Many-body localisation: new results for weak interactions

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Phys. Rev. Lett. **133**, 116502 (2024) + WIP

Jeanne Colbois (Toulouse → Singapore → Grenoble)
Nicolas Laflorencie (Toulouse)
Asmi Haldar (Toulouse)

Pdf of the talk
Pdf of paper
List of References

SCAN ME

Université de Toulouse

FONDATION SIMONE ET CINO DEL DUCA INSTITUT DE FRANCE 1975

Indo-French Workshop in classical and quantum dynamics in out of equilibrium systems, ICTS Bangalore, December 2024

Plan of the talk

Quick Recap on Many-Body Localization (MBL) : motivations & hallmarks

Status of MBL : Controversies, and current views

Introduction

The rest of the talk: Stepping away from the « strong » interaction regime

Results

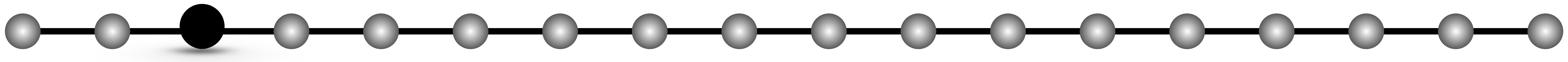
Related :Correlations as markers of route to ergodicity

Nicolas' talk
Friday

From single to many: Anderson to Many-Body Localization

Single particle in a random potential

$$\mathscr{H} = \sum_i \left[t\left(c_i^\dagger c_{i+1} + \mathrm{hc}\right) + \epsilon_i n_i \right]$$



From single to many: Anderson to Many-Body Localization

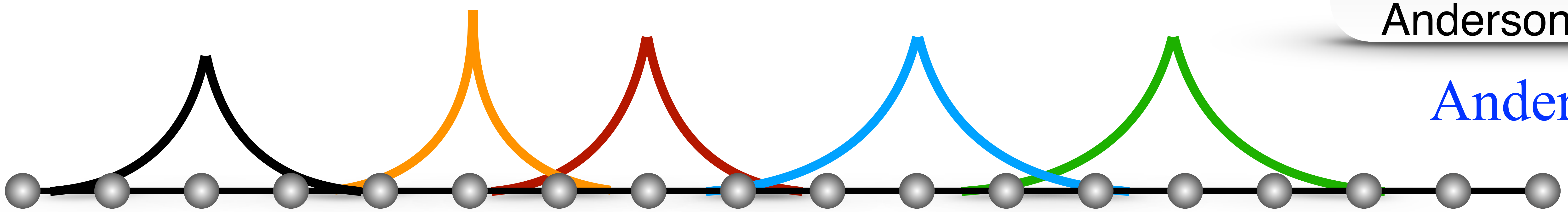
Single particle in a random potential

$$\mathcal{H} = \sum_i \left[t\left(c_i^\dagger c_{i+1} + \text{hc}\right) + \epsilon_i n_i \right] = \sum_m \tilde{\epsilon}_m b_m^\dagger b_m$$

$$b_m = \sum_i \phi_i^m c_i$$

$$\left|\phi_i^{(m)}\right|^2 \sim \exp\left(-\frac{|i - i_0^{(m)}|}{\xi_m}\right)$$

Anderson localized orbitals



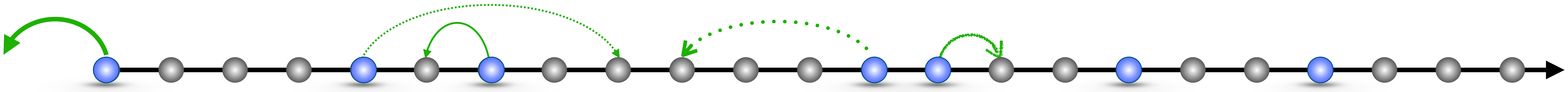
Anderson localization

From single to many: Anderson to Many-Body Localization

Many interacting particles in a random potential

$$\mathscr{H} = \sum_i \left[t\left(c_i^\dagger c_{i+1} + \mathrm{hc}\right) + \epsilon_i n_i + V n_i n_{i+1} \right]$$

$$= \sum_m \tilde{\epsilon}_m b_m^\dagger b_m \quad + \sum_{j,k,l,m} V_{jklm} b_j^\dagger b_k^\dagger b_l b_m$$



Intuition: Interactions favour delocalisation / thermalization

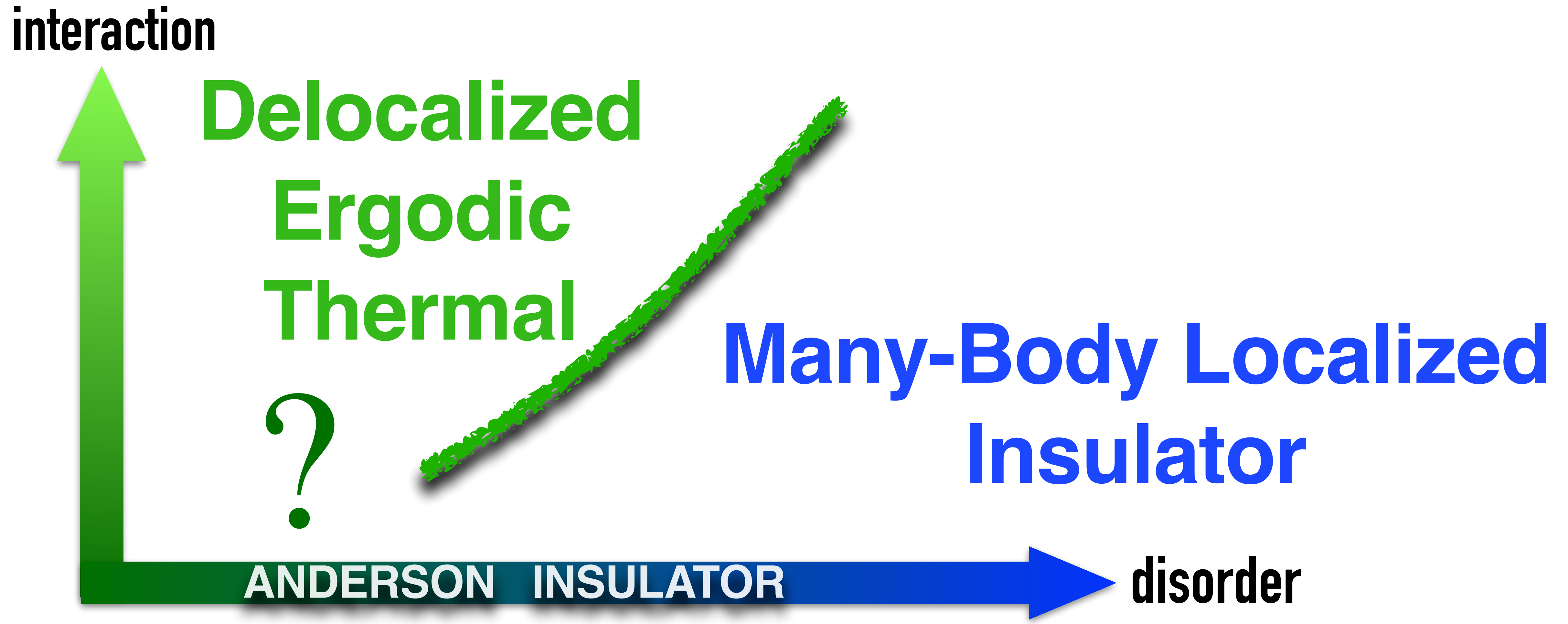
Localization can survive interactions :

Many-Body Localized (MBL) phase & Ergodic to MBL phase transition

Gornyi, Mirlin, Polyakov (2005)

Basko, Aleiner, Altshuler (2006)

Pal, Huse (2010)



Minimal Spin-chain model for MBL

Interacting electrons in 1d

quantum tuneling

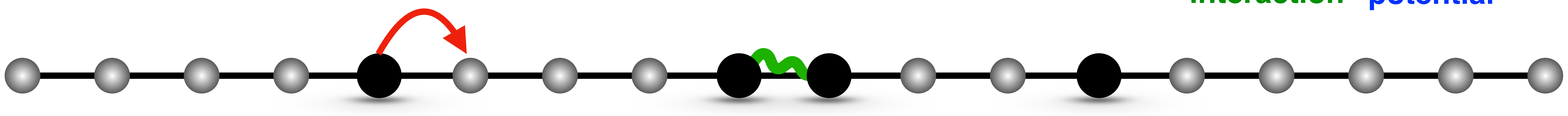
$$H = \sum_i \left[t\left(c_i^\dagger c_{i+1} + \text{hc}\right) + V n_i n_{i+1} + \epsilon_i n_i \right]$$

short-range interaction

random potential

Only existing symmetry (neither needed nor impeding for MBL) :

Particle number conservation



$$\Delta = V$$

Eq. : XXZ spin chain in random field

$$H = \sum_i \left[\frac{t}{2}\left(S_i^+ S_{i+1}^- + \text{hc}\right) + \Delta S_i^z S_{i+1}^z + h_i S_i^z \right] + C$$

spin-flip

Ising interaction

random magnetic field

Total magnetization S^z conservation

Special case : Random-field Heisenberg spin chain $\Delta = 1$

$$h_i \in [-h, h]$$

Minimal Spin-chain model for MBL

Interacting electrons in 1d

$$H = \sum_i \left[t \left(c_i^\dagger c_{i+1} + \text{hc} \right) + V n_i n_{i+1} + \epsilon_i n_i \right]$$

quantum tuneling — short-range interaction — random potential

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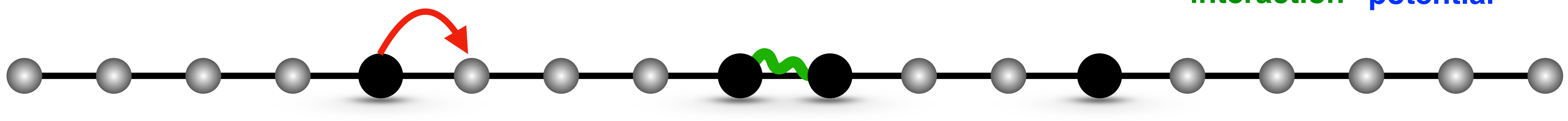

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spin-flip — Ising interaction — random magnetic field

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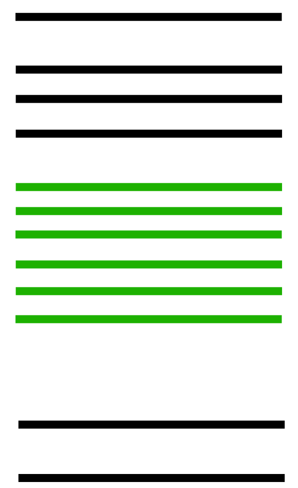
Special case : Random-field Heisenberg spin chain $\Delta = 1$

$h_i \in [-h, h]$

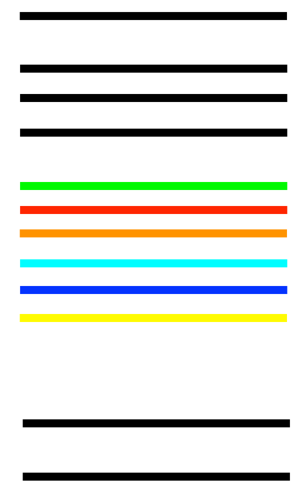
- Expect two family of eigensstates

Ergodic, Thermal states



Disorder h →

Many-Body Localized states

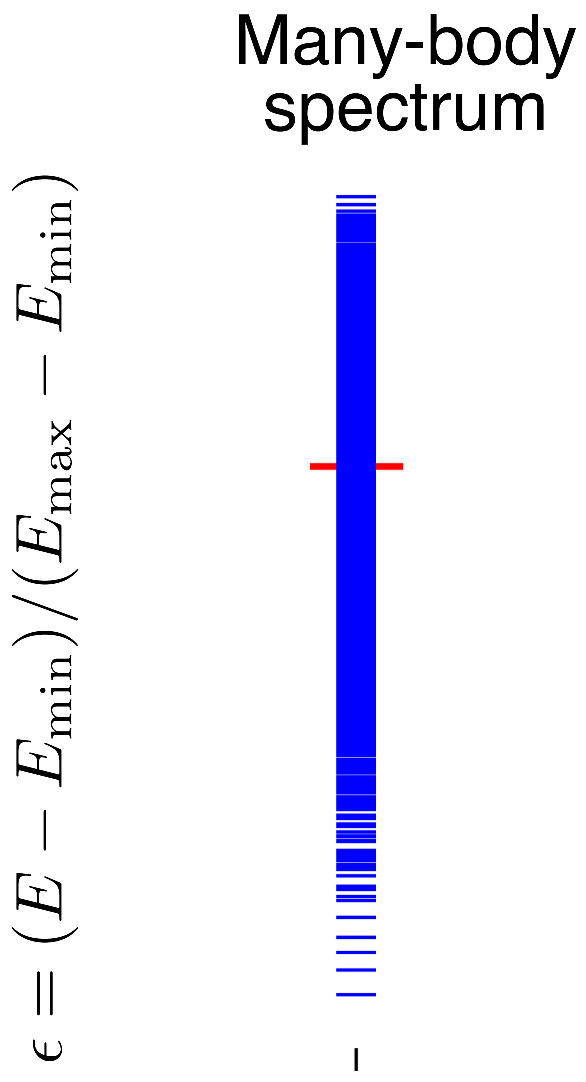


Eigenstates look all the same (~ Random Matrix Theory)

Eigenstates all different (do not "speak" to each other), behave as ground-states

Specs of Many-Body Localization

1. Spectral statistics

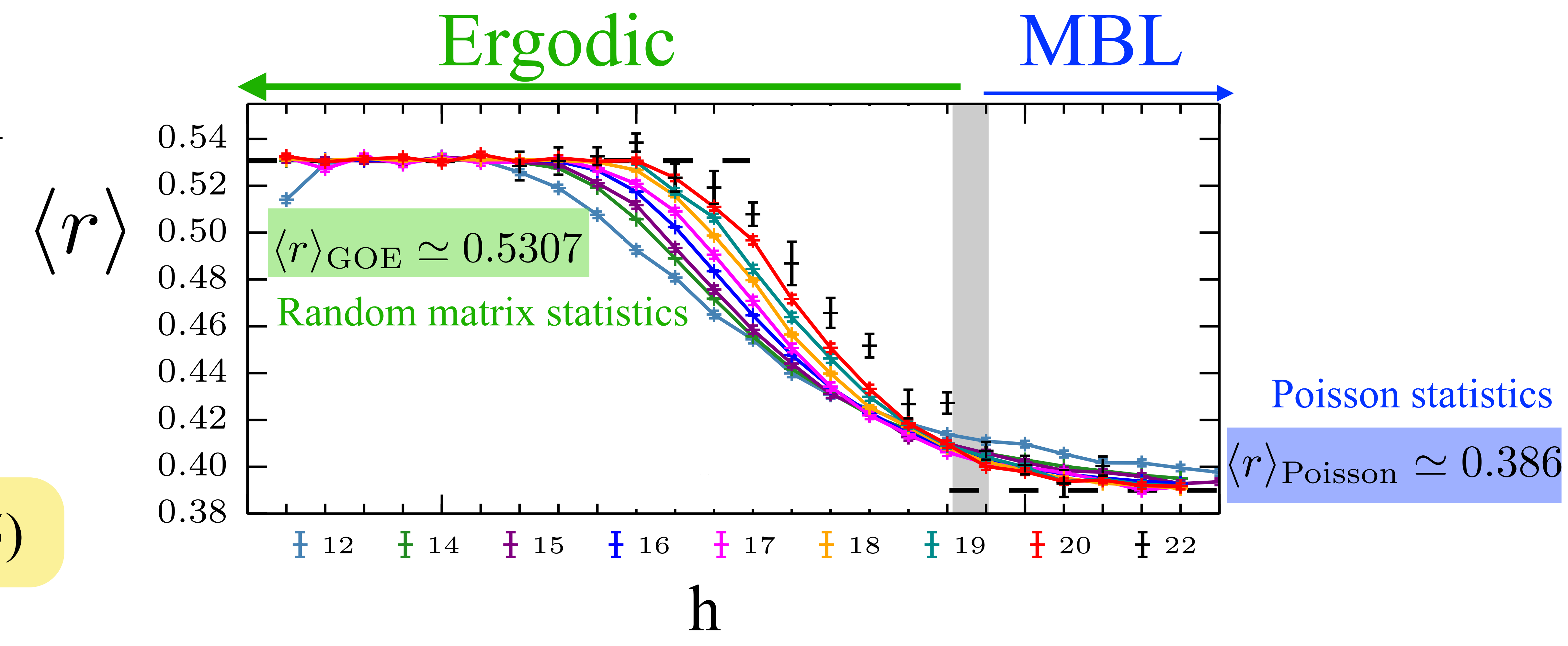


Level spacings $s_n = E_n - E_{n-1}$

Ratio of consecutive gaps

$$r = \min(s_n, s_{n+1}) / \max(s_n, s_{n+1})$$

Luitz *et al.* (2015)



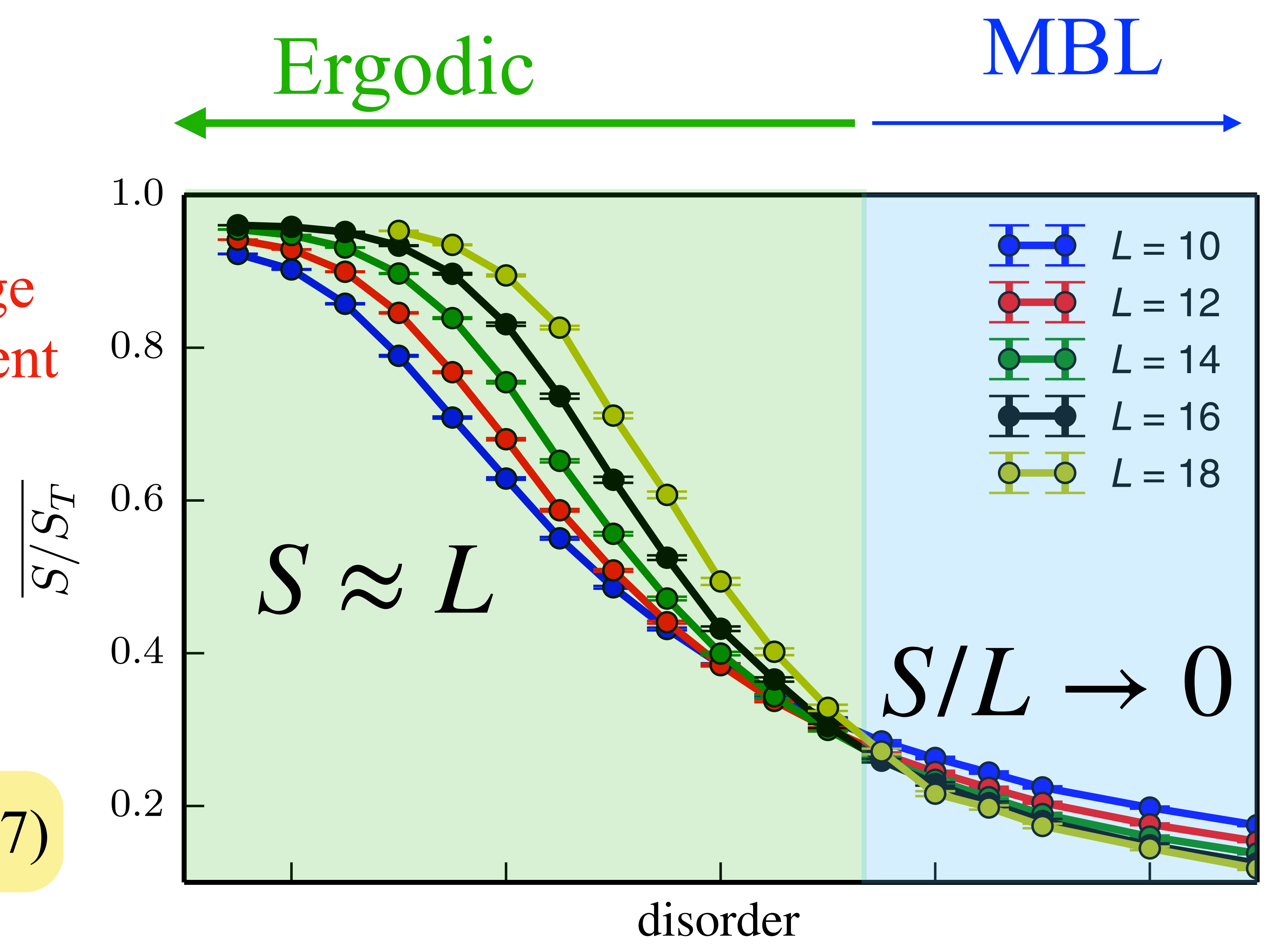
Specs of Many-Body Localization

1. Spectral statistics

2. Entanglement : Volume vs. Area law

Eigenstates have large (volume) entanglement

Khemani *et al.* (2017)



MBL eigenstates have low entanglement

(~ close to product states)

Specs of Many-Body Localization

1. Spectral statistics
2. Entanglement : Volume vs. Area law
3. Out of equilibrium dynamics

Dynamics after quench : $|\Psi(t)\rangle = e^{-\mathrm{i}Ht}|\Psi(0)\rangle$

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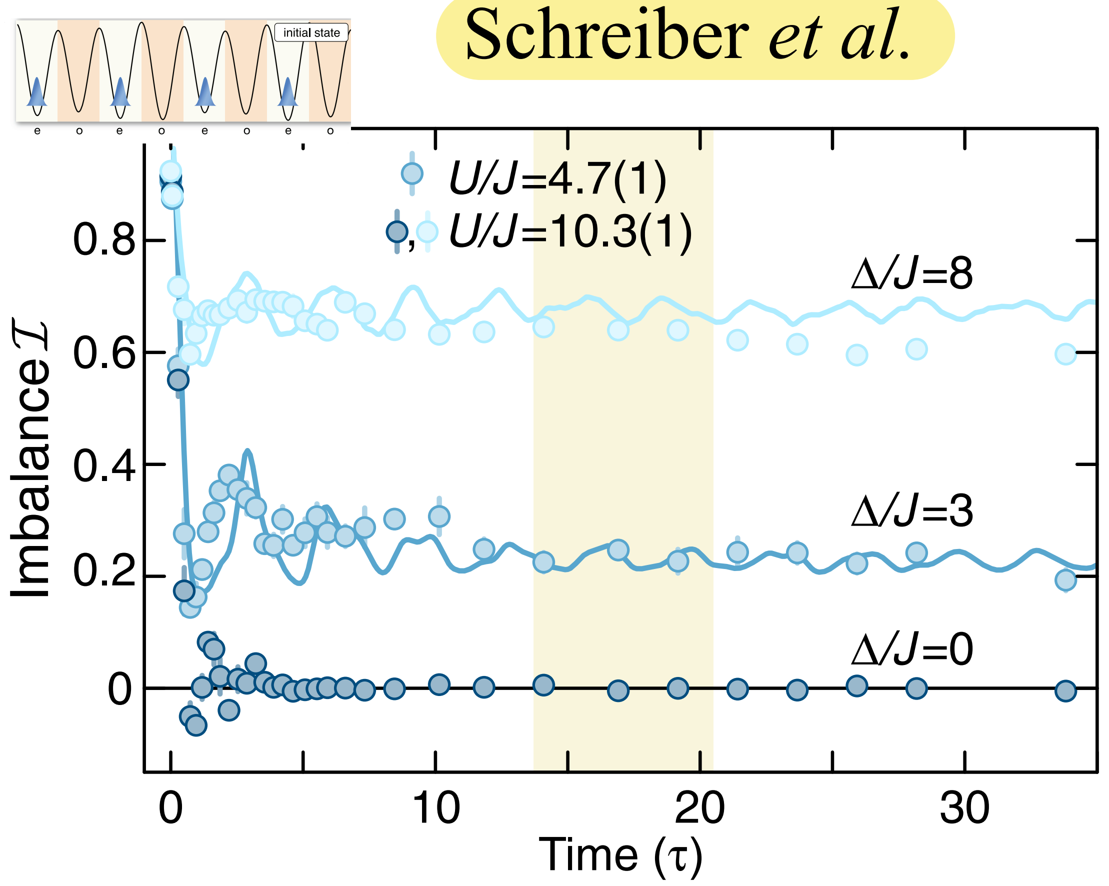
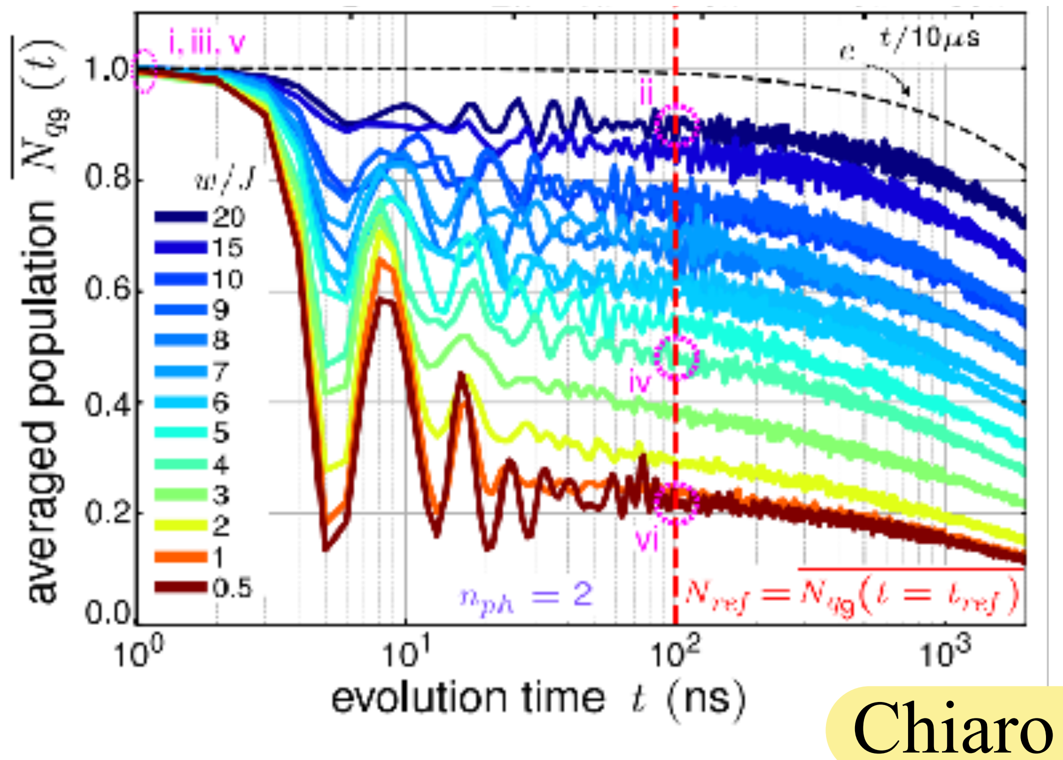
Memory of initial state

