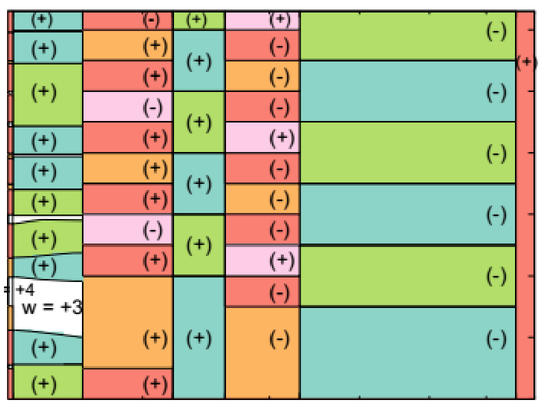
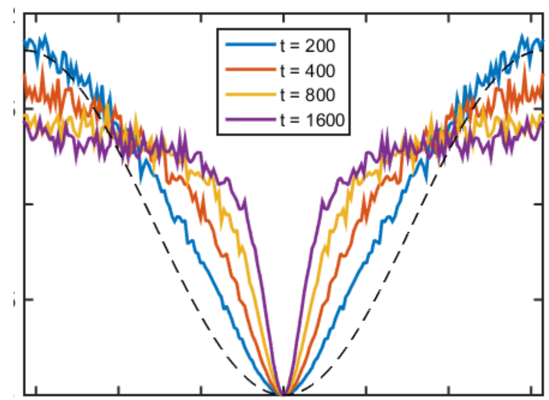
Emanuele Dalla Torre

From Floquet Engineering to Pre-thermalization

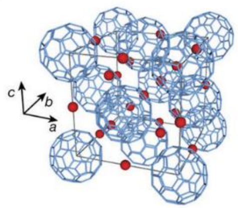




Why Floquet Engineering ?

Superconductors

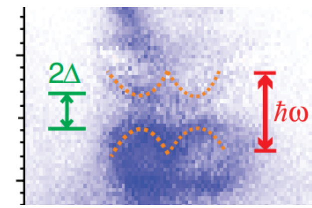
→ Light-enhanced superconductivity



[Cavalleri group – Nature 2016]

Topological insulators

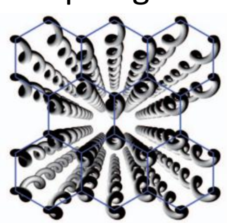
→ Floquet band structure



[Gedik group – Science 2013]

Wave guides

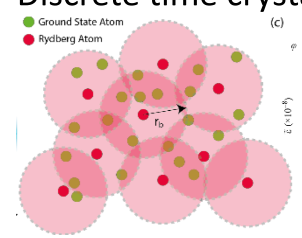
→ Photonic topological insulators



[Segev-Szameit group – Science 2018]

Rydberg atoms

→ Discrete time crystals



[Lukin group – Nature 2017]

Floquet Engineering - idea

Periodically driven Hamiltonian $H(t) = H(t+T)$

↕

Stroboscopic time evolution $|\psi(nT)\rangle = \left(U(T)\right)^n |\psi_0\rangle$

↕

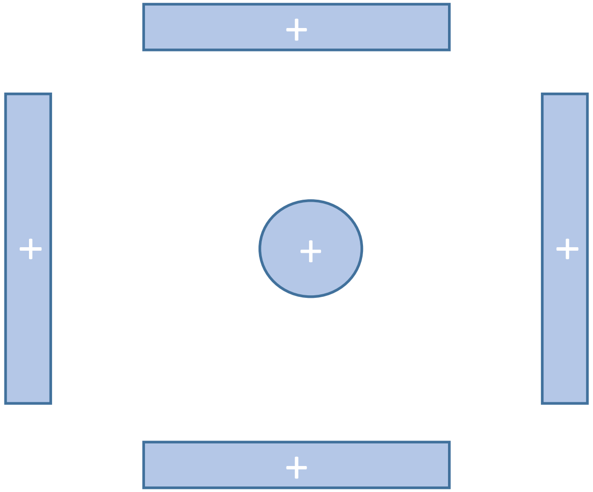
Effective Floquet Hamiltonian $|\psi(nT)\rangle = e^{-i\,H_F\,n\,T}|\psi_0\rangle$

$$U(T) = e^{-i\,H_F\,T}$$

H_F is coooool!

Eckardt, RMP 2017

Example 1 – Pauling trap



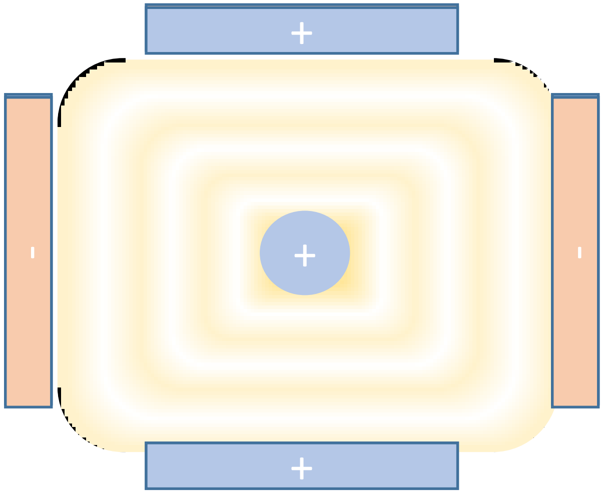
Trapping : $\begin{cases} \vec{\nabla}\phi = 0 \\ \nabla^2\phi > 0 \end{cases}$

But…

$$\nabla^2\phi = -\vec{\nabla}\cdot\vec{E} = -4\pi\rho = 0$$

→ No static trapping in vacuum

Example 1 – Pauling trap



$$H(t) = \frac{p^2}{2m} + V(x^2 - y^2)\cos(\Omega t)$$

$$H_{av} = \frac{p^2}{2m}$$

Magnus expansion

$$H_{\mathrm{F}} = H_{av} + \frac{1}{\Omega}\int dt \int dt' [H(t), H(t')] + \ \ldots$$

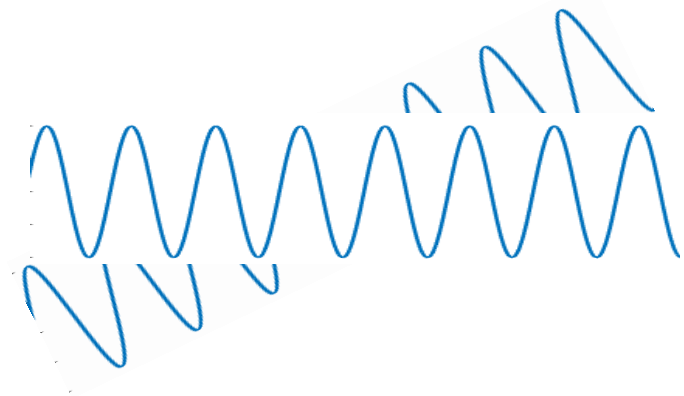
$$H_{\mathrm{F}} = \frac{p^2}{2m} + \frac{V^2}{\Omega^2\, m}(x^2 + y^2)$$

