SYNTHETIC QUANTUM MATTER

ROSARIO FAZIO

The Abdus Salam
International Centre
for Theoretical Physics

SIMULATIONS OF PHYSICAL MODELS & DESIGN OF NEW PHENOMENA

- A *(biased) historical* journey through the realisation of artificial structures for the study of many-body phenomena

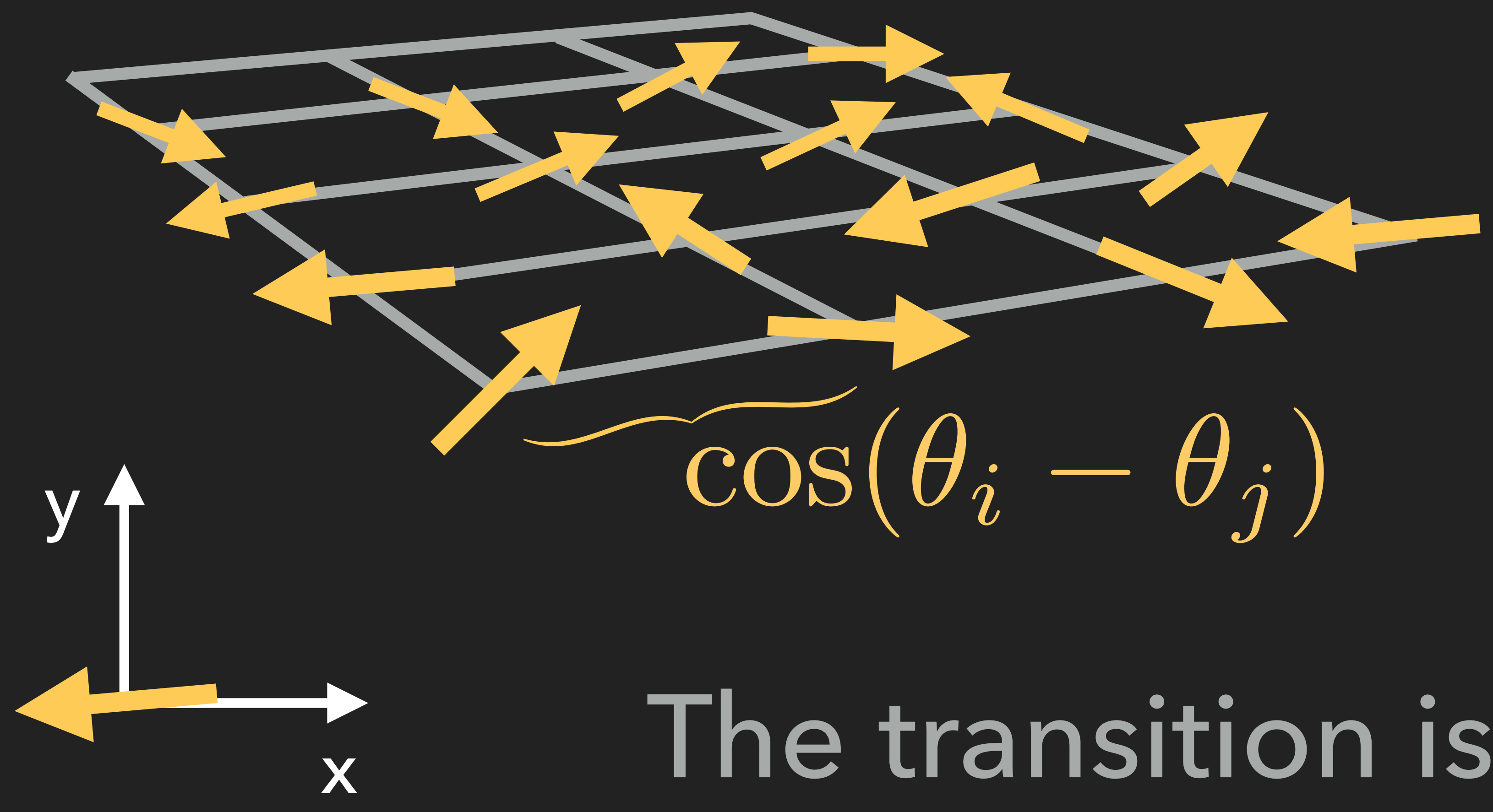
- The motivations … (from classical statistical mechanics and the foundations of quantum mechanics to quantum technologies) …

    - (Quantum) simulators

    - Platforms to realise physical phenomena that are unlike/impossible to observe in nature.

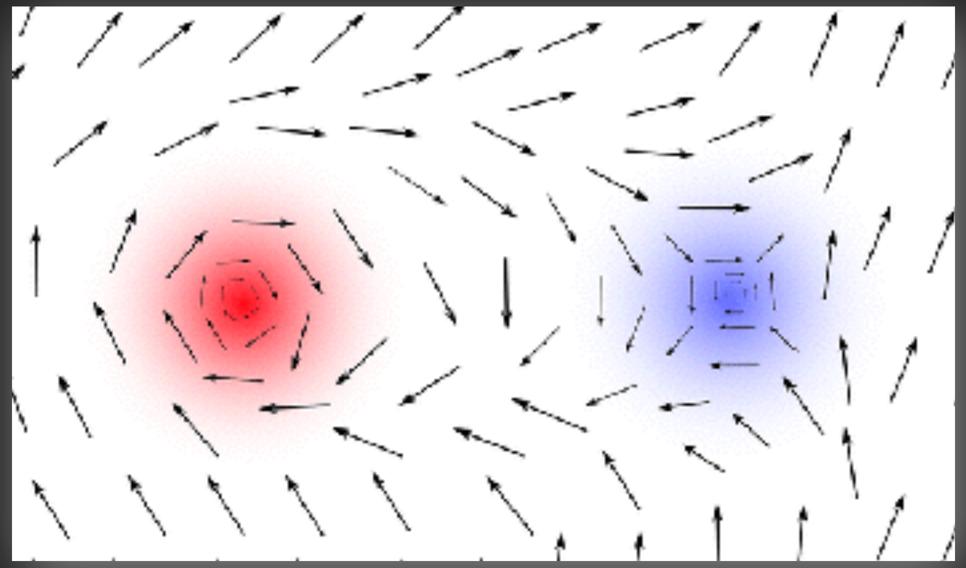
- Time-crystals, extra-dimensions, …

A TOPOLOGICAL TRANSITION IN MAGNETS



There is a transition at a finite temperature from a paramagnetic phase to an ordered magnetic phase.

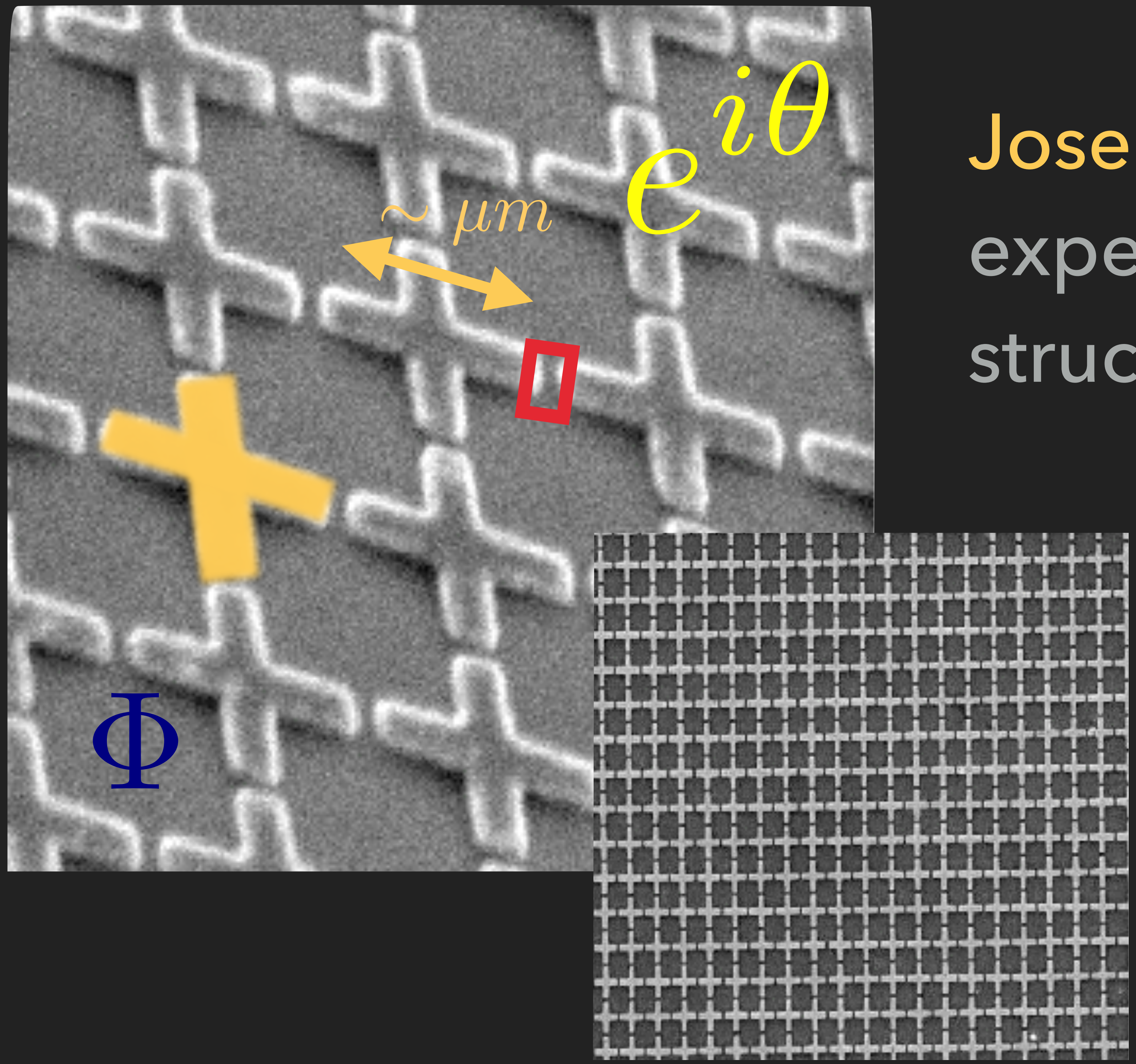
The transition is "non-conventional", it is determined by the properties of topological excitations (magnetic vortices)



