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Observation of Liquid Time Crystals

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Mark Whitehead

"Liquid time crystals", arXiv:2202.05407
"Unsteady dynamics of a classical wave-droplet entity", Phys. Rev. E **104**, 015106 (2021)
"Stop and go locomotion of superwalking droplets", Phys. Rev. E **103**, 043102 (2021)
"Emergence of superwalking droplets", J. Fluid Mech. **906,** A3 (2021)
"Superwalking droplets", Phys. Rev. Lett. **123**, 024503 (2019)
"Hong-Ou-Mandel-like two droplet correlations", Chaos **28**, 096104 (2018)

OUTLINE

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Historical remarks

Liquid time crystals

Transport phenomena

Fundamentals

Broken symmetry		Lost conservation law
space translation	P	optical lattices
space rotation	L	vortex lattices
time translation	E	time lattices

dynamical systems!
driven, non-equilibrium

Time crystals:

Selected for a Viewpoint in *Physics*
PRL **109,** 160401 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

Quantum Time Crystals

Frank Wilczek
Center for Theoretical Physics Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 29 March 2012; published 15 October 2012)

Selected for a Viewpoint in *Physics*
PRL **109,** 160402 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

Classical Time Crystals

Alfred Shapere[1] and Frank Wilczek[2]
[1]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40502 USA*
[2]*Center for Theoretical Physics, Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 USA*
(Received 3 April 2012; published 15 October 2012)

PRL **114,** 251603 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

Absence of Quantum Time Crystals

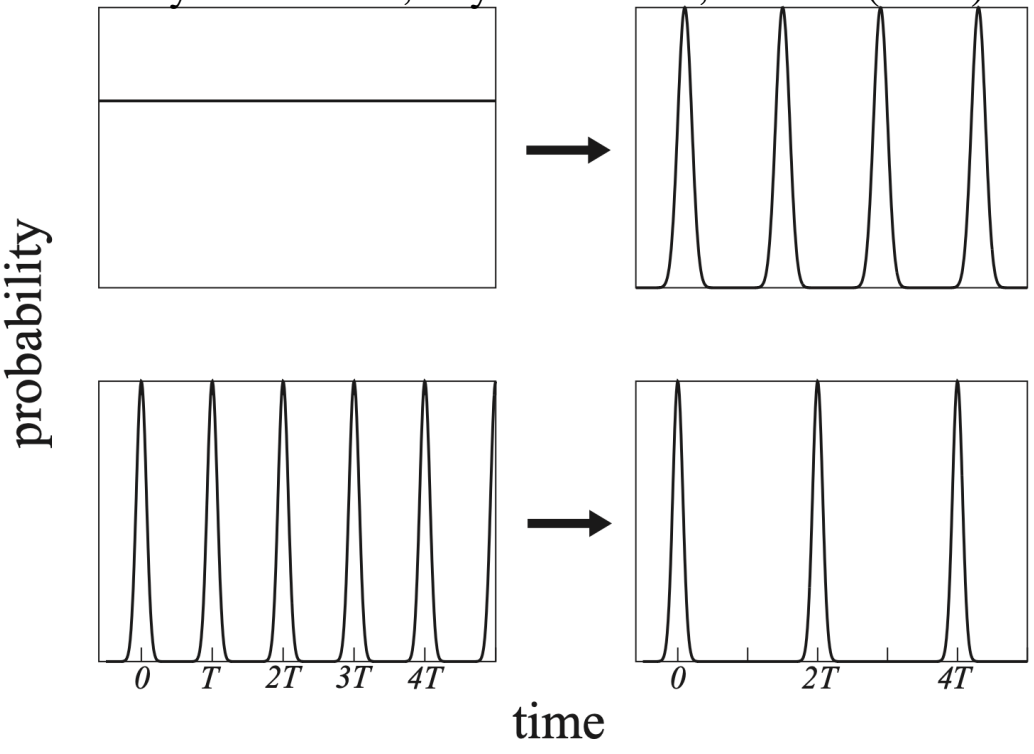
Haruki Watanabe[1,*] and Masaki Oshikawa[2,†]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*
(Received 28 March 2015; published 24 June 2015)

Time crystals: the name lives on

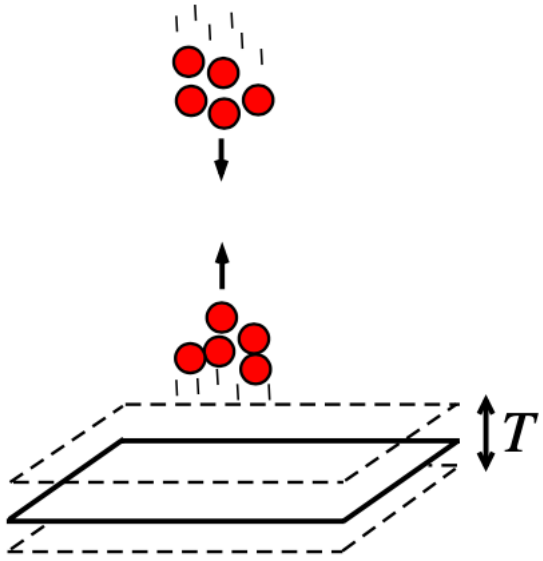
Floquet / discrete time crystals

discrete time translation symmetry breaking (subharmonic response)

Krzysztof Sacha, Phys.Rev.A **91**, 033617 (2015).

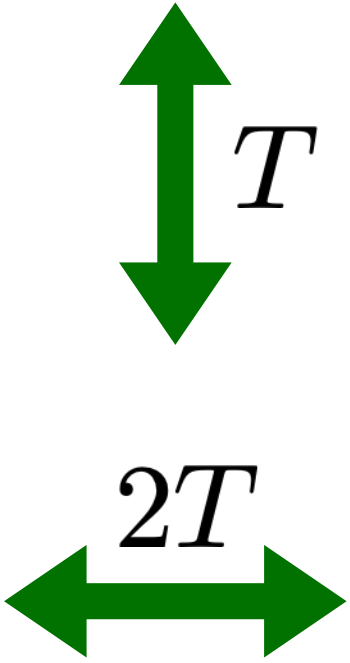


Rep. Prog. Phys. 81, 016401 (2018)



drive T **response k*T** **Hannaford expt**

Time crystals: the concept



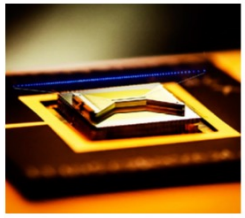
Leonardo, Rapunzel and the Mathematics of Hair

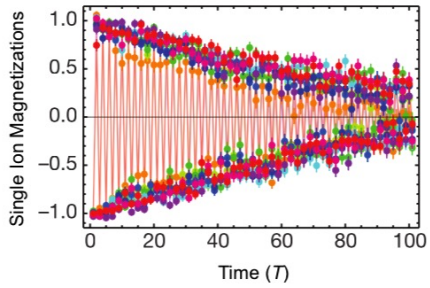
Professor Raymond E. Goldstein FRS

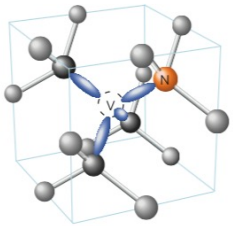
https://youtu.be/3ns2wy-LgsY

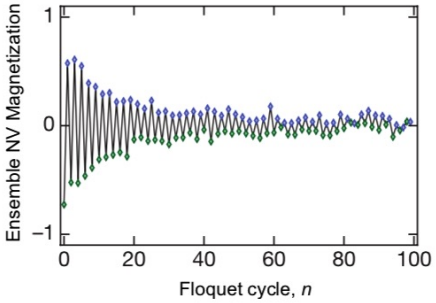
Time crystals: the new generation

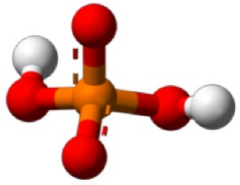
Monroe group, Nature **543**, 217 (2017).
Lukin group, Nature **543**, 221 (2017).
Barrett group, Phys. Rev. Lett. **120**, 180603 (2018).

