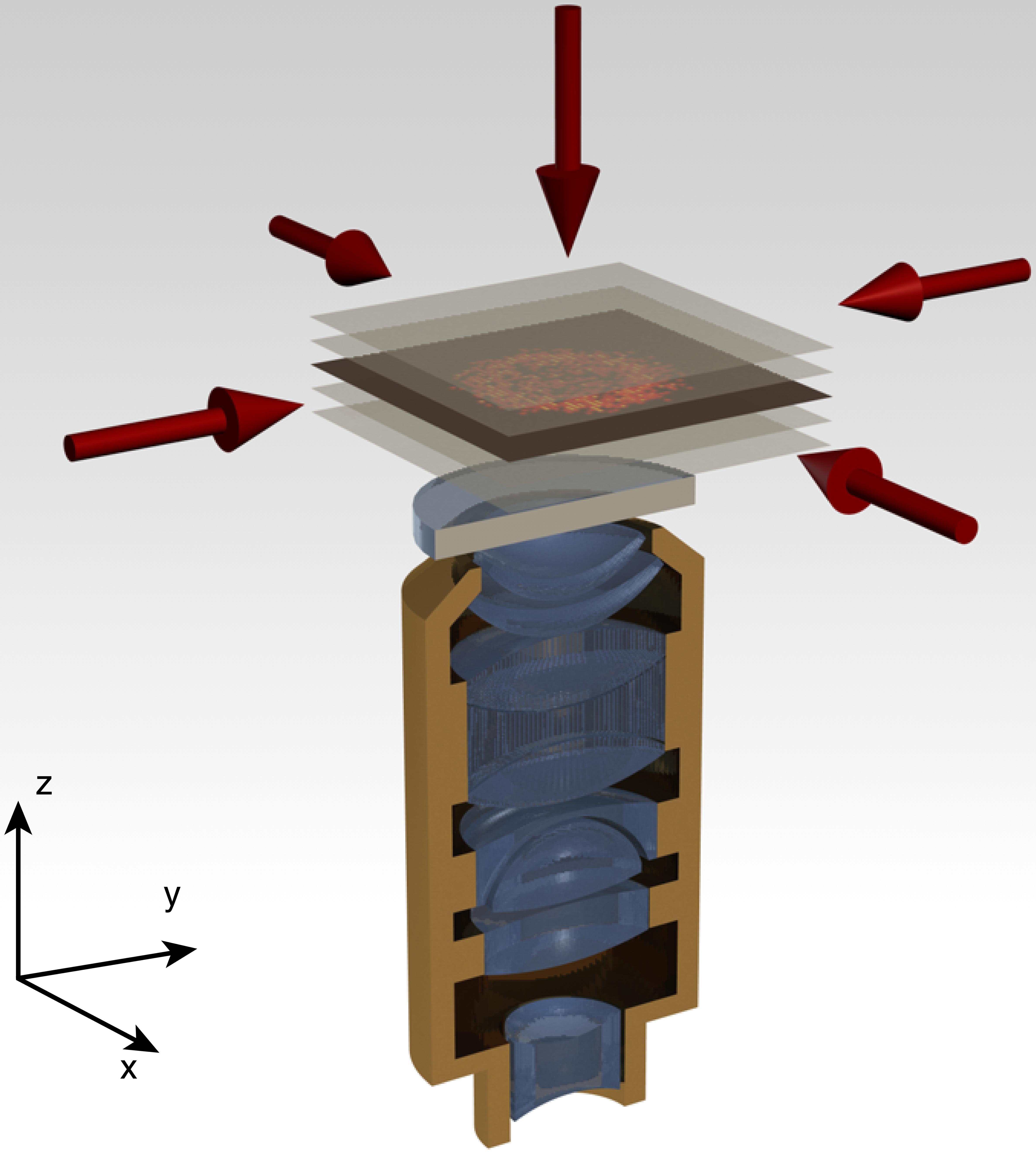
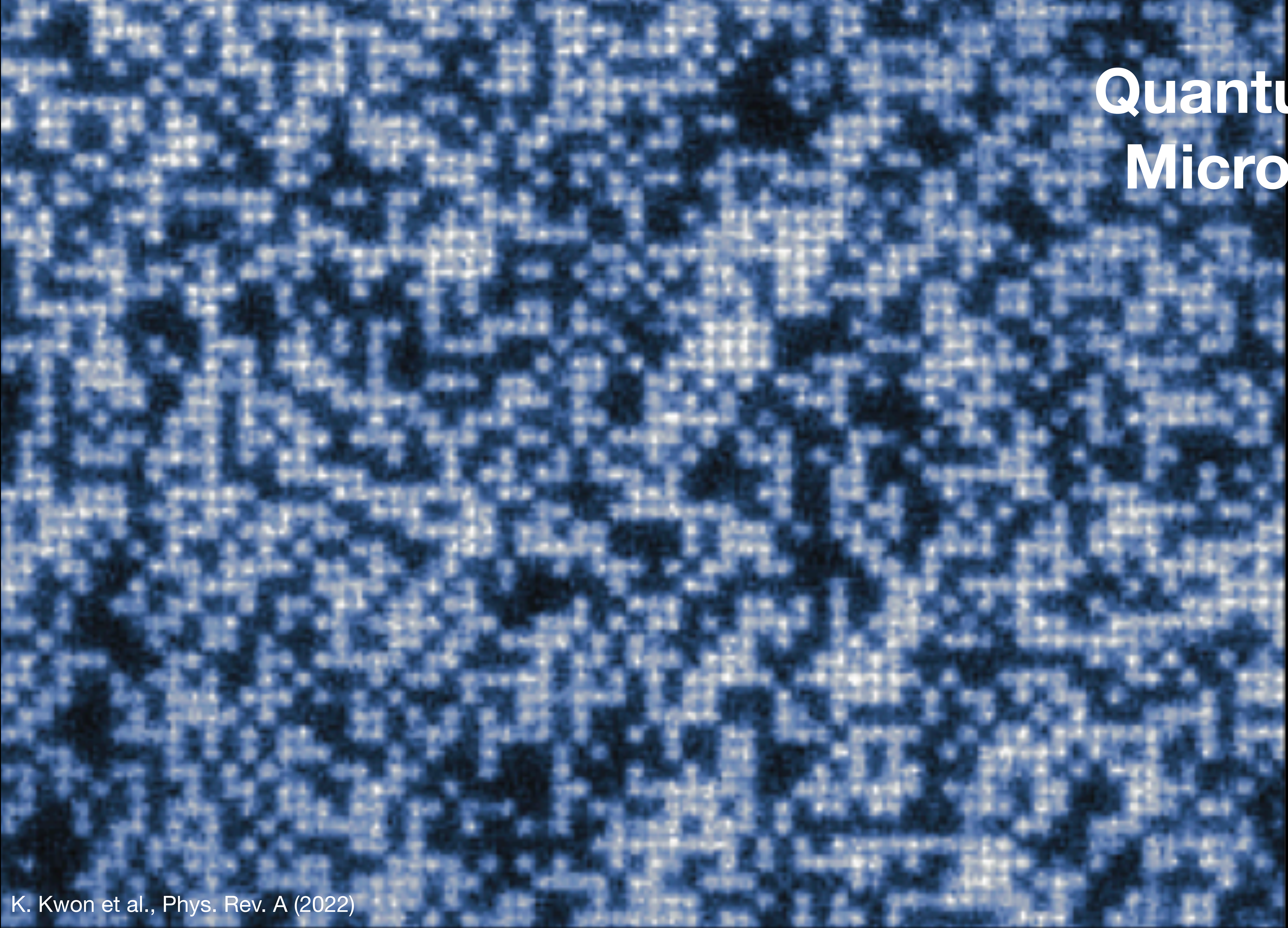
Quantum Gas Microscopy



Quantum Gas Microscopy

W. Bakr et al., Science (2010)
J. Sherson et al., Nature (2010)



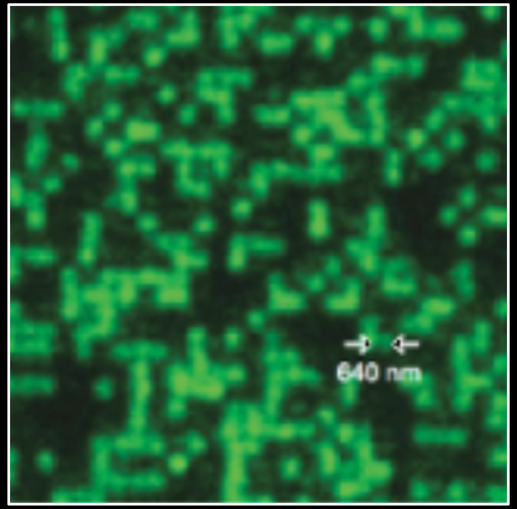
Quantum Gas Microscopy

K. Kwon et al., Phys. Rev. A (2022)

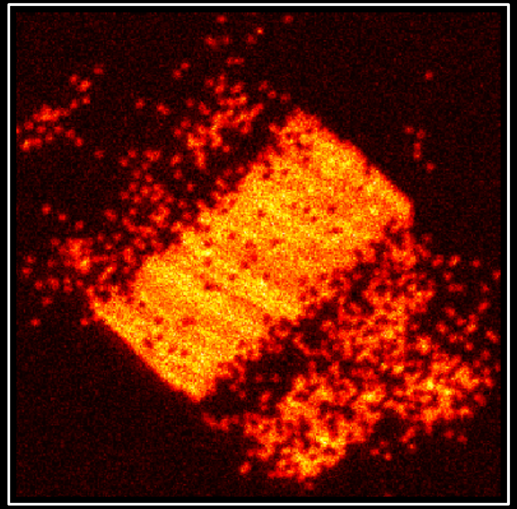
W. Bakr et al., Science (2010)
J. Sherson et al., Nature (2010)

Quantum gas microscopes

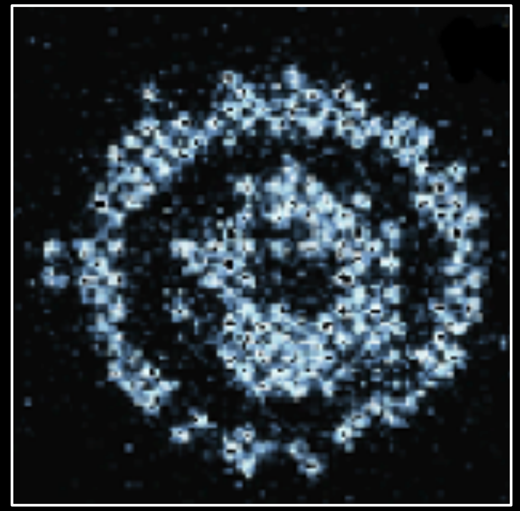
BOSONS



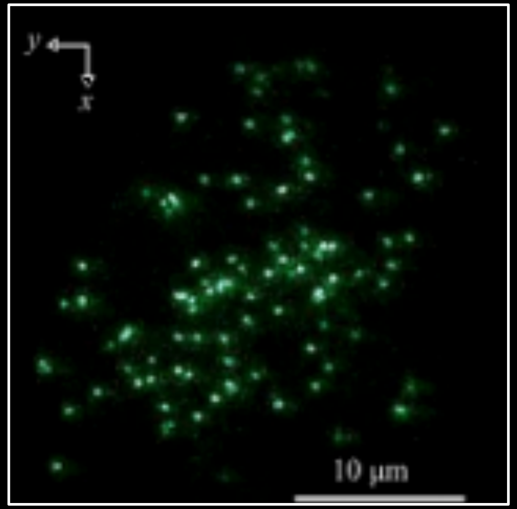
Harvard, ^{87}Rb



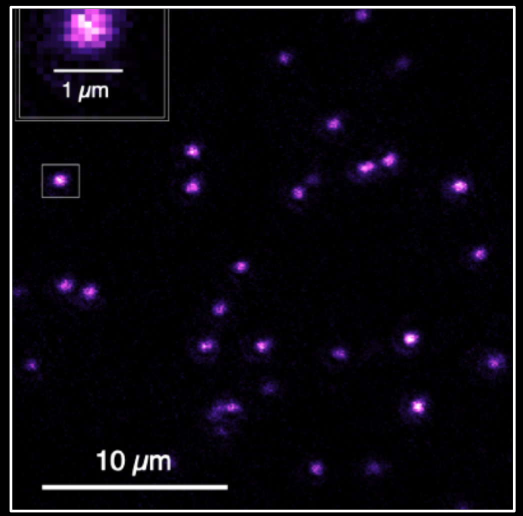
Munich, ^{87}Rb



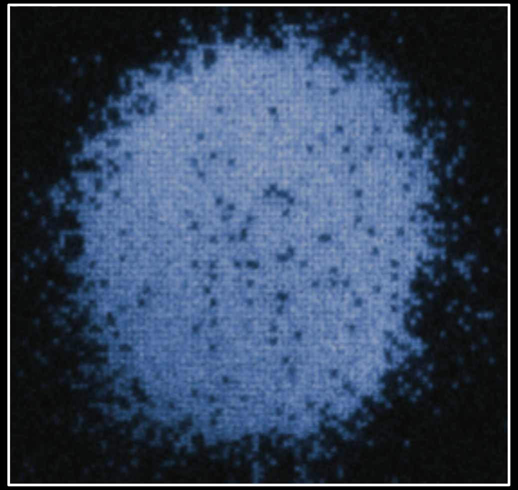
Tokyo, ^{174}Yb



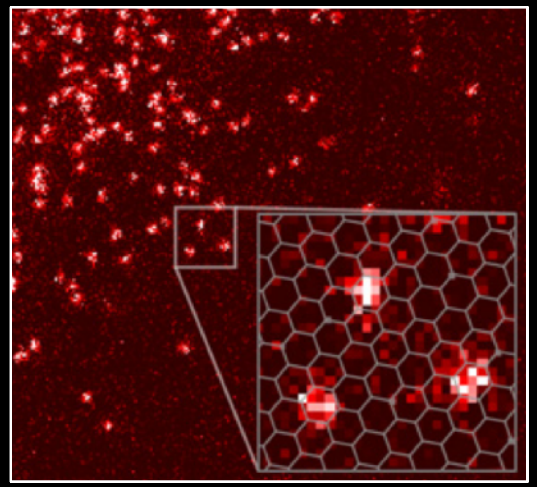
Kyoto, ^{174}Yb



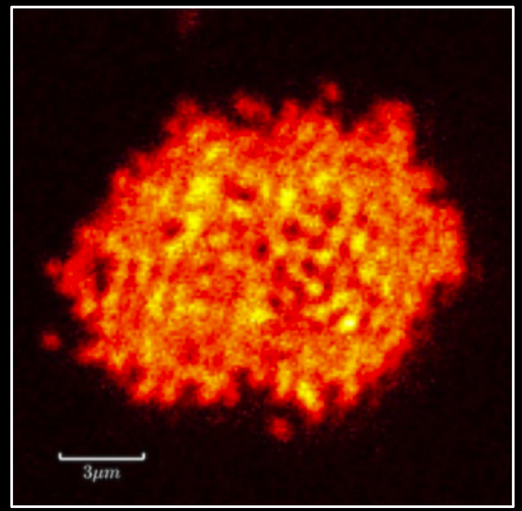
Aarhus, ^{87}Rb



KAIST, ^{7}Li

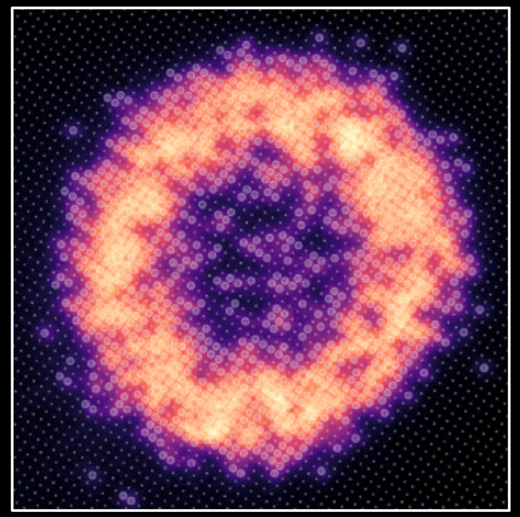


RIKEN, ^{87}Rb

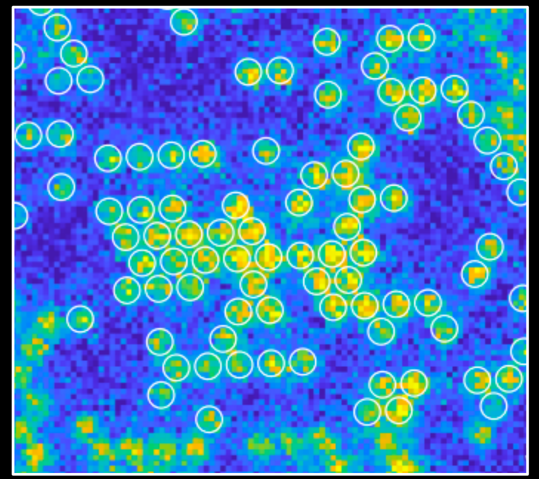


USTC, ^{87}Rb

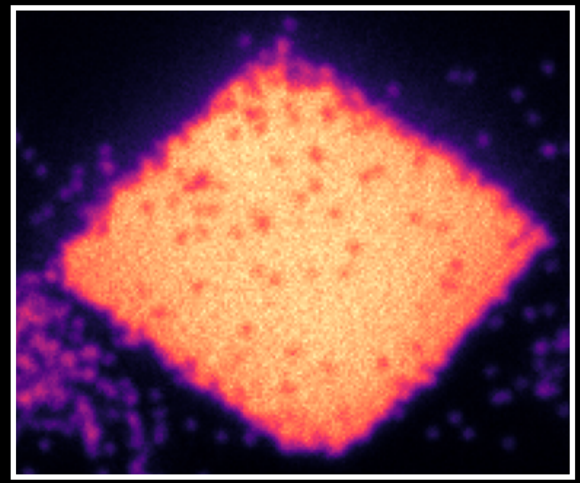
Harvard, ^{16x}Er



Munich, ^{133}Cs

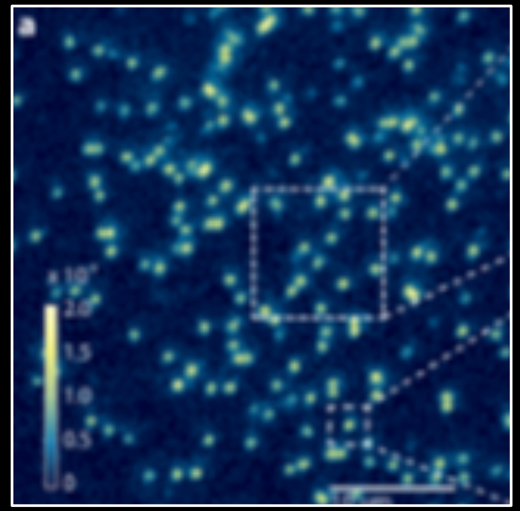


Chicago, ^{133}Cs

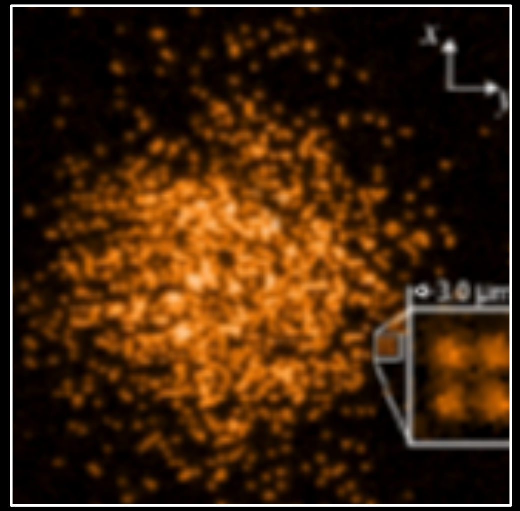


Munich, ^{133}Cs

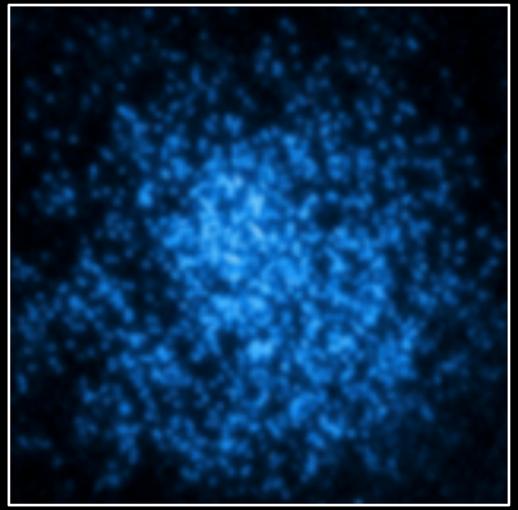
FERMIONS



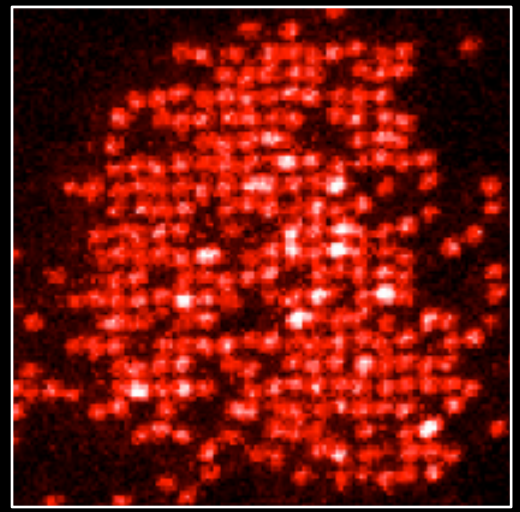
Glasgow, ^{40}K



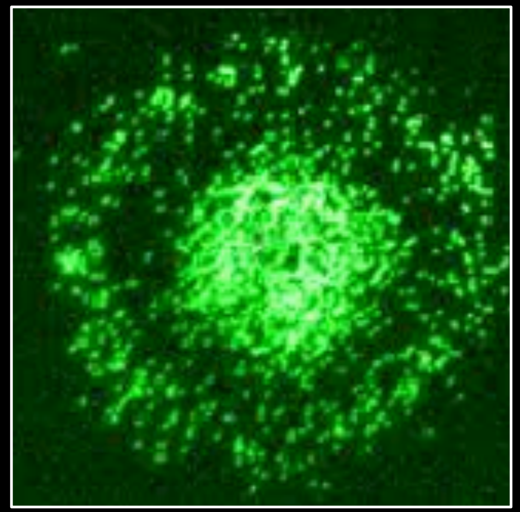
MIT, ^{40}K



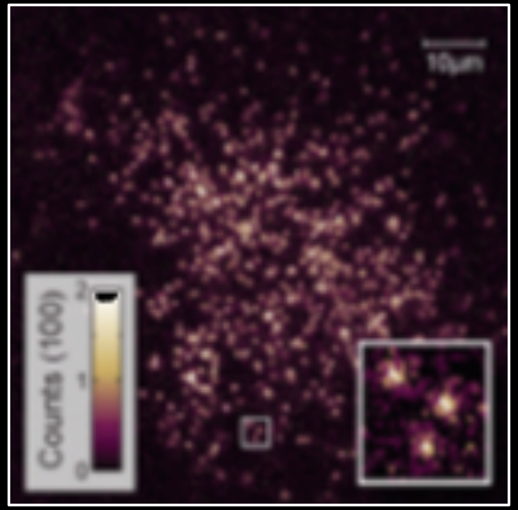
Harvard, ^{6}Li



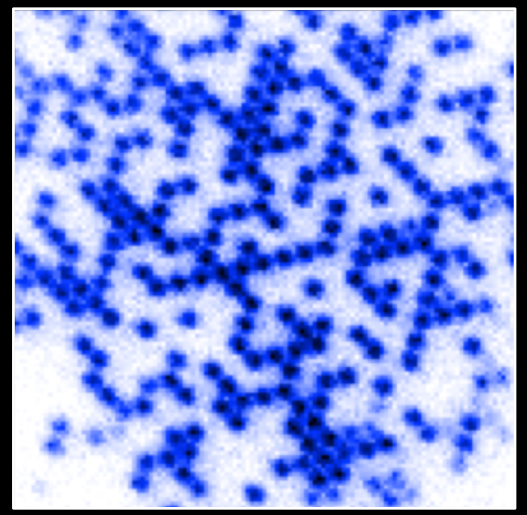
Munich, ^{6}Li



Princeton, ^{6}Li

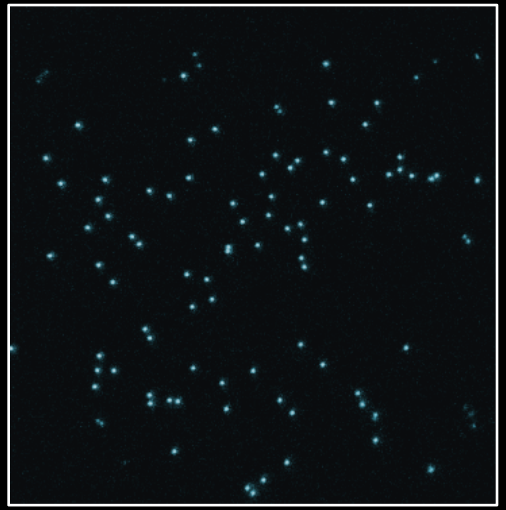


Toronto, ^{40}K



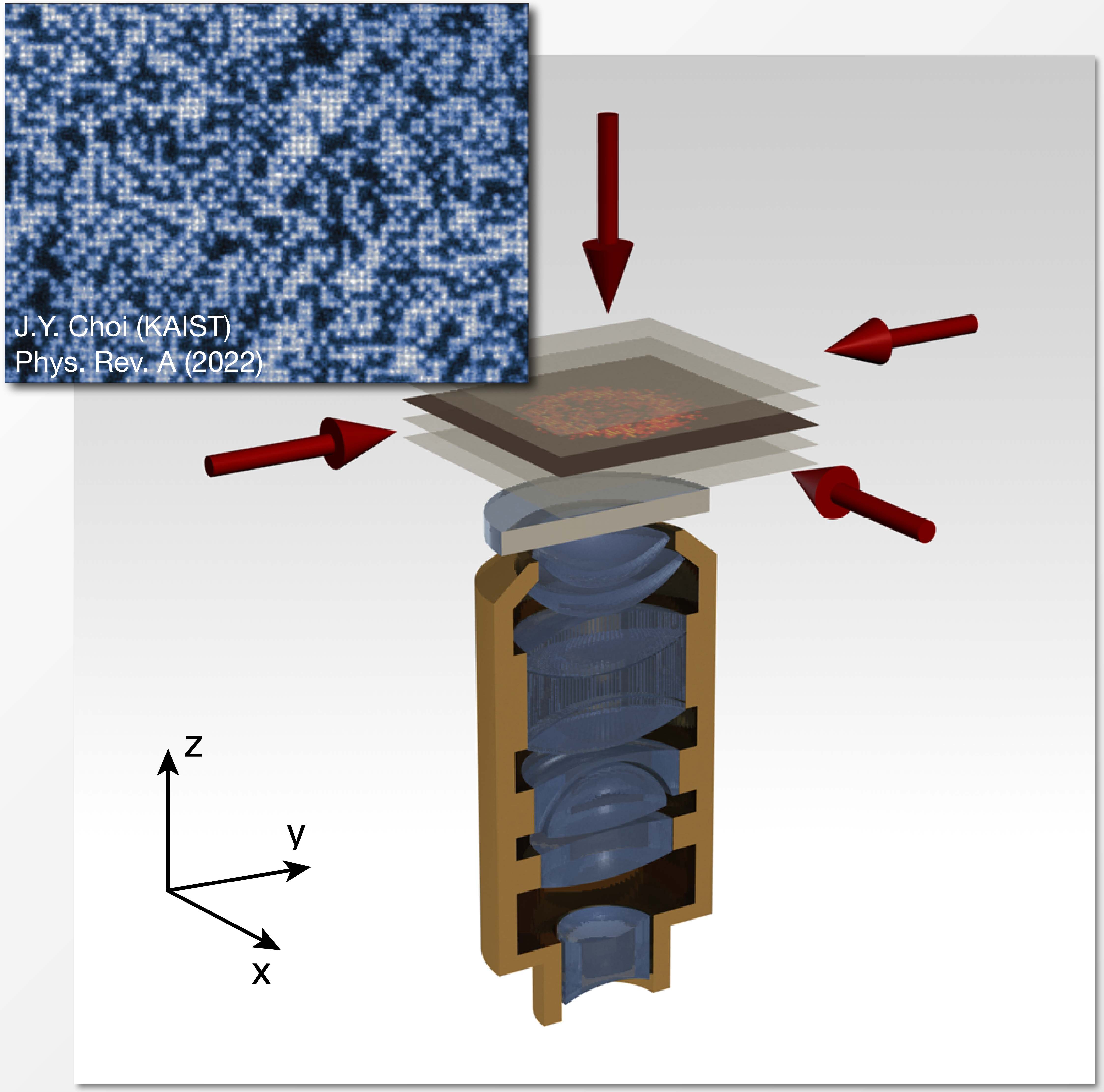
Virginia, ^{6}Li

MOLECULES

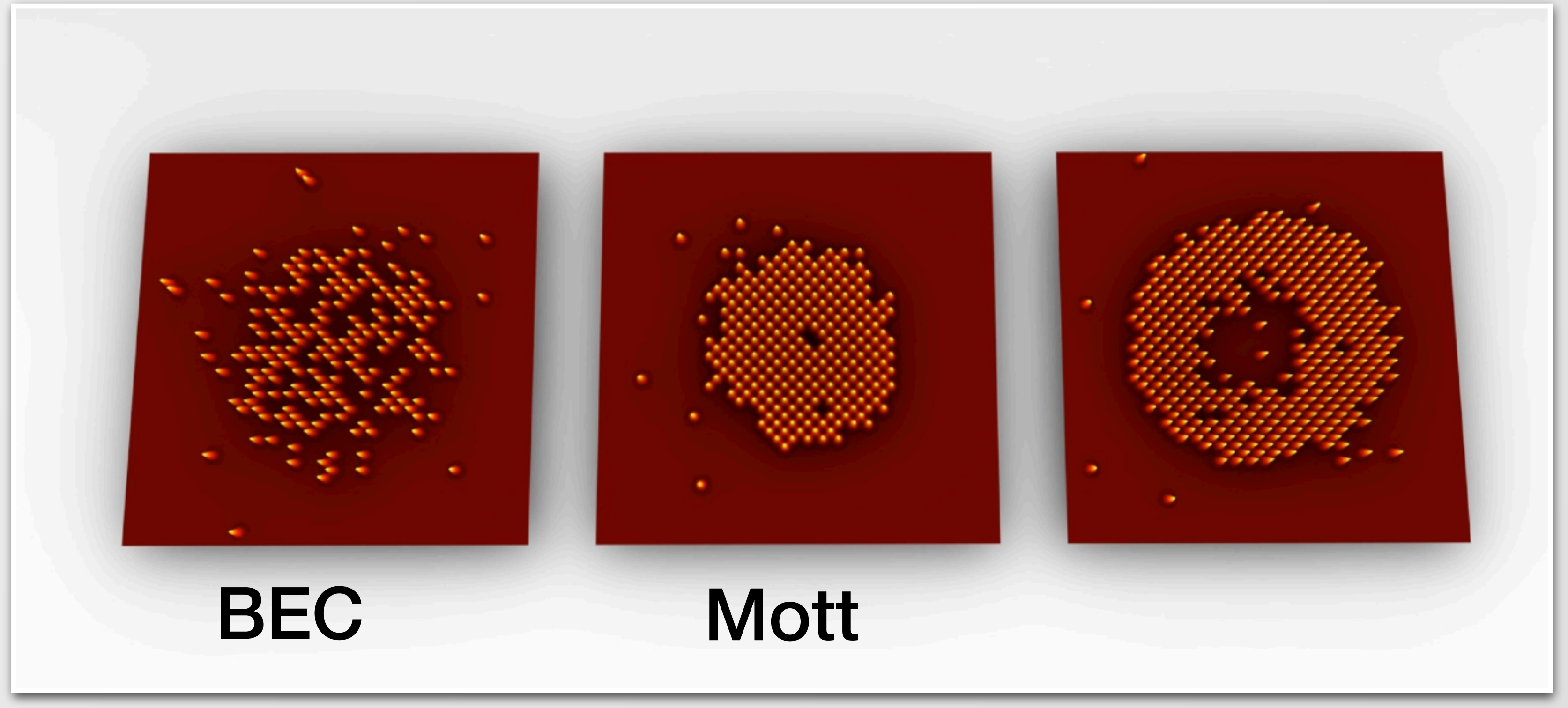


Princeton, NaRb

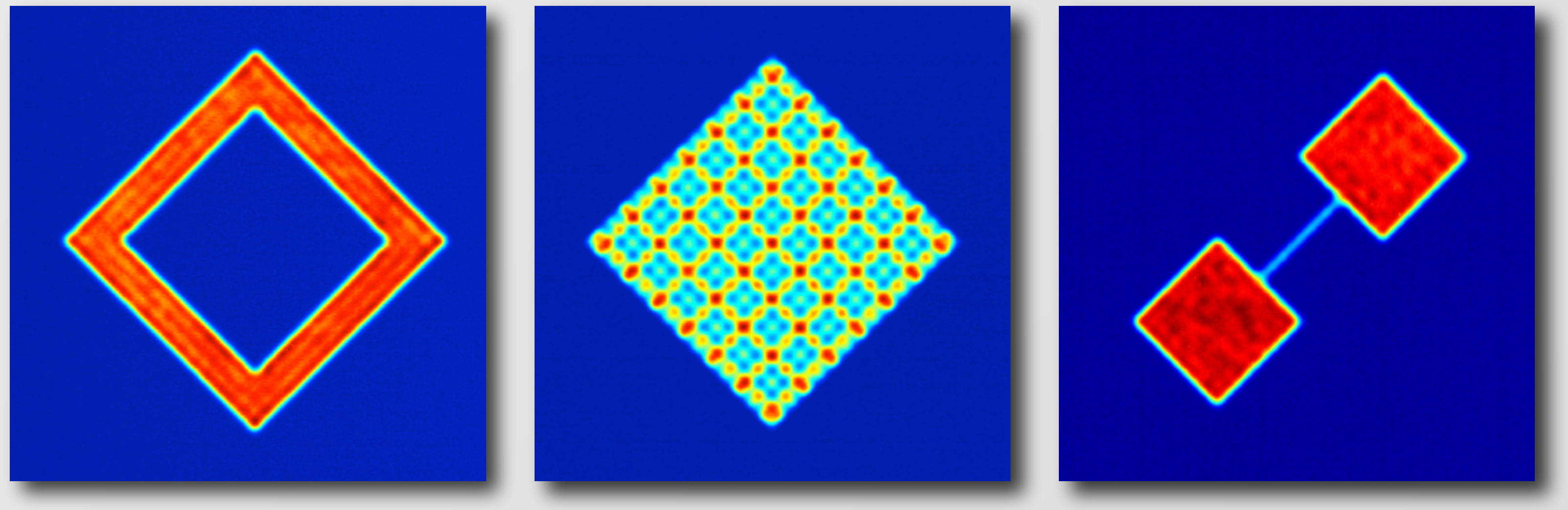
Quantum Gas Microscopy



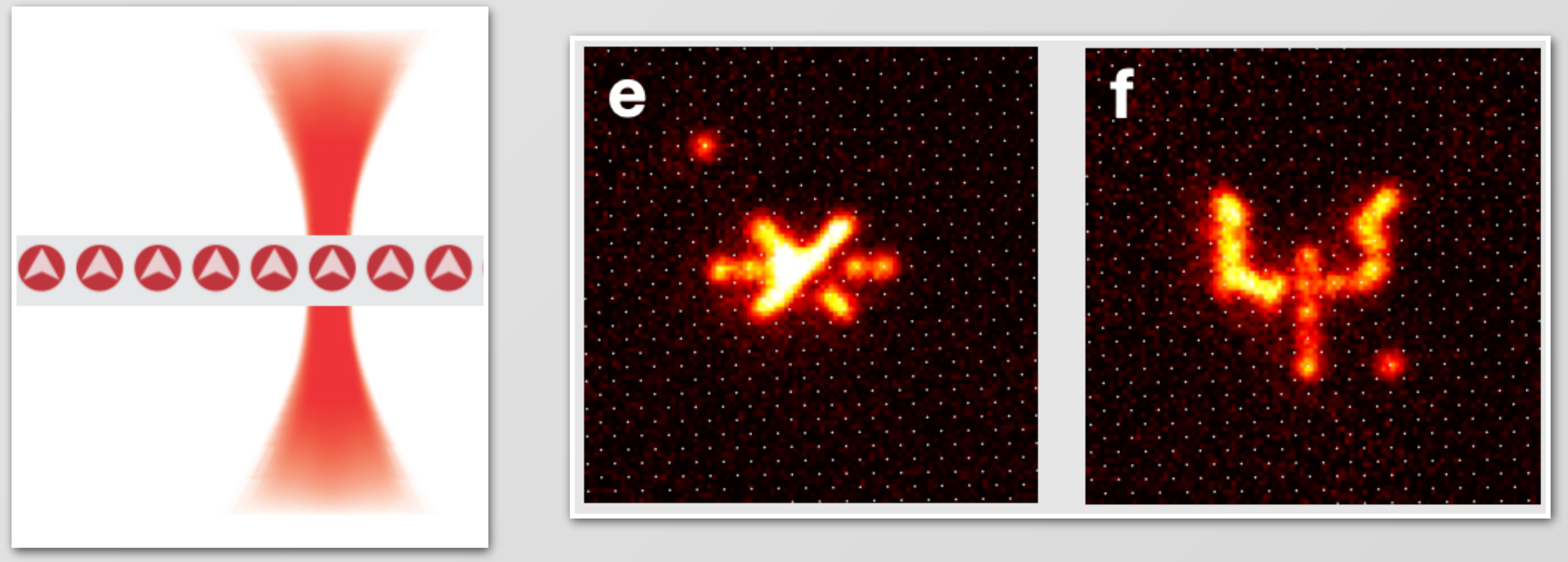
Single atom detection



Potential Engineering



Single Atom Adressing

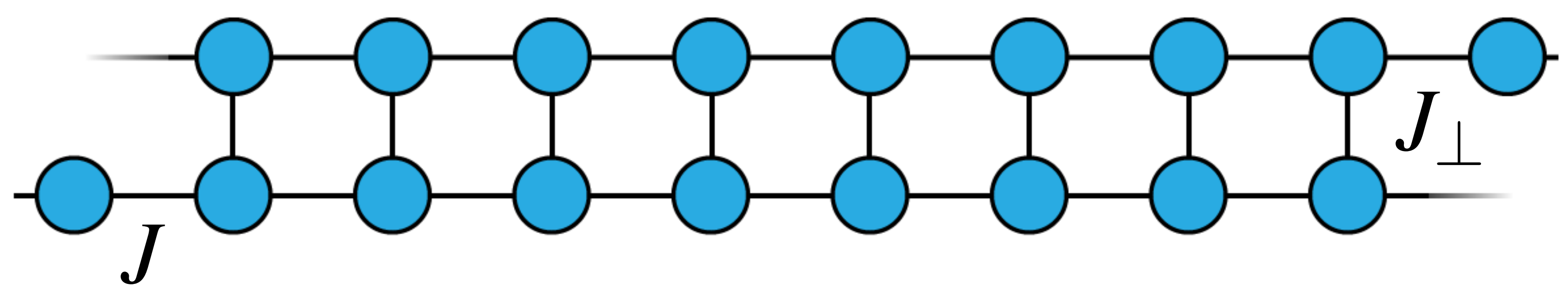


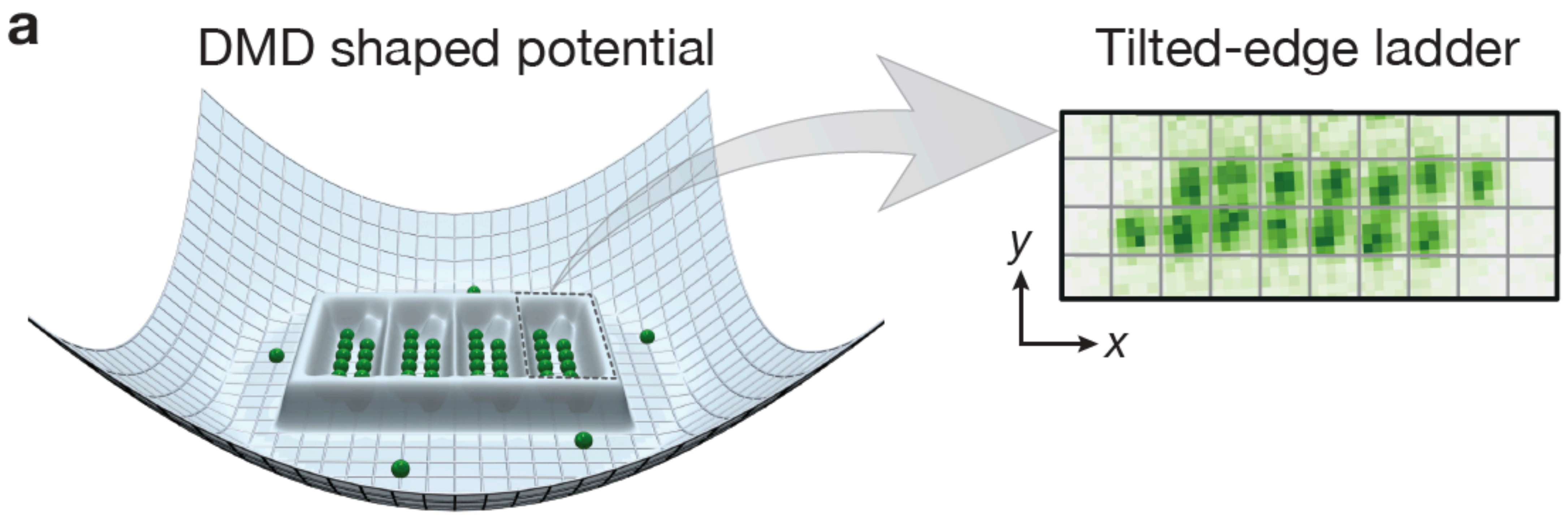
W. Bakr et al., Science (2010) & J. Sherson et al., Nature (2010)
Addressing: C. Weitenberg et al., Nature (2011)

Flexible Geometries and Large Sizes

Quantum Ladders with flexible edge geometries

(SPT Spin-1 Haldane Phase)





