Dynamics of Cavity QED Simulators of Frustrated Quantum Matter

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SPICE workshop, Ingelheim, June 2024

In collaboration with : Darrick Chang (ICFO) and Jamir Marino (JGU)

arXiv:2311.05682
arXiv:2312.11624

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
QuCoLiMa TRR 306
QUANTERA ERA-NET Cofund in Quantum Technologies

Theory

Theory

Spintronics

Spin waves

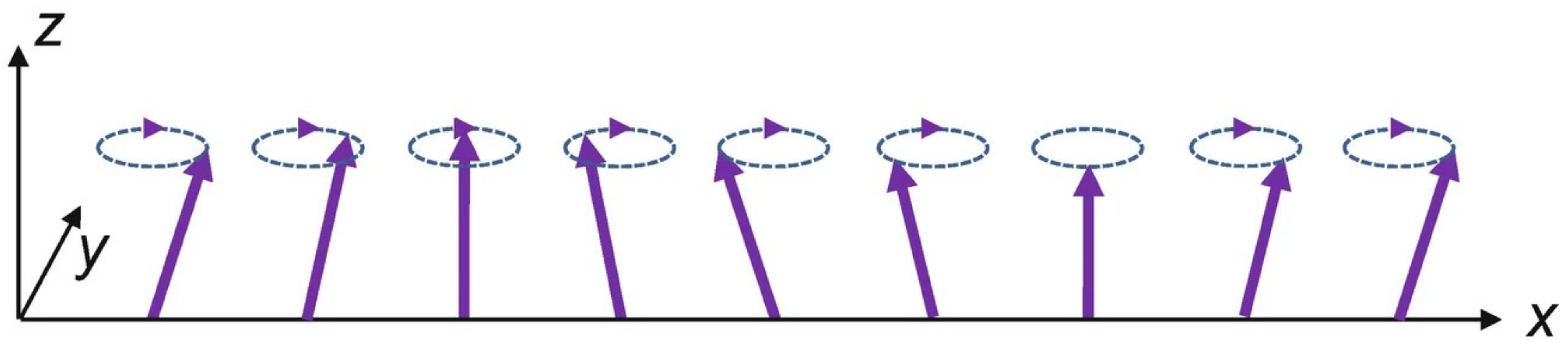

Figure: Rezende, *Fundamentals of Magnonics*

Spin size $\frac{S}{\hbar} \approx 14$ (for YIG)

Quantum fluctuations $\sim e^{-S/\hbar} \ll 1 \rightarrow$ **classical**

Landau-Lifshiftz-Gilbert equation

$$\frac{d\vec{S}}{dt} = -\gamma\left(\vec{S} \times \vec{H}_{\mathrm{eff}} - \eta\vec{S} \times \frac{d\vec{S}}{dt}\right)$$

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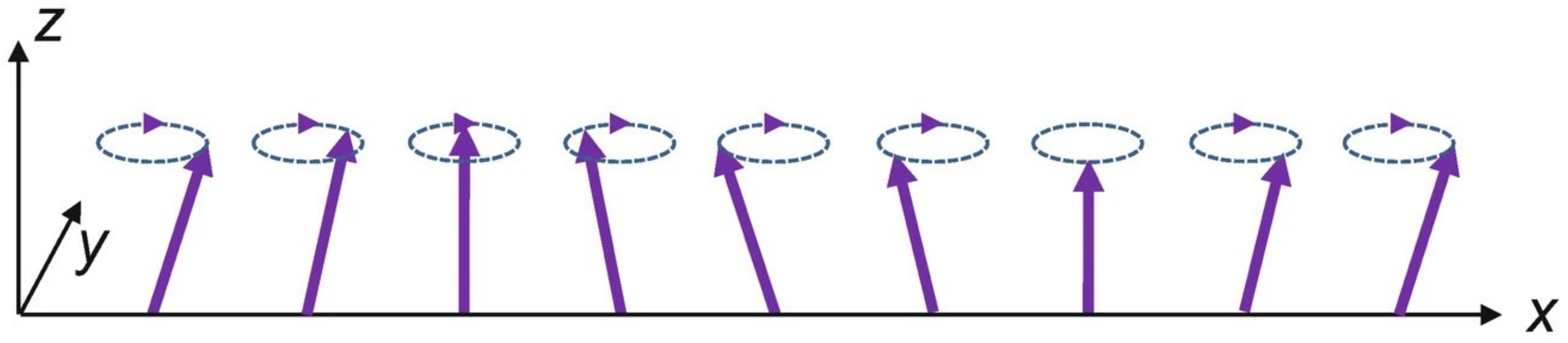

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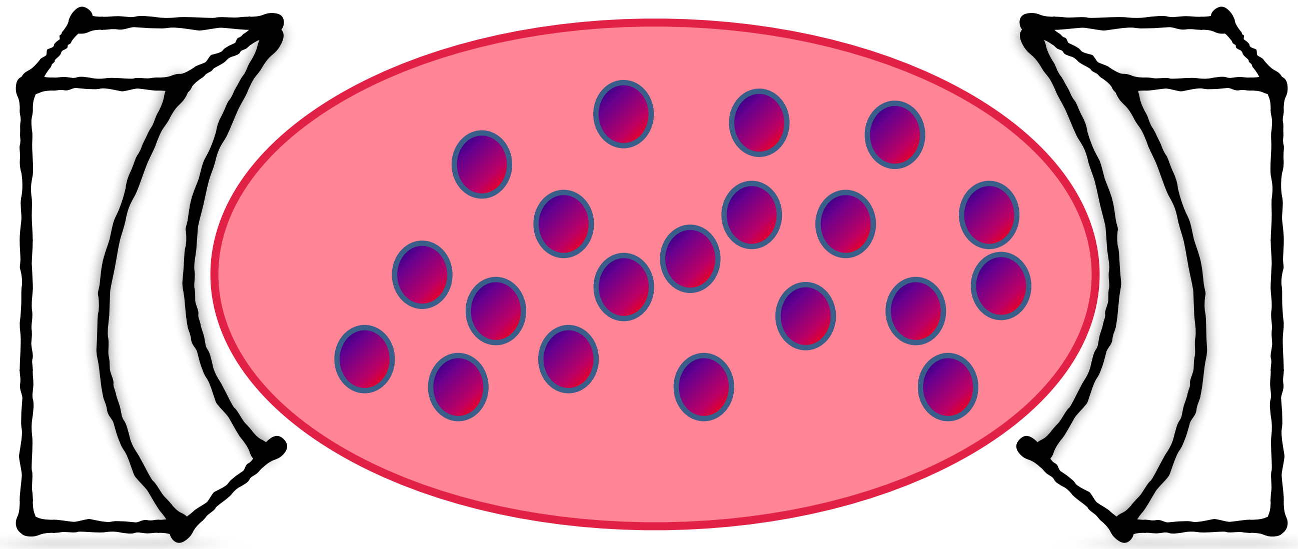
Cavity QED

Collective interactions



$$H \sim (a + a^\dagger) \sum_i \sigma_i^x$$

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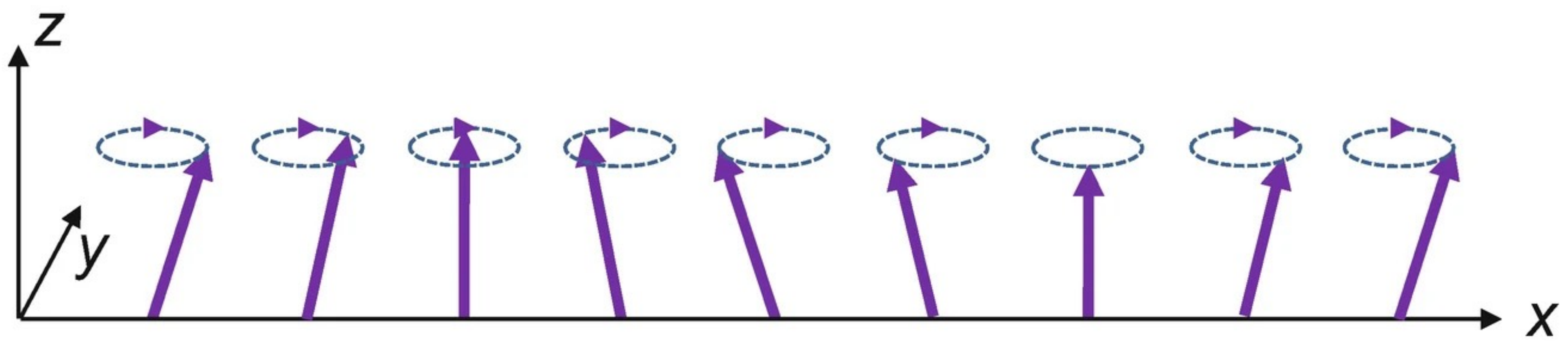

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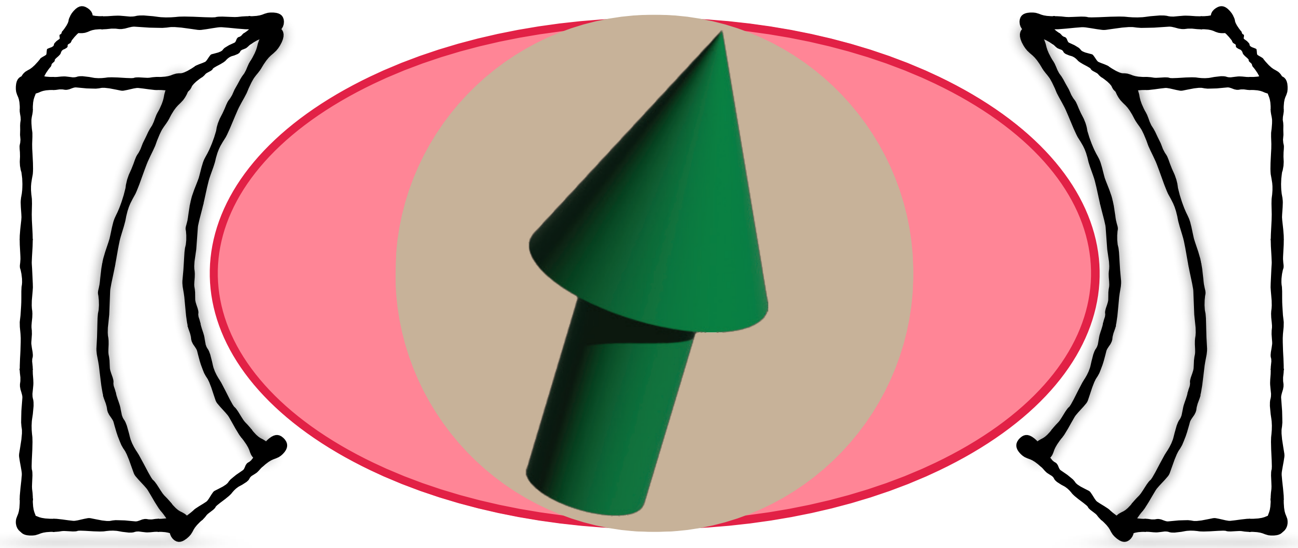

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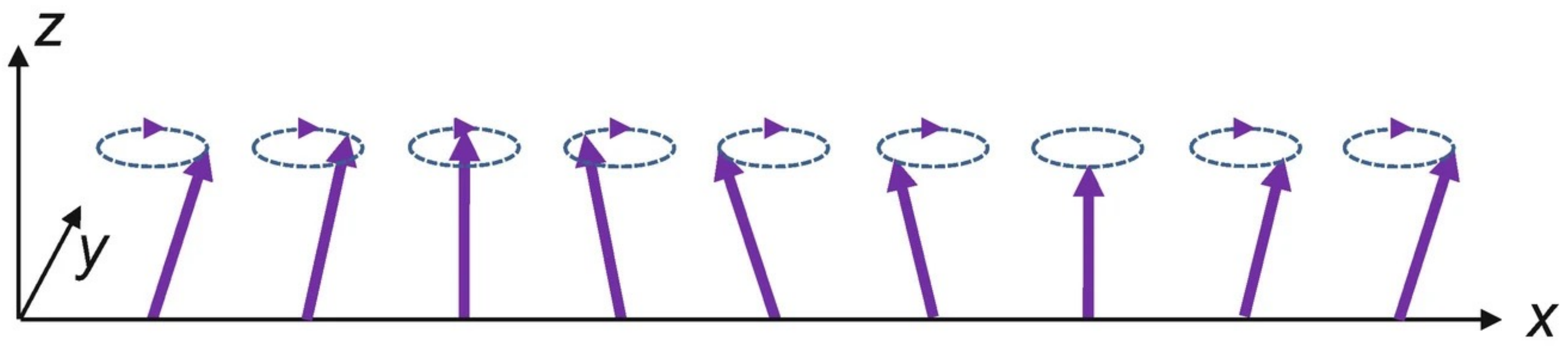

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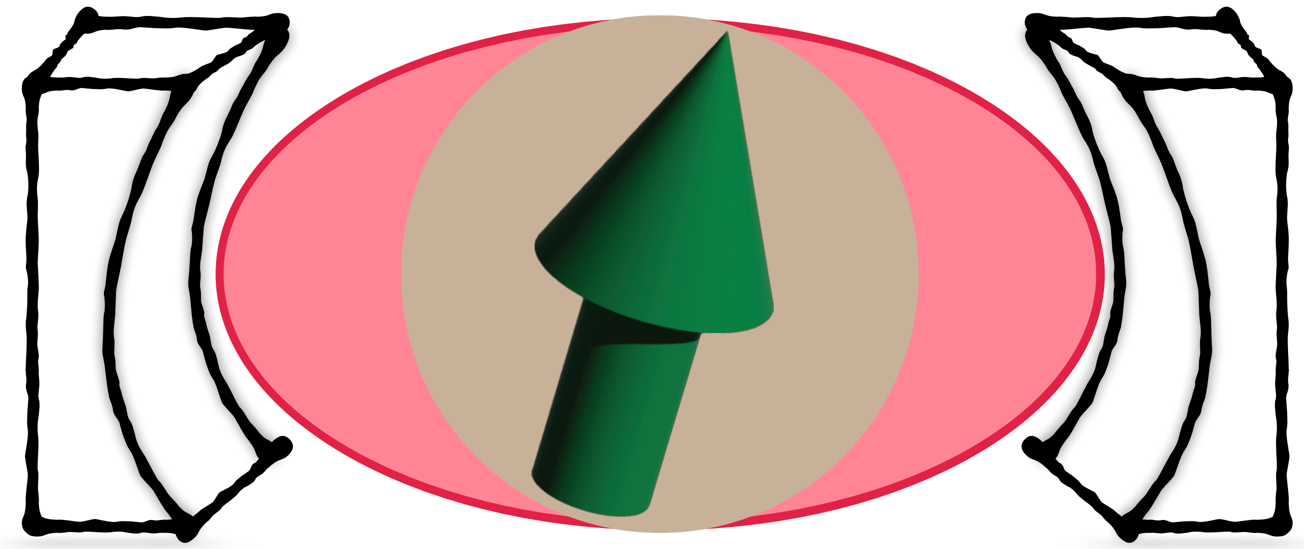

$$H \sim (a + a^\dagger) \sum_i \sigma_i^x = (a + a^\dagger)\, S^x$$

$$\frac{S}{\hbar} \sim 10^5$$

→ Mean field classical dynamics

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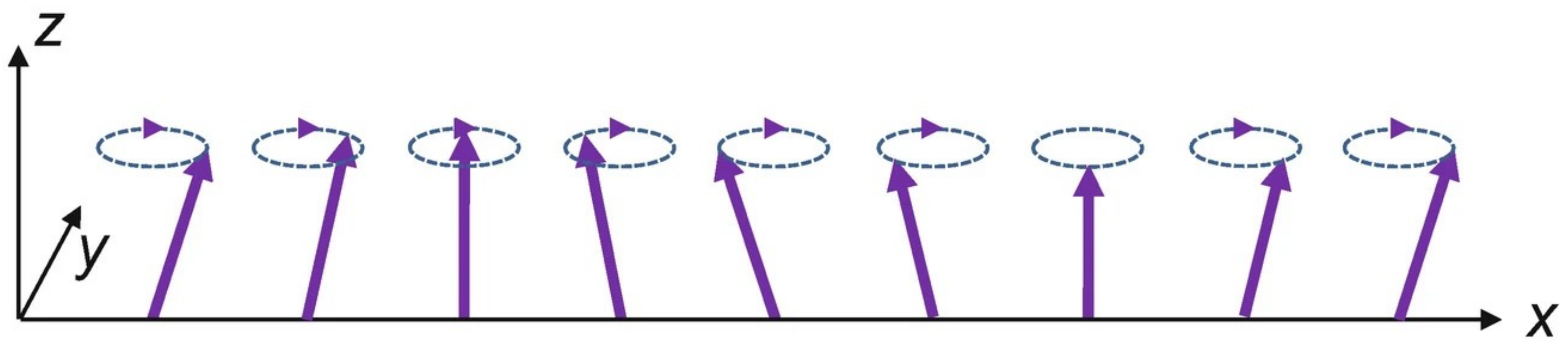

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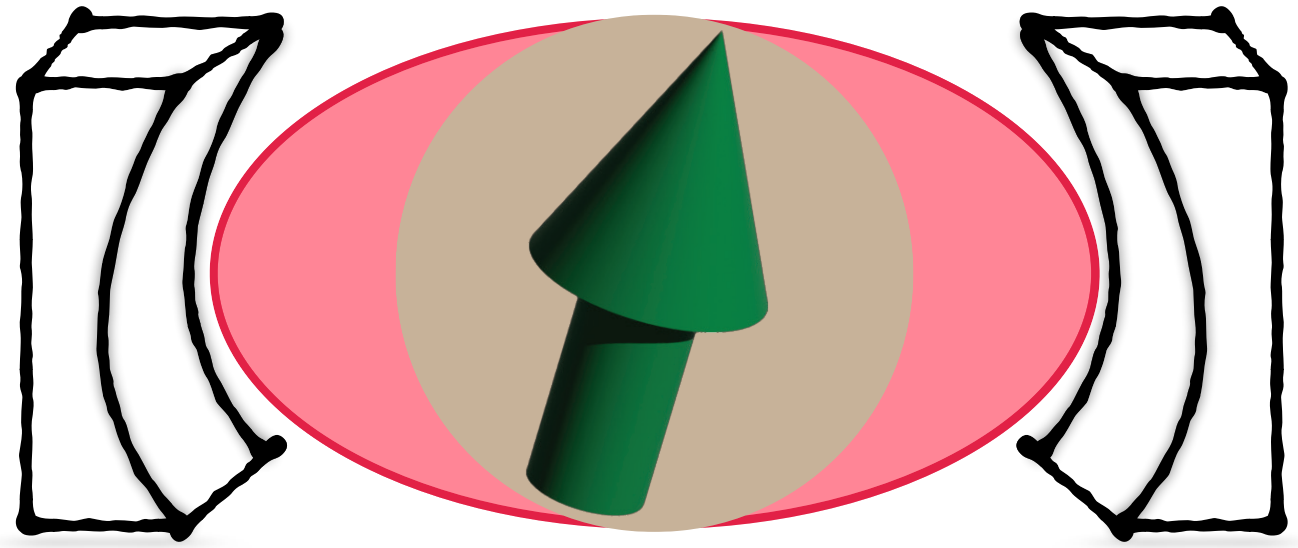

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Quantum effects are typically suppressed

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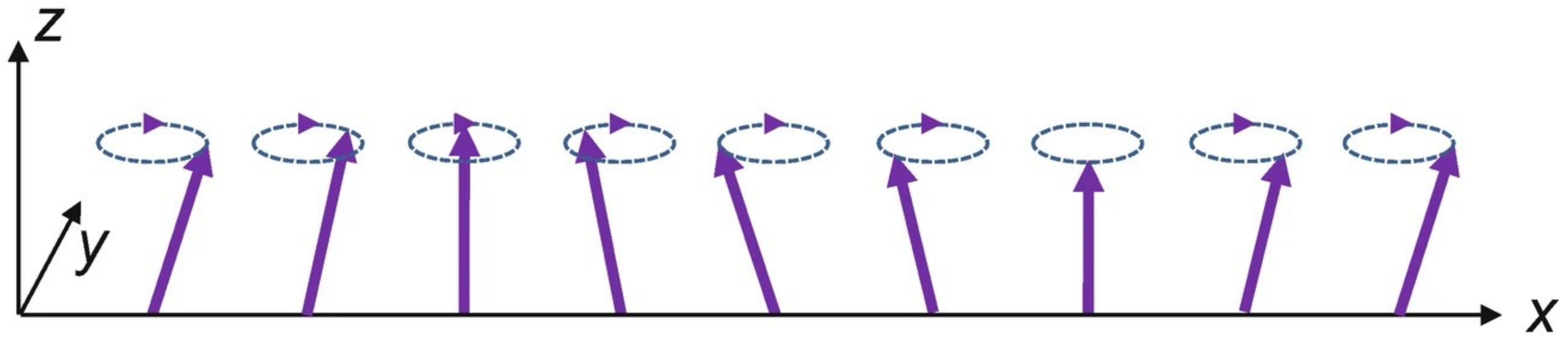

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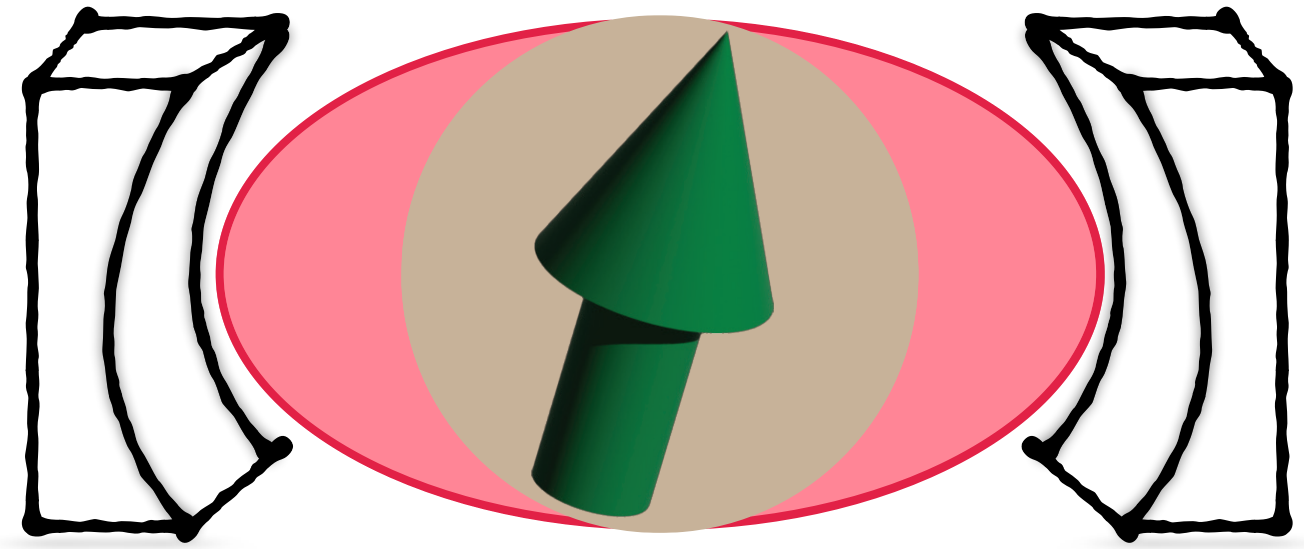


$$H \sim (a + a^\dagger) \sum \sigma_i^x = (a + a^\dagger)\, S^x$$

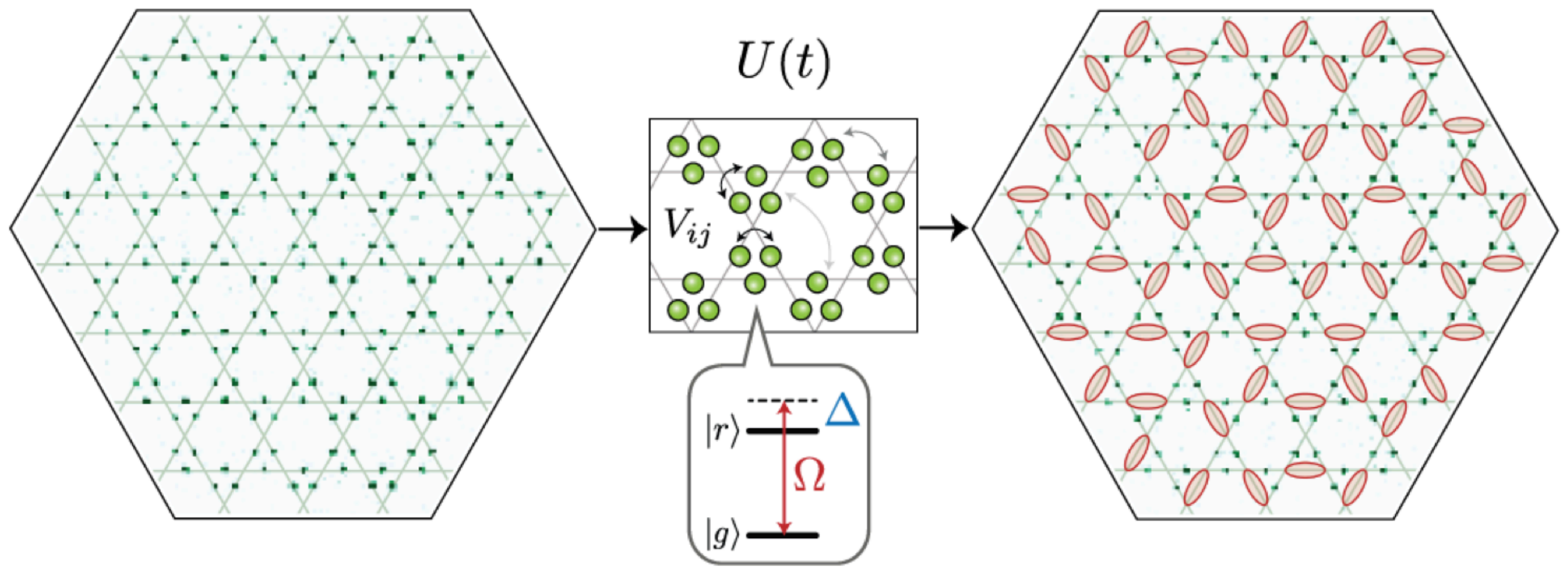
Quantum effects are typically suppressed

