Probing Many-Body Localisation with Ultracold Atoms

Michael Schreiber, **Henrik Lüschen**, Pranjal Bordia
Sean Hodgman, Ulrich Schneider

Sebastian Hild, Jae-Yoon Choi,
Johannes Zeiher, Tarik Yefsah, Christian Gross

Humboldt Research Awardees:
E. Demler, C. Chin, N. Cooper, C. Salomon, W. Ketterle

Max-Planck-Institut für Quantenoptik
Ludwig-Maximilians Universität

funding by
€ MPG, European Union, DFG
$ DARPA (OLE)
erc synergy

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Outline

1 Many-Body Localisation

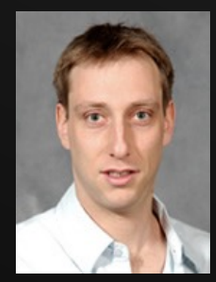
- MBL of Interacting Fermions in Quasi-Random Potentials
- Coupling of 1D MBL systems - Anderson vs MBL
- **Anderson & MBL under Light Scattering (Henrik)**
- **Anderson & MBL in Driven Systems (Henrik)**

2 Signatures of MBL in 2d ?

- Probing MBL transition using domain wall dynamics

Many-Body Localisation using Ultracold Atoms

M. Schreiber et al. Science **349**, 842 (2015)
P. Bordia et al. arXiv 1509.00478



E. Altman

R. Vosk

M. Fischer

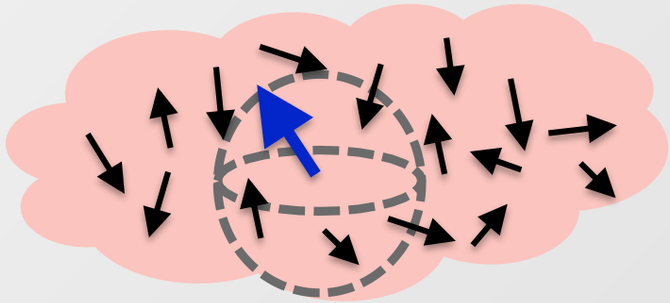
Motivation

Thermalization

Quantum correlations in local d.o.f are rapidly lost as these get entangled with the rest of the system.

Classical hydro description of remaining slow modes (conserved quantities, and order parameters).

Many-body localization



Local quantum information persists indefinitely.

Need a fully **quantum** description of the long time dynamics!

?

The many-body localization transition = elusive interface between quantum and classical worlds

Approaching Many-Body Localization from Disordered Luttinger Liquids
C. Karrasch, J. E. Moore
Subjects: Strongly Correlated Electrons (cond-mat.str-el)
28. arXiv:1506.00592 [pdf, other]
Protection of topological order by symmetry and many-body loc
Andrew C. Potter, Ashvin Vishwanath
Comments: 17 pages, 4 figures
Subjects: Disordered Systems and Neural Networks (cond-mat.
29. arXiv:1505.07089 [pdf, other]
Dynamics of many-body localisation in a translation invariant qu
Merlijn van Horssen, Emanuele Levi, Juan P. Garrahan
Comments: 5 pages, 4 figures
Subjects: Statistical Mechanics (cond-mat.stat-mech); Quantum
30. arXiv:1505.06343 [pdf, ps, other]
Many-body ground state localization and coexistence of localize
Yucheng Wang, Haiping Hu, Shu Chen
Comments: 5 pages, 6 figures
Subjects: Disordered Systems and Neural Networks (cond-mat.
31. arXiv:1505.05386 [pdf, other]
Revisiting Many-body Localization with Random Networks of Te
Benoît Descamps, Frank Verstraete
Comments: 3 figures
Subjects: Quantum Physics (quant-ph)
32. arXiv:1505.05147 [pdf, other]
Many-Body Localization of Symmetry Protected Topological States
Kevin Slagle, Zhen Bi, Yi-Zhuang You, Cenke Xu
Comments: 5 pages 2 figures
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Tot
J. Goold, C. Gogolin, S. R. Clark, J. Eisert, A. Scardicchio, A. Silva
Comments: Slight Restructuring of the manuscript and additional analysis performed
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Xiao
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36.
Mar
Ran
Com
Sub
37.
Loca
Alexander L. Burin
Comments: Modified version after review
Subjects: Disordered Systems and Neural Networks (cond-mat.dis-nn)
38. arXiv:1503.06147 [pdf, other]
Many-body localization characterized from a one-particle perspective

Pioneering work:
D. M. Basko, I. L. Aleiner, B. L. Altschuler, Ann. Phys. (2006).

Good review/intro:
D. A. Huse, R. Nandkishore, V. Oganesyan,
Annu. Rev. Cond. Mat. 6, 15 (2015)

R. Vosk & E. Altman,
Annu. Rev. Cond. Mat. 6, 383 (2015)

No Experiments!

Two Experiments!
ultracold atoms &
ions (see C. Monroe group)

ntum Physics (quant-ph)

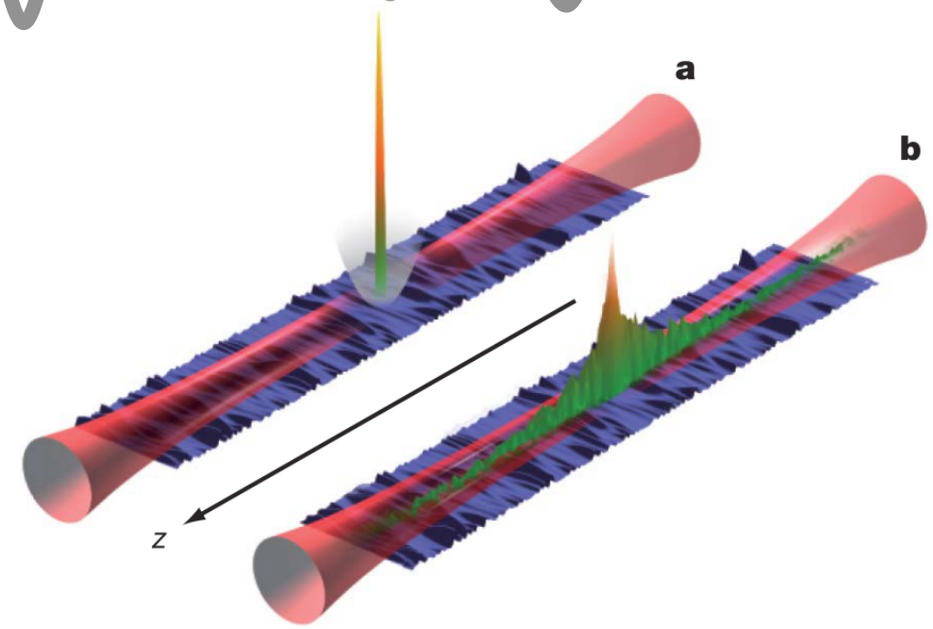
at.stat-mech); Strongly Correlated Electrons (cond-mat.str-el)

le particle and many-body problems

Measuring Localisation

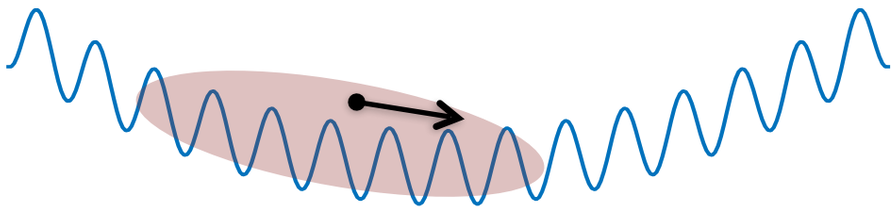
Anderson localization:

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



Many-body localization:

Fastest timescale: local probe!

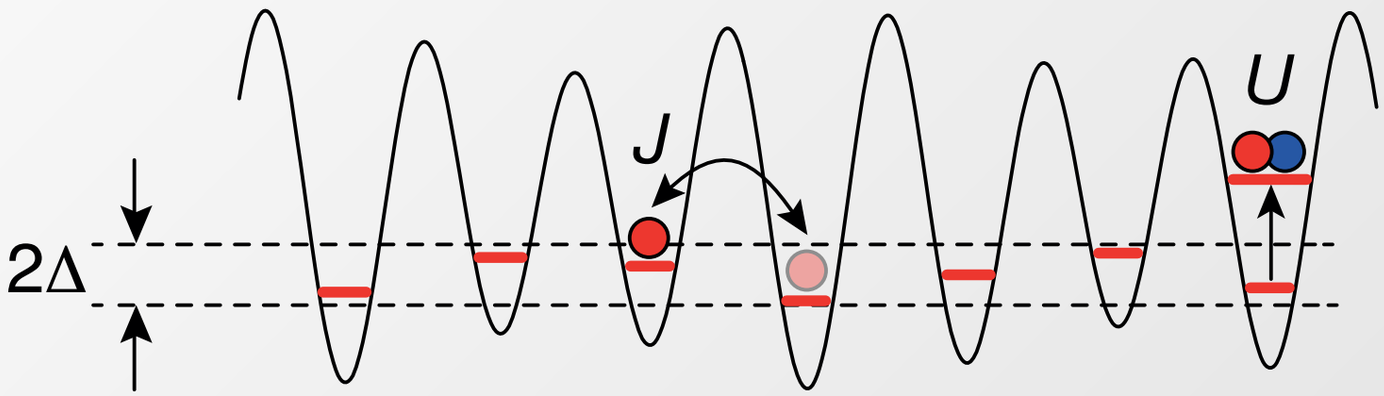


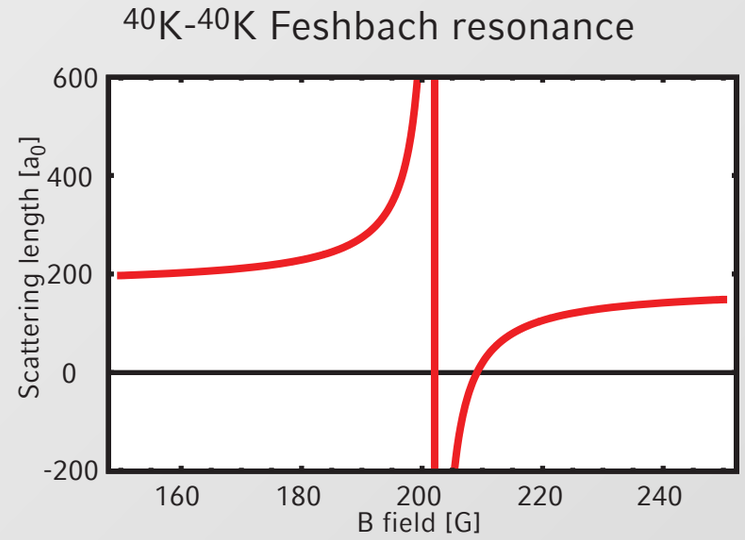
Slowest timescale: global probe

Kondov et al. (DeMarco) Phys. Rev. Lett. 114, 083002 (2015)

Our System - 1D Quasi-Disordered Fermi-Hubbard

$$H = -J\sum_{i,\sigma}\left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i+1,\sigma} + H.c.\right) + \Delta\sum_{i,\sigma} sin\left(2\pi\alpha i + \phi\right)\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i,\sigma} + U\sum_{i}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$