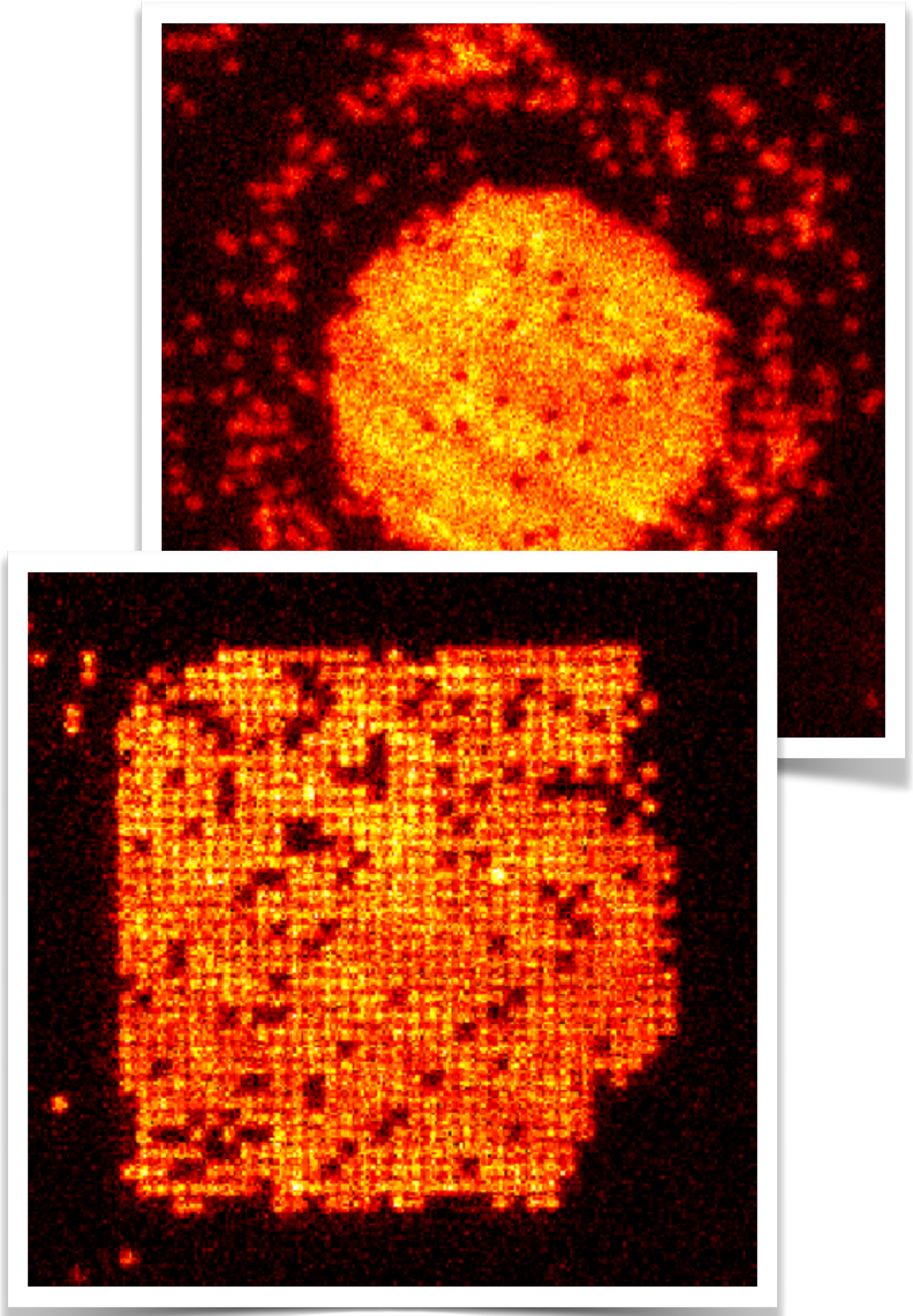
Fully tuneable coupling strengths +dimensionality +flux +frustration

P. Sompet *et al.* Nature **606,** 484 (2022)
Tweezer SPT: Léséluc *et al.* Science **365**, 6455 (2019)

Large Homogeneous 2D Systems

(2000-5000 atoms, filling 95-98%)

Cs experiment in collaboration with M. Aidelsburger

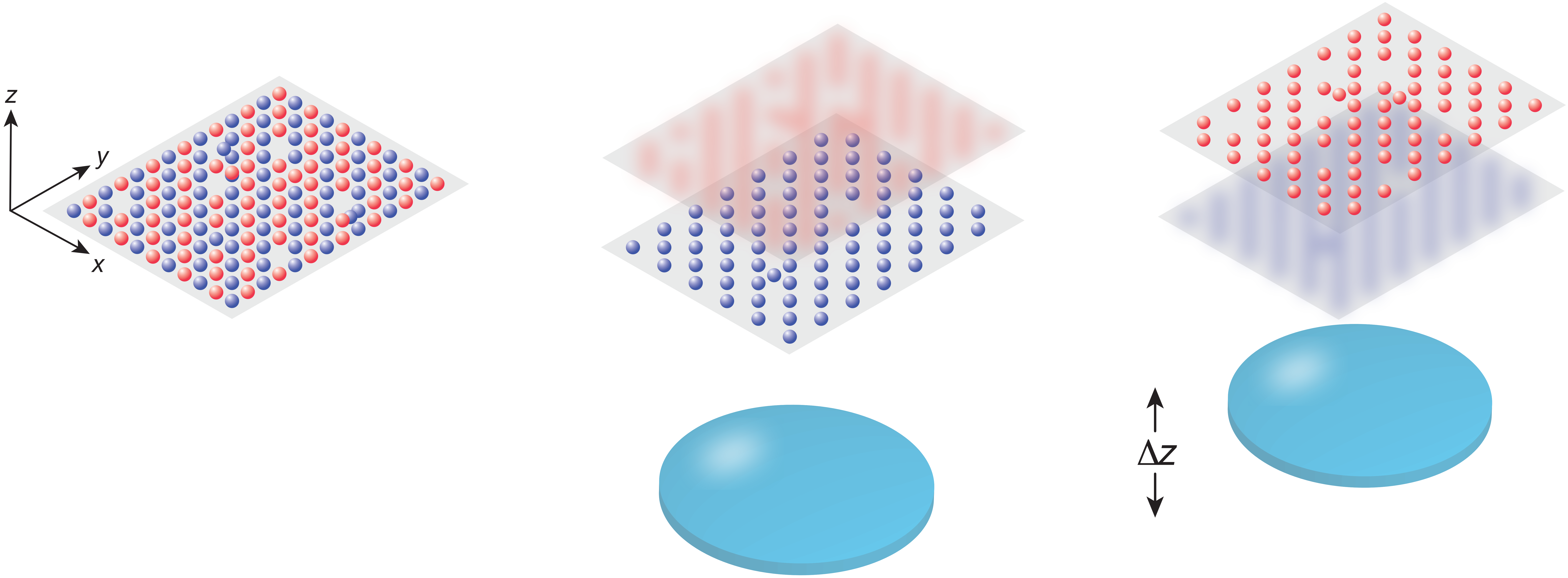


Cs Quantum Gas Microscope

Rb Quantum Gas Microscope

see also: C. Chiu *et al.* Phys. Rev. Lett. **120**, 243201 (2018)
Idea: J.-S. Bernier *et al.* Phys. Rev. A **79**, 061601 (2009)
T.-L. Ho & Q. Zhou arXiv:0911.5506

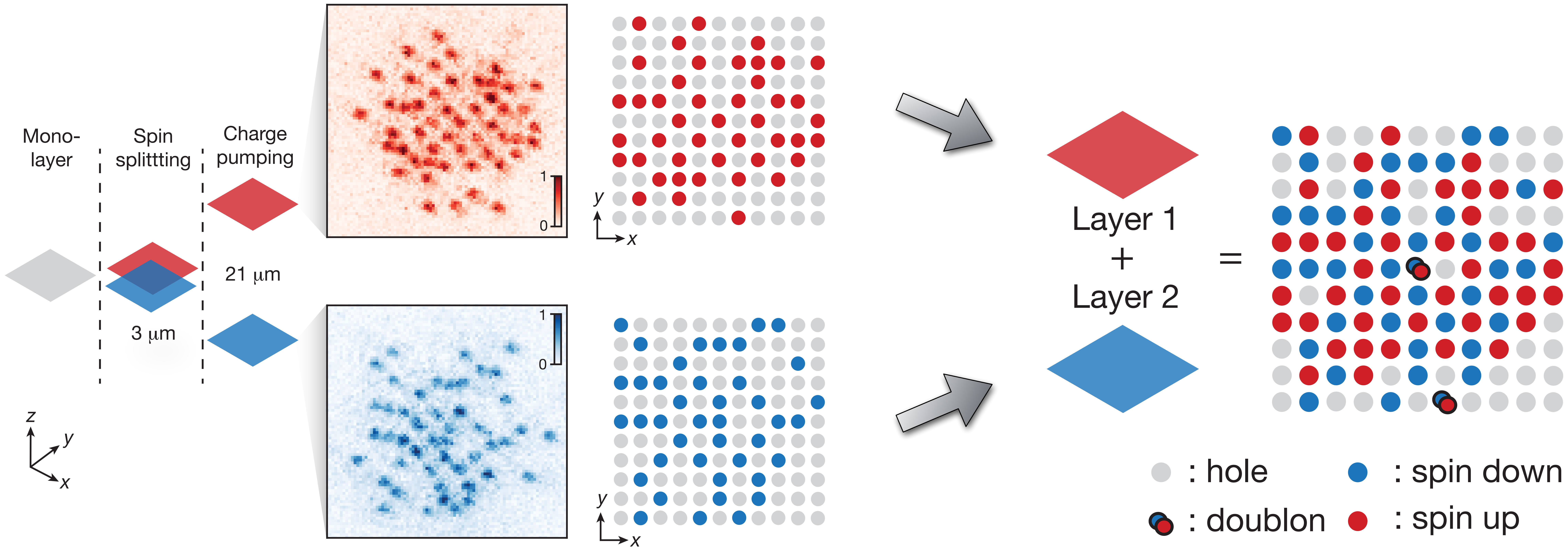
Spin & Charge Resolved Imaging



J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020)

LMU

Full Spin & Density Resolved Detection



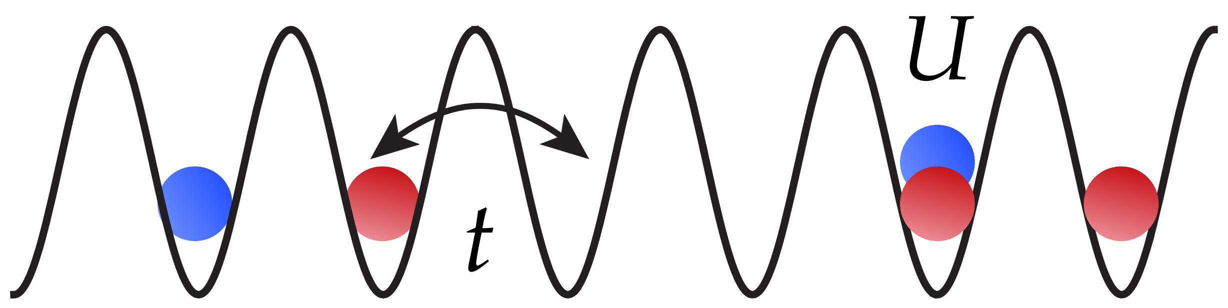
Density and spin readout: M. Boll et al. Science **353**, 1257 (2016), J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020), see also Harvard (Greiner), Princeton (Bakr) arXiv:2203.15023, MIT (Zwierlein) arXiv:2208.05948

Full Spin & Density Resolved Detection

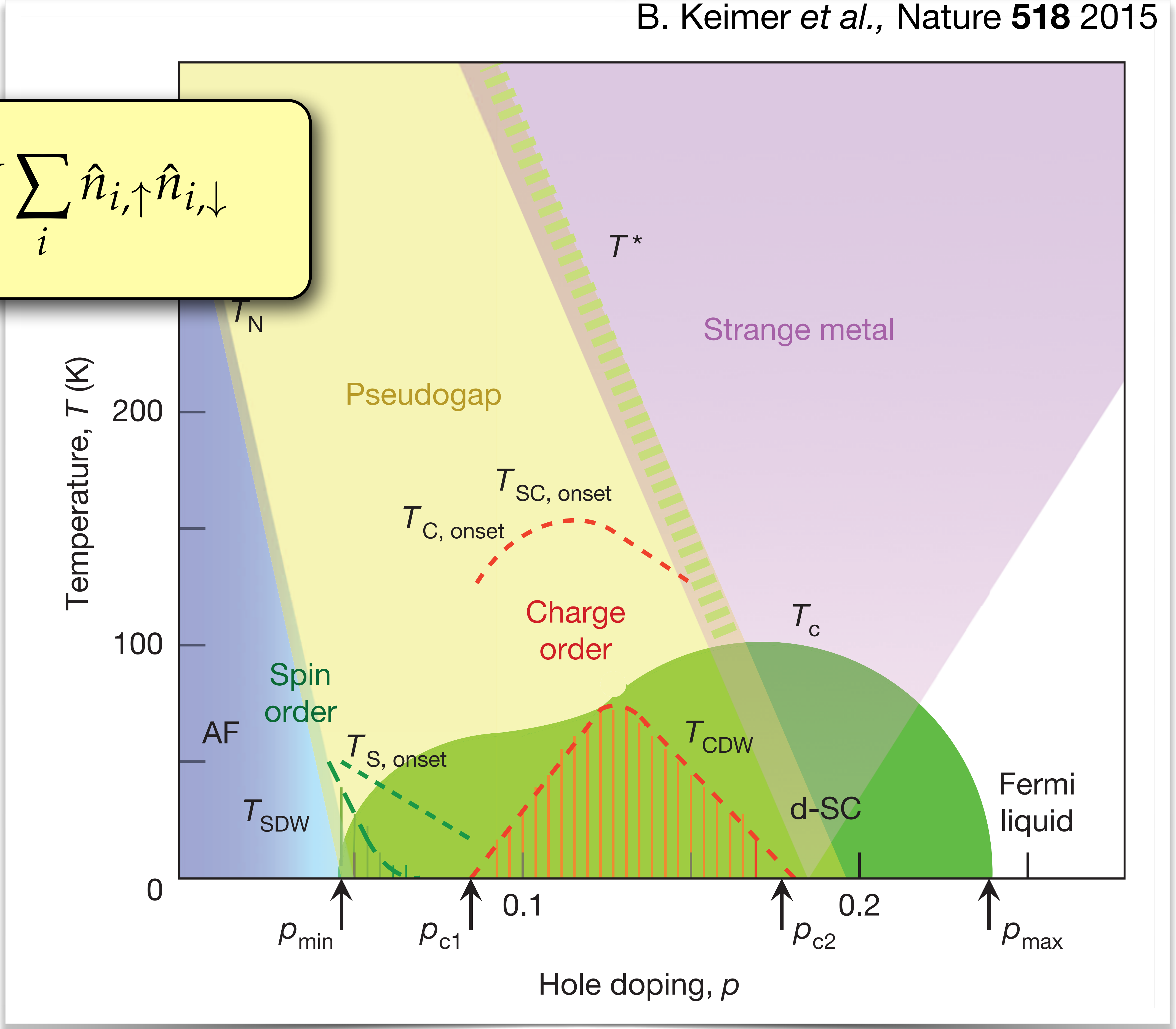
Density and spin readout: M. Boll et al. Science **353**, 1257 (2016), J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020), see also Harvard (Greiner), Princeton (Bakr) arXiv:2203.15023, MIT (Zwierlein) arXiv:2208.05948

Fermi Hubbard Model (FHM)

Fermi-Hubbard Model

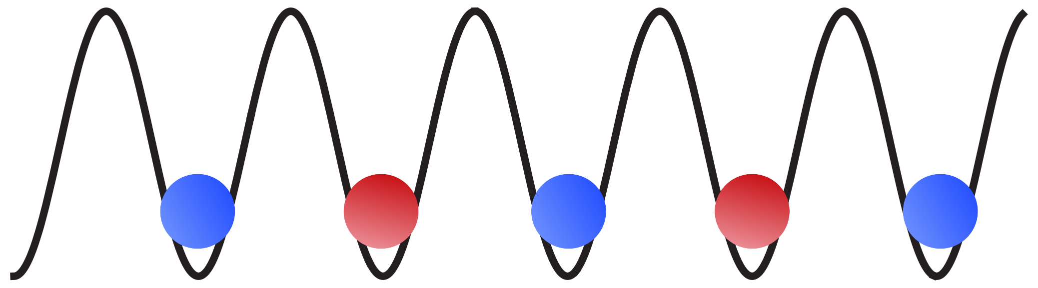


$$\hat{H} = -t \sum_{\langle i,j \rangle,\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$



AFM Heisenberg Model

Half filling & strong interaction

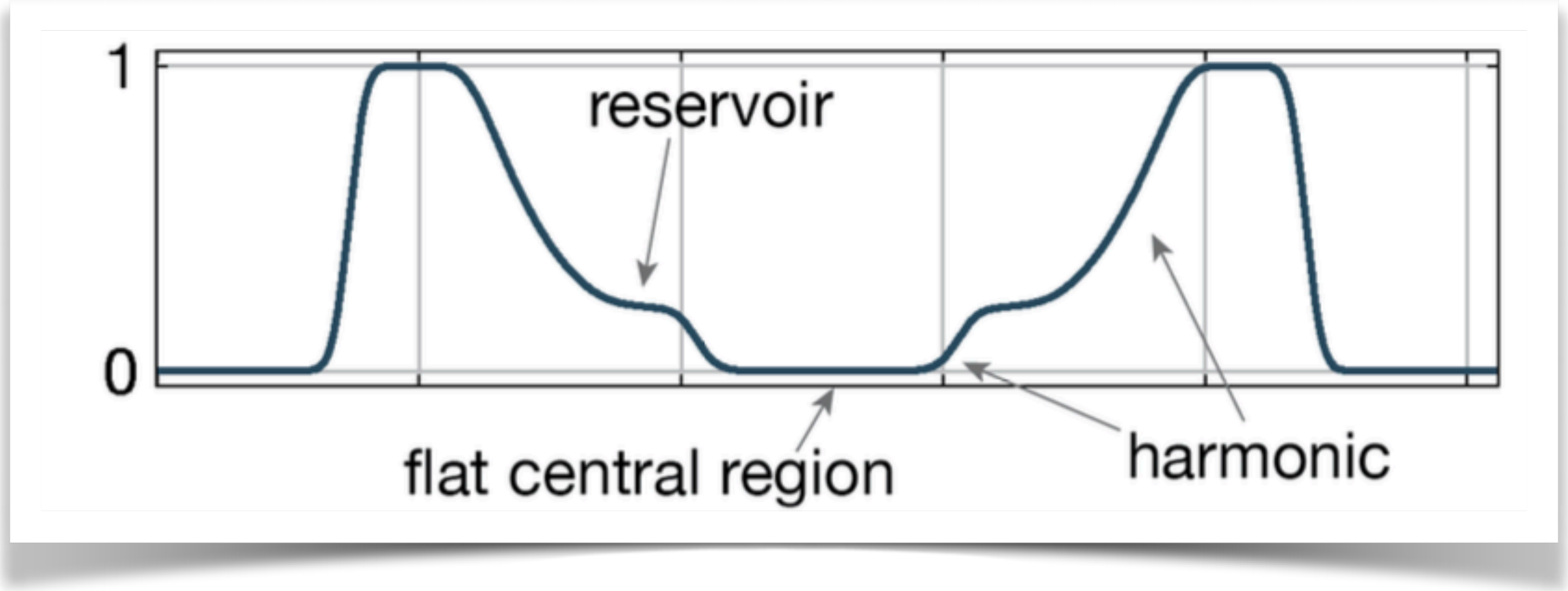


$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \qquad J = \frac{4t^2}{U}$$

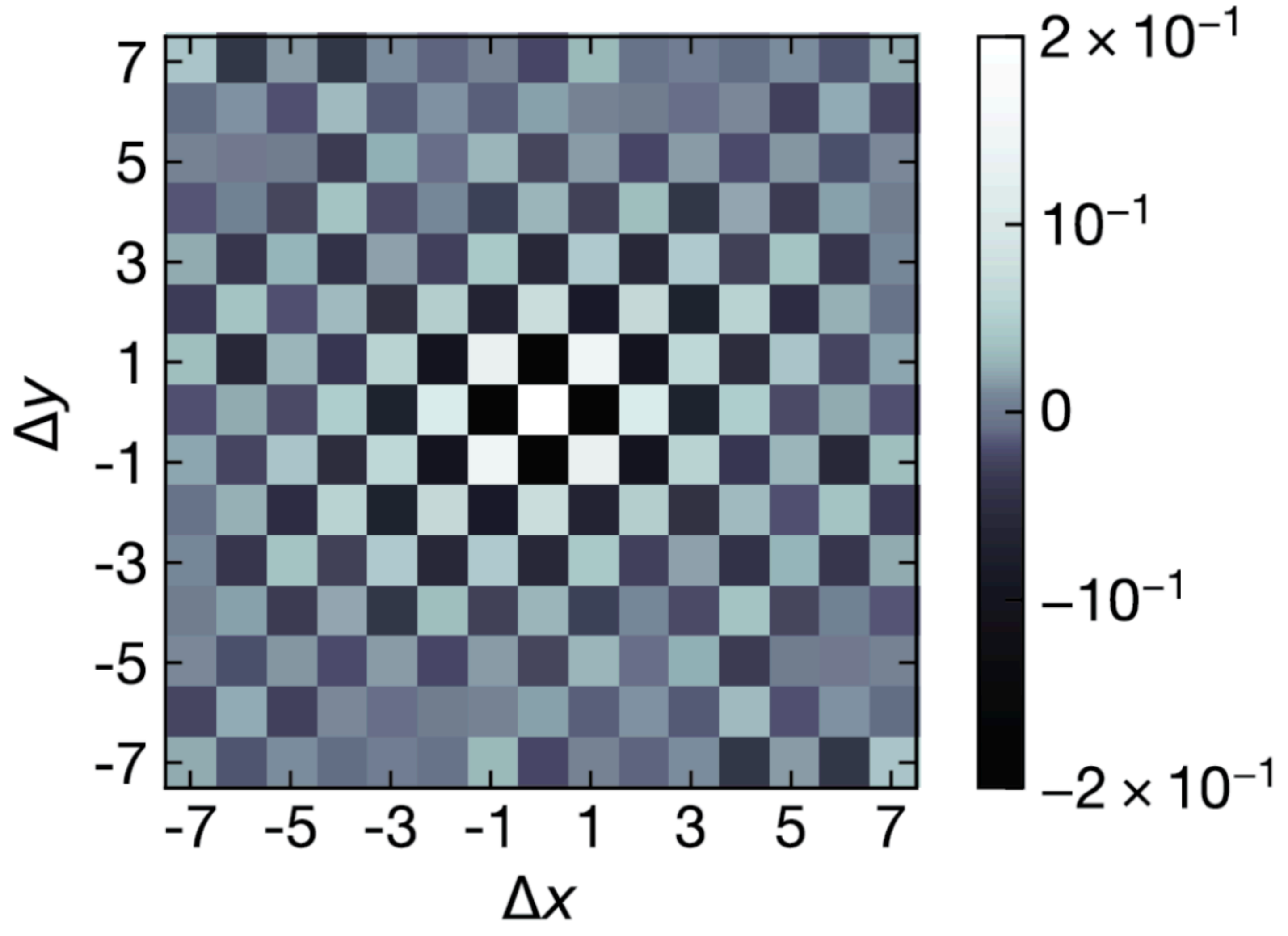
Away from half filling: ***t-J* model**
competition between

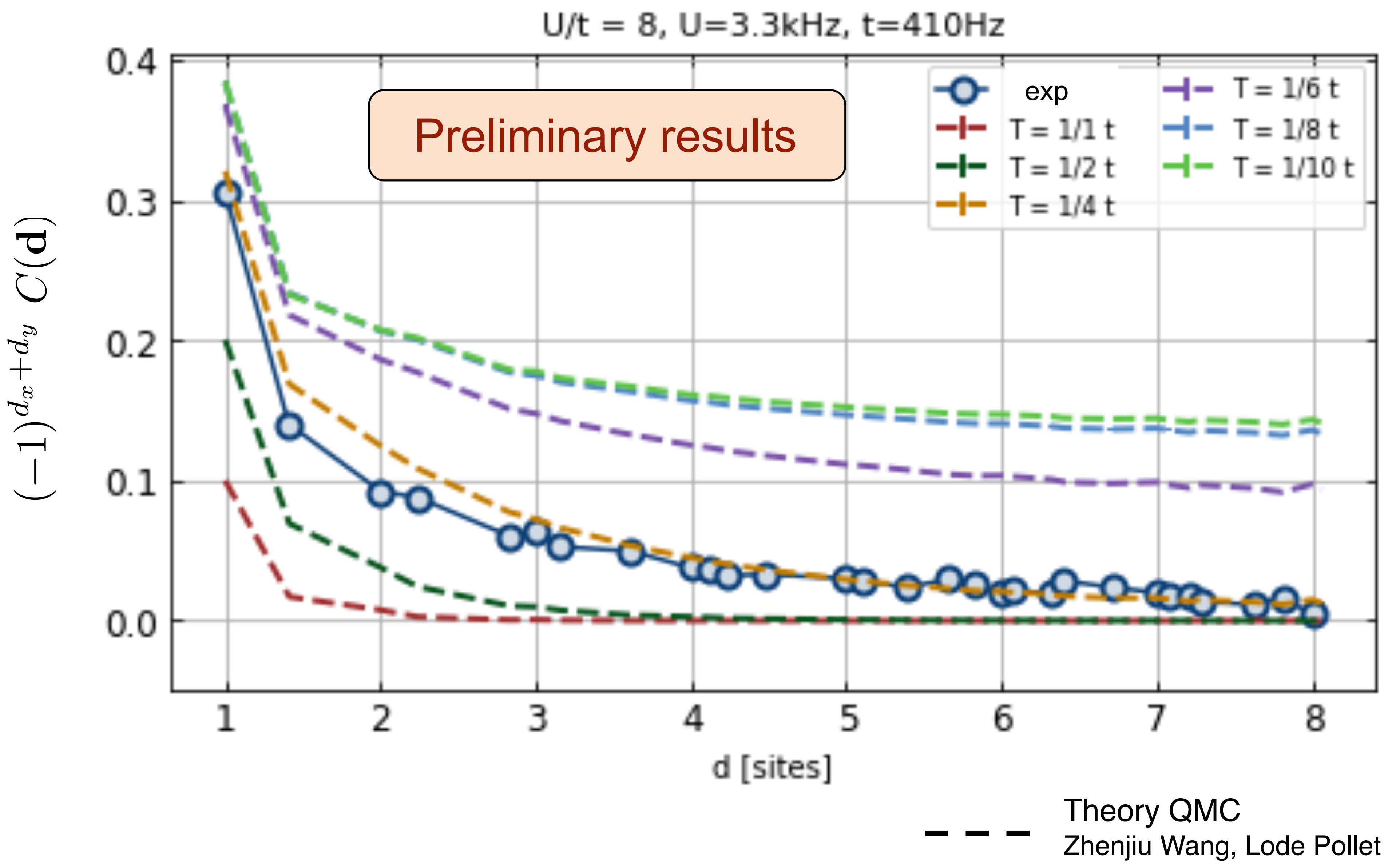
hole delocalization ⟷ ***magnetic order***

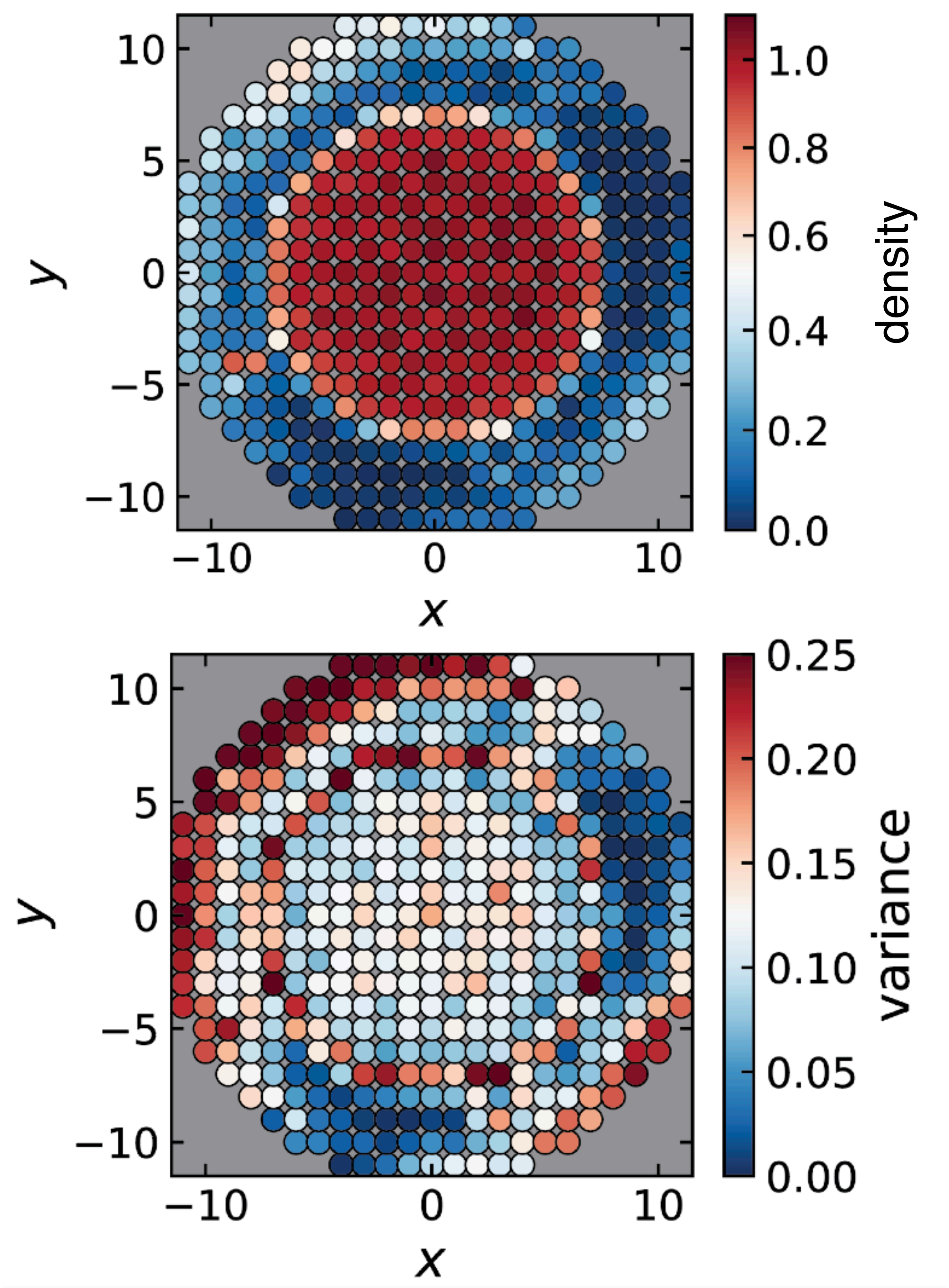
A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017), L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)



$$\frac{\langle \hat{S}_i^z \hat{S}_j^z \rangle - \langle \hat{S}_i^z \rangle \langle \hat{S}_j^z \rangle}{\sigma(\hat{S}_j^z)\sigma(\hat{S}_i^z)}$$





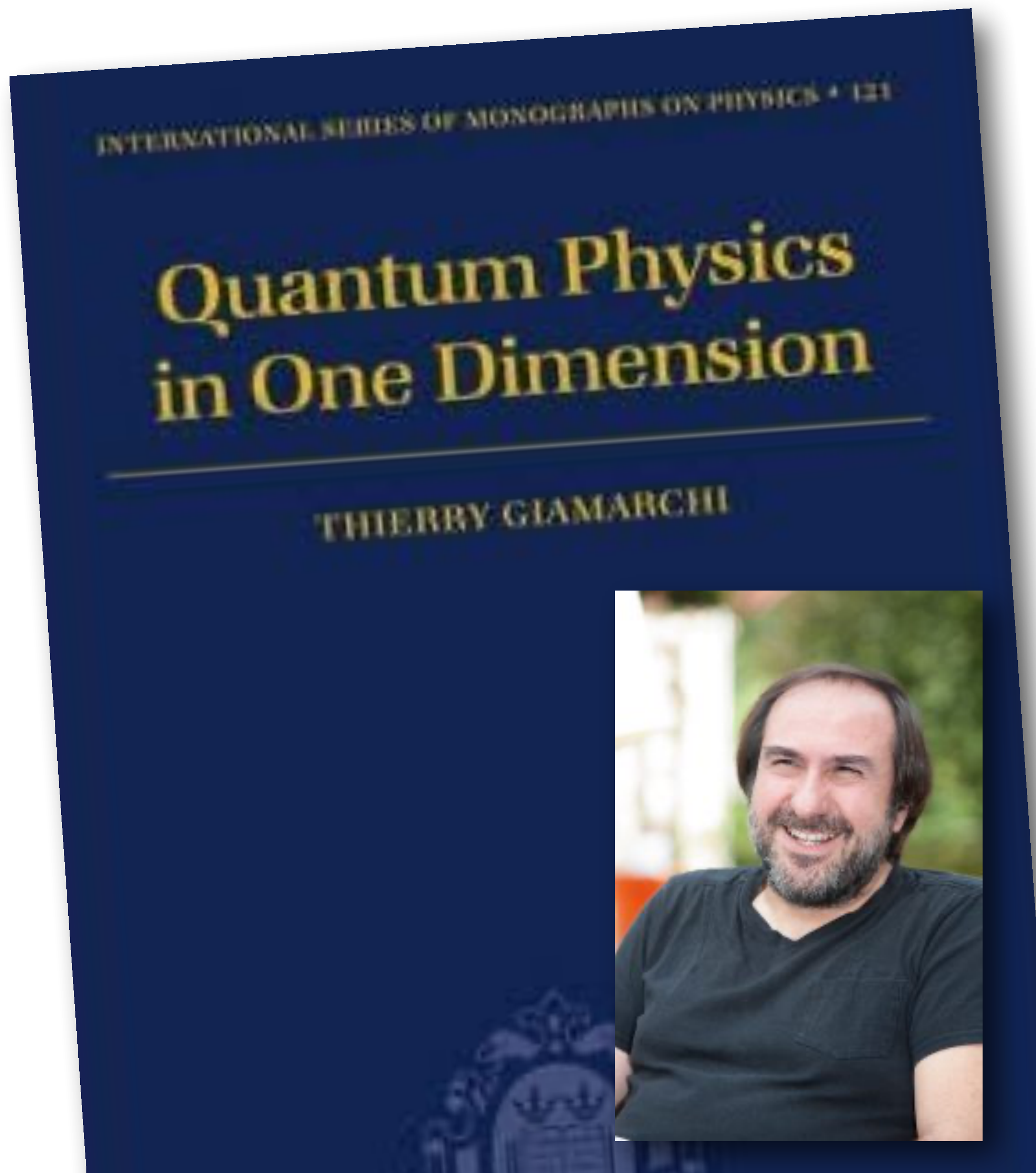


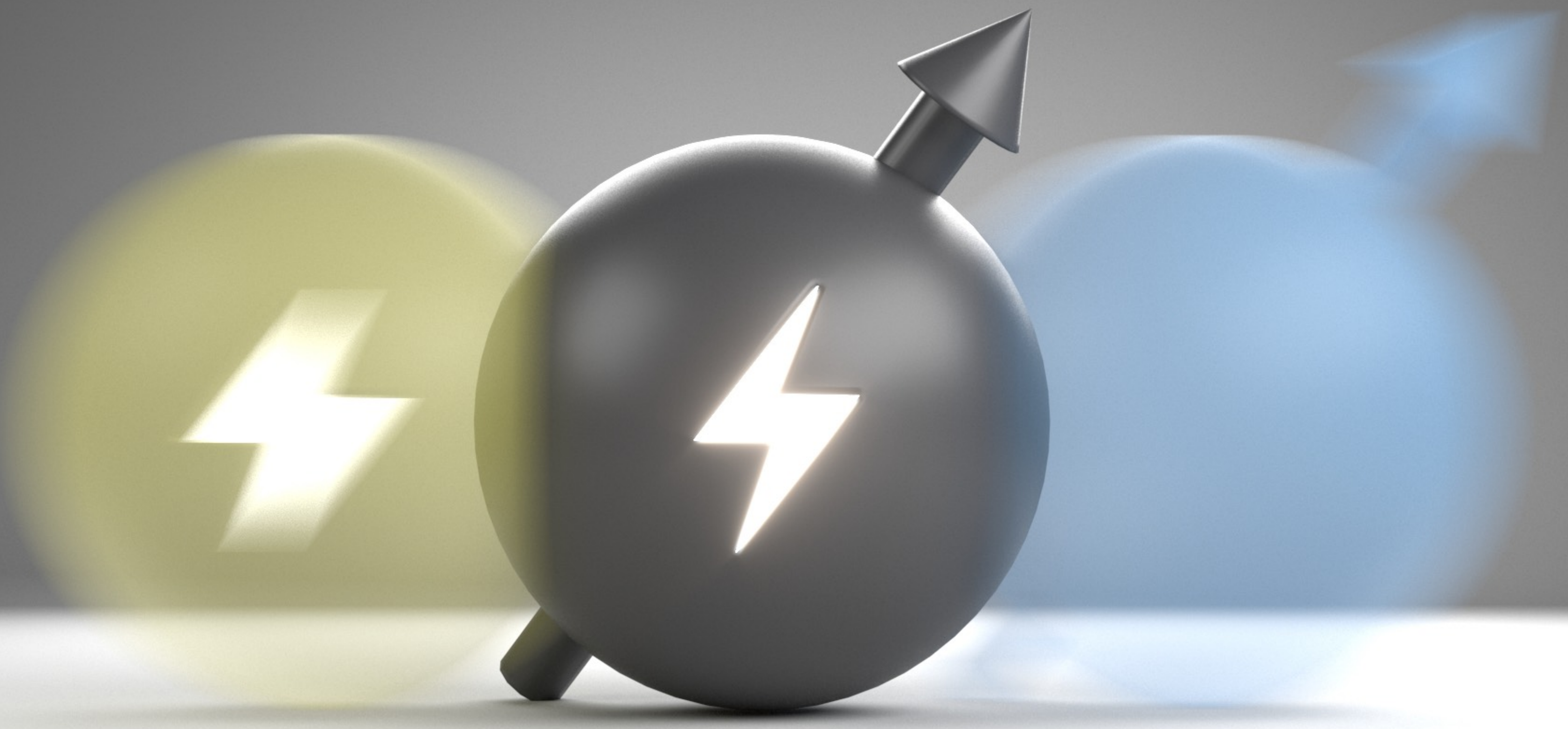
$$T/t \sim 0.2 - 0.25$$

<u>See also:</u>

Harvard: Parsons et al., Science (2016), Mazurenko et al. Nature (2017), **MIT:** Cheuk et al., Science (2016)**, Princeton:** Brown et al., Science (2017)**, Bonn:** Drewes et al., PRL (2017)

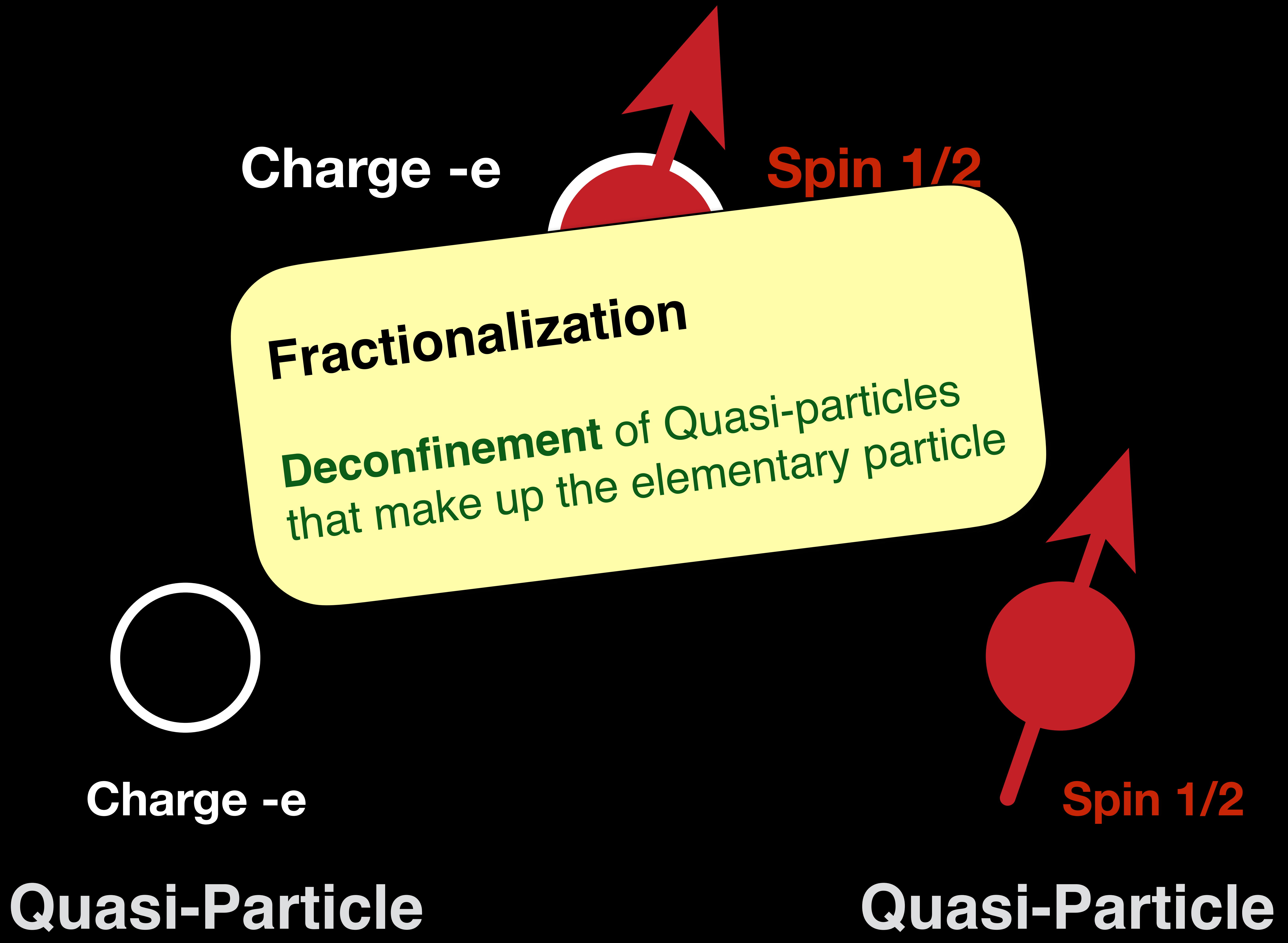
Doping in 1D Fermi Hubbard Model





J. Vijayan *et al.* Science **367**, 186 (2020)

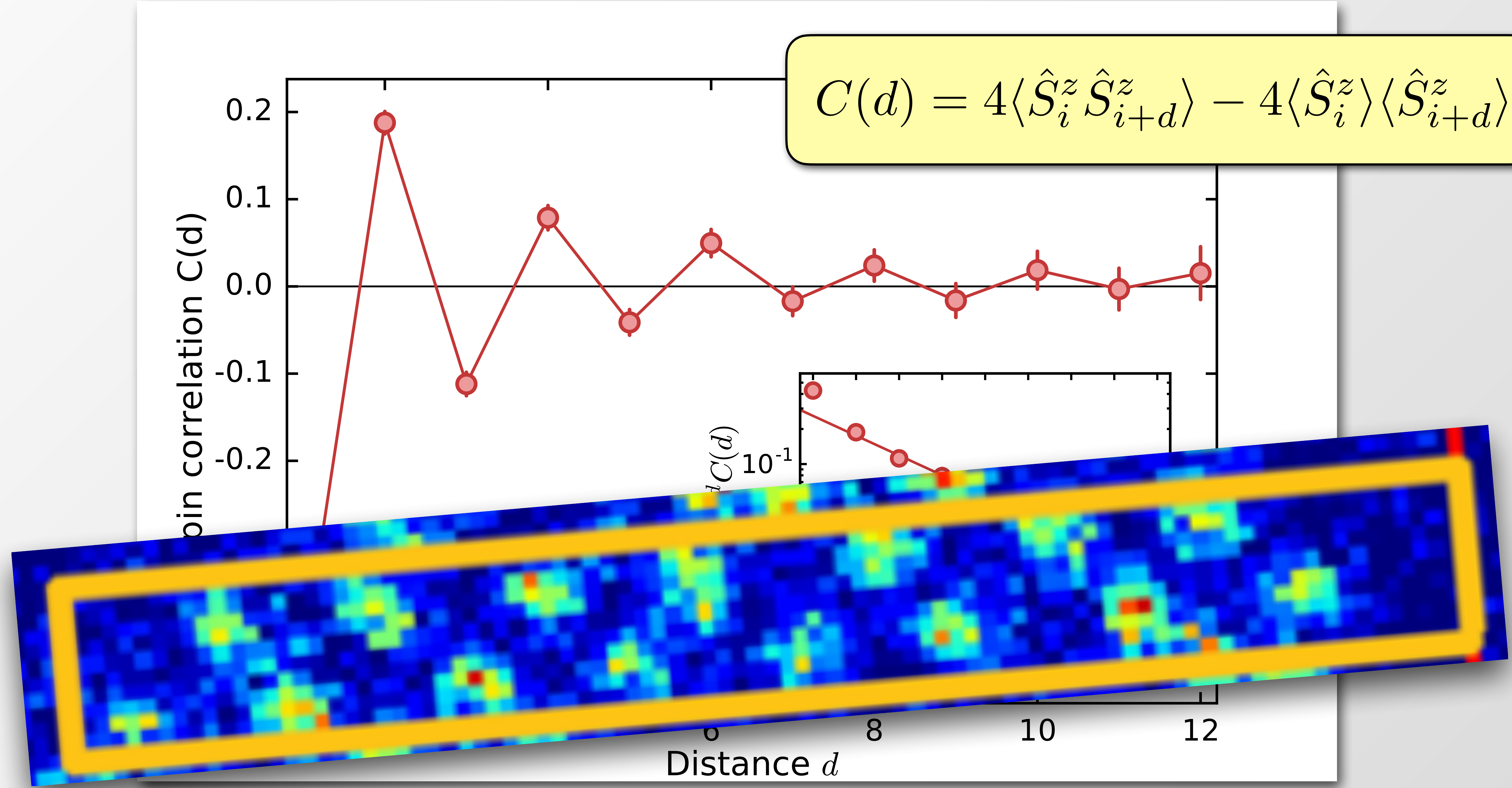
The Electron



Incommensurate Magnetism

Postselection to $M_z = 0$!

