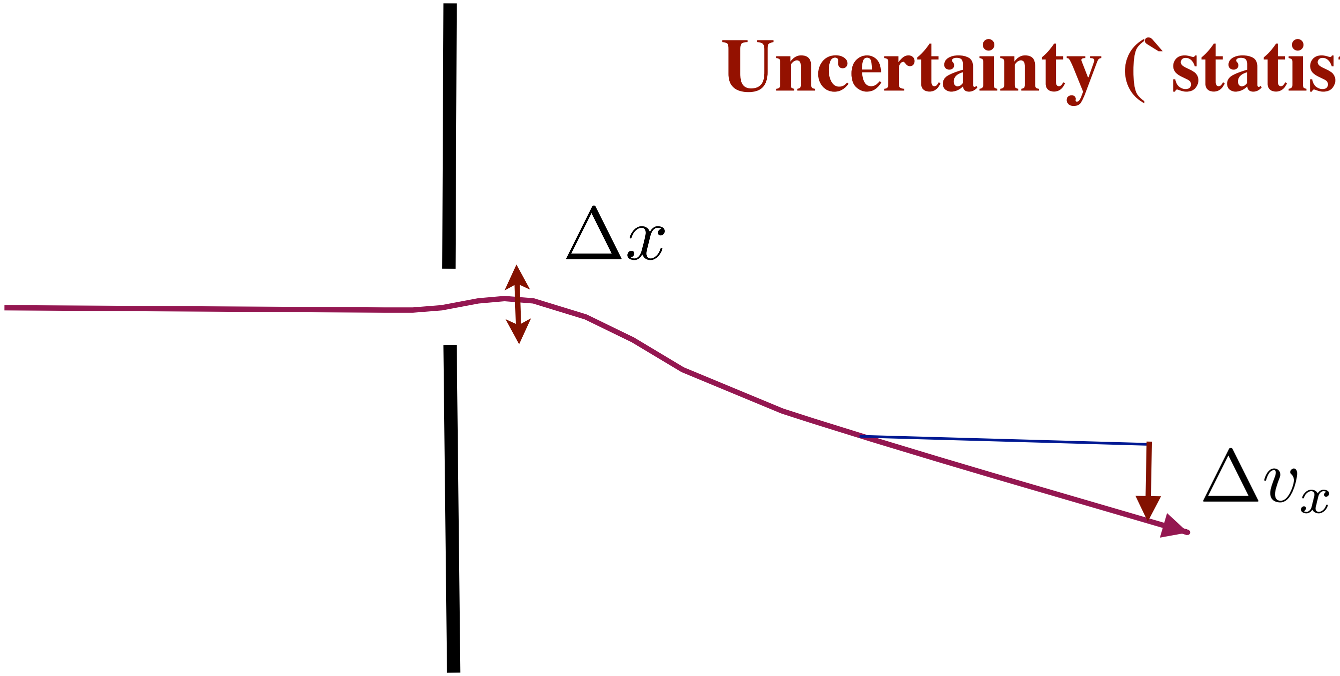
And in the bouncing droplet experiments?

- there is no measurement problem
- 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

Uncertainty (`statistical scatter') relations

Couder & Fort (2005)



Spatial confinement of a plane wave: $\Delta x \, \Delta k_x \geq 1/2$

Heisenberg's Uncertainty Principle:

De Broglie relation: $p = \hbar k \longrightarrow \Delta p_x \, \Delta x \;\geq\; \hbar/2$

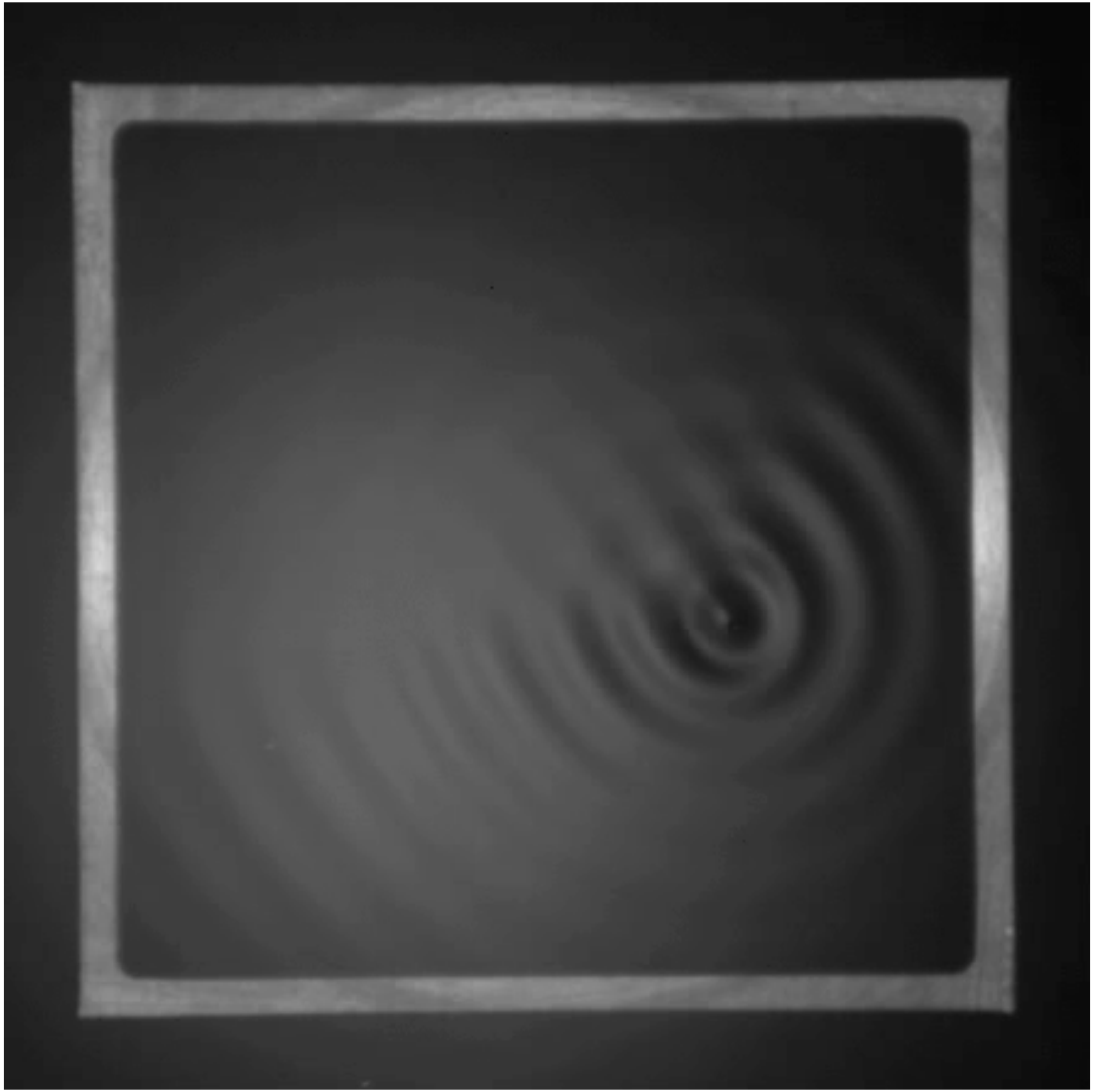
Hydrodynamic Uncertainty relation:

Guidance equation: $v = F(k) \longrightarrow$

$$\boxed{\Delta v_x \, \Delta x \;\geq\; F'(k)/2}$$

Droplet tunneling

Eddi et al. (2009)



Droplet tunneling

Eddi et al. (2009)

- probability of tunneling decreases with wall width and distance from threshold
- tunneling requires proximity to Faraday threshold, pronounced waves

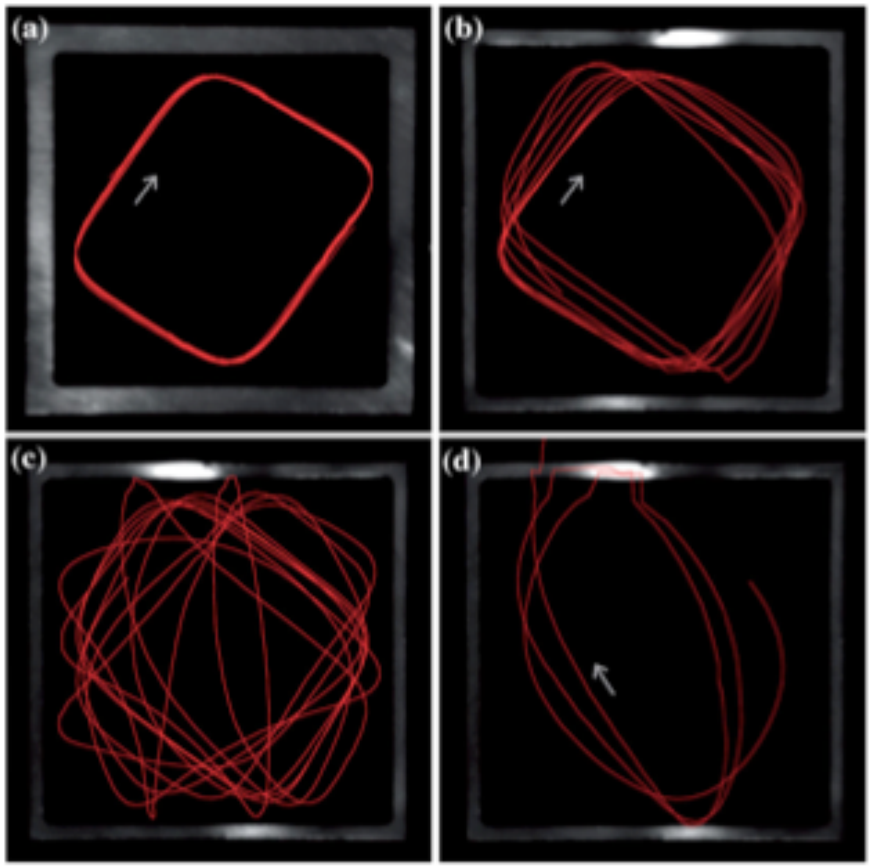
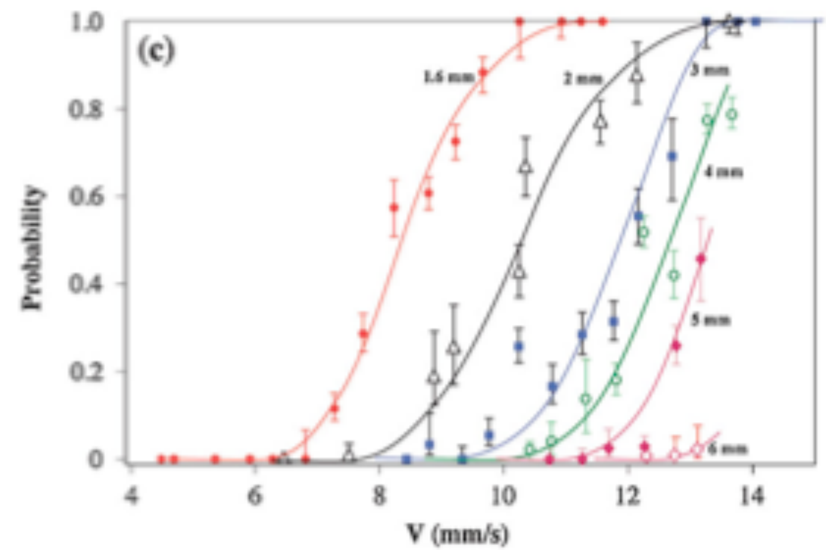
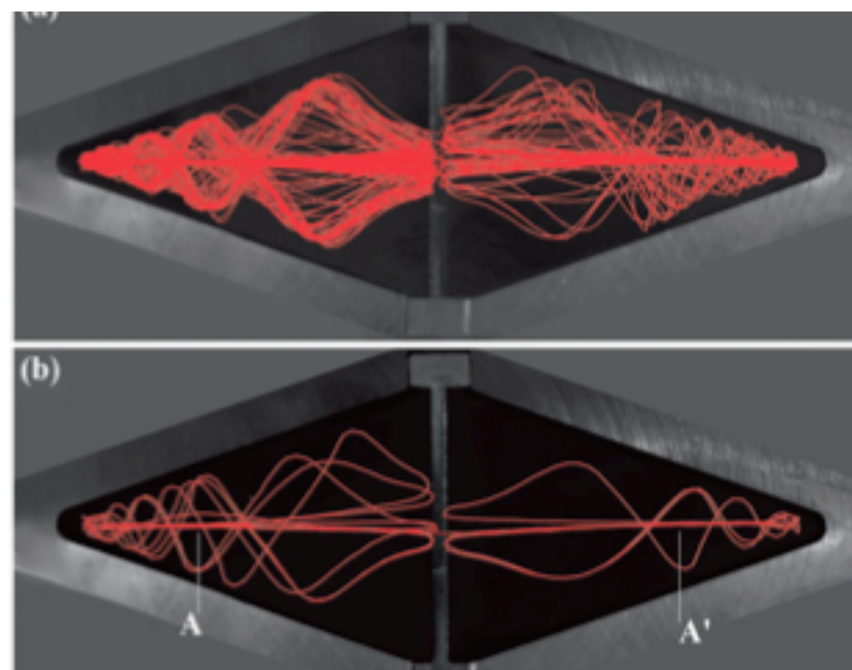
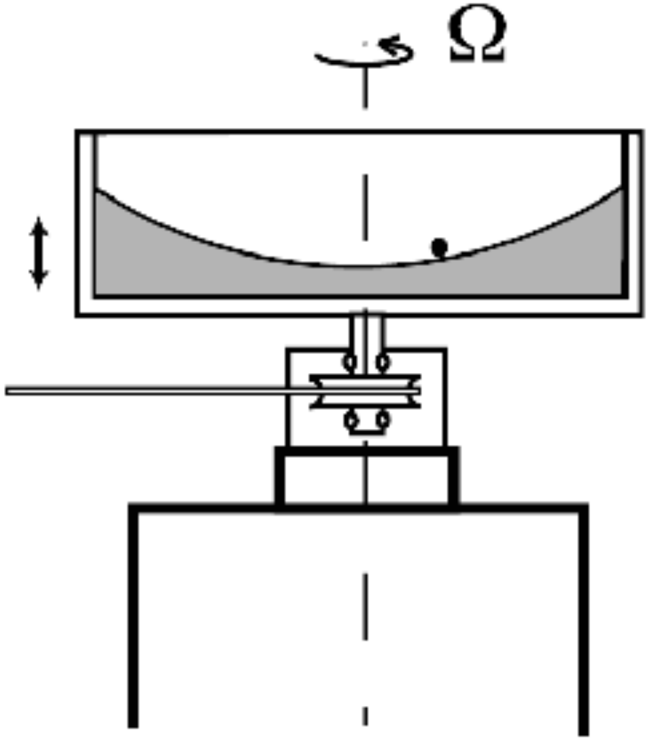