Without interactions *U*=0 : Aubry-André model

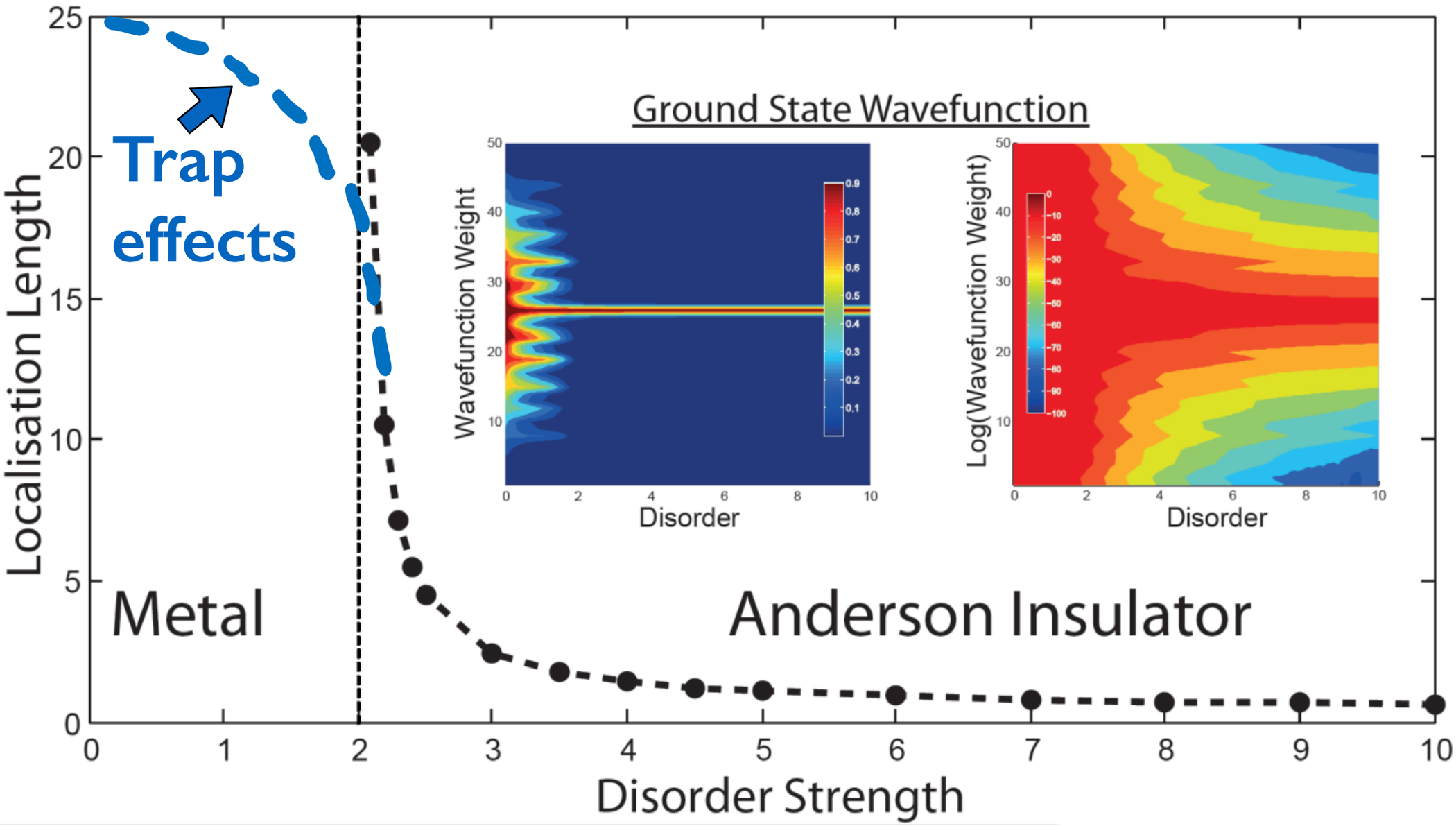
- Homogenous tunneling but quasi-random onsite energies
- α is the incommensurability ratio, irrational, in the experiment ≈ 0.721

All eigenstates extended for Δ/J < 2

All eigenstates exponentially localised for Δ/J > 2

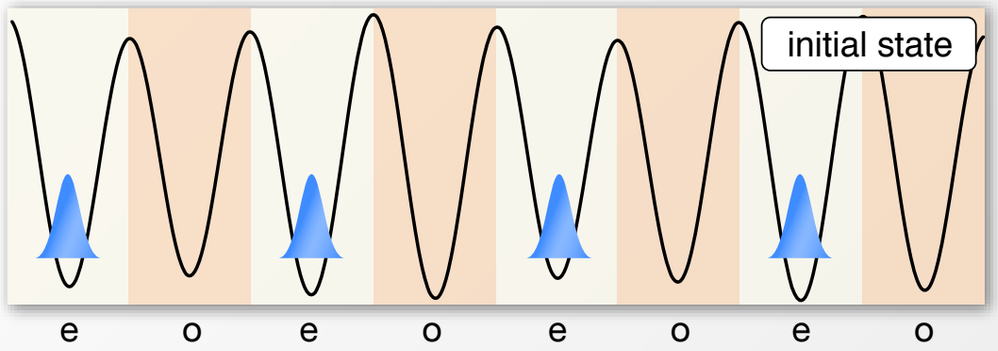
G. Roati et al. Nature (2008)

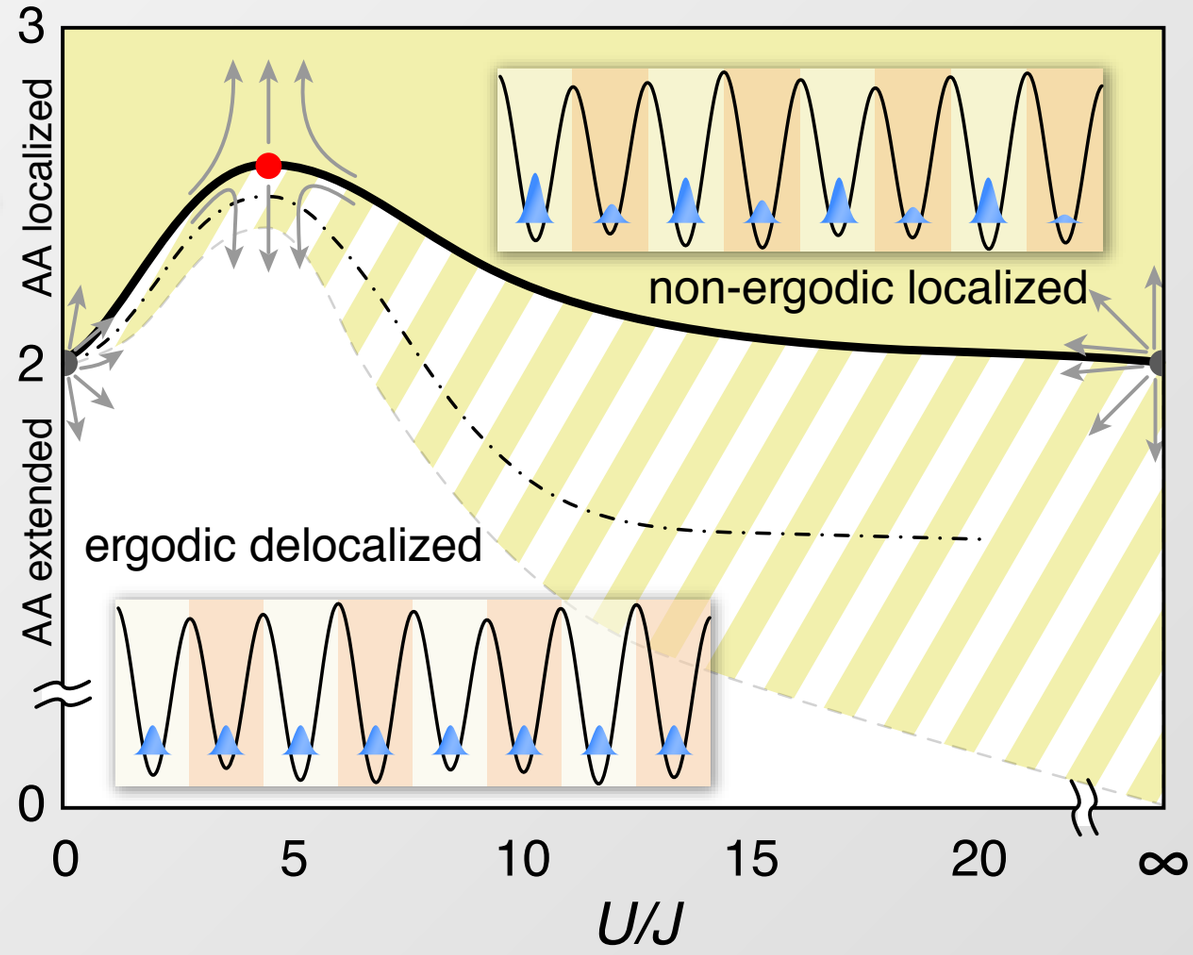
Single Particle Orbitals



$$\xi_{sp} = \ln^{-1}(\Delta/2J)$$

Probing the Interacting Aubry-André Model





Three Step Procedure

1) Prepare CDW (with different doublon densities)
2) Evolve in disorder
3) Readout CDW (disorder averaged)

Main Observable: **Imbalance** $I = \dfrac{N_e - N_o}{N_e + N_o}$

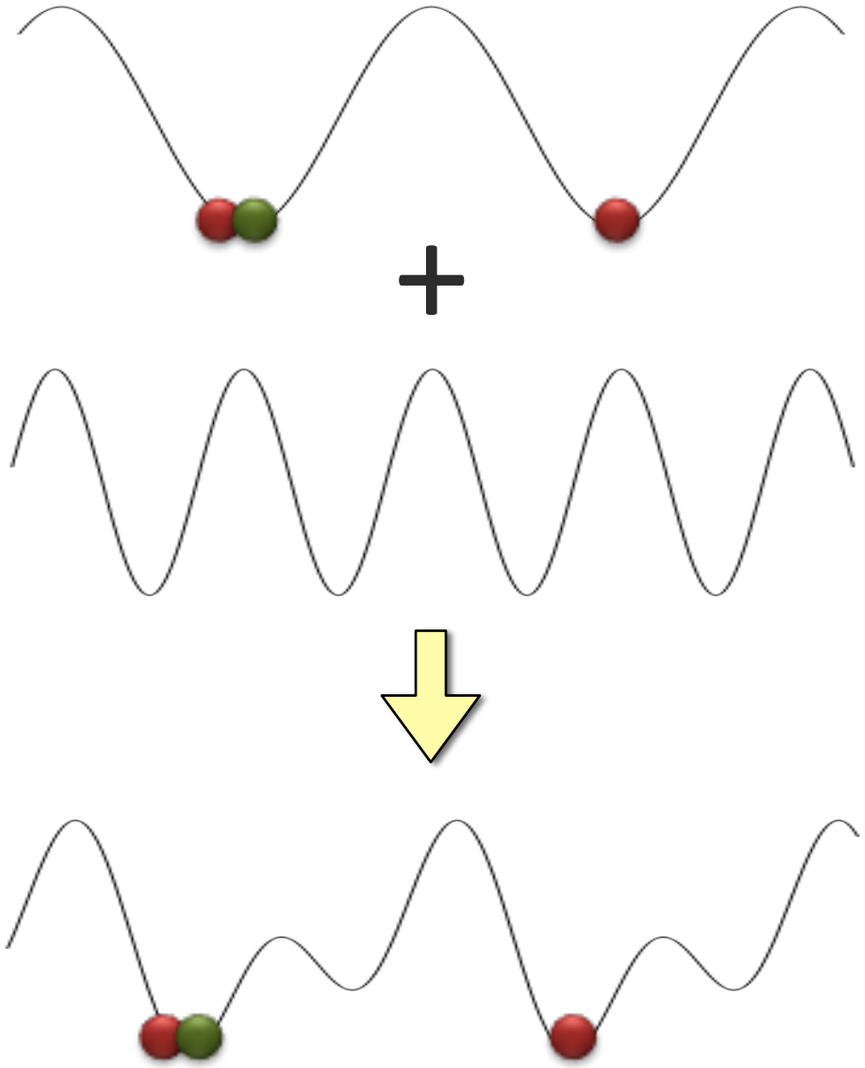
Hamming Distance

$D(t) = \frac{N}{2}\left[1 - I(t)\right]$

(see P. Hauke & M. Heyl, PRB 2015)