Example 1 – Pauling trap

Video credit: Harvard Natural Sciences Lecture Demonstrations

Example 2 – lattice shaking

$$H(t) = \sum_i J(c_i^+ c_{i+1} + H.c.) + V\, i\, n_i \cos(\Omega t)$$

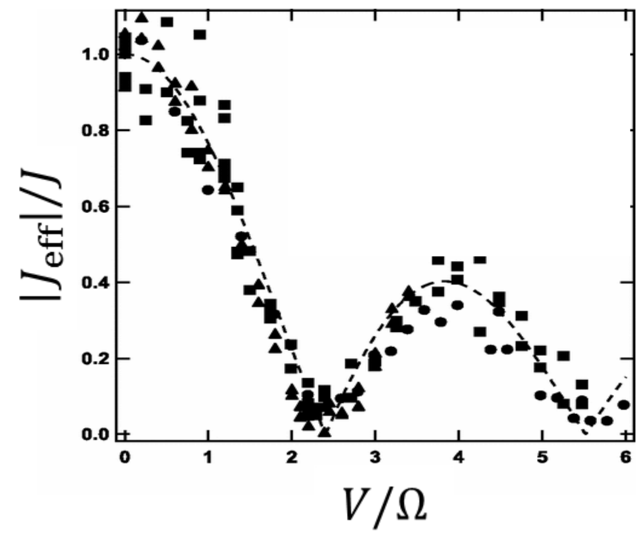


"Gauge transformation" (rotating frame)

$$H(t) = J \sum (e^{i V \cos(\Omega t)} c_i^+ c_{i+1} + H.c.)$$

$$H_F \approx H_{av} = J J_0\left(\frac{V}{\Omega}\right) \sum_i (c_i^+ c_{i+1} + H.c.)$$

J_{eff}



Morsch-Arimondo PRL 2007 & PRL 2008

Outline

Periodically driven spin chain

- **Periodically driven Ising model → Time crystal**

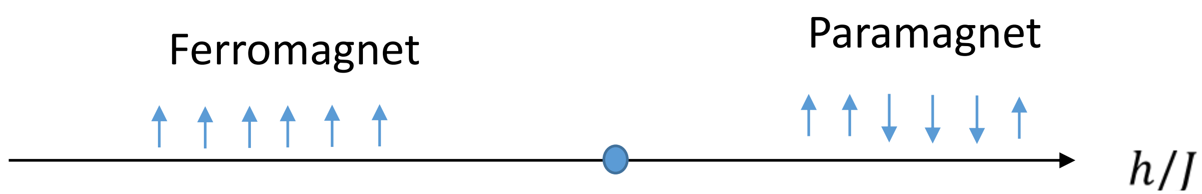
  Russomanno, Dalla Torre (EPL 2016)
  Russomanno, Friedman, Dalla Torre (PRB 2017)

- **Many body kicked rotor → Prethermalization**

  Rajak, Citro, Dalla Torre (arXiv:1801.01142)

Ising model : static

$$\hat{H}(t) = \sum_{j} \left(-J\hat{\sigma}^z_j\hat{\sigma}^z_{j+1} + h(t)\hat{\sigma}^x_j\right) \qquad h(t) = h_0$$

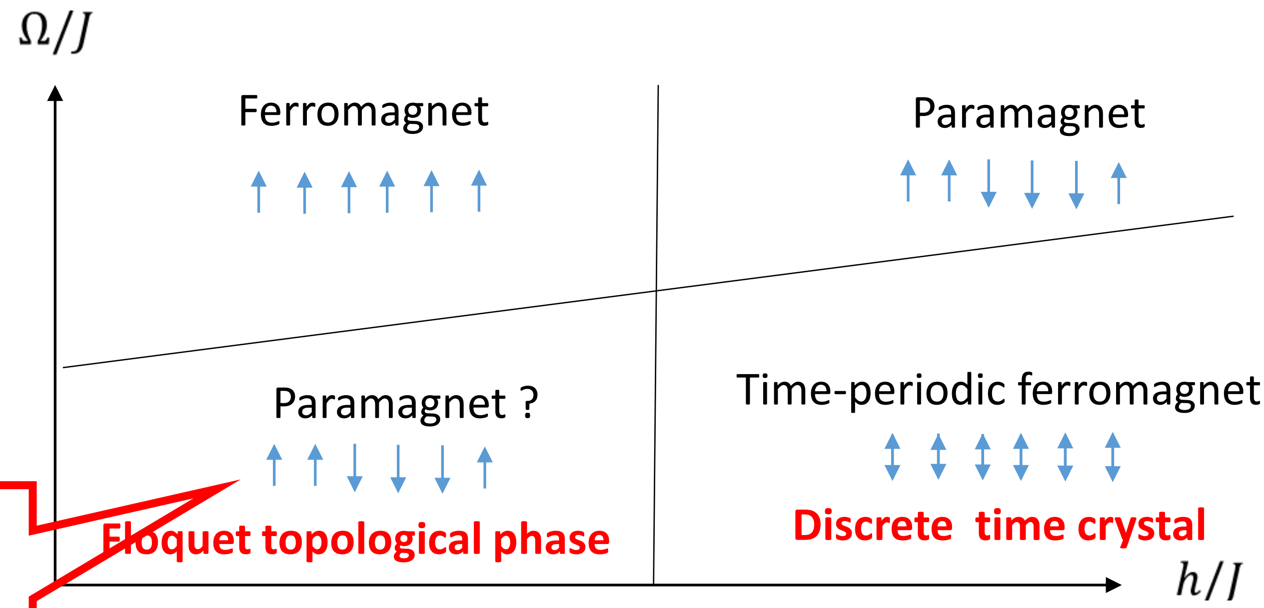


Quantum phase transition

Ising model : periodic drive

$$\hat{H}(t) = \sum_j \left(-J\hat{\sigma}^z_j\hat{\sigma}^z_{j+1} + h(t)\hat{\sigma}^x_j\right)$$

$$h(t) = h_0 + \delta h \cos(\Omega t)$$



Non local order

$$\hat{\beta}^y_j = \left(\prod_{k=1}^{j-1}\hat{\sigma}^x_k\right)\hat{\sigma}^z_j\hat{\sigma}^y_{j+1}$$

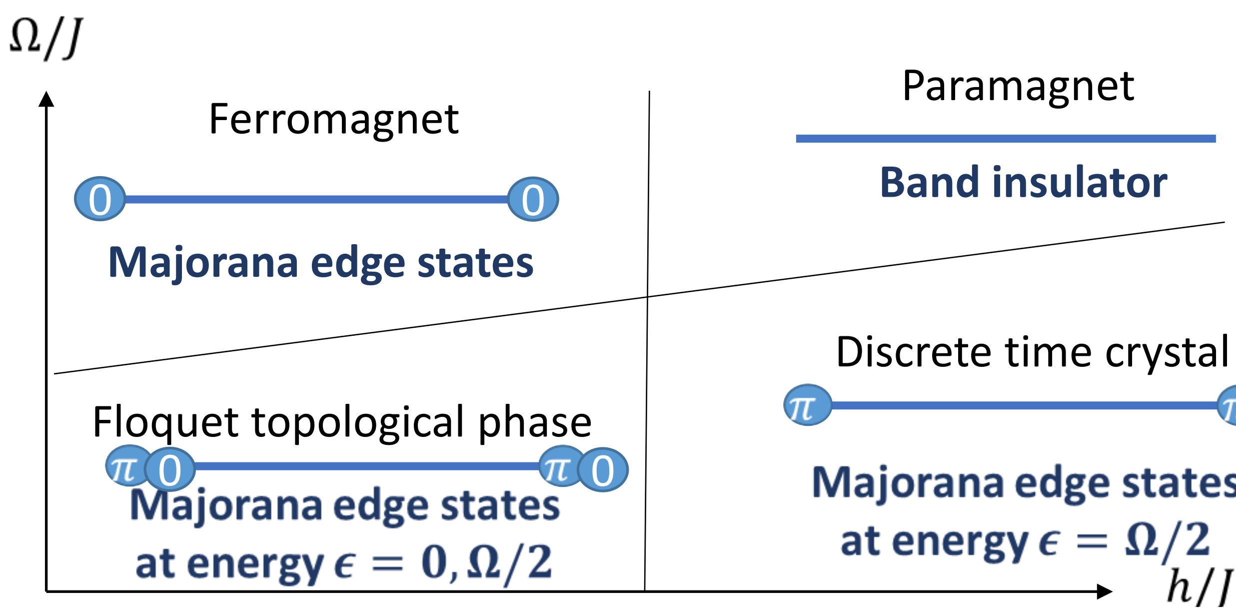
Else, Bauer, Nayak (PRL 2016)