Berezinskii-Kosterlitz-Thouless transition (1971-1973)

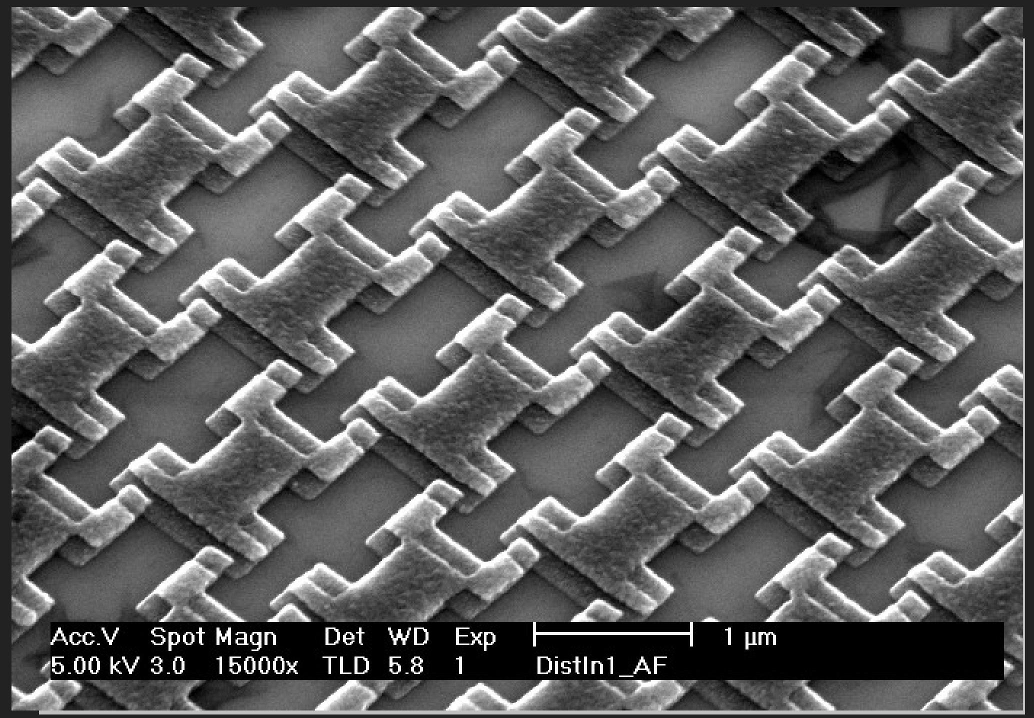
vortex-antivortex unbinding, no spontaneous symmetry breaking...

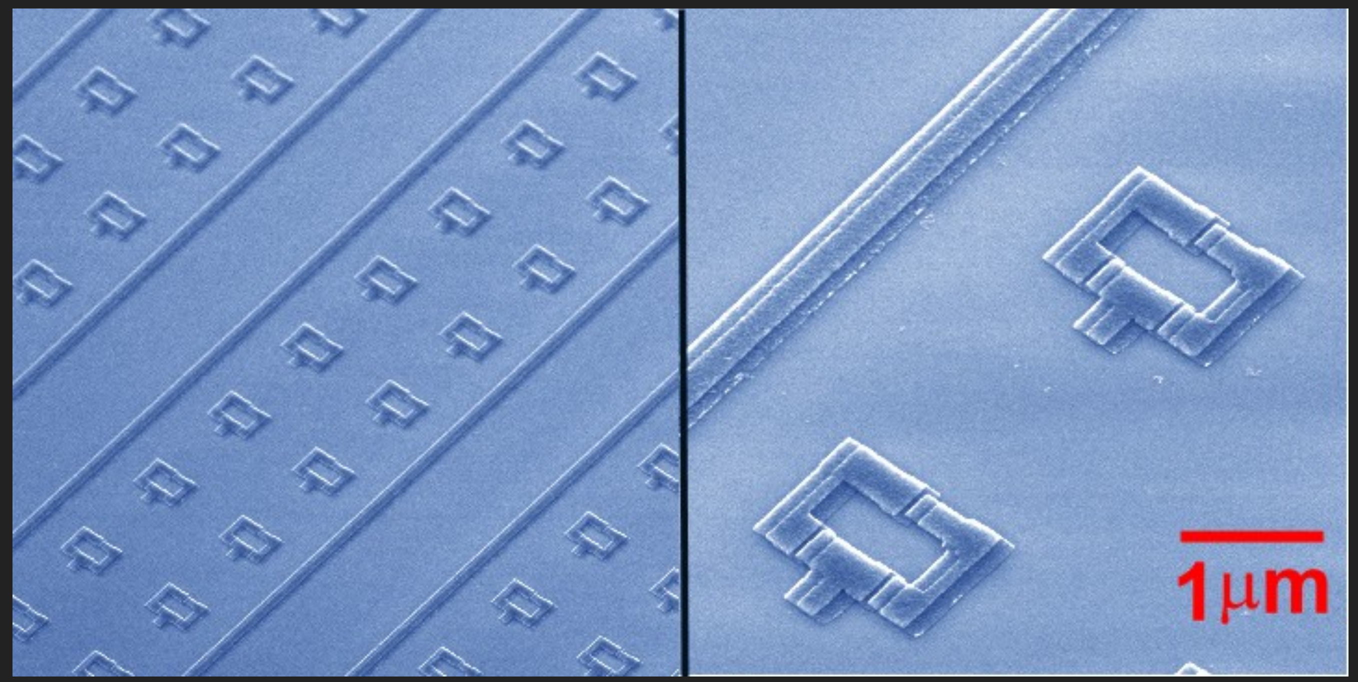
A TOPOLOGICAL TRANSITION IN A PLANAR MAGNET (THE SIMULATOR)

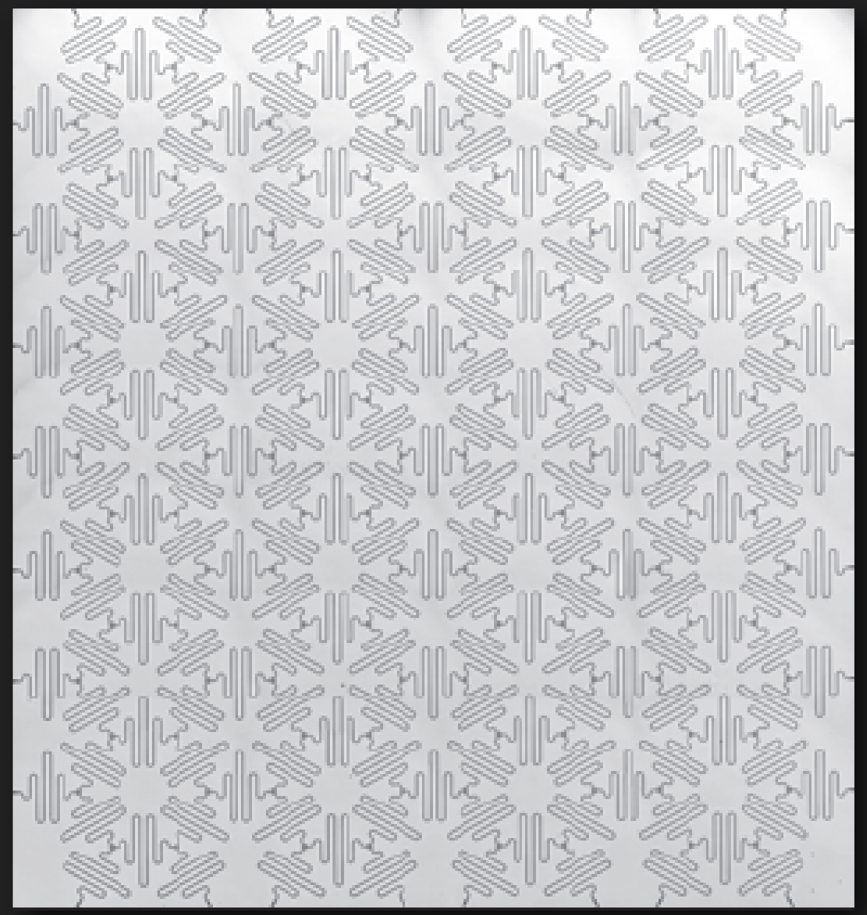


Josephson junction arrays were first realised in the 80's and lead to the experimental verification of the BKT transition in artificially fabricated structures (Resnick et al1981, van der Zant, Mooij, Delsing, …).

Versatility of JJA important in studying a variety of phenomena important in statistical physics and condensed matter: frustrated systems, quantum critical points, synchronisation, …