Preparing the CDW Wave

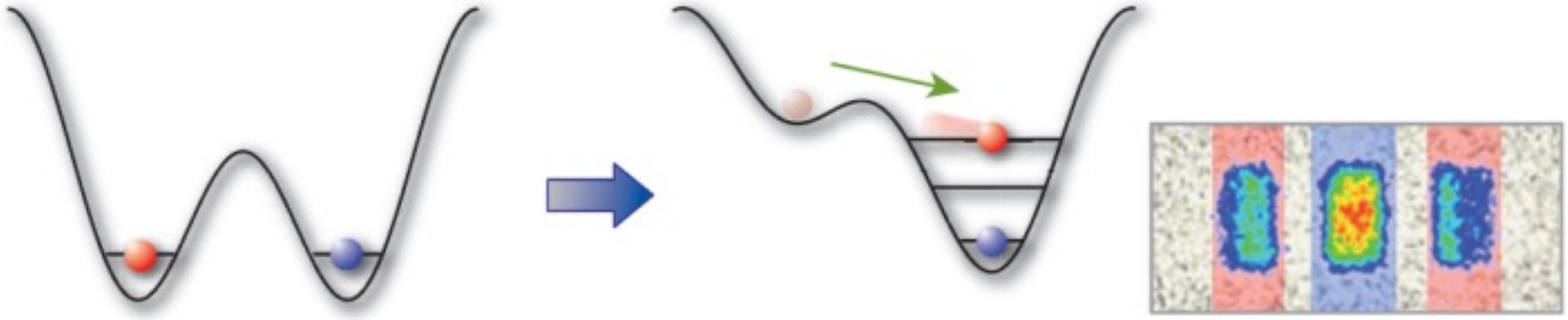
Superimpose **two lattices**, with: $\lambda_l = 2\lambda_s$ (here 532 nm & 1064 nm)



