Title: Many-Body Localization Through the Lens of Ultracold Quantum Gases

Date: May 23, 2017 04:00 PM

URL: http://pirsa.org/17050030

Abstract: <p>A fundamental assumption of quantum statistical mechanics is that closed isolated systems always thermalize under their own dynamics. Progress on the topic of many-body localization has challenged this vital assumption, describing a phase where thermalization, and with it, equilibrium thermodynamics, breaks down.

In this talk, I will describe how we can realize such a phase of matter with ultracold fermions in both driven and undriven optical lattices, with a focus on the relevance of realistic experimental platforms. Furthermore, I will describe new results on the observation of a regime exhibiting extremely slow scrambling, even for "infinite-temperature states" in one and two dimensions. Our results demonstrate how controlled quantum simulators can explore fundamental questions about quantum statistical mechanics in genuinely novel regimes, often not accessible to state-of-the-art classical computations.</p>

Probing Many-Body Localization with Ultracold Quantum Matter

Pranjal Bordia

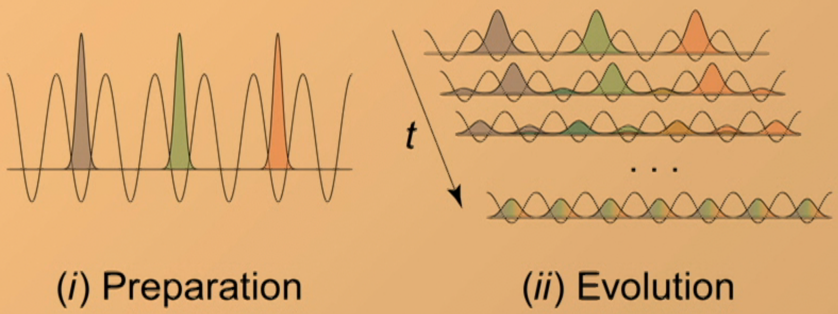
Experiments:
Henrik Lüschen, Sebastian Scherg,
Thomas Kohlart, Michael Schreiber,
Sean Hodgman, Ulrich Schneider,
Immanuel Bloch

Theory:
E. Altman, M. Knap,
S. Gopalakrishnan, M. Fischer, F. Alet

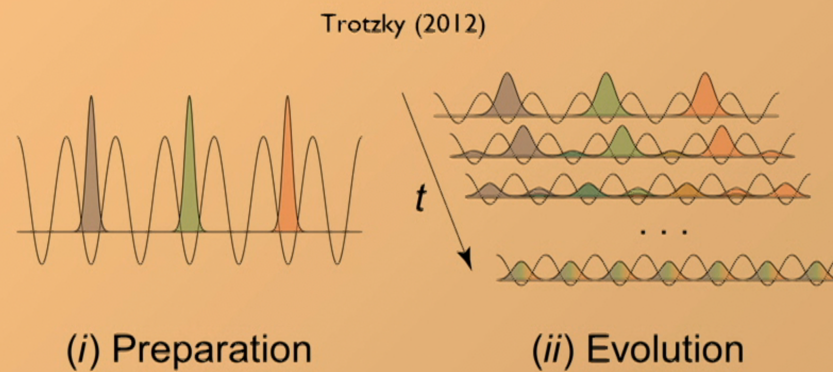
Perimeter Institute
Waterloo
23 May 17

Classical vs Quantum Worlds

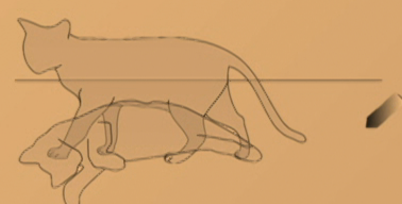
Trotzky (2012)



Classical vs Quantum Worlds

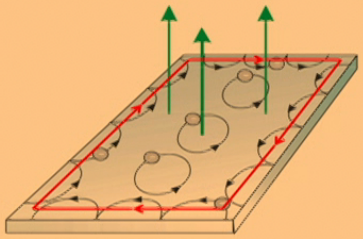


Can a large system evade a classical fate?

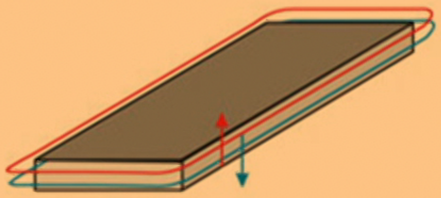


Near ground states

Quantum Hall effect

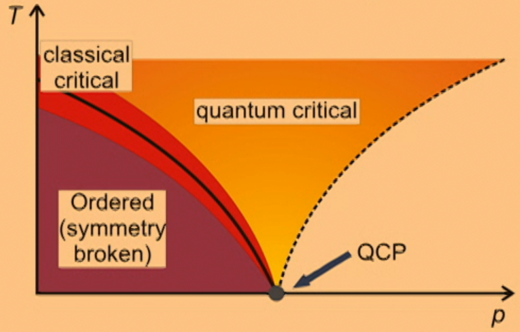


Topological insulators



Fermi liquid

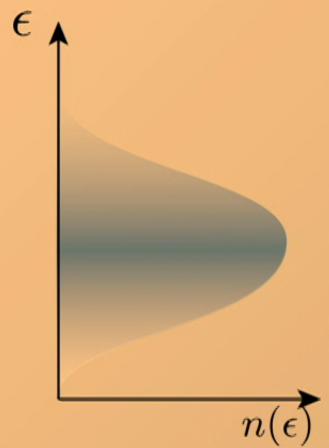
Quantum critical points



ETH

System serves its own “bath” in excited states

Local thermalization



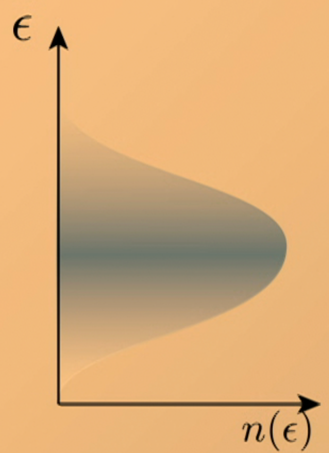
Deutsch 91, Srednicki 94, Rigol 08

ETH

System serves its own “bath” in excited states

Local thermalization

Ergodicity causes demise of (accessible) quantum correlations.



Well known example - integrable systems

Newton's cradle

Wikipedia

Well known example - integrable systems

Extensive number of *conservation laws* prohibit thermalization despite interactions

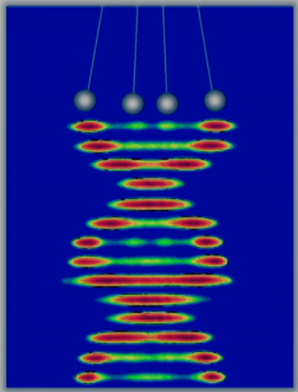
most likely,

fine-tuned, one-dimensional

Can we find non-ergodic systems which are more ***robust*** in ***higher-dimensions?***

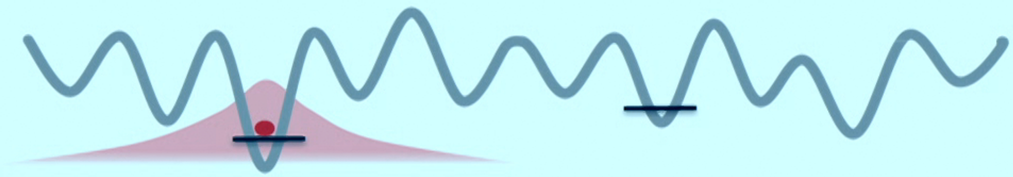
Newton's cradle

Wikipedia



Kinoshita (2006)

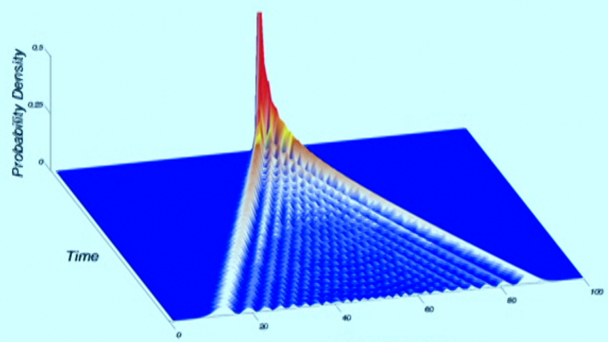
Anderson localization



P.W. Anderson

Vanishing probability of resonance
Absence of transport
Failure of ETH

No disorder

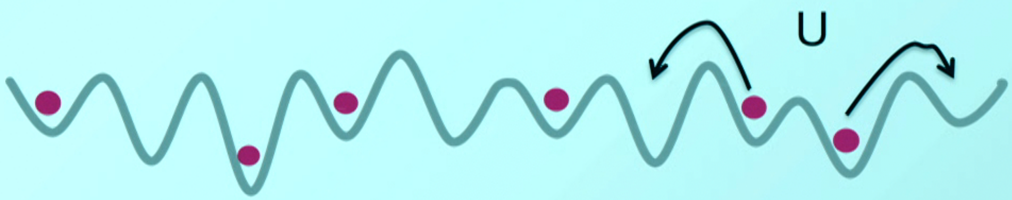


Interactions

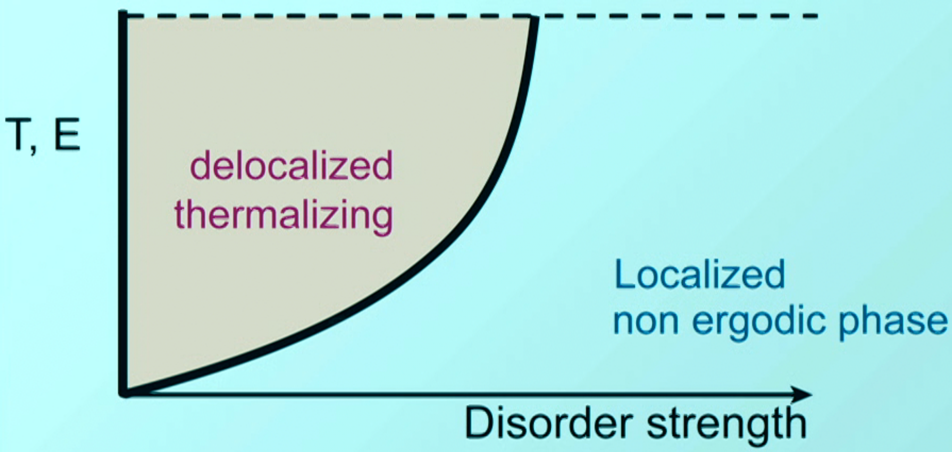
Can localization survive interactions?

Interactions

Can localization survive interactions?



MBL = stability of Anderson localization to interactions

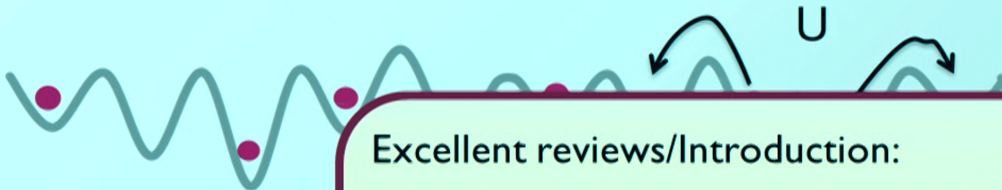


Basko, Aleiner, Altshuler (2005)
Gornyi, Mirlin, Polyakov (2005)

Systems with bounded spectrum:
Oganesyan and Huse (2007)
Imbrie (2015,16)

Interactions

Can localization survive interactions?

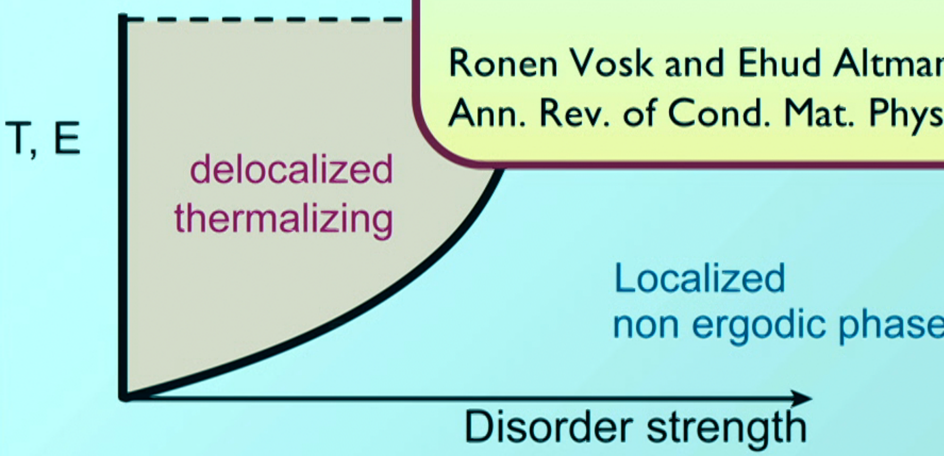


MBL = stab … ctions

Excellent reviews/Introduction:

Rahul Nandkishore and David Huse
Ann. Rev. of Cond. Mat. Phys. (2015)

Ronen Vosk and Ehud Altman
Ann. Rev. of Cond. Mat. Phys. (2015)



…er, Altshuler (2005)
…, Mirlin, Polyakov (2005)

Systems with bounded spectrum:
Oganesyan and Huse (2007)
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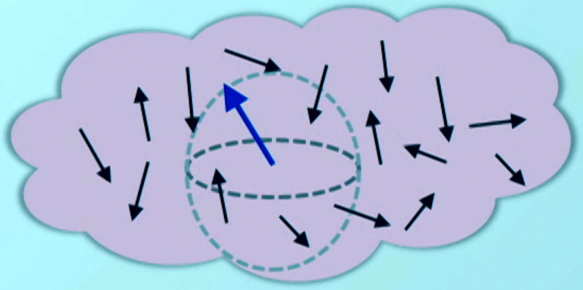
Highly excited states

Thermalization(ETH)

Highly **non-local** memory
Classical hydrodynamics

Breakdown of ergodicity (MBL)



Local **memory**
Quantum dynamics
A **robust exception** to thermalization

"Disorder"

Highly excited states

Thermalization(ETH)

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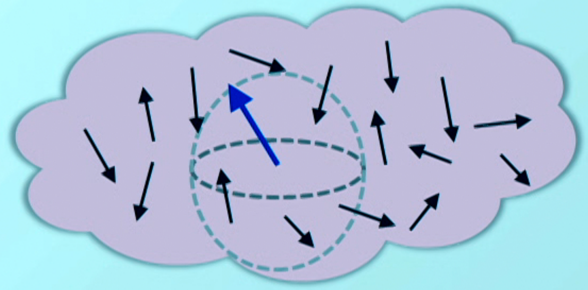


Local **memory**
Quantum dynamics
A **robust exception** to thermalization

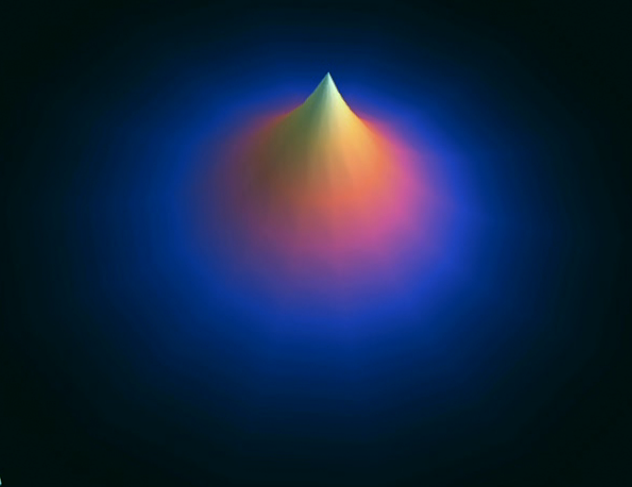
"Disorder"

1D Expt.: Schreiber, Science (2015) + Ions (Monroe)

How can we create and probe such systems?

↓

1) Need no underlying bath – Isolated system
2) A probe to measure non-thermal behavior



MBL in Two Dimensions

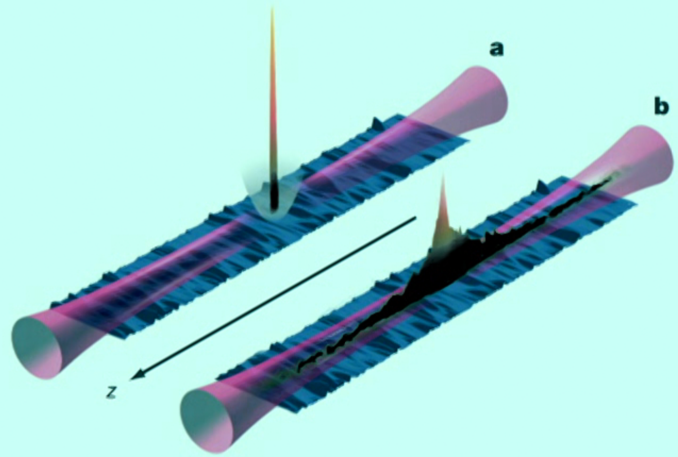
Bordia et.al.
arXiv 1704.03063

Joint work with
Prof. M. Knap, TU Munich
Prof. S. Gopalakrishnan, CUNY

Experiments

Ready…Set…Go!

