Emergent behavior in out-of-equilibrium quantum many-body systems

Davide Rossini

Congresso di Dipartimento

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IN SUPREMÆ DIGNITATIS 1343
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Outline

Can **equilibrium** quantum many-body phenomena be observed in **out-of-equilibrium** contexts?

- Quantum phase transitions
- Emergent scales & scaling behavior
- Soft quantum quenches
- Open quantum systems
- Monitored quantum dynamics

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Equilibrium quantum transitions

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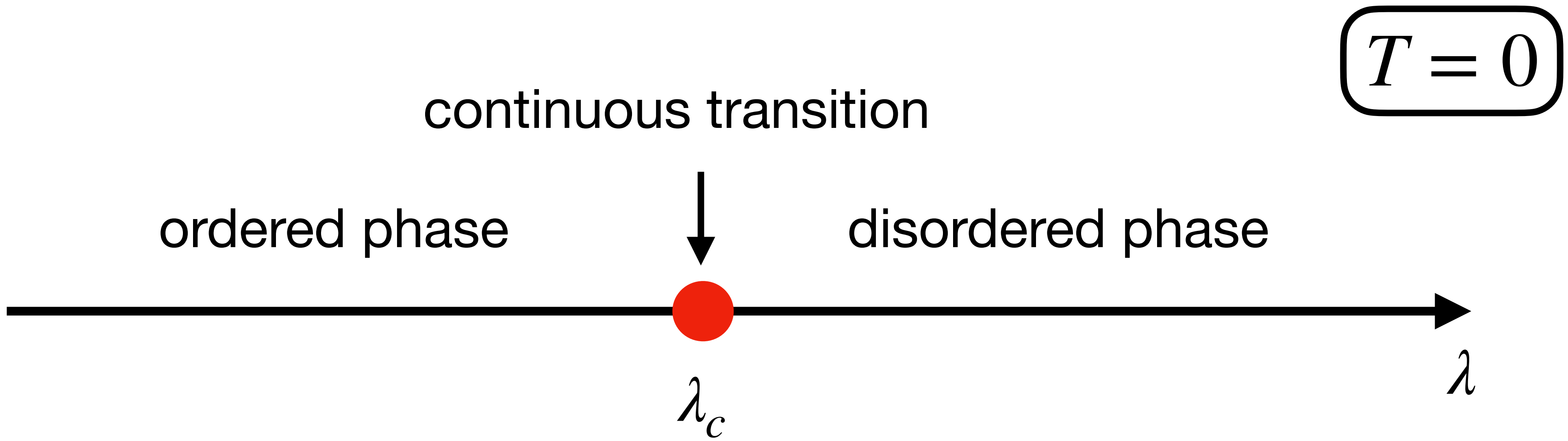
Why equilibrium quantum transitions matter



Microscopic details become irrelevant:

- diverging correlation length $\xi \sim |\lambda - \lambda_c|^{-\nu}$
- vanishing energy scales $\Delta \sim \xi^{-z}$
- universality

S. Sachdev, *Quantum Phase Transitions* (Cambridge, 2011)
S.L. Sondhi, S.M. Girvin, J.P. Carini, D. Shankar, *Rev. Mod. Phys.* **69**, 315 (1997)

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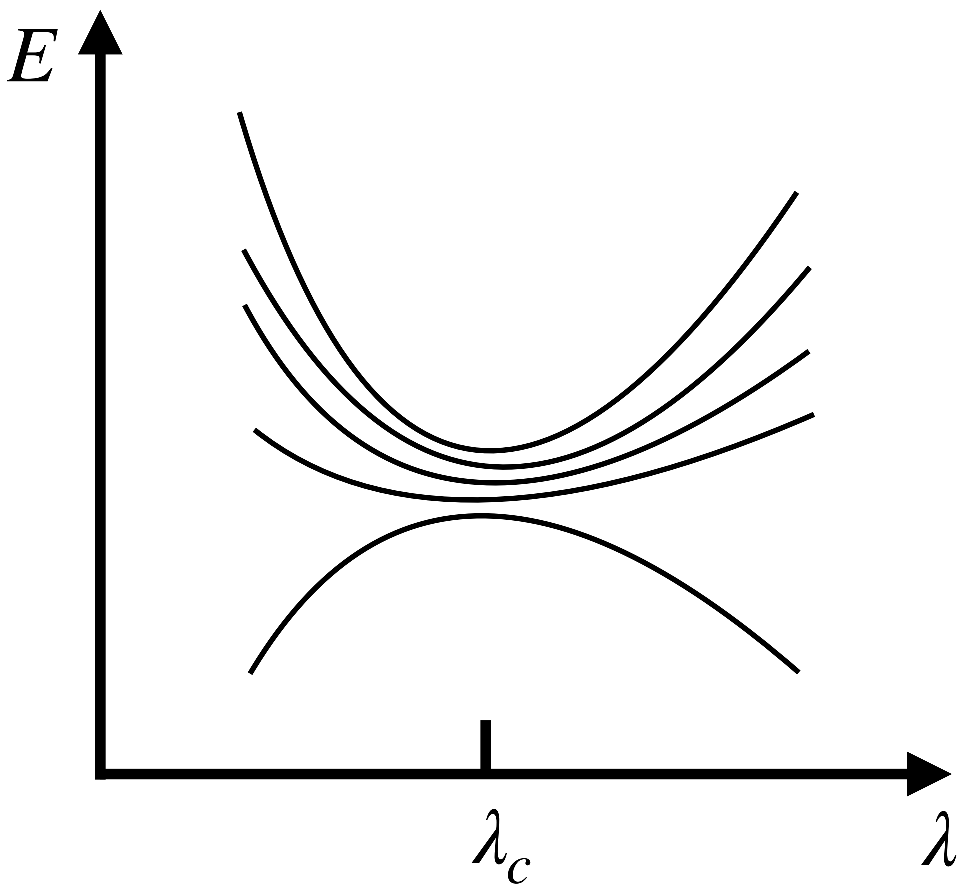
Spectral viewpoint

Continuous quantum transitions

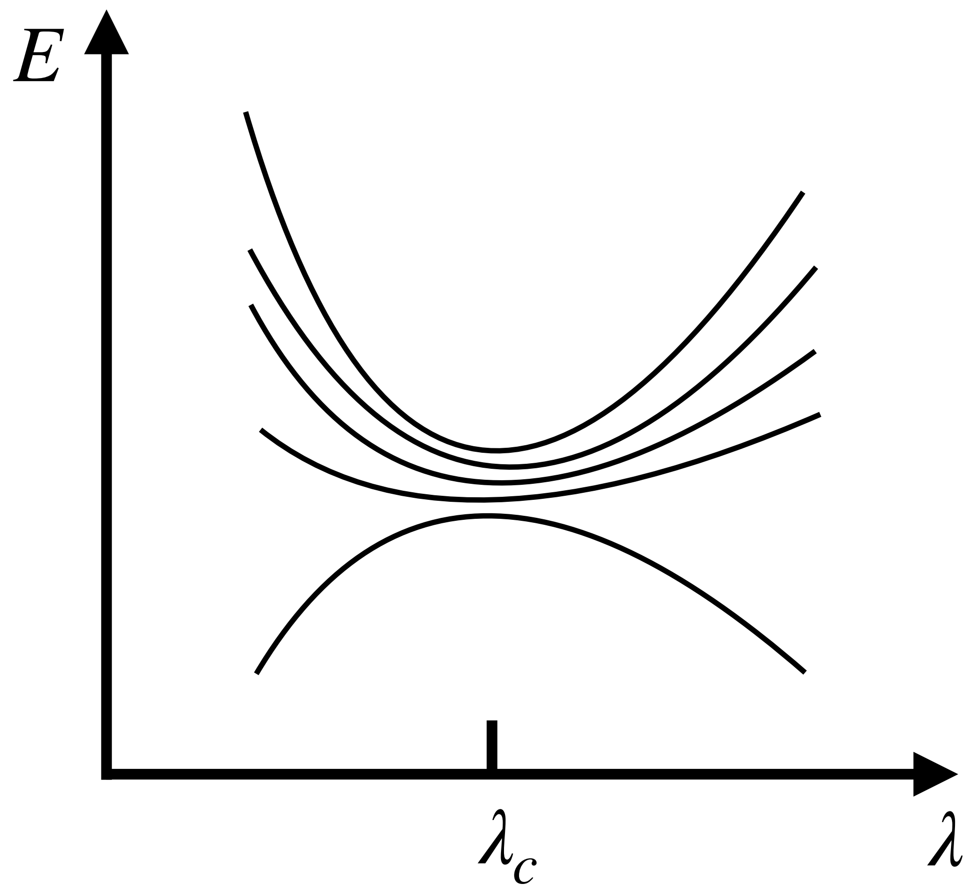


collapsing tower of low-energy states

$$\Delta \sim L^{-z}$$

Spectral viewpoint

Continuous quantum transitions



collapsing tower of low-energy states

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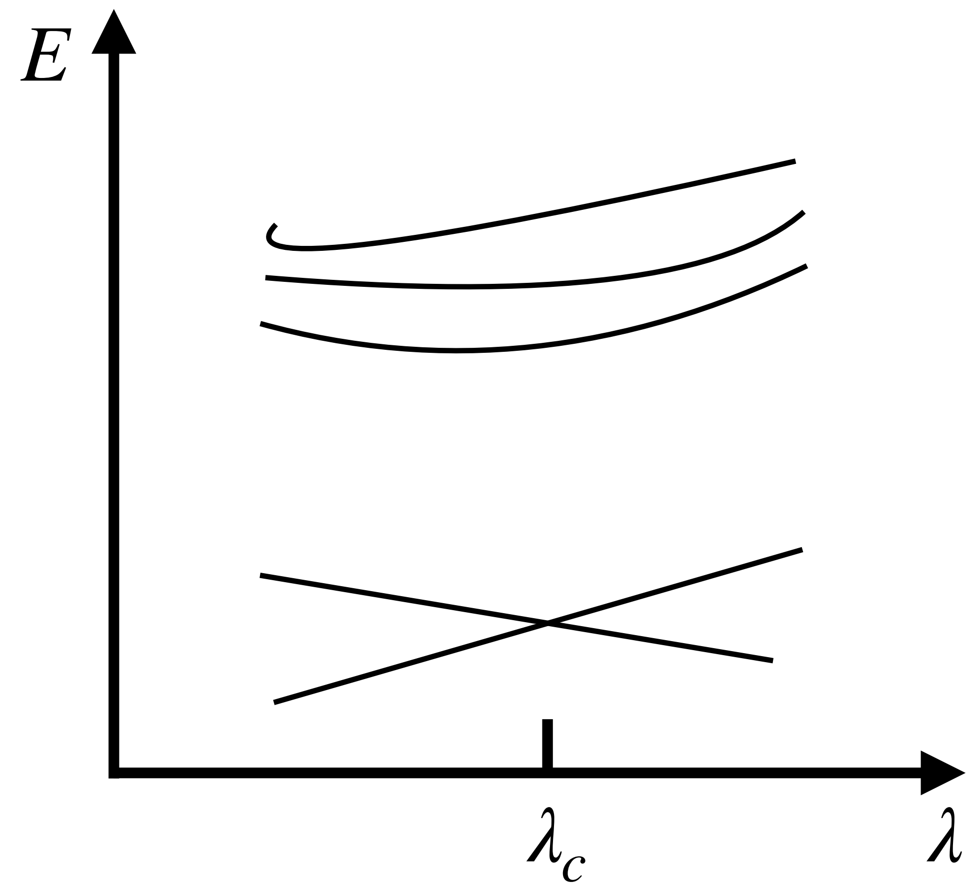
First-order quantum transitions