Adiabatic ramp-up with correct relative phase

All particles localised on even sites I>95%

Site resolved even-odd detection



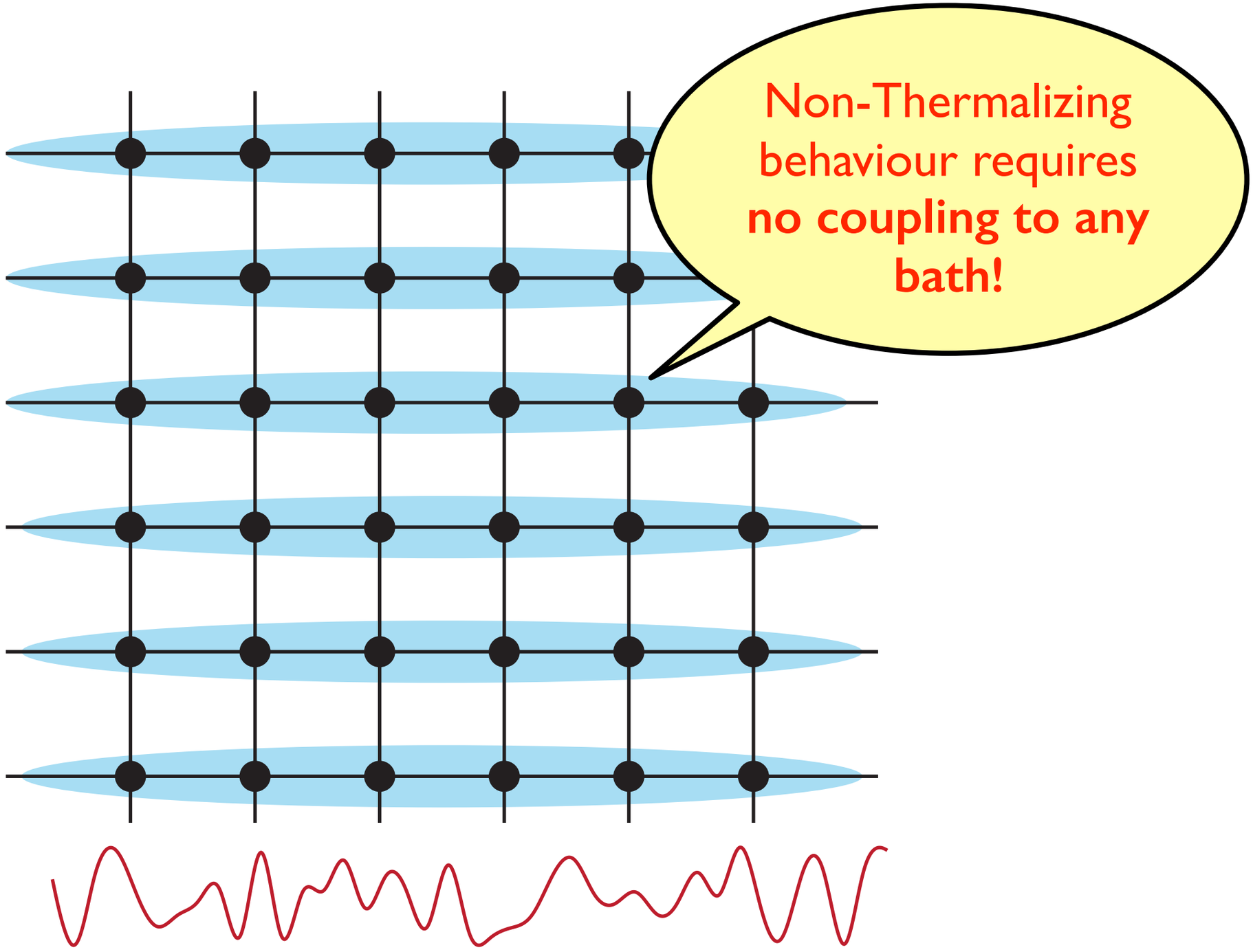
Merge wells in presence of tilt

Band mapping

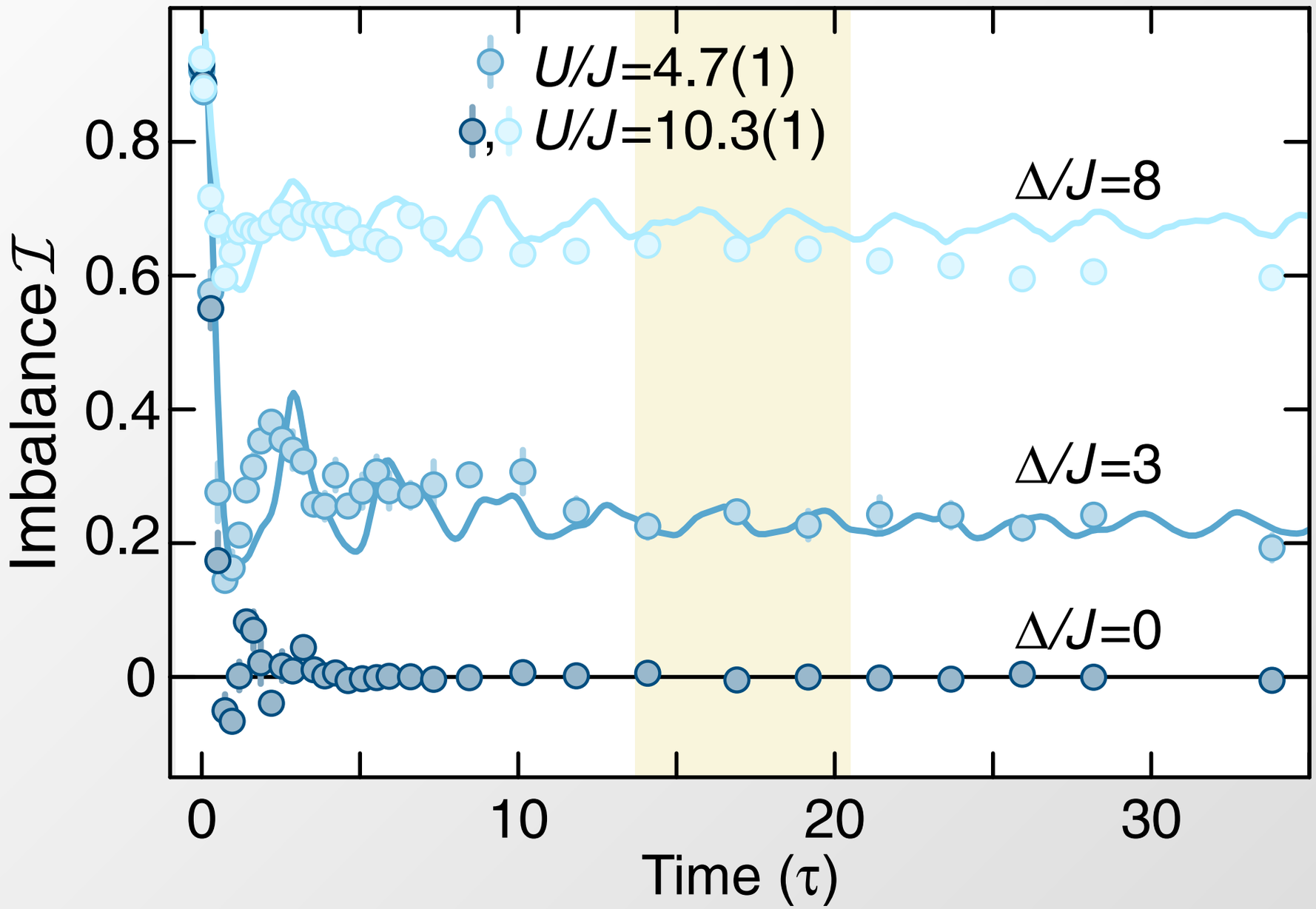
Absorption imaging after TOF

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

Experimental Setup 1D

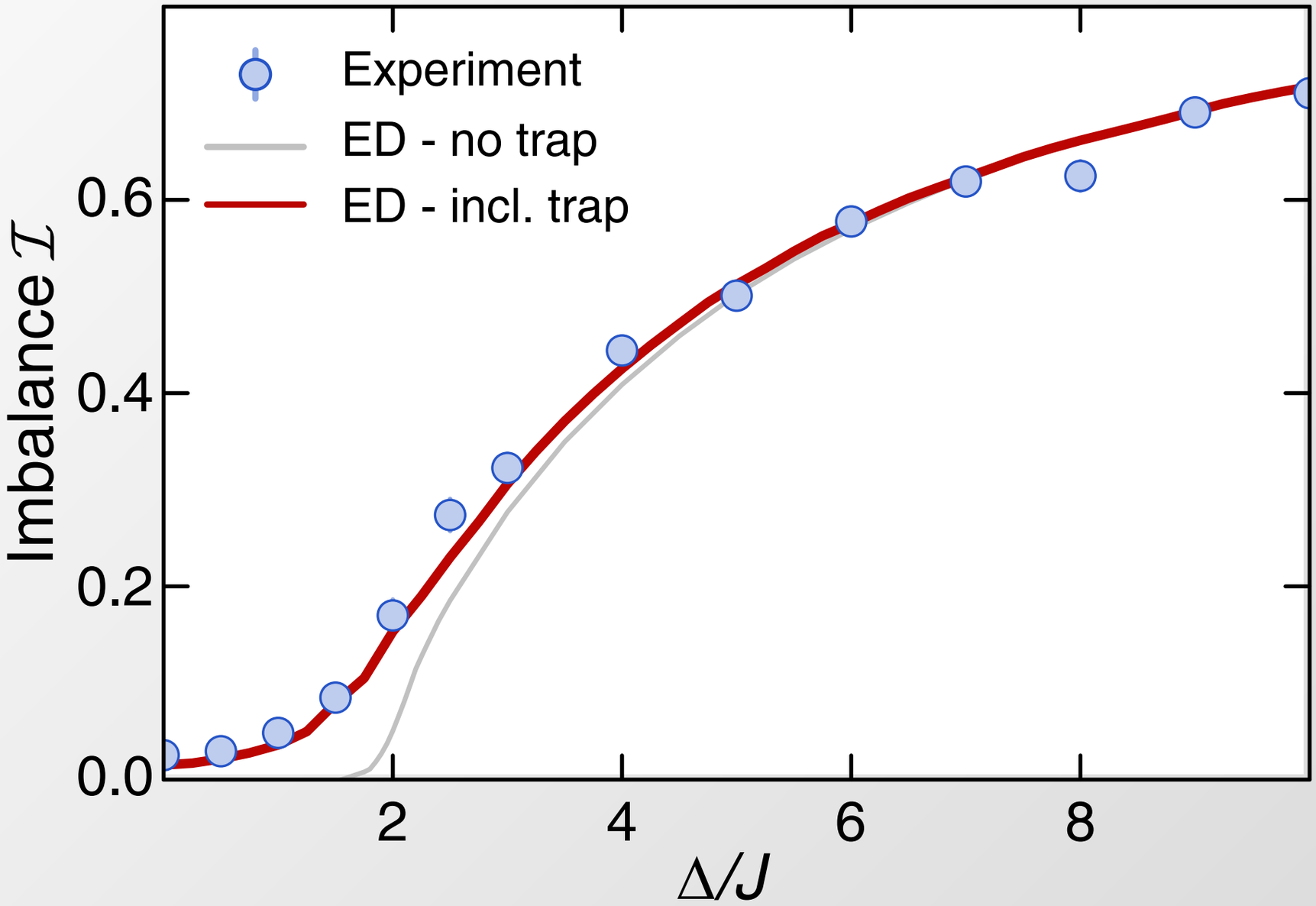


Time Evolution

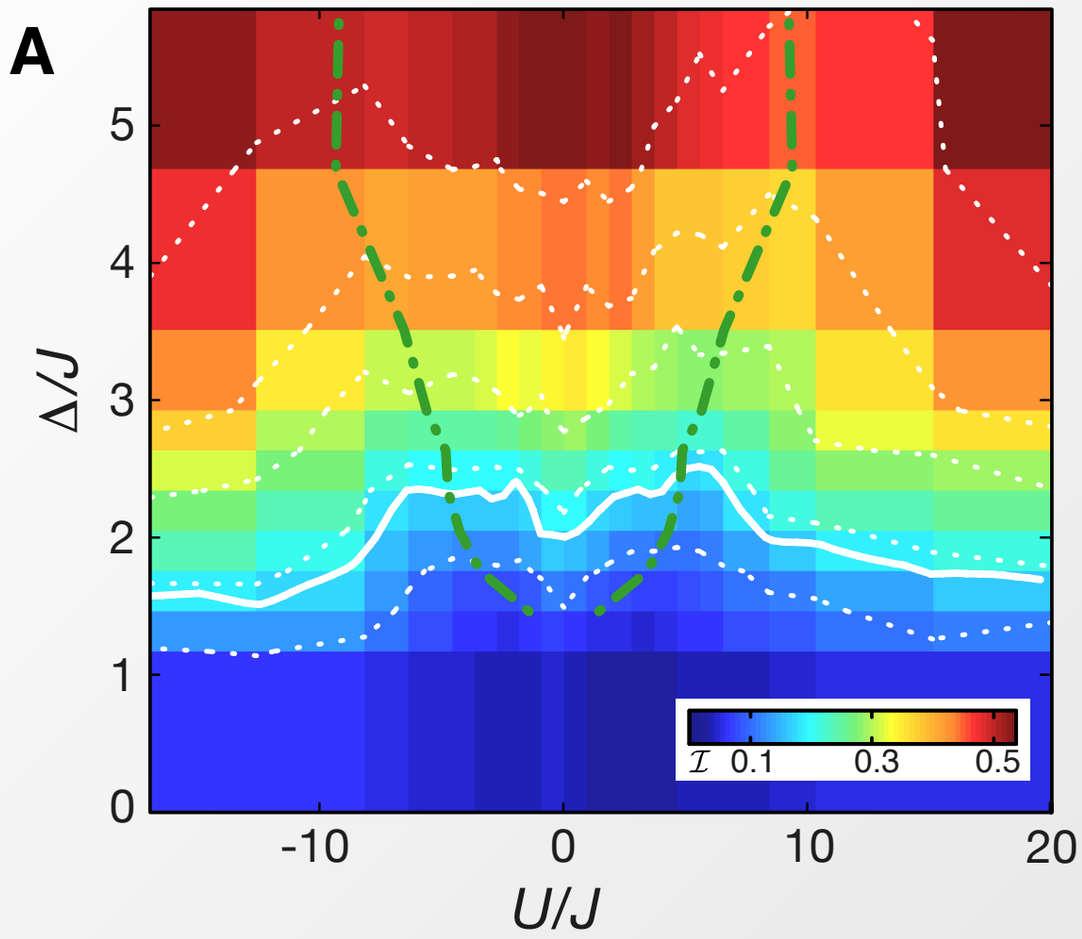


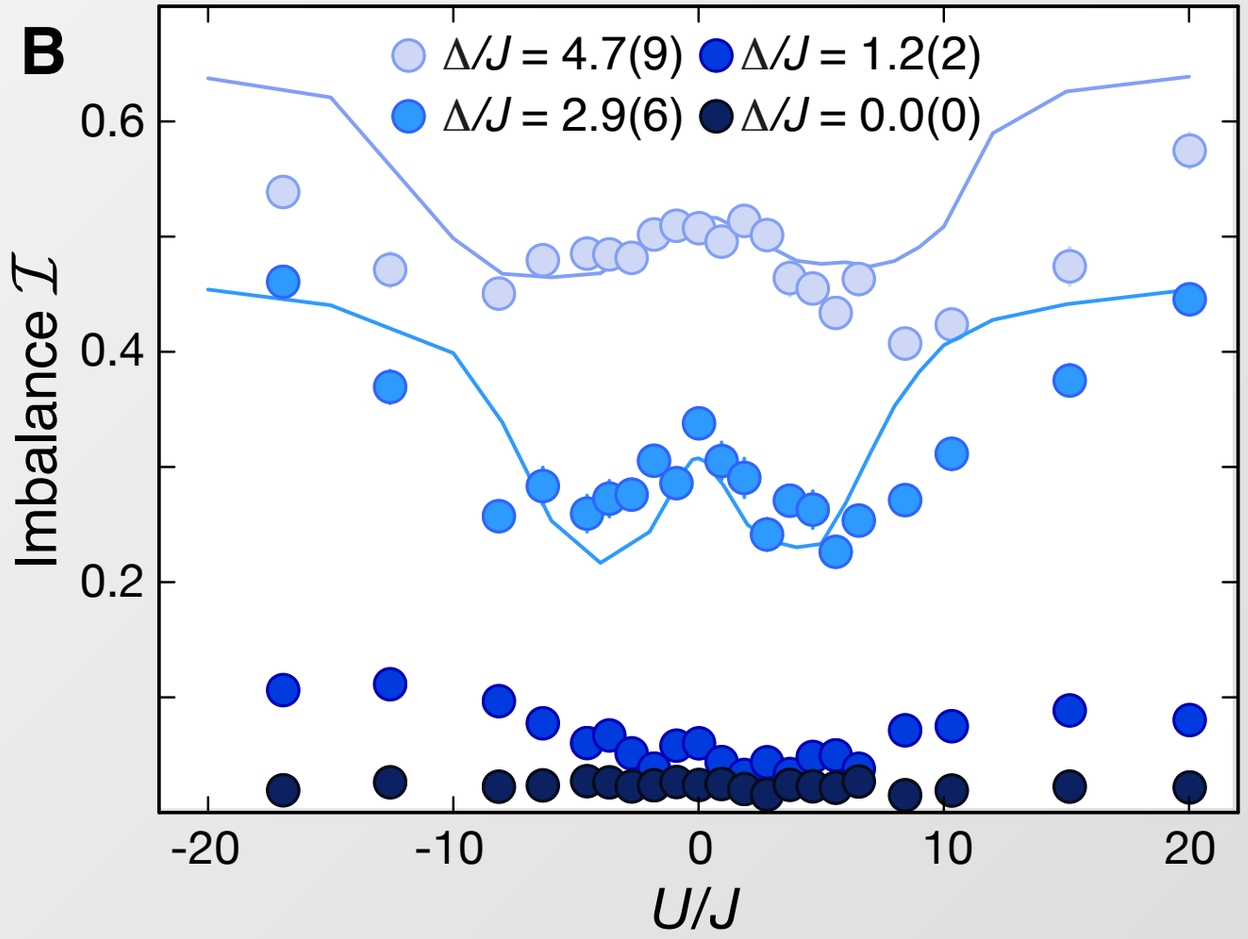
Non-ergodic, non-thermalizing quantum evolution !