Small spins

Strong but non-collective interactions

Experiments

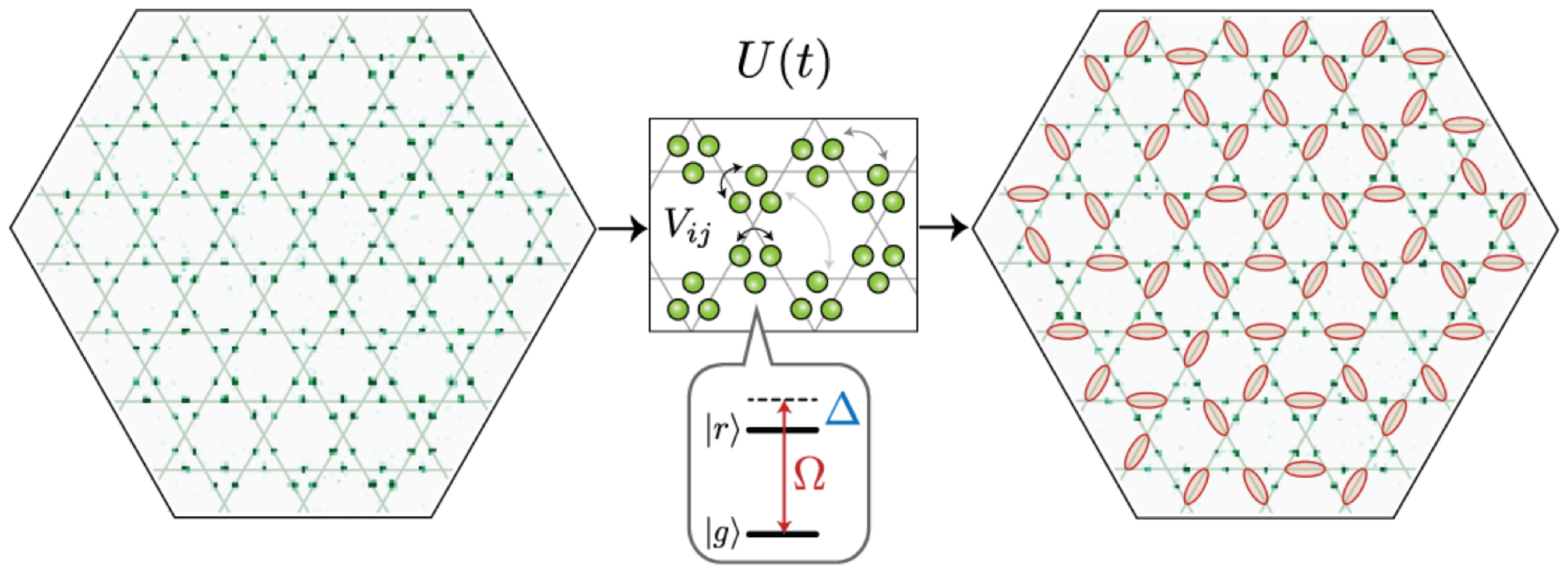
Experiments



Spin Liquids

Semeghini et al., Sci '21 / Chiocchetta et al., Nat Com '21

Experiments



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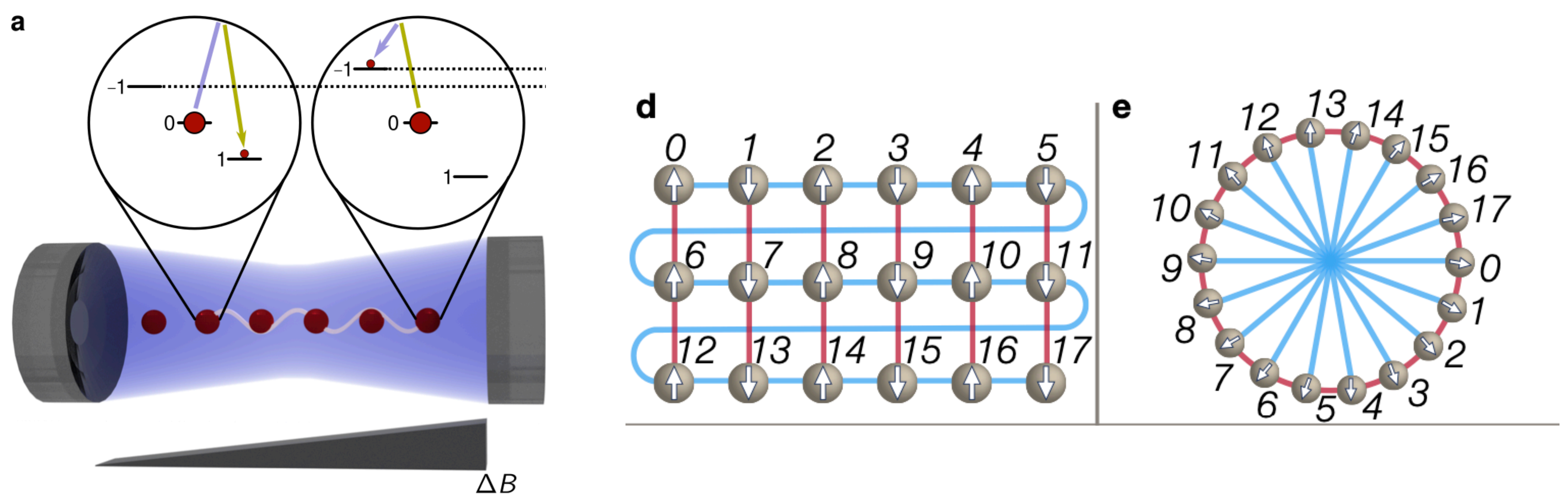

Programmable arrays

Periwal et al., Nat '21/ Setharam et al., PRR&PRB '22

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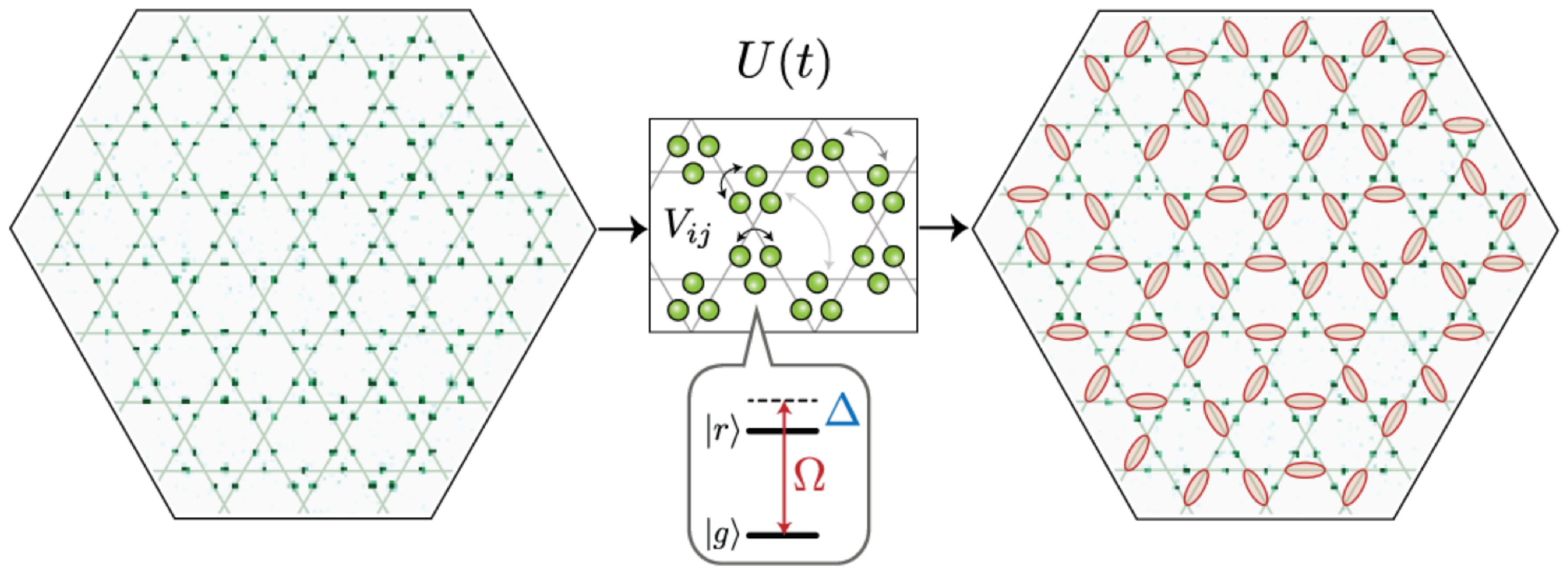

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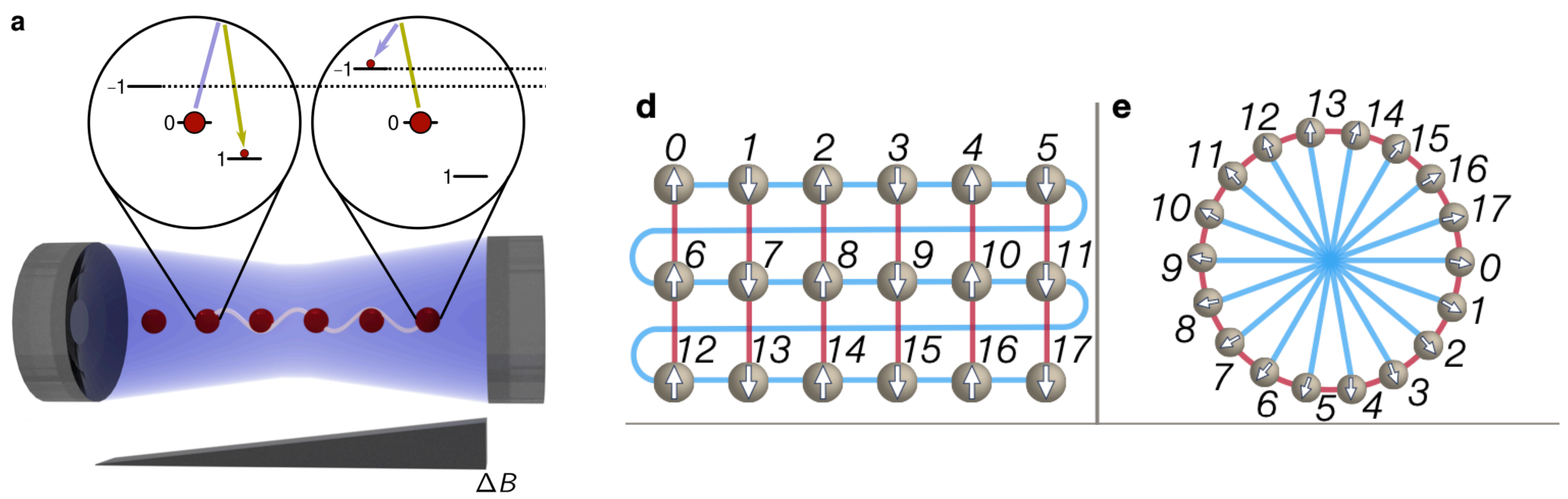

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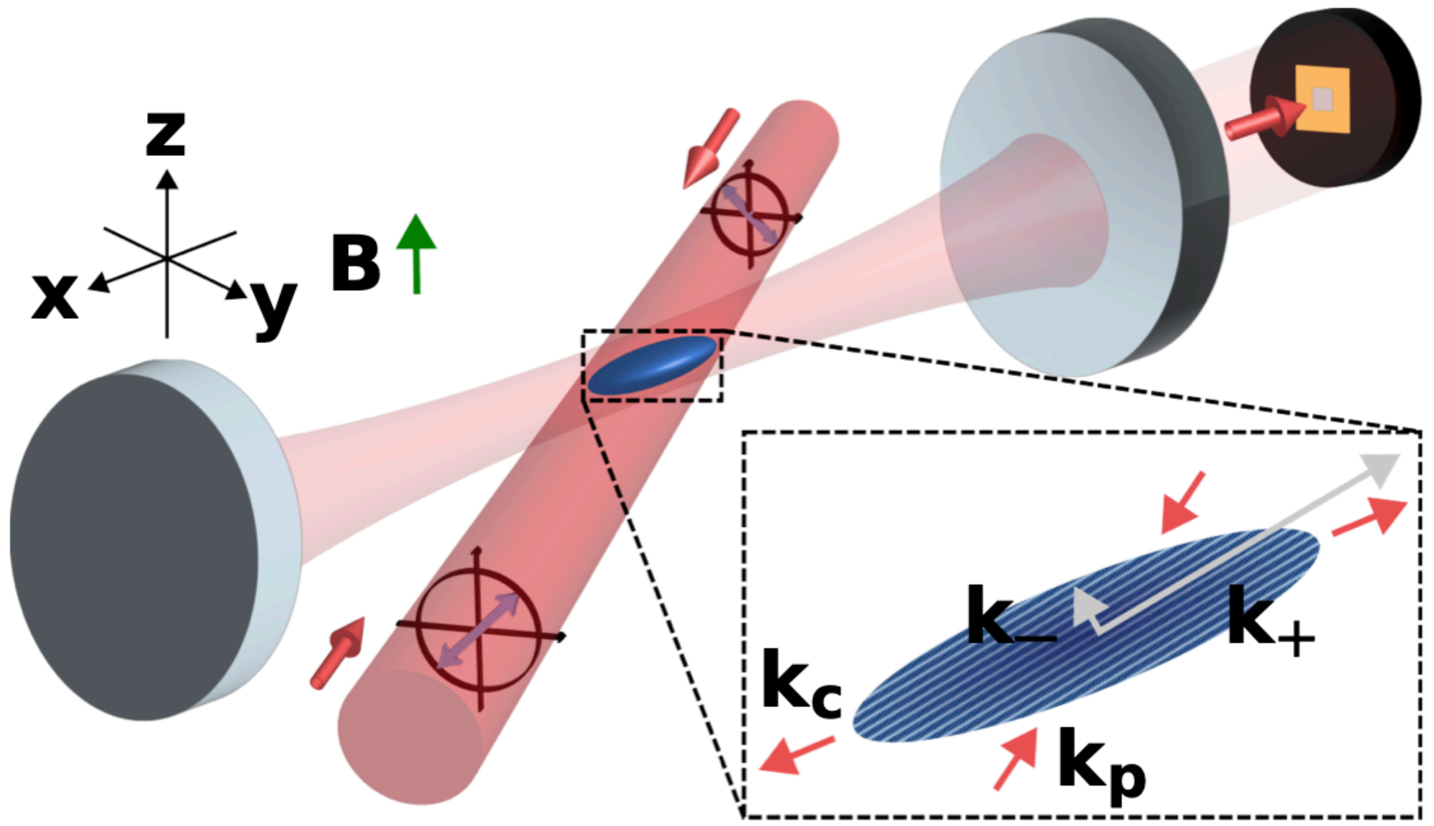

Density waves (fermions)

Zwettler et al., '24

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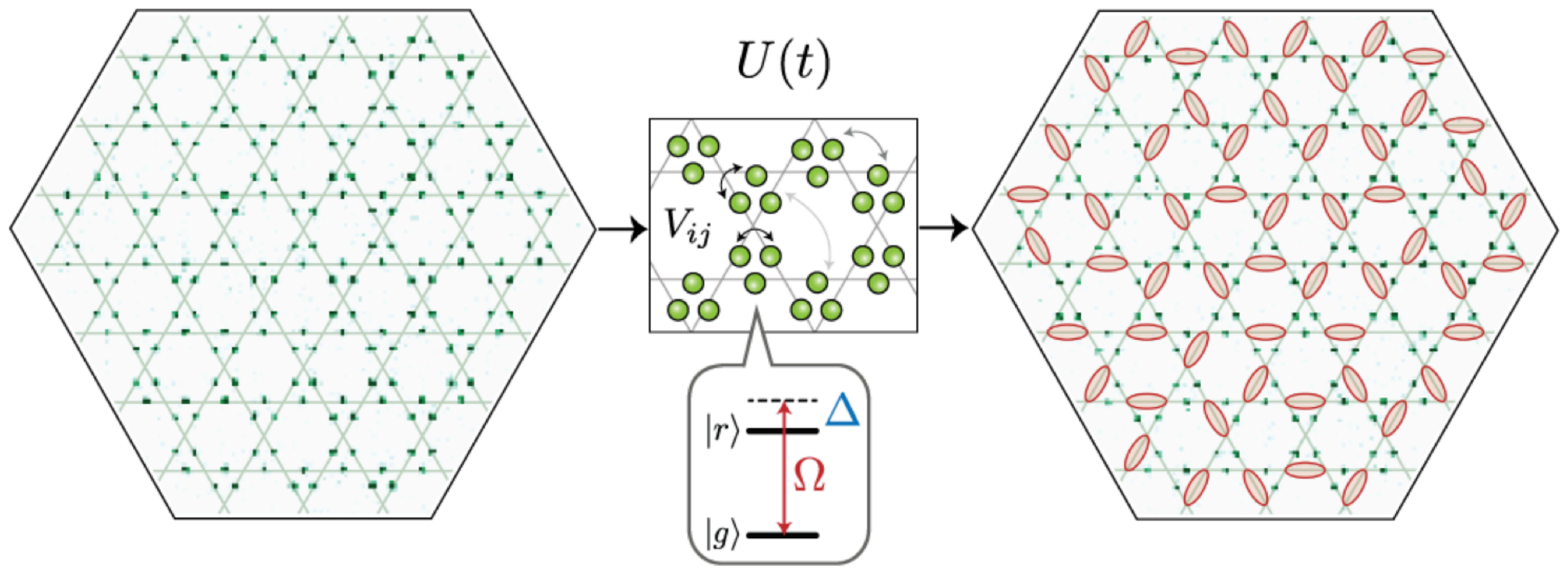

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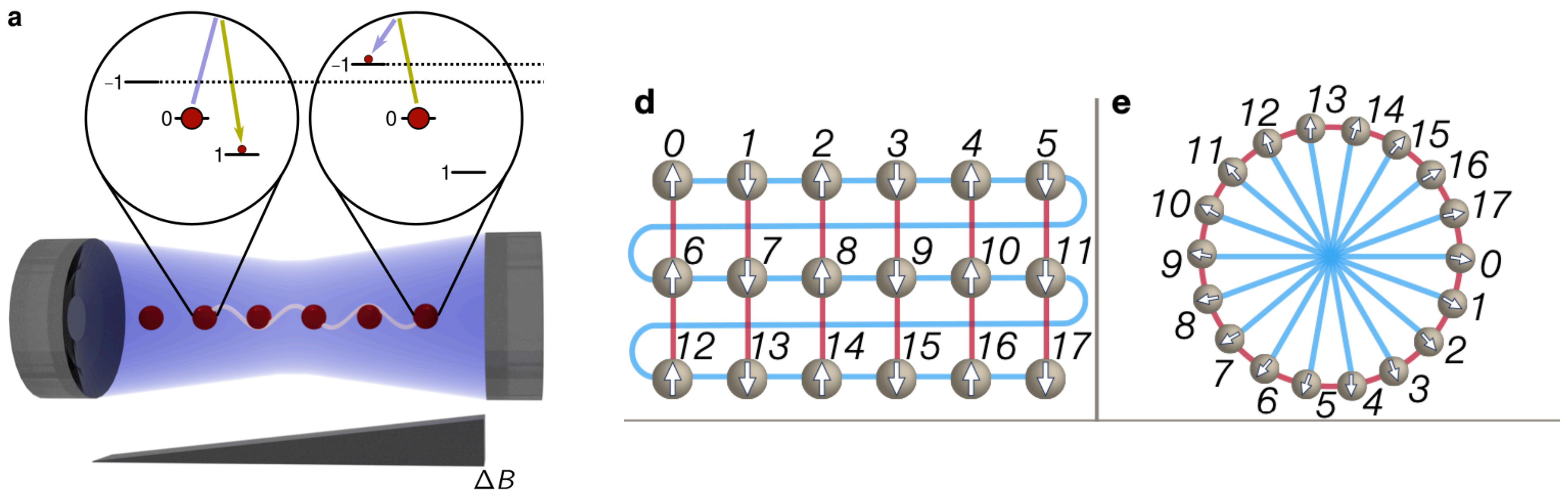

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this talk: **HH**, D. Chang, J. Marino,
arXiv 2311.05682
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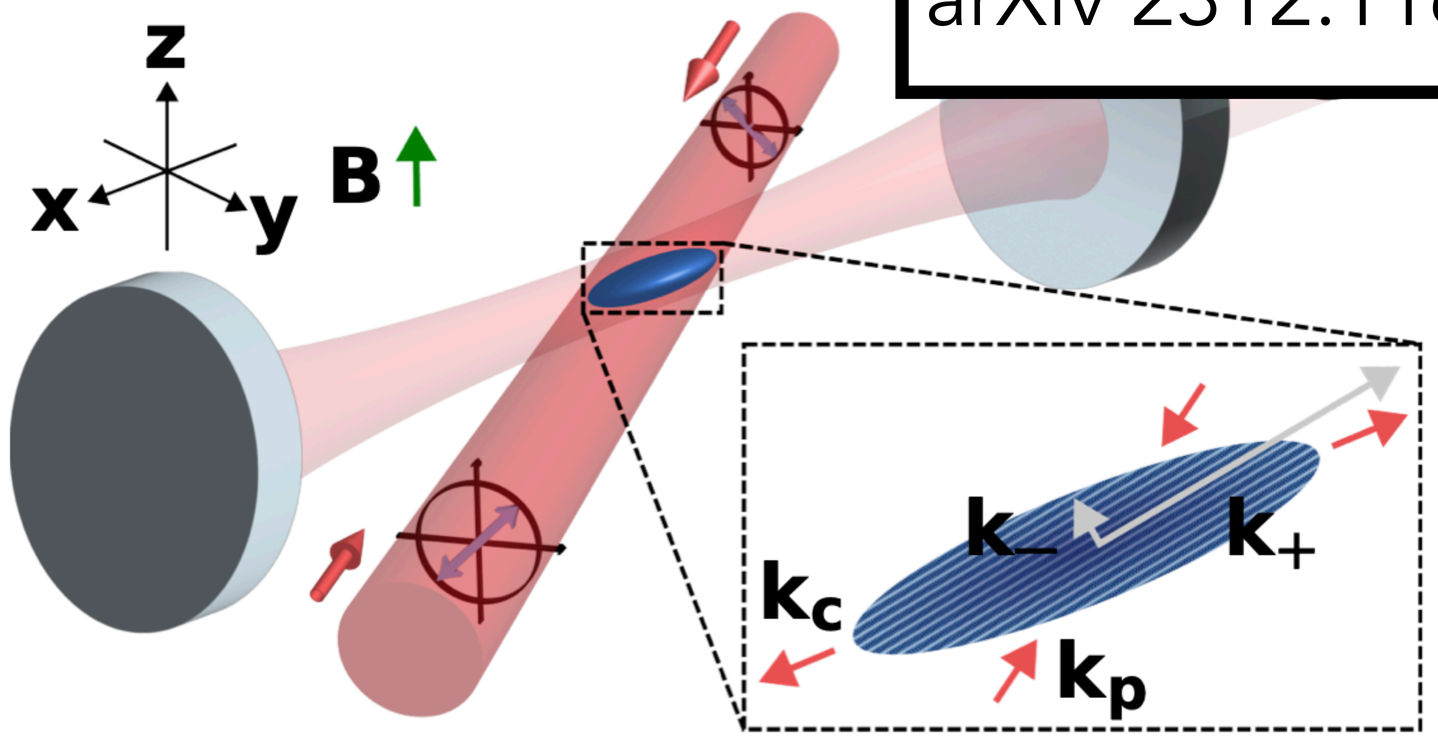

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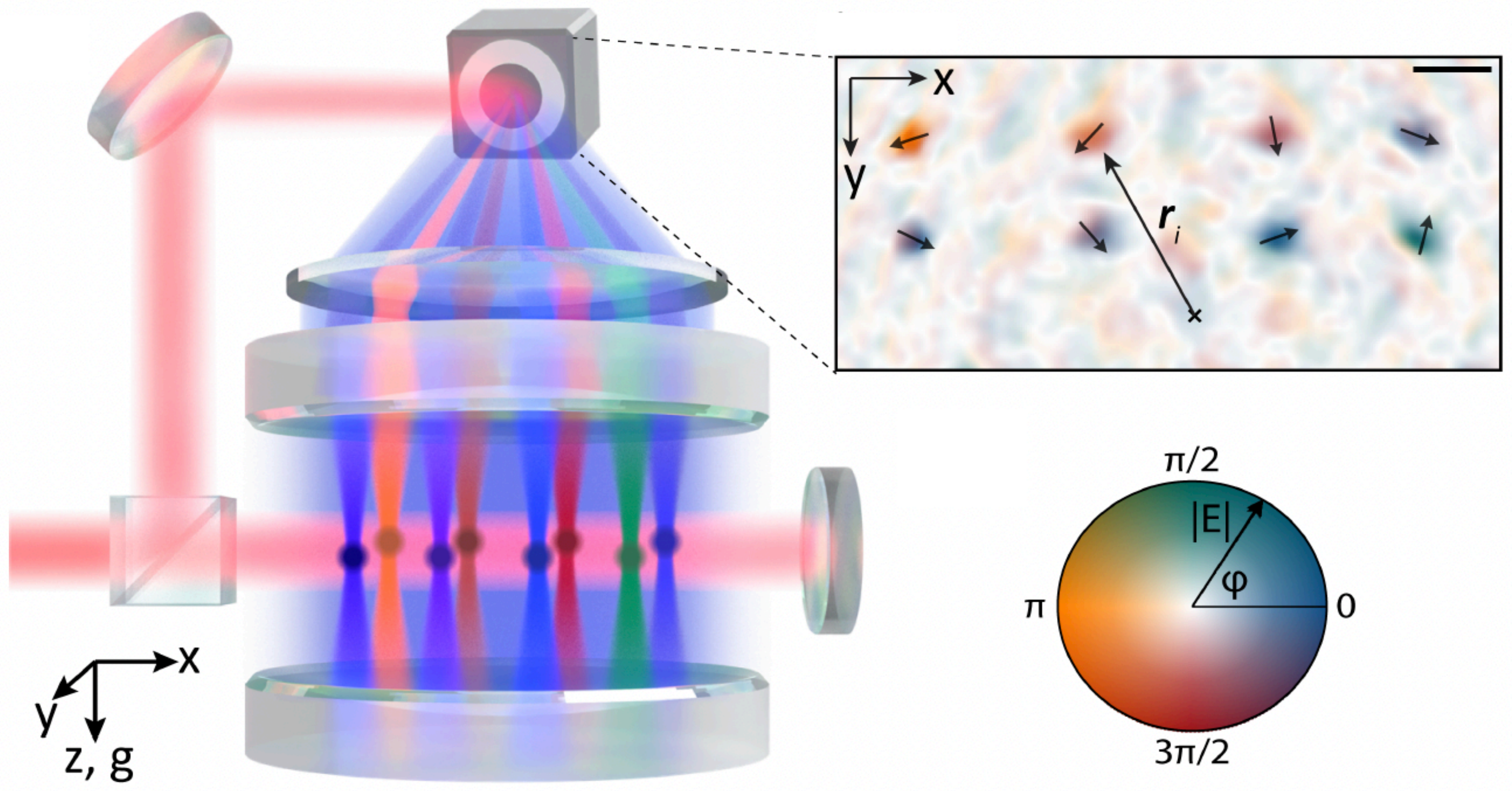

Spin Glasses

Kroeze et al., arXiv:2311.04216 / Marsh et al., PRX ’24/ Buchhold et al. PRA ’13 / Strack & Sachdev, PRL ’11

What is a glass?

What is a glass?

Simple example: Sherrington-Kirkpatrick model

Sherrington & Kirkpatrick '75

$$H = h\sum_i \sigma_i^z + \sum_{ij} J_{ij}\sigma_i^x\sigma_j^x$$

$$\overline{J_{ij}} = 0,\ \overline{J_{ij}J_{ij}} = J^2/N \longrightarrow$$

Conflicting couplings
(FM or AFM ?)