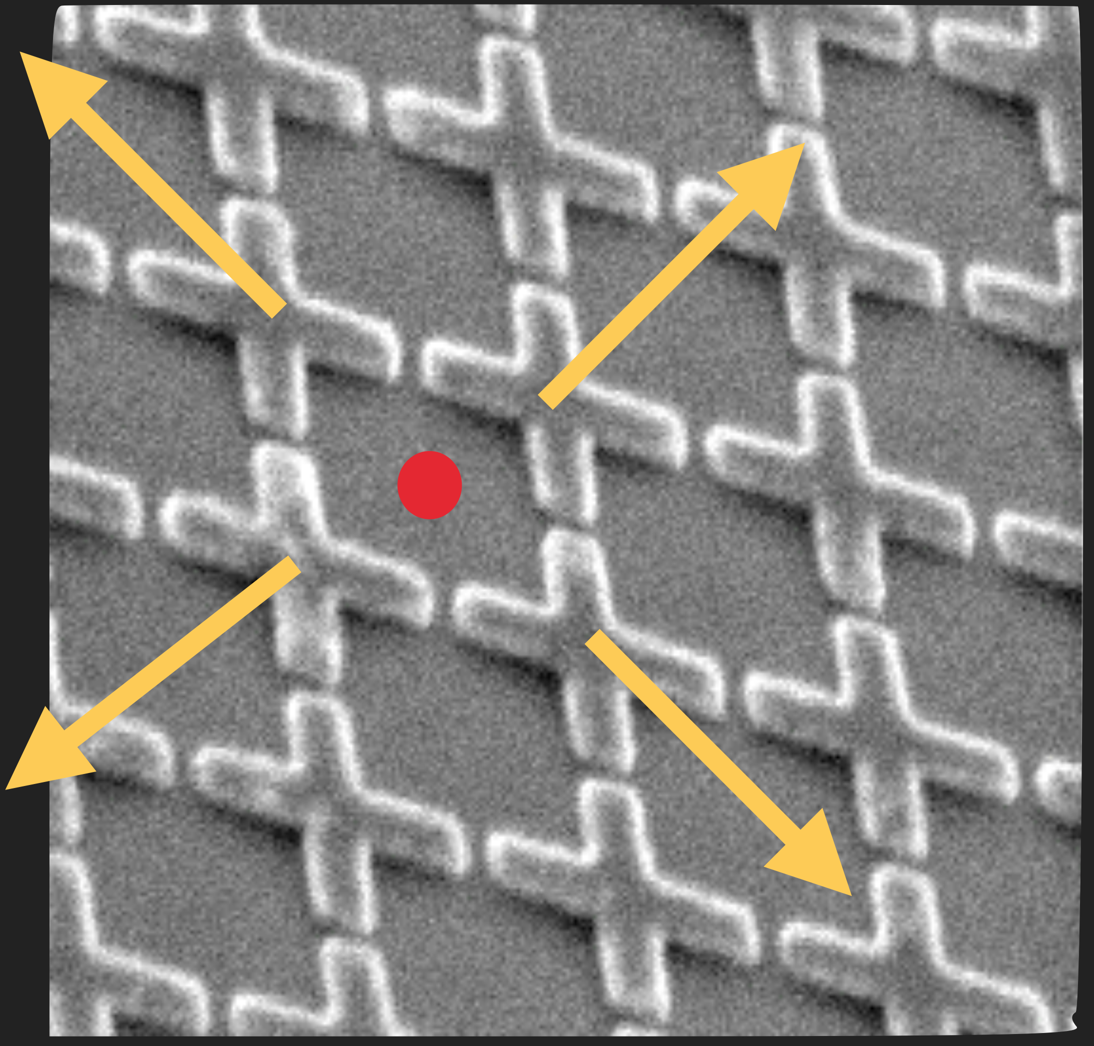


90s

2000 - …

2010 - 2020

JOSEPHSON ARRAYS & FUNDAMENTALS OF QUANTUM MECHANICS

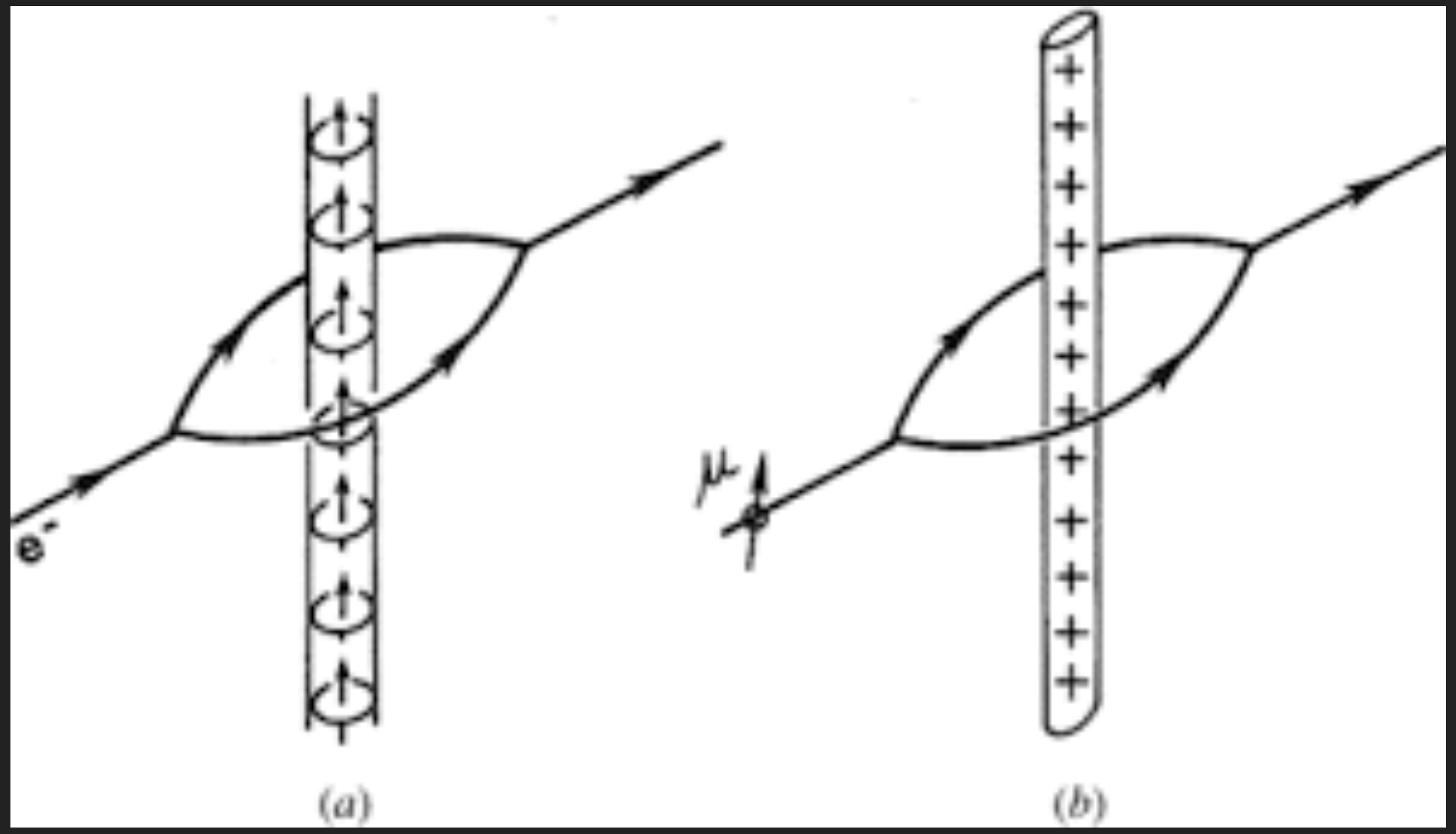


How far do experiments on the so-called "macroscopic quantum systems" such as superfluids and superconductors test the hypothesis that the linear Schrödinger equation may be extrapolated to arbitrarily complex systems?

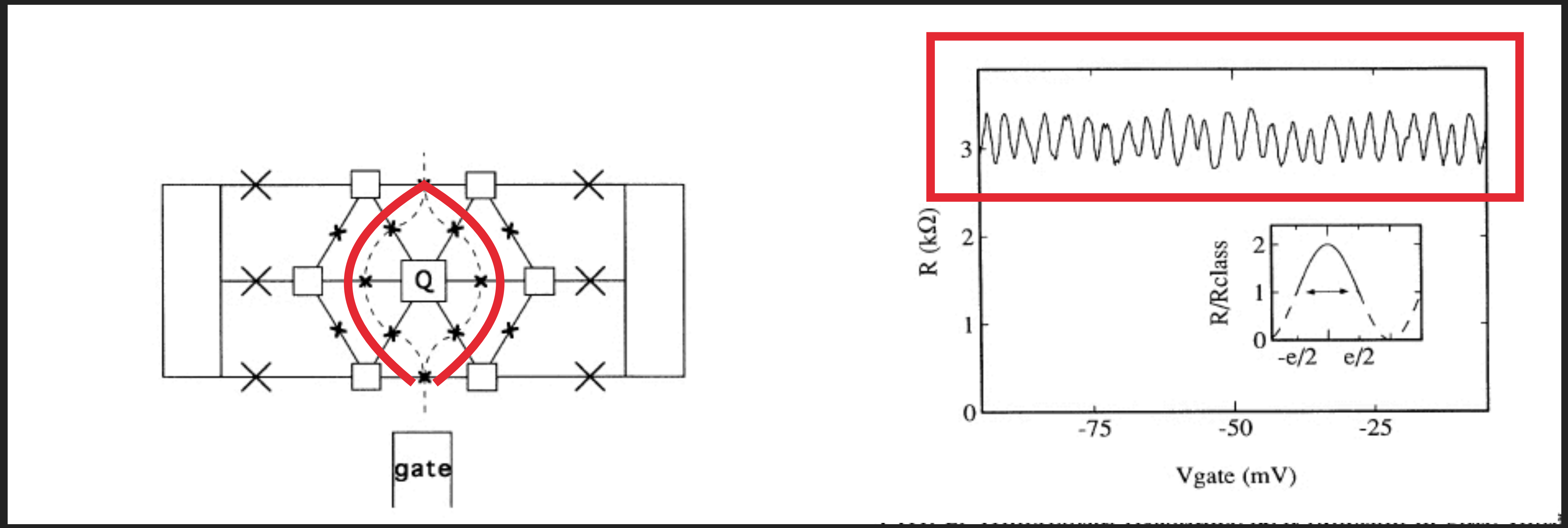
JJAs to study Macroscopic Quantum Phenomena, quantum vortex dynamics, role of dissipation on quantum effects