- Experiments

Schreiber *et al.*



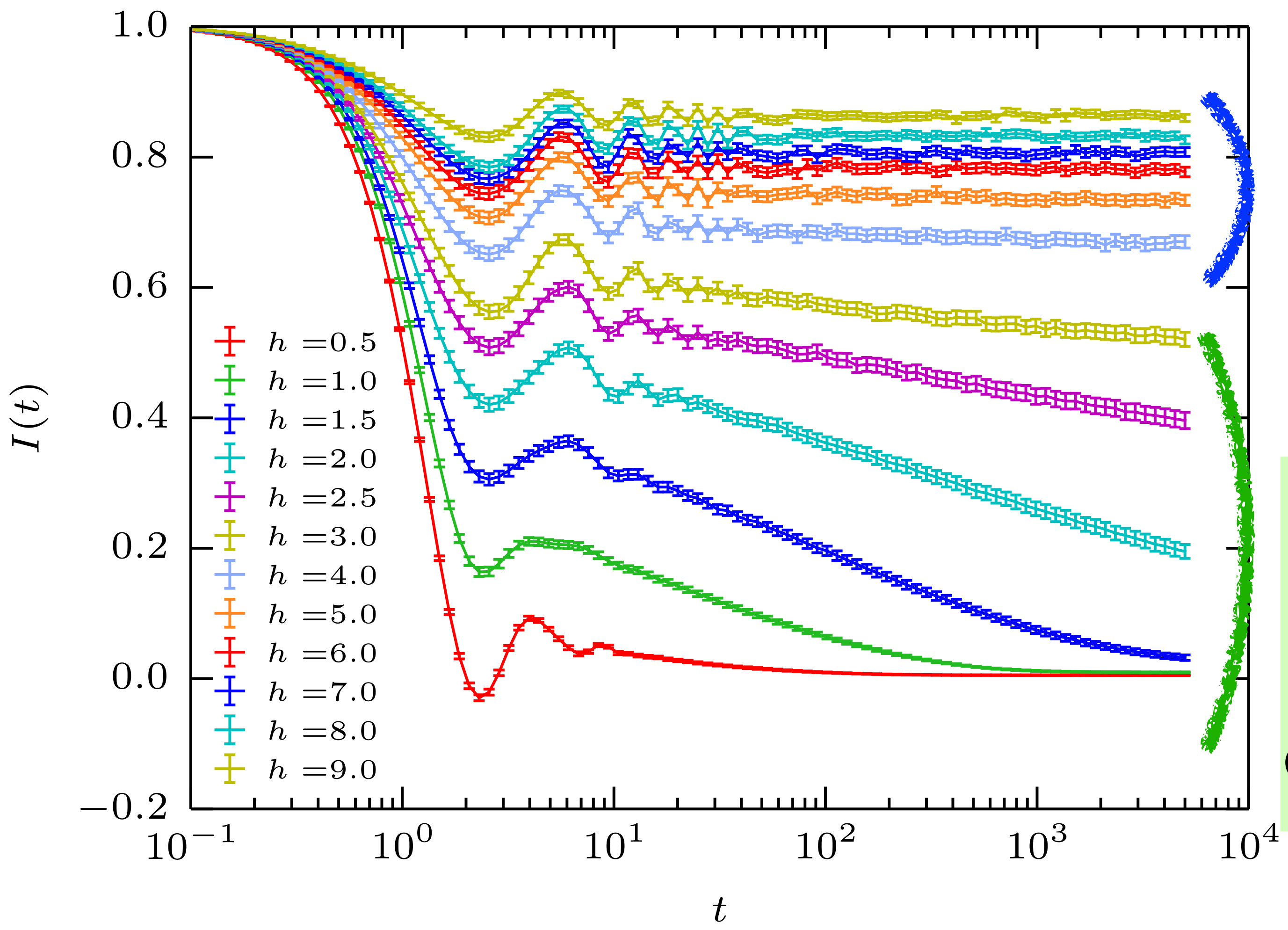


Chiaro *et al.*

- Numerics:

$|\Psi_0\rangle = |\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\cdots\rangle$

$$I(t) = \frac{4}{L}\sum_i \langle\Psi_0|S_i^z S_i^z(t)|\Psi_0\rangle$$



Strong disorder: MBL
Memory of the initial state
even at infinite time

Weak disorder: Ergodic
No Memory
converges to thermal ensemble

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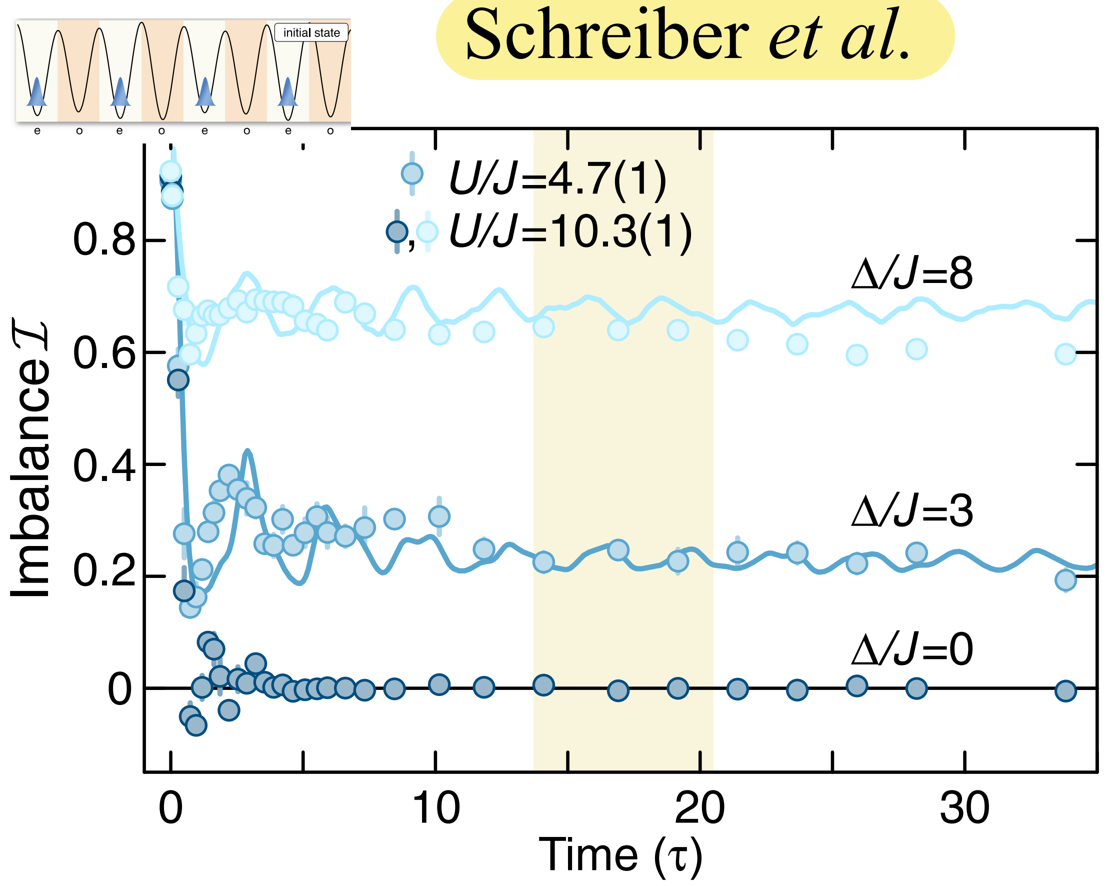

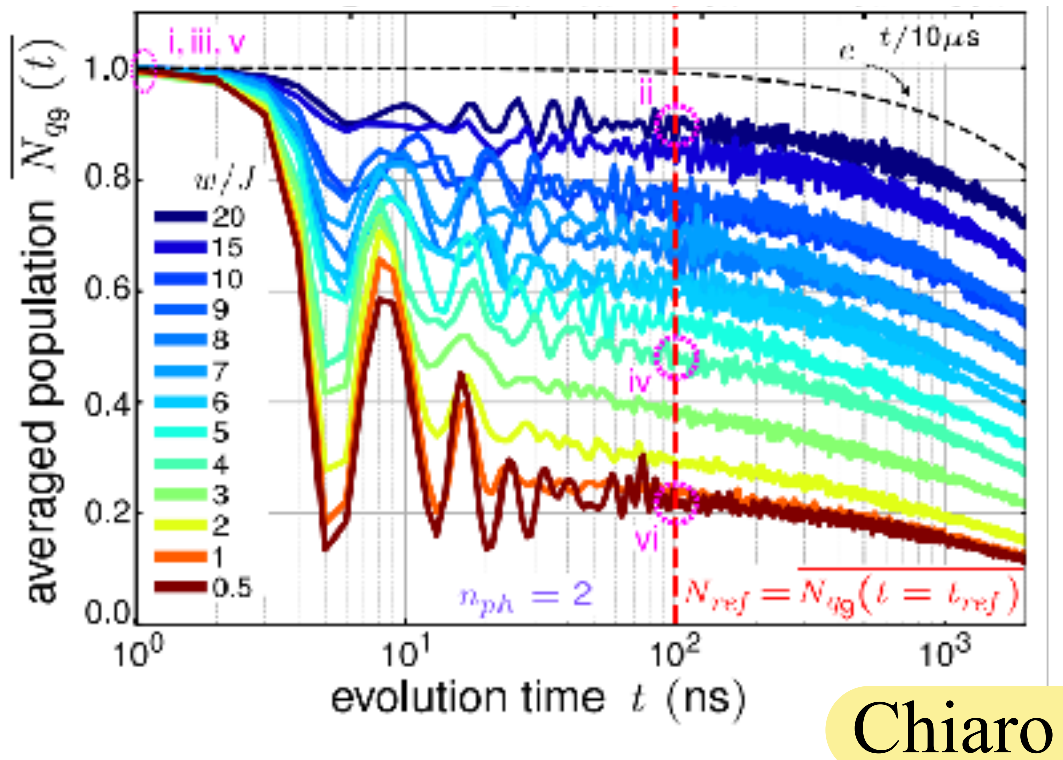

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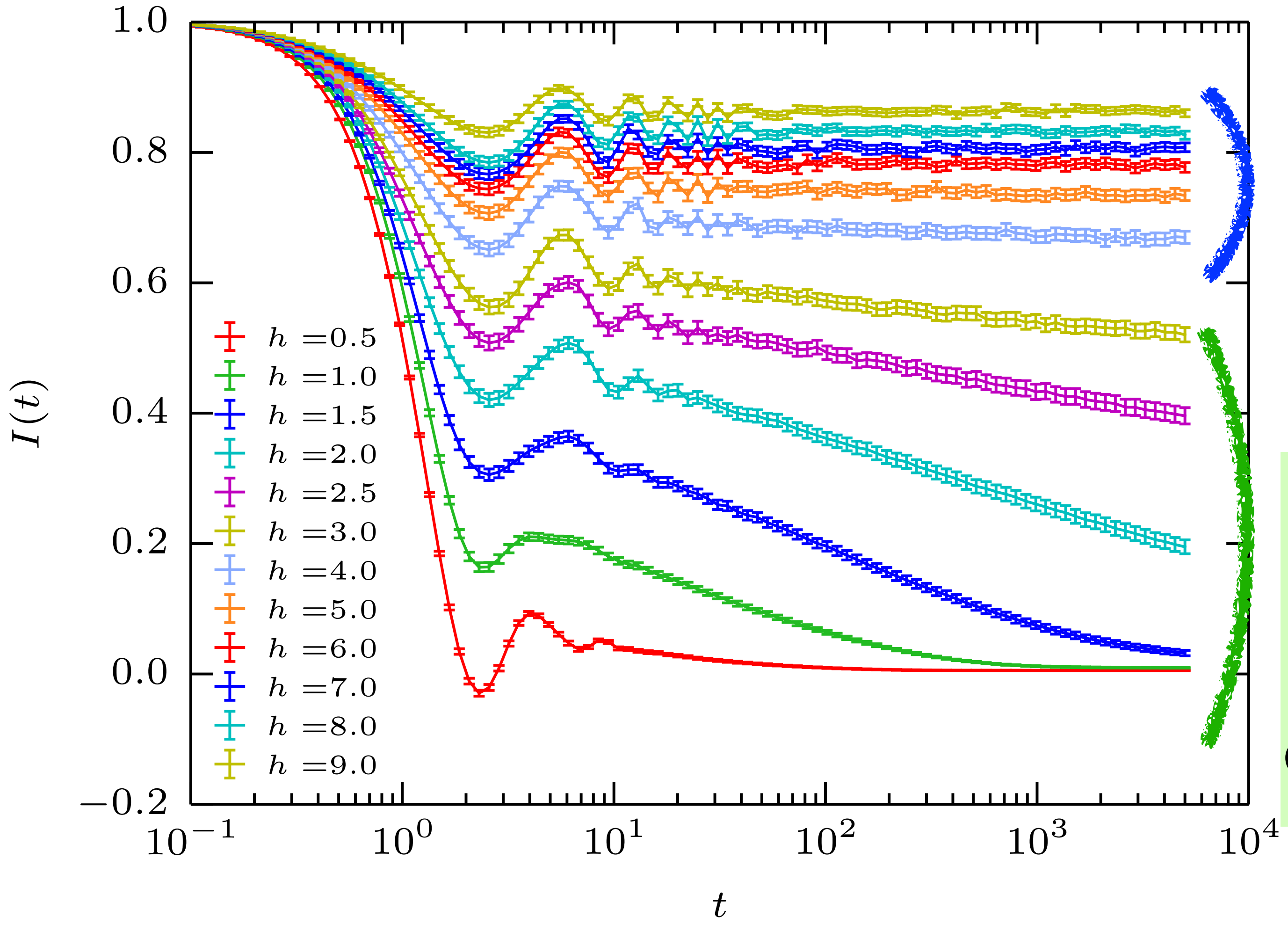

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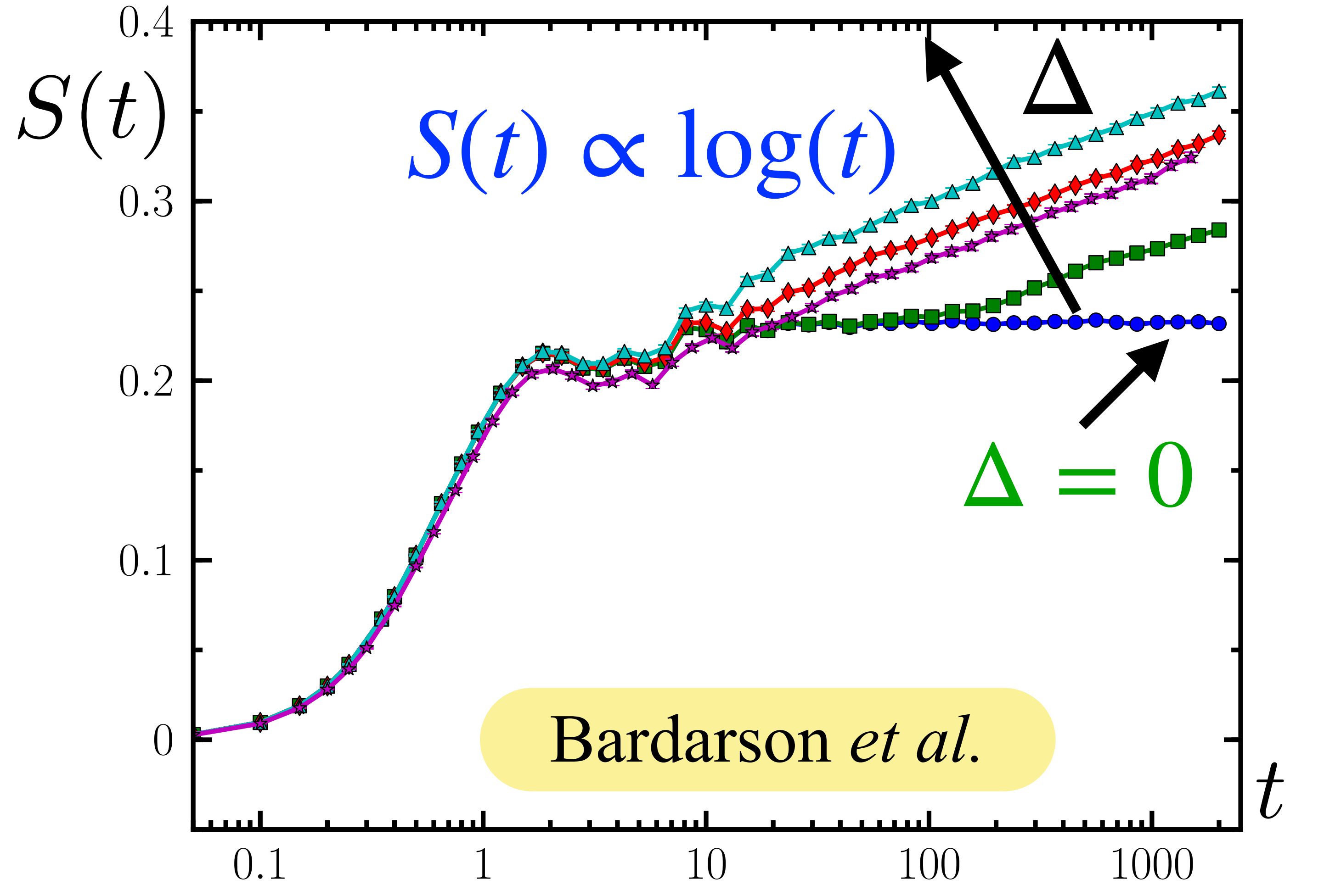
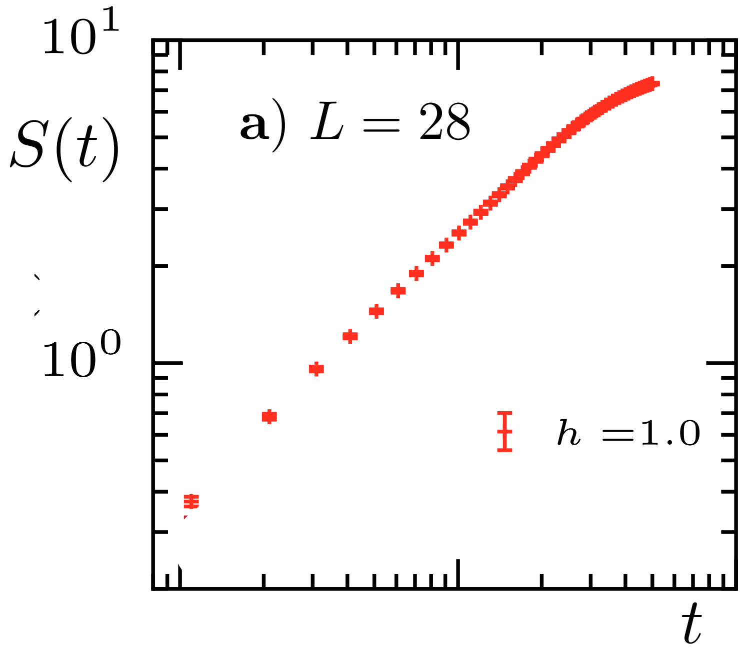
Memory of the initial state
even at infinite time

Weak disorder: Ergodic
No Memory
converges to thermal ensemble

Slow (log) growth of information

MBL: Logarithmic spread





$S(t) \propto t$

Ergodic
Ballistic spread

Many-Body Localization (~2008-2018)

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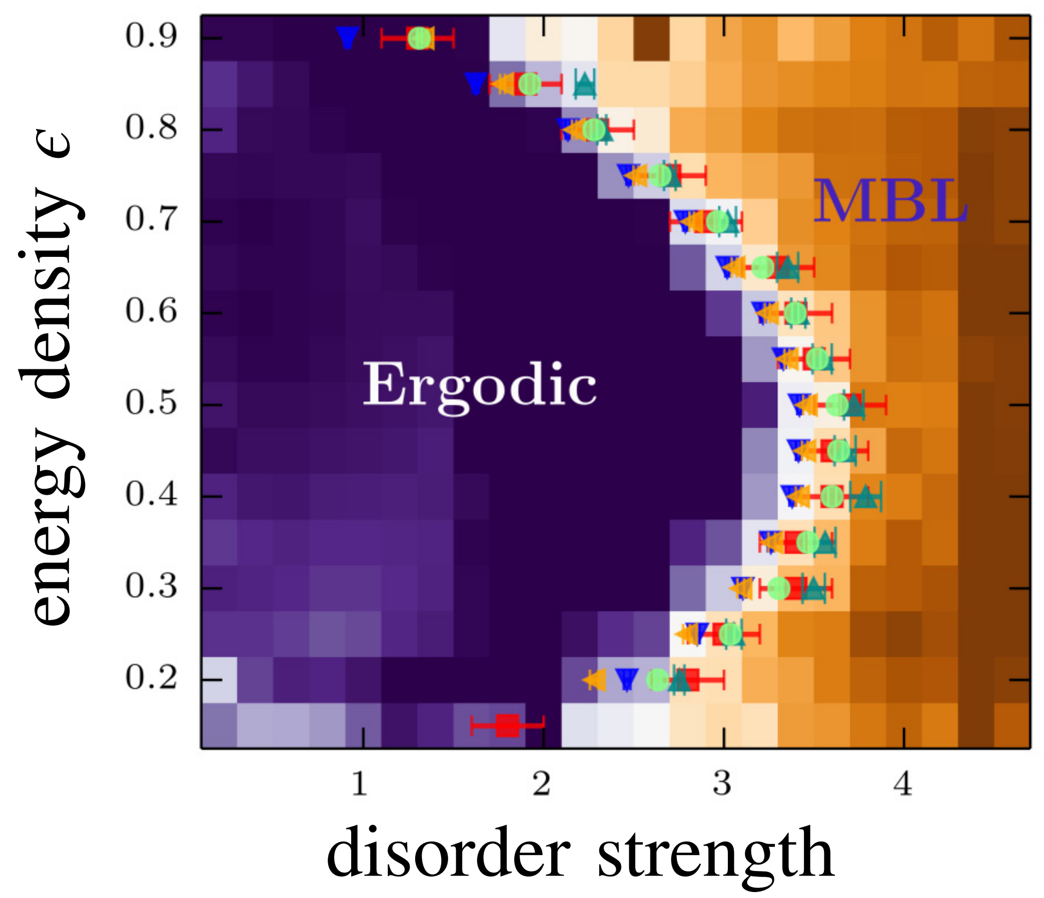


Luitz *et al.* (2015)

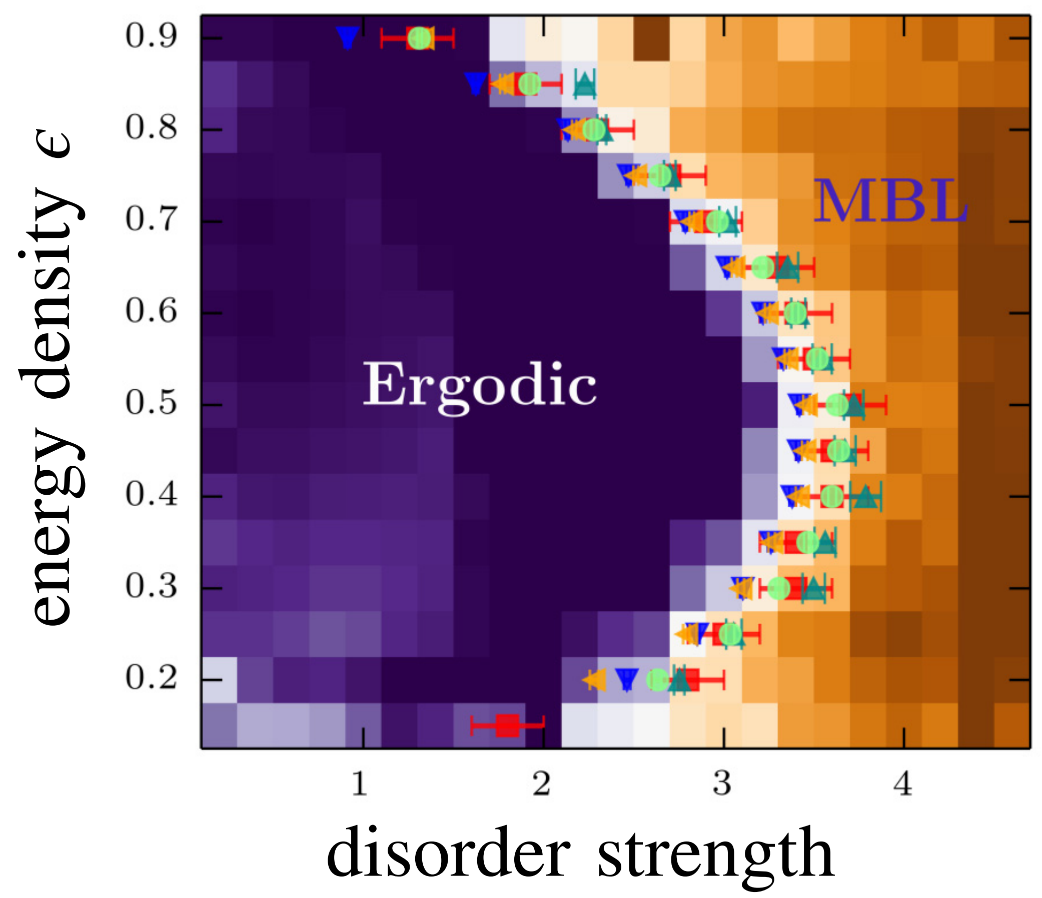
Numerics

After a lot of work the MBL problem seemed well understood (*) (**)