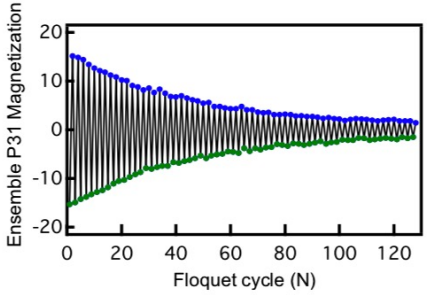


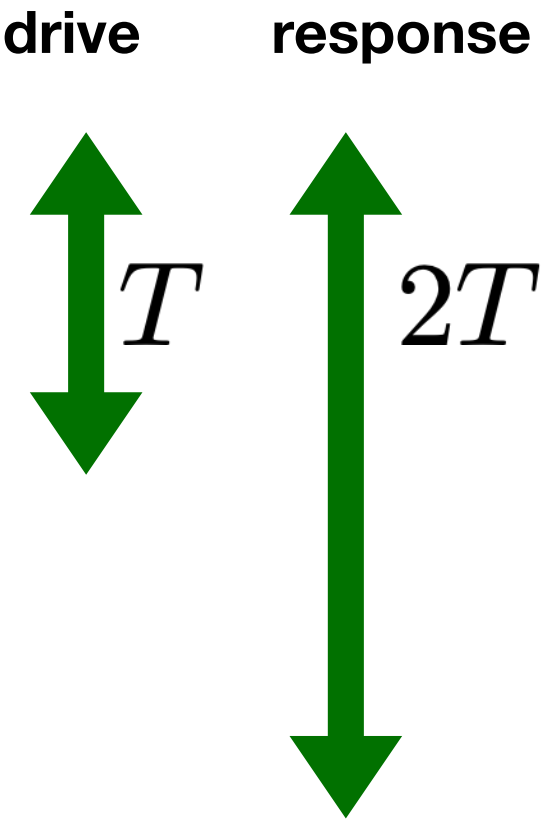












Time crystals: with quantum computers

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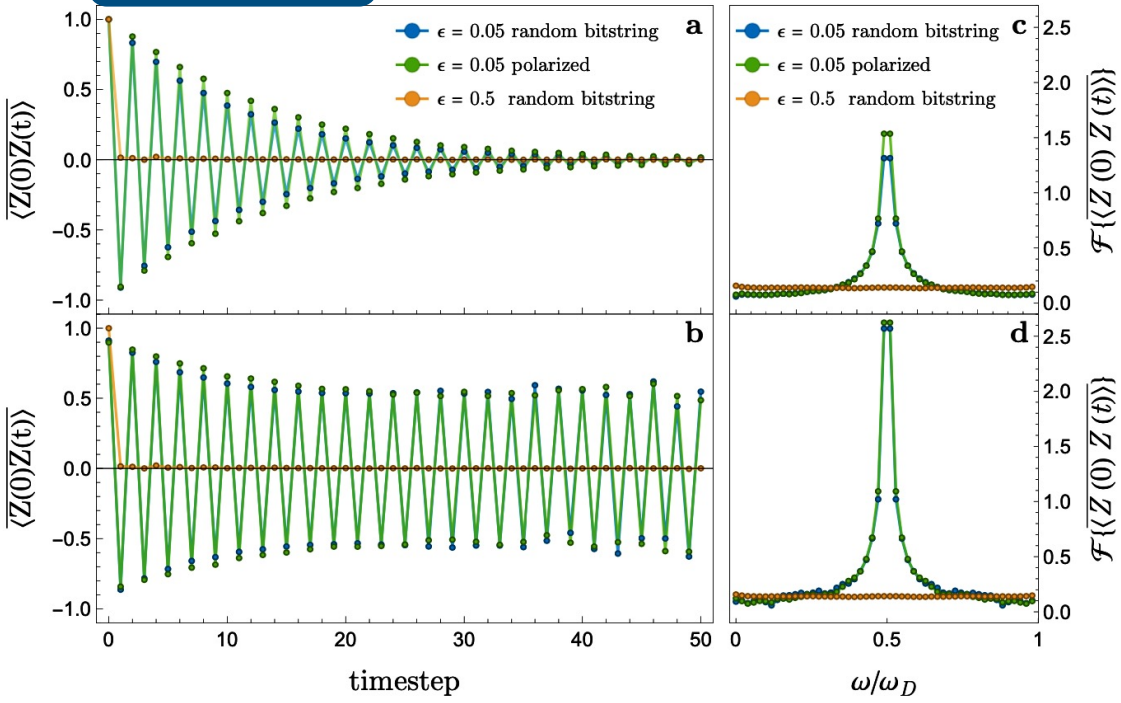
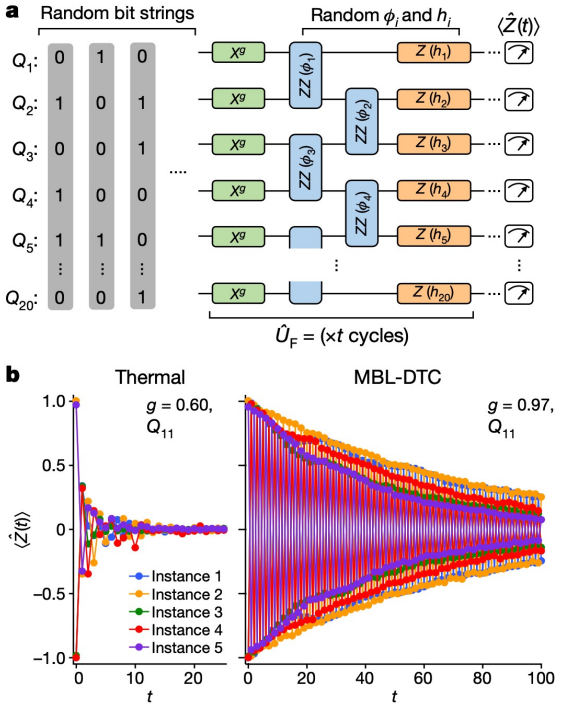
Frey & Rachel, Science Adv., **9** eabm7652 (2022)

IBM



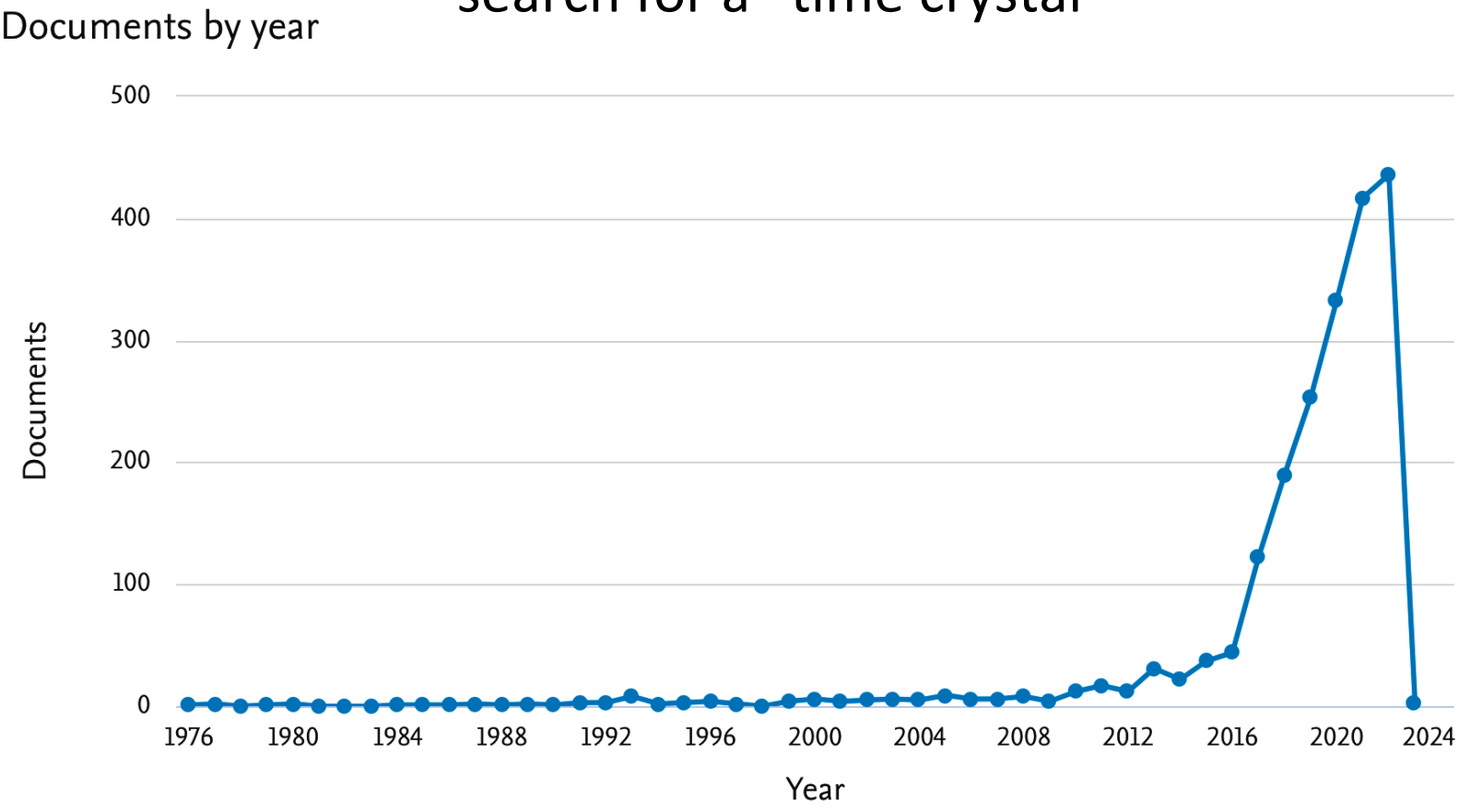
Mi et al., Nature, **531** 601(2022)