U=0 - Anderson Localization



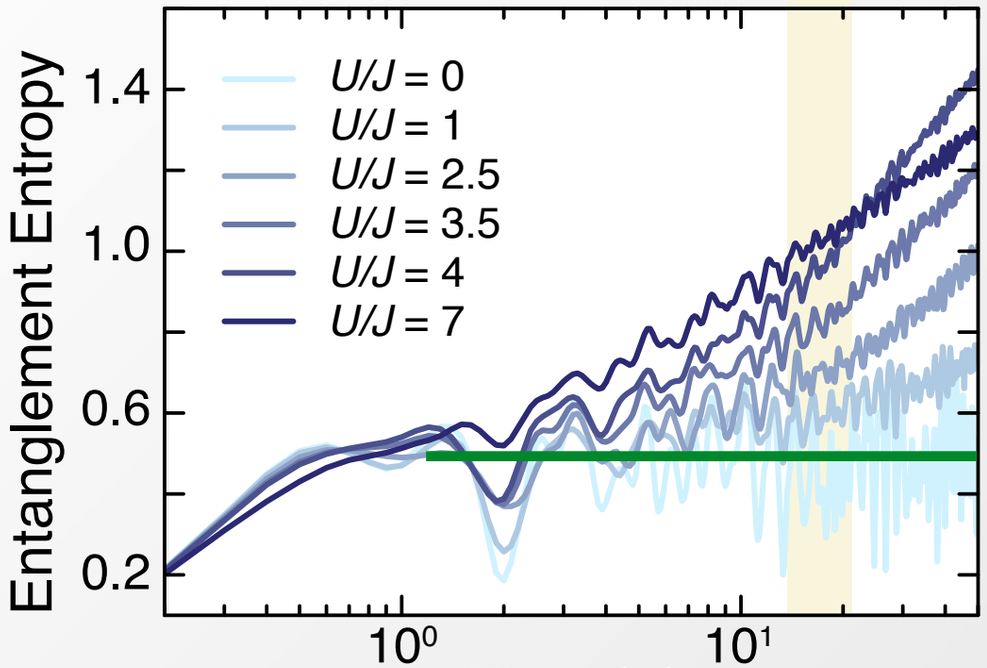
Imbalance vs U/J



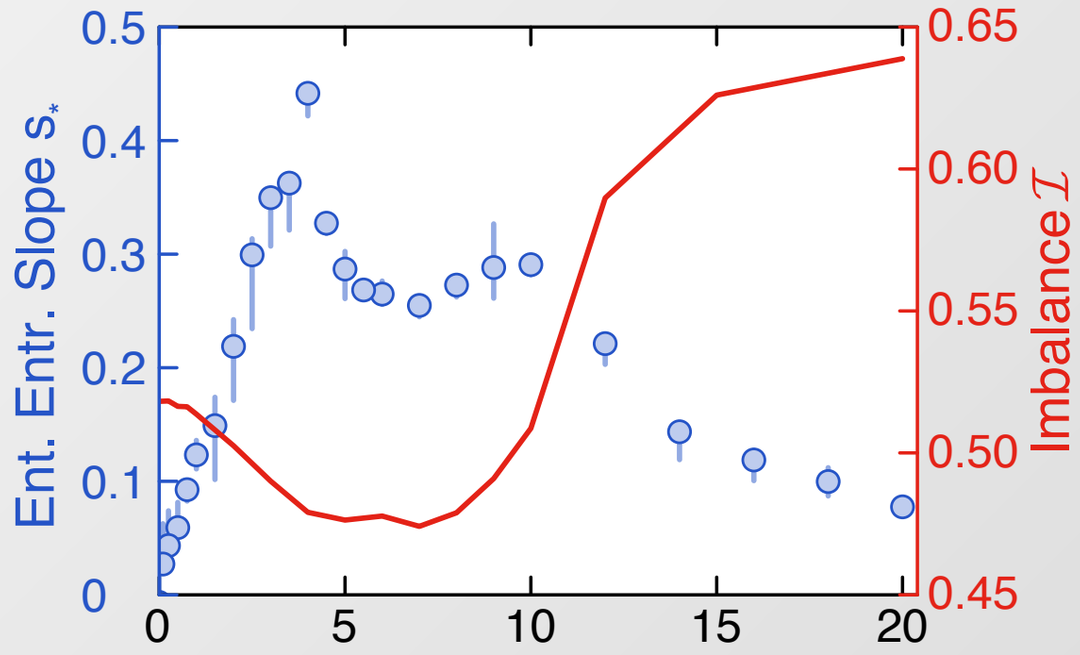


1) **Localisation for all Interactions**
2) Characteristic W-shape
3) Dynamical U vs -U symmetry

Numerics - Entanglement Entropy



Characteristic log(t)
entanglement entropy growth



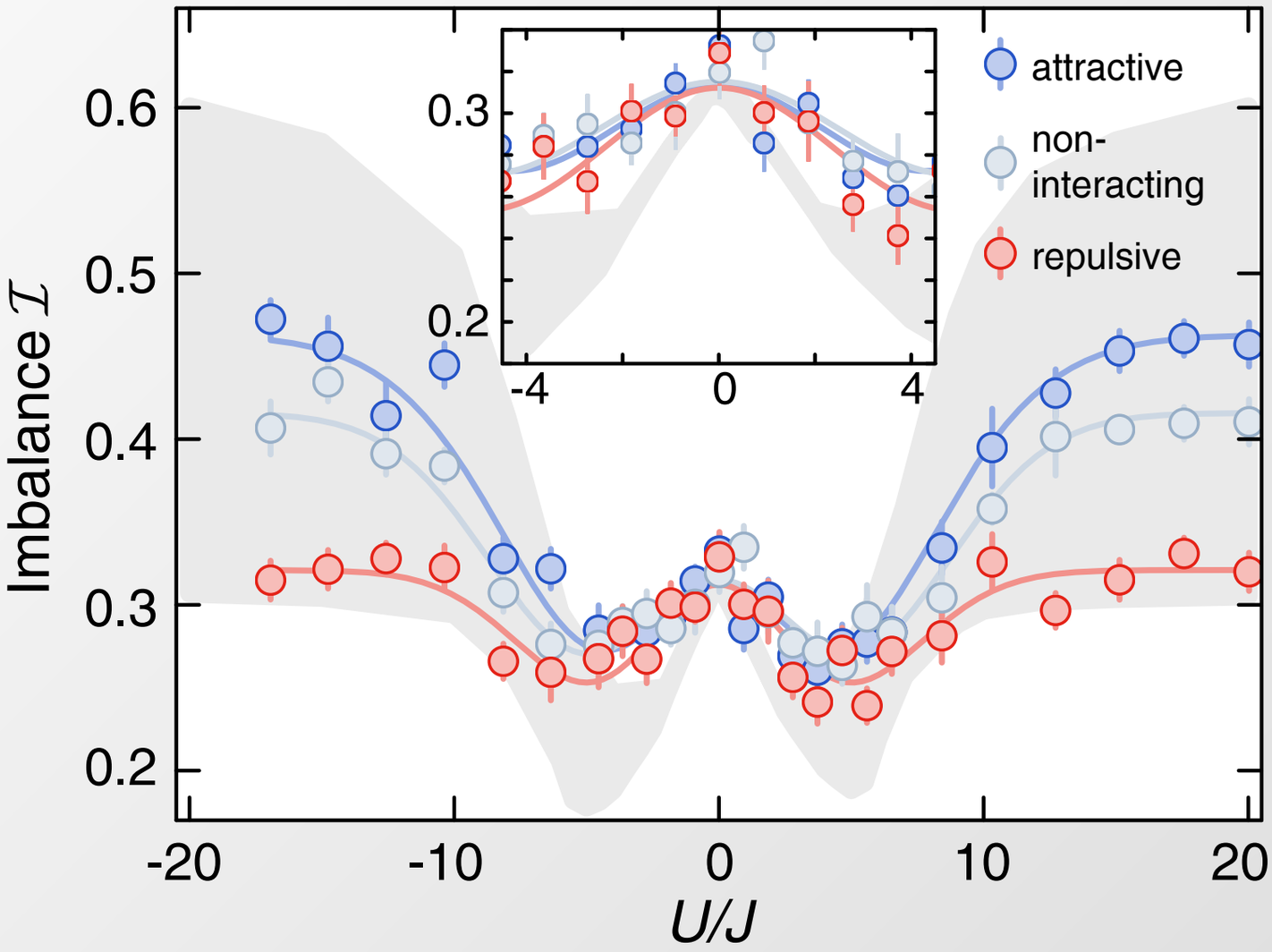
Maximum in entanglement entropy slope
connected to minimum of imbalance

DMRG Simulations $\Delta/J = 5$

$$S = s_0 + s^* \log(t/\tau)$$

JH Bardarson, F Pollmann, JE Moore
Physical Review Letters (2012)

Influence of Initial Doublon Fraction



>50% doubloons

40% doublons

no doublons

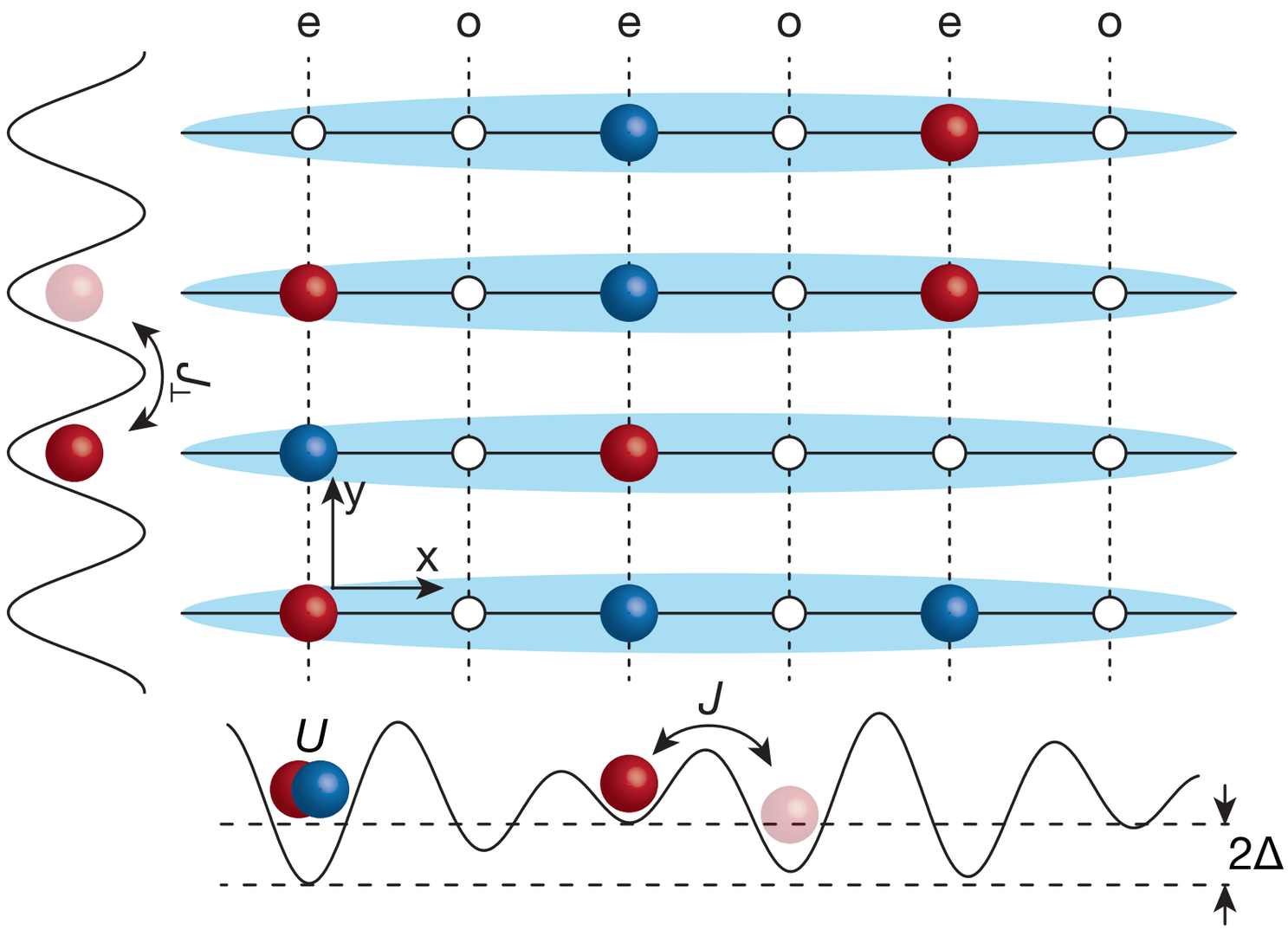
Kinetic energy of doublons for large U $J_{\mathrm{dbl}} = J^2/U$