Russomanno, Friedman, Dalla Torre (PRB 2017)

Ising model : periodic drive

Jordan-Wigner transformation

$$\hat{H}(t) = \sum_j \left(-J\hat{\sigma}^z_j\hat{\sigma}^z_{j+1} + h(t)\hat{\sigma}^x_j\right) \Rightarrow H = \sum_j J\,(c_i + c_i^\dagger)(c_{i+1} - c_{i+1}^\dagger) + h(t)c_i^\dagger c_i$$



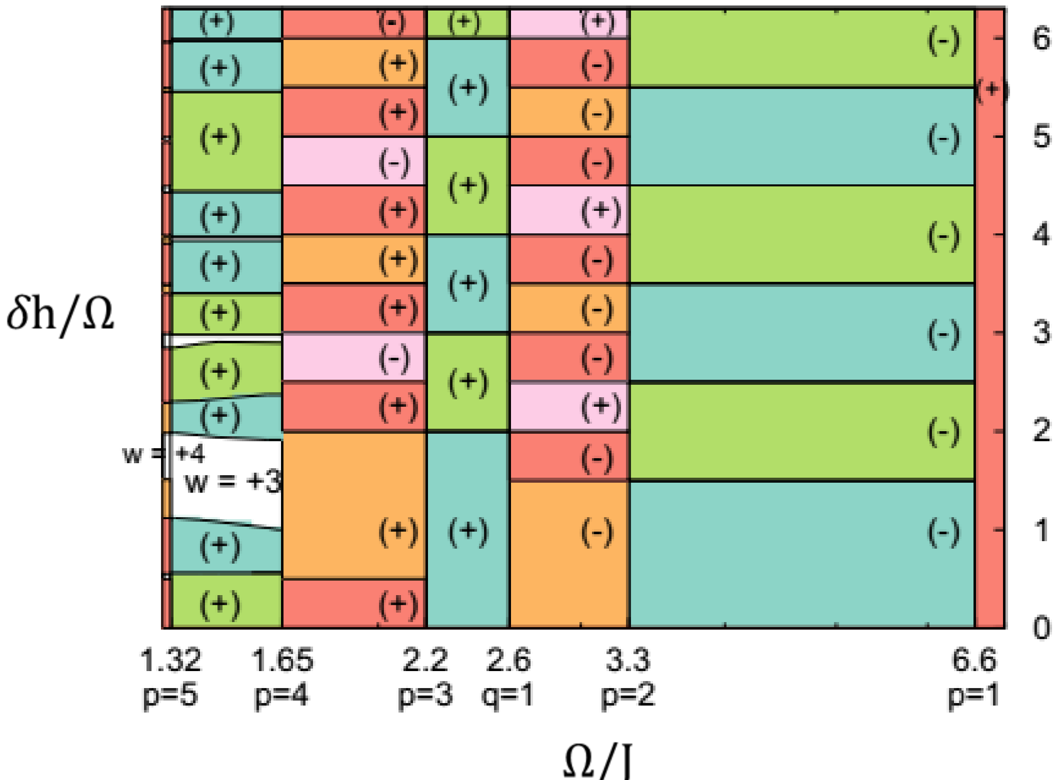
End of the story?

Else, Bauer, Nayak PRL 2016

Ising model : periodic drive

$$\hat{H}(t) = \sum_{j} \left(-J\hat{\sigma}^z_j\hat{\sigma}^z_{j+1} + h(t)\hat{\sigma}^x_j\right)$$

$$h(t) = 2.3\,J + \delta h \cos(\Omega\, t)$$



- Paramagnet
- Ferromagnet
- Time crystals
- Topological phases
- Floquet topological phase

Russomanno, Dalla Torre (EPL 2016)
Russomanno, Friedman, Dalla Torre (PRB 2017)

The problem : heating

Break integrability = Add interactions

↓

Thermalize (Eigenstate thermalization hypothesis)

↓

Steady state = infinite temperature

$$Z = 1$$

How to prevent heating?

✓ Integrability

✓ Disorder (many-body localization)

✓ **High-frequency drive (prethermalization)**

Classical many-body:

?

Quantum many-body:

Choudhury & Mueller PRA 2014 - Bukov *etal* PRL 2015 - Abanin *etal* PRL 2015 – Goldman *etal* PRA 2015 - Chandra & Sondhi PRB 2016 – Canovi PRE 2016 - Abanin *etal* CMP 2017 - Lellouch *etal* PRX 2017 - Kuwahara *etal* Annals 2017 - Weidinger & Knap SR 2017 – Zeng & Sheng PRB 2017 – Else *etal* PRX 2017 - Abanin etal PRB 2017.

Coupled Kicked rotors

$$H = \sum_{j=1}^{N} \left[\frac{p_j^2}{2} - \kappa \cos(\phi_j - \phi_{j+1}) \sum_{n=-\infty}^{+\infty} \delta(t - n\tau) \right].$$

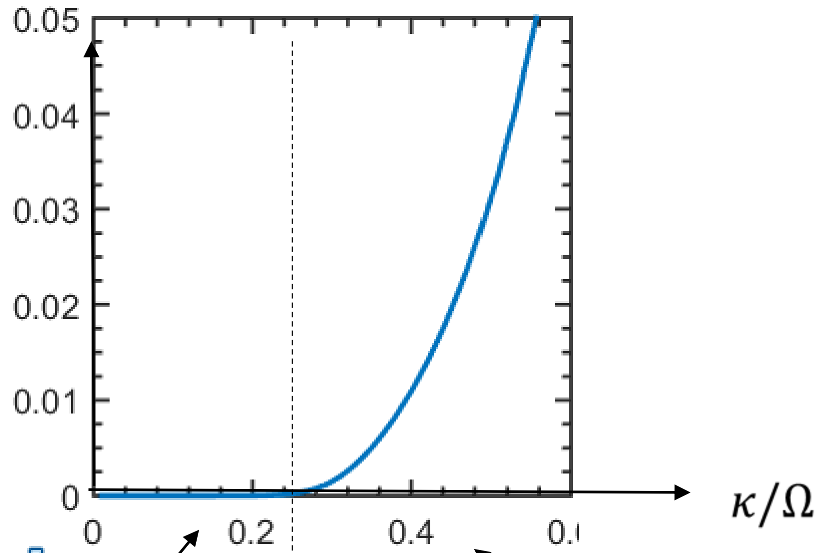
Always diffusive

Kaneko & Konishi (1989)

Chirikov & Vecheslavov (1997)

