

Many-Body Localisation from an Exp. Ultracold Atom Perspective

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

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

Theory Collaboration: E. Altman, M. Fischer, R. Vosk, D. Huse, V. Kemani



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
- Anderson & MBL in Driven Systems

2

Evidence for Many-Body Localisation

Phase Transition 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 [PRL in press]

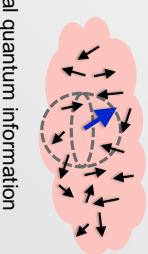


MBL

Thermalization



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



Many-body localization

Local quantum information persists indefinitely.

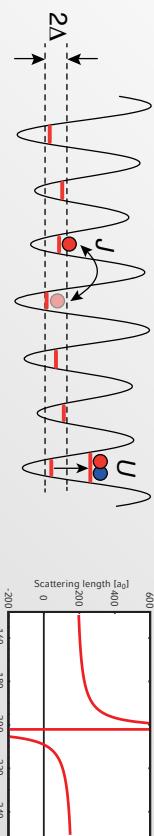
Classical hydro description of remaining slow modes (conserved quantities, and order parameters).

Need a fully quantum description of the long time dynamics!

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

Motivation

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



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

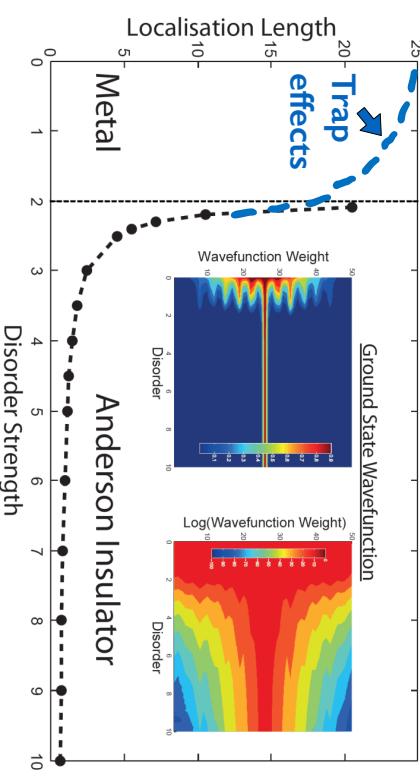
- Homogenous tunneling but quasi-random onsite energies
- α is the incommensurability ratio, irrational; in the experiment ≈ 0.721

All eigenstates extended for $\Delta/J < 2$
All eigenstates exponentially localized for $\Delta/J > 2$

G. Roati et al. Nature (2008)



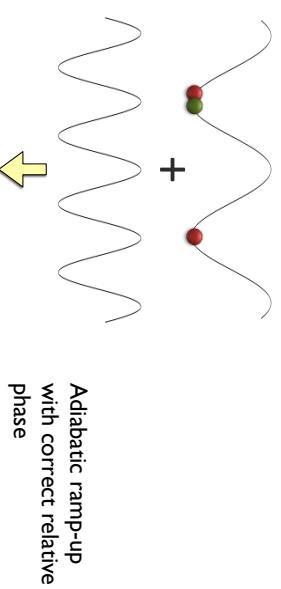
Single Particle Orbitals



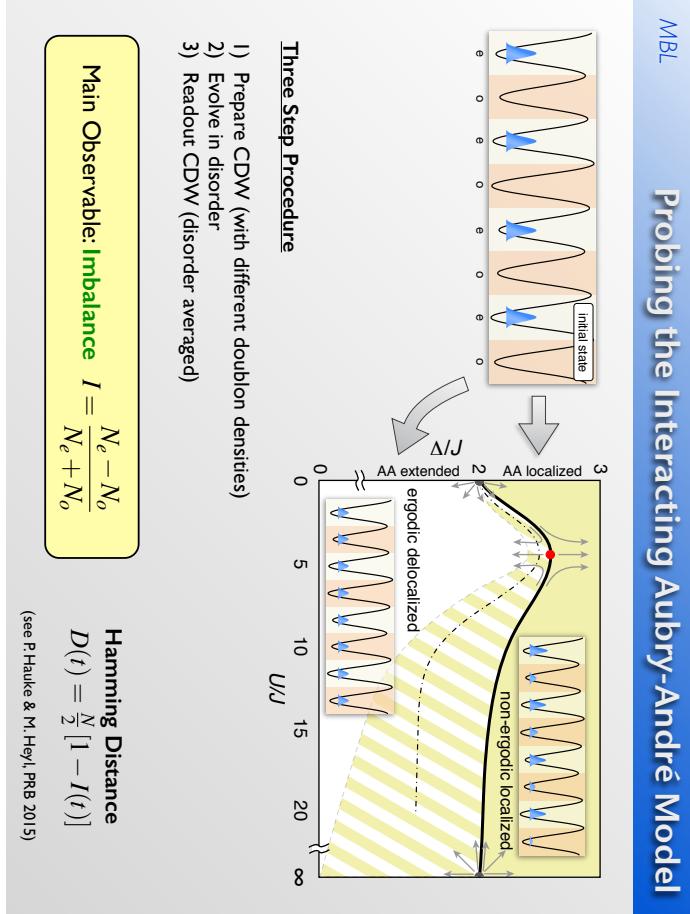
$$\xi_{sp} = \ln^{-1}(\Delta/2J)$$

Preparing the CDW Wave

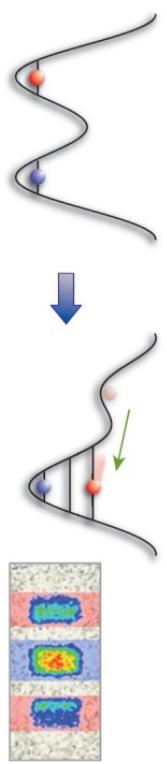
Superimpose two lattices, with: $\lambda_l = 2\lambda_s$ (here 532 nm & 1064 nm)



