learning from noise in complex quantum systems

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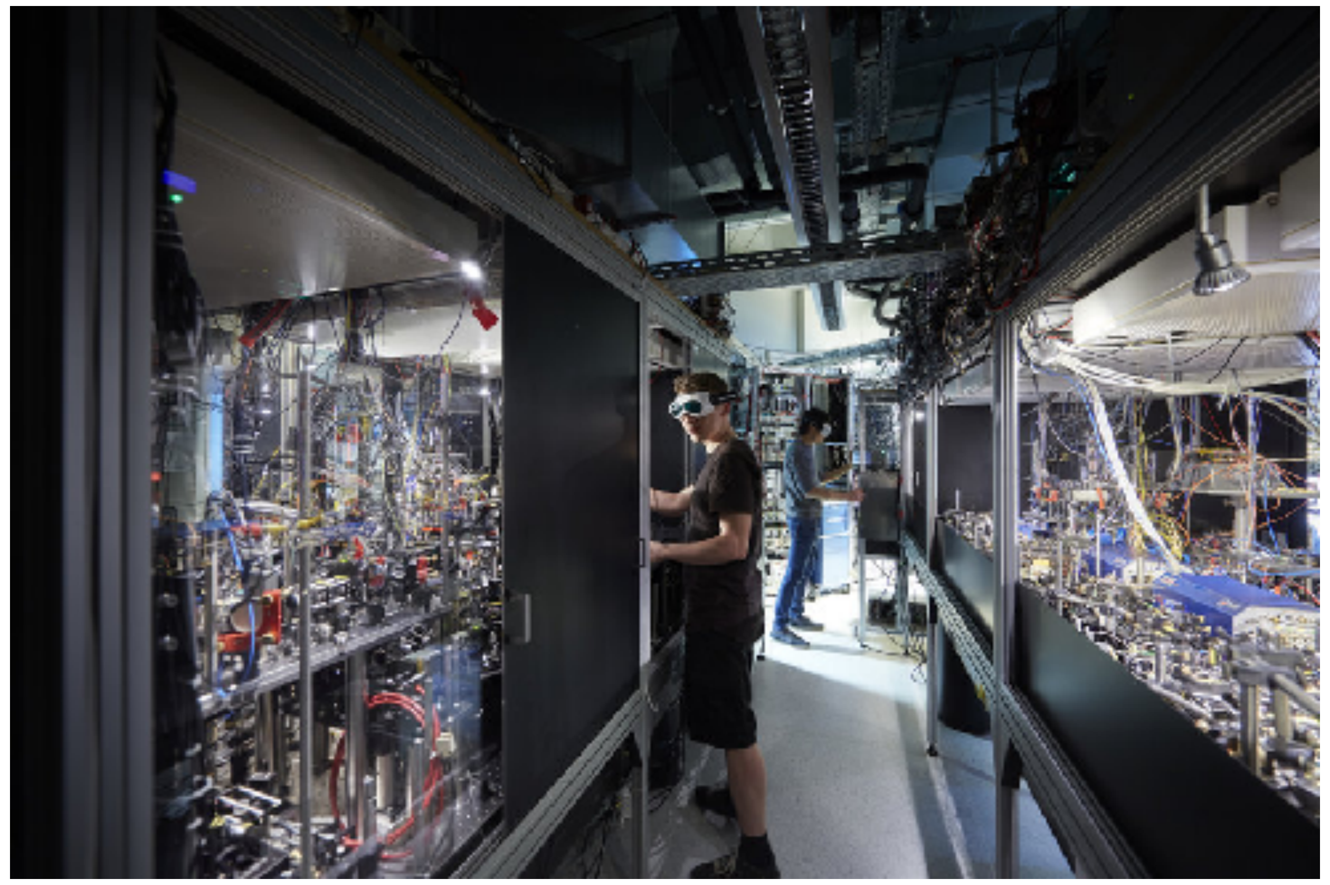
wienand, karch, impertro, schweizer, mcculloch, vasseur, **sg**, aidelsburger, bloch, *nature physics* (2024)
rosenberg…khemani, **sg**, prosen, roushan, *science* **384**, 48 (2024)
le, zhang, **sg**, rigol, weiss, *nature* **618**, 494 (2023)
wei…**sg**, yao, bloch, zeiher, *science* **376**, 716 (2022)
mahmood, chaudhuri, **sg**, nandkishore, armitage, *nature physics* **17**, 627 (2021)

how quantum is many-body dynamics?

- Do we really need a quantum computer to simulate quantum dynamics?
  - Yes, if we want to do it exactly for all possible observables
  - What if we just care about some subset of quantities, to some accuracy?



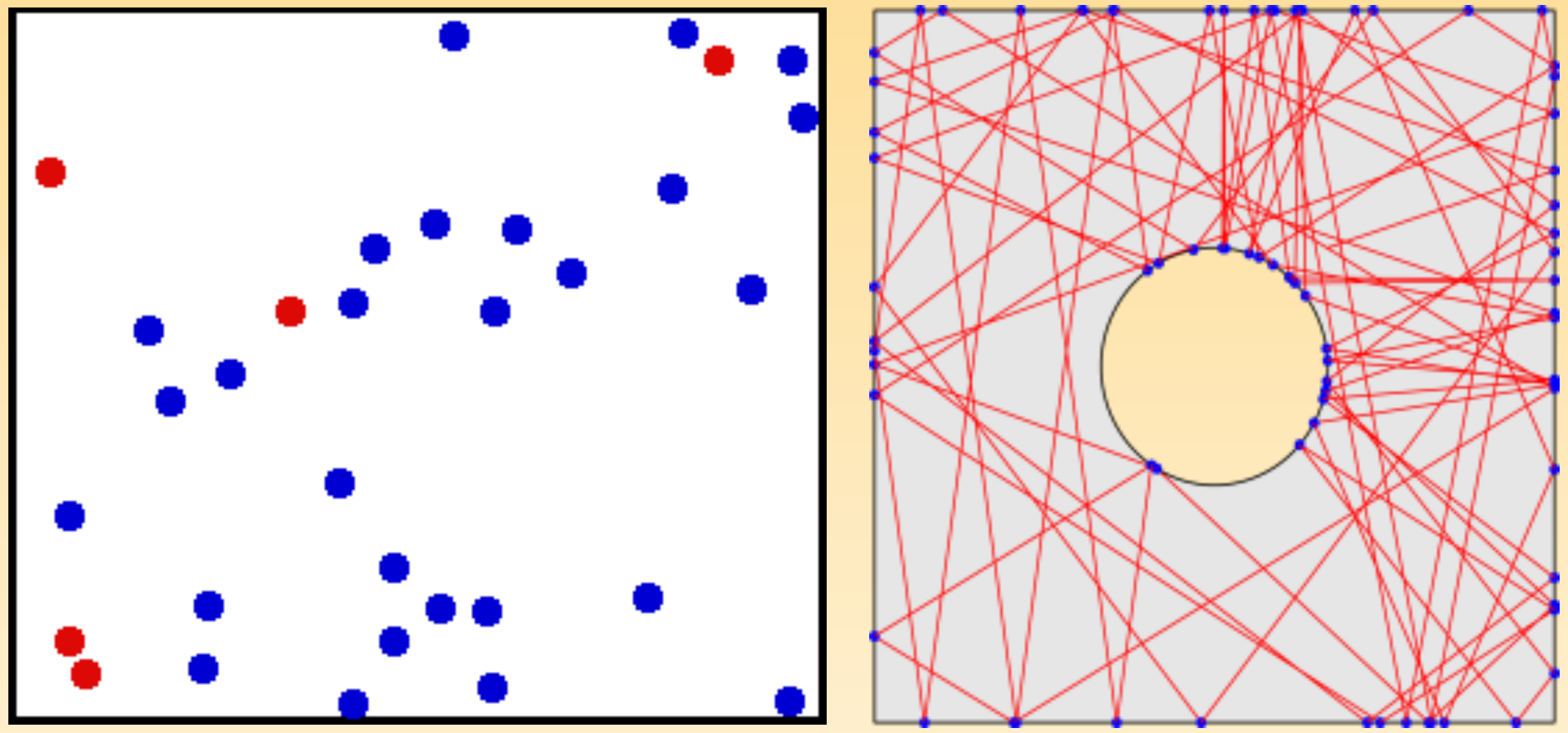
vs.

how **complex** is many-body dynamics?

understanding fluid flow

replace complex dynamics
with randomization
good news: tractable
and fault tolerant
bad news: uninformative
(e.g., about details of model)

coarse-graining



predicting individual particle trajectories

good and bad news:
exponentially sensitive to details
(because of chaos),
need exponential accuracy

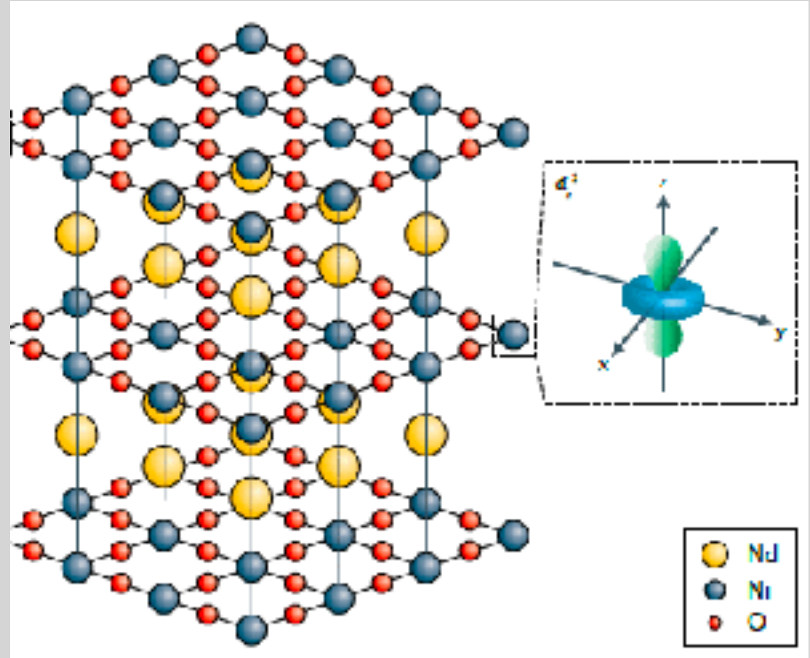
does not tell you anything qualitative
beyond whether your algorithm works

task complexity

what tasks do we care about?

structure/# of moving parts

effective classical theories
must fail somewhere around here

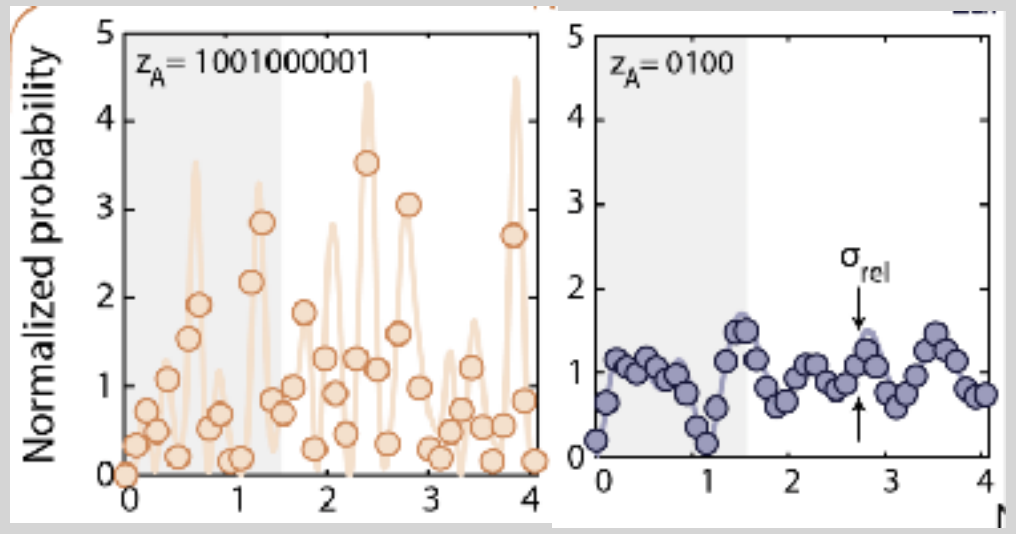


solid-state transport, $T > 0$

simple questions (conductivity)
that we care about
but might not reveal
underlying mechanisms
classical hydrodynamic description

random circuit sampling

classically unspoofable by design
but of no* practical relevance
**noise sensor?? [Shaw et al. 2024]*



task complexity

what tasks do we care about?