FIG. 4 (color online). The recorded trajectories of the walker inside the square trap of side $L = 55$ mm. In (a) $e = 4.5$ mm and $V = 9.95$ mm/s. In (b) $e = 2.5$ mm and $V = 9$ mm/s. The probability of escape P is of the order of 1%. In (c) $e = 2.5$ mm and $V = 11.8$ mm/s. $P \simeq 10\%$. In (d) $e = 2.5$ mm and $V = 13.2$ mm/s. $P \simeq 30\%$.





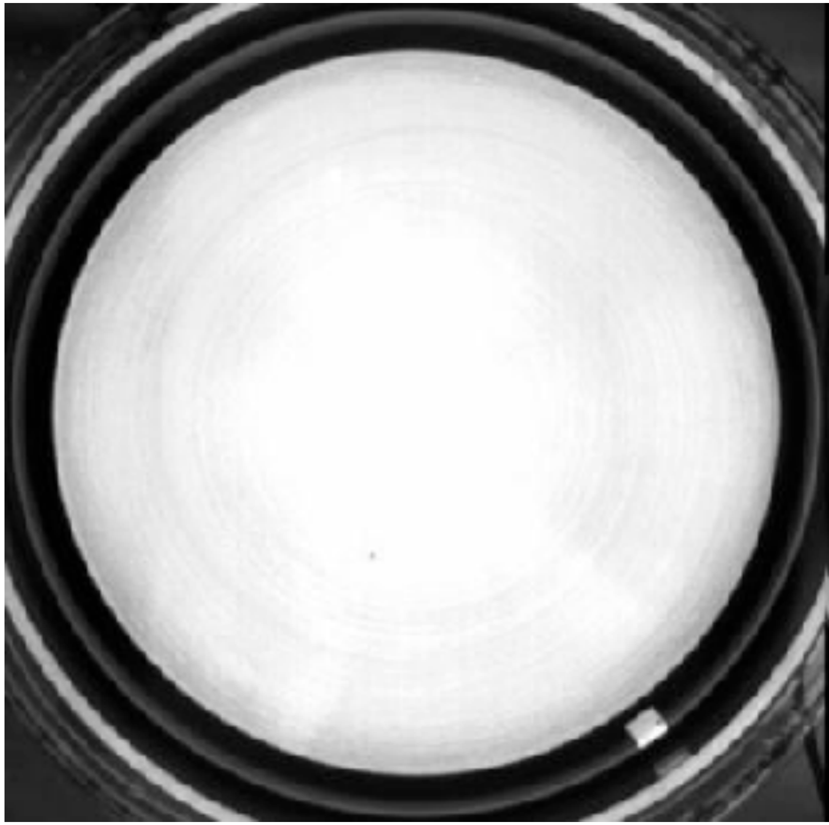


Walker on a rotating bath

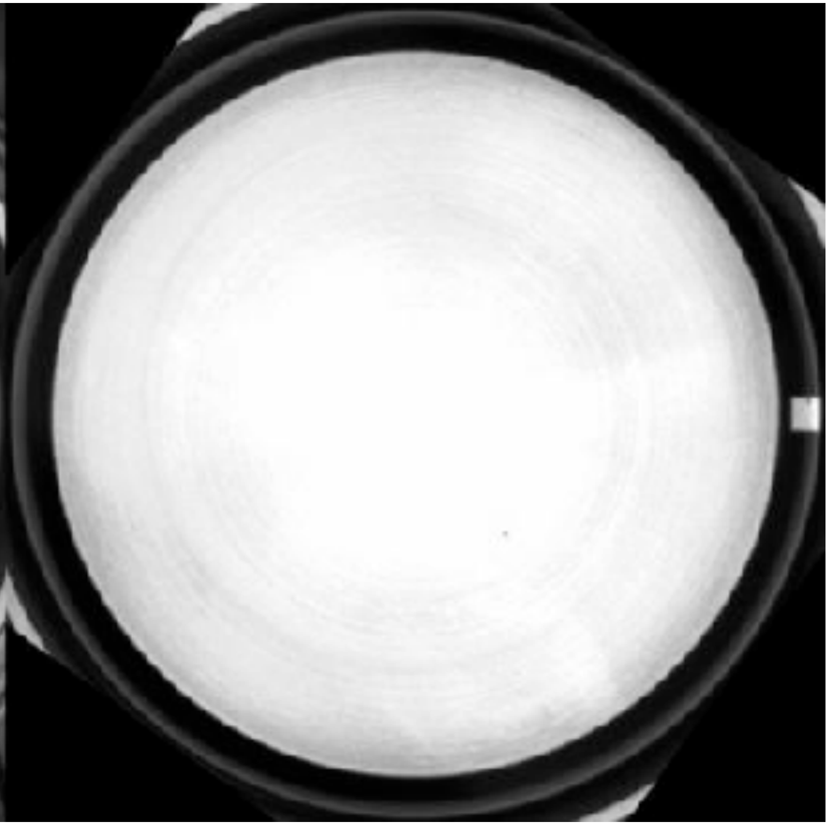
Fort et al, *PNAS* **107** (41) 17515-17520 (2010)

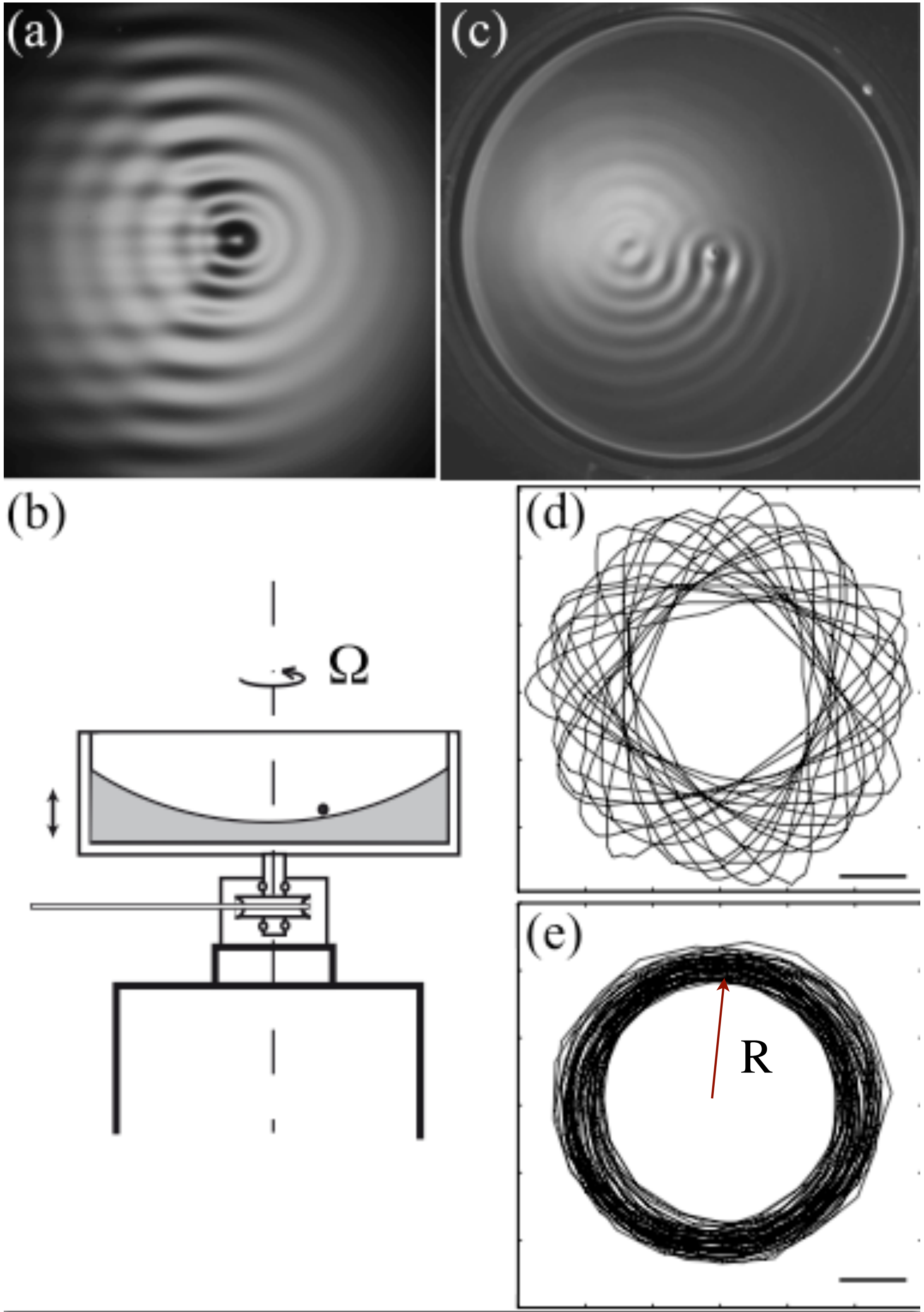
- parabolic interface represents an isopotential surface

Lab frame



Rotating frame





Inertial orbits

Fort et al. (2010)