(*) at least in 1d

(**) albeit **not** the Ergodic / MBL phase transition

Many-Body Localization (~2008-2018)



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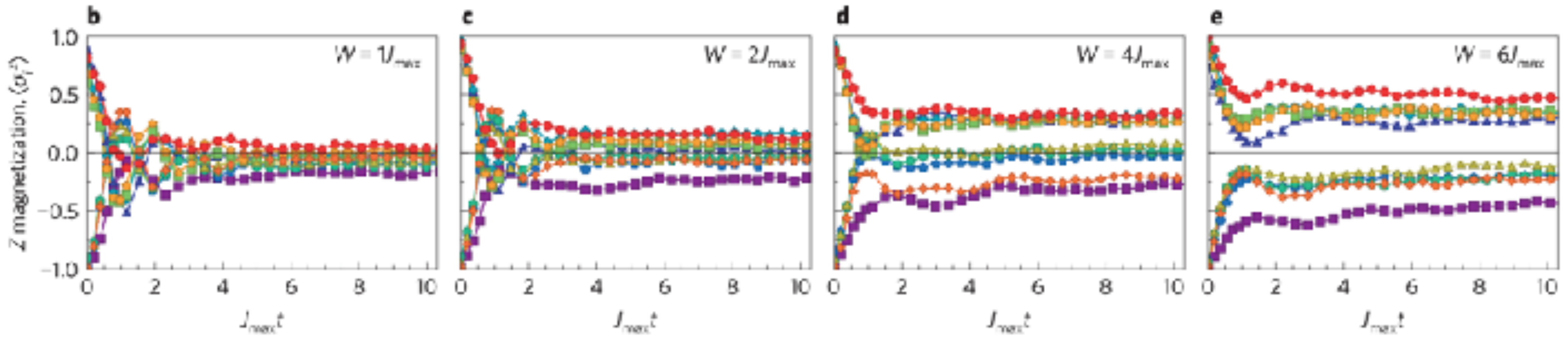
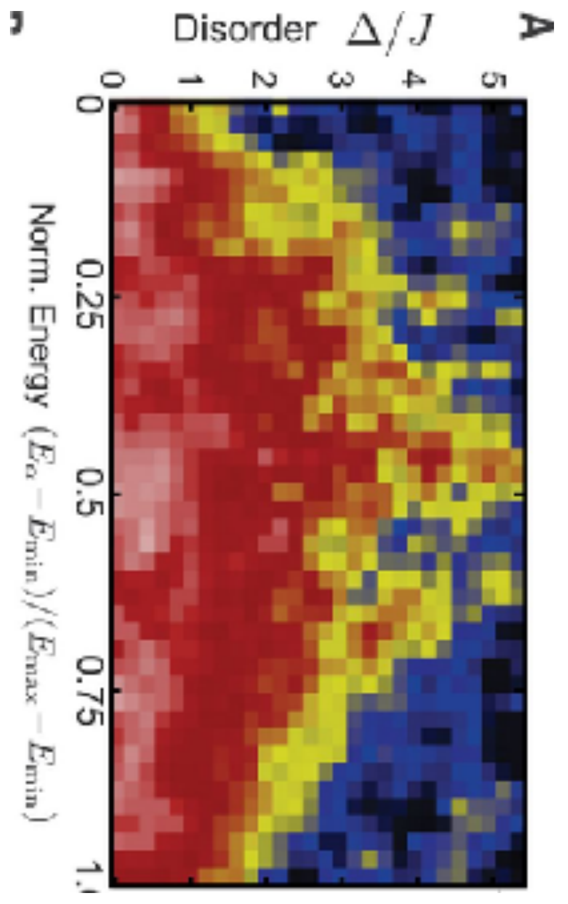
Numerics

Experiments

Cold-atom, trapped ions,
superconducting qubits …



Smith *et al* (2017)



Roushan *et al.* (2017)

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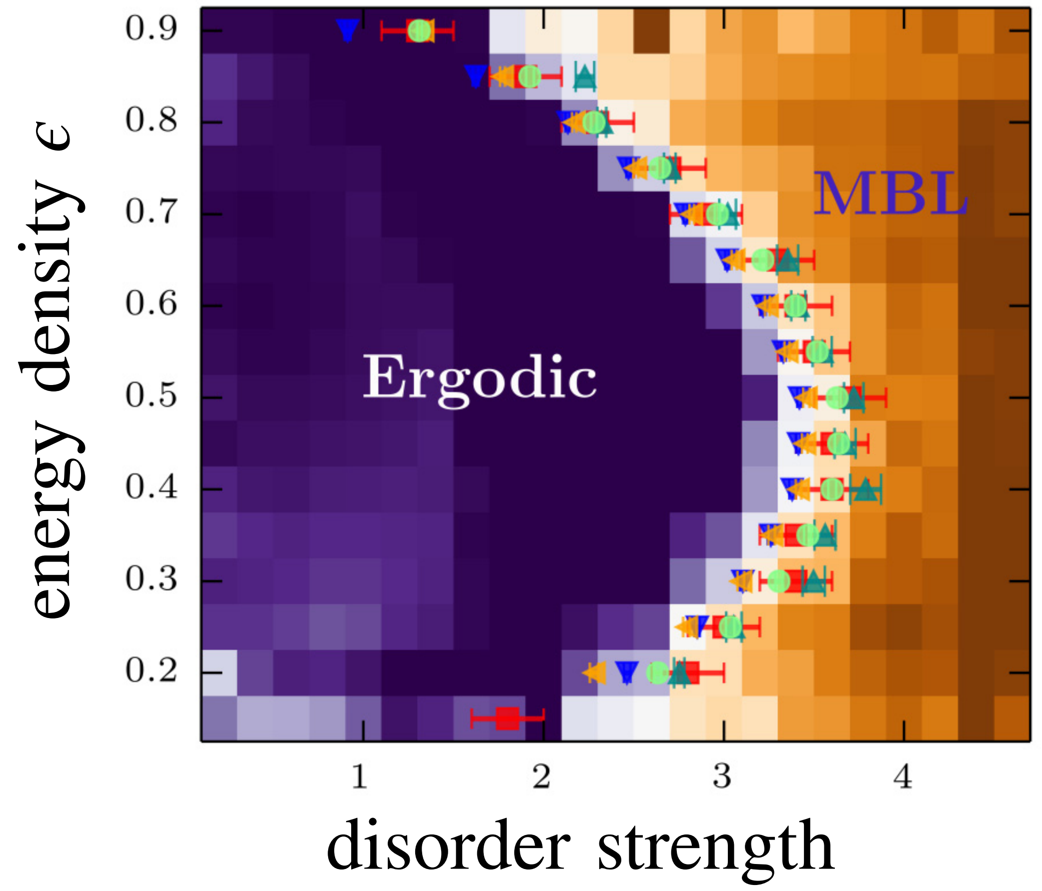

Luitz *et al.* (2015)

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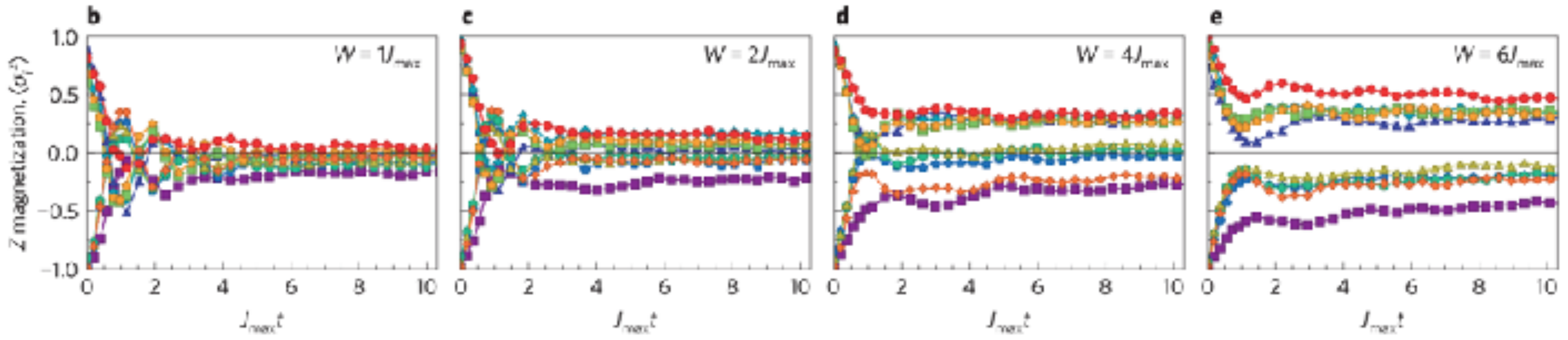

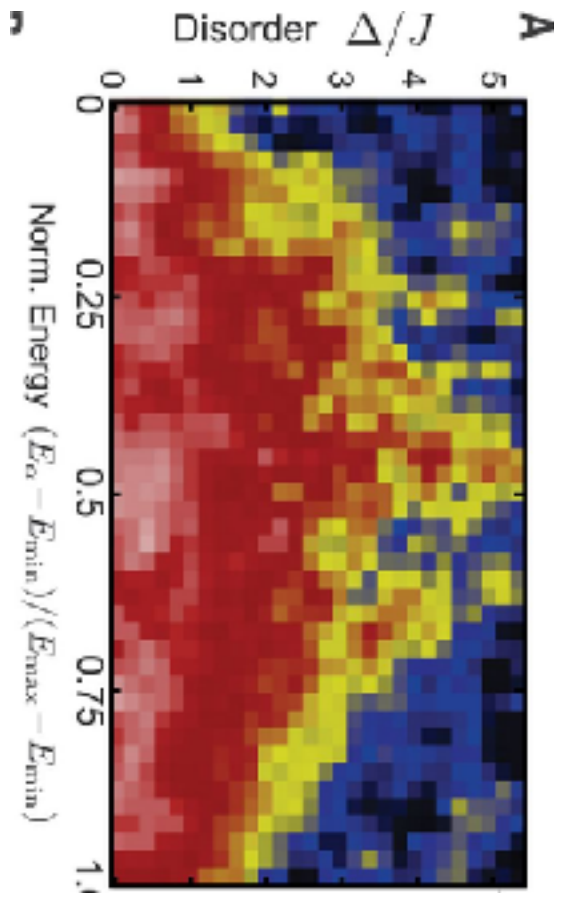

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Phenomenology

Oganesyan, Huse, Serbyn, Abanin, Papic

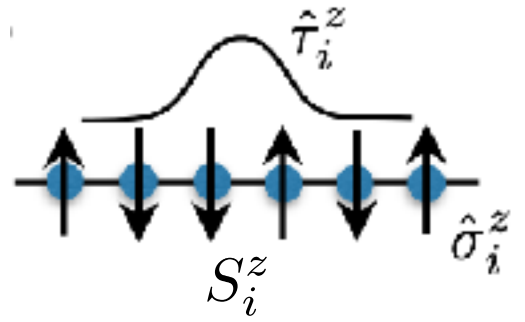
Local integral of motions (liom's)

$$H_{\rm MBL} = -\sum_i h_i \tau_i^z + \sum_{i,j} J_{ij}\tau_i^z\tau_j^z + \sum_{i,j,k} J_{ijk}\tau_i^z\tau_j^z\tau_k^z + \dots$$

"Fixed point" MBL Hamiltonian

$$[H, \tau_i^z] = 0$$

$$\tau_i^z = \tilde{Z} S_i^z + \sum_{r,\alpha} \exp(-r/\xi) S_{i+r}^\alpha$$



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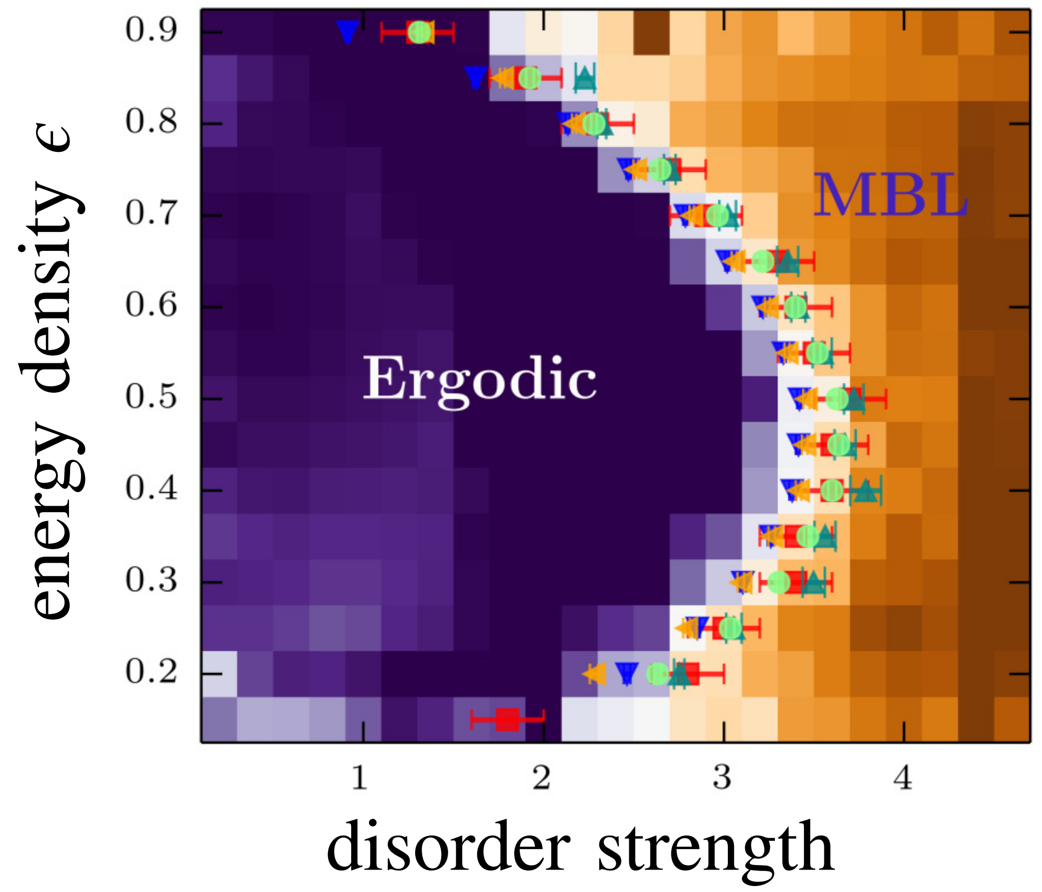

Luitz *et al.* (2015)

Numerics

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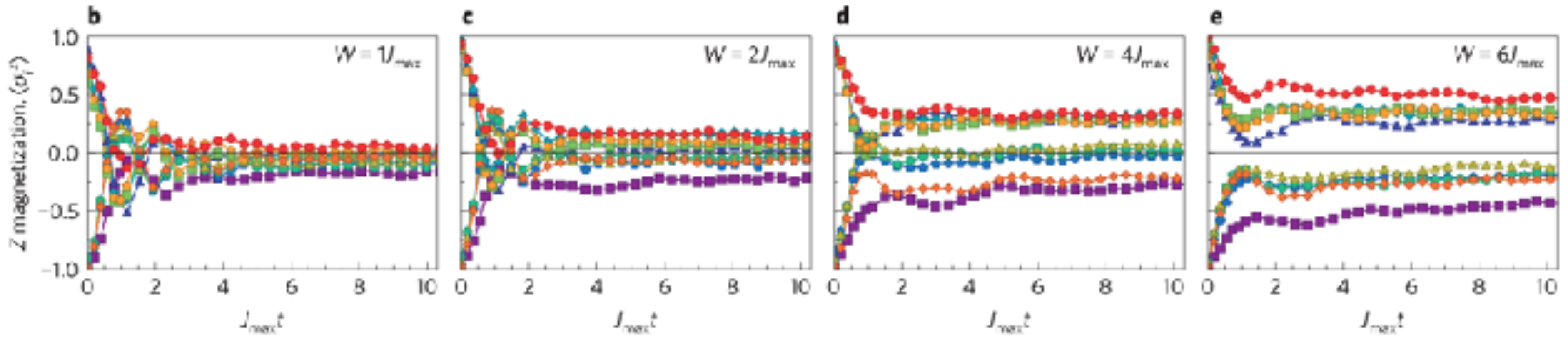

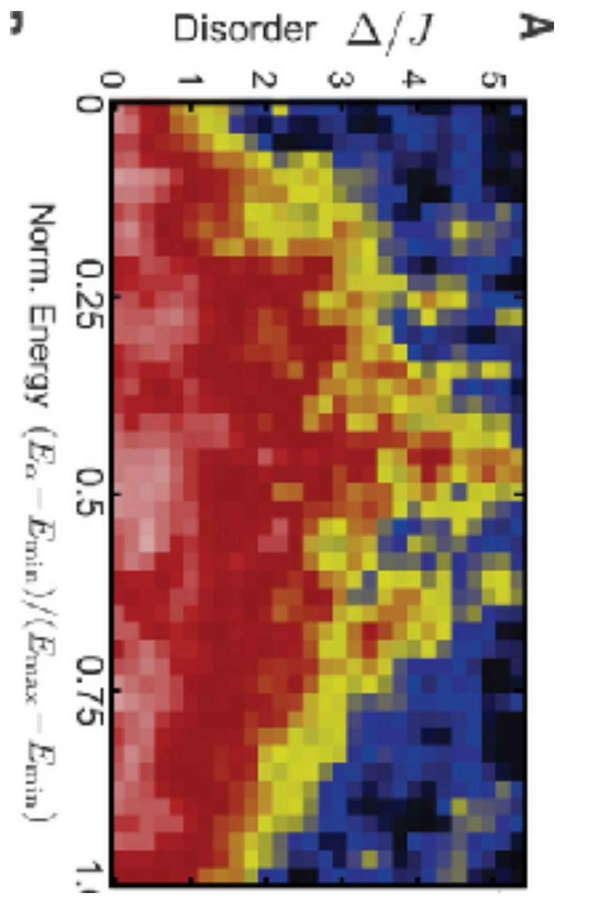

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Phenomenology

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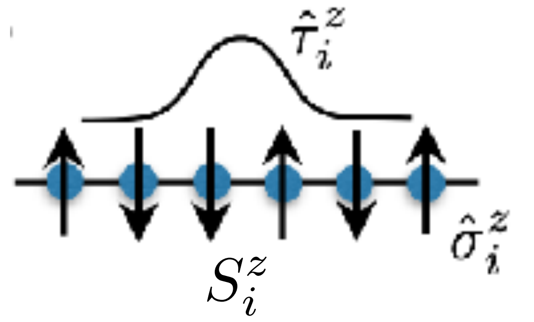


Oganesyan, Huse, Serbyn, Abanin, Papic

Imbrie, De Roeck *et al.*

Proof (?) for one model

MBL : really ? (2019-)

EPL, **128** (2019) 67003
doi: 10.1209/0295-5075/128/67003

Can we study the many-body localisation transition?

R. K. Panda[1,2], A. Scardicchio[1,3], M. Schulz[1], S. R. Taylor[1(a)] and M. Žnidarič[4]

PHYSICAL REVIEW E **102**, 062144 (2020)

Quantum chaos challenges many-body localization

Jan Šuntajs,[1] Janez Bonča,[2,1] Tomaž Prosen,[2] and Lev Vidmar[1,2]

ELSEVIER
Annals of Physics
Volume 427, April 2021, 168415

Distinguishing localization from chaos: Challenges in finite-size systems

D.A. Abanin[a 1], J.H. Bardarson[b 1], G. De Tomasi[c 1], S. Gopalakrishnan[d e 1], V. Khemani[f 1], S.A. Parameswaran[g 1], F. Pollmann[h i 1], A.C. Potter[j 1], M. Serbyn[k 1], R. Vasseur[l 1]

PHYSICAL REVIEW E **104**, 054105 (2021)

Dynamical obstruction to localization in a disordered spin chain

Dries Sels[1,2] and Anatoli Polkovnikov[3]

PHYSICAL REVIEW B **105**, 224203 (2022)

Challenges to observation of many-body localization

Piotr Sierant[1,2] and Jakub Zakrzewski[2,3,*]

PHYSICAL REVIEW B **105**, 174205 (2022)

Editors' Suggestion

Avalanches and many-body resonances in many-body localized systems

Alan Morningstar,[1] Luis Colmenarez,[2] Vedika Khemani,[3] David J. Luitz,[4,2] and David A. Huse[1,5]

1. Finite-size effects in numerics
2. Anomalously weak relaxation but not MBL?
3. Avalanches & Resonances

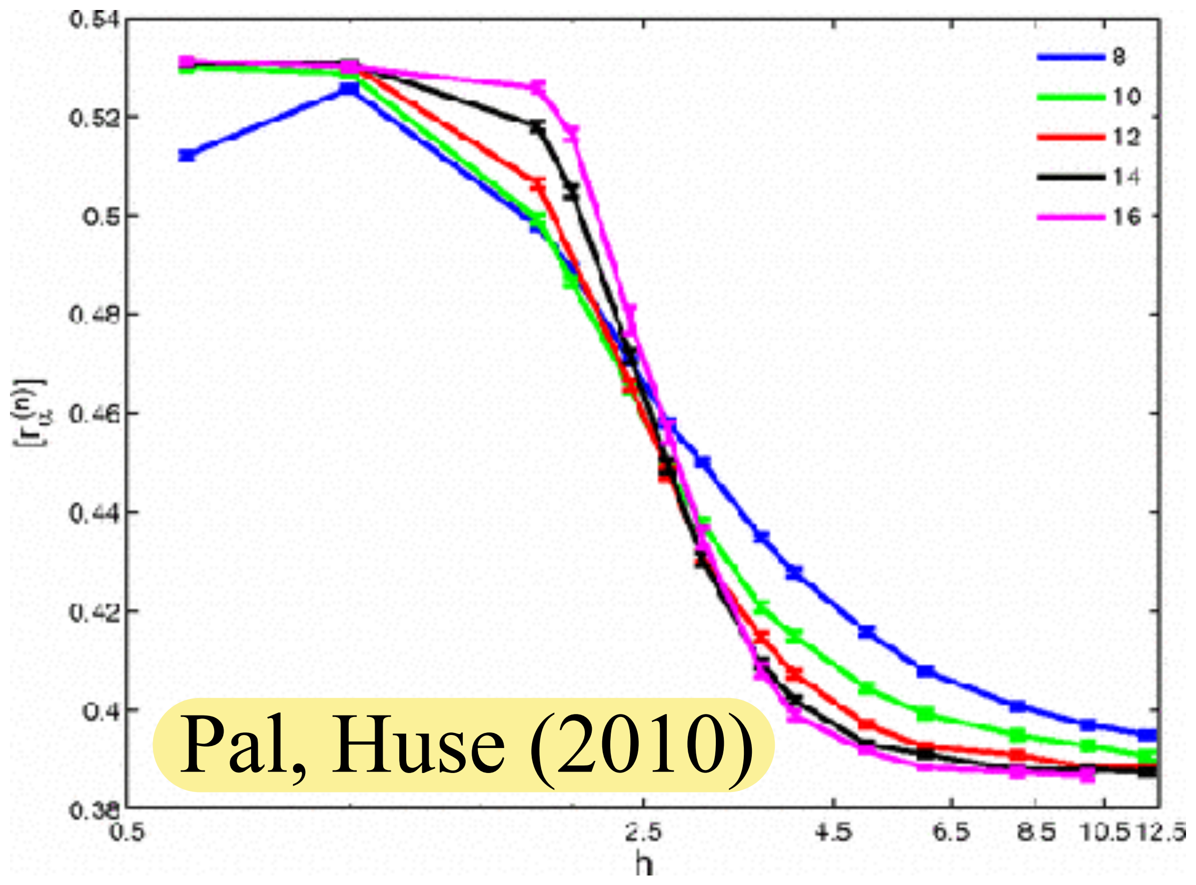
The internal clock of many-body delocalization

