USING MPO FOR OUT-OF-EQUILIBRIUM DYNAMICS

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collaborators J. I. Cirac, N. Pancotti (MPQ),

M. Knap (TUM), D. Huse (Princeton)

MPQ

Max Planck Institut
of Quantum Optics
(Garching)

Quantum Thermodynamics
KITP 25-29 June 2018

Can TNS help us understand the long time of quantum many-body systems?

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thermalization

THERMALIZATION

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Closed quantum system initialized out of equilibrium

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GGE

Rigol et al. PRL 2007
Cramer et al. PRL 2008
Calabrese et al. PRL 2011
Ilievski et al. PRL 2015

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non-integrable systems

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ETH mechanism

Deutsch PRA91
Srednicki PRE94
Rigol et al. Nature 2008

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numerical simulations of real time evolution

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Tensor Network States are efficient Ansätze for quantum many-body states

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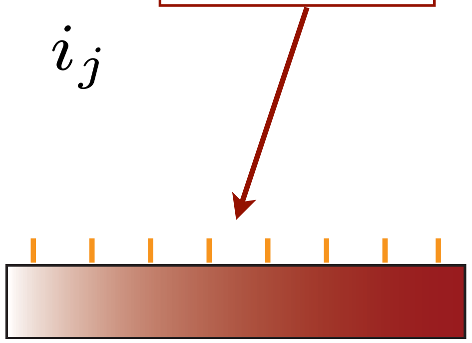
$$|\Psi\rangle = \sum_{i_j} c_{i_1 \dots i_N} |i_1 \dots i_N\rangle$$



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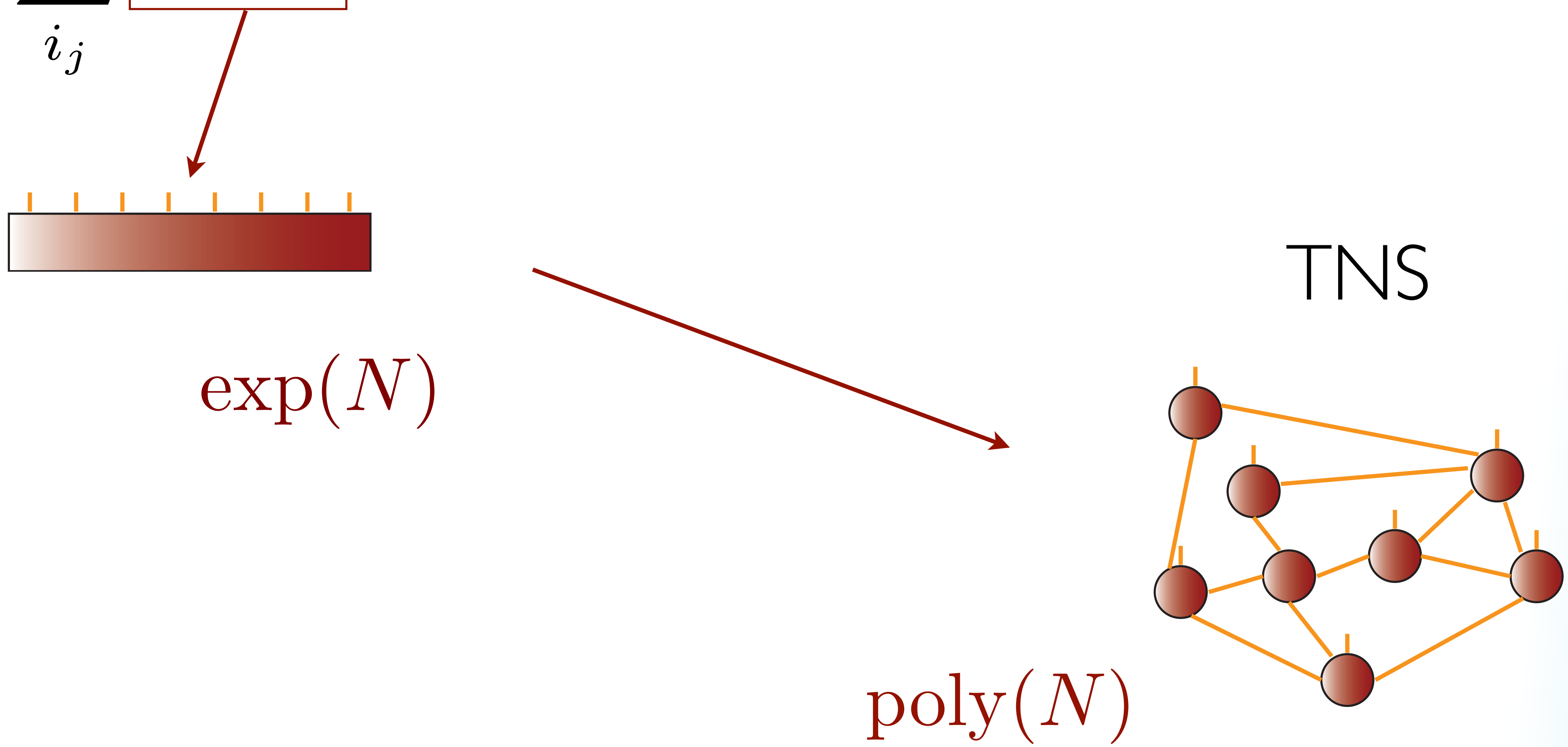

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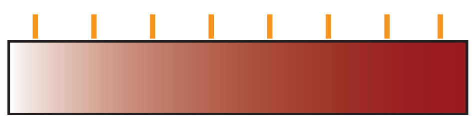
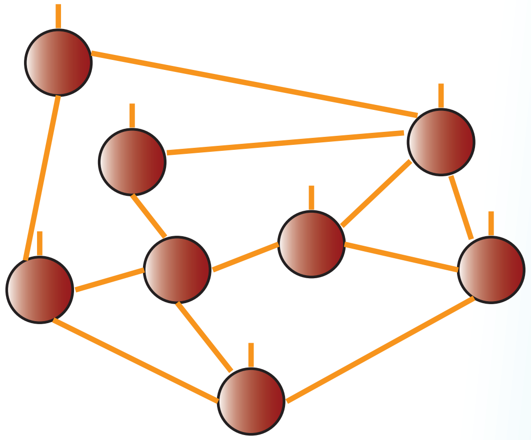


$\exp(N)$

entanglement based ansatz

TNS



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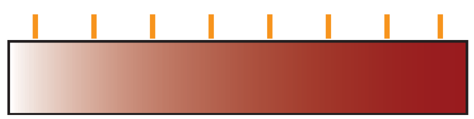

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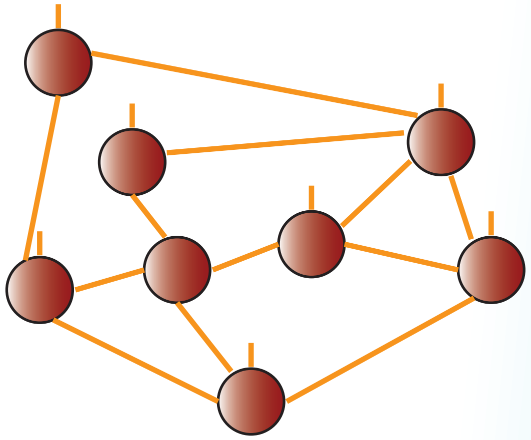


$\mathrm{poly}(N)$

algorithms exist to simulate time evolution

Entanglement growth in non-equilibrium scenarios limits the applicability of MPS

global quench
in 1D

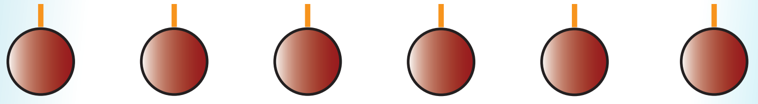
$t = 0$ $t = \infty$

global quench in 1D

$t = 0$

$t = \infty$

product state



easy to write as MPS

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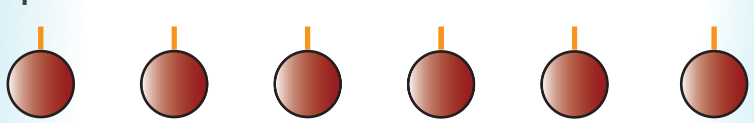

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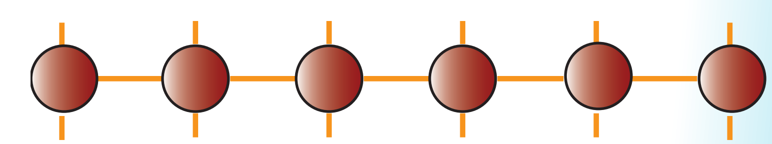
local observables

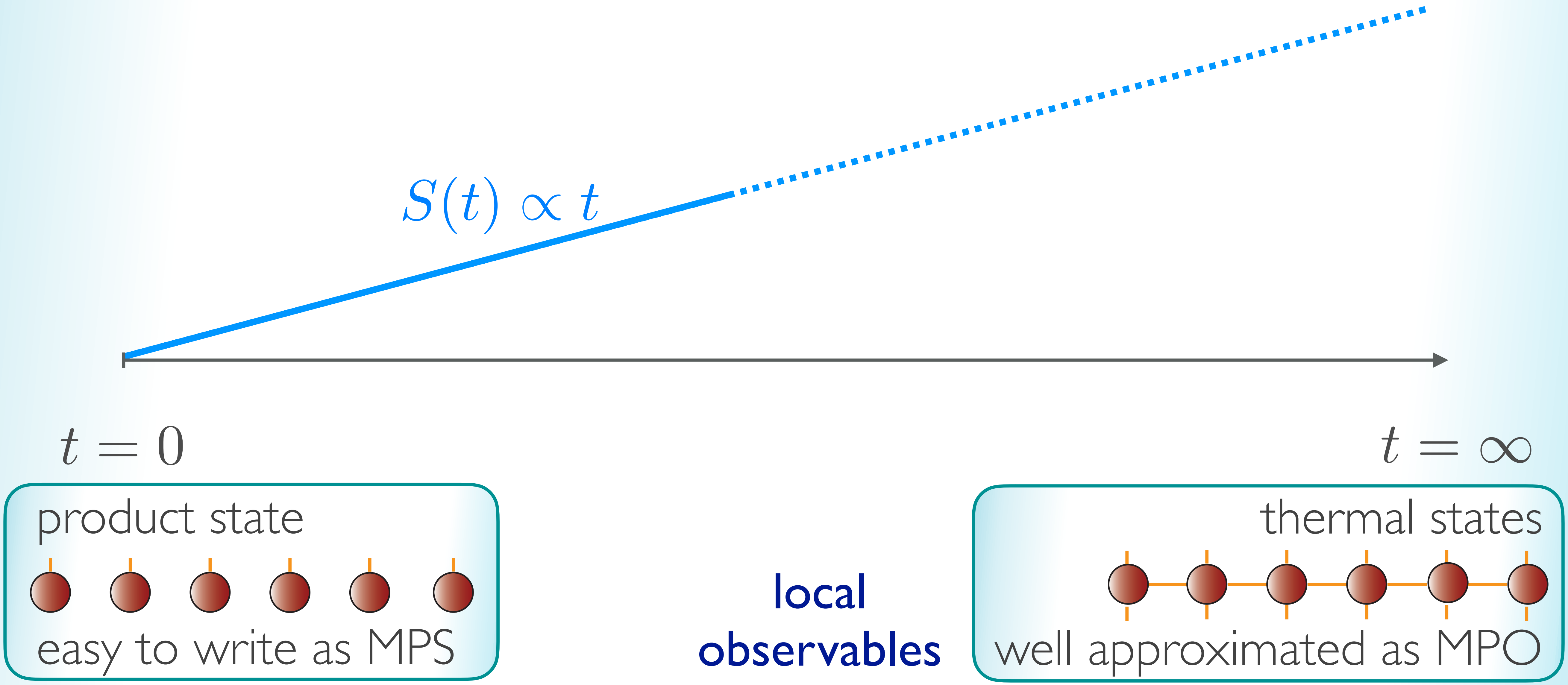
$t = \infty$

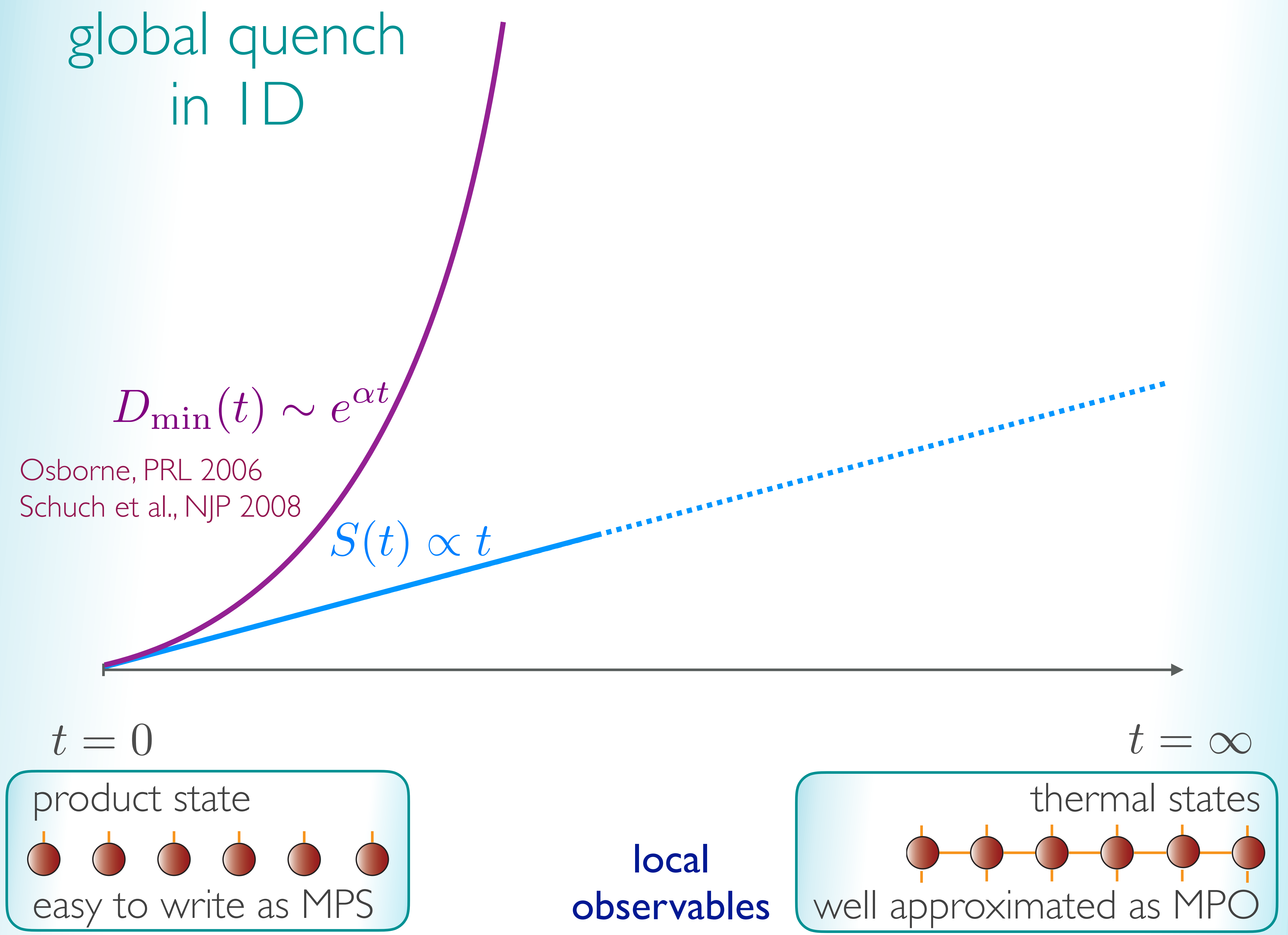
thermal states



well approximated as MPO

global quench in 1D




global quench
in 1D
$D_{\text{min}}(t) \sim e^{\alpha t}$
Osborne, PRL 2006
Schuch et al., NJP 2008
$S(t) \propto t$
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product state
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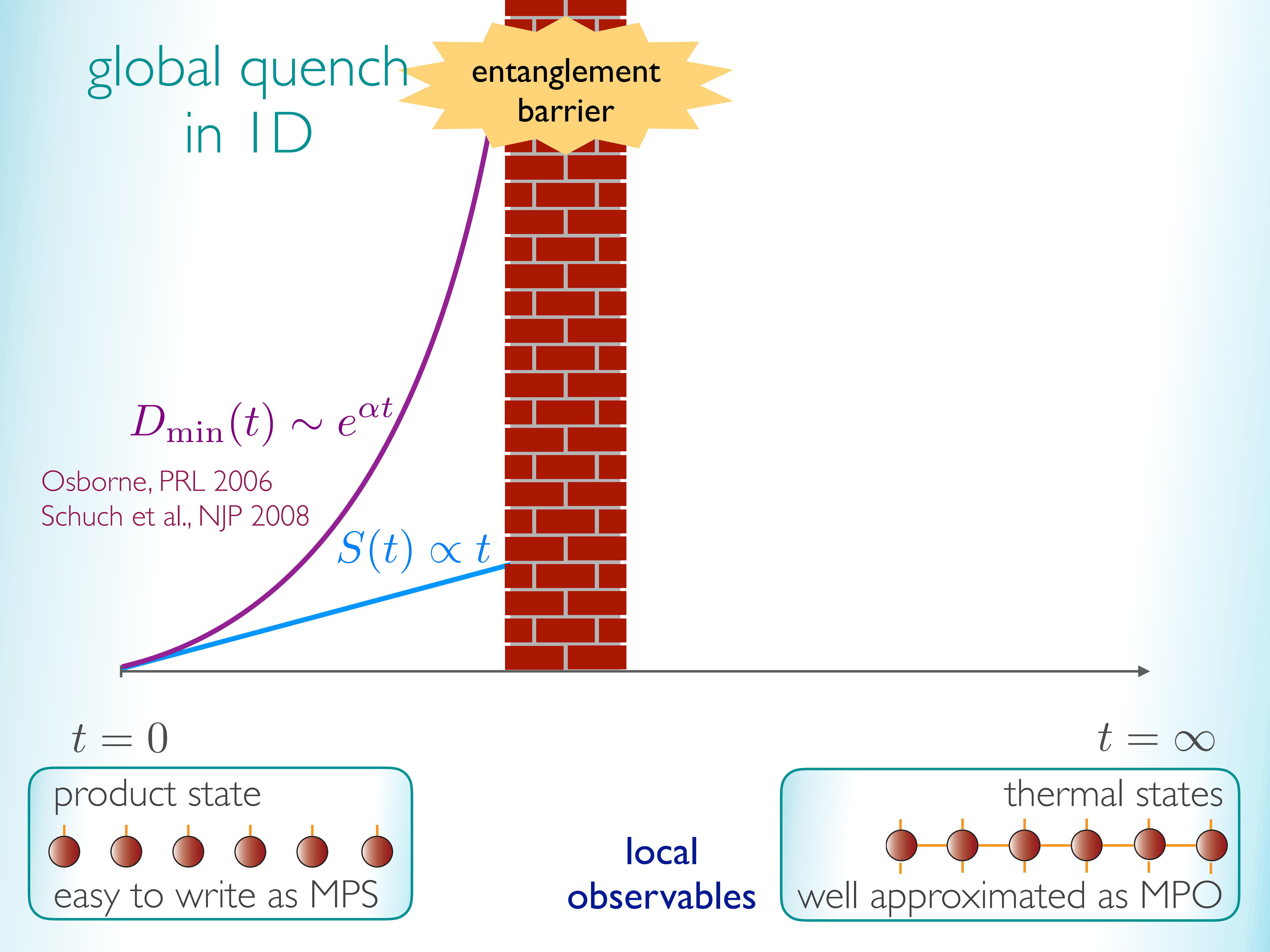
global quench
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entanglement
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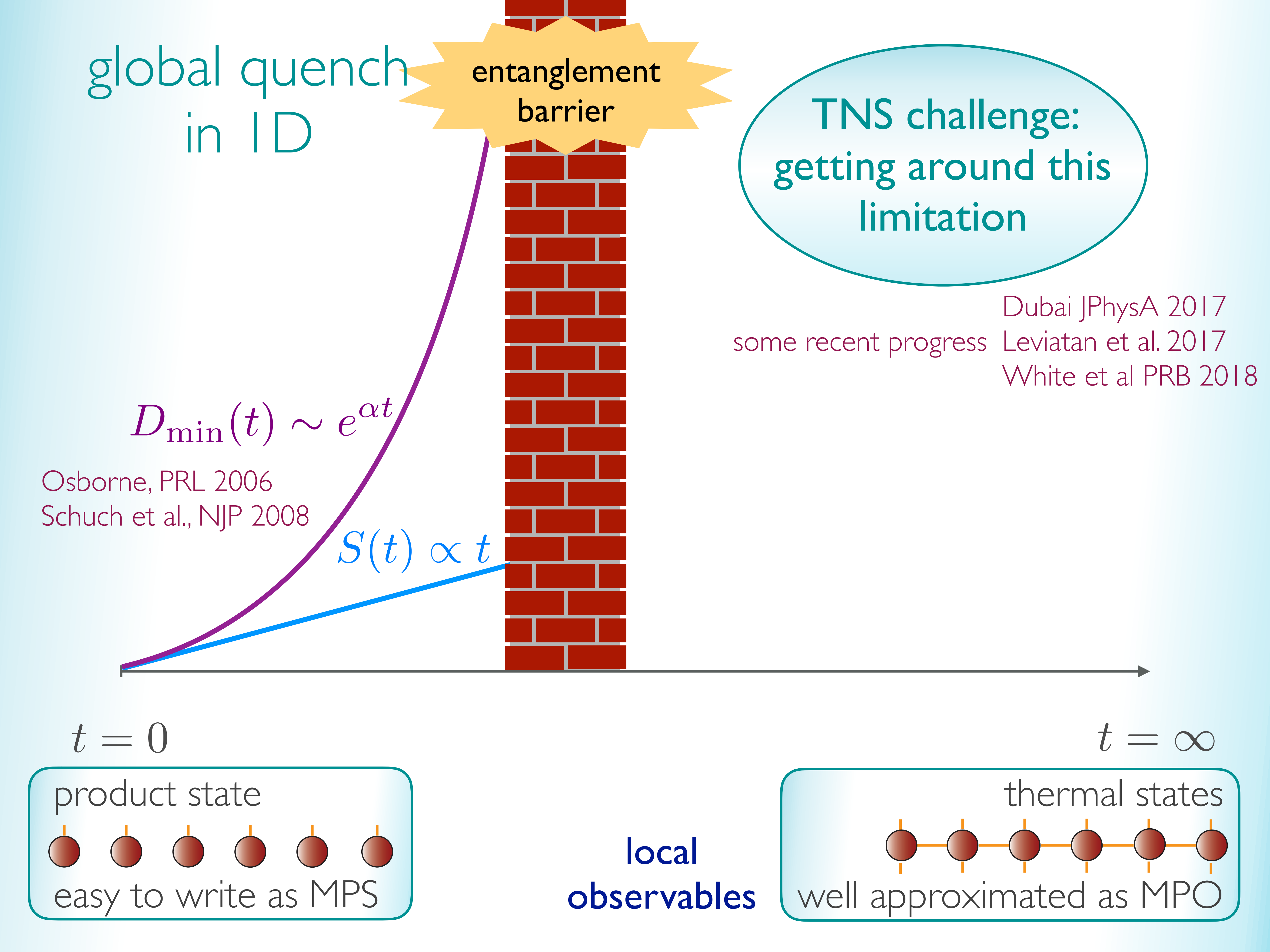