Doublons see effectively larger disorder $\frac{J_{\mathrm{dbl}}}{\Delta} \ll \frac{J}{\Delta}$

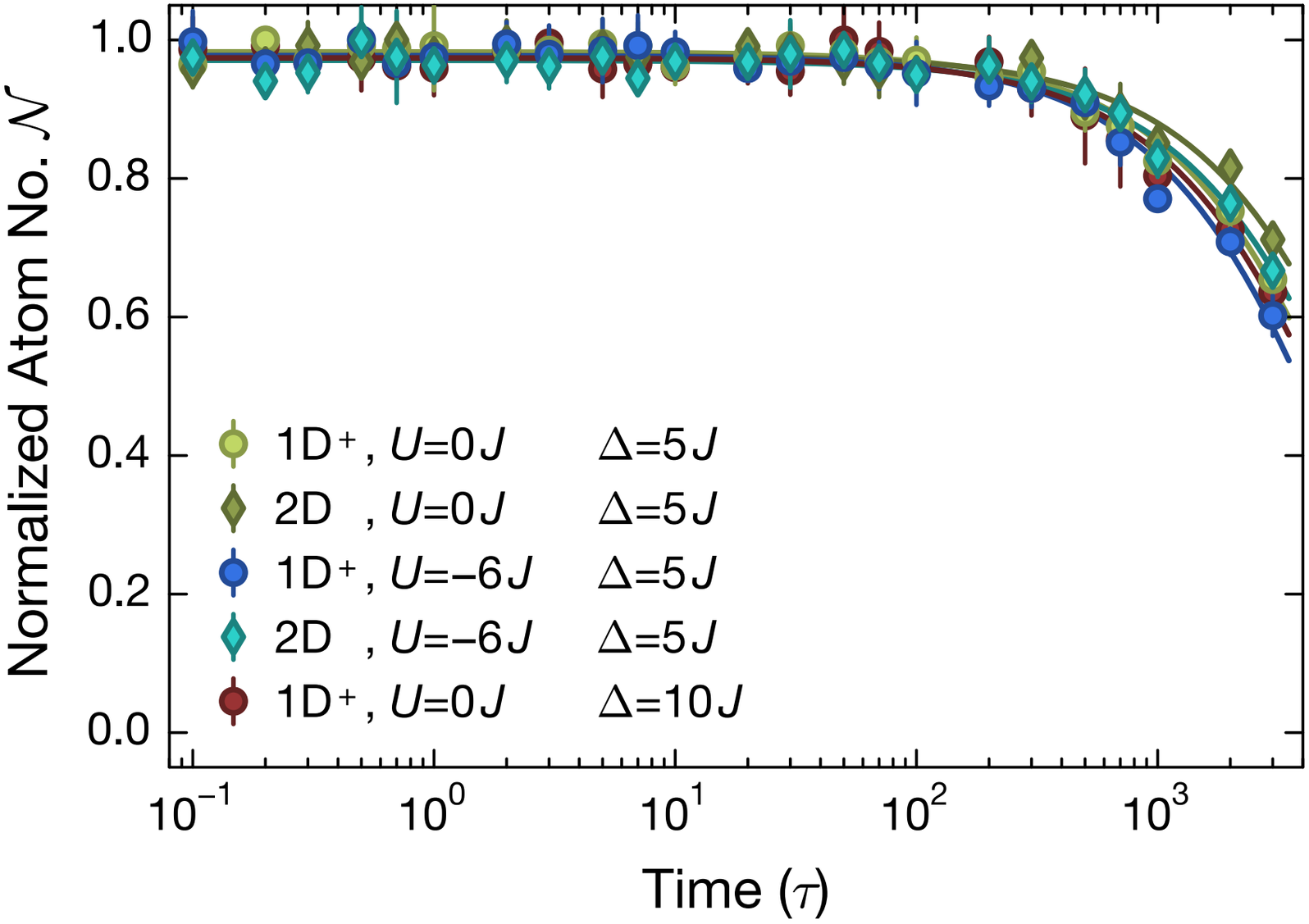
Changing Dimensionality & Very Long Time Behaviour

P. Bordia et al. arXiv 1509.00478

Experimental Setup 2D

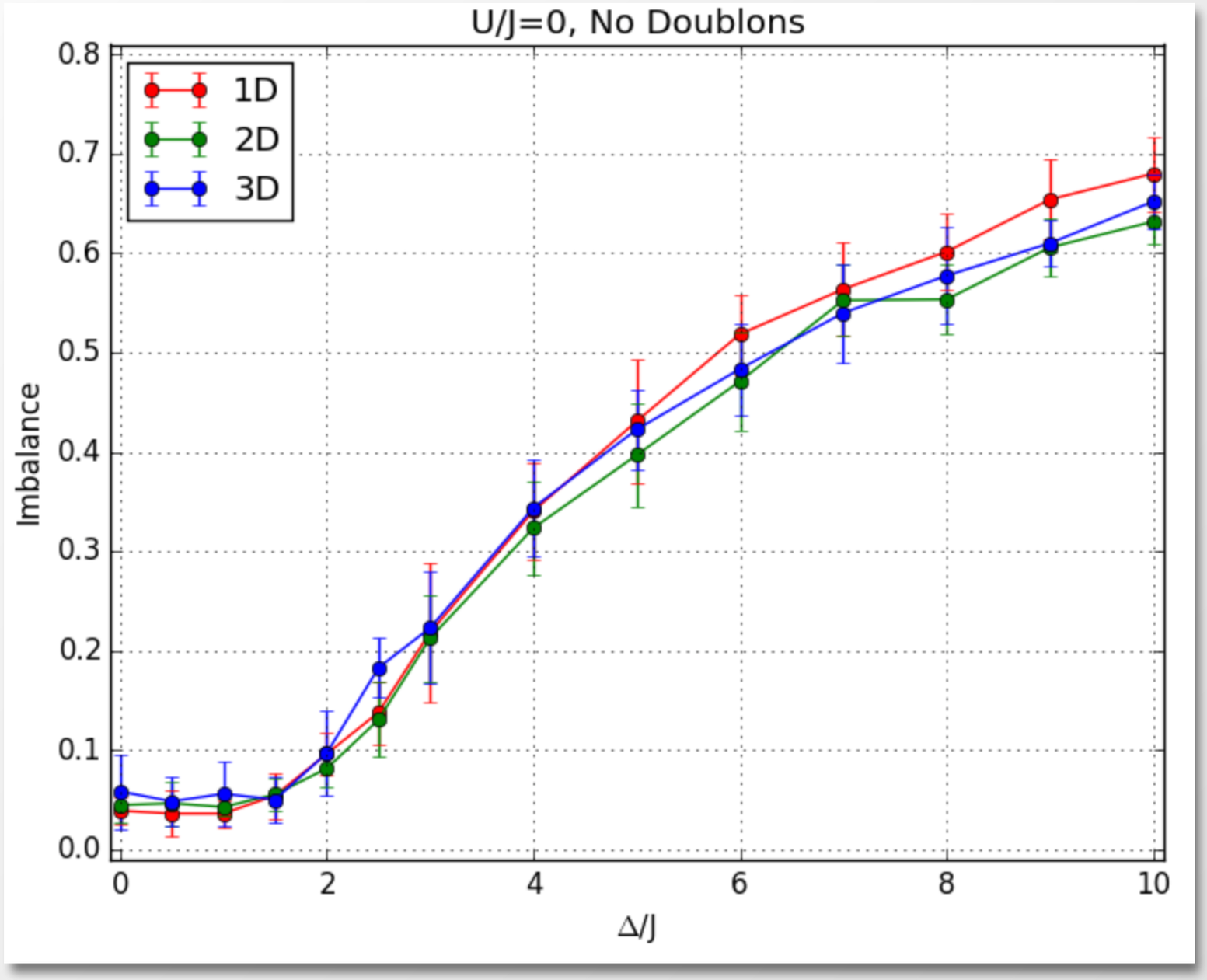


Particle Number Lifetime



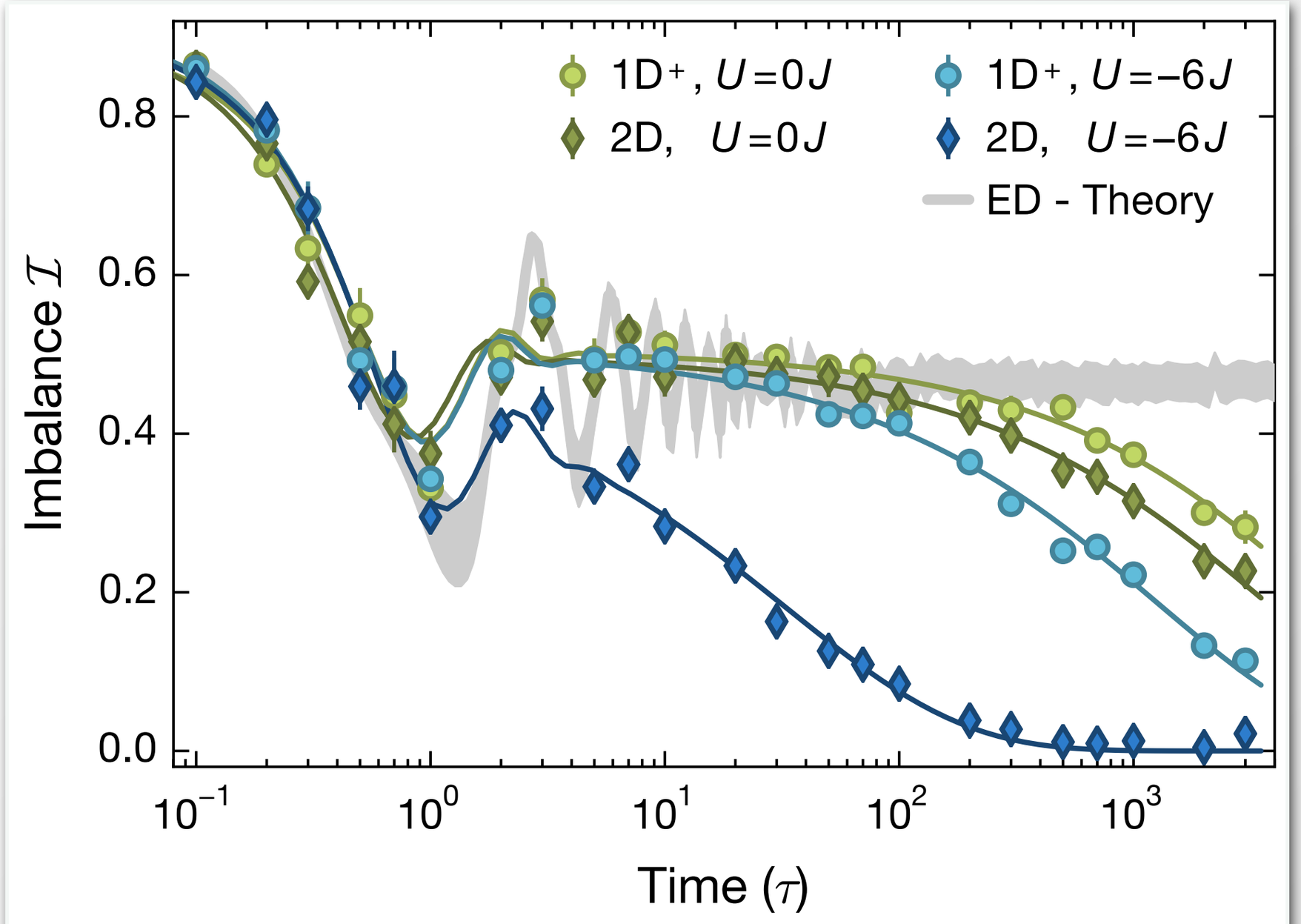
Atom lifetime enables us to **observe dynamics** up to **2000-4000 τ** !