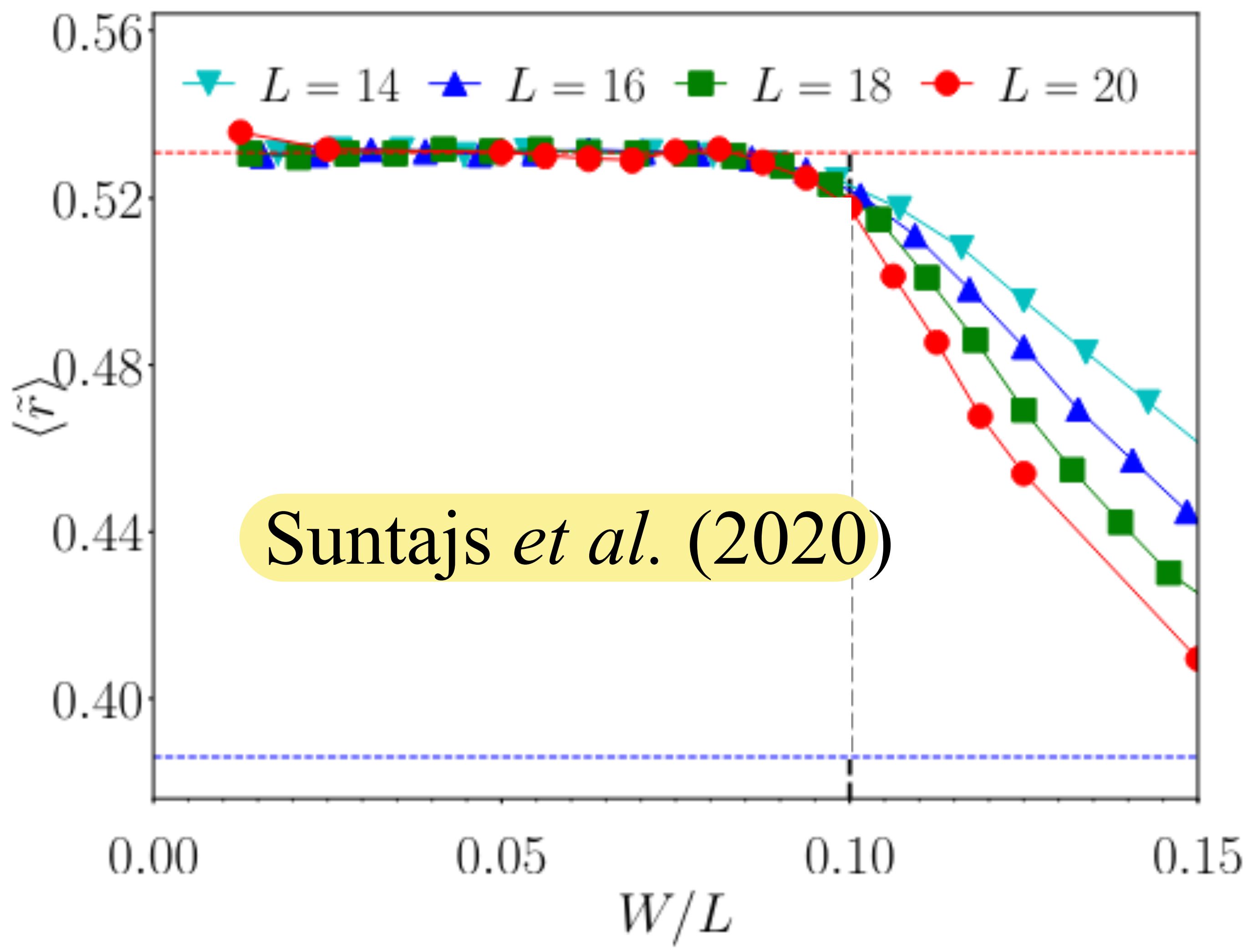
Ferdinand Evers, Ishita Modak, Soumya Bera

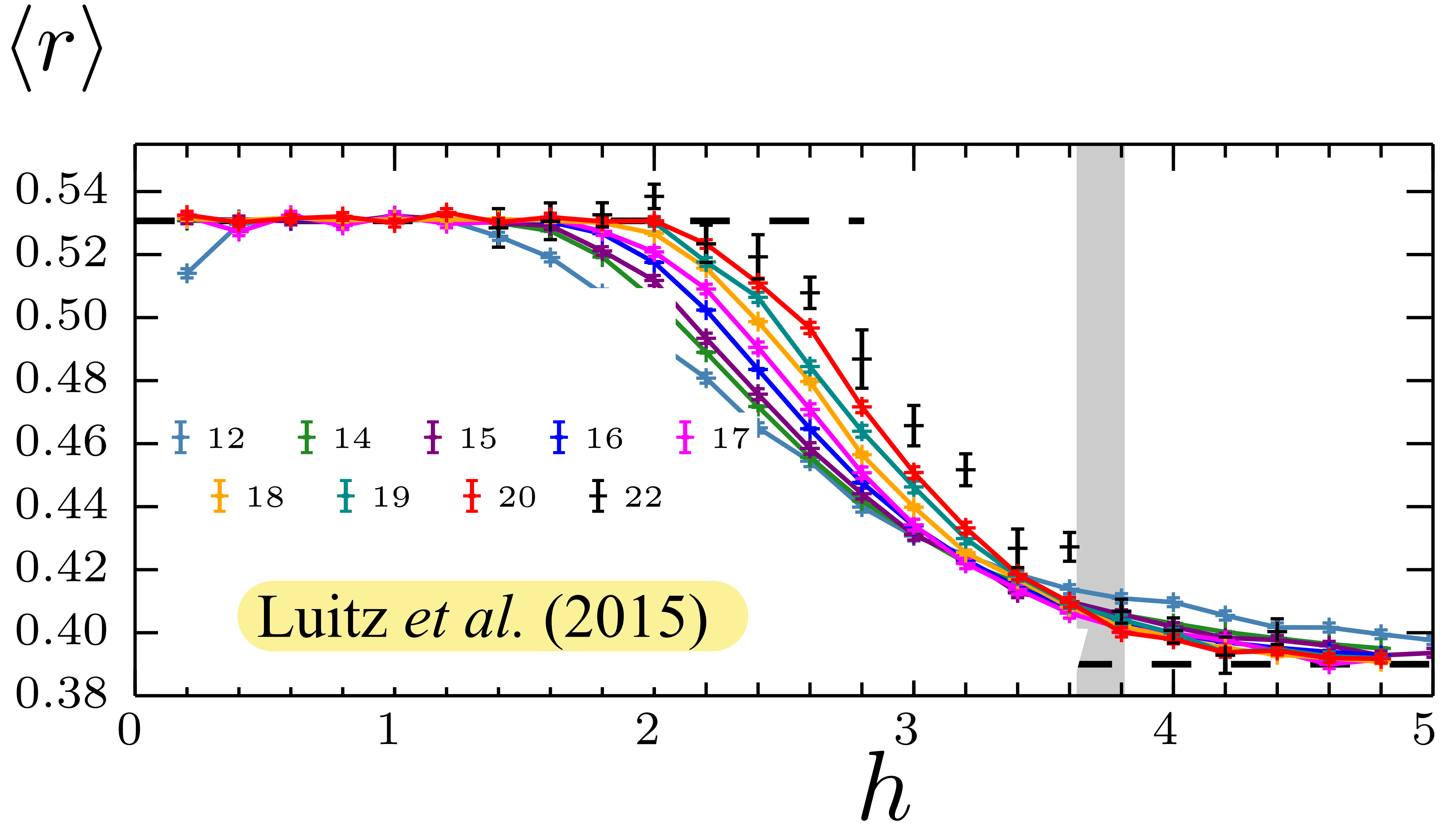
After a decade of many claims to the opposite, there now is a growing consensus that generic disordered quantum wires, e.g., the XXZ-Heisenberg chain, do not exhibit many-body localization

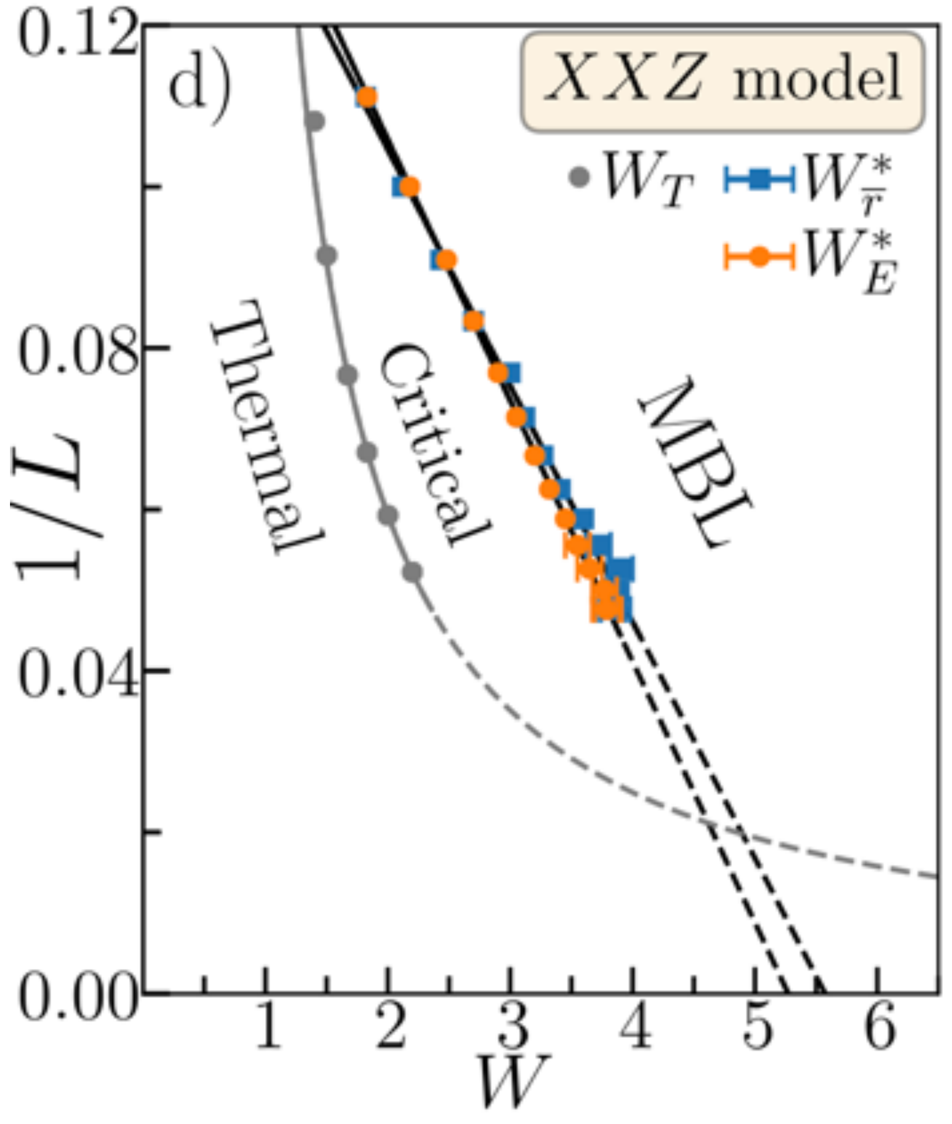
Finite-size effects & their interpretations : some examples …

▸Gap Ratio



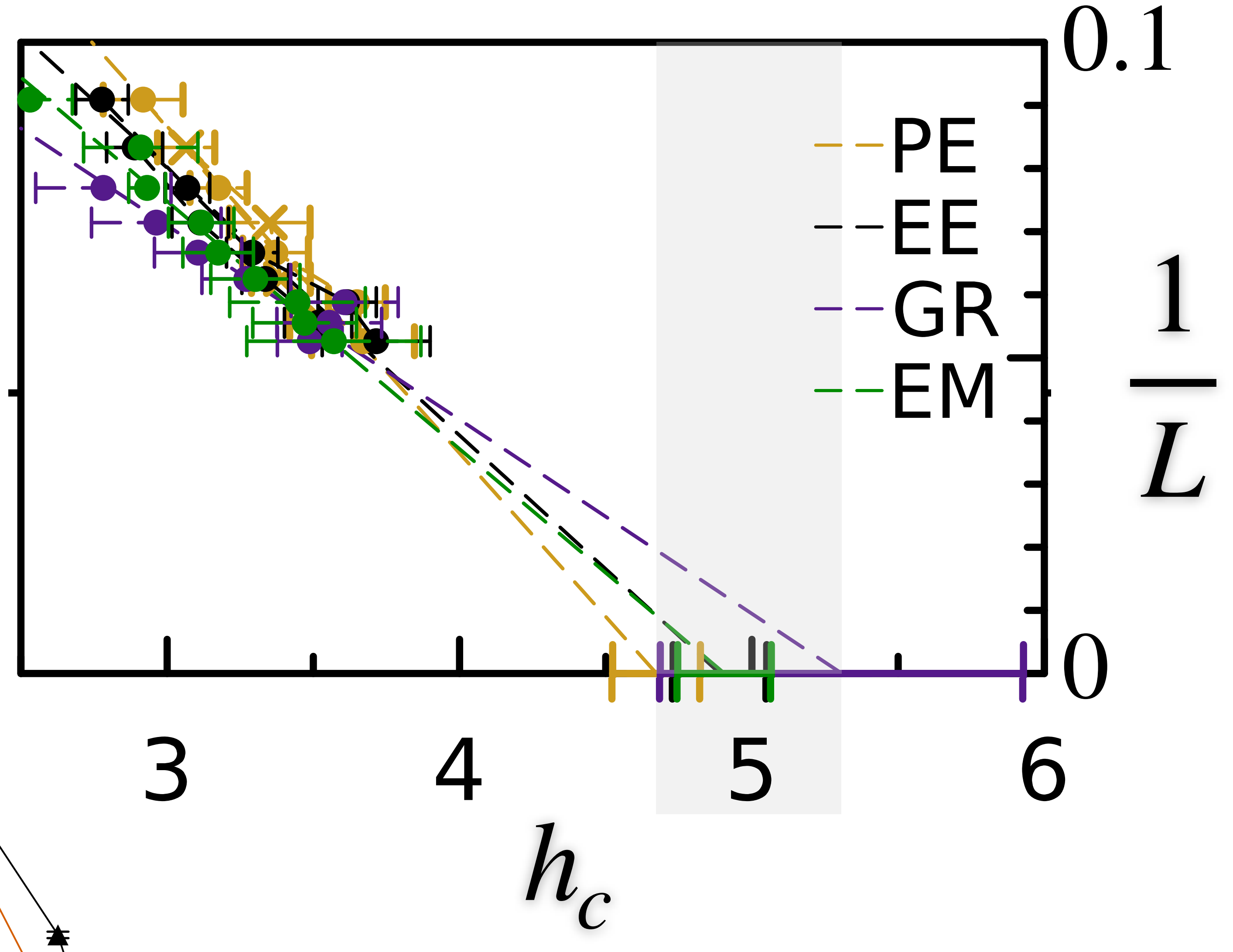


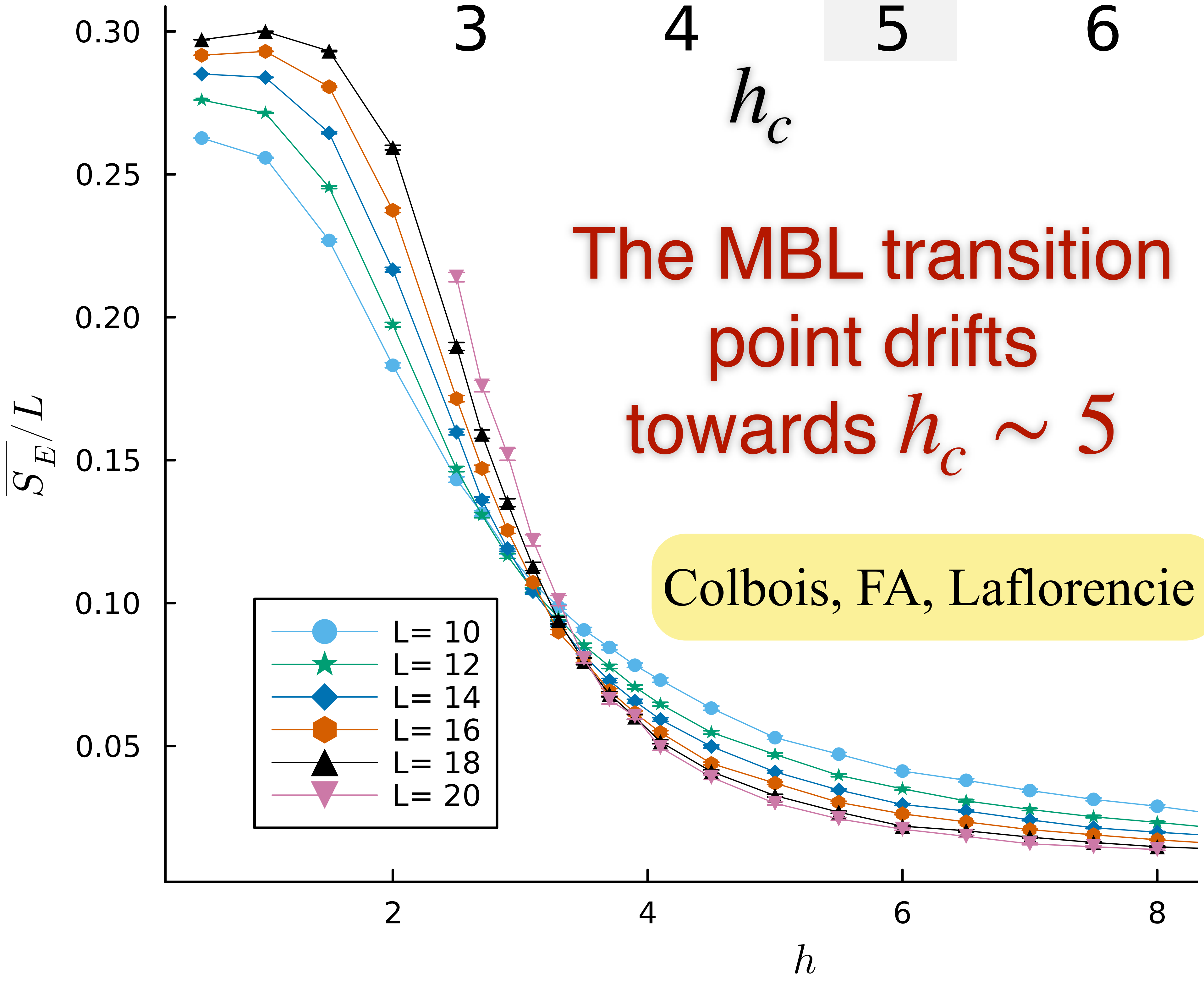




Sierant *et al.* (2020)

▸Entanglement





The MBL transition point drifts towards $h_c \sim 5$

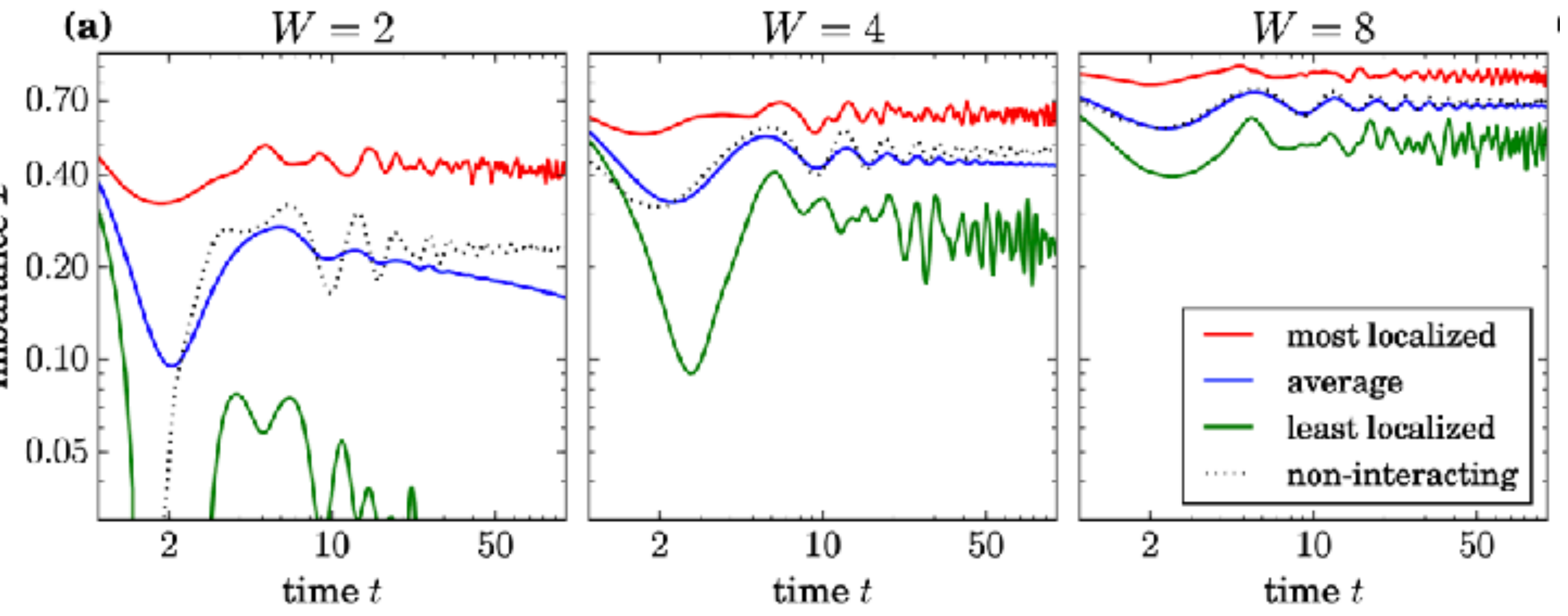
Colbois, FA, Laflorencie

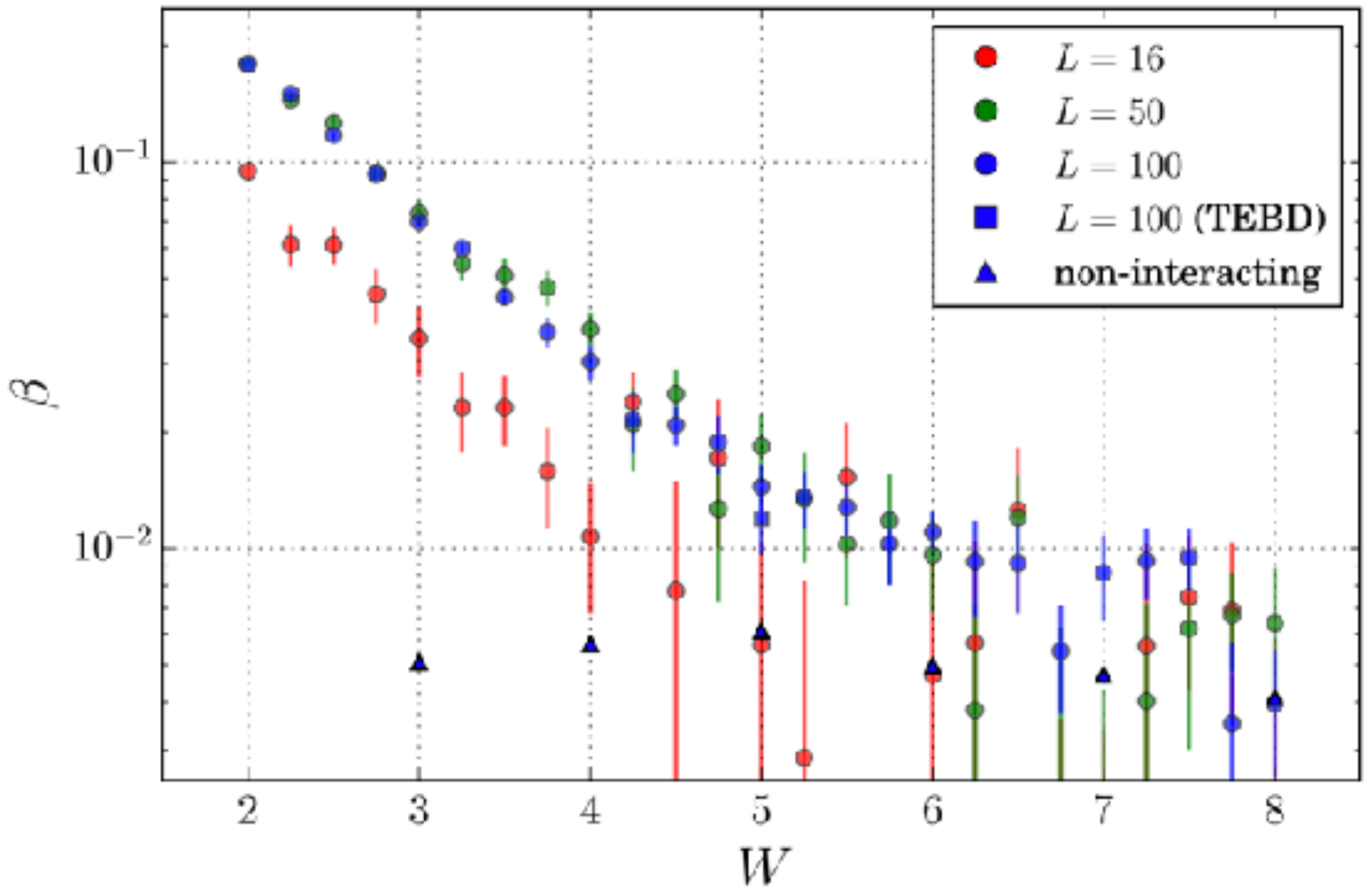
Very slow dynamics inside the MBL phase

Dynamics after quench : $|\Psi(t)\rangle = e^{-\mathrm{i}Ht}|\Psi(0)\rangle$

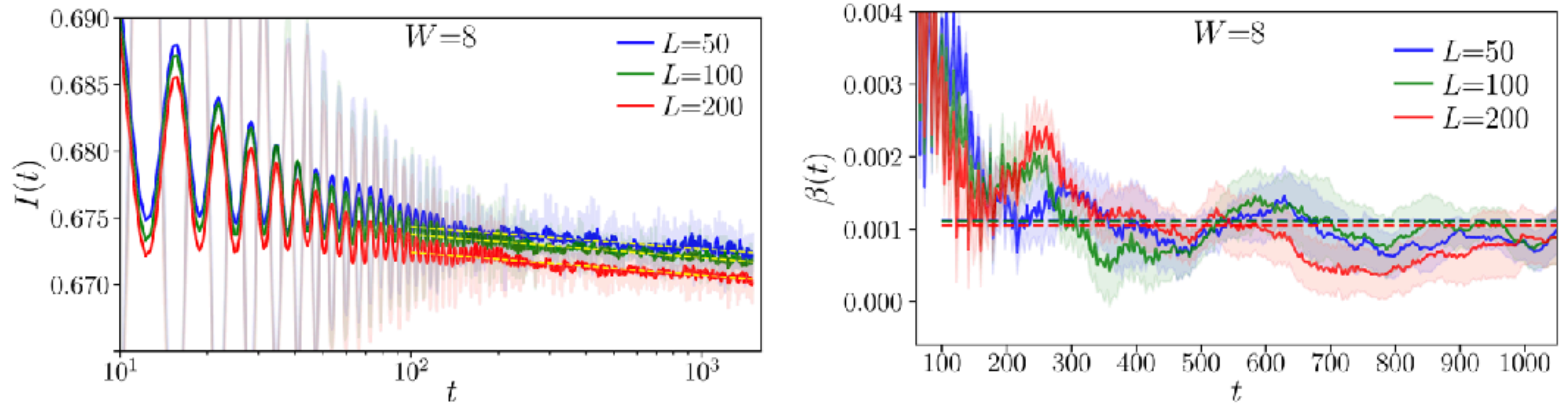
Larger-scale dynamics of Imbalance decay using Matrix-Product-States methods (t-DMRG, TEBD, TDVP)