global quench in 1D
entanglement barrier
TNS challenge: getting around this limitation
some recent progress
Dubai JPhysA 2017
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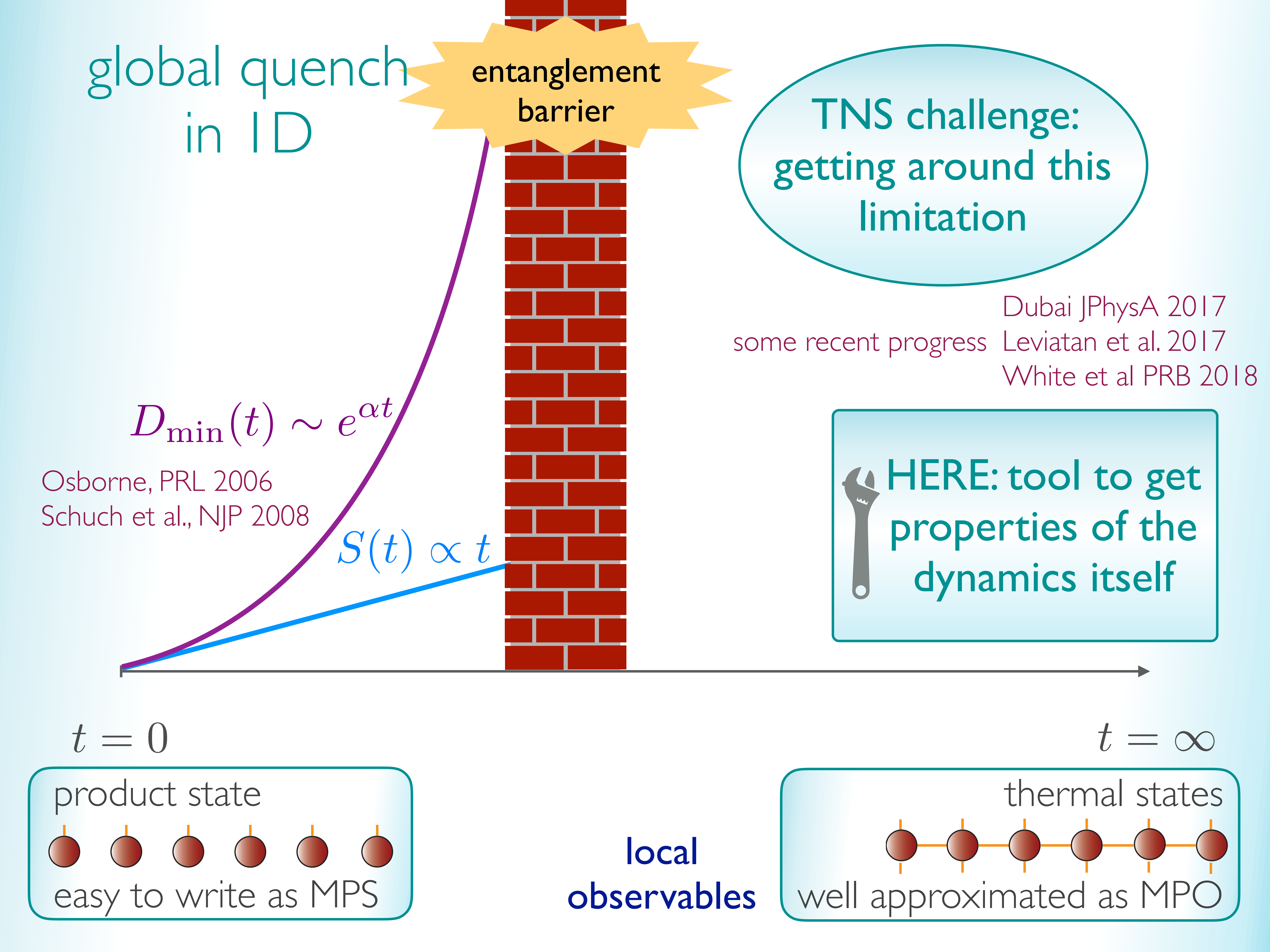
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HERE: tool to get properties of the dynamics itself
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finding operators that evolve slowly

finding operators that evolve slowly

can set a long timescale

A DIFFERENT PERSPECTIVE

What are the slowest evolving (local) operators?

Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

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$$\frac{dA(t)}{dt} = i[H, A(t)]$$

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numerical study using ED/TNS

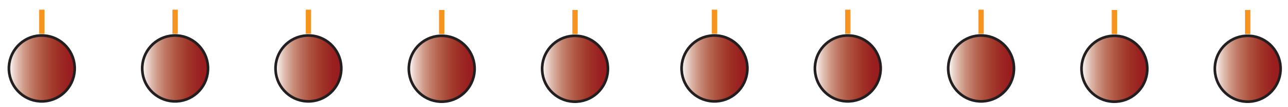
Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

Scenario

1D non-integrable spin chain

$$H = \sum_i \left(\sigma_z^i \sigma_z^{i+1} + g\sigma_x^i + h\sigma_z^i\right)$$

only local
conserved quantity
is energy density



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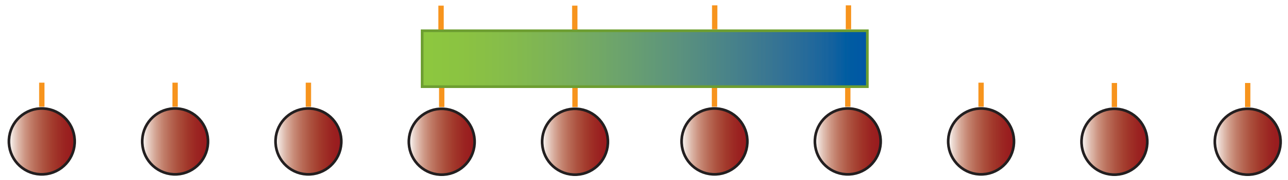
operator acting on M central sites



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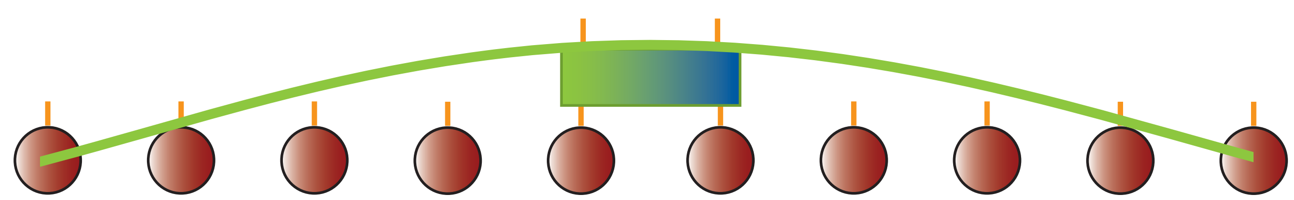

natural one if local conserved quantity:
inhomogeneity of energy density

but not minimum

Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

(ALMOST) LOCAL CONSERVED OPERATORS

Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

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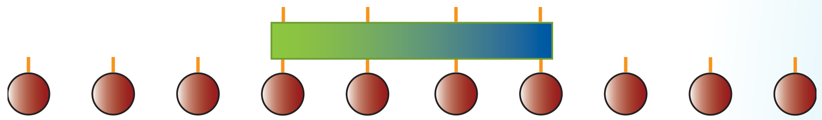

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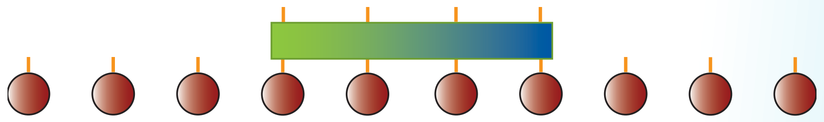
(ALMOST) LOCAL CONSERVED OPERATORS

Goal: minimizing $\|[H, A_M]\|$



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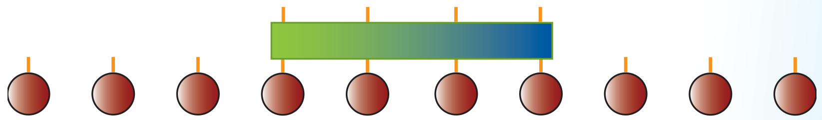

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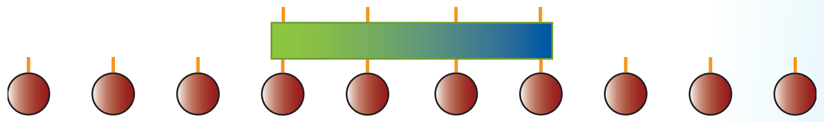

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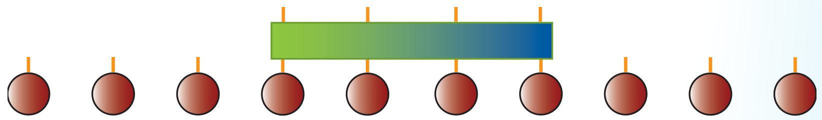

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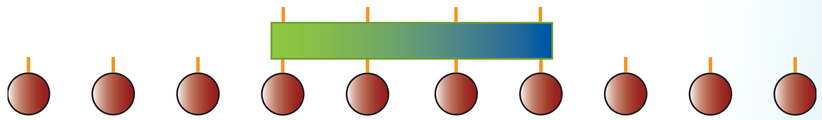

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$$\rho \sim I + \epsilon A_M$$

high T state

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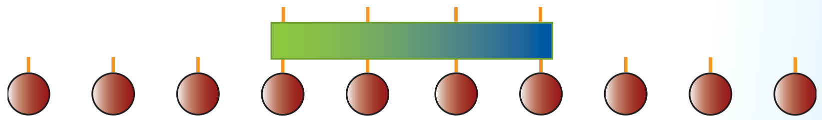

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$$|\langle A_M(t)\rangle - \langle A_M\rangle_\beta| \geq 1 - \frac{1}{2}\lambda_M t^2$$

lower bound thermalization time $\tau \geq \frac{1}{\sqrt{\lambda_M}}$

Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

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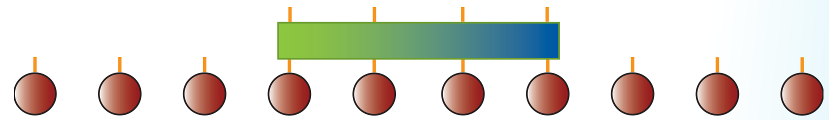

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also slowest evolving at short times

Kim, MCB, Cirac, Hastings, Huse, PRE92, 012128 (2015)

can be applied to systematically study different systems can be applied to systematically study different systems

MBL

MANY BODY LOCALIZATION

Anderson localization: single particle states localized due to disorder

- environment destroys localization

MANY BODY LOCALIZATION

Anderson localization: single particle states localized due to disorder

environment destroys localization

interactions + disorder = interesting scenario

weak interactions ⇒ MBL phase

Basko, Aleiner, Altshuler, Ann. Phys. 2006
Gornyi, Mirlin, Polyakov, PRL 2005

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Gornyi, Mirlin, Polyakov, PRL 2005

many-body localization

Altman, Vosk, Ann.Rev.CM 2015
Nandkishore, Huse, Ann.Rev.CM 2015

highly excited states localized

system will not thermalize

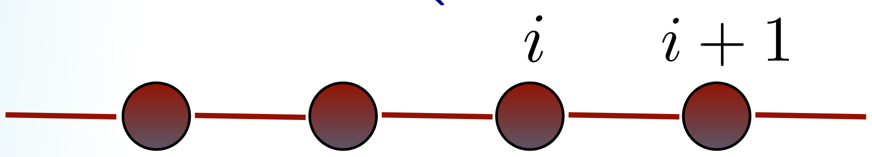
TNS *success stories*

Znidaric, Prosen, Prelovsek, PRB 2008
Gogolin, Müller, Eisert, PRL 2011
Bardarson, Pollmann, Moore, PRL 2012
Bauer, Nayak, JStatMech 2013; Chandran et al PRB 2015; Pollmann et al PRB 2016; Khemani et al PRL 2016; Pekker PRB 2017; Wahl et al 2017…

MANY BODY LOCALIZATION

the model

$$H = \sum \left(S_x^{[i]} S_x^{[i+1]} + S_y^{[i]} S_y^{[i+1]} + J S_z^{[i]} S_z^{[i+1]} + h_i S_i^z \right)$$



Oganesyan, Huse, PRB 2007
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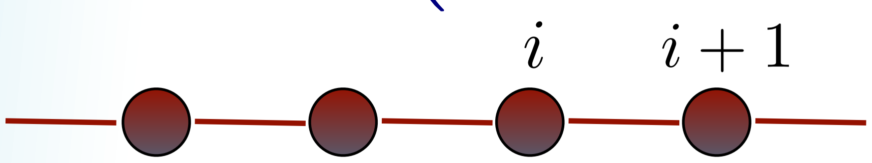

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J=0 ⇒ non-interacting XY

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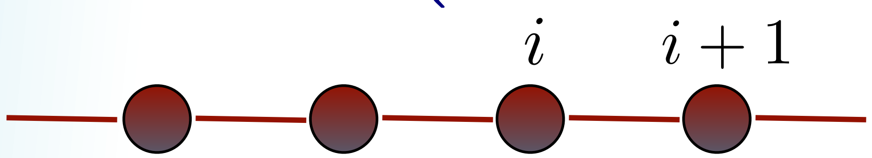

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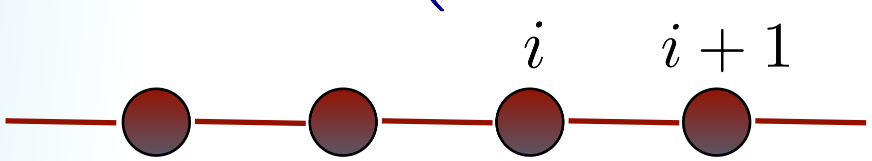


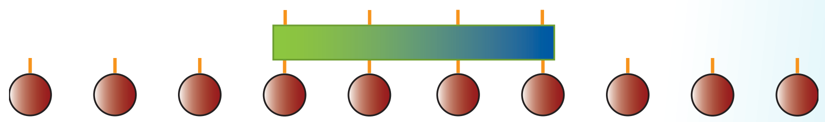
Oganesyan, Huse, PRB 2007
Pal, Huse, PRB 2010
Luitz et al., 2014

J=0 ⇒ non-interacting XY

Anderson localized for h>0

J=1 ⇒ shows MBL for h~3-3.5

operator acting on M sites



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N. Pancotti et al PRB 97, 094206 (2018)

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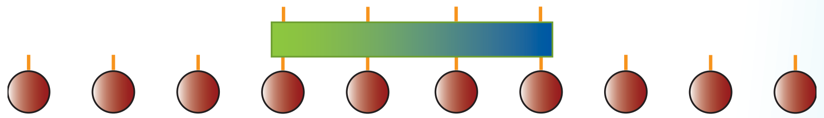

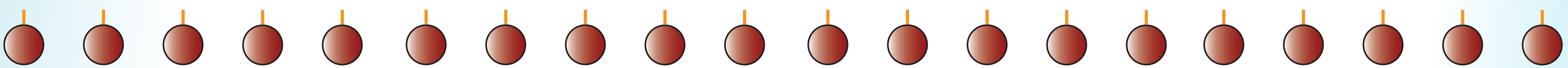

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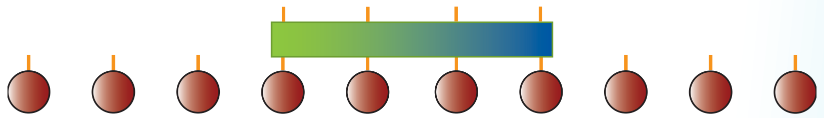