Diffusion coefficient

$$D = \frac{\langle p(T)^2 \rangle - \langle p(0)^2 \rangle}{T}$$

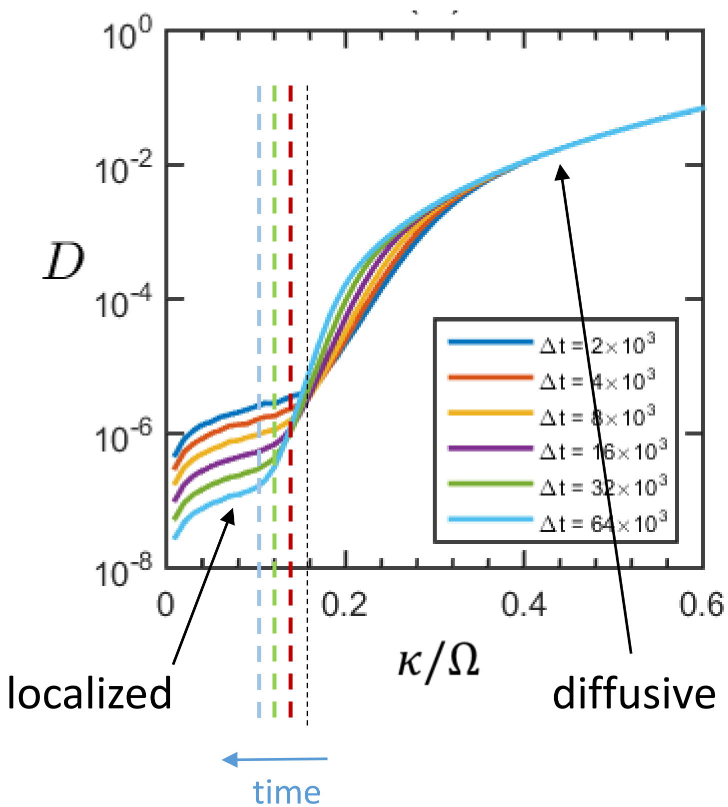


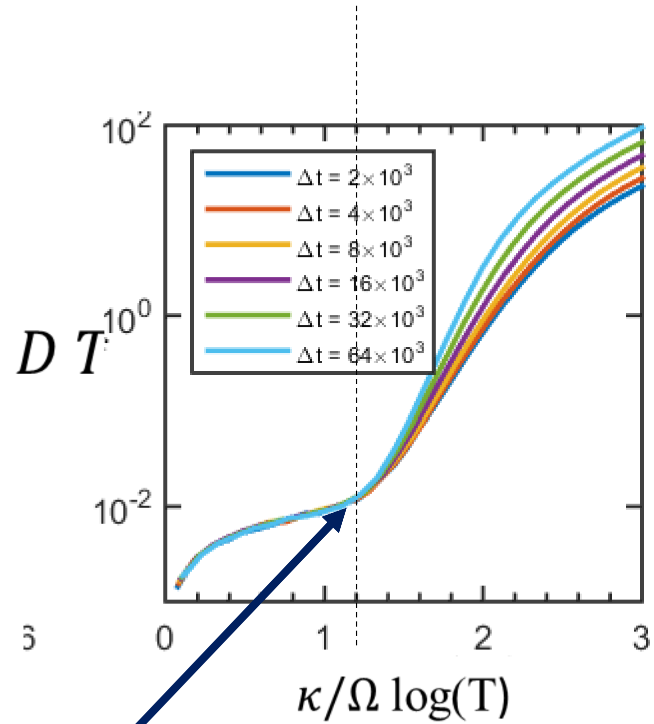
High frequency = localized

Low frequency = diffusive

Coupled kicked rotors – scaling analysis

$$D = \frac{\langle p(T)^2 \rangle - \langle p(0)^2 \rangle}{T}$$

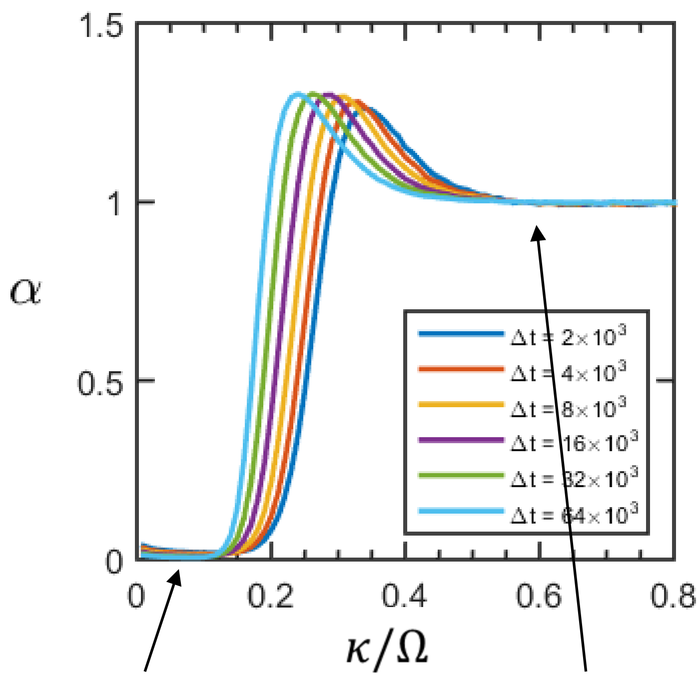




$$\frac{\kappa}{\Omega}\log(T) = 1.2$$

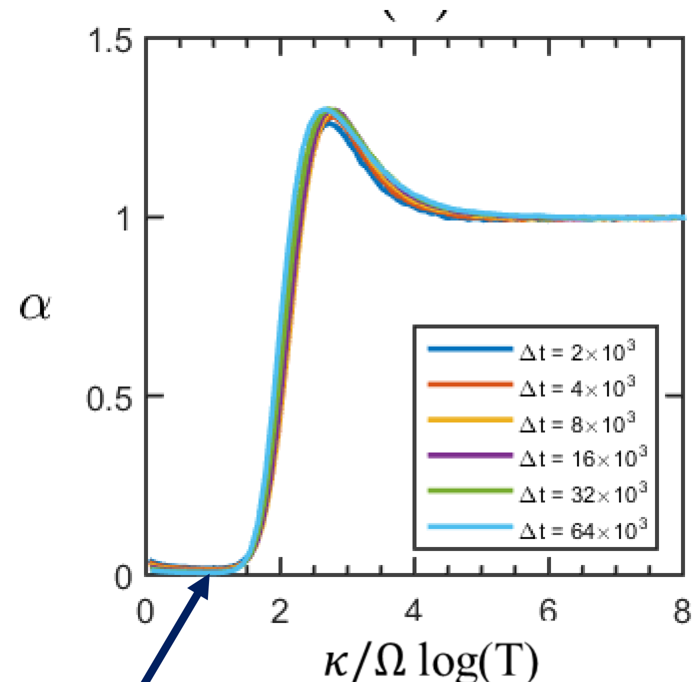
Coupled kicked rotors – scaling analysis

$$\langle p(T)^2 \rangle = A\, t^{\alpha}$$



Localized

Diffusive



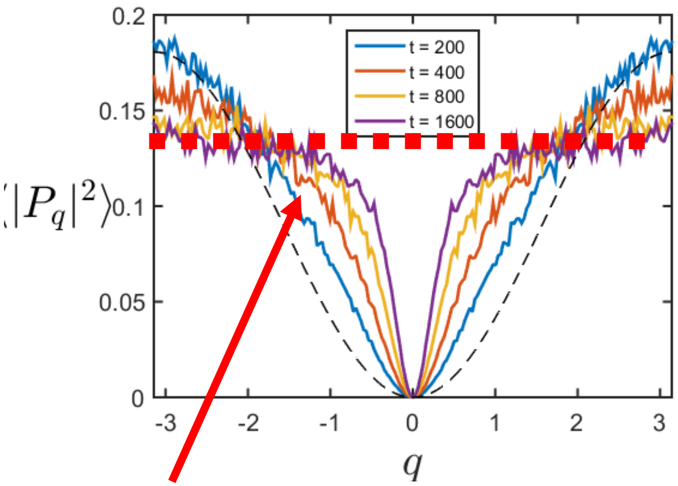
$$\frac{\kappa}{\Omega}\log(T) = 1.2$$

"Marginal localization"

$$\frac{\kappa}{\Omega}\log(T^*) = 1.2 \quad \Rightarrow \quad T^* = \exp\left(\frac{\Omega}{\kappa}\right)$$