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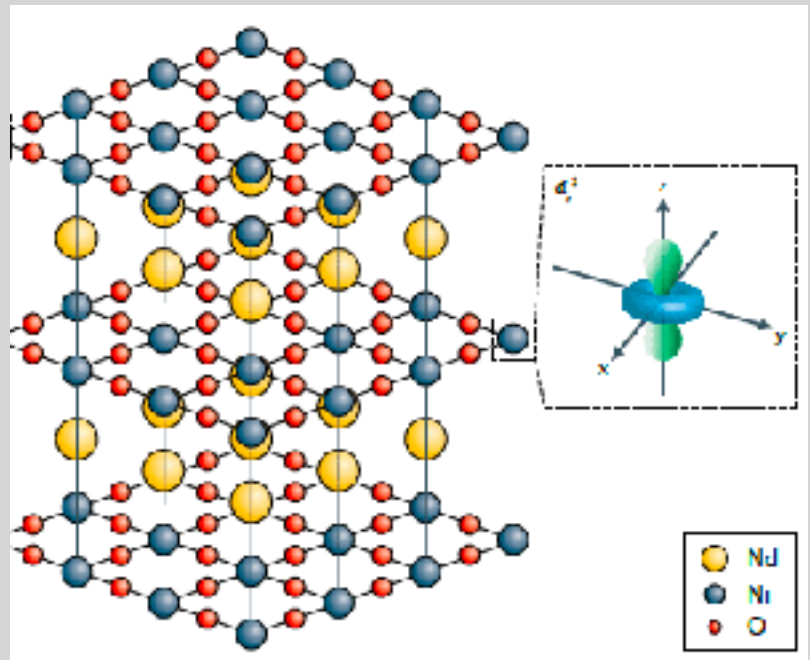
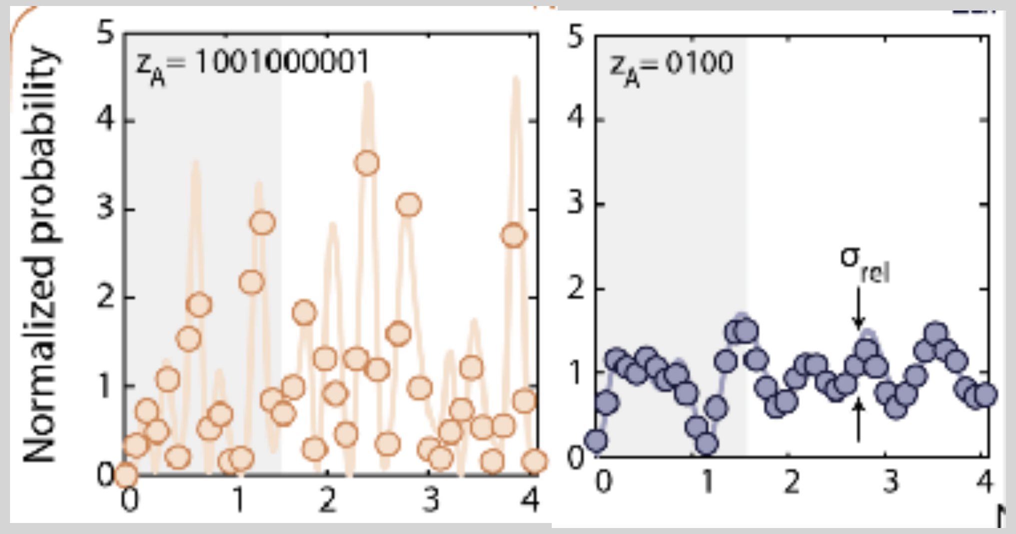


solid-state transport, $T > 0$

- We want design principles for better/more interesting materials
- We need to know *what about* an existing material makes it useful/interesting
- We need observables that help us isolate *mechanisms*: reduced descriptions that capture the observed phenomena
- Neither limit is helpful: transport can have many mechanisms, RCS does not probe structure since there is no structure to probe

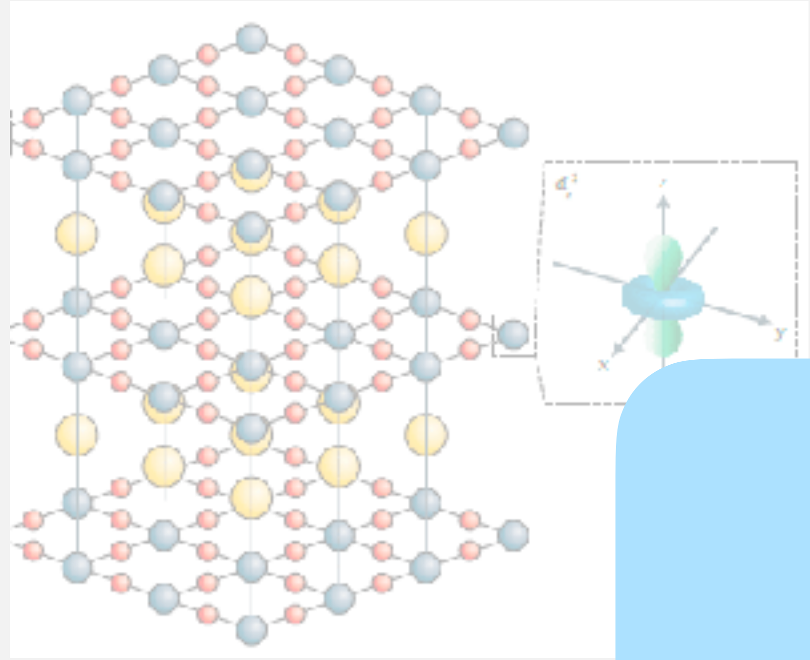
random circuit sampling



task complexity

regime of intermediate complexity

# of moving parts



solid-state transpor

In between: dynamics of fluctuations in interacting many-body systems

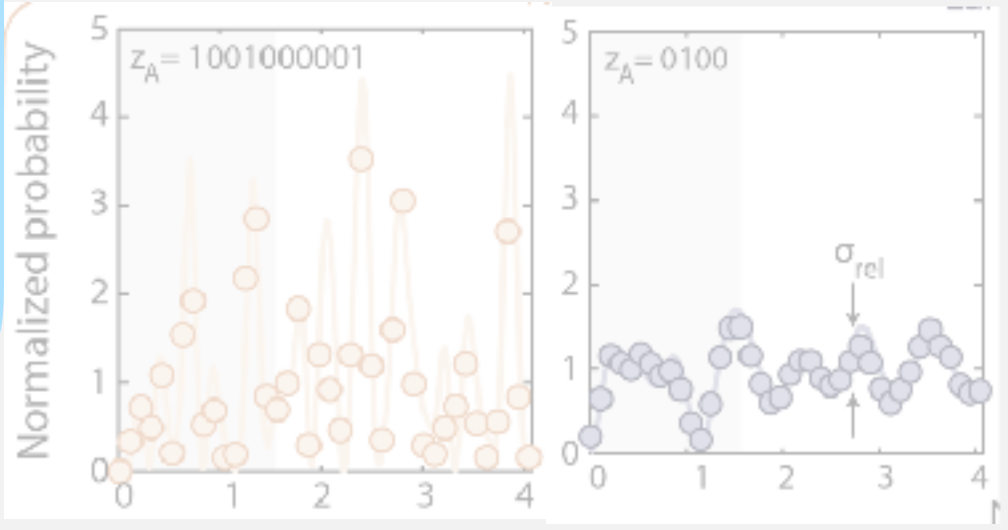
Carry information about dynamical mechanisms

Explore the boundaries of validity of classical descriptions

New universality classes of fluctuations

Experiments teach us things we did not know or expect

random circuit sampling



task complexity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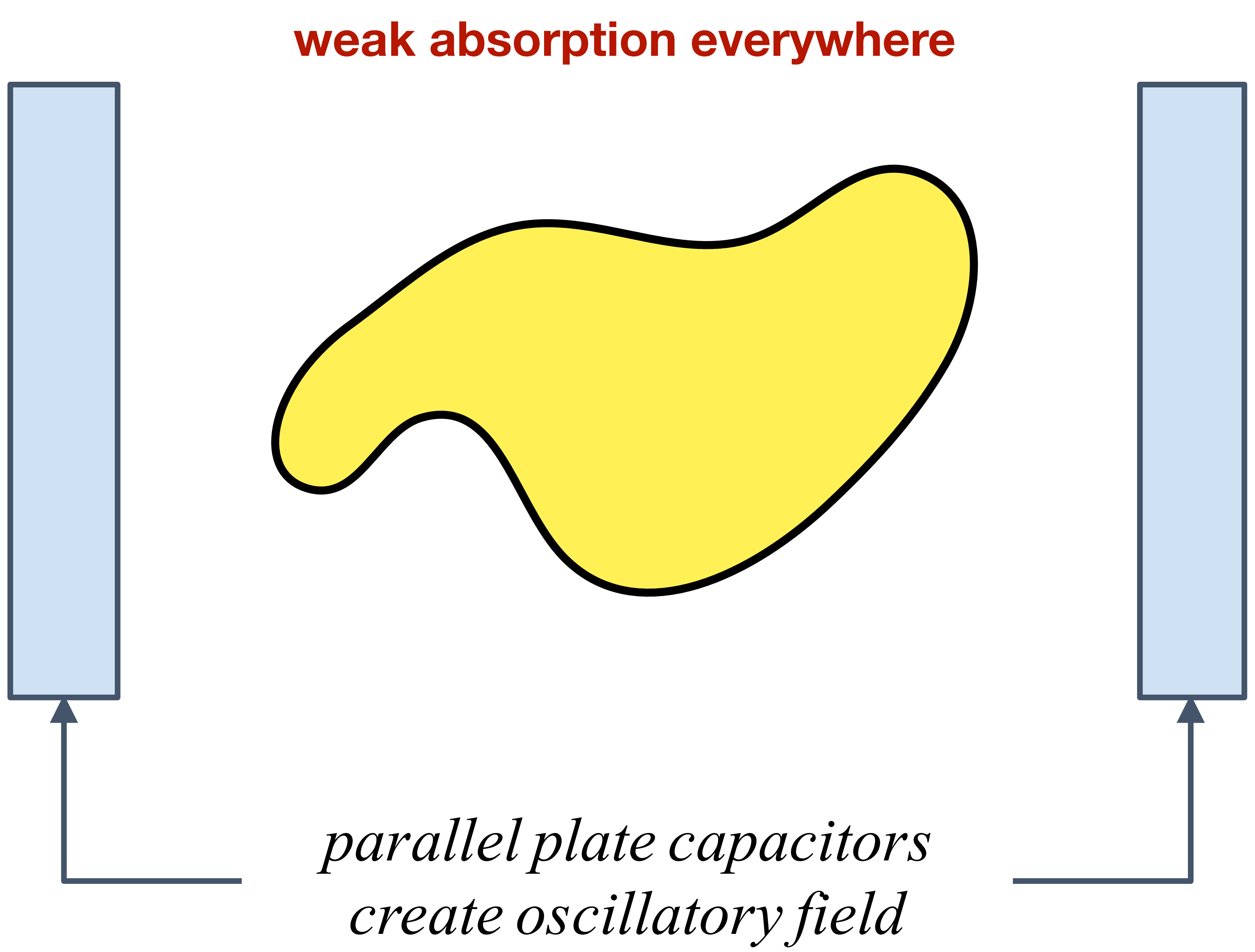
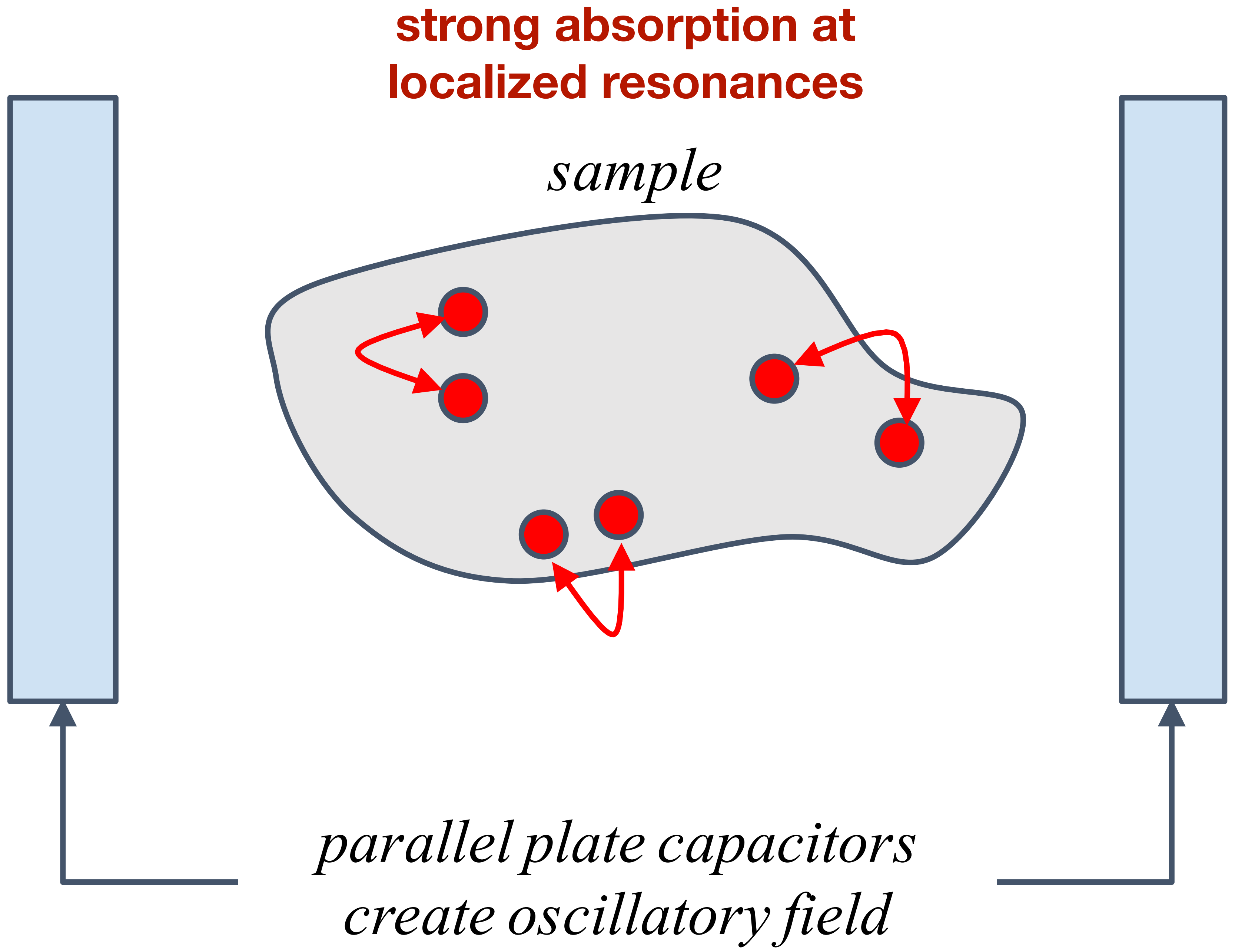
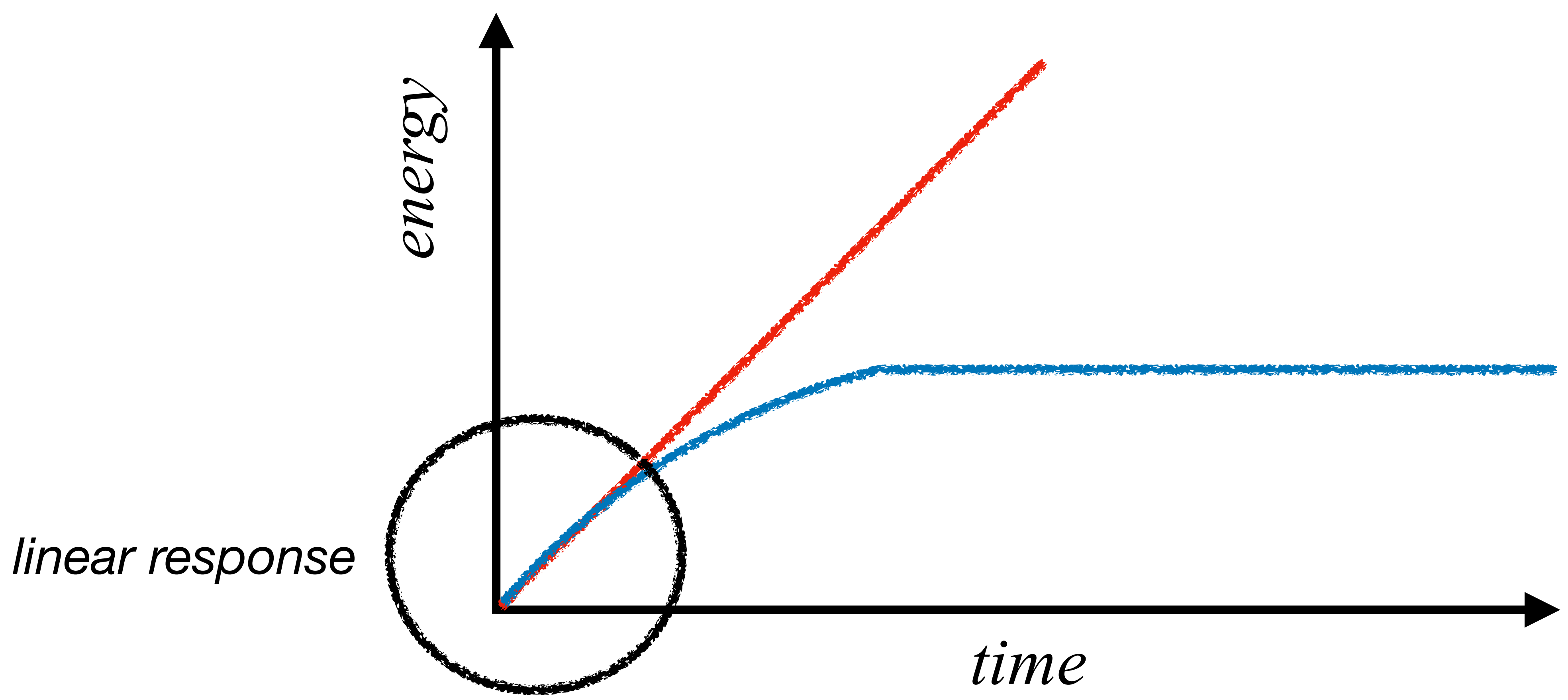
example 1: pump-probe spectroscopy