Aharonov-Casher effect

(Elion et al '93)



particle-vortex duality

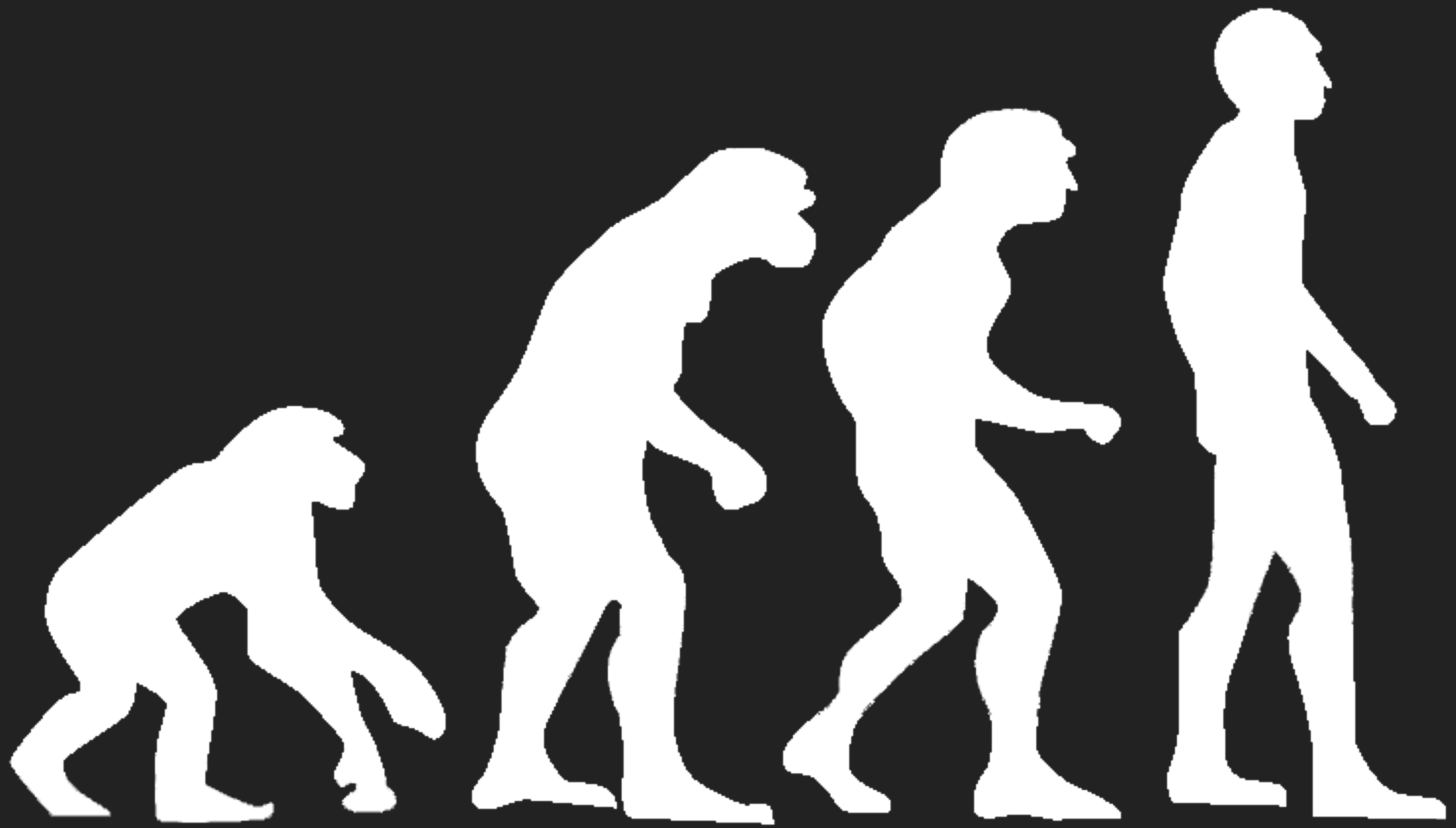


SYNTHETIC QUANTUM MATTER

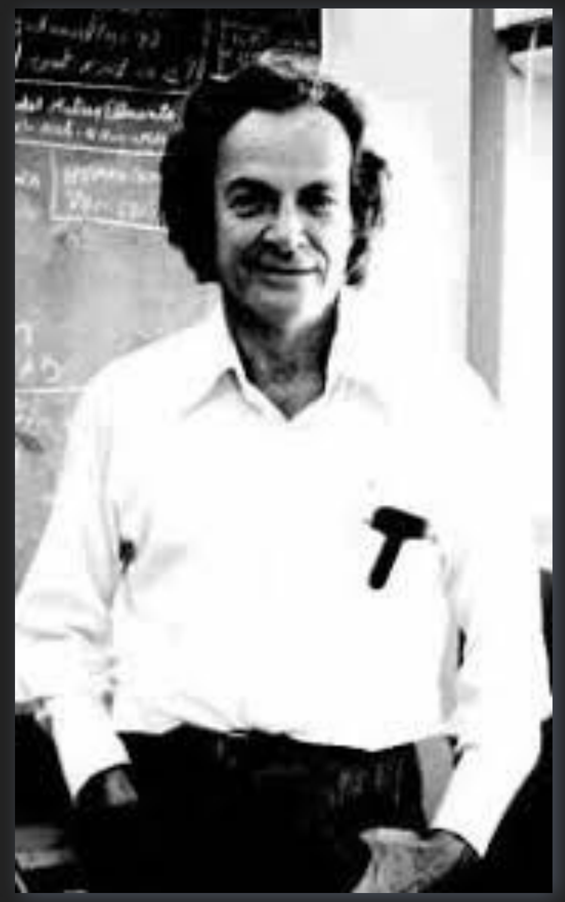
. . . IN THE ERA OF QUANTUM TECHNOLOGIES