Doggen *et al.* (2018)



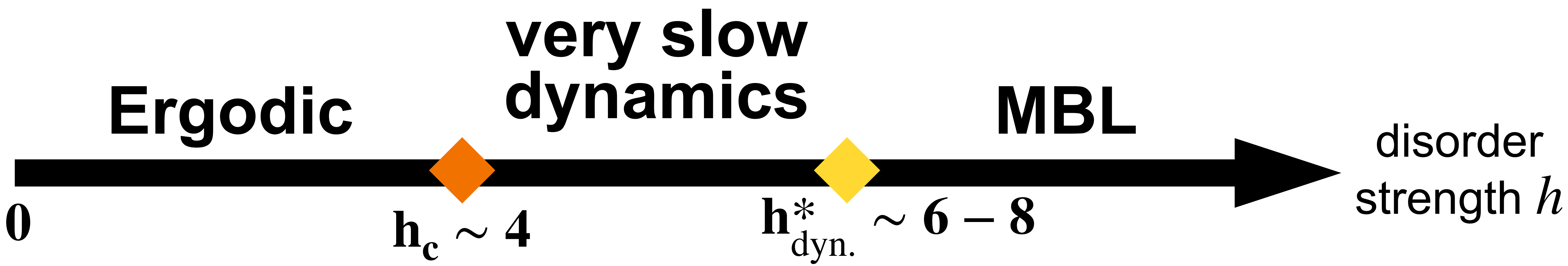


Sierant, Zakrzewski (2022)



Very slow decay of the imbalance $I(t) \sim t^{-\beta}$

Suggested dynamical phase diagram



Searching for the invisible : Avalanche and resonances

- Idea: the liom picture cannot explain the transition to the ergodic phase. Other phenomenological approaches emerged:

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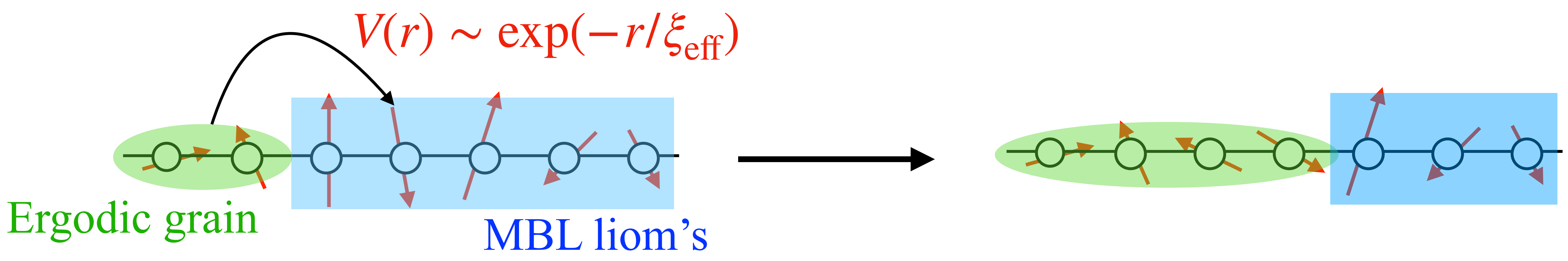
Avalanche instability

De Roeck, Huveneers

An ergodic grain can thermalise its neighbourhood, which is then included in the grain, thermalize again its neighbourhood .. and eventually leads to full thermalization



- The ergodic grain (initial size n_0) grows as $n_0 \to n_0 + r$ if the coupling V(r) is larger than effective level spacing $2^{-(n_0+r)}$
- For large enough initial "localization" length $\xi_{\text{eff}} > \xi^* = 2/\ln 2$, this leads to an instability towards thermalised phase : **avalanche**

→ Avalanches never observed so far on systems with realistic disorder…

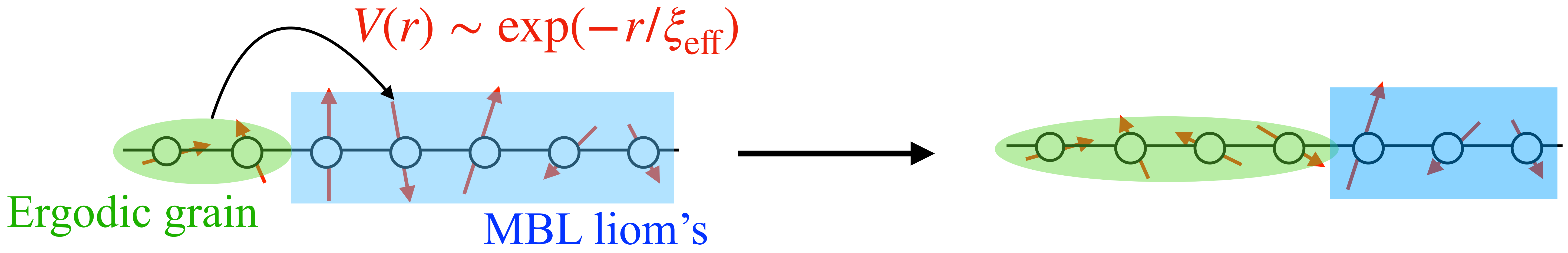
Searching for the invisible : Avalanche and resonances

- Idea: the liom picture cannot explain the transition to the ergodic phase. Other phenomenological approaches emerged:

Avalanche instability

De Roeck, Huveneers

An ergodic grain can thermalise its neighbourhood, which is then included in the grain, thermalize again its neighbourhood .. and eventually leads to full thermalization



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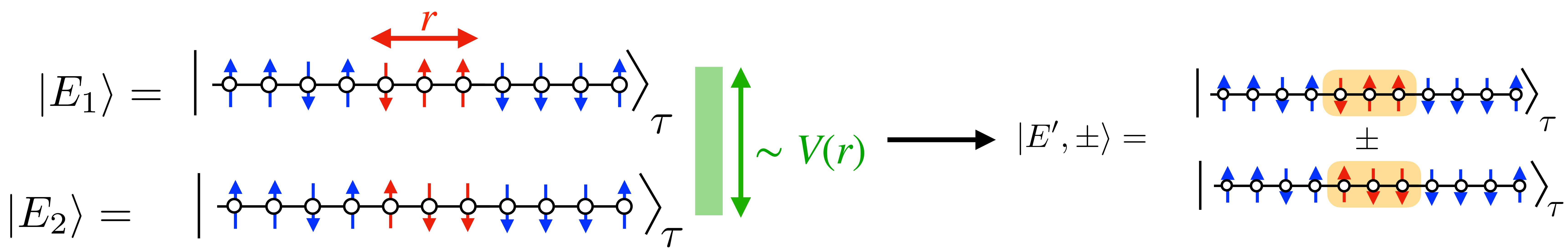
Many-body resonances

More « direct » hybridisation between liom states by local operators



→ Hints of such many-body resonances in some (mostly phenomenological, some microscopic) models

Crowley, Chandran (2020-22)

Garratt, Roy, Chalker (2021-22)

Morningstar *et al.* (2022)

Sketch of the new phenomenology

Morningstar *et al.* (2022) Long *et al.* (2023)

Crossover Region | « Pre-thermal MBL » | MBL

Well understood with ETH

Where numerics/ experiments are often stuck, finite-size effects are not understood, previously thought as the critical region near the MBL point

on finite-size, finite-time observations, all features of MBL

Well described with liom model

Disorder

True MBL transition point (never probed in numerics so far)

- By « **forcing** » or « **searching** » for **rare events (extreme values)** for the random field Heisenberg chain

$$H_{\mathrm{RFHC}} = \sum_i \left[S_i^x S_{i+1}^x + S_i^y S_{i+1}^y + S_i^z S_{i+1}^z + h_i S_i^z \right]$$

Morningstar *et al.* (2022)

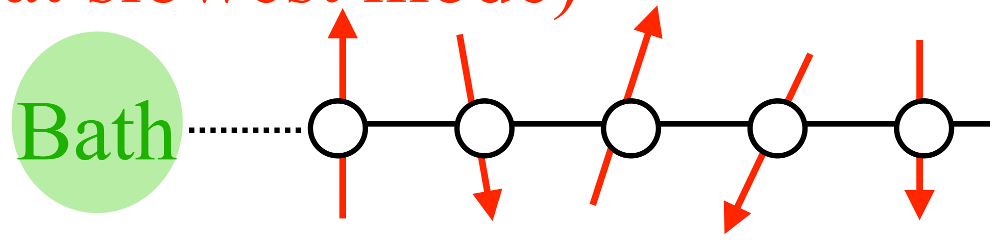
~ 3.5 | ~ 5.7 | ~ 8.5 | ~ 20 | h

Average gap ratio goes Poisson (standard measure)

The **minimal** gap is 1/4^L (Poisson prediction)

O(1) eigenstates (out of 2^L) display **system-wide resonances**

Forcing avalanches by coupling to a bath (and look at slowest mode)



Ha, Morningstar, Huse (2023)

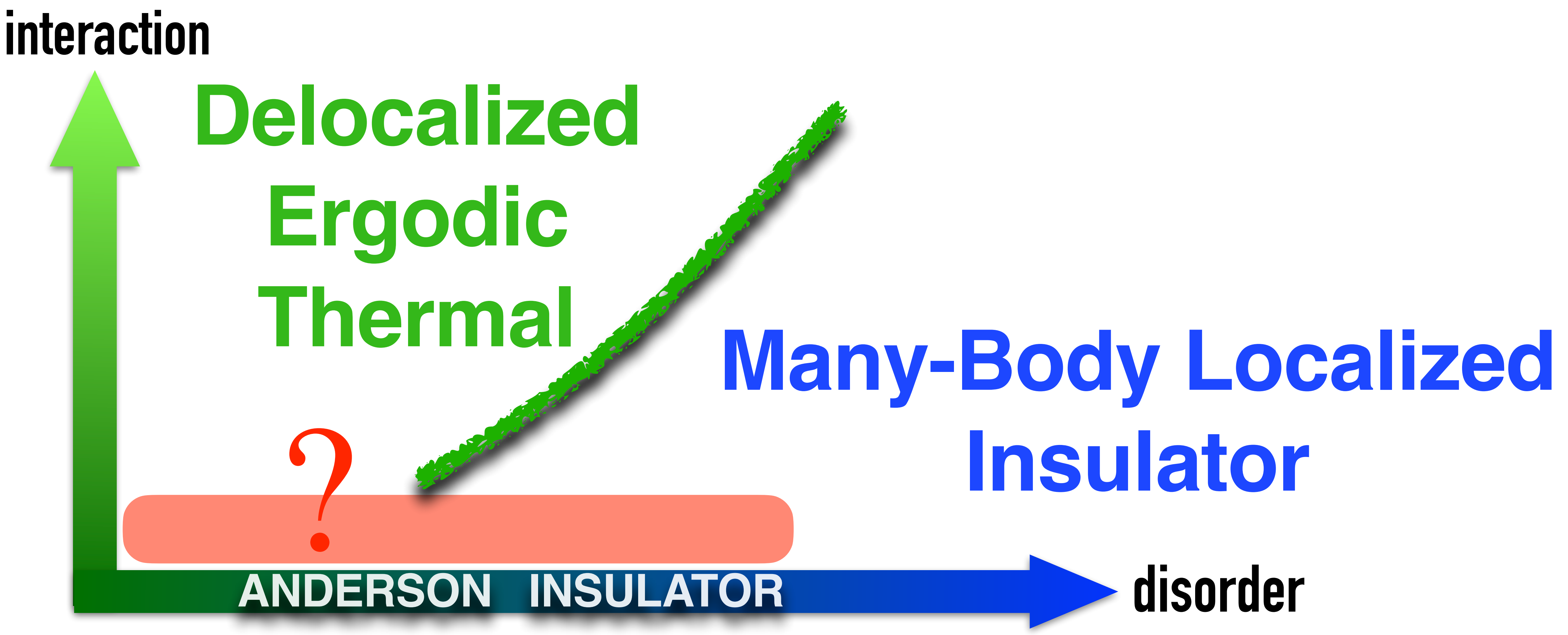
Stepping away from the « strong » interaction regime

J. Colbois, FA, N. Laflorencie Phys. Rev. Lett. **133**, 116502 (2024)

Original motivation: Can localization survive interaction?

What happens at weak Δ ?

Most studies focused on the « strongly interacting » Heisenberg chain $\Delta = 1$



Stepping away from the « strong » interaction regime

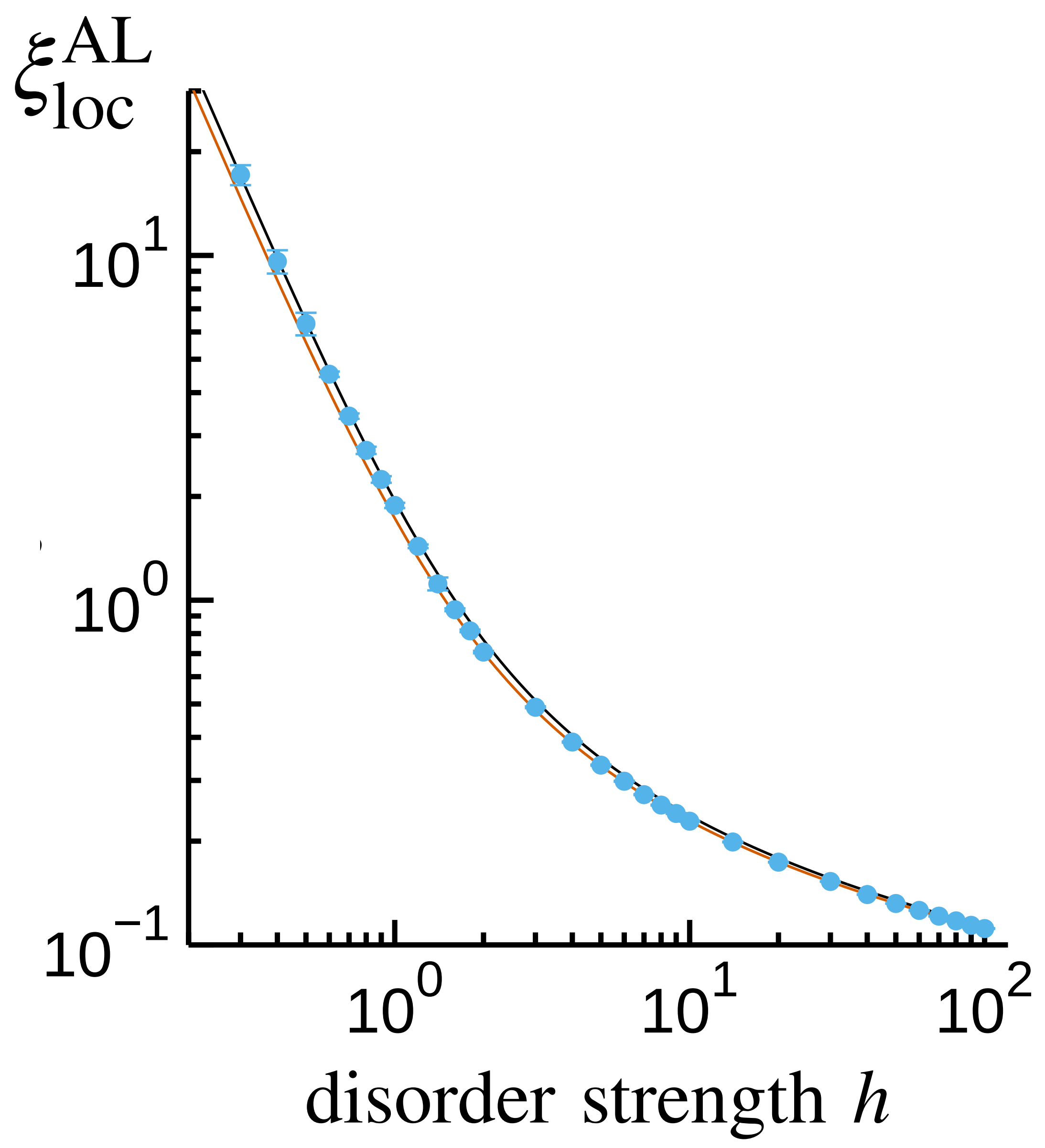
- Consider the weak interaction limit $\Delta \to 0$: $H_{\mathrm{XXZ}} = \sum_i \left[S_i^x S_{i+1}^x + S_i^y S_{i+1}^y + \Delta S_i^z S_{i+1}^z + h_i S_i^z \right] \longrightarrow H_{\mathrm{MBAL}} = \sum_i \left[S_i^x S_{i+1}^x + S_i^y S_{i+1}^y + h_i S_i^z \right]$

Many-body Anderson insulator

- Idea: Any reasonable definition of the many-body localization length should converge to the (non-interacting) Anderson localization length ξ_{loc}^{AL}

$$\xi_{\mathrm{loc}}^{\mathrm{AL}} = 1/\ln\left[1 + \left(h/h_0\right)^2\right] \sim \begin{cases} h^{-2} & \text{(weak disorder)} \\ \dfrac{1}{\ln h} & \text{(strong disorder)} \end{cases}$$

Colbois, Laflorencie (2023)



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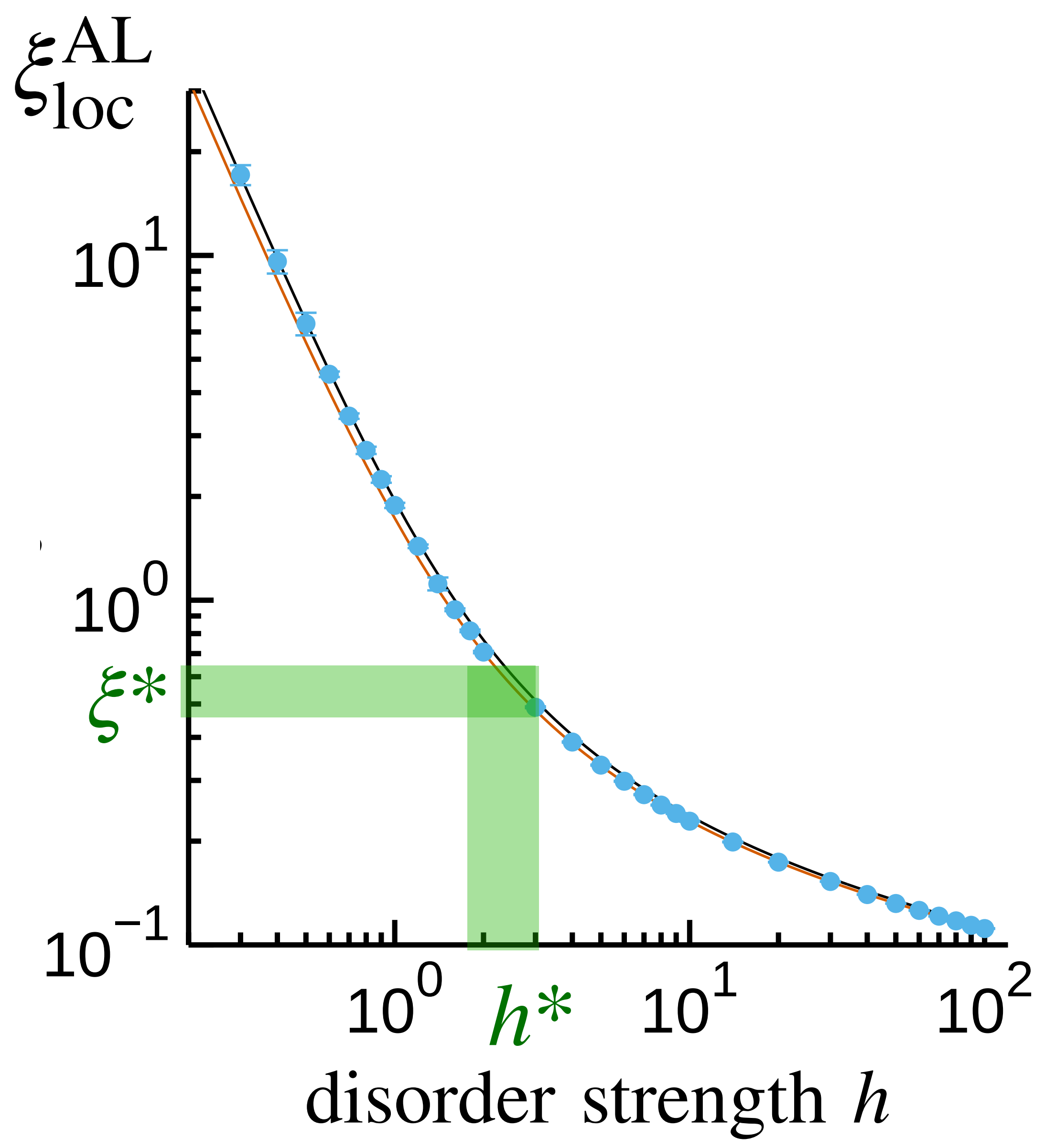

- Naive / Literal application of the avalanche criterion $\xi_{\mathrm{eff}} > \xi^*$ for infinitesimal interactions :

There is a critical disorder h* below which MBL is not stable

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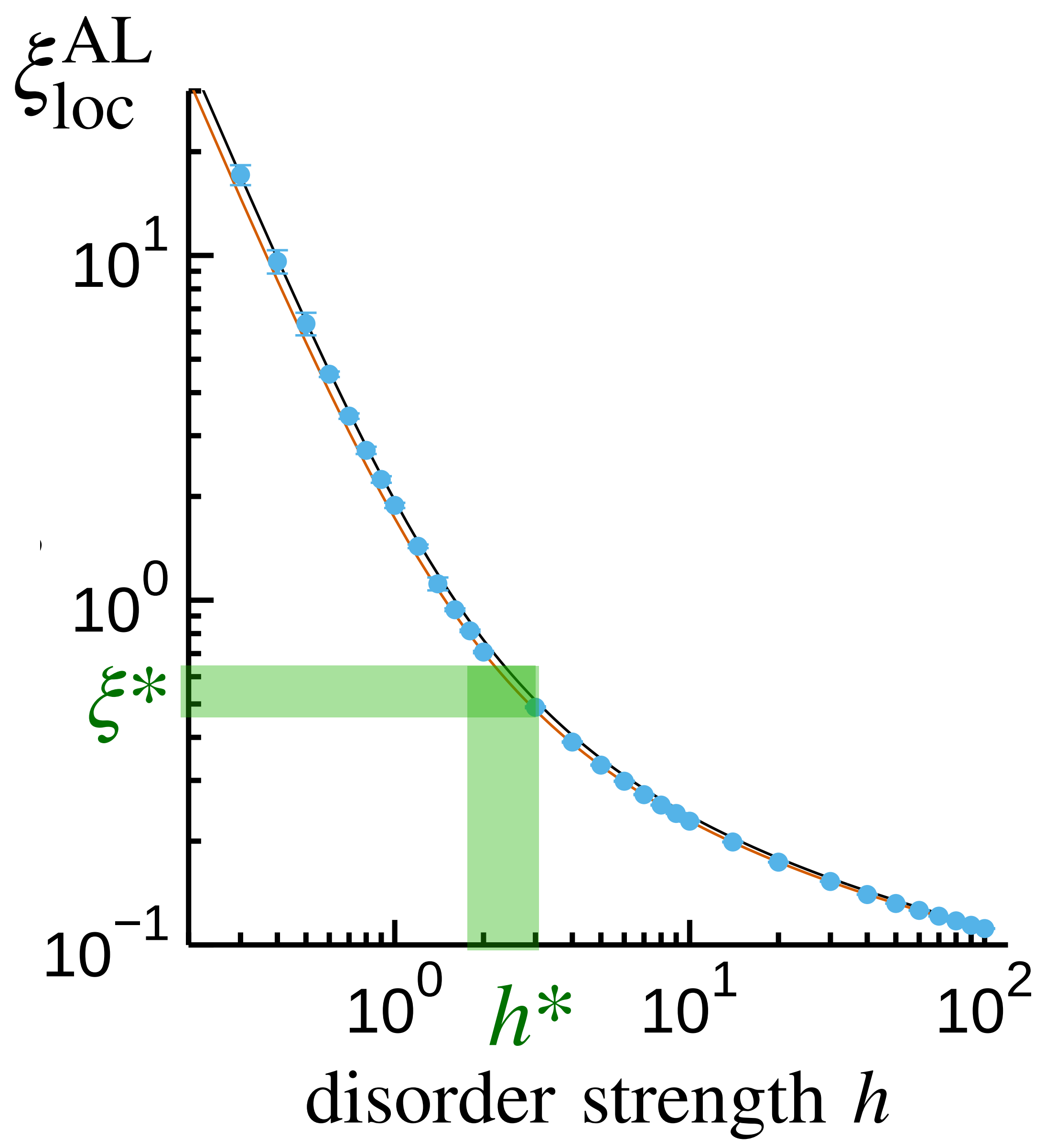