All particles localised
on even sites >95%



Site resolved even-odd detection

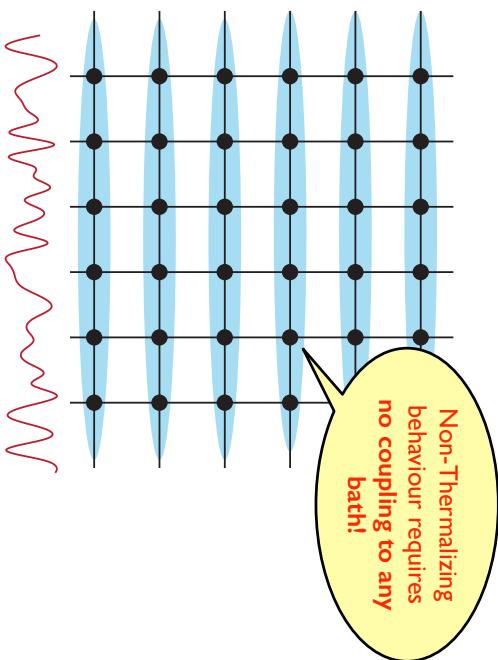


Merge wells in presence of tilt
Band mapping
Absorption imaging after TOF

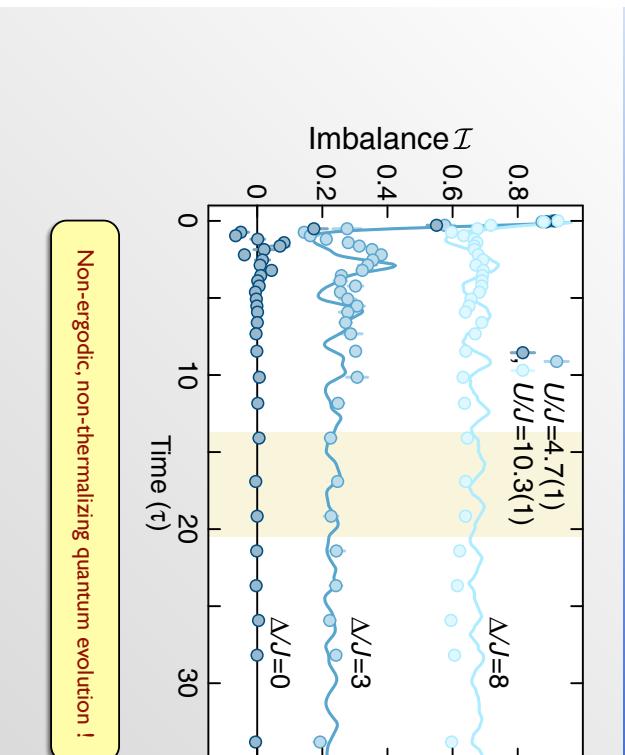
$$I = \frac{N_e - N_o}{N_e + N_o}$$



Experimental Setup 1 D



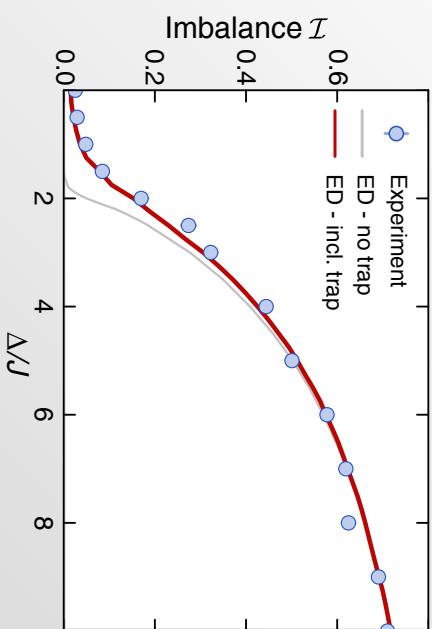
Time Evolution

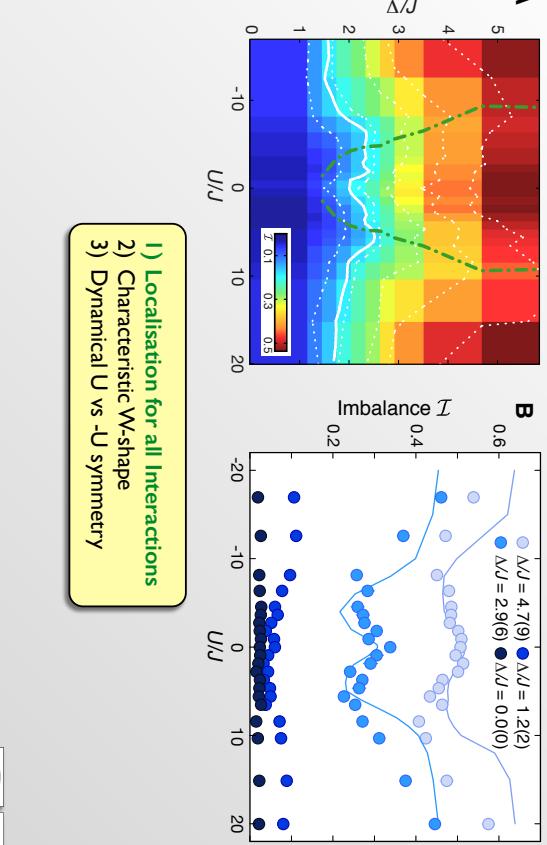


Non-ergodic, non-thermalizing quantum evolution !