competing ground states

$$\Delta \sim \exp(-cL^d)$$

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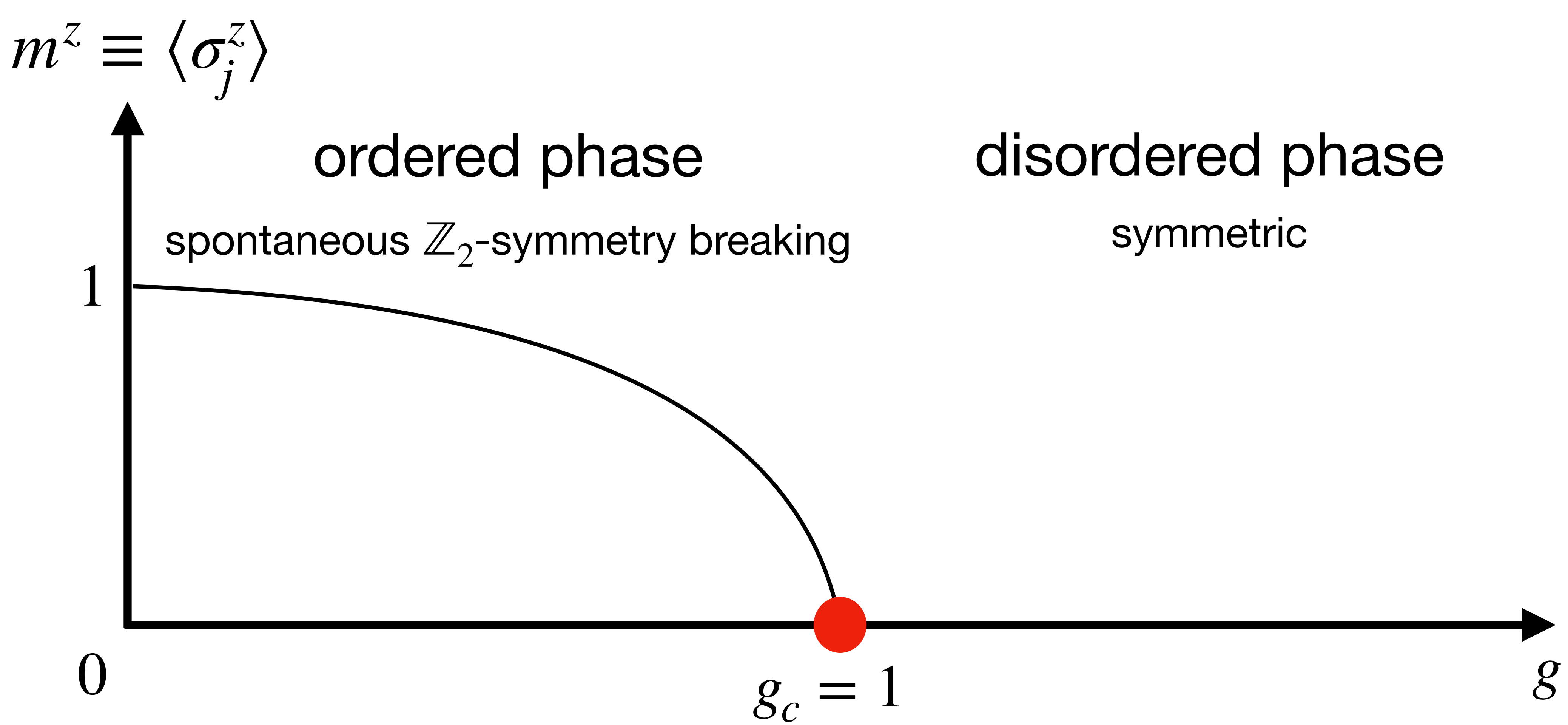
A paradigmatic example: the Quantum Ising chain

$$H = -\sum_j \left(\sigma_j^z \sigma_{j+1}^z + g\sigma_j^x\right)$$

<u>Continuous quantum transition</u>



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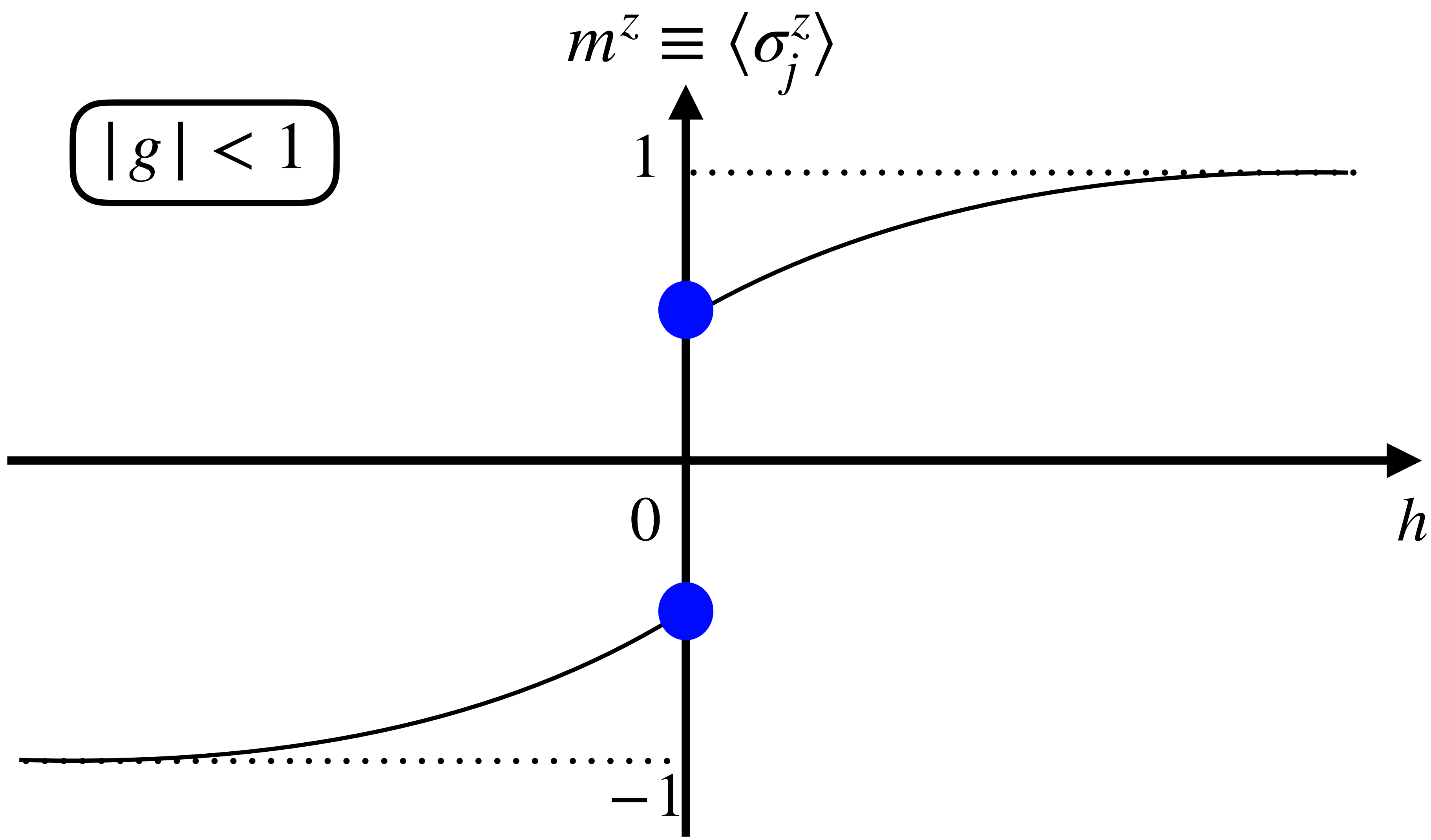

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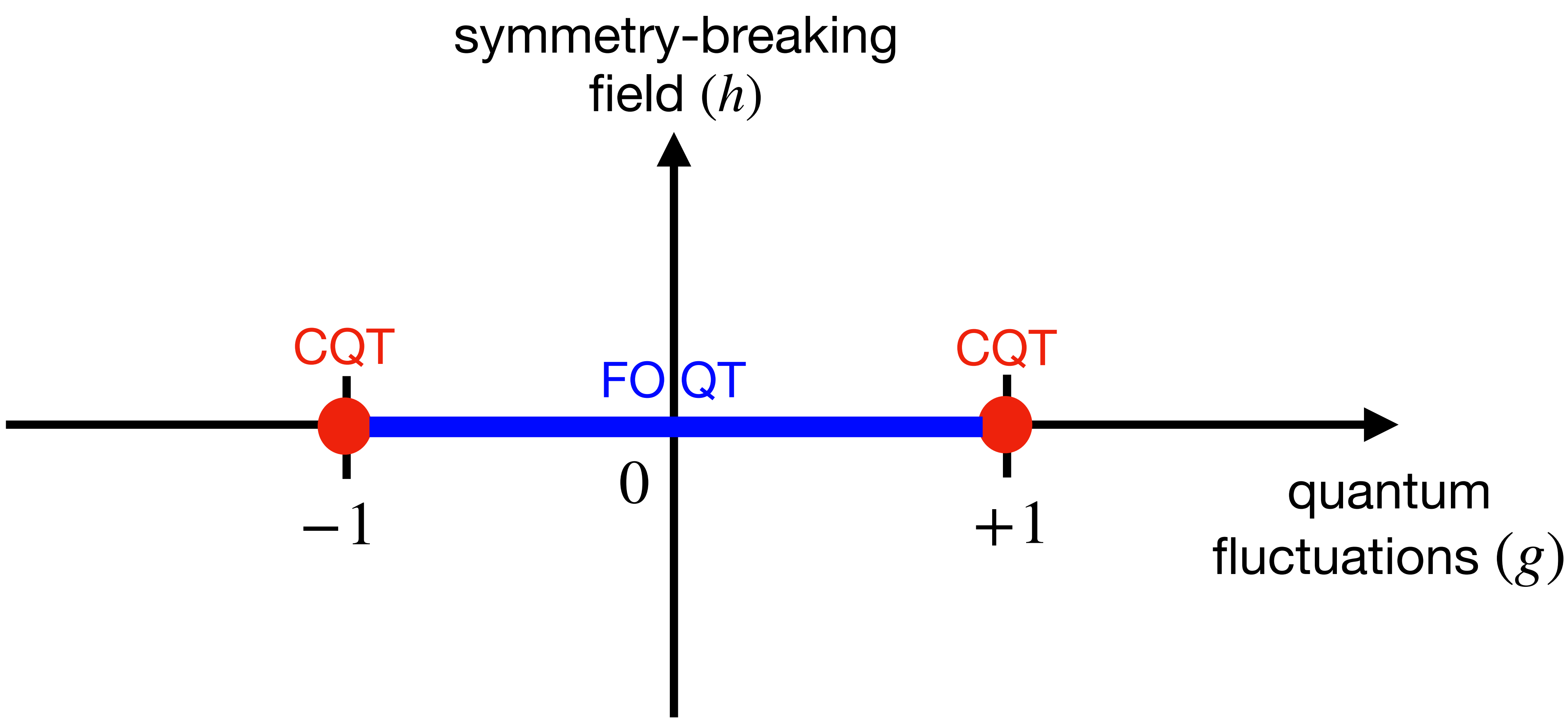
<u>Zero-temperature phase diagram</u>