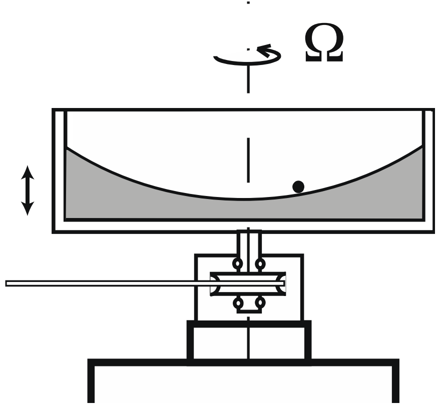
- response to a transverse force
- execute circular orbits on which inertial, Coriolis forces balance:

$$\rho V^2/R = 2\rho\Omega V$$

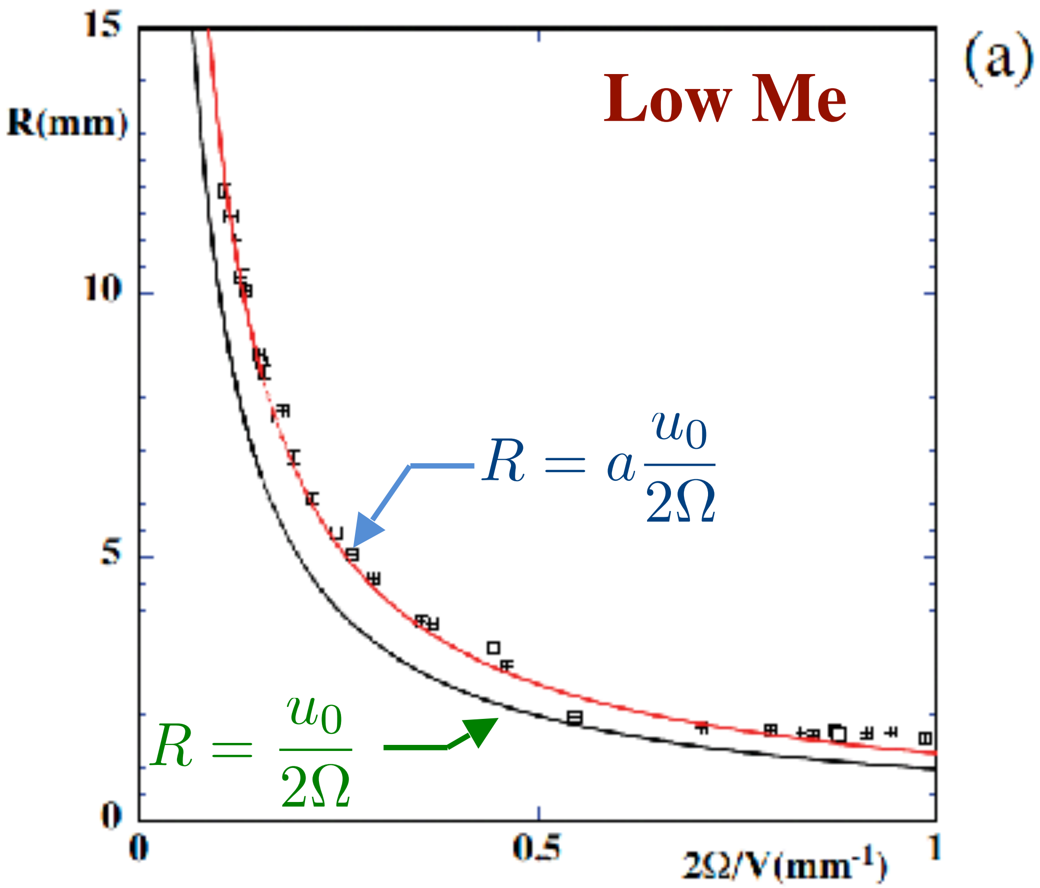
- one expects an orbital radius:

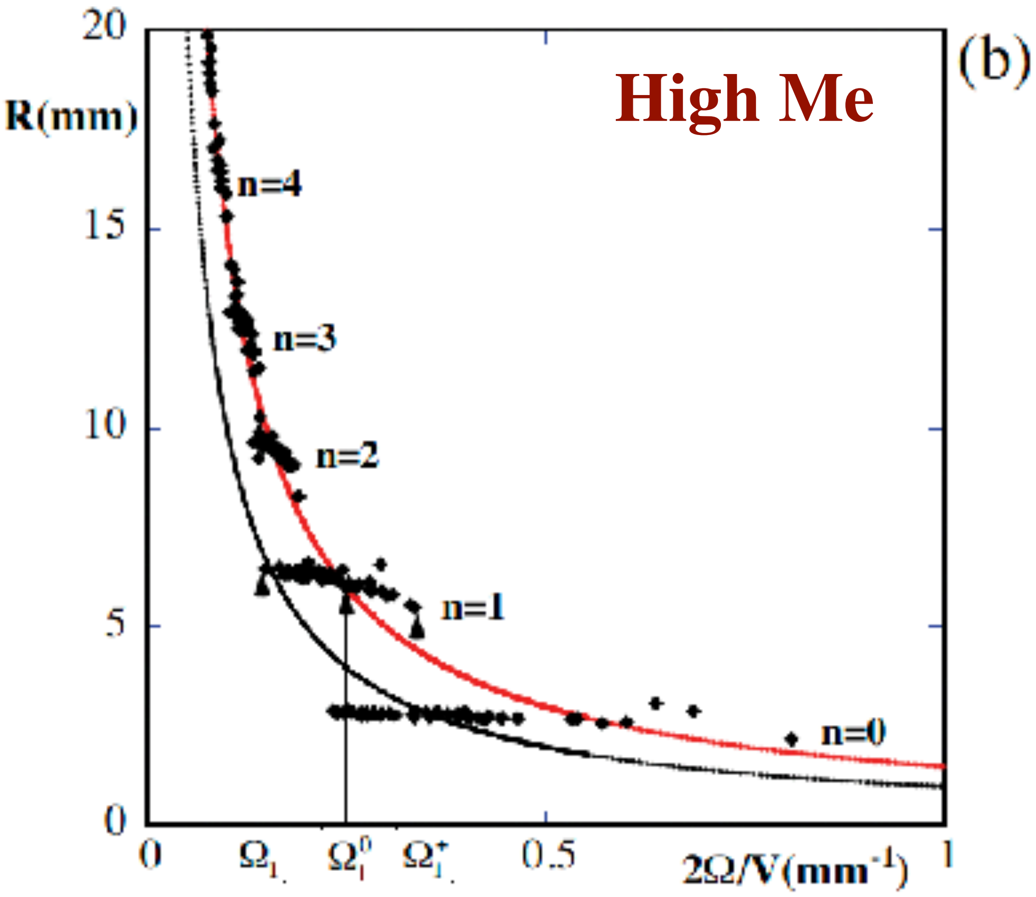
$$R = V/(2\Omega)$$

Dependence of orbital radius on rotation rate



- at low Me, offset from classical suggests enhanced walker mass
- at high Me, orbital quantization emerges since drop interacts with its own wake



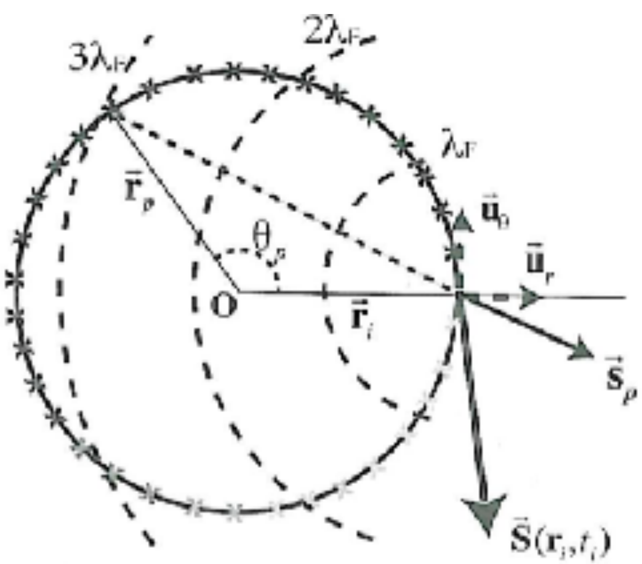


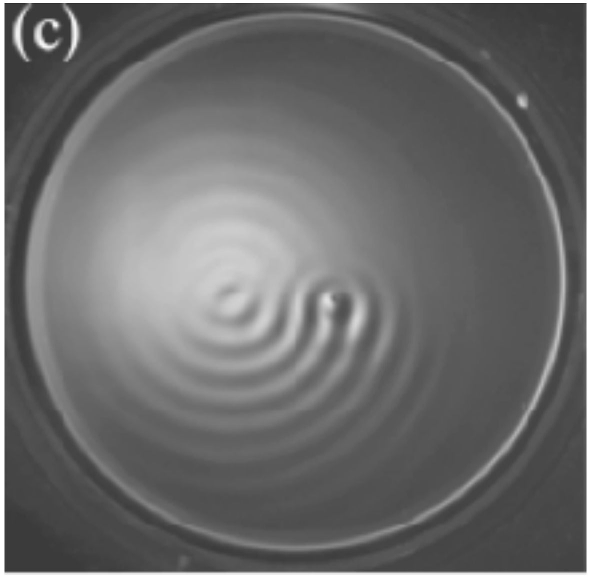
Quantized orbital states

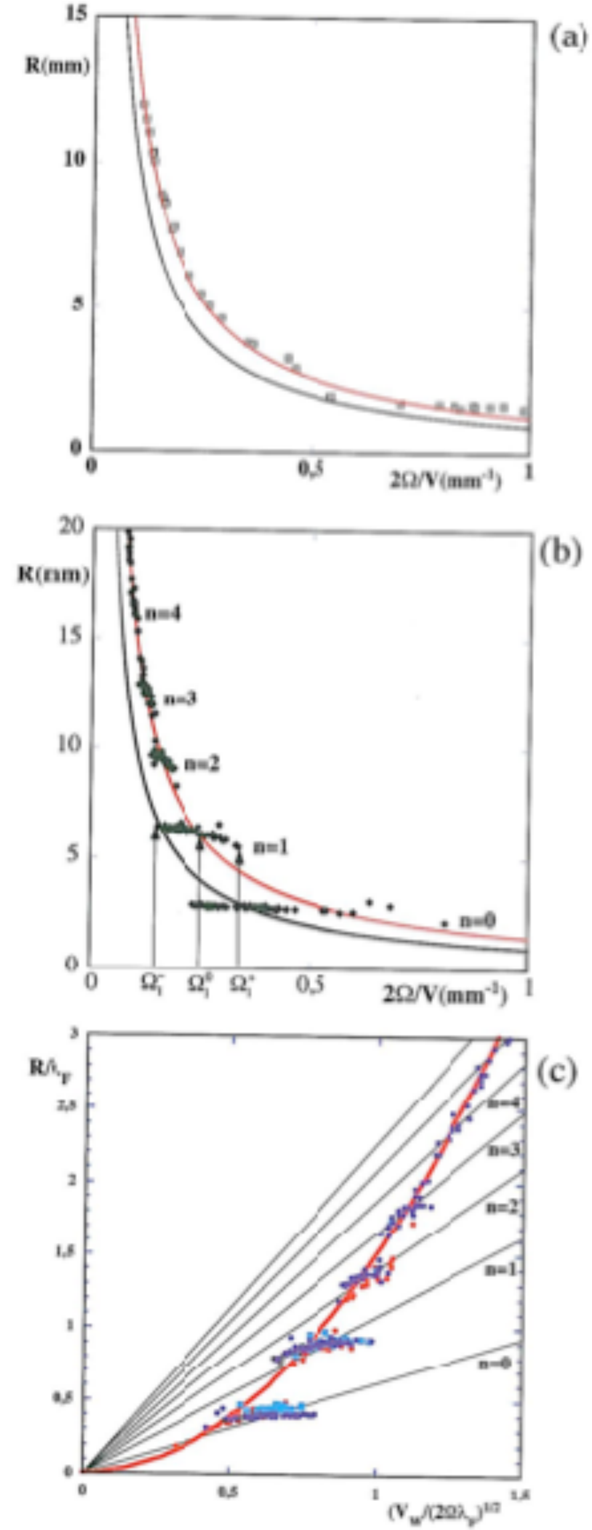
- emerge as Faraday threshold is approached

$$R_n \sim \frac{1}{2}(n + 1/2)\lambda_F$$

- 3rd force, memory effect (associated with interaction with wave field) induces quantization