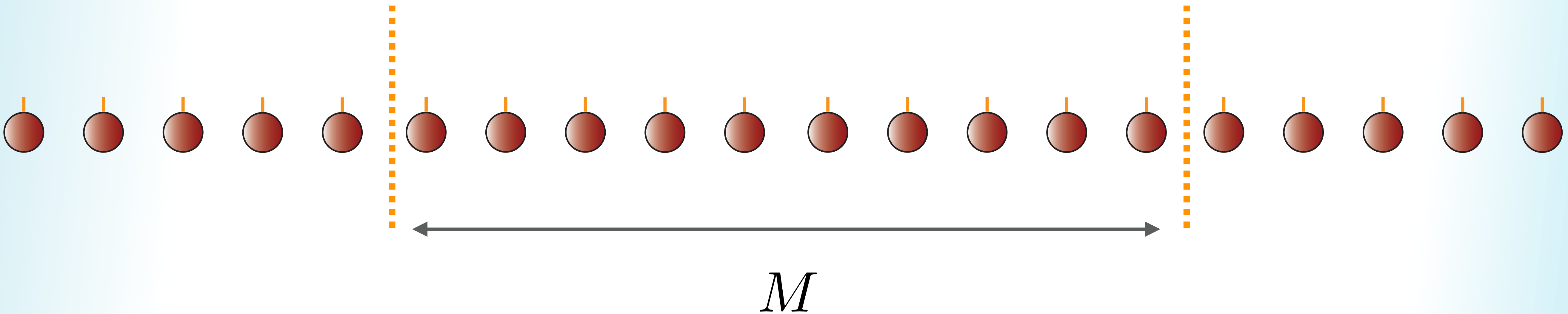

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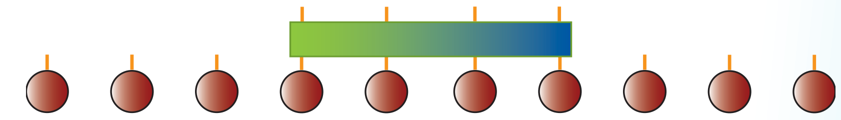

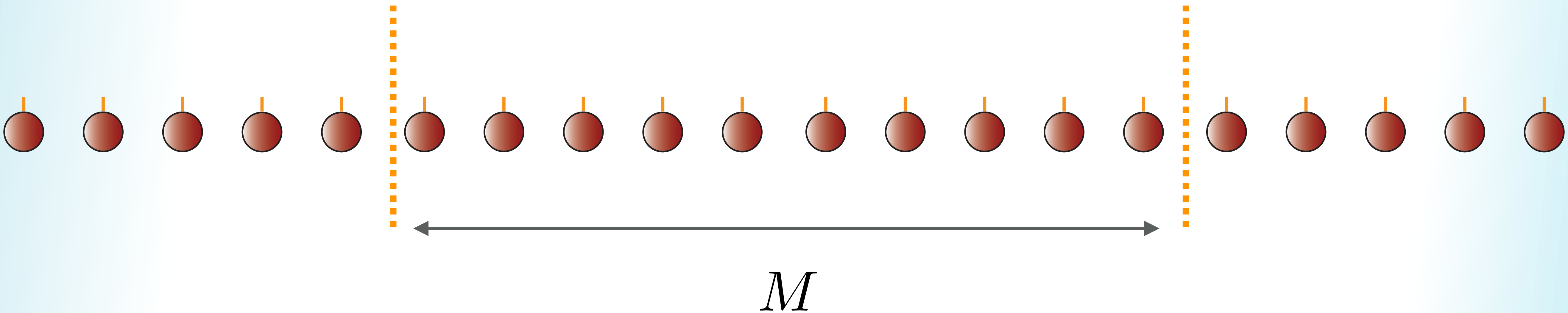

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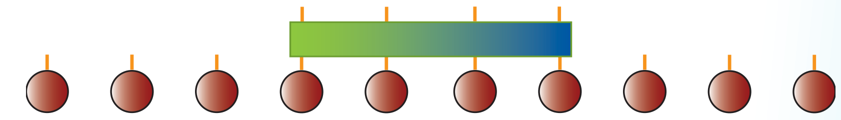
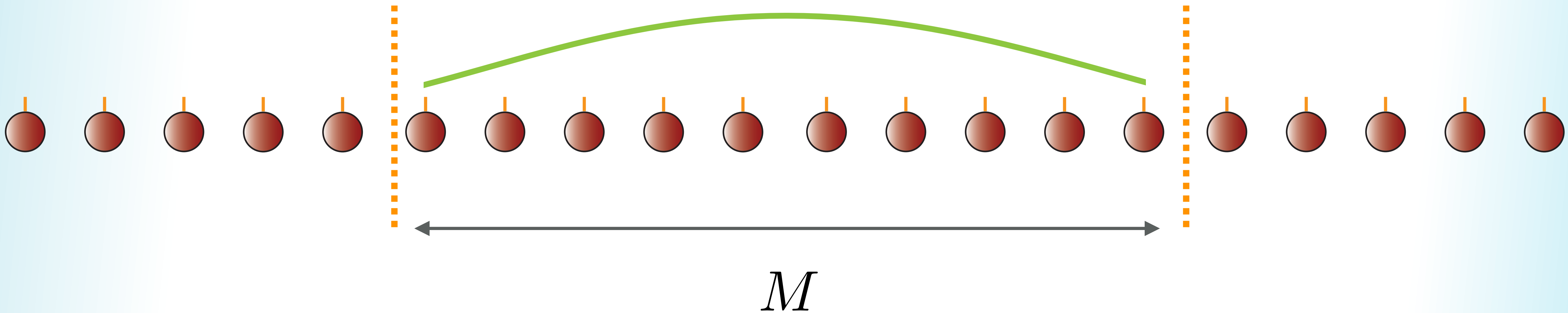
operator acting on M sites





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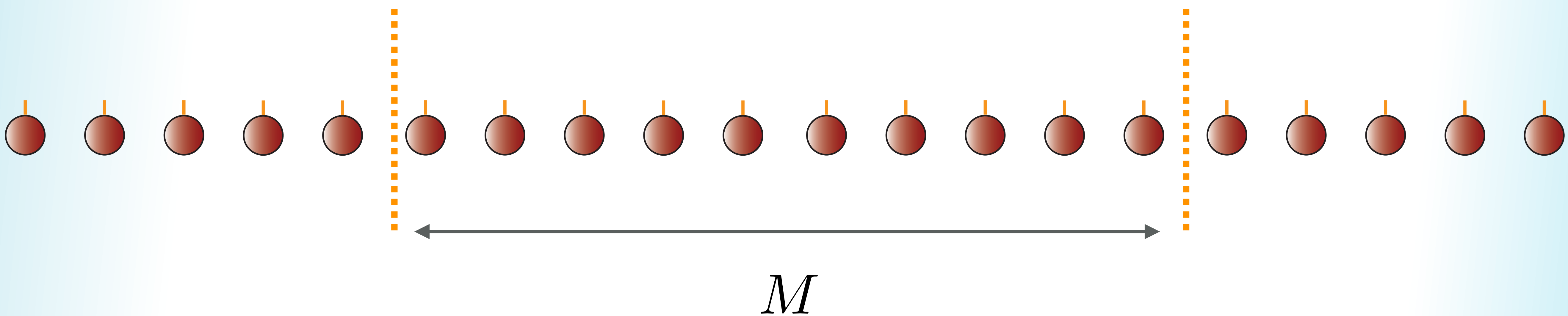
in the localized regime: l-bit model

$$H_{\text{eff}} = \sum_{i=0}^{N-1} \epsilon_i \tau_z^{[i]} + \sum_{i,j=0}^{N-1} K_{ij}^{(2)} \tau_z^{[i]} \tau_z^{[j]} + \sum_{i,j,k=0}^{N-1} K_{ijk}^{(3)} \tau_z^{[i]} \tau_z^{[j]} \tau_z^{[k]} + \ldots,$$



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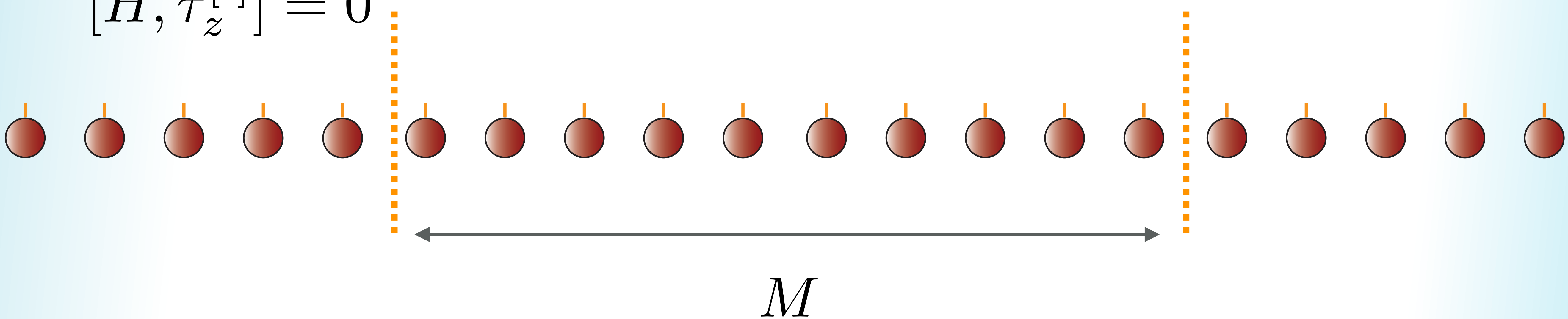
$\tau_z^{[i]}$ exponentially localized

$$[H, \tau_z^{[i]}] = 0$$



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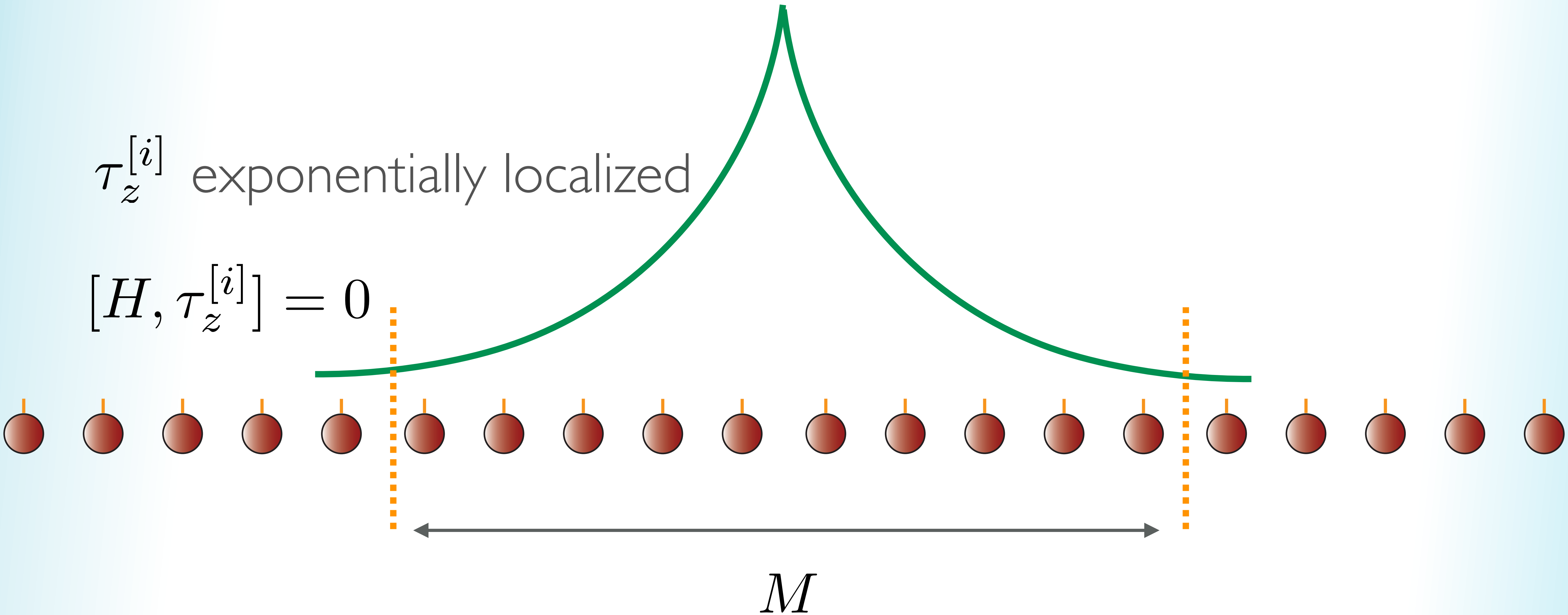

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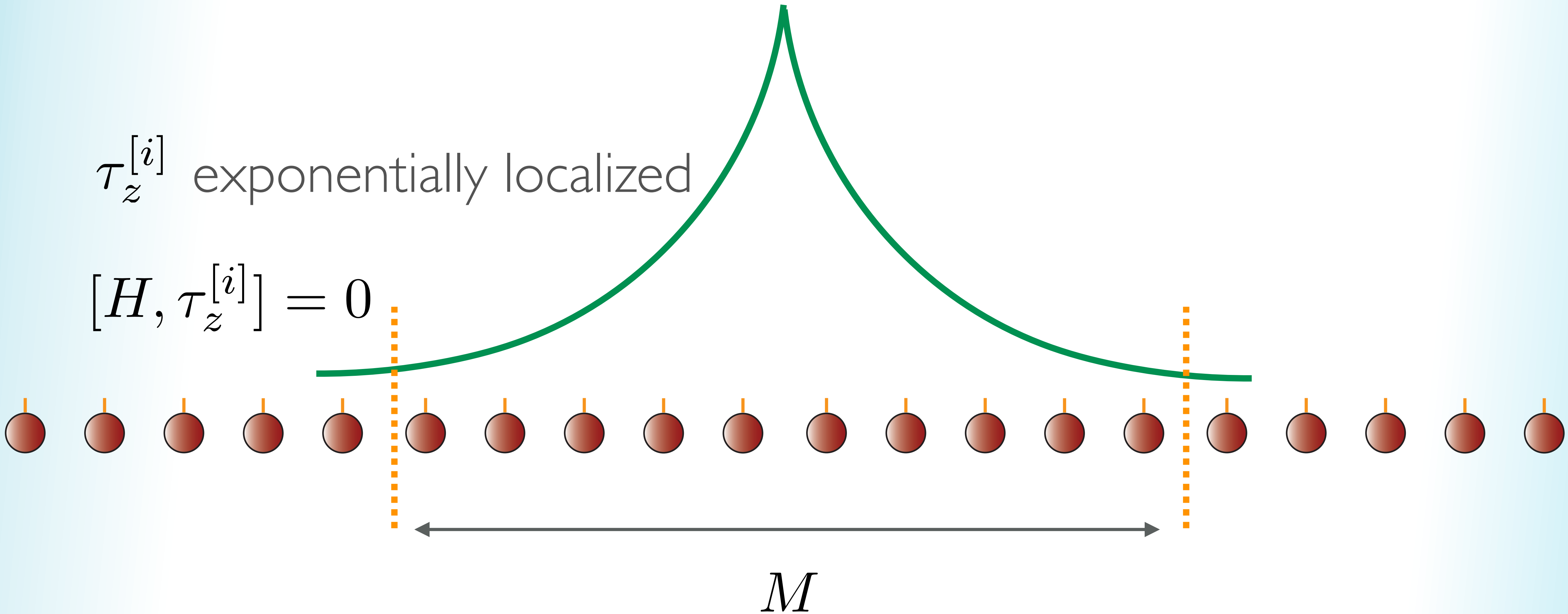

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truncated support → expect exponentially small

see also Chandran et at. PRB 2015

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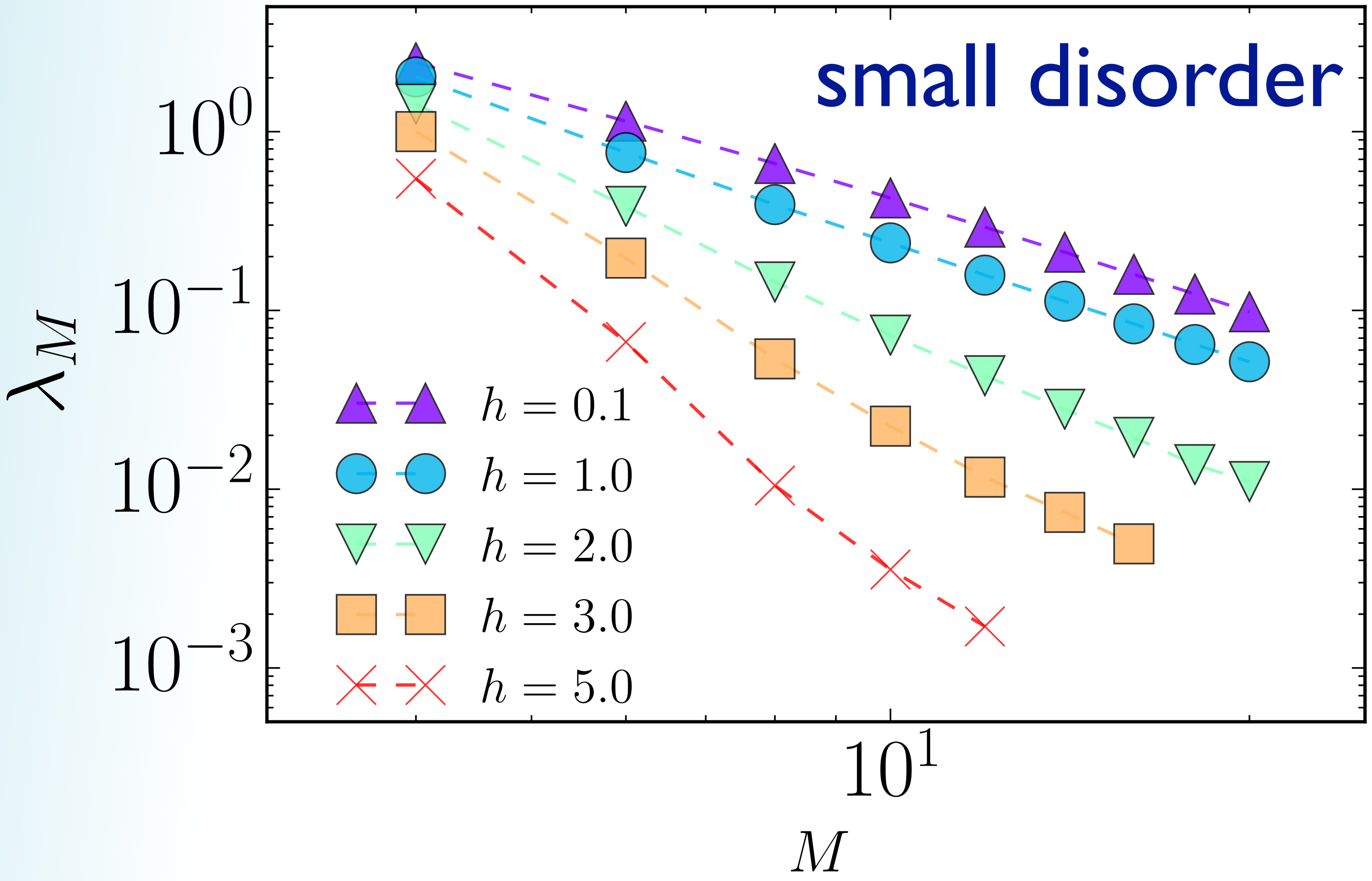
averaging over disorder