$T \ll T^*$

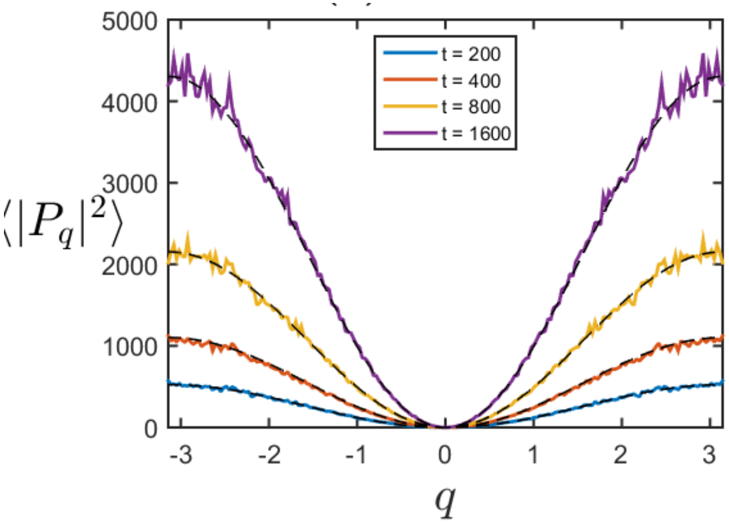
$\langle P^2 \rangle$ =const



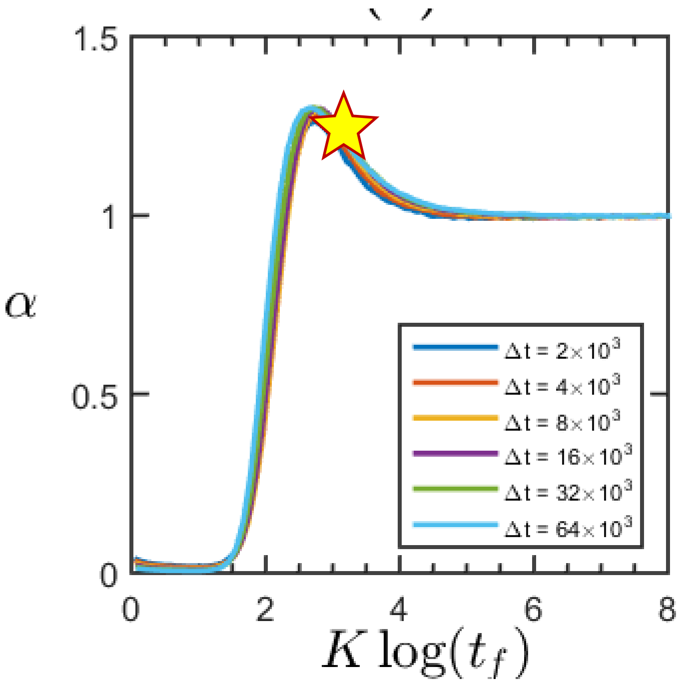
Prethermalization

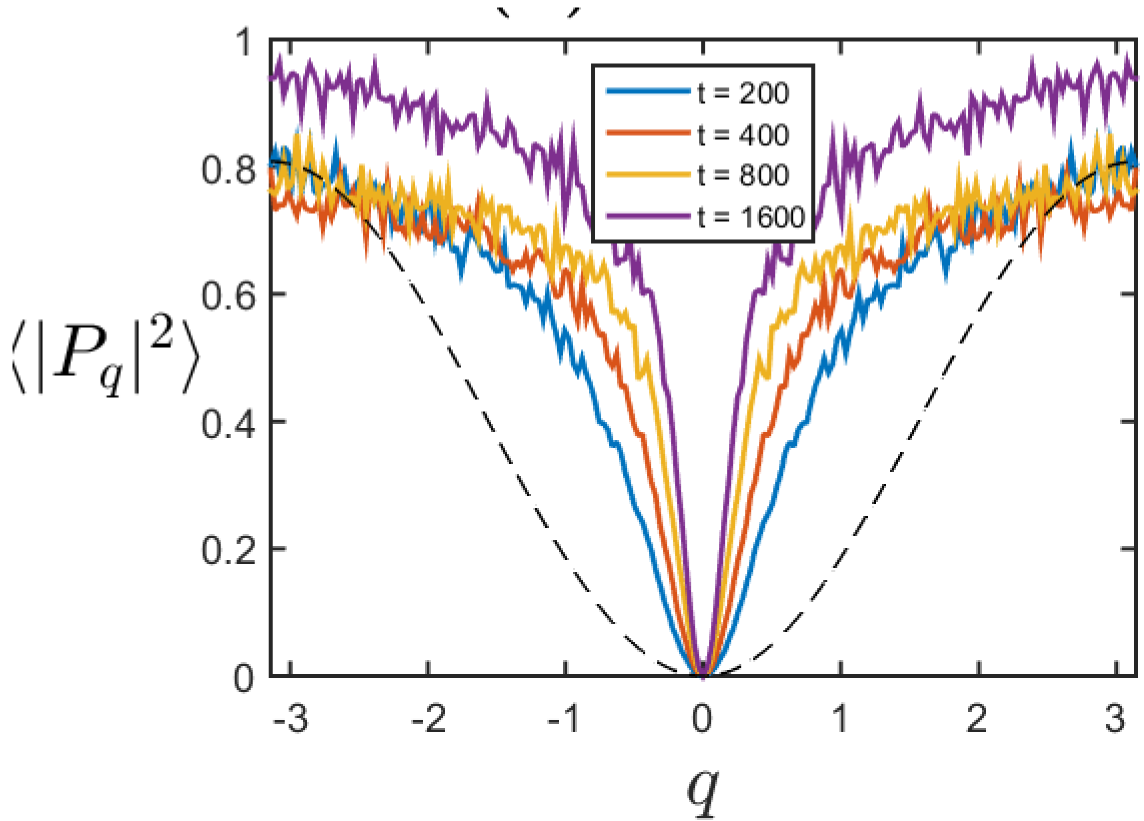
$T \gg T^*$

$\langle P^2 \rangle = D\,t$



Super-diffusion





Coupled kicked rotors – quadratic expansion

$$H = \frac{1}{2}\sum_q \left[|P_q|^2 + K(q)|\phi_q|^2 \sum_{n=-\infty}^{+\infty} \delta(t - n\tau)\right],$$