J. Billy et. al. Nature 2008 (Inst. Opt.)
G. Roati et. al. Nature 2008 (LENS)



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J. Billy et. al. Nature 2008 (Inst. Opt.)
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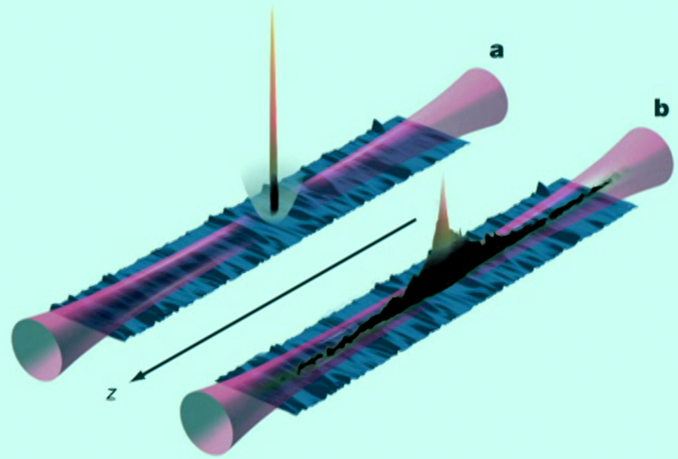
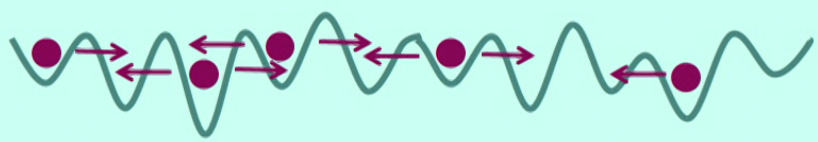
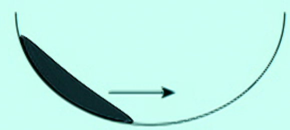


<u>Many-body version</u> Ready…Set…Go!

Fastest timescales: local probe



Previous bulk transport experiments : slowest timescale
Kondov (DeMarco), 2015 and J-y. Choi (Bloch/Gross), 2016



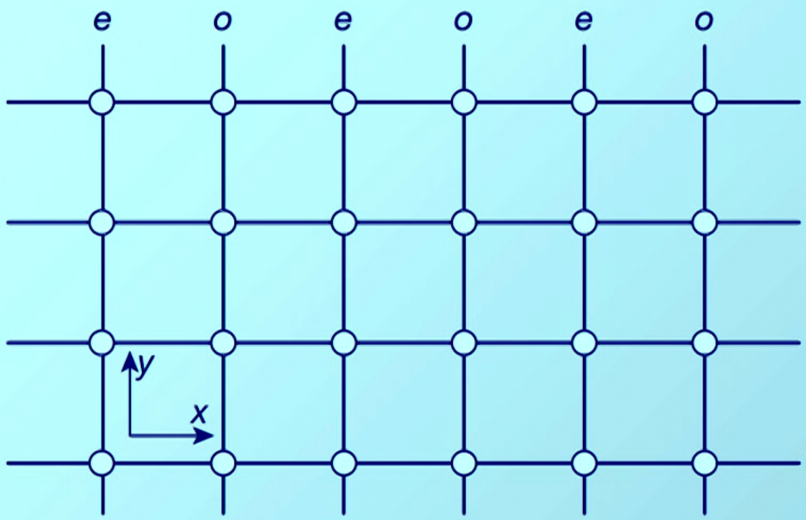
2D

Model and Experiment

$$\hat{H} = -J \sum_{\langle \mathbf{i},\mathbf{j} \rangle,\sigma} (\hat{c}^{\dagger}_{\mathbf{j},\sigma} \hat{c}_{\mathbf{i},\sigma} + \text{h.c.}) + \Delta \sum_{\mathbf{i},\sigma} [\cos(2\pi\beta_x m) + \cos(2\pi\beta_y n)] \hat{n}_{\mathbf{i},\sigma} + U \sum_{\mathbf{i}} \hat{n}_{\mathbf{i},\uparrow} \hat{n}_{\mathbf{i},\downarrow}$$

2D

Model and Experiment



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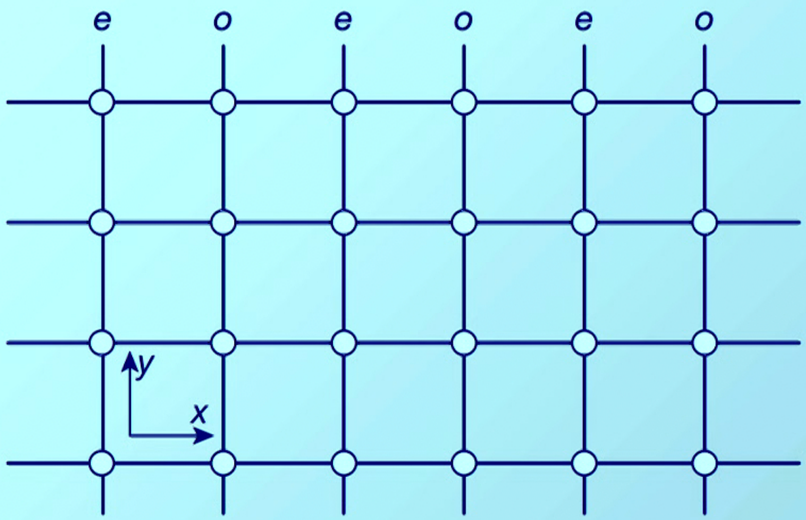
Model and Experiment



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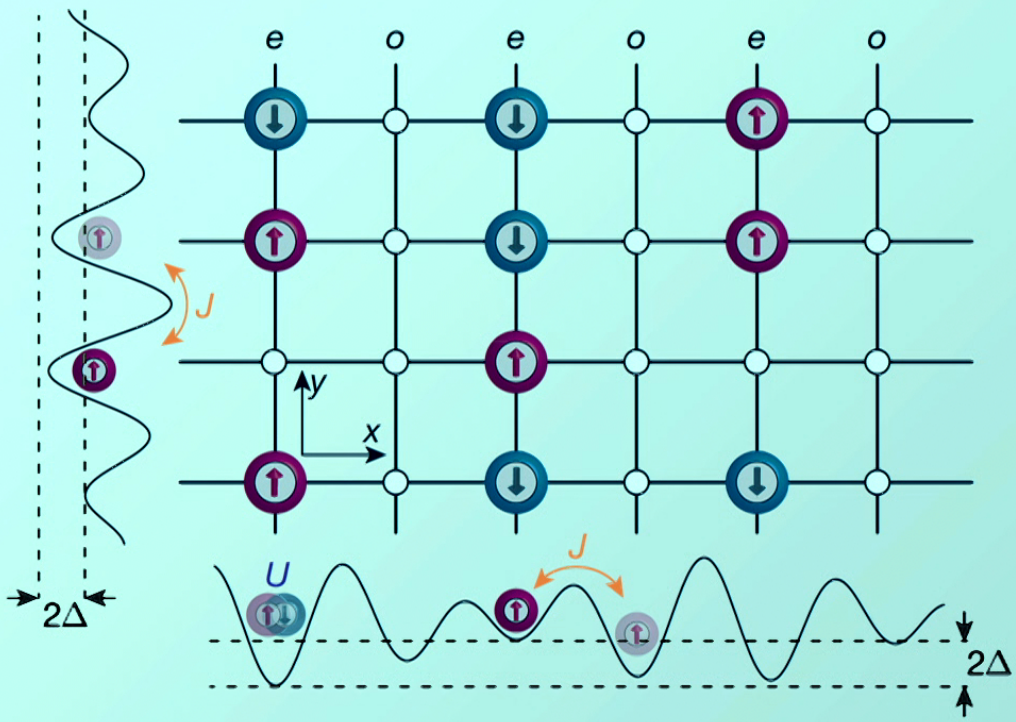

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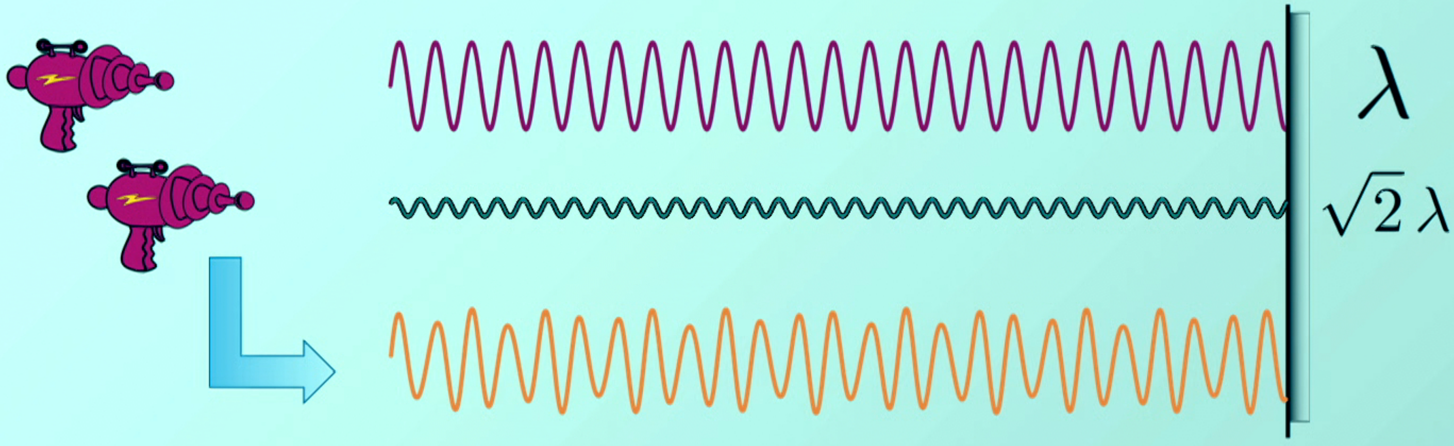
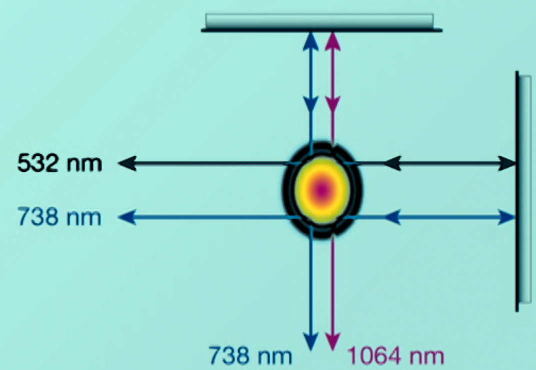
Making



Quasi-periodic potentials (not random)

Single particle **exponential localization**

Aubry, André (1980)



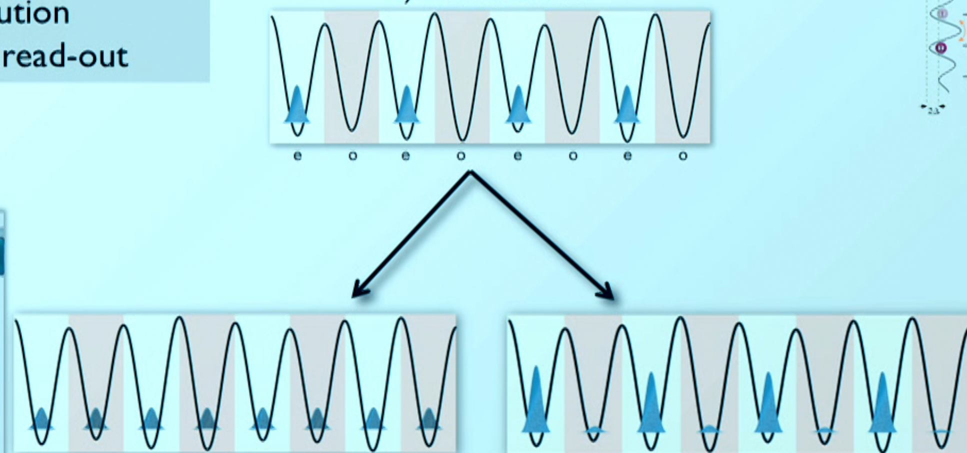
Far-from-equilibrium state

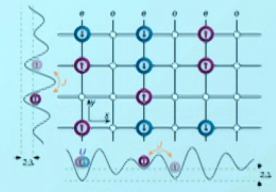
Probing

Three step procedure:

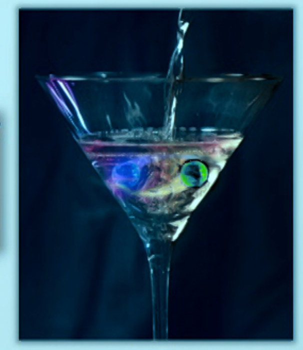
1) Create density-wave
2) Time-evolution
3) Imbalance read-out

1) Initial state





Fully mixed



Retains memory

Far-from-equilibrium state

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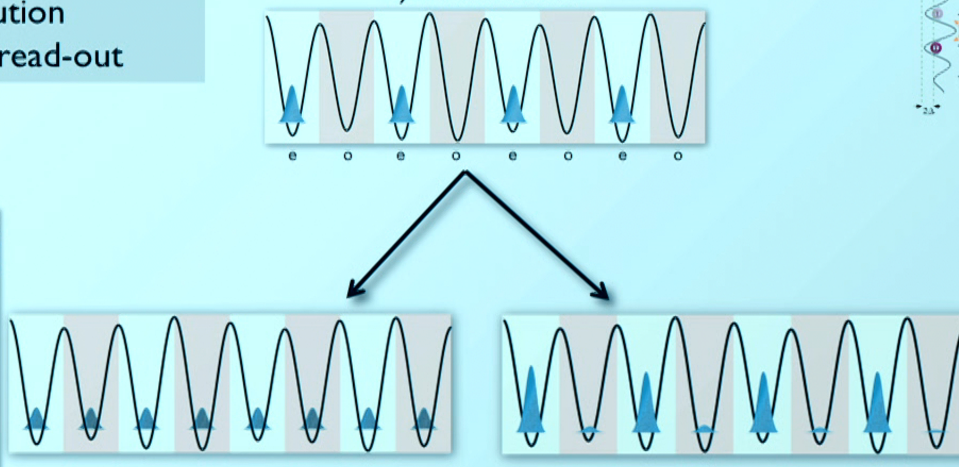
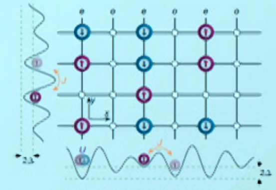
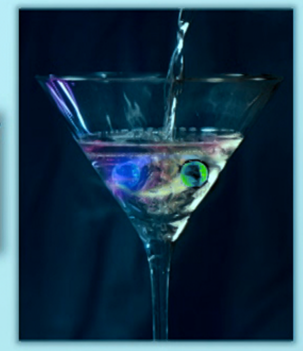




Fully mixed



Retains memory

3) Macroscopic order parameter, Imbalance

$$\mathcal{I} = \frac{N_e - N_o}{N_e + N_o}$$

Far-from-equilibrium state

Probing

<u>Three step procedure:</u>

1) Create density-wave
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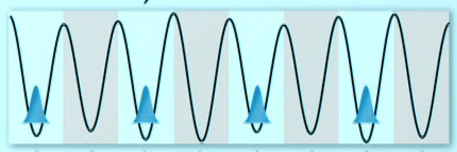
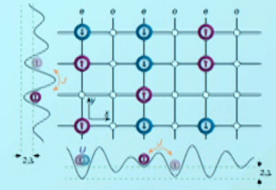
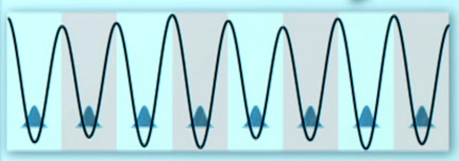
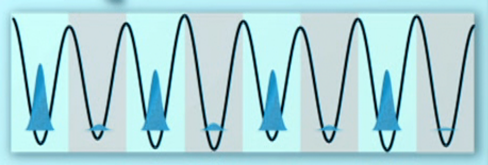
3) Imbalance read-out

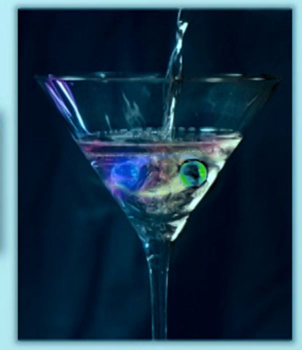
1) Initial state











Fully mixed

Retains memory

Thermal, = 0

> 0, MBL

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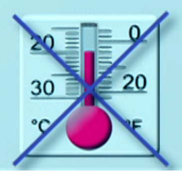