$$C(d) = 4\langle \hat{S}_i^z \hat{S}_{i+d}^z \rangle - 4\langle \hat{S}_i^z \rangle \langle \hat{S}_{i+d}^z \rangle$$



$\xi(0, T)$ **Largest possible decays length !**

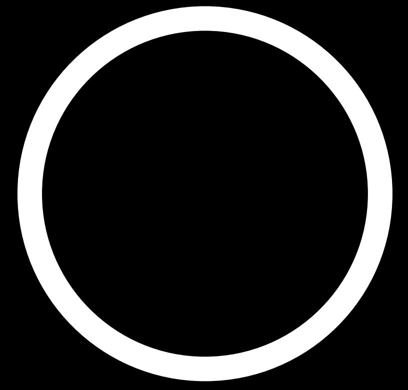
The Electron

Charge -e

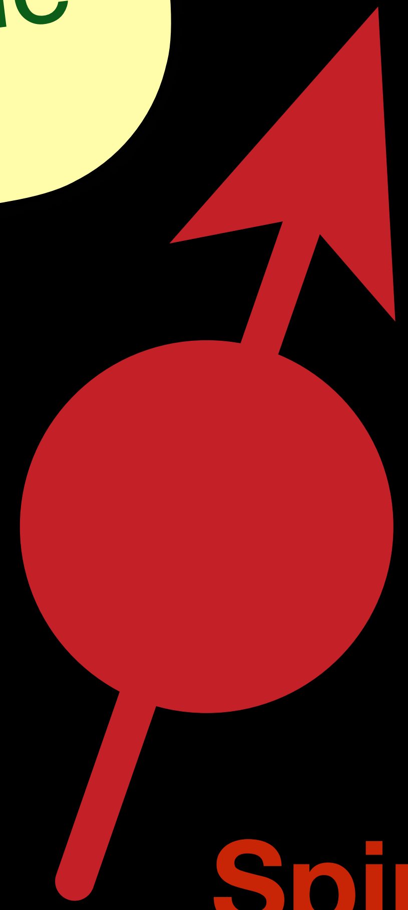
Spin 1/2

Fractionalization

Deconfinement of Quasi-particles that make up the elementary particle



Charge -e

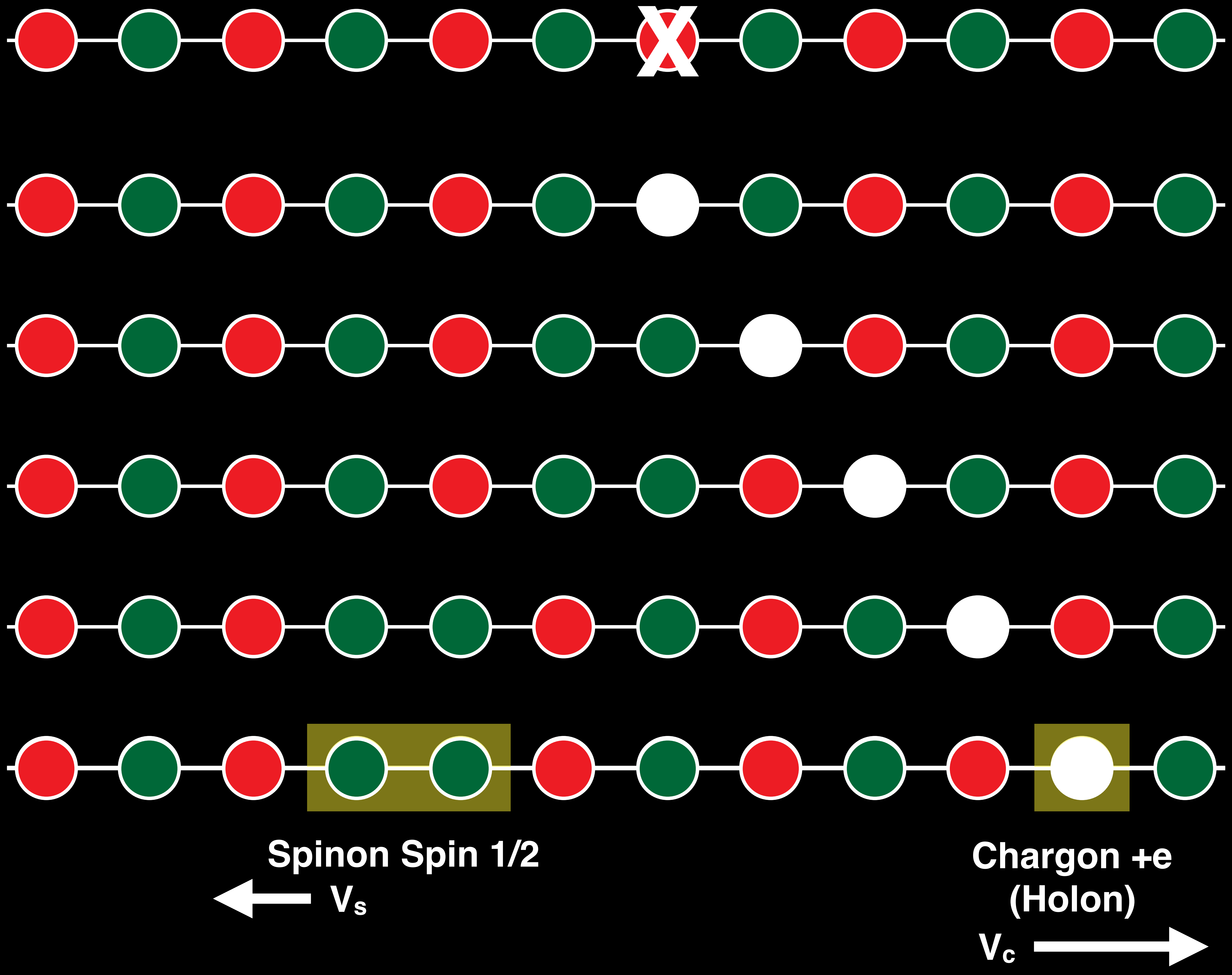


Spin 1/2

Quasi-Particle

Quasi-Particle

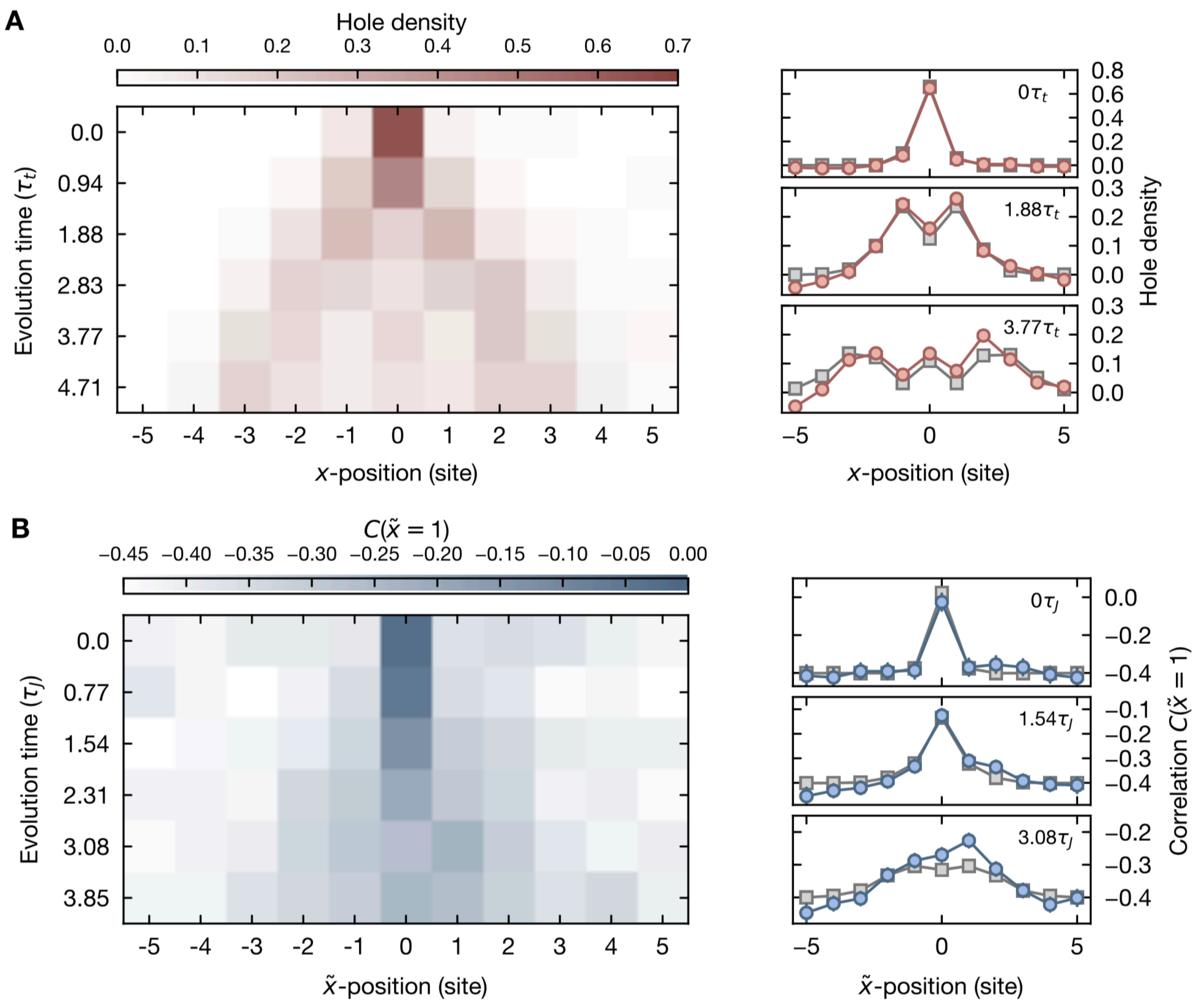
Fractionalization



DMRG Simulation:
C. Kollath, U. Schollwöck, W. Zwerger
Phys. Rev. Lett. **95**, 176401 (2005)

1.
J. Vijayan *et al. Science* **367**, 186 (2020)

Dynamical Spin Charge Separation



Hole Dynamics

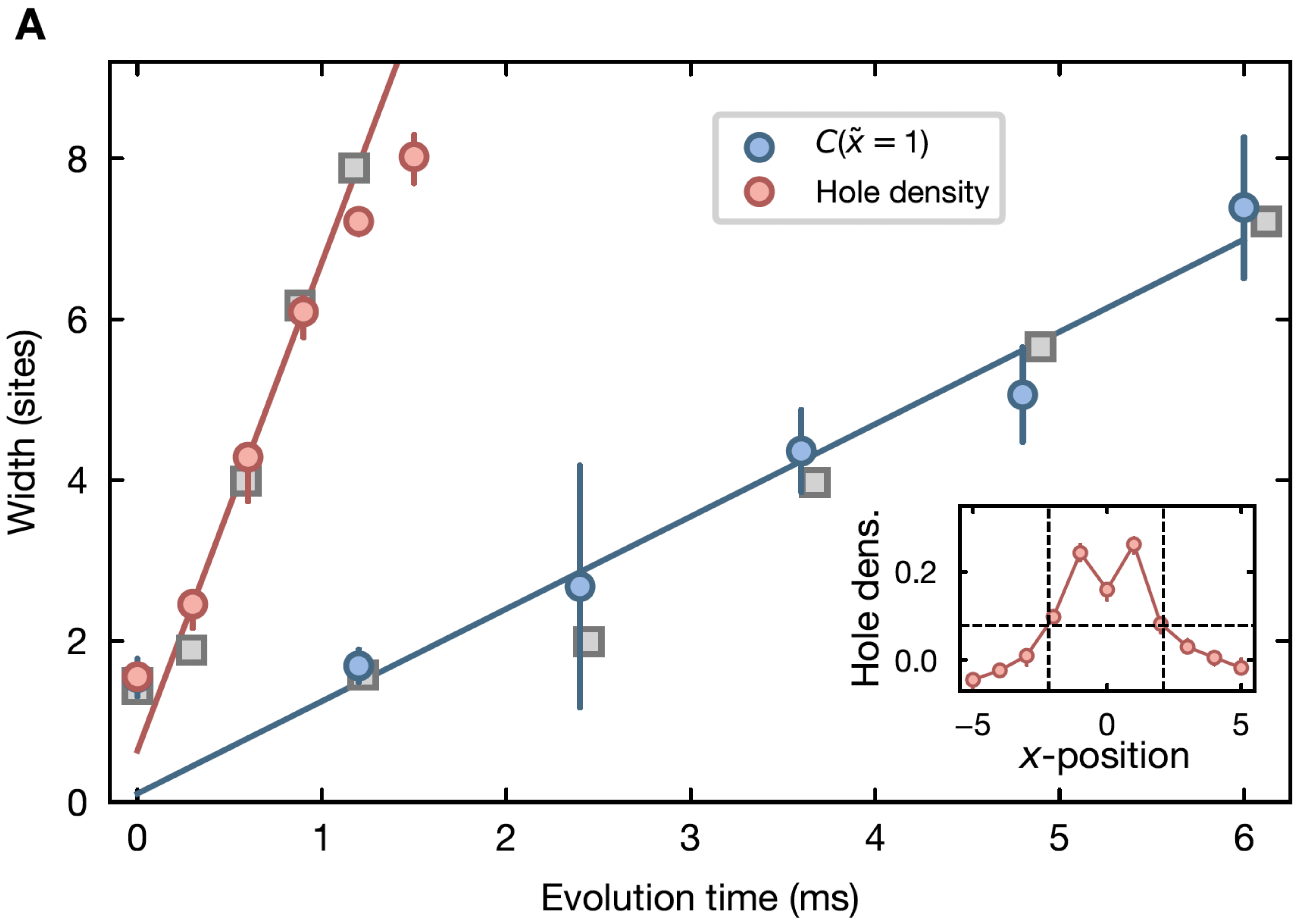
$$\langle \hat{h}_i \rangle$$

Spin Dynamics

$$C(1) = \langle \hat{S}^z_i \hat{S}^z_{i+1} \rangle$$

(squeezed space)

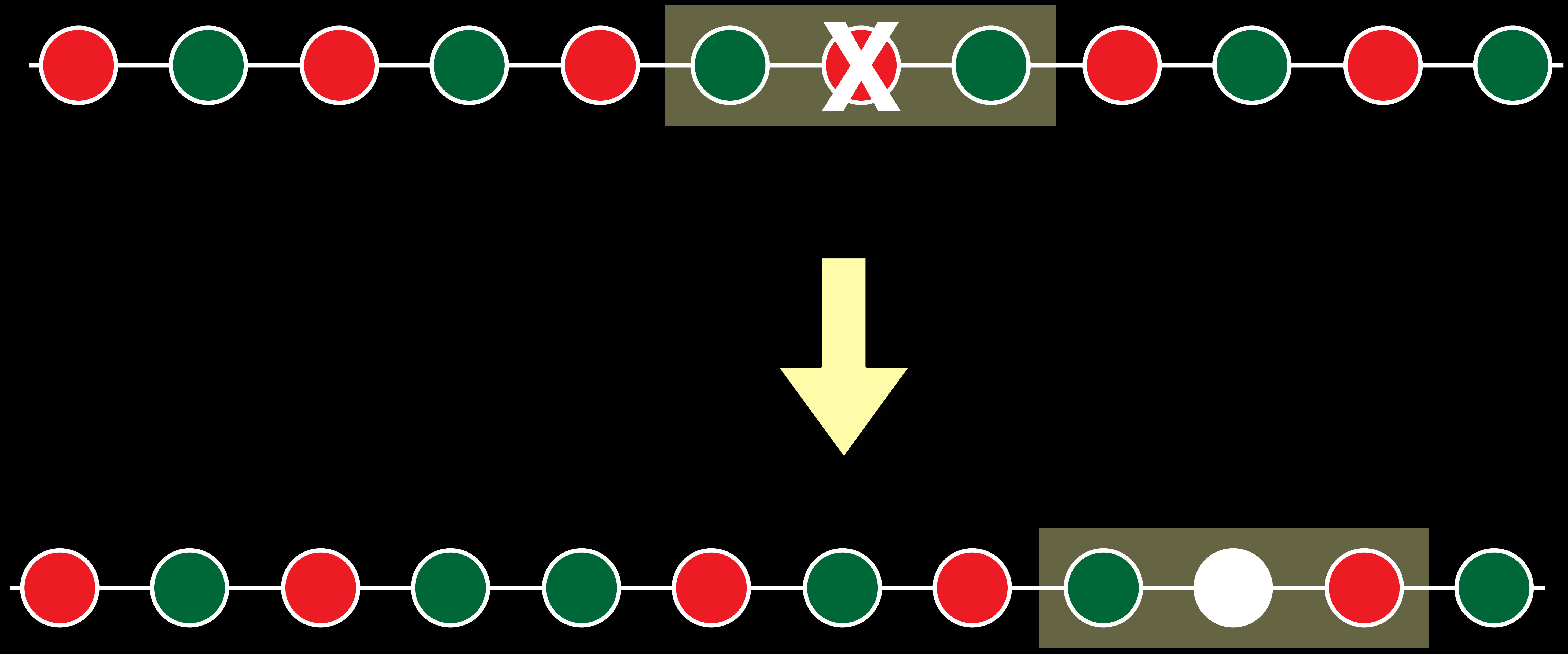
Spin & Charge Velocities



Fractionalization - Hole Shedding Spinon

Spin attached to hole

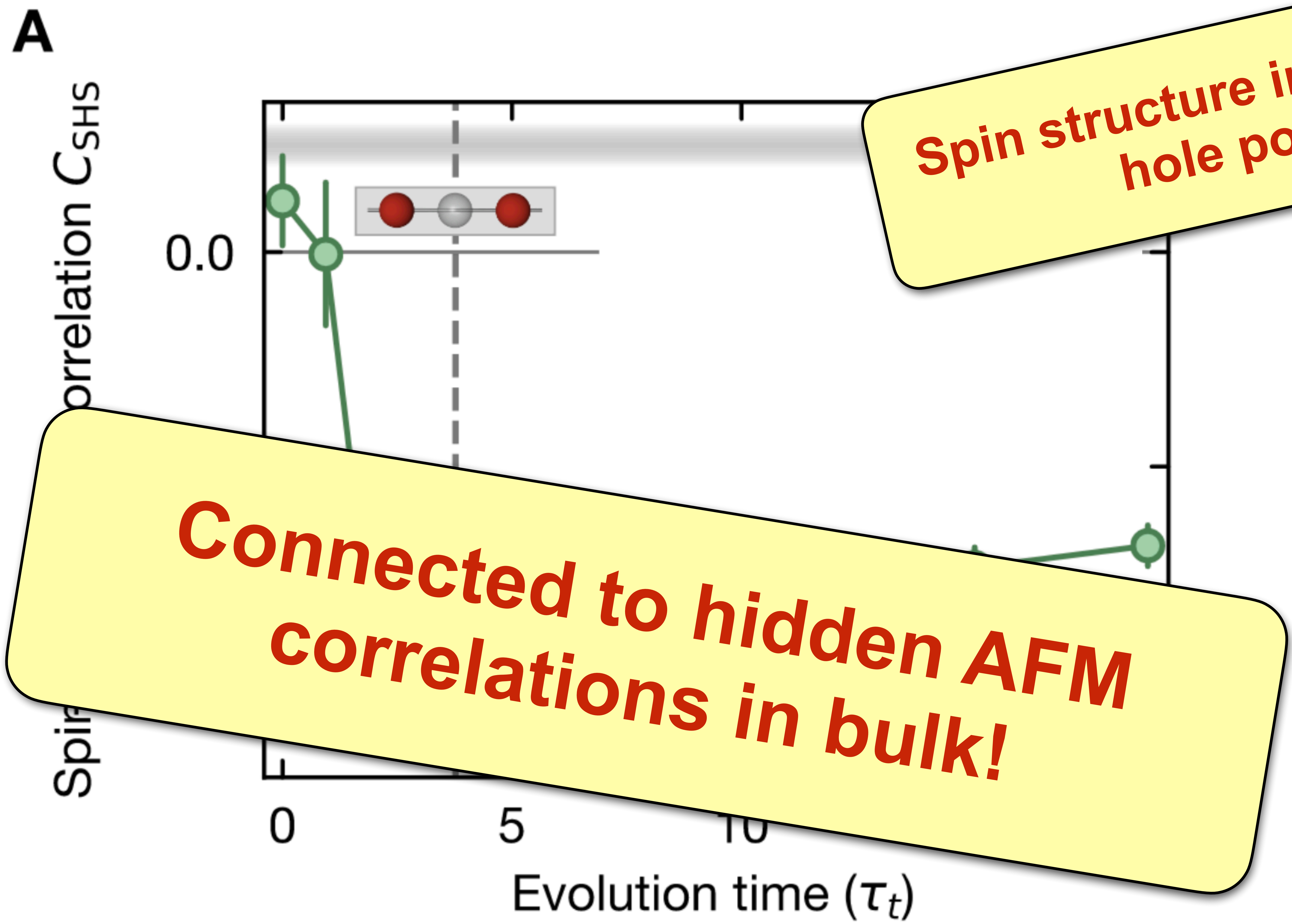
$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle > 0$$



$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle < 0$$

Hole got rid of spin

Spin-Hole-Spin Correlations



Spin structure independent of hole position!

Connected to hidden AFM correlations in bulk!

$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle$$

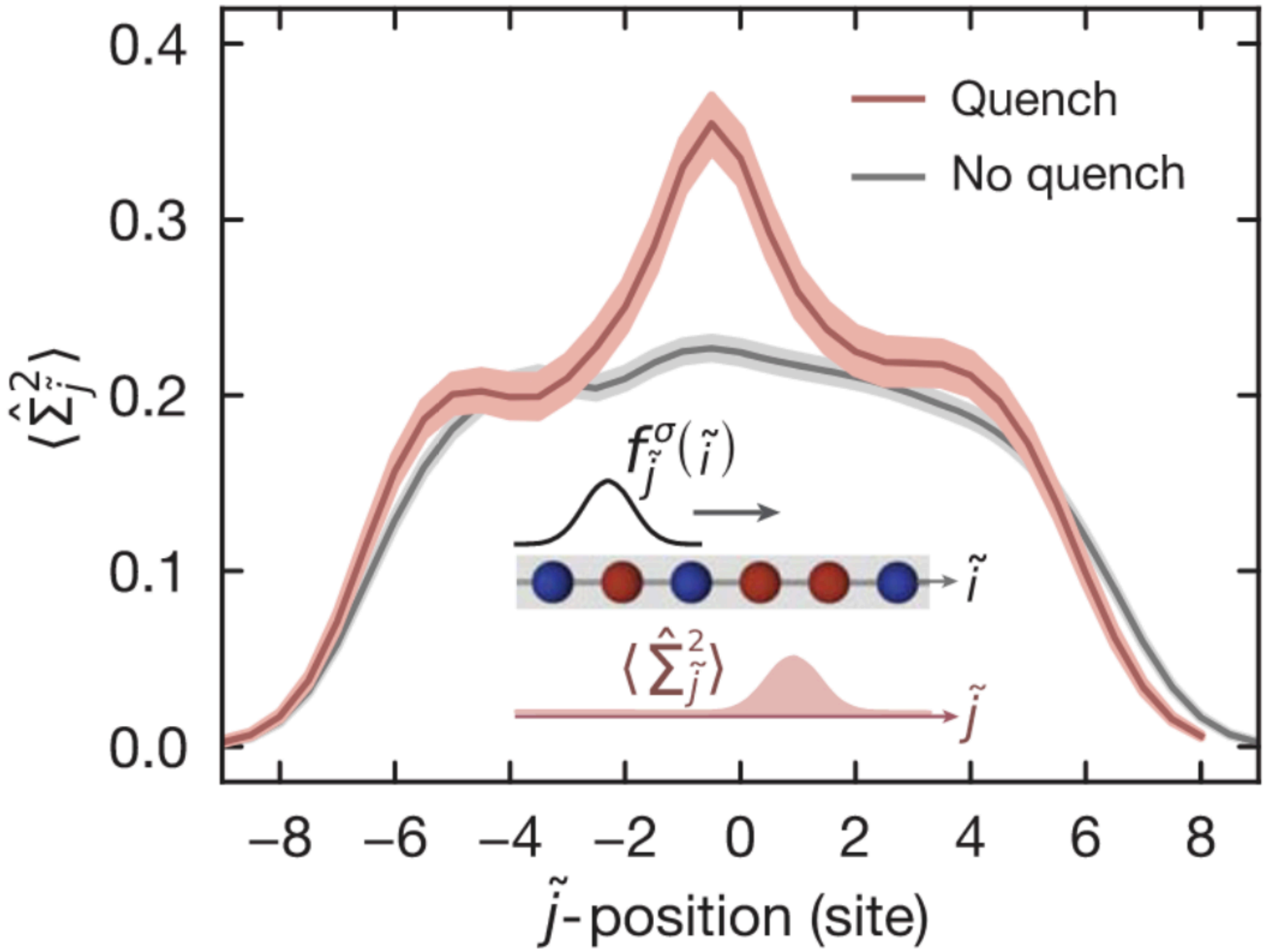
Detection of the Spin-1/2 Spinon

$$\hat{\Sigma}_j^2 = \left(\Sigma_i \hat{S}_i^z f_j^\sigma(i)\right)^2$$

$$\langle \hat{\Sigma}_j^2 \rangle - \langle \hat{\Sigma}_j^2 \rangle_{BG} = 1/4$$

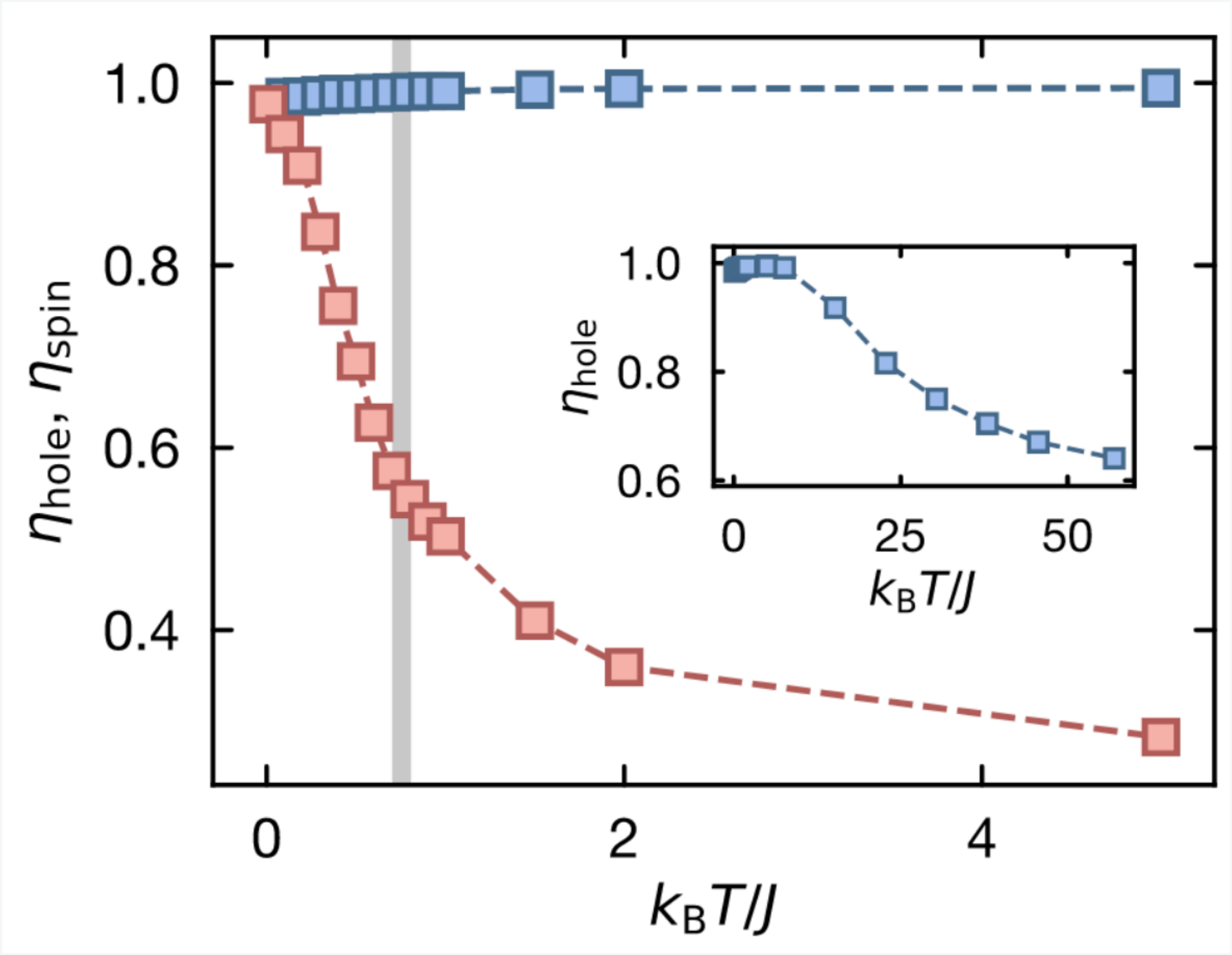
Probe Magnetization Fluctuations in Region σ

J. Vijayan *et al. Science* **367**, 186 (2020)



See also: Kivelson, S. & Schrieffer, J. R. Fractional charge, a sharp quantum observable. *Physical Review B* **25**, 6447–6451 (1982).

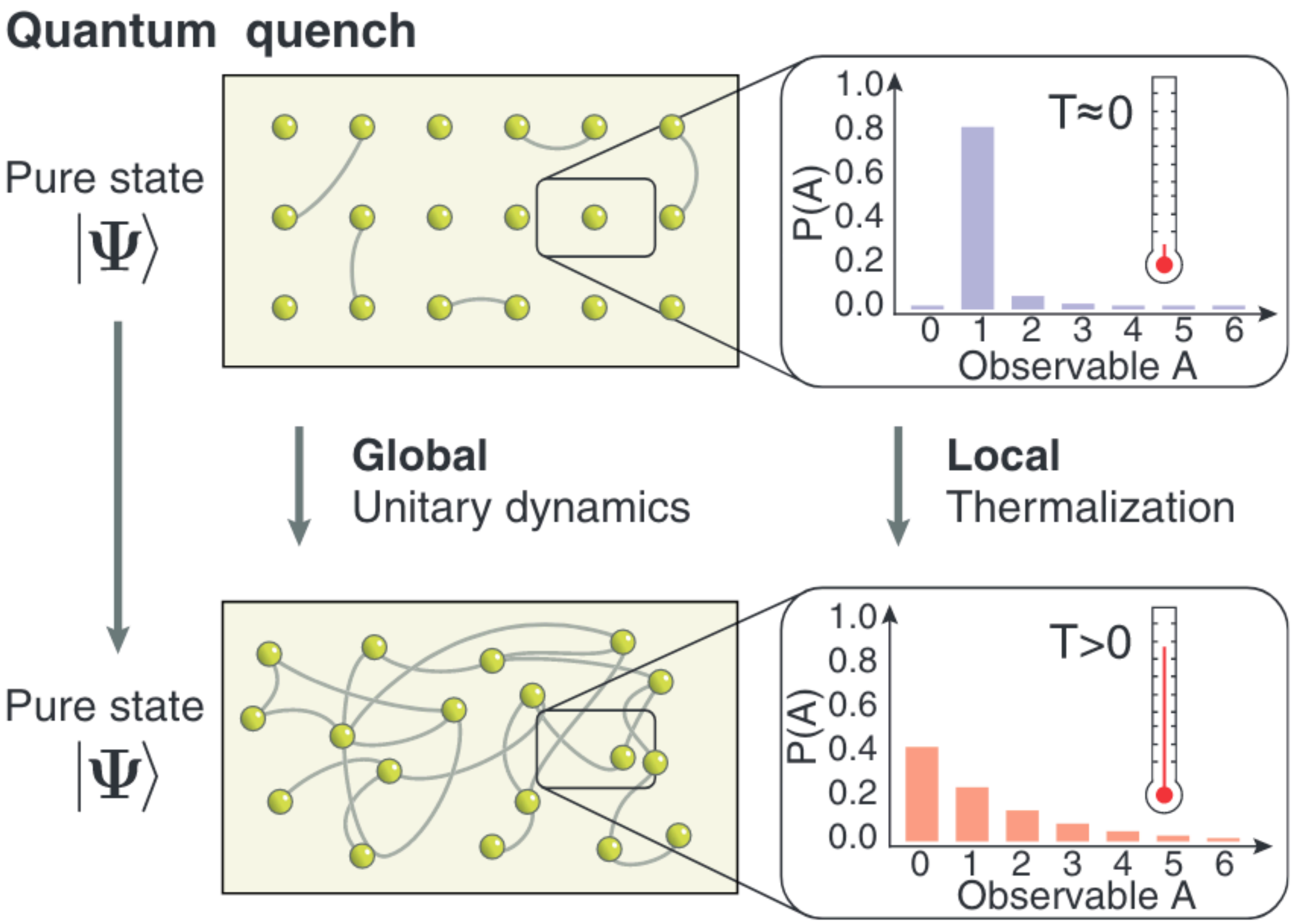
Fractionalization at Finite Temperatrues

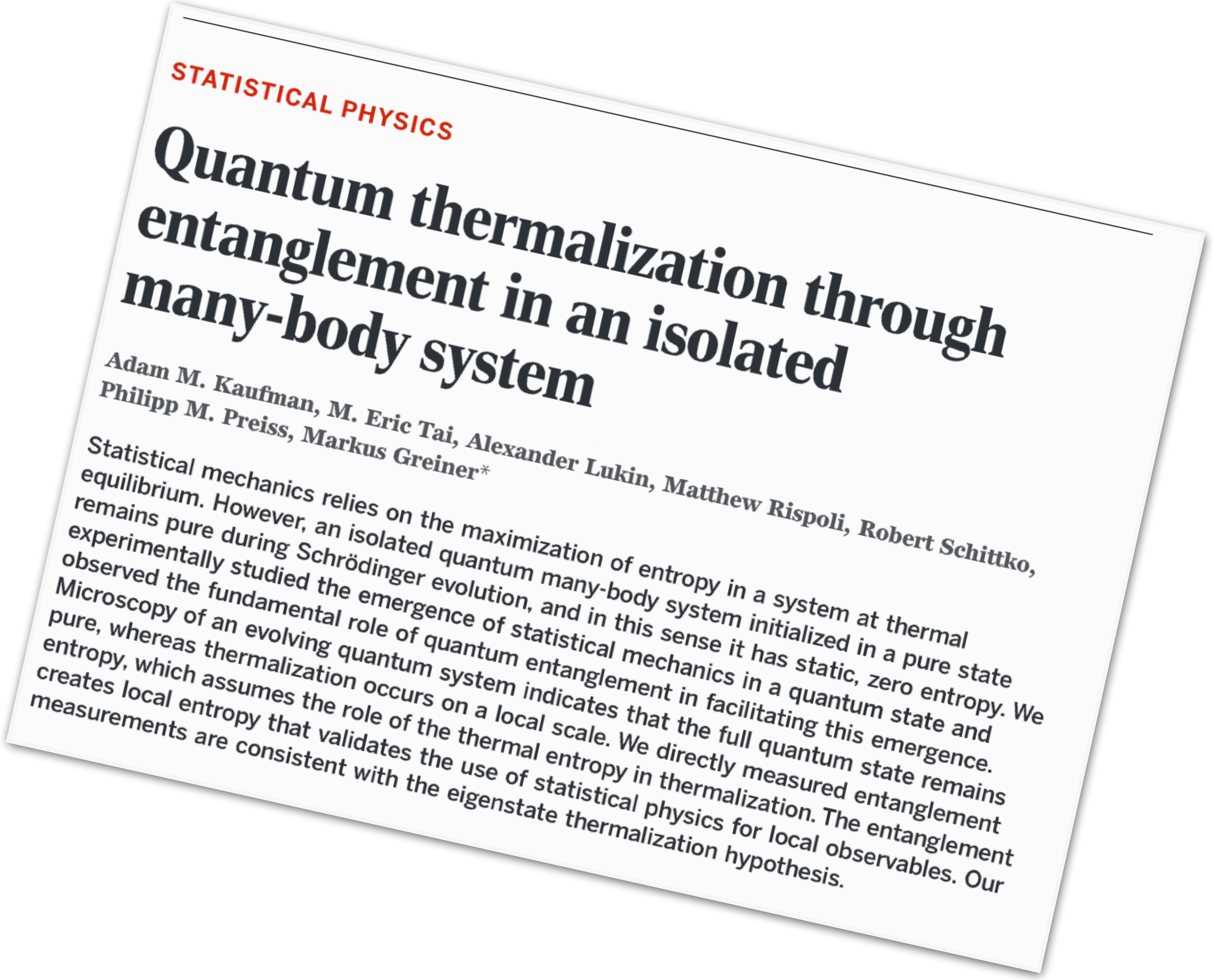


Holon created with **unit efficiency**
Spinon created with **50-60% efficiency**

Probing Thermalization in a QMB System

Thermalization in an Isolated QMB System




STATISTICAL PHYSICS

Quantum thermalization through entanglement in an isolated many-body system

Adam M. Kaufman, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, Markus Greiner*

Statistical mechanics relies on the maximization of entropy in a system at thermal equilibrium. However, an isolated quantum many-body system initialized in a pure state remains pure during Schrödinger evolution, and in this sense it has static, zero entropy. We experimentally studied the emergence of statistical mechanics in a quantum state and observed the fundamental role of quantum entanglement in facilitating this emergence. Microscopy of an evolving quantum system indicates that the full quantum state remains pure, whereas thermalization occurs on a local scale. We directly measured entanglement entropy, which assumes the role of the thermal entropy in thermalization. The entanglement creates local entropy that validates the use of statistical physics for local observables. Our measurements are consistent with the eigenstate thermalization hypothesis.

A. Kaufmann *et al.* Science 2016

ETH assumes that locally: $$\rho_A = \frac{1}{Z_A} e^{-\beta E_n}$$

$$S_{VN} = -\,tr\left(\rho_A \log \rho_A\right) = S_{th}$$

Remaining System acts as "Thermal Reservoir" for smaller subsystem.