Landau orbits

- charge of mass m, charge q orbits magnetic field $\mathbf{B}$

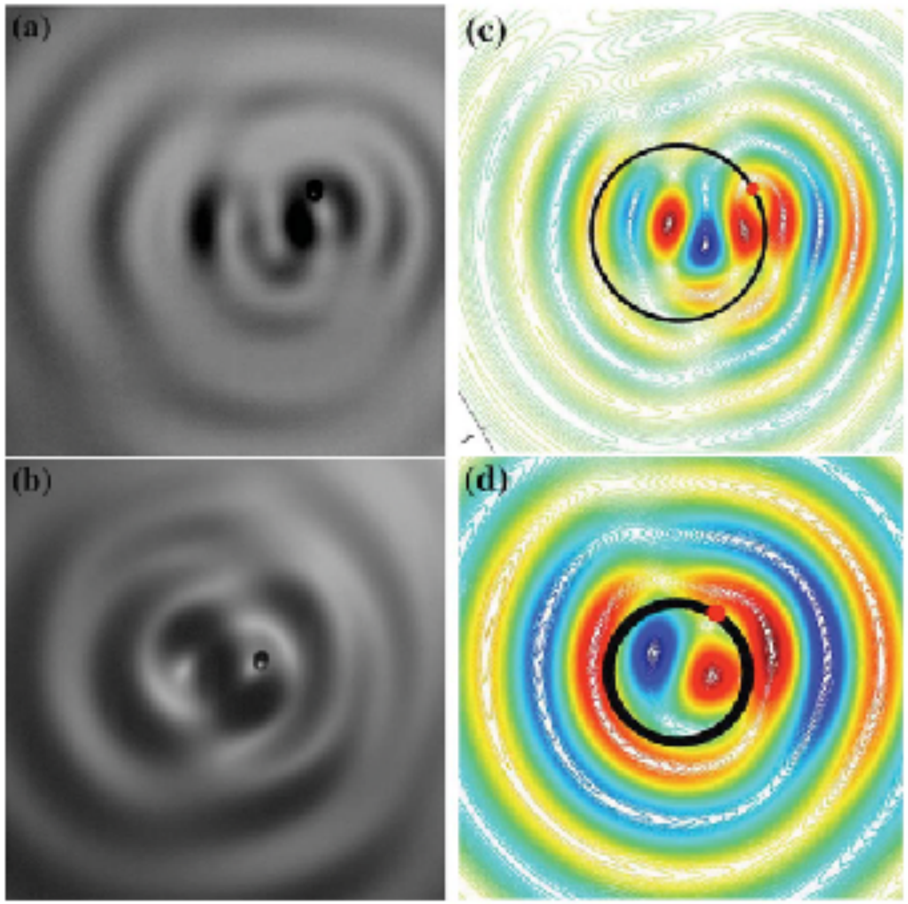
Inertial orbits

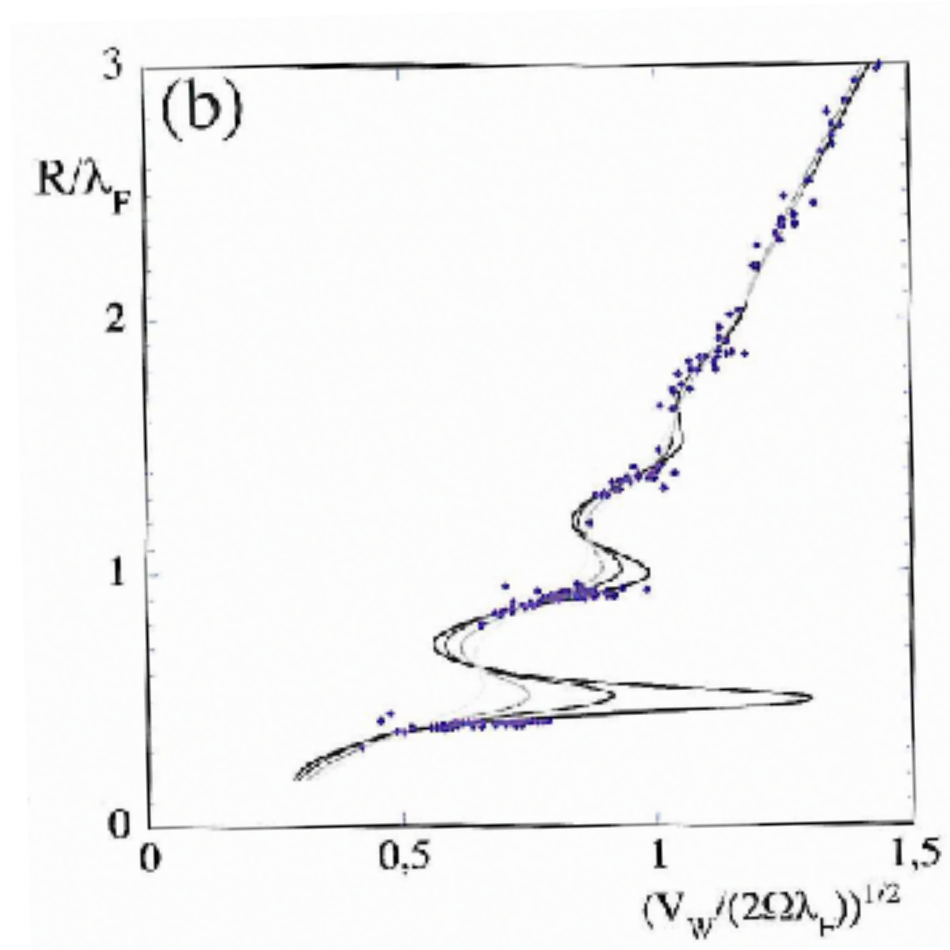
- walker of mass m orbits a vortex $2\mathbf{\Omega}$

Landau orbits		Inertial orbits
$\mathbf{F_B} = q(\mathbf{v} \wedge \mathbf{B})$	Force	$\mathbf{F_C} = -m(\mathbf{v} \wedge 2\mathbf{\Omega})$
$R_L = mv/(qB)$	Radius	$R_C = v/(2\Omega)$
$\tau_L = m/(qB)$	Period	$\tau_C = 1/(2\Omega)$
$R_n = \frac{1}{\pi}(n+1/2)\lambda_{dB}$ Larmor levels	Orbit levels	$R_n \sim \frac{1}{2}(n+1/2)\lambda_F$ Couder levels
λ_{dB} de Broglie wavelength	Quantum step	λ_F Faraday wavelength

Accompanying theoretical modeling

- path-memory model captures orbiter wave field, emergent orbital radii



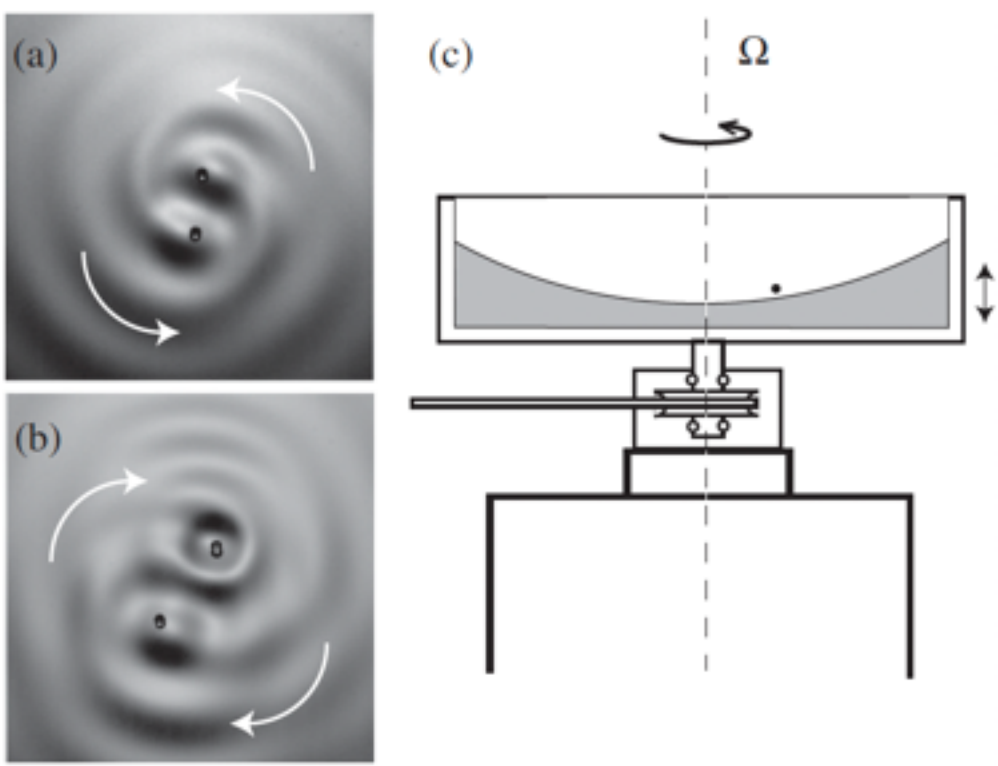


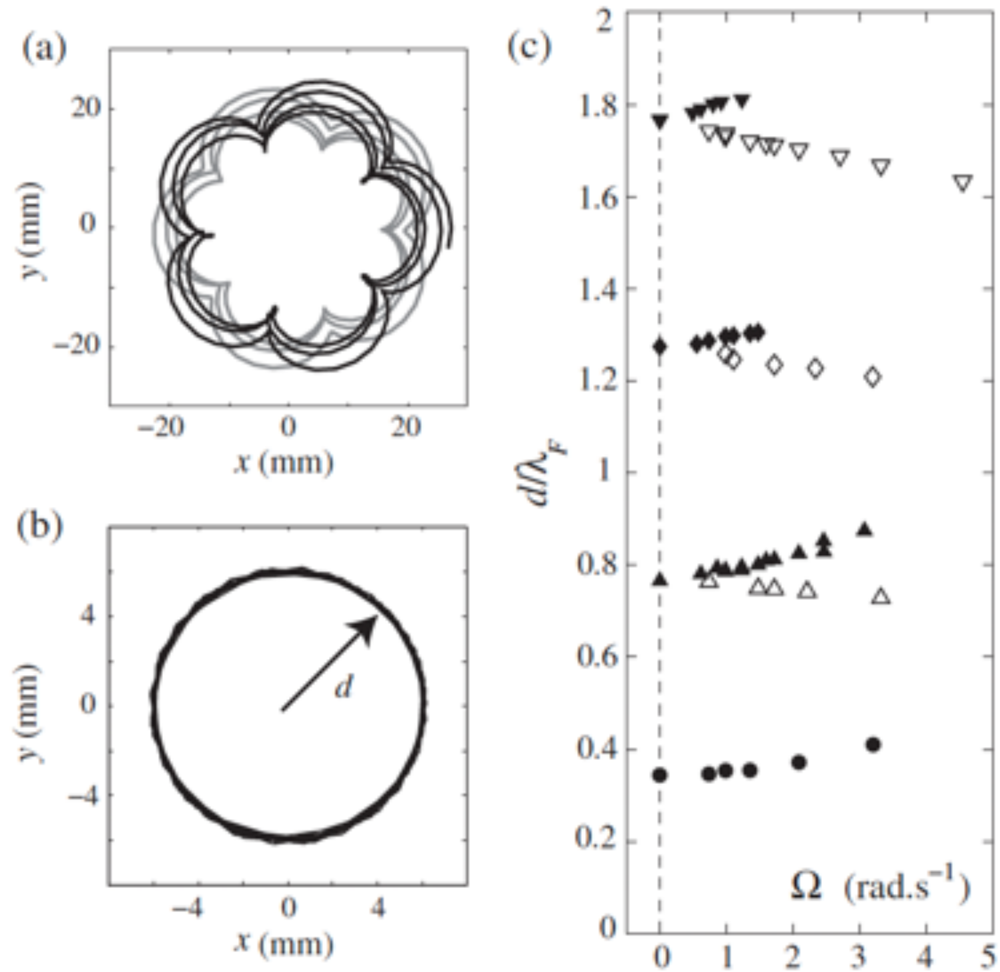
- can associate wave forms, quantized wave modes, with trajectories
- does not rationalize orbital stability, or consider the chaotic, high Me limit