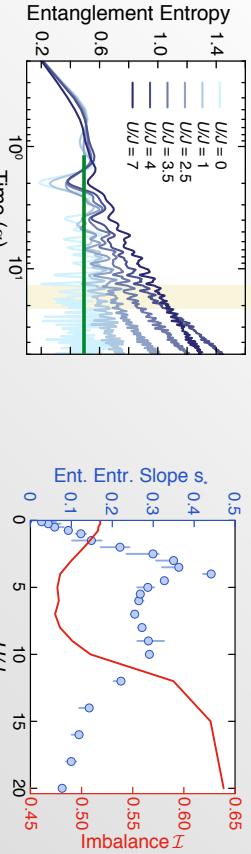


U=0 - Anderson Localization





Numerics - Entanglement Entropy

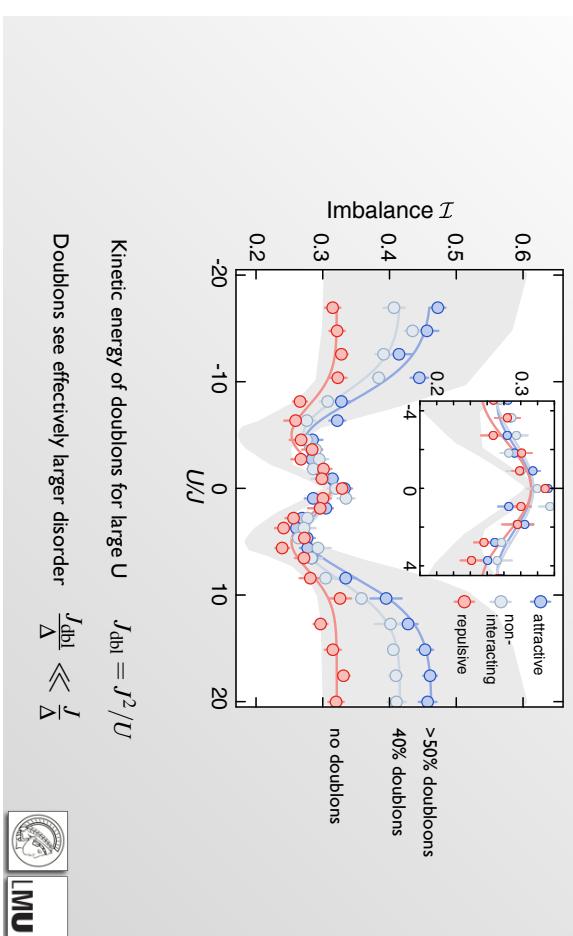


Maximum in entanglement entropy slope connected to minimum of imbalance

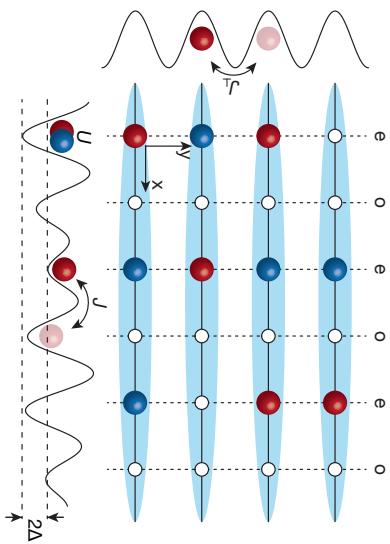
DMRG Simulations $\Delta/J = 5$

$$S = S_0 + s^* \log(t/\tau)$$

Changing Dimensionality & Very Long Time Behaviour

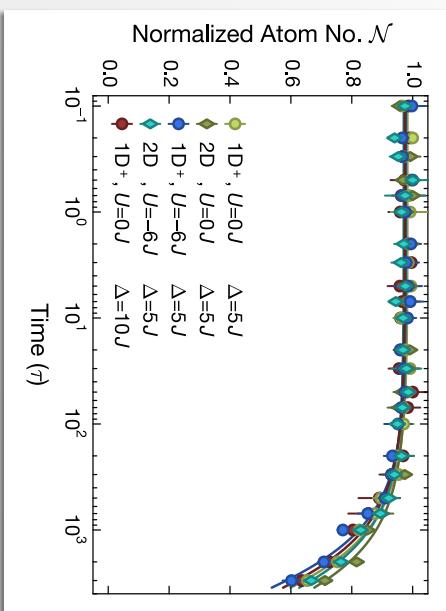


Experimental Setup 2D



Dimensionality

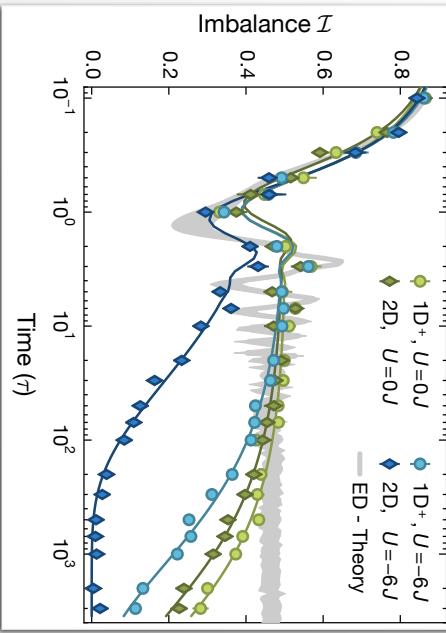
Particle Number Lifetime



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

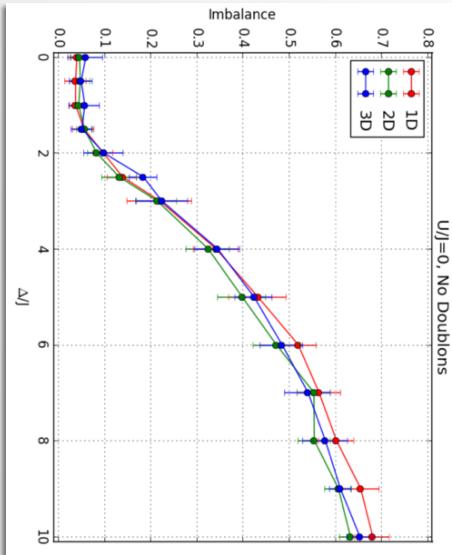
Dimensionality

Destruction of MBL



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

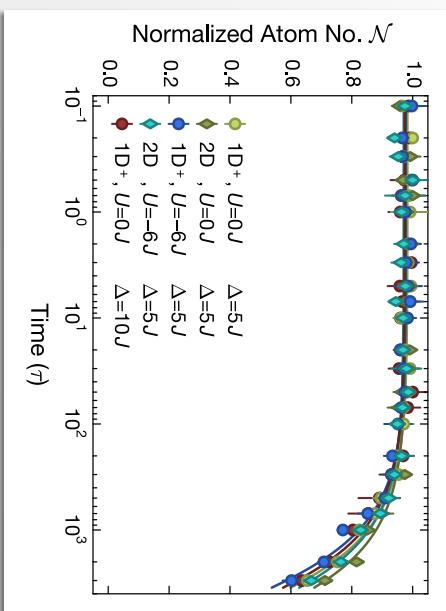
1d Quasiperiodic Disorder - different couplings along y & z