Entanglement Entropy **is** Thermal Entropy in a QMB System

To Show:

1) Global State Remains Pure

2) Locally, system looks thermal

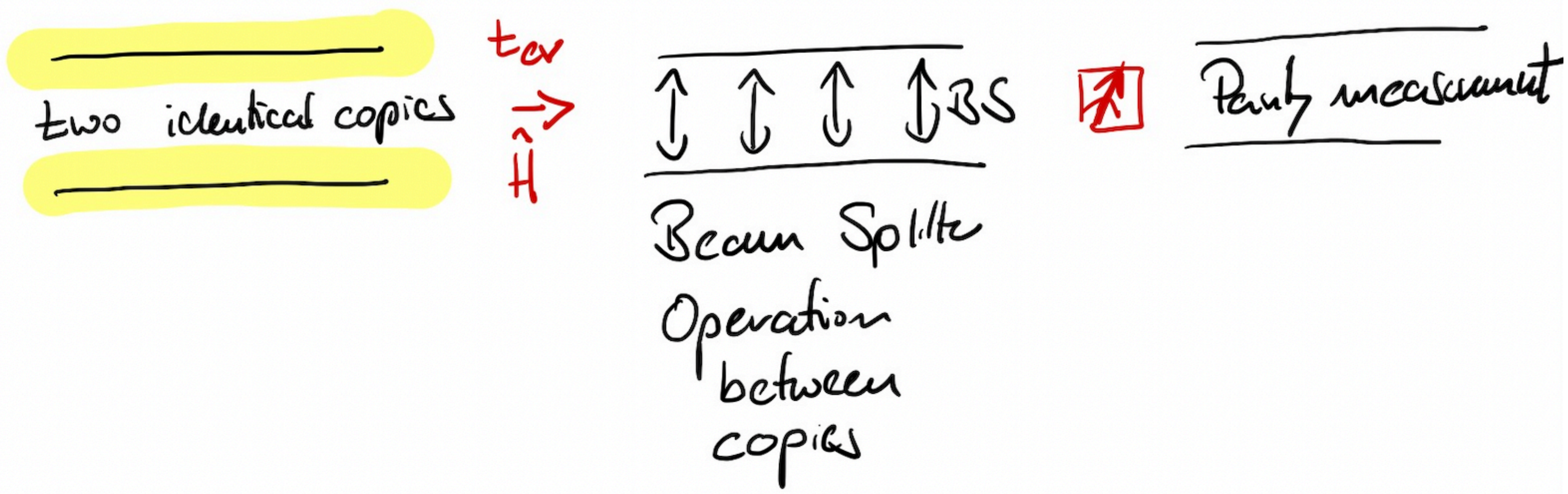
3) Probe local vN Entanglement Entropy

(or related quantity)

A. Kaufmann *et al.* Science 2016

Probing Renyi Entropy

Probing State Purity via Many-Body Quantum Interference (here for bosons)



Purity $tr\left(\rho^2\right)$

Renyi-2 Entropy $S_2(\rho) = -\log\left(tr\left(\rho^2\right)\right)$

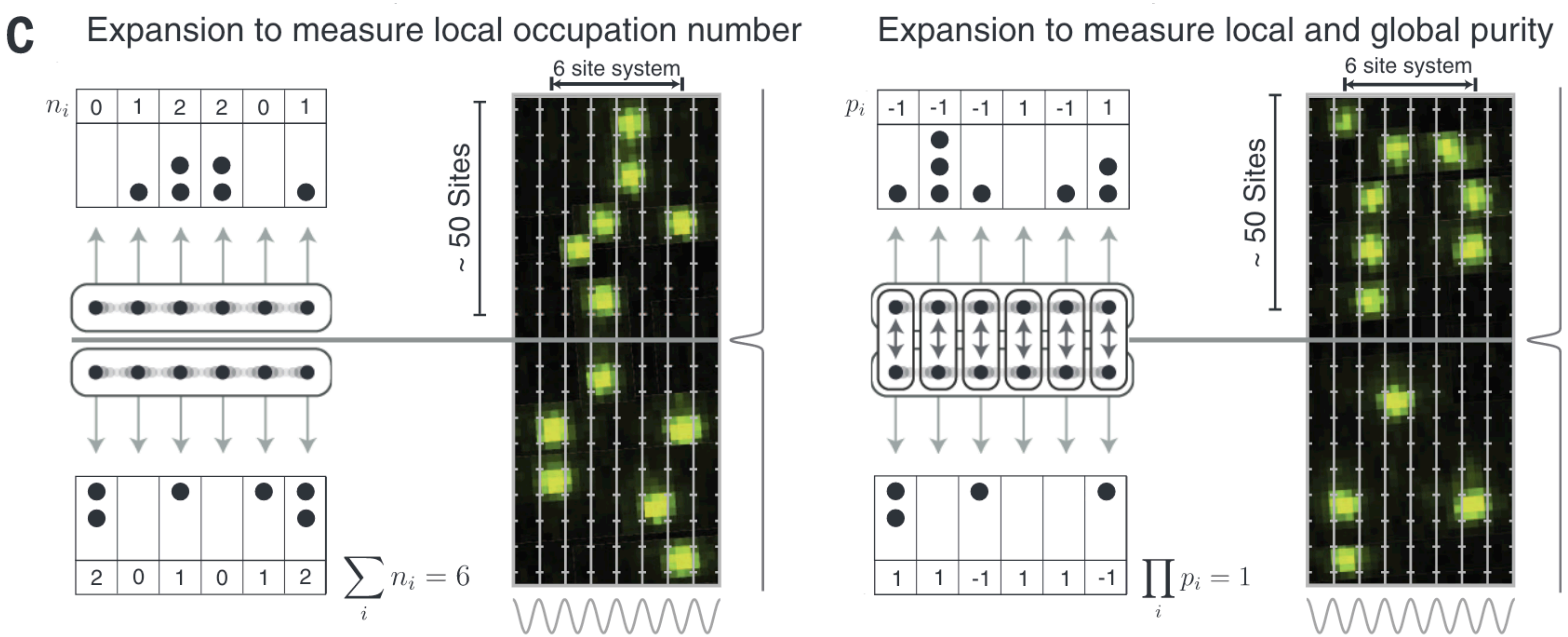
Bounds von Neumann Entropy

$$S_{vN} \geq S_2(\rho)$$

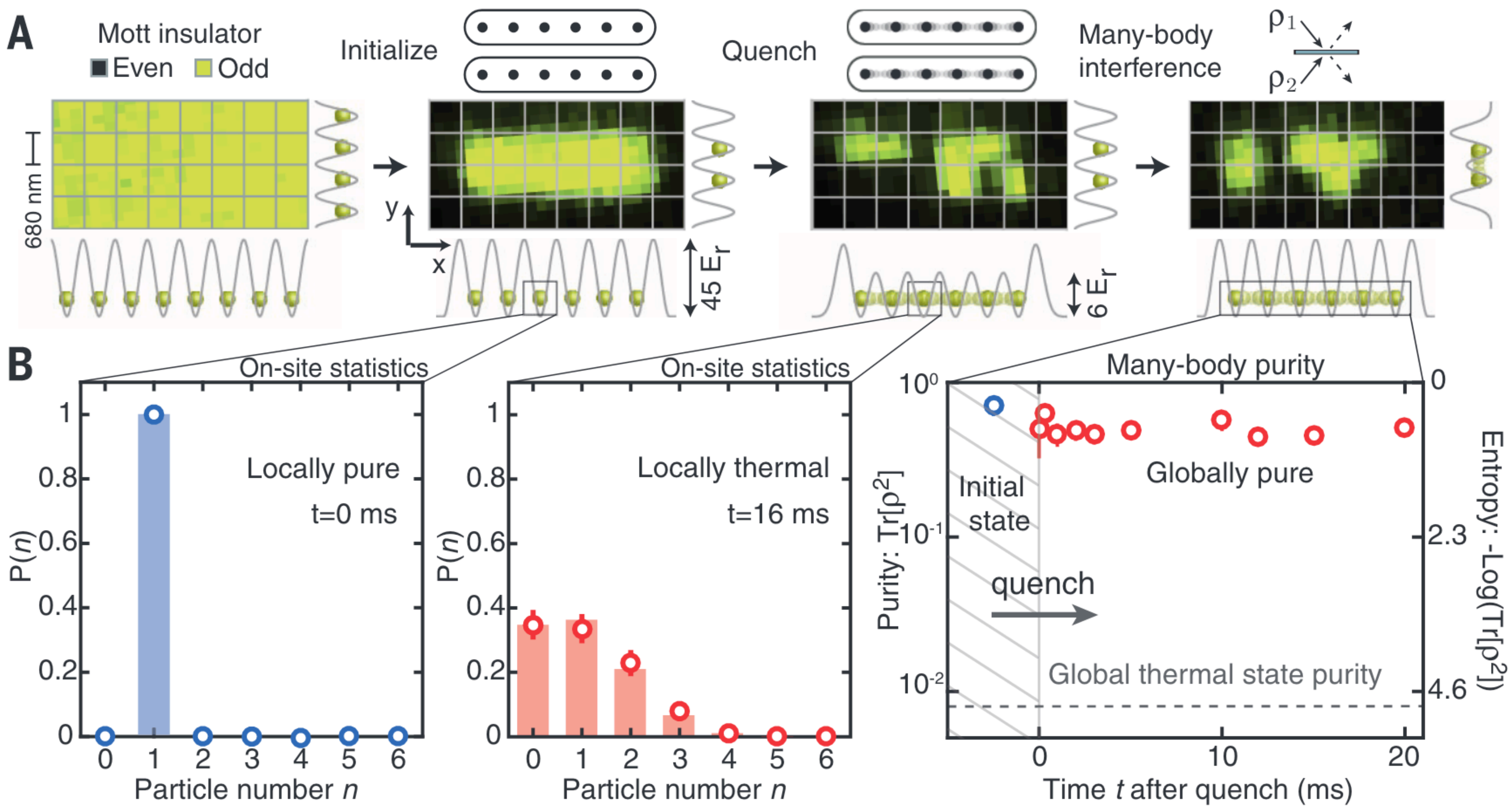
see C.M. Alves & D. Jaksch PRL 2004
A. Daley et al. PRL 2012

Measure Renyi-2 Entropy

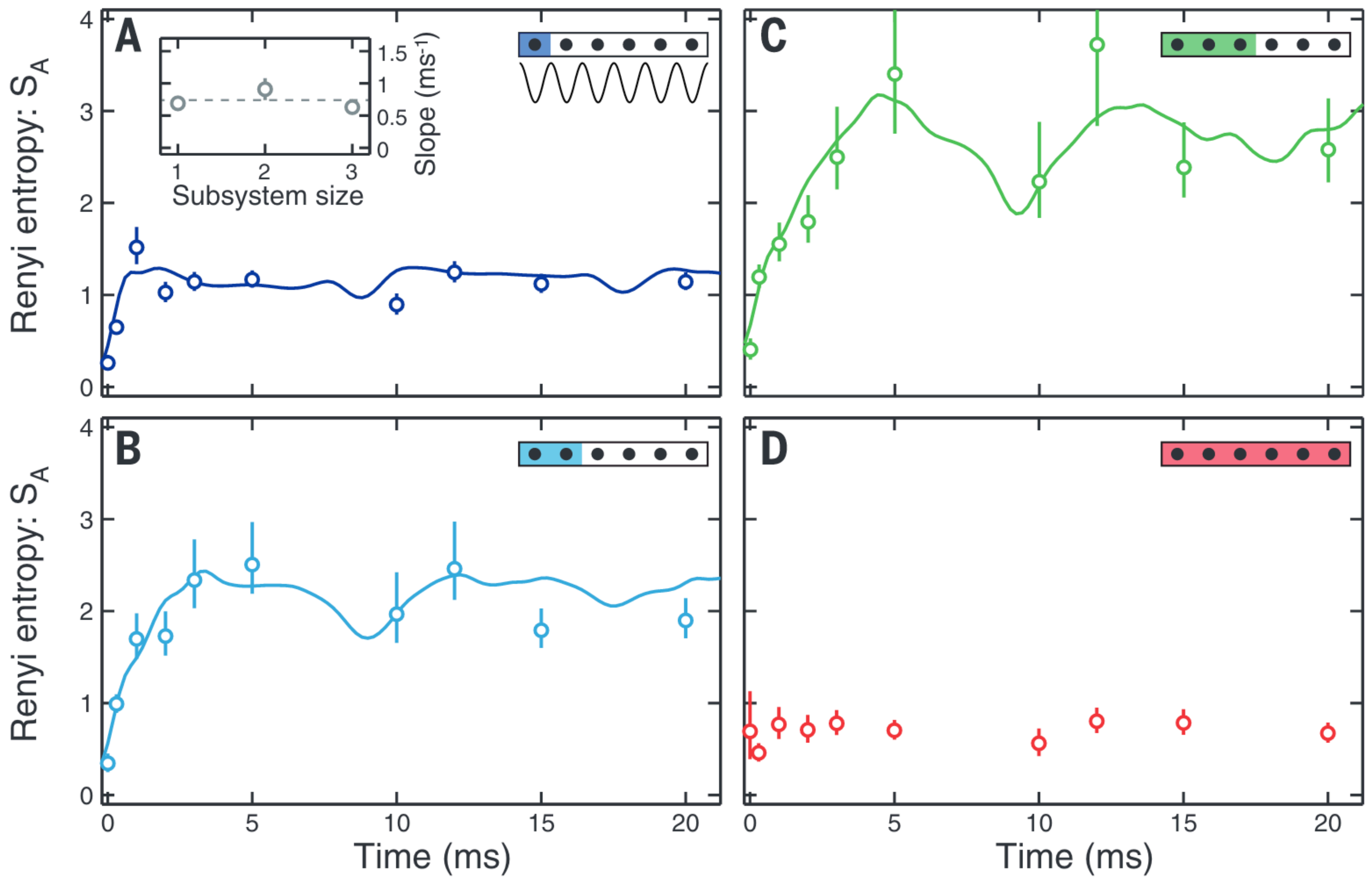
$$tr(\rho^2) = \langle \hat{P} \rangle = \langle \Pi_i p_i^{(k)} \rangle$$



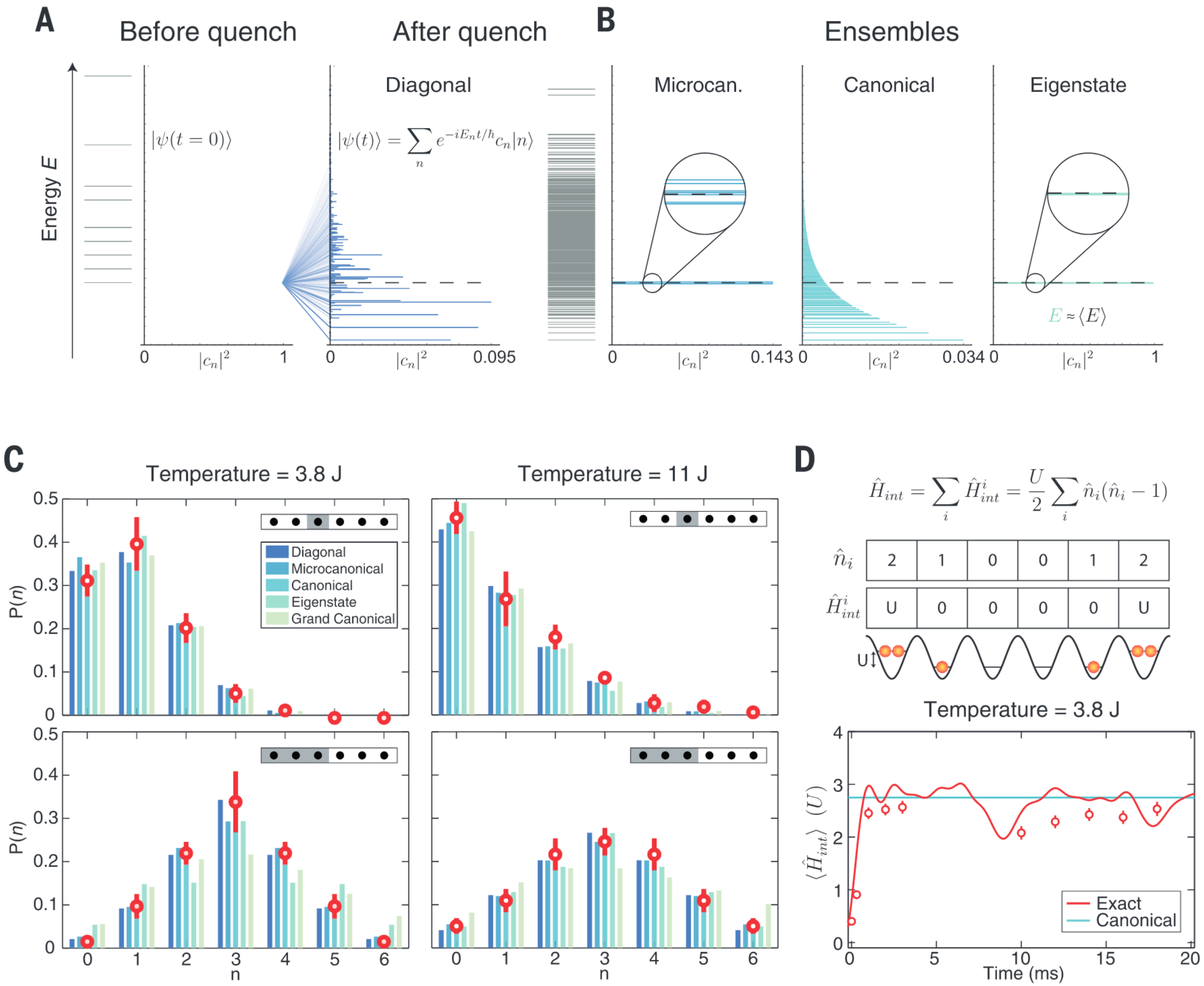
Thermalization in an Isolated QMB System



Thermalization in an Isolated QMB System



Thermalization in an Isolated QMB System



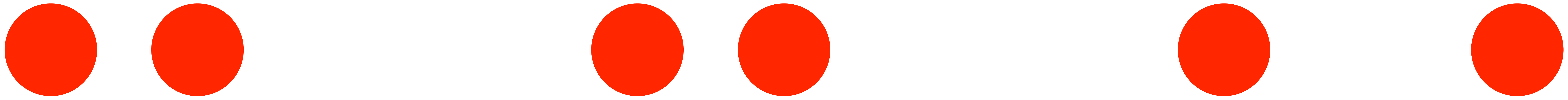
Promising: Double Quantum Advantage (in Space & Time)

But also challenging for experiments!

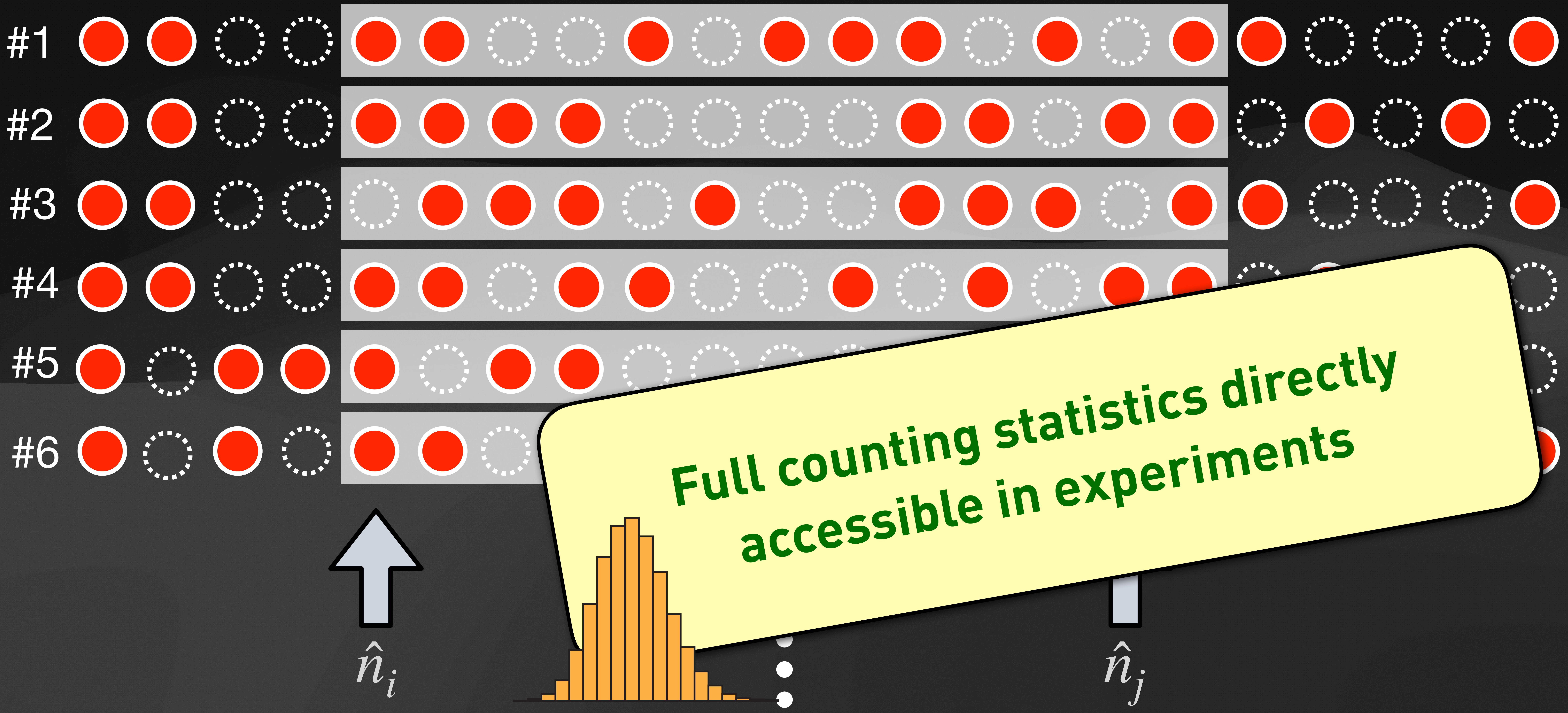
- Large System Sizes
- Homogeneous Systems
- Long Time Evolutions

$$e^{-i\hat{H}t/\hbar}$$

...Time evolution...



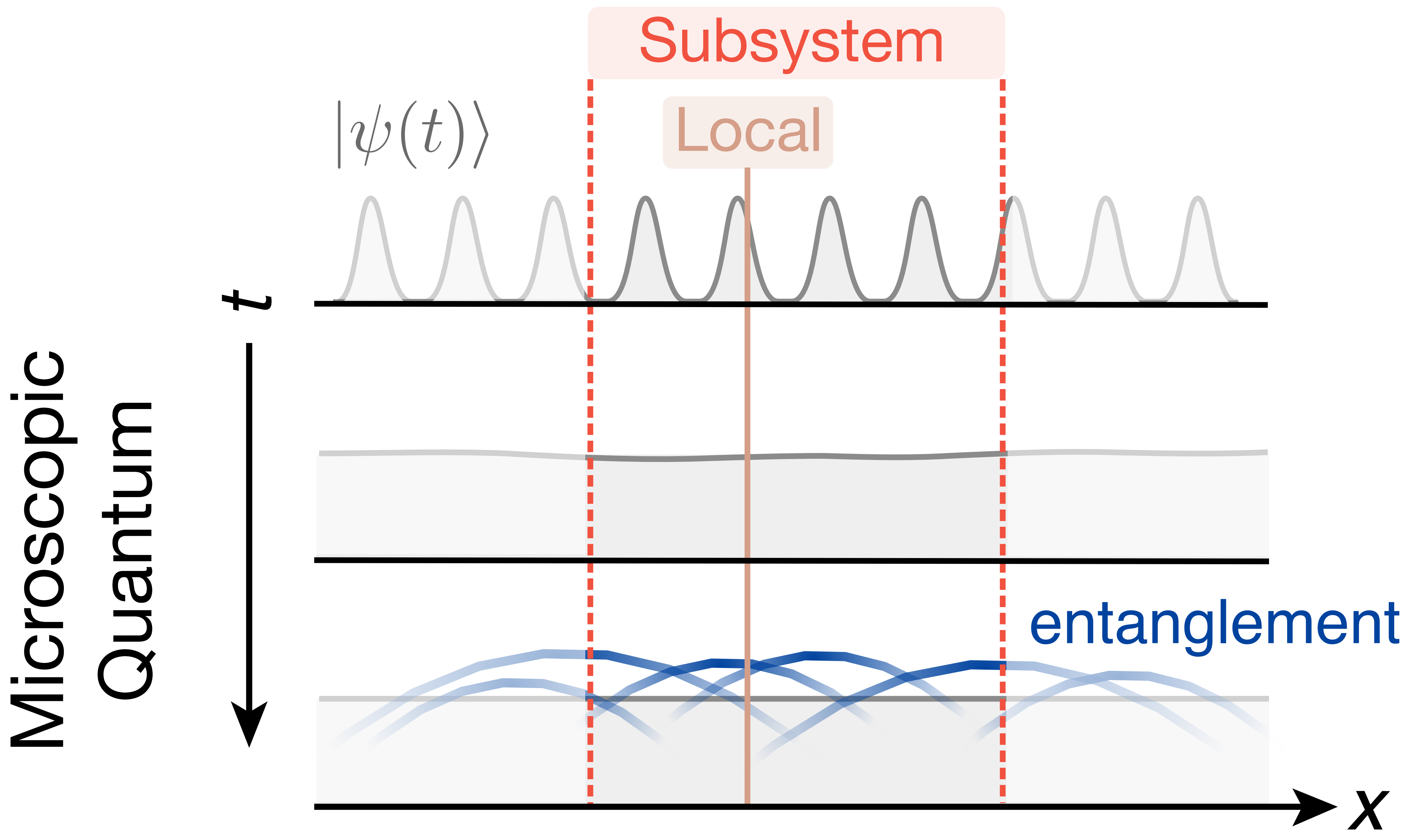
Quantum Transport - Atom-by-Atom

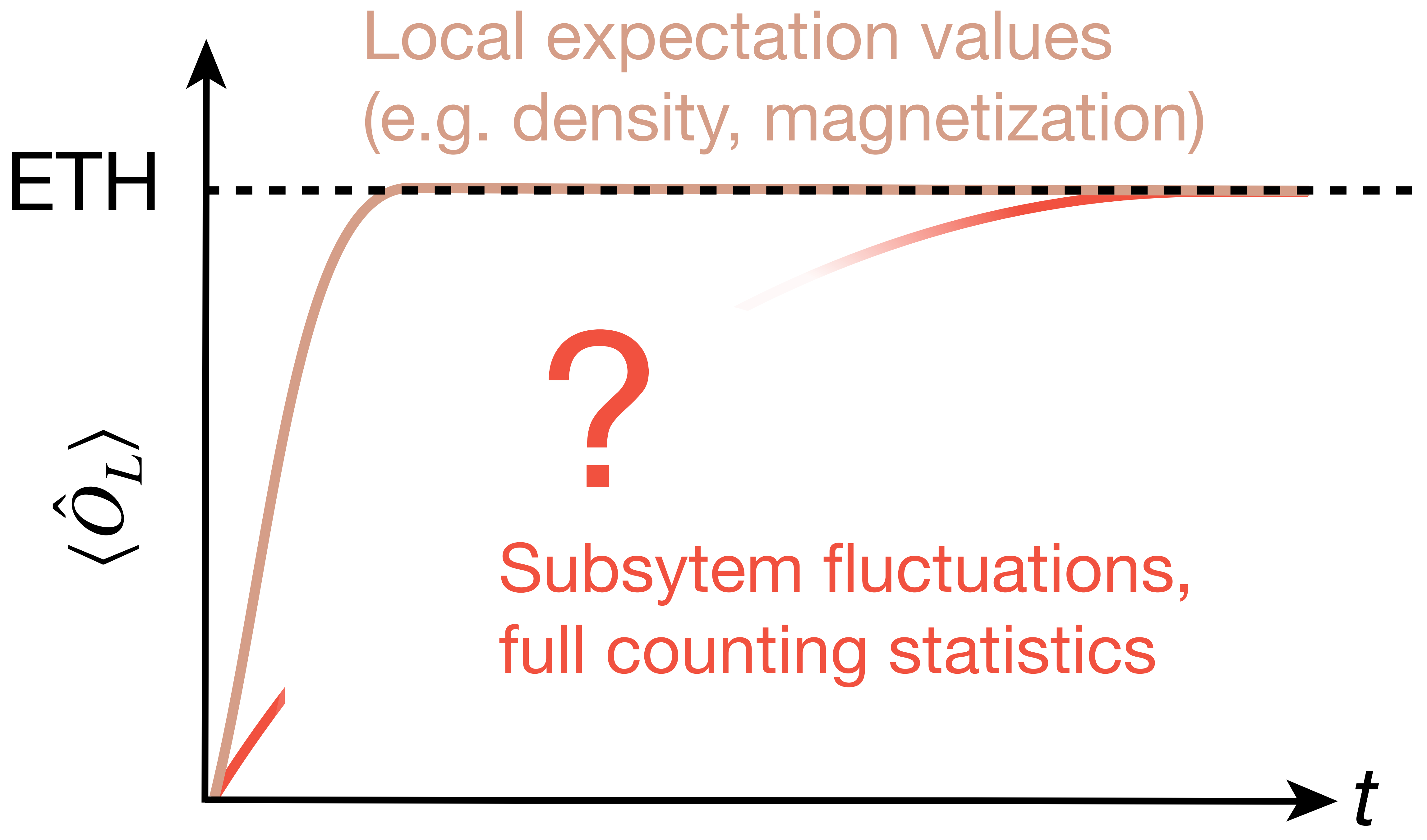


See also: (Endres group) J. Choi *et al.*, Nature **613**, 468 (2023)

Dynamics for Thermalisation

Stages of Dynamics





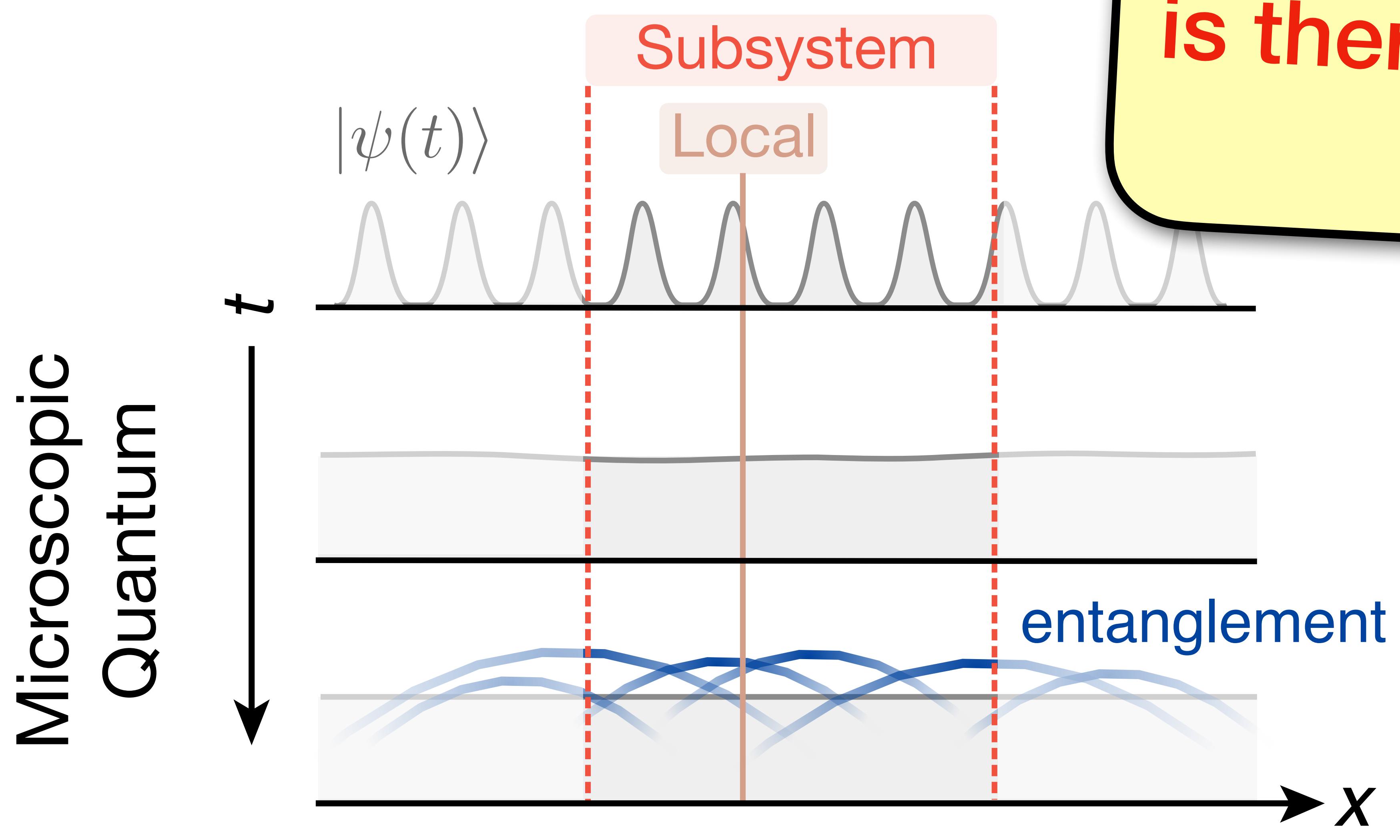
Eigenstate Thermalisation Hypothesis
J. M. Deutsch, Phys. Rev. A **43**, 2046 (1991).
M. Srednicki, Phys. Rev. E **50**, 888 (1994).
M. Rigol, V. Dunjko, and M. Olshanii, Nature **452**, 854 (2008).
R. Nandkishore, Phys. Rev. B **92**, 245141 (2015).
L. D'Alessio, Y. Kafri, A. Polkovnikov, and M. Rigol Adv. Phys. **65**, 239 (2016).

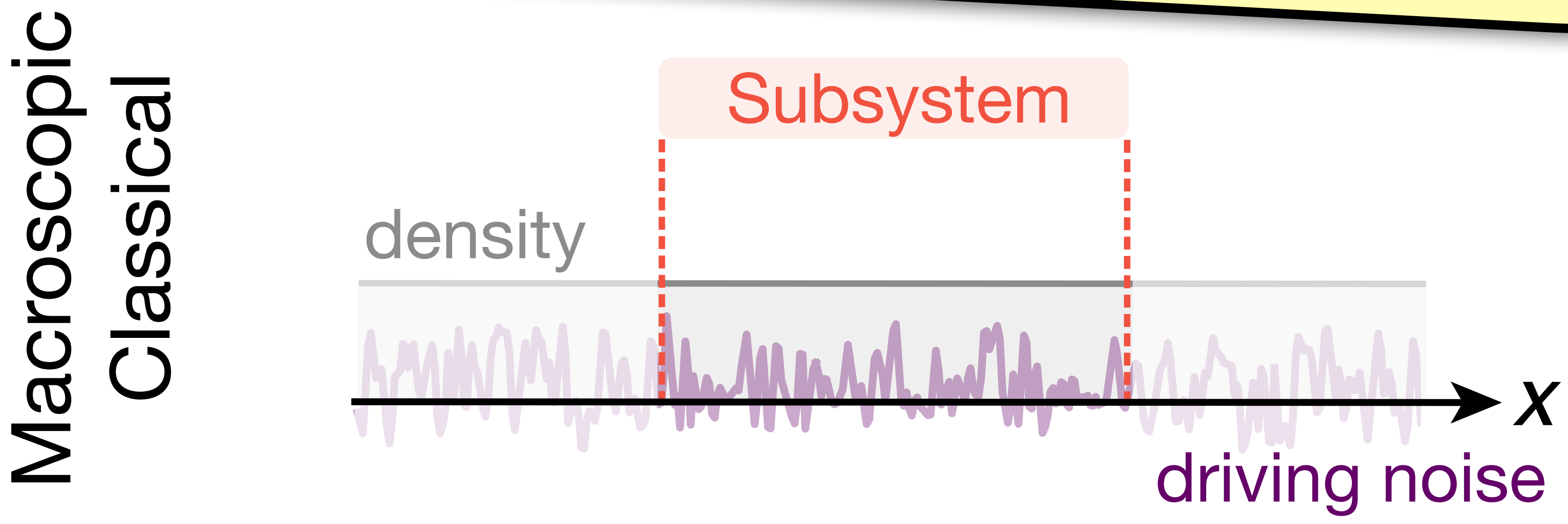
Experiments Thermalisation
A. M. Kaufman et al., Science **353**,794 (2016).

Dynamics for Thermalisation

Can this work for quantum systems as well ???
is there an emergent hydrodynamics of fluctuations

Stages of Dynamics





Classical Systems: Macroscopic Fluctuation Theory

$$\partial_t n + \partial_x j = 0, \quad j = -D(n)\,\partial_x n + \sqrt{2\,D(n)\,\chi(n)}\,\xi$$

Nonlinear stochastic PDE

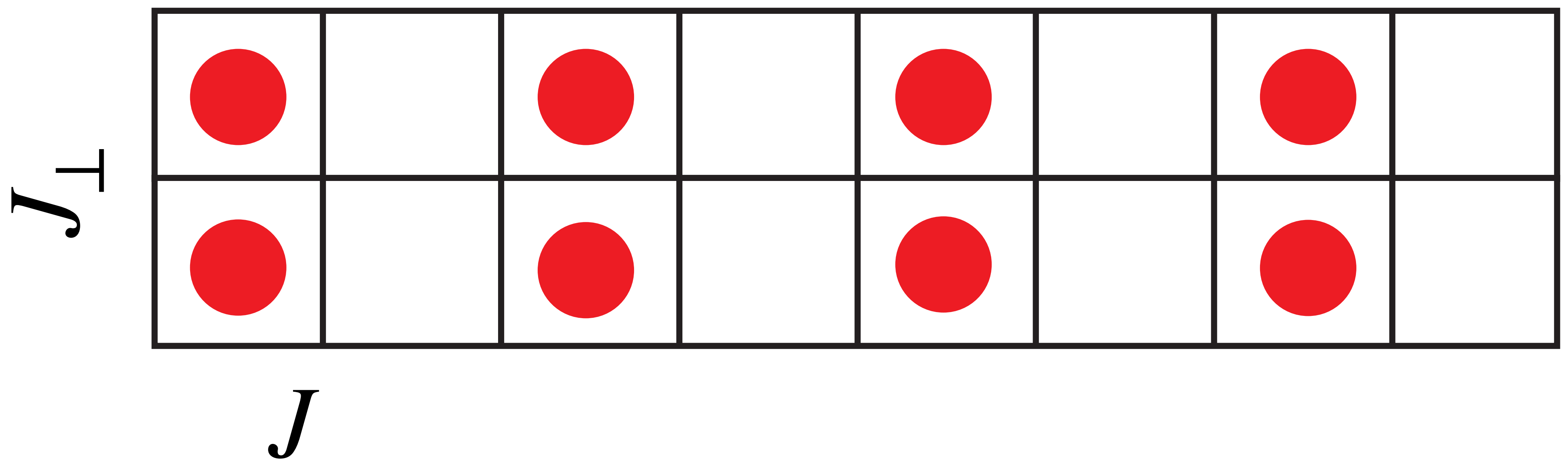
Bertini, L., De Sole, A., Gabrielli, D., Jona-Lasinio, G. & Landim, C.
Rev. Mod. Phys. **87**, 593–636 (2015).