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Emergent scaling variables

$$H(\lambda) = H_0 + \lambda Q$$

Near a transition, observables depend on dimensionless ratios of competing scales

$$\kappa = \frac{E_\lambda(L)}{\Delta_0(L)}$$

$E_\lambda(L)$ ⟵ energy variation associated with λQ

$\Delta_0(L)$ ⟵ lowest energy gap

$$\tau_T = \frac{T}{\Delta_0(L)}$$

T ⟵ temperature ($k_B = 1$)

scaling variables

$$O(L, \lambda, T) \approx L^{-y_o}\, \mathcal{O}(\kappa, \tau_T)$$

M. Campostrini, A. Pelissetto, E. Vicari, *Phys. Rev. B* **89**, 094516 (2014)

M. Campostrini, J. Nespolo, A. Pelissetto, E. Vicari, *Phys. Rev. Lett.* **113**, 070402 (2014)

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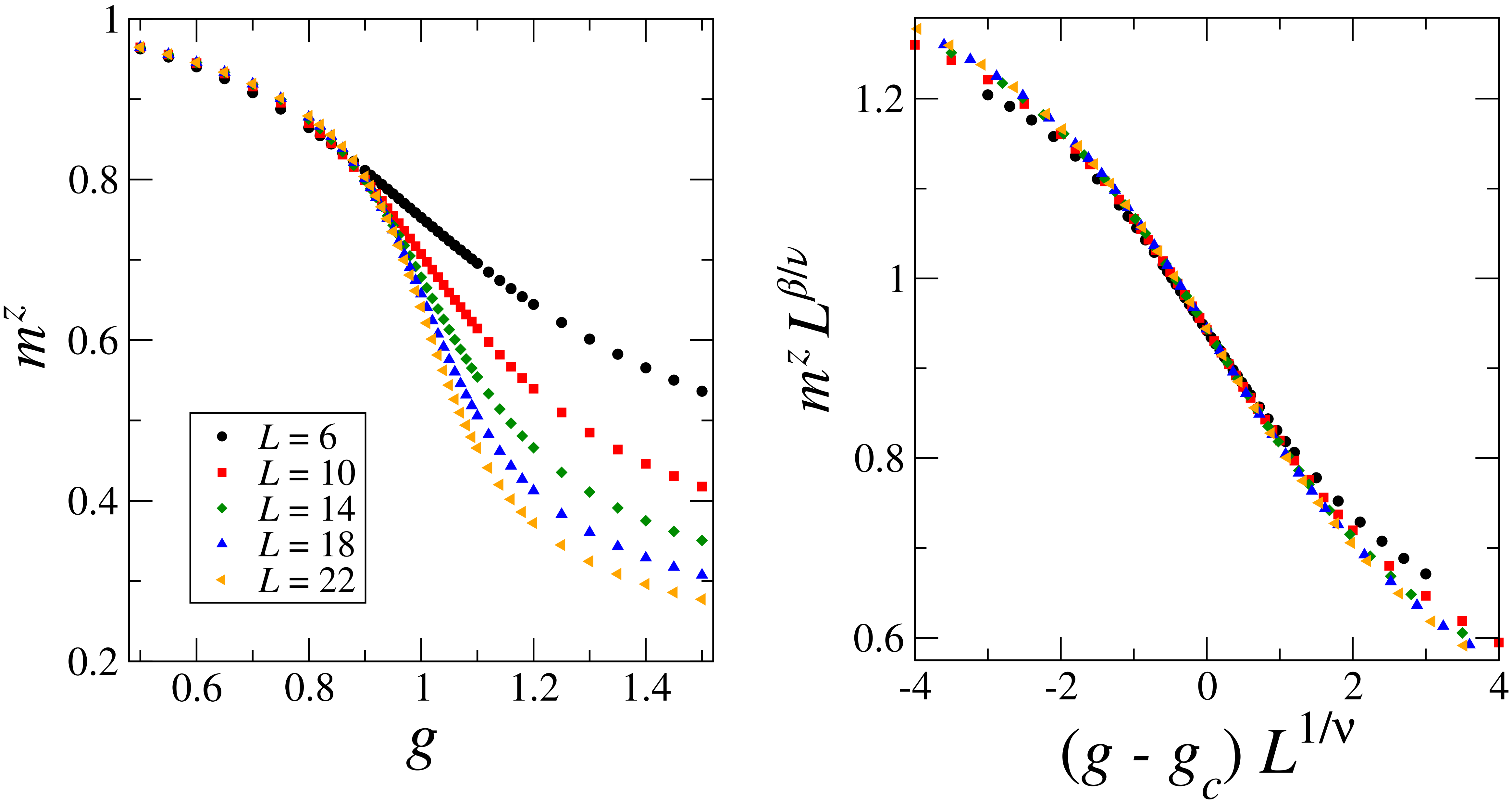
Finite-size scaling @ CQT

$$m^z \approx L^{-y_m} \mathscr{M}(\kappa) \qquad\qquad \kappa = (g - g_c)\, L^{y_g}$$

At a CQT, critical exponents can be viewed as scaling dimensions associated with operators and perturbations.



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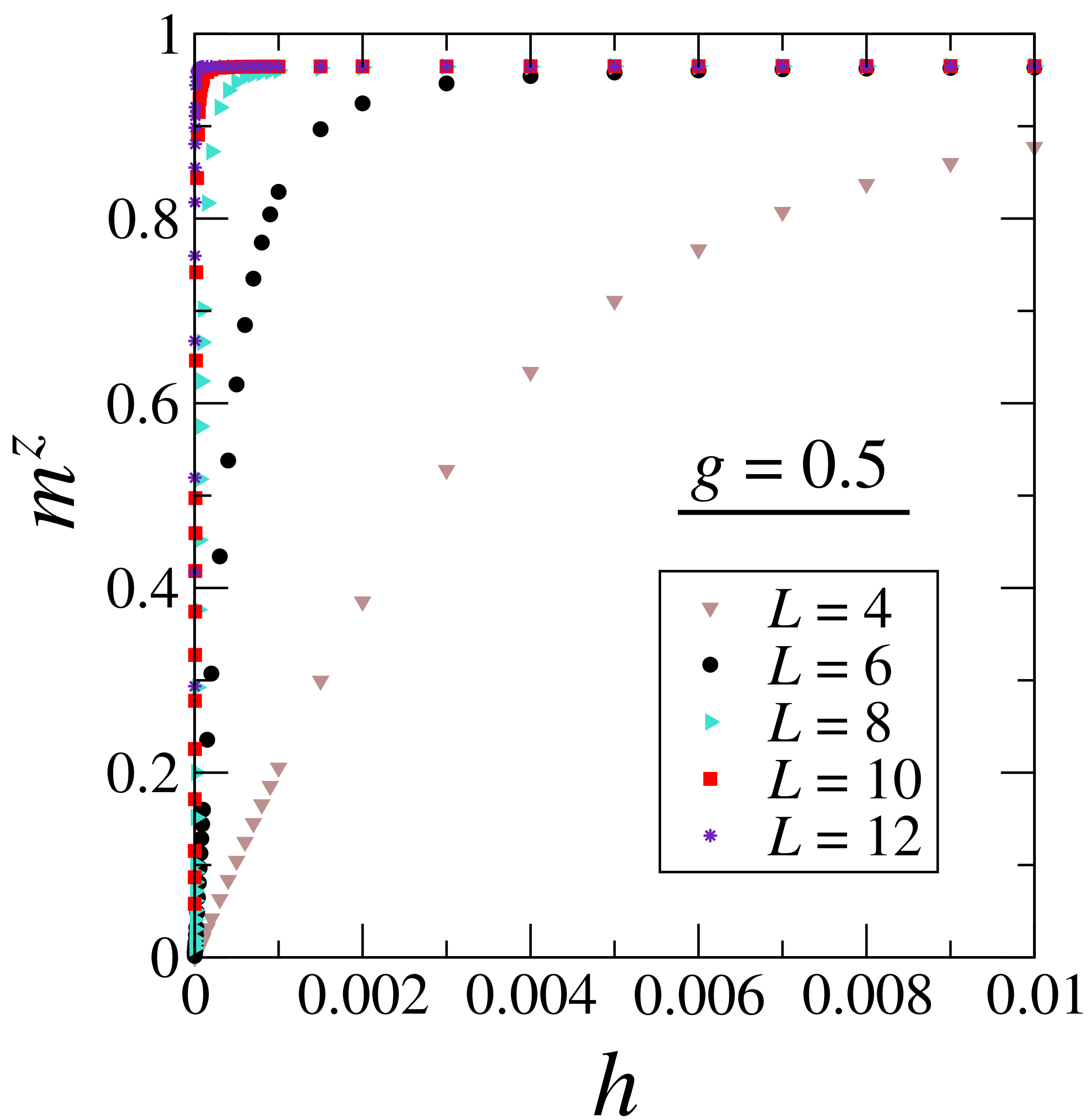
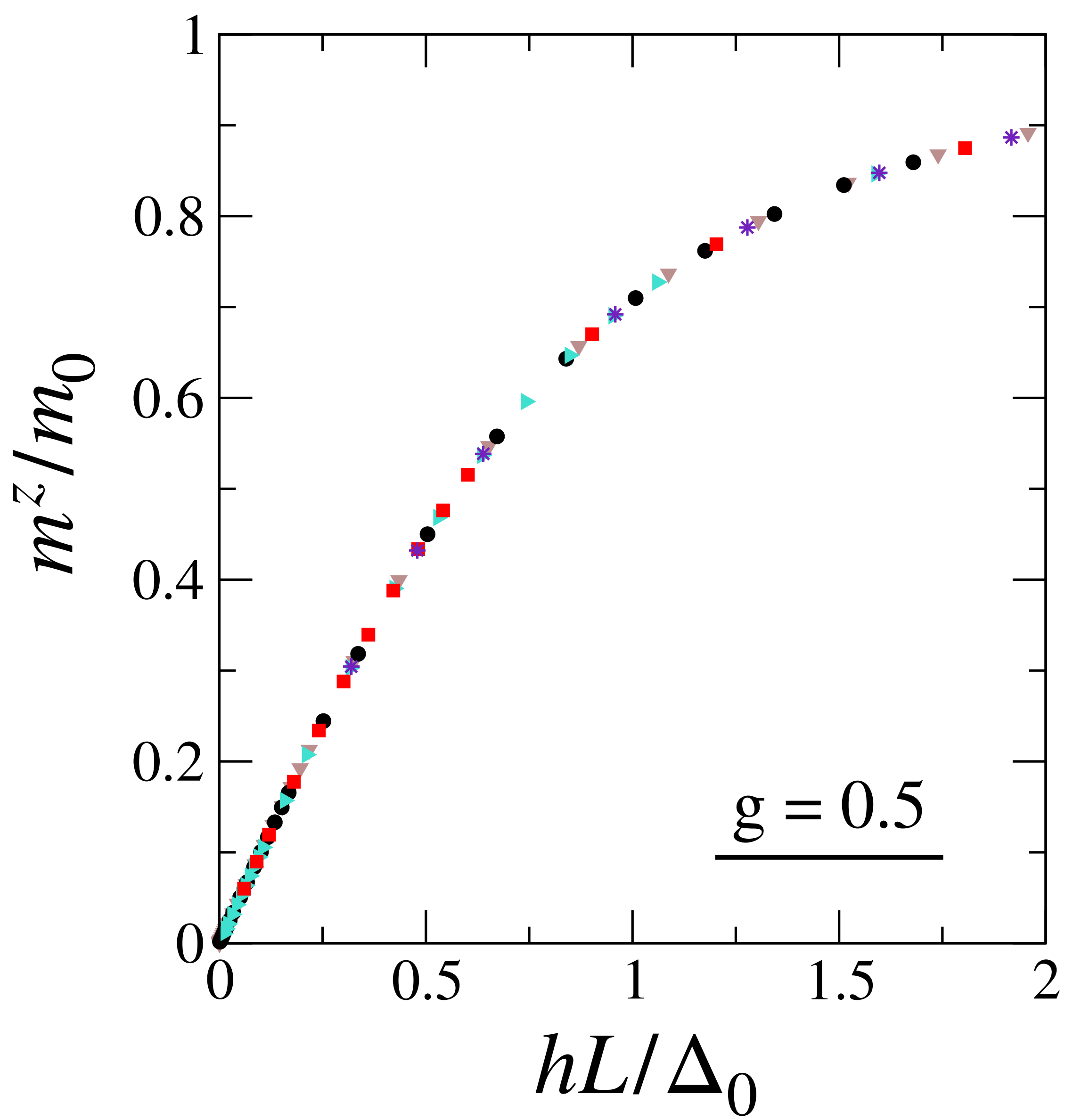
Finite-size scaling @ FOQT

$$m^z \approx m_0 \,\mathcal{M}(\kappa) \qquad\qquad \kappa = hL/\Delta_0$$

At a FOQT, there are no diverging correlation lengths.
Scaling arises by the competition between two quasi-degenerate ground states.