↓

QUANTUM SIMULATORS



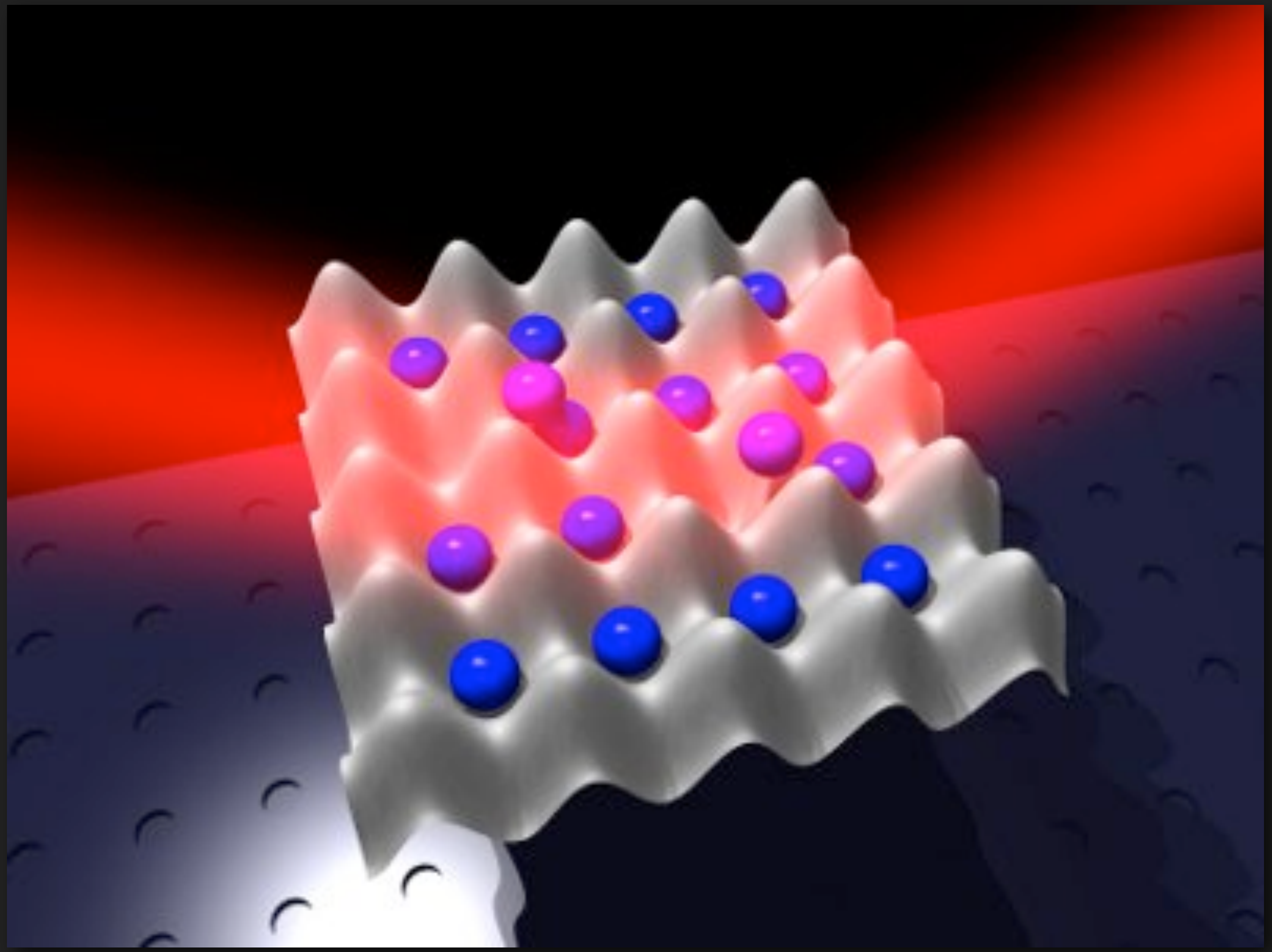
QUANTUM SIMULATORS



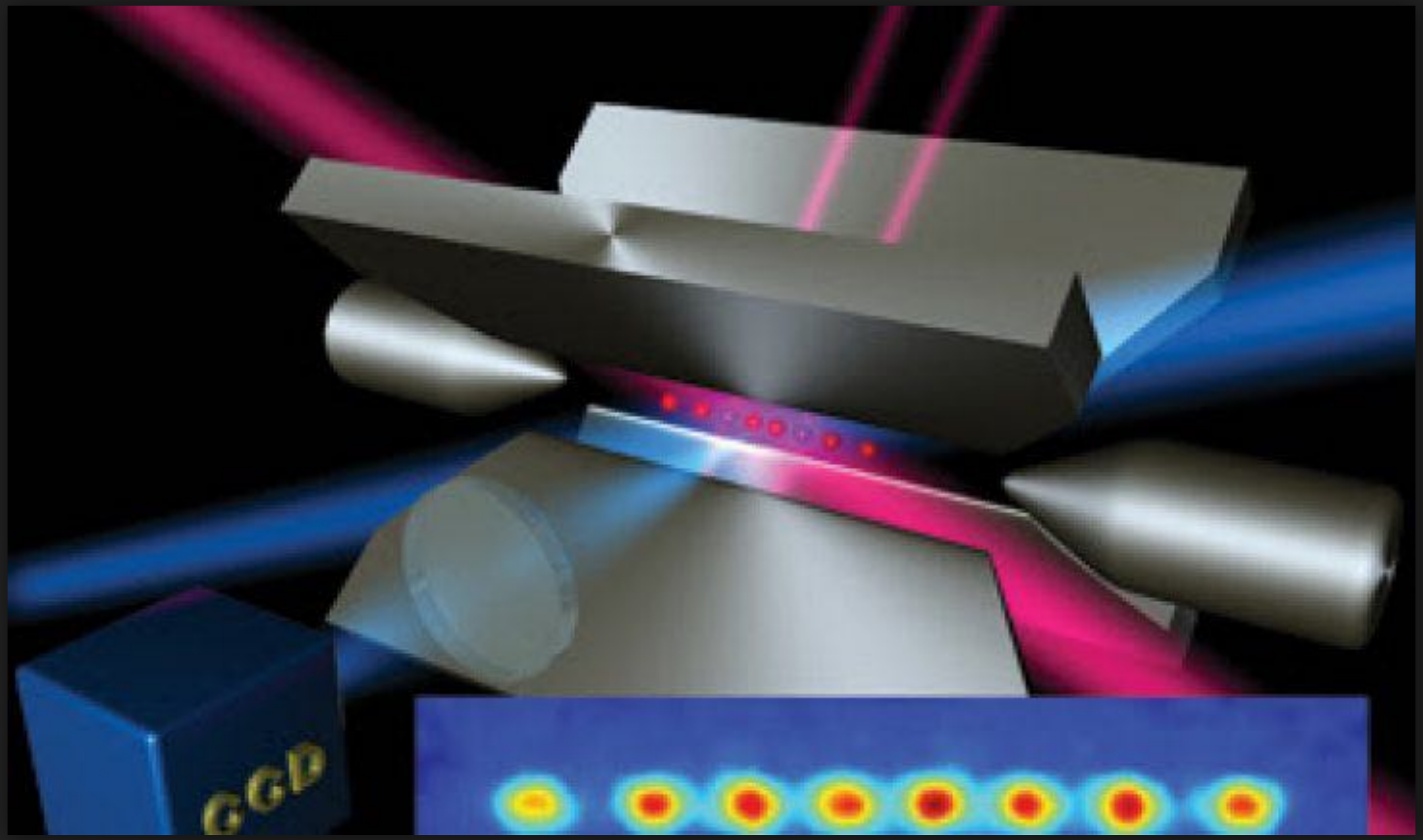
Quantum simulator: an experimental *controllable* system that reproduces the physics of a given model Hamiltonian (Feynman '82)

- Questions not accessible via classical computation because the exp-large dimension of the Hilbert space (e.g. complex quantum ground states or dynamics in solid state systems)
- Questions that are not directly "tractable/identified" in "nature" (e.g. thermalisation, defect formation, foundations of quantum mechanics…)
- New states of matter (e.g. time-crystals,exotic qp,…) Time-crystals, extra-dimensions, …

QUANTUM SIMULATORS



$$|\Psi(1,2,\ldots,N;t\rangle$$



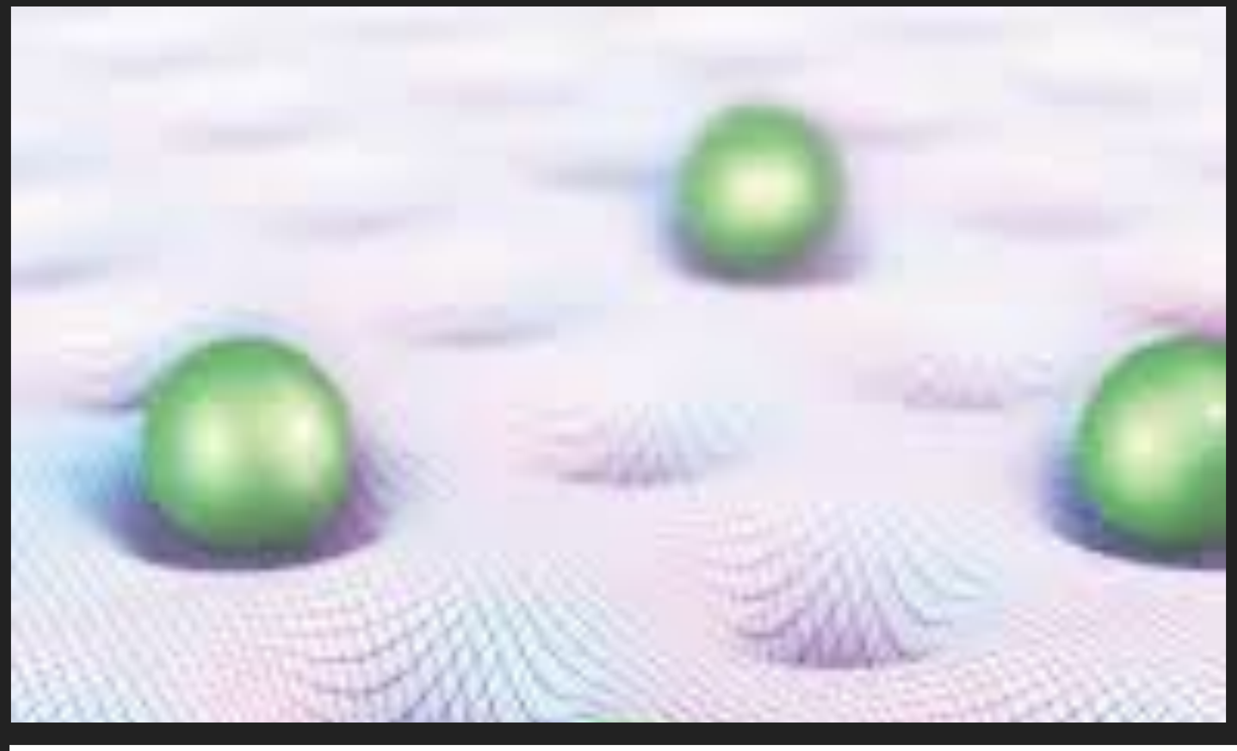
...

QUANTUM SIMULATORS

- Fermions/Bosons
- A variety of different models (Hubbard,Anderson, spin models, …)
- Lattice structures, topology, synthetic dimensions,
- Frustration
- Disorder, interaction range
- …

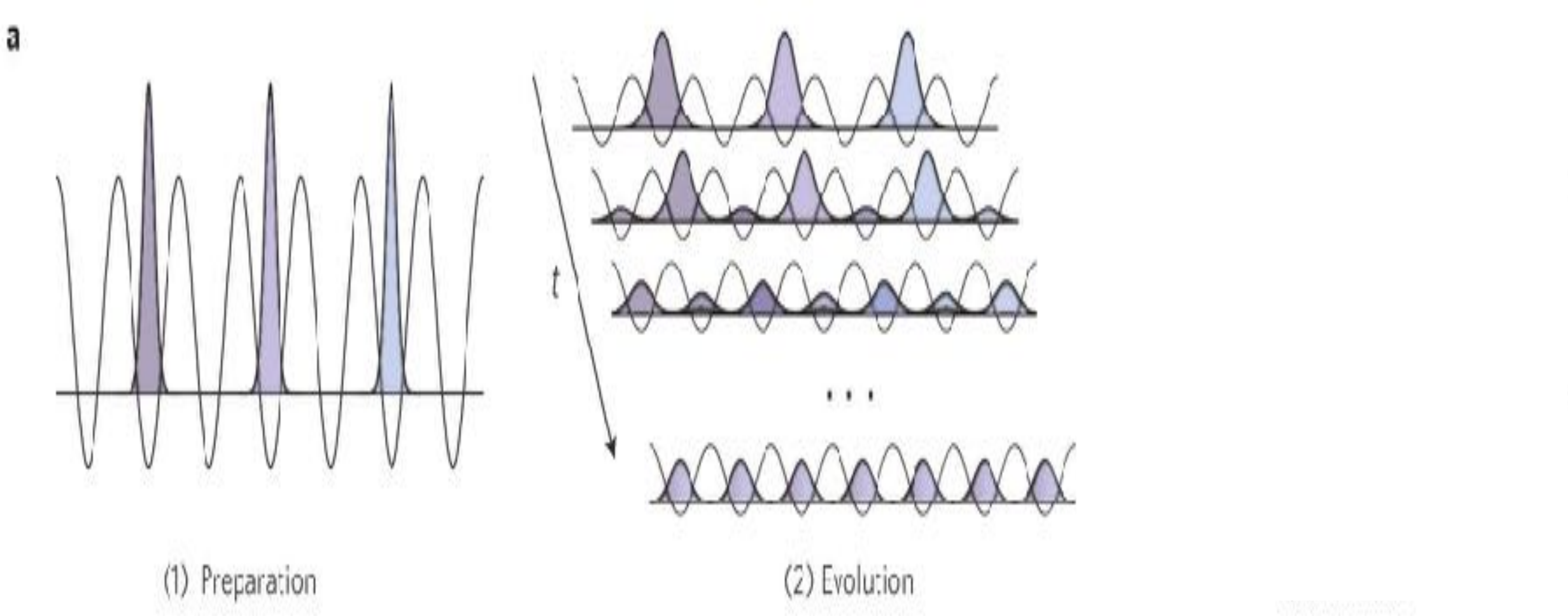
- Ground state/equilibrium properties
- Quantum dynamics
- Controlled environments
- …