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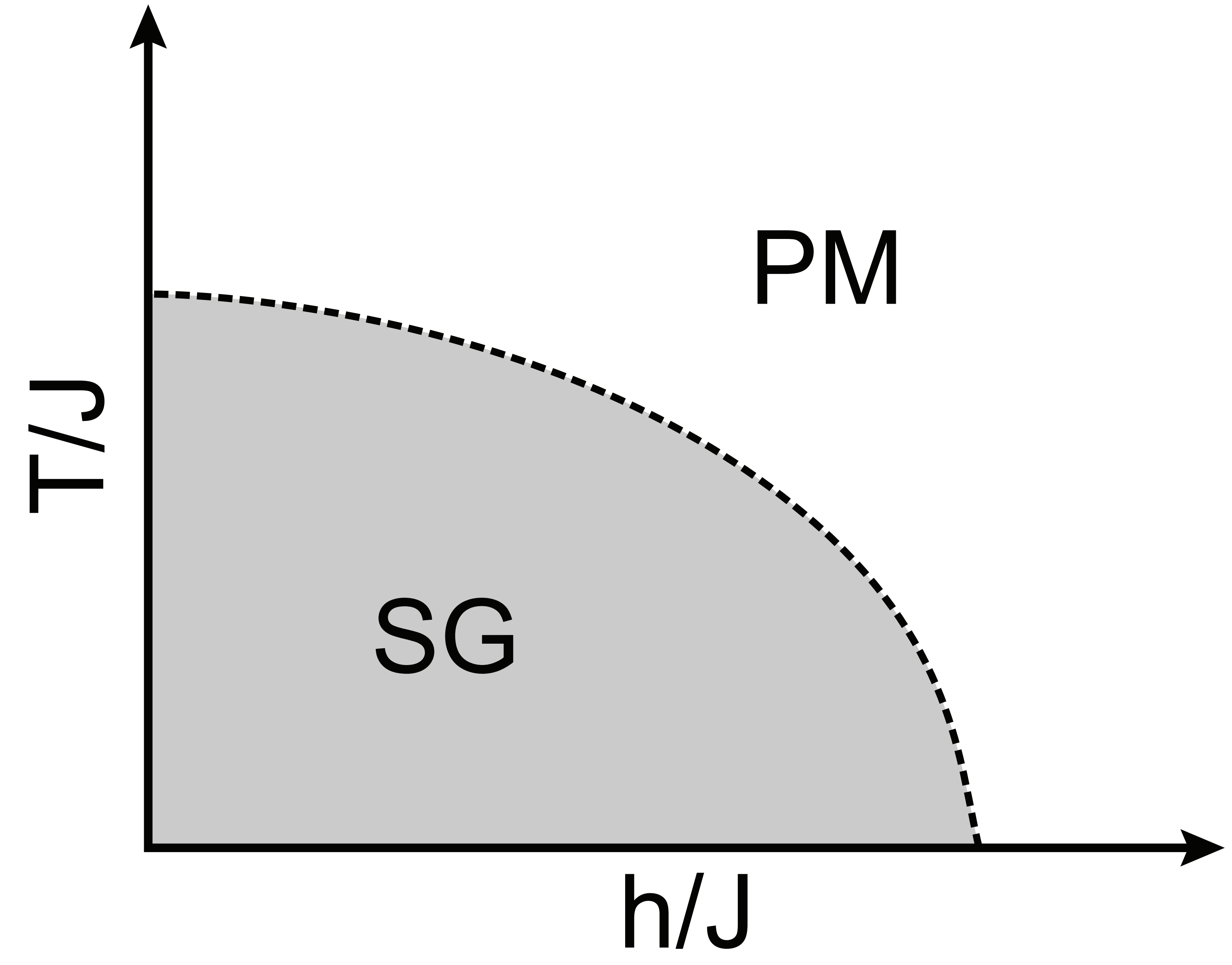

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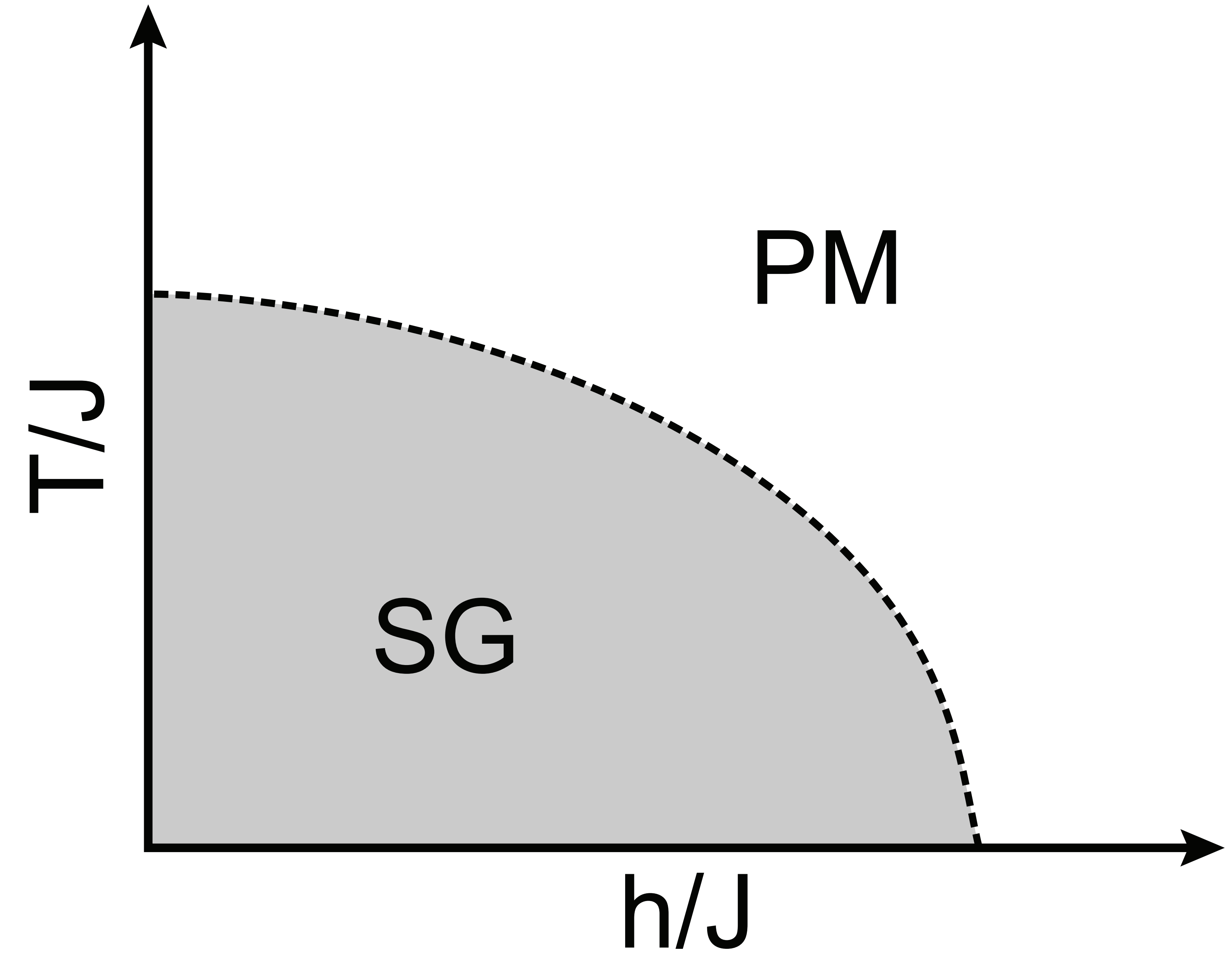
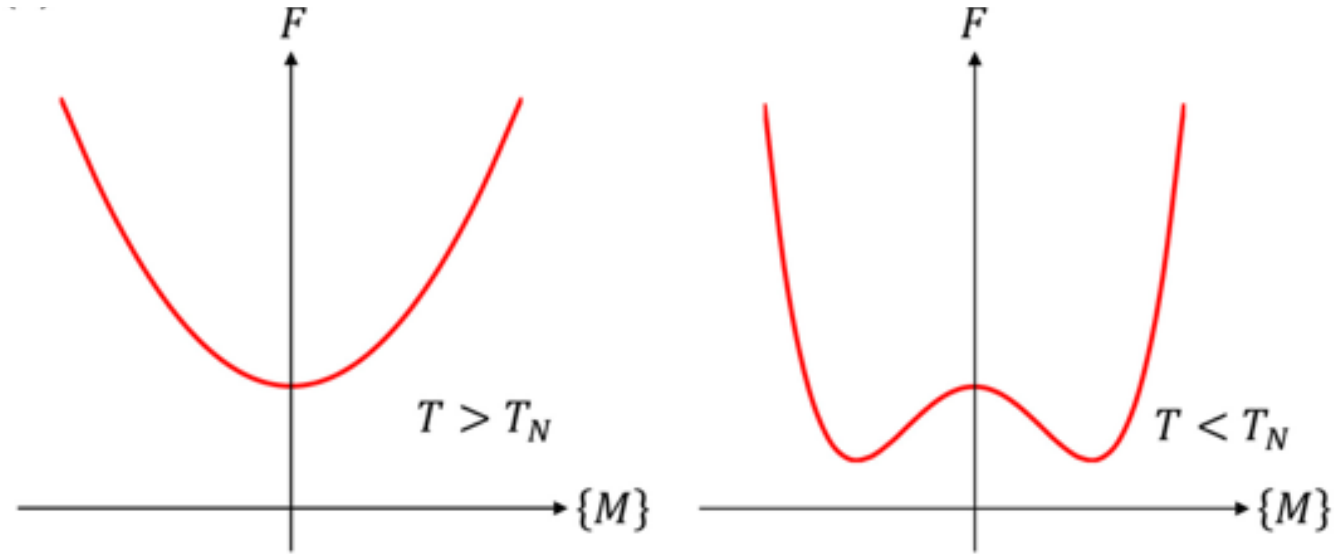
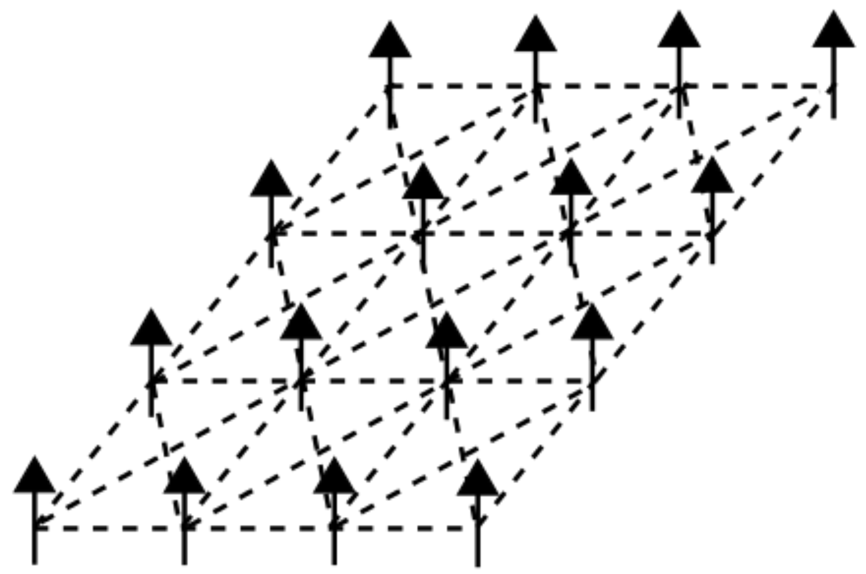


``Generic" phase transition





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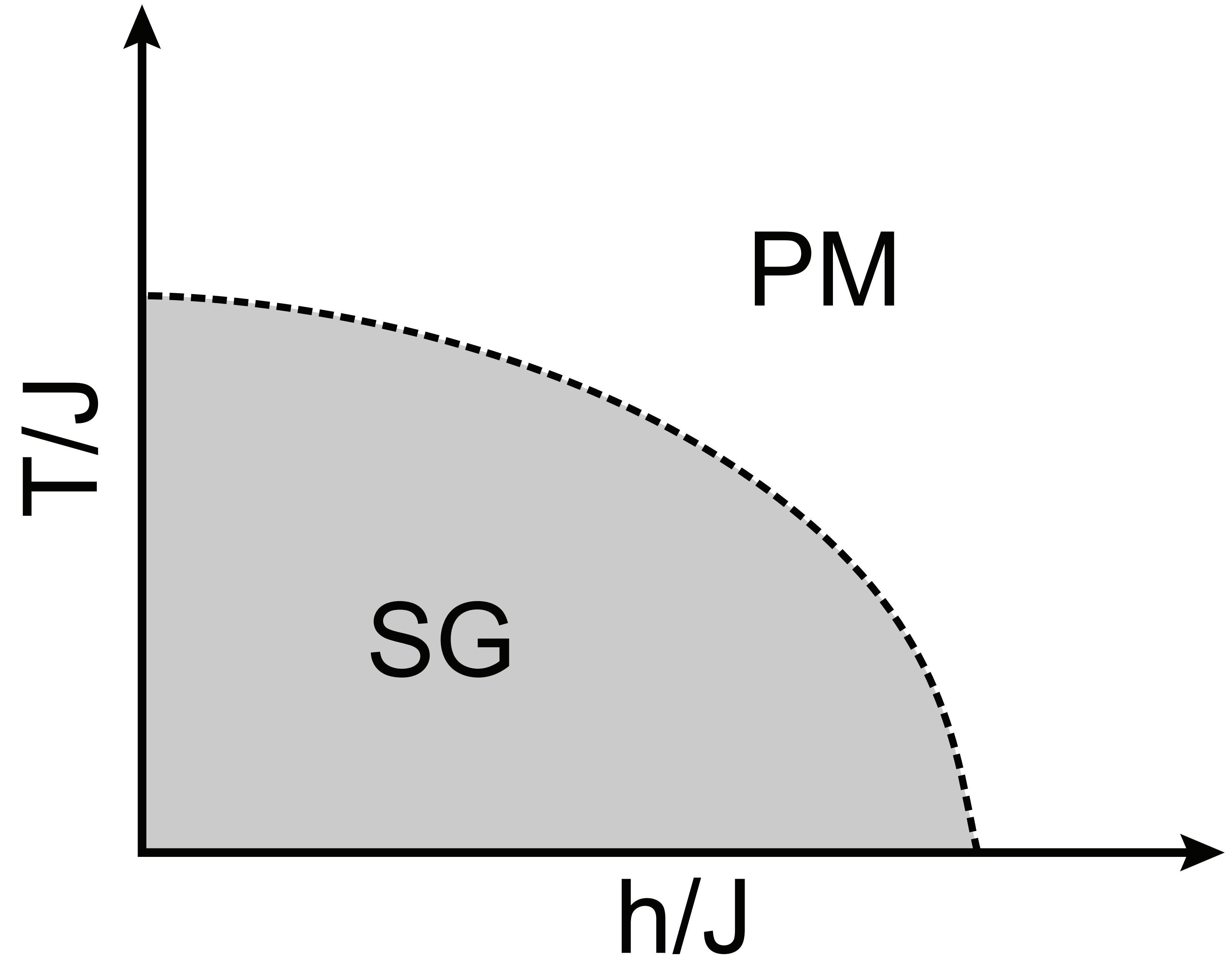

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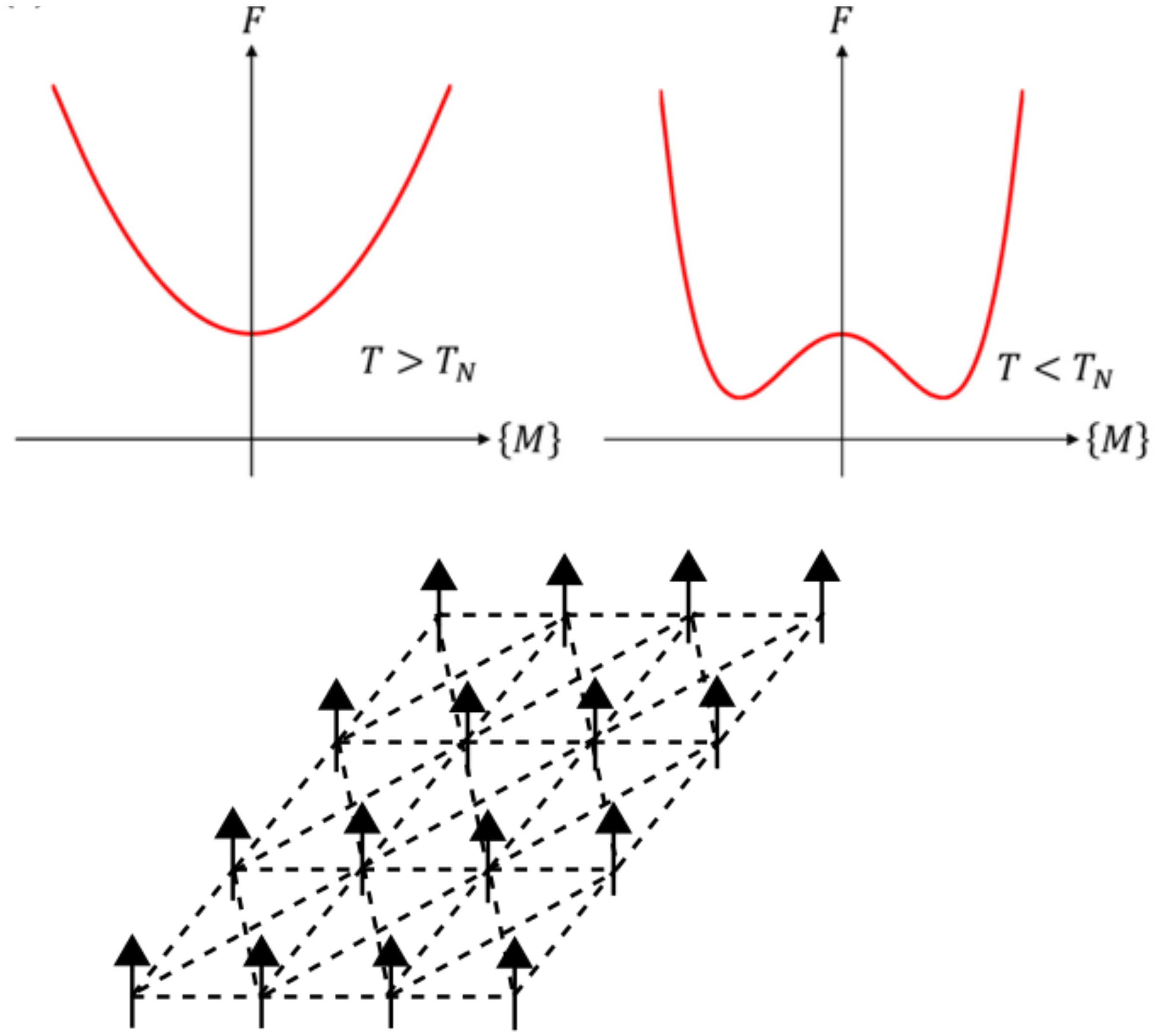
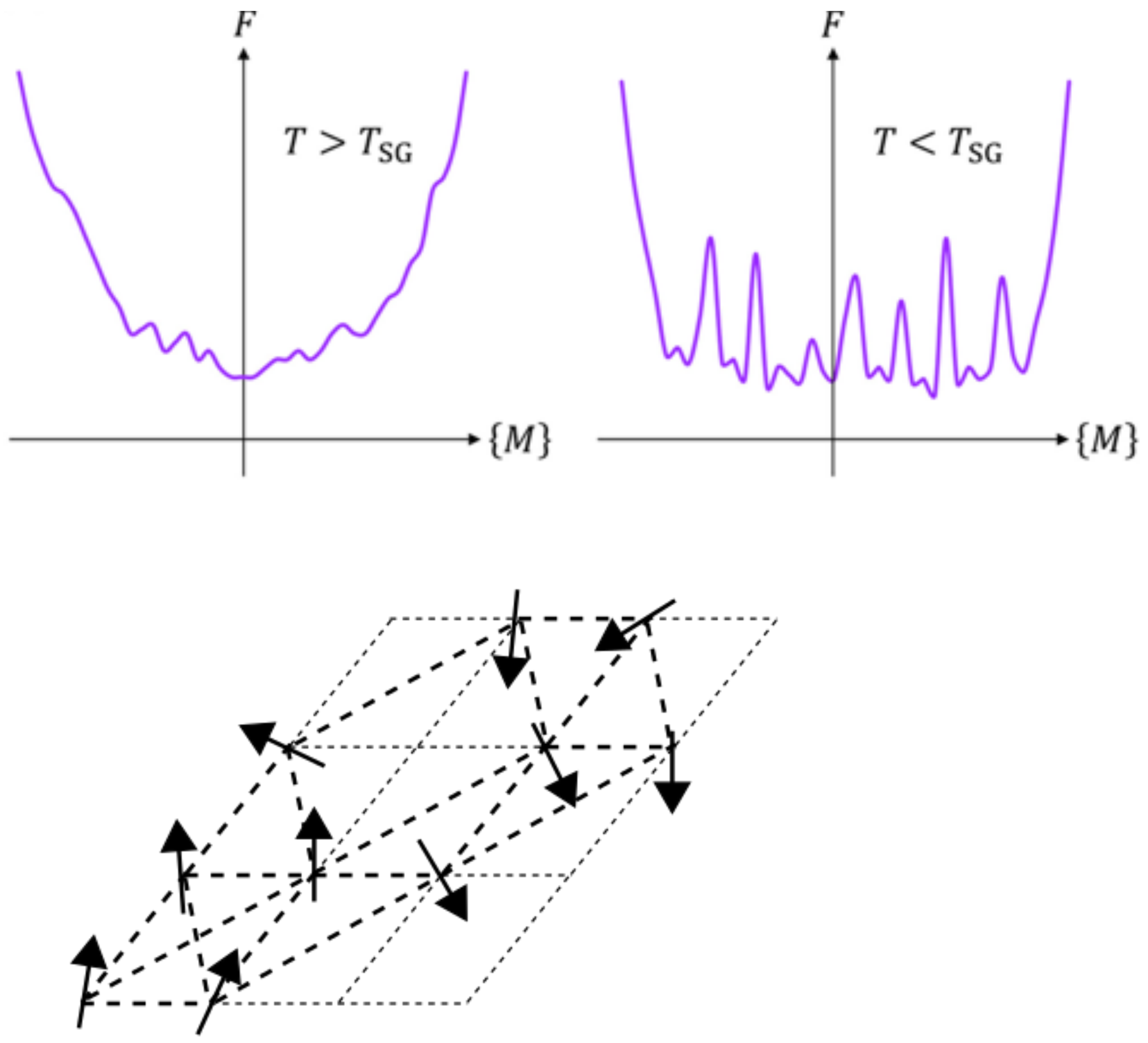
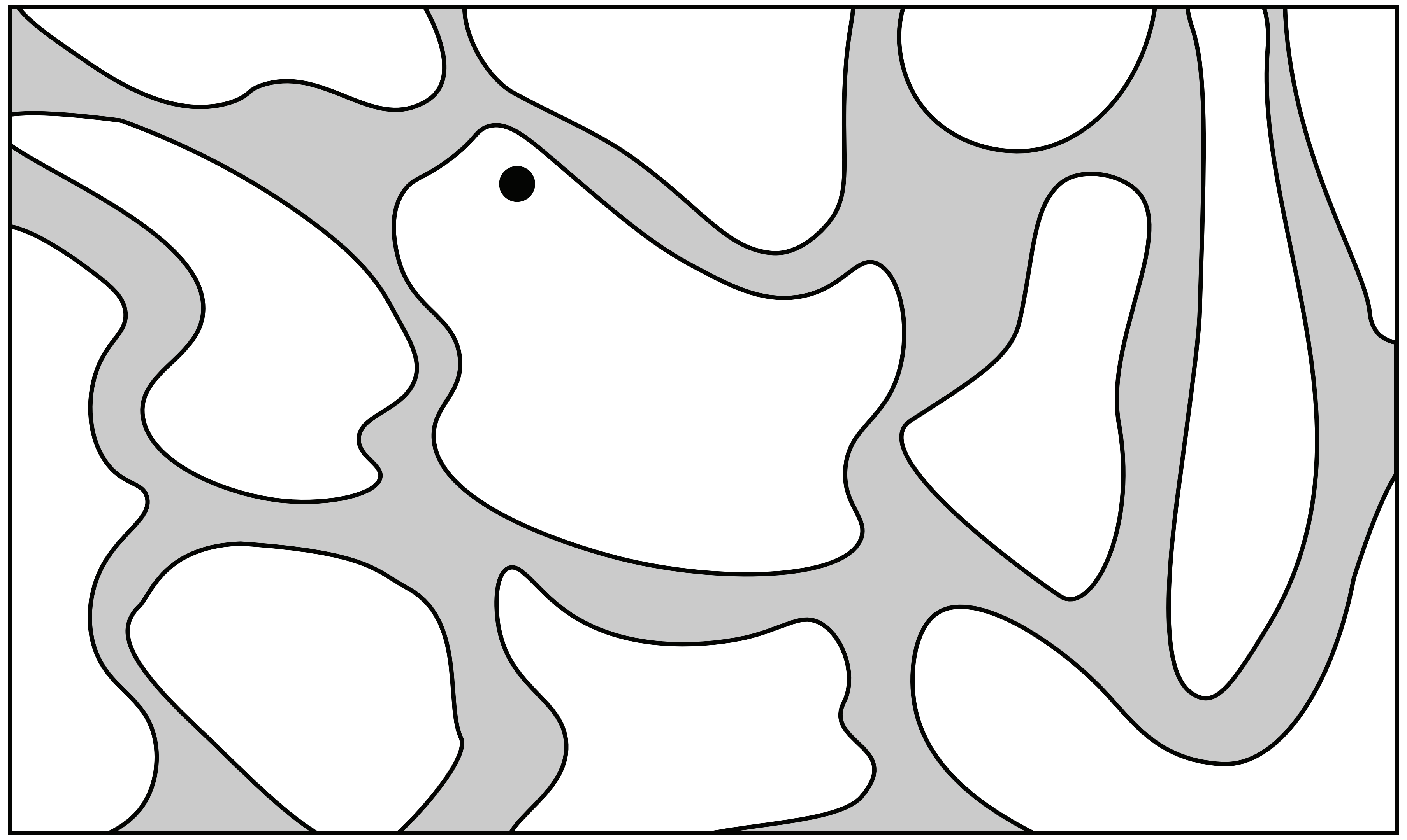


Glass phase transition



Rugged free energy landscape



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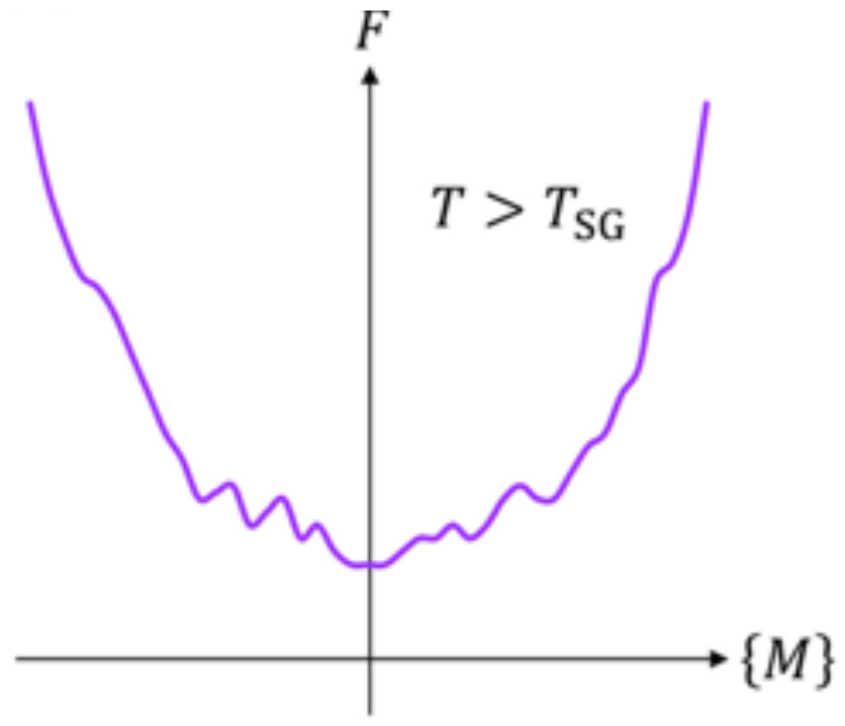
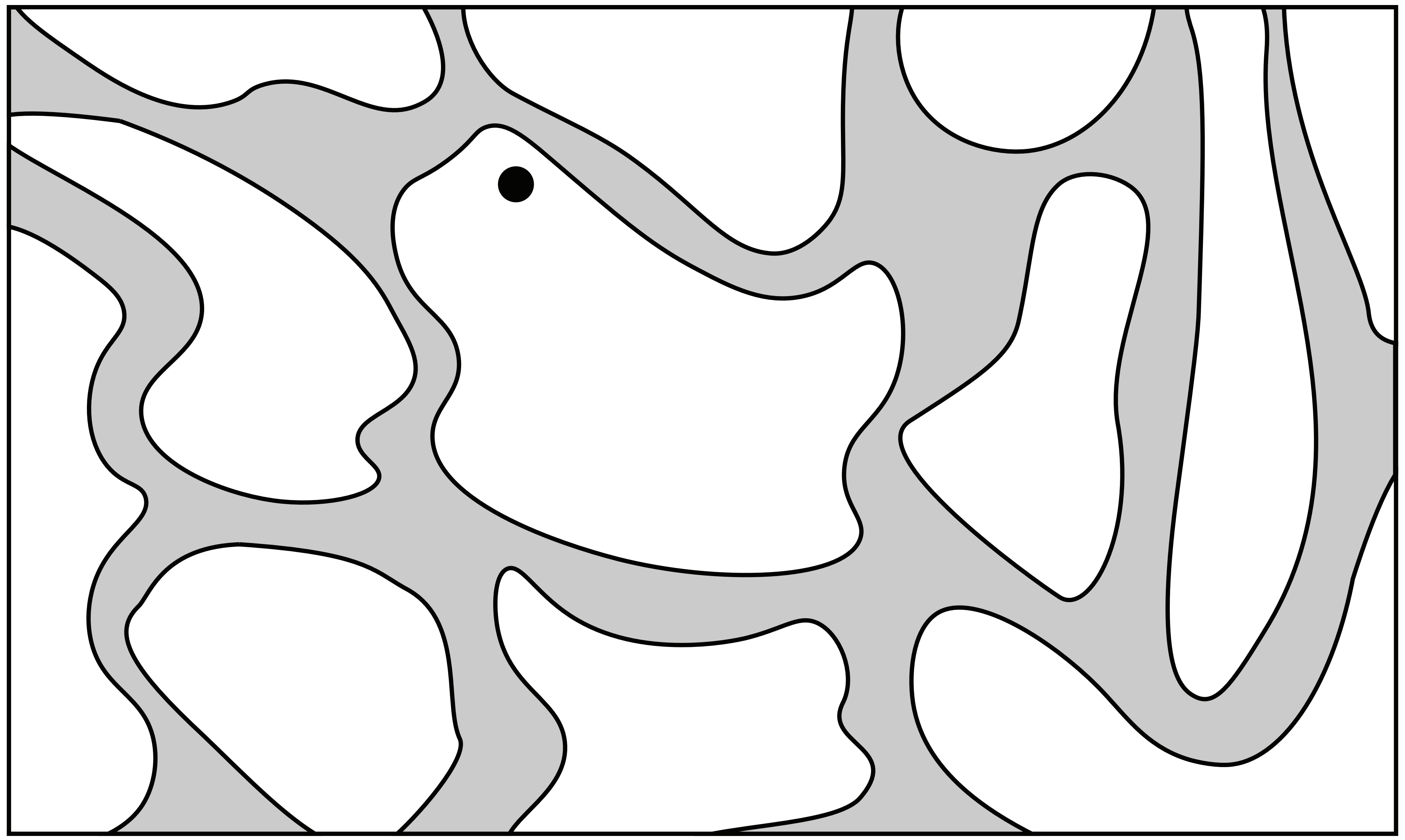
Unusual relaxation