U=0 - Dimensionality

Dimensionality

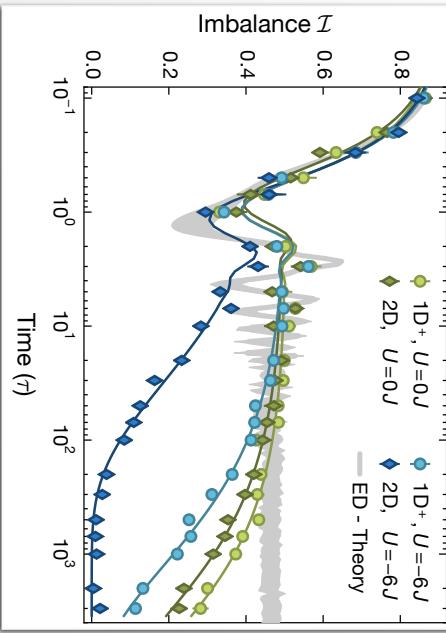
Particle Number Lifetime



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

Dimensionality

Destruction of MBL



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

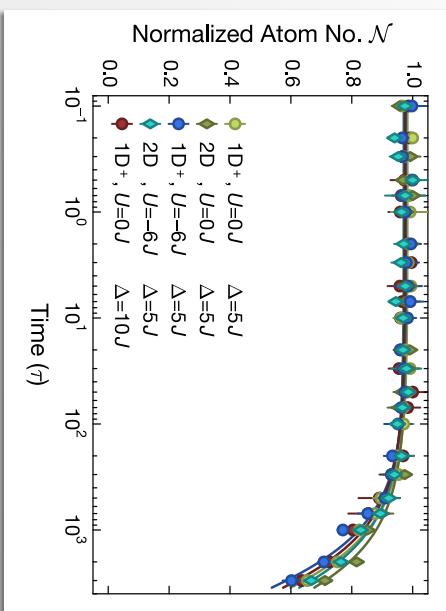
Dimensionality

Particle Number Lifetime

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

Dimensionality

Particle Number Lifetime



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

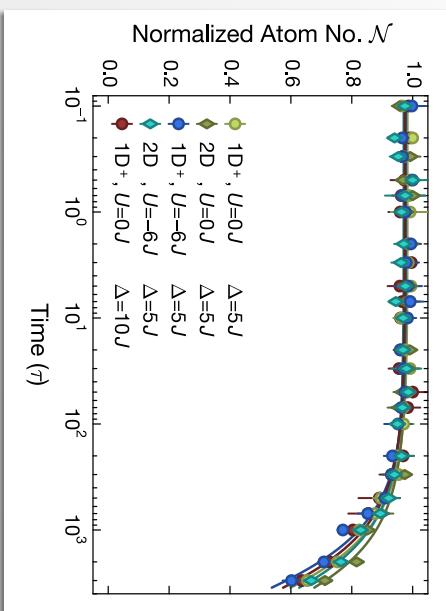
Dimensionality

Particle Number Lifetime