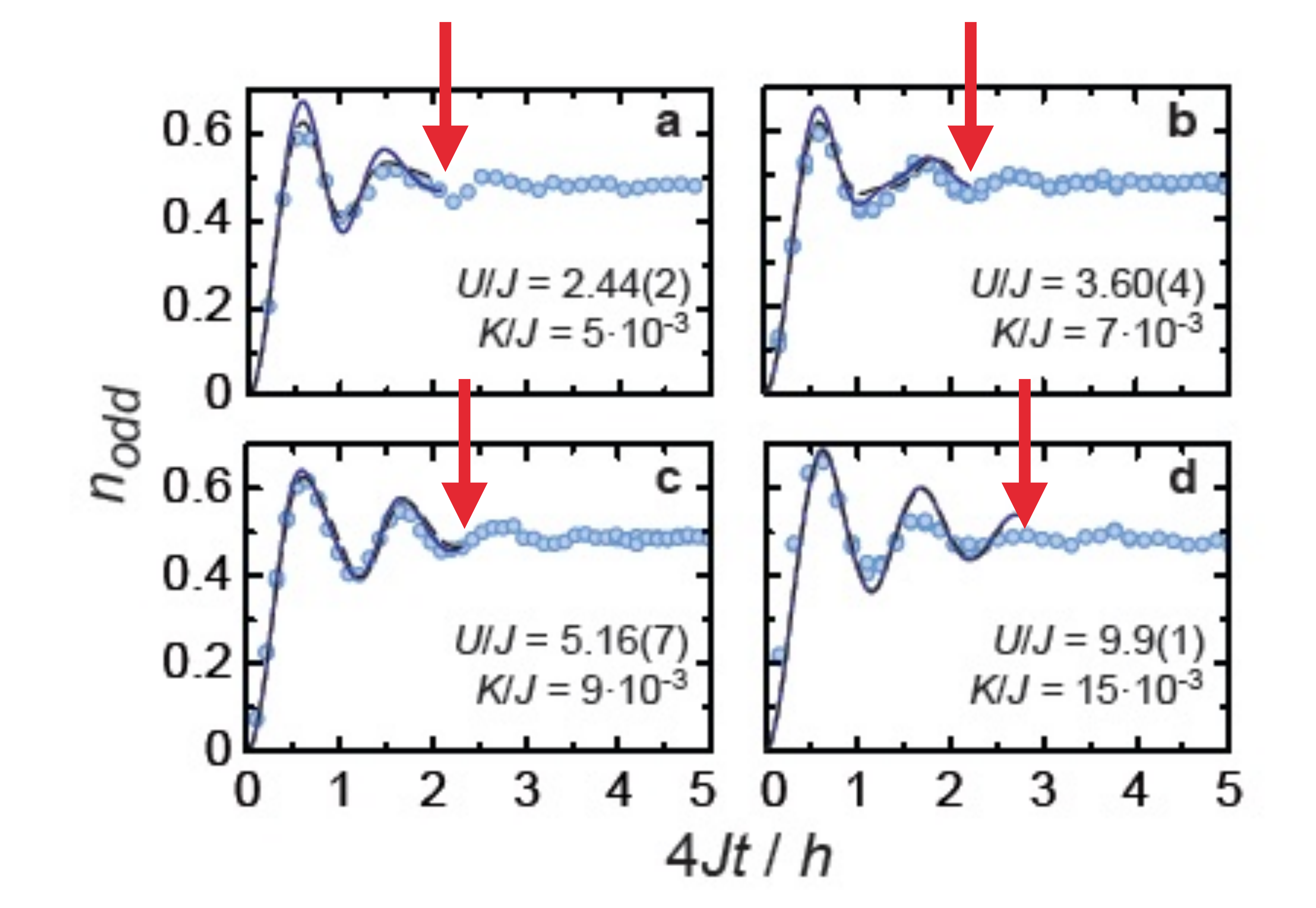
A POWERFUL QUANTUM SIMULATOR?



Following the dynamics, by means of numerical simulation, of a many-body quantum system becomes increasingly hard.

S. Trozky *et al*, Nat. Phys. (2012)





It poses interesting questions about the verifiability of quantum simulators

… how?

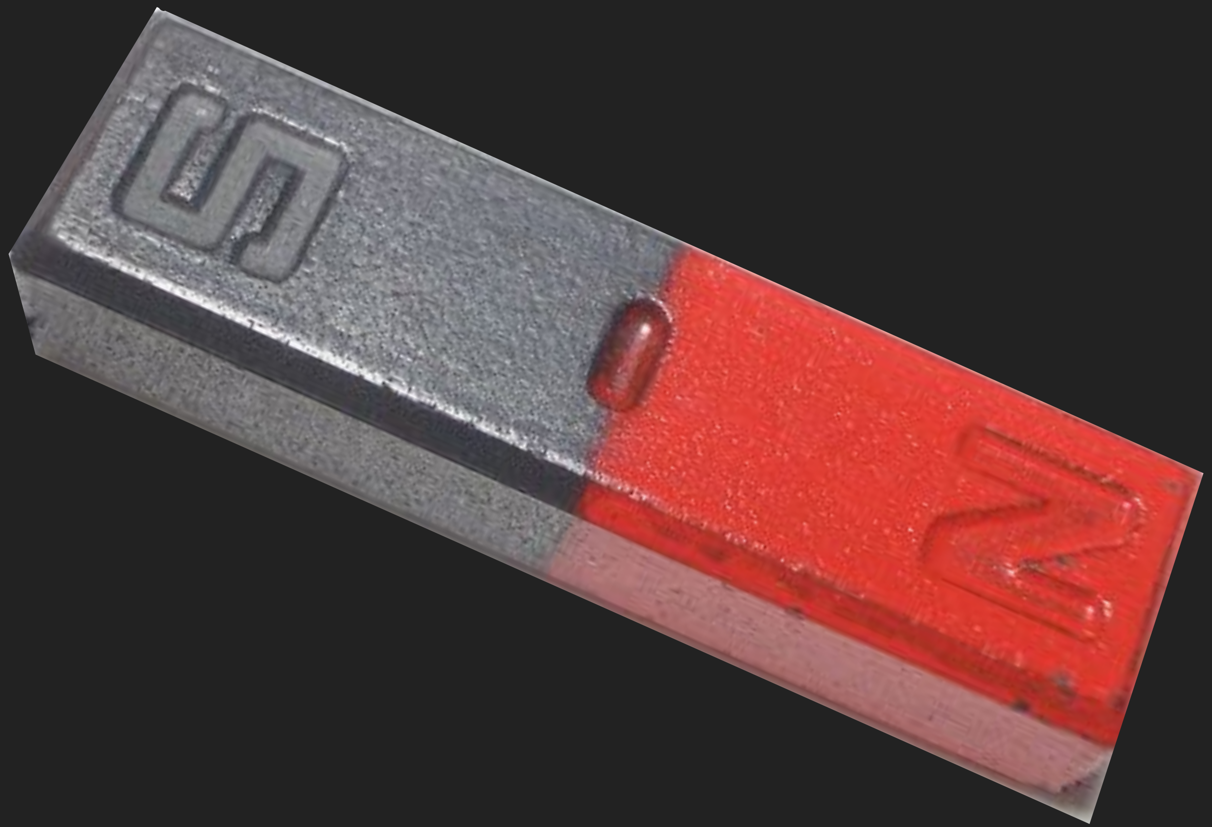
QUANTUM SIMULATORS

… a way to realise new physical phenomena not/(unlike to) observed in nature

TIME CRYSTALS

F. Wilczek (2012)

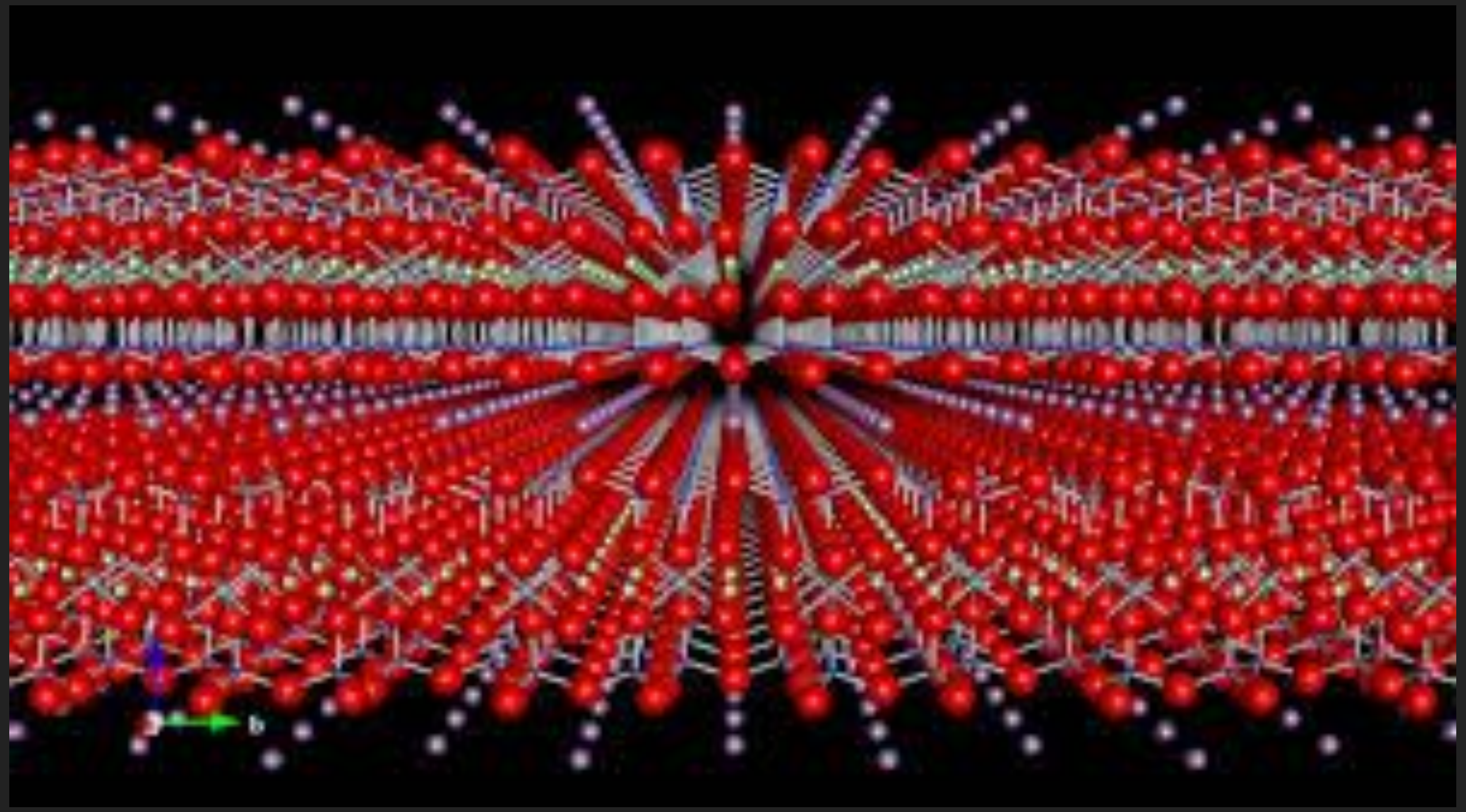
ORDERED STATES



Microscopic constituents have interactions that are invariant under translation/rotation …

The disordered state satisfies all the symmetries

The ordered state is less symmetric



TIME CRYSTALS

Can time-translational invariance be spontaneously broken?