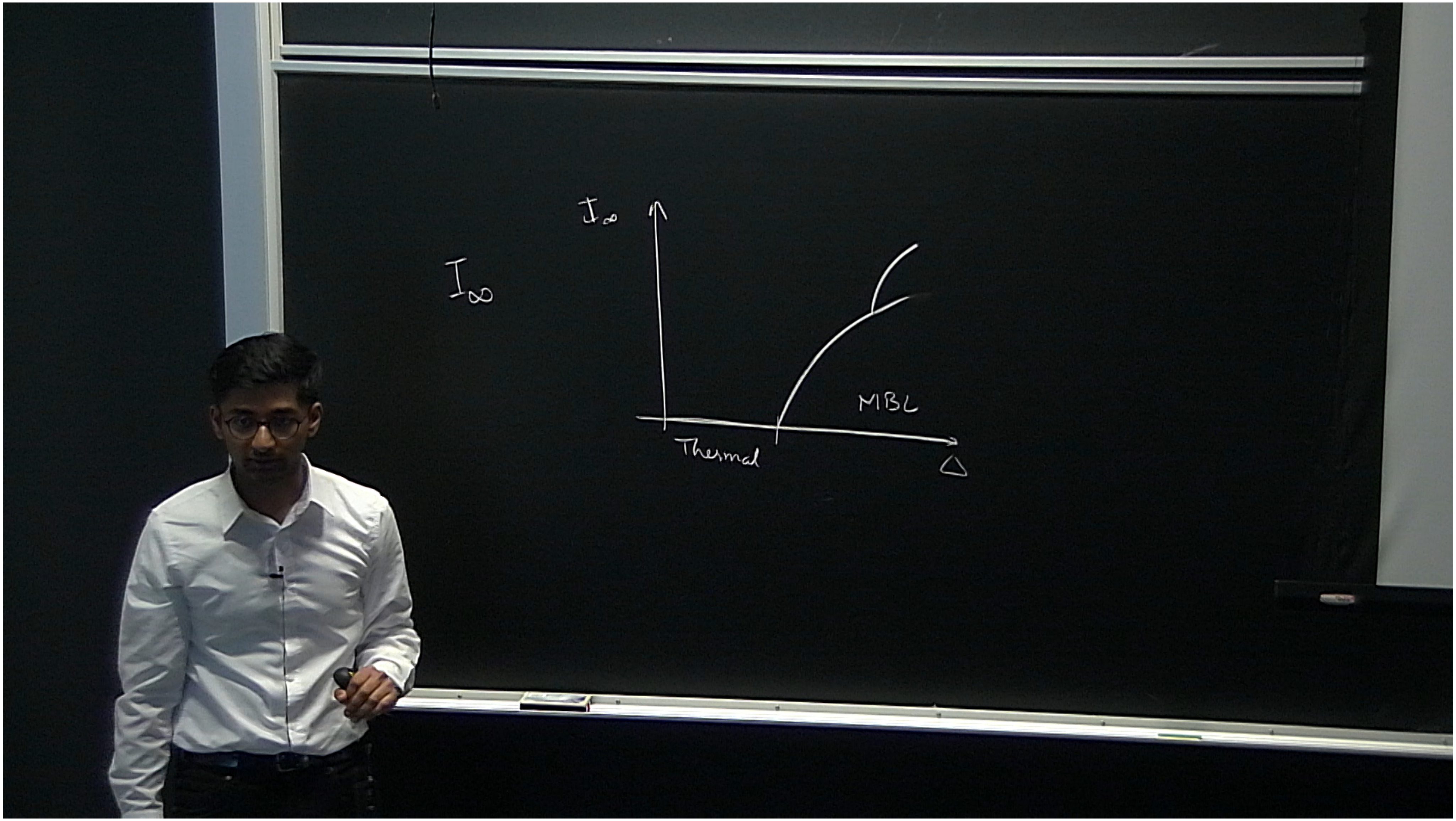
I_∞
I_∞
MBL
Thermal
Δ

Non-interacting system, U=0

Aubry-André Model

$$\hat{H} = -J \sum_{\langle \mathbf{i},\mathbf{j}\rangle,\sigma} (\hat{c}^\dagger_{\mathbf{j},\sigma}\hat{c}_{\mathbf{i},\sigma} + \text{h.c.}) + \Delta \sum_{\mathbf{i},\sigma} [\cos(2\pi\beta_x m) + \cos(2\pi\beta_y n)]\hat{n}_{\mathbf{i},\sigma} + U \sum_{\mathbf{i}} \hat{n}_{\mathbf{i},\uparrow}\hat{n}_{\mathbf{i},\downarrow}$$

Critical disorder Δ/J = 2 for single-particles

All eigenstates localized beyond the critical strength

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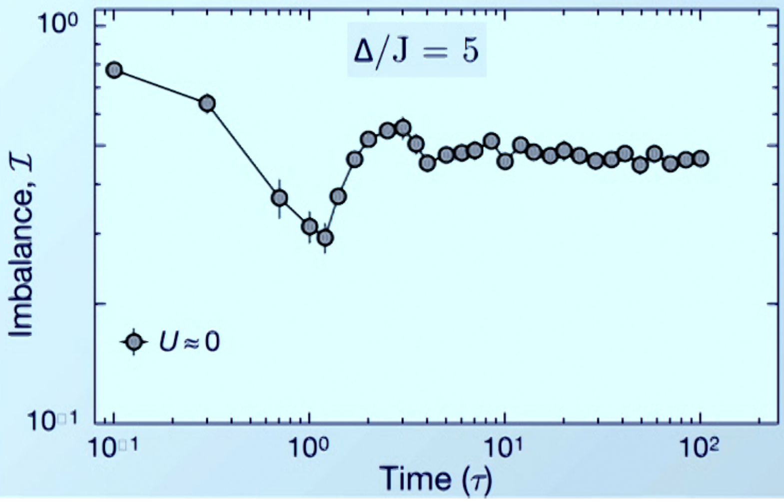

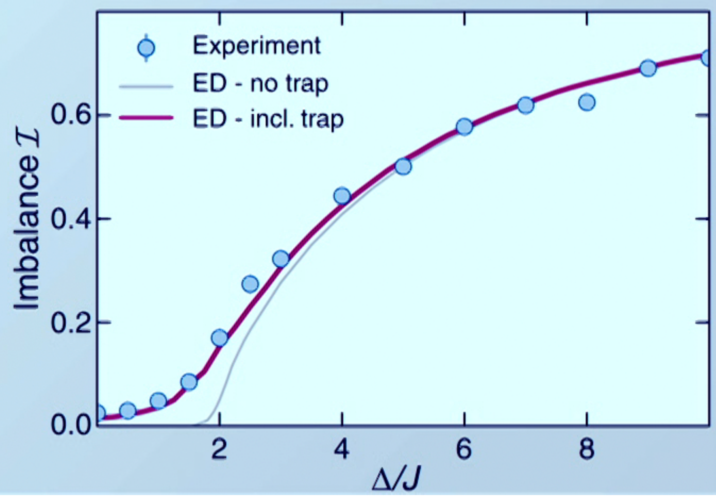

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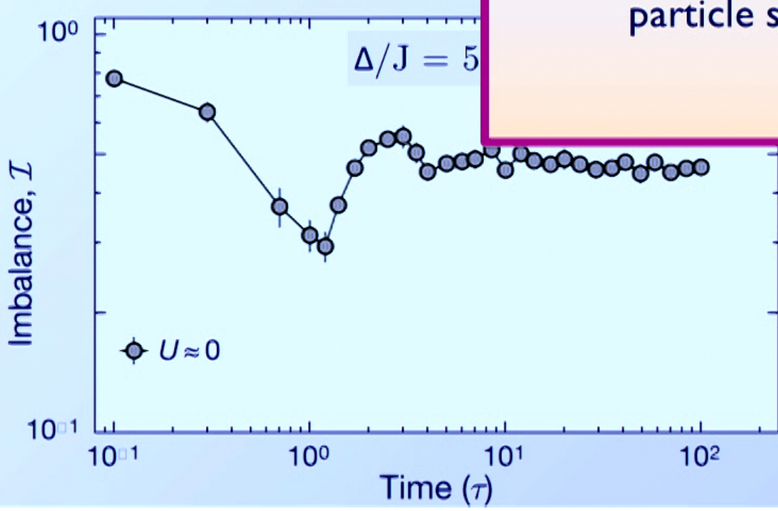
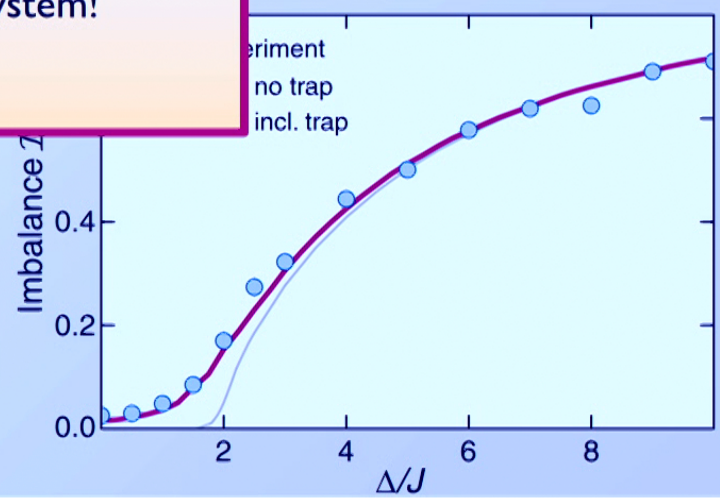
Critical disorder Δ/J = 2 for single-particles

All ... al strength

Well benchmarked single-particle system!

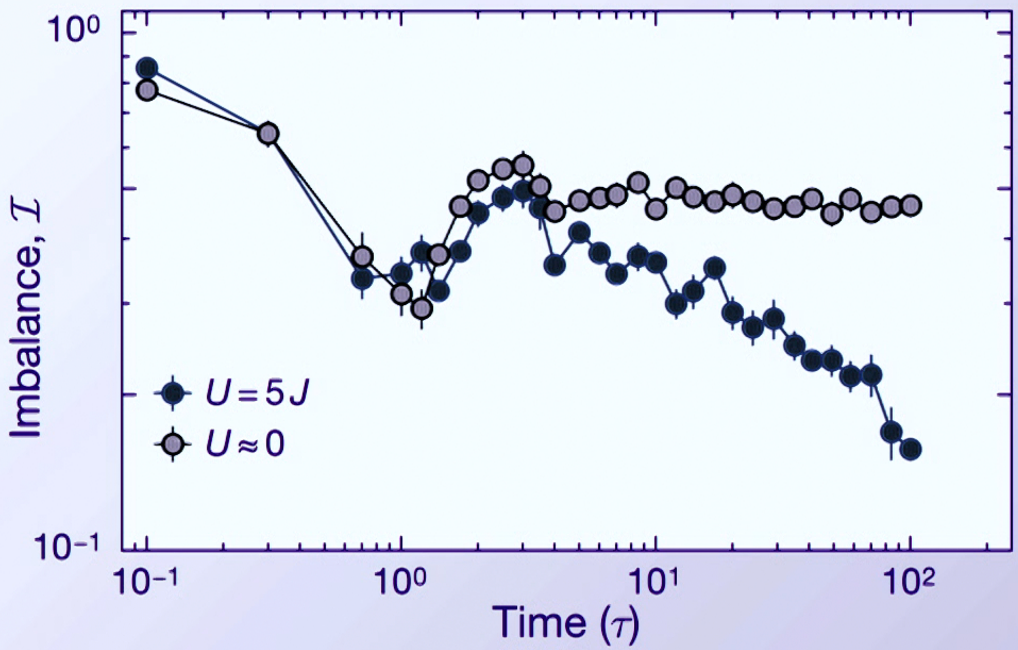




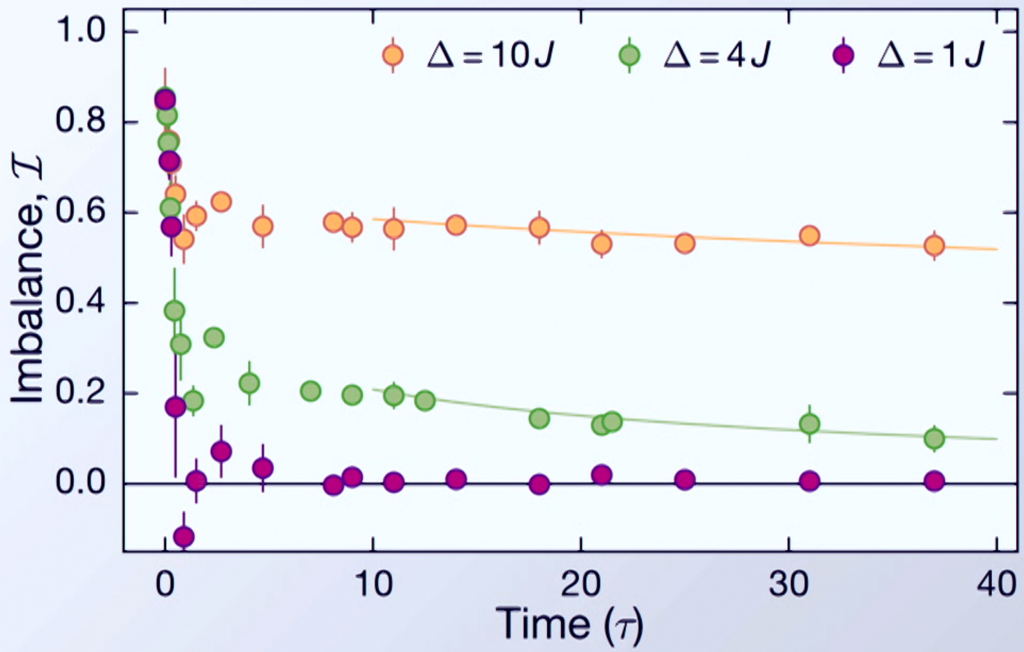
U = 5J

Interacting dynamics

$$\hat{H} = -J \sum_{\langle \mathbf{i},\mathbf{j} \rangle,\sigma} (\hat{c}^{\dagger}_{\mathbf{j},\sigma} \hat{c}_{\mathbf{i},\sigma} + \mathrm{h.c.}) + \Delta \sum_{\mathbf{i},\sigma} [\cos(2\pi\beta_x m) + \cos(2\pi\beta_y n)] \hat{n}_{\mathbf{i},\sigma} + U \sum_{\mathbf{i}} \hat{n}_{\mathbf{i},\uparrow} \hat{n}_{\mathbf{i},\downarrow}$$