Eddi *et al.*, *PRL* (2012)

Analog Zeeman splitting of orbiting pairs

- the Zeeman effect is the splitting of spectral lines in the presence of a uniform **B**
- invoke Coriolis-Lorentz equivalence: orbital radii split by applied rotation
- for orbiting pairs, change proportional to applied rotation $\frac{\Delta r}{\lambda_F} \sim \Omega$



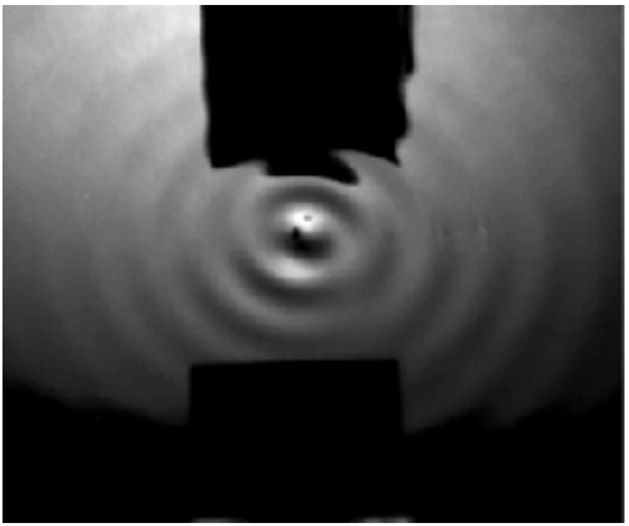


Walkers in a central force

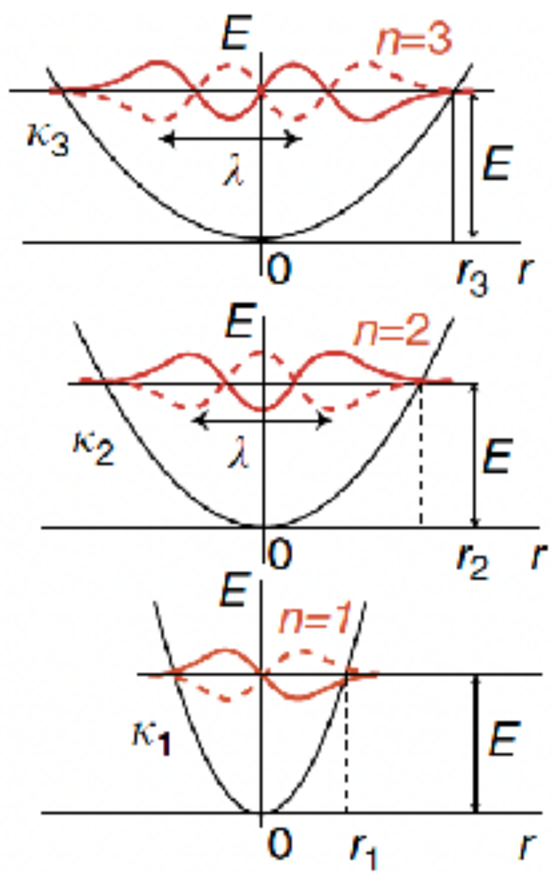
Perrard *et al*. (2014ab)
Labousse *et al*. (2015)

- ferrofluid suspended within the walking droplets
- vertical magnetic field with radial gradient gives rise to simple harmonic potential