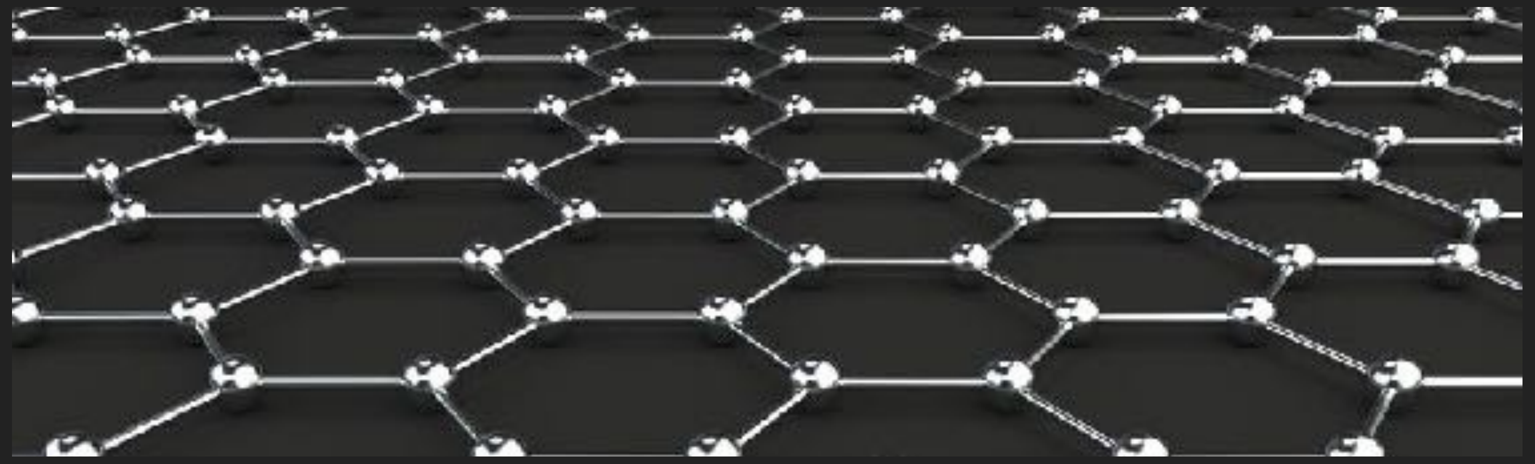
$\boxed{\text{Time-crystal}}$

[2012 - 2020]

TIME CRYSTALS

- Do laws of nature allow for the existence of a time-crystalline phase?
- …if yes, how to define/characterise a time crystal?
- …where to look for it?
- How much do we know of its relations to other phenomena?
- Is it “useful”?

TIME CRYSTALS VS SPACE CRYSTALS



Time-crystals cannot be understood as simple transliterations of their space-analogs

TIME CRYSTALS

Time-crystals cannot be understood as simple transliterations of their space-analogs

No-go theorem: systems in thermal equilibrium cannot manifest any time-crystalline behavior

Watanabe & Oshikawa 2015

$$\lim_{V \to \infty} \langle \phi(\vec{x}, t)\phi(\vec{x'}, t')\rangle \underset{|\vec{x}-\vec{x'}| \to \infty}{\longrightarrow} f(t-t')$$

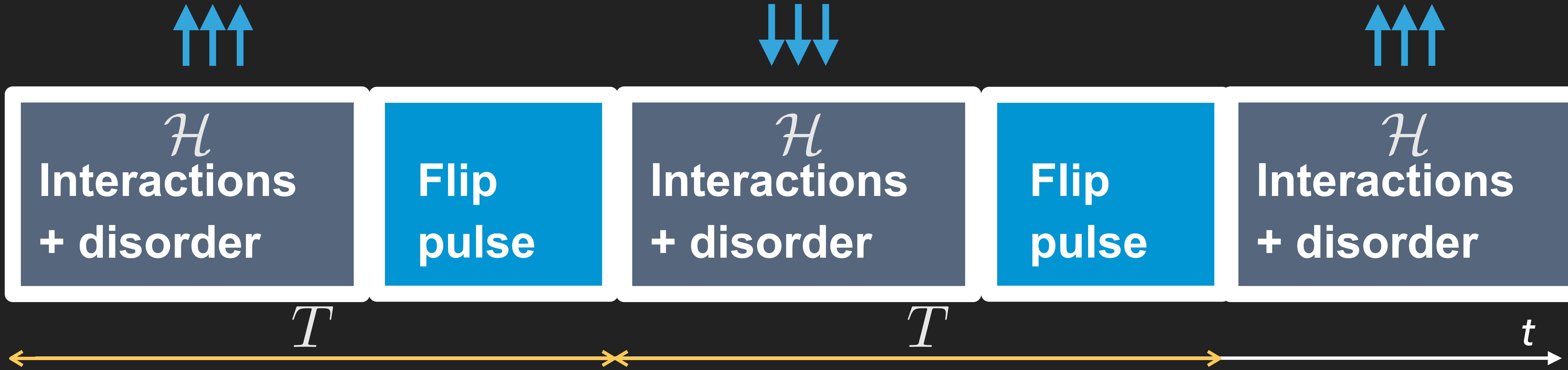
FLOQUET TIME CRYSTALS

$$\mathcal{H}(t+T) = \mathcal{H}(t)$$

TTSB in periodically driven systems

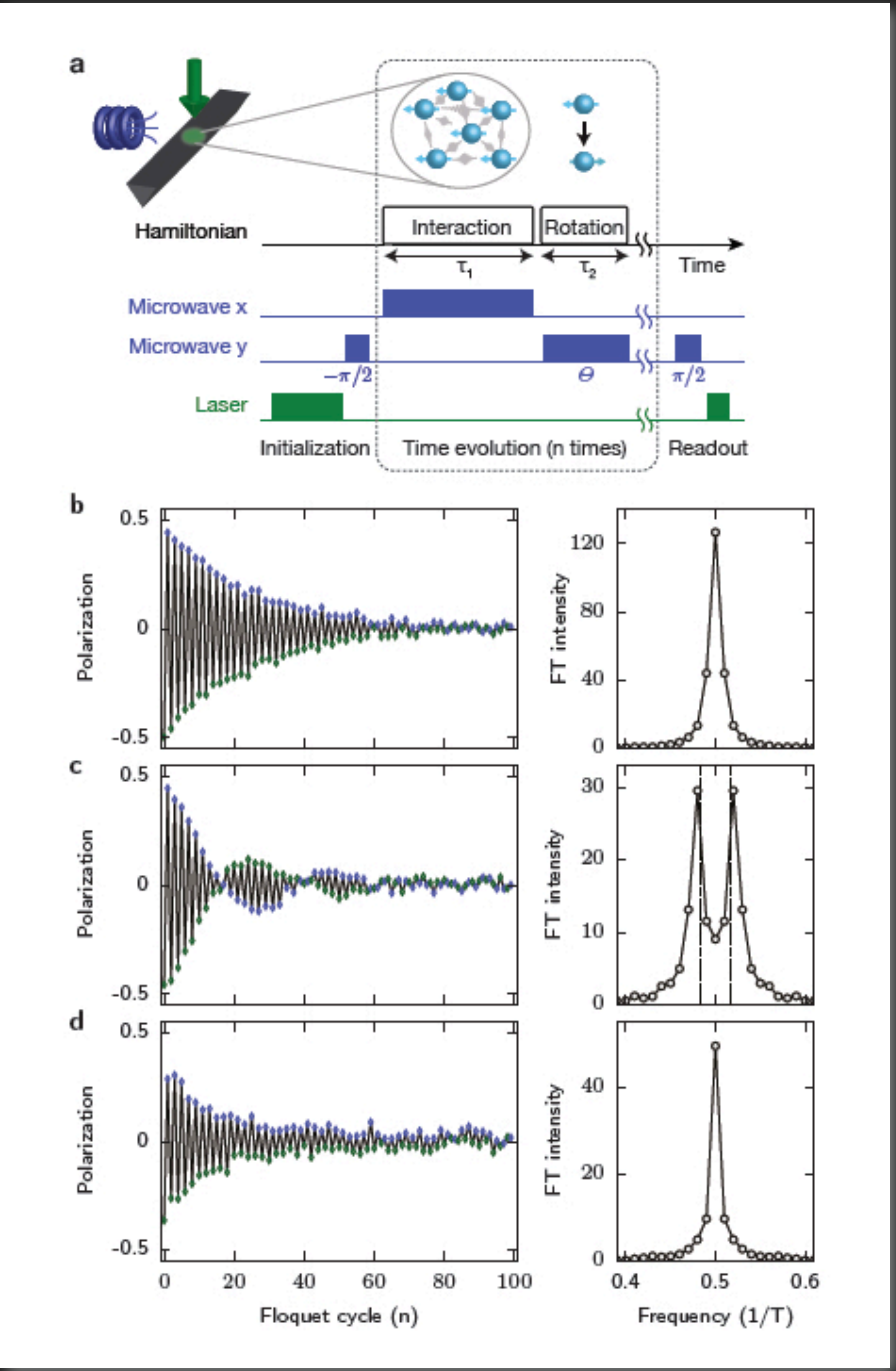
Else *et al* (2016)
Khemani *et al* (2016)