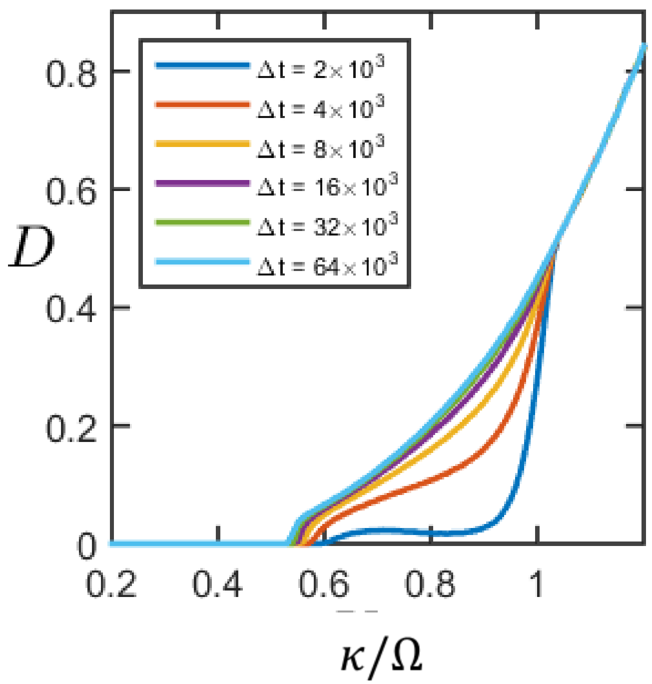
$$K(q) = \frac{4\kappa}{\Omega}\sin^2\left(\frac{q}{2}\right).$$

Kicked rotor
("Chirikov standard map")

→ Transition at $\kappa/\Omega = 1$

Coupled kicked rotors – quadratic instability

Initial state: $\phi_j \approx 0$



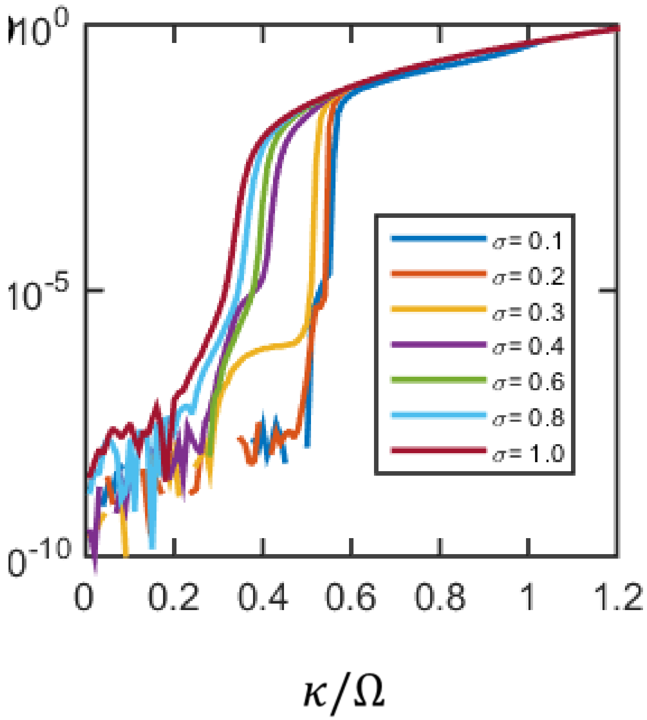
$$H^4 = -\frac{\kappa}{24}\sum_{j=1}^{N}(\phi_j - \phi_{j+1})^4 \sum_{m=1}^{\infty} \cos\left(\frac{2\pi m}{\tau}t\right),$$

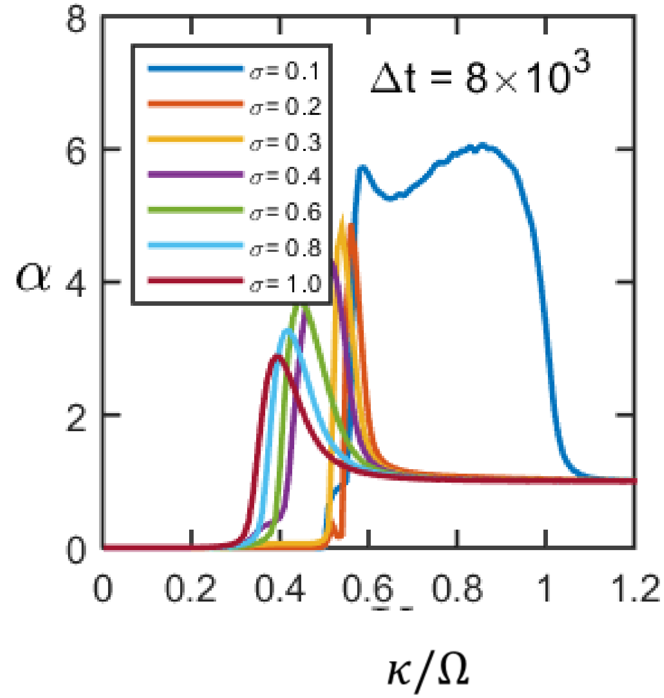
$$\Rightarrow \quad 2\pi m \leq 4\cos^{-1}(1 - 2\kappa/\Omega)$$

$$m = 4 \quad \Rightarrow \quad \frac{\kappa}{\Omega} > 0.5$$

Coupled kicked rotors – from quadratic to marginal

Initial state: $\langle \phi_j^2 \rangle = \sigma$





From Floquet Engineering to Pre-thermalization

Periodically driven spin chain

- **Periodically driven *quantum* Ising model**

  → **Time crystal & Floquet topological phases**

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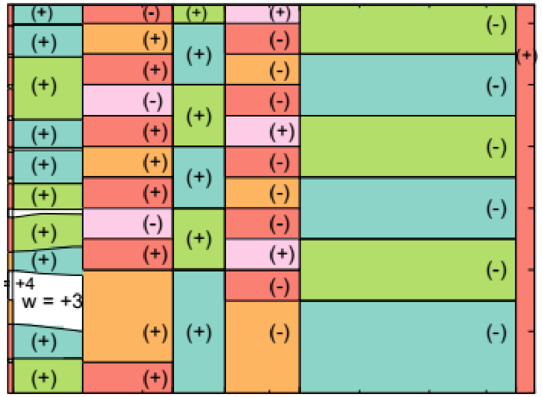
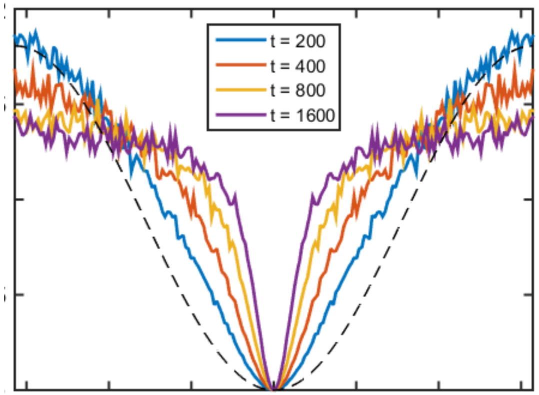