Google



Time crystals: growing literature

search for a “time crystal”



Plenty of semantics…

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time crystal

- subharmonic response
- crypto-equilibrium
- eigenstate order
- many-body localization
- quantum
- …

coffee

- caffeine
- milk
- soy
- ice
- crypto-equilibrium
- …

must or must not contain

…but no universally accepted definition

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Making Liquid Time Crystals

Bouncing and walking droplets: Couder group since 2005

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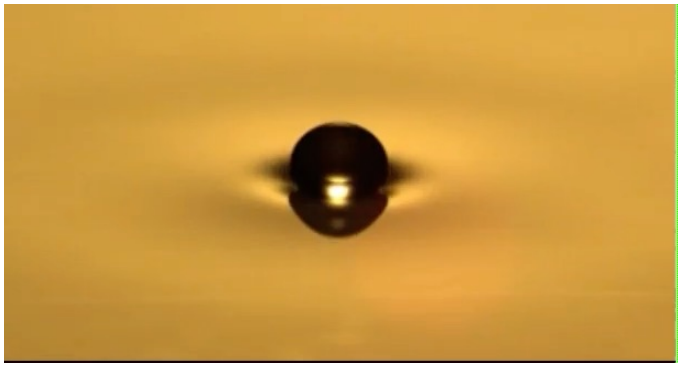
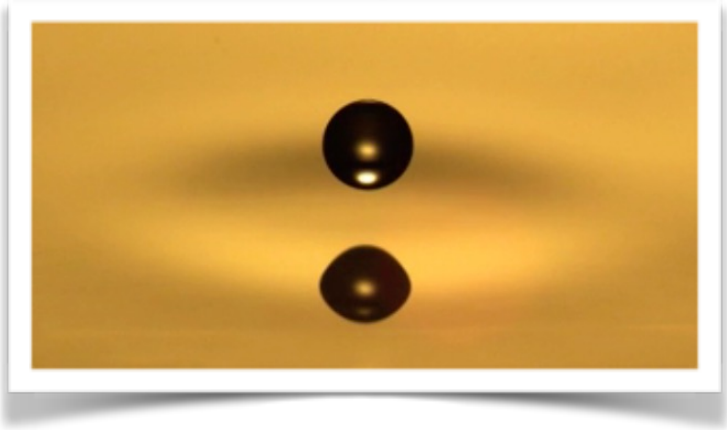
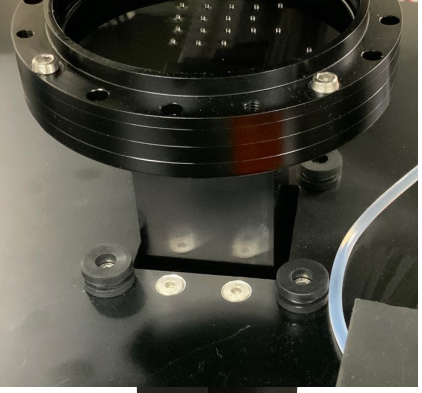
Movies: Harris & Bush, http://thales.mit.edu/bush/index.php/4801-2/