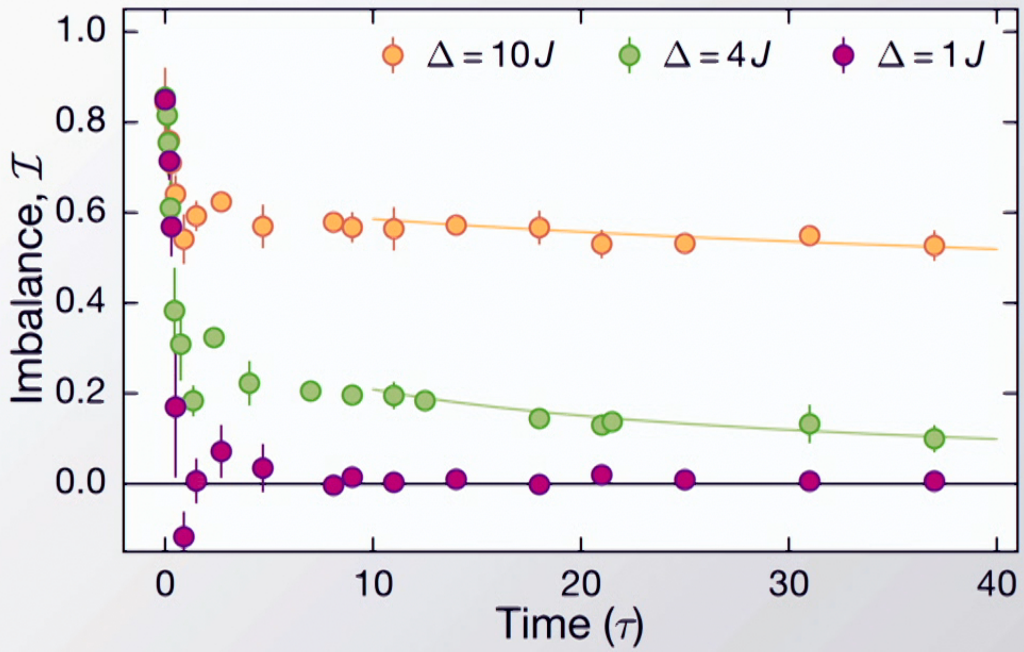


Time evolution

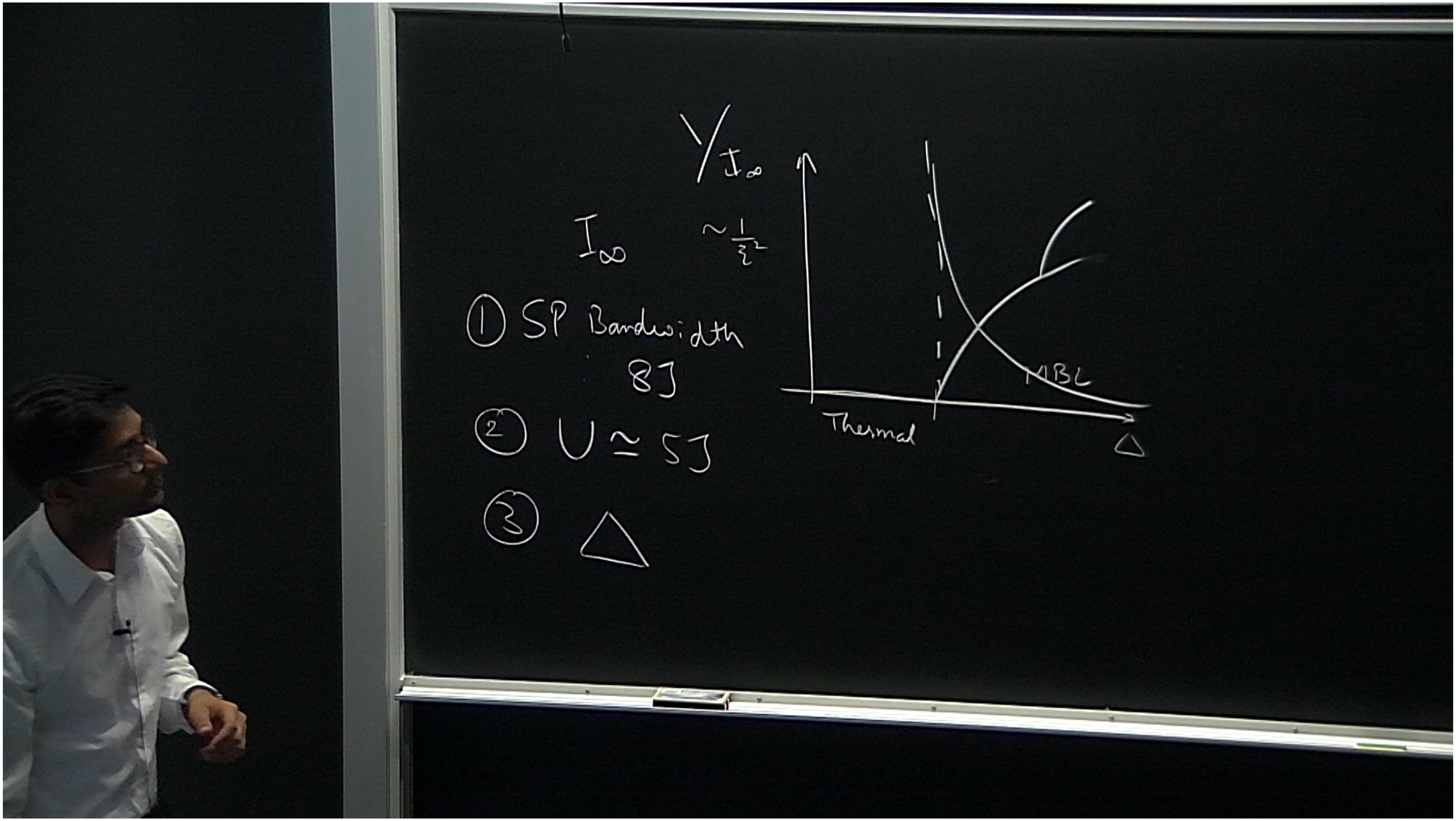


Real-time dynamics - 1

Time evolution

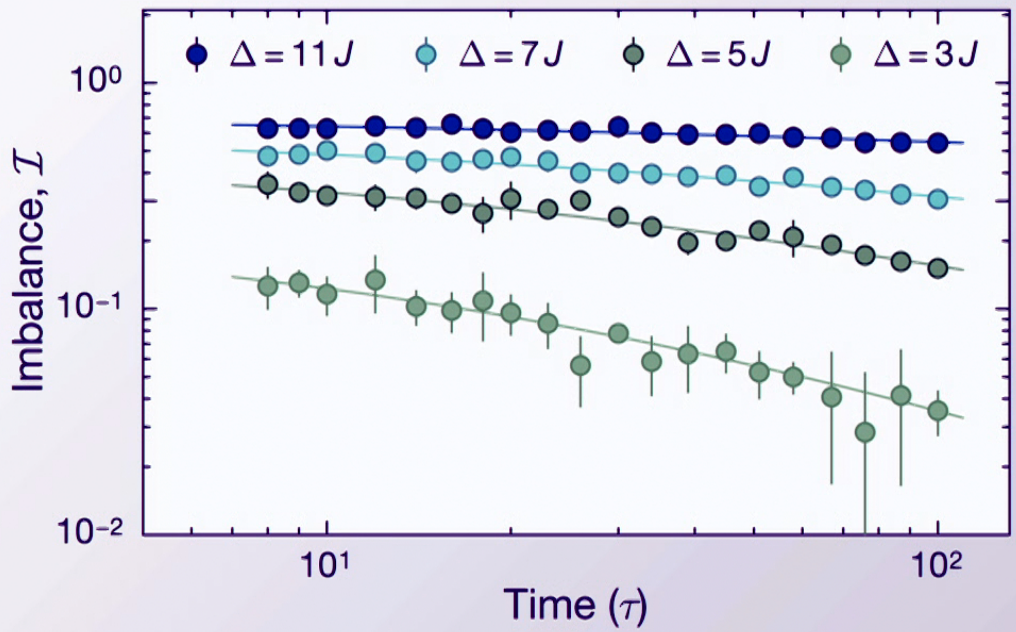


1) Extremely *slow* relaxation dynamics for moderate disorders!
2) *Not* the usual ergodic paradigm

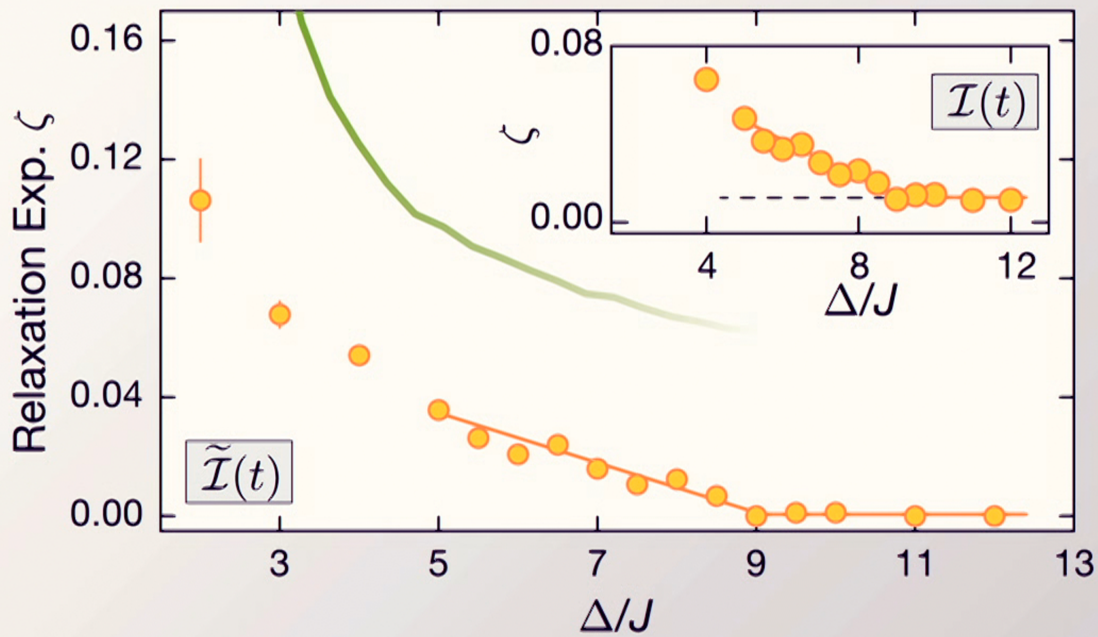

Y/I∞
I∞ ~ 1/ξ²
① SP Bandwidth
8J
② U ≃ 5J
③ Δ
Thermal
MBL
Δ

Real-time dynamics - 2

Continuous slowing

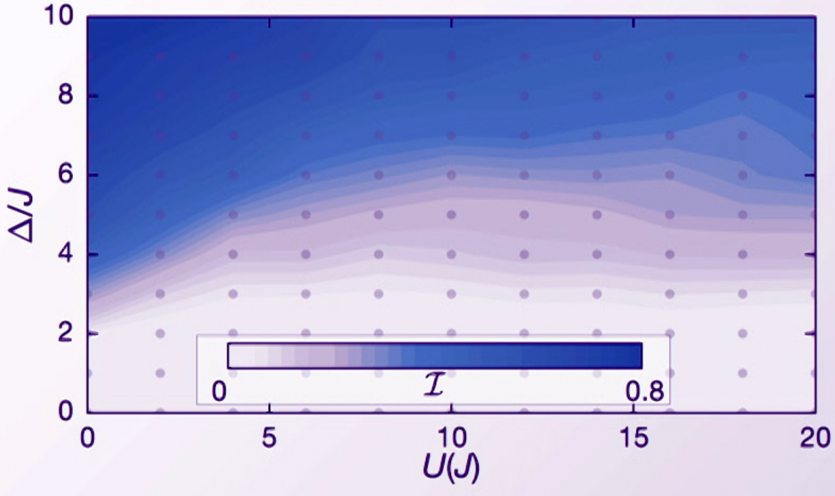


Relaxation exponents

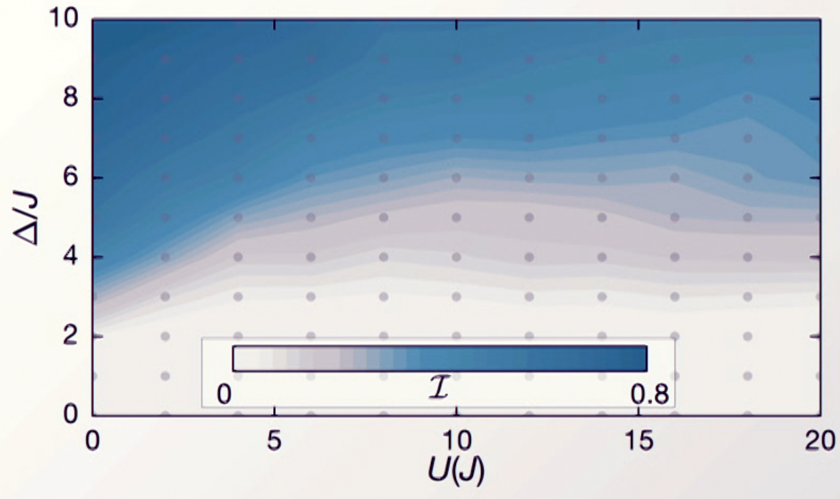


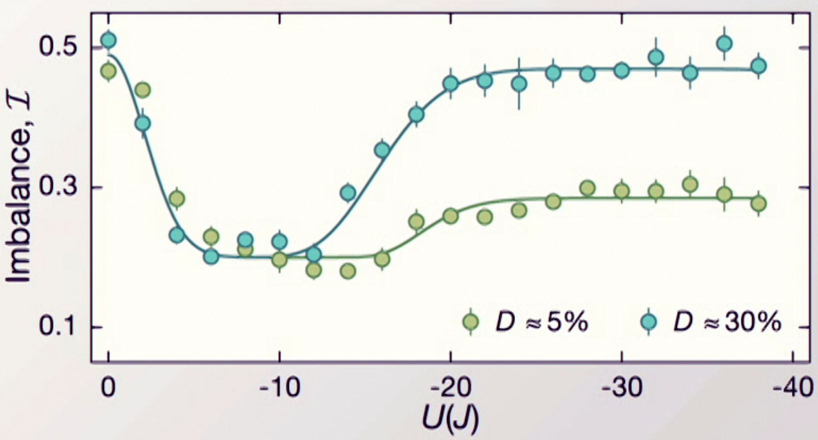
I. Relaxation indistinguishable from background beyond Δ_c
II. Critical phase needs further theoretical understanding

Localization vs Interactions



Localization vs Interactions

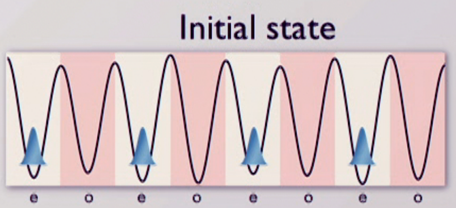




1) Slow-relaxation dynamics **wide range**– not fine tuned

2) Energy-density dependence

3) Hard-core interactions not the same as non-interacting



Novel platform

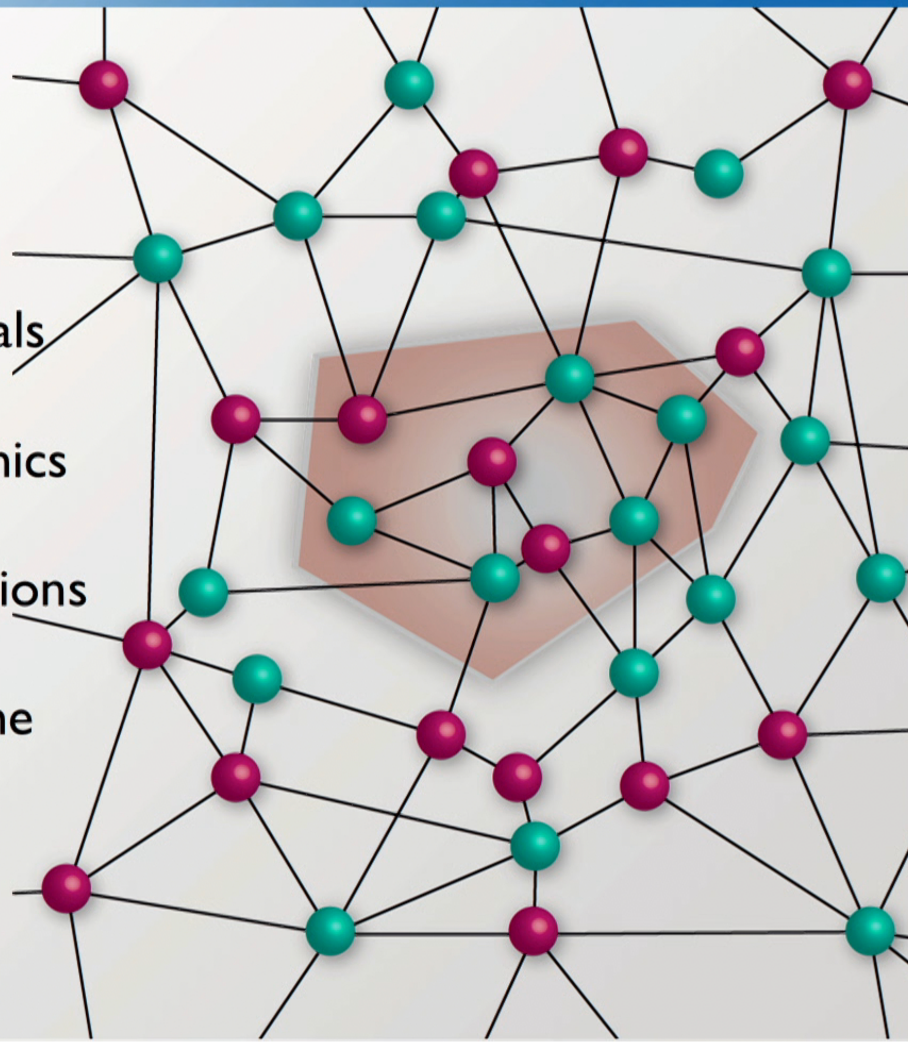
Summary

I. Quasi-periodic potentials

II. Non-equilibrium dynamics

III. Localization vs Interactions

IV. "MBL-like" glassy regime



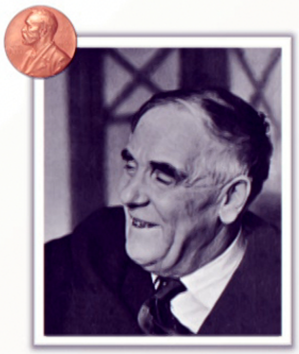
Outline

1. Introduction to Thermalization and MBL
2. Probing MBL in Two Dimensions
3. Floquet MBL Systems

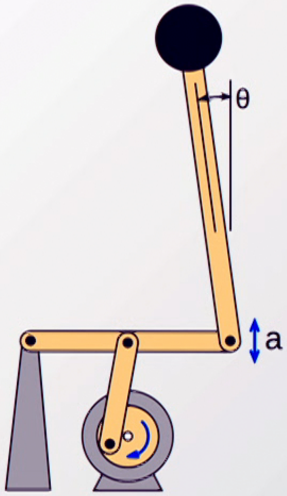

Periodically Driven
MBL Systems
Bordia et.al.,
Nat. Phys. 13, 460–464 (2017)
Joint work with
Prof. M. Knap
TU Munich