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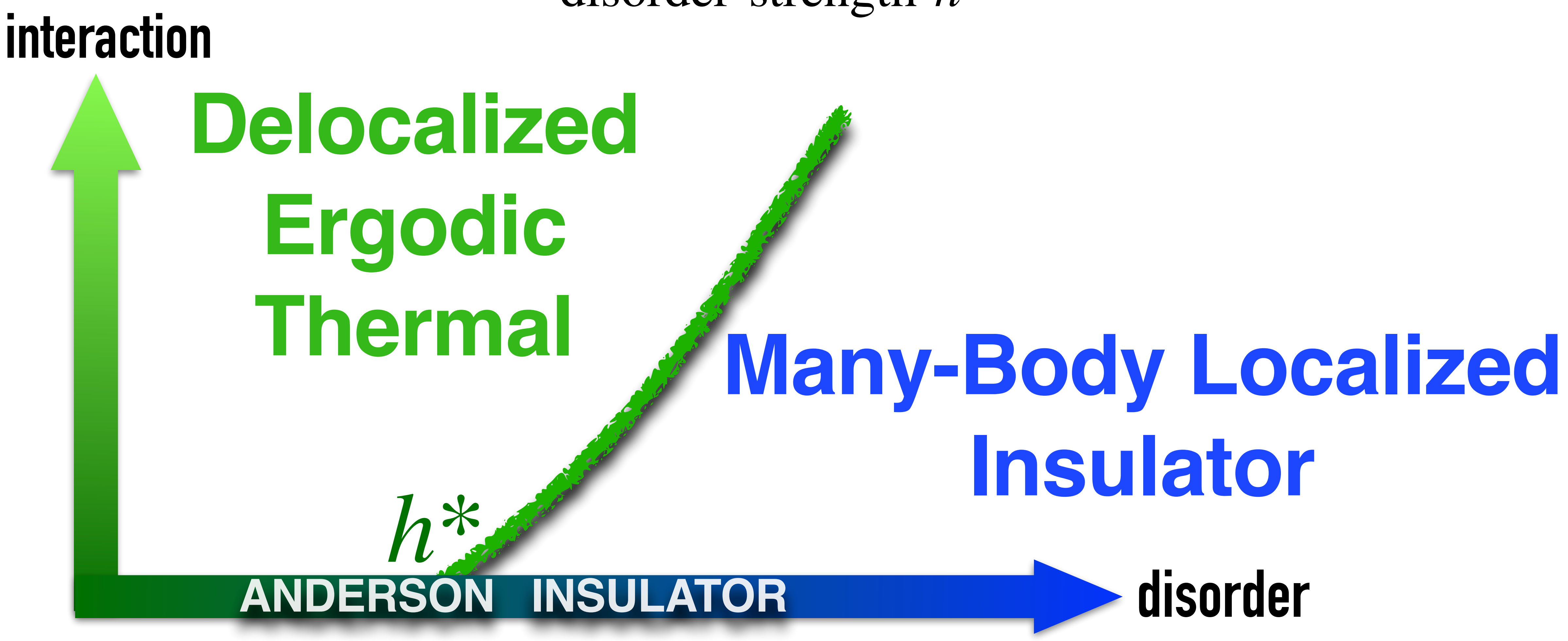
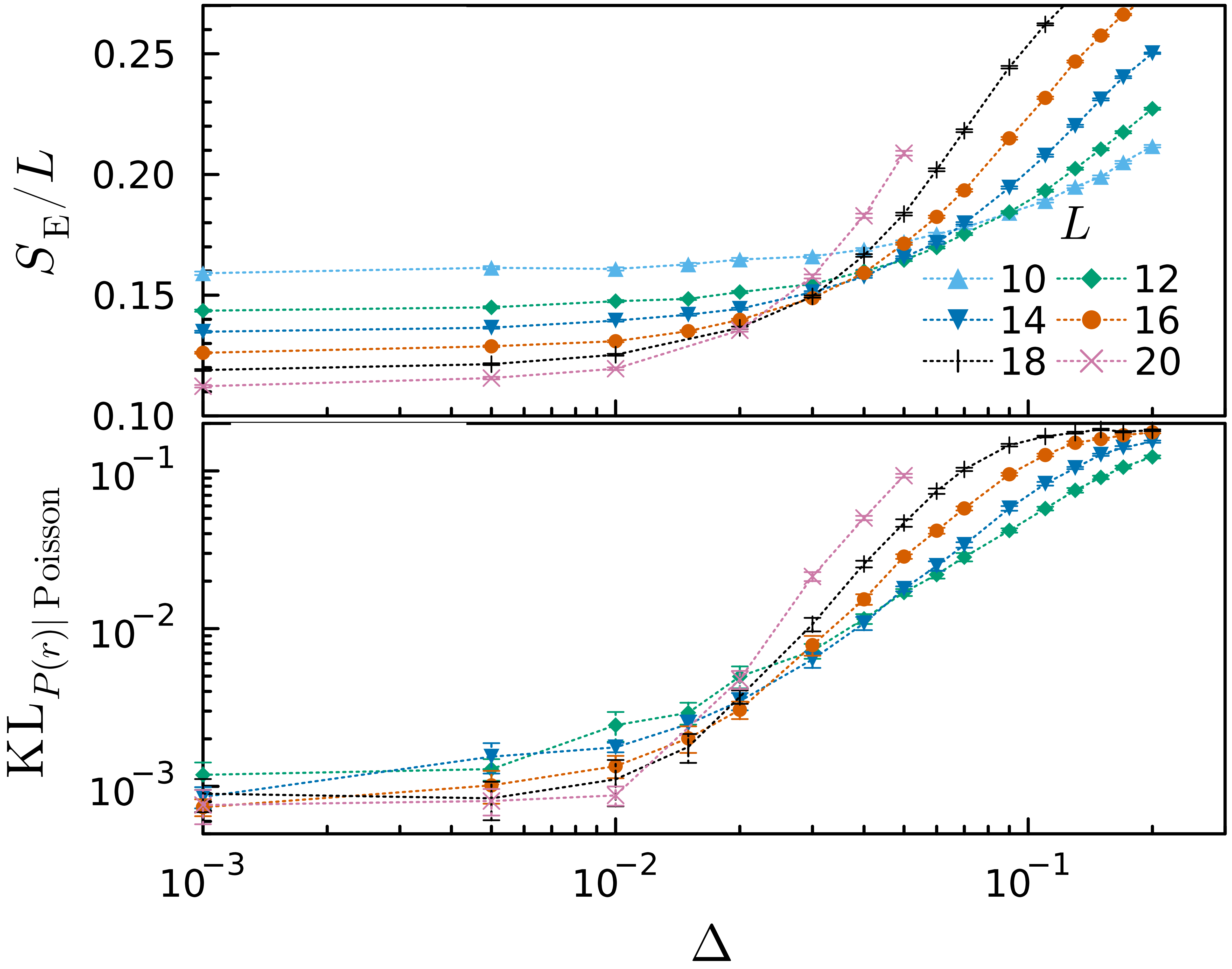


Numerical for small $\Delta \ll 1$

- Shift-invert computations of mid-spectrum eigenstates for $L \in [10 - 21]$ using standard estimates (entanglement entropy, spectral statistics, multifractal analysis and local observables)



Working at fixed (small) disorder

$$h = 1 \ (\xi_{\text{loc}}^{\text{AL}} \approx 2)$$

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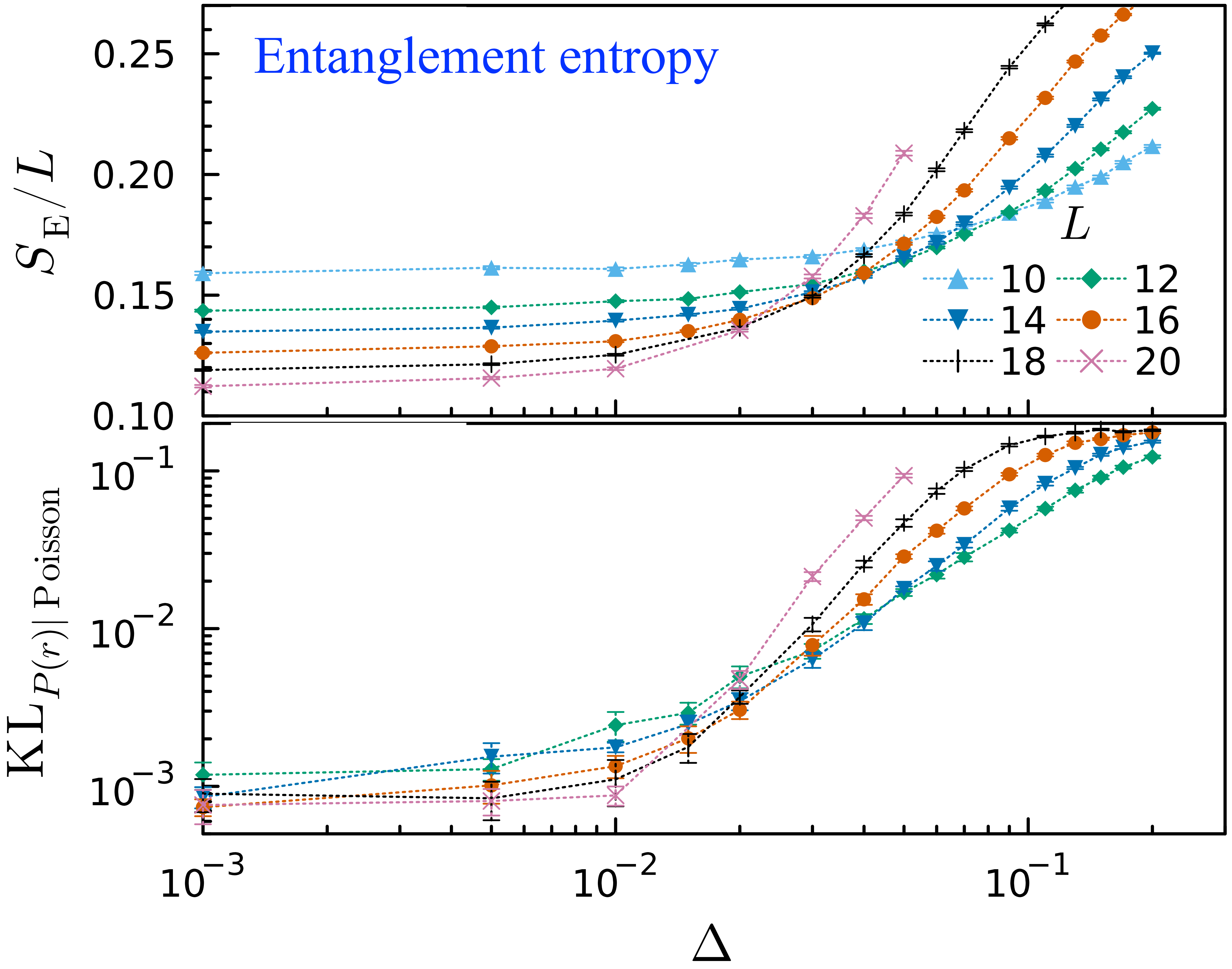

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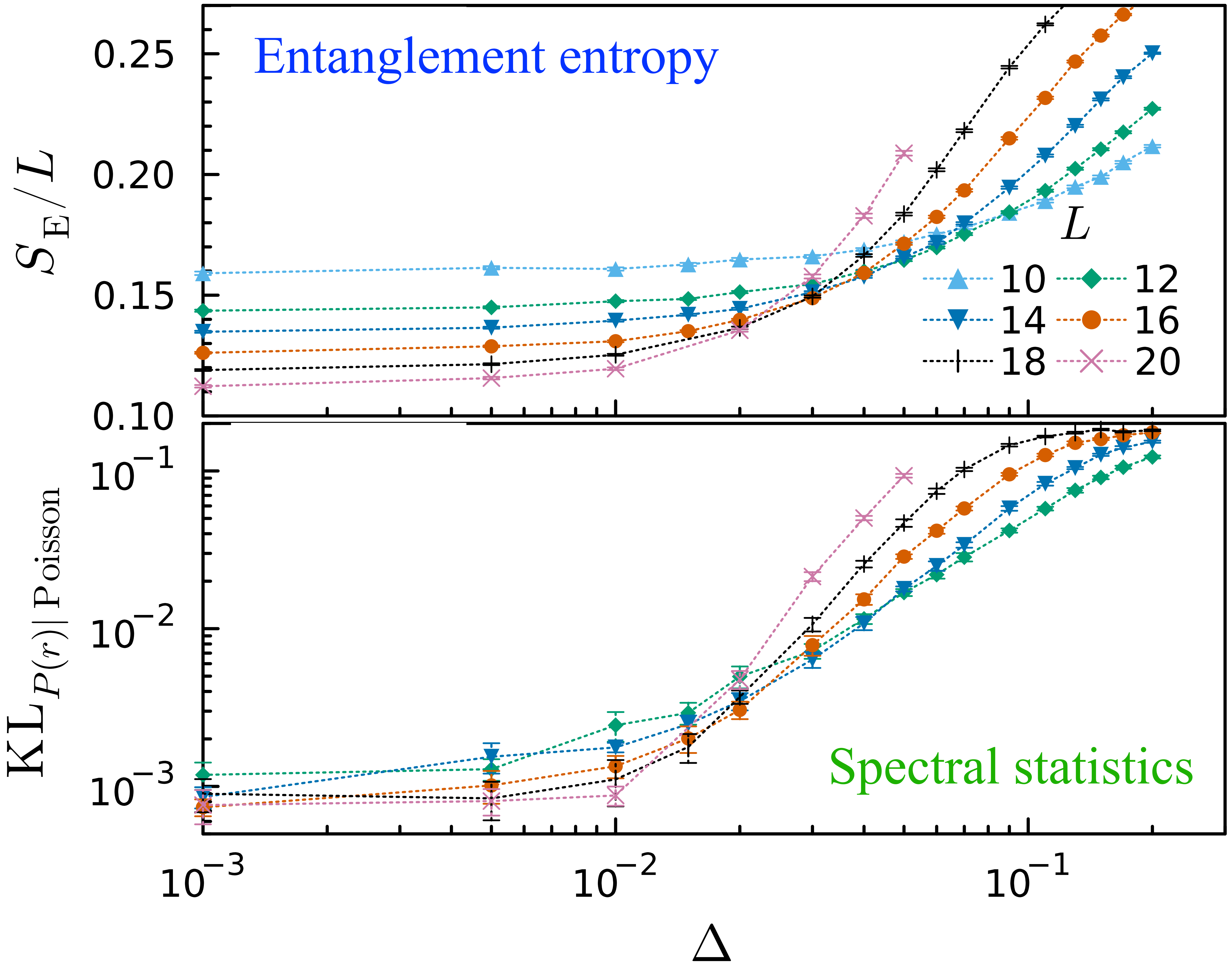

$$\text{KL}_{P(r)|\text{Poisson}} = \int_0^1 P(r) \ln \left[P(r) \frac{(1+r)^2}{2} \right] \mathrm{d}r$$

$$\xrightarrow[L \gg 1]{} \begin{cases} 0 & \text{if Poisson} \\ \approx 0.19 & \text{GOE} \end{cases}$$

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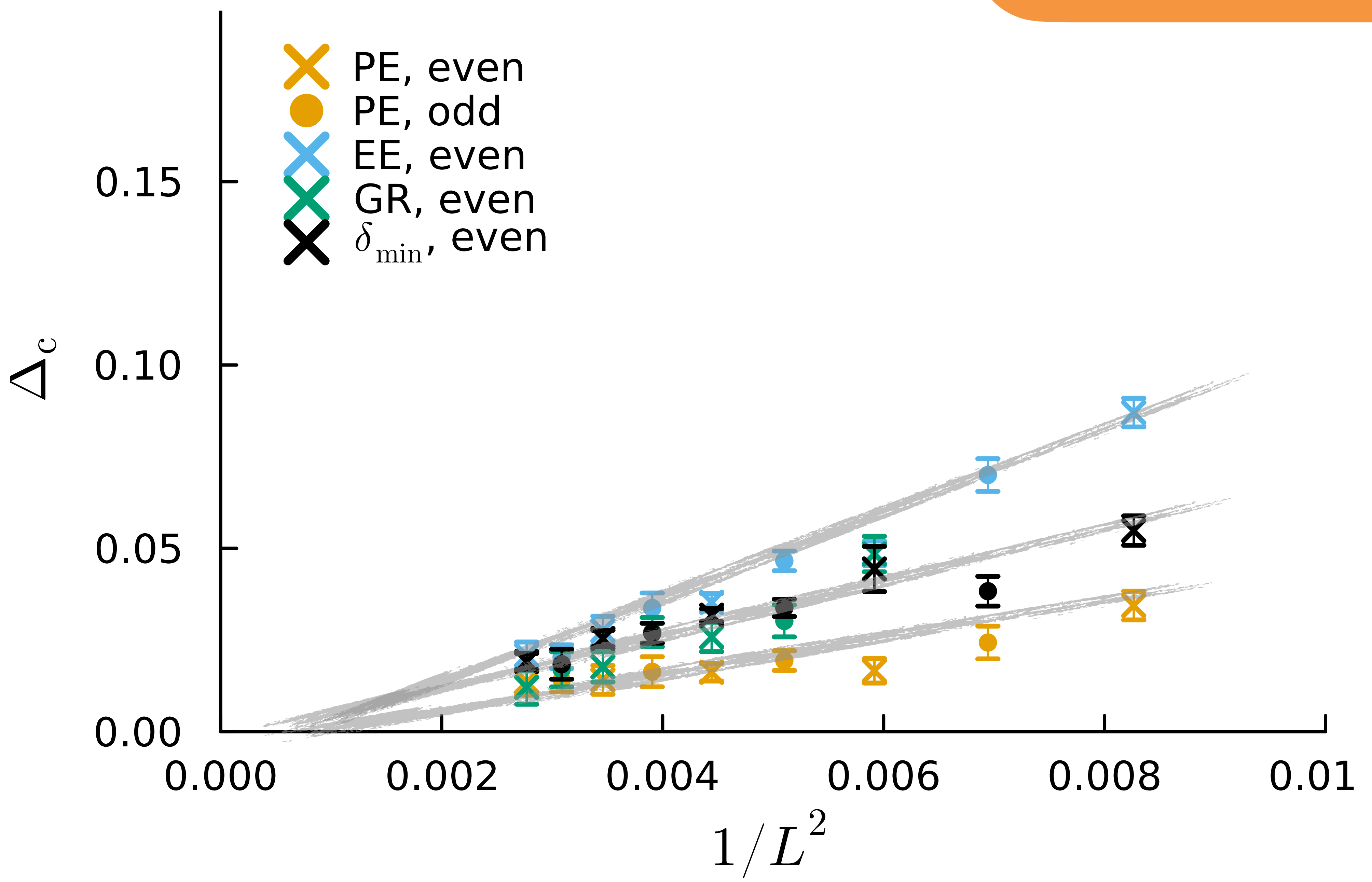
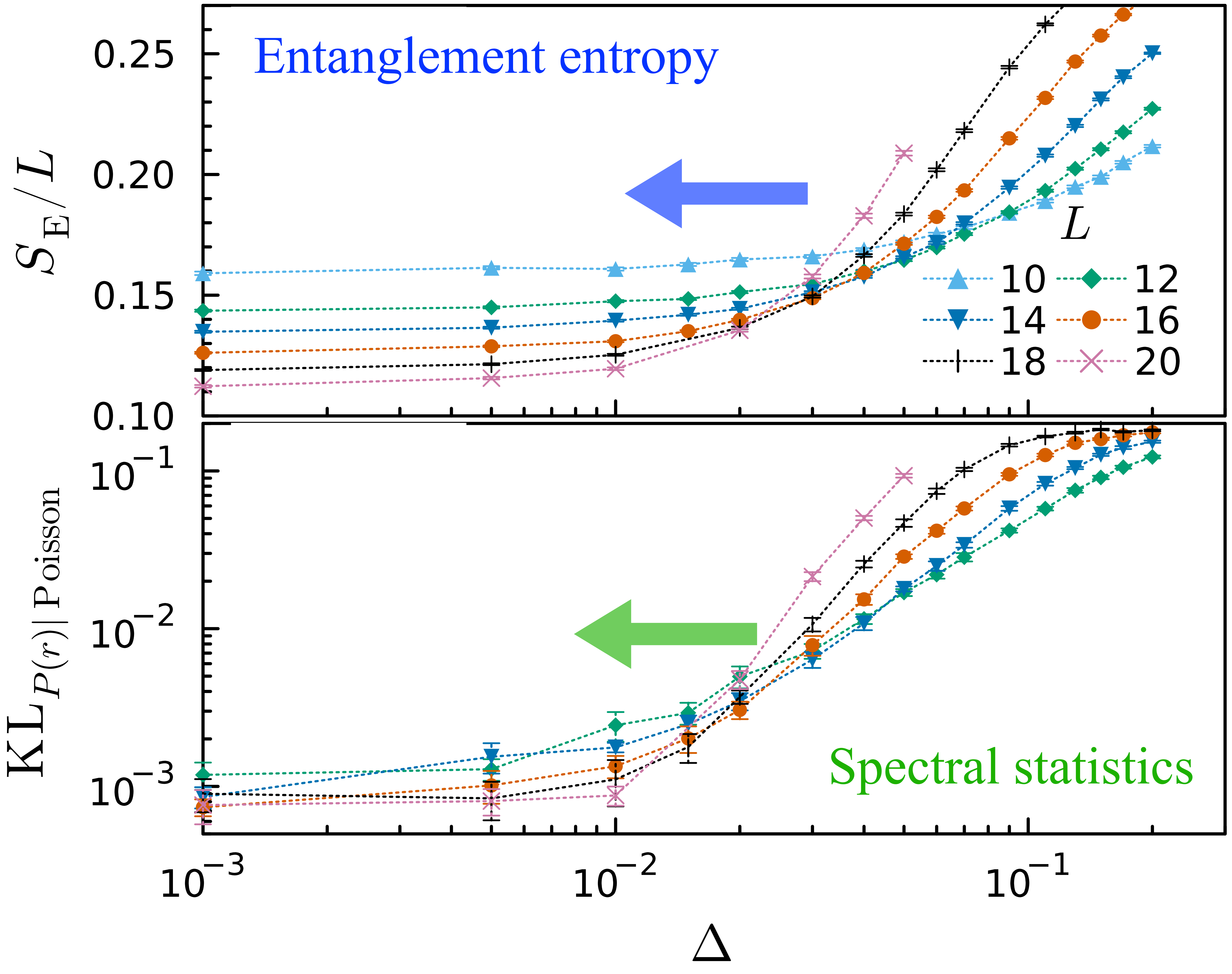