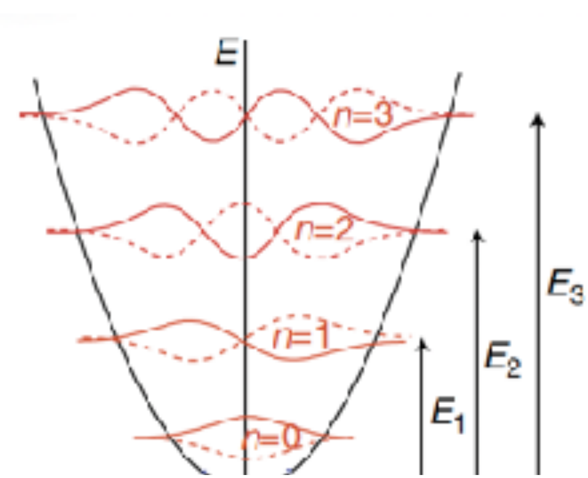
Video: Stéphane Perrard

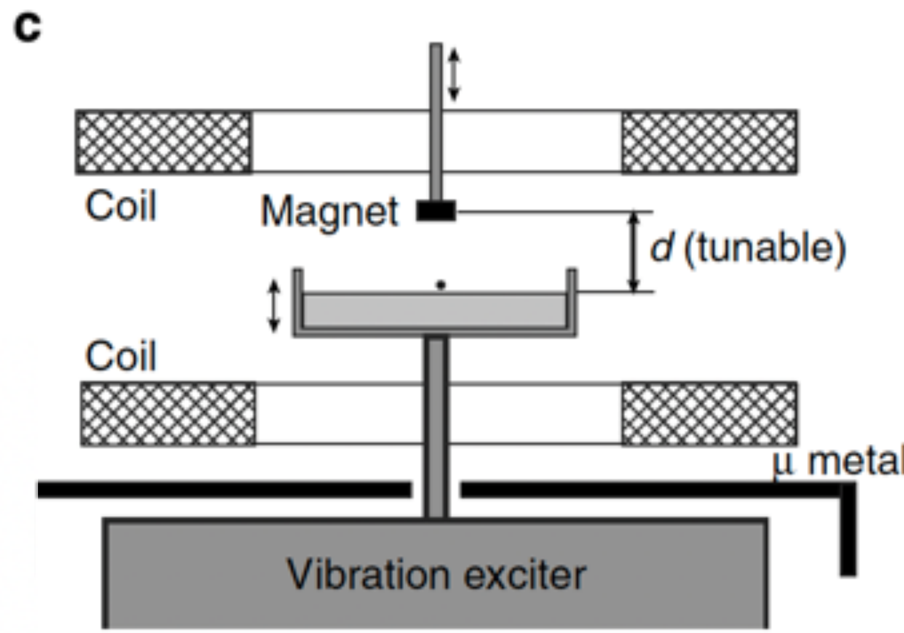


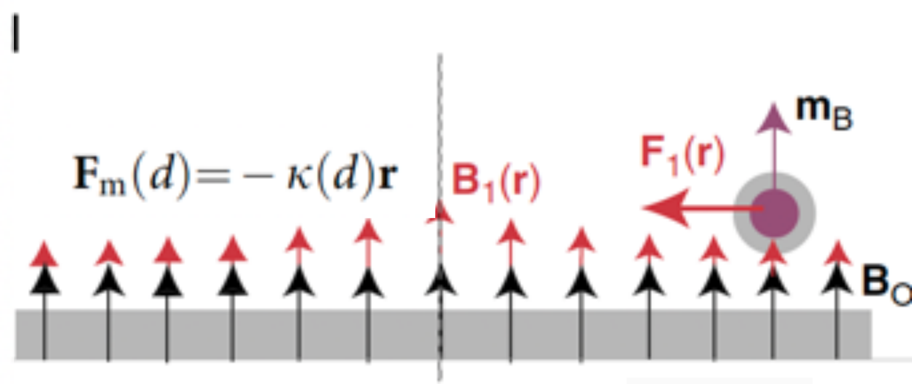
Walker SHO



QM SHO

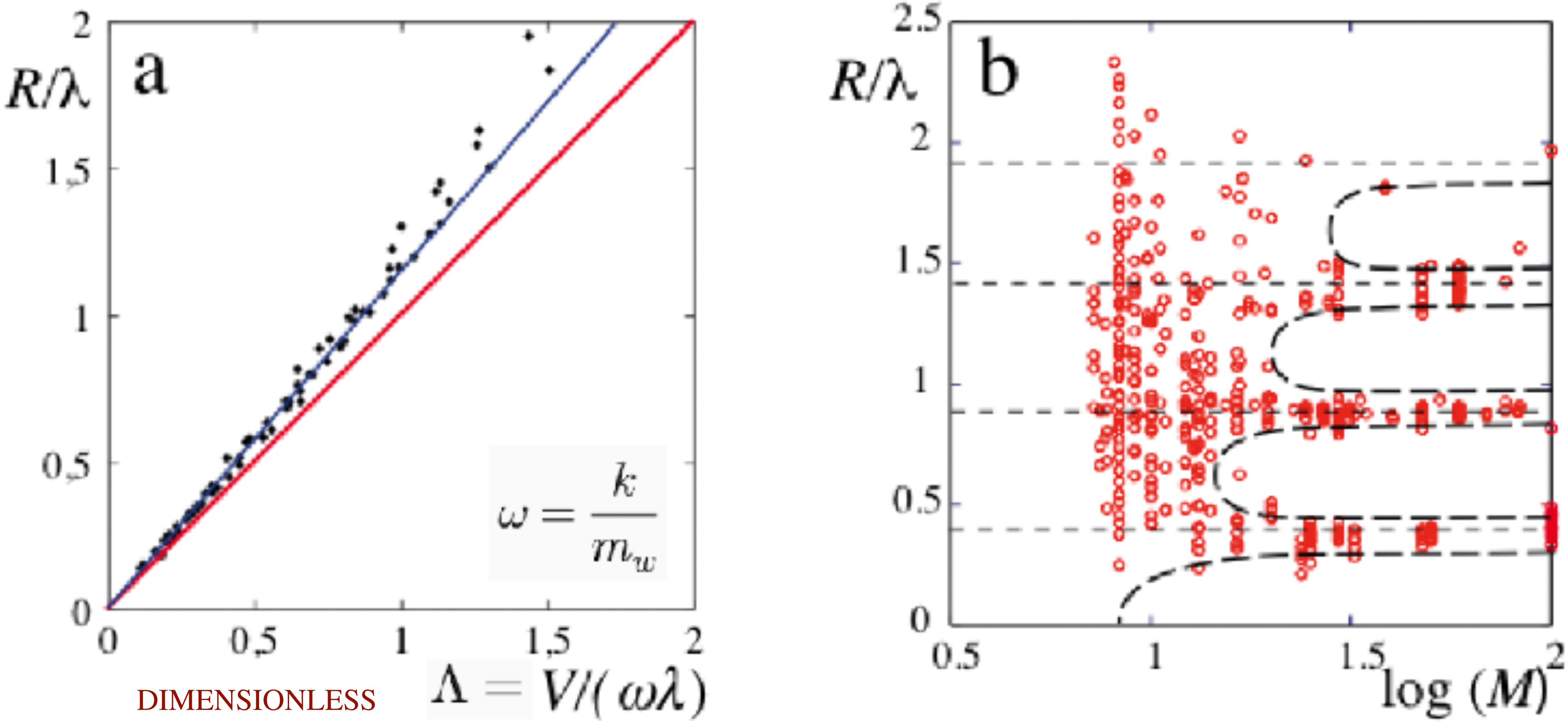






Spring frequency: $\omega = \frac{k}{m_w}$

Walkers in a central force

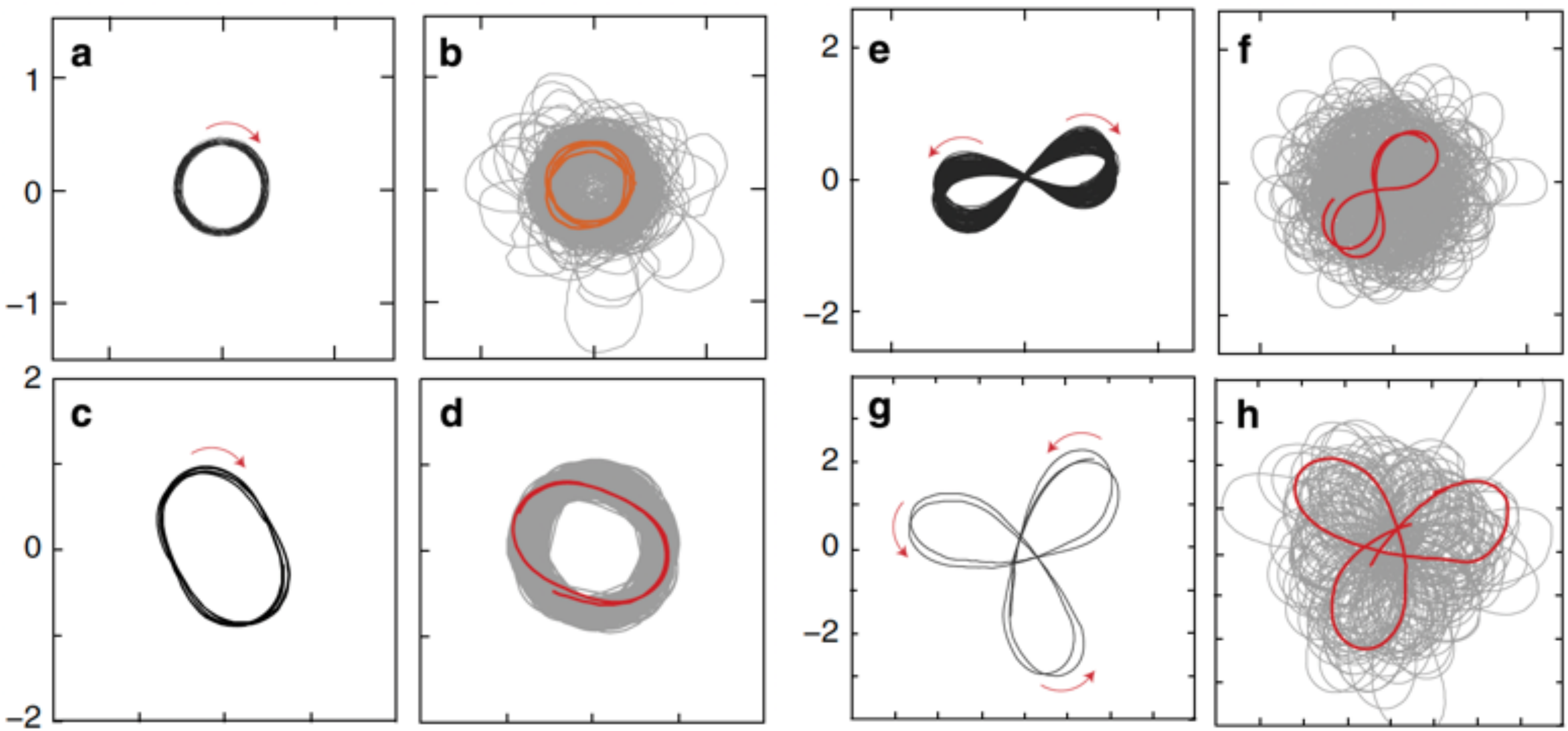


DIMENSIONLESS
WIDTH OF POTENTIAL WELL

- memory parameter: $M = \frac{T_M}{T_F} = \frac{\gamma - \gamma_F}{\gamma} =$ number of bounces felt by walker
- at low M, continuous dependence of orbital radius on applied voltage
- at high M, only a discrete set of orbital radii are accessible

Periodic and weakly aperiodic orbits

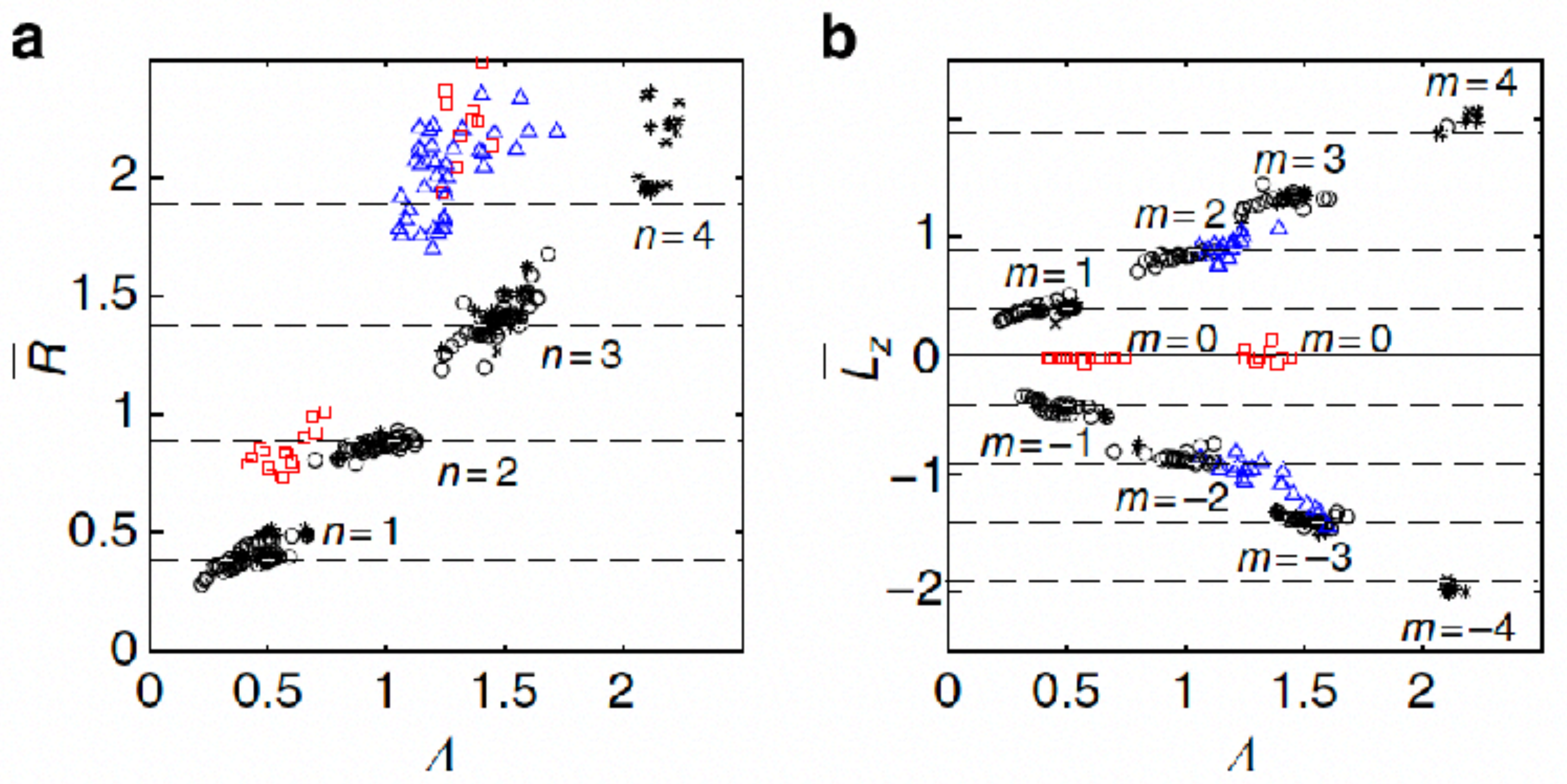
- circular, oval, lemniscate and trefoil trajectories arise
- steady periodic orbits tend to destabilize to precessing states as M increases
- different states may coexist, arise at the same point in parameter space



Orbital quantization

- characterize periodic orbits in terms of mean radius (energy) and angular momentum

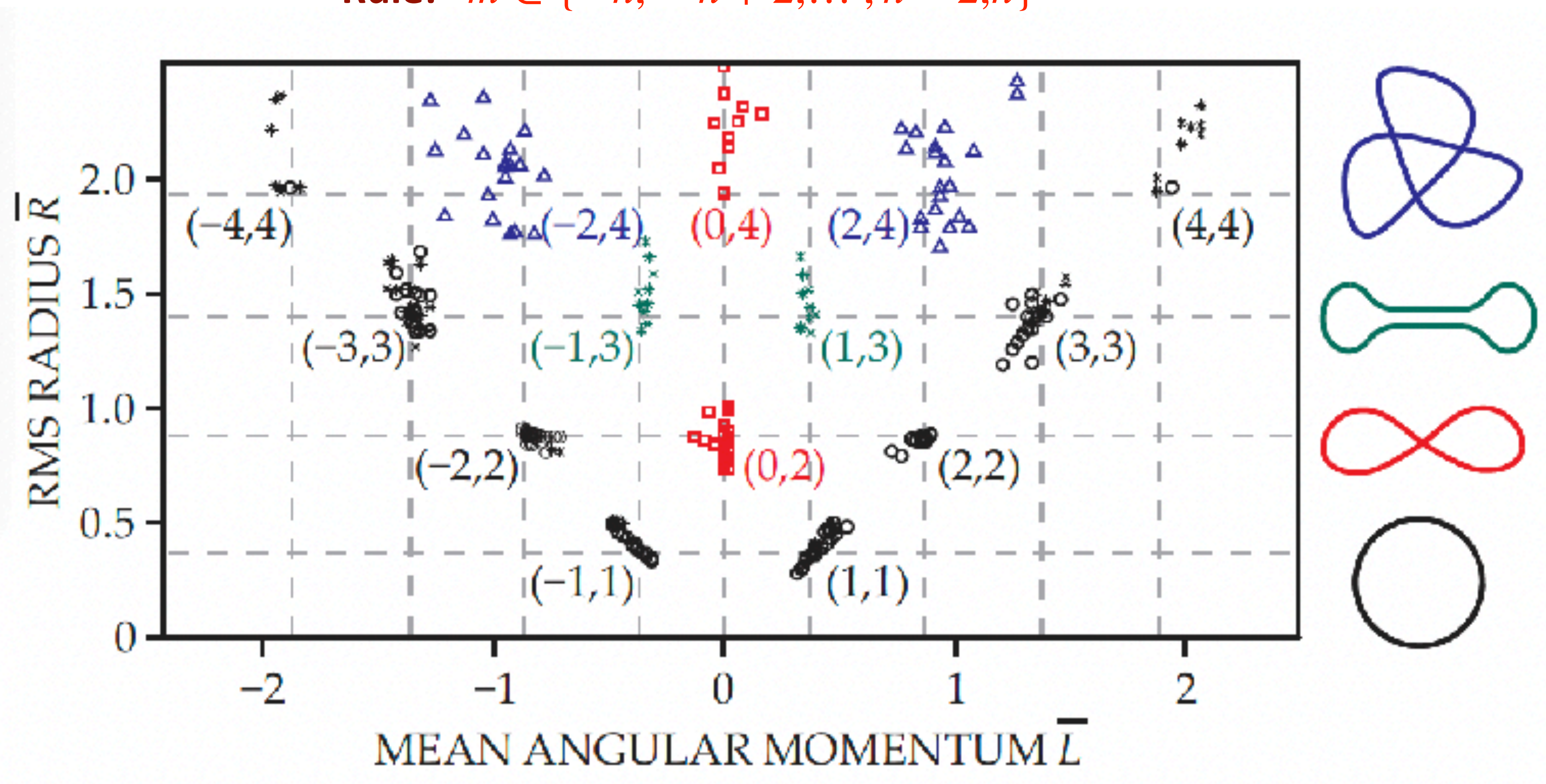
$$\bar{R} = \frac{\sqrt{\langle R^2 \rangle}}{\lambda_F} = \frac{1}{N}\sqrt{\sum_{k=1}^{N} \frac{r_k^2(t)}{\lambda_F^2}}. \qquad \bar{L}_z = \frac{\langle L_z \rangle}{m_W \lambda_F V} = \frac{1}{N}\sum_{k=1}^{N}\left(\frac{\mathbf{r}_k}{\lambda_F} \times \frac{\mathbf{V}_k}{V}\right)$$