Our System

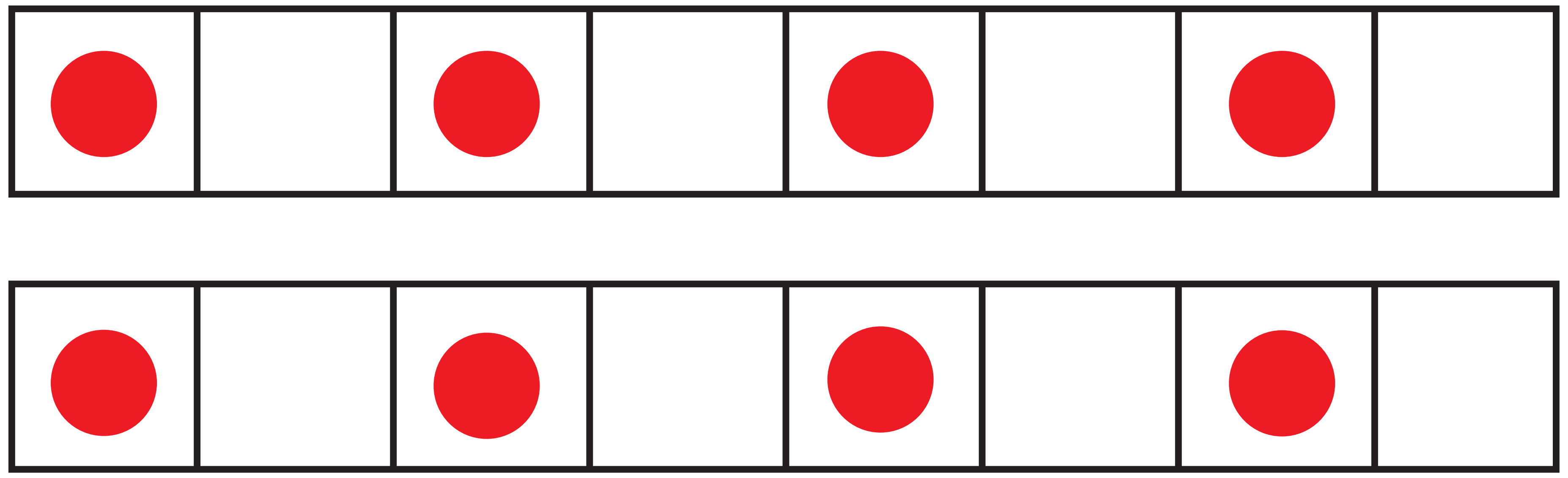
Hardcore bosons

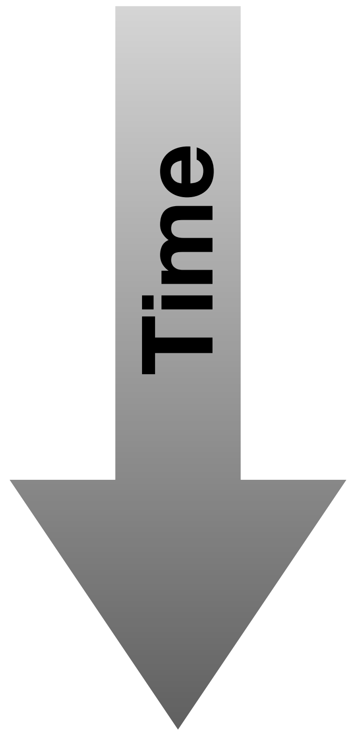
(on a ladder (2x50 sites) with tunable coupling)

Coupled ladders (interacting)

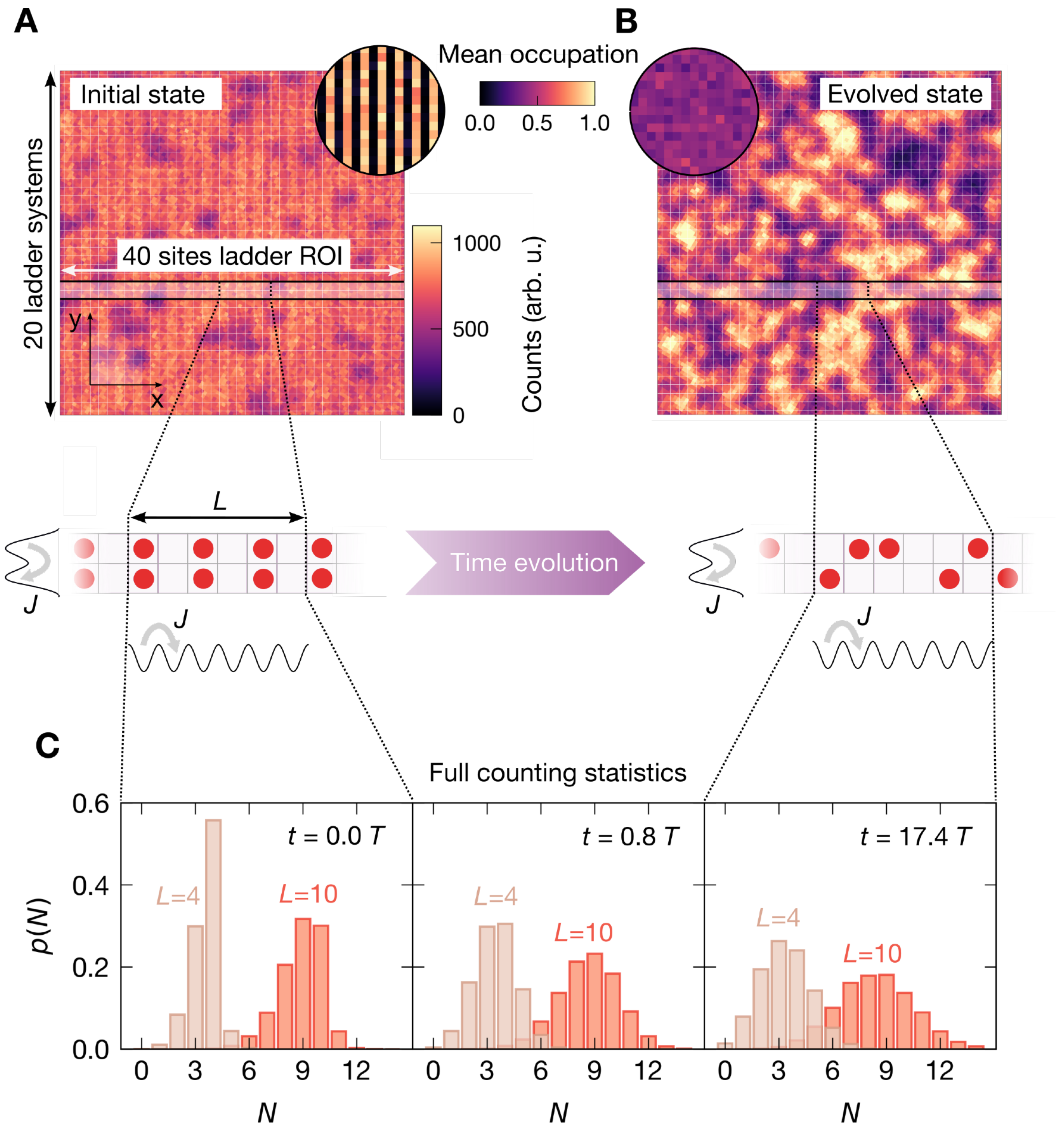


1d chains (free fermions)





Thermalisation: Integrable vs. Chaotic

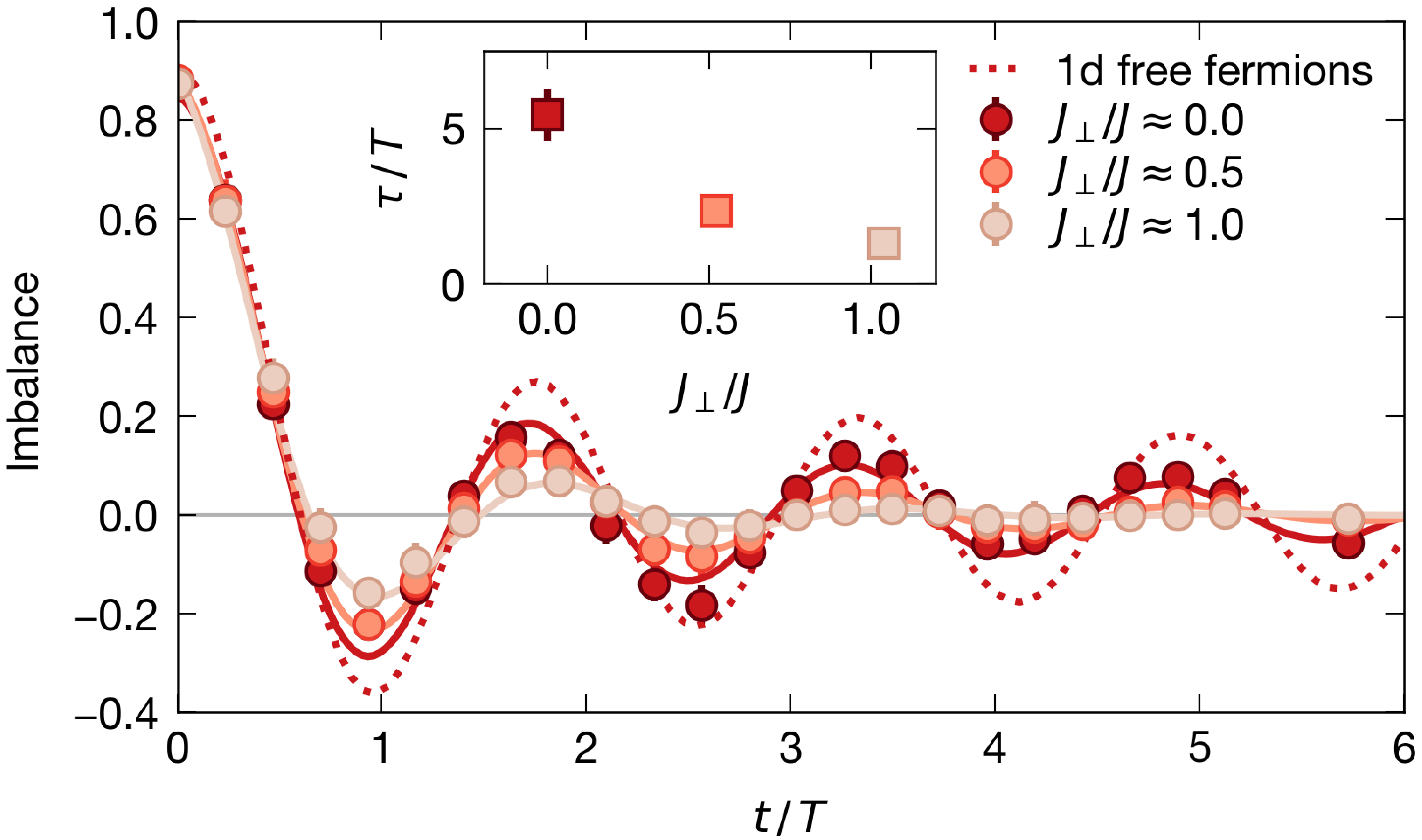


Hardcore bosons (tuneable ladder coupling)

Full counting statistics on different subsystem sizes

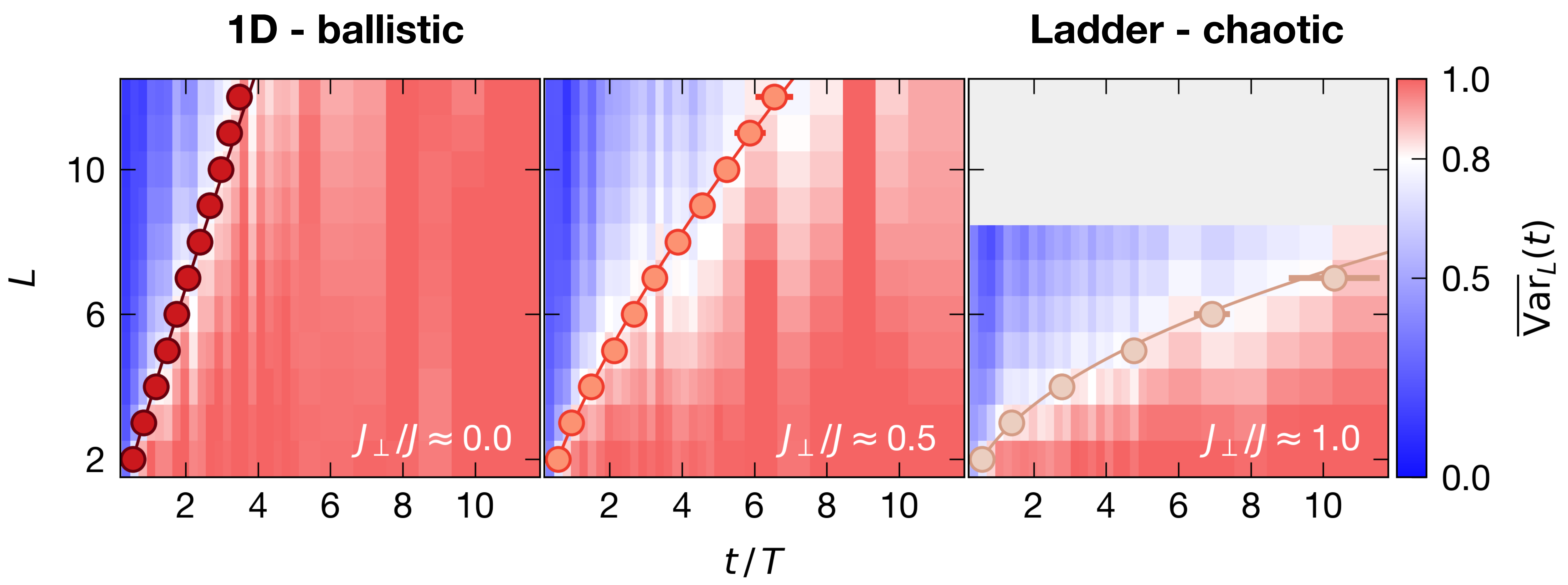
Related:
A.M. Kaufman *et al.*
Science **353**, 794 (2016)
and thermalisation
experiments by D. Weiss (PennState)

Local equilibration



See also: S. Trotzky *et al.* Nat. Phys. **8**, 325 (2012)

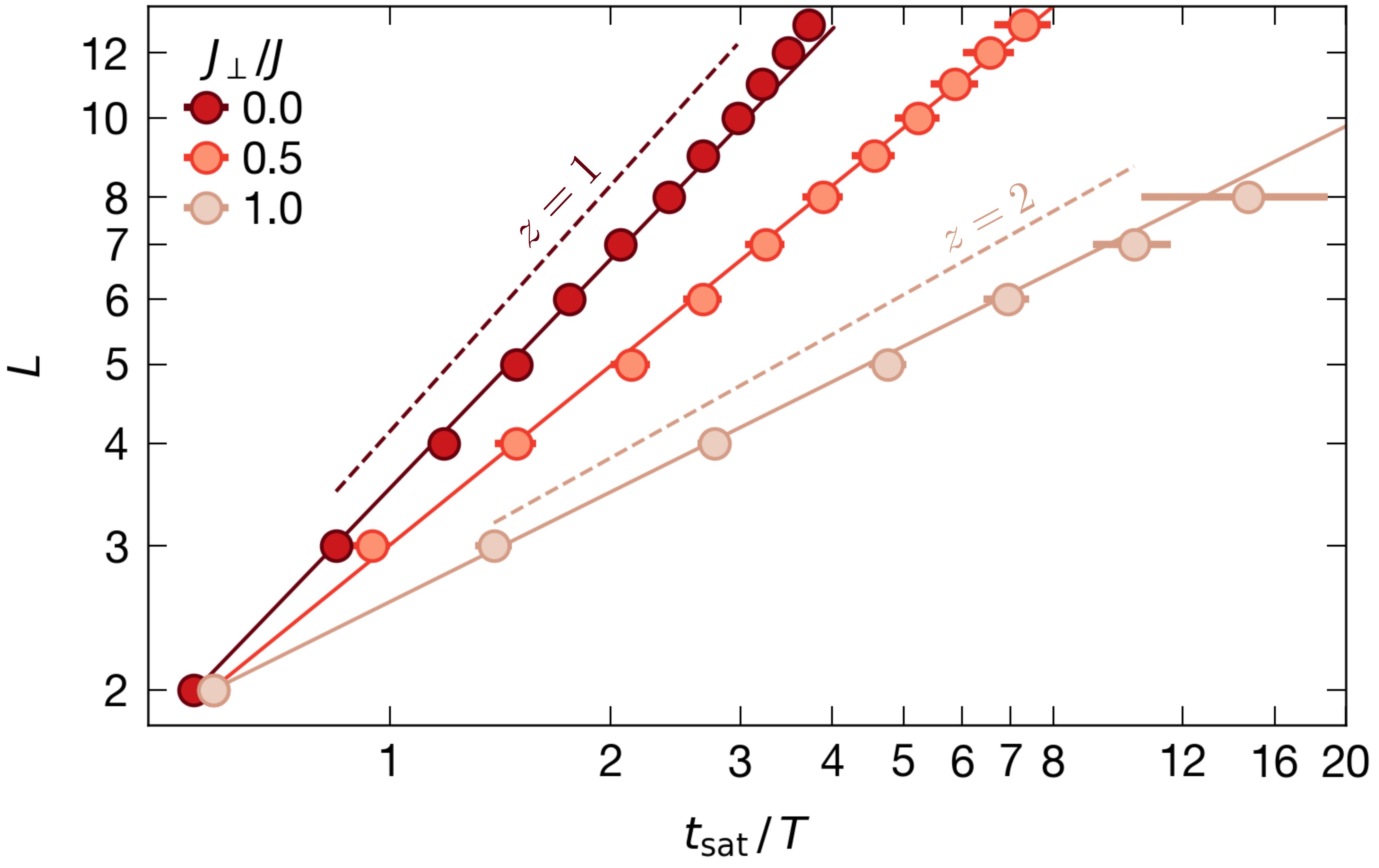
Subsystem fluctuations



$$\mathrm{Var}_L(t) \approx \sqrt{\frac{2Dt}{\pi a^2}}$$

MFT prediction

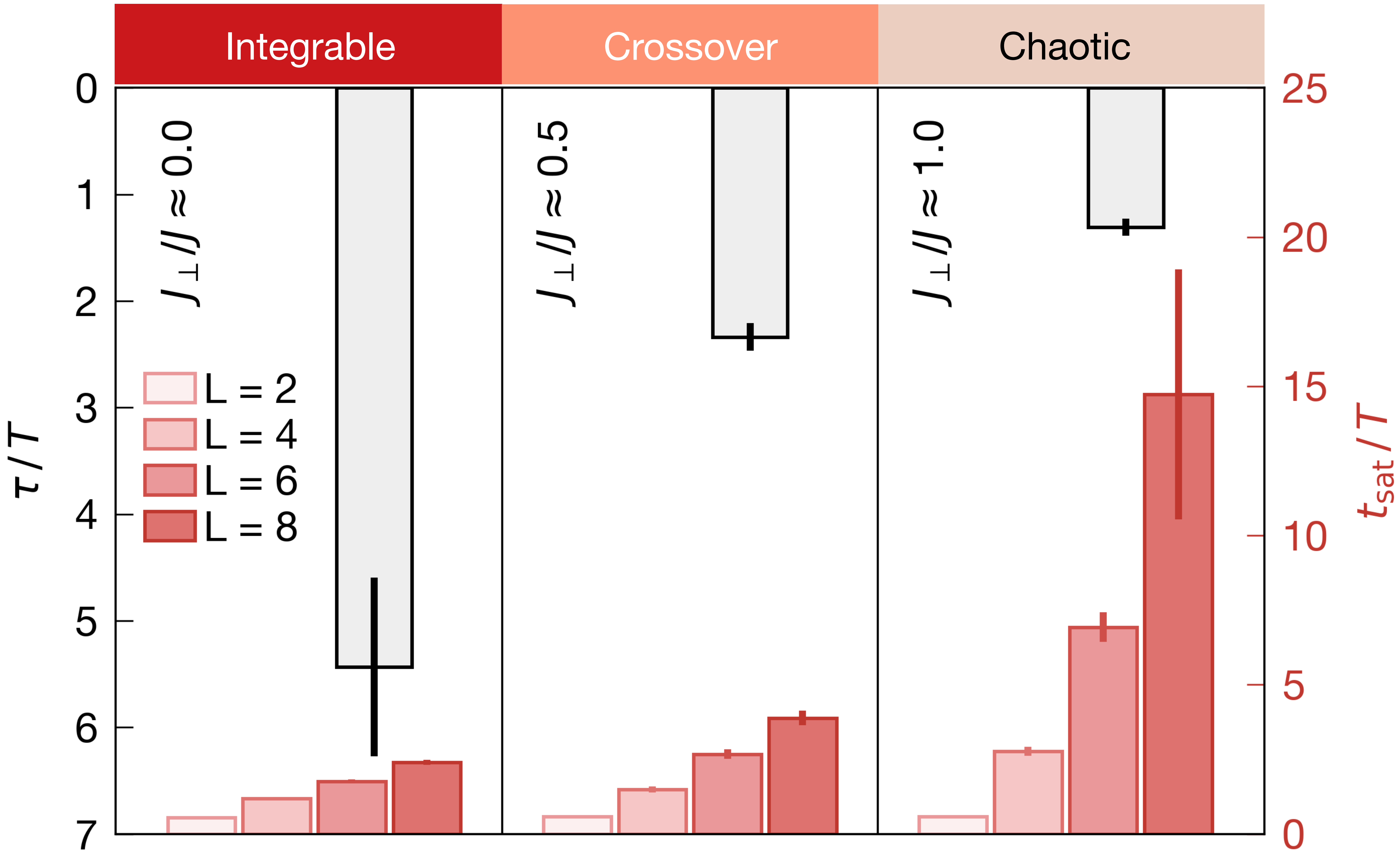
- Enables quantitative determinatio[n] of **dynamical exponent z** and **diff**[…] **constant**
- **Global equilibrations** takes longer and longer for larger subsystem



$$L \propto t_{sat}^{1/z}$$

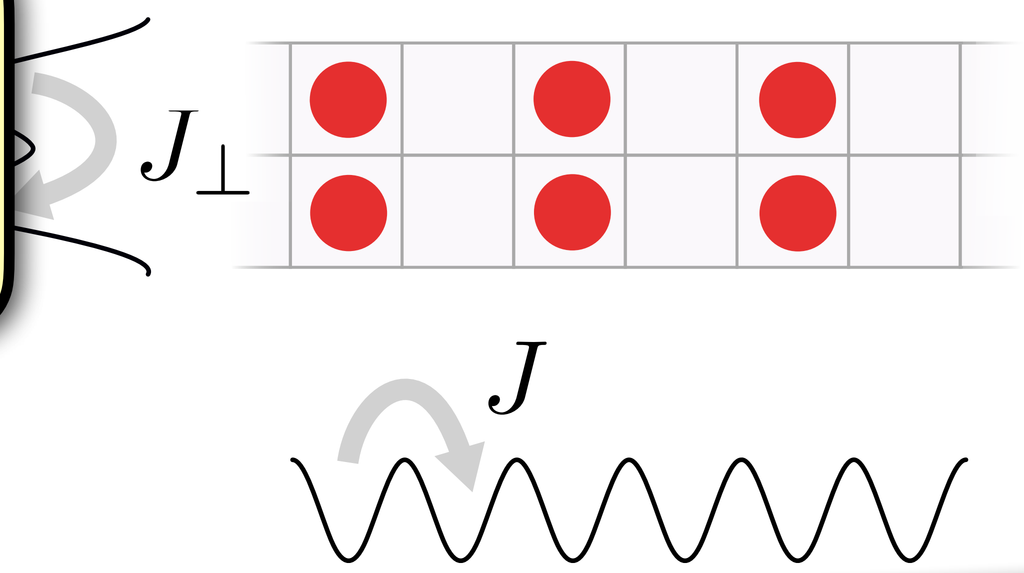
Determination of dynamical exponent

Timescales - Integrable to Chaotic



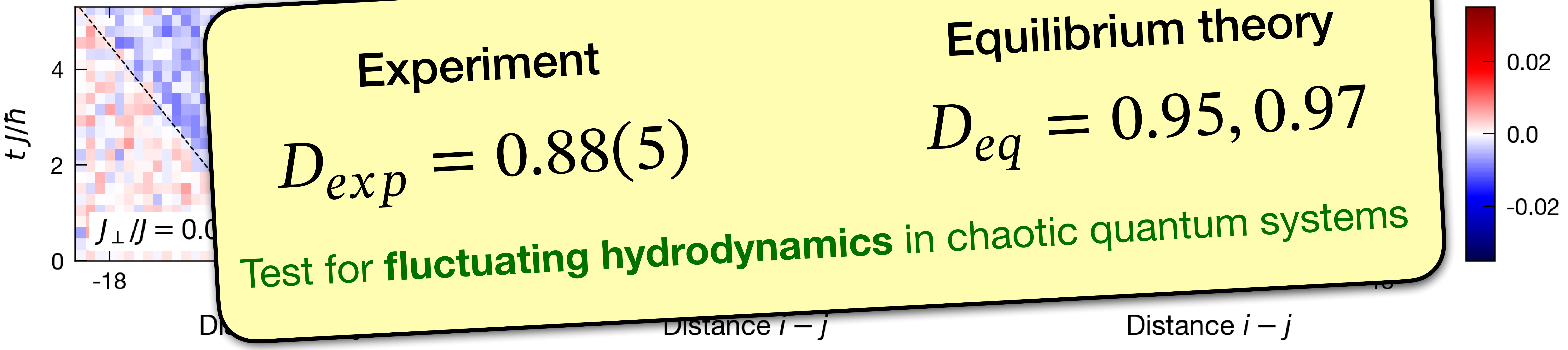
Density-Density Correlations

$$C(i-j) = \langle \hat{N}_i \hat{N}_j \rangle - \langle \hat{N}_i \rangle \langle \hat{N}_j \rangle$$



Hardcore bosons
(tuneable ladder coupling)

Integrable (free fermions)



Experiment

$$D_{exp} = 0.88(5)$$

Equilibrium theory

$$D_{eq} = 0.95, 0.97$$

Test for **fluctuating hydrodynamics** in chaotic quantum systems

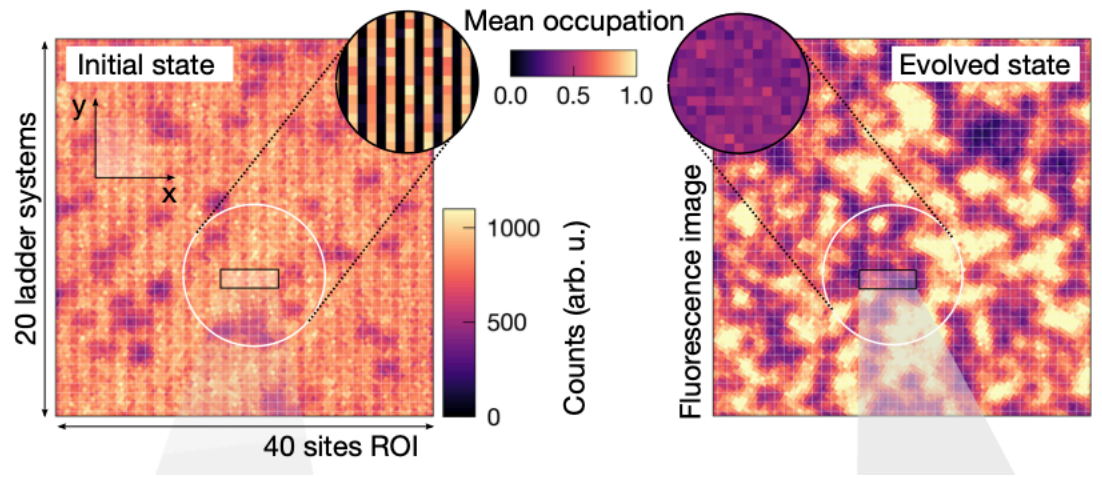
Rung Density-Density Correlations

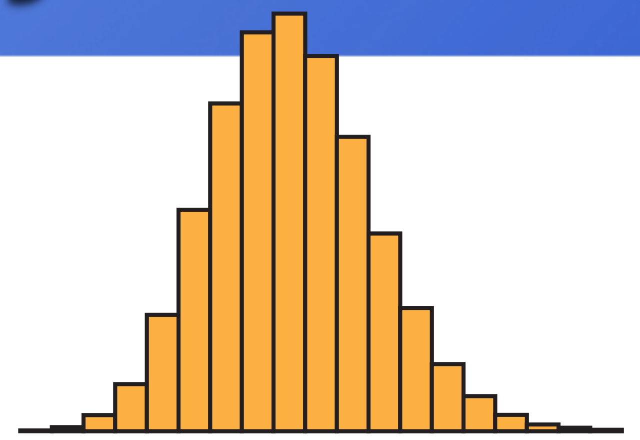
See also:
M. Cheneau, ..., I. Bloch, S. Kuhr, Nature (2012)
Y.-G. Zheng, ..., Z.-S. Yuan, J.-W. Pan, arXiv:2210.08556

Equilibrium transport theory:
R. Steinigeweg et al., Phys. Rev. B (2014)
T. Rakovszky, C. W. von Keyserlingk & F. Pollmann Phys. Rev. B (2022)

LMU

Summary Slide - Fluctuation Hydrodynamics





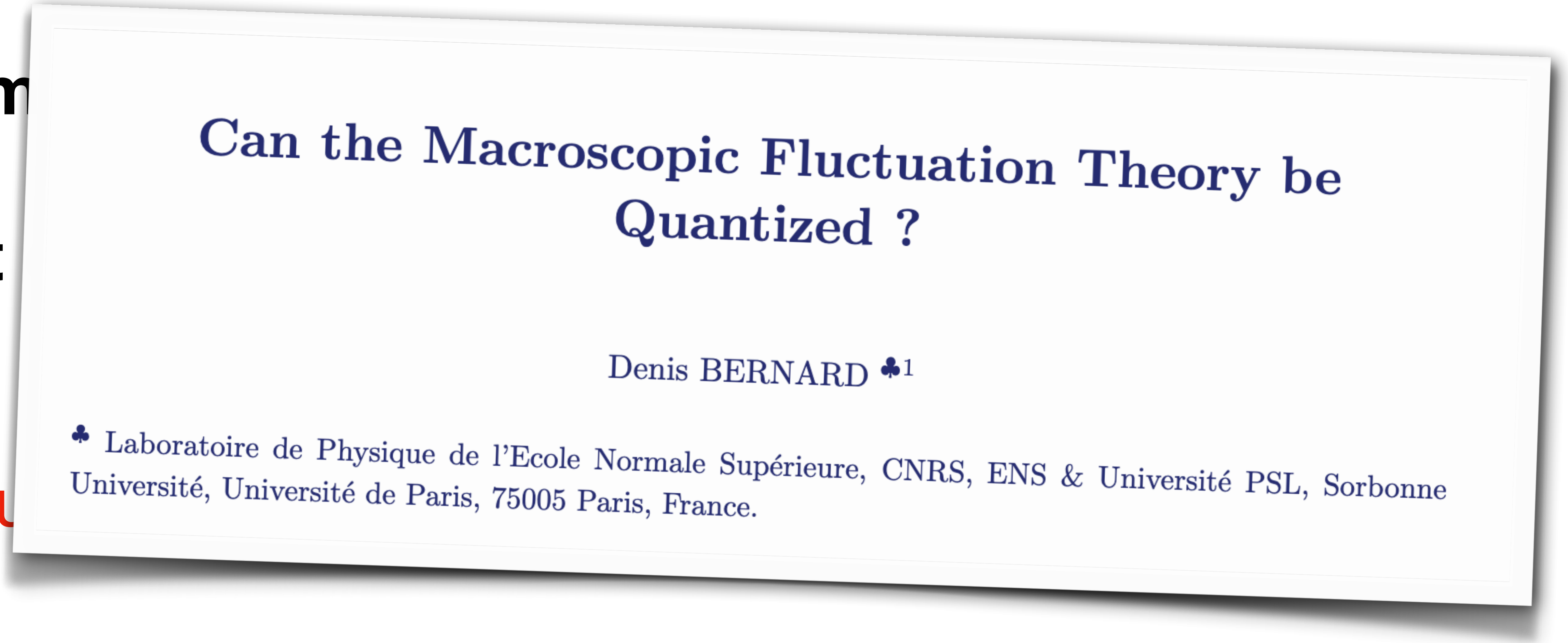
- **Full counting statistic / fluctuations** powerful new observables for quantum transport

- **(Nonlinear) Noisy classical dynamics** can efficiently describe **charge fluctuation dynamics in chaotic quantum many-body systems** via MFT

- Test of **fluctuation-dissipation theorem**

- Determination of **equilibrium transport** through out-of-equilibrium dynamics

- When does MFT fail? Higher order cumu



Can the Macroscopic Fluctuation Theory be Quantized ?

Denis BERNARD ♣1

♣ Laboratoire de Physique de l'Ecole Normale Supérieure, CNRS, ENS & Université PSL, Sorbonne Université, Université de Paris, 75005 Paris, France.

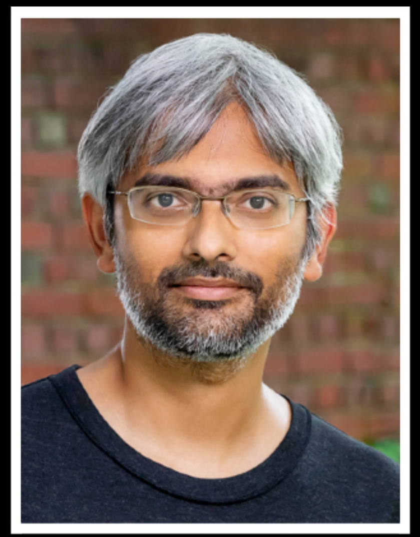
Random Unitary Circuits: E. McCulloch, J. De Nardis, S. Gopalakrishnan & R. Vasseur Full arXiv:2302.01355
Quantising MFT: D. Bernard J. Phys. A: Math. Theor. 54, 433001 (2021).

KPZ Spin Transport in Heisenberg Quantum Magnets

Numerical Evidence

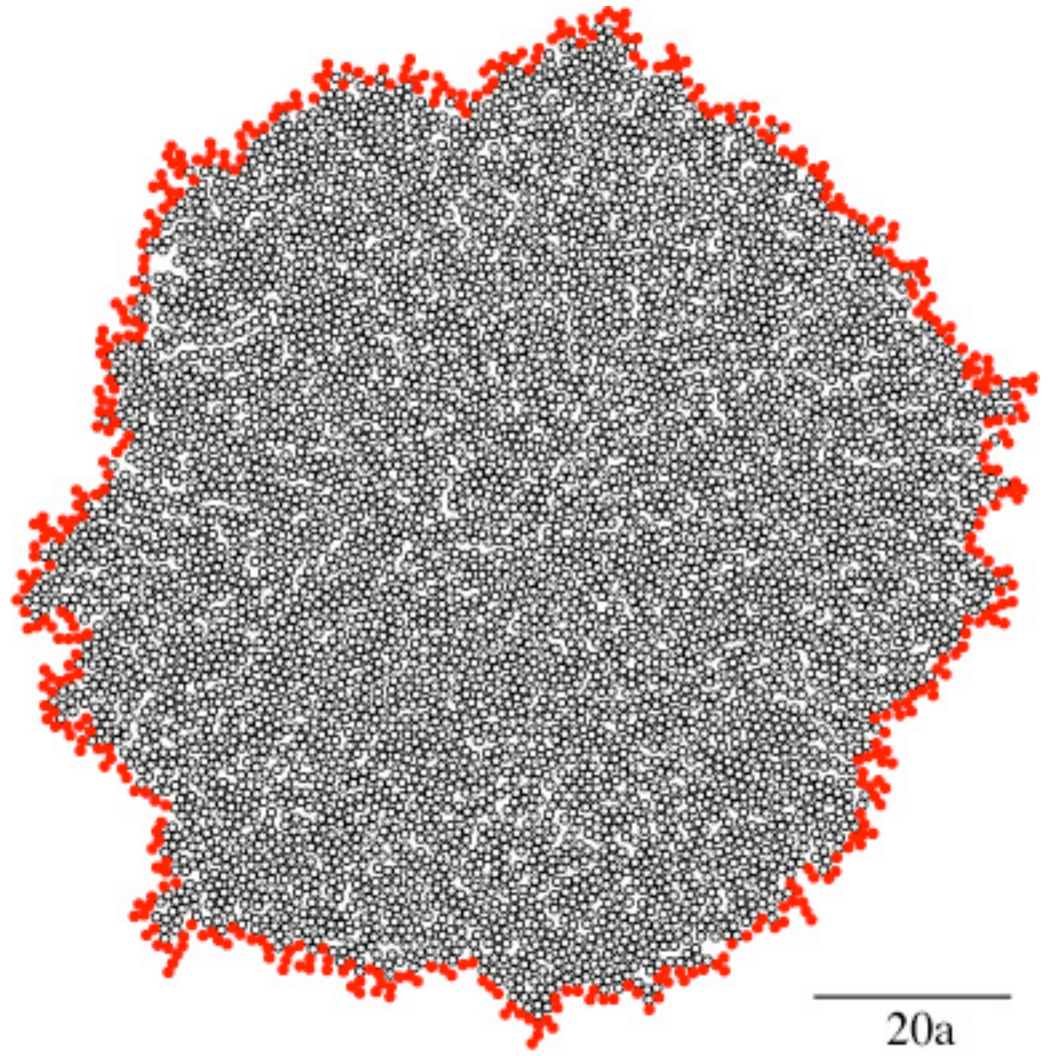
M. Ljubotina et al., Nature Comm. (2017)
M. Ljubotina et al., Phys. Rev. Lett. (2019)
Review: see V. Bulchadini, S. Gopalakrishnan, E. Ilievski J. Stat. Mech. 084001 (2021)

Experiment & Theory



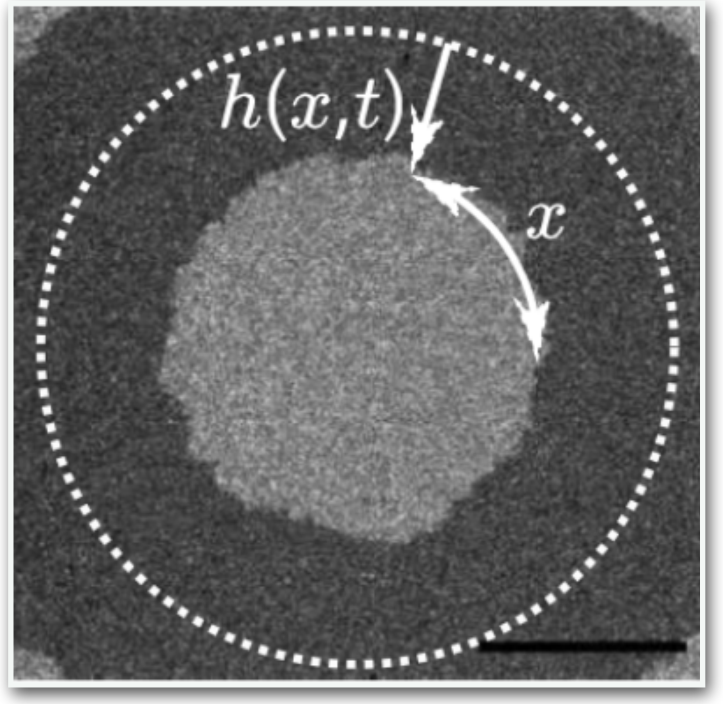
Experiment: D. Wei, A. Rubio-Abadal, K. Srakaew, C. Gross, J. Zeiher, I.B.
Theory: B. Ye , F. Machado, J. Kemp. N. Yao & S. Gopalakrishnan
Science **376**, 716–720 (2022)
See also: E. Rosenberg et al arXiv:2306.11457 (Google)

Growth of Interfaces



Bacterial/Tumor Growth
(Eden Growth Process)

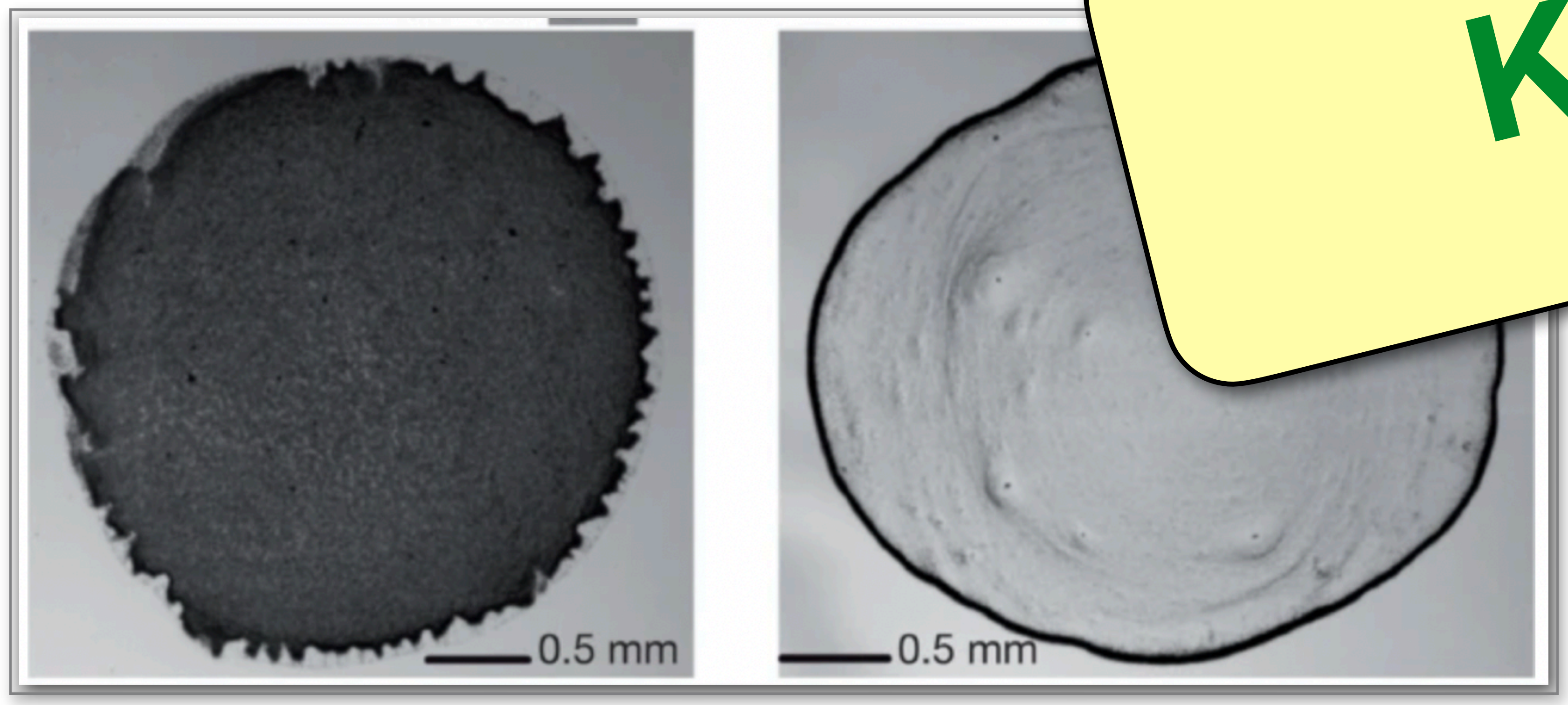
Liquid Crystals
Takeuchi PRL 2020



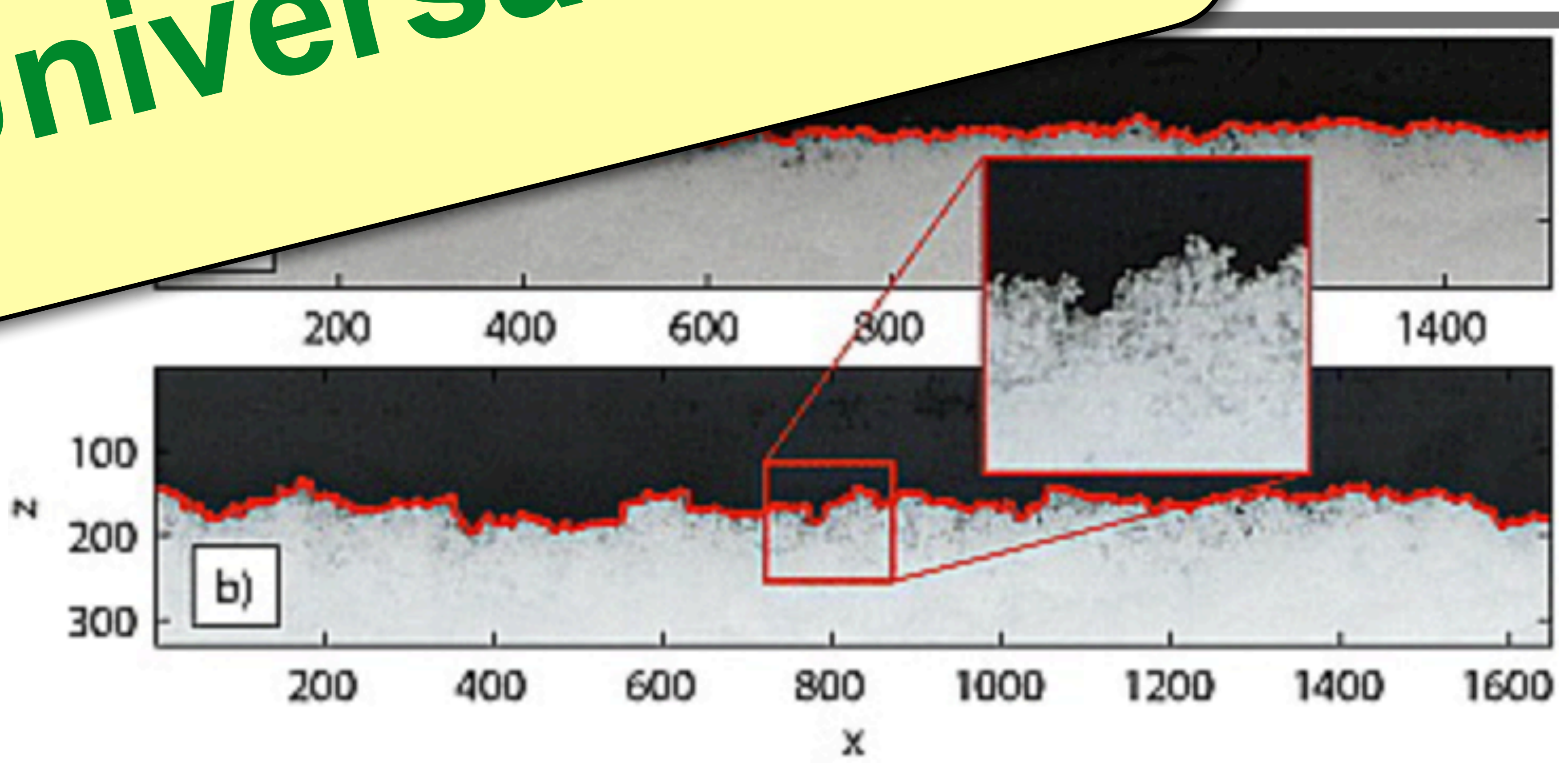
Traffic flow
de Gier *et al.* PRE 2019

ire, Forest Fires
Burning Paper

KPZ Universality!