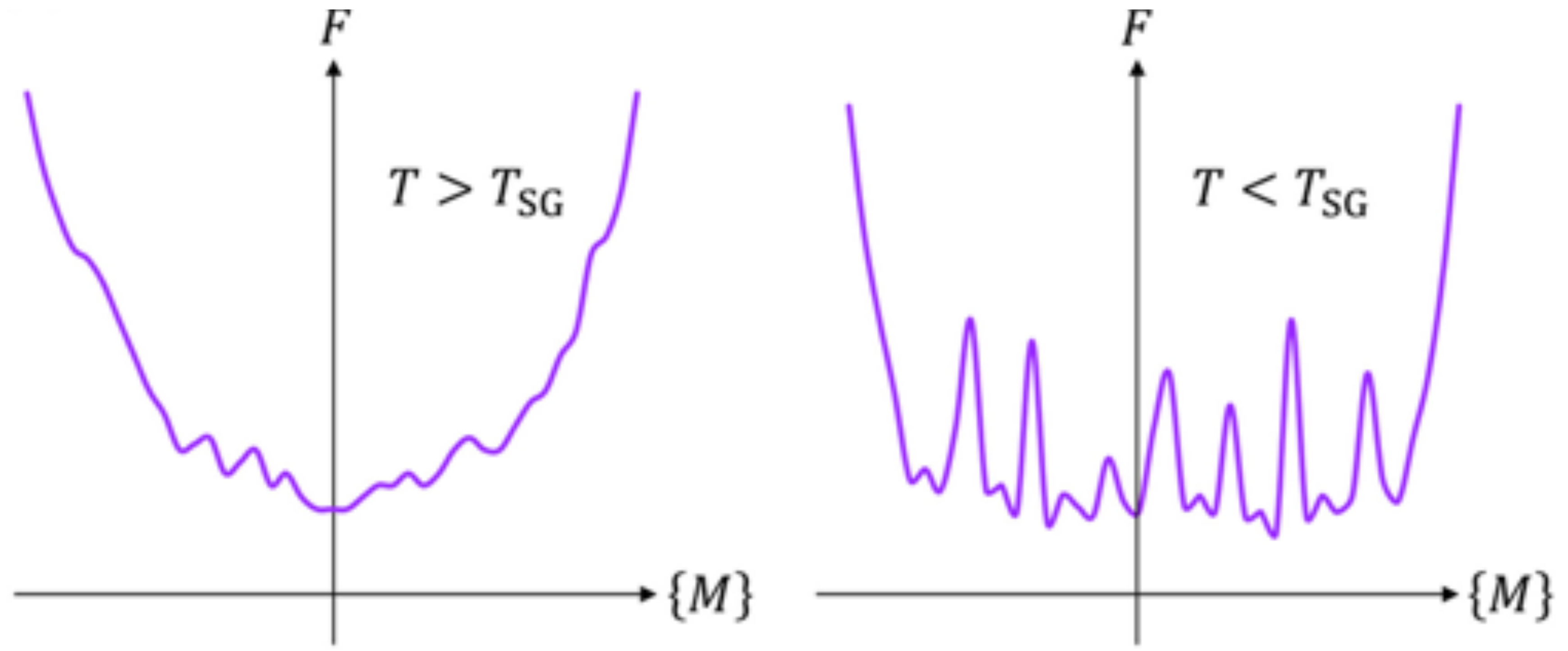


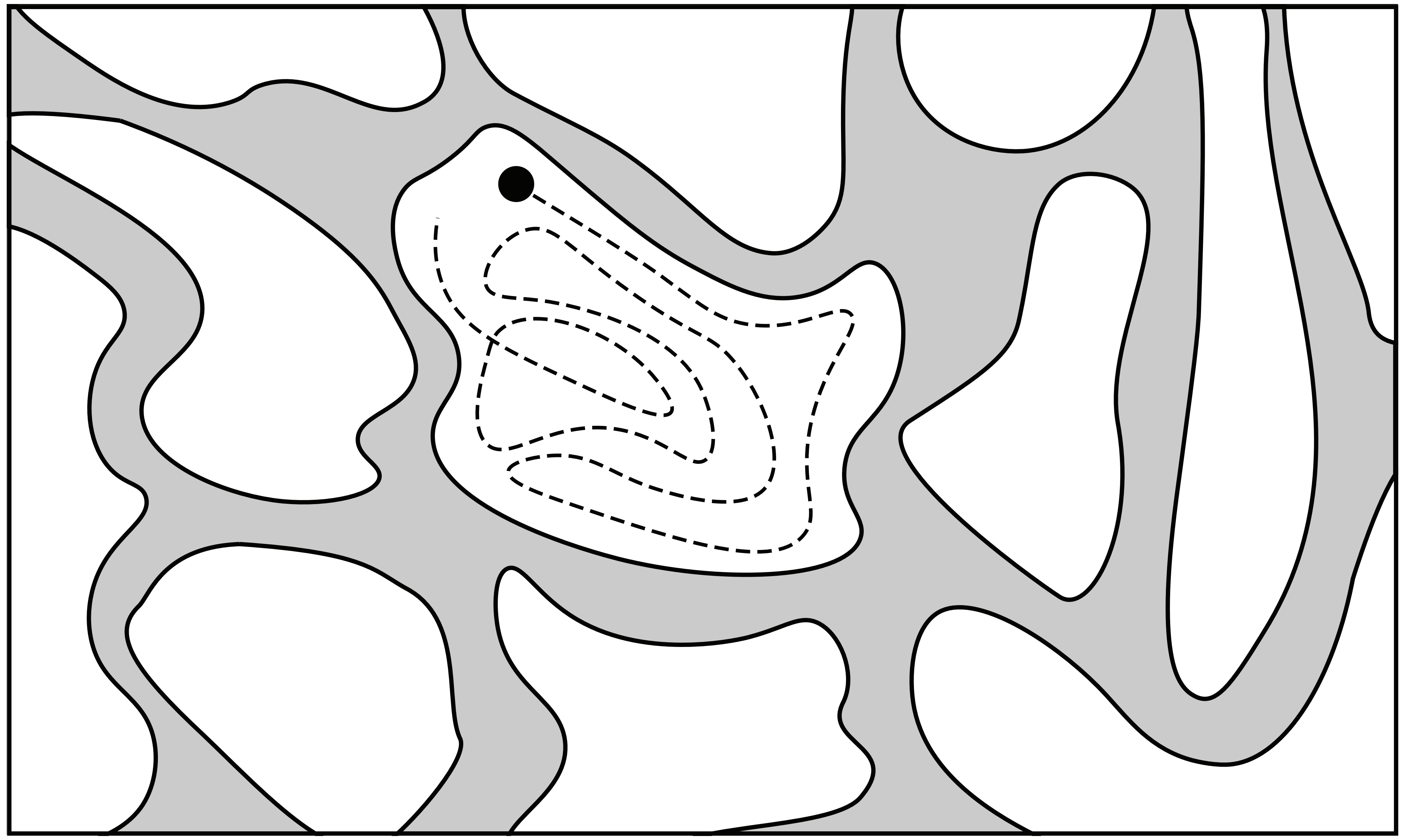
What is a glass?

Unusual relaxation

(Quasi) ergodicity at short times

Effective temperature T_1 of quick fluctuations





What is a glass?

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(Quasi) ergodicity at short times

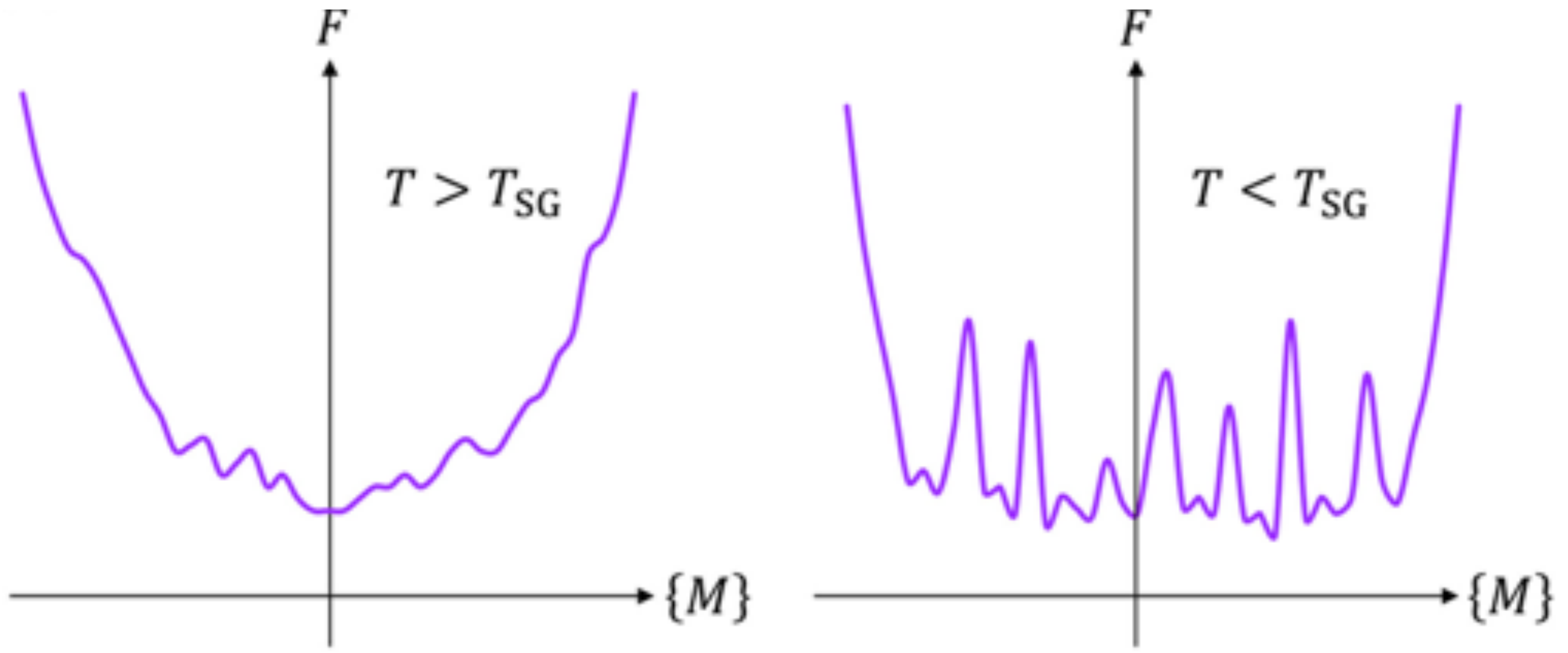
↓

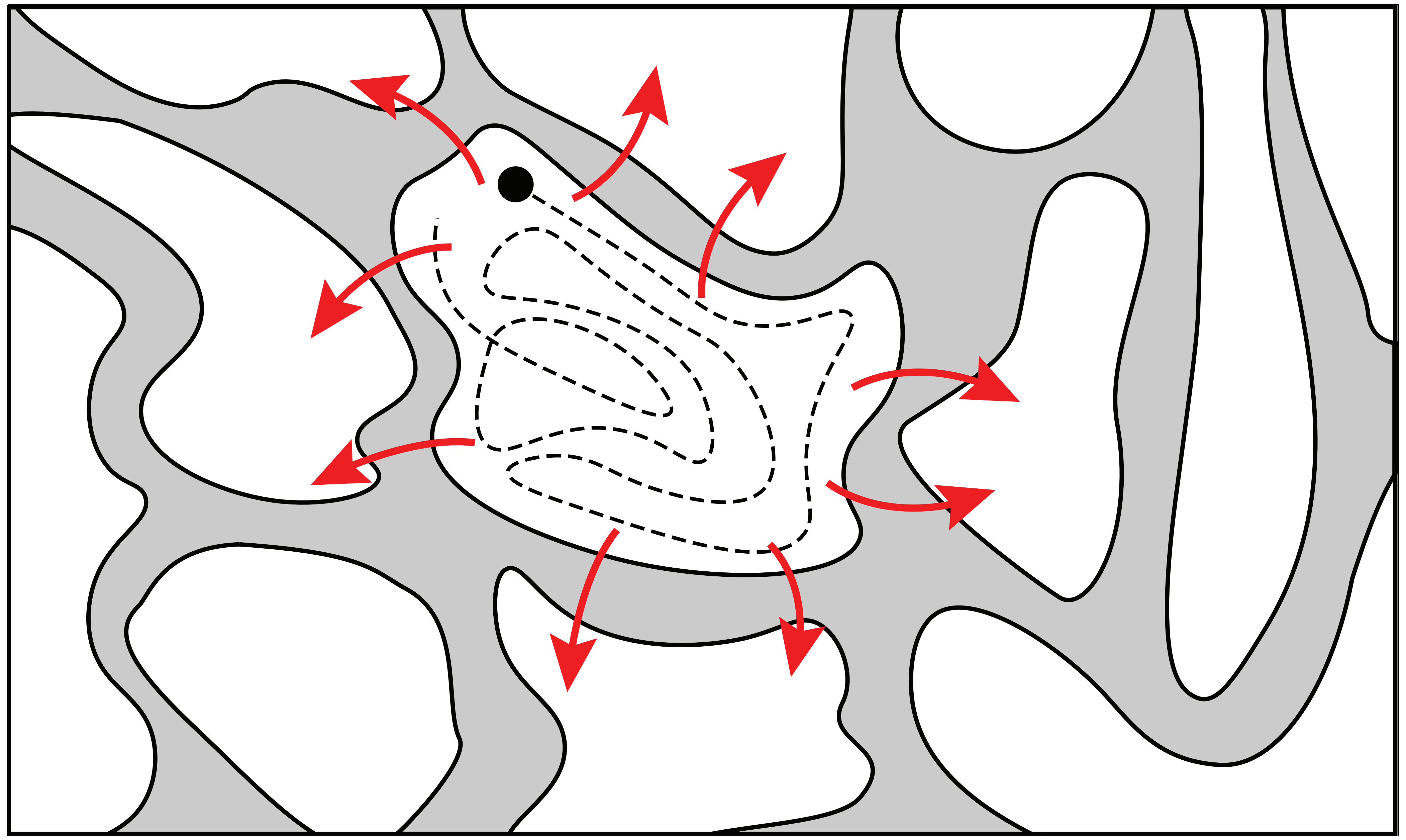
Effective temperature T_1 of quick fluctuations

Energy barriers obstruct more ``flips"
→ Slow thermalization

Equilibration becomes slower with time (aging)

Effective temperature T_2 for fluctuations over longer timescales





Spin glasses in solid state systems

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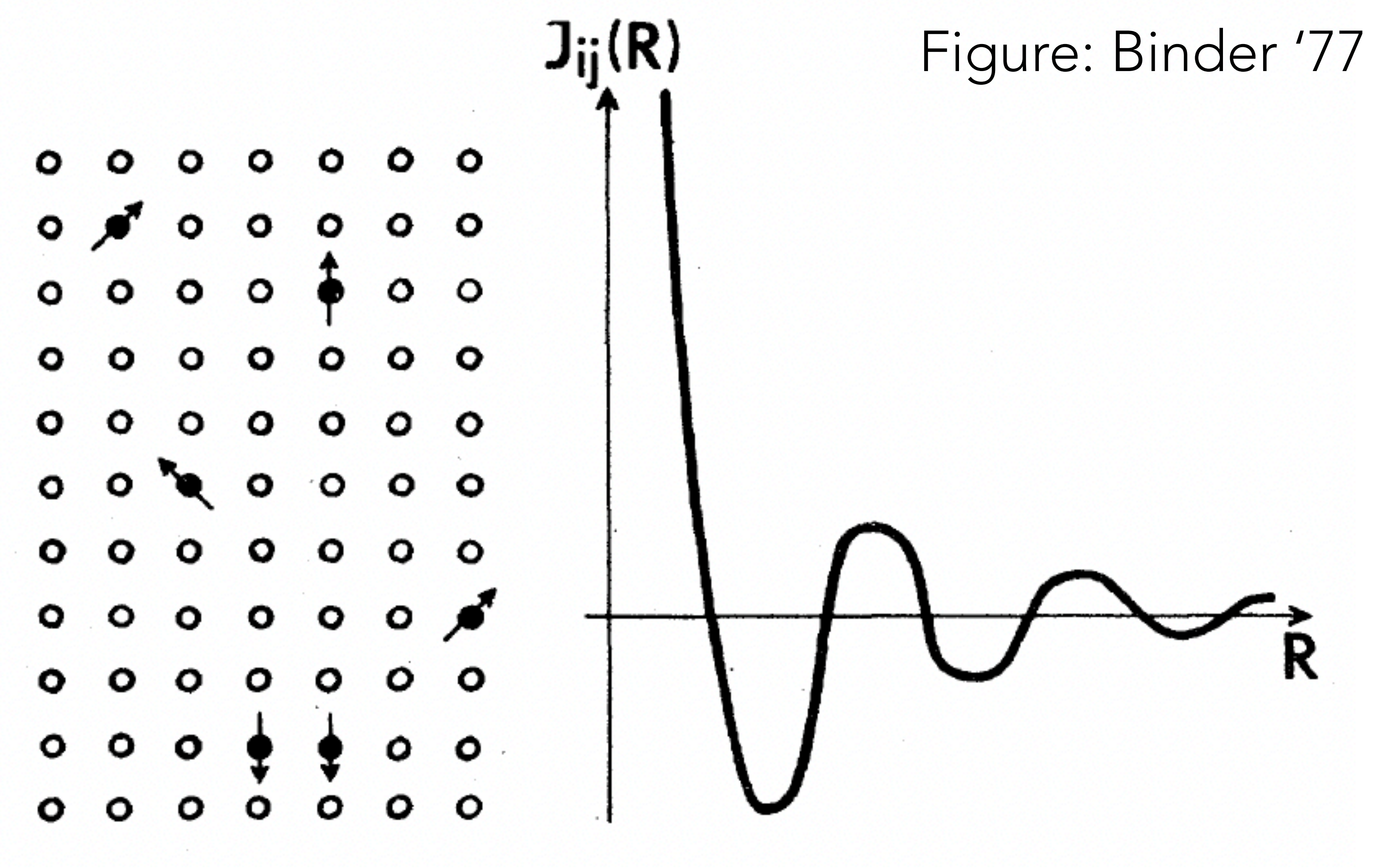
Figure: Binder '77



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RKKY coupling of moments $$J(R) \sim \frac{\cos(2k_f R + \theta_0)}{(k_f R)^3}$$

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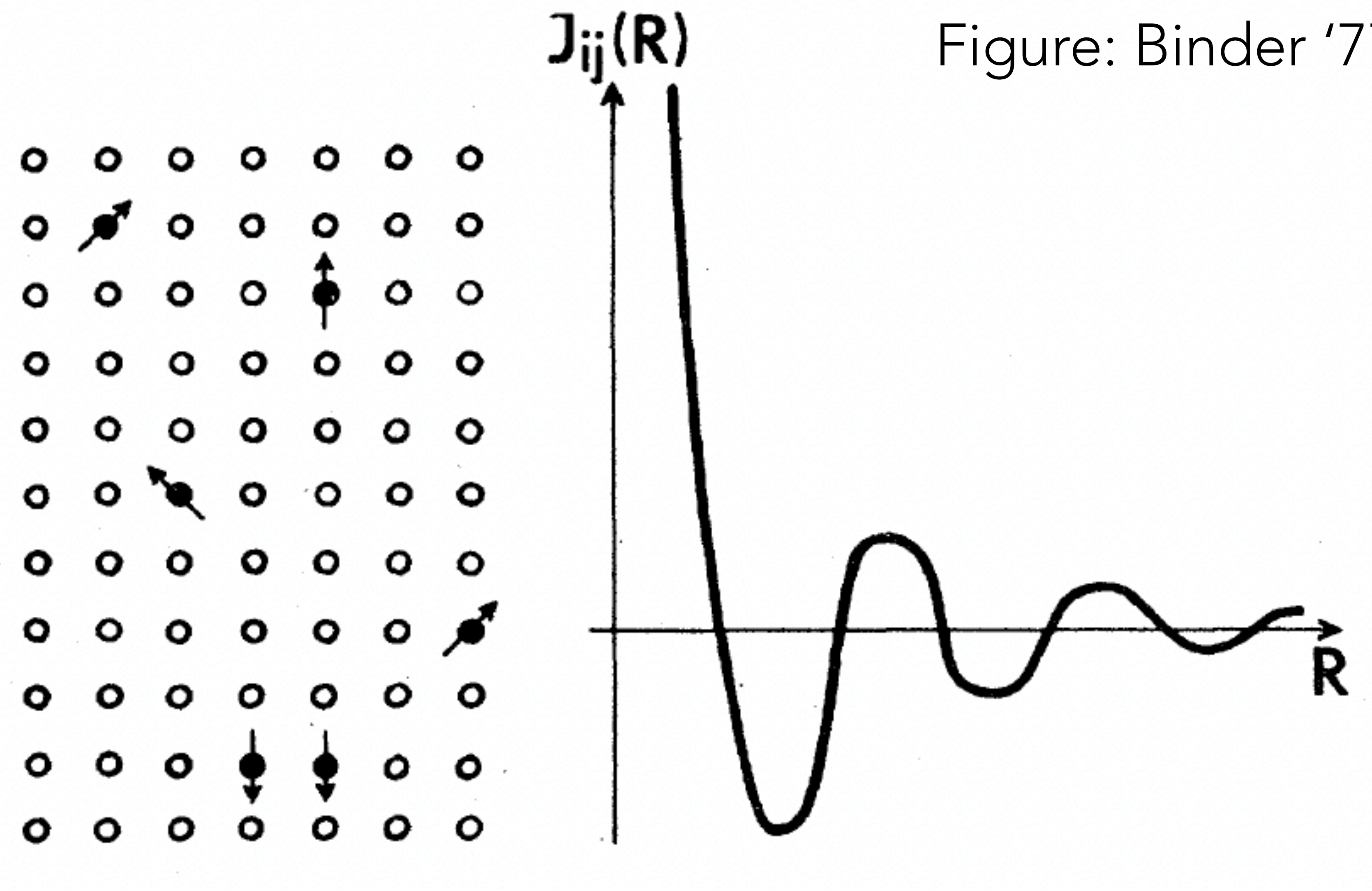