U=0 - Dimensionality



1d Quasiperiodic Disorder - different couplings along y & z

Destruction of MBL



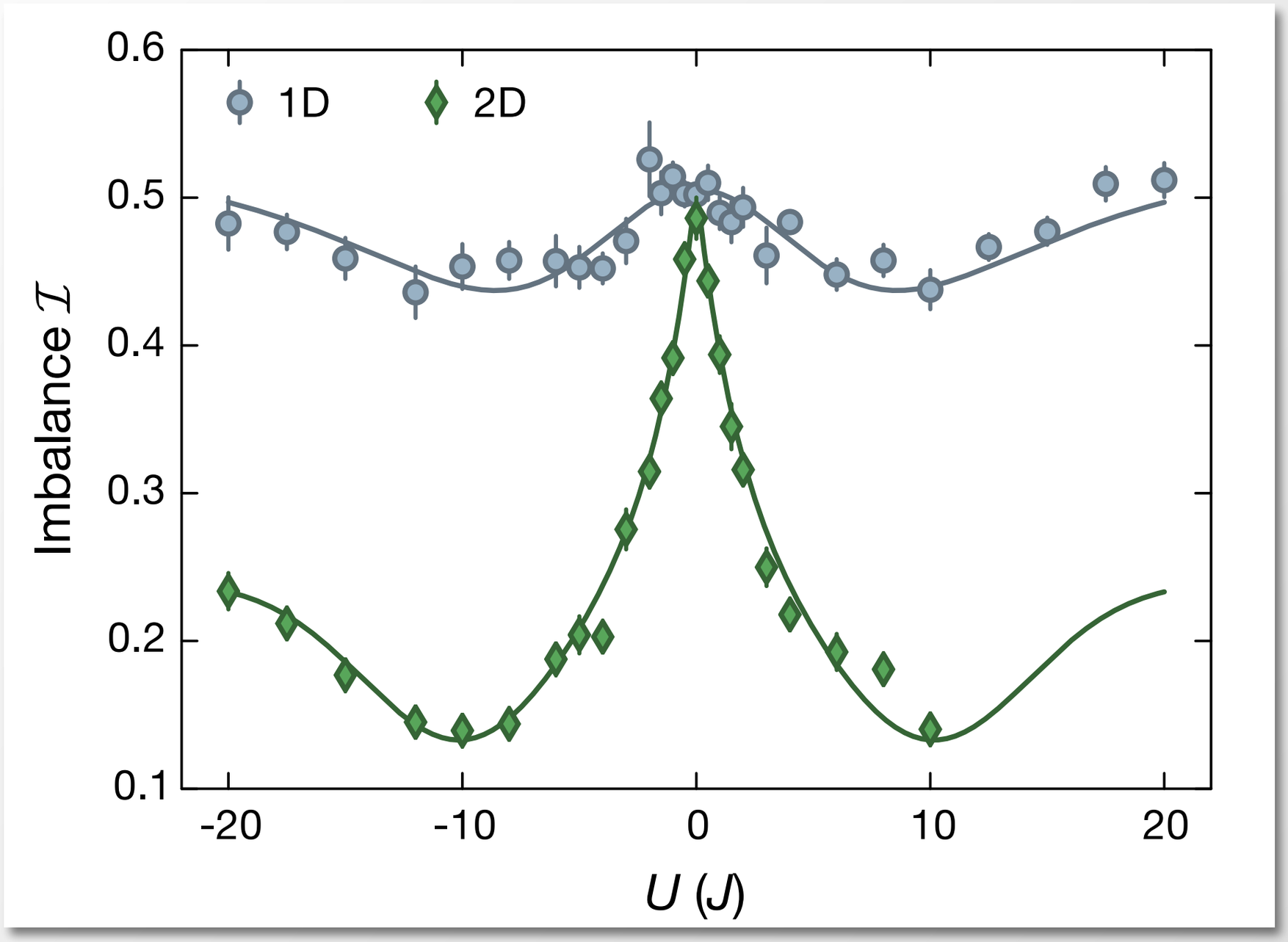
Long time decay fit

$$o \cdot e^{(-t/\tau)^{\alpha}}$$

- MBL unstable for coupling between tubes
- Fundamental difference between Anderson and MBL!

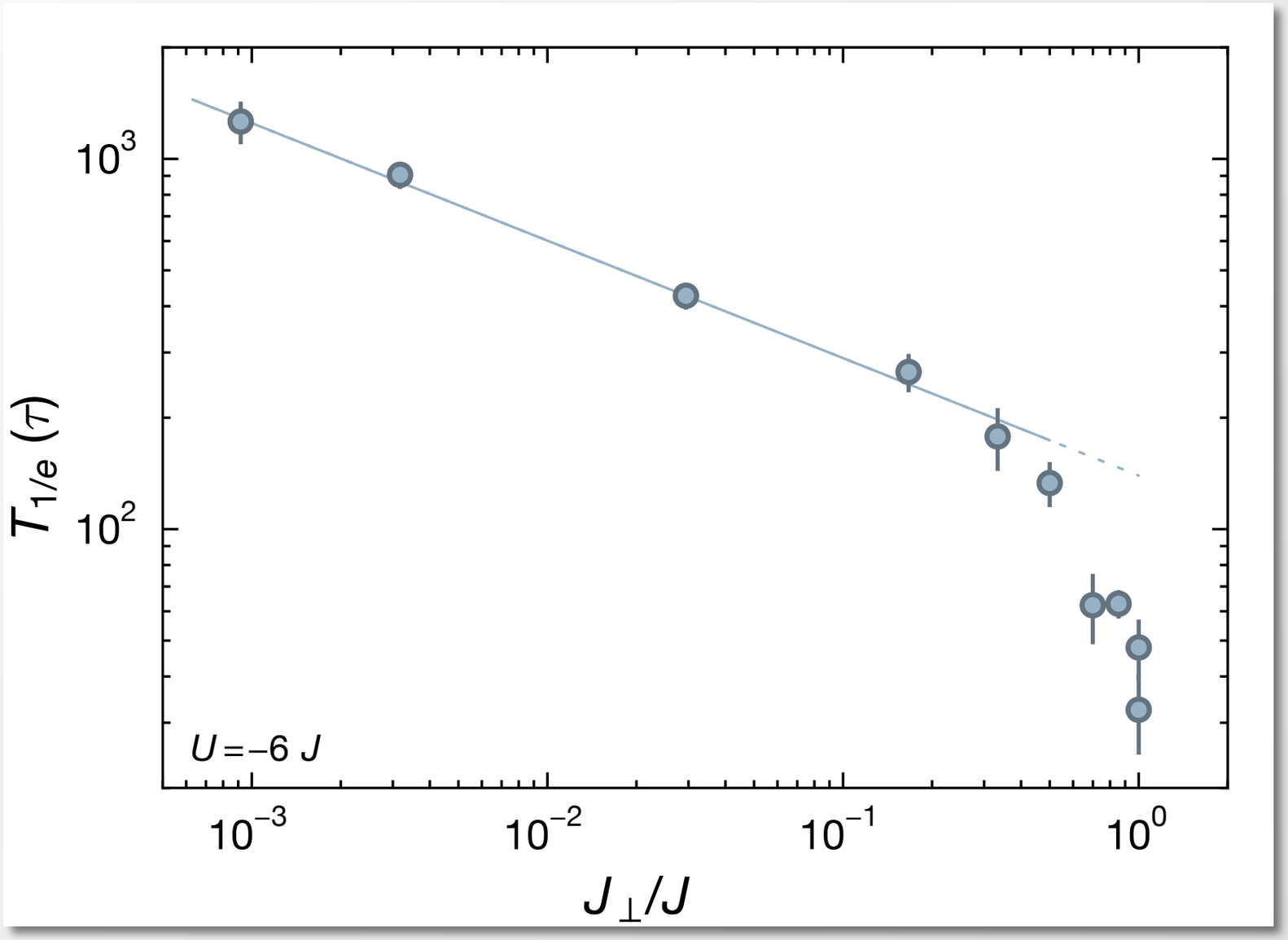
cf. Reichl, Mueller 1508.00472v2 & Bar Lev, Reichman: 1508.05391