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

Dimensionality

Particle Number Lifetime

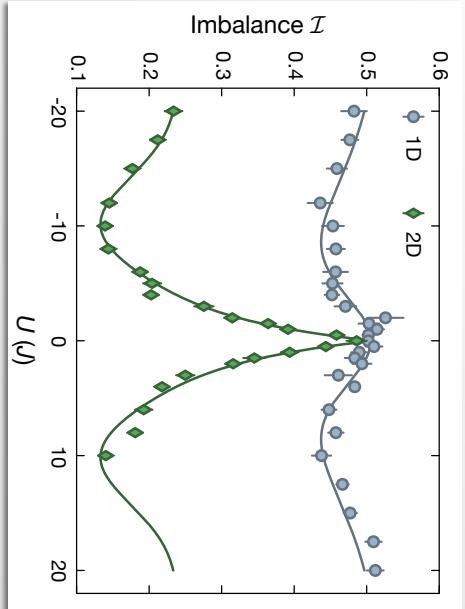


Atom lifetime enables us to **observe dynamics up to 2000-4000 τ !**

Destruction of MBL in Higher Dimensions

MBL

Systematic Analysis

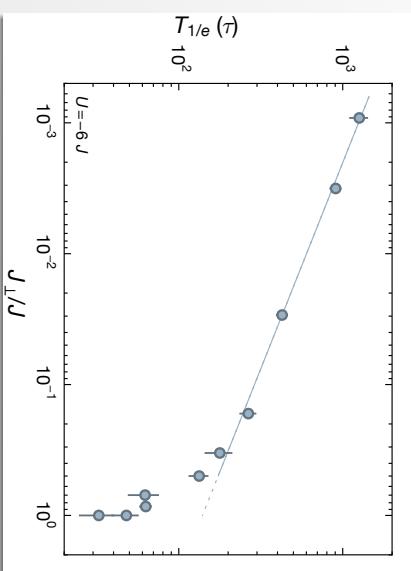


Id Quasiperiodic Disorder - different couplings along y & z

MBL

MBL Lifetime Limit

$$\Delta = 5J$$

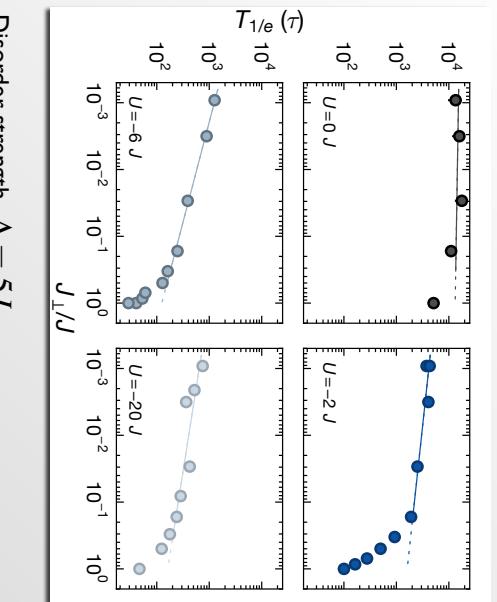


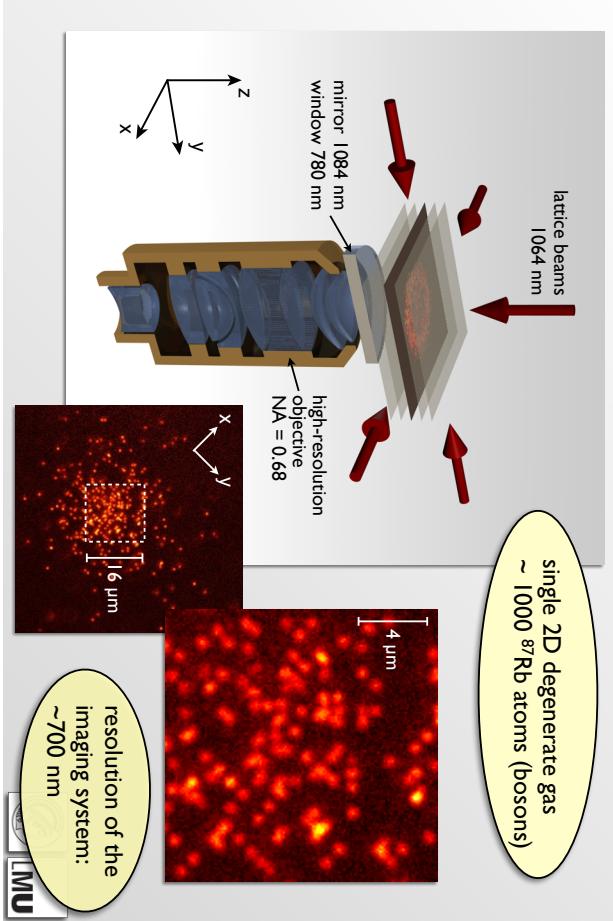
MBL lifetime limited only by residual transverse coupling.