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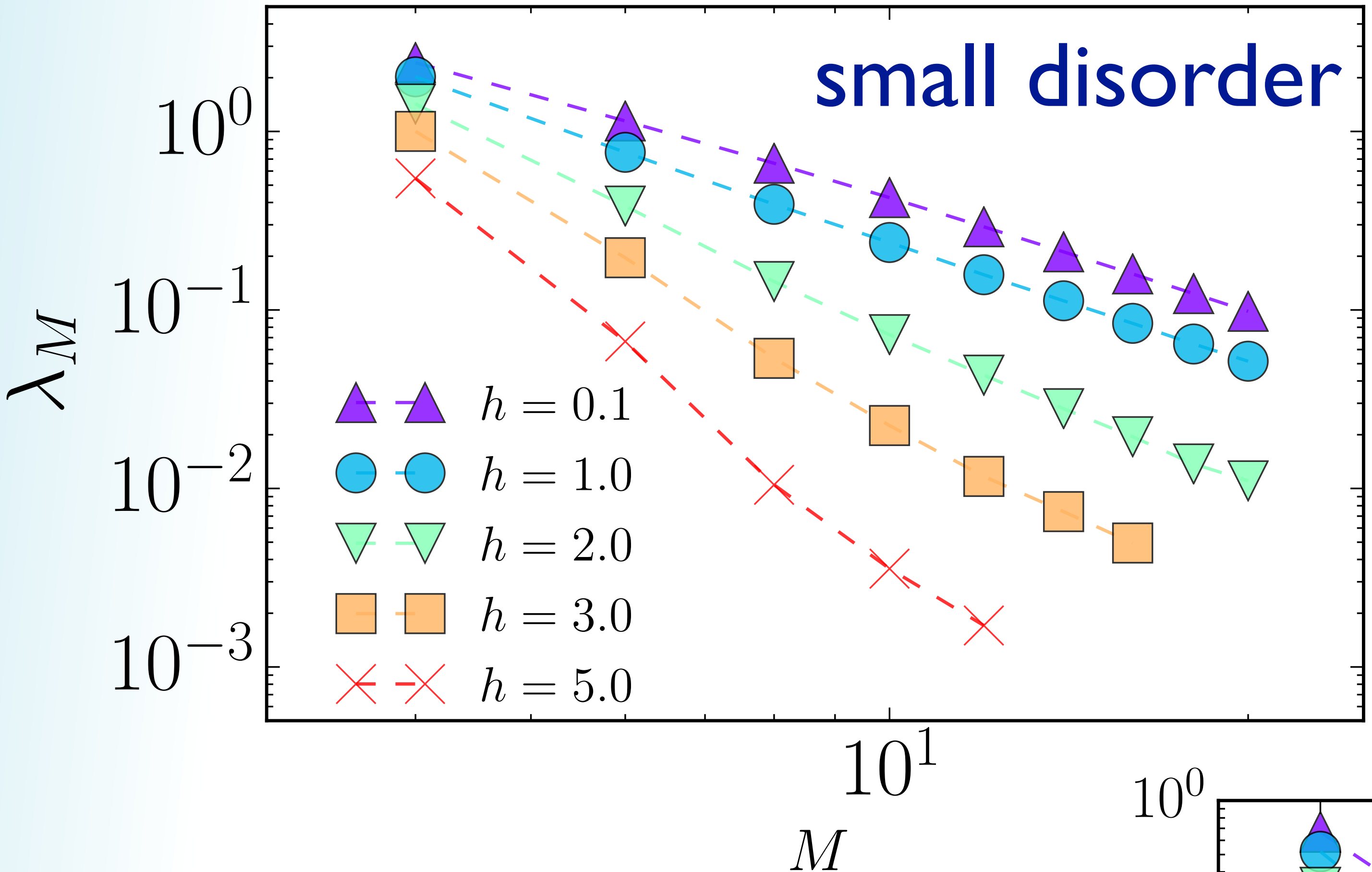

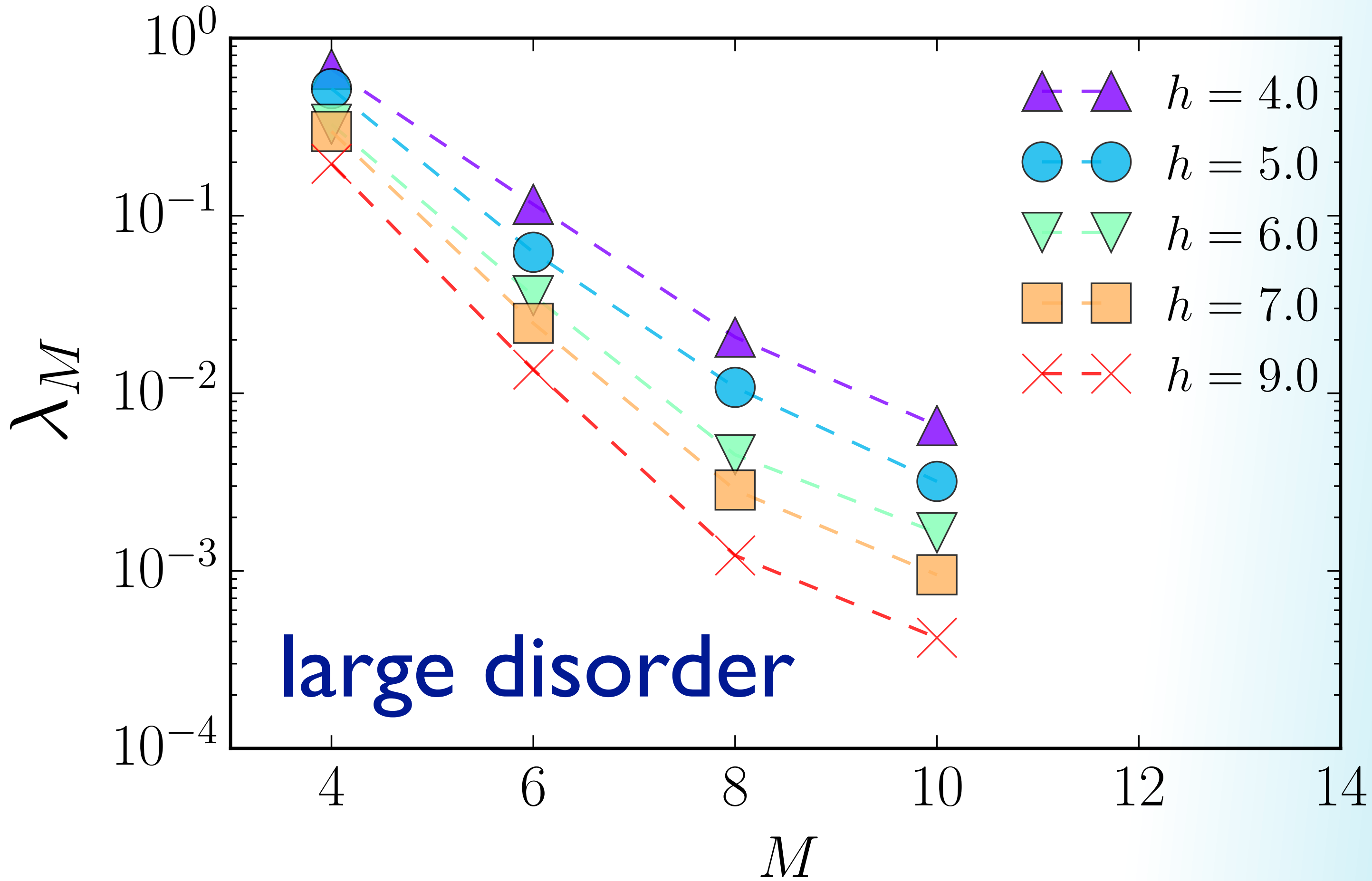

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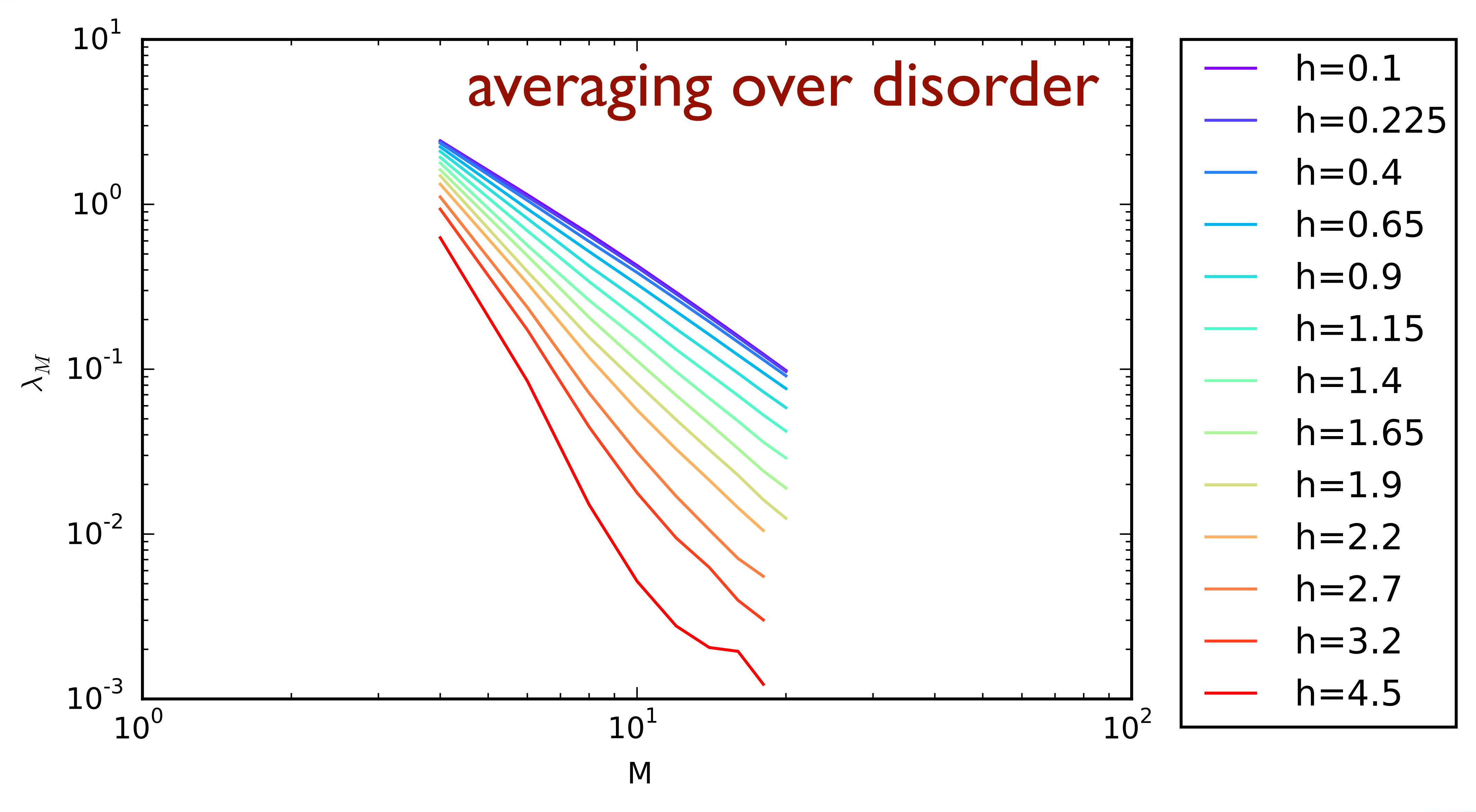
ALMOST CONSERVED QUANTITIES & MBL



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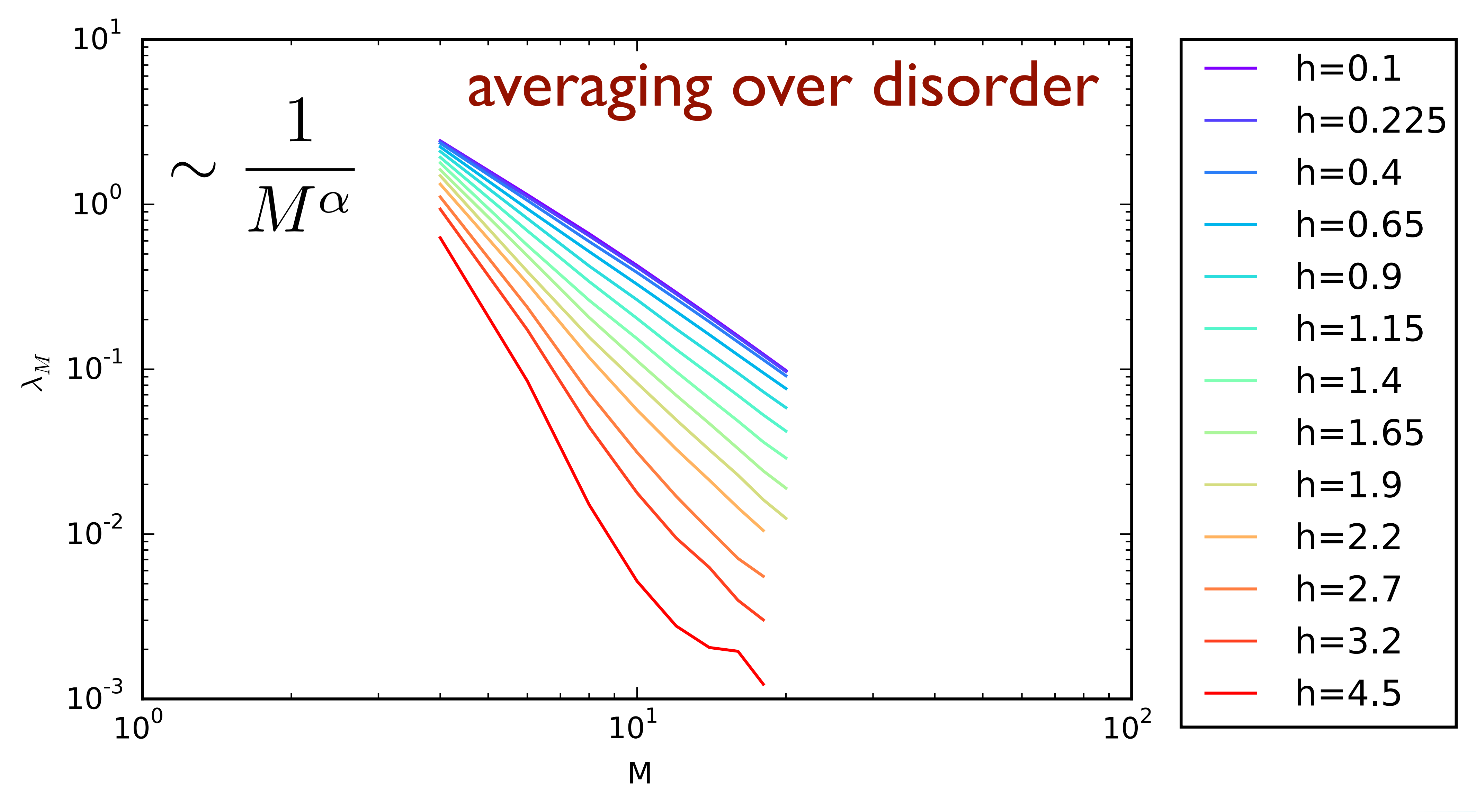

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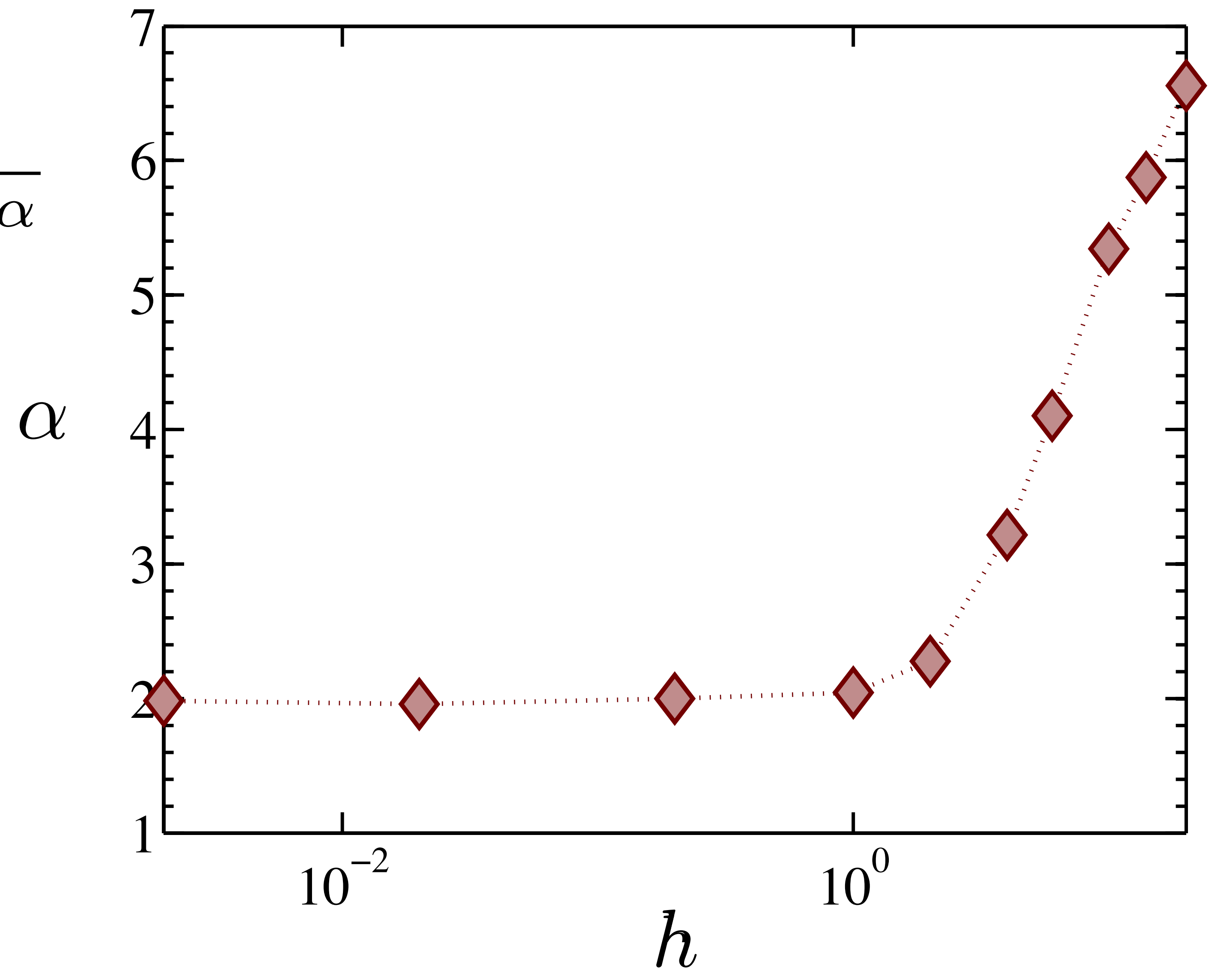
ALMOST CONSERVED QUANTITIES & MBL

$$\sim \frac{1}{M^{\alpha}}$$



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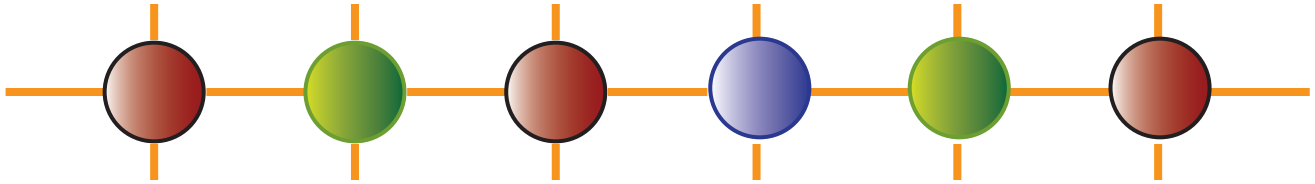
constructive method