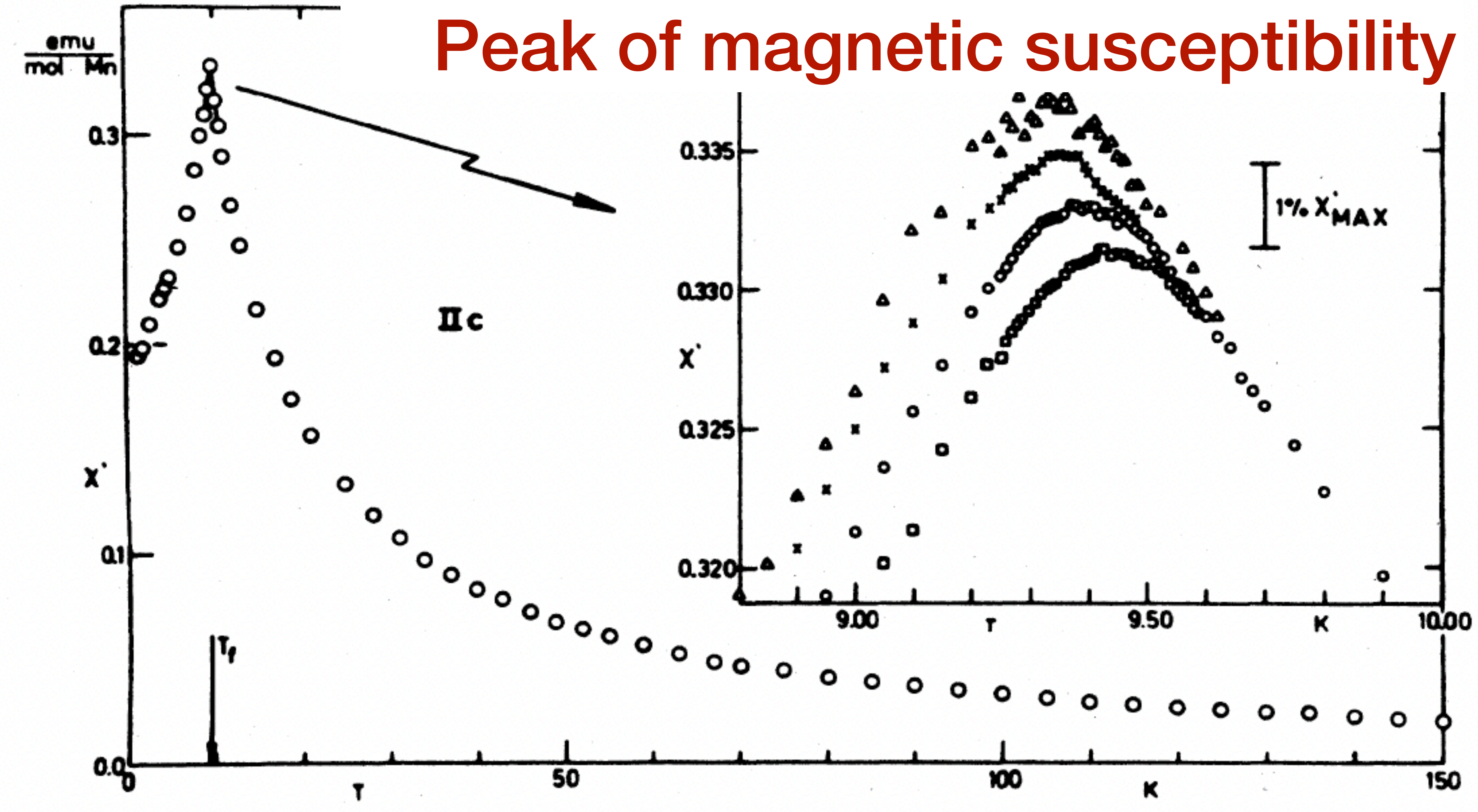

From Mulder et al. '81

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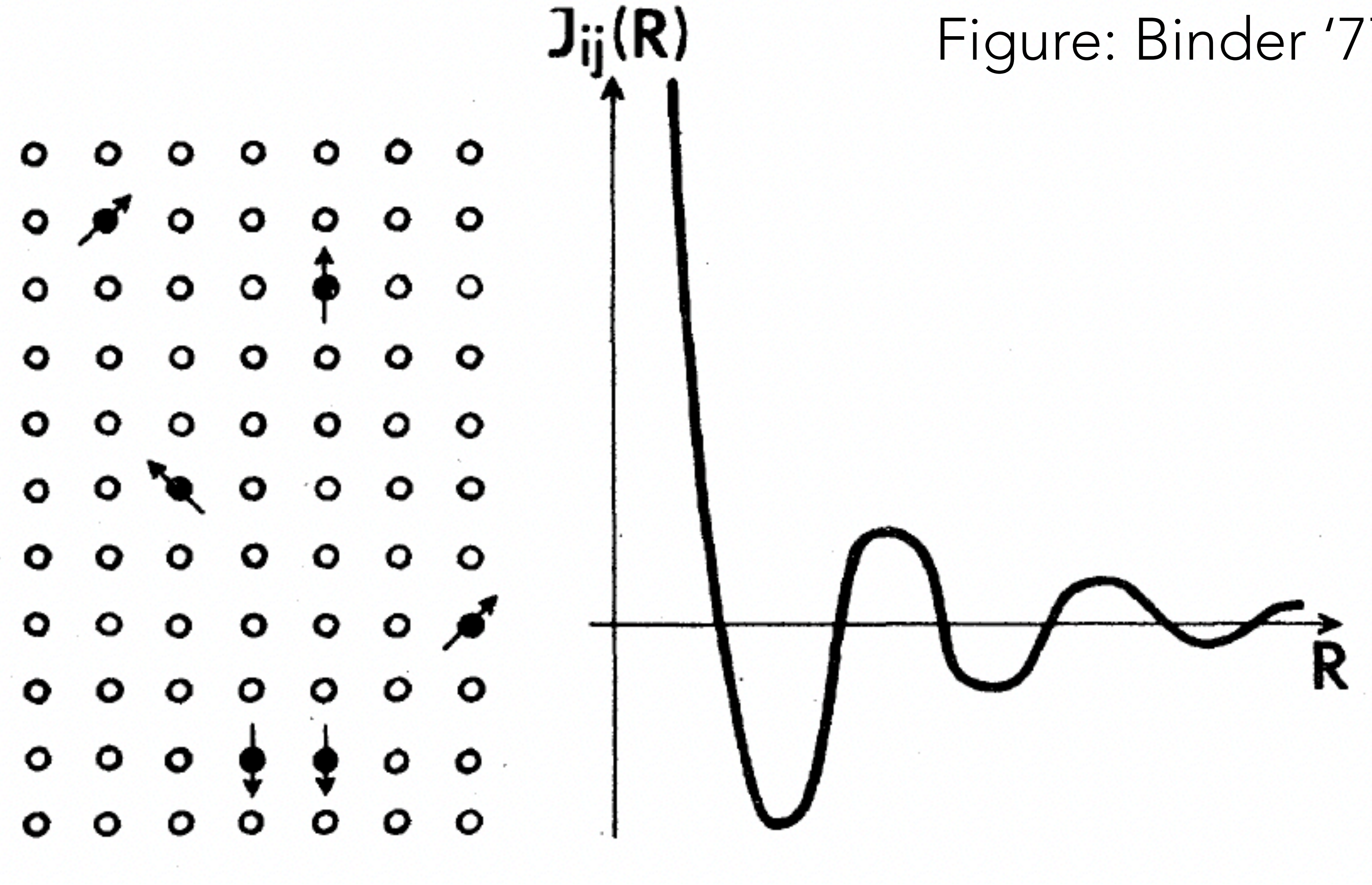
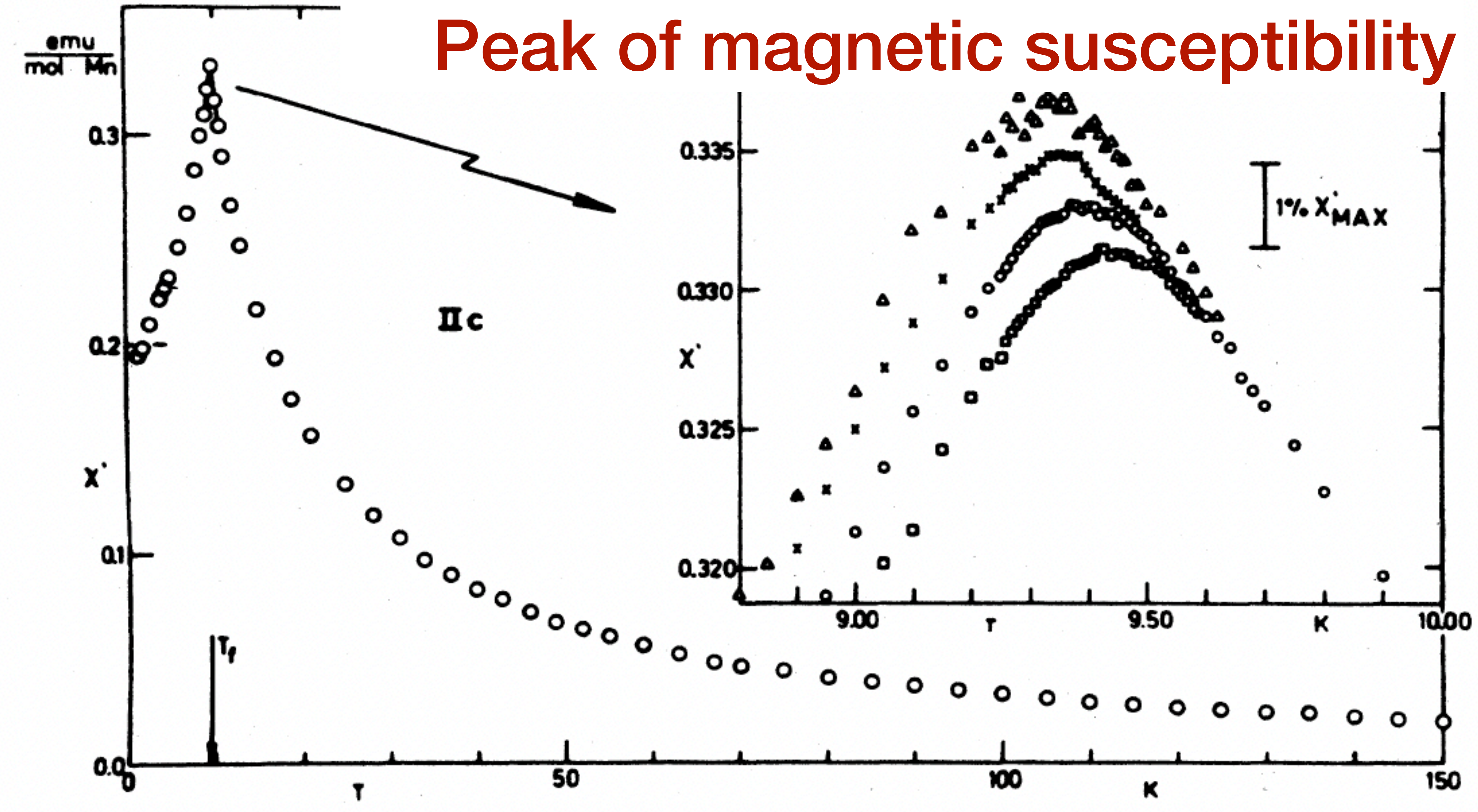


Figure: Binder '77

Peak of magnetic susceptibility



From Mulder et al. '81

- Short range interactions
- Lack of control
- Only access to certain macroscopic quantites

Experimental realization

Experimental realization

Confocal cavity QED platforms

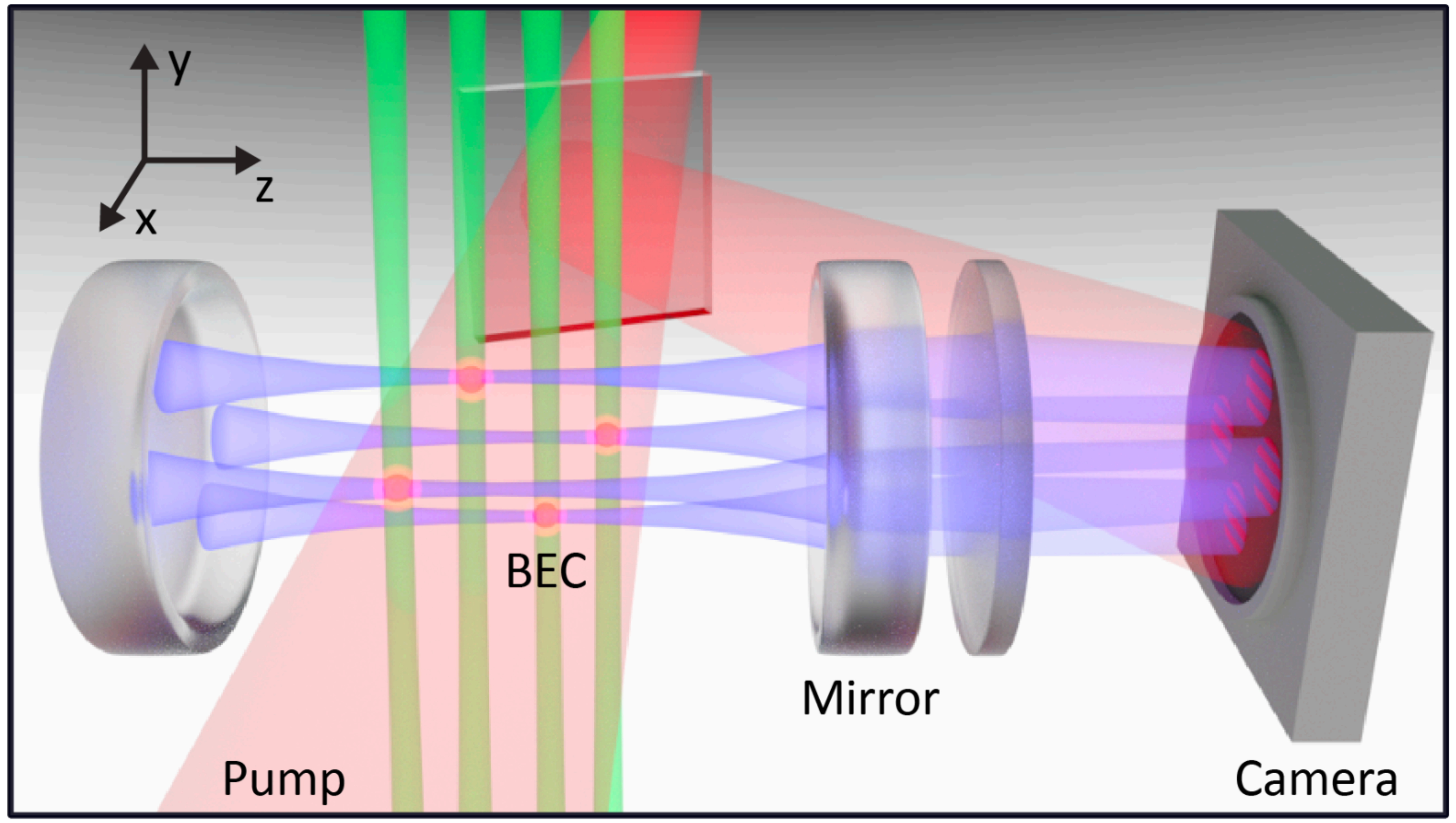


Figure: Marsh et al., PRX '21

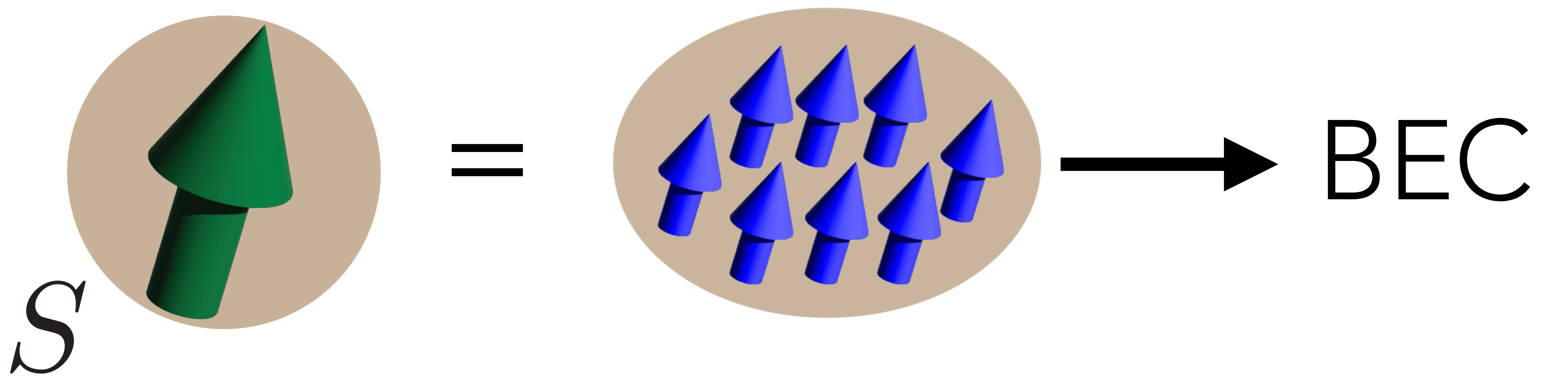
Experimental realization

Confocal cavity QED platforms

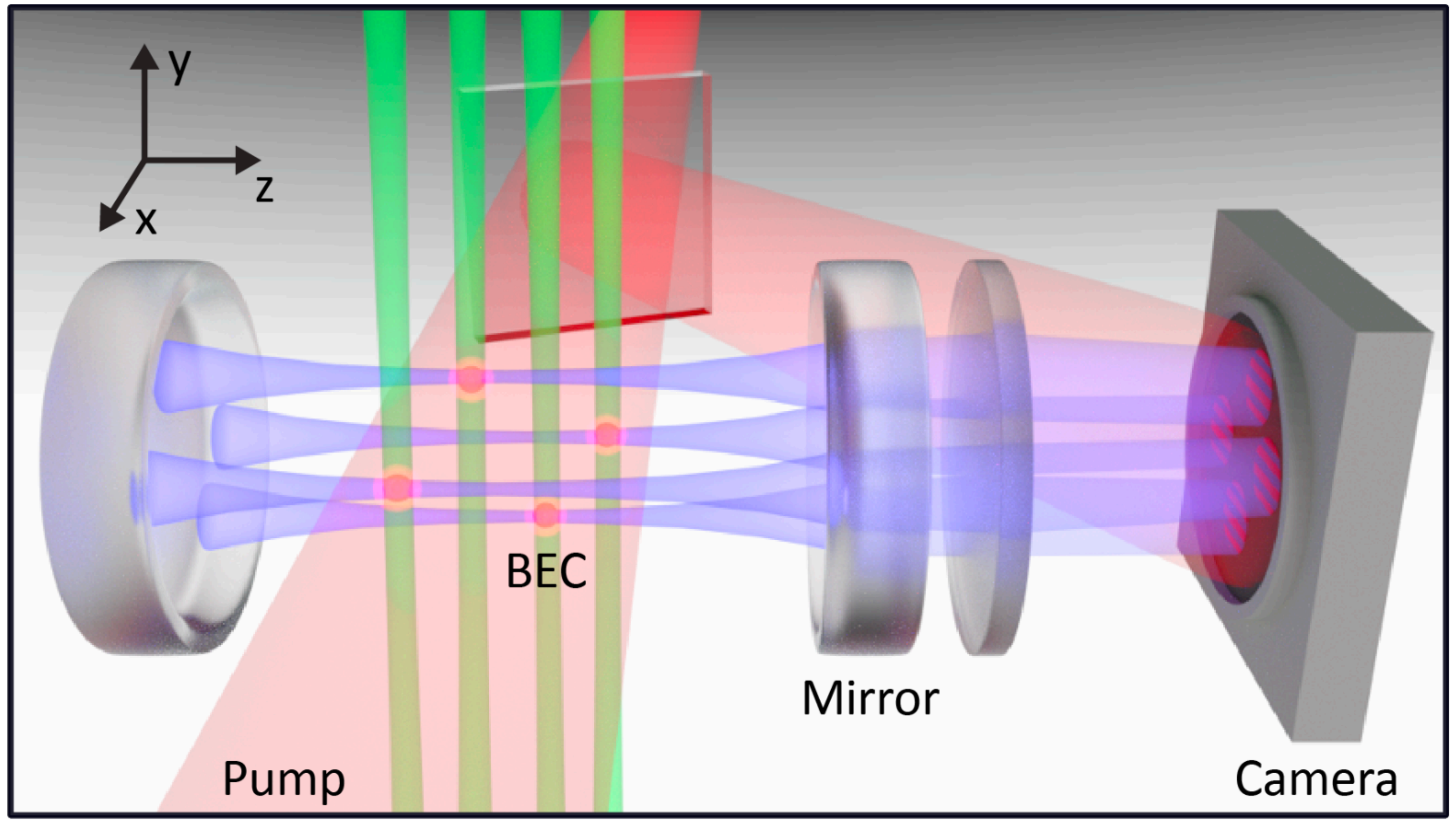
Cavity mediated couplings:

$$H_{int} \propto -\sum_{ij} J_{ij} S_i^x S_j^x + \ldots$$

Guo et al., PRA '19
Marsh et al., PRX '21



$$J_{ij}/J_0 = \delta(r_i - r_j) + \delta(r_i + r_j) + \frac{1}{\pi}\cos(\frac{2r_i \cdot r_j}{w_0^2})$$



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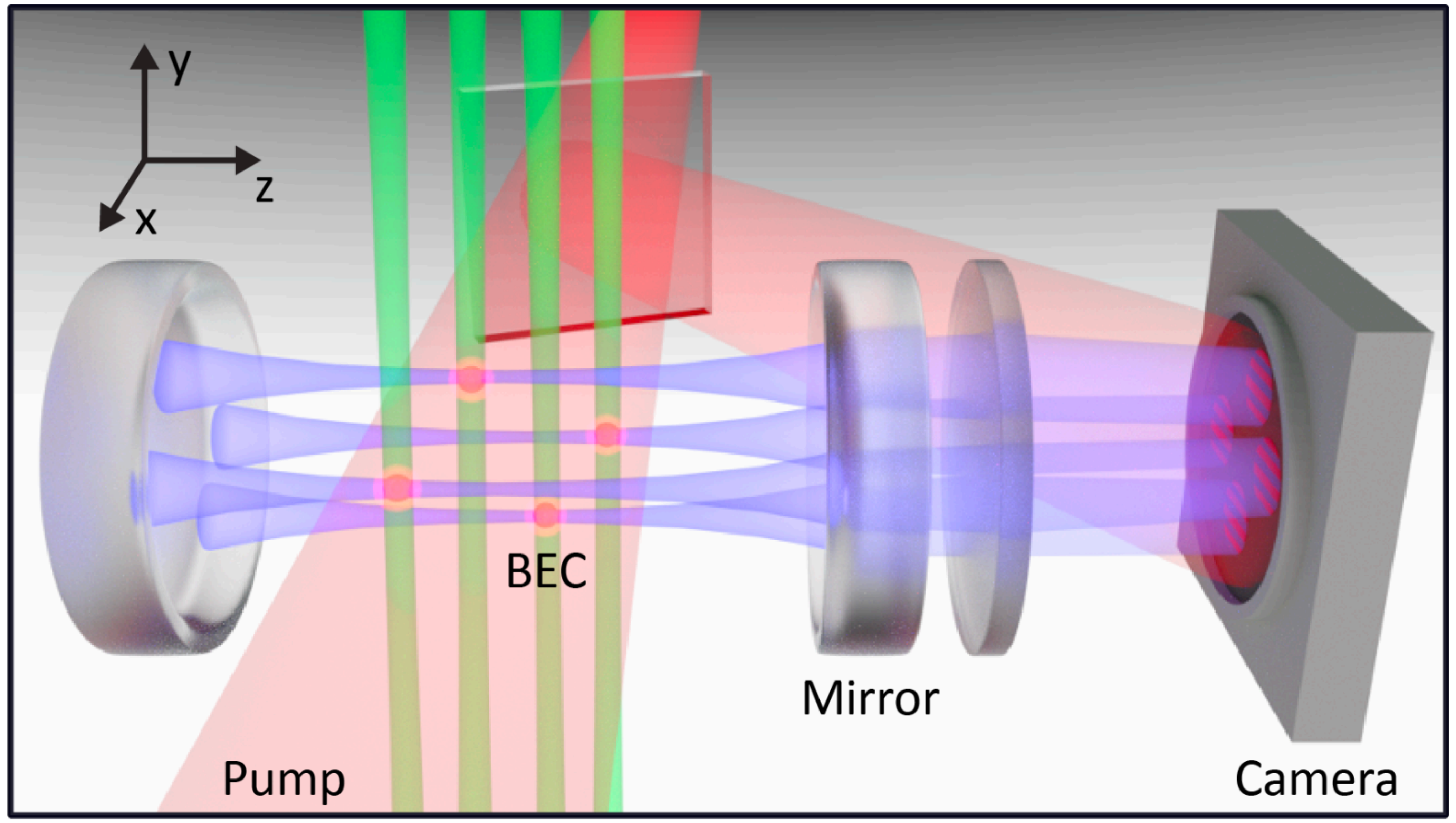

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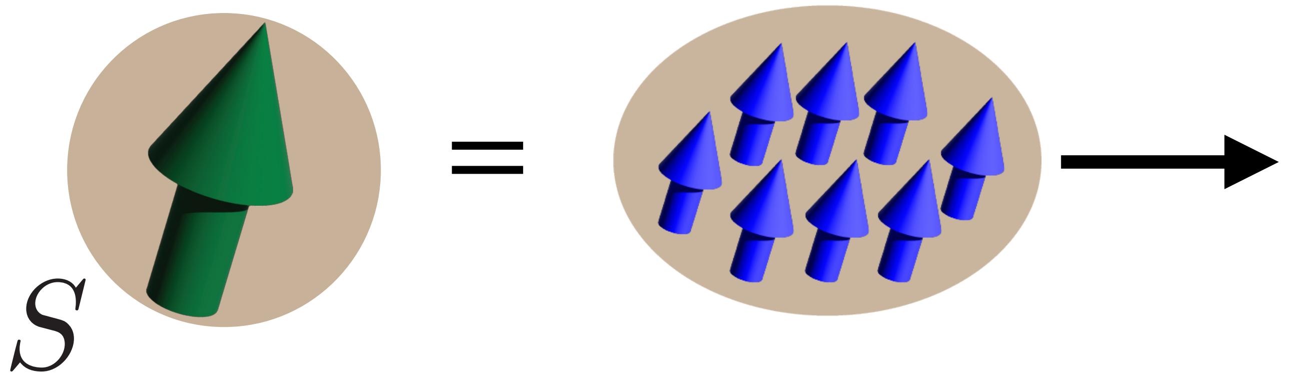

Long range + sign changing

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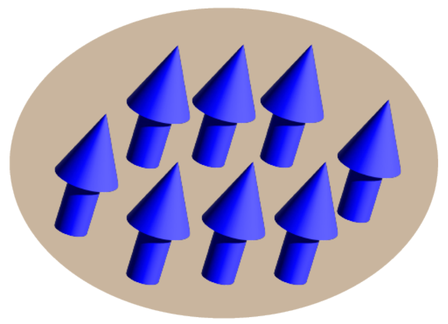
S =  → BEC

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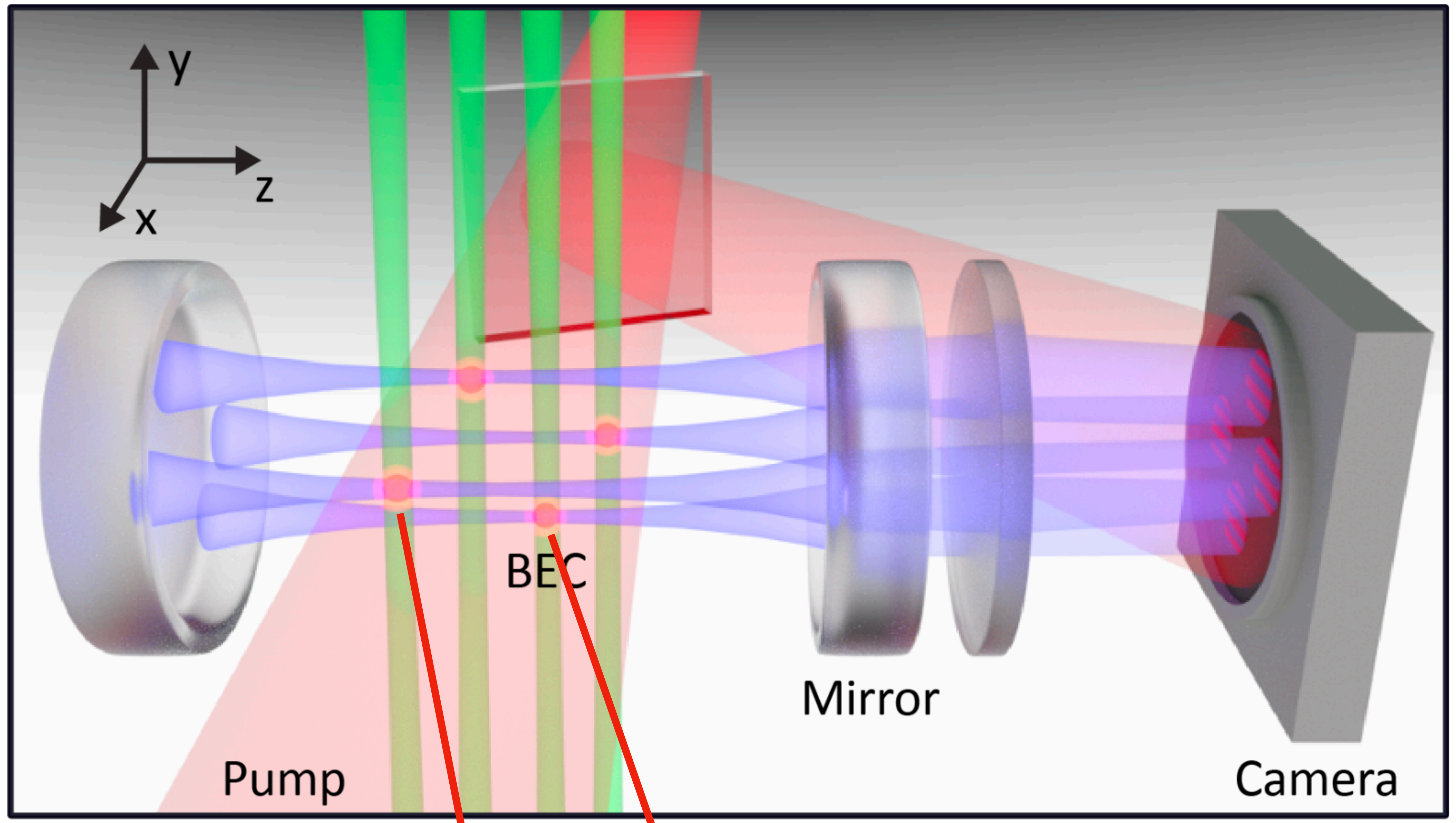
For large spins ($S \sim 10^5$) → direct imaging of spin configuration.