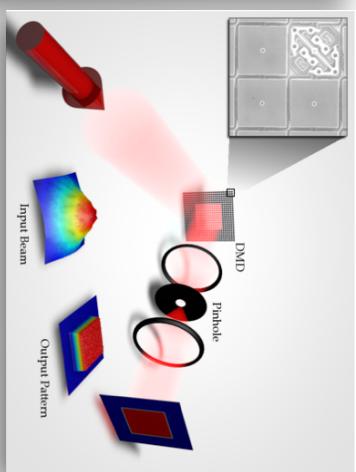
Preliminary

Evidence for a Many-Body Localisation Phase Transition in 2D





Arbitrary Light Patterns

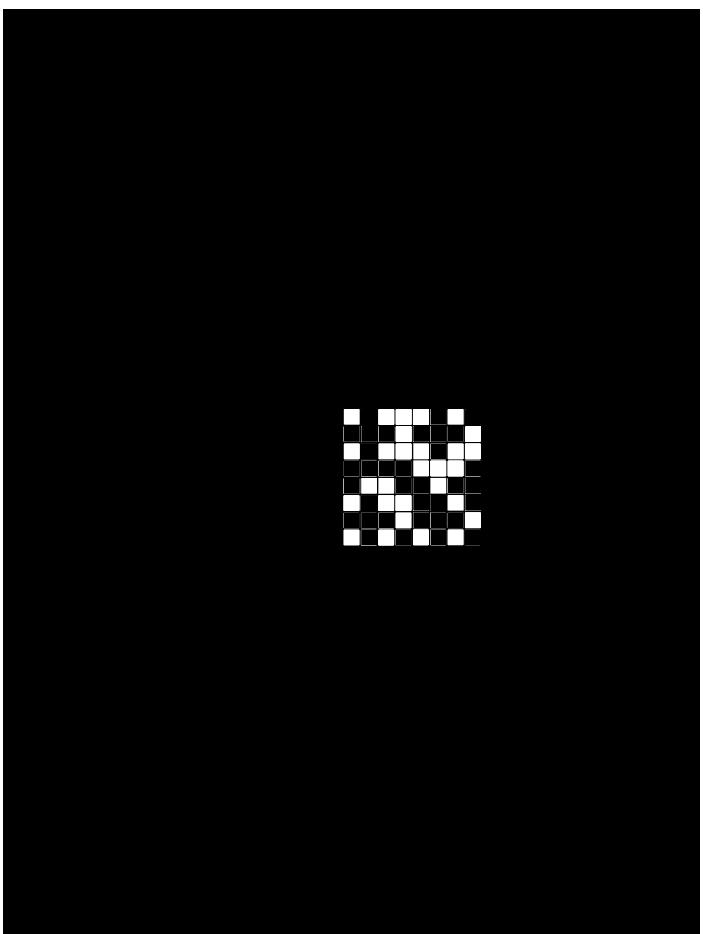
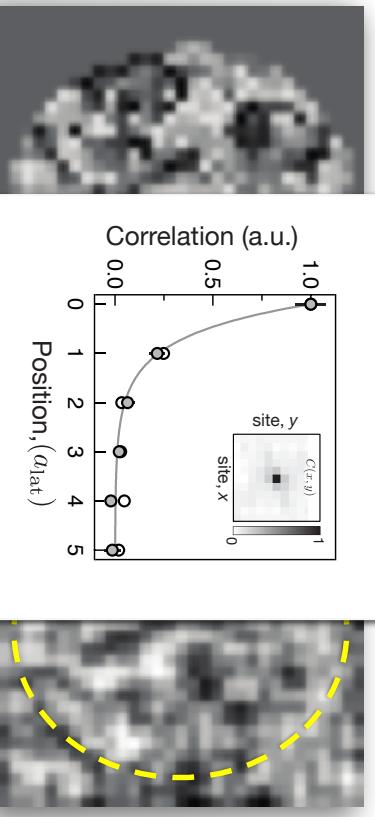


Quantum wires Exotic lattice

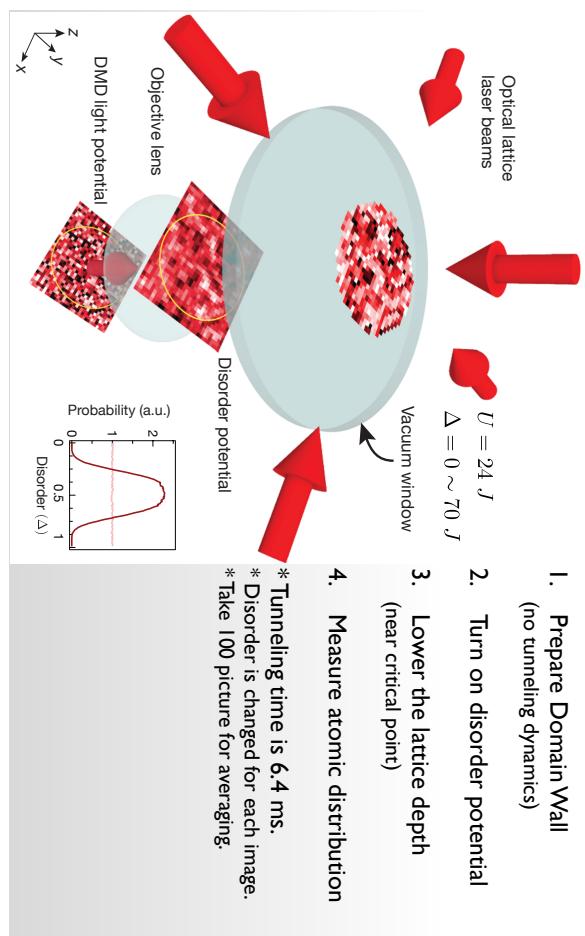
Excellent characterization of disorder !!