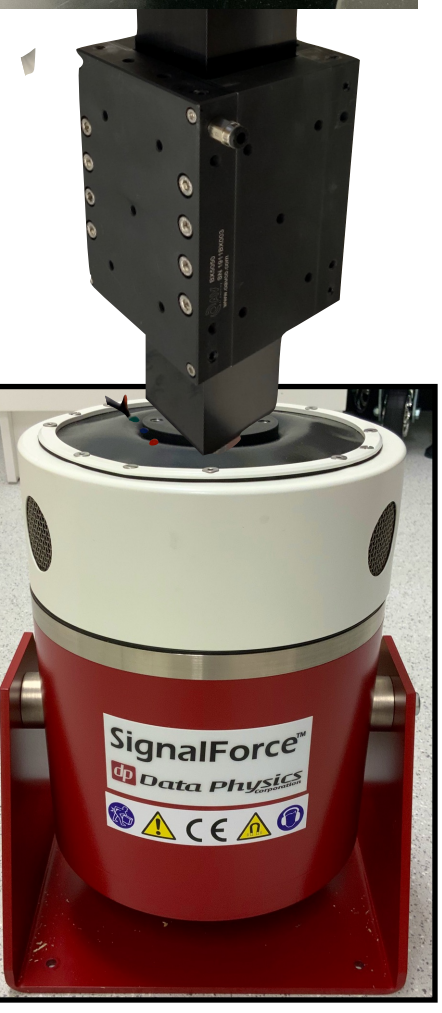
continuous time:
lab frame

stroboscopic time:
Floquet frame



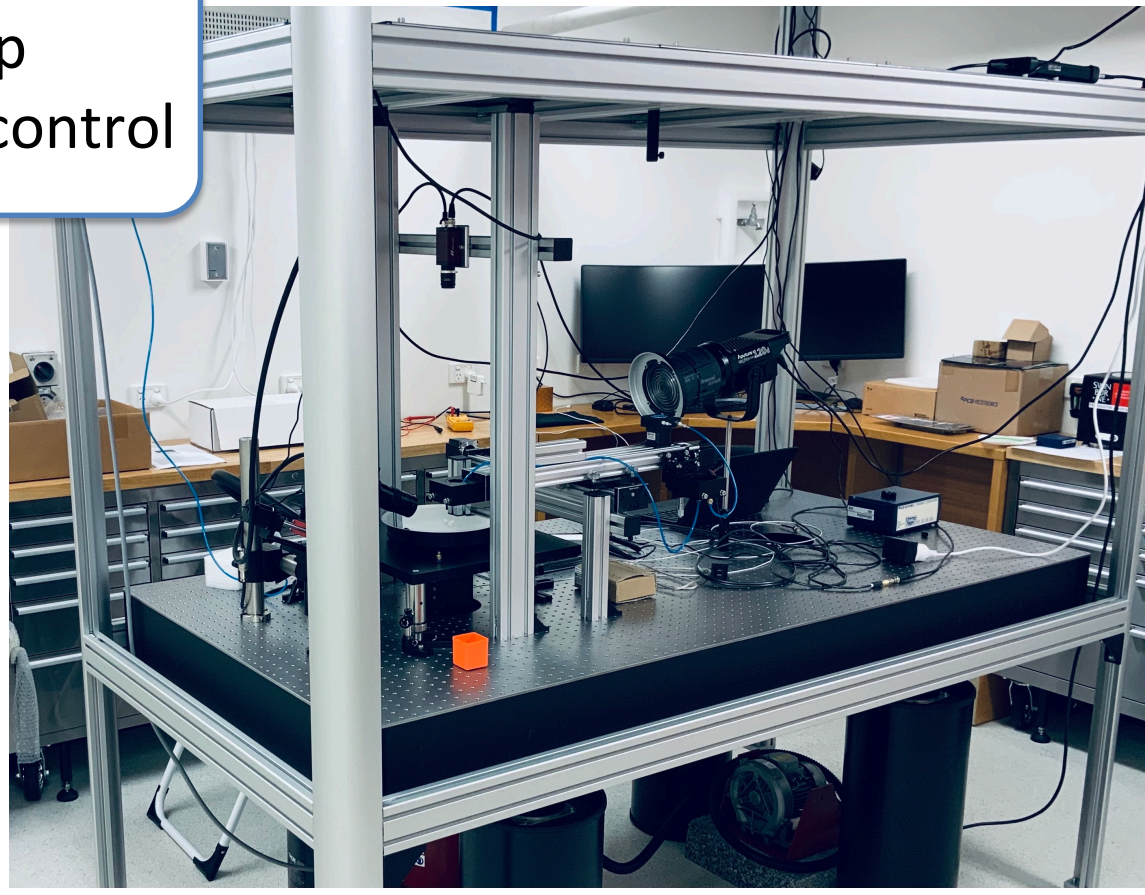






high-speed imaging

closed loop
feedback control



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Driving Amplitude

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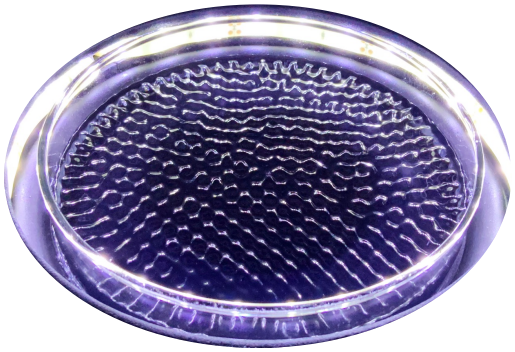
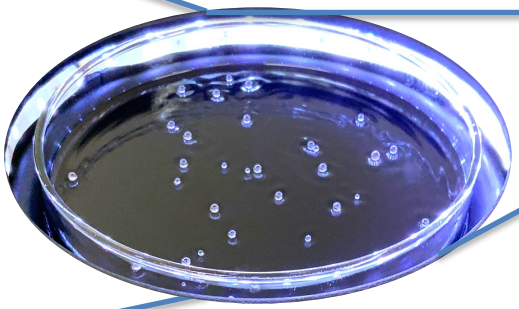
Faraday waves
4 g

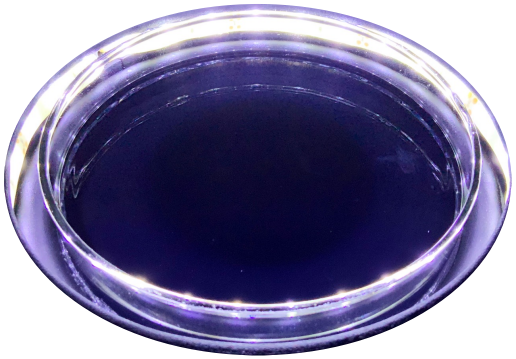
walking
3.5 g

bouncing
1 g

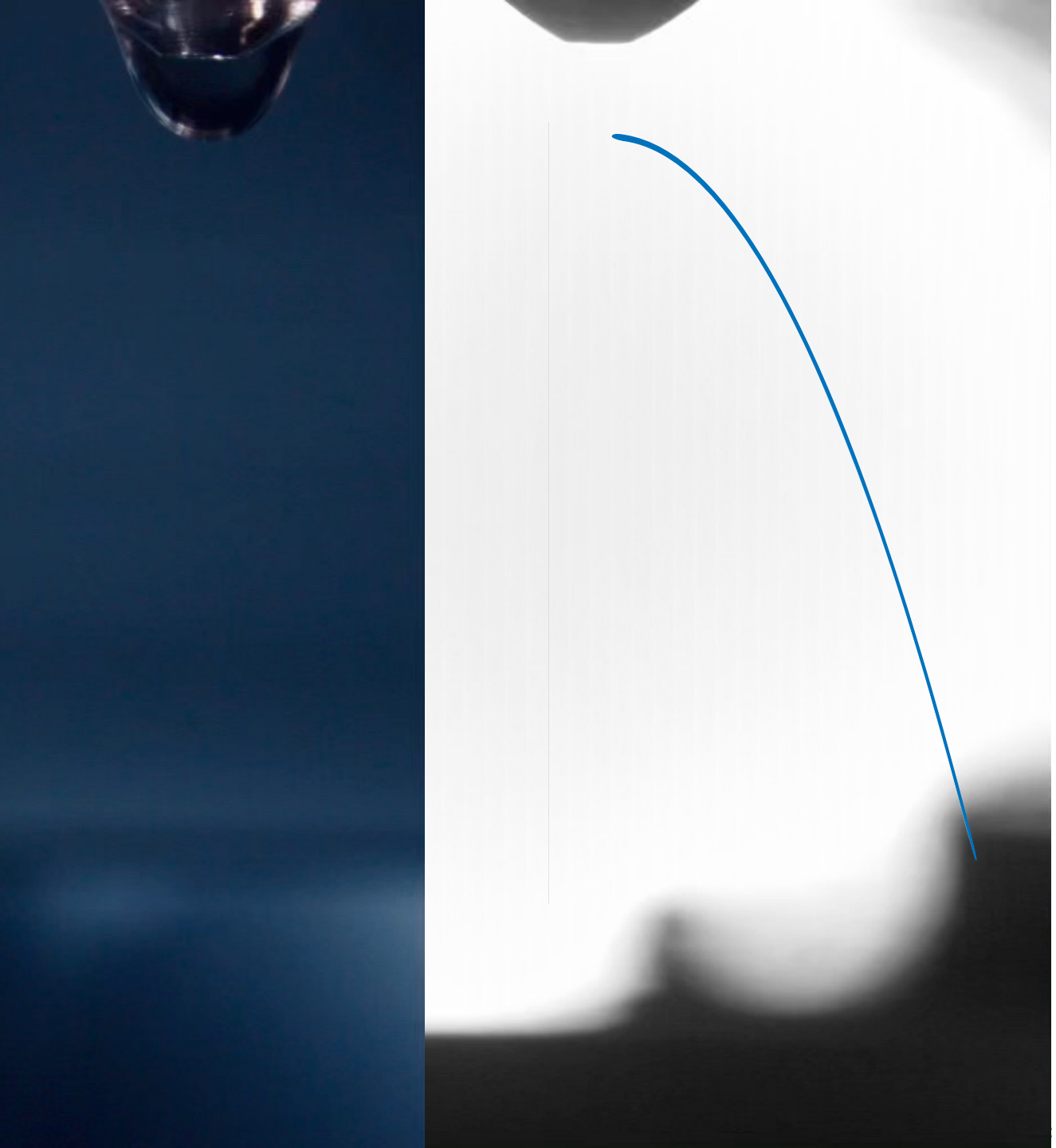
coalesce
0 g







Droplet generator



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Droplets

Liquid Time Crystals

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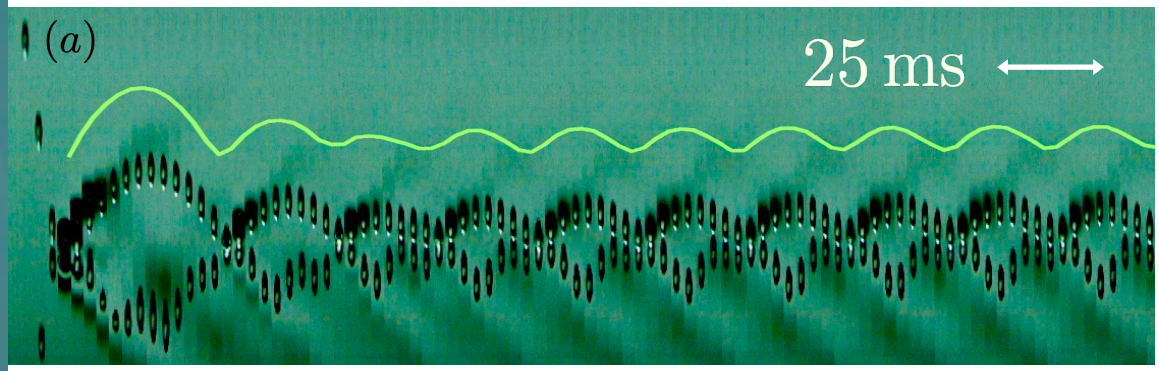