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Turning to out-of-equilibrium conditions

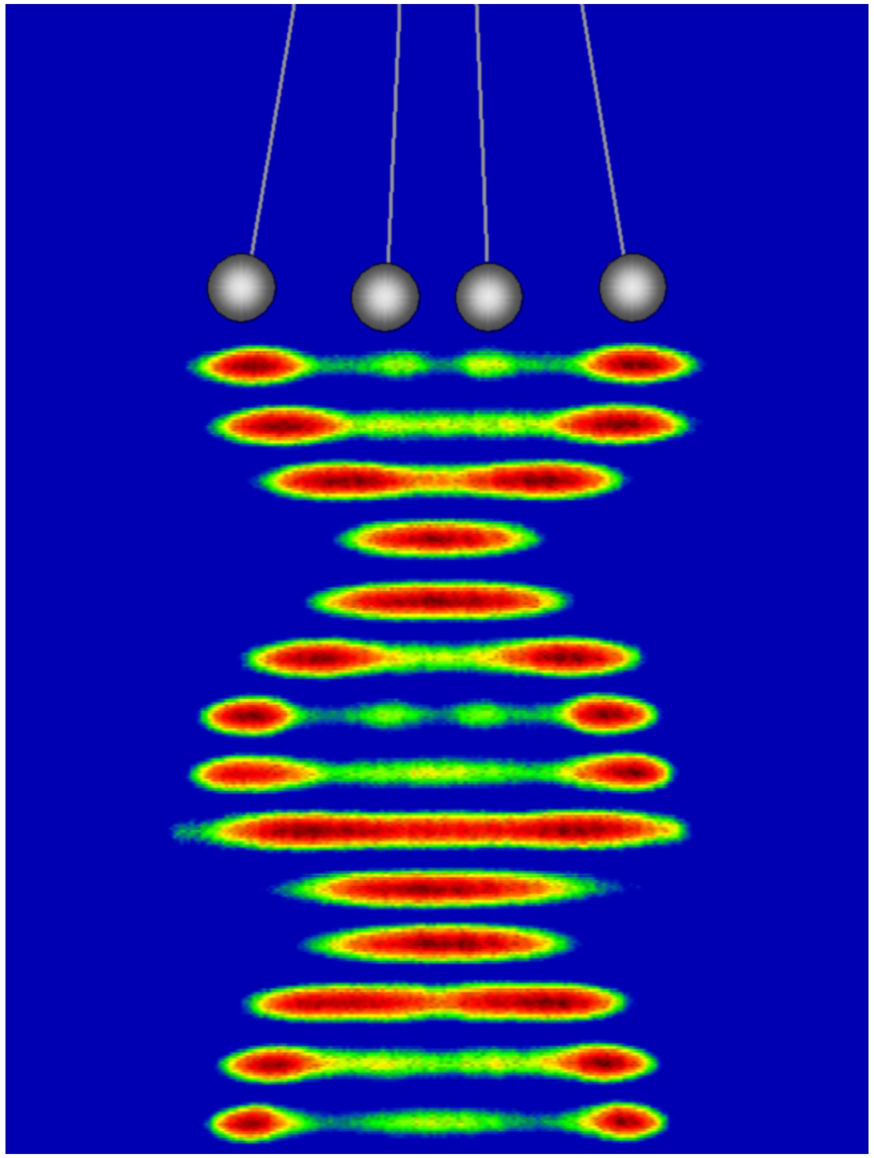
Isolated quantum dynamics

Quantum quench:

$$H[\lambda(t)] = H_0 + \lambda(t)\, P$$

$$\lambda(t) = \begin{cases} \lambda_i & \text{for } \; t < 0 \\ \lambda_f & \text{for } \; t > 0 \end{cases}$$

$$|\,\Psi(t)\rangle = e^{-i\,H[\lambda_f]\,t}\,|\,\Psi_{\rm gs}(\lambda_i)\rangle$$



T. Kinoshita, W. Trevor, D.S. Weiss, *Nature* **440**, 900 (2006)

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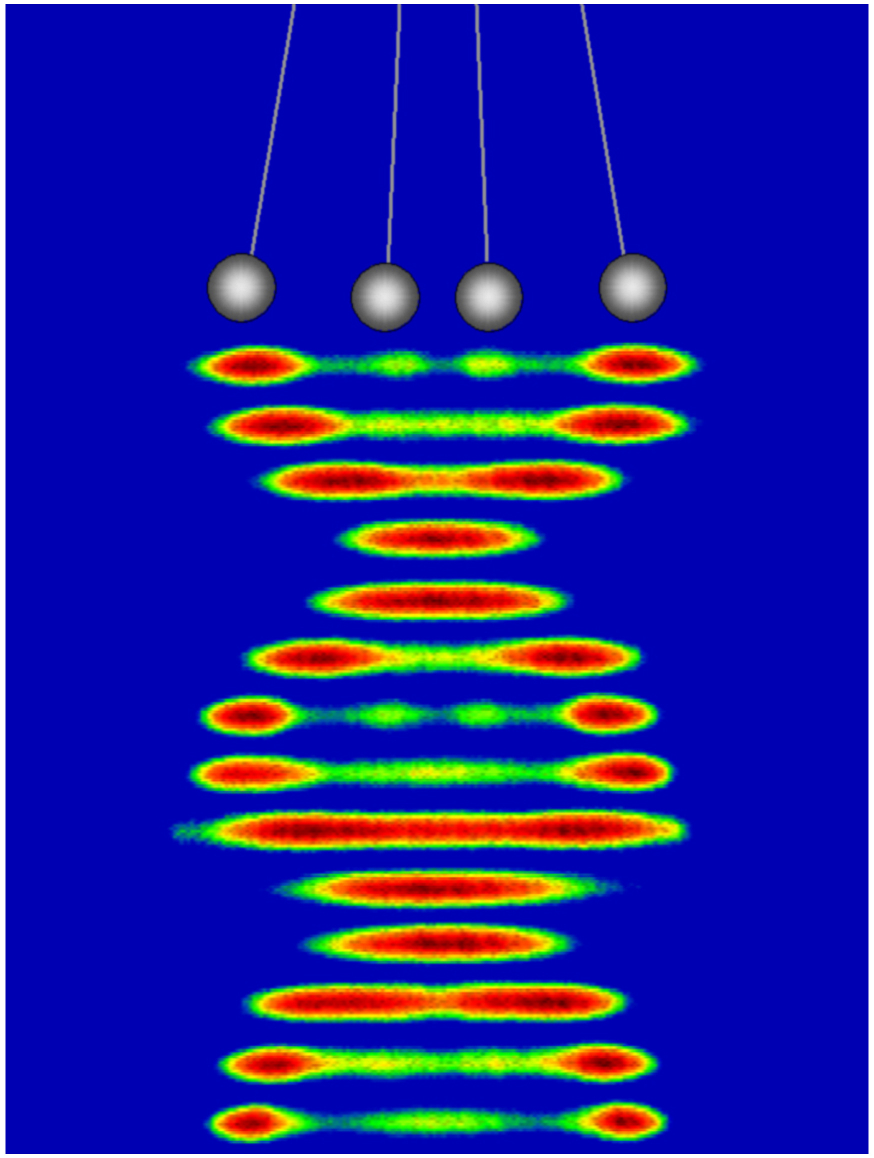
$$|\Psi(t)\rangle = e^{-i\,H[\lambda_f]\,t}\,|\Psi_{\rm gs}(\lambda_i)\rangle$$

A new scaling variable enters:

$$\theta = \Delta_0(L)\; t$$

D. Rossini, E. Vicari, *Phys. Rep.* **936**, 1 (2021)



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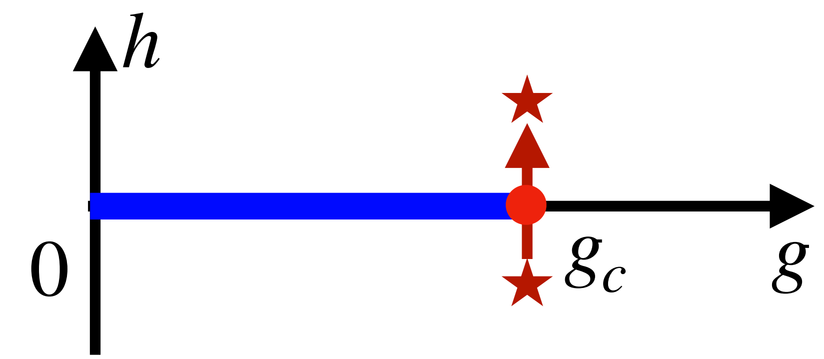
Scaling after a quench @ CQT

$$H = -\sum_j (\sigma_j^z \sigma_{j+1}^z + \sigma_j^x) - h(t) \sum_j \sigma_j^z$$



$$\kappa_i = h_i \, L^{y_\lambda}$$

$$\kappa_f = h_f \, L^{y_\lambda}$$

soft quench

Scaling after a quench @ CQT

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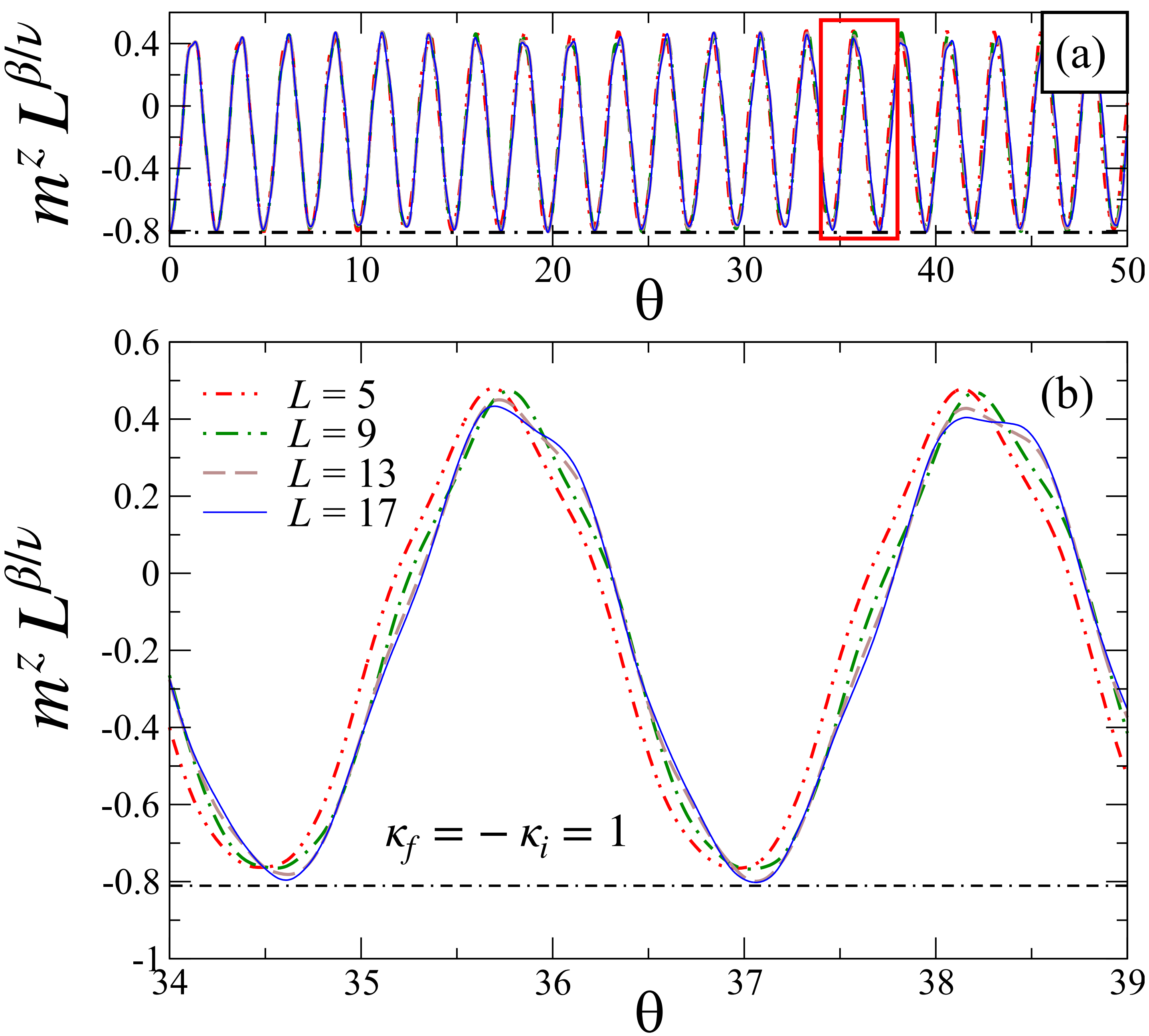