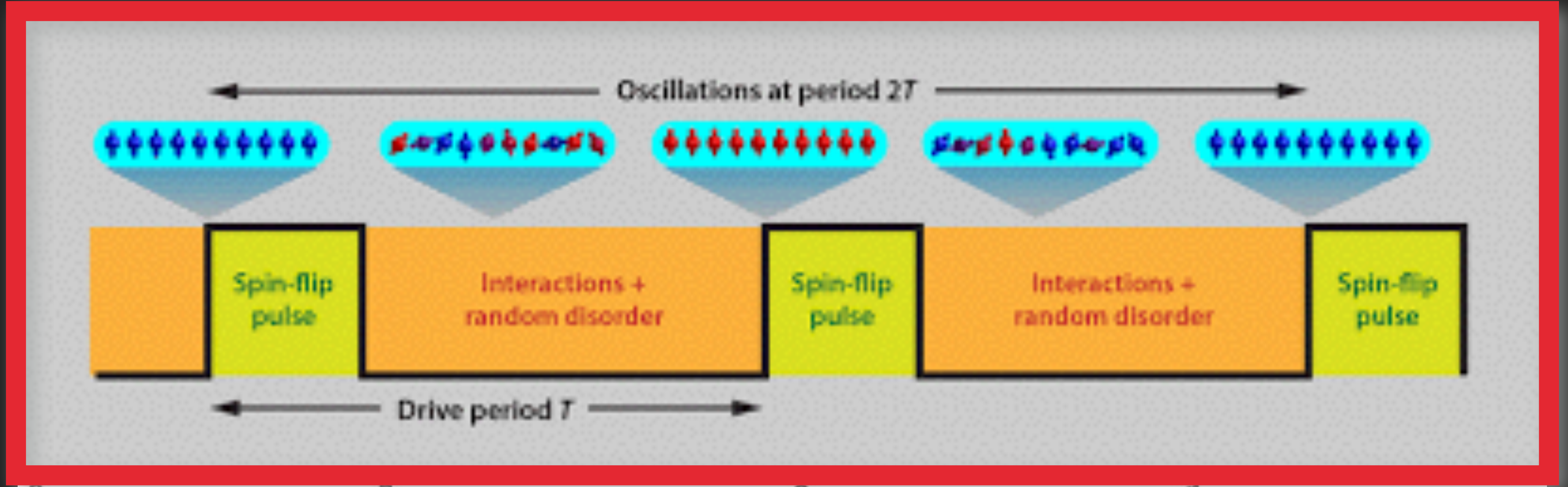
In the thermodynamic limit $$\langle O(t+nT)\rangle = \langle O(t)\rangle$$

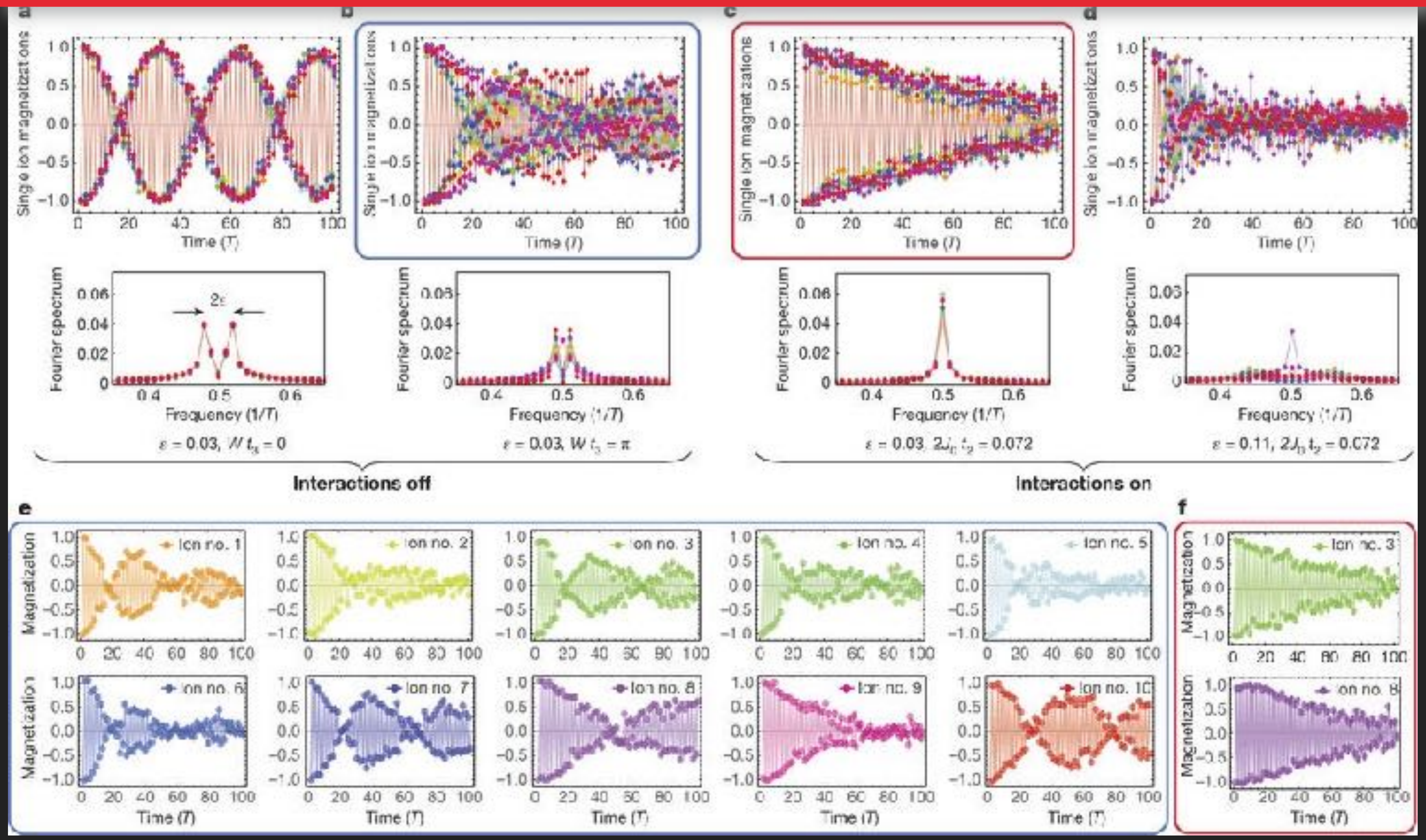


FLOQUET TIME CRYSTALS

Experimental realisation of Floquet time-crystals
Choi *et al* 2017
Zhang *et al* 2017



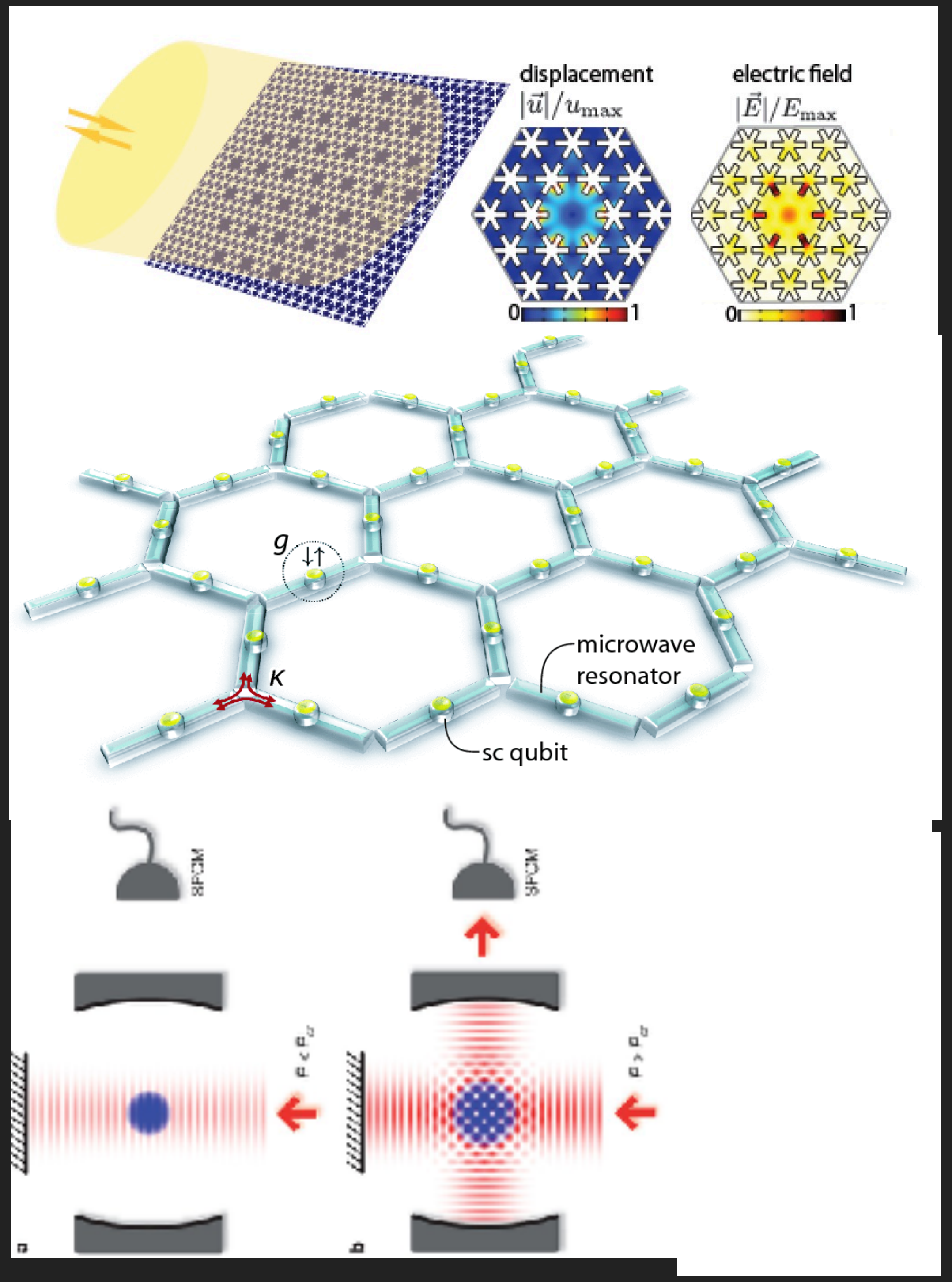




CONTINUOUS TIME CRYSTALS

Time-crystals in dissipative many-body open systems

Iemini *et al* 2018



- Many-body" limit cycles as time-crystals in open systems.
- These limit cycles can be understood as a macroscopic synchronised dynamics characterised by a time-dependent order parameter

$$\frac{d}{dt}\hat{\rho} = \hat{\mathcal{L}}[\hat{\rho}]$$

TIME CRYSTALS - FUTURE (?)

- Several important extensions (quasi-crystals, topological time-crystals, dissipative TC, attempts to go to higher dimensions, …)

- Connections to synchronization

- Applications to quantum technologies: collective states involving many quantum subsystems often offer features of enhanced resilience to the effects of the surrounding environment

- Applications to quantum technologies: application to nano-devices (nano-engines?)

CONCUSIONS

- Simulation
- Imagination

Thank you!