Double quantization

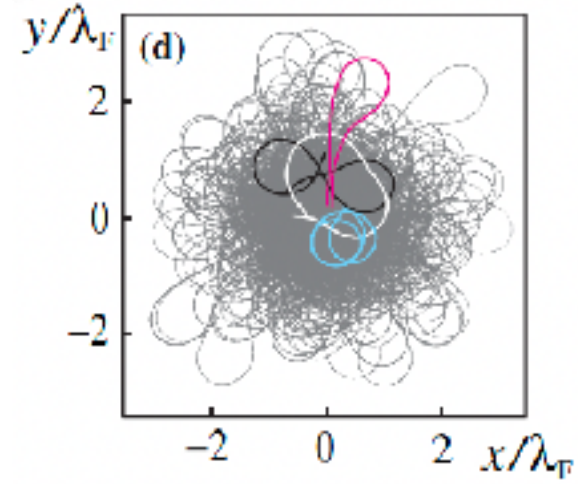
- orbits quantized in both mean radius (energy) and angular momentum
- orbits characterized in terms of states (n, m) reflecting R, L

Rule: $m \in \{-n, -n+2, \dots, n-2, n\}$



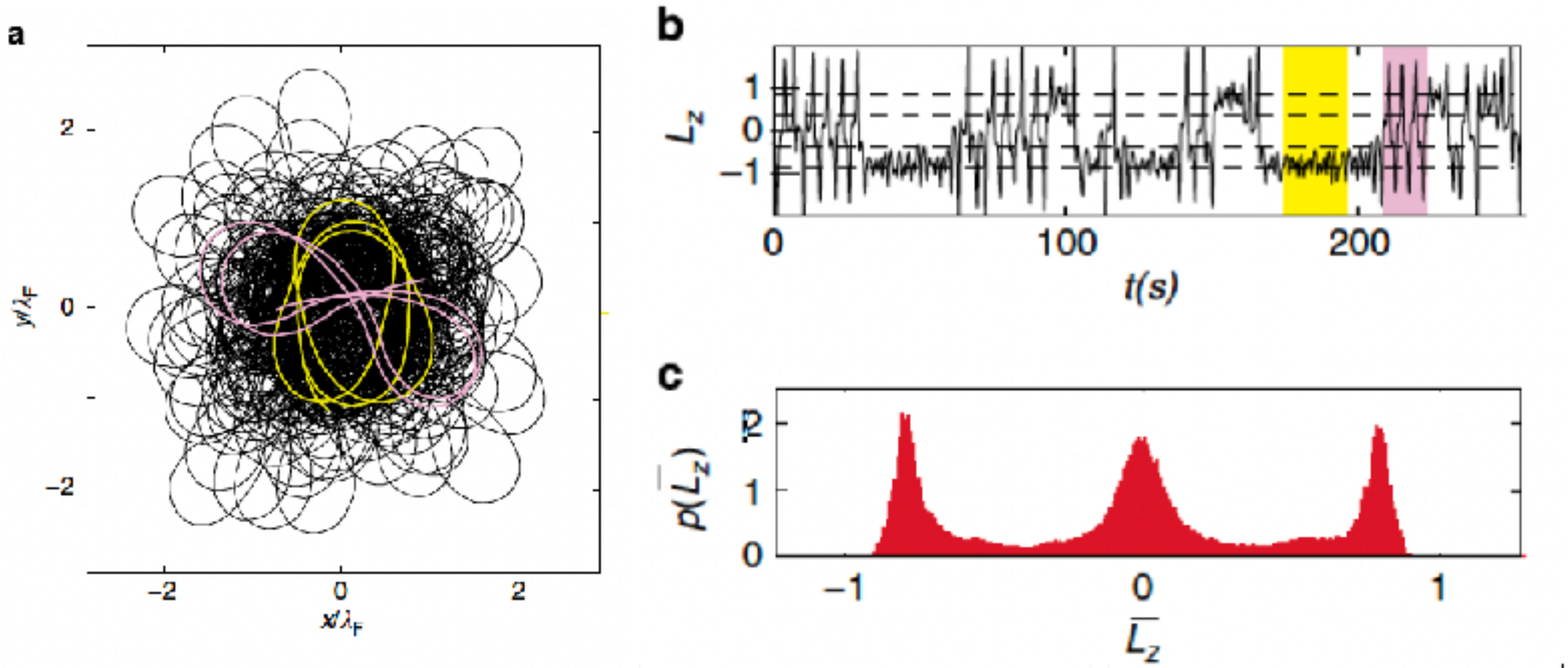
S. Perrard, M. Labousse, M. Miskin E. Fort, Y. Couder, Nature Communication, 5, 3219 (2014)

The chaotic regime at high memory



- droplet switches intermittently between a small number of accessible periodic states

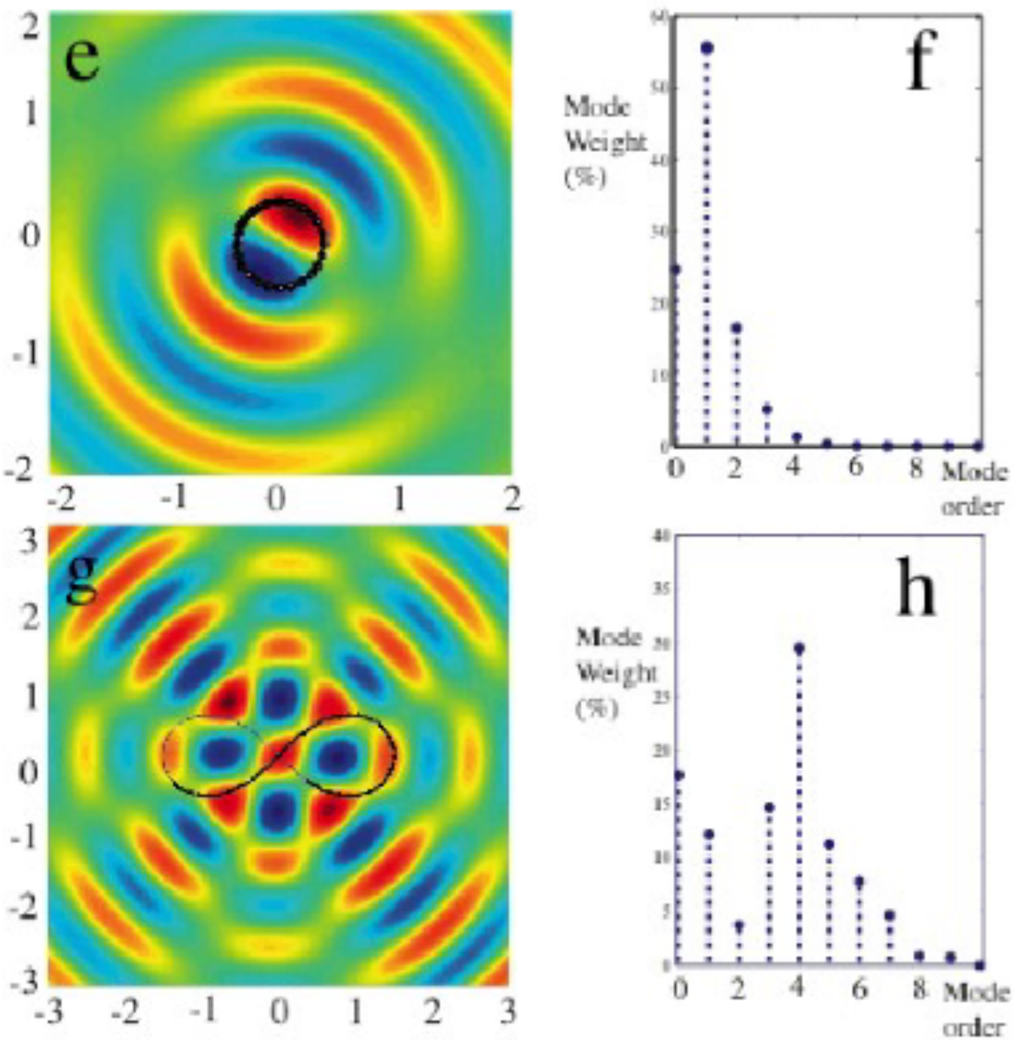
"The detuned trajectory is thus formed from a succession of sequences of pure eigenstates with intermittent transitions between them."



Wave-particle adaptation

"The trajectories that eventually emerge are those for which the trajectory shape and the global wave field have achieved a mutual adaptation."

$$h(\mathbf{r},\ t_i) = A_0 J_0(k_F r) + \sum_{n=1}^{+\infty} J_n(k_F r)\left[A_n \cos(n\theta) + B_n \sin(n\theta)\right]$$



- deduced wave forms of observed periodic trajectories assuming each impact generates a form:

$$h(\mathbf{r}_i,\ t_i) = \sum_{j=-\infty}^{i-1} e^{\frac{t_i - t_j}{\tau}} e^{\frac{|\mathbf{r}_i - \mathbf{r}_j|}{\delta}} J_0\left(k_F|\mathbf{r}_i - \mathbf{r}_j|\right)$$

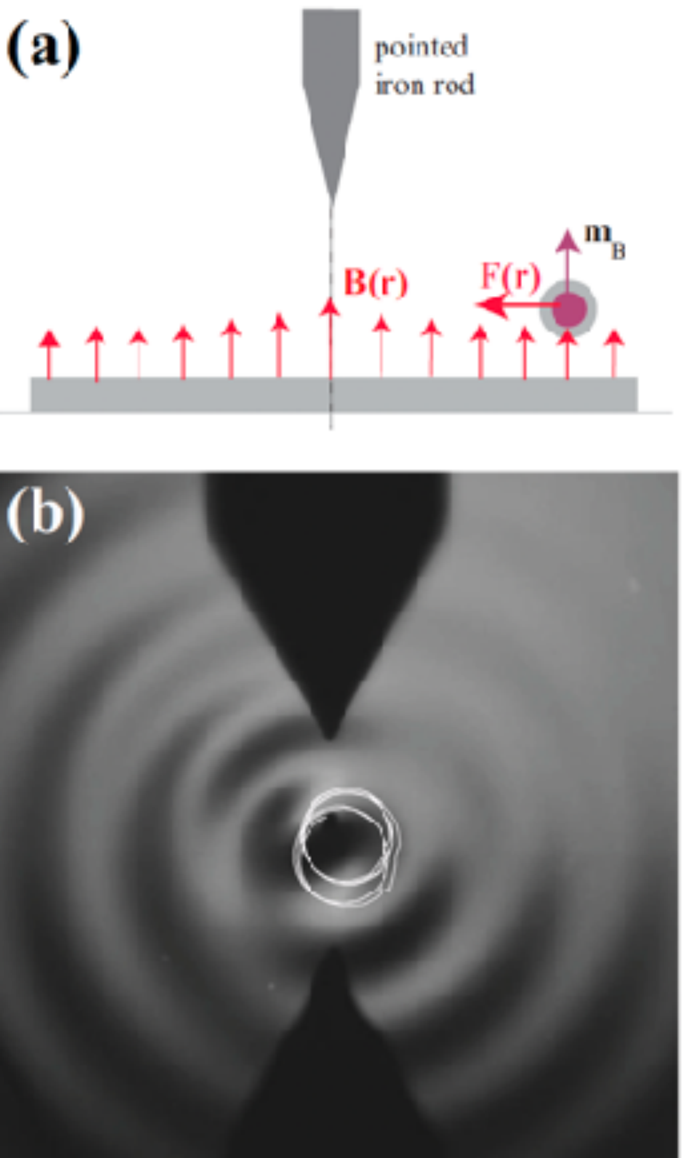
- symmetries of trajectories reflected in associated wave forms

- associate wave modes, energy states, with trajectories

PHYSICAL REVIEW E **94**, 042224 (2016)

Self-attraction into spinning eigenstates of a mobile wave source by its emission back-reaction

Matthieu Labousse,[1,2,*] Stéphane Perrard,[2] Yves Couder,[2] and Emmanuel Fort[1,†]
[1]*Institut Langevin, ESPCI Paris, PSL Research University, CNRS, 1 rue Jussieu, 75005 Paris, France*
[2]*Matière et Systèmes Complexes, Université Paris Diderot, CNRS, Sorbonne Paris Cité, Bâtiment Condorcet, 10 rue Alice Domon et Léonie Duquet, 75013 Paris, France*
(Received 1 June 2016; published 27 October 2016)