Measurement after objective

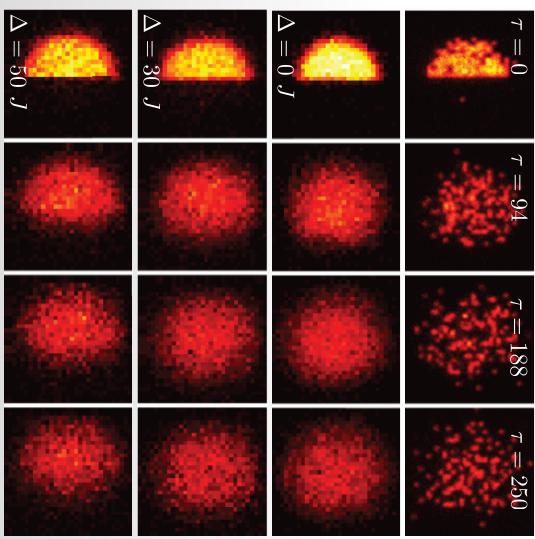
Disorder Potential



System Summary



Domain Wall Dynamics

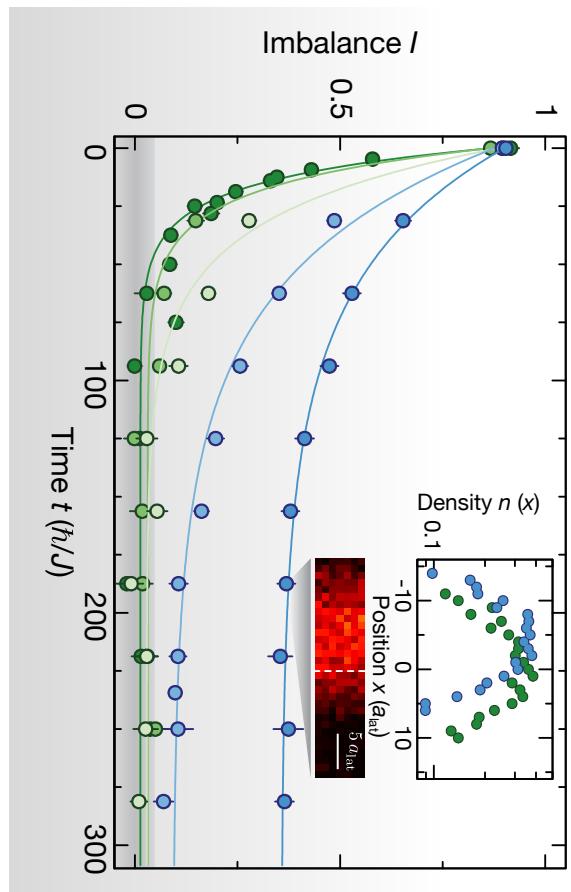


Without disorder
Initial energy =
Temperature after long
time evolution
(thermalized)

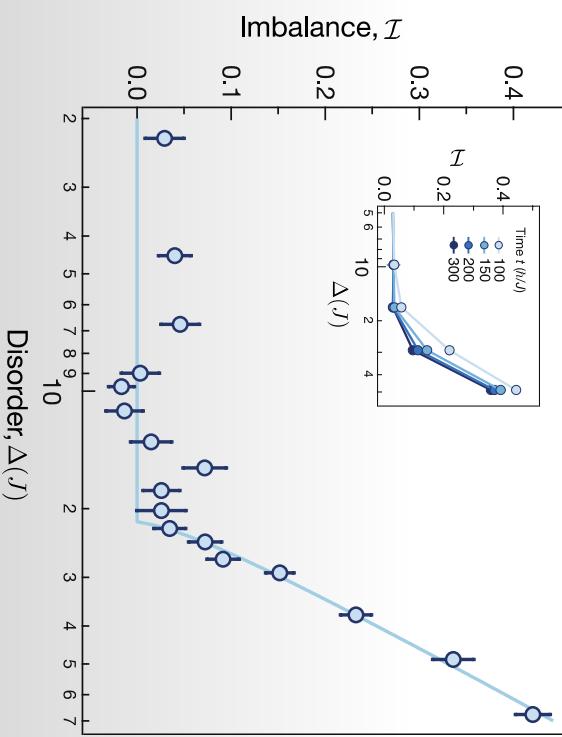
With disorder

Domain wall is stucked!
(non-thermalized)