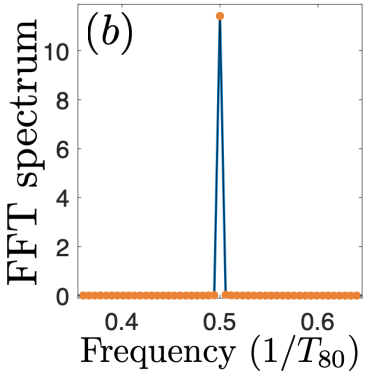

N > 100,000

Phases of matter

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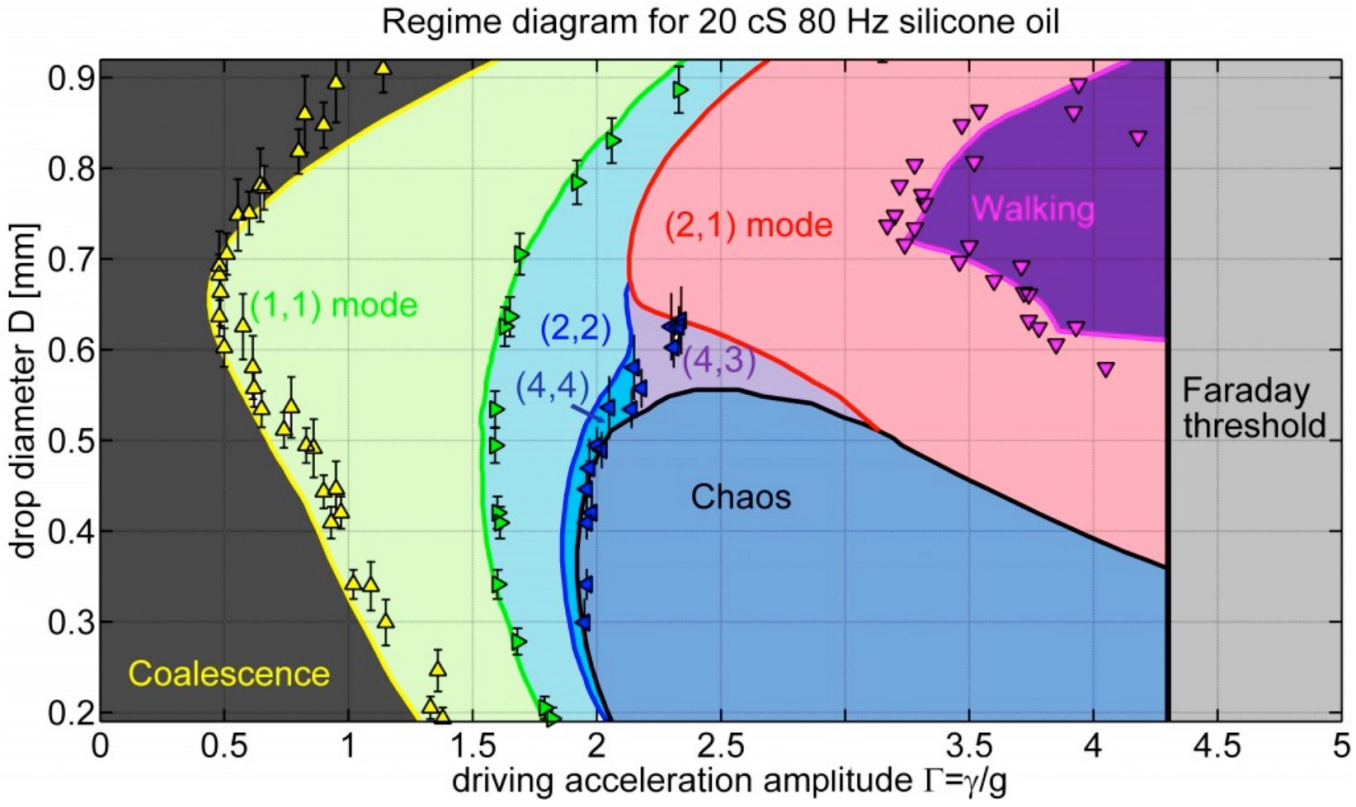
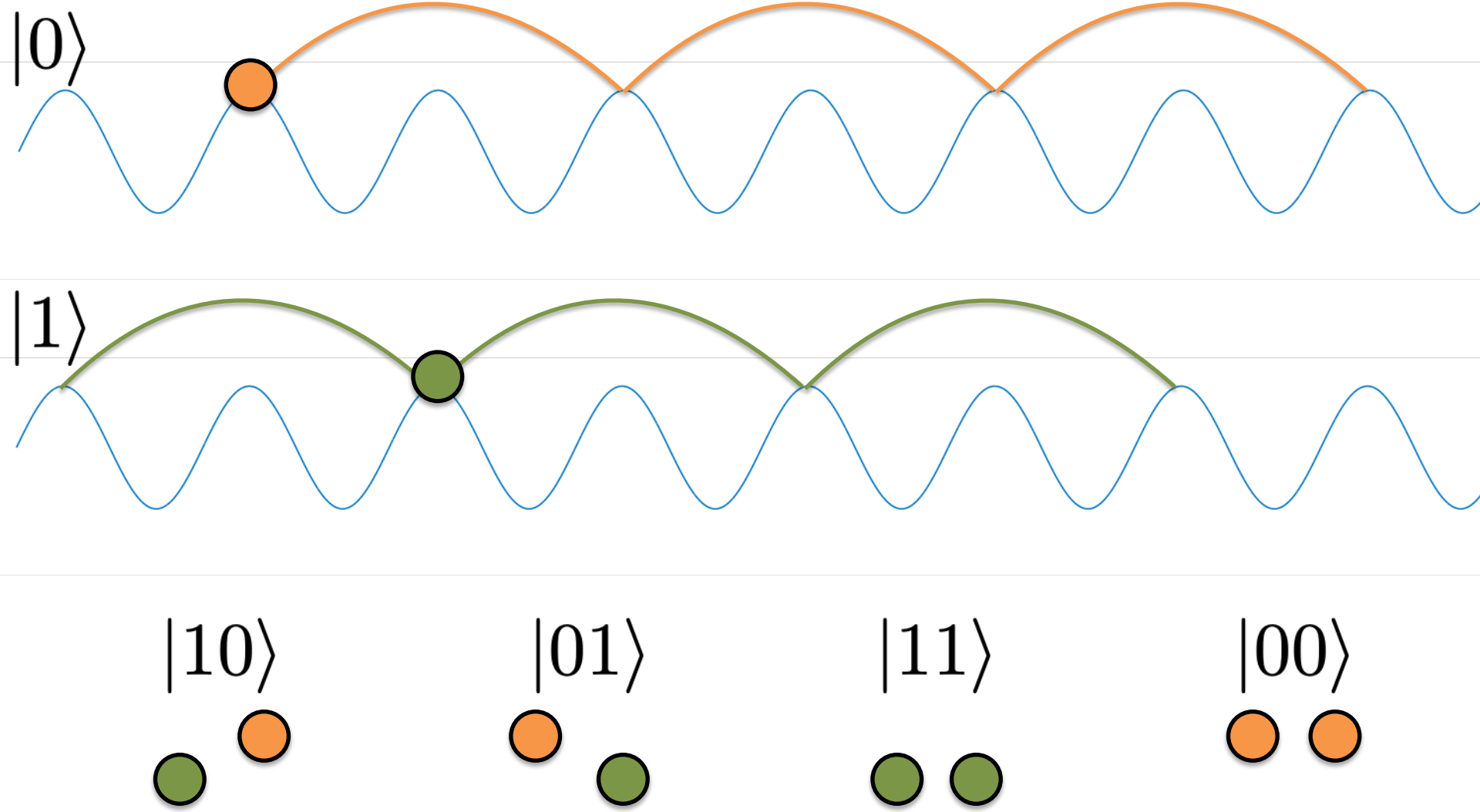
J. Moláček and J. W. M. Bush