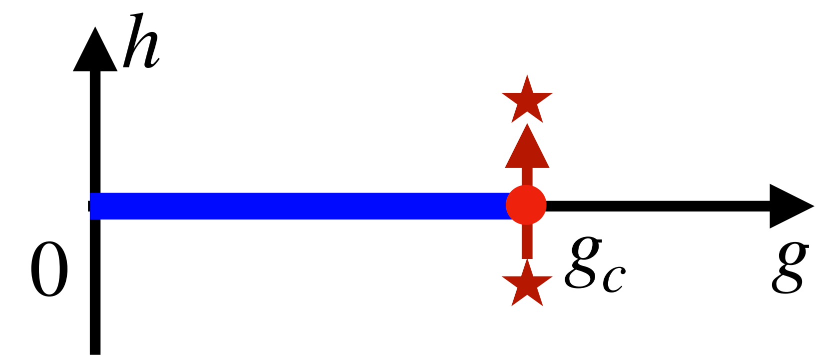

$$\kappa_i = h_i L^{y_\lambda}$$

$$\kappa_f = h_f L^{y_\lambda}$$

soft quench

$$\boxed{\theta = L^{-z} t}$$

$$m^z(t) \approx L^{-y_m} \mathscr{M}\left[\theta; \kappa_i, \kappa_f\right]$$

A. Pelissetto, D. Rossini, E. Vicari, *Phys. Rev. E* **97**, 032148 (2018)

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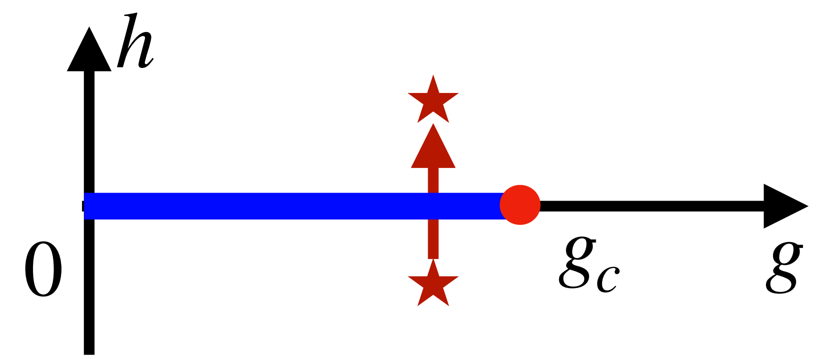
Scaling after a quench @ FOQT

$$H = -\sum_j (\sigma_j^z \sigma_{j+1}^z + g\sigma_j^x) - h(t)\sum_j \sigma_j^z$$



$$\kappa_i = h_i\, L / e^{-aL}$$
$$\kappa_f = h_f\, L / e^{-aL}$$

soft quench

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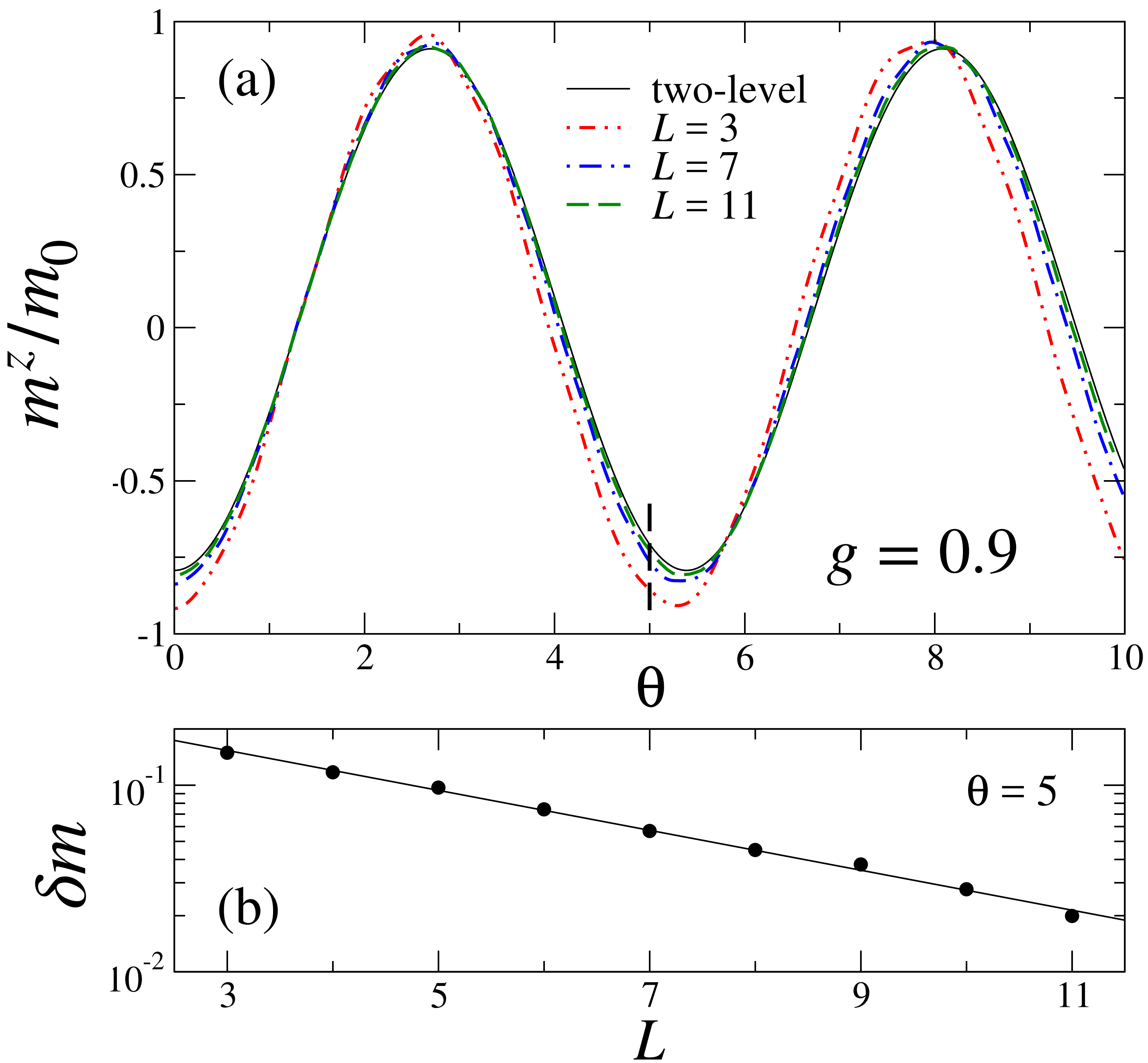

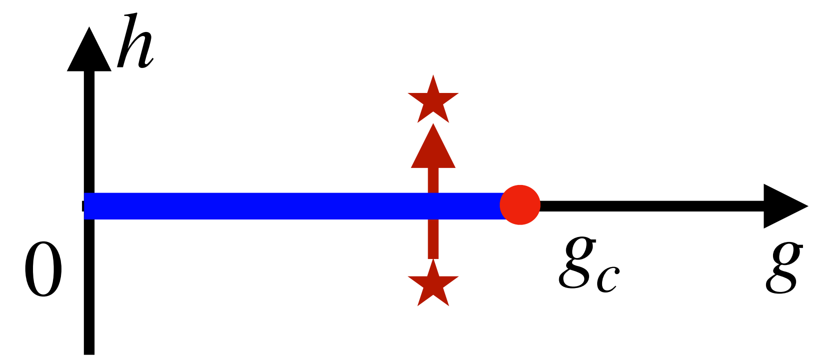

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soft
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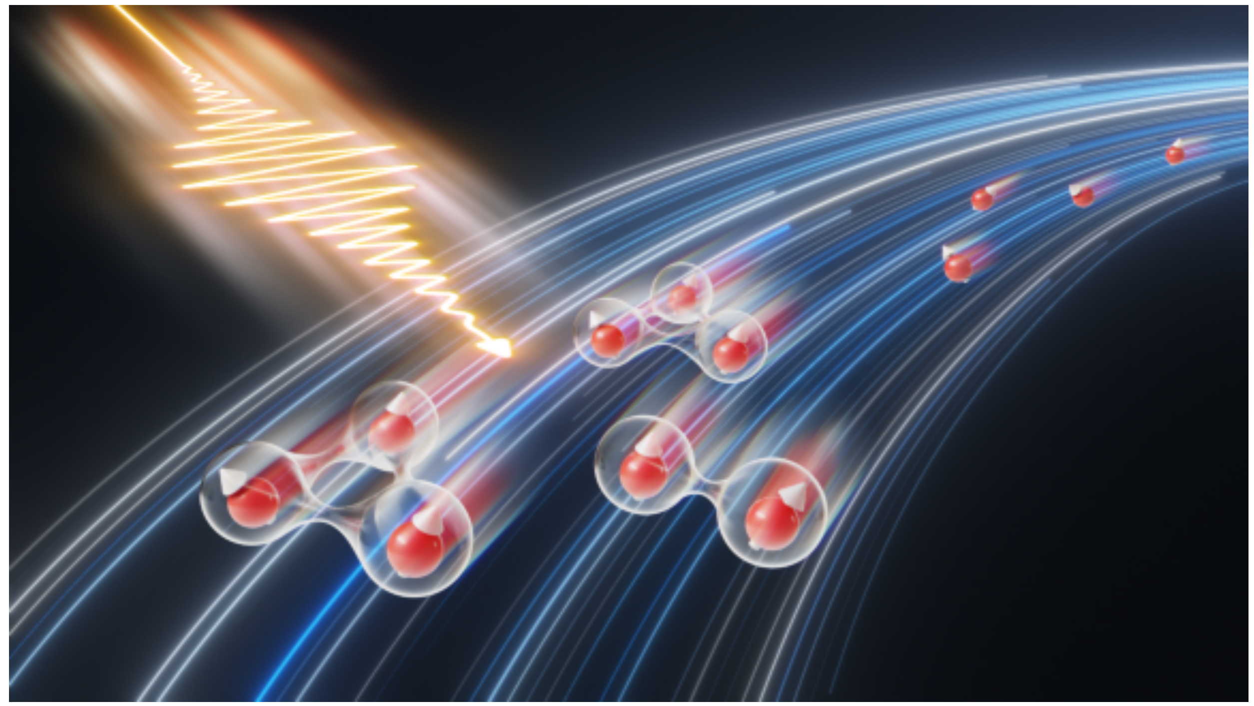
May scaling survive in open quantum systems?



$$\dot{\rho} = -\, i\big[H, \rho\big] + u \sum_{\mu} \mathscr{D}[L_\mu]\, \rho$$

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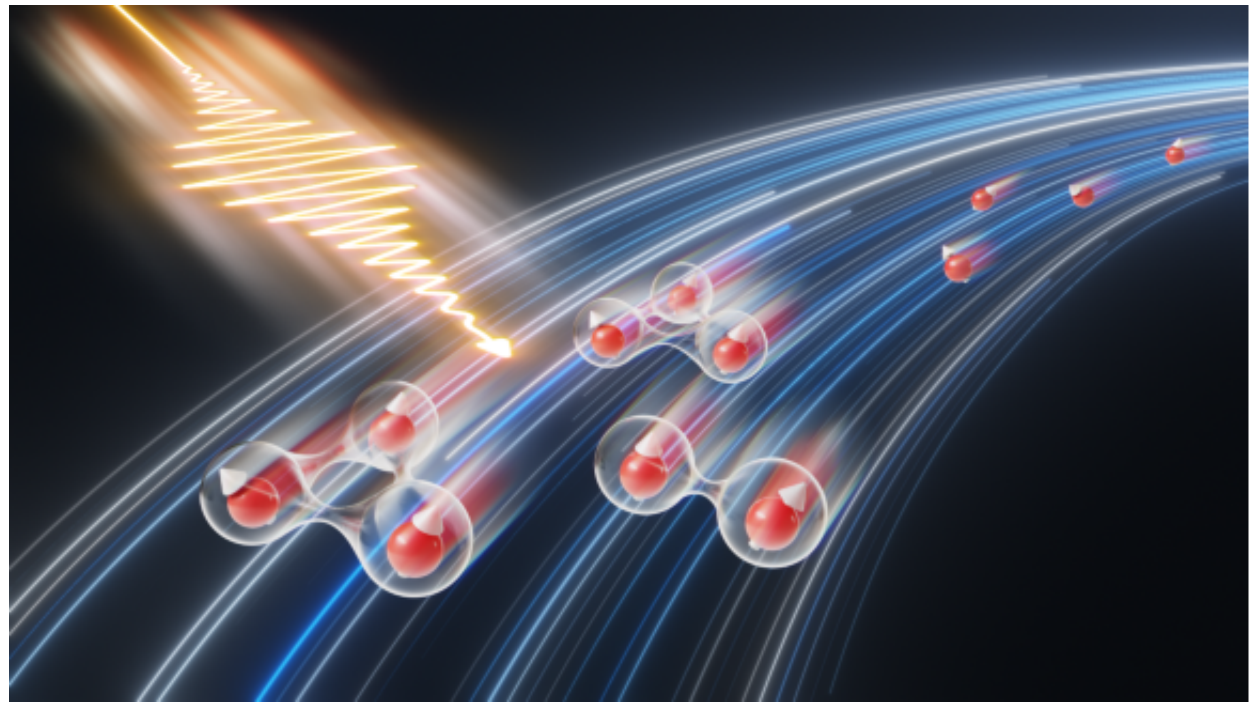