Imbalance of domain wall

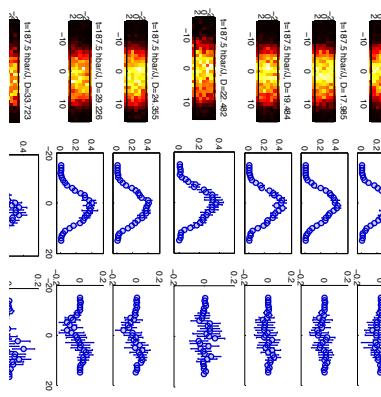


Delocalization-to-Localization

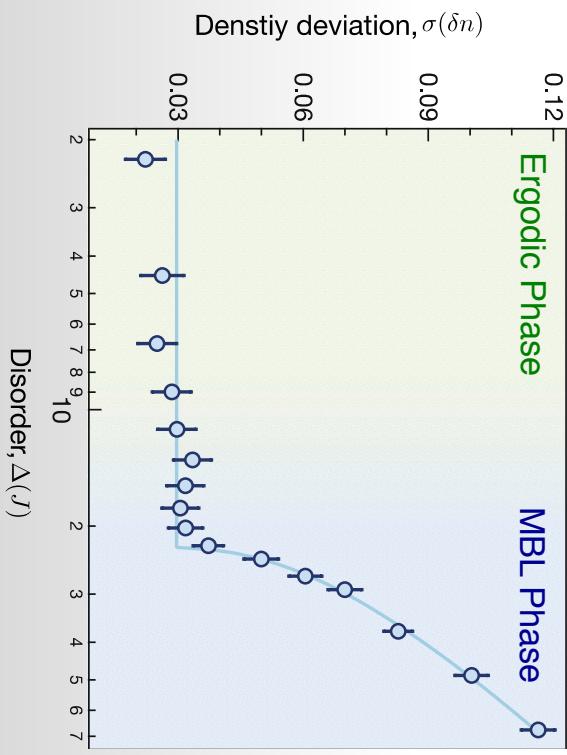




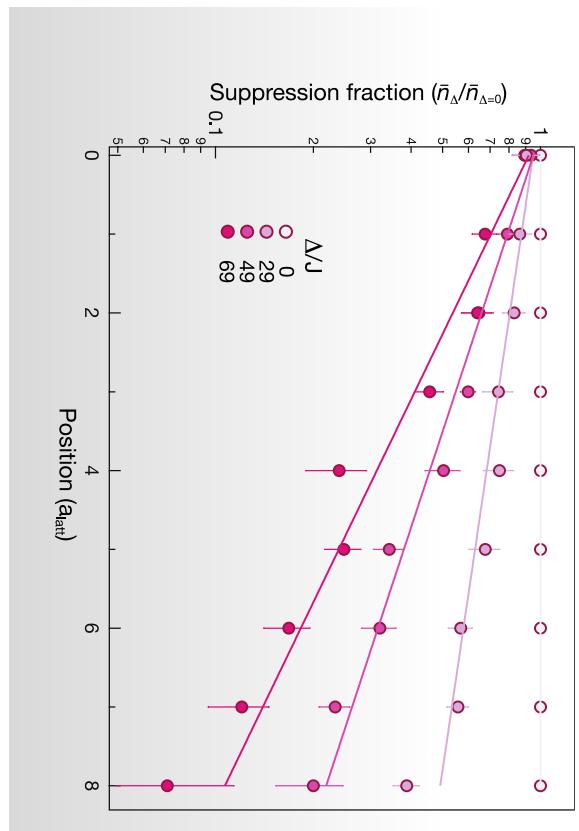
Domain Wall
distribution after
200 tunnelling times.



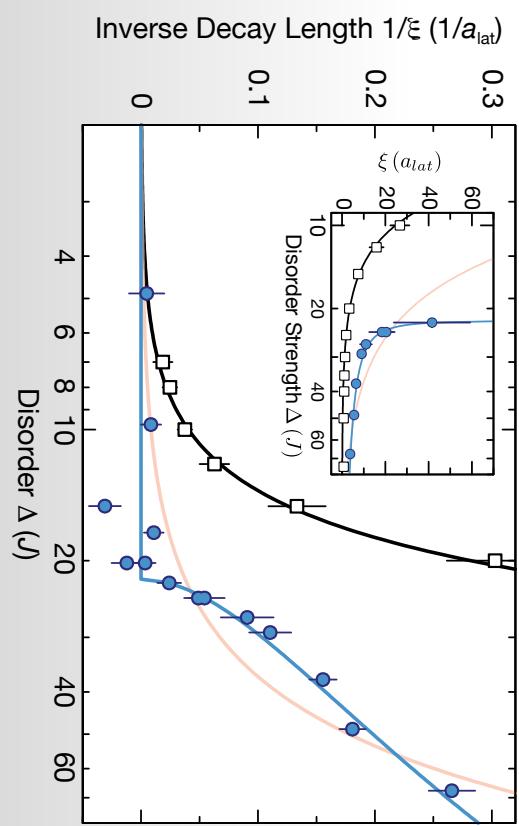
Delocalization-to-Localization



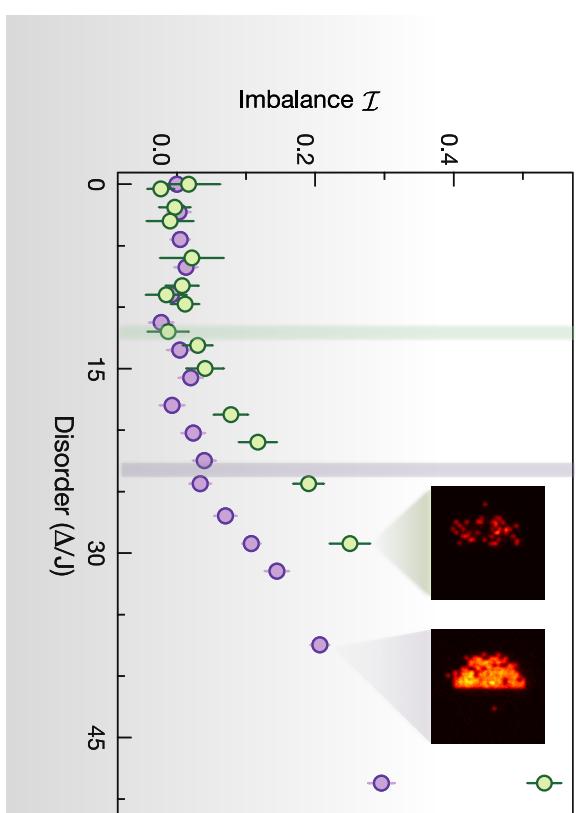
Disorder Effect in Real Space II



Diverging Length Scale



Role of Interaction



MBL

s

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



Groups of: E. Altman, I. Bloch,
J. Dalibard & P. Zoller