Classical system

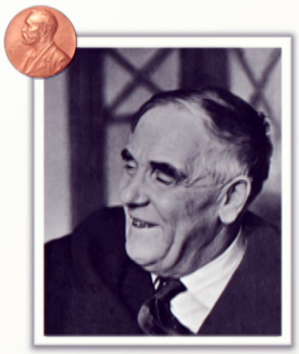
Kapitza pendulum



Пётр Леонидович Капица
Pyotr Leonidovich Kapitsa



Kapitza pendulum



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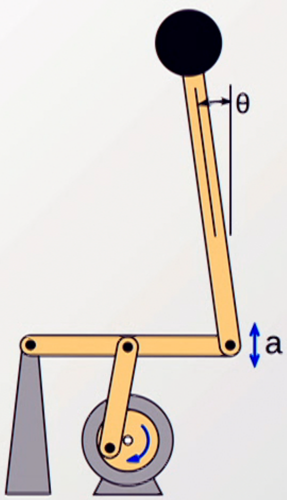
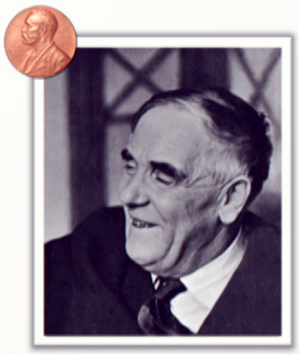
Pyotr Leonidovich Kapitsa



https://www.youtube.com/watch?v=rwGAzy0noU0

Kapitza pendulum



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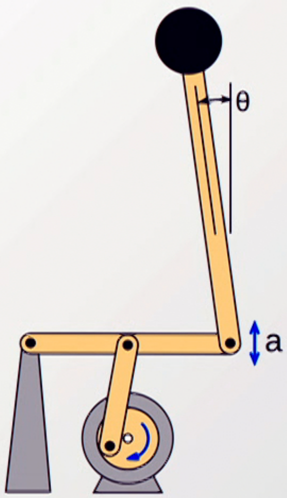

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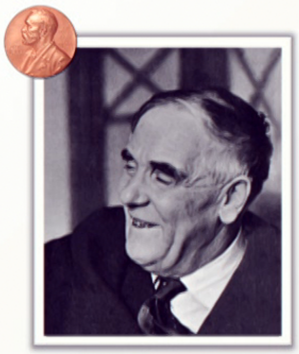
Classical system

Kapitza pendulum



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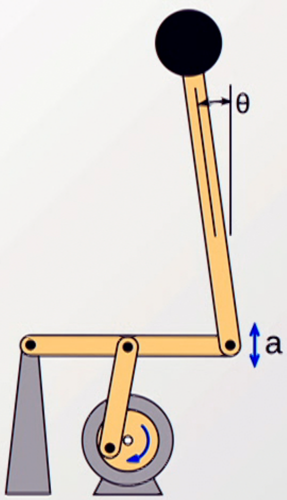
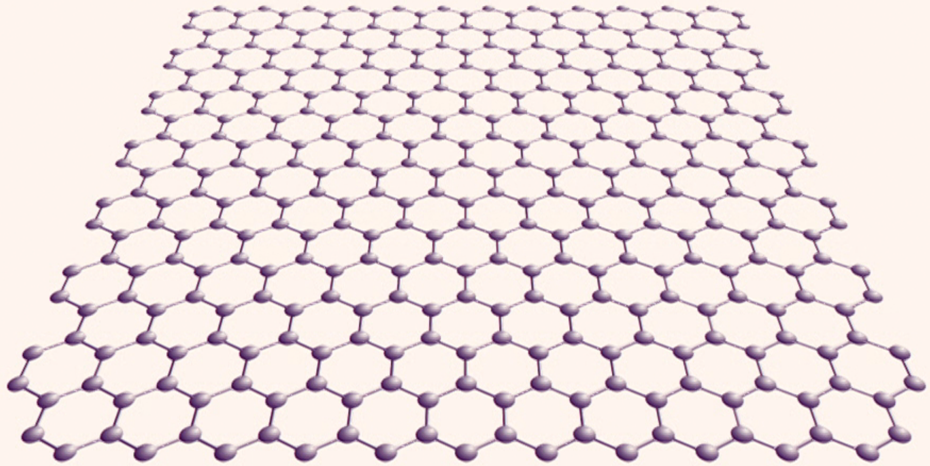


1) *Not* feedback-stabilized
2) A *new* “stable” state in the driven system

Quantum regime

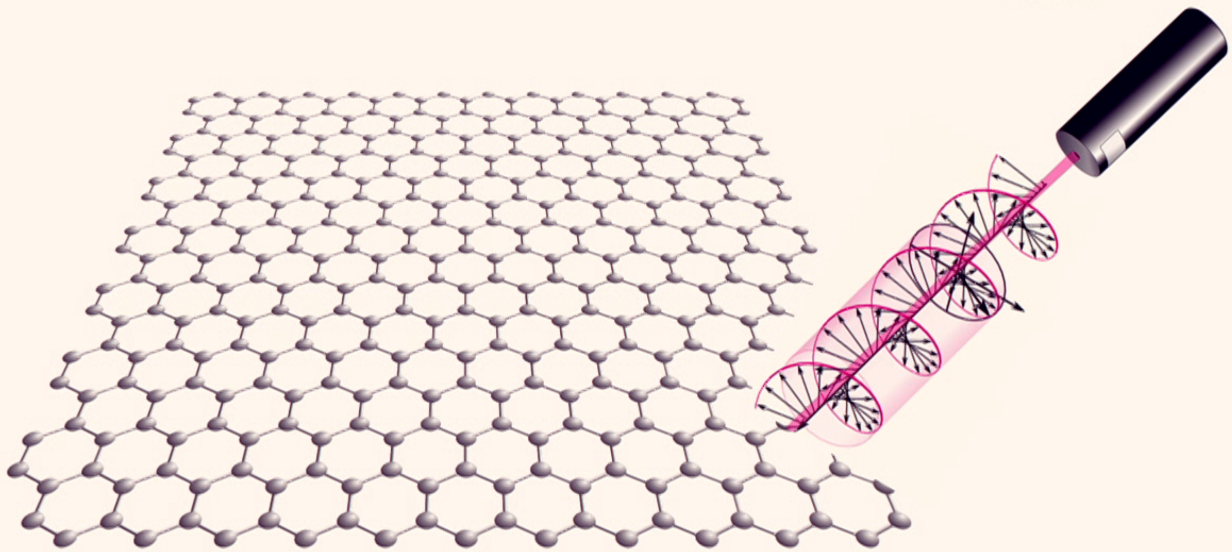
Photovoltaic Hall Effect in Graphene



Oka & Aoki, PRB 2009

Quantum regime

Photovoltaic Hall Effect in Graphene



Oka & Aoki, PRB 2009

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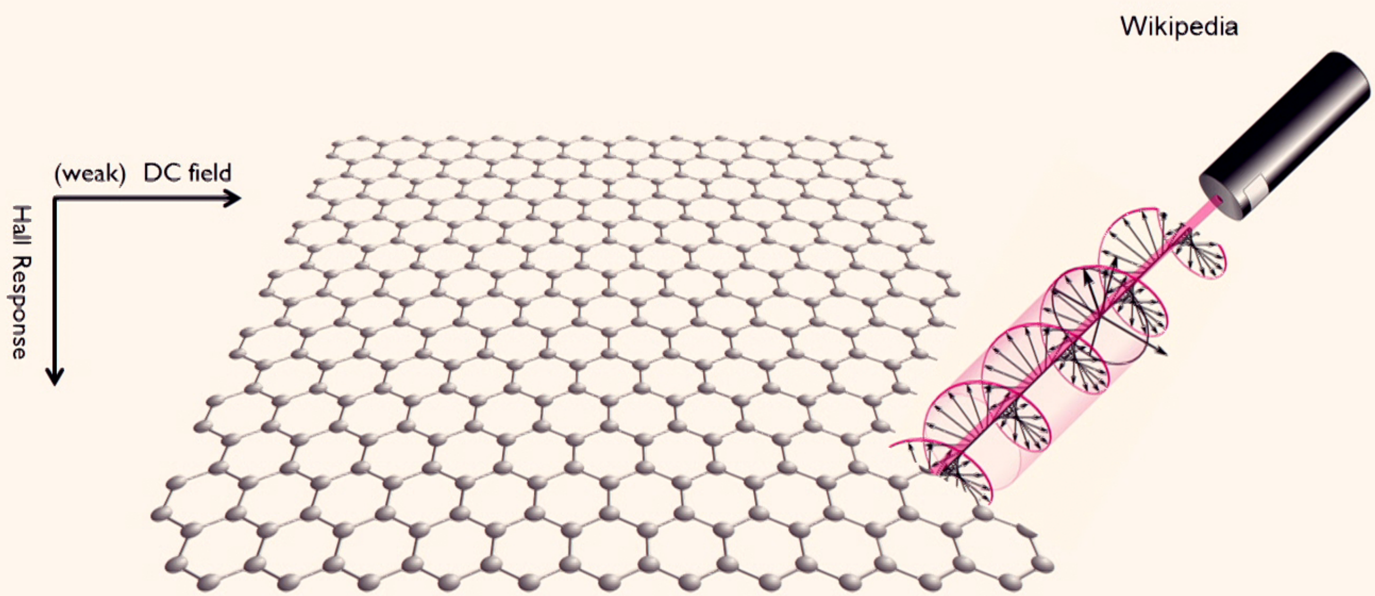

Oka & Aoki, PRB 2009

Quantum regime

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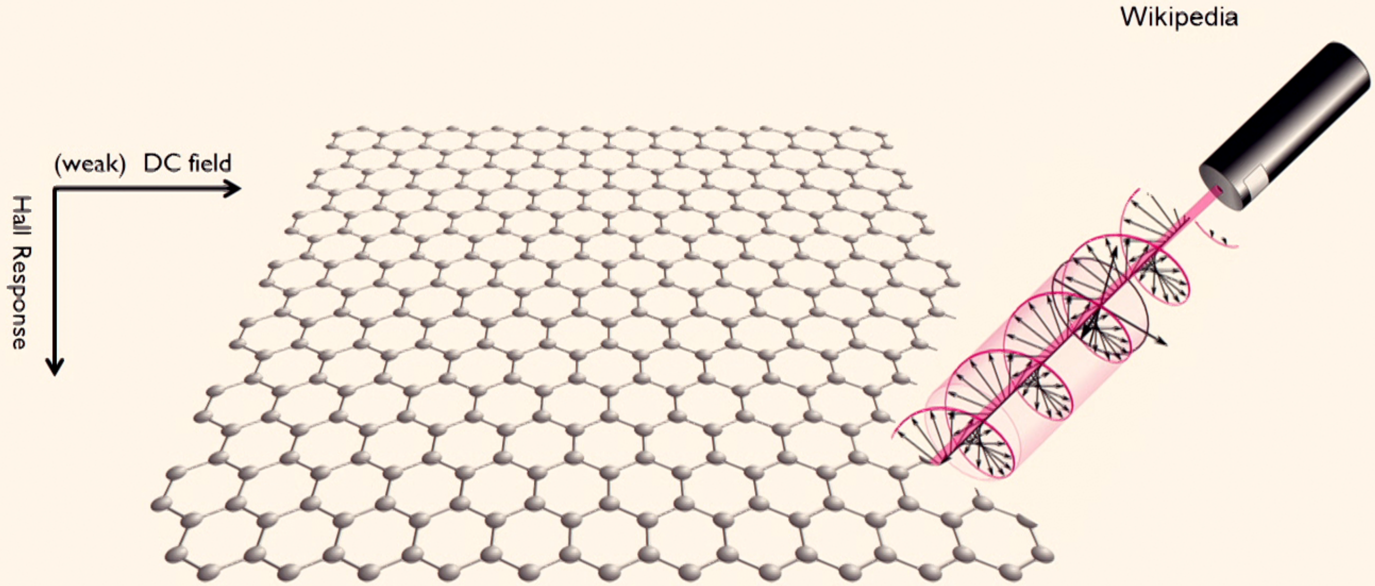
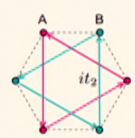


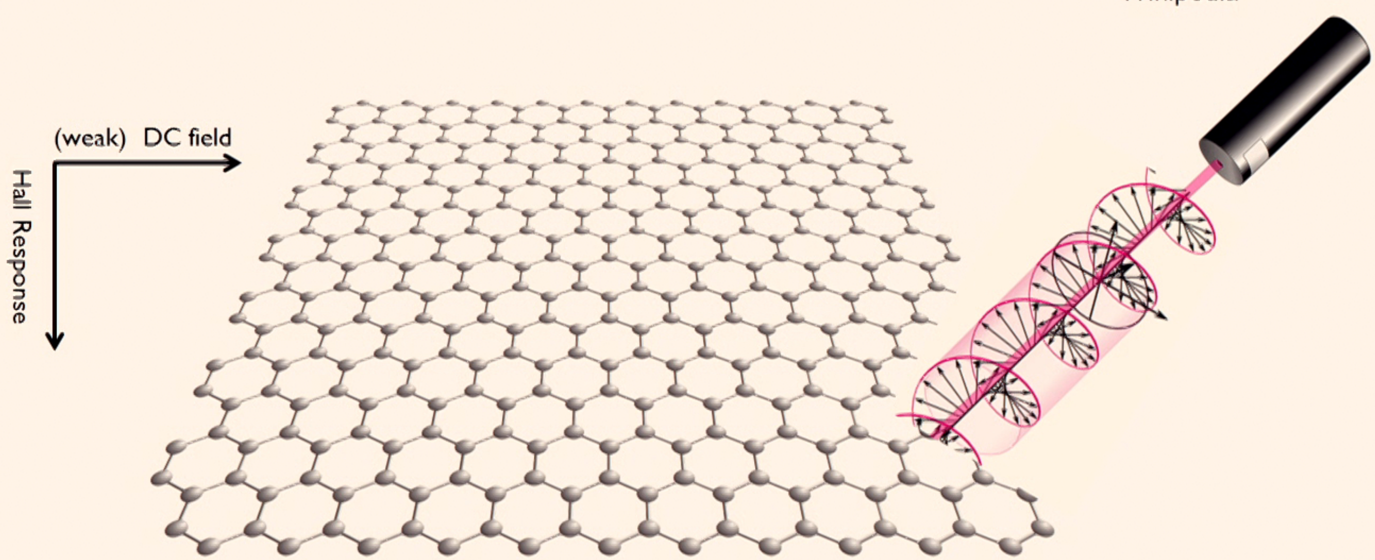
Oka & Aoki, PRB 2009



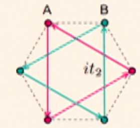
Topological Haldane Model, Esslinger, ETH Zurich