$$\dot{\rho} = -\,i\big[H,\rho\big] + u\sum_{\mu}\mathscr{D}[L_\mu]\,\rho$$

Dissipation induces a new relevant time scale

An additional scaling variable enters:

$$\gamma = u/\Delta_0(L)$$

D. Rossini, E. Vicari, *Phys. Rep.* **936**, 1 (2021)

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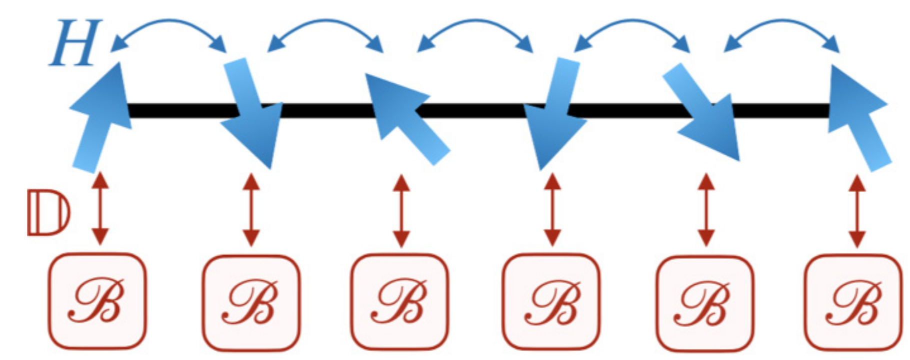
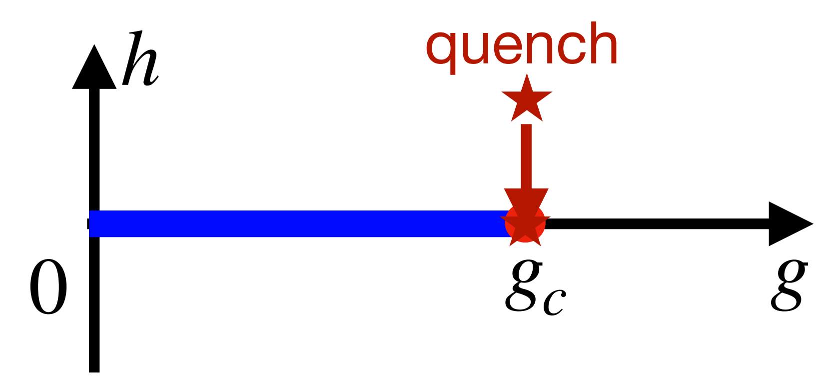
Scaling with dissipation @ CQT

$$H = -\sum_j (\sigma_j^z \sigma_{j+1}^z + \sigma_j^x) - h(t) \sum_j \sigma_j^z$$

$$\mathscr{D}[\rho] = \sum_j \sigma_j^- \rho \sigma_j^+ - \frac{1}{2}\{\rho, \sigma_j^+ \sigma_j^-\}$$





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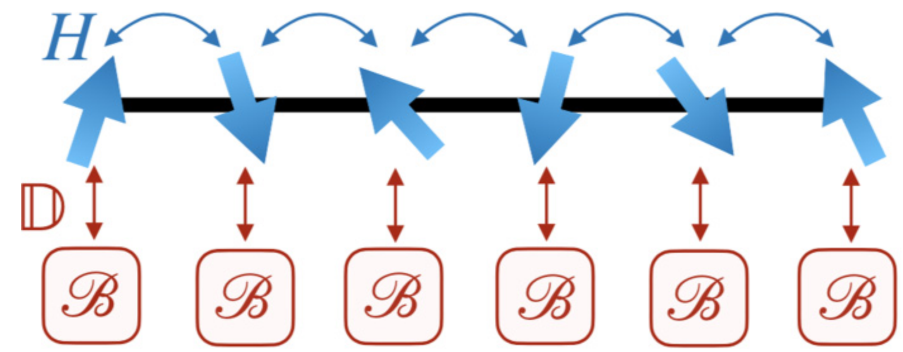

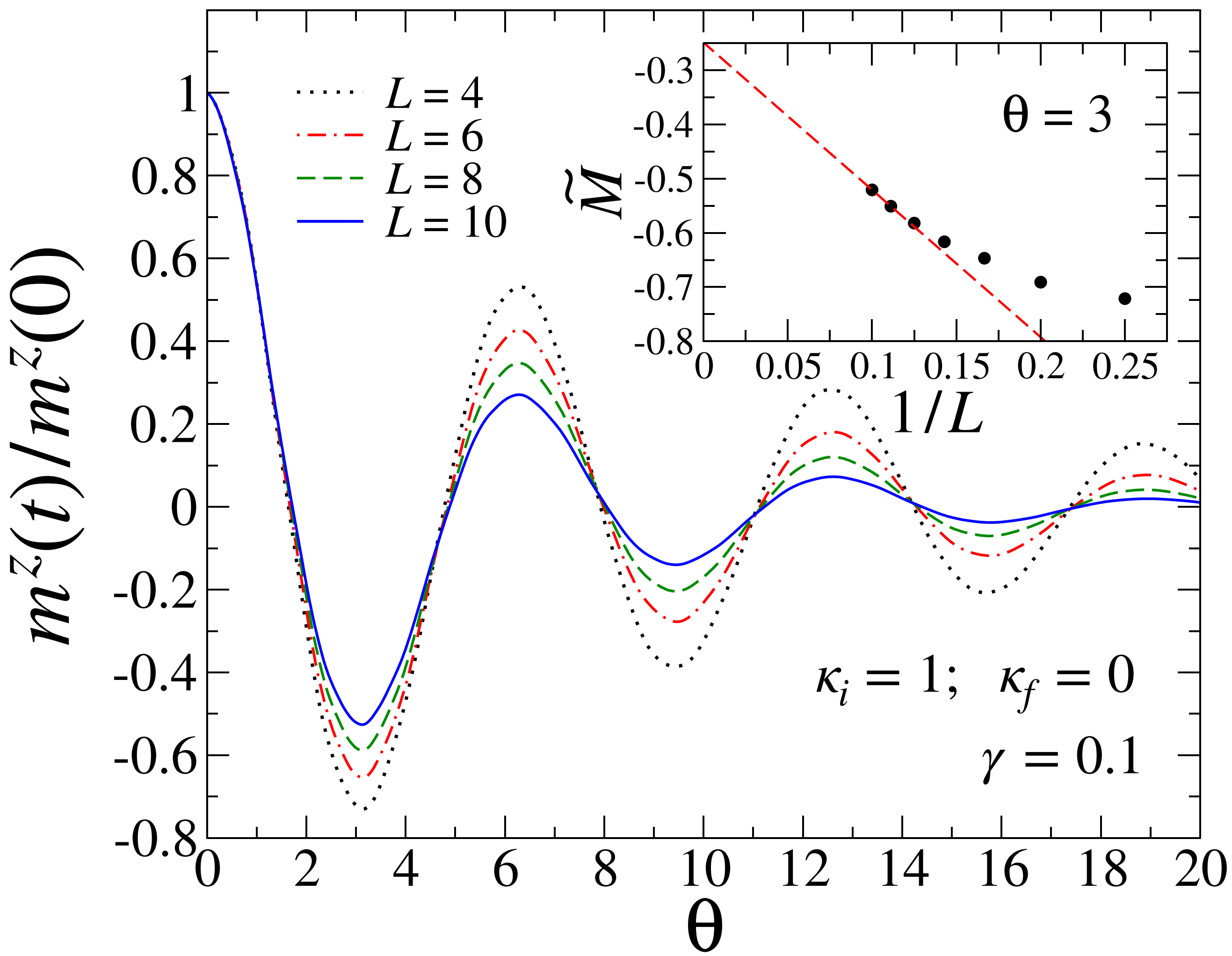

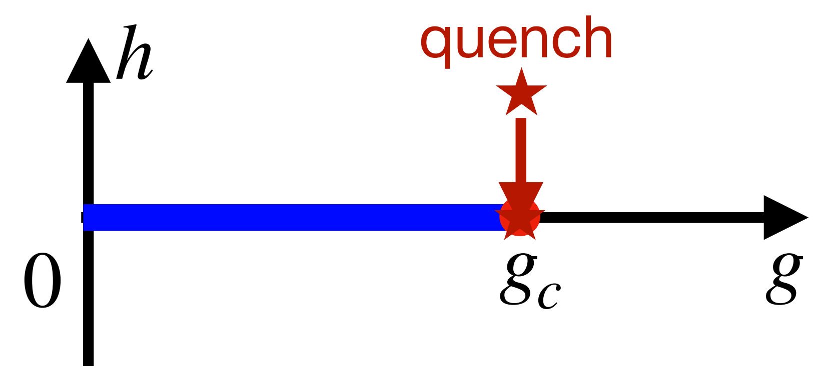

$$\boxed{\gamma = L^z u}$$

$$m^z(t) \approx L^{-y_m} \mathscr{M}\left[\theta; \kappa_i, \kappa_f, \gamma\right]$$

G. Di Meglio, D. Rossini, E. Vicari, *Phys. Rev. B* **102**, 224302 (2020)

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Scaling with dissipation @ FOQT

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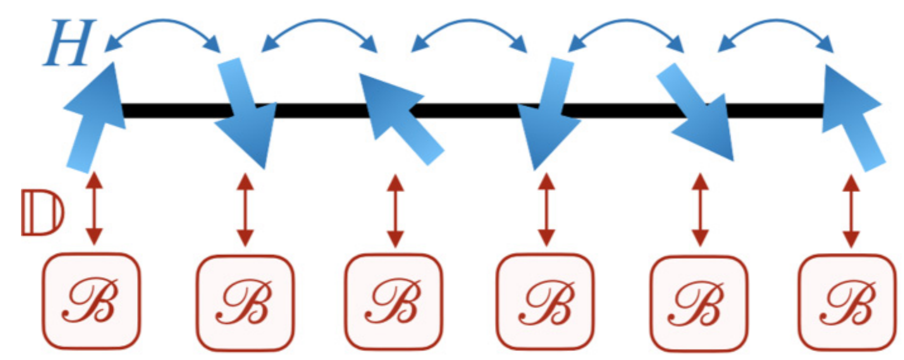