Kroeze et al., arXiv:2311.04216



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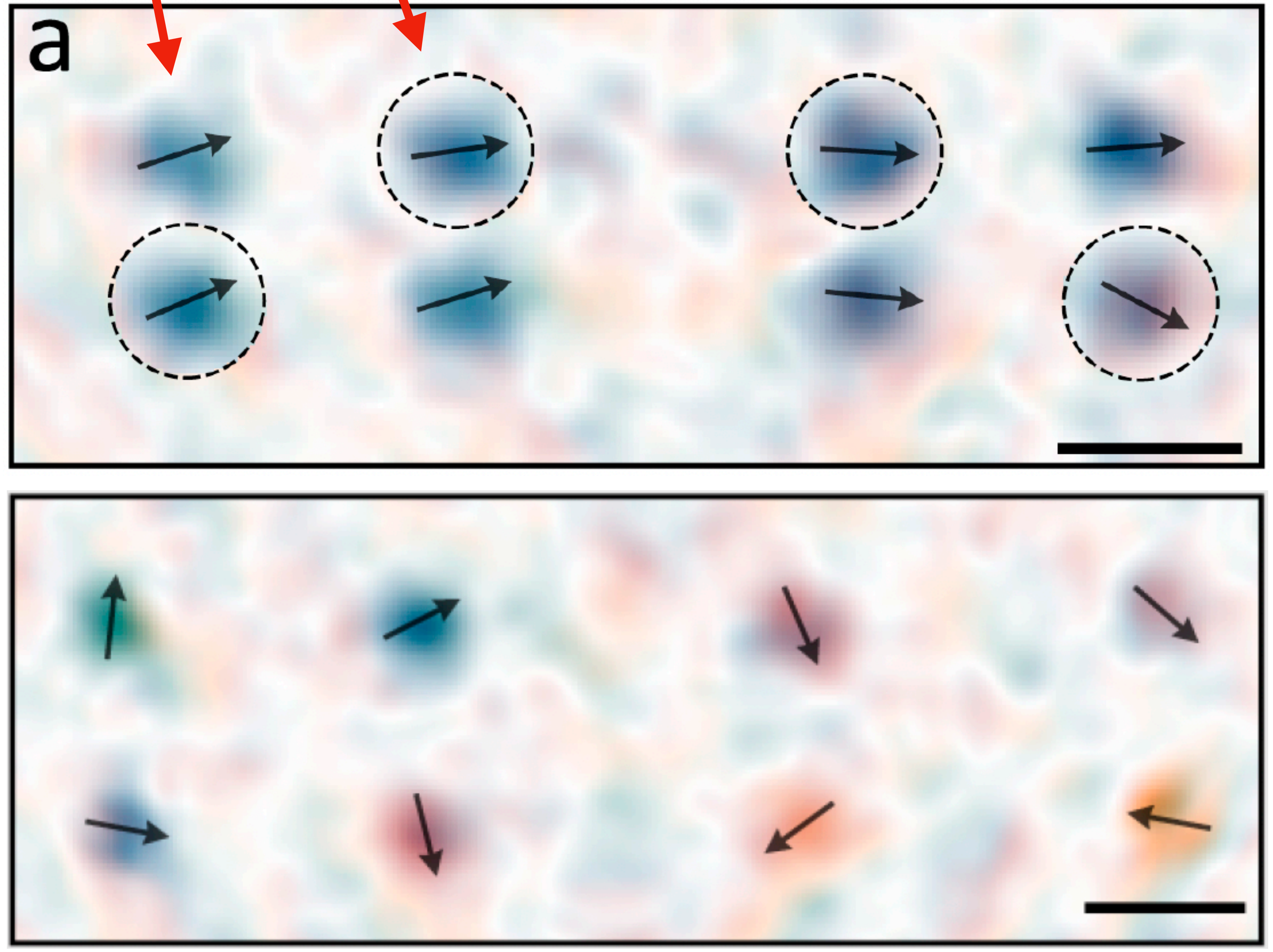

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A simple model for cavity spin glass

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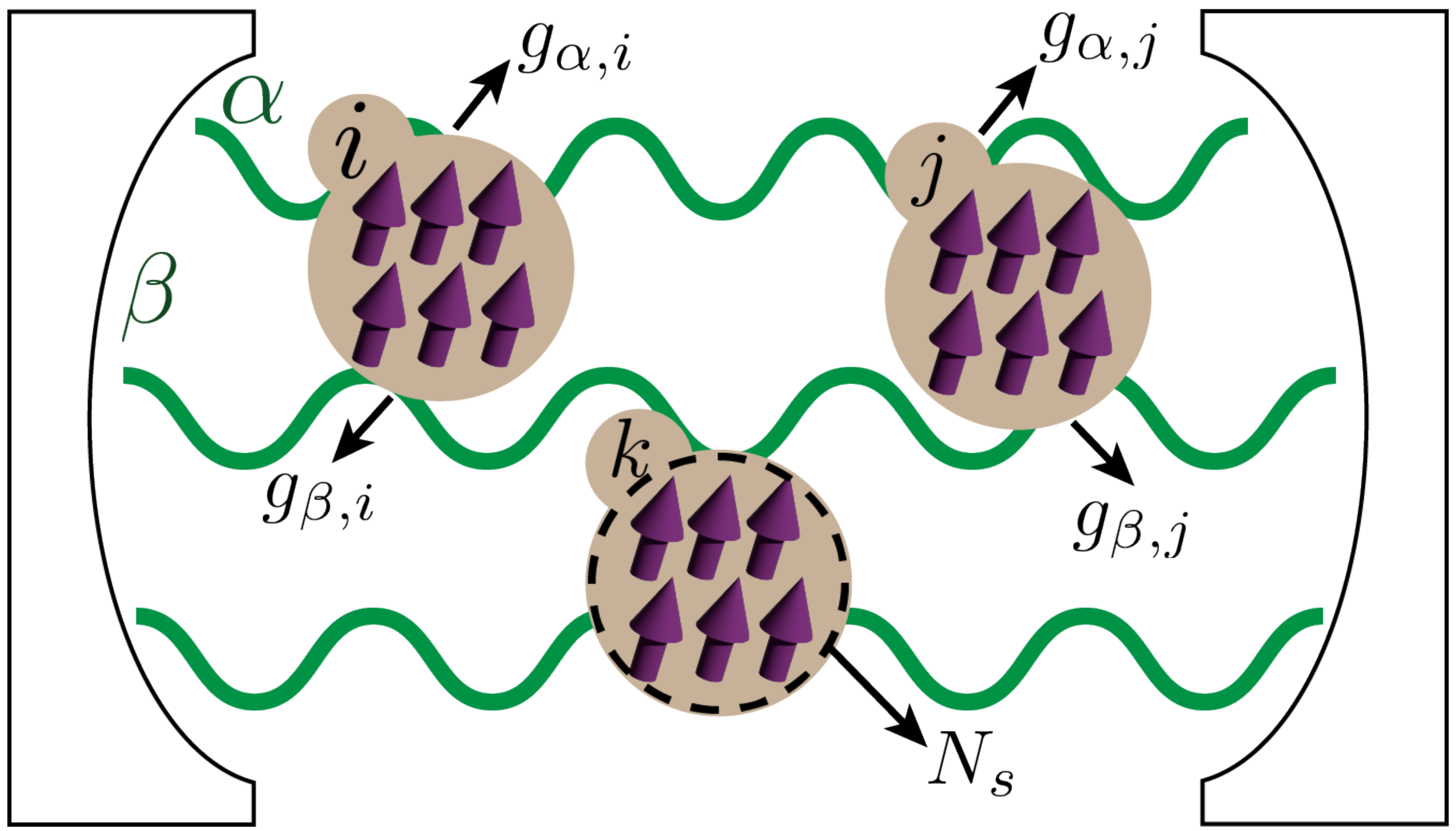
$$H = \omega_c \sum_{\alpha=1}^{M} a_\alpha^\dagger a_\alpha + \frac{\Delta}{2} \sum_{i=1}^{N} S_{i\lambda}^z - \sum_{\alpha}^{M} \sum_{i}^{N} \sum_{\lambda}^{N_s} g_{\alpha,i} (a_\alpha + a_\alpha^\dagger) S_i^x$$

$$\mathscr{L}\rho = \kappa \sum_{\alpha=1}^{M} \mathscr{D}[a_\alpha]\rho \qquad \overline{g_{\alpha,i}} = 0 \qquad \overline{g_{\alpha,i} g_{\beta,j}} = \delta_{\alpha\beta}\delta_{ij} g^2/\sqrt{2S(N+M)}$$



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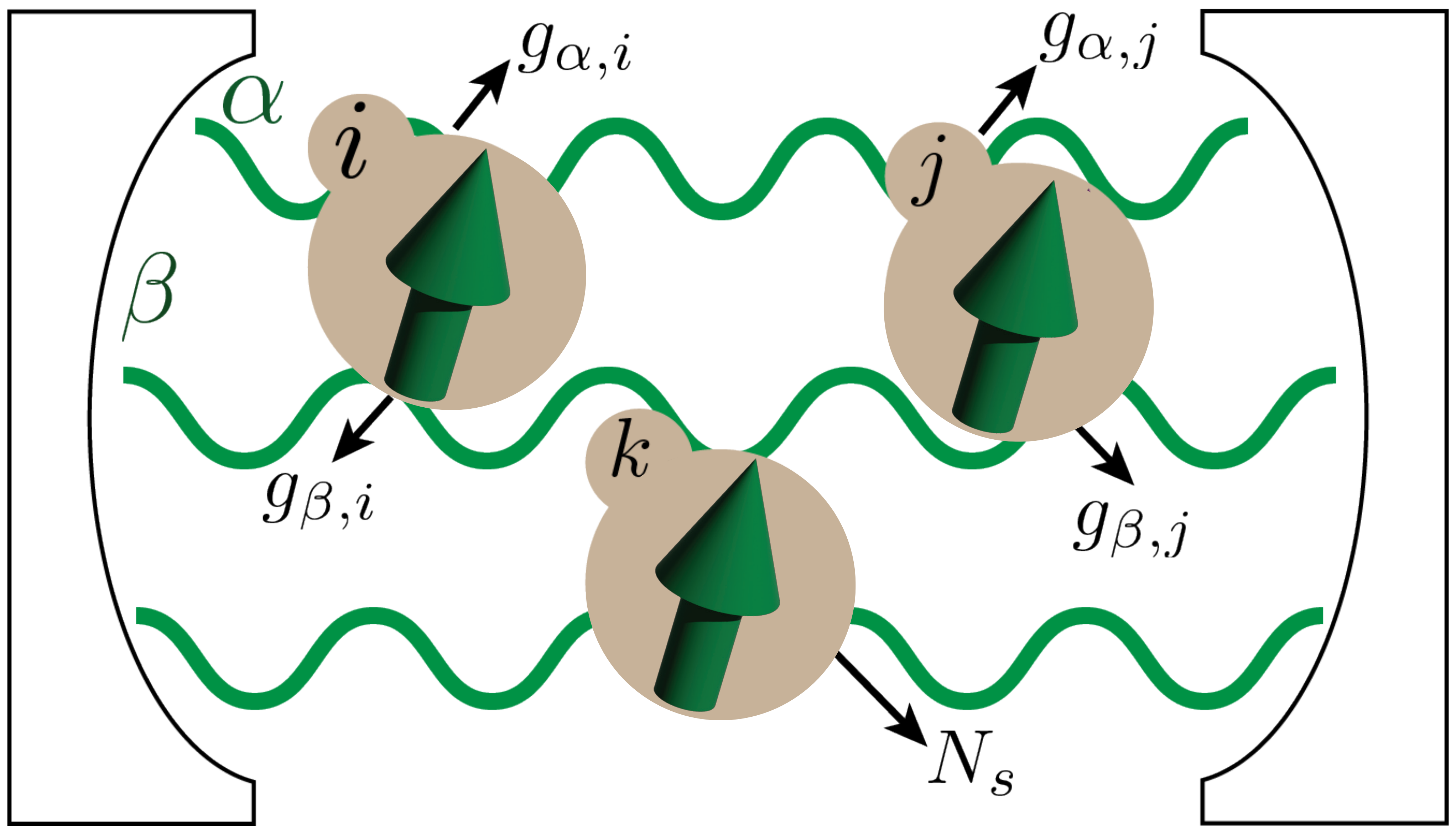
$$H = \omega_c \sum_{\alpha=1}^{M} a_\alpha^\dagger a_\alpha + \frac{\Delta}{2} \sum_{i=1}^{N} S_{i\lambda}^z - \sum_{\alpha}^{M} \sum_{i}^{N} \sum_{\lambda}^{N_s} g_{\alpha,i} (a_\alpha + a_\alpha^\dagger) S_i^x$$

$$\mathscr{L}\rho = \kappa \sum_{\alpha=1}^{M} \mathscr{D}[a_\alpha]\rho \qquad \overline{g_{\alpha,i}} = 0 \qquad \overline{g_{\alpha,i} g_{\beta,j}} = \delta_{\alpha\beta}\delta_{ij} g^2 / \sqrt{2S(N+M)}$$



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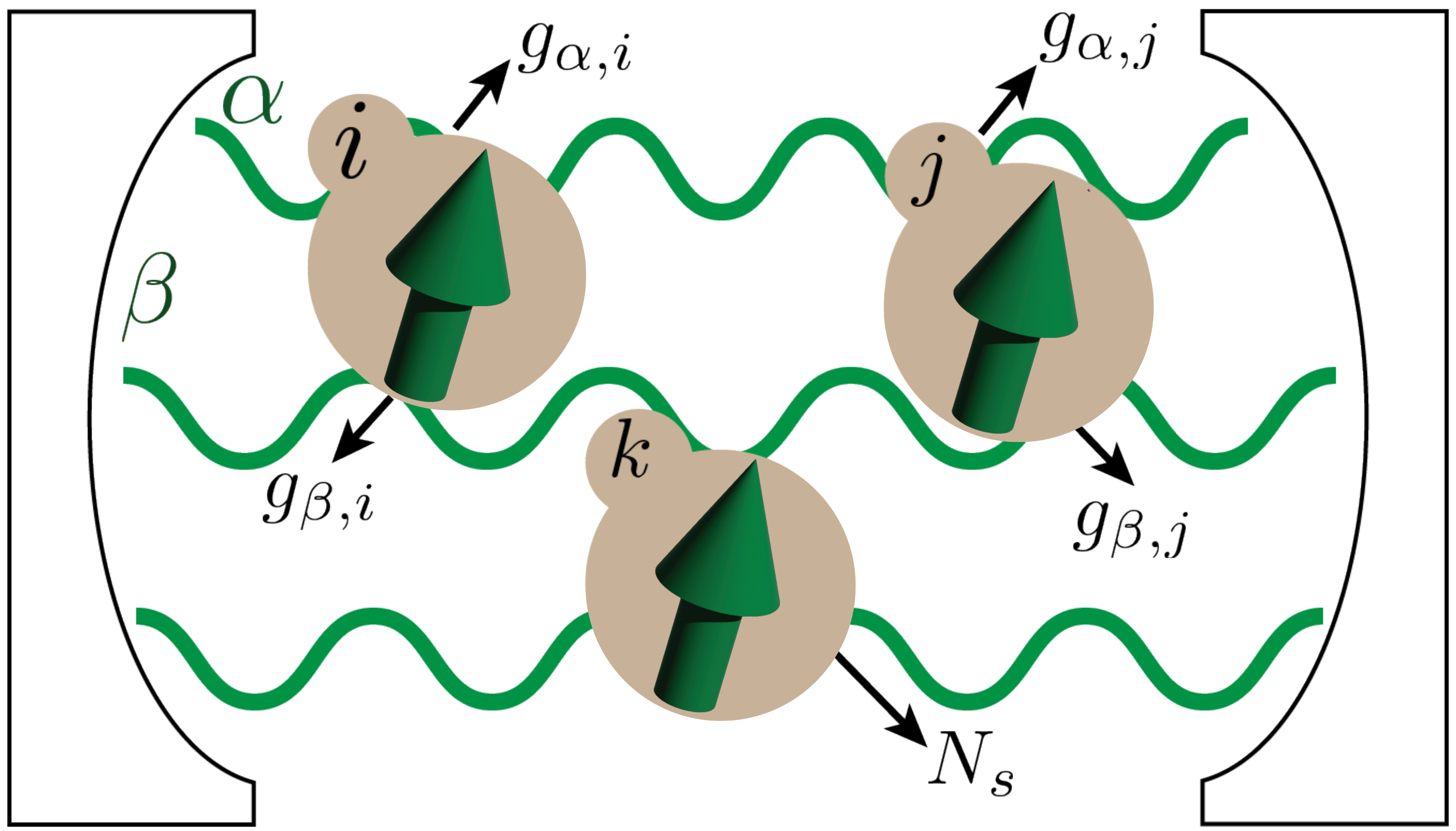
$$H = \Delta \sum_i S_i^z - \frac{4\omega_c^{-1}}{2S(N+M)} \sum_{ij}^{N} \sum_{\alpha}^{M} g_{\alpha,i}\, g_{\alpha,j}\, S_i^x S_j^x$$



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 # patterns ≈ # groundstates

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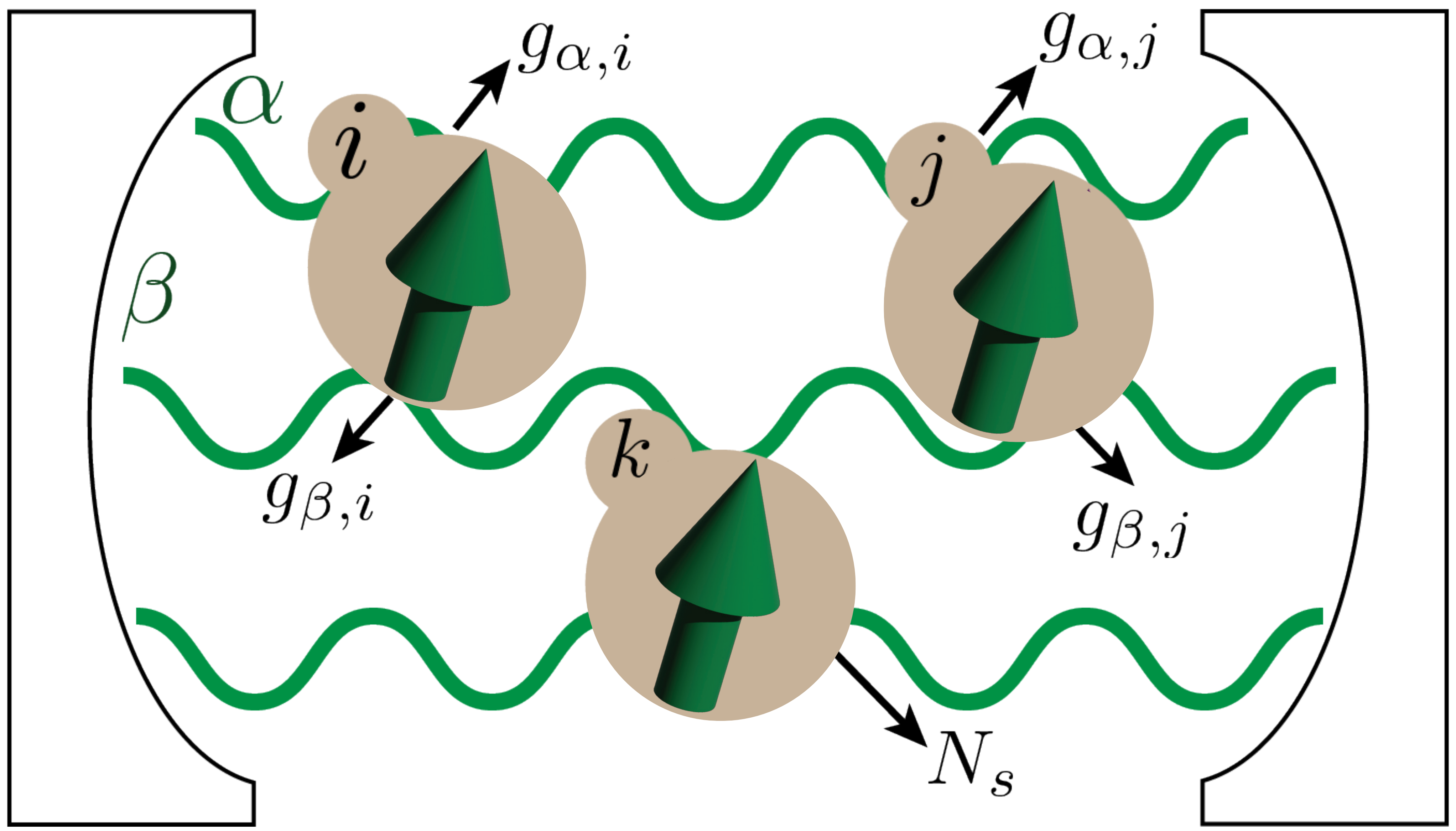

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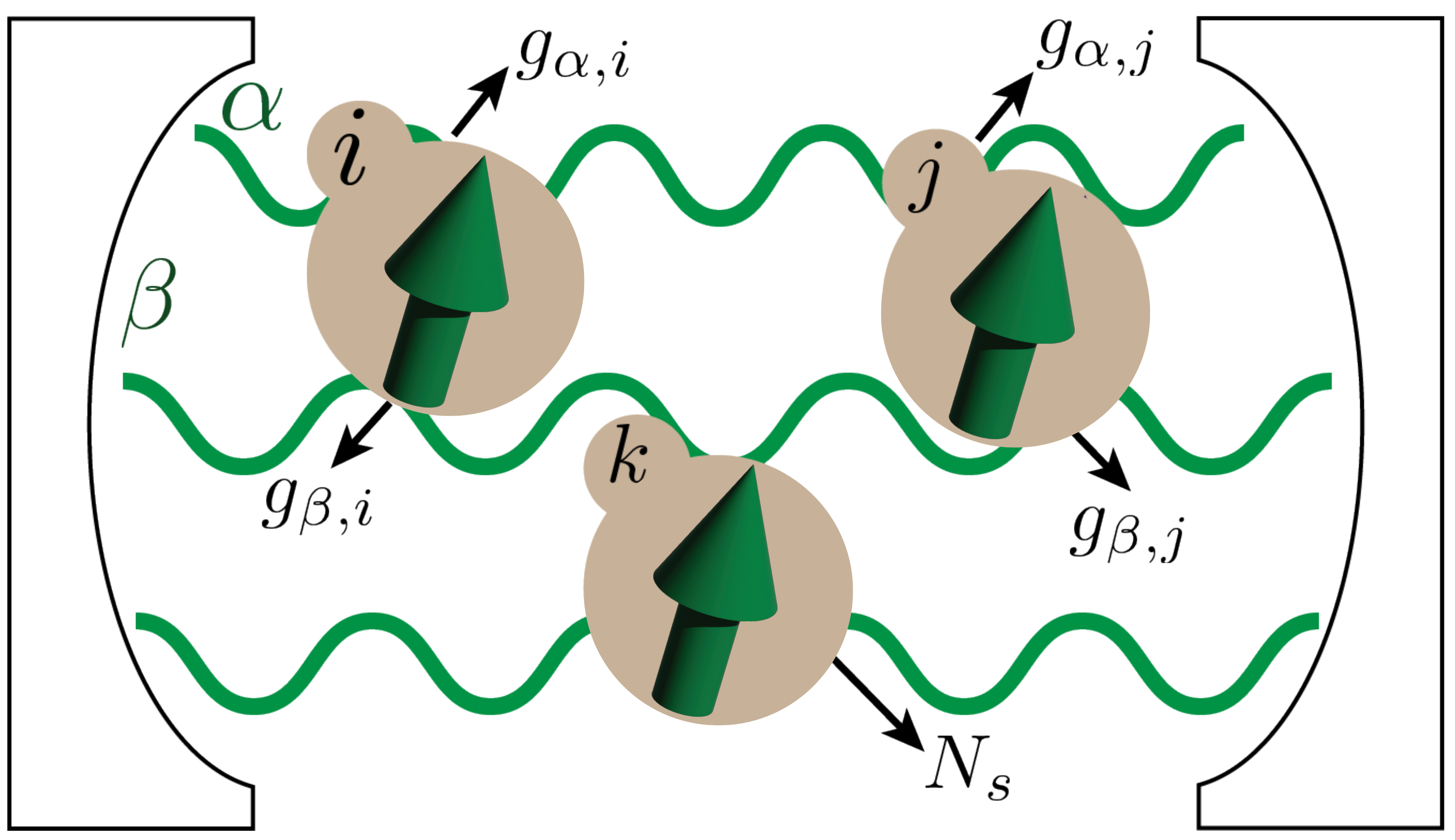

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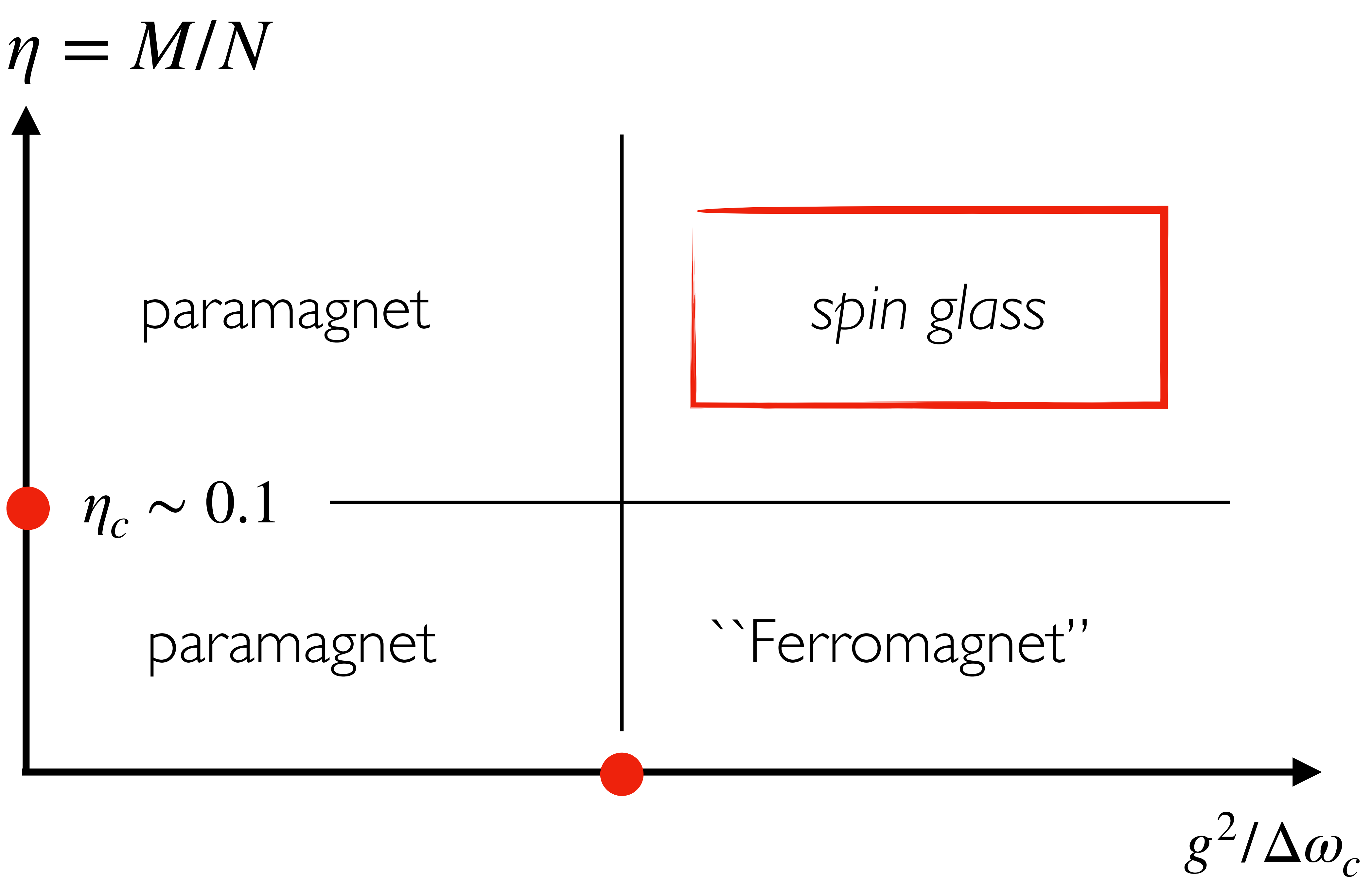
$$\frac{\#\text{ cavity modes } (M)}{\#\text{ atomic clouds } (N)} = \eta$$