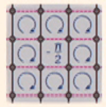
Quantum regime

Photovoltaic Hall Effect in Graphene



Oka & Aoki, PRB 2009

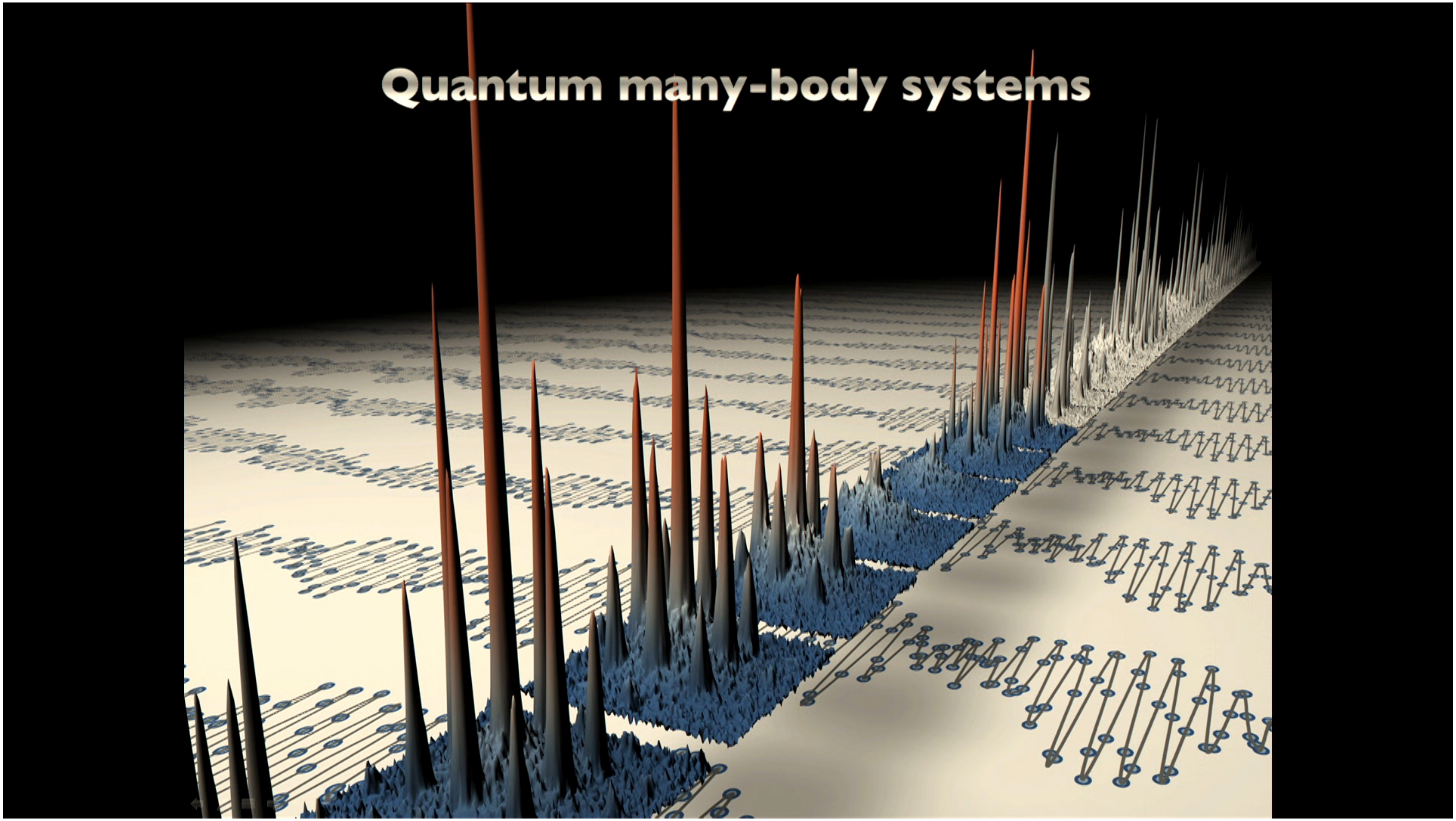


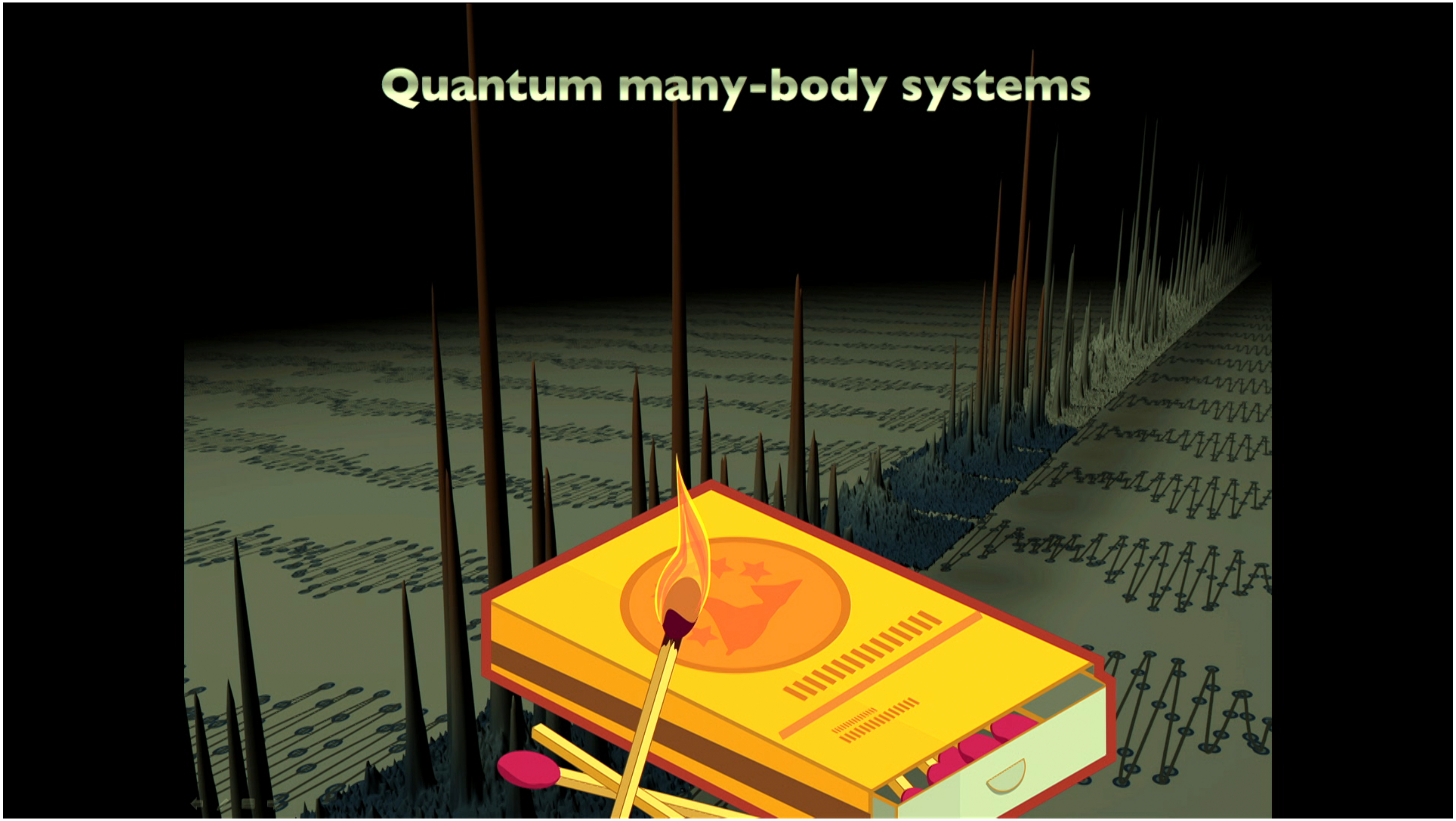


Topological Haldane Model, Esslinger, ETH Zurich

Harper-Hofstadter Model, Bloch/Ketterlee, LMU/MIT

+ See also Speilman, Zwierlein, Dalibard, Greiner etc.

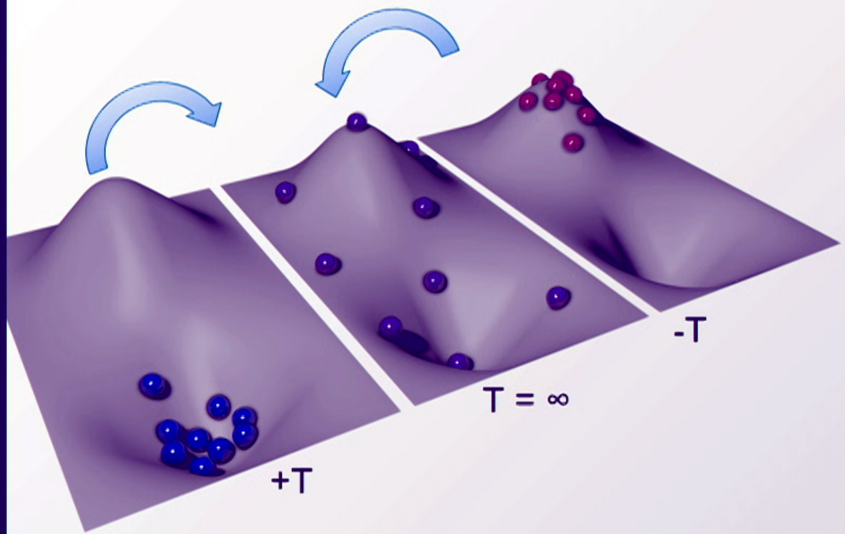

Quantum many-body systems


Quantum many-body systems

Floquet-ETH

Ergodic systems

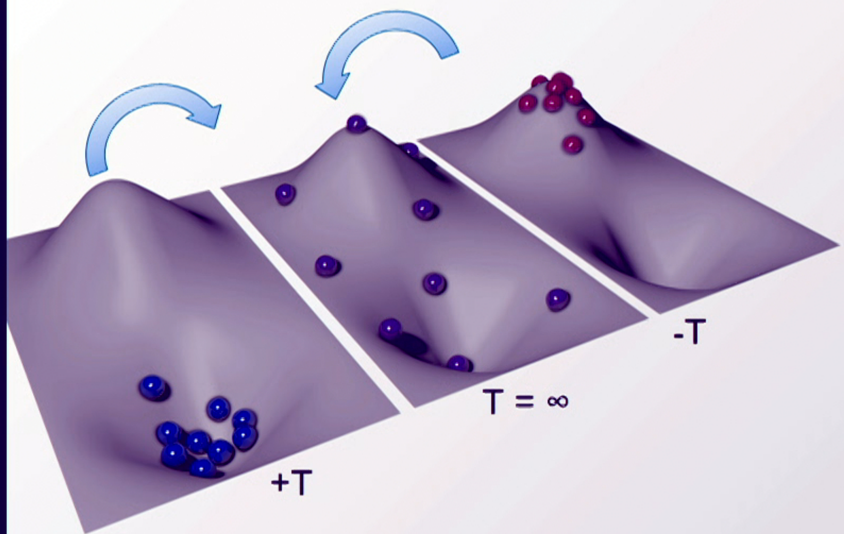
$$\hat{H}(t) = \hat{H}(t+T)$$



Lazarides (2014) | D'Alessio (2014) | Ponte (2014)

Ergodic systems

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



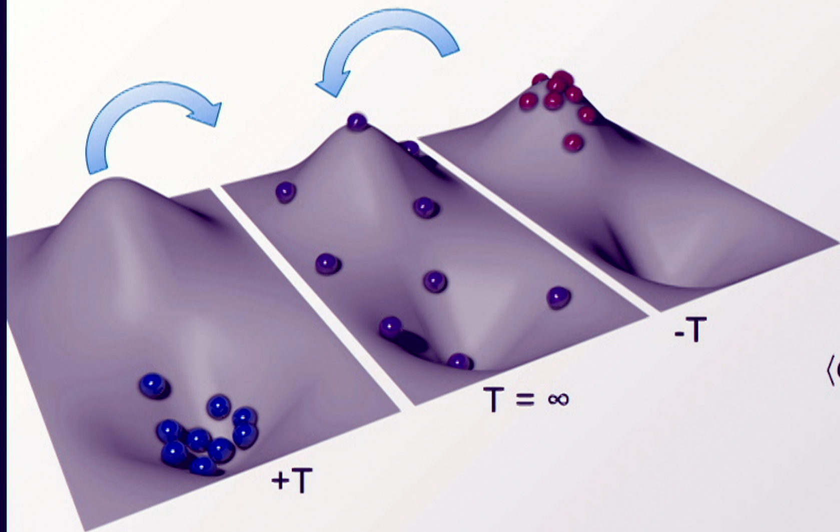
Most ergodic systems - heat to a featureless, infinite T state

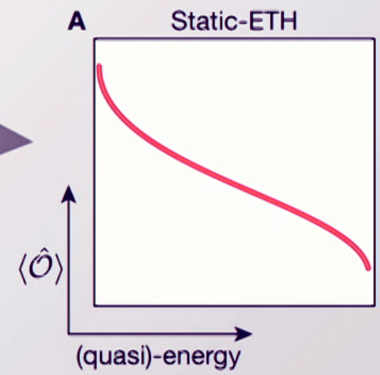
Spatially extended modes overlap and absorb energy from the drive

Lazarides (2014) | D'Alessio (2014) | Ponte (2014)

Ergodic systems

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





$$\rho_A = \frac{1}{Z_A} e^{-\beta H_A}$$

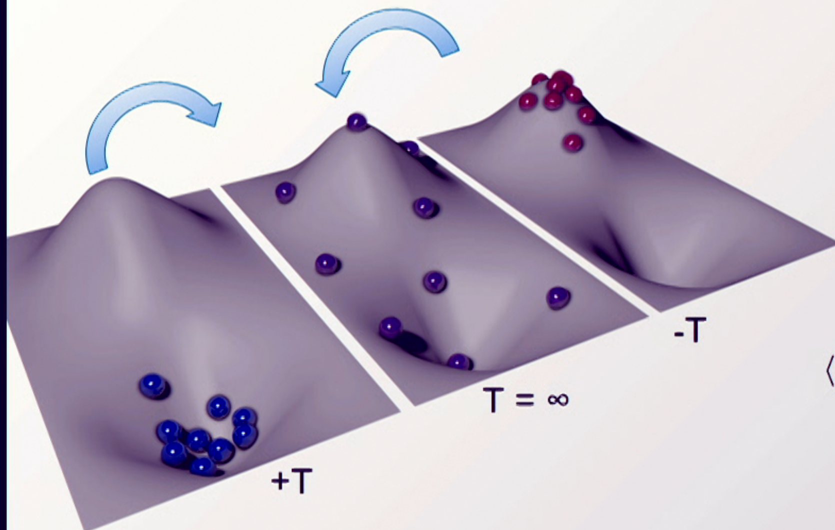
Most ergodic systems - heat to a featureless, infinite T state

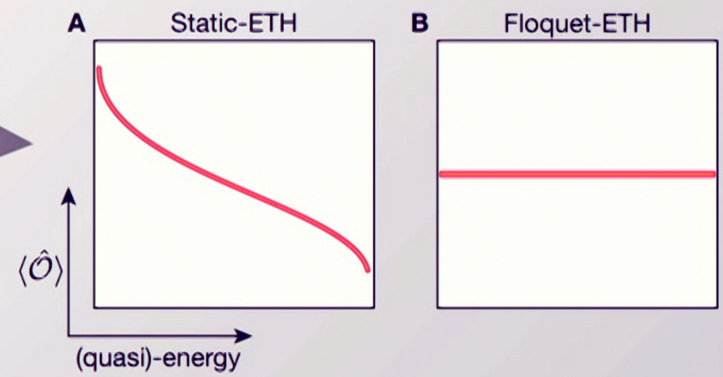
Spatially extended modes overlap and absorb energy from the drive

Lazarides (2014) | D'Alessio (2014) | Ponte (2014)

Ergodic systems

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





$$\rho_A = \frac{1}{Z_A} e^{-\beta H_A} \qquad \rho_A \propto 1$$

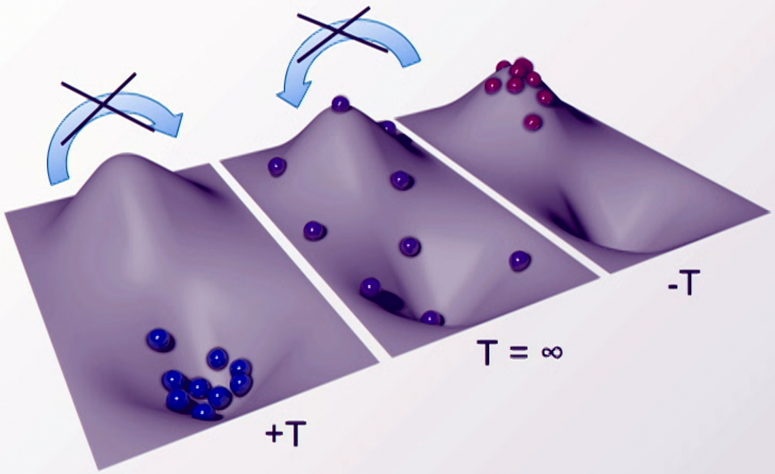
Most ergodic systems - heat to a featureless, infinite T state

Spatially extended modes overlap and absorb energy from the drive

Lazarides (2014) | D'Alessio (2014) | Ponte (2014)