physics question: are there long-lived excitations in disordered interacting systems?

response of metals vs. insulators

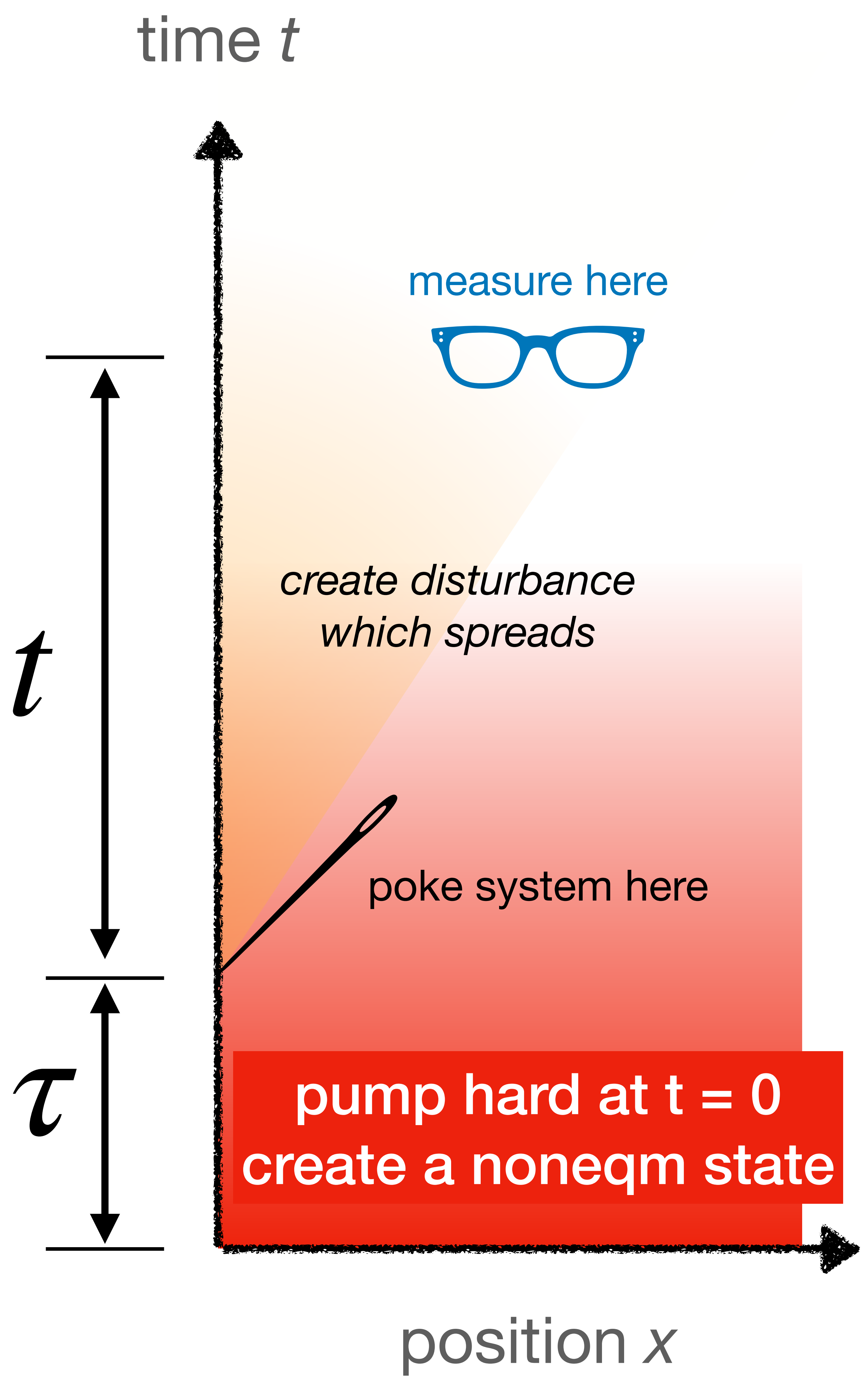




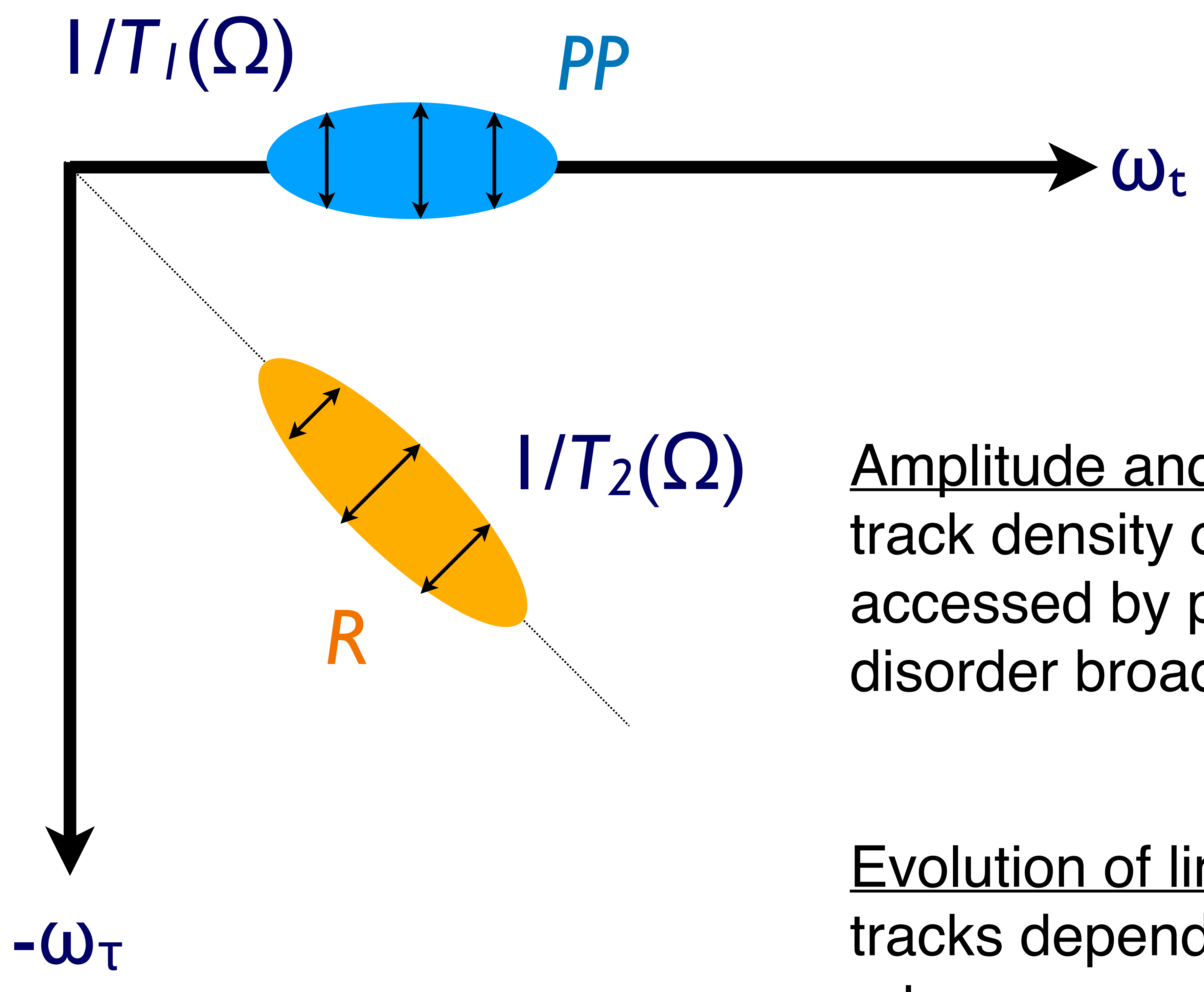


To understand mechanisms for finite-frequency absorption, need to go beyond linear response

pump-probe response



Related to higher-order fluctuations by fluctuation-dissipation theorem

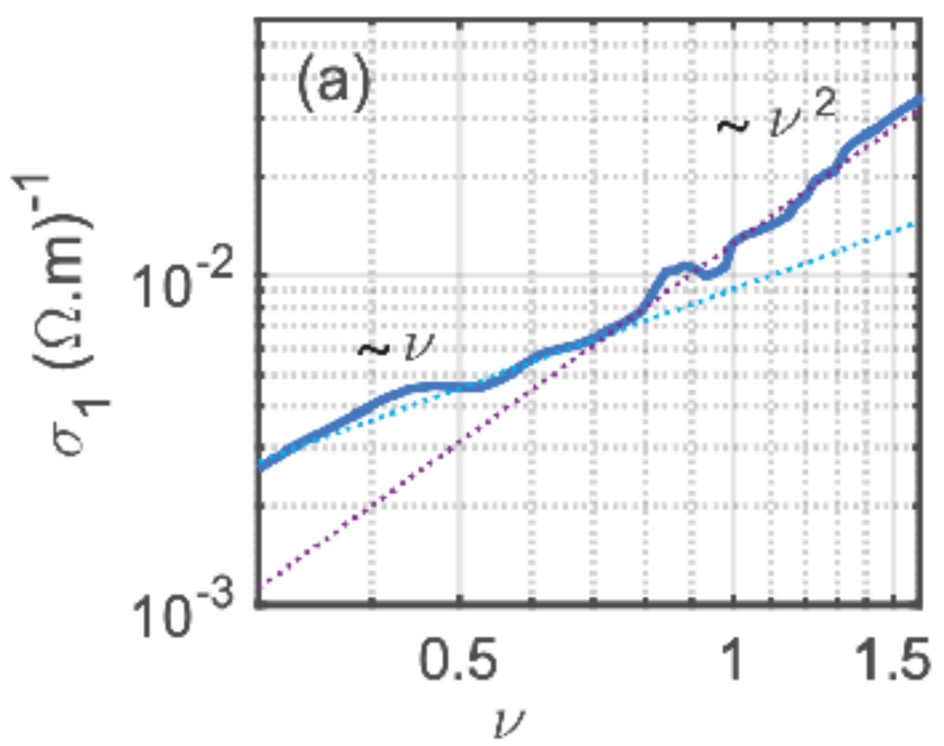


Amplitude and location of peaks ~
track density of states of excitations accessed by probe (dispersion, disorder broadening)