Drifts of crossing points with L



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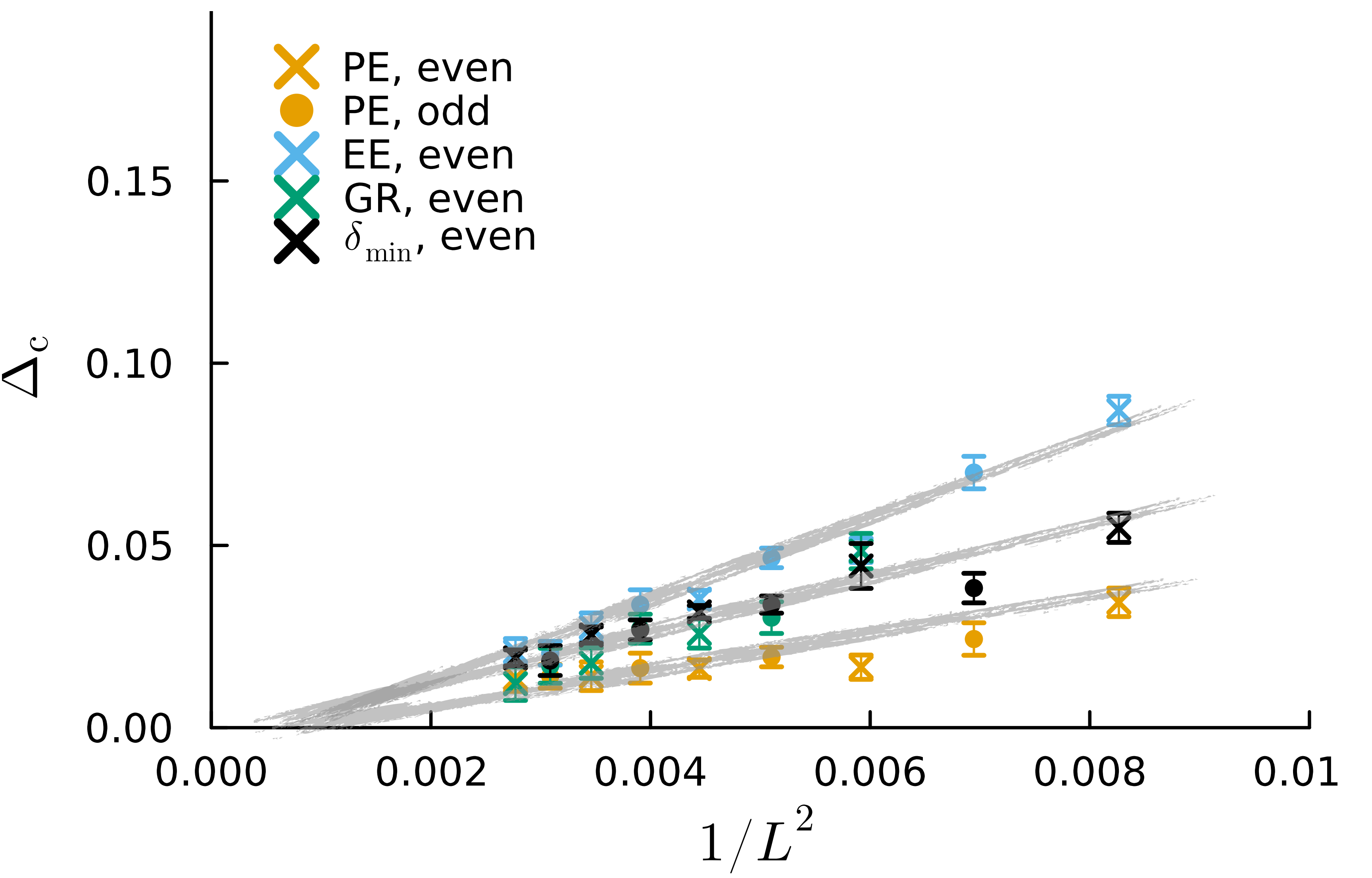
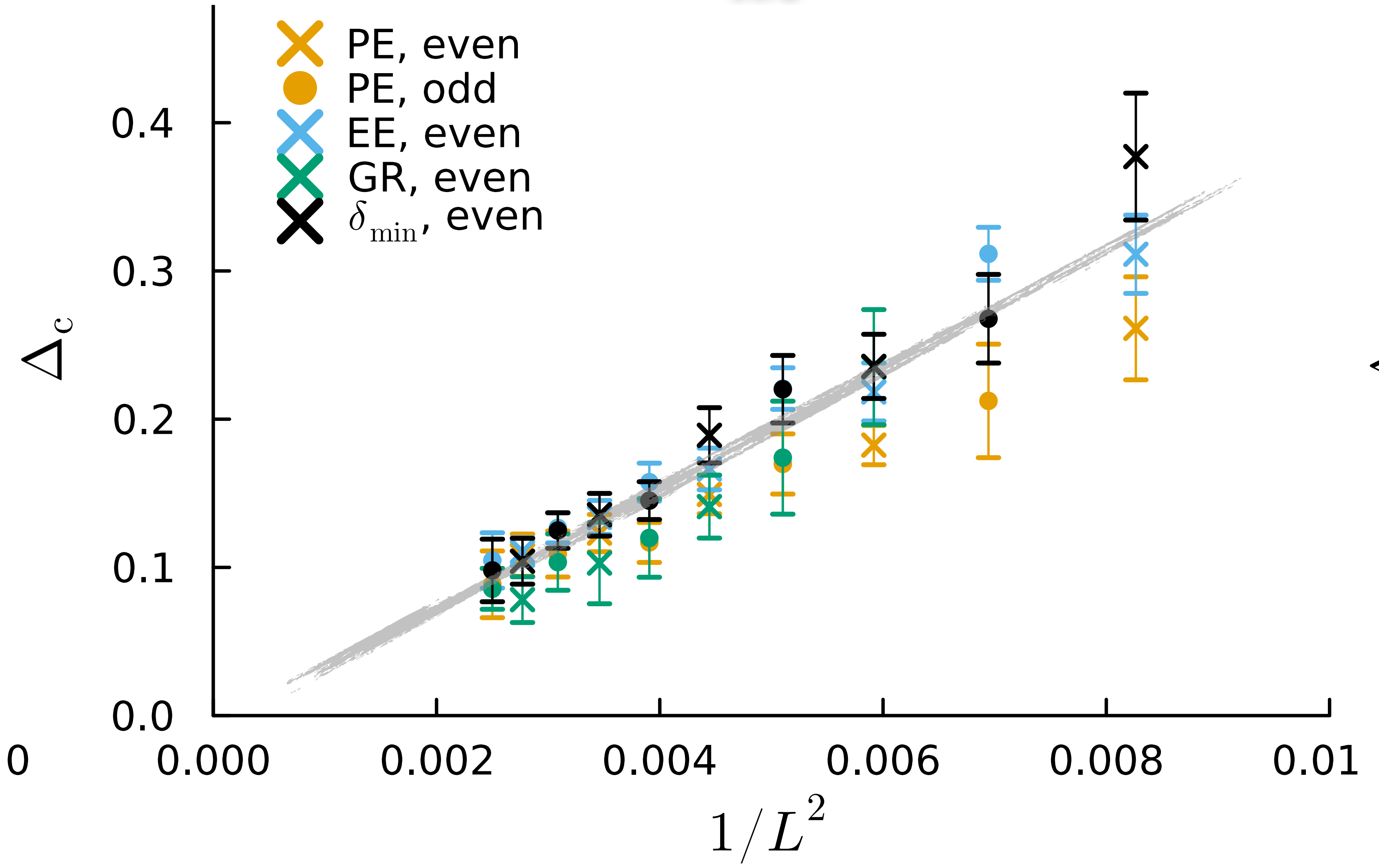
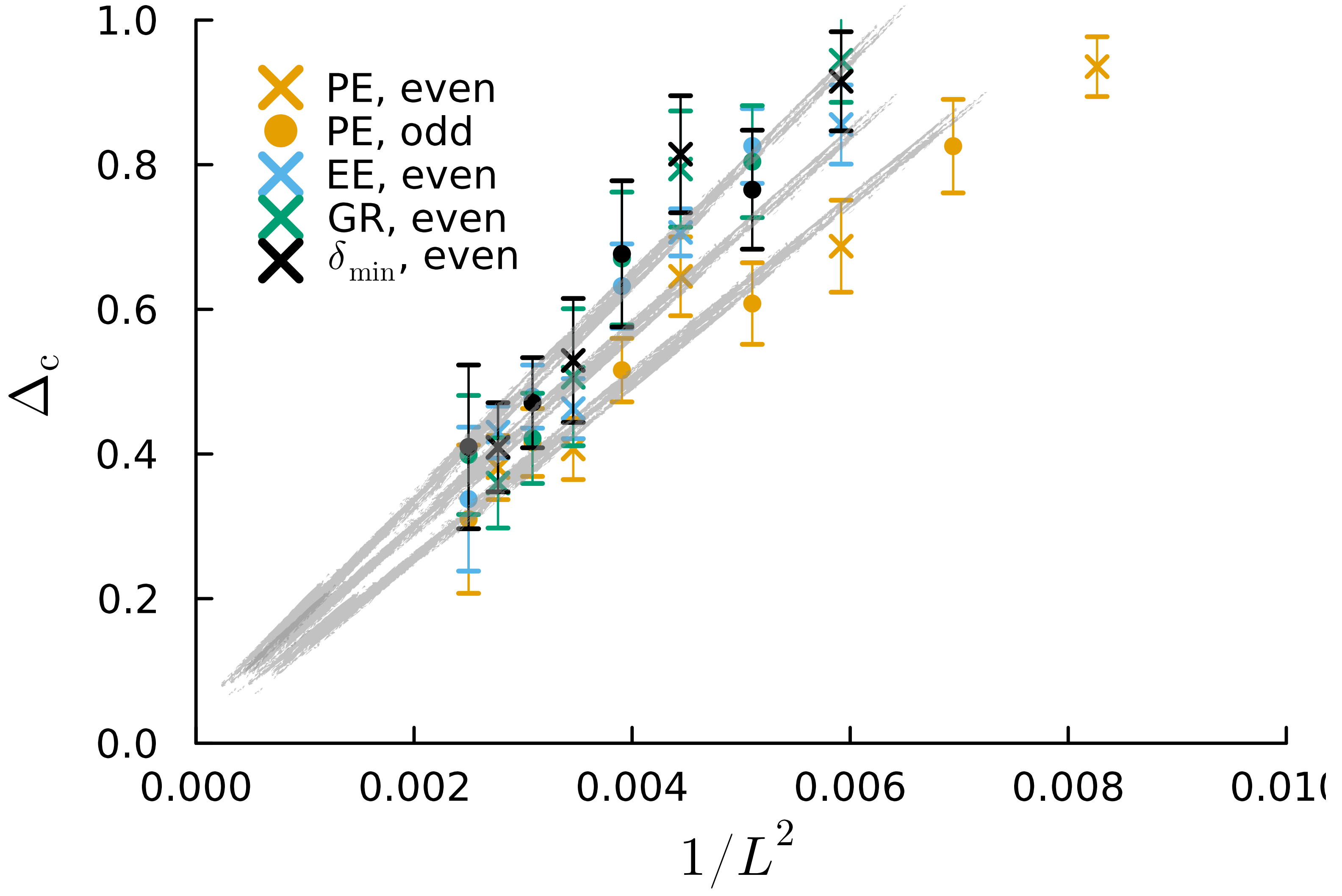
$h = 1$ ($\xi_{\mathrm{loc}}^{\mathrm{AL}} \approx 2$)



$h = 2$ ($\xi_{\mathrm{loc}}^{\mathrm{AL}} \approx 0.7$)



$h = 3$ ($\xi_{\mathrm{loc}}^{\mathrm{AL}} \approx 0.5$)



Numerics at intermediate $\Delta < 1$

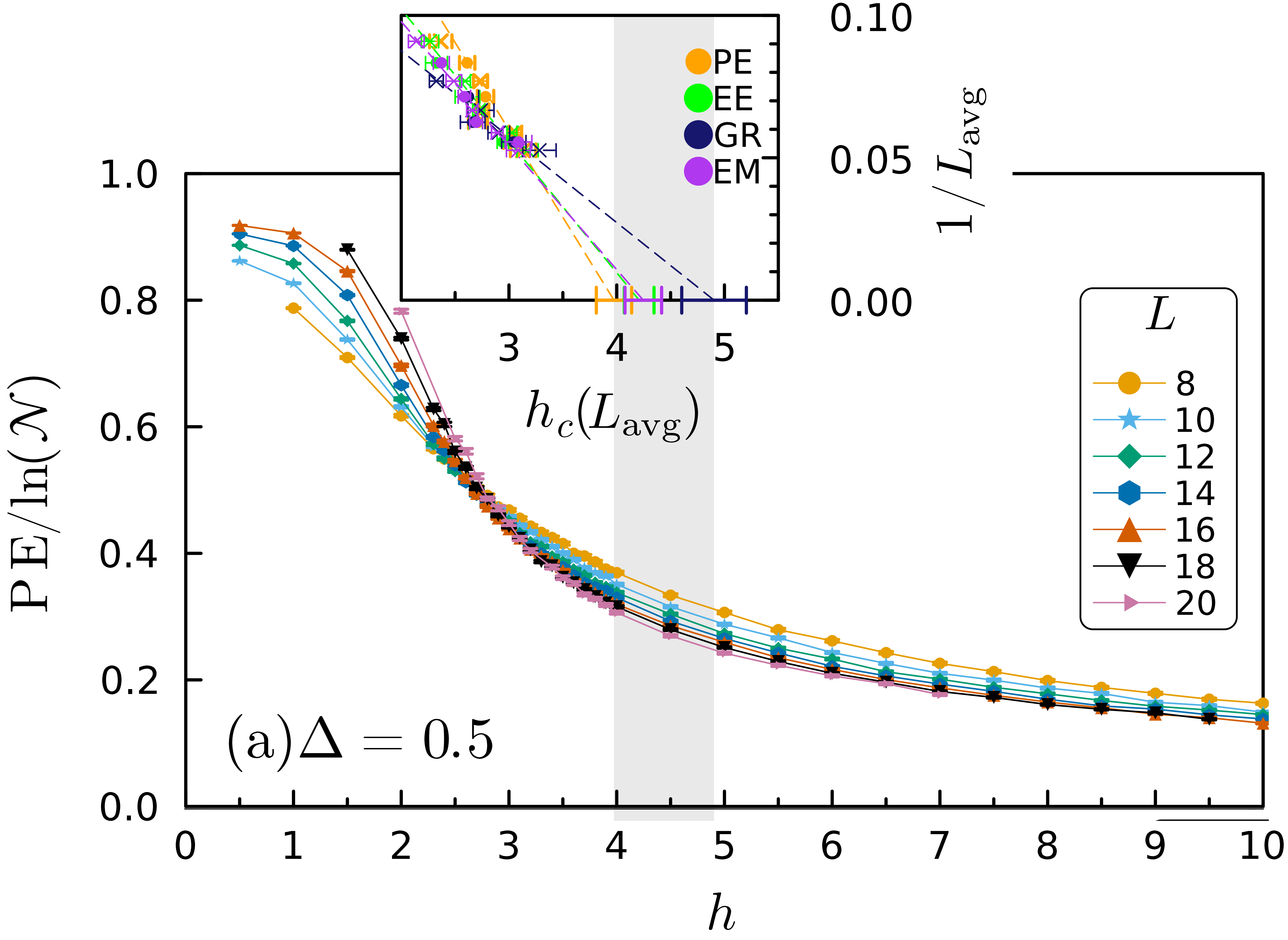
Working at fixed interaction Δ

Participation entropy (PE)

$$S_1^p = -\sum_i p_i \ln(p_i)$$

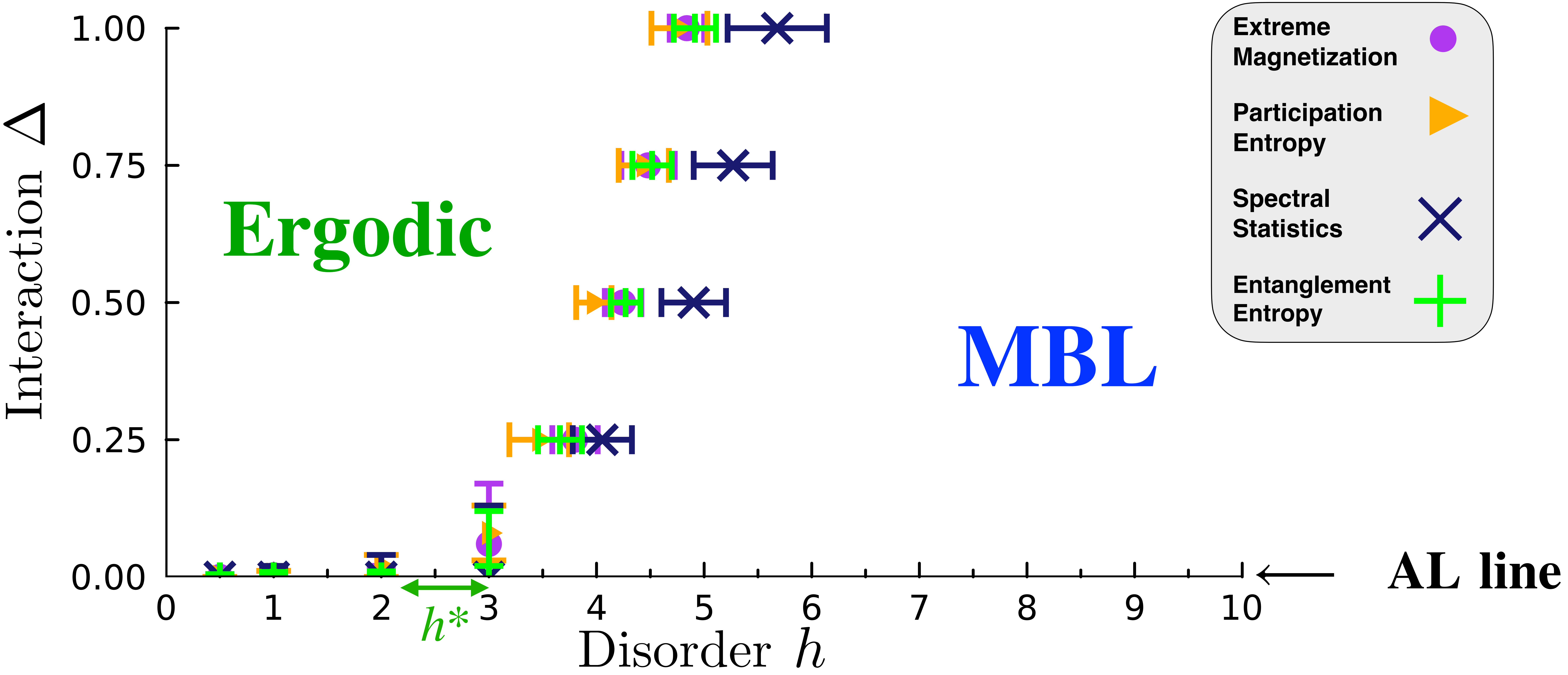
$$p_i = |\langle n|i\rangle|^2$$

Characterizes localization of eigenstates in the computational basis $|n\rangle = \sum_i n_i |i\rangle$



Phase diagram

Phys. Rev. Lett. **133**, 116502 (2024)



Conclusions : Q&A's

Phys. Rev. Lett. **133**, 116502 (2024)

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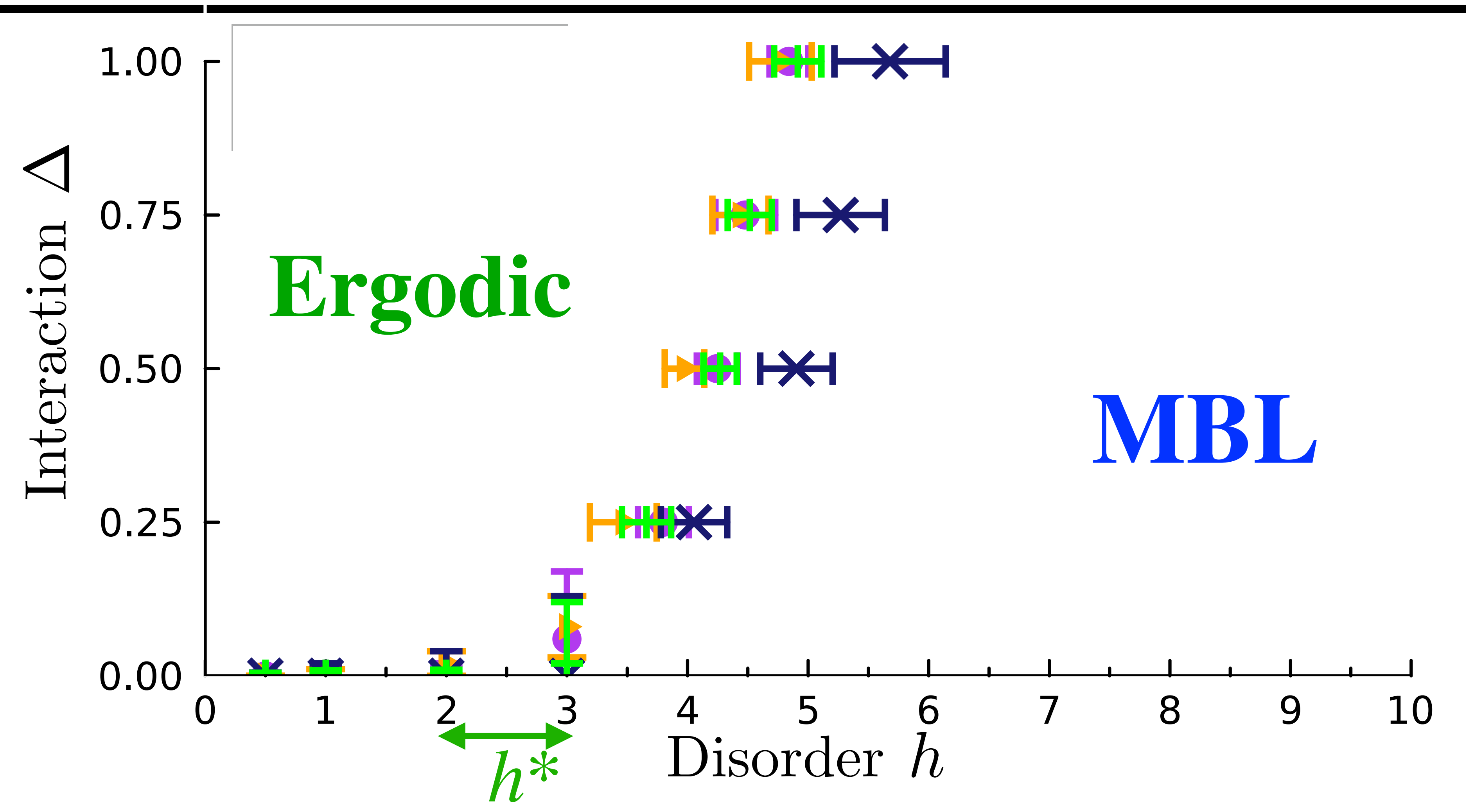

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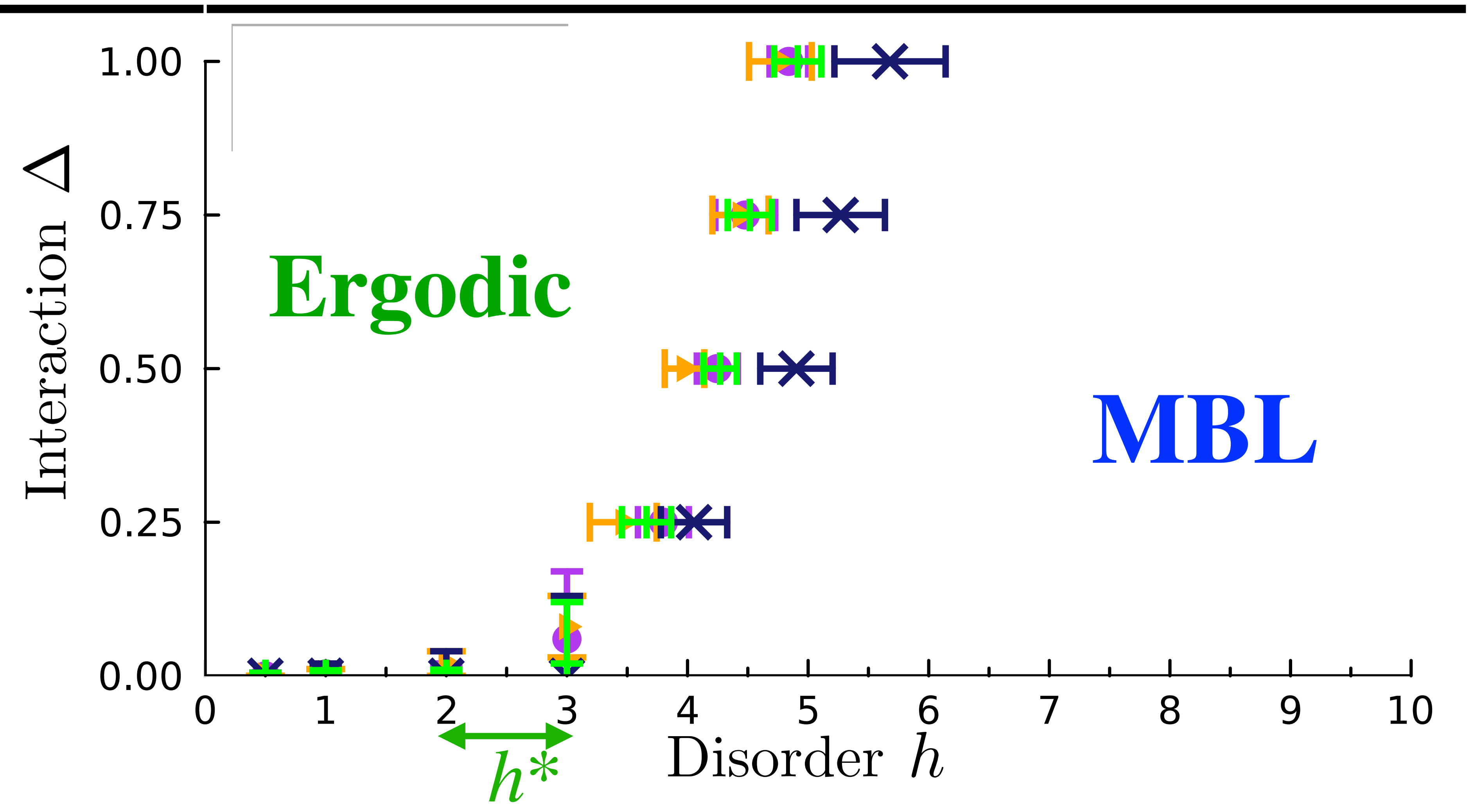