J. Fluid Mech. (2013), *vol.* 727, *pp.* 612–647. © Cambridge University Press 2013



(2,1) Bouncing Degeneracy



Time Crystals Galore

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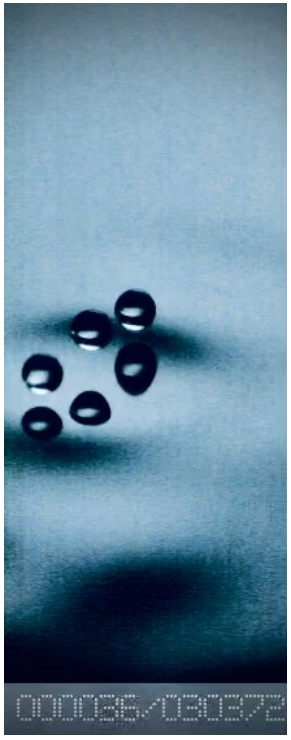
- antiferromagnetic time crystal in 1D



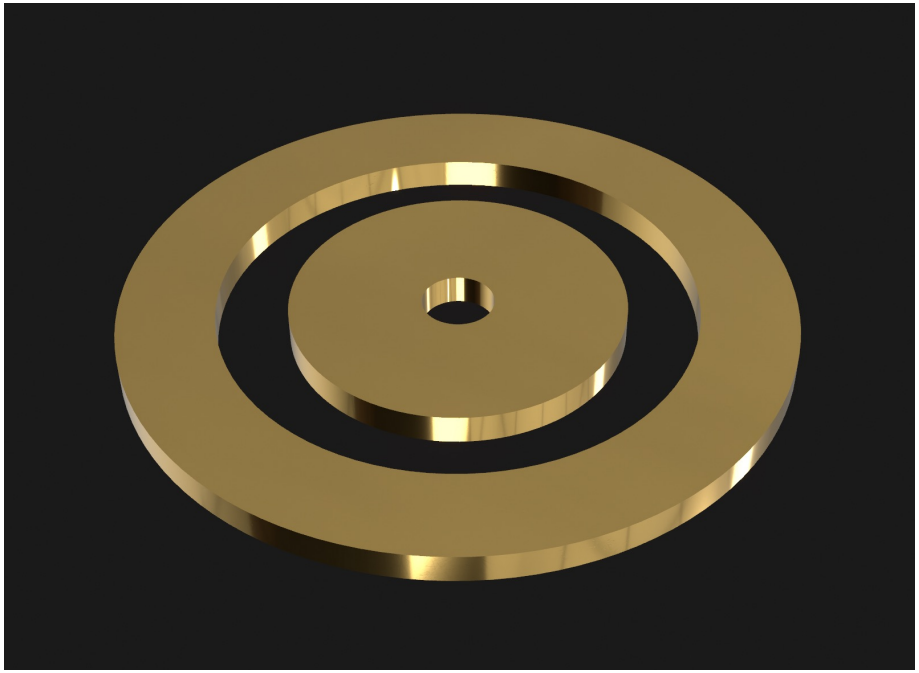
- antiferromagnetic time crystal in 2D

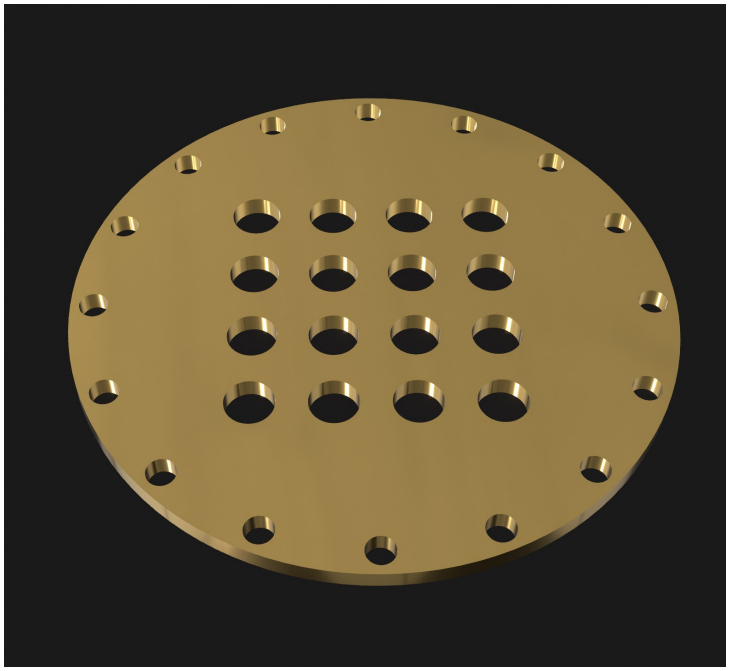
- impurity doped disordered time crystal