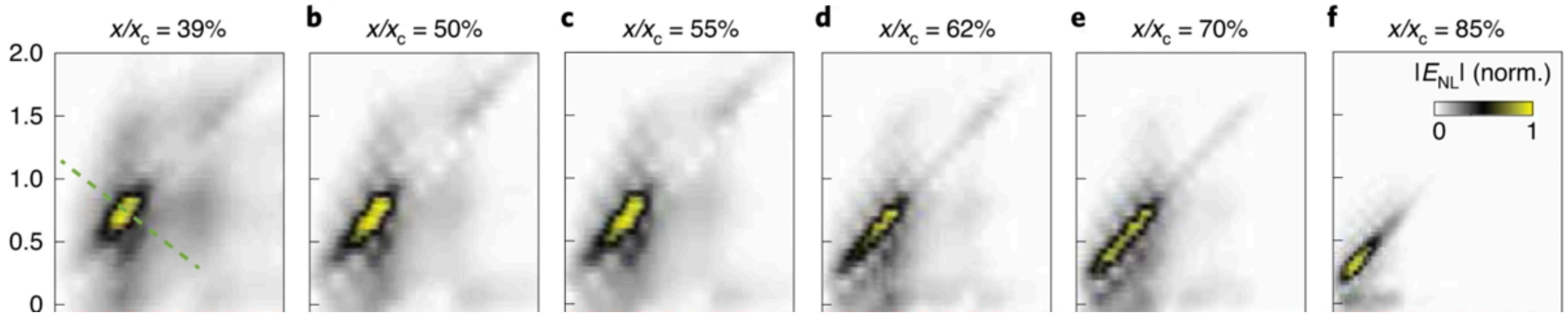
Evolution of linewidths ~
tracks dependence of relaxation rates on energy of excitation

pump-probe response in the electron glass

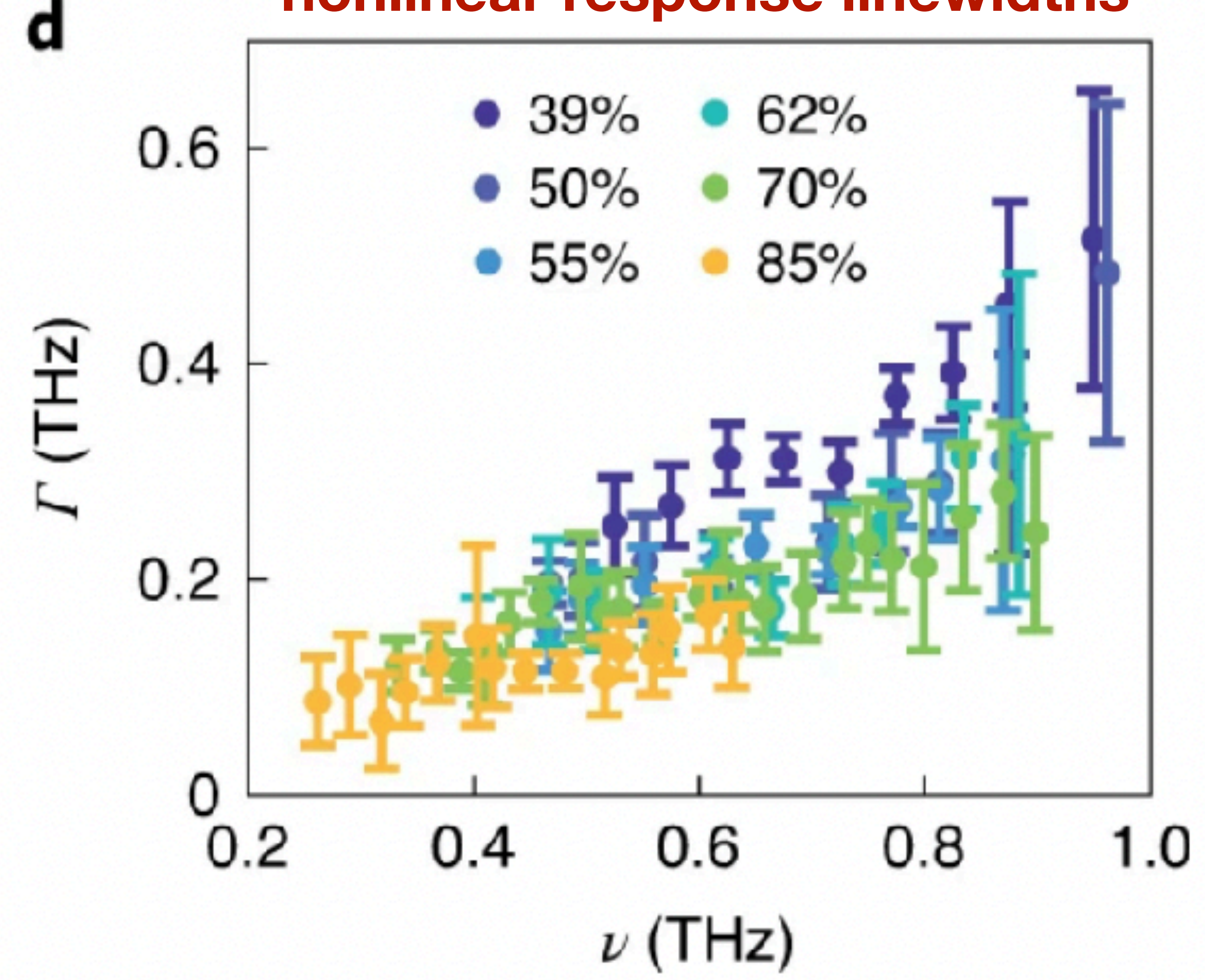
conductivity



nonlinear response



nonlinear response linewidths



- P-doped Si: metal-insulator transition with higher % doping
- Why do the lines grow sharper with decreasing disorder?
  - **Still no quantitative theory**
- Why is linewidth proportional to frequency at low temperatures?
  - Dipolar interactions between localized particle-hole excitations

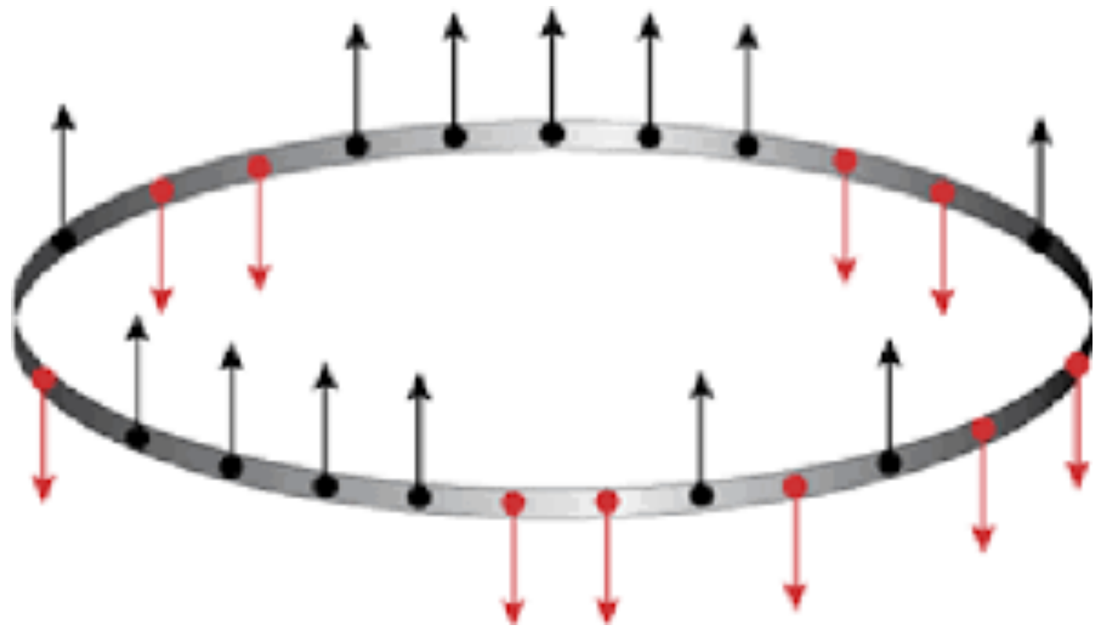
immanuel bloch | johannes zeiher | pedram roushan | david wei | eliott rosenberg | norman yao | vedika khemani | romain vasseur | tomaž prosen

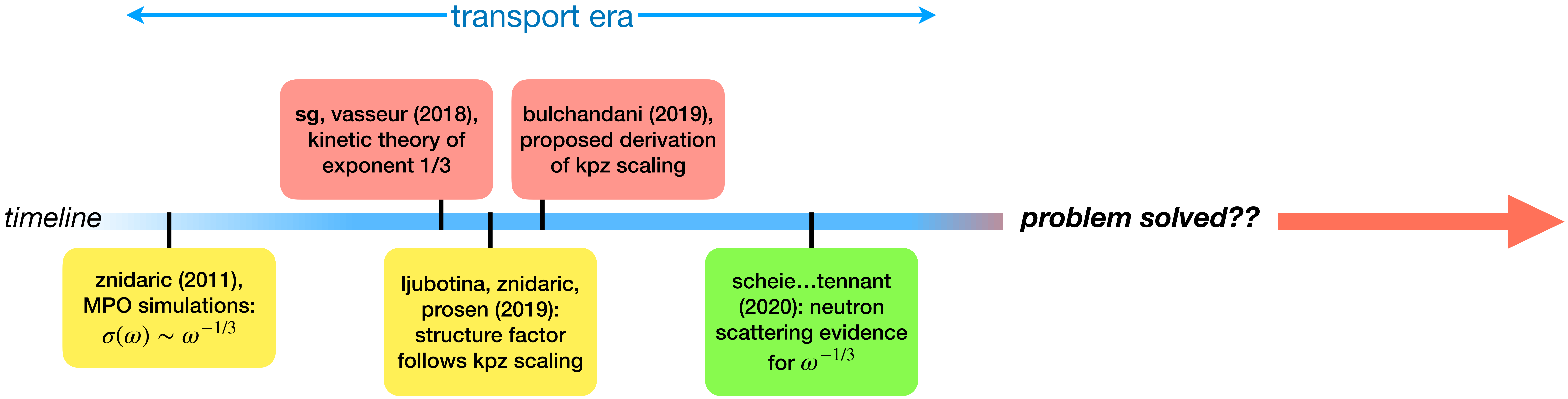
example 2: full counting statistics in quantum spin chains

physics question: what causes divergent spin conductivity in the heisenberg model?

transport in heisenberg spin chain

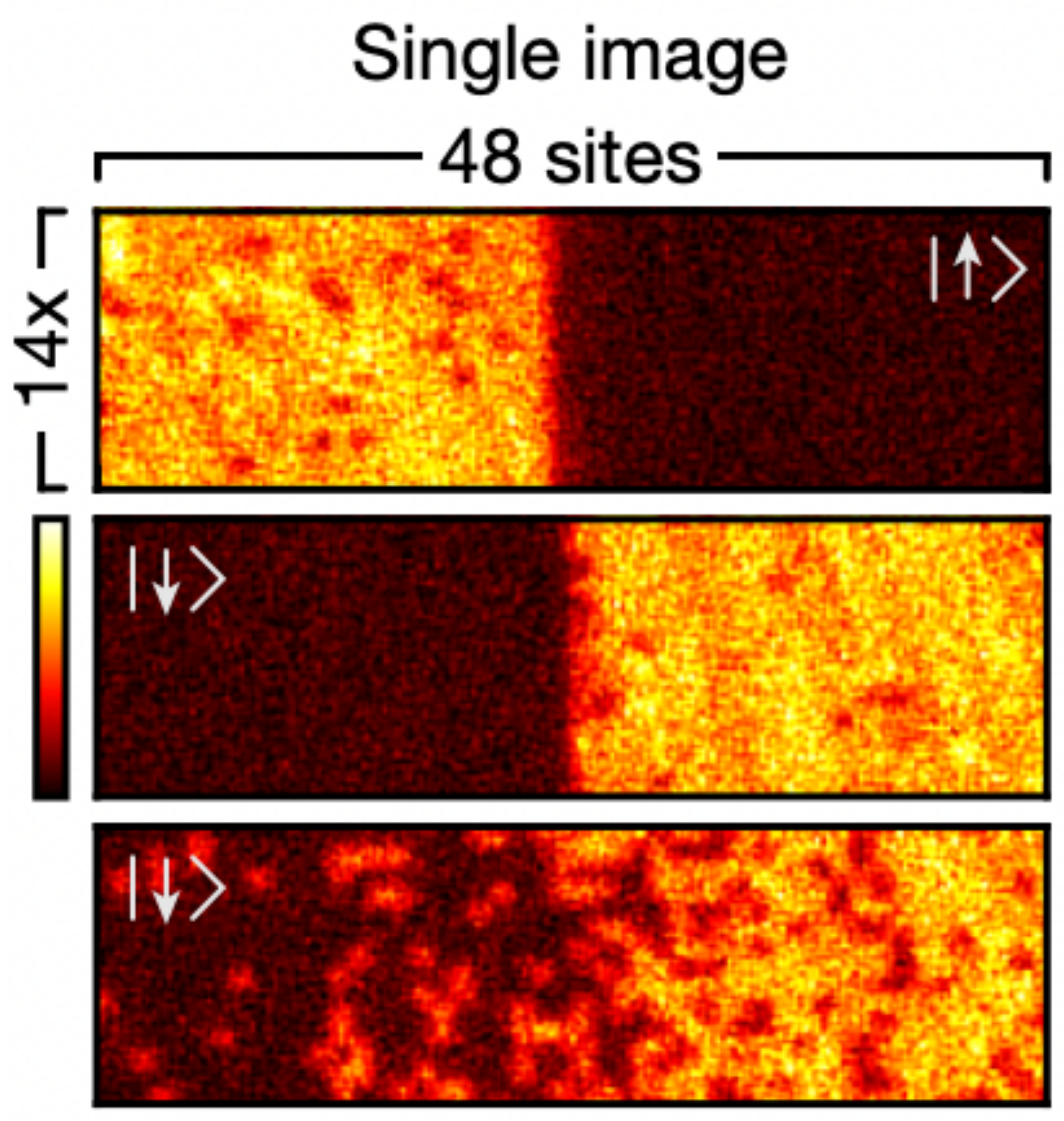
- One of the simplest interacting models: quantum spins that can point in any direction and interact with their neighbors
- Exact formal solution for finite systems [Bethe, 1931]
- Spin conductivity at nonzero temperatures has remained an open question