$\eta < \eta_c$ → Easy to choose the groundstate
Spins retrieve one of the patterns

Hopfield, PNAS '82 / Amit, Gutfreund & Sompolinsky, PRL '85 / Marsh et al., PRX '21

$\eta > \eta_c$ → Frustration → **spin glass**

Gopalakrishnan, Lev & Goldbart, PRL '11 / Strack & Sachdev, PRL '11
Buchhold et al., PRA '13



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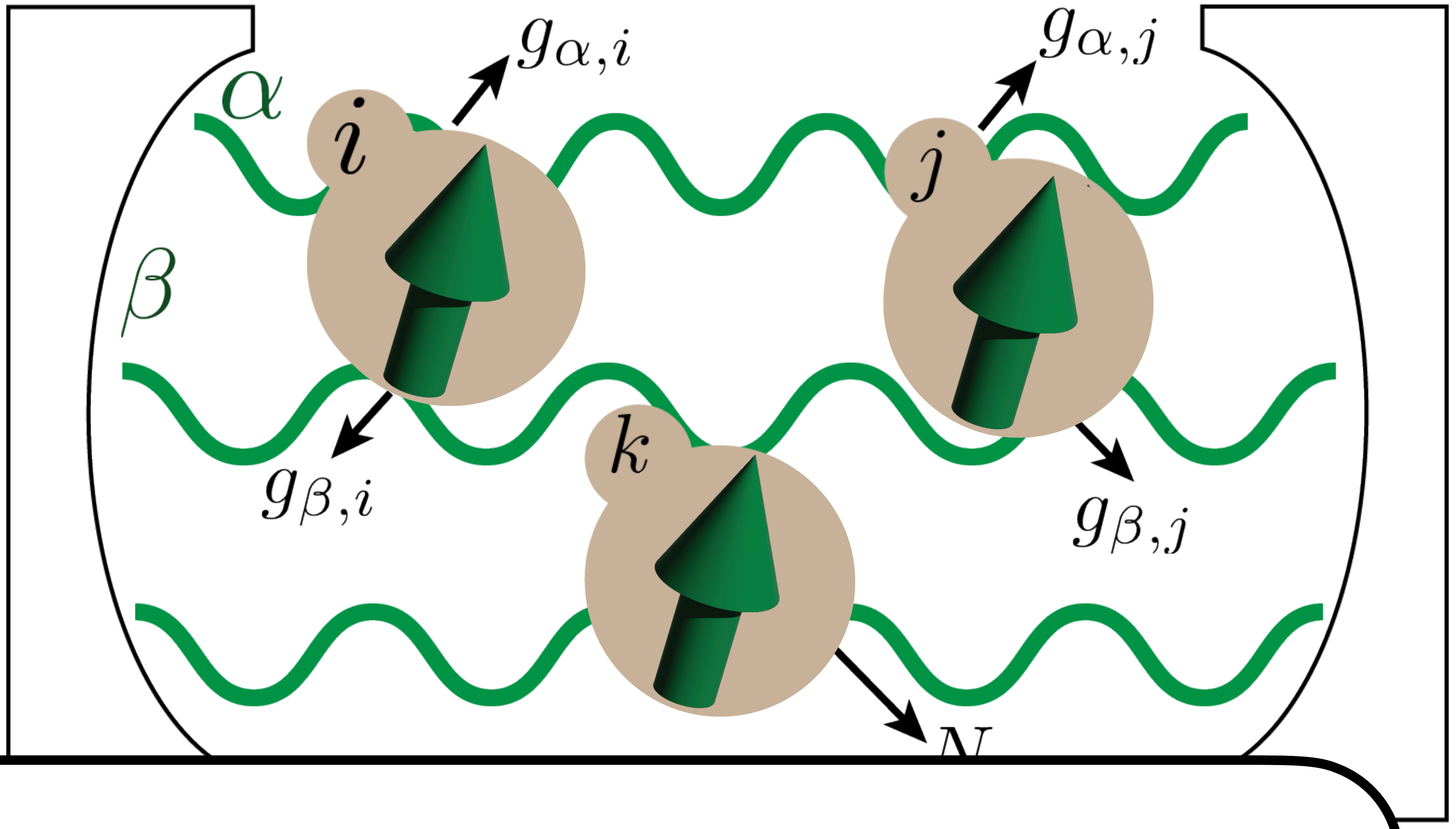


Adiabatic elimination:

 # patterns ≈ # groundstates

To solve for non-eq. dynamics

Disordered systems are very complicated, but **averaging makes life easier**

Write spins in terms of fermions $\sigma^\alpha = -i\epsilon_{\alpha\beta\gamma}\psi^\beta\psi^\gamma$ $\{\psi^\alpha, \psi^\beta\} = \delta_{\alpha\beta}$ $(\alpha, \beta = x, y, z)$

Use non-equilibrium field theory

#

#

Buchhold et al., PRA '13

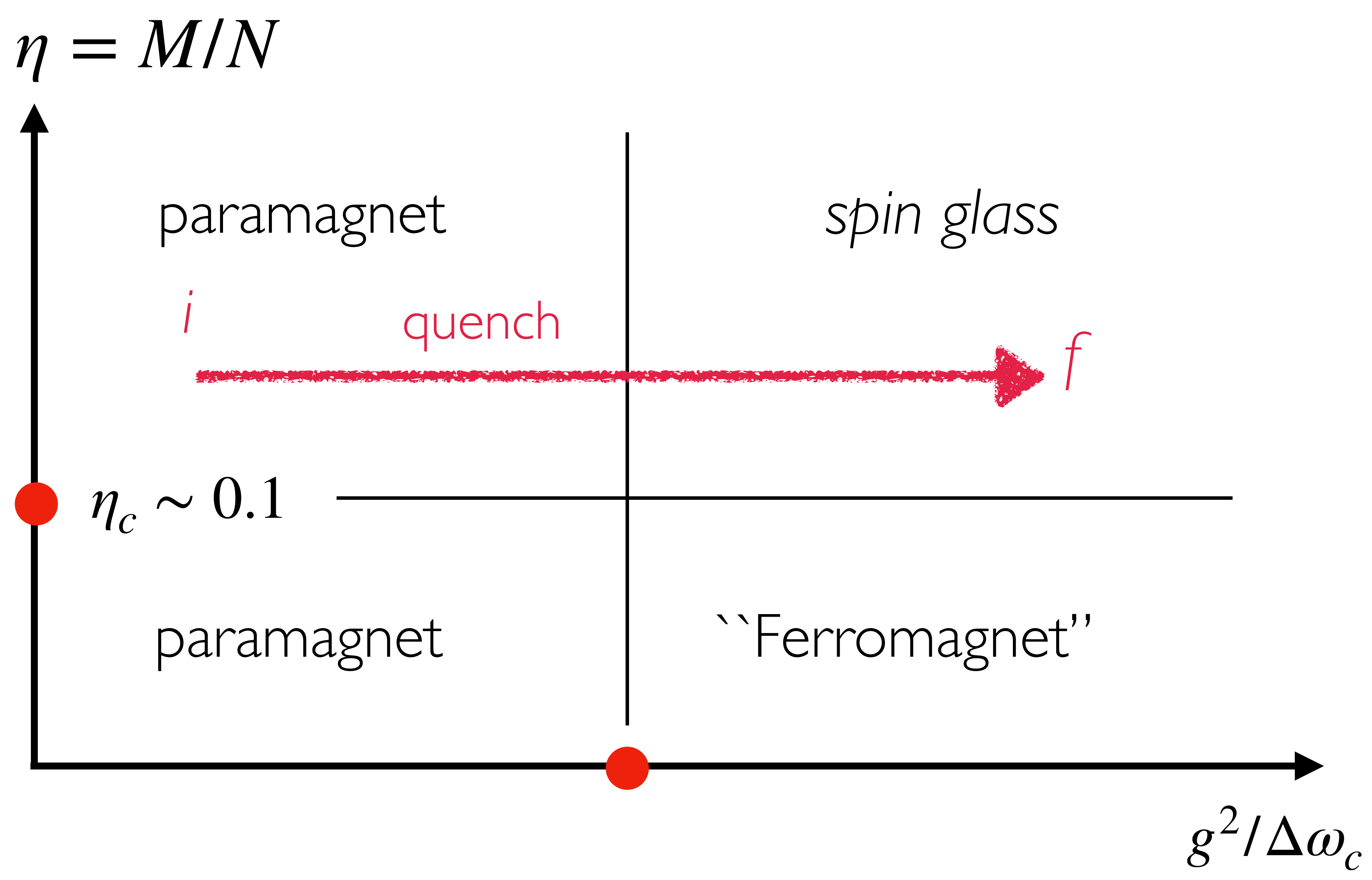
$g^2/\Delta\omega_c$

Quench dynamics

Quench dynamics

Start from $|\rightarrow\rangle|\rightarrow\rangle \ldots |\rightarrow\rangle$

Sudden change of coupling $g_i \rightarrow g_f$



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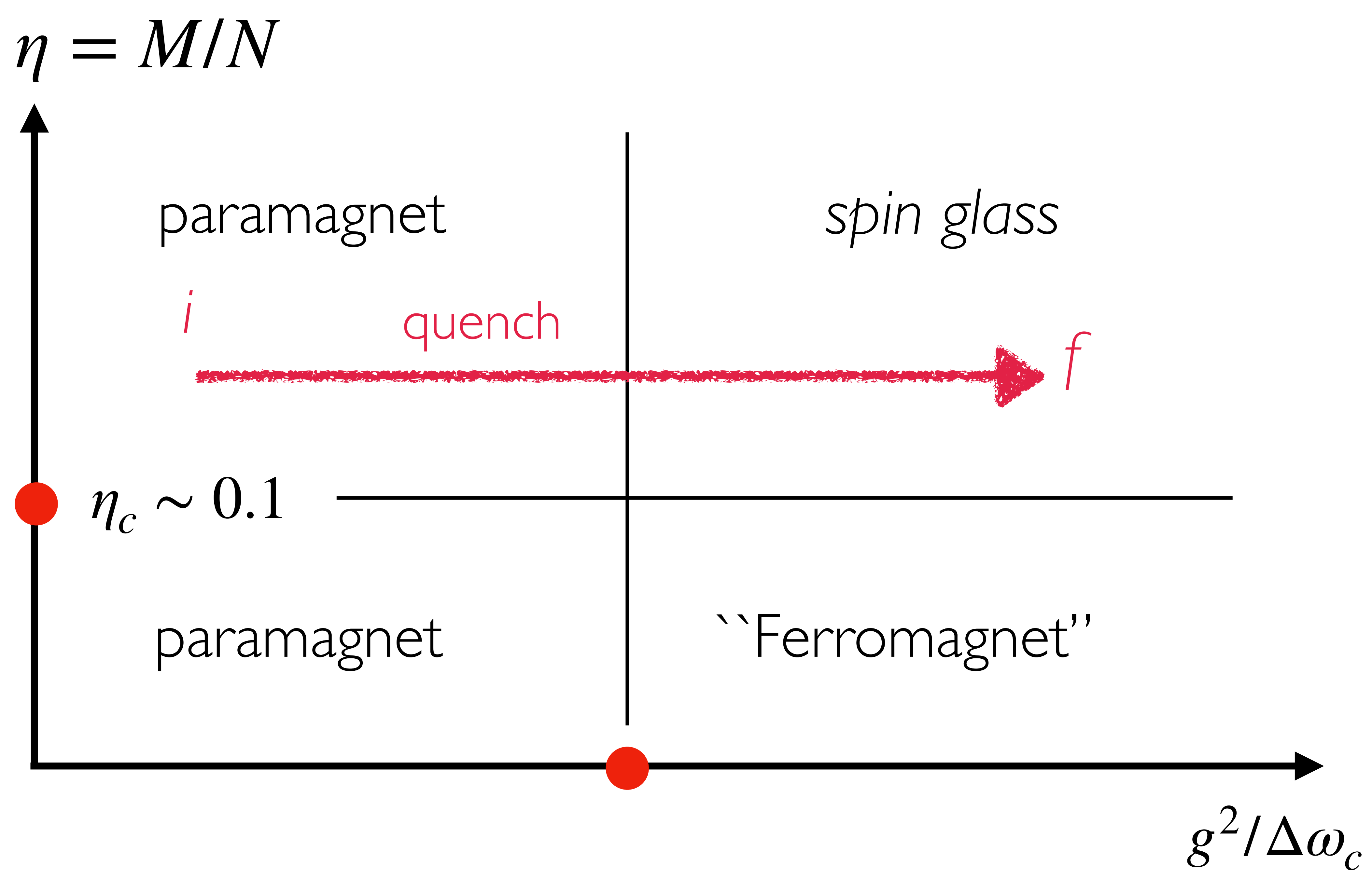
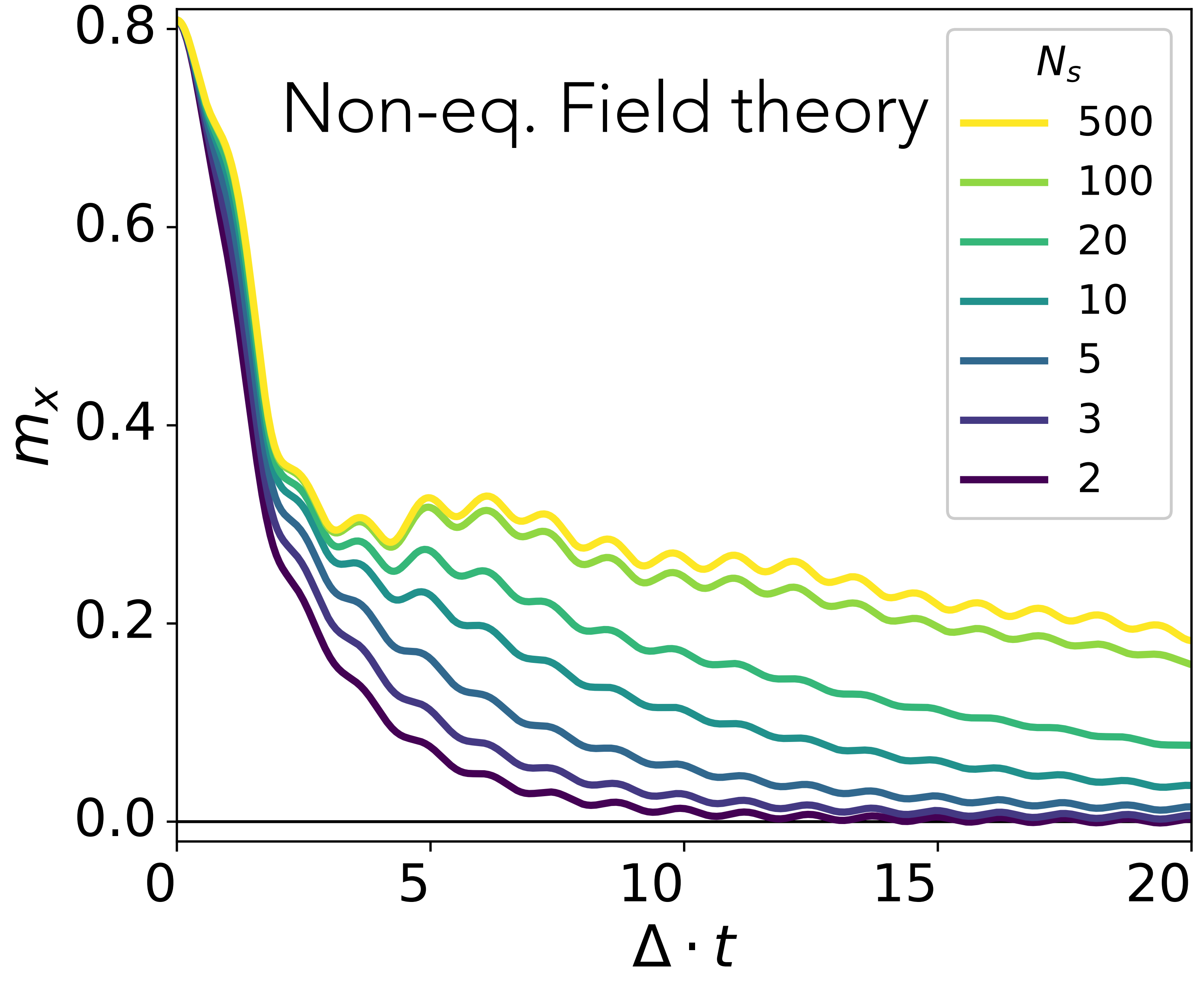
Let's try different spin sizes





Long lasting prethermal plateau

Quantum fluctuation accelerate relaxation

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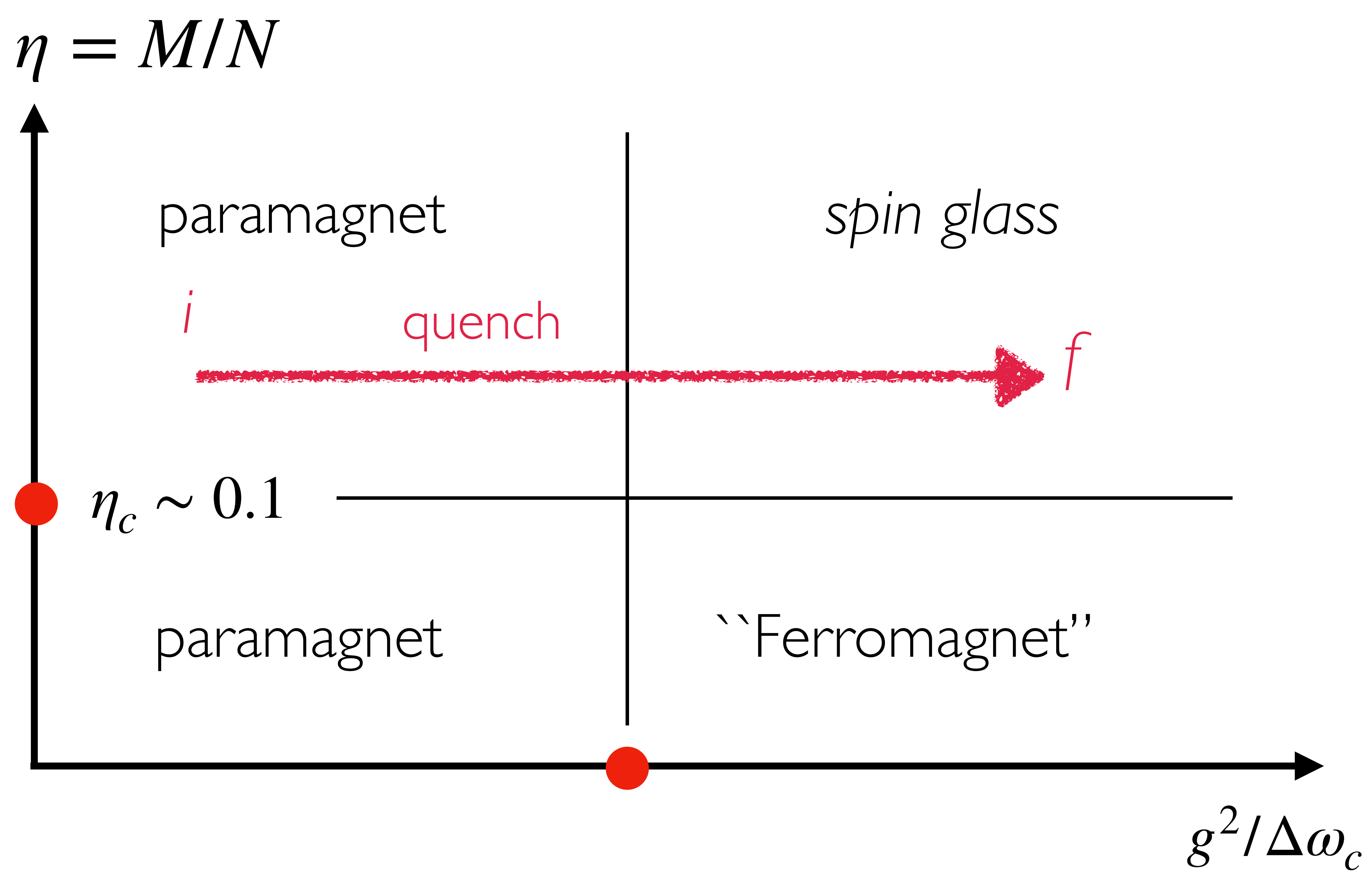

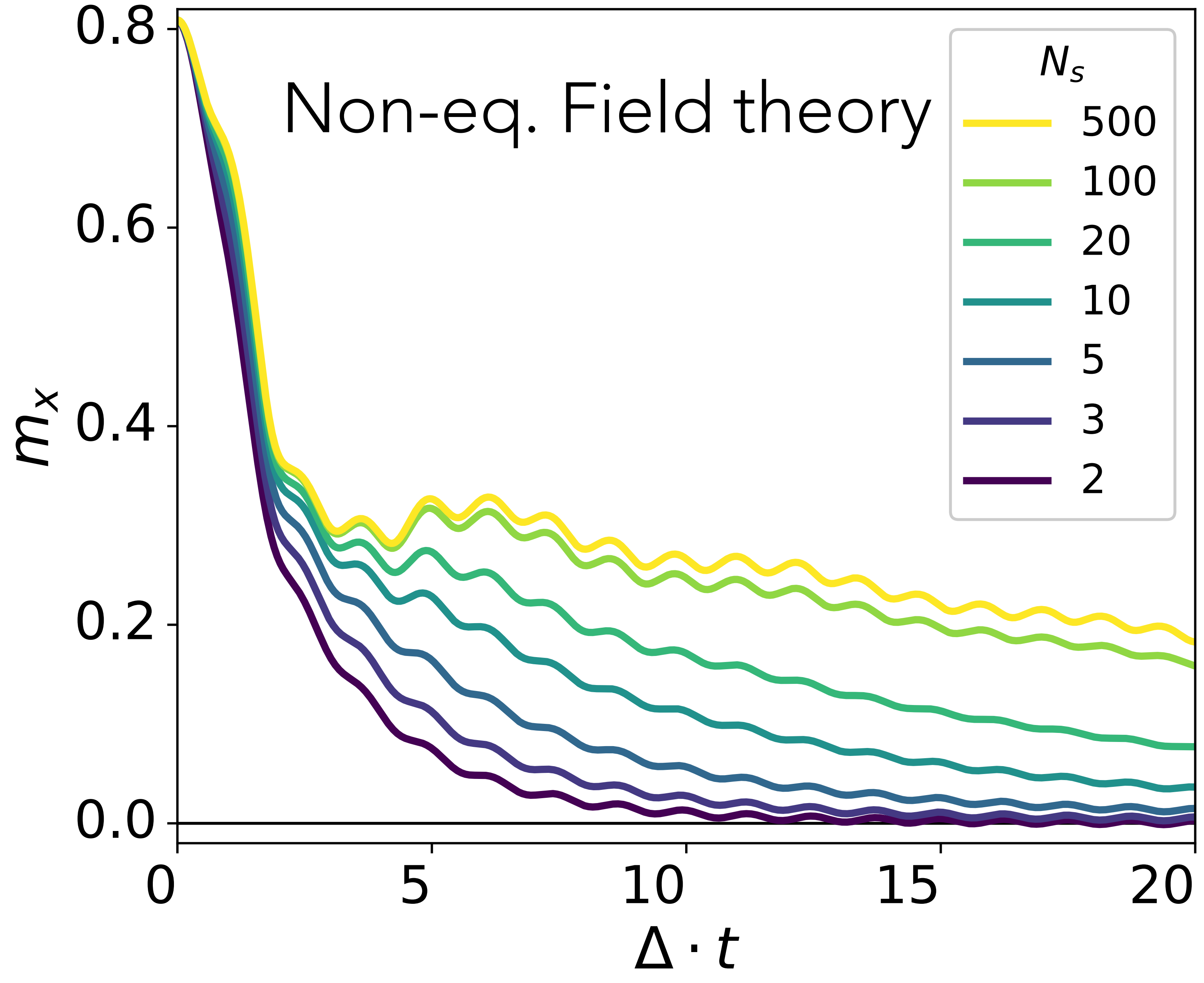

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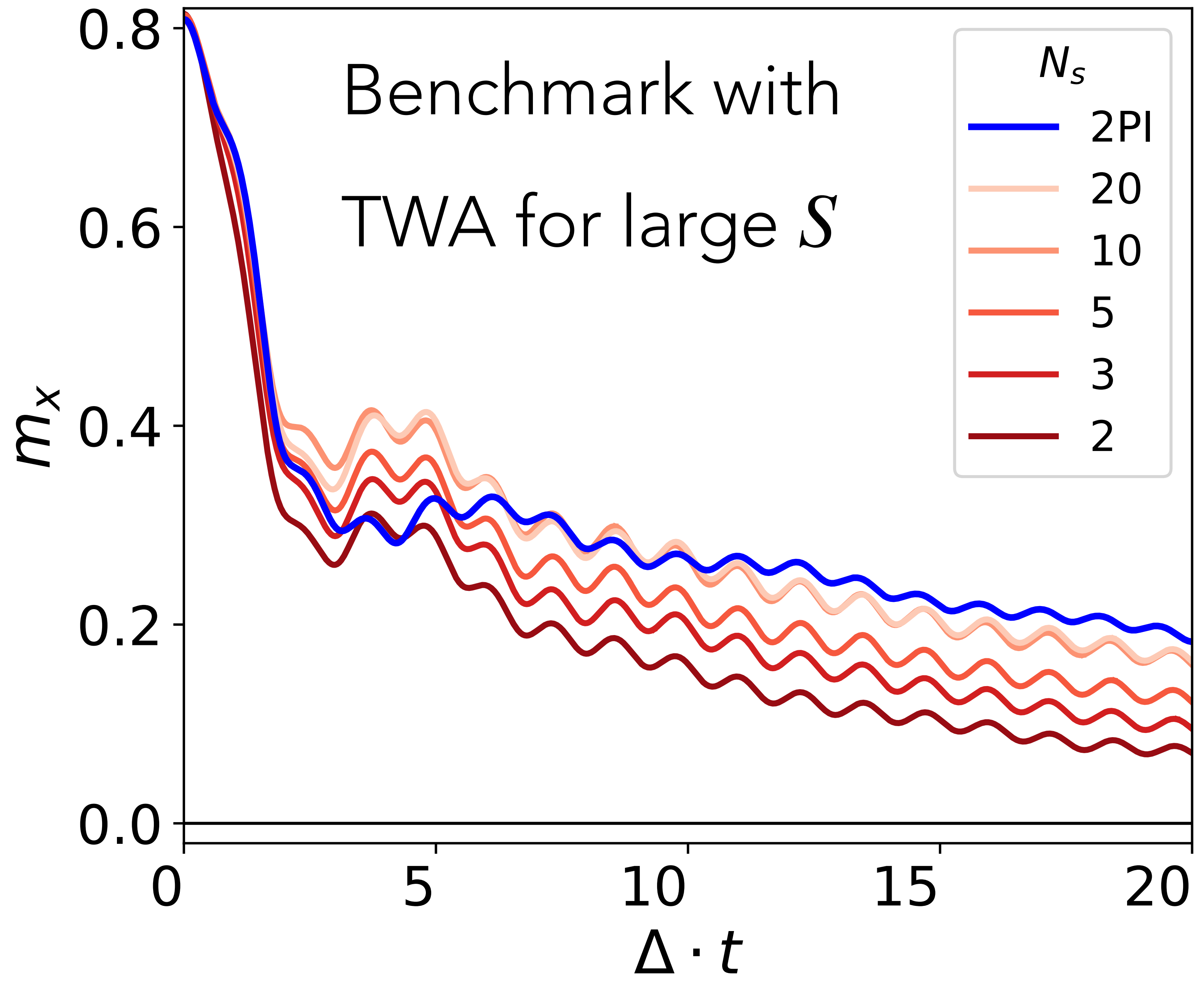
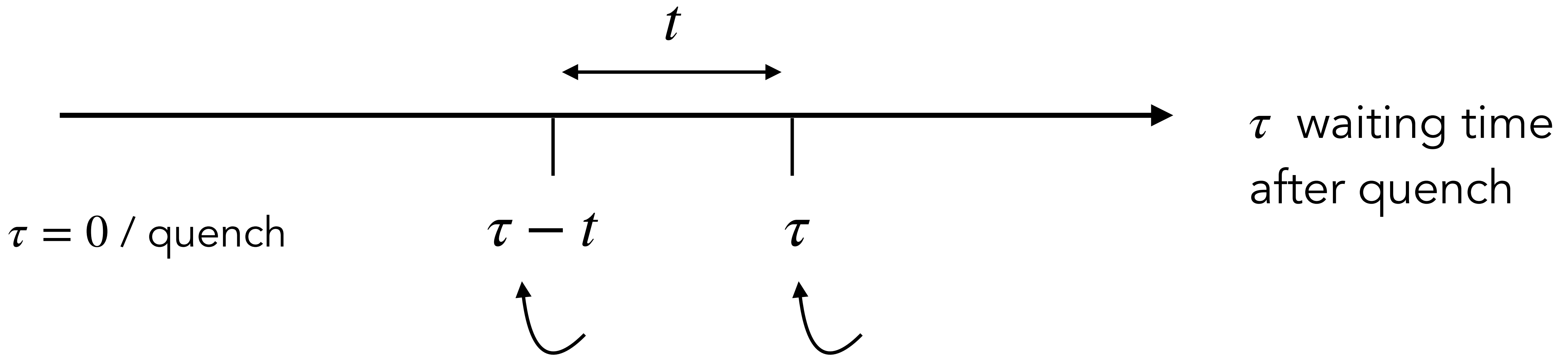