Non-ergodic systems

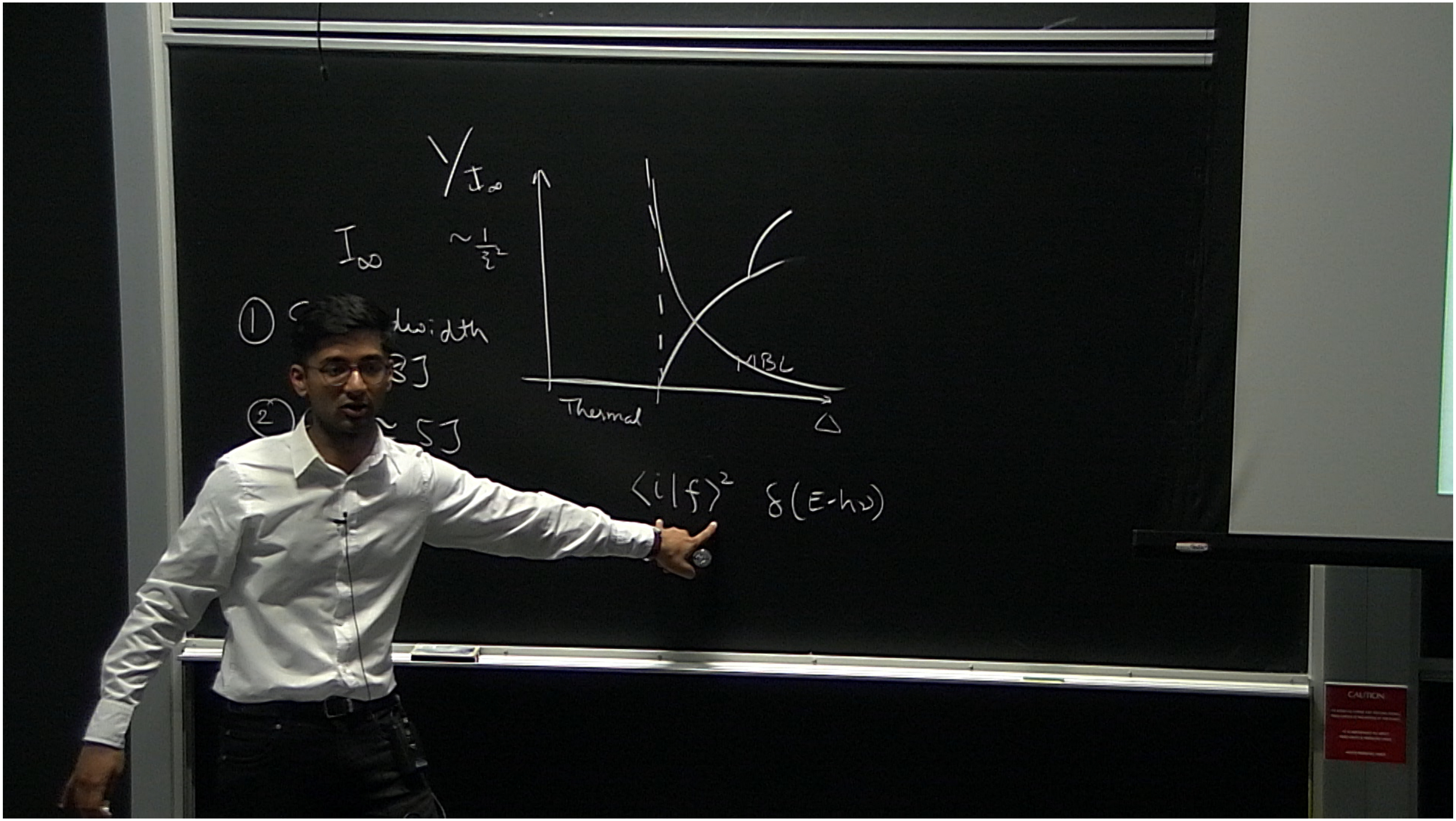
$$\hat{H}(t) = \hat{H}(t+T)$$



MBL - Protection at high-frequency, delocalization at low-frequency

~ Fermi's golden rule: energy detuning and overlaps + destructive interference

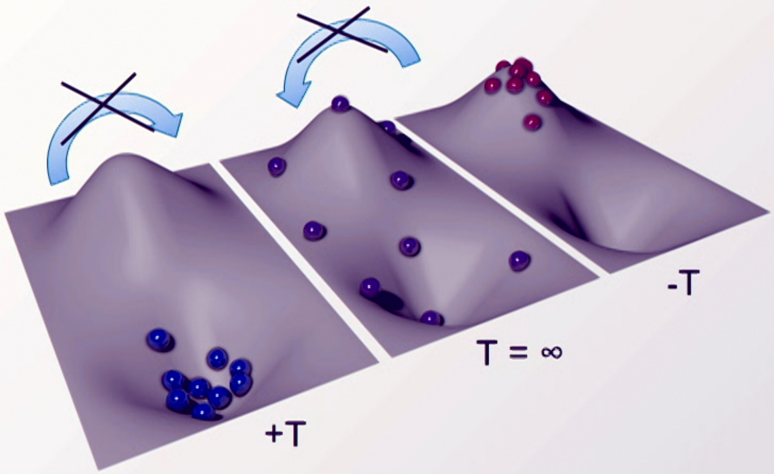
Ponte (2015) | Lazarides (2015) | Abanin (2016)

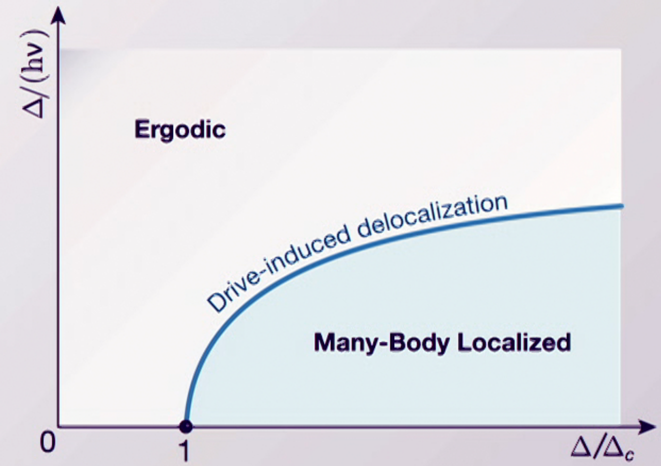

Y/I_∞
$I_\infty \sim \frac{1}{\xi^2}$
① dwidth
3J
② ~ 5J
Thermal
MBL
Δ
$\langle i|f\rangle^2 \; \delta(E-h\nu)$

Floquet-MBL

Non-ergodic systems

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





$$A/\nu \sim 1$$

MBL - Protection at high-frequency, delocalization at low-frequency

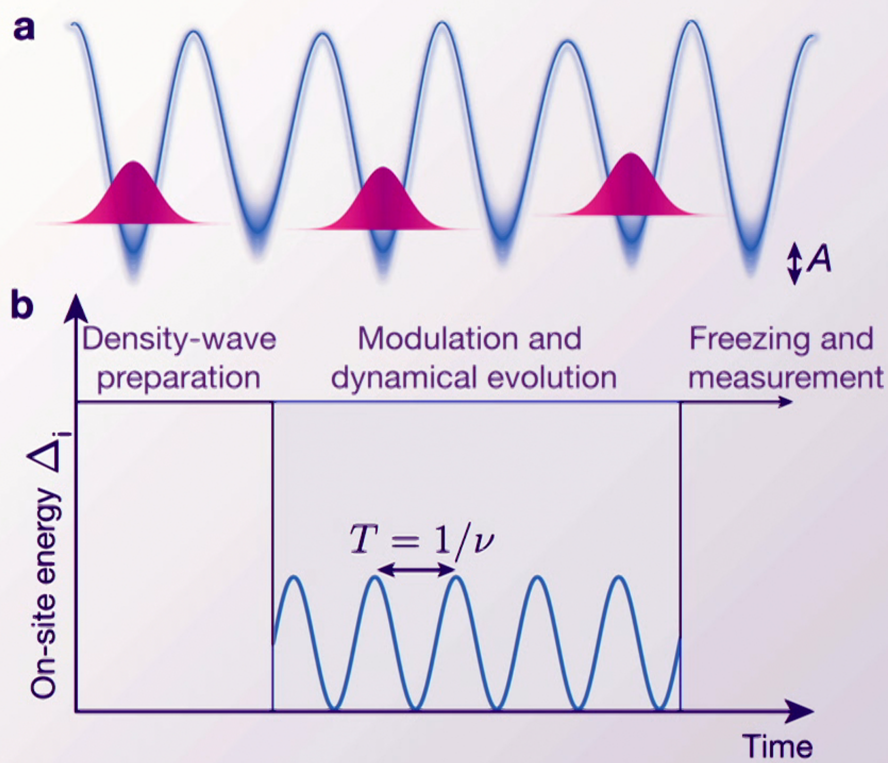
~ Fermi's golden rule: energy detuning and overlaps + destructive interference

Ponte (2015) | Lazarides (2015) | Abanin (2016)

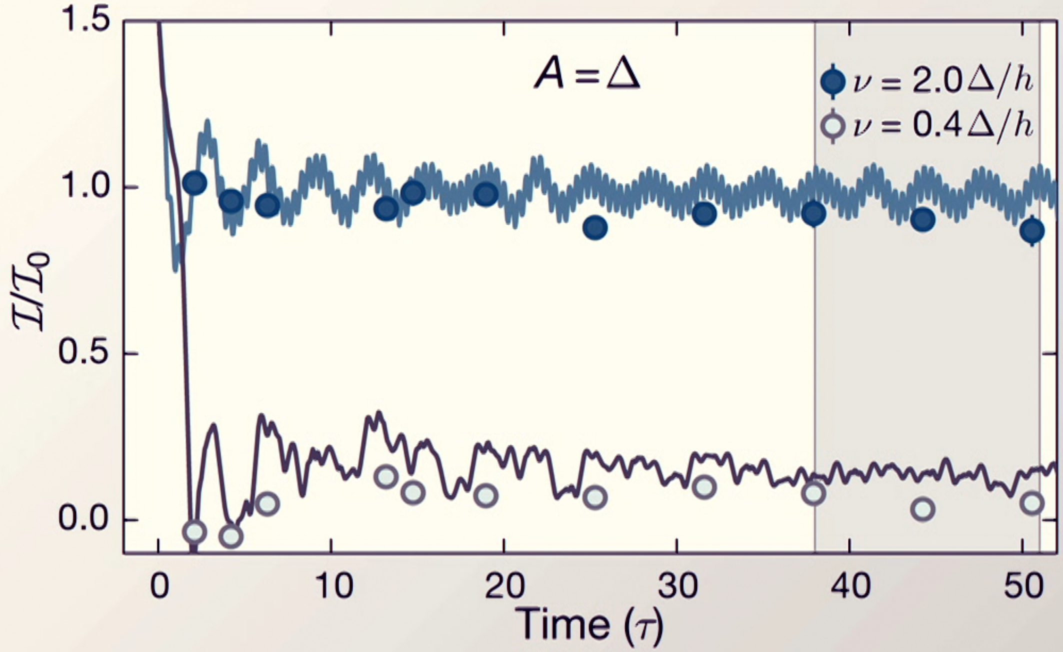
1D System

Experiment

$$\Delta_i = \Delta_i[1 + A\sin(2\pi\nu t)]$$



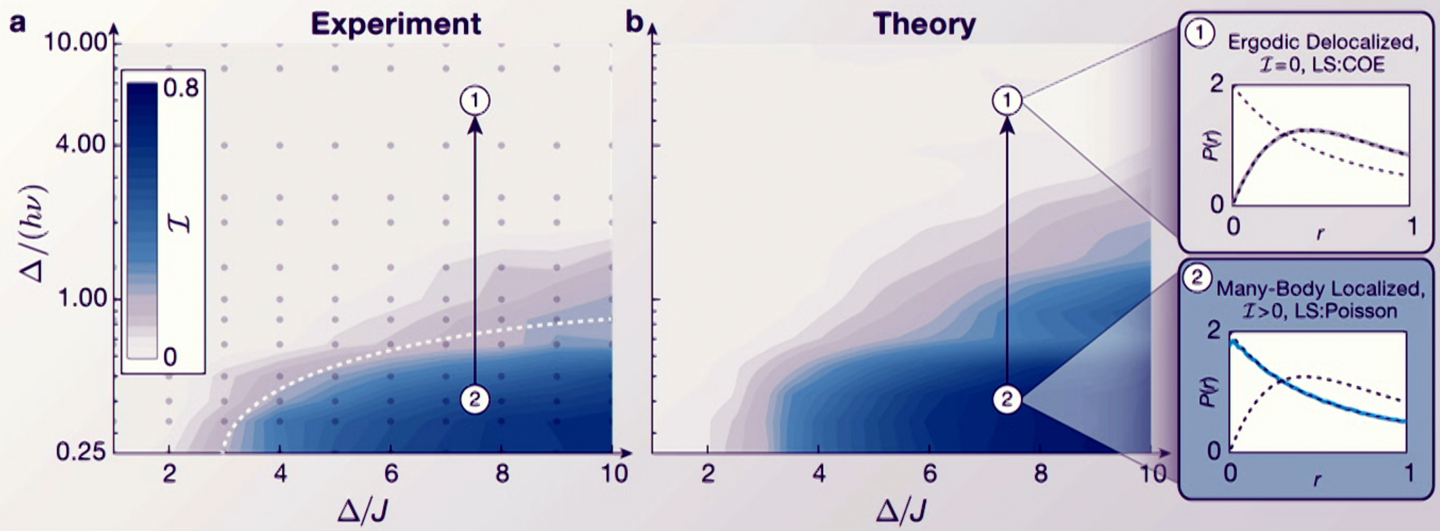
Real-time dynamics



Strong frequency dependent response
Localization for **high-frequencies**

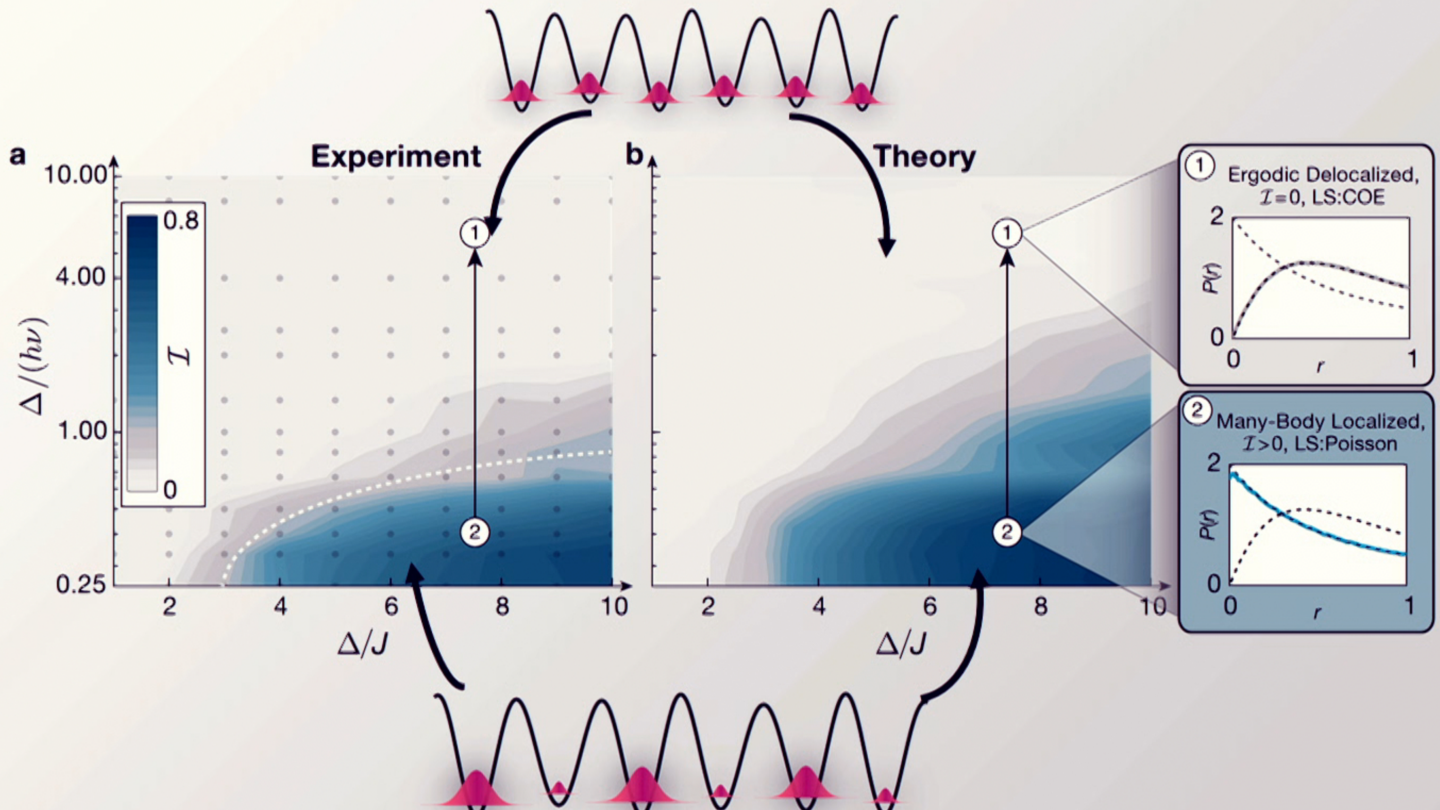
Frequency dependence

"Phase" - diagram



Frequency dependence

"Phase" - diagram



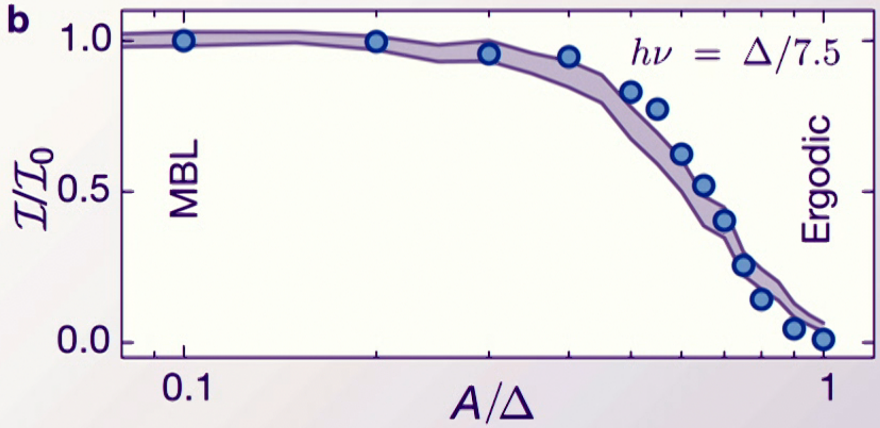
Low frequency protection?

$$\Delta_i = \Delta_i[1 + A\sin(2\pi\nu t)] \qquad A/\nu \sim 1$$

Strength of the drive

Low frequency protection?