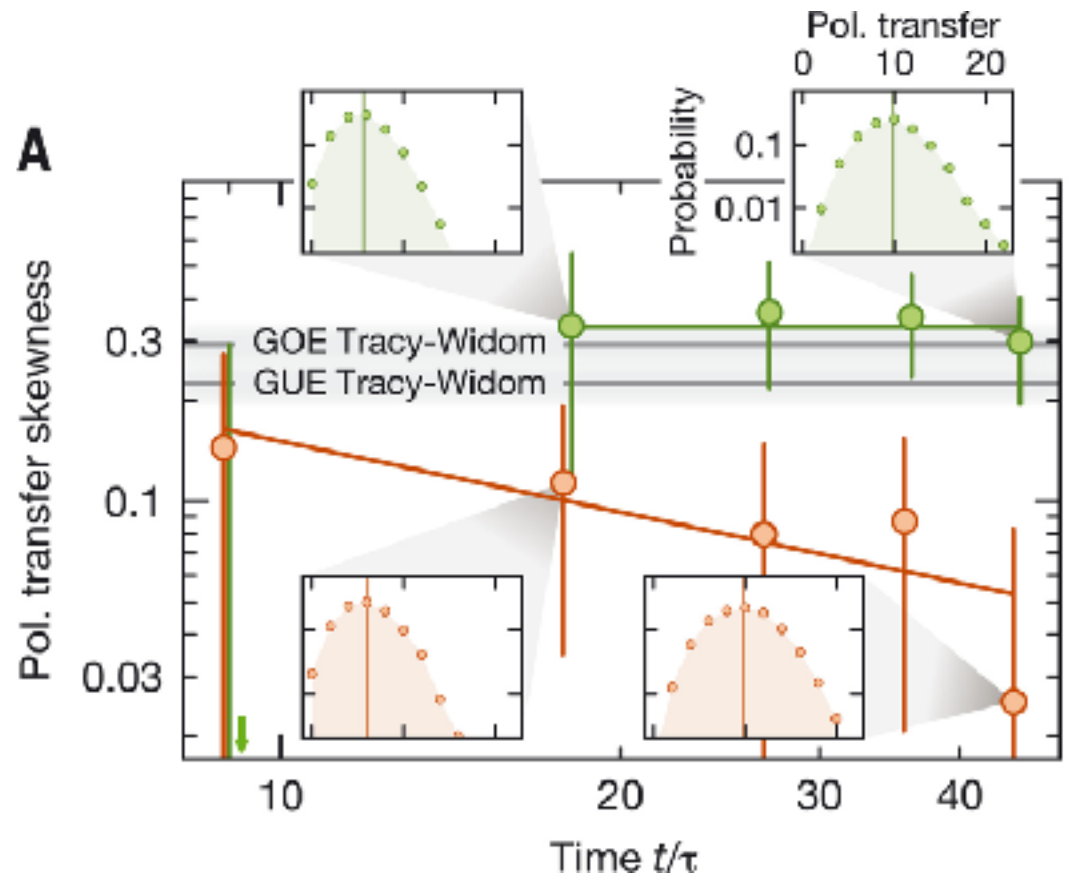


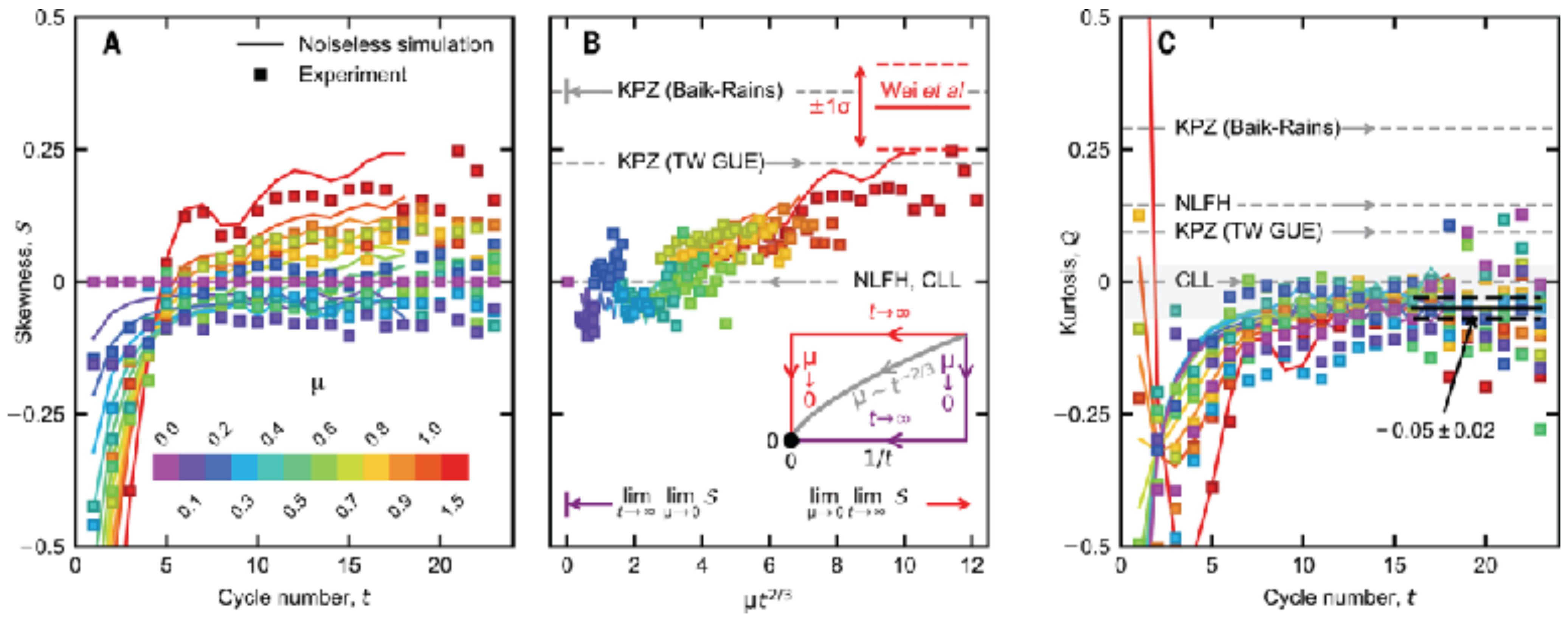
full counting statistics

- Not restricted to measuring expectation values or correlators
- Can take simultaneous snapshots of all the spins
- Experimental protocol:
  - Initialize two half-systems separated by a barrier, at (sharp) particle numbers Q_L, Q_R
  - Lower the barrier and run the dynamics to some time t
  - Measure all the particle positions
  - This gives a distribution of measurement outcomes of the operator $\hat{Q}_R$ (magnetization transfer)
- The full asymptotic distribution is known for KPZ universality class [Spohn, Hairer, Sasamoto…]



full counting statistics in heisenberg spin chains





transport era ← → era of fluctuations

timeline

znidaric (2011), MPO simulations: $\sigma(\omega) \sim \omega^{-1/3}$

sg, vasseur (2018), kinetic theory of exponent 1/3

ljubotina, znidaric, prosen (2019): structure factor follows KPZ scaling

bulchandani (2019), proposed derivation of kpz scaling

scheie…tennant (2020): neutron scattering evidence for $\omega^{-1/3}$

krajnik, ilievski, prosen (2021): symmetry argument for non-kpz fluctuations

wei…sg, yao, bloch, zeiher (2021): observation of *nongaussian fluctuations* (consistent with kpz)

de nardis, sg, vasseur (2022): modified kpz ansatz with correct symmetries

rosenberg…khemani, sg, prosen, roushan (2023): experiments inconsistent with modified kpz ansatz

valli…prosen, zarand (2024): numerics inconsistent with modified kpz ansatz

what went wrong?

- Simple two mode hydrodynamics:

$$\partial_t \vec{S} + \partial_x(\phi \vec{S}) = D\partial_x^2 \vec{S} + \partial_x \vec{\xi}$$

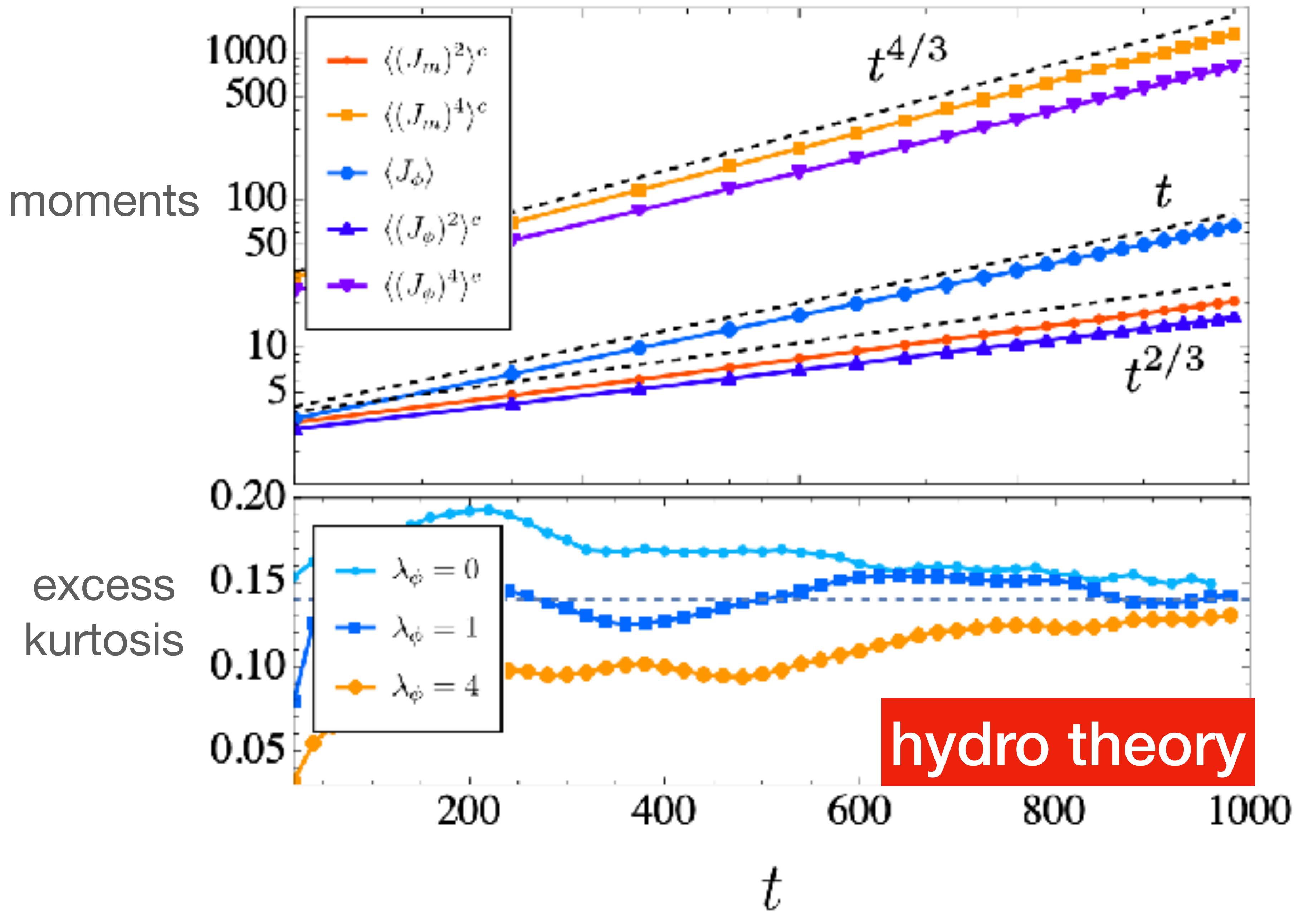
$$\partial_t \phi + \partial_x(c_1 \phi^2 + c_2 S^2) = D\partial_x^2 \phi + \partial_x \eta$$

- All terms dictated by symmetry and existence of a conserved energy current (because of integrability)

- Argument for z = 3/2:

  - Velocity ϕ has fluctuations of order $\sqrt{\ell}$ in a region of size ℓ

  - Time taken to traverse the region: $\ell/\sqrt{\ell} \sim \ell^{3/2}$



what went wrong?