- **Many body *classical* kicked rotor**

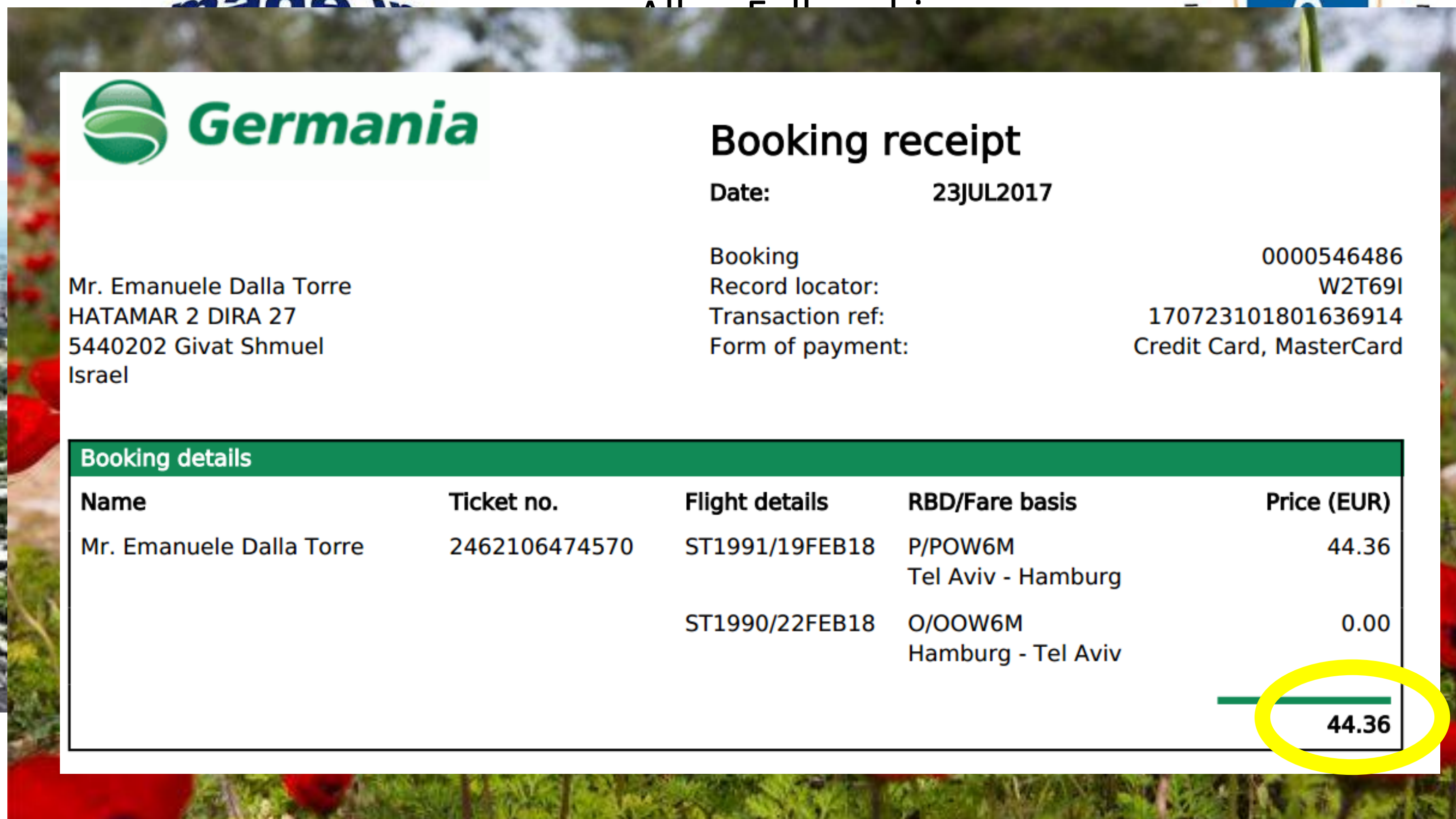
  → **Localization & Prethermalization**

  Rajak, Citro, Dalla Torre (arXiv:1801.01142)



How, who, and where?

$$ **Israel Science Foundation,**



Germania

Booking receipt

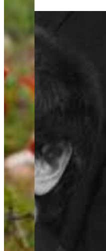
Date: **23JUL2017**

Mr. Emanuele Dalla Torre
HATAMAR 2 DIRA 27
5440202 Givat Shmuel
Israel

Booking	0000546486
Record locator:	W2T69I
Transaction ref:	170723101801636914
Form of payment:	Credit Card, MasterCard

Booking details

Name	Ticket no.	Flight details	RBD/Fare basis	Price (EUR)
Mr. Emanuele Dalla Torre	2462106474570	ST1991/19FEB18	P/POW6M Tel Aviv - Hamburg	44.36
		ST1990/22FEB18	O/OOW6M Hamburg - Tel Aviv	0.00
				44.36



1st Italy-Israel meeting on nonequilibrium Physics
Bar-Ilan University (April 11-13, 2016)

THE JERUSALEM POST

ITALIAN AND ISRAELI PHYSICISTS CONFER AT BAR-ILAN UNIVERSITY

BY LIDAR GRAVÉ-LAZI / APRIL 13, 2016 06:05

"Italy is Israel's most important European partner in the field of science."

SAVE THE DATE: 2nd meeting in Salerno (September 4-7, 2018)

Non-equilibrium Many-Body Quantum Physics

Periodically-driven systems

Dr. Atanu Rajak:
Dynamic localization of
a many-body kicked rotor

Topology in one dimension

Bat-El Friedman:
String order and
duality transformations

Dynamics of closed systems

Maty Aharonian:
colliding condensates
(Landau criterion)

Quantum optics

Mor Roses:
Real-time dynamics
of the extended Dicke model

Strongly correlated materials

David Dentelski:
Short vs. Long-range
superconducting fluctuations

Dr. Marcello Strinati:
Non-linear optics

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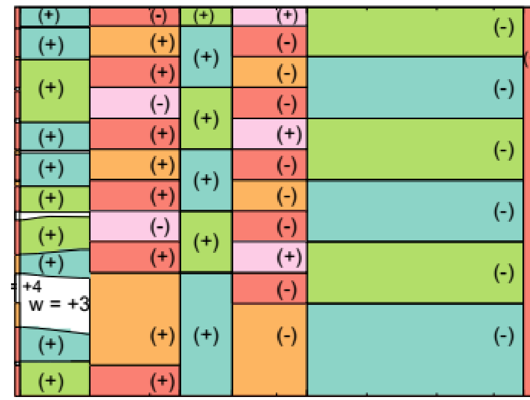