Glass dynamics

Glass dynamics

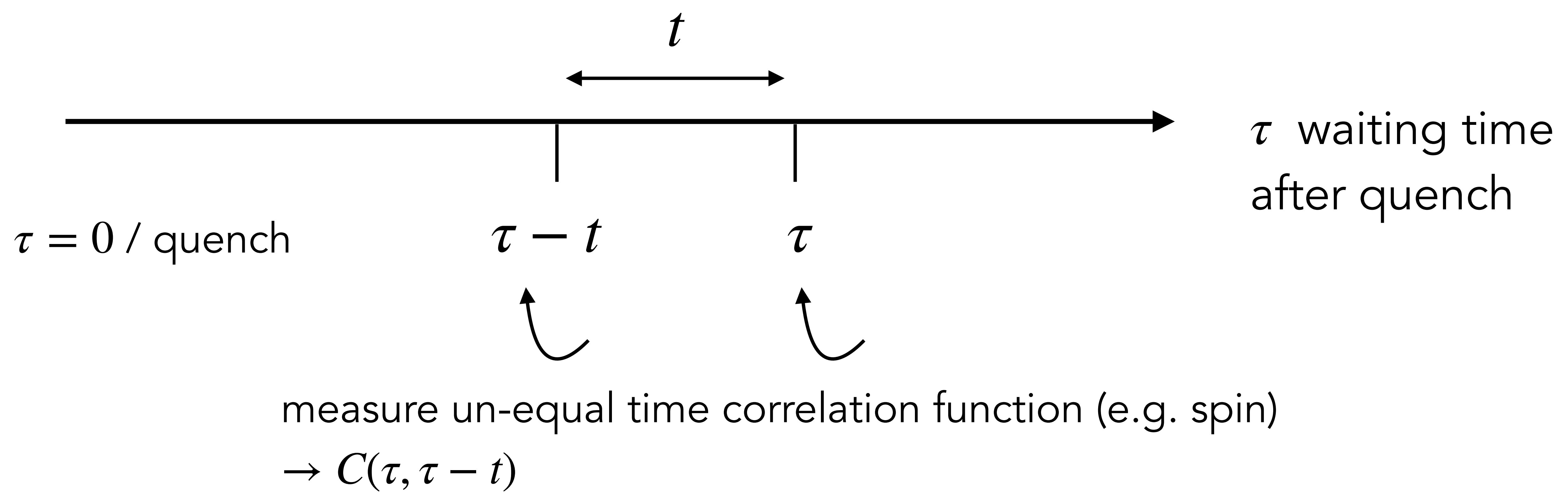


Long-time correlations

$$C(\tau, \tau - t) = \frac{1}{S^2} \overline{\langle S_i^x(\tau) S_i^x(\tau - t) \rangle}$$

measure un-equal time correlation function (e.g. spin)
$\rightarrow C(\tau, \tau - t)$

Glass dynamics



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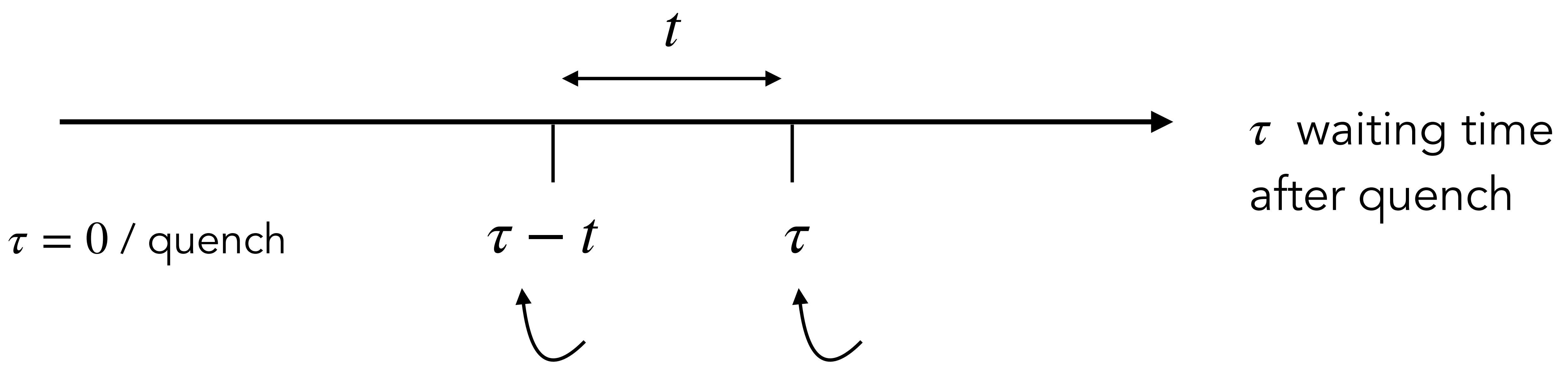

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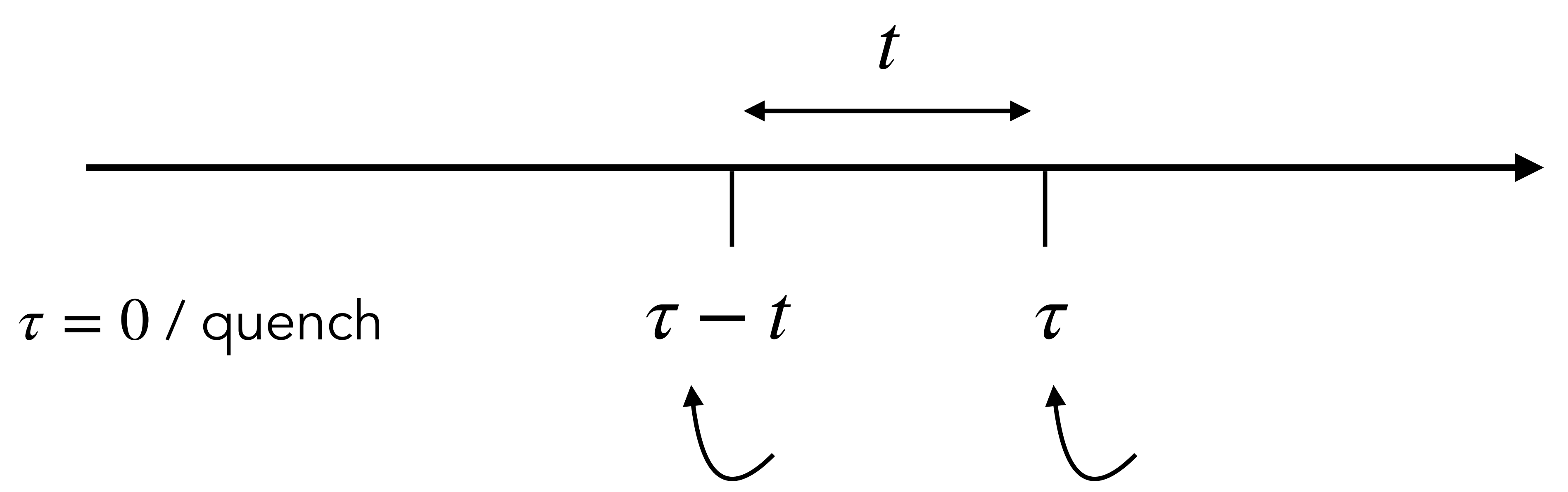
Edwards-Anderson order parameter for spin glass

Glass dynamics



τ waiting time after quench

measure un-equal time correlation function (e.g. spin)
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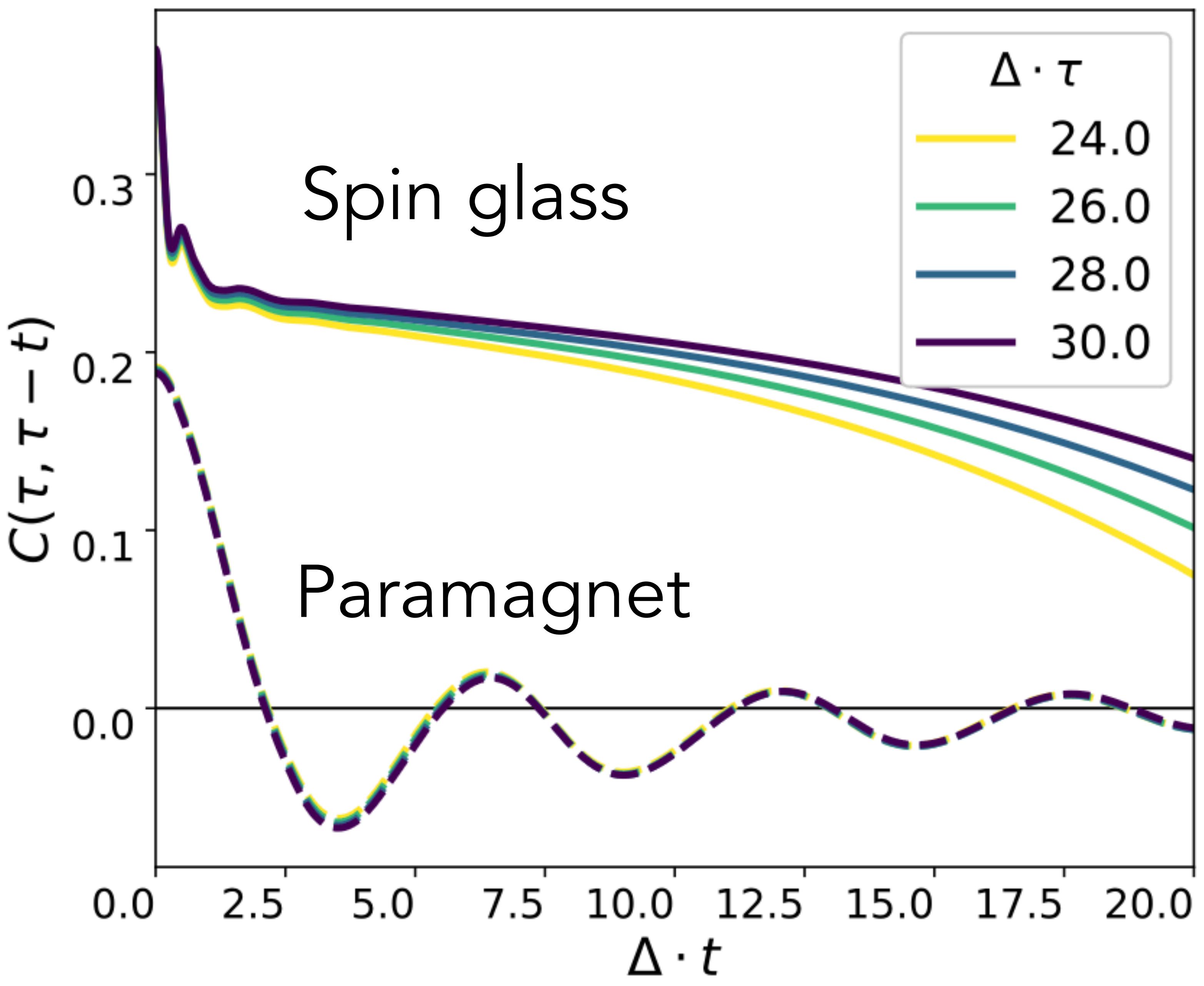

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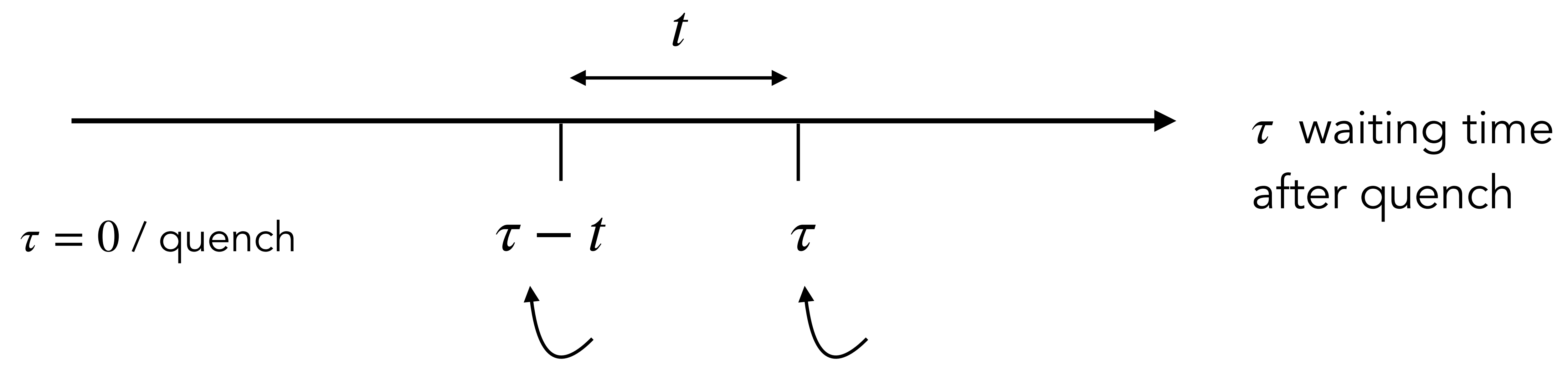

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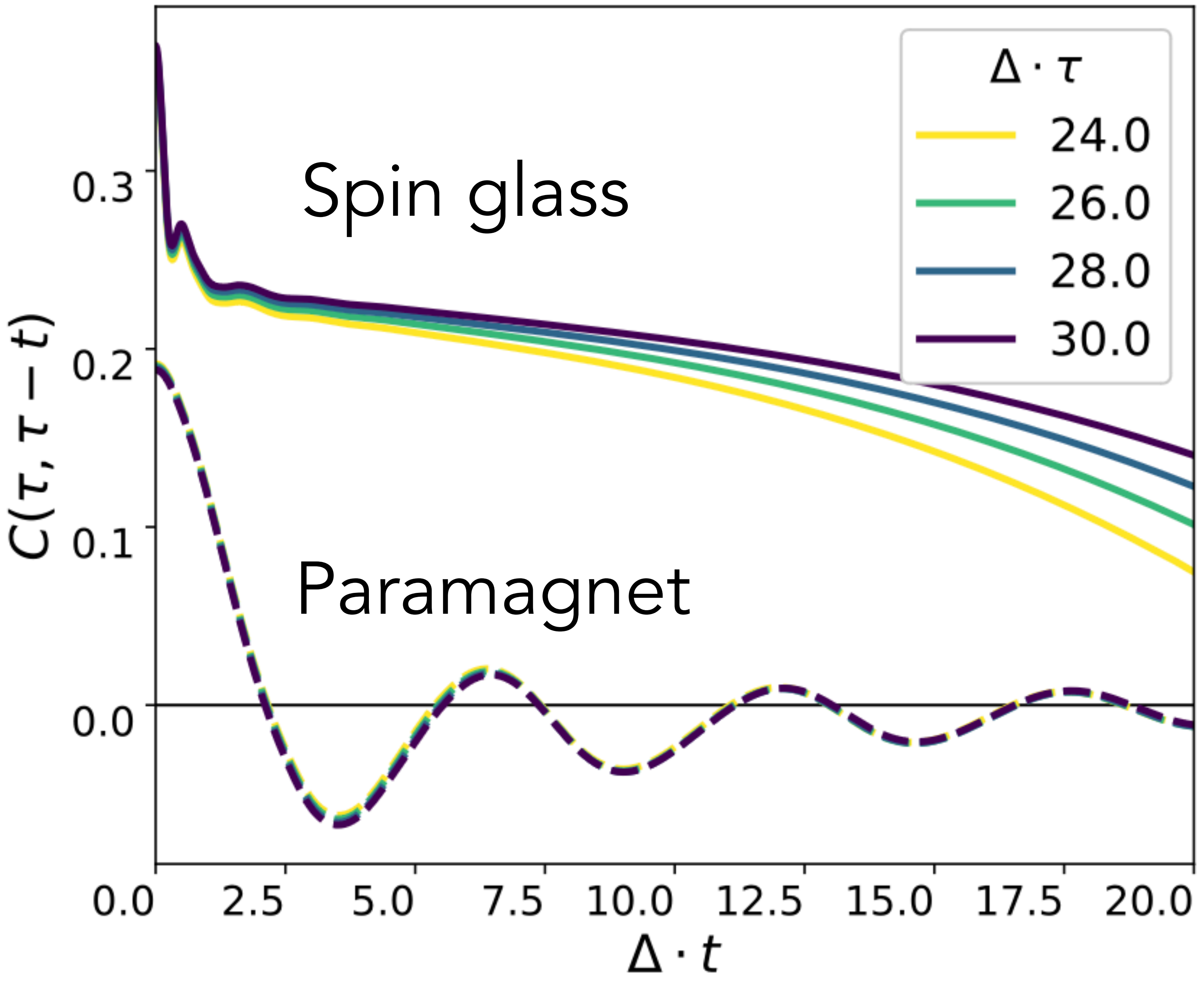
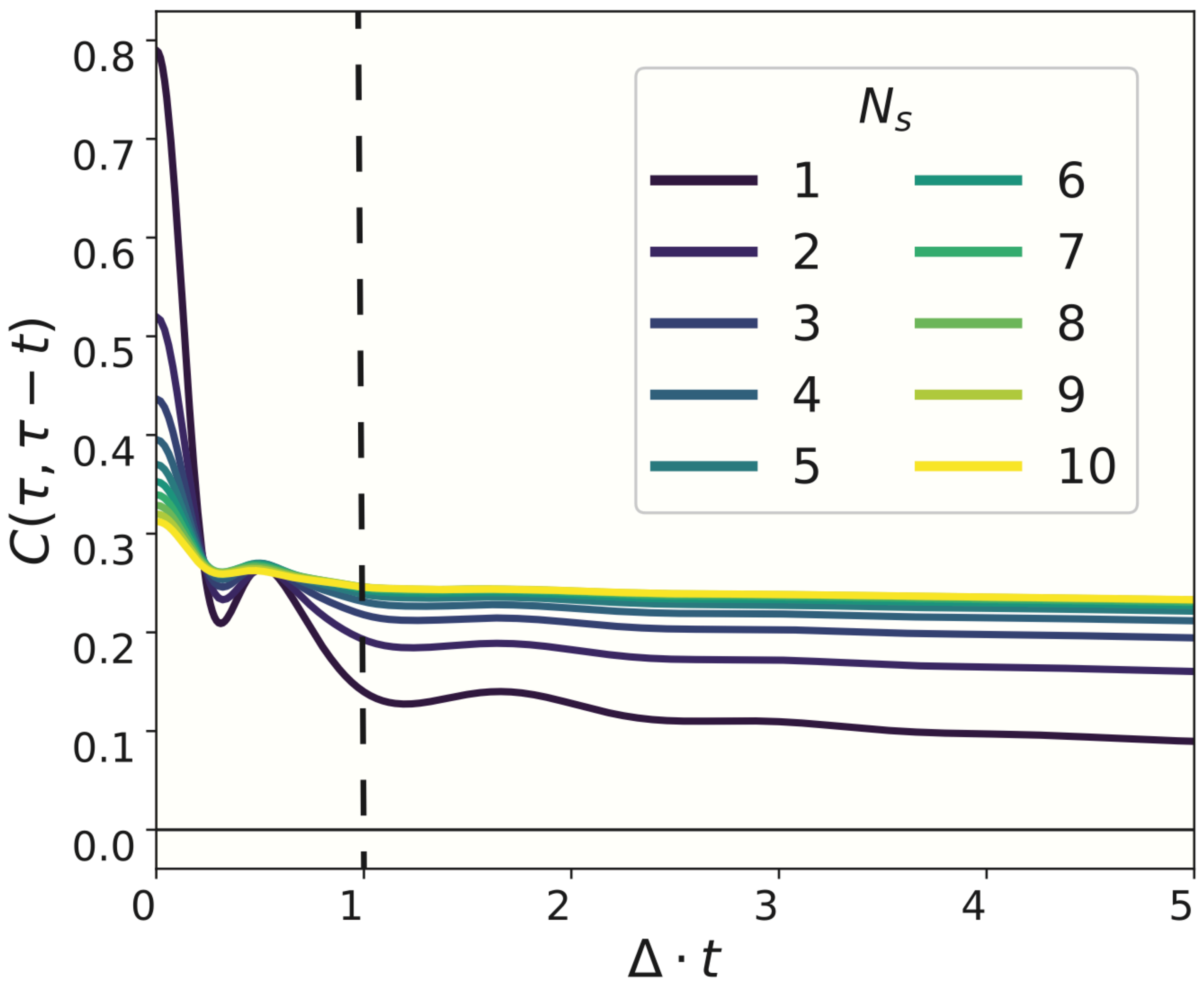


Quantum fluctuations melt spin glass



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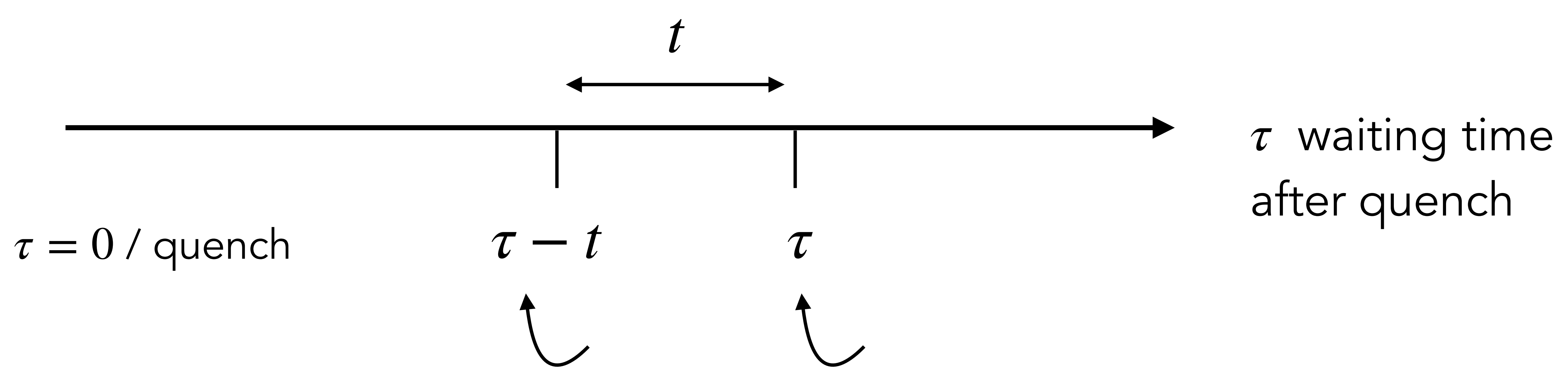

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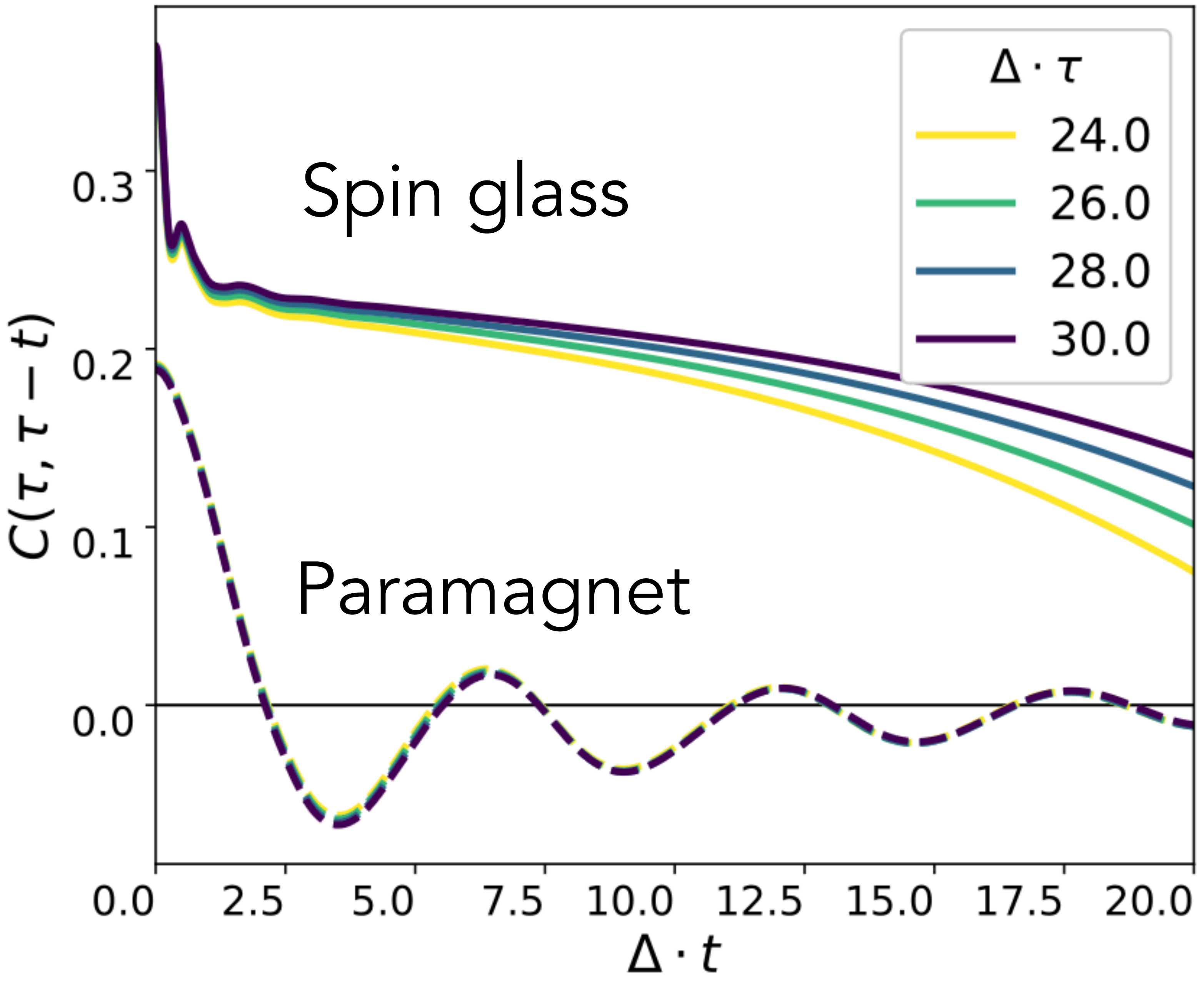

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