- Simple two mode hydrodynamics:

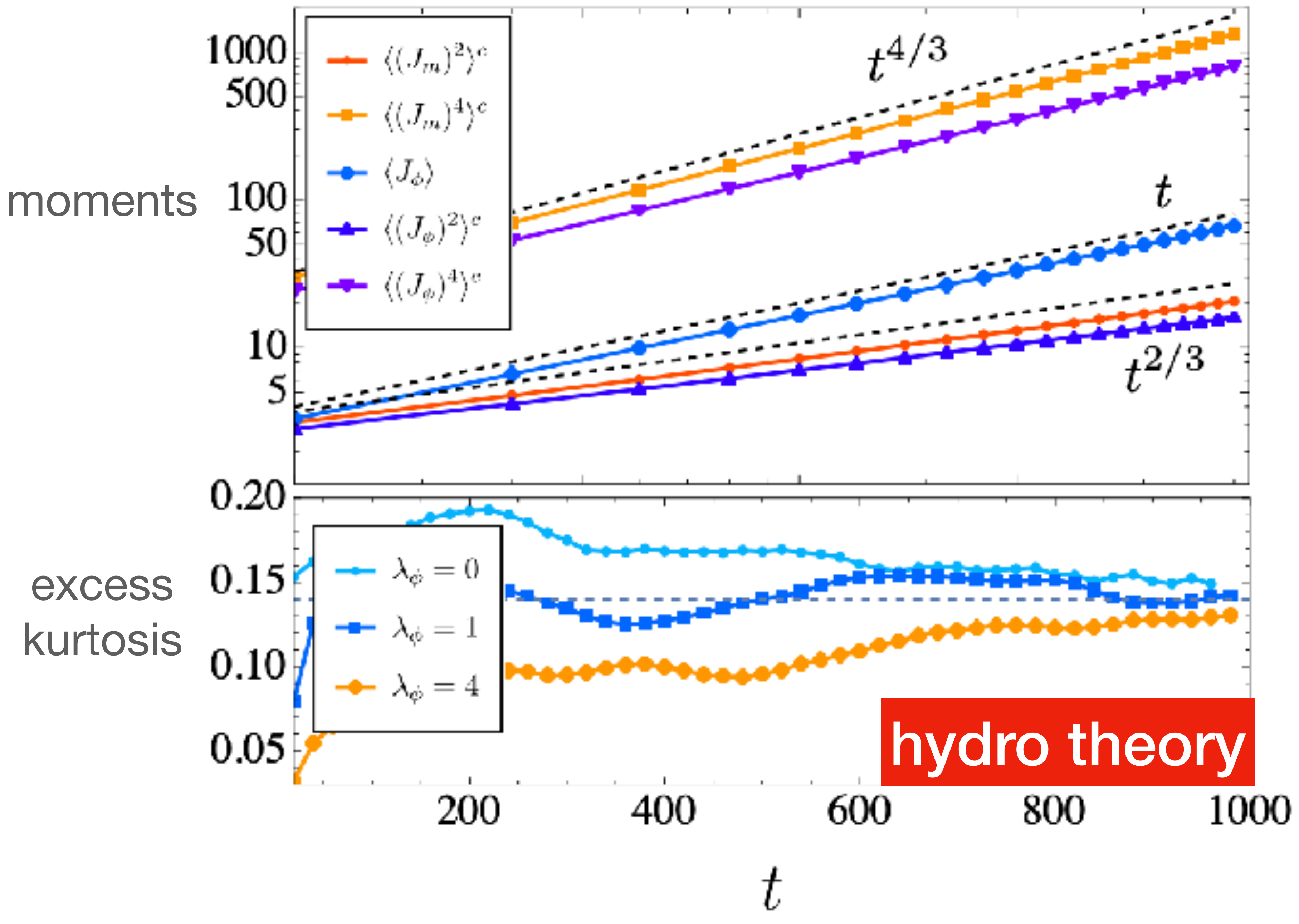
$$\partial_t \vec{S} + \partial_x(\phi \vec{S}) = D\partial_x^2 \vec{S} + \partial_x \vec{\xi}$$

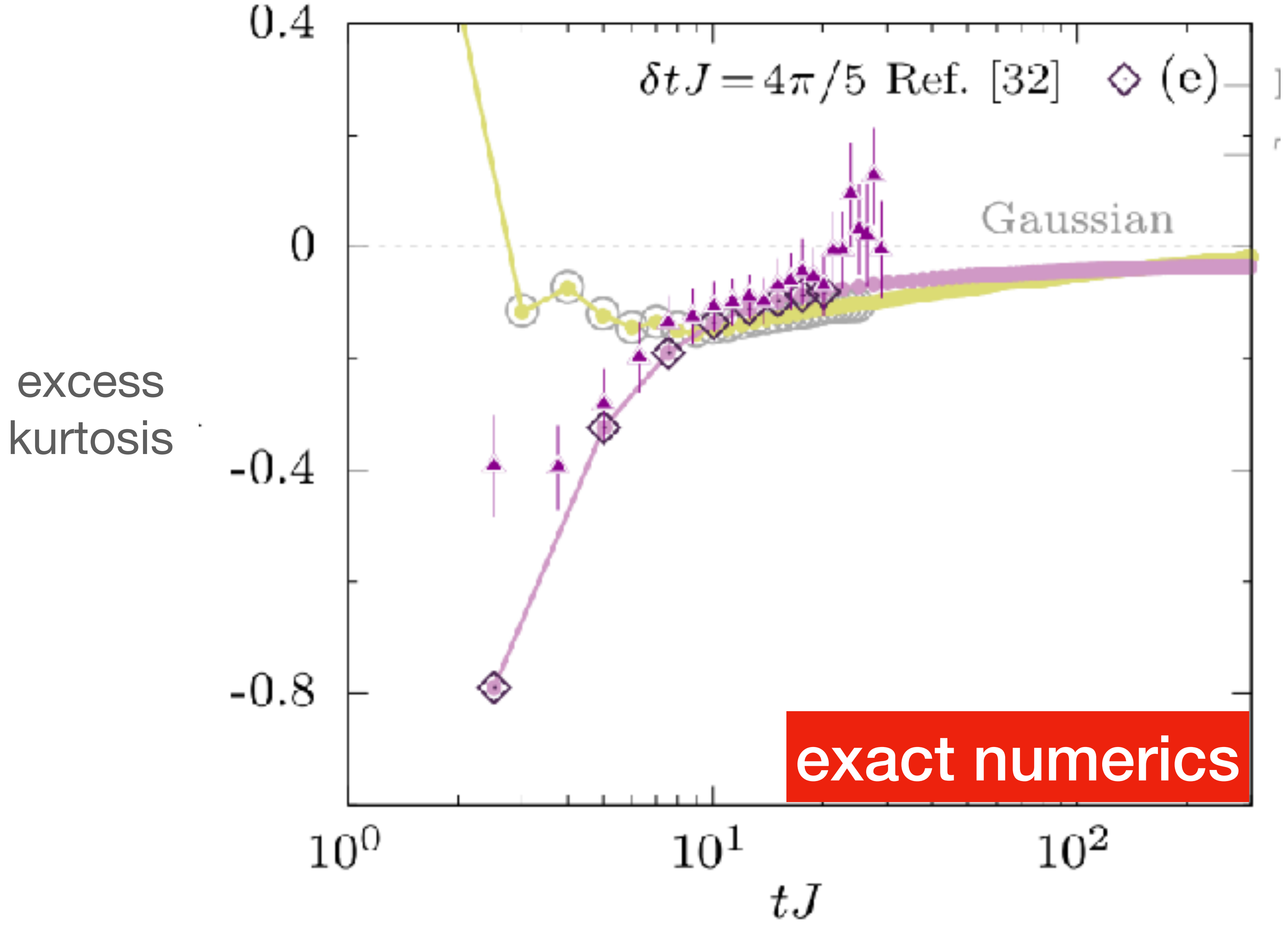
$$\partial_t \phi + \partial_x(c_1\phi^2 + c_2 S^2) = D\partial_x^2 \phi + \partial_x \eta$$

- All terms dictated by symmetry and existence of a conserved current (because of integrability)

hydro theory

- Argument for z = 3/2:
  - Velocity ϕ has fluctuations of order $\sqrt{\ell}$ in a region of size ℓ
  - Time taken to traverse the region: $\ell/\sqrt{\ell} \sim \ell^{3/2}$
- What could go wrong?
- We made a standard assumption of δ-correlated noise: dangerous when there are long-lived modes





new universality class of diffusion

- Simplify from superdiffusion to regular diffusion

- New universality class of diffusion with anomalous nongaussian fluctuations
  [sg, morningstar, vasseur, khemani (2022); krajnik, ilievski, prosen (2022)]

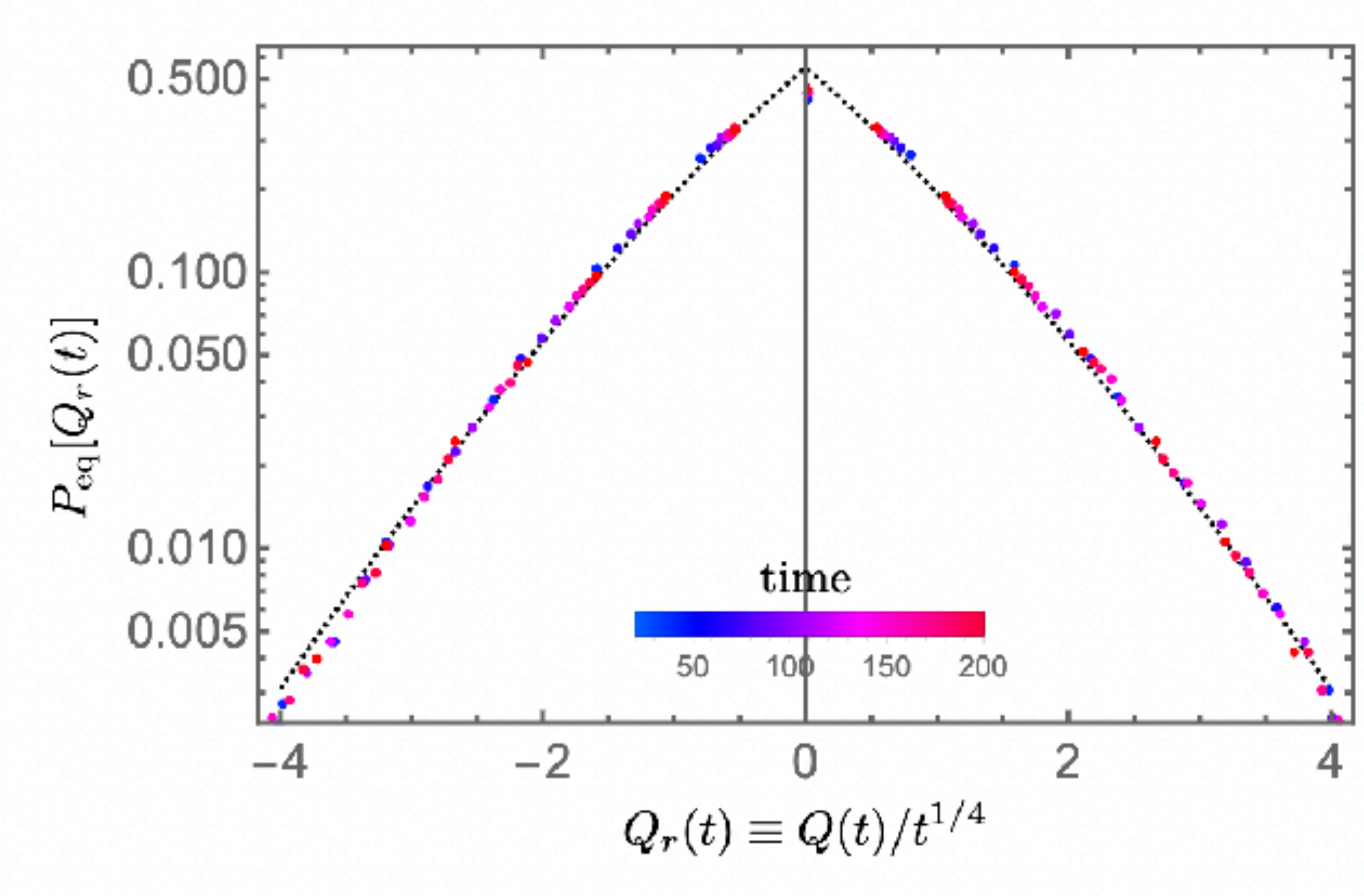
- Basic physical idea: Brownian motion

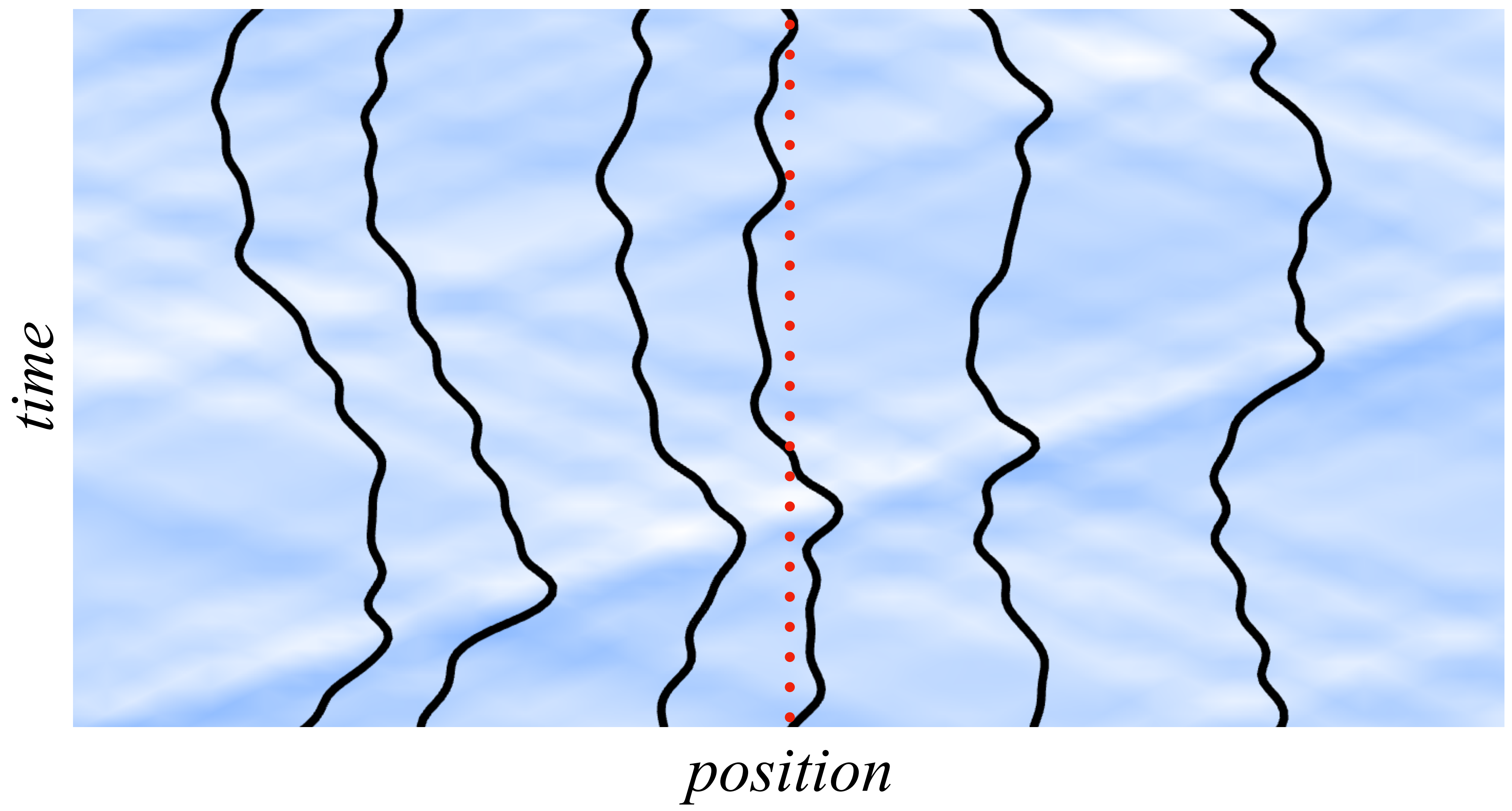
  $$\dot{x}_i(t) = \eta(x_i(t))$$

  where η fluctuates because of ballistically propagating sound waves

- Normal hydro treats noise as uncorrelated in spacetime, but here it has ballistic correlations