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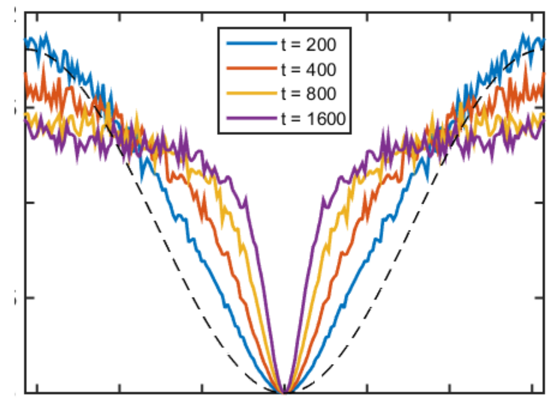
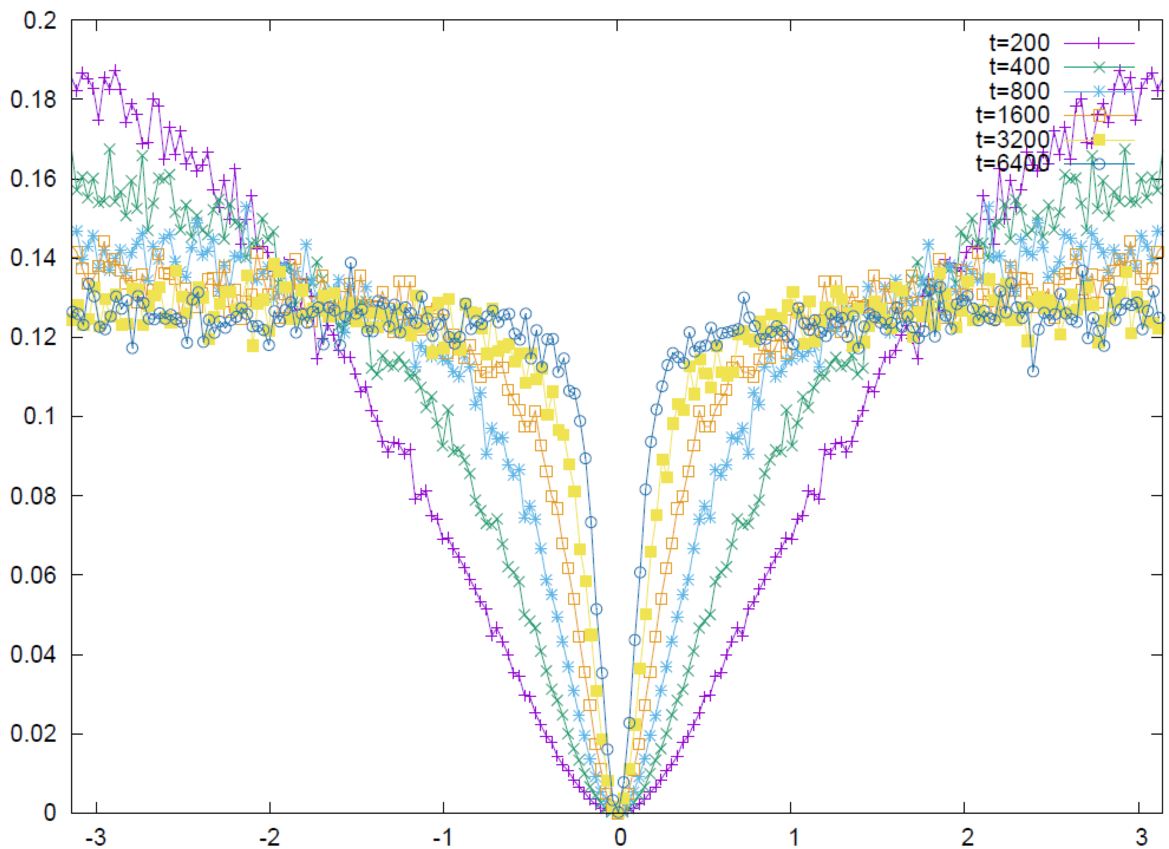
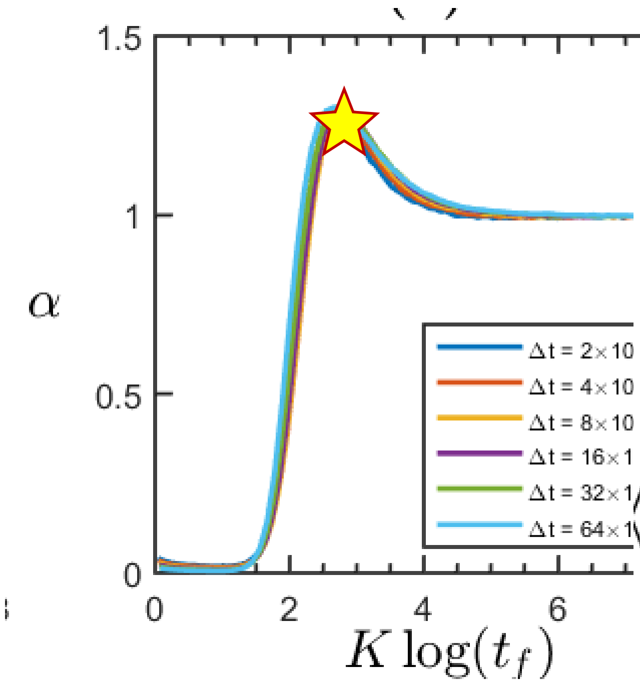


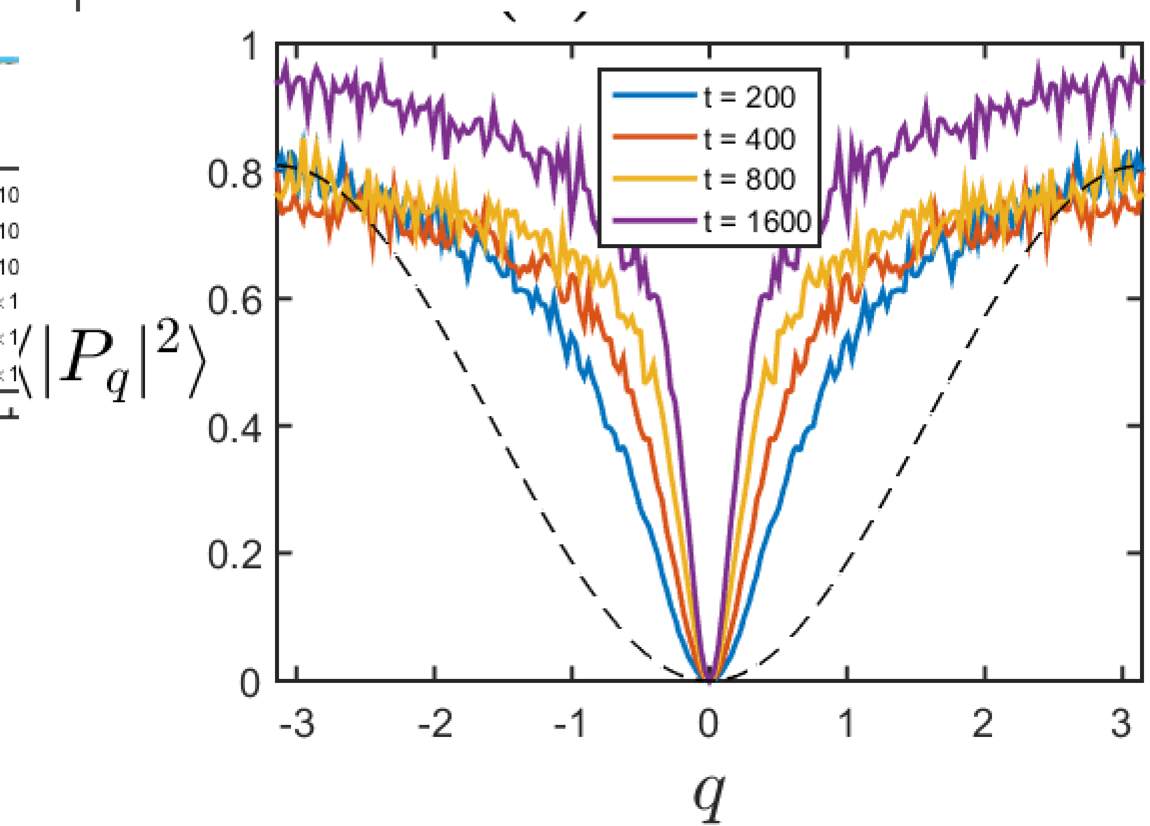
Extra slides

Prethermalization (longer times)



Super-diffusion





Finite size effect