On-demand loading

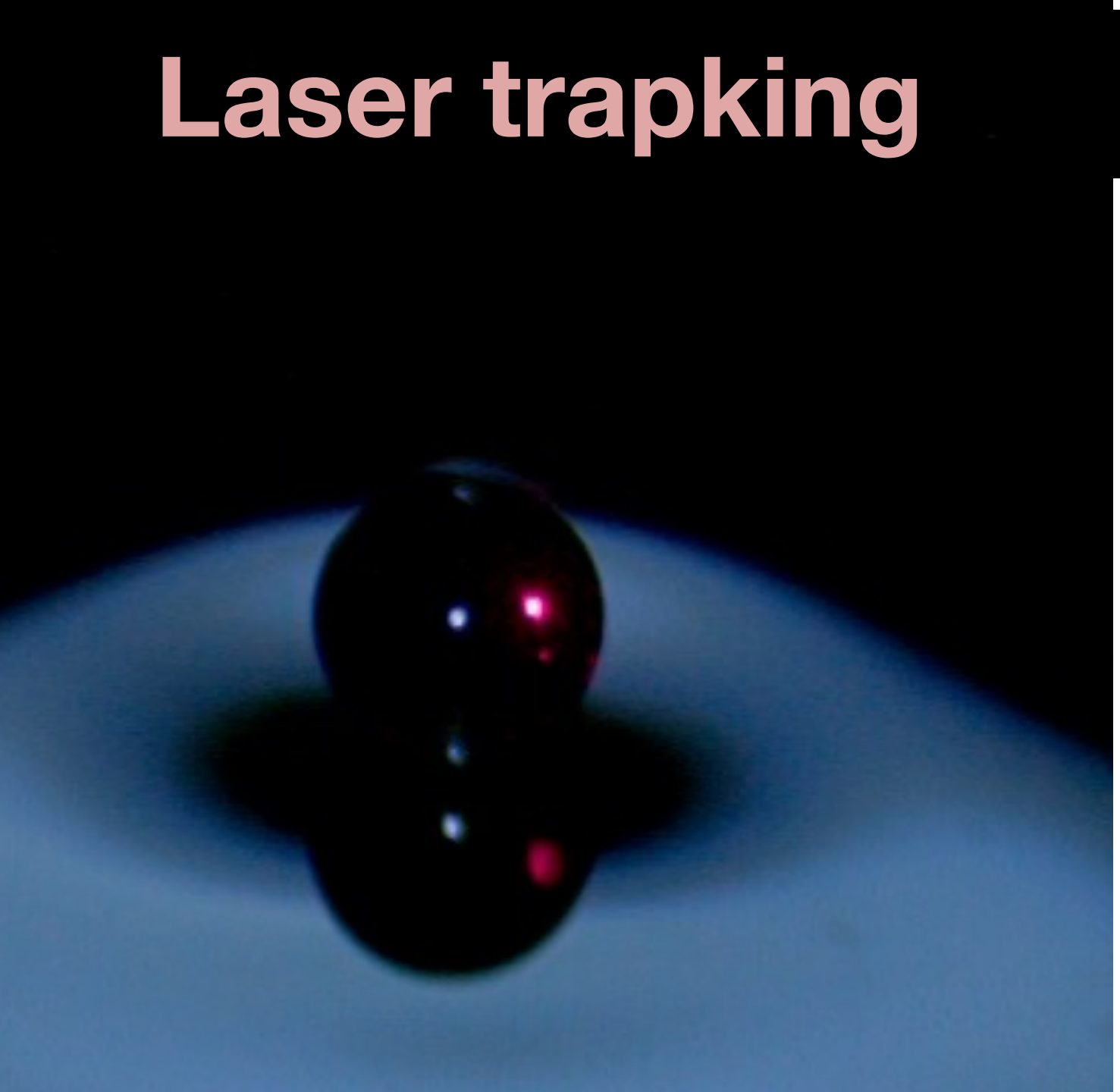
Recent improvements

Spatial trapping potentials





Laser trapking



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…for one slide

ARTICLES
PUBLISHED ONLINE: 14 DECEMBER 2015 | DOI: 10.1038/NPHYS3584
nature physics

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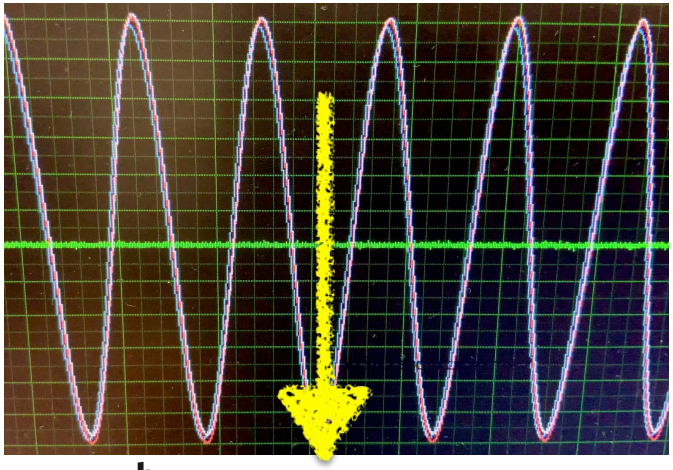
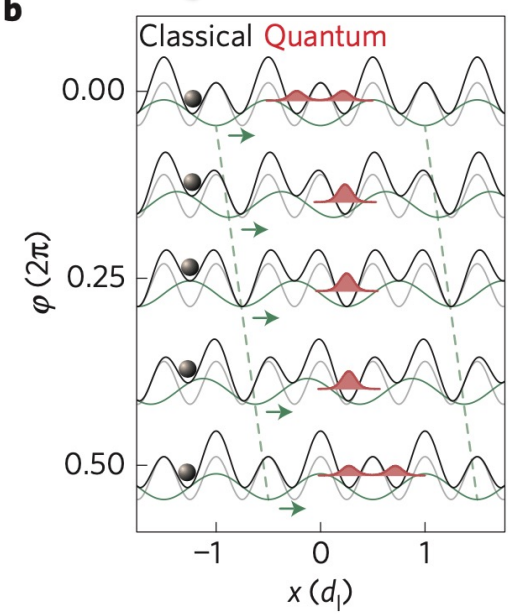
A Thouless quantum pump with ultracold bosonic atoms in an optical superlattice

M. Lohse[1,2]*, C. Schweizer[1,2], O. Zilberberg[3], M. Aidelsburger[1,2] and I. Bloch[1,2]

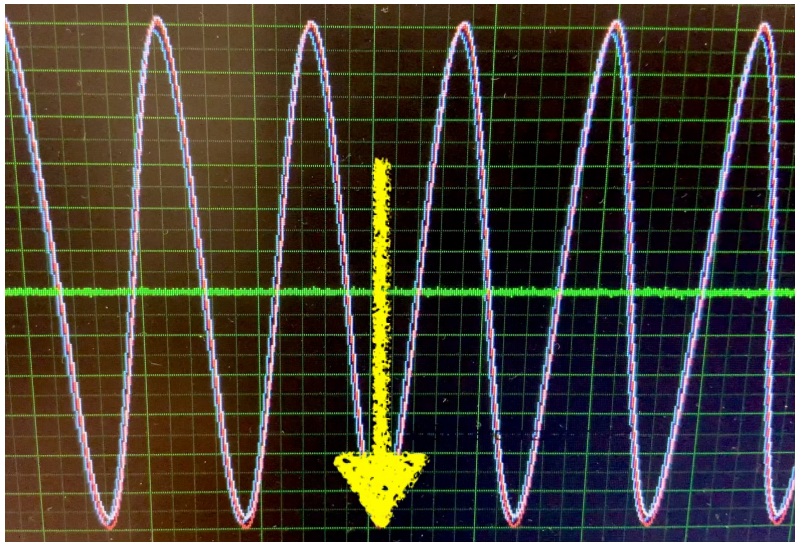
$$\hat{H}(\varphi) = -\sum_j [J_1(\varphi) a_j^\dagger a_j + J_2(\varphi) a_{j+1}^\dagger b_j + \text{h.c.}]$$
$$+ \frac{\Delta(\varphi)}{2} \sum_j (a_j^\dagger a_j - b_j^\dagger b_j),$$

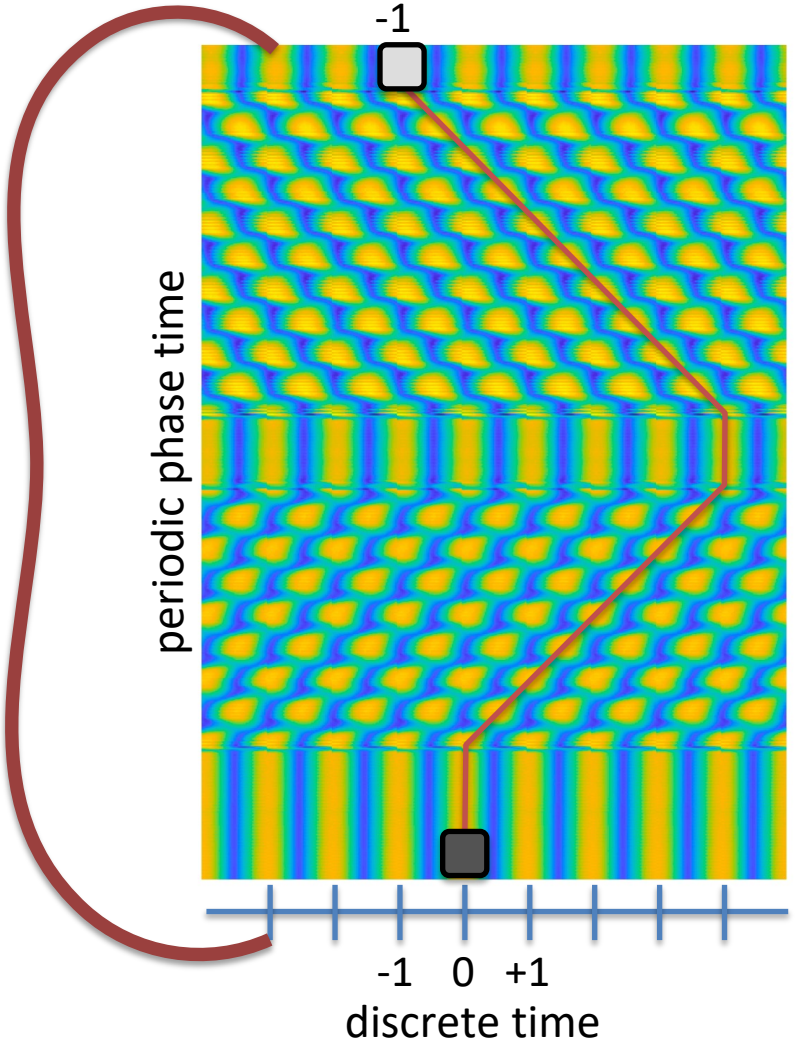
After one cycle, the lattice configuration is identical to the starting point, but the atom ends up in the double well next to the initial one. In contrast to this, a classical particle would not move because the positions of the individual sites do not change. This illustrates the importance of quantum tunneling for the pumping.