- Anomalous noise arises in chaotic systems with certain symmetries, e.g., graphene at charge neutrality [sg, mcculloch, vasseur (2024)]






immanuel bloch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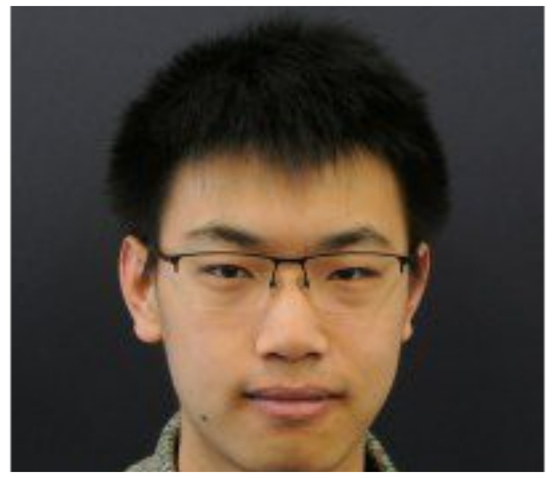
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marcos rigol


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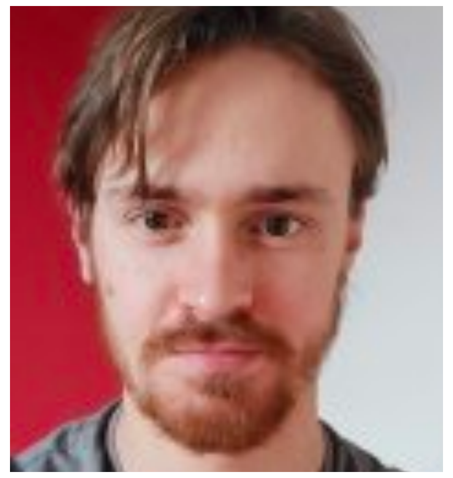
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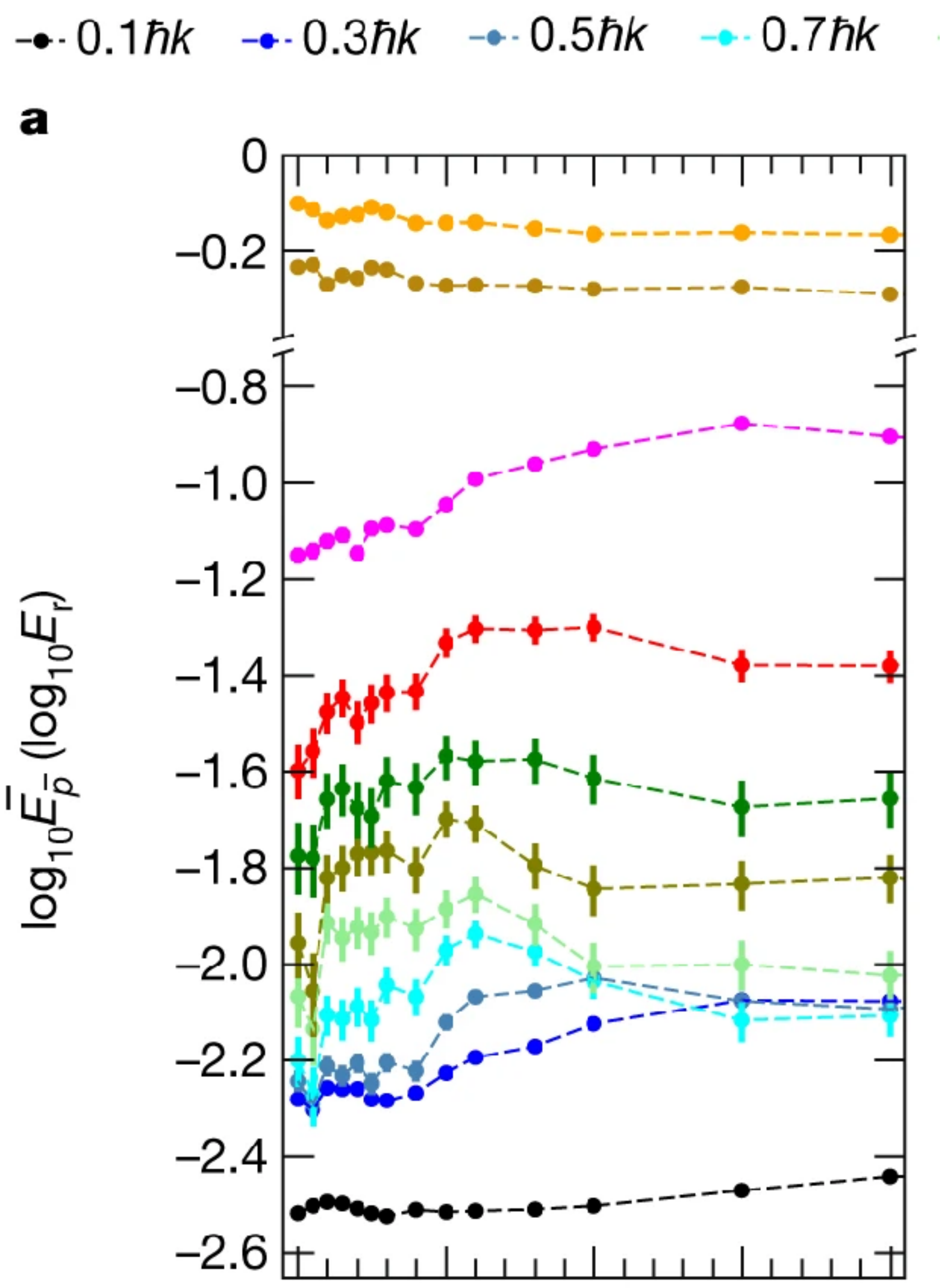
example 3:
hydrodynamics of fluctuations

physics question: when does a system approach local thermal equilibrium?

density-wave quenches

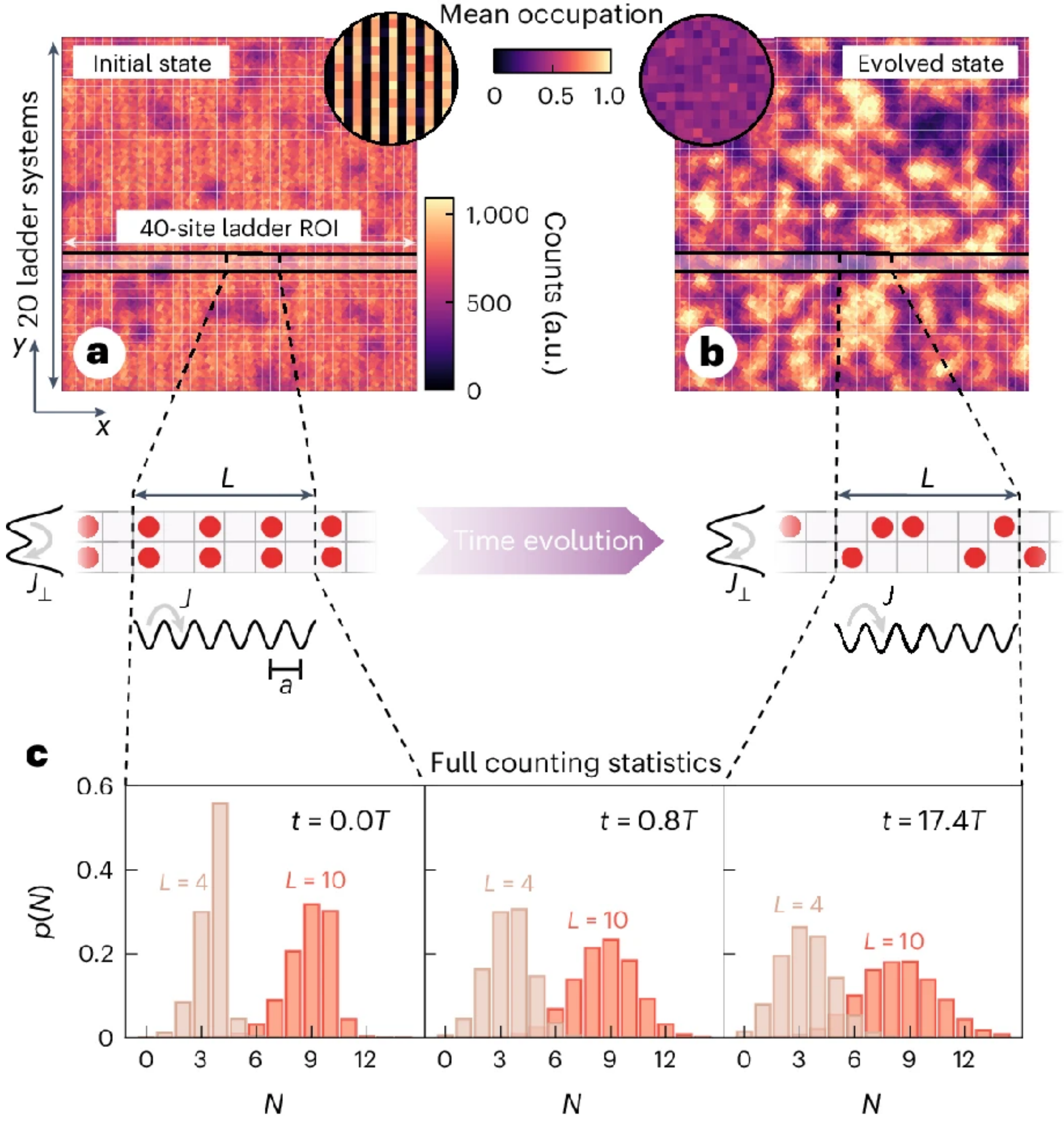
- Create a density wave at fixed wave-vector k
- When does the system return to equilibrium?
- Conventional expectation: timescale $\tau \sim 1/k$ (ballistic) or $\sim 1/k^2$ (diffusive)
- Experiments on interacting bosonic gases (PSU) measuring Green's functions $\langle b_q^\dagger(t) b_q(t) \rangle$ after a quench show long timescales ($\sim 1/q \gg 1/k^2$) for small q
- Where do these long timescales come from?
  equilibration of fluctuations

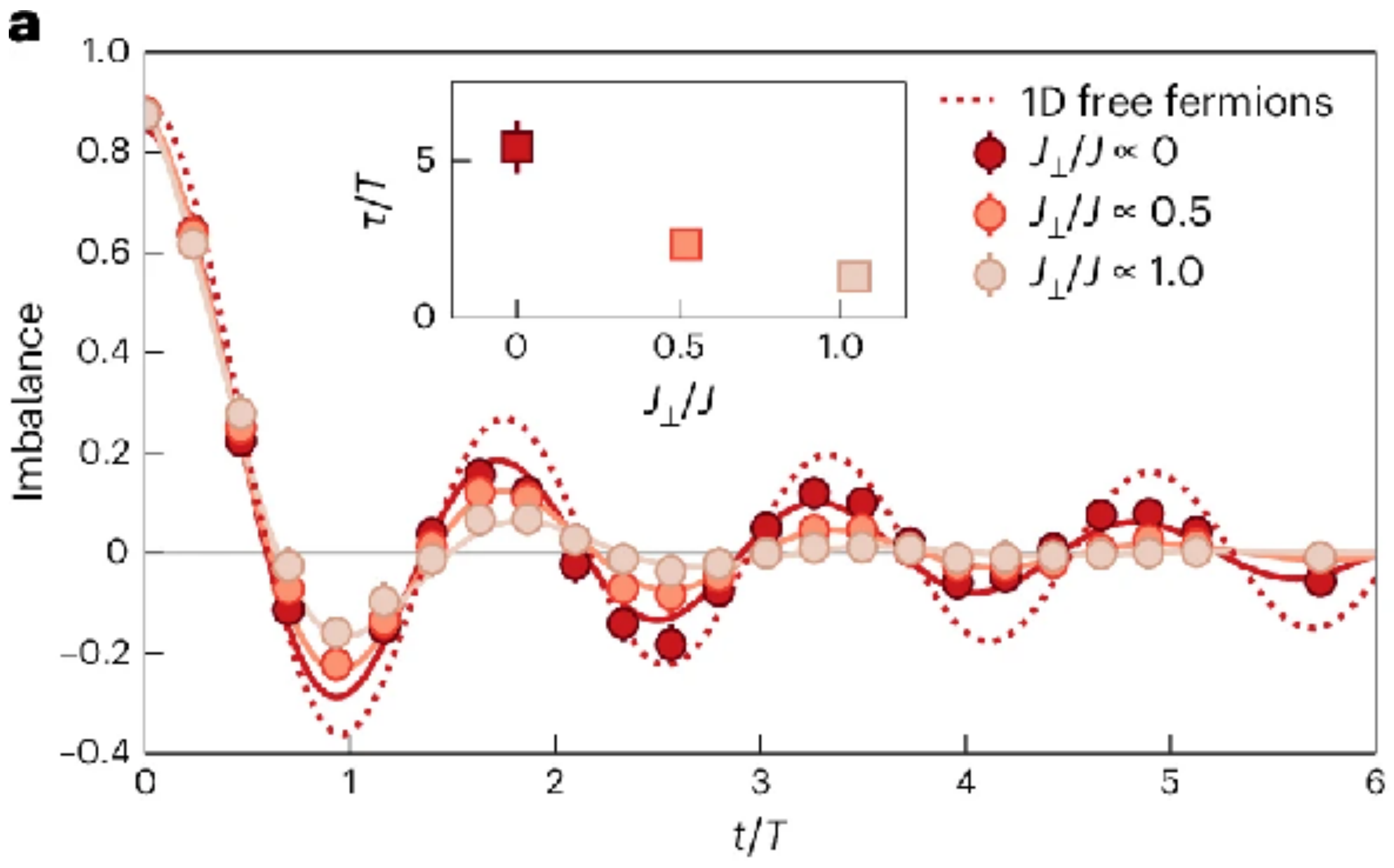
$\langle b_q^\dagger b_q \rangle$ for various q