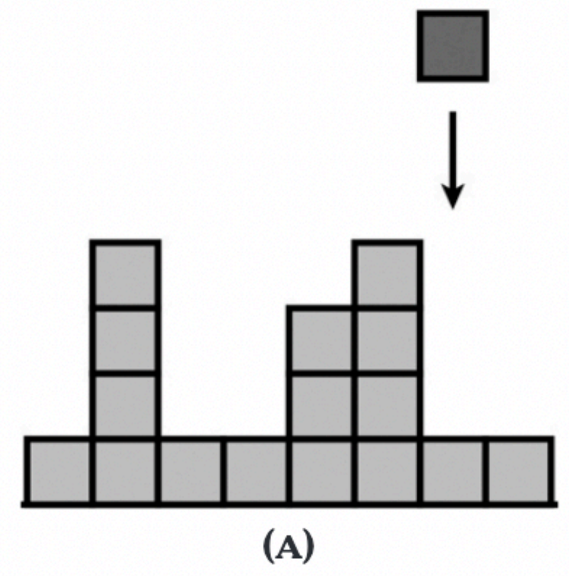


Coffee Stains Funker
Yunker *et al.* Nature 2021

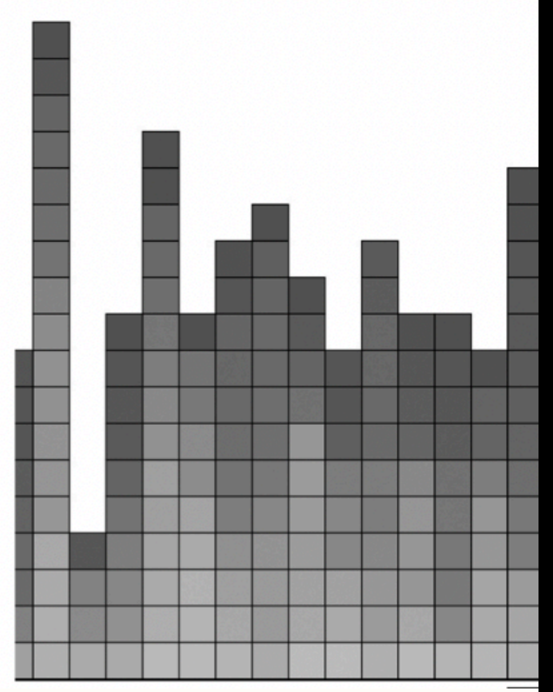


Snow Surfaces

Growth of Interfaces

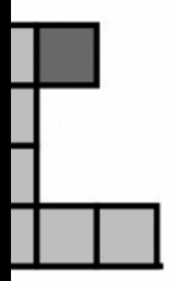


Random [redacted]
(non-stic[redacted]

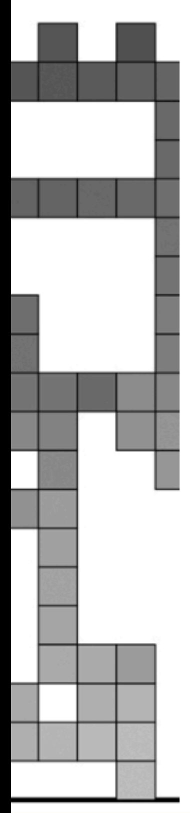


Random D[redacted]
(non-stick[redacted]

[redacted]



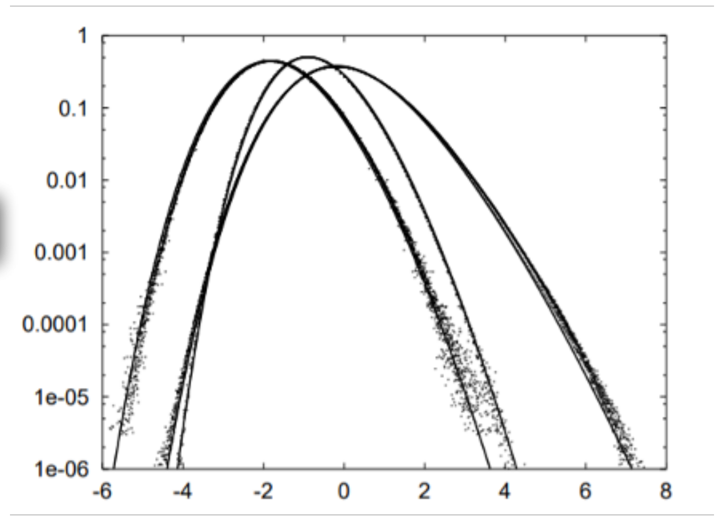
[redacted]on



[redacted]on
[redacted]

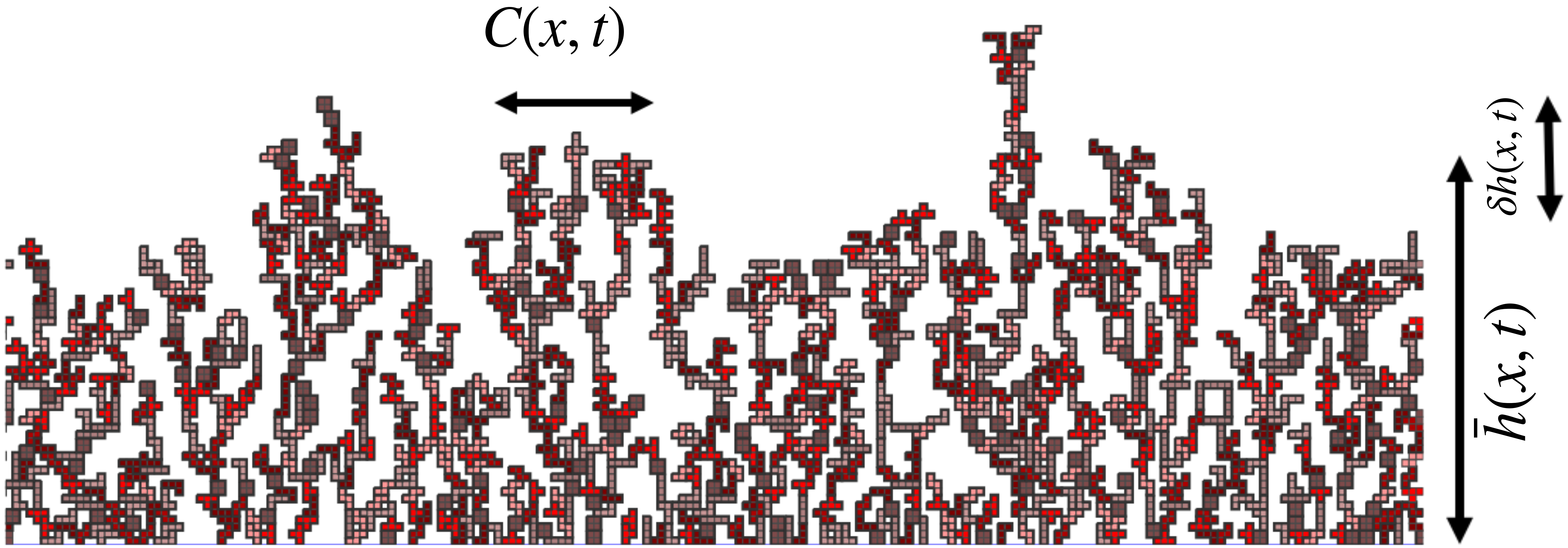
KPZ Universality Class (1D)

$$h(x,t) \simeq v_\infty t + A t^{1/3} \chi(X,t)$$



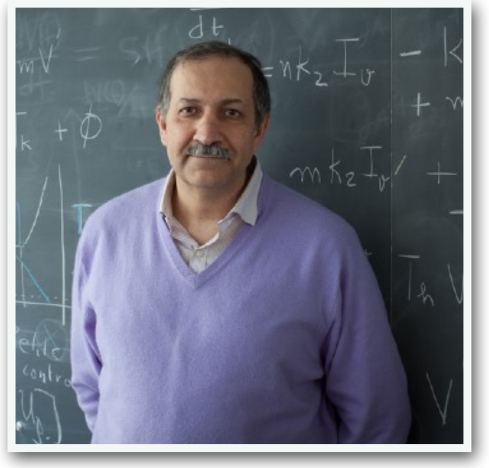
KPZ Universality Class

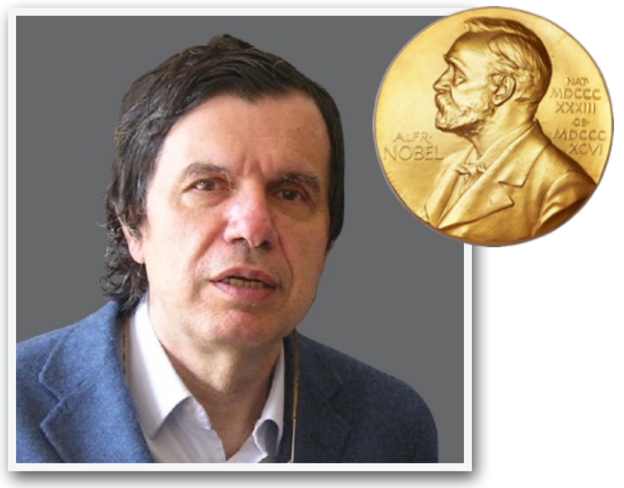
- $t^{1/3}$ height fluctuation with **GOE/GUE Tracy-Widom** Limit
- $t^{2/3}$ transv. spatial correlations



$$\delta h \propto t^{\beta} \qquad \beta = 1/3$$
$$\xi \propto t^{1/z} \qquad z = 3/2$$

I. Corwin, Notices of the AMS **63**, 230 (2016)
K. Takeuchi Physica A **504,** 77 (2018)





Kardar-Parisi-Zhang Equation

$$\frac{\partial h(\vec{x},t)}{\partial t} = \nu \nabla^2 h + \frac{\lambda}{2}(\nabla h)^2 + \eta(\vec{x},t)$$

Martin Hairer
Fields Medal
(2014)

Non-linear stochastic differential equation describing **temporal change of height field**

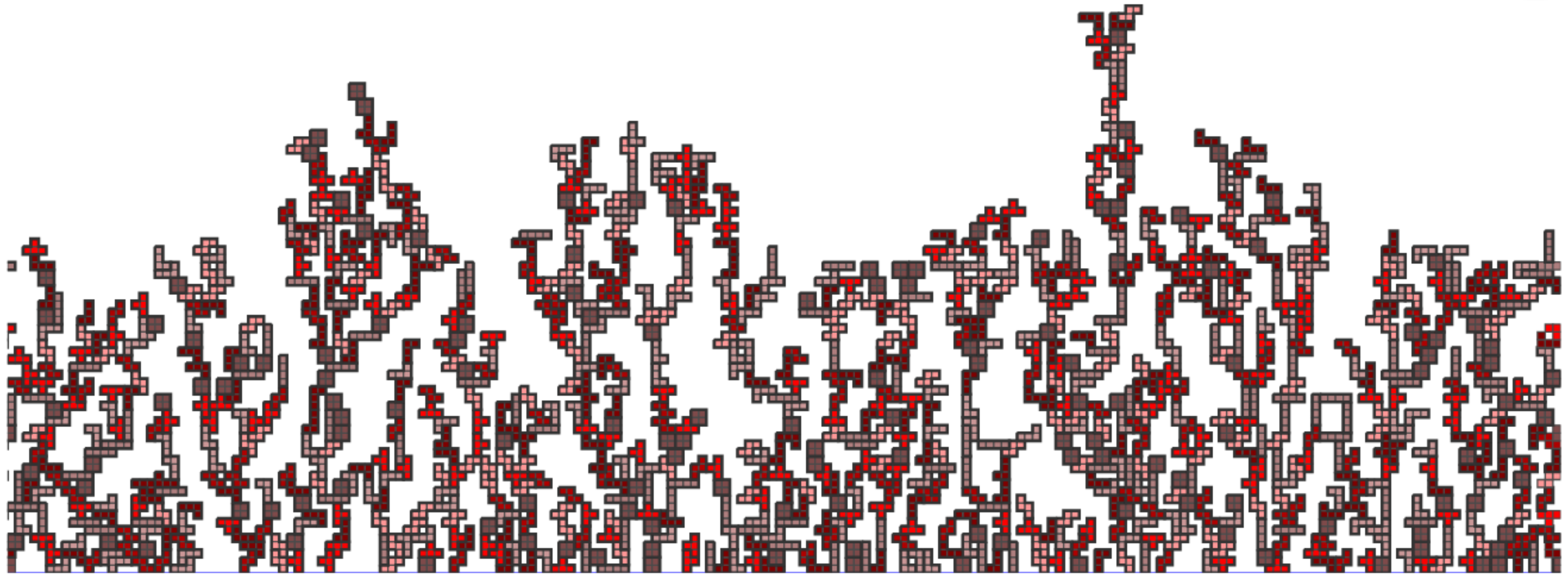
M. Kardar, G. Parisi & Y.-C. Zhang PRL **56,** 889 (1986)

C.A. Tracy & H. Widom Comm. Math. Phys. **159,** 151 (1994)

C.A. Tracy & H. Widom Comm. Math. Phys. **177,** 727 (1994)

M. Prähofer & H. Spohn PRL **84**, 4882 (2000)

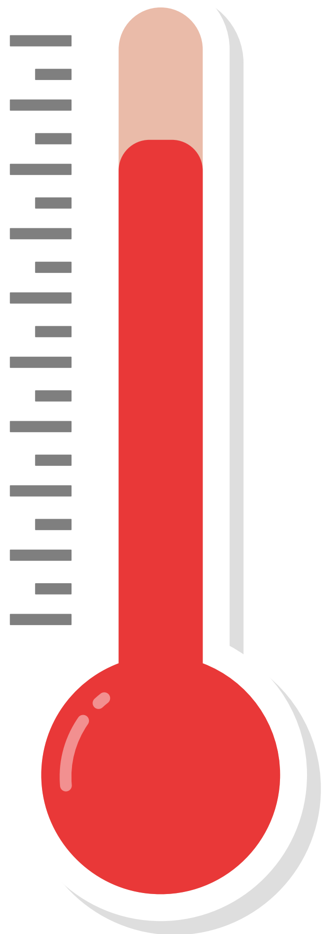
$$\hat{S}^z(x,t) \sim \partial_x h(x,t)$$



Growth of interfaces/surface growth

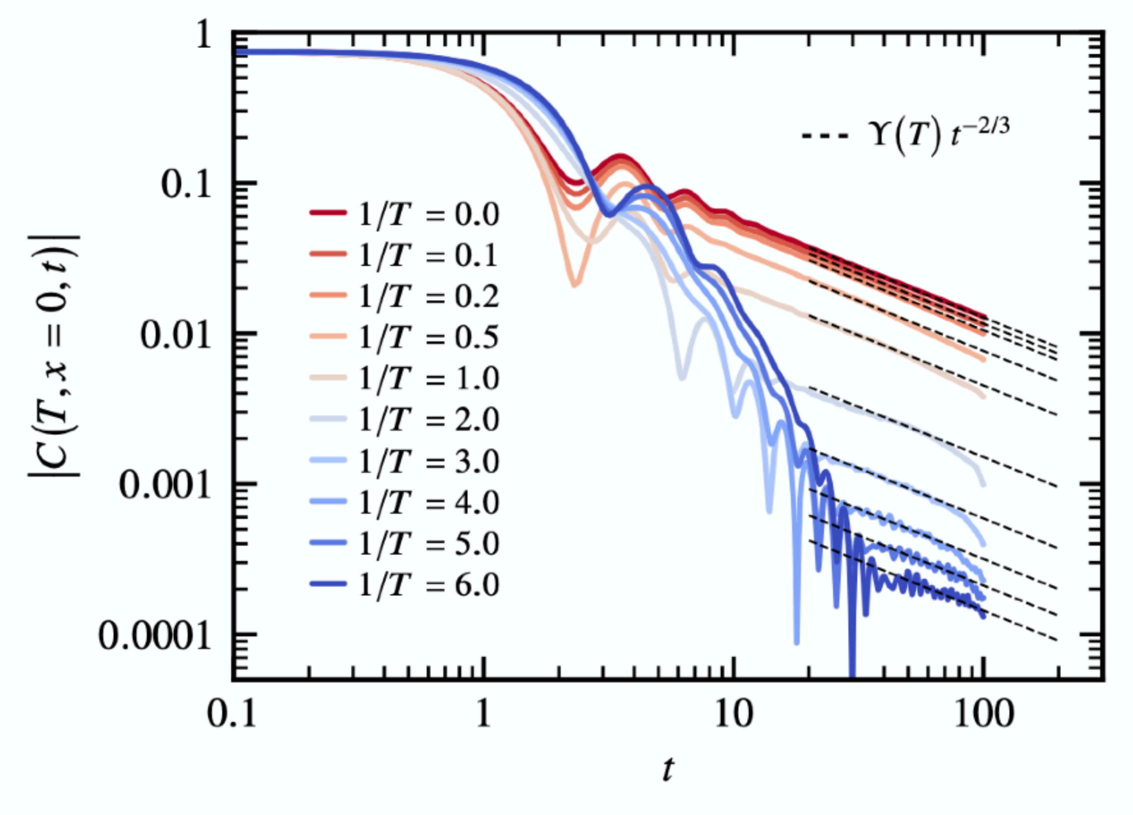
I. Corwin, Notices of the AMS **63**, 230 (2016)

KPZ Universality

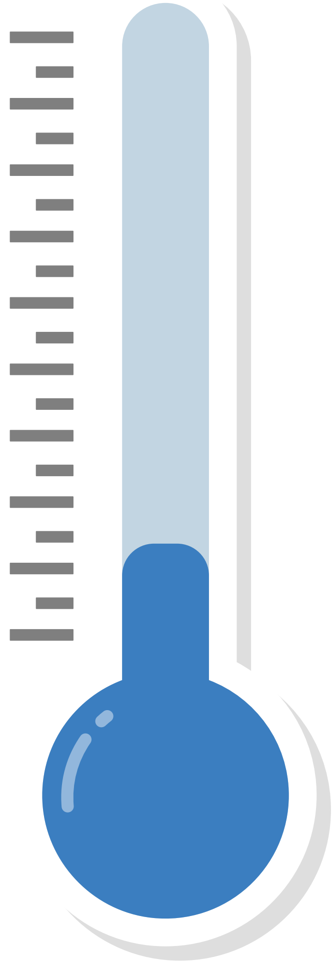


High (Infinite) T
Low-q, Long Times

Crossover
M. Dupont, N.E. Sherman &
J.E. Moore PRL 2021



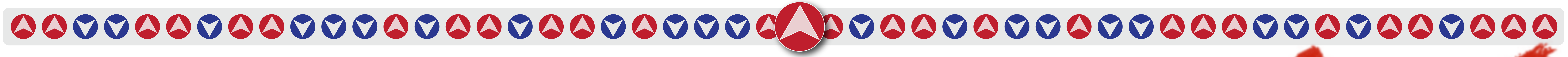
Tomanaga-Luttinger Liquid

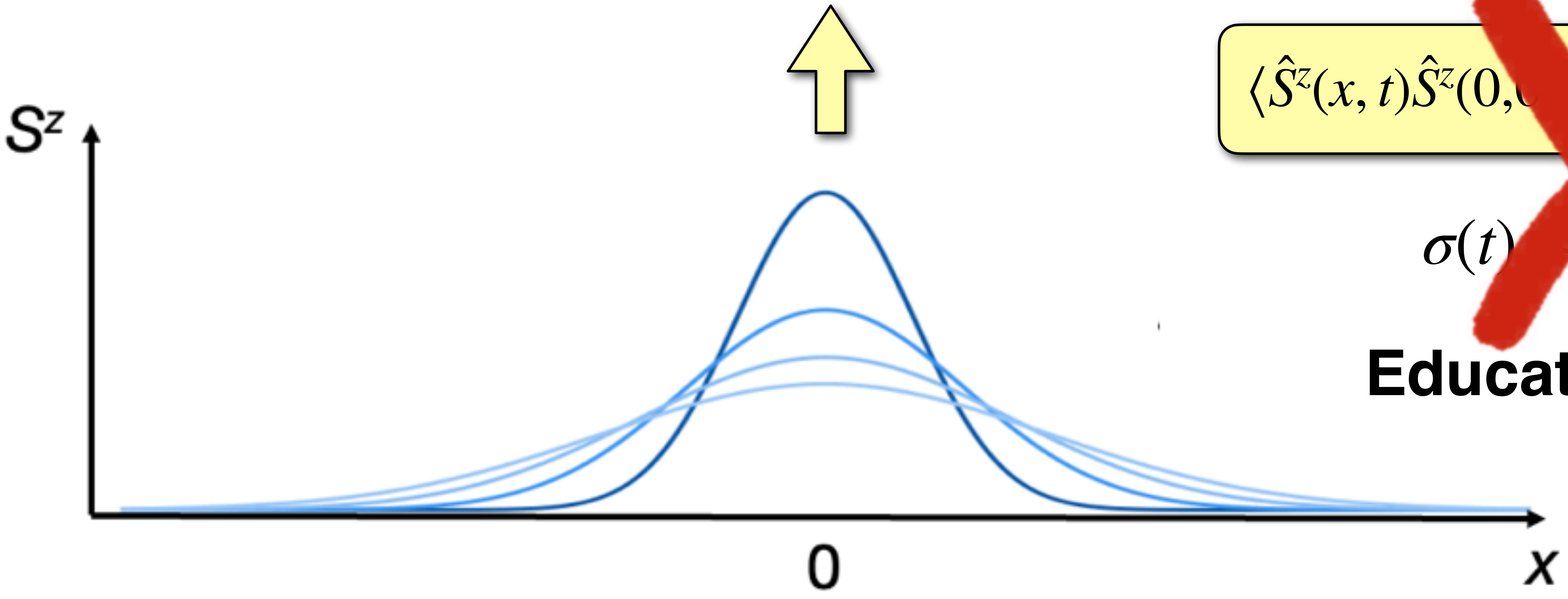


Low T
High-q (Spinons)

Infinite T Heisenberg Dynamics

How does **a single spin** spread in this environment?



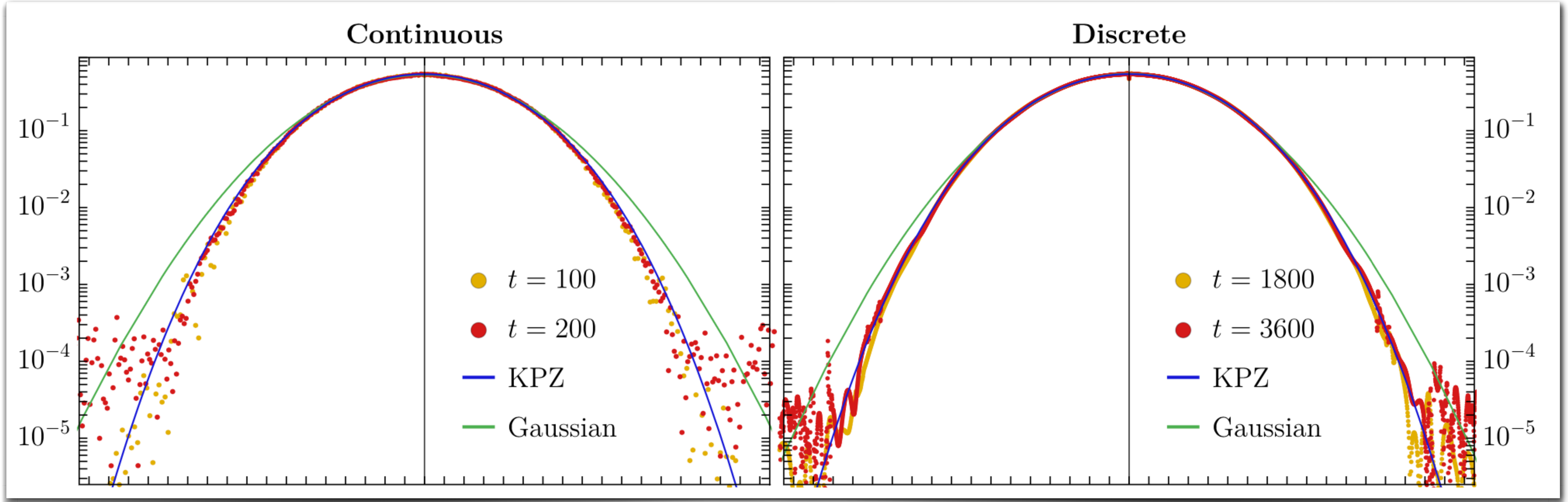


$\langle \hat{S}^z(x,t)\hat{S}^z(0,0)\rangle \sim f_{Gauss}\left(x/t^{1/2}\right)$

$\sigma(t) \sim t^{1/z} \sim t^{1/2}$

Educated Guess !

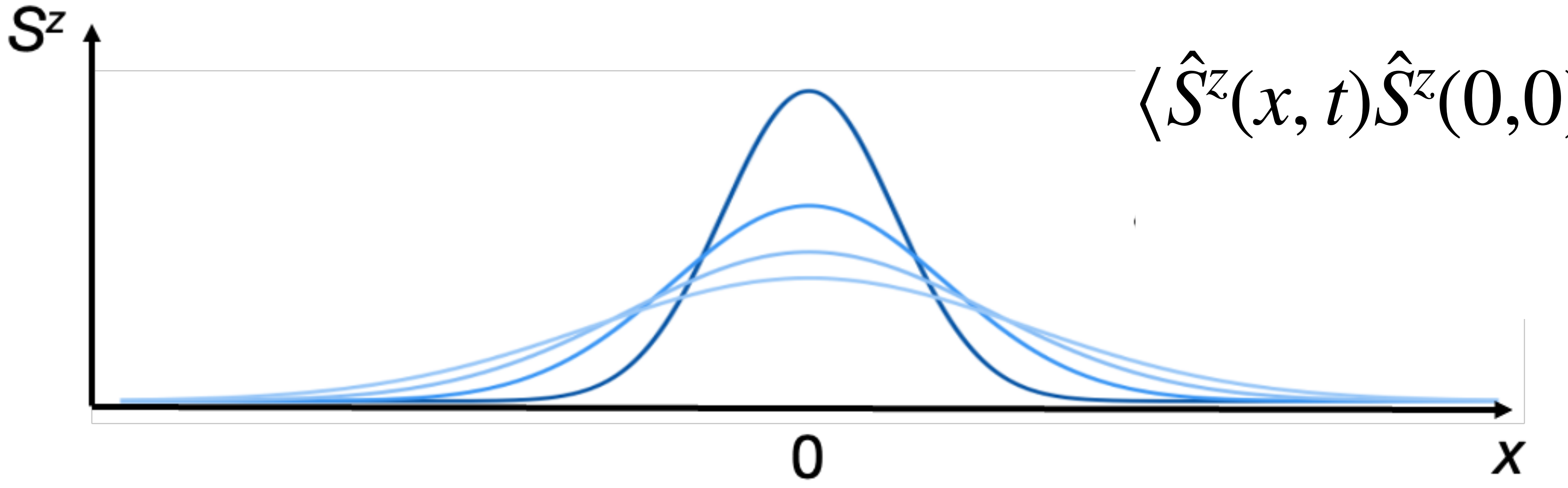
Numerical Evidence - Infinite T Heisenberg Dynamics



M. Ljubotina *et al.*, Nature Comm. (2017)
M. Ljubotina *et al.*, Phys. Rev. Lett. (2019)
Review: see V. Bulchadini, S. Gopalakrishnan, E. Ilievski
J. Stat. Mech. 084001 (2021)

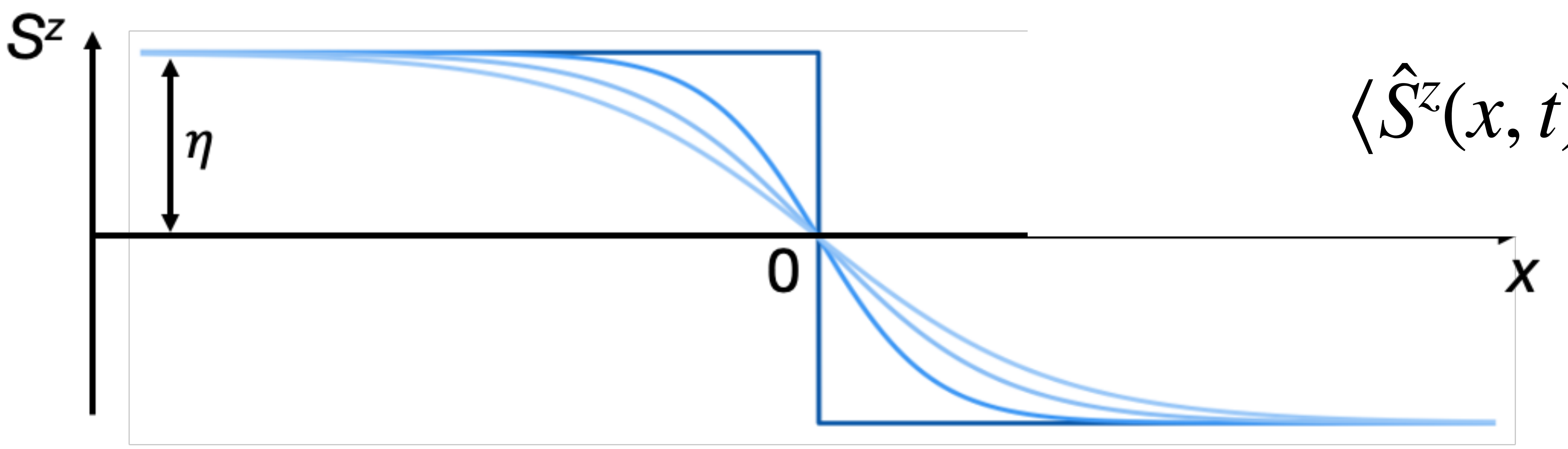
Tomaž Prosen
Ljublijana

Numerical Evidence - Infinite T Heisenberg Dynamics



$$\langle \hat{S}^z(x,t)\hat{S}^z(0,0)\rangle \sim f_{KPZ}\left(x/t^{1/z}\right) = f_{KPZ}\left(x/t^{2/3}\right)$$

Consider **spin domain wall** at $T \to \infty$



$$\langle \hat{S}^z(x,t)\hat{S}^z(0,0)\rangle \overset{\eta \to 0}{\sim} \partial_x \langle \hat{S}^z(x,t)\rangle_{DW}$$

M. Ljubotina *et al.*, Nature Comm. (2017)
M. Ljubotina *et al.*, Phys. Rev. Lett. (2019)
Review: see V. Bulchadini, S. Gopalakrishnan, E. Ilievski
J. Stat. Mech. 084001 (2021)

Anomalous Transport!

Connecting Spin Transport Hydrodynamics to KPZ Equation

Quantum Numerics $\langle \hat{S}^z(x,t)\hat{S}^z(0,0)\rangle \sim f_{KPZ}\left(x/t^{1/z}\right)$

Solutions of KPZ Equation

Spatio-Temporal Correlations of Height Field

$$C(x,t) = \langle \left[h(x,t) - h(0,0) - t\langle \partial_t h\rangle\right]^2 \rangle$$

Slope Correlations of Height Field

$$\langle \partial_x h(x,t)\, \partial_x h(0,0)\rangle \sim \partial_x^2 C(x,t) \sim f_{KPZ}\left(x/t^{1/z}\right)$$

Conjecture

$$\langle \hat{S}^z(x,t)\,\hat{S}^z(0,0)\rangle \sim f_{KPZ}\left(x/t^{1/z}\right)$$

$$\langle \partial_x h(x,t)\,\partial_x h(0,0)\rangle \sim f_{KPZ}\left(x/t^{1/z}\right)$$

$$\hat{S}^z(x,t) \sim \partial_x h(x,t)$$

Magnetization Profile

$$\hat{P}(t) \sim h(0,t)$$

Polarization Transfer

Consequences / Predictions

Magnetisation Profile KPZ scaling function $f_{KPZ}(x/t^{2/3})$

Polarisation Transfer (Domain Wall) $\langle \hat{P}(t) \rangle \propto t^{1/z} = t^{2/3}$

$z = 3/2$

Dynamical exponent

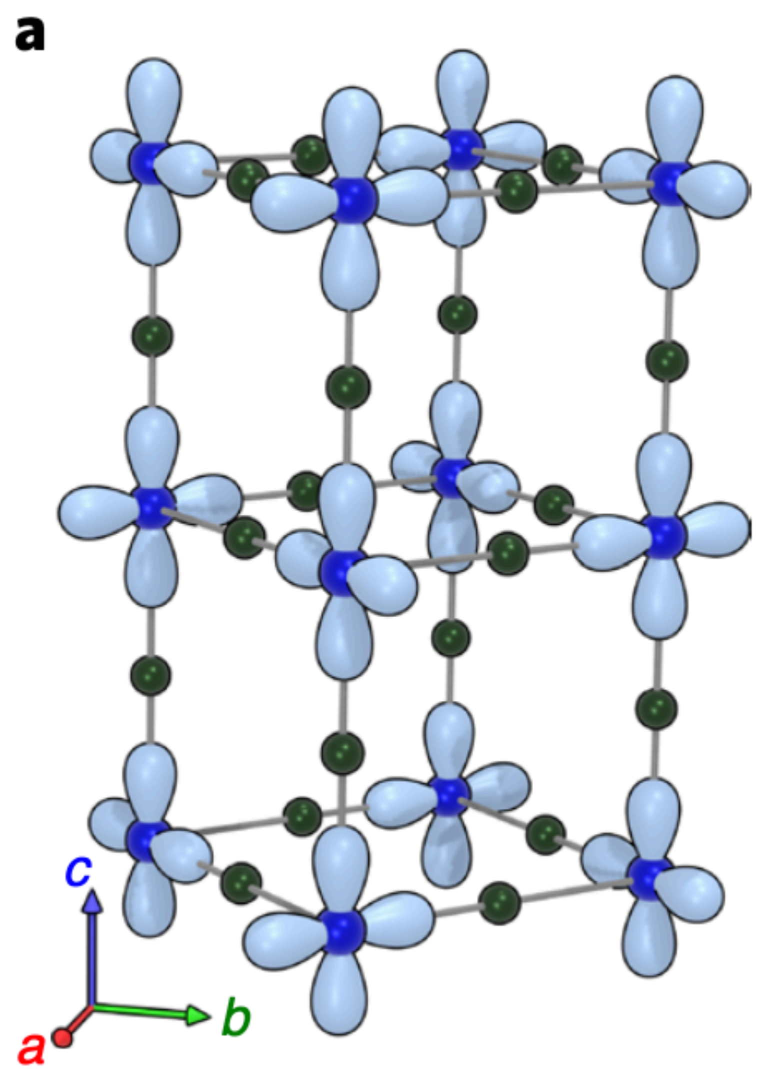
Fluctations (Time) $\delta P(t) = \delta h = A t^{1/3} \chi(0,t) = A\, t^{\beta} \chi(0,t)$

Tracy-Widom Distribution function

$\beta = 1/3$

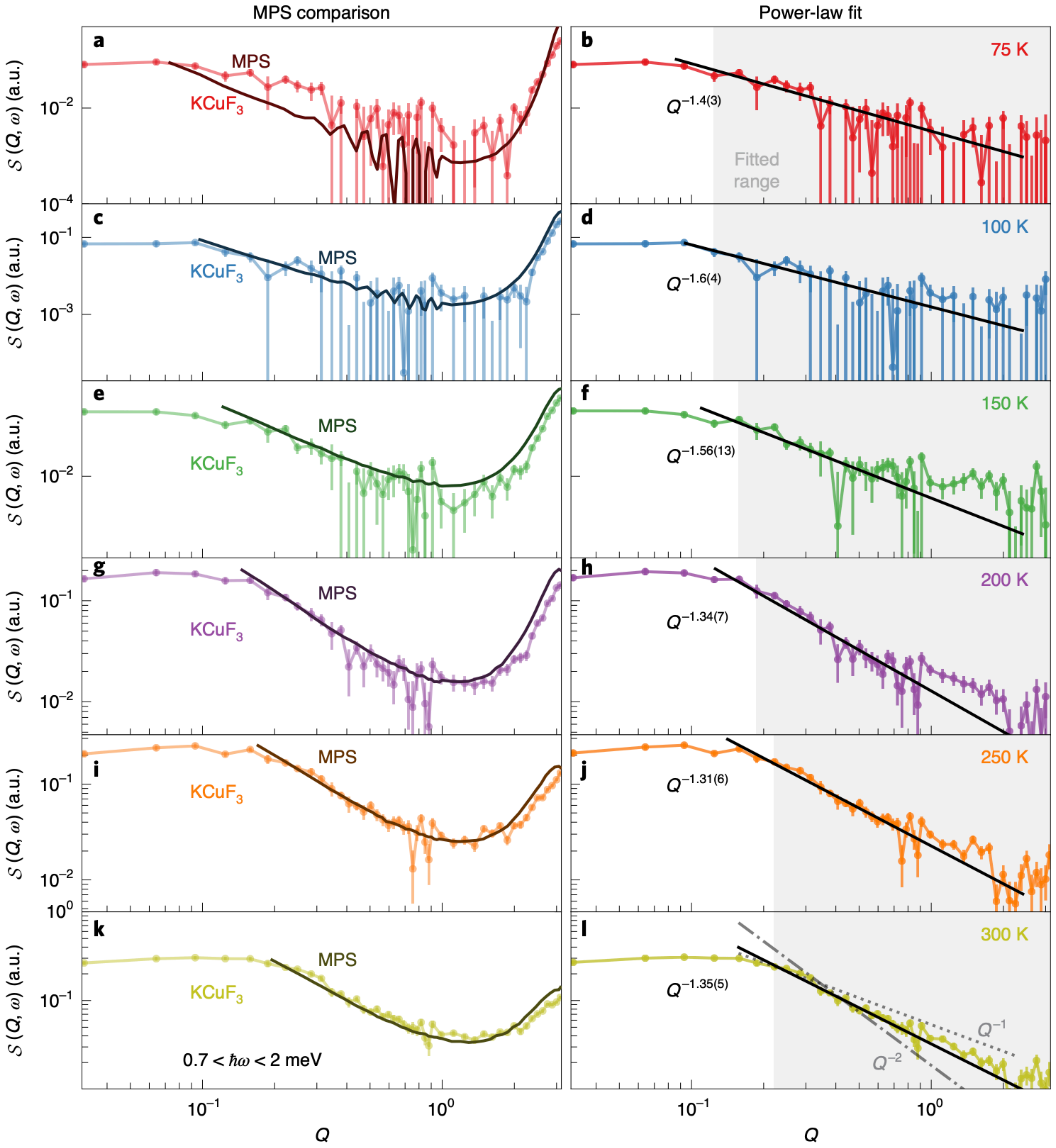
Fluctuations

Superdiffusive Transport in Spin Chains - Neutron Scattering



$KCuF_3$

A. Scheie *et al.*
Nature Phys. **17**,
726–730 (2021)



Dynamical Structure Factor

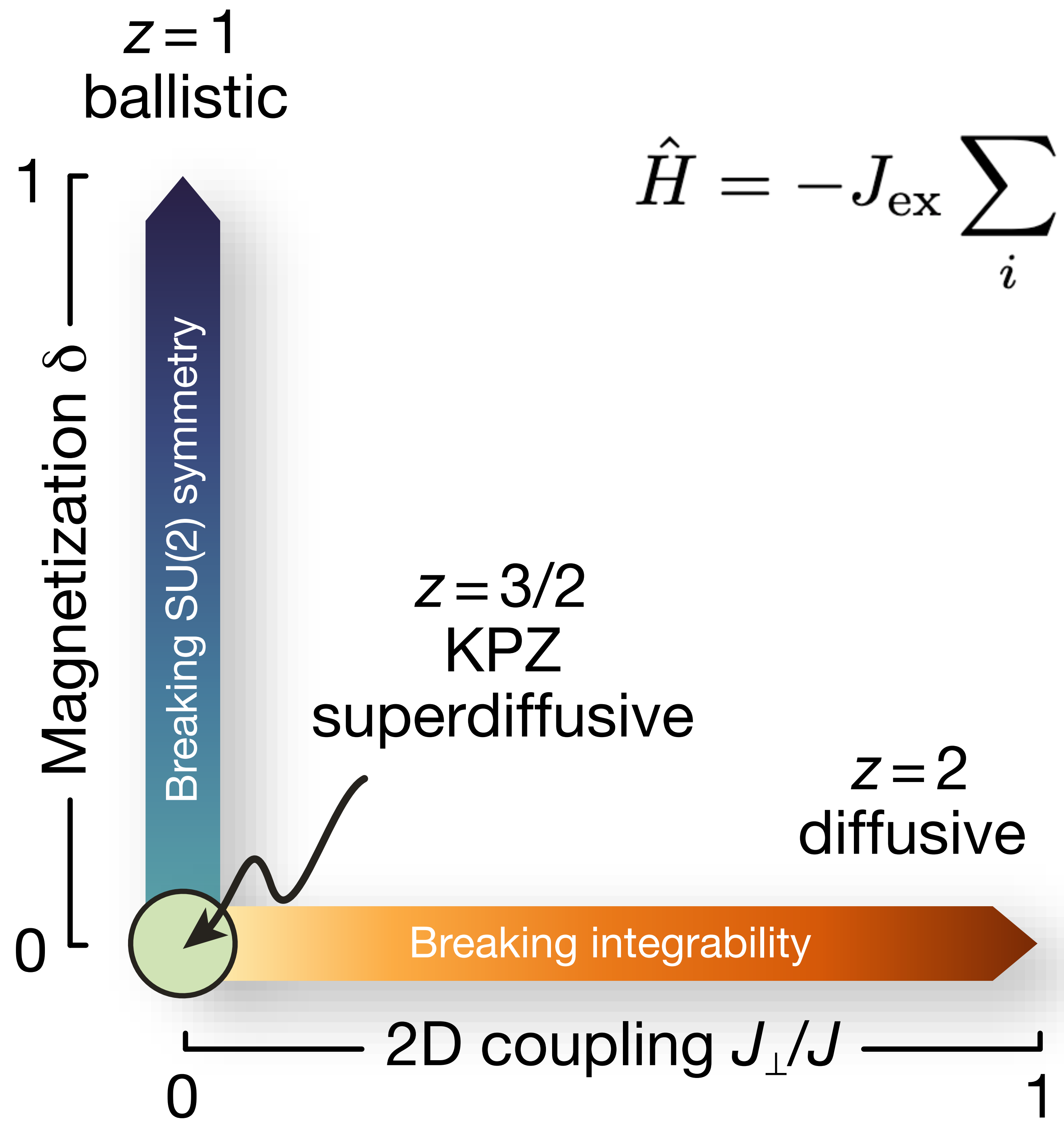
$$S(Q, \omega \to 0) \approx Q^{-z}$$

@ 300K

$z = 1.35(5)$

Alan Tennant,
Oak Ridge National Lab

Heisenberg Model Revisited



$$\hat{H} = -J_{\rm ex} \sum_i \left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y + \Delta \hat{S}_i^z \hat{S}_{i+1}^z \right)$$

Here: $\Delta = 1$

Space time scaling

$$x \sim t^{1/z}$$

- $z=1$ ballistic
- $1<z<2$ superdiffusive
- $z=2$ diffusive

Subtle interplay of **integrability** (stable quasiparticles) & **Non-abelian SU(2) symmetry** in Heisenberg model.