Destruction of MBL in Higher Dimensions



1d Quasiperiodic Disorder - different couplings along y & z

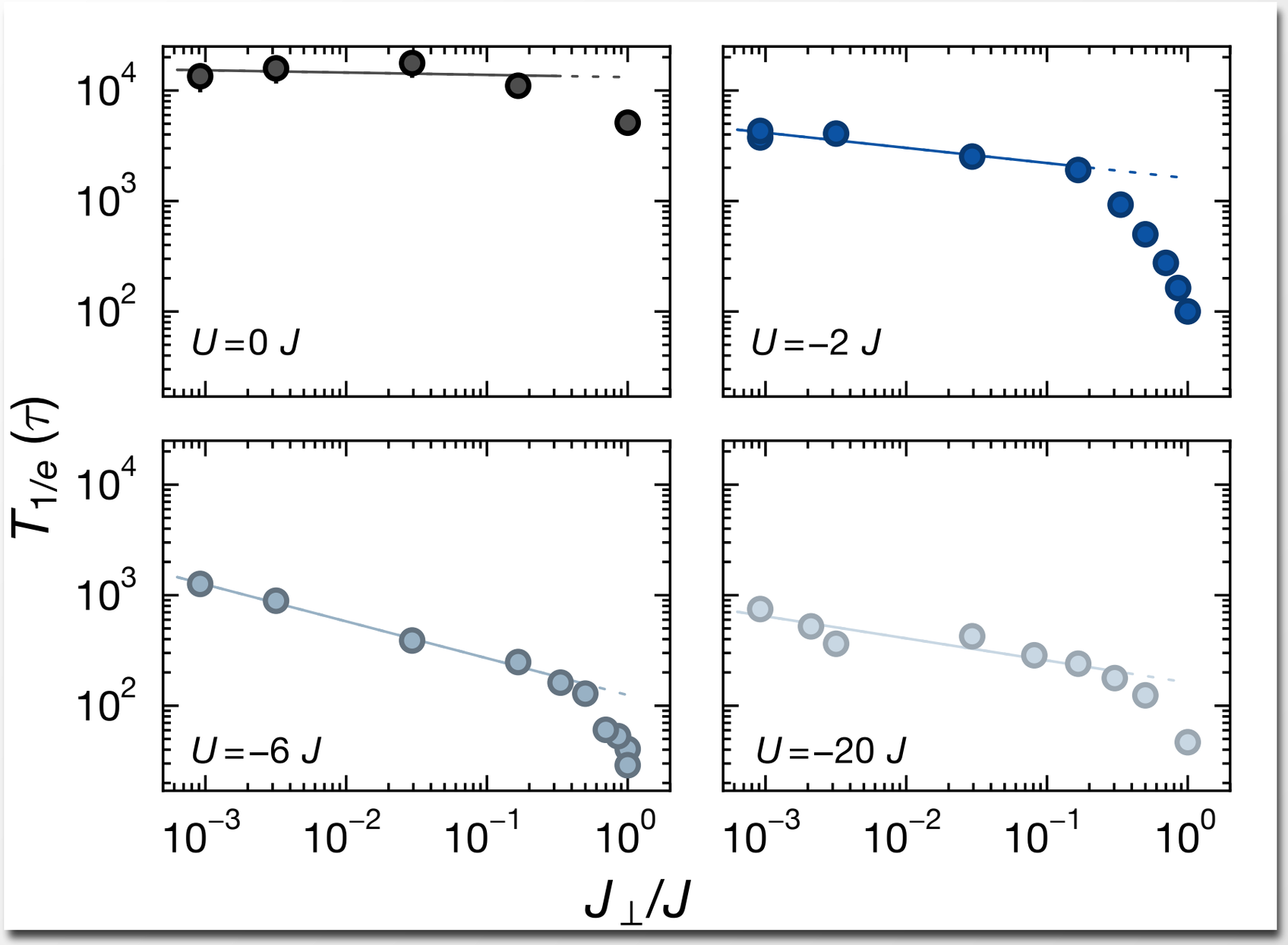
MBL Lifetime Limit



$$\Delta = 5J$$

MBL lifetime limited only by **residual transverse coupling**.

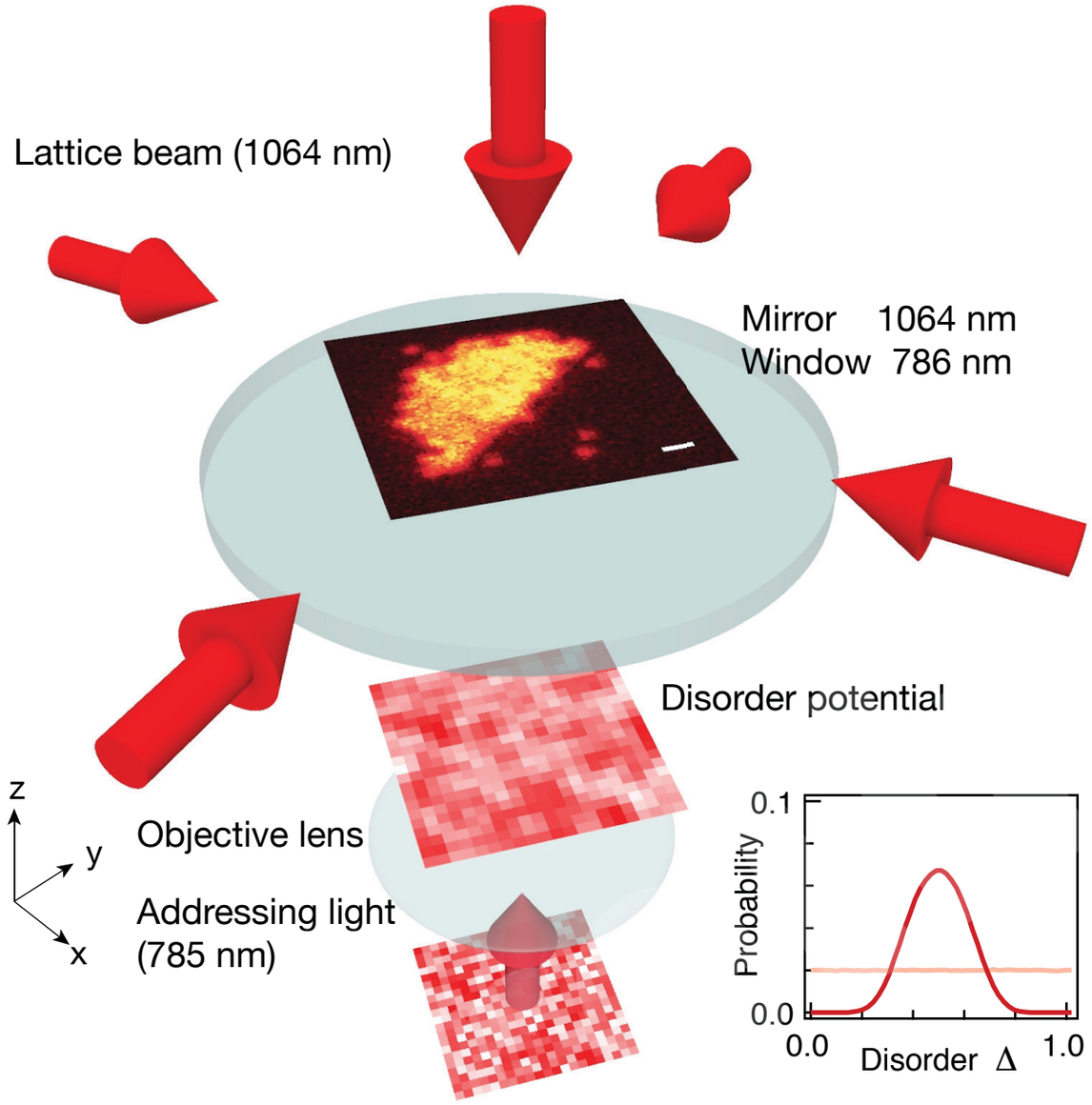
Systematic Analysis



Disorder strength $\Delta = 5J$

Probing the MBL Transition via Domain Wall Dynamics

Domain Wall Dynamics in Disorder

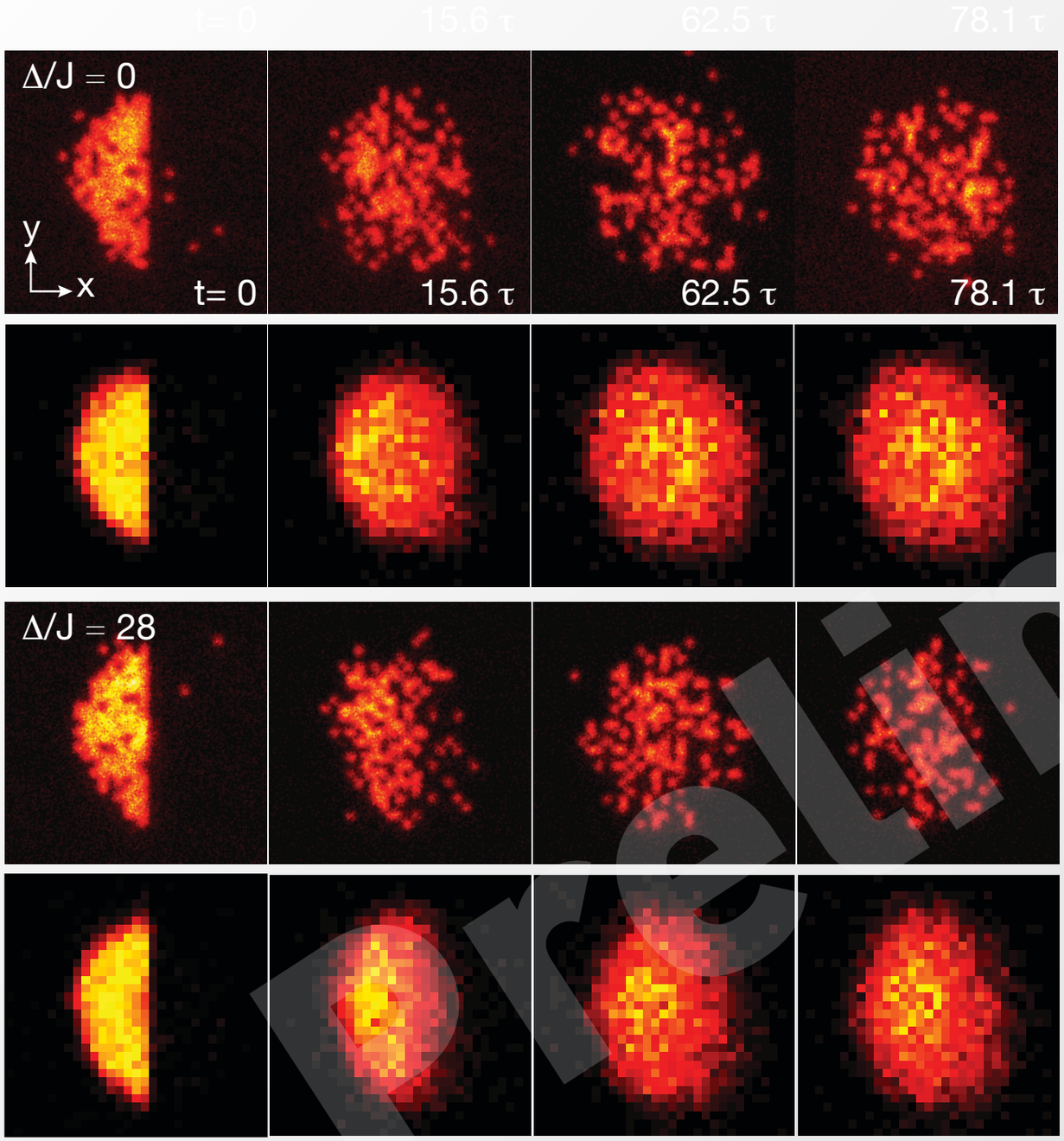


2D interacting bosons in disorder

Parameters: U/J ~ 20

true 2D (correlated) disorder

Time Evolution of Domain Wall in Disorder



$$\Delta/J = 0$$

System spreads over entire system size (thermalizing)

$$\Delta/J = 28$$

Domain wall gets stuck! (non-thermalizing)

So far: good qualitative and in parts quantitative understanding!

- MBL for different dimensionalities? 1D/2D/3D - Disorder Dimension
- **Coupling to outside world** - Photon Scattering destruction of MBL?
- Optical Conductivity - Ergodic vs MBL phase
- Local fluctuation measurements with Quantum Gas Microscopes
- Measuring **localization length**? dynamical (domain walls)? impurities?
- Critical slowing down?
- Entanglement Entropy growth?
- MBL in driven systems

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