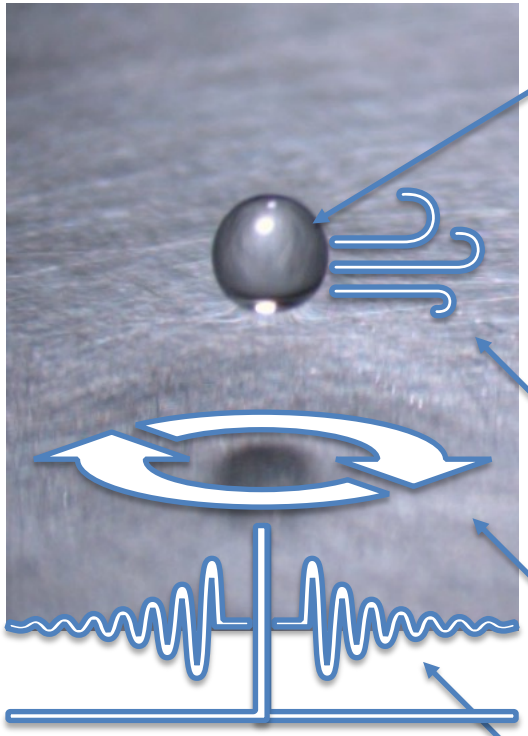
“Time traveling” droplets: topological LTC transport





THANK YOU!

System Characteristics



- peculiar dispersion relation

$$\omega_n = \sqrt{\sigma/\rho}\, k_n^{3/2}$$

$$k_n = [n(n-1)(n+2)]^{1/3}/R_d$$

- turbulent air currents (aerodynamic lift + drag)
- Marangoni vortex rings
- Faraday waves

Theoretical (minimal) Model

Moláček and Bush, Journal of Fluid Mechanics **727**, 582 (2013).

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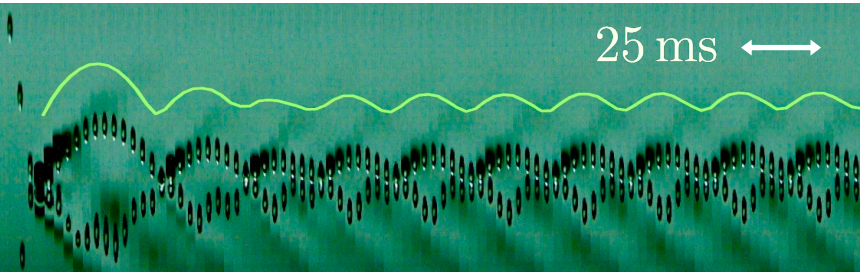
$$m\ddot{z} = F_N(t) - m[g + \gamma_f \sin(\omega t)]$$

$$F_N(t) = H(-\bar{z})\max\{-k\bar{z} - b\dot{\bar{z}}, 0\}$$



height above fluid $h(\mathbf{x}, t) = \sum_{n=1}^{N(t)} h_n$

$$h_n(\mathbf{x}, \mathbf{x}_n, t, t_n) = A\cos(\omega t/2)\frac{J_0(k_F|\mathbf{x} - \mathbf{x_n}|)}{\sqrt{t - t_n}}\mathrm{e}^{-(\mathrm{t}-\mathrm{t_n})/(\mathrm{T_F Me})}$$

$$m\ddot{\mathbf{x}} + D(t)\dot{\mathbf{x}} = -F_N(t)\boldsymbol{\nabla}h(\mathbf{x}, t)$$

Superwalkers

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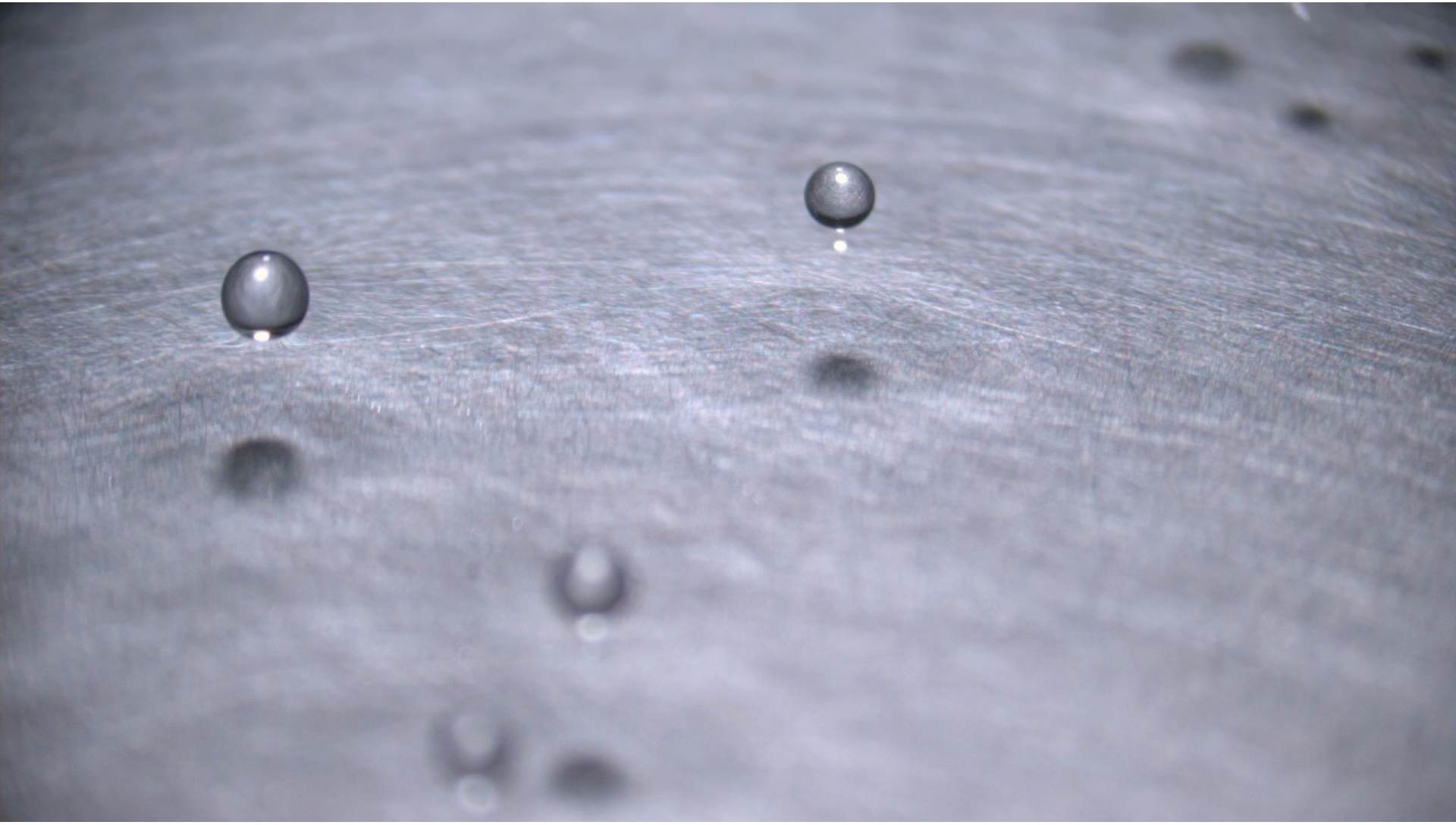

Making (Faraday) Waves

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