Numerical Evidence:

M. Ljubotina *et al.,* Nature Comm. (2017)
M. Ljubotina *et al.*, Phys. Rev. Lett. (2019)

Understanding (generalied GHD, SU(2) & Integrability,…)

S. Gopalakrishnan and R. Vasseur, Phys. Rev. Lett. (2019)
J. De Nardis, Phys. Rev. Lett. (2019)
S. Gopalakirshnan, R. Vasseur, and B. Ware, PNAS (2019)
V. B. Bulchandani, Phys. Rev. B (2020)

Reviews:

B. Bertini at el. Rev. Mod. Phys. (2020)
V. B. Bulchandani, S. Gopalakrishnan, and E. Ilievski, arXiv:2103.01976

Exp.: A. Scheie *et al.* Nature Physics (2021)
Related: Transport via Spin-Spirals
S. Hild *et al.* Phys. Rev. Lett. (2014)
P.N. Jepsen *et al.* Nature (2020)

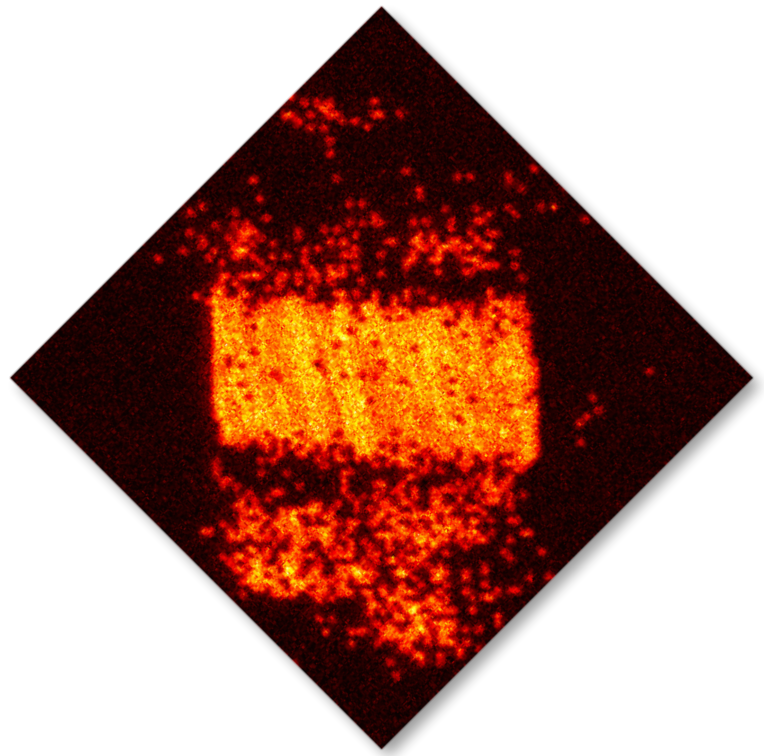
Our System - 1000 Spin Heisenberg System

^{87}Rb

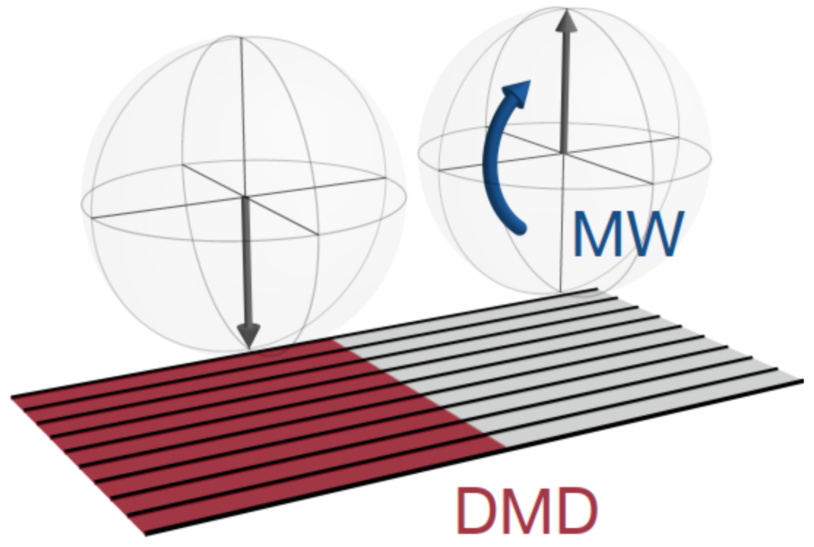
$$\hat{H} = -J \sum \left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y + S_i^z \hat{S}_{i+1}^z \right)$$

State Preparation

① **Mott insulator**



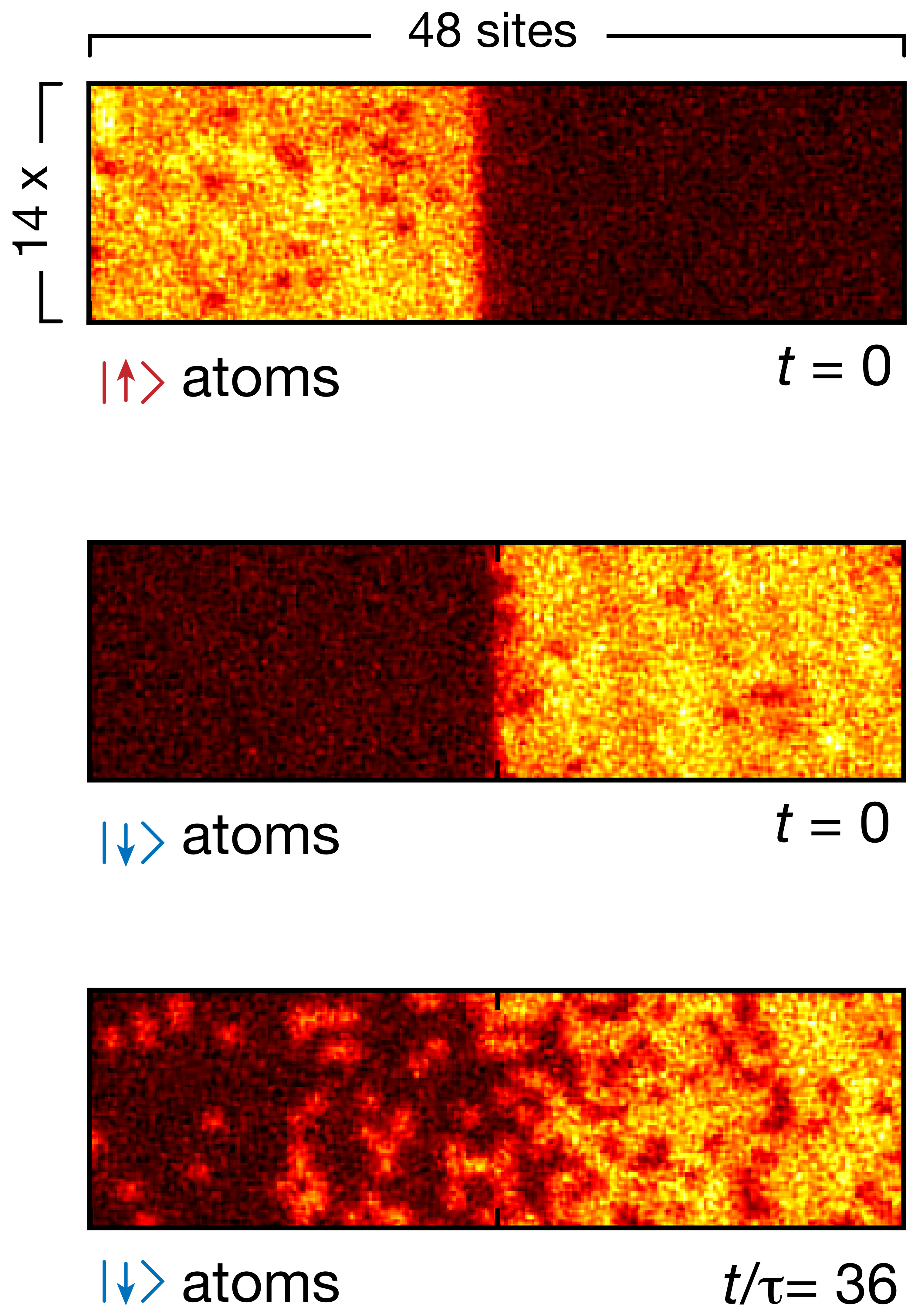
② **Spin DW**



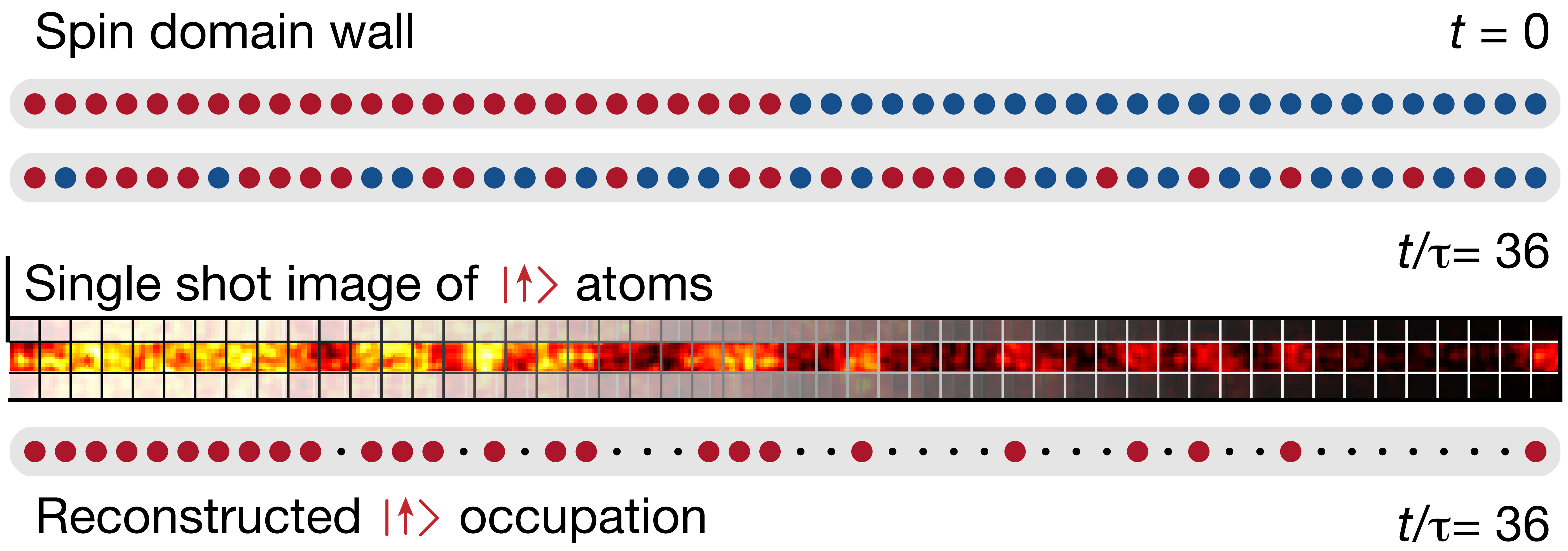
D. Wei *et al.*, Science **376**, 716 (2022)

Spin Dynamics in Heisenberg Domain Wall

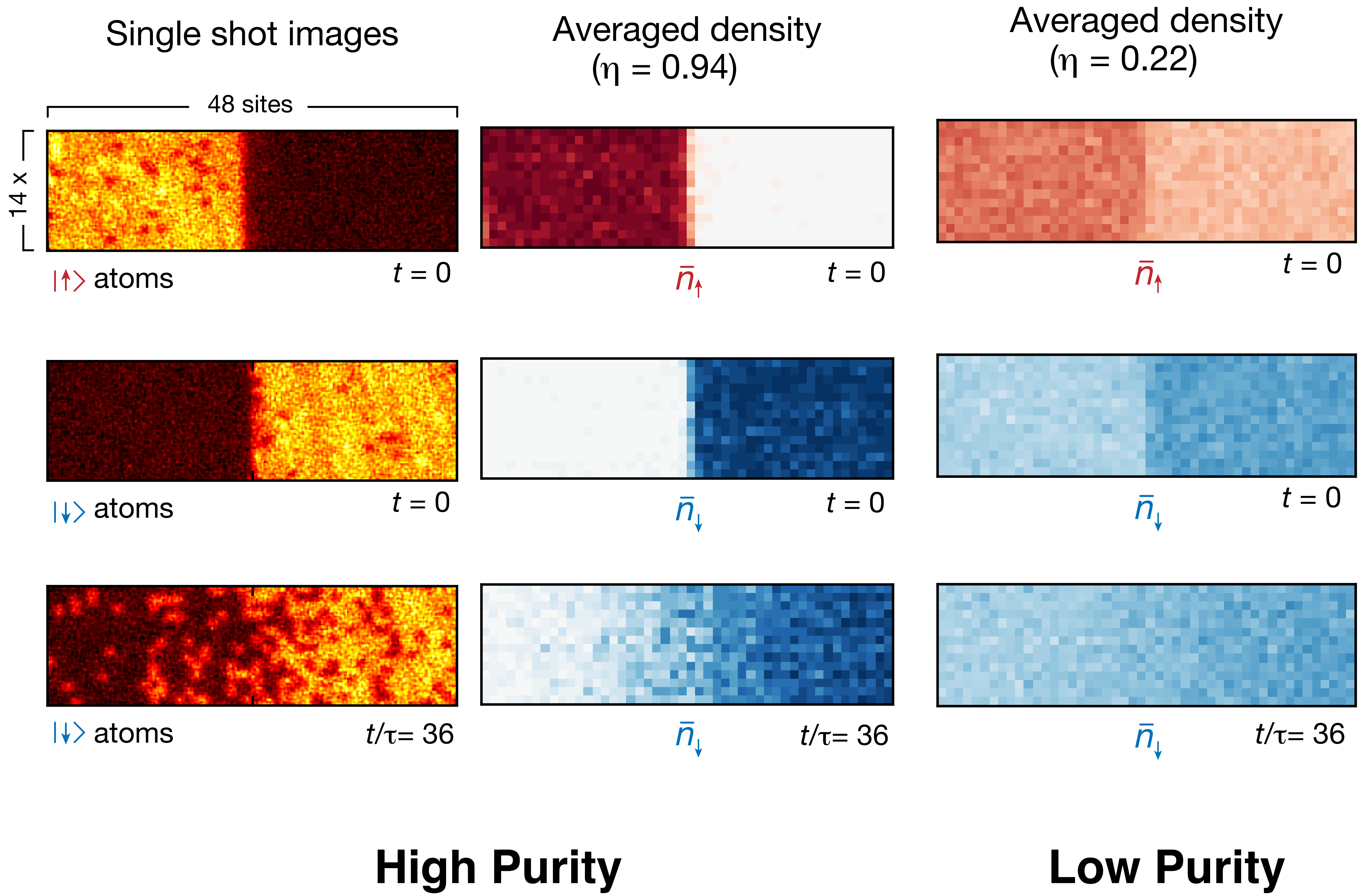
Single shot images



Box potential!
No harmonic confinement.

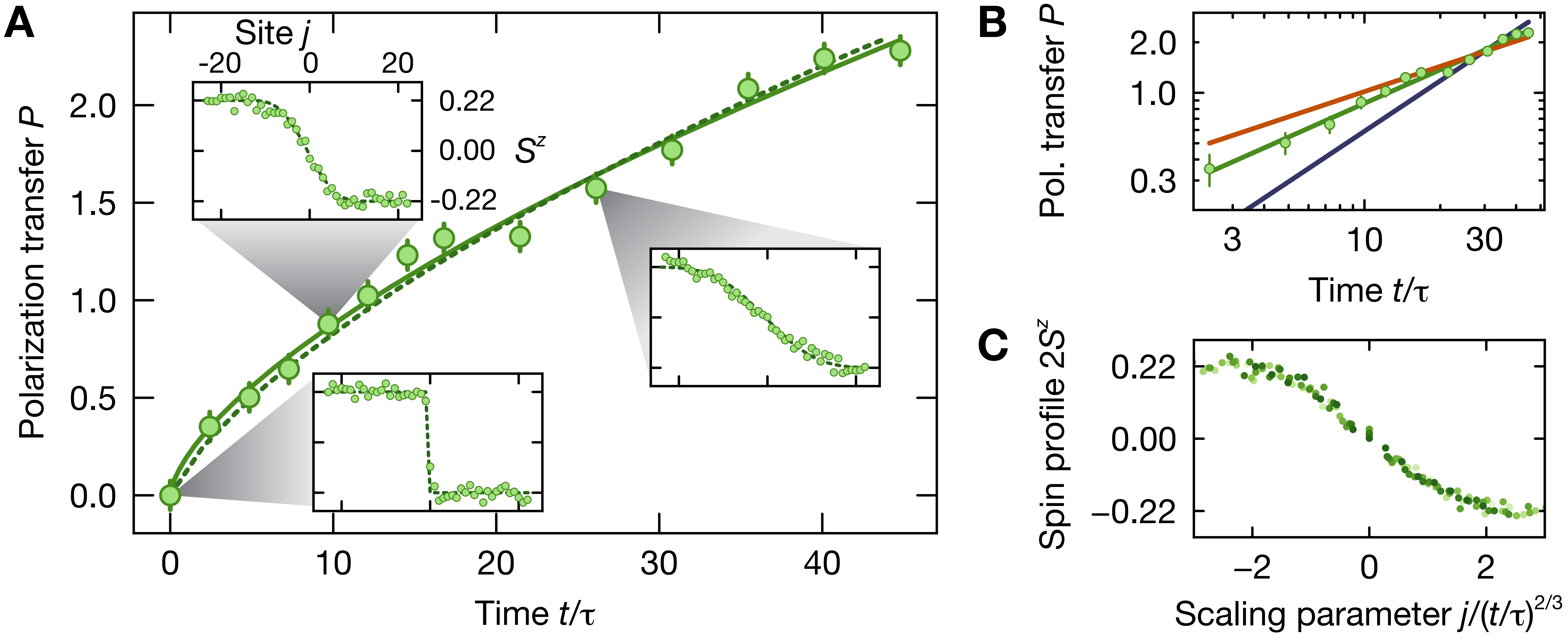


Experimental Measurement - 1000 Spin Heisenberg System



$$\rho \sim (1 + \eta\sigma_z)^{N/2} \otimes (1 - \eta\sigma_z)^{N/2}$$

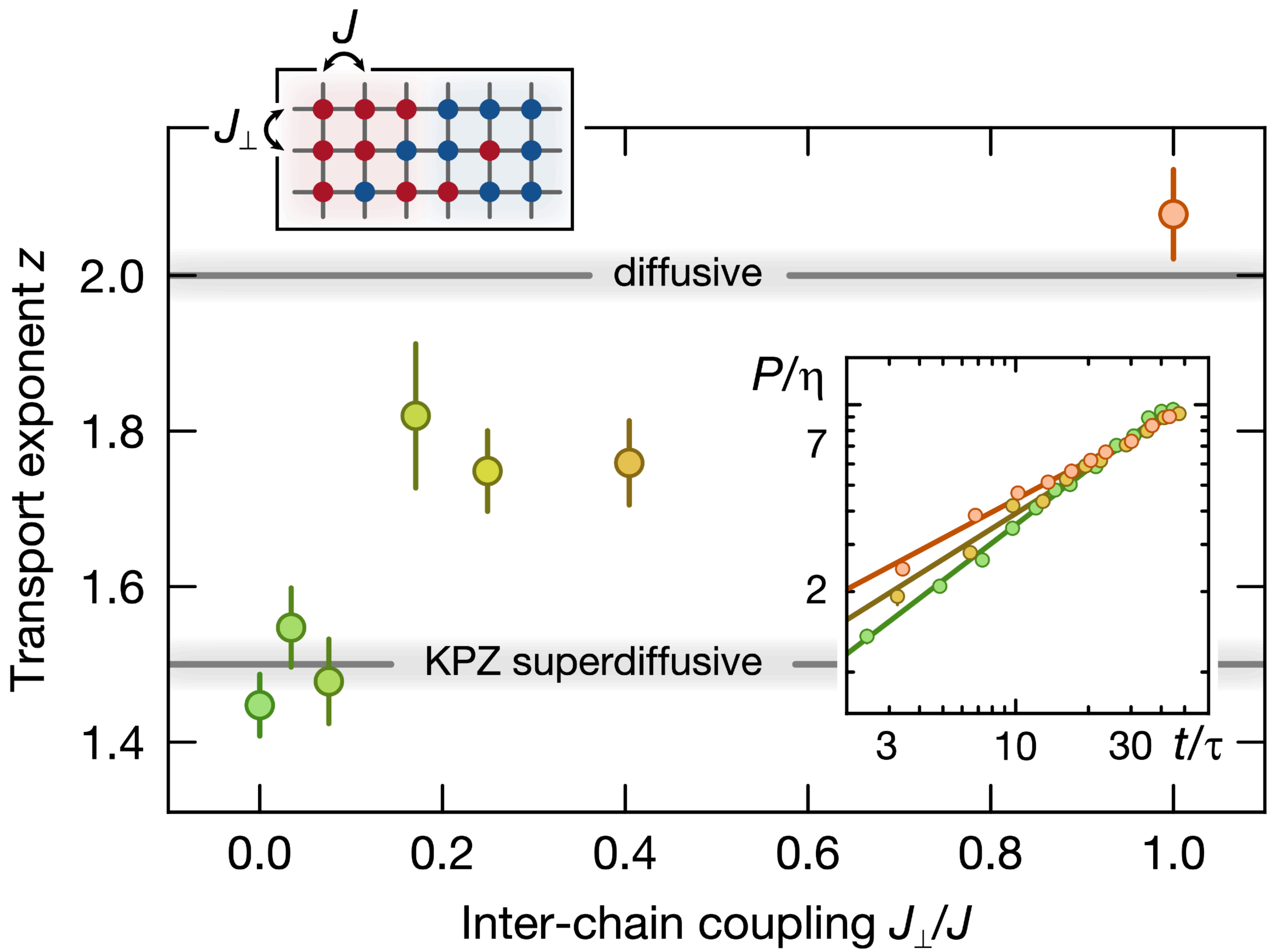
Polarisation Transfer



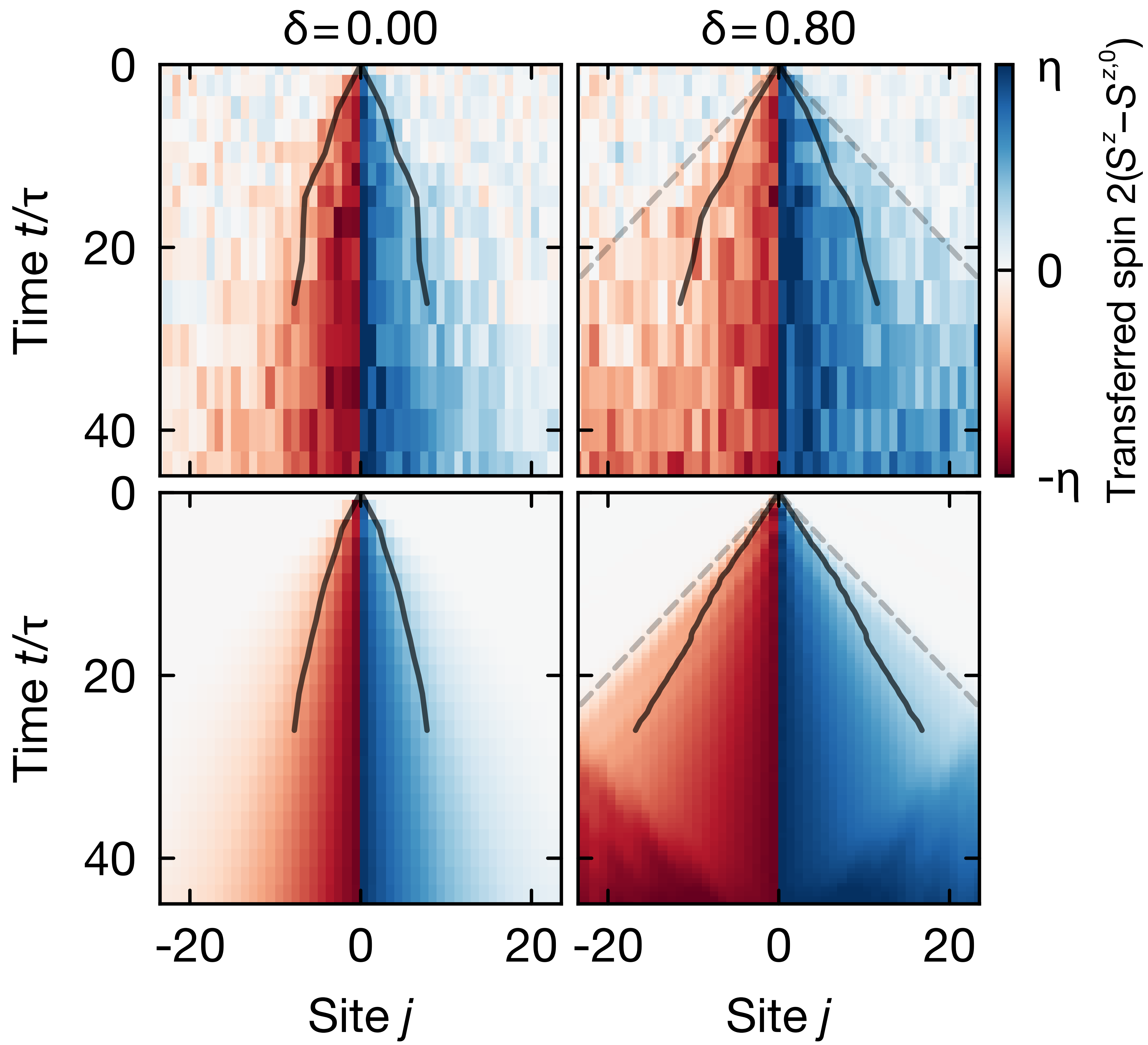
$$P(t) \sim t^{1/z} \qquad z_{fit} = 1.54(7)$$

M. Ljubotina *et al., Nature Comm. (2017)*.
M. Ljubotina *et al.*, *Phys. Rev. Lett.* (2019)
Exp. Spin Chains: A. Scheie *et al.* Nat. Phys. (2021)

Breaking Superdiffusion - Breaking Integrability

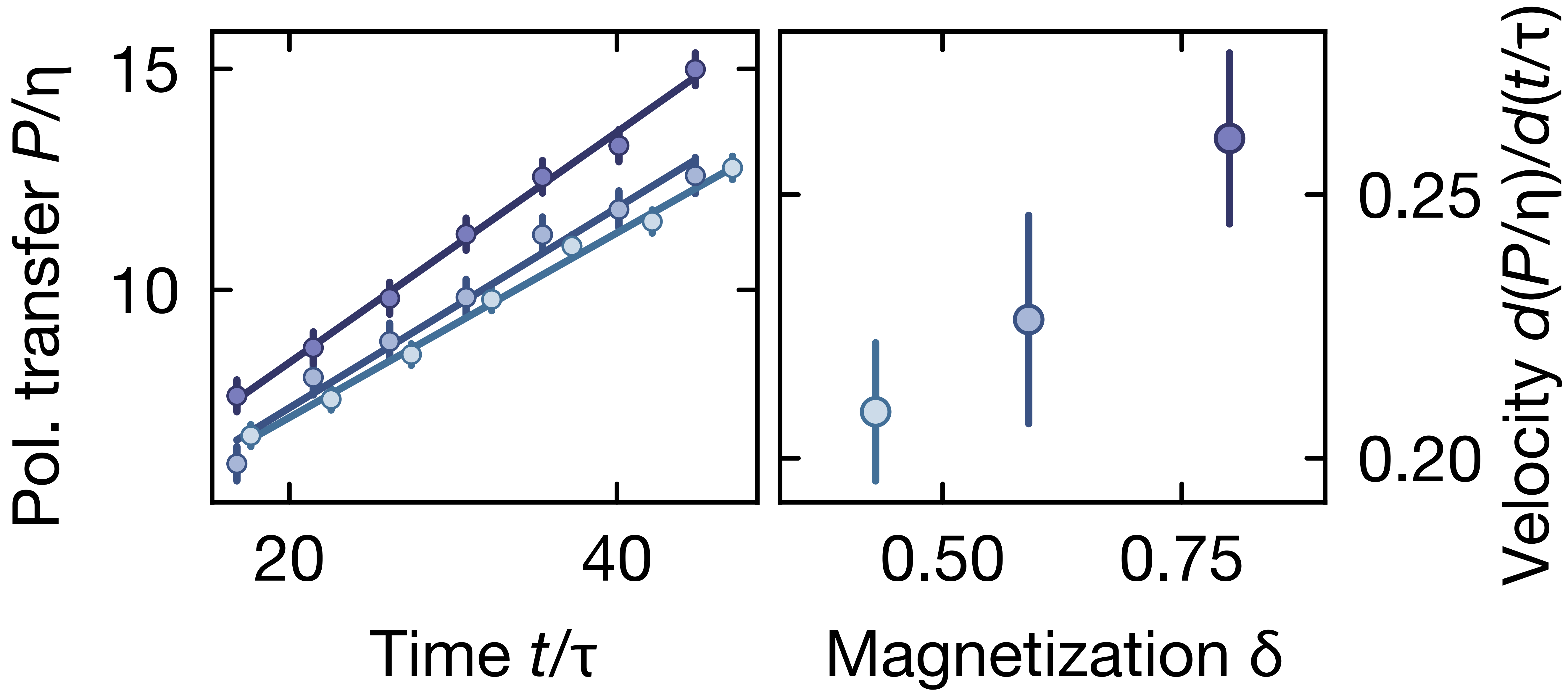


Breaking Superdiffusion - Breaking Non-Abelian Symmetry

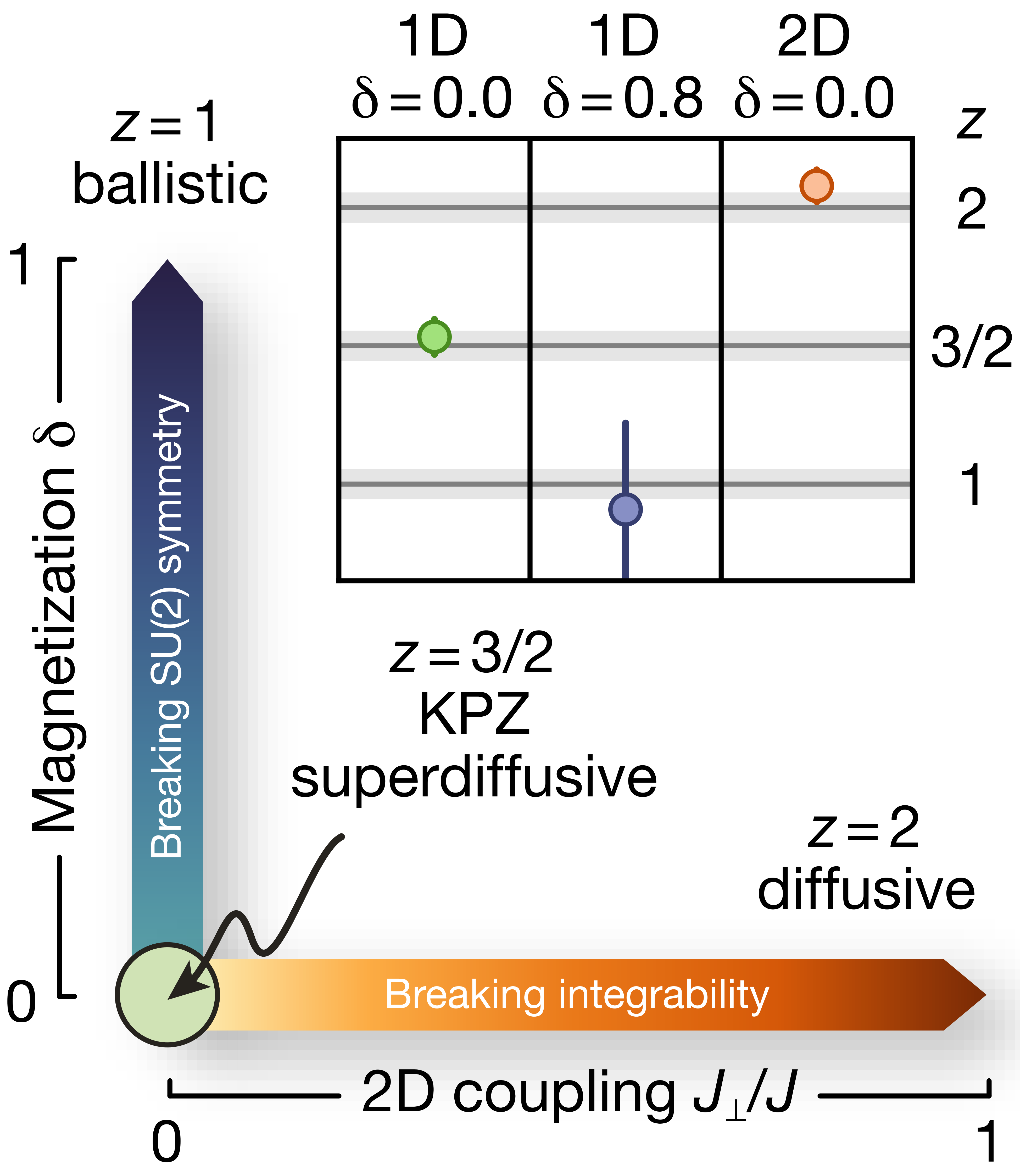


$\delta \neq 0$

Magnetizing System



Ballistic-Superdiffusion-Diffusion



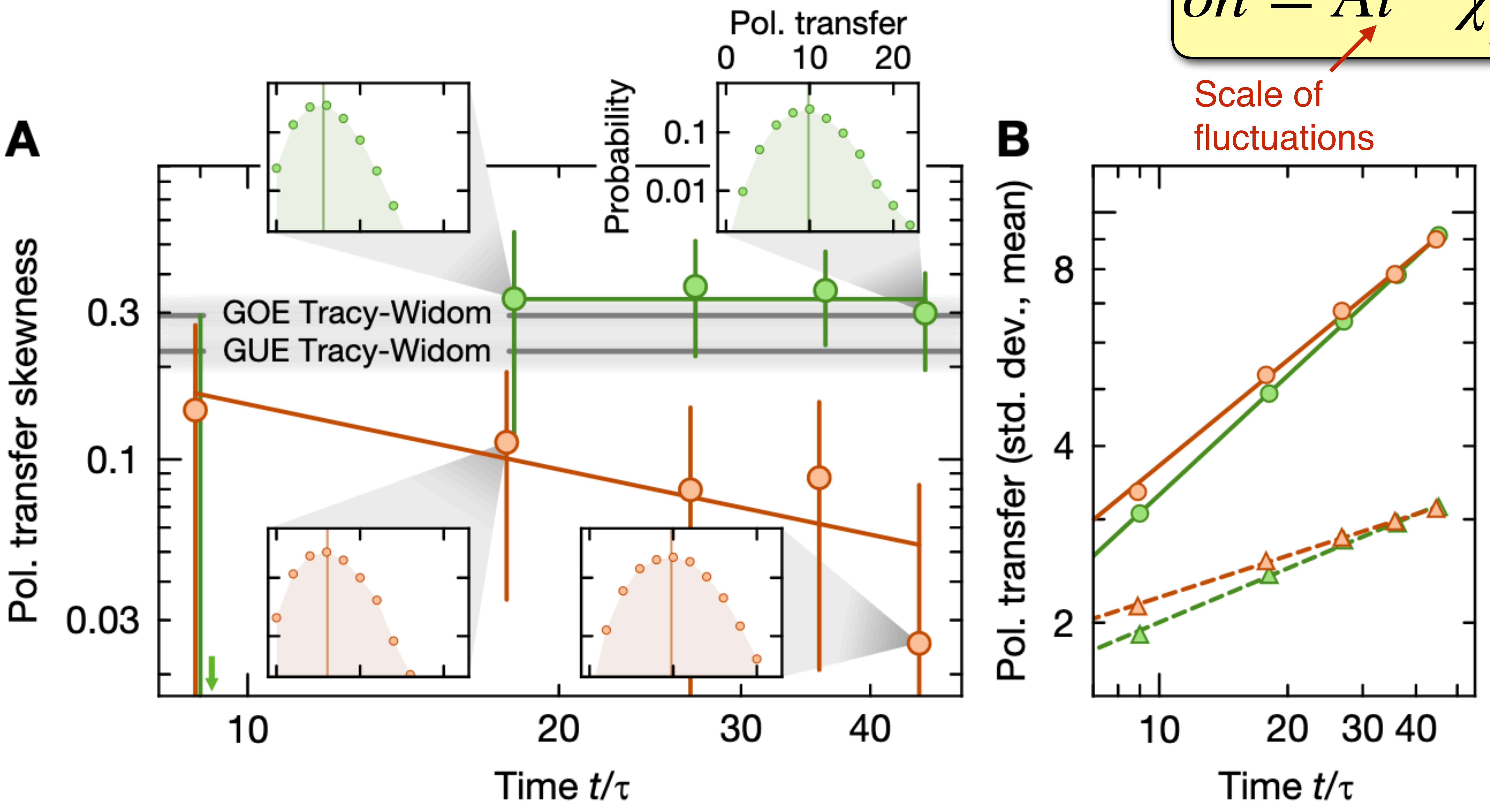
Tracy-Widom Distribution Functions

Polarization transfer ⟺ height field (at origin) of KPZ equation

$$\delta h = A t^{1/3} \chi(0,t) \overset{\text{Test!}}{=} A\, t^{\beta} \chi(0,t)$$

Scale of fluctuations

Tracy-Widom Distribution (non vanishing skewness)



Mean $z = 1.49(2)$

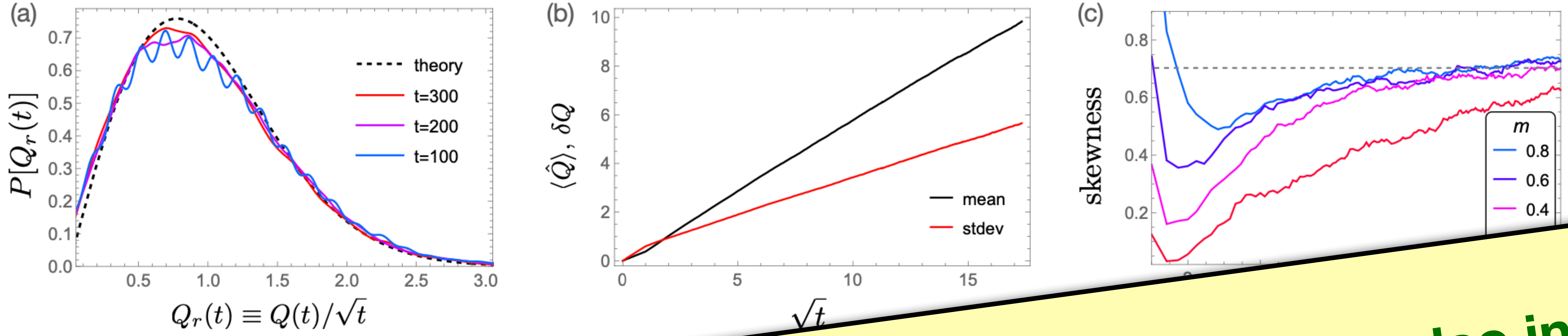
Standard Deviation $\beta = 0.31(1)$

KPZ Universality
$\beta = 1/3$

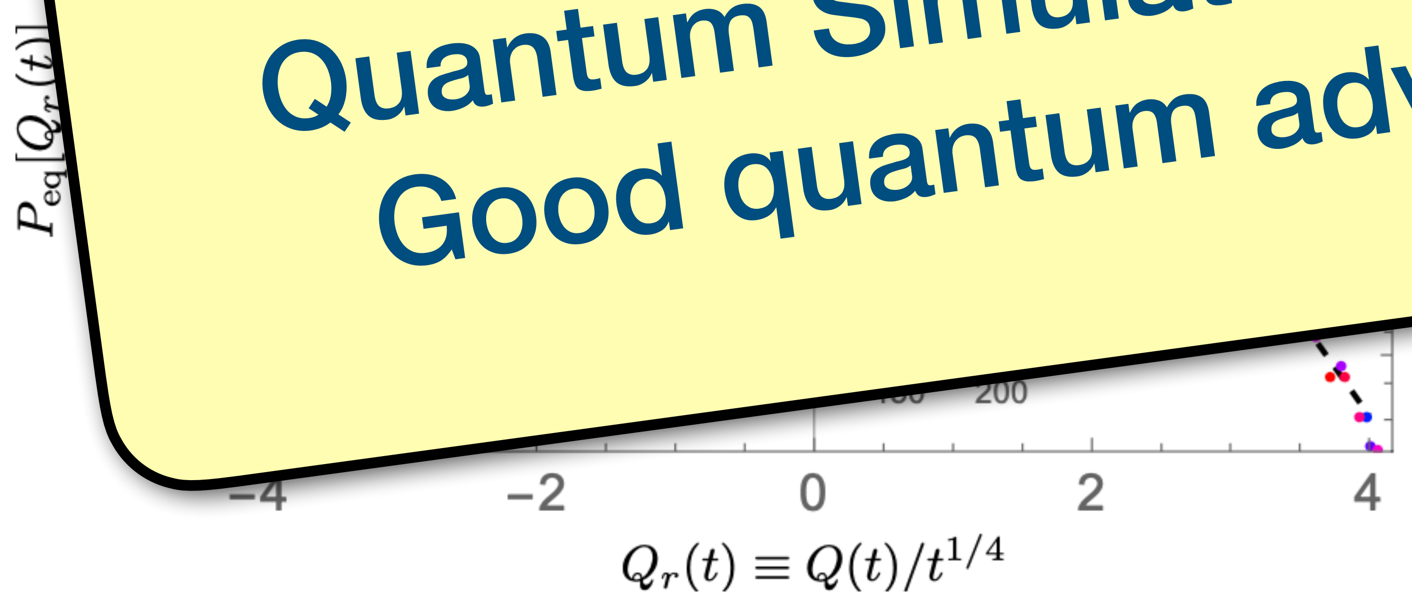
Full Counting Statistics & Anomalous Transport

Anomalous Transport in XXZ
(easy axis)

$$\hat{H} = -J_{\text{ex}} \sum_i \left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y + \Delta \hat{S}_i^z \hat{S}_{i+1}^z \right) \qquad \Delta > 1$$



Full Counting Statistics
out-of-equilibrium (m>0)



Can we discover new transport regimes also in 2D?
Quantum Simulators offer powerful new tools to probe this!
Good quantum advantage (double exponential) regime!!

S. Gopalakrishnan, A. Morningstar, R. Vasseur & V. Khemani arXiv.2203.09526
see also: Ž. Krajnik et al., Phys. Rev. Lett. 128, 160601 (2022).