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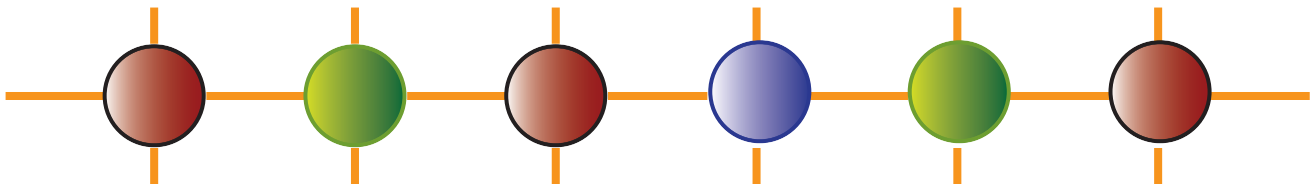

analyze weight of components with different support

$$\sigma_i^{[m]} \otimes \cdots \otimes \sigma_j^{[m+d]}$$

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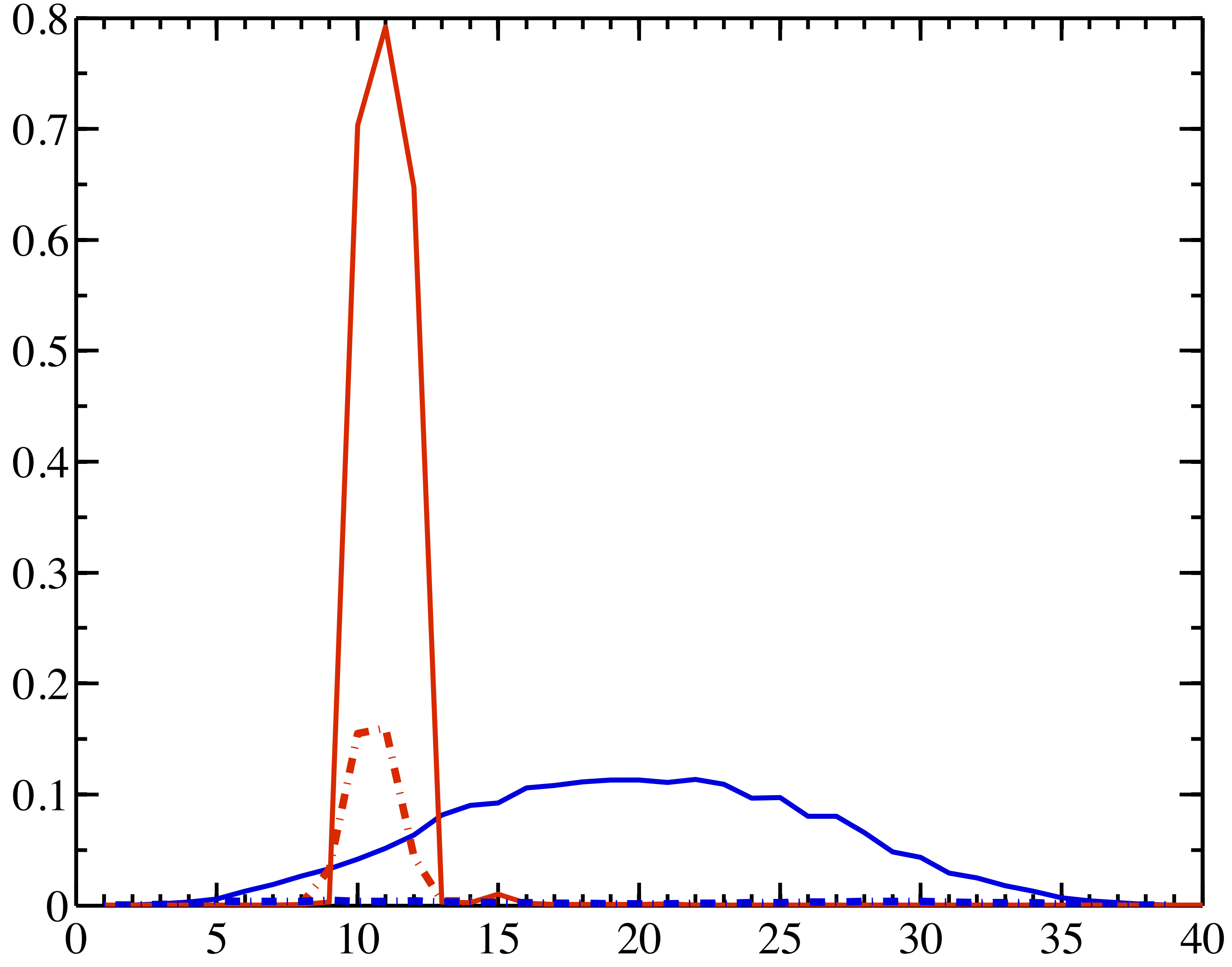
composition of slow operators: how local?

landscape of terms with fixed range



single realization $M = 40$

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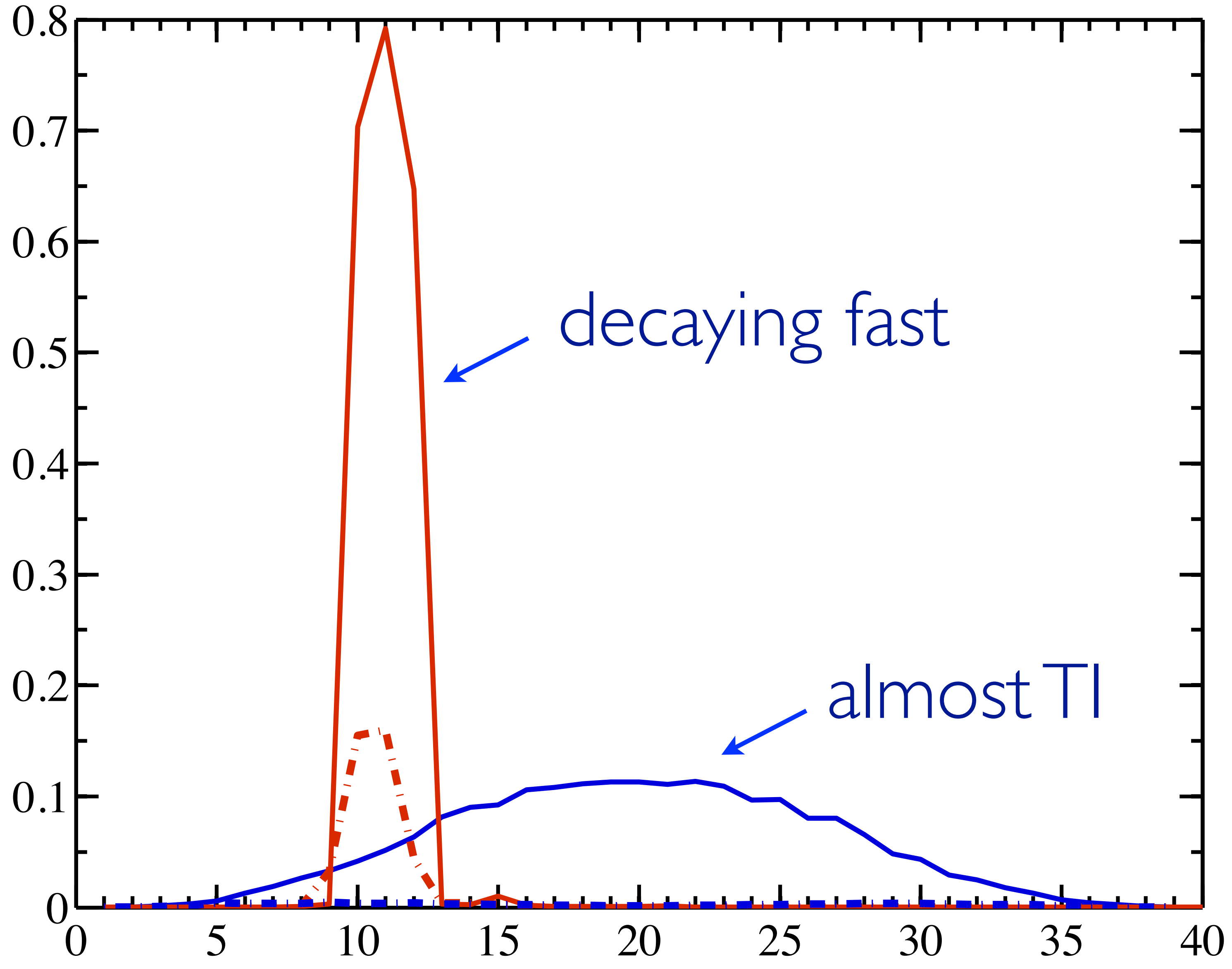

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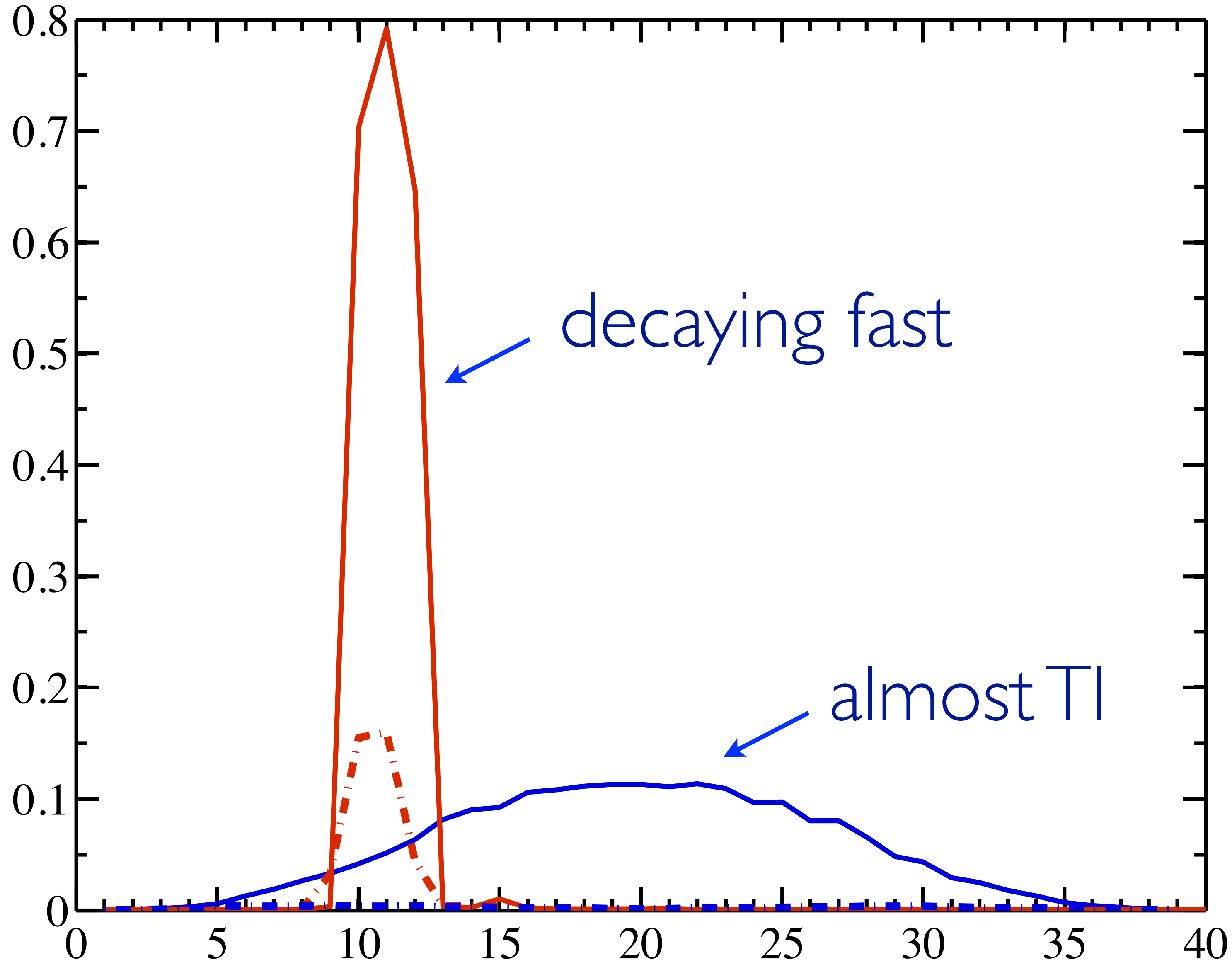

and much more information in the statistics!

single realization $M = 40$

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Statistics of small commutators

Well described by Extreme Value Theory

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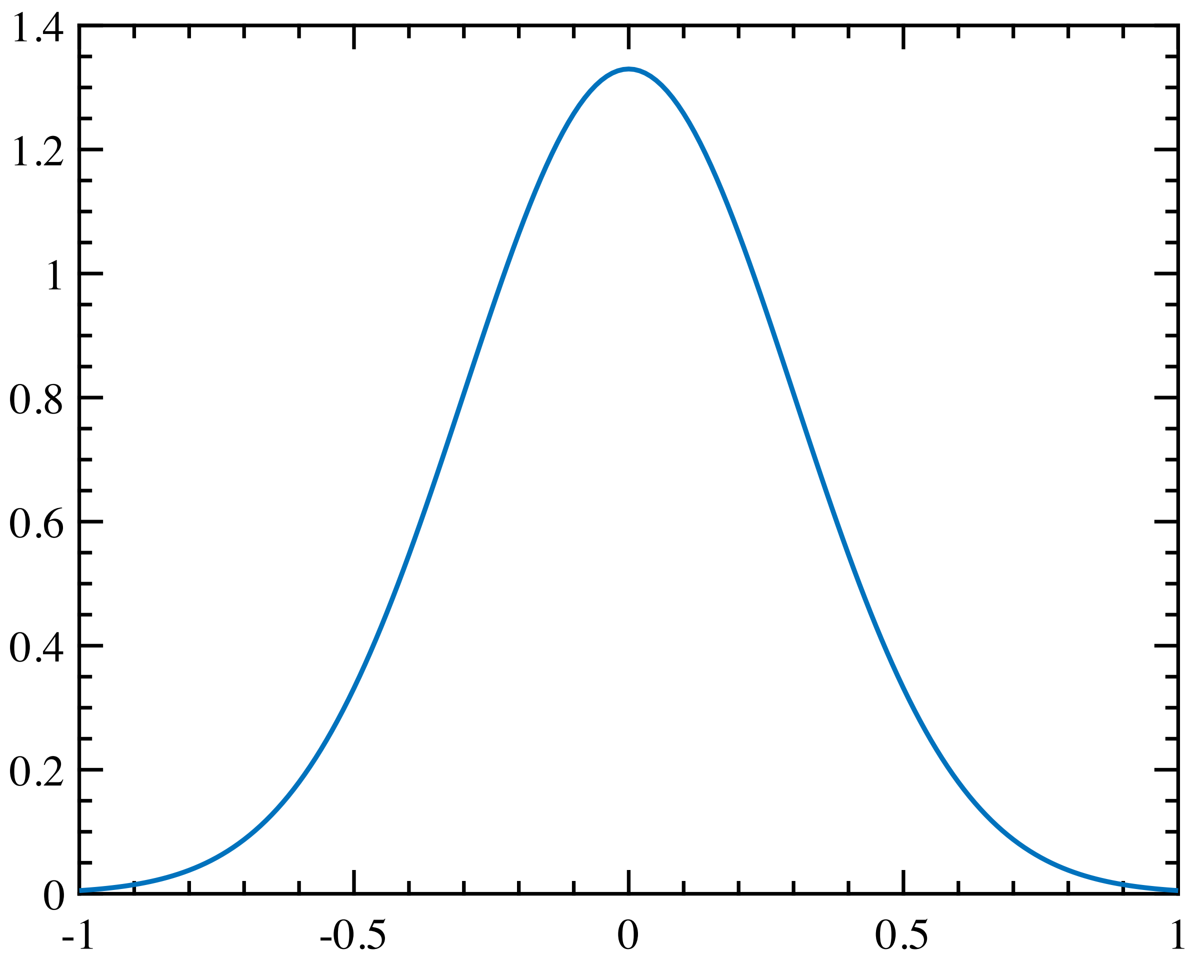
Q: extreme values when sampling from a pdf



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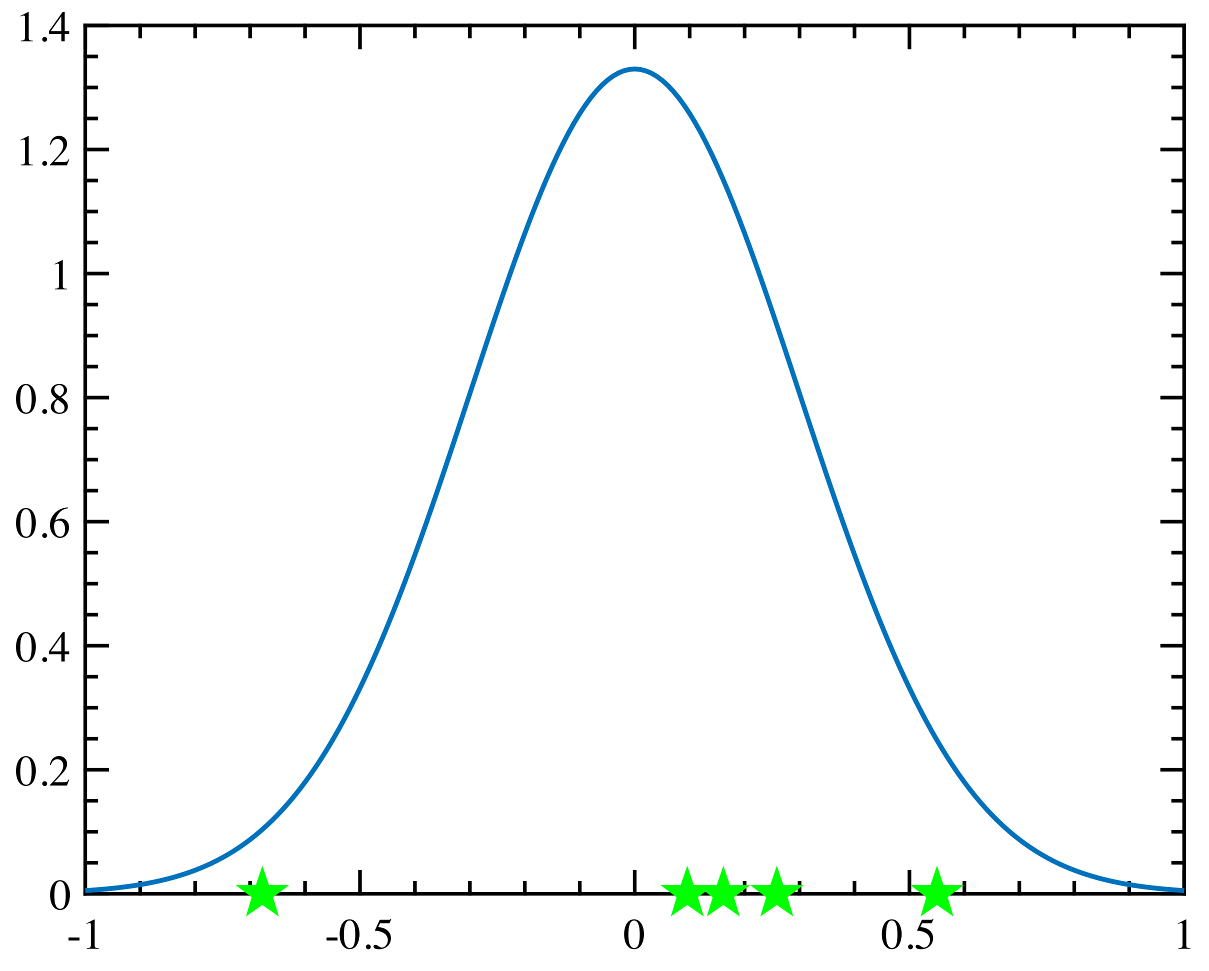

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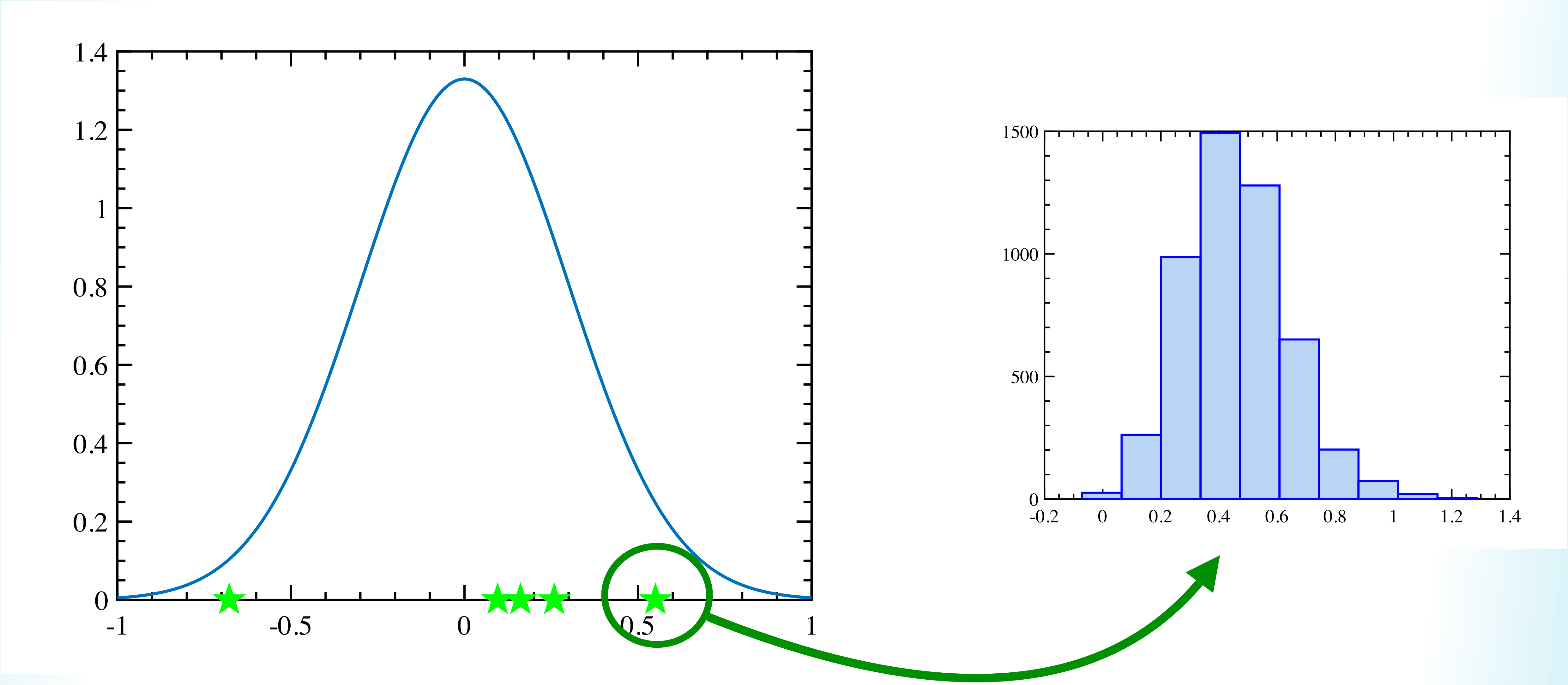