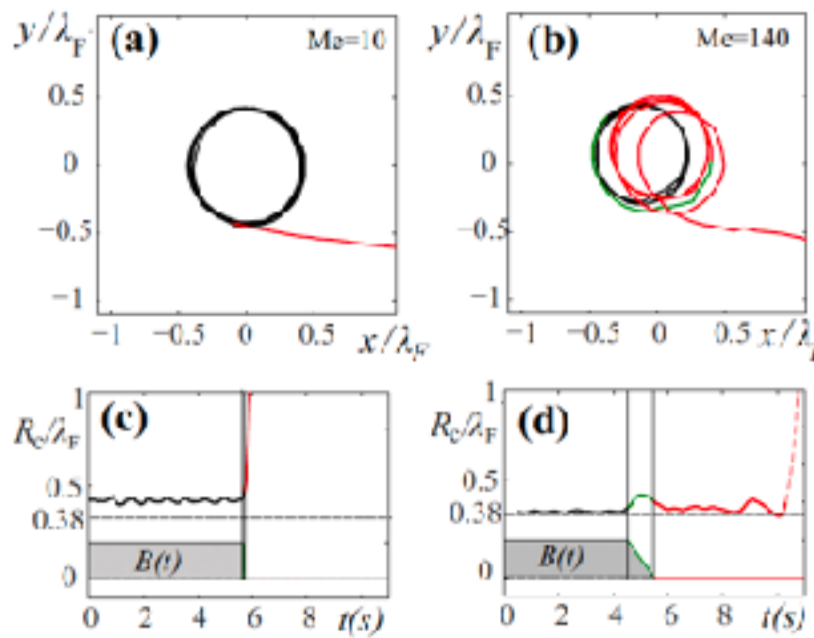
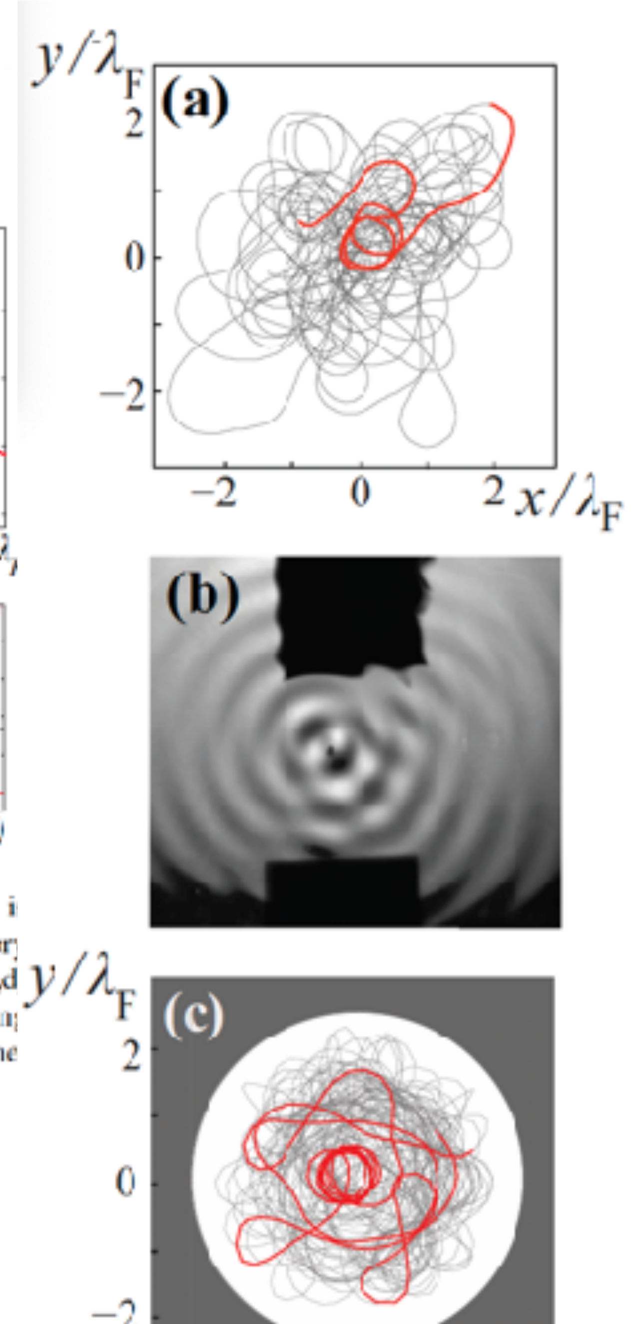


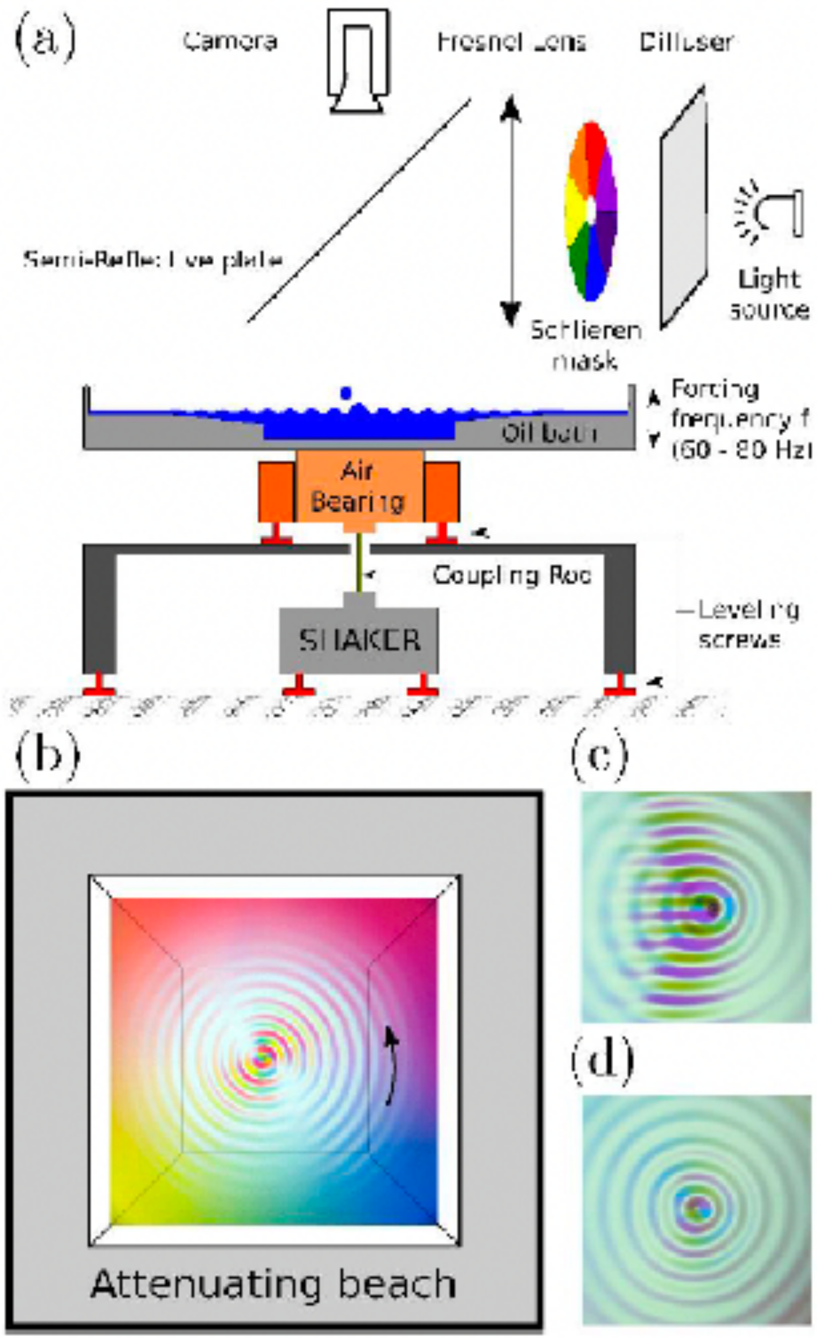
FIG. 2. Typical trajectories observed when the confinement is turned off for two values of the memory parameters. (a) Short memory (Me ≈ 10). (b) Long memory (Me ≈ 140) (see Movie S1 [36]). (c,d) Temporal evolution of the normalized trajectory radius R_c/λ_F along these two trajectories (black: magnetic field on, green: transition time and red: no central force.

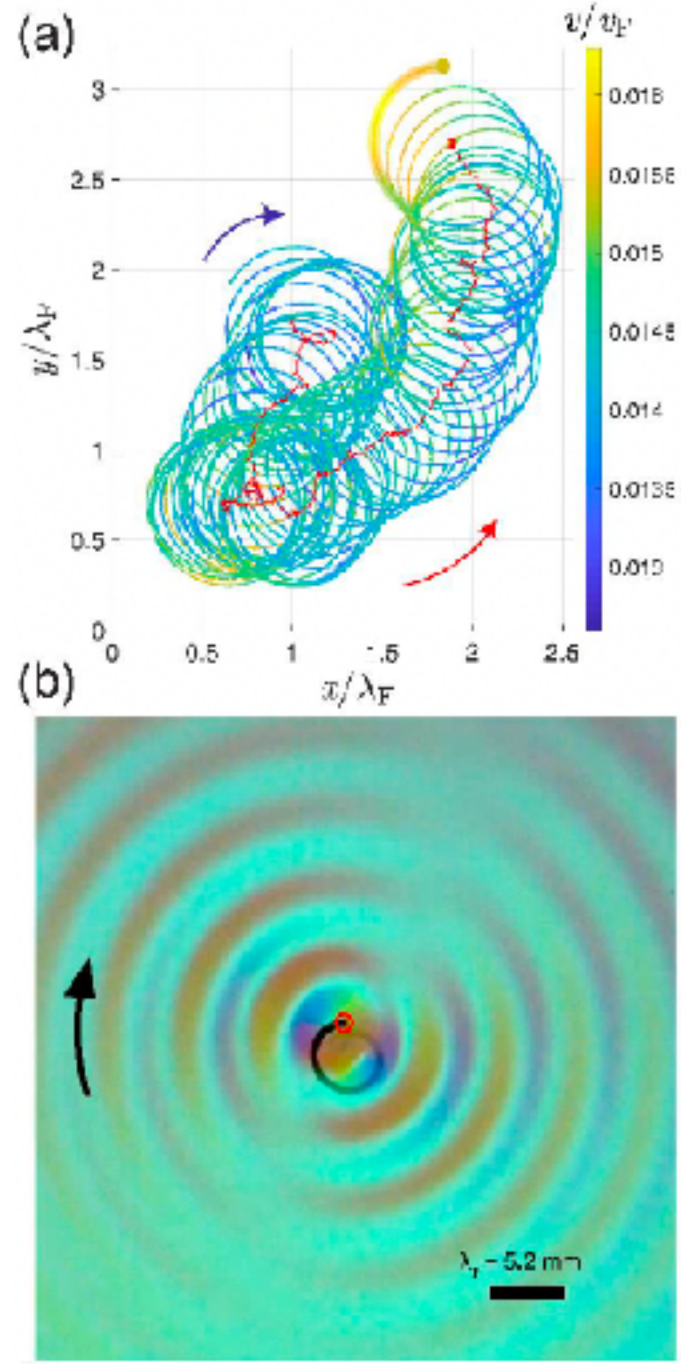


Hydrodynamic spin states

Bernard-Bernardet *et al*. (2023)

- weak topographical confinement enables spin states





Couder's walking droplets

... are a million times larger than the largest quantum particles

... exhibit quantum behavior previously thought to be peculiar to the microscopic realm

... their dynamics are non-Markovian, they quantum features arise because of their path memory

... the represent a macroscopic realization of a pilot-wave system

But can this system really inform the microscopic world?

Or is it all just a strange coincidence?

“We believe that the debate on hidden variables is not closed.”

- Yves Couder, Krogerup Hojskole, August 12, 2011

`We are all living in the gutter, but some of us are staring at the stars.' - Oscar Wilde