Experimental Evidence for KPZ

1. Superdiffusive transport (z=3/2) can arise from linear model!

2. Polarisation fluctuation scale (β =1/3)

3. Skewness of Polarisation fluctuation distribution constant
(and compatible with Tracy-Widom GOE/GUE)

4. Breaking SU(2) symmetry OR breaking integrability destroys KPZ behaviour

D. Wei *et al.* Science **376**, 716–720 (2022)
see also: A. Scheie *et al.* Nature Phys. **17**, 726–730 (2021)

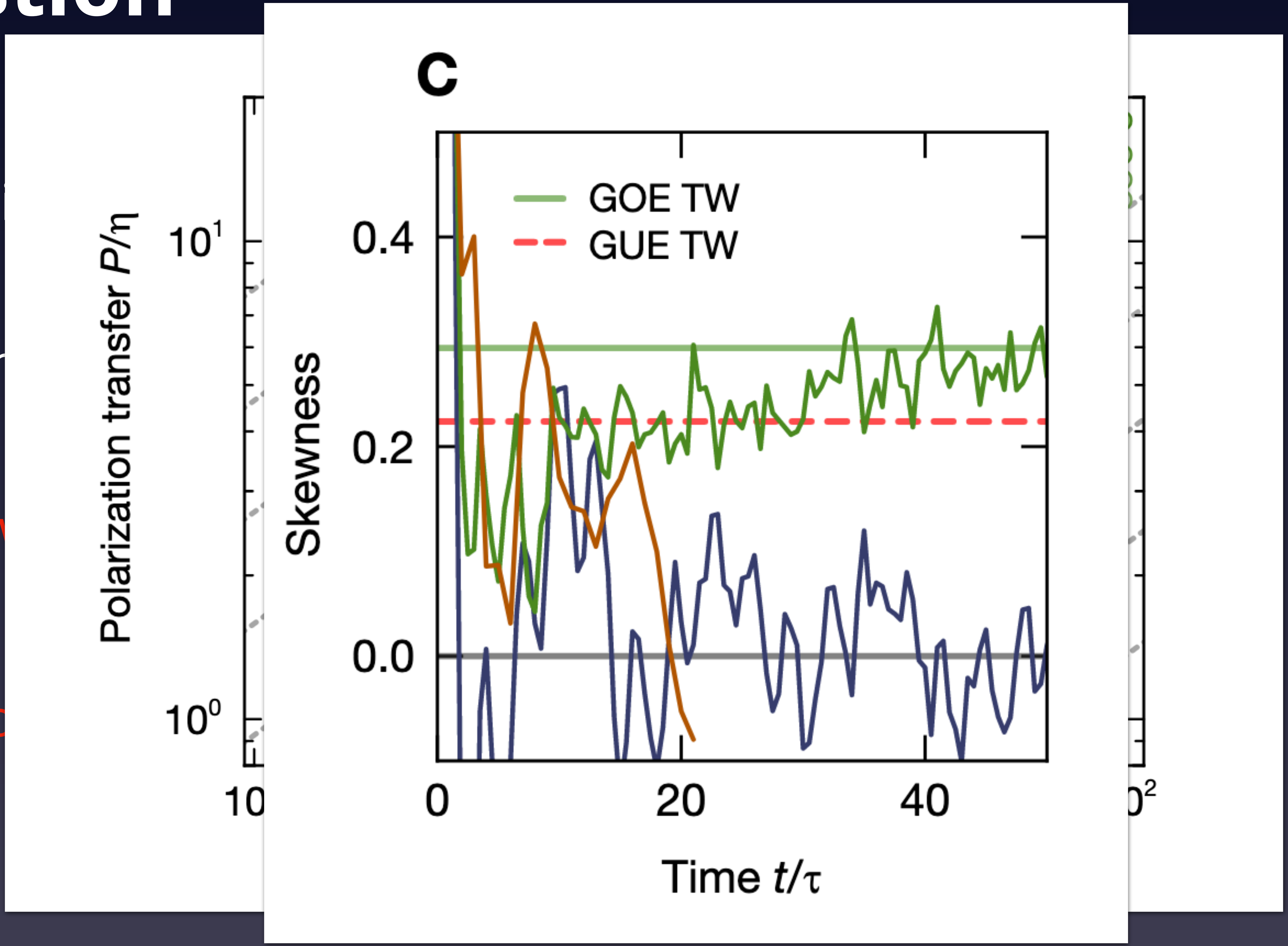
Open Question

1 Superdiffusi

2 Higher mom … ll visibility

3 Maybe a ne

4 Derivation c … model?



see also: E. Rosenberg *et al* arXiv:2306.11457 (exploring low domain wall visibilities)

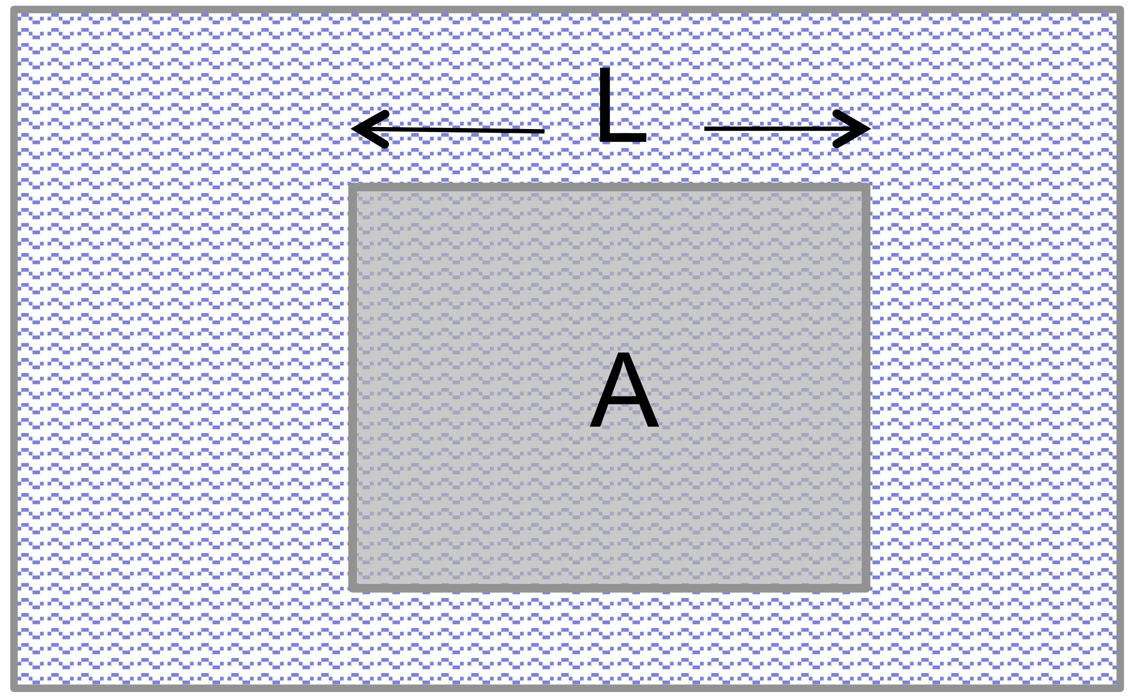
Briefly: Probing MBL

Eigenstate Thermalisation Hypothesis

Deutsch (91), Srednicki (94,98), Rigol, Dunjko & Olshanii (2009), D'Alessio, Kafri, Polkovnikov, Rigol, Adv. Phys. **65**, 239 (2016)

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

$$S_A \equiv \mathrm{tr}\left[\rho_A \ln \rho_A\right] \propto L^d$$

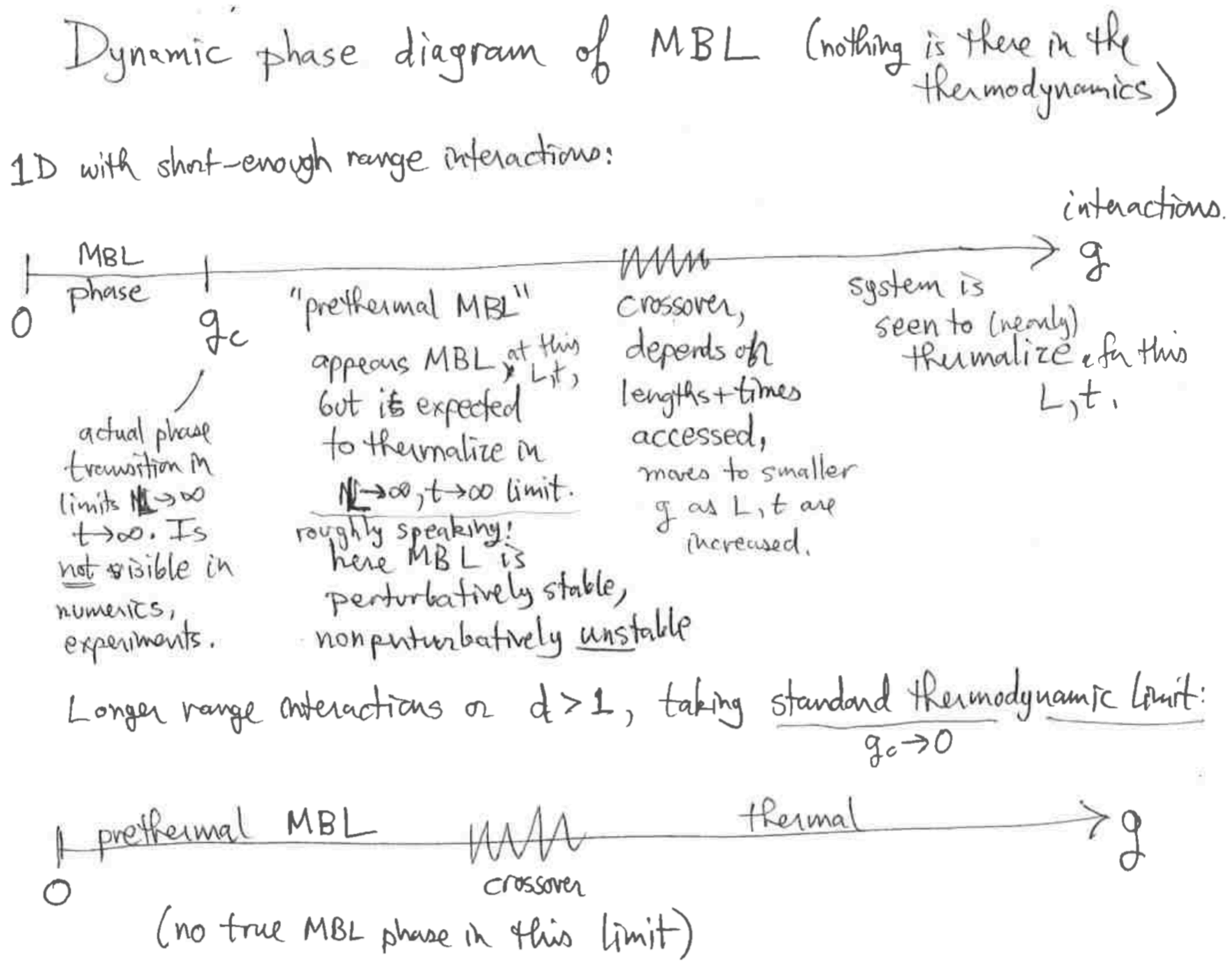


Are there scenarios when this fails?

System fails to act as its own heat bath!

Nandkishore et al., Annu. Rev. Cond. Mat. 2015; Altman et al. Annu. Rev. Cond. Mat. 2015,

Phase Diagram - D. Huse Lecture (?)



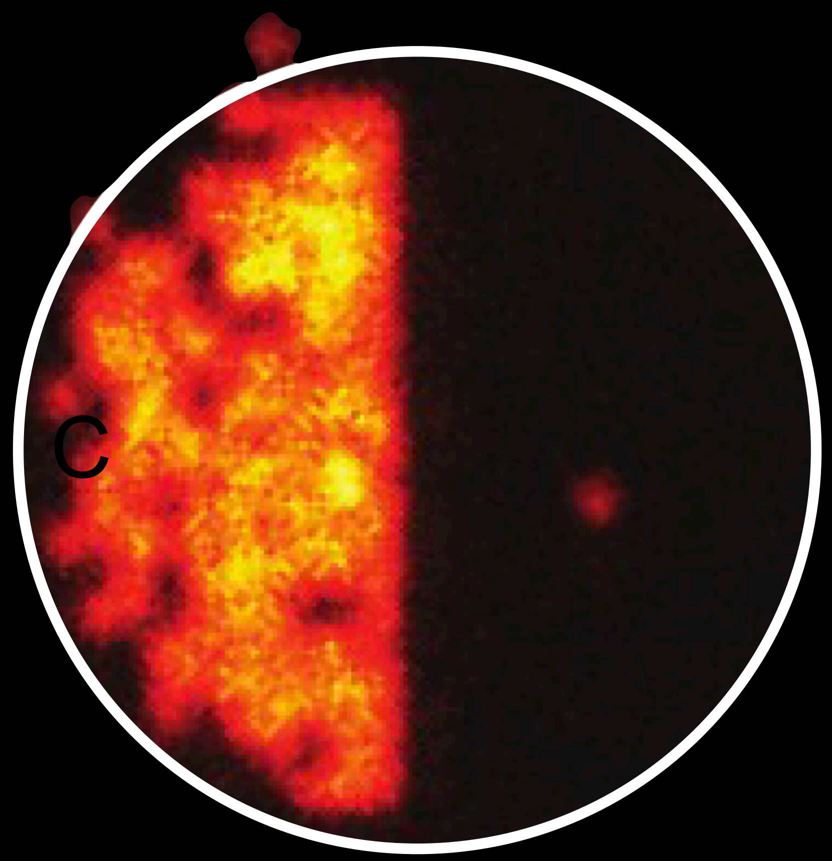
Important Points

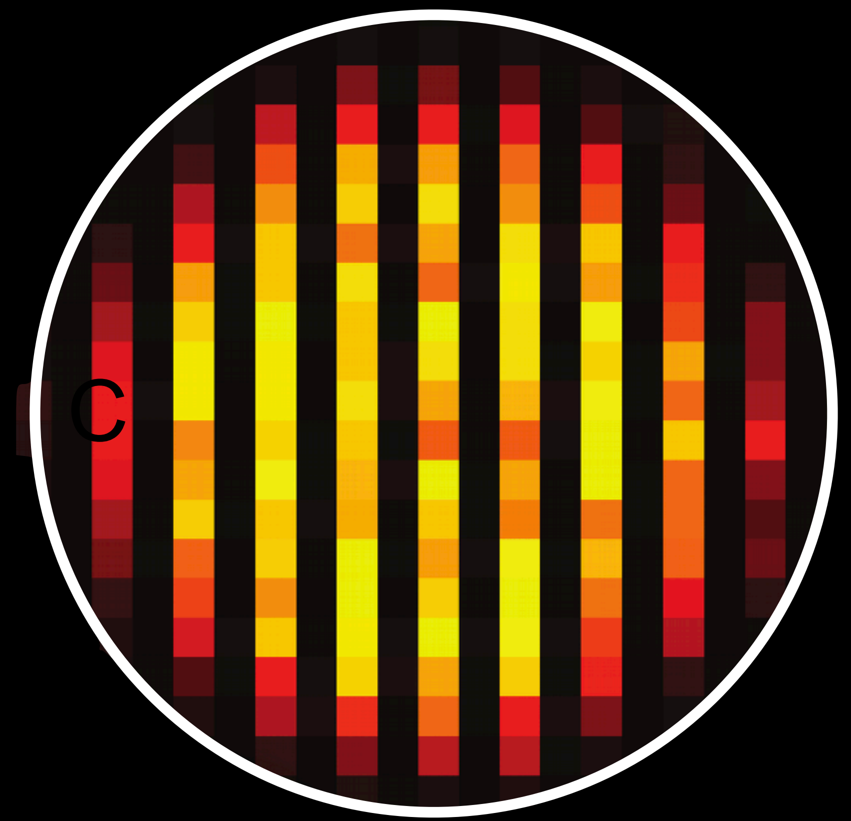
Very little theoretically known about MBL in d>1
(**stability of MBL unclear**)

Calls for particularly precise characterization of the experiments
(validation through a quantum simulator)

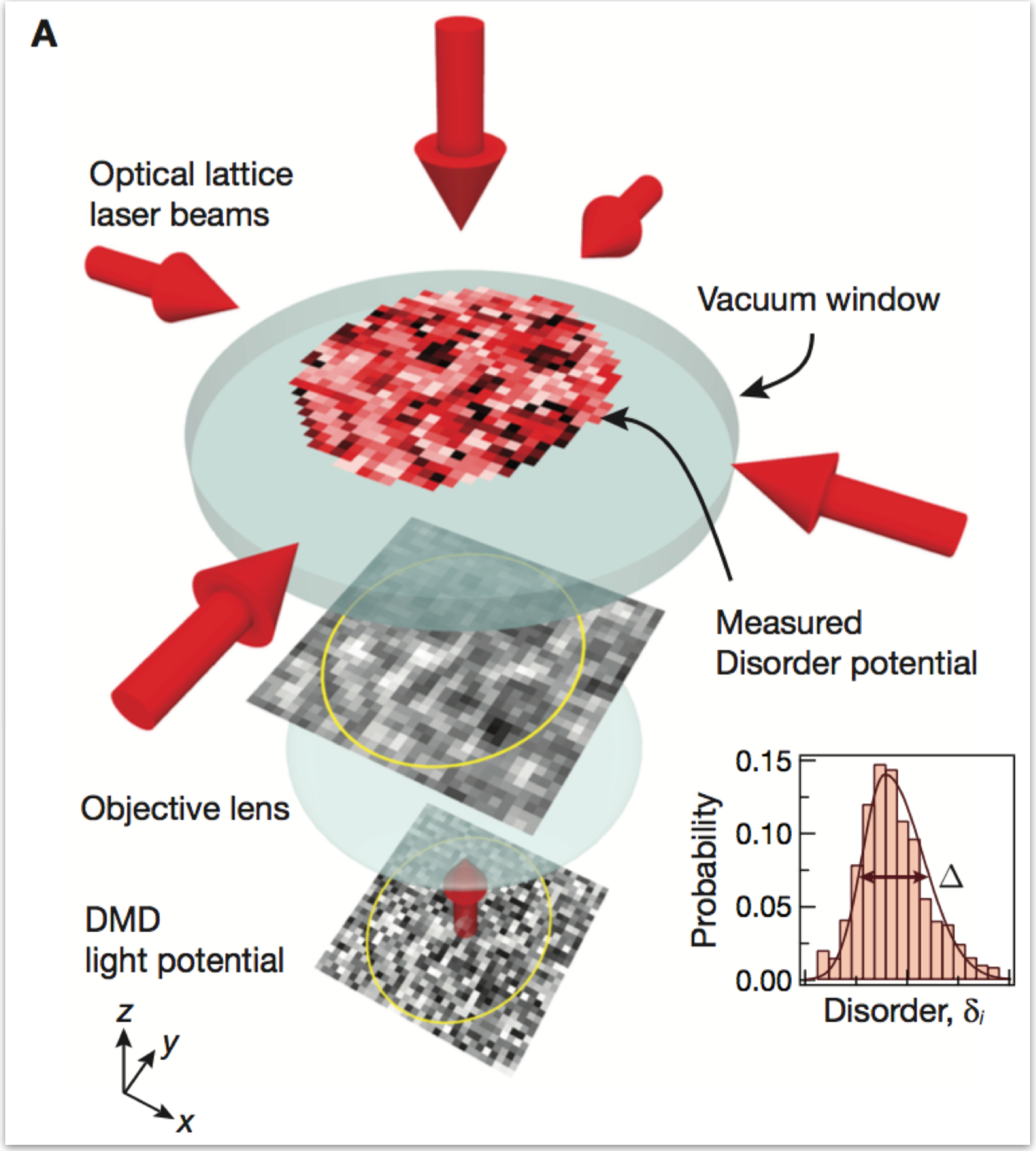
Experiments (almost) isolated from environment
but **small residual coupling** limits observation time (>1000 t)

Probing MBL on Different Length and Timescales





System Summary



1. Prepare Domain Wall
   (no tunneling dynamics)

2. Turn on disorder potential

3. Lower the lattice depth
   (near critical point)

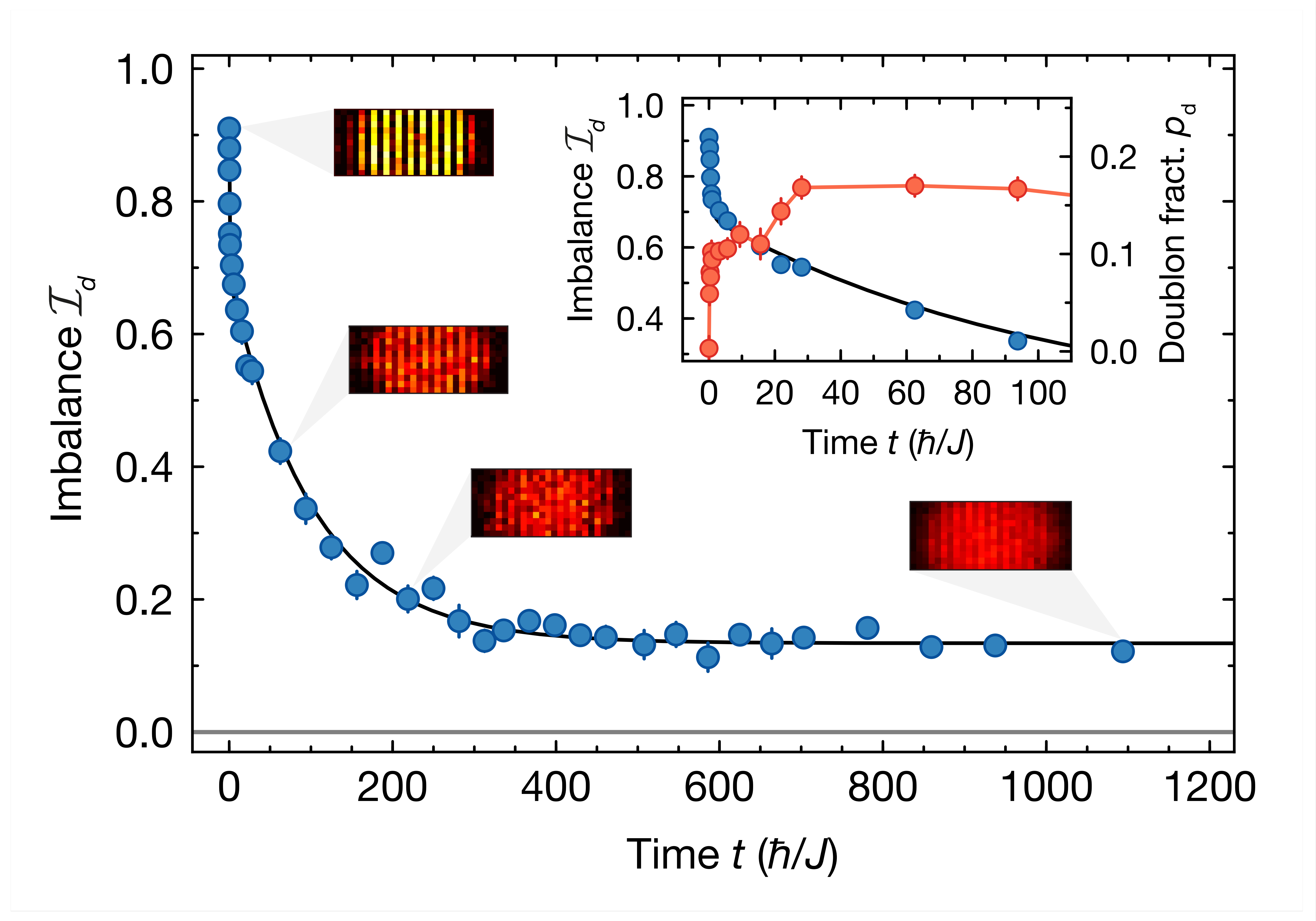
4. Measure atomic distribution

* Tunneling time is 6.4 ms.
* Disorder is changed for each image.
* Take 100 picture for averaging.

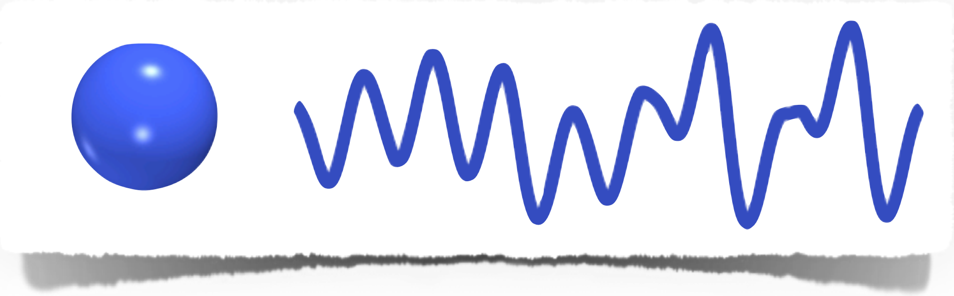
$$U = 24J$$

$$\Delta = 0 - 20J$$

Dynamics without mixture



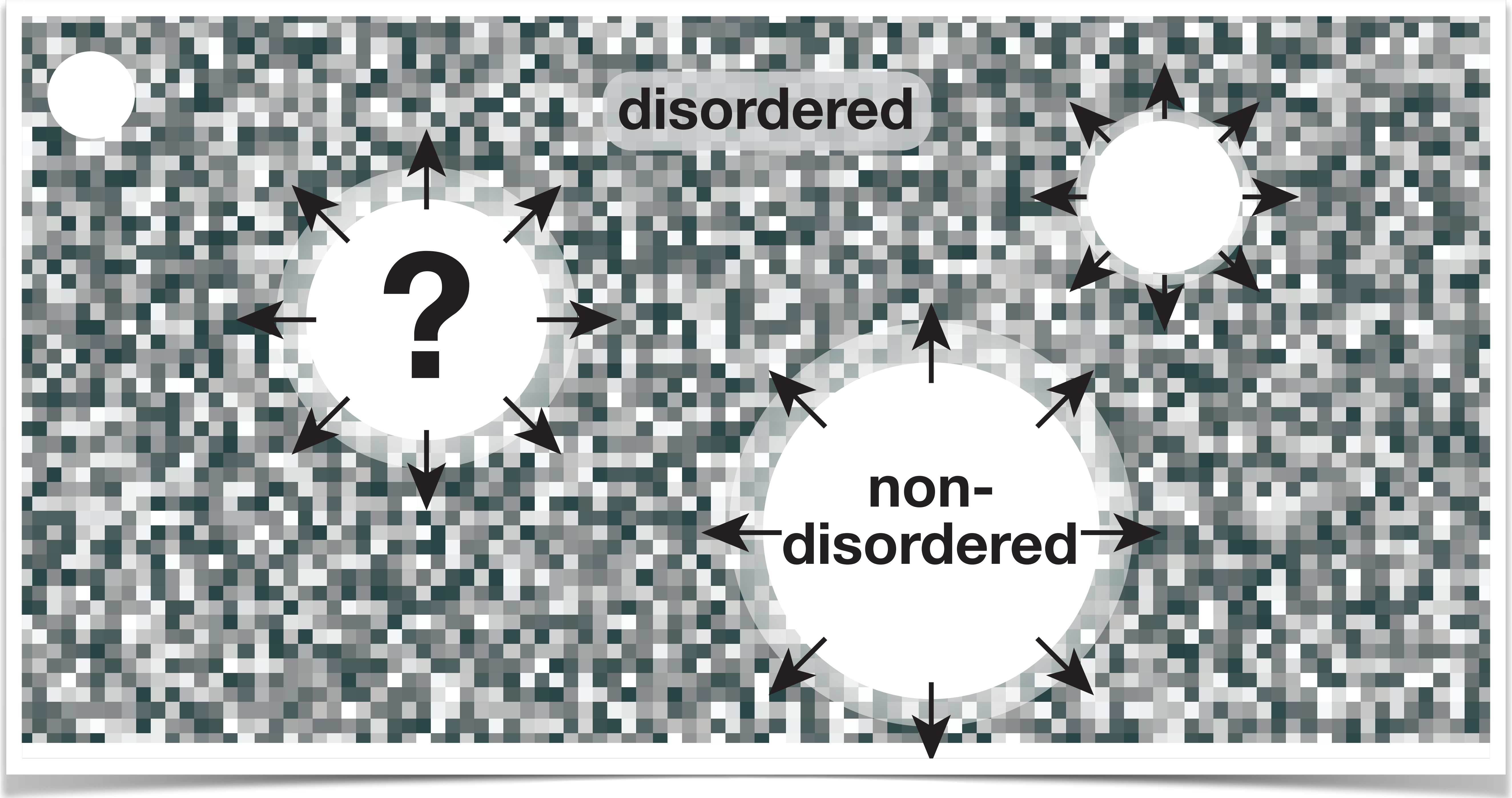
τ_1~0.6 ħ/*J* τ_2~105 ħ/*J* τ_3 > 2500 ħ/*J*



Band width	**8 *J***
Interactions	***U* = 25 *J***
Disorder	**Δ = 28 *J***

A. Rubio-Abadal, J-y. Choi *et al.,* PRX 2019

Probing MBL Instabilities



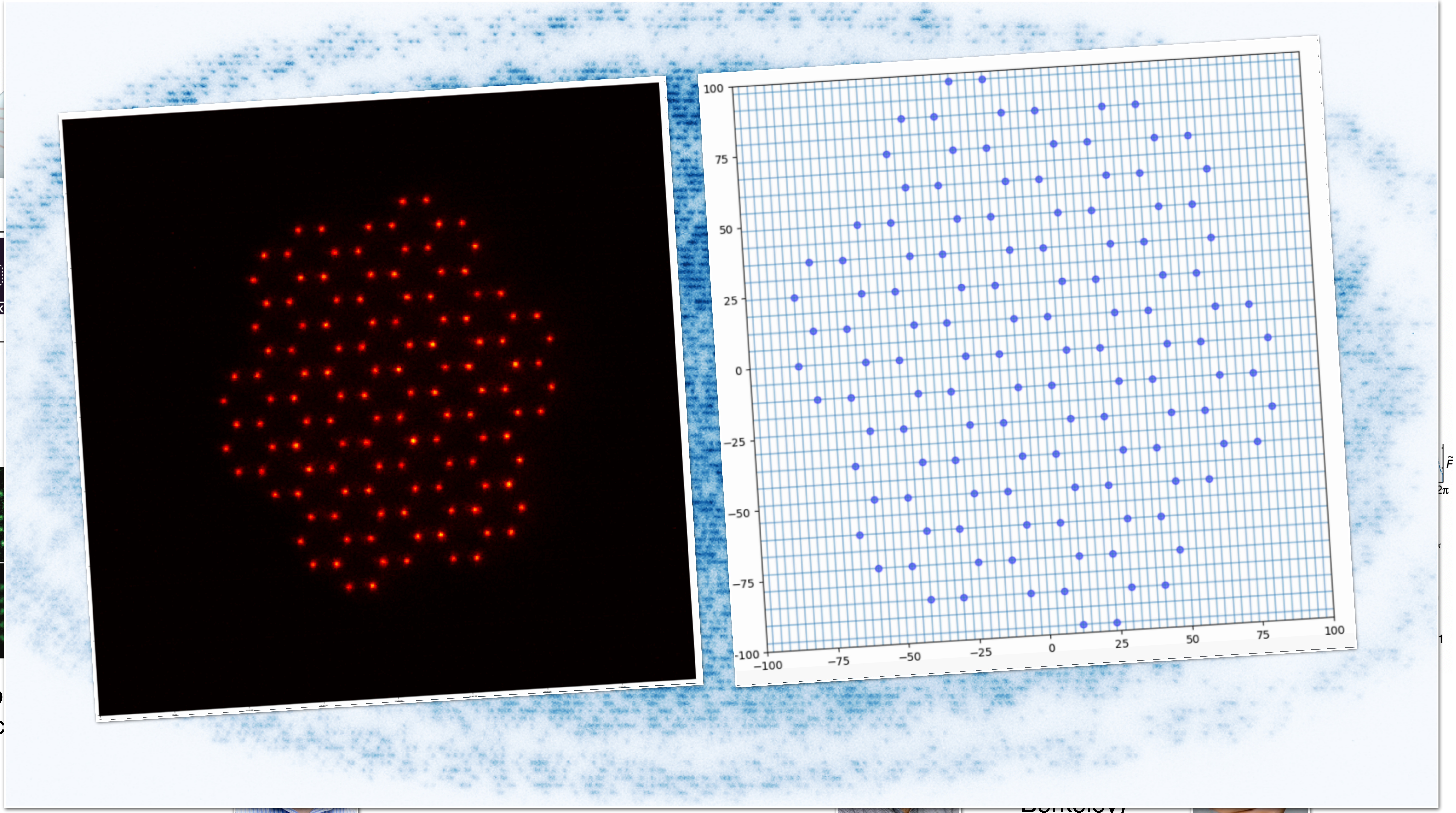
Engineered disorder with **controlled non-disordered (ergodic) grains!**

Avalanches?
Stability?
Range?
Timescales of Instability?

⋮

Where Next?

Enhanced Programmability



Hubb
(Princ

Berkeley)

Outlook

Opportunities

- (Precision) Many-body physics, New detection methods, Novel quantum phases, Non-equilibrium dynamics
- **Materials science**, **High-energy physics, Quantum chemistry**, **Coherent Quantum annealing**, **Optimization, Metrology** ….

Challenges

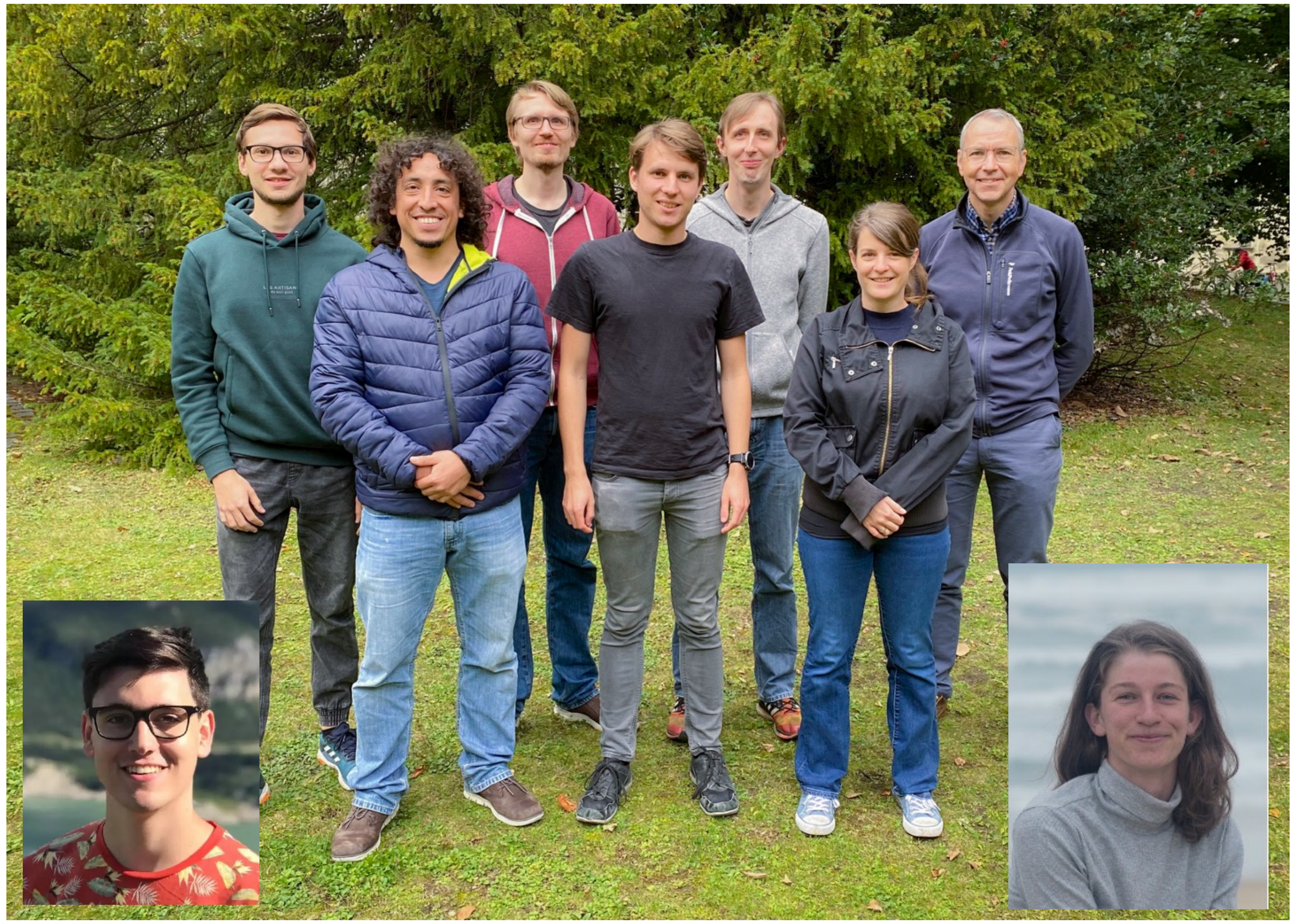
- **Programmability**, **scalability**, **reducing calibration errors**
- **Certification** and **verification**; demonstration of *practical* quantum advantage.
- Developing **applications relevant to industry and other fields of science**, and connections to an end-user base (e.g. spin models / optimization)
- **Entropy management** (cooling)
- **Cycle times**

Cs Quantum Gas Microscope Team

Ignacio
Perez

Simon
Karch

Christian
Schweizer



Scott Hubele

Sophie Häfele

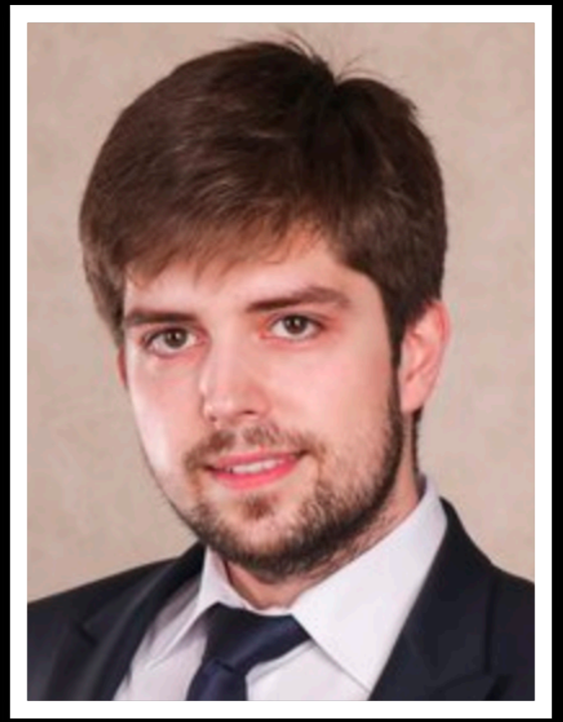
Alexander Impertro,
Cesar Cabrera
Hendrik von Raven,
Julian Wienand
Till Klostermann,
Monika Aidelsburger, IB

Theory

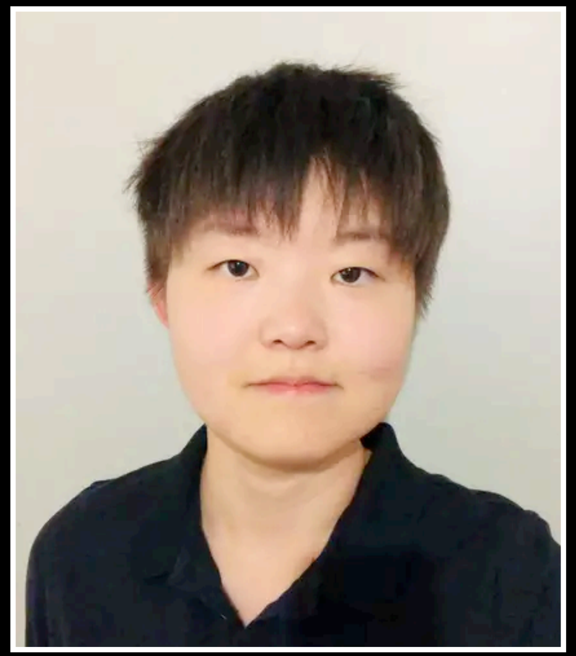
Ewan
McCulloch

Romain
Vasseur

Sarang
Gopalakrishnan



Petar Bojovic



Si Wang

Thomas Chalopin

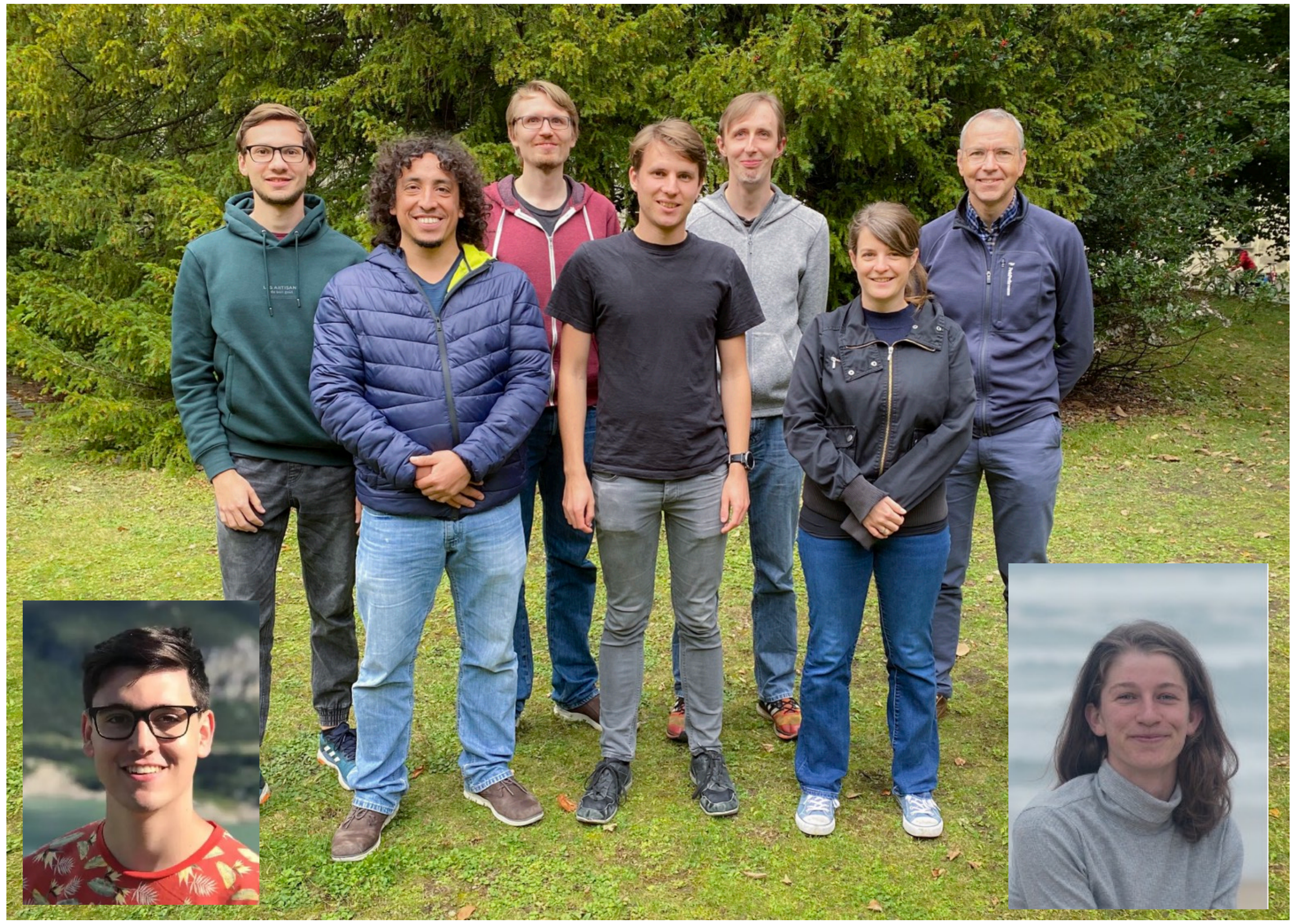

Daniel Adler
Suchita Agarwal
David Wei
Johannes Zeiher
Pascal Weckesser
Simon Hollerith
Kritsana Srakaew
1974
CROSS HATCH
REAL

Cs Quantum Gas Microscope Team

Ignacio
Perez

Simon
Karch

Christian
Schweizer



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Monika Aidelsburger, IB

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Vasseur

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