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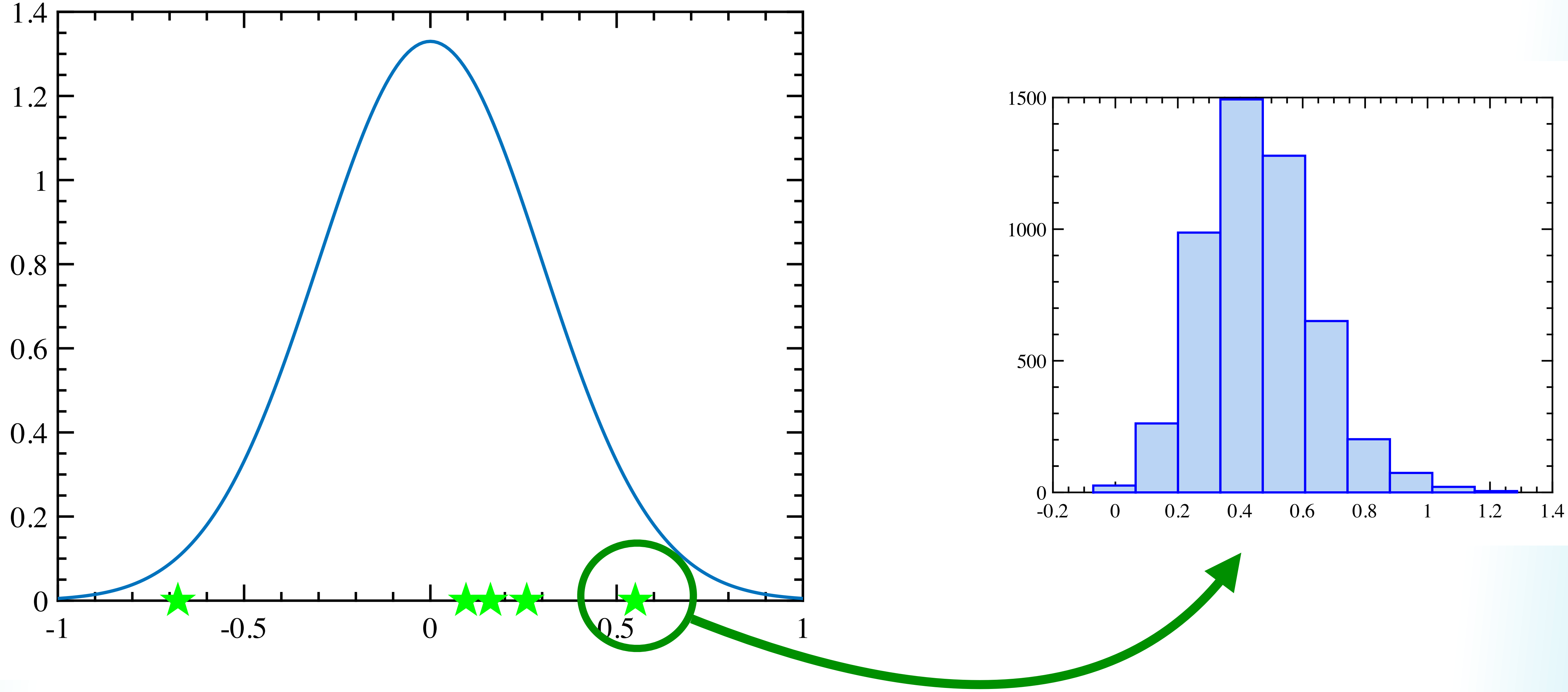
Statistics of small commutators

EVT

when is there a limit,
it is of the form



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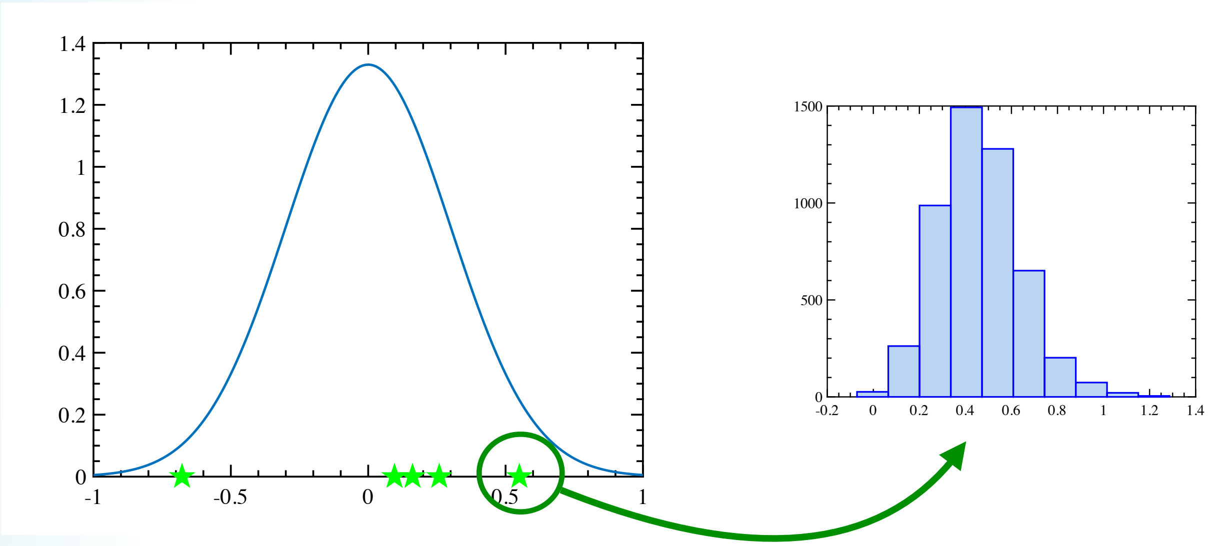

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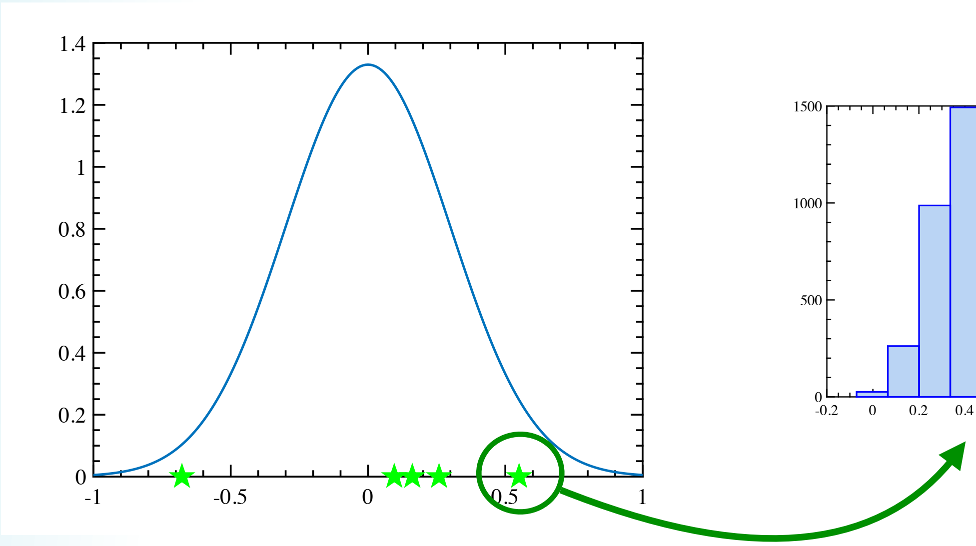

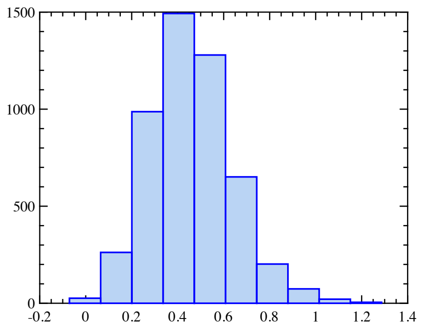

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GEV

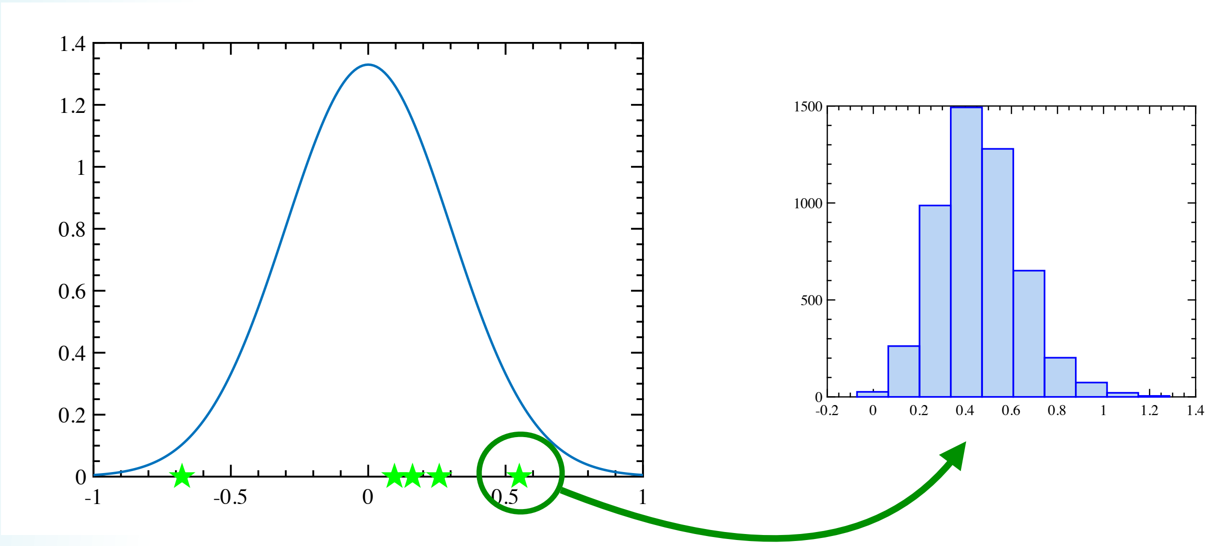
$$G_\zeta(y) = \exp\left[-(1+\zeta y)^{-\frac{1}{\zeta}}\right]$$

rescaled and centered

CDF for extrema

N. Pancotti et al PRB 97, 094206 (2018)

Statistics of small commutators



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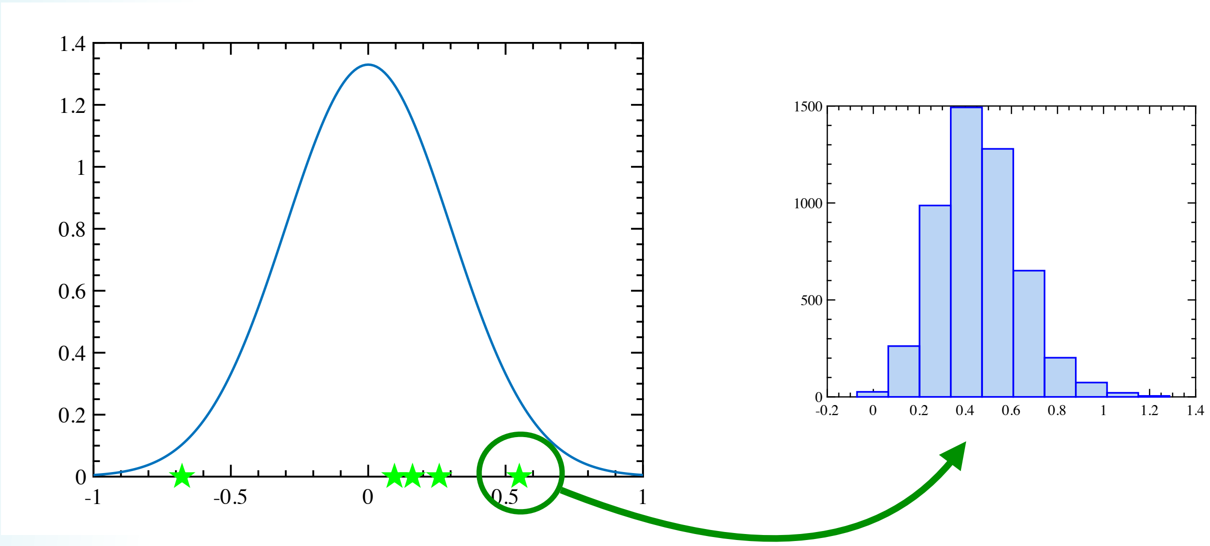

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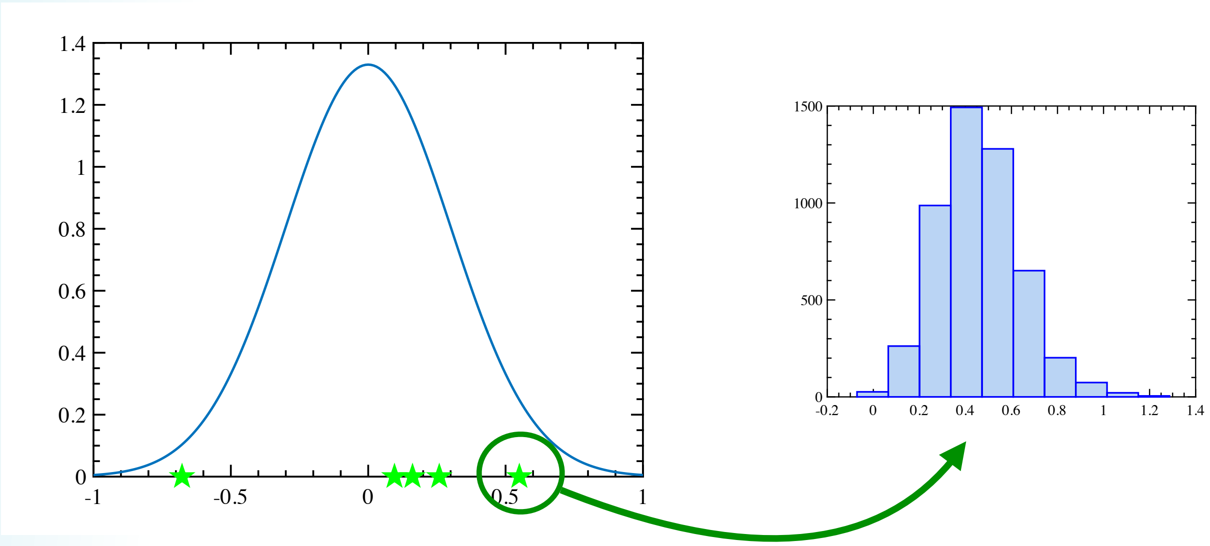

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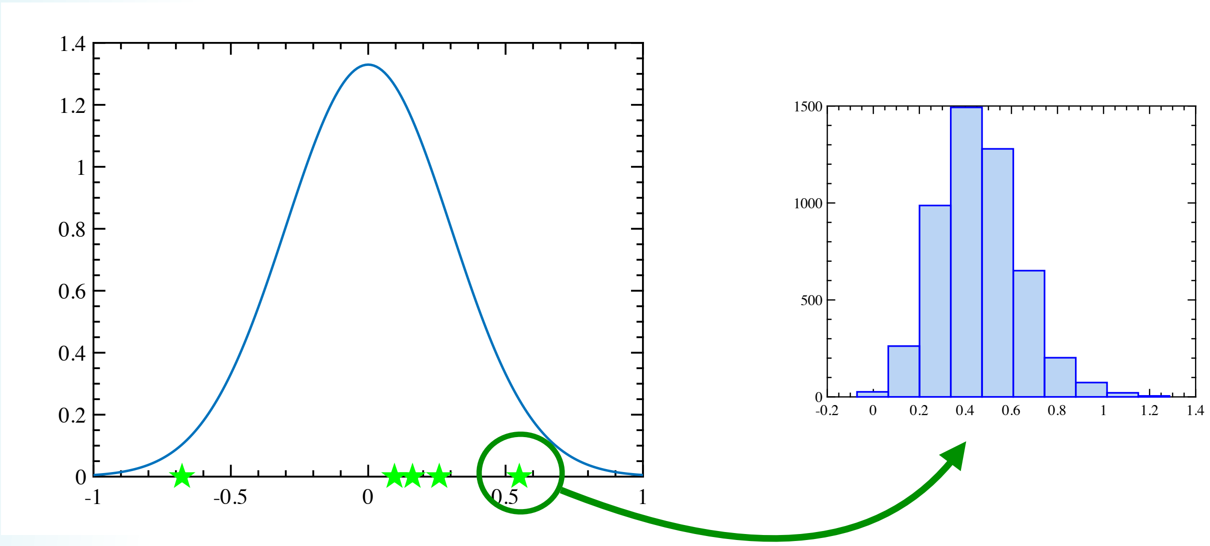

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$\zeta < 0$ Weibull: bounded light tails

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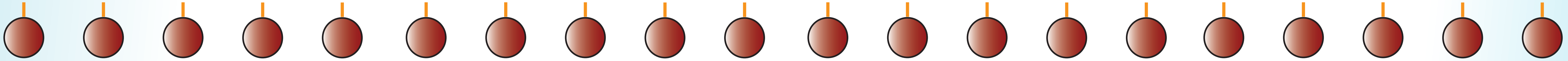

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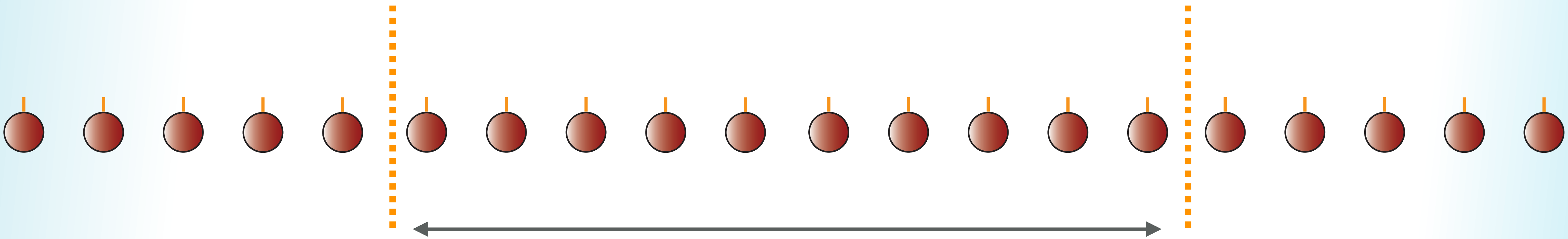