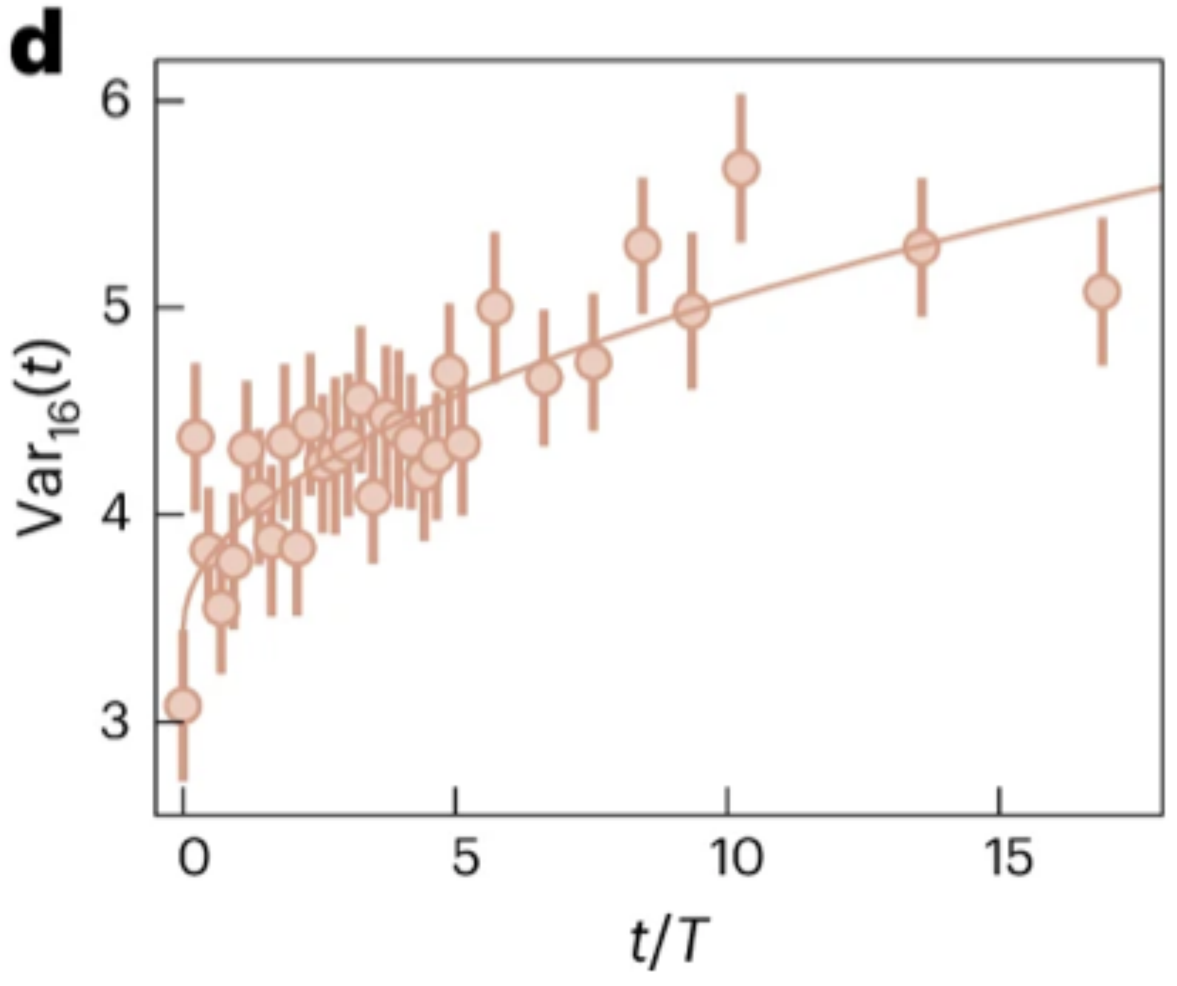


equilibration of fluctuations

- Initialize system in a state with no number fluctuations
- State rapidly approaches uniform density, but its large-scale density fluctuations are suppressed
- Density fluctuations build up with *quantitatively* the equilibrium diffusion constant: stringent test of fluctuating hydrodynamics
- These fluctuations infect all large-scale correlations in nonperturbative ways

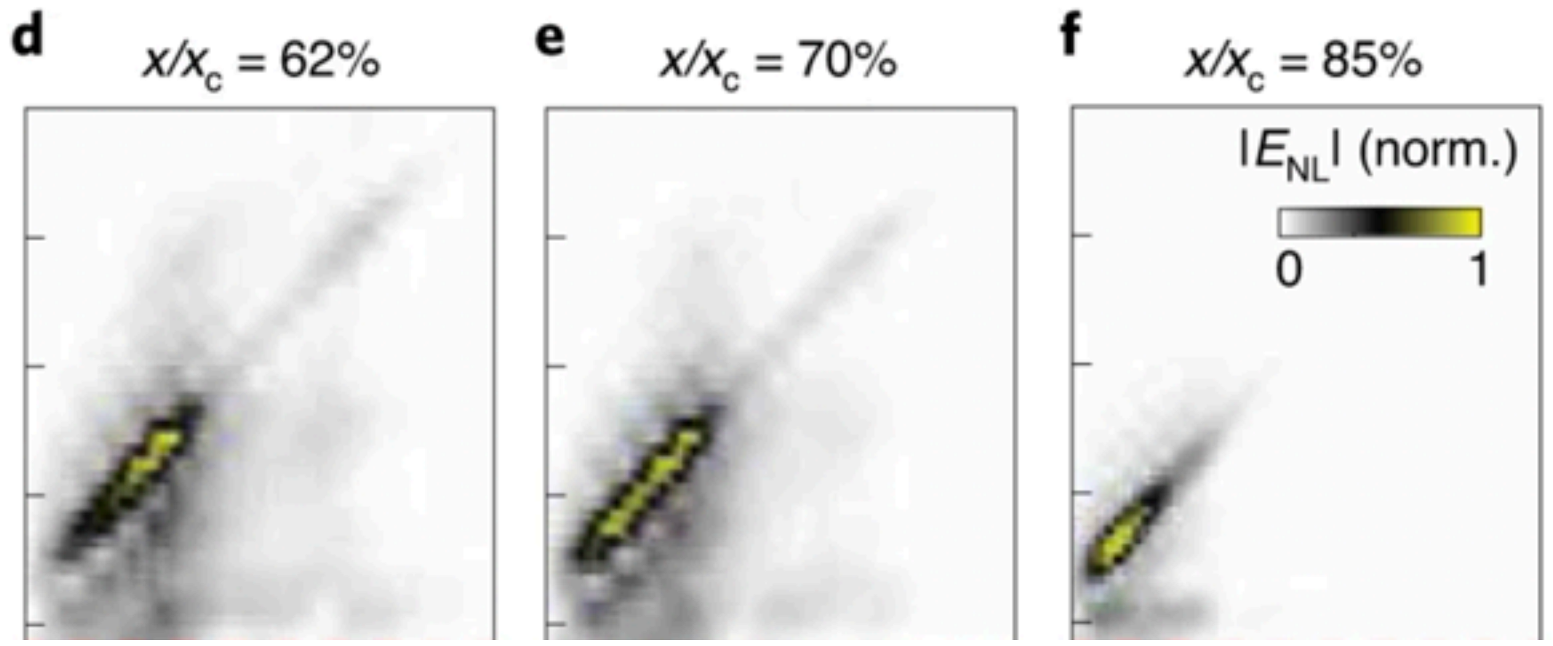


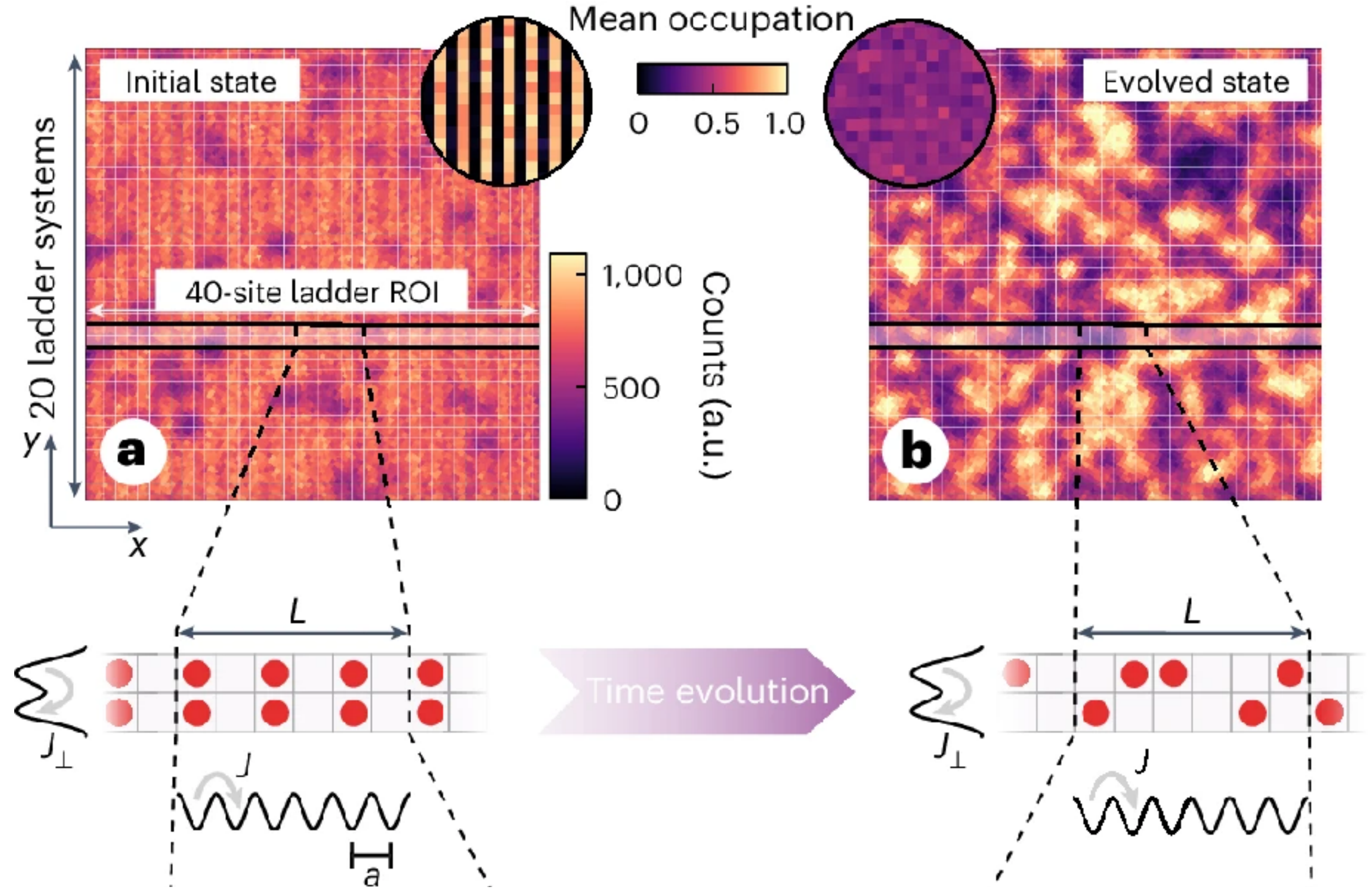




summary

- Experiments probing fluctuations have led to surprising insights into many-body physics:
  - Existence of marginally stable excitations in disordered systems
  - Inconsistency between average spin transport (KPZ) and higher-order fluctuations (not KPZ) in Heisenberg model
  - Generic long timescales after spatially uniform/short-wavelength quenches
- All results are at or beyond the current numerical frontier





outlook (i)

- Need for effective classical theories that go beyond conventional linearized hydro
- Can we learn hydrodynamic equations from experimental data?
    - Fick's law $\hat{j} = \partial_x \hat{n} + \hat{\xi}, \;\Rightarrow \langle \hat{j}\hat{j} \rangle - \langle \hat{\partial}_x n \partial_x \hat{n} \rangle = \langle \hat{\xi}\hat{\xi} \rangle$
    - Can extract noise correlation length from experiment
    - Experimentally extract length and timescales for onset of hydrodynamics

Local Readout and Control of Current and Kinetic Energy Operators in Optical Lattices

Alexander Impertro, Simon Karch, Julian F. Wienand, SeungJung Huh, Christian Schweizer, Immanuel Bloch, and Monika Aidelsburger

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- Are there automated (e.g., machine learning) ways to learn hydrodynamics from many snapshots?

outlook (ii)

- What are the inherent limits to classical simulation of quantum systems?
  - Noisy dynamics is easy to simulate
  - Strongly chaotic systems are insensitive to noise
  - Allows for efficient “dissipation-assisted” classical simulations [Rakovszky, Pollmann, von Keyserlingk]
- What about systems in dimensions higher than 1, complex systems with long-range connectivity?
  - No good classical toolbox [though in-principle efficient methods exist, cf. Aharonov et al. (2021)]
  - What interesting coherent phenomena can occur in such systems? Only way to find out is experiment…