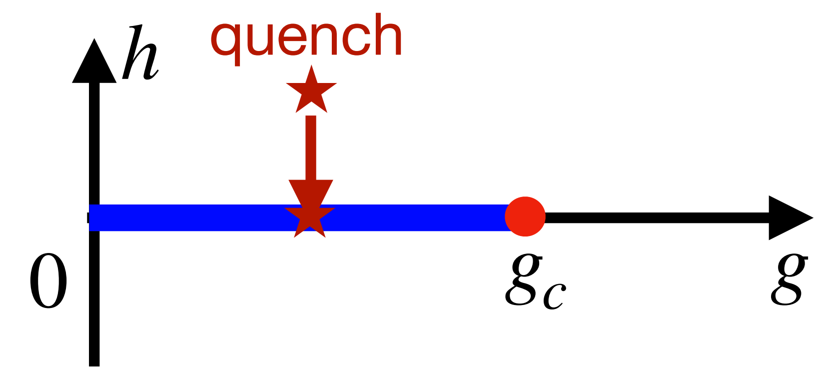

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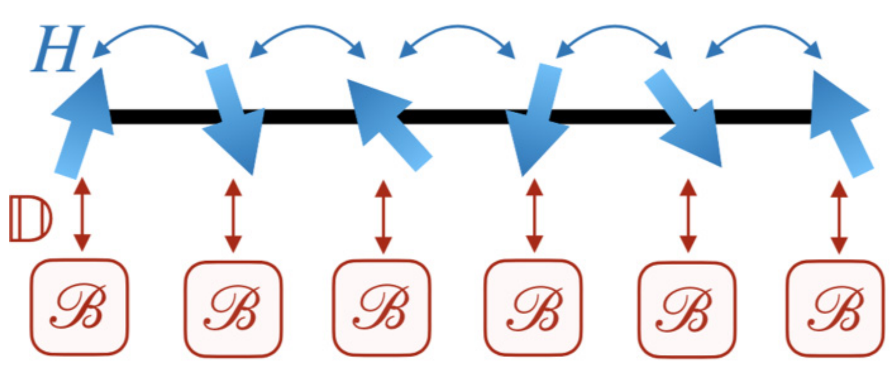

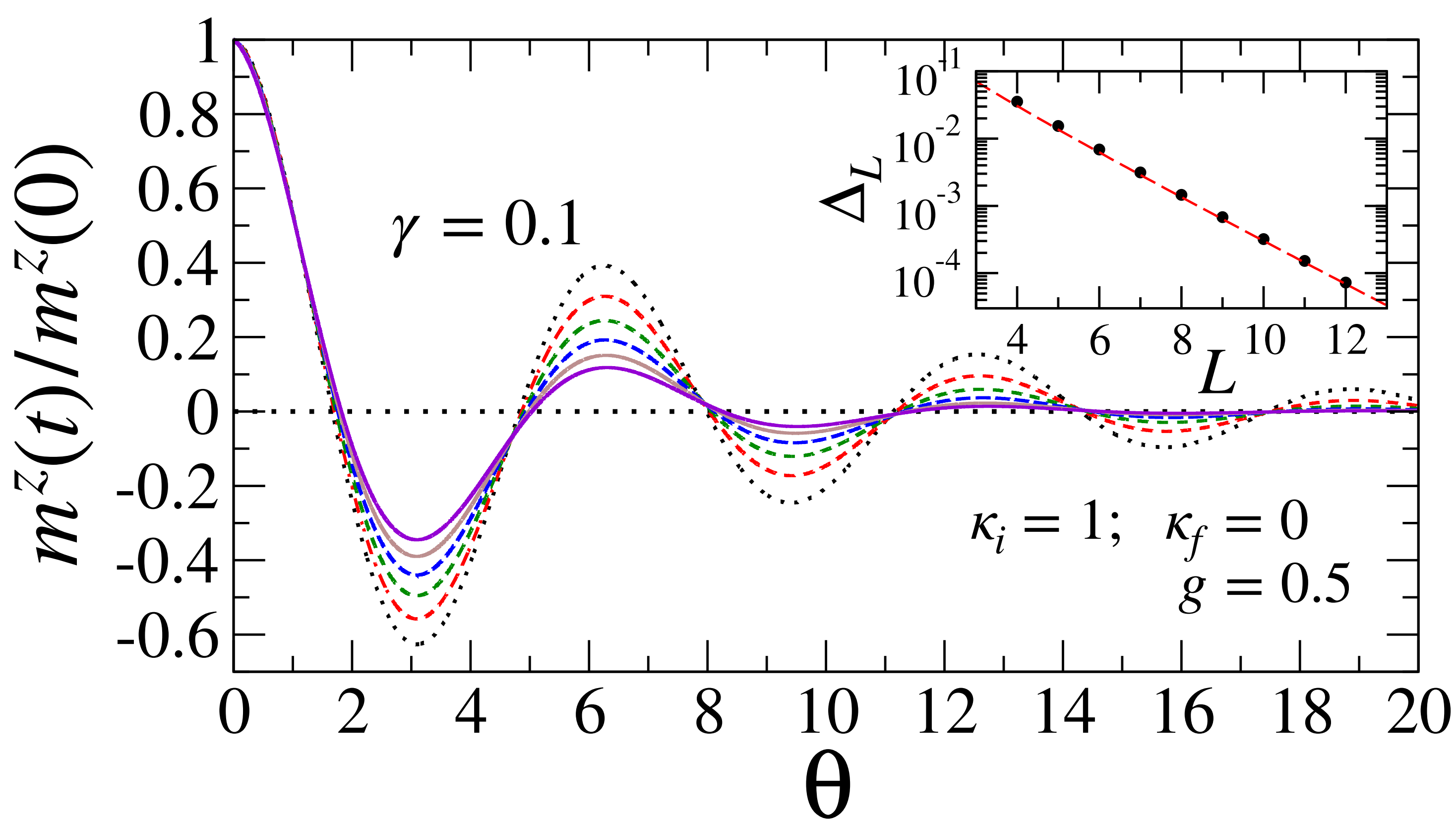

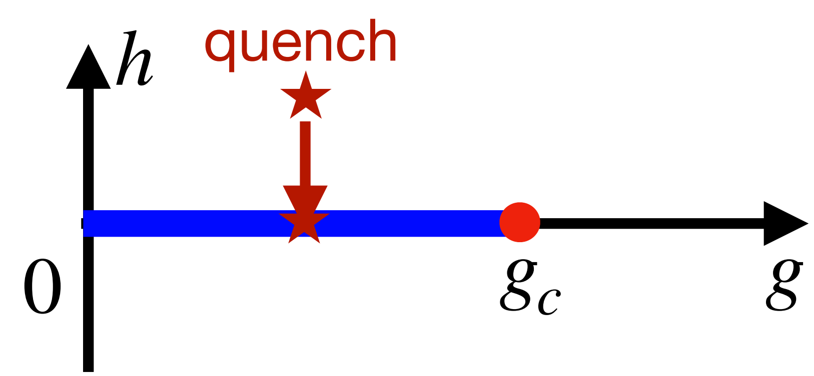

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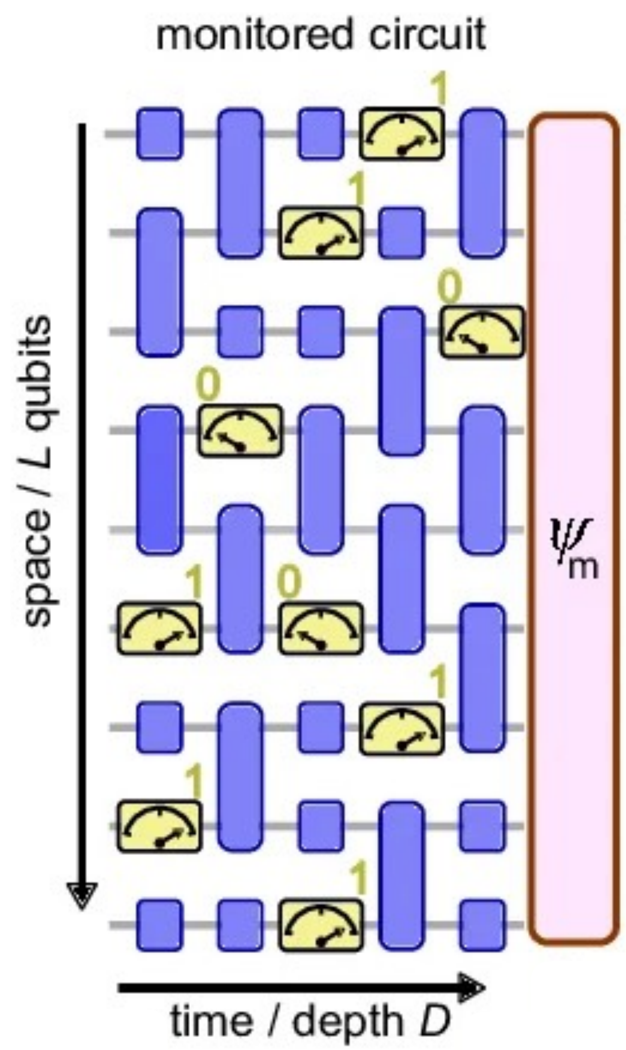
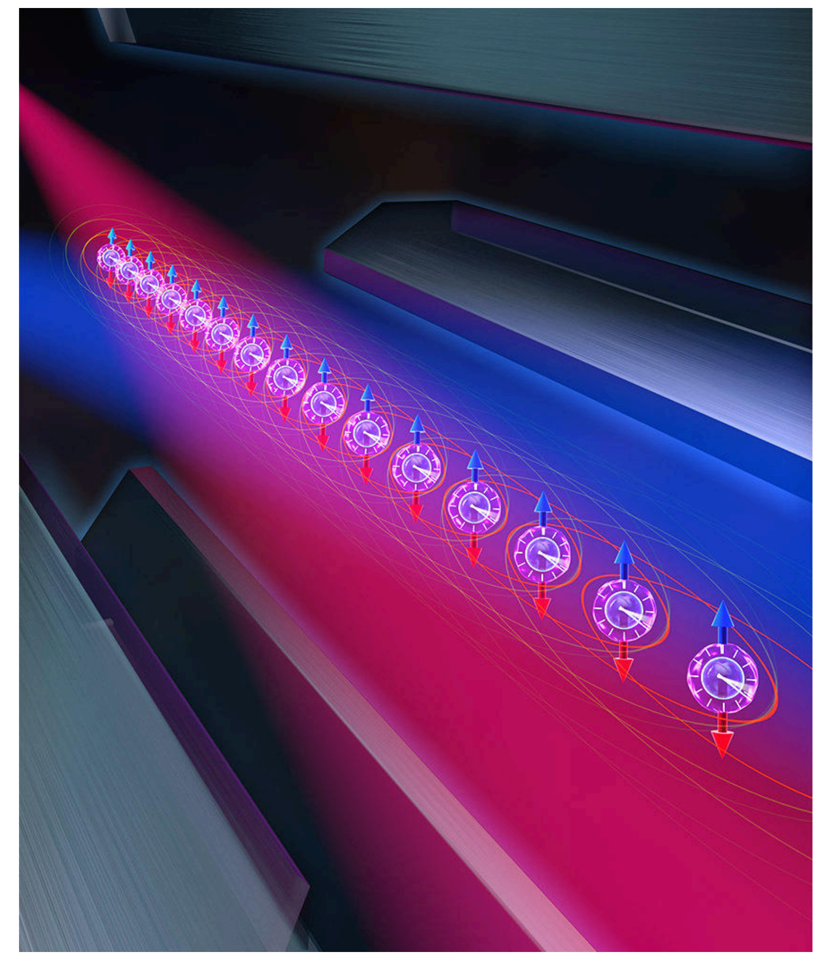
Measurement-induced quantum many-body dynamics