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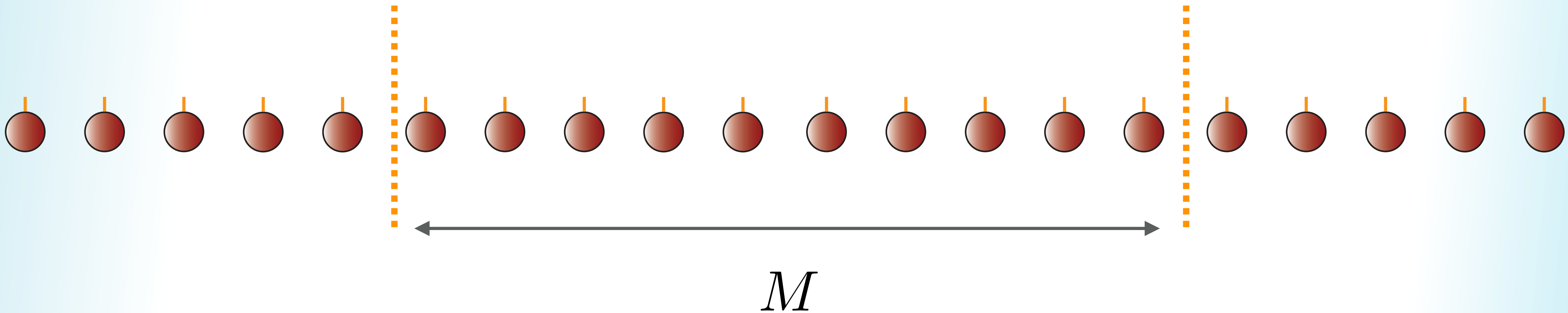

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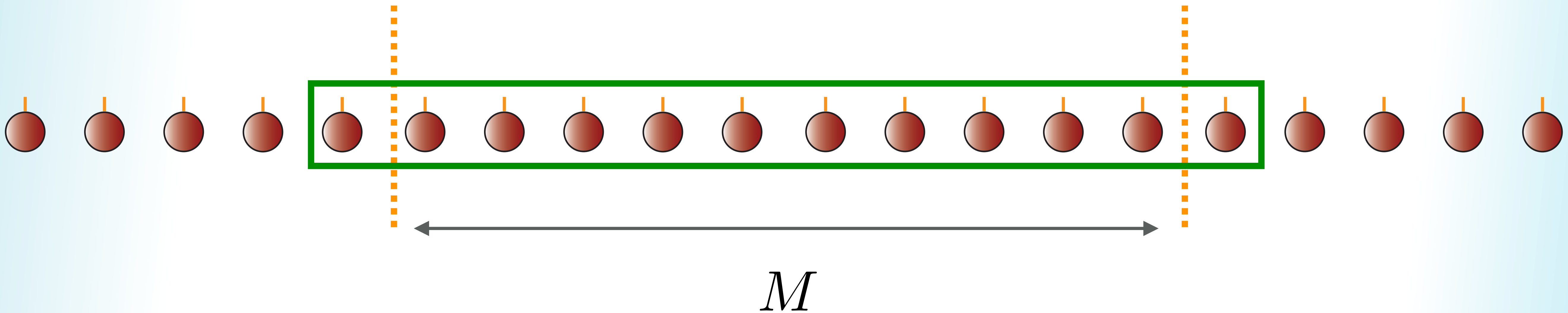
Statistics of small commutators

minimum eigenvalue of an effective
Hamiltonian on vectorized operators

$$H_{\mathrm{eff}} \approx \left(H \otimes \mathbb{I} - \mathbb{I} \otimes H^T\right)^2_{M+2}$$



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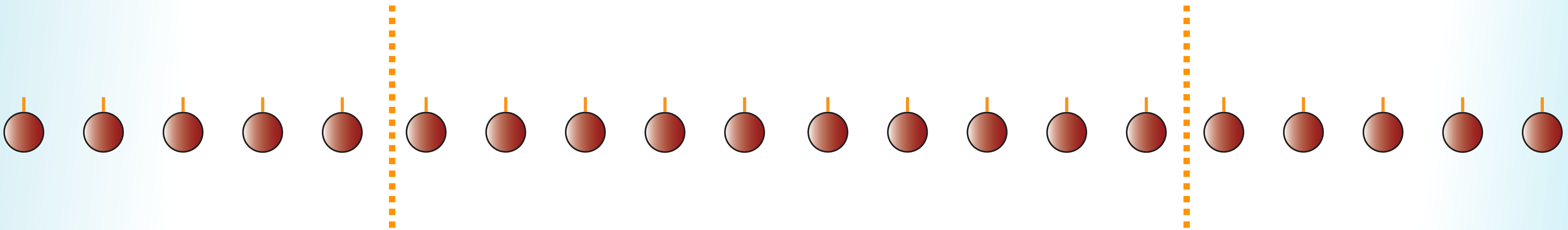
Statistics of small commutators

EVT rare regions affect the distribution of commutators



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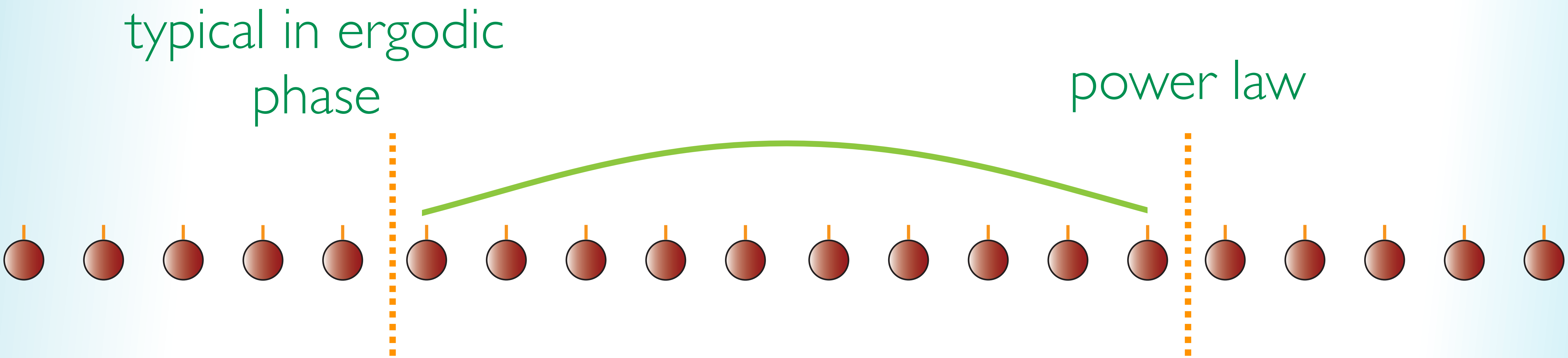

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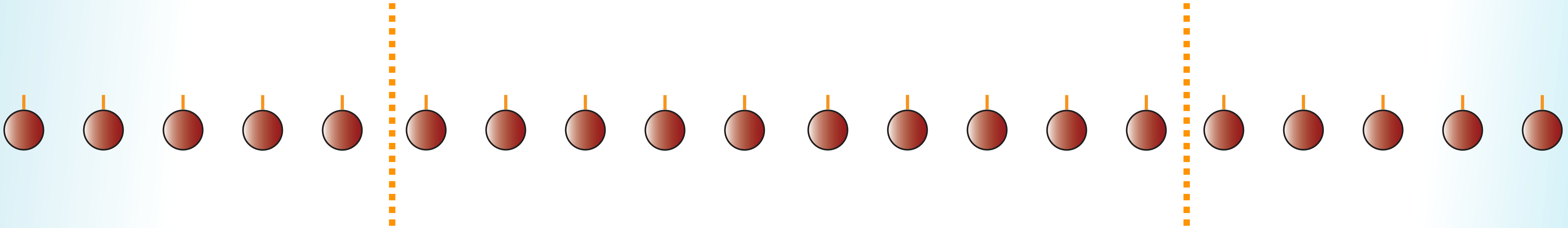

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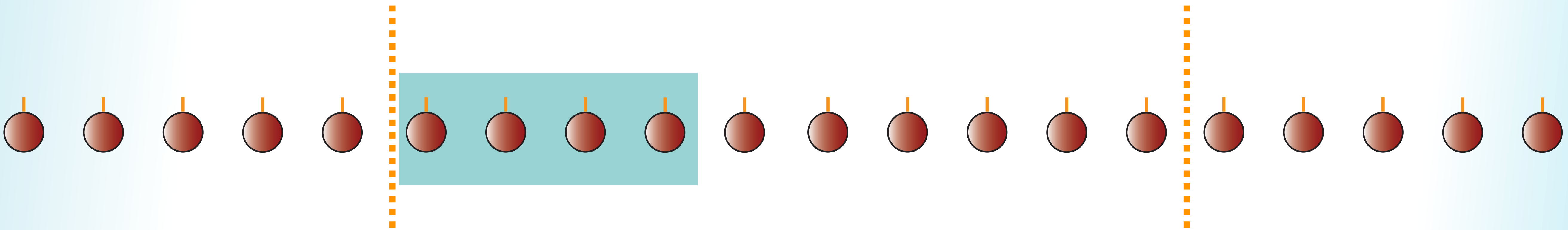

higher effective disordered

$$p(\ell < M) \sim c^{\ell}$$

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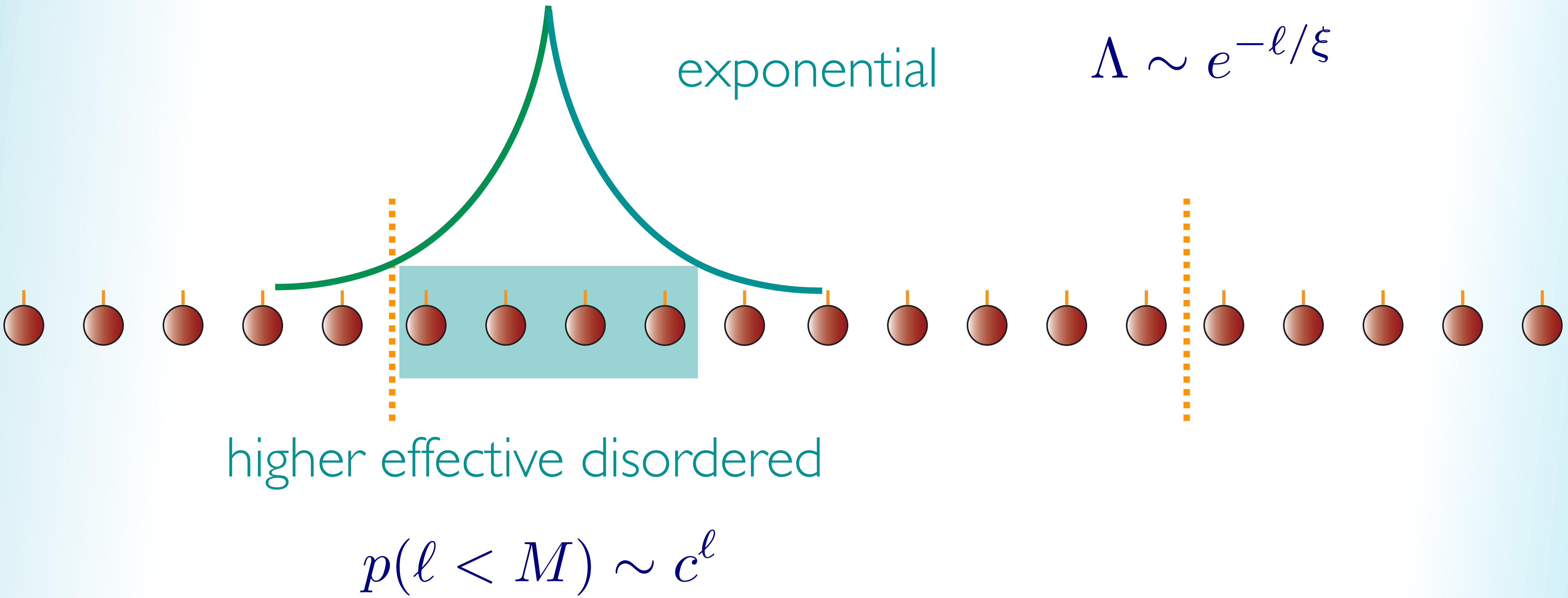

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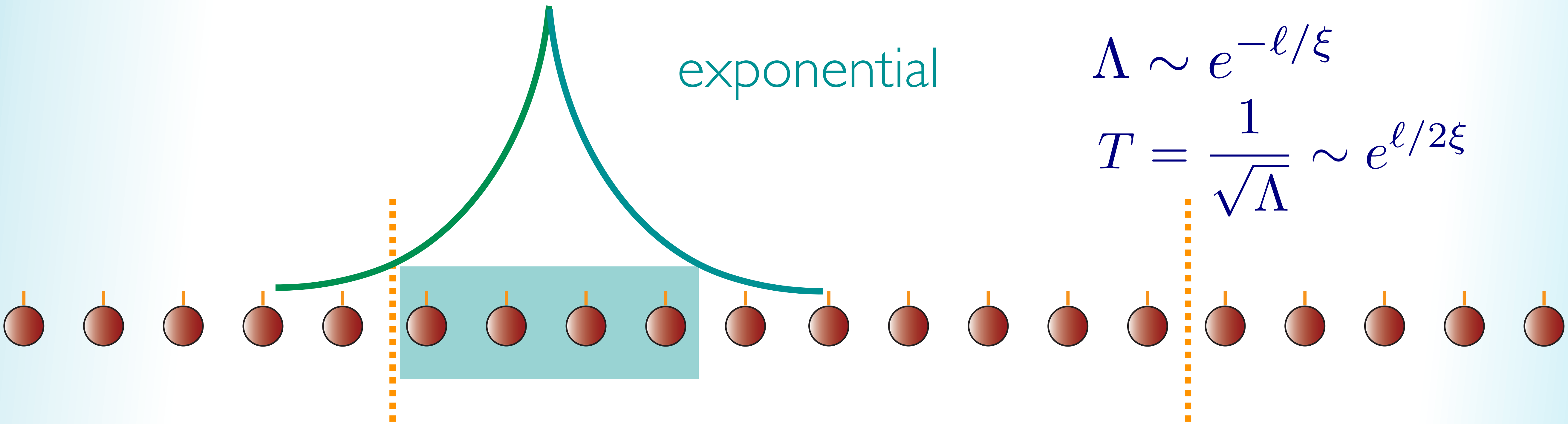

$$\Lambda \sim e^{-\ell/\xi}$$

$$T = \frac{1}{\sqrt{\Lambda}} \sim e^{\ell/2\xi}$$

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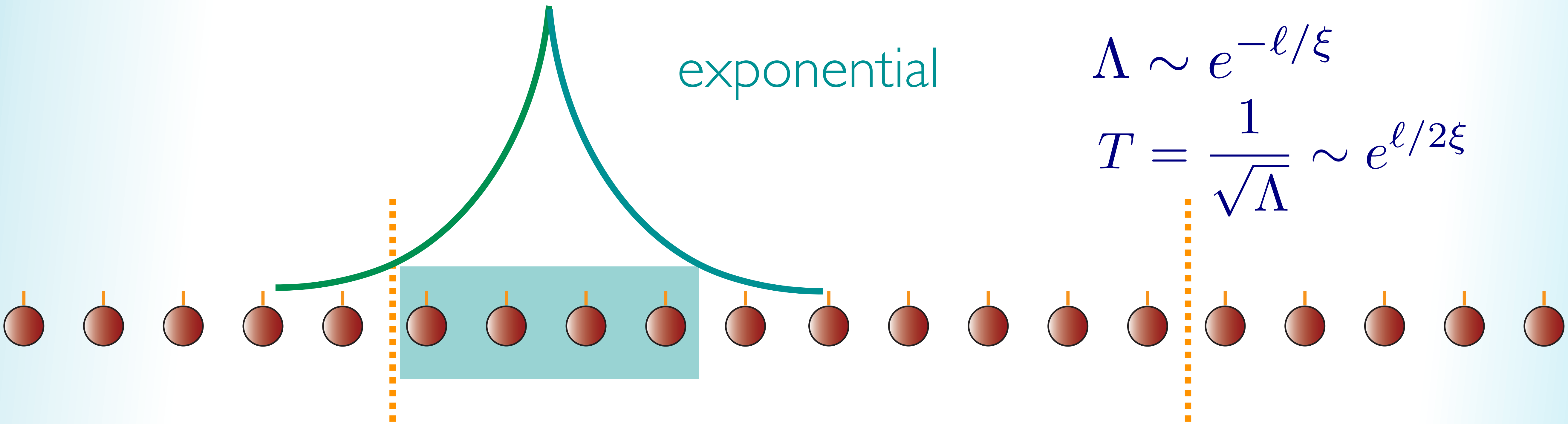

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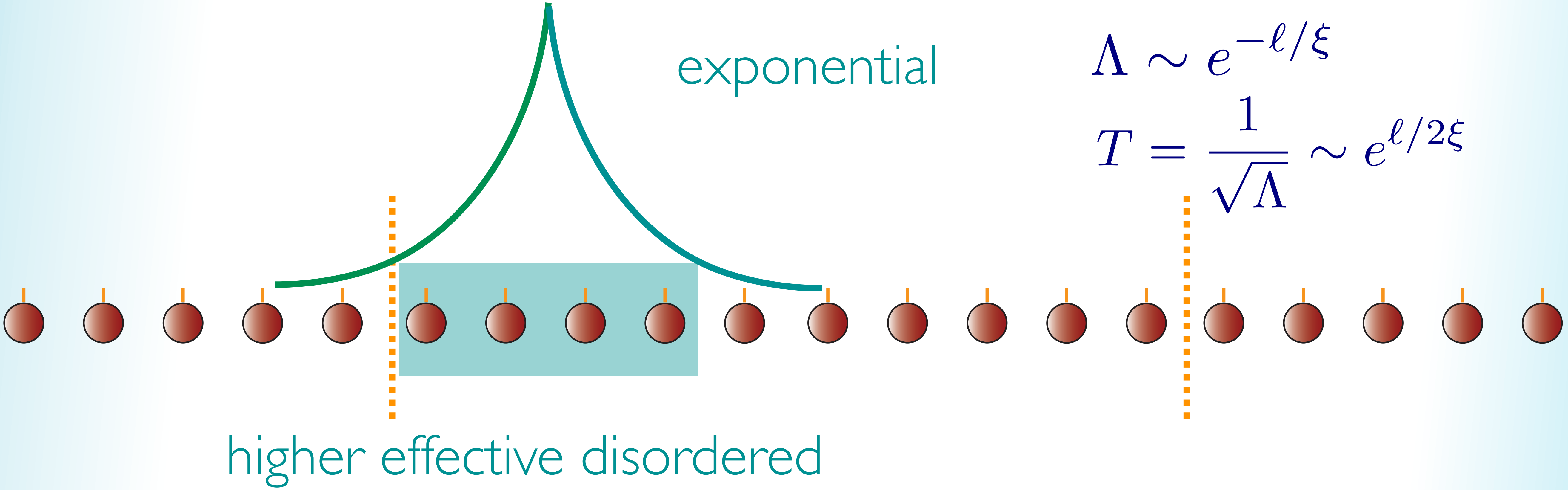

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Fréchet distribution

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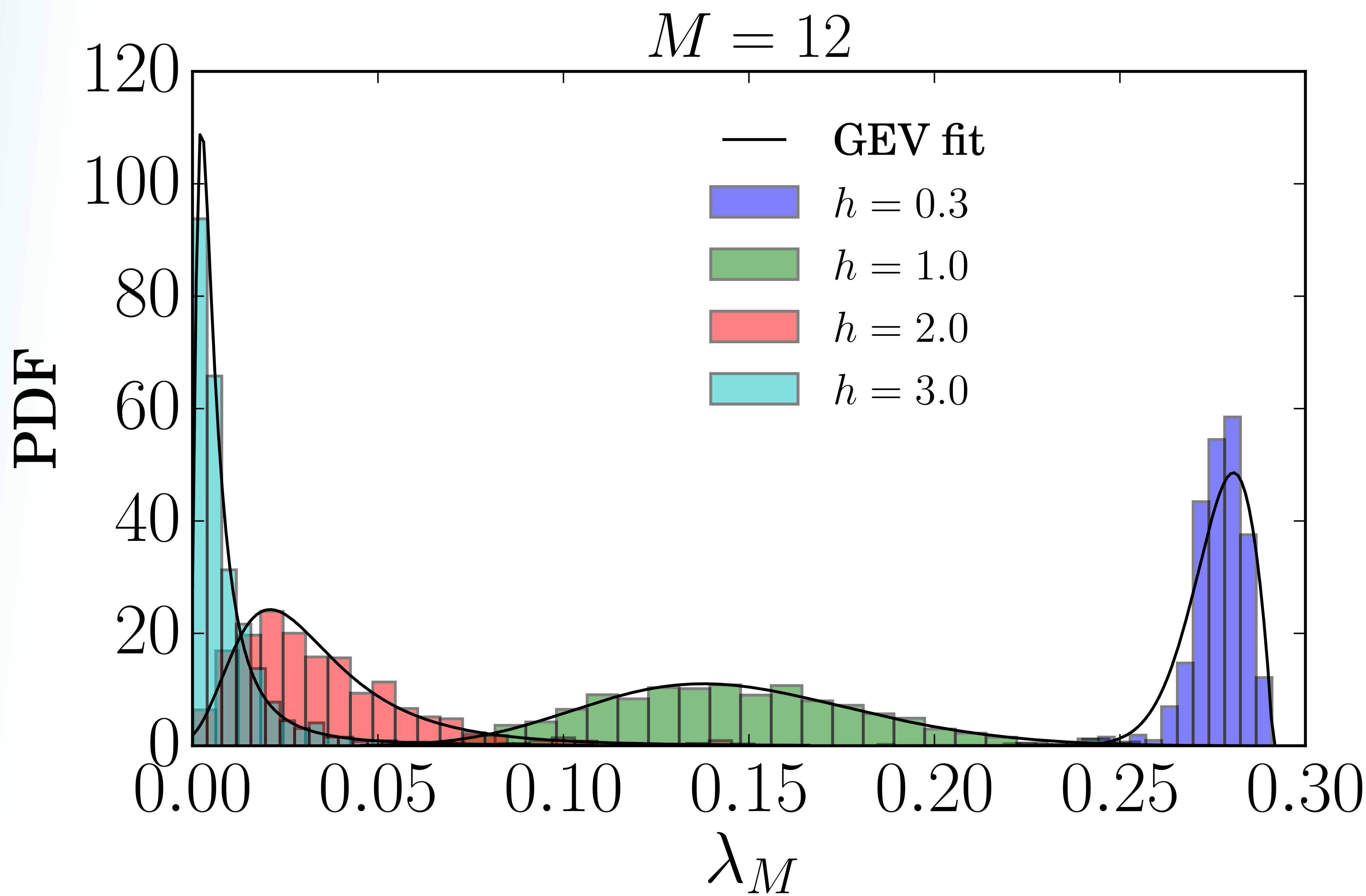
Statistics of small commutators

good fit to generalised extreme value distribution



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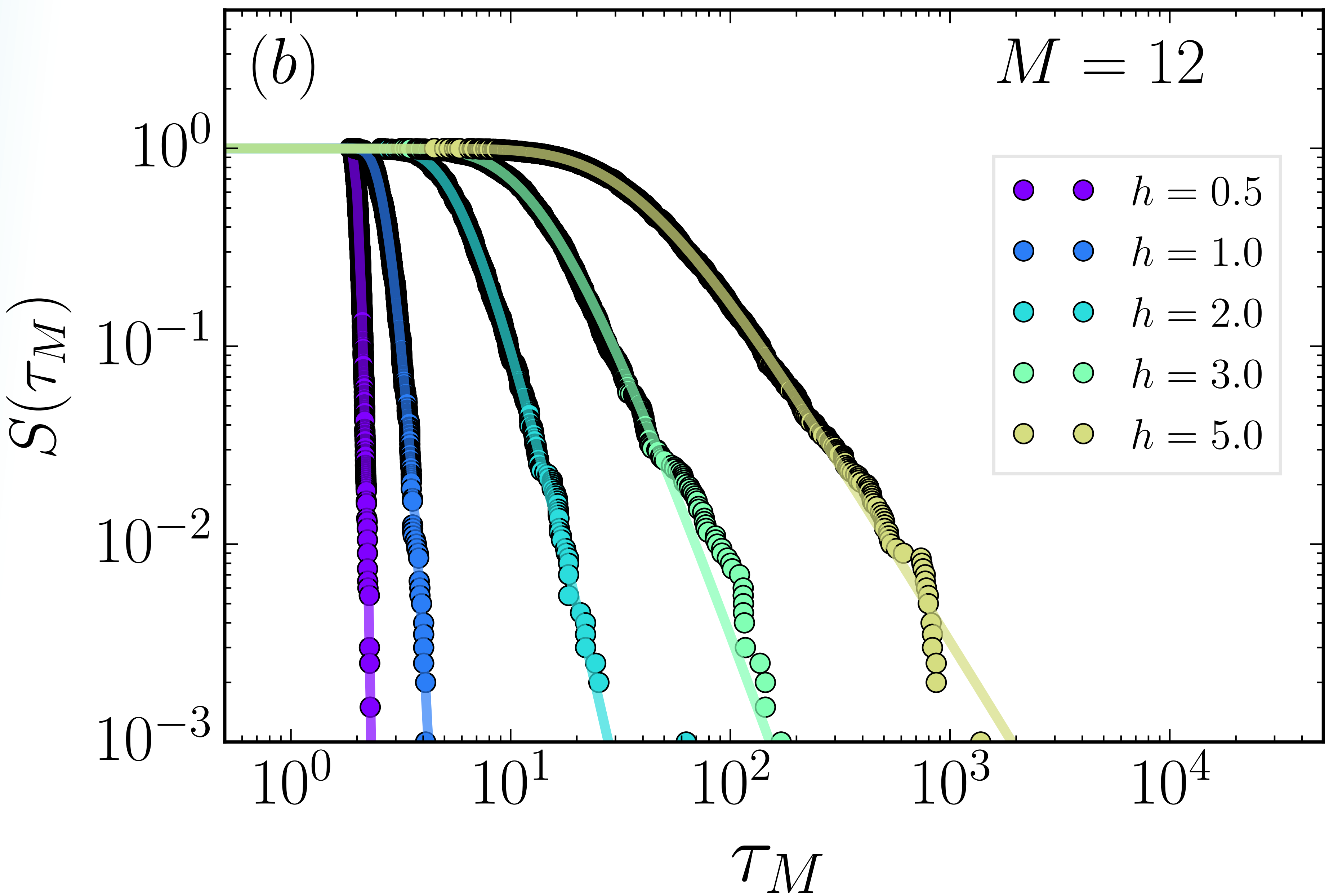
Statistics of small commutators

survival rate (probability of extremely large values)



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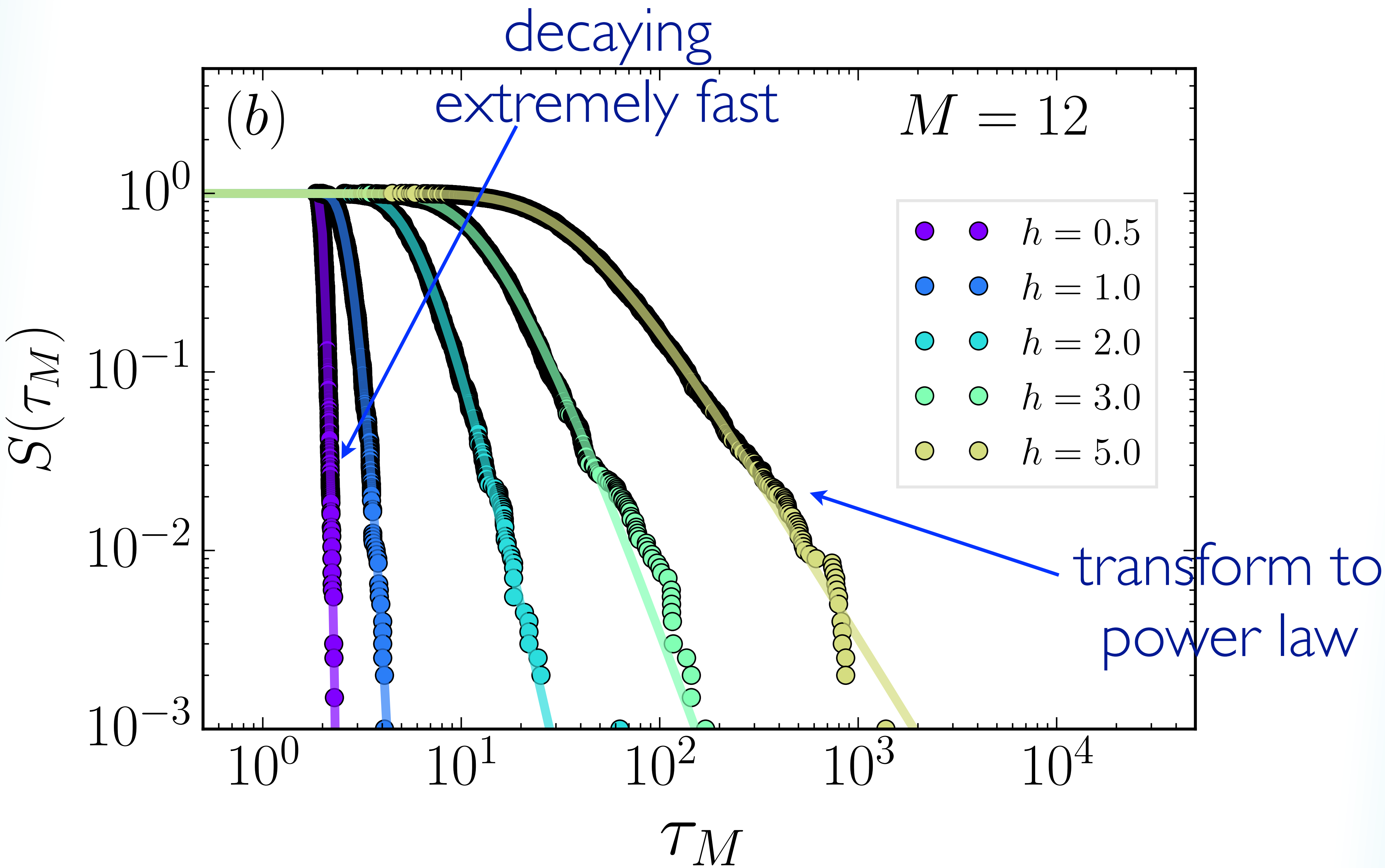

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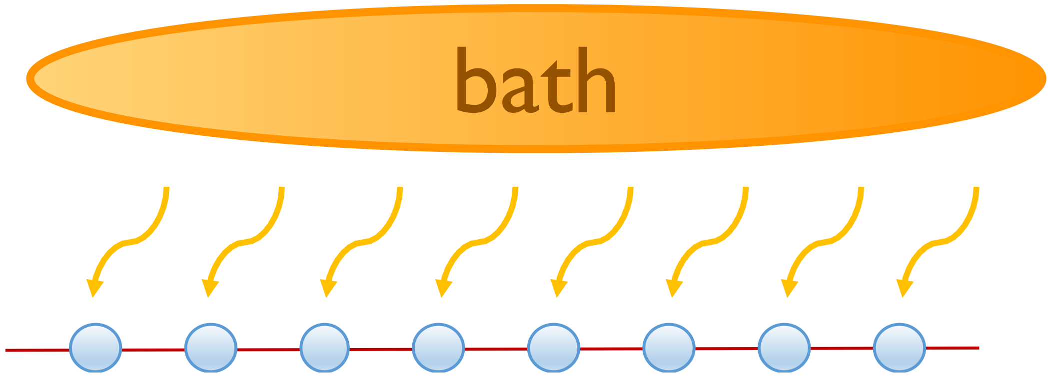
$$\left(\quad \right)$$

dissipative dynamics

$$\Bigg(\qquad \Bigg)$$

dissipative dynamics

non-equilibrium steady states



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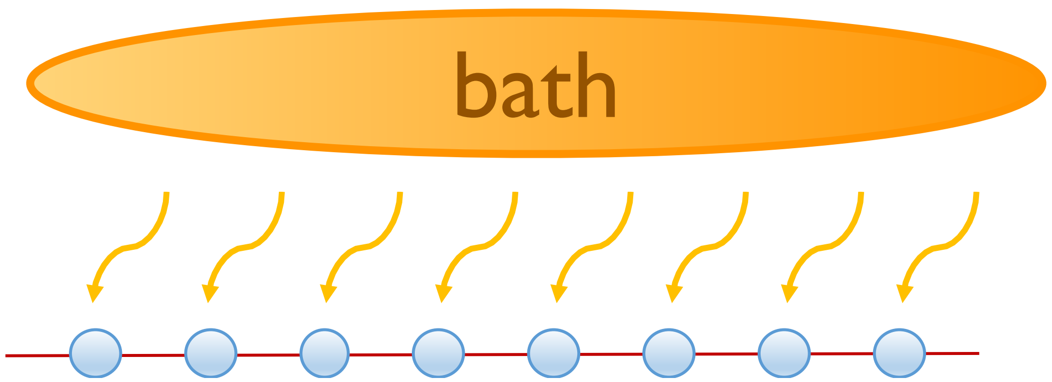
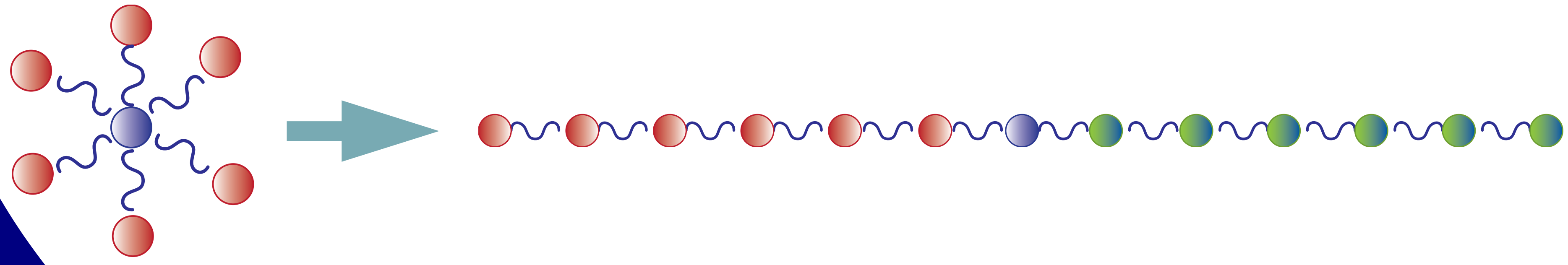


exact description system+bath

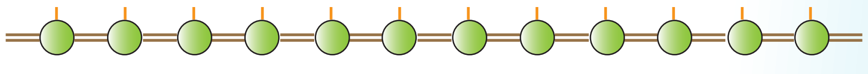


$\left(\quad \right)$

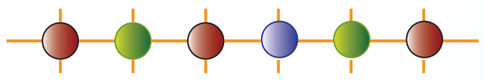
TO CONCLUDE

Various TNS tools can be used for time evolution

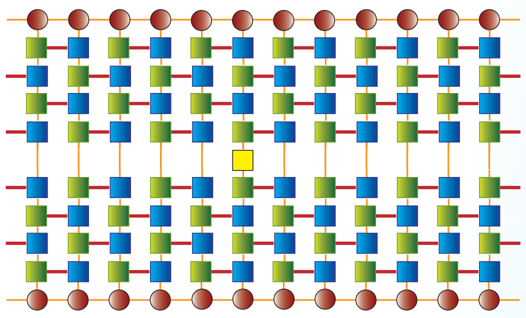
evolving the (pure state) ansatz



evolving operators: Heisenberg picture



observables as TN to contract



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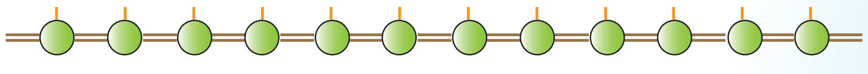
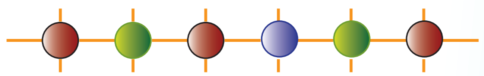
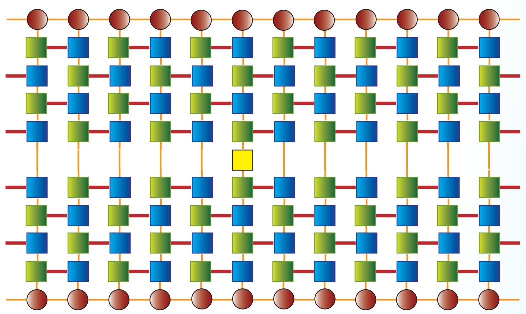
TO CONCLUDE

Various TNS tools can be used for time evolution

evolving the (pure state) ansatz 

evolving operators: Heisenberg picture 

observables as TN to contract 

global quenches

valid for limited times only

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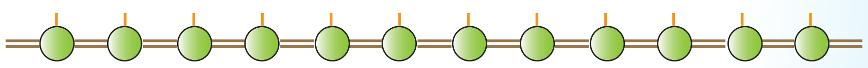

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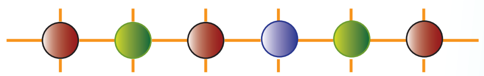

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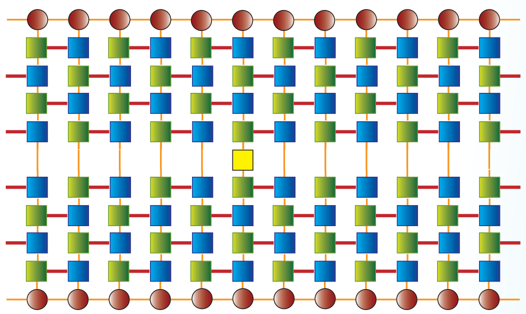

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different perspective: slow operators

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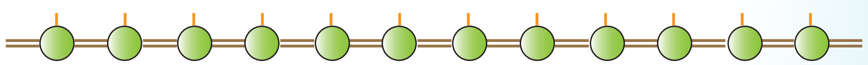

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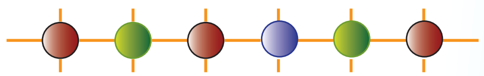

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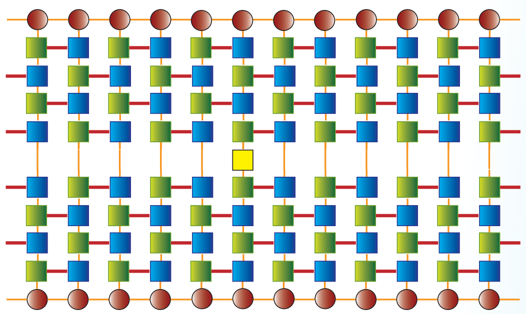

global quenches

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different perspective: slow operators

applied to MBL scenario → signatures of localization, and rare regions in the statistics

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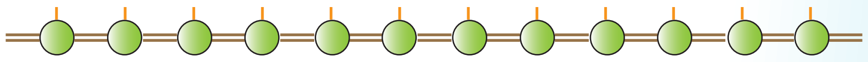
THANKS

Various TNS tools can be used for time evolution

evolving the (pure state) ansatz



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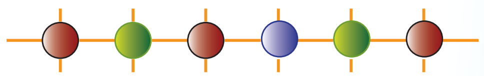

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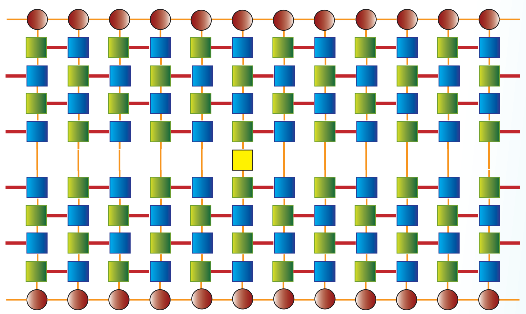

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