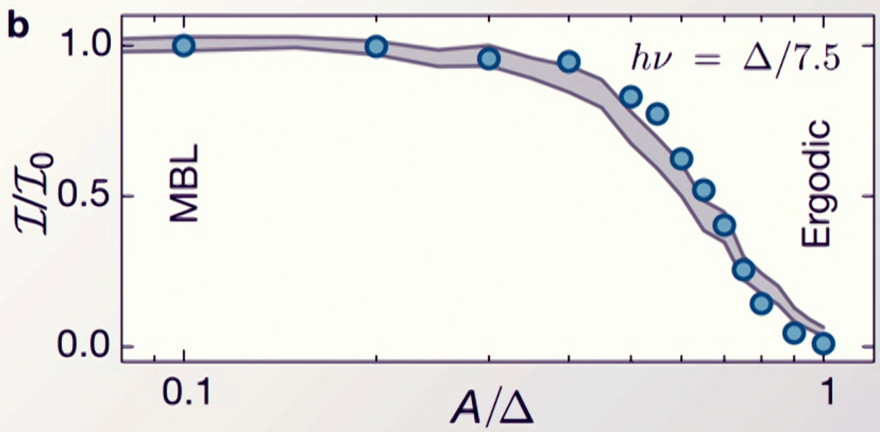
$$\Delta_i = \Delta_i[1 + A\sin(2\pi\nu t)] \qquad A/\nu \sim 1$$



Strength of the drive

Low frequency protection?

$$\Delta_i = \Delta_i[1 + A\sin(2\pi\nu t)] \qquad A/\nu \sim 1$$



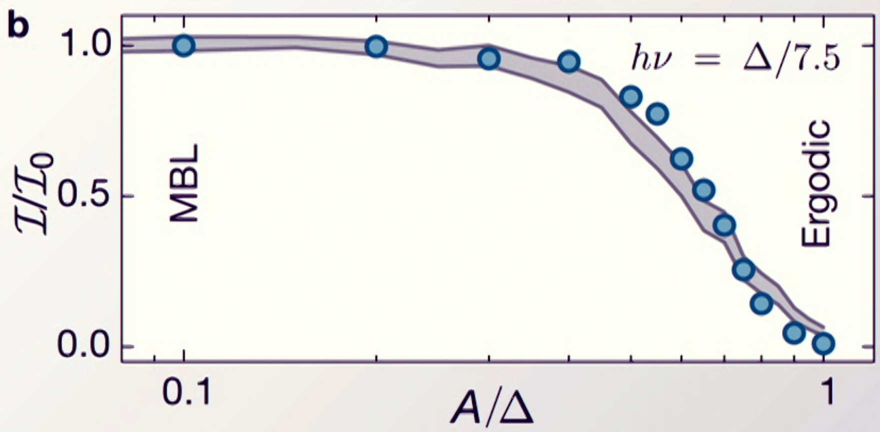
Open problem

Implications on noise/braiding (see. Khemani 2014)

Strength of the drive

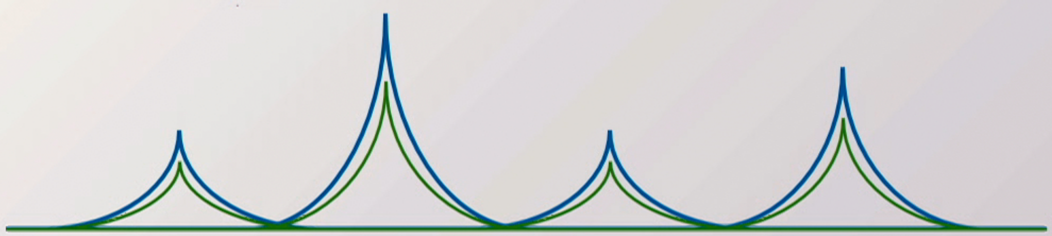
Low frequency protection?

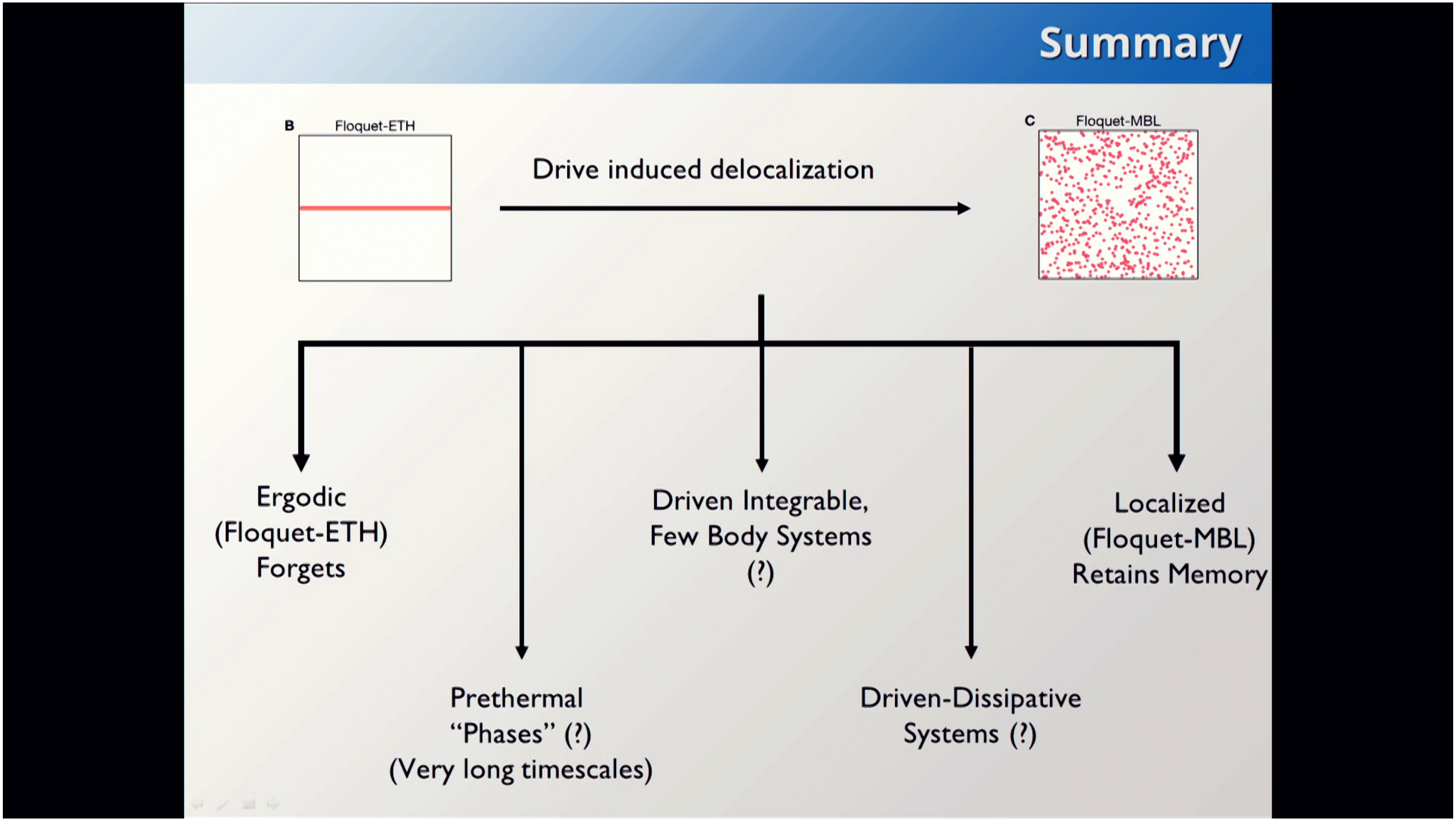
$$\Delta_i = \Delta_i[1 + A\sin(2\pi\nu t)] \qquad A/\nu \sim 1$$



Open problem

Implications on noise/braiding (see. Khemani 2014)





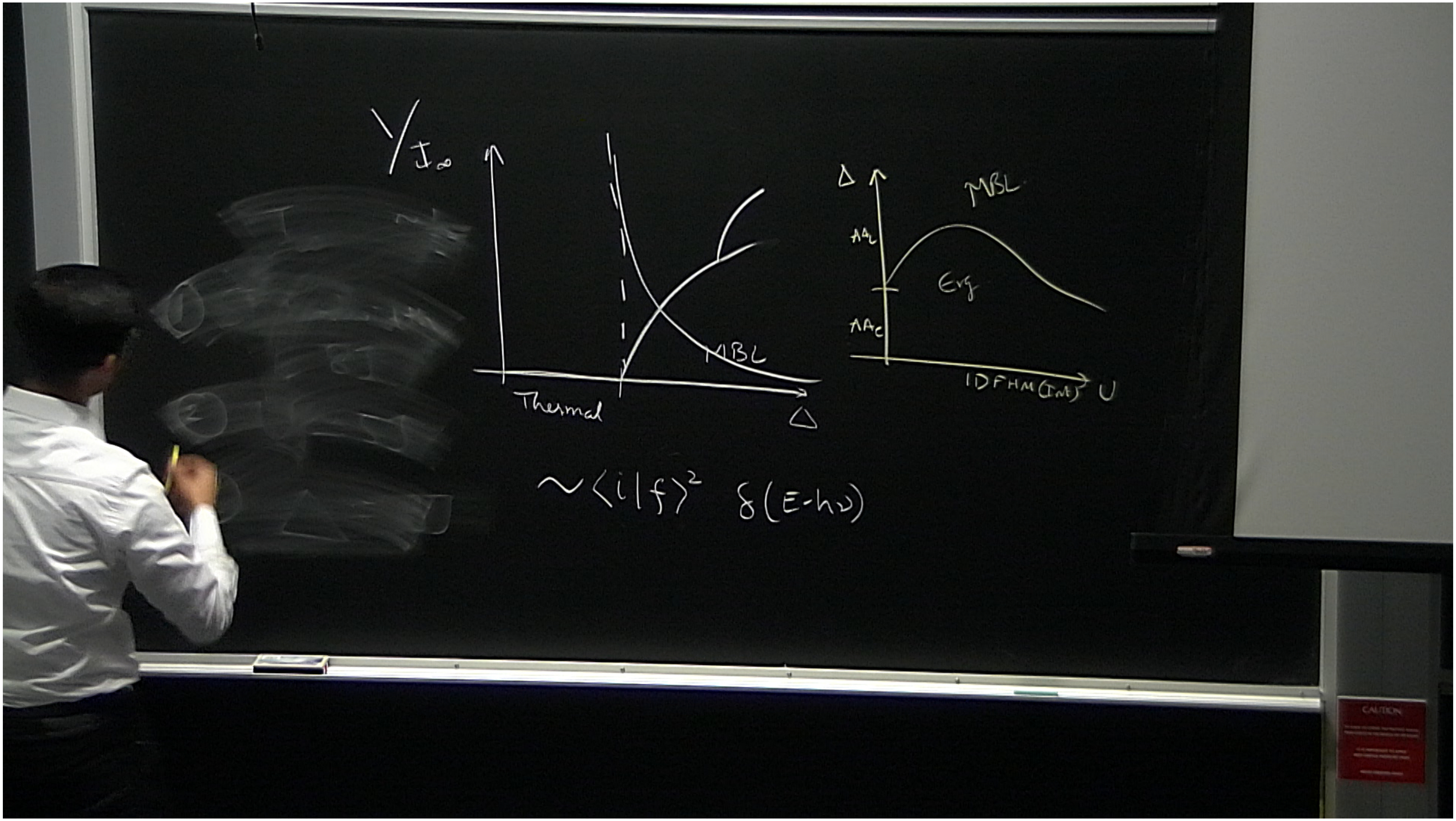
Summary
B
Floquet-ETH
Drive induced delocalization
C
Floquet-MBL
Ergodic
(Floquet-ETH)
Forgets
Prethermal
"Phases" (?)
(Very long timescales)
Driven Integrable,
Few Body Systems
(?)
Driven-Dissipative
Systems (?)
Localized
(Floquet-MBL)
Retains Memory

Outlook

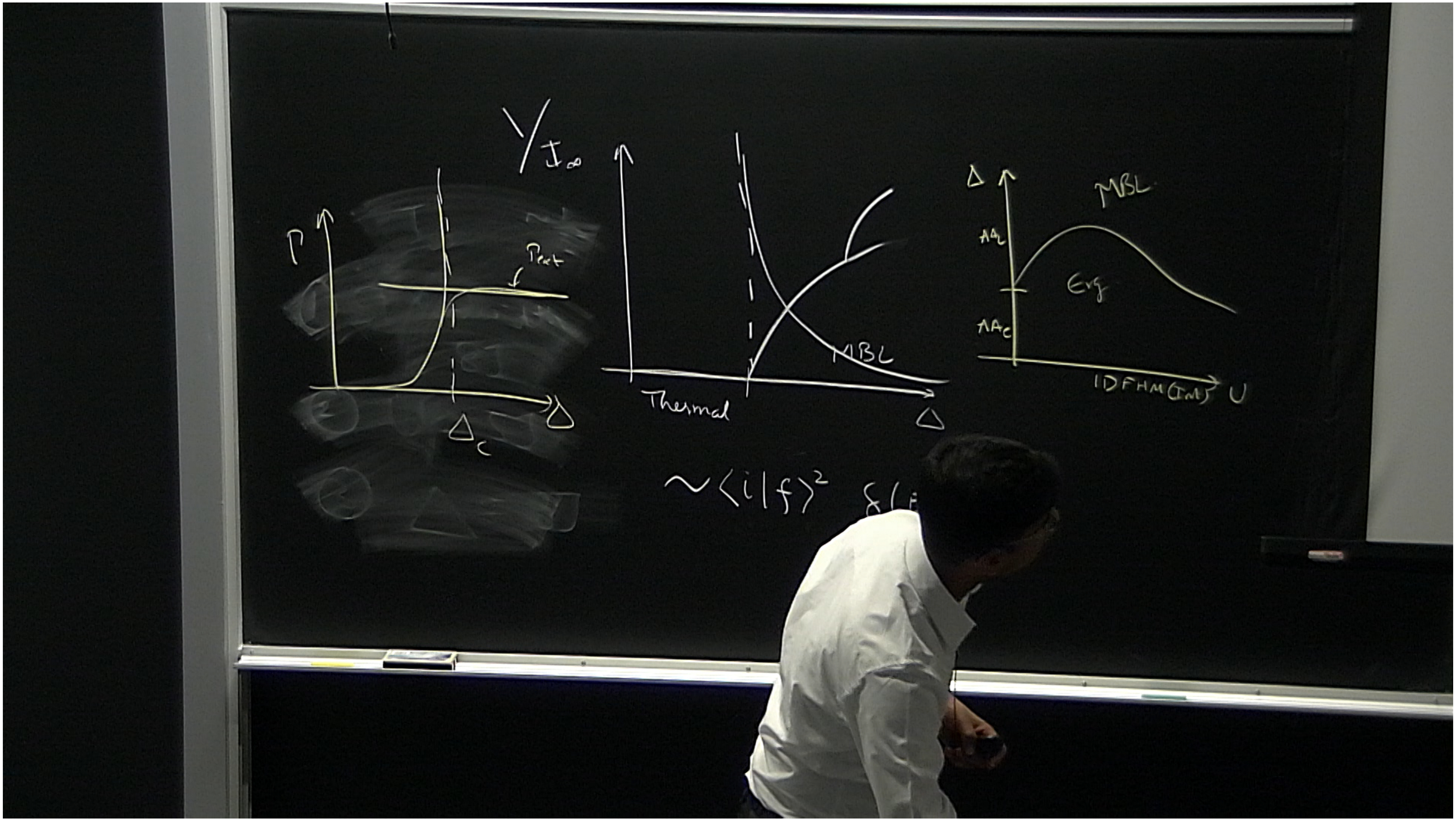
- True disorder vs Quasi-periodic
- Longer time dynamics in the critical phase
- Optical conductivity: ergodic, critical and localized region
- Disorder effects on equilibrium phase transitions e.g. BKT
- Entanglement entropy (EE) /Out-of-time-ordered correlator (OTOC) type measures
- Mobility edges and non-ergodic metal phases
- Floquet topological/prethermal phases
- Driven-dissipative systems

Experiments: Henrik Lüschen, Sebastian Scherg, Thomas Kohlart, Michael Schreiber, Sean Hodgman (ANU Australia), Ulrich Schneider (Cambridge, UK), Immanuel Bloch

Theory: E. Altman (UC Berkeley), M. Knap (TU Munich), S. Gopalakrishnan (CUNY), M. Fischer (ETH Zurich), F. Alet (LPT Toulouse)



Thermal
MBL
Δ
Δ
MBL
Erg
IDFHM
U
$\sim \langle i|f \rangle^2 \, \delta(E-h\nu)$


Thermal
MBL
Erg
MBL
Δ_c
$\sim \langle i|f\rangle^2$

Coupling Identical MBL Systems

Bordia PRL (2016)