Y. Li, X. Chen, M.P.A. Fisher, *Phys. Rev. B* **98**, 205136 (2018), *ibid.* **100**, 134306 (2019)
B. Skinner, J. Ruhman, A. Nahum, *Phys. Rev. X* **9**, 031009 (2019)
X. Cao, A. Tilloy, A. De Luca, *SciPost Phys.* **7**, 024 (2019)
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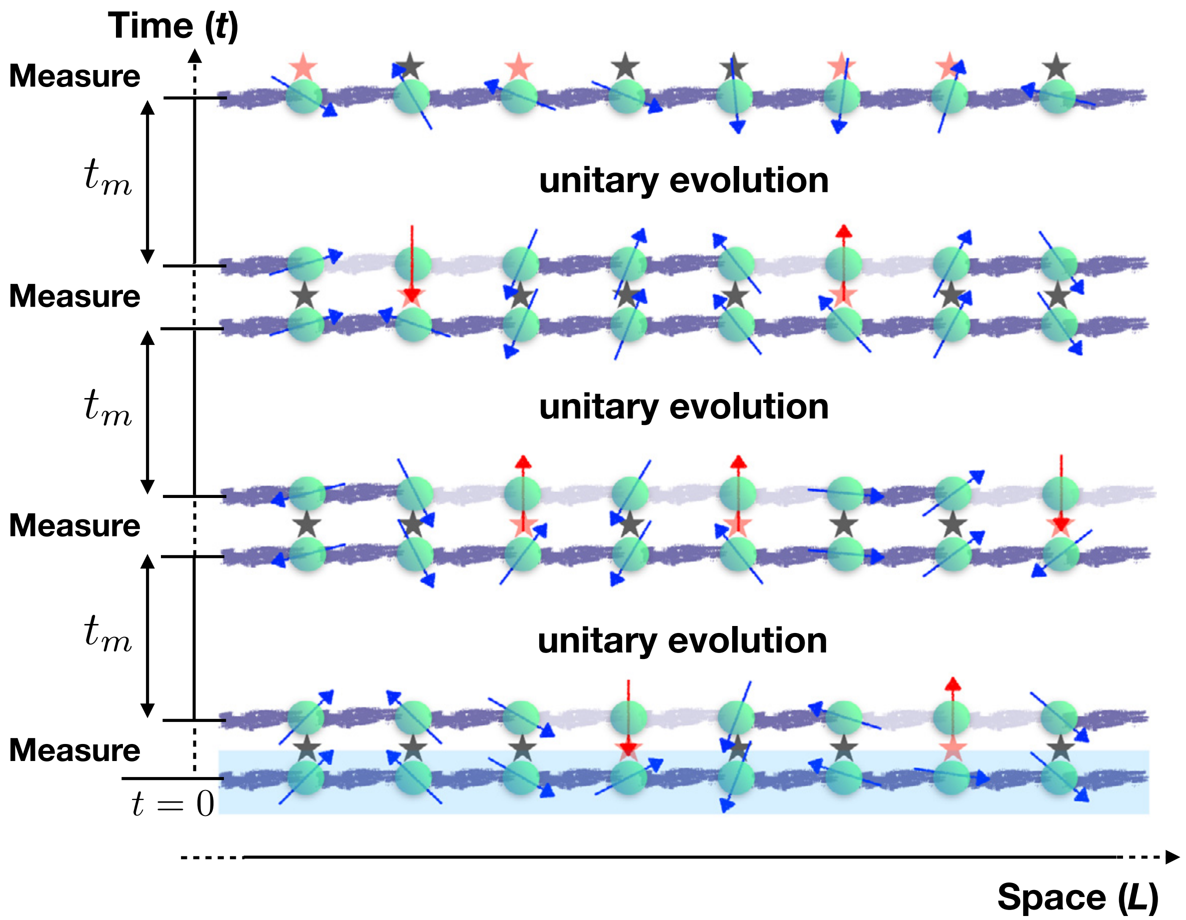
Does scaling survive here?



A quantum spin chain, initially at criticality, is perturbed with local (onsite) projective measurements.

They occur after every time interval t_m, with uniform probability p per site.

In between two measurement steps, the system evolves unitarily.

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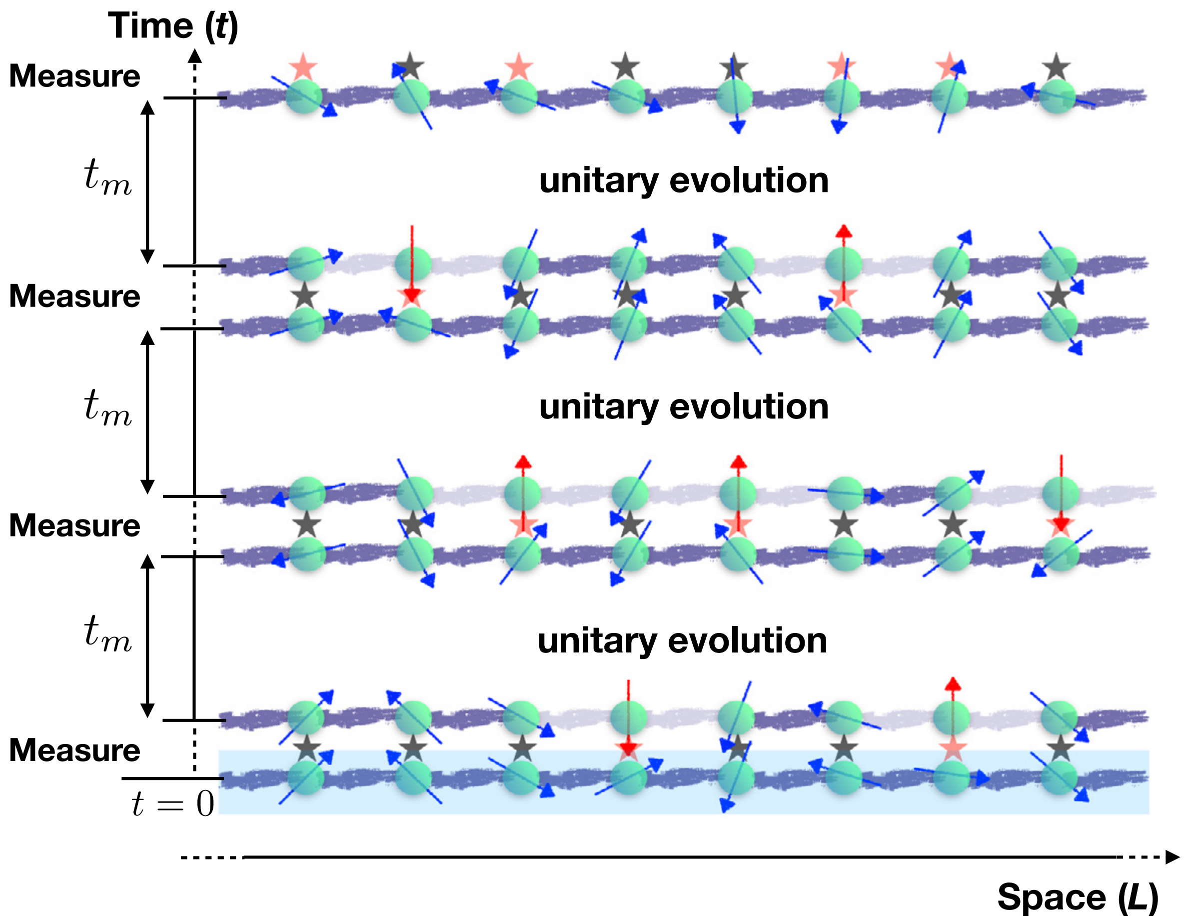

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In between two measurement steps, the system evolves unitarily.

- Scaling variable for the time interval: $\Delta_0(L)\, t_m$
- Scaling variable for the probability measurements: $p\, L^{z+d}$

D. Rossini, E. Vicari, *Phys. Rev. B* **102**, 035119 (2020)

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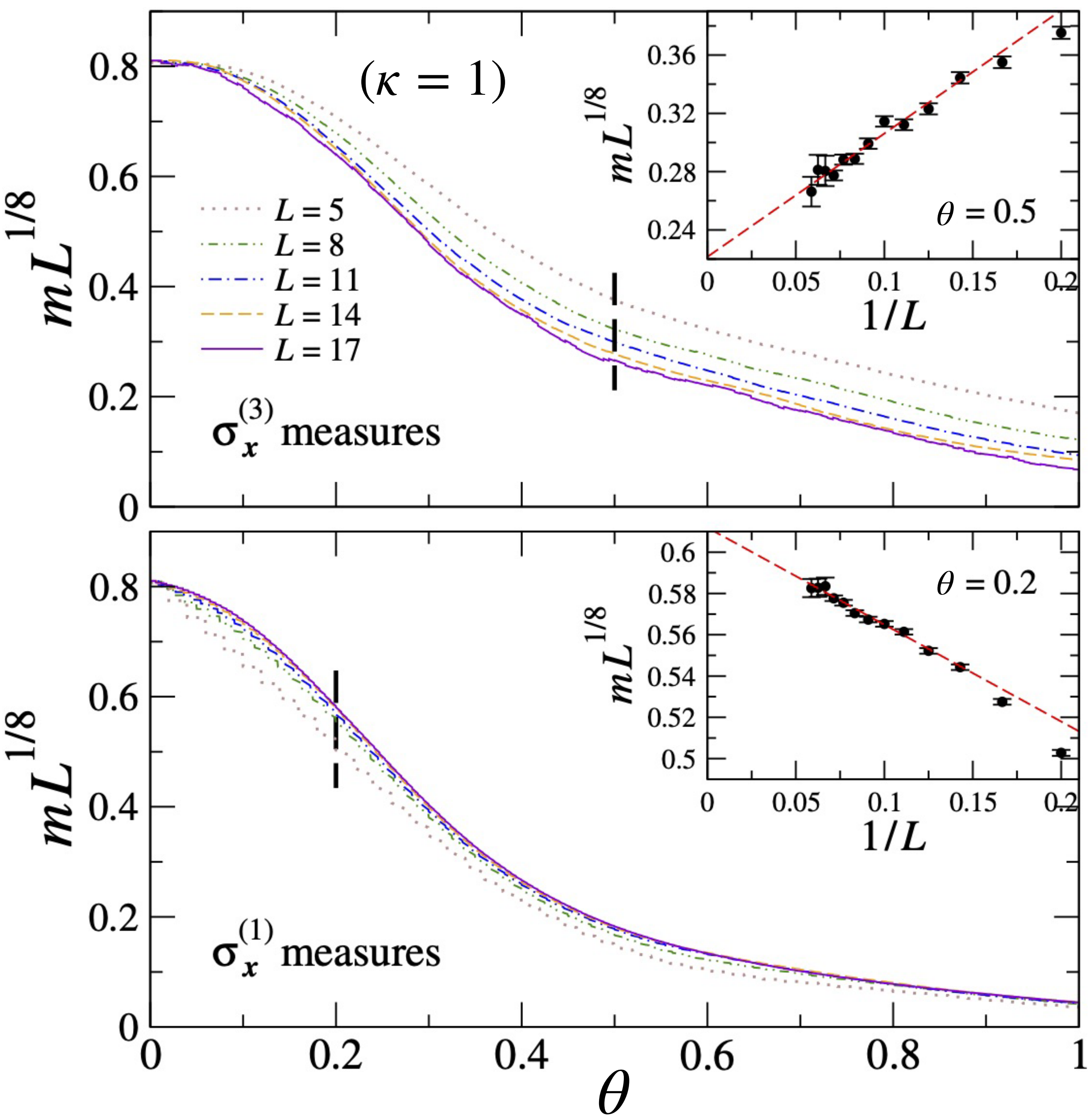
Scaling in monitored systems @ CQT

$$H = -\sum_j \left(\sigma_j^z \sigma_{j+1}^z + \sigma_j^x + h\sigma_j^z\right)$$



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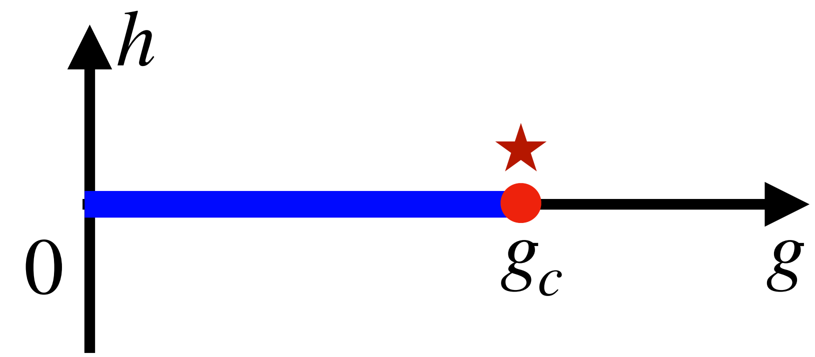

$t_m = 0.1$, $\boxed{p = L^{-(z+d)}}$

We keep t_m fixed

→ this originates $O(L^{-1})$ corrections

The probability p of measuring is

→ per unit of time (L^{-z})

→ per unite of space (L^{-d})

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Conclusion

Distinct spectral mechanisms lead to **emergent scaling behavior**

Continuous transitions → critical gap closing

First-order transitions → competing ground states

- Scaling behavior survives *quantum dynamics*
- *Dissipation & measurements* induce new scaling variables
- Universality not restricted to equilibrium if only low-energy modes are excited

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