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Imbalance after a quench

A. Haldar *et al.*, Work in progress

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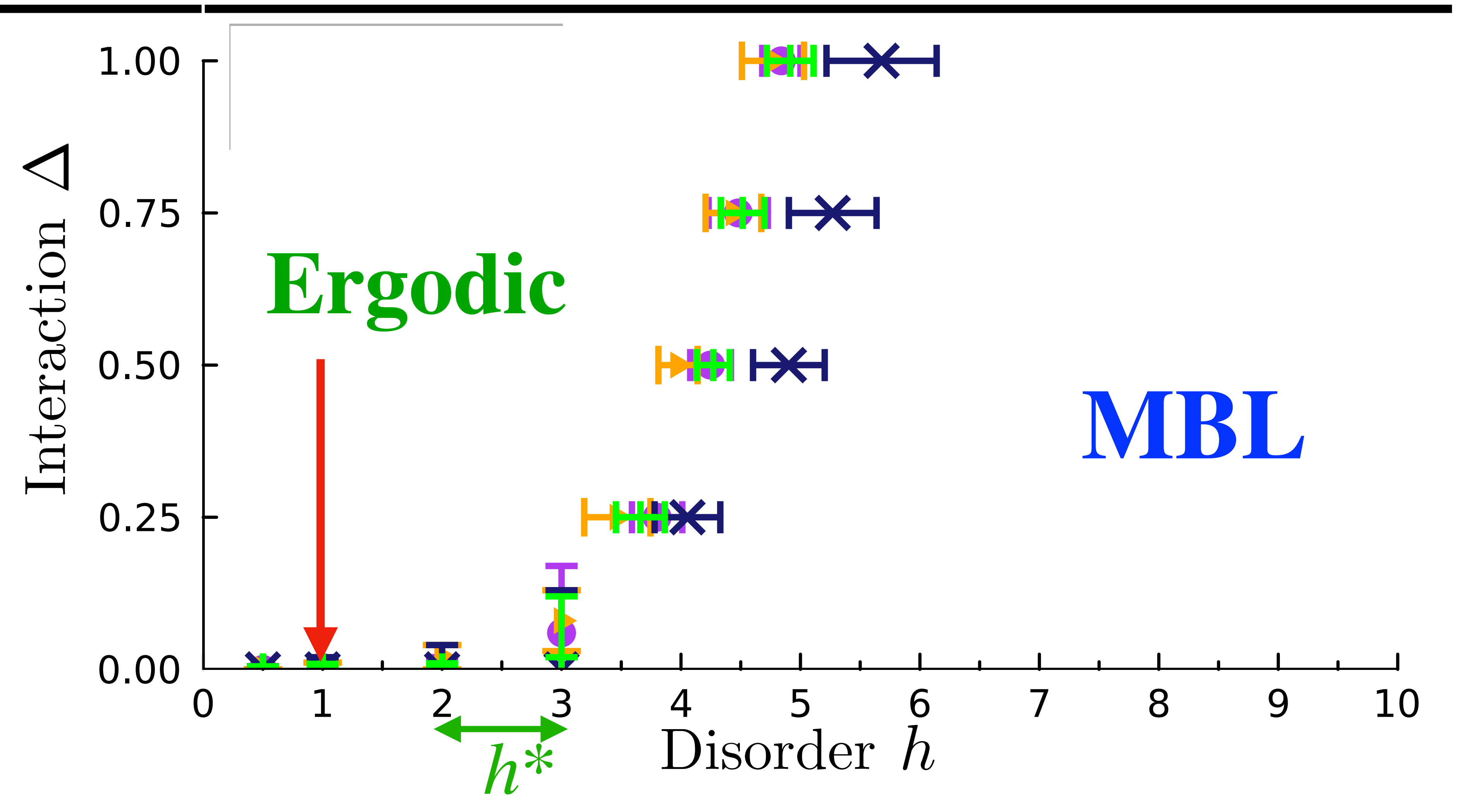

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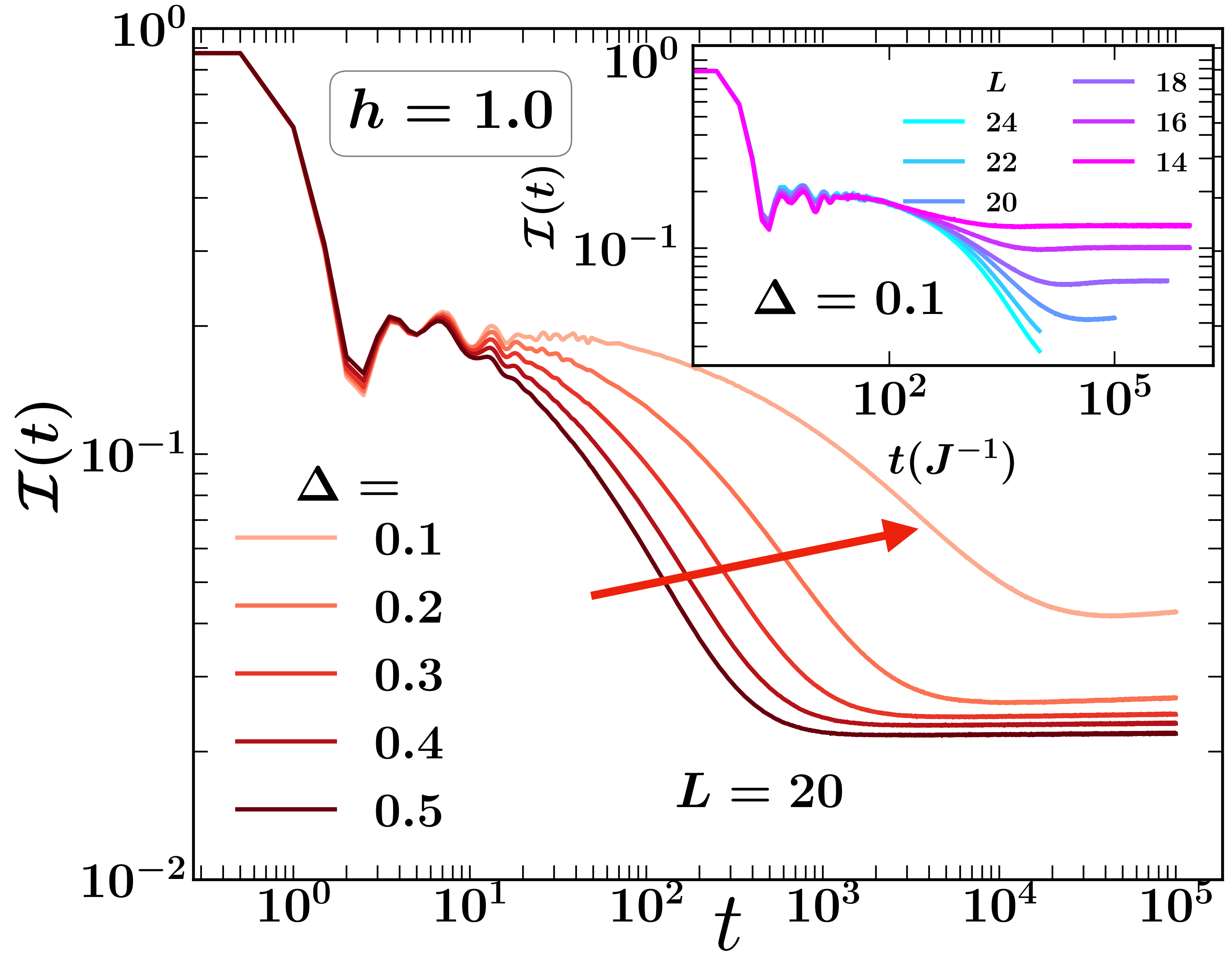

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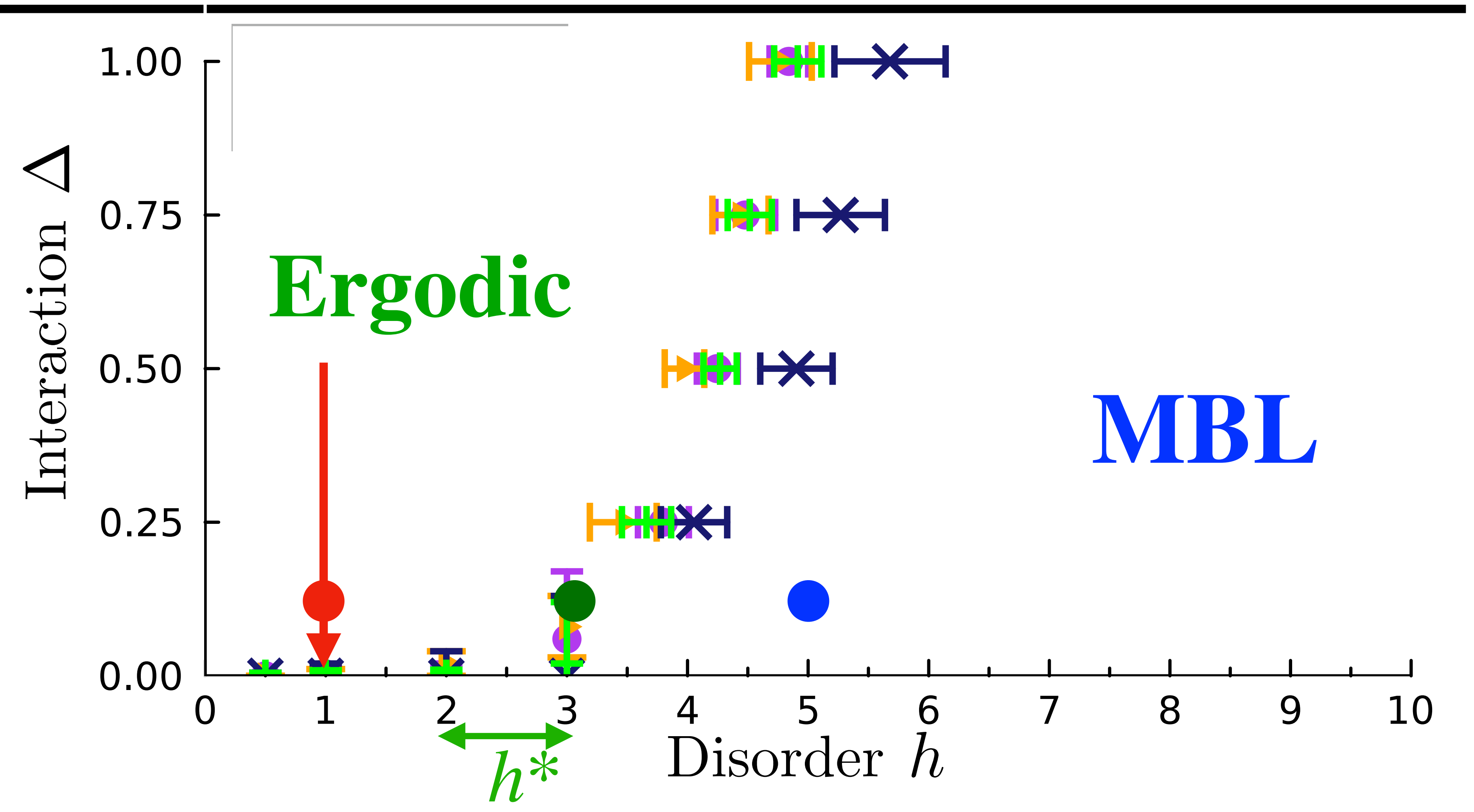

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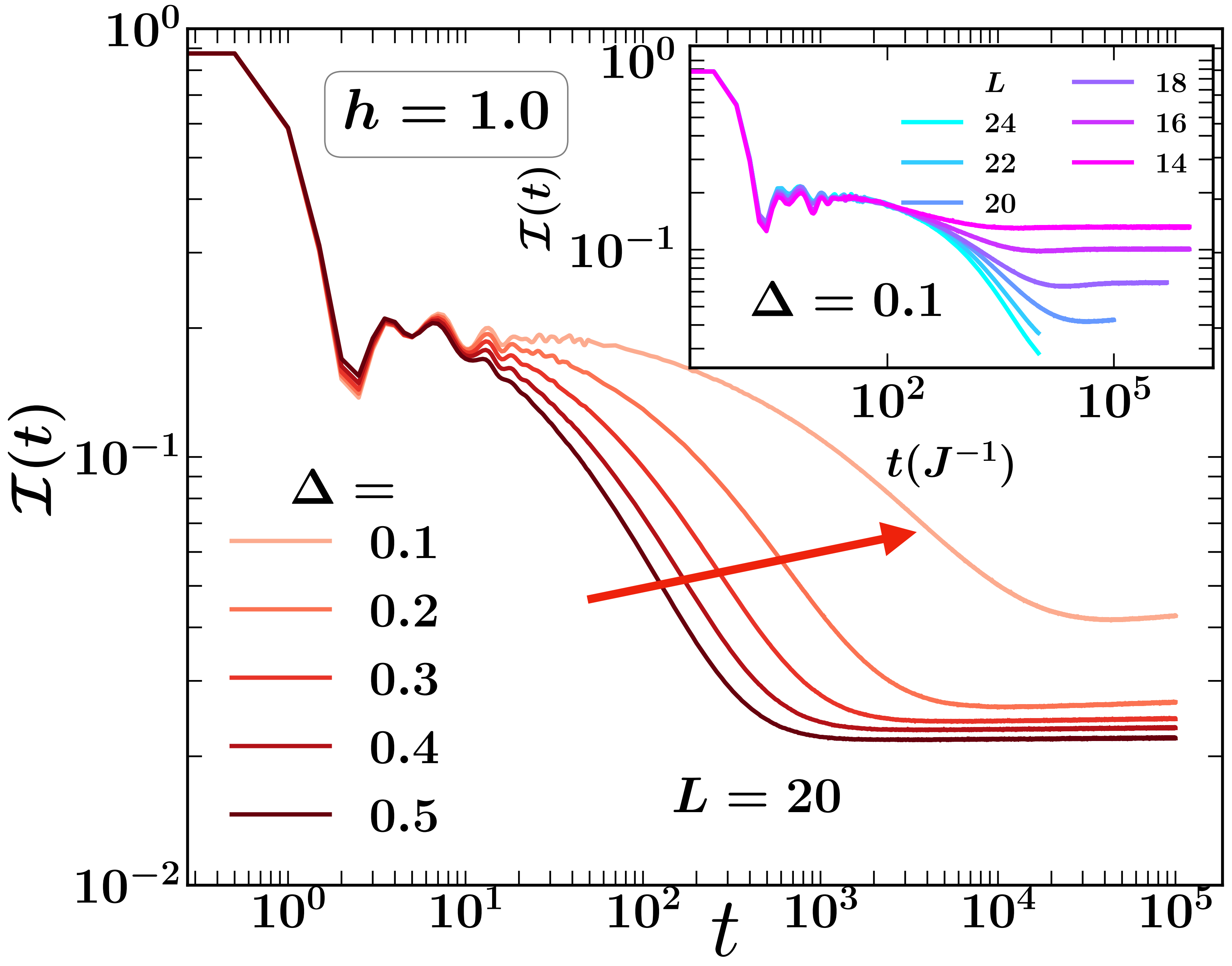

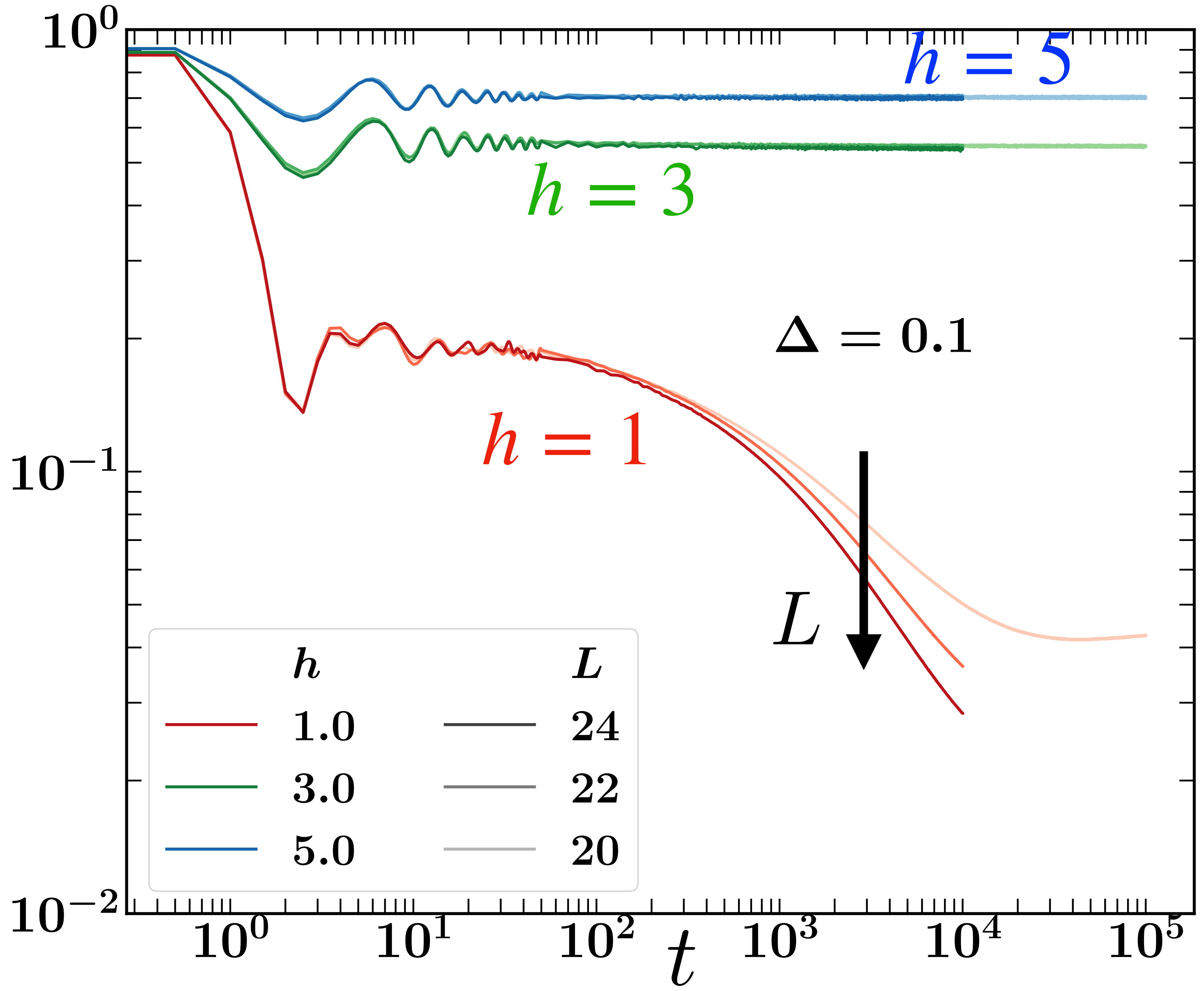

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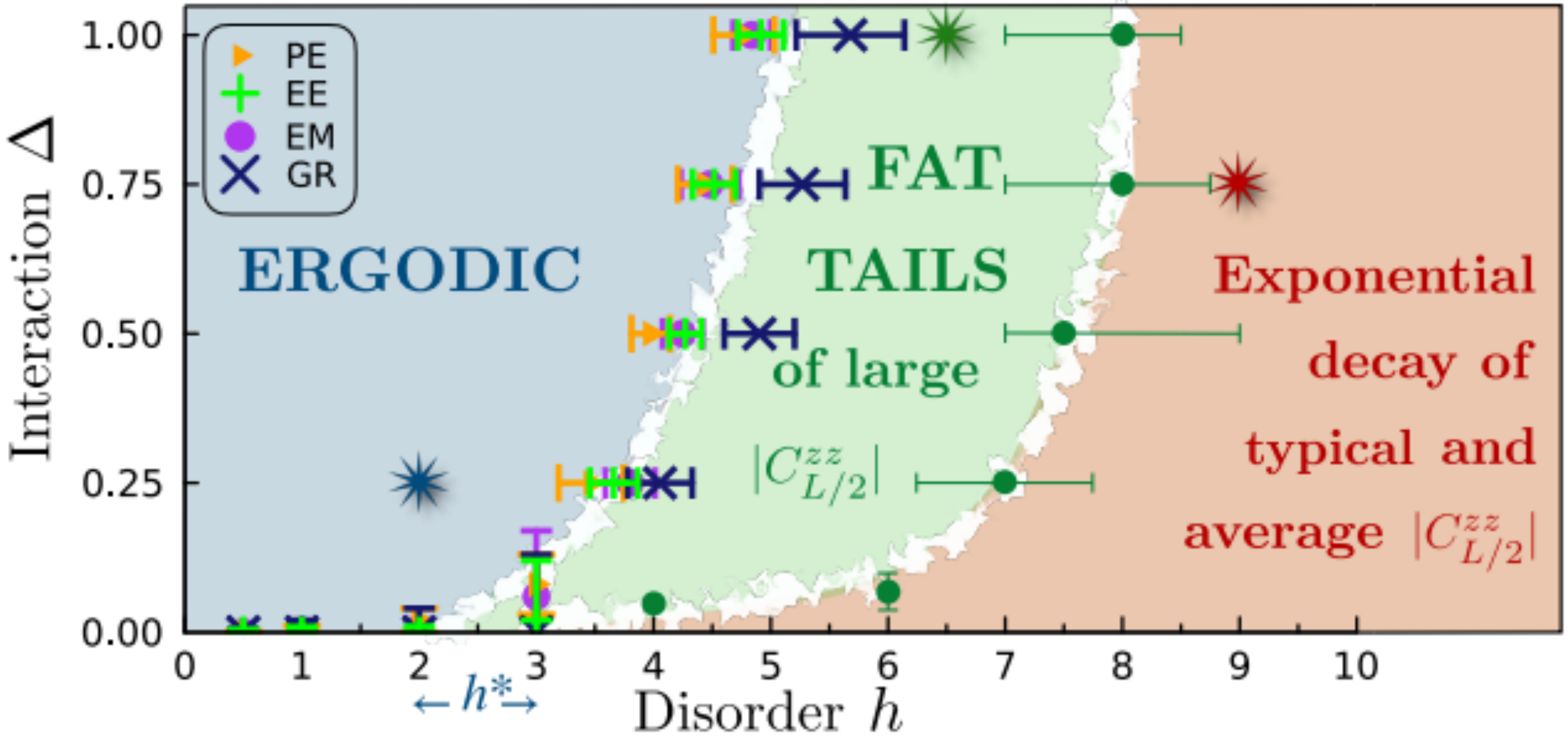
For more colors … see Nicolas' talk on Friday

arXiv:2410.10325, (PRB in press)



Extremal Magnetization

Extremal Magnetization (EM) = which spin in the chain is most polarised? $\delta_{\rm min} = \min_i(1/2 - |\langle S_i^z \rangle|)$

Laflorencie, Lemarié, Macé (2020)

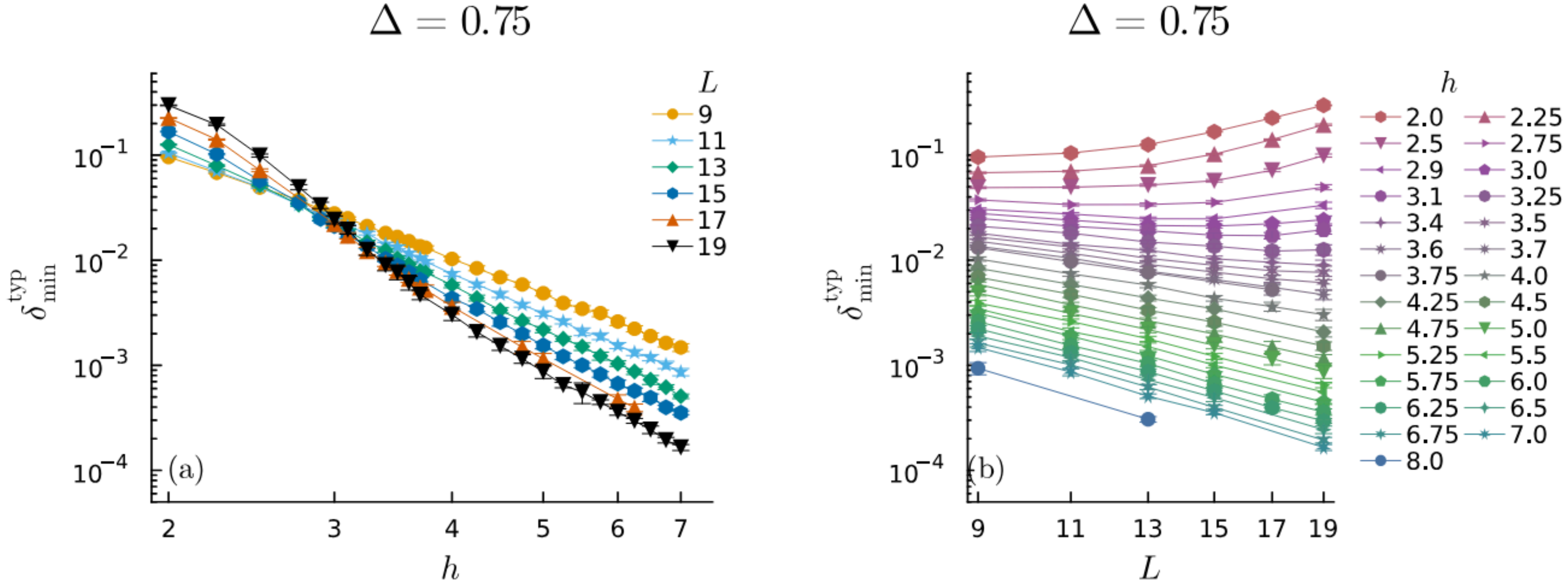
Ergodic

$\delta_{\rm min}^{\rm typ} \to 1/2$

Localized regimes (AL, MBL)

$\delta_{\rm min}^{\rm typ} = L^{-\gamma(h)}$

$$\gamma_{\rm AL} = \frac{1}{2\xi_{\rm AL}\ln(2)}$$



System-wide resonances (?)

$$|E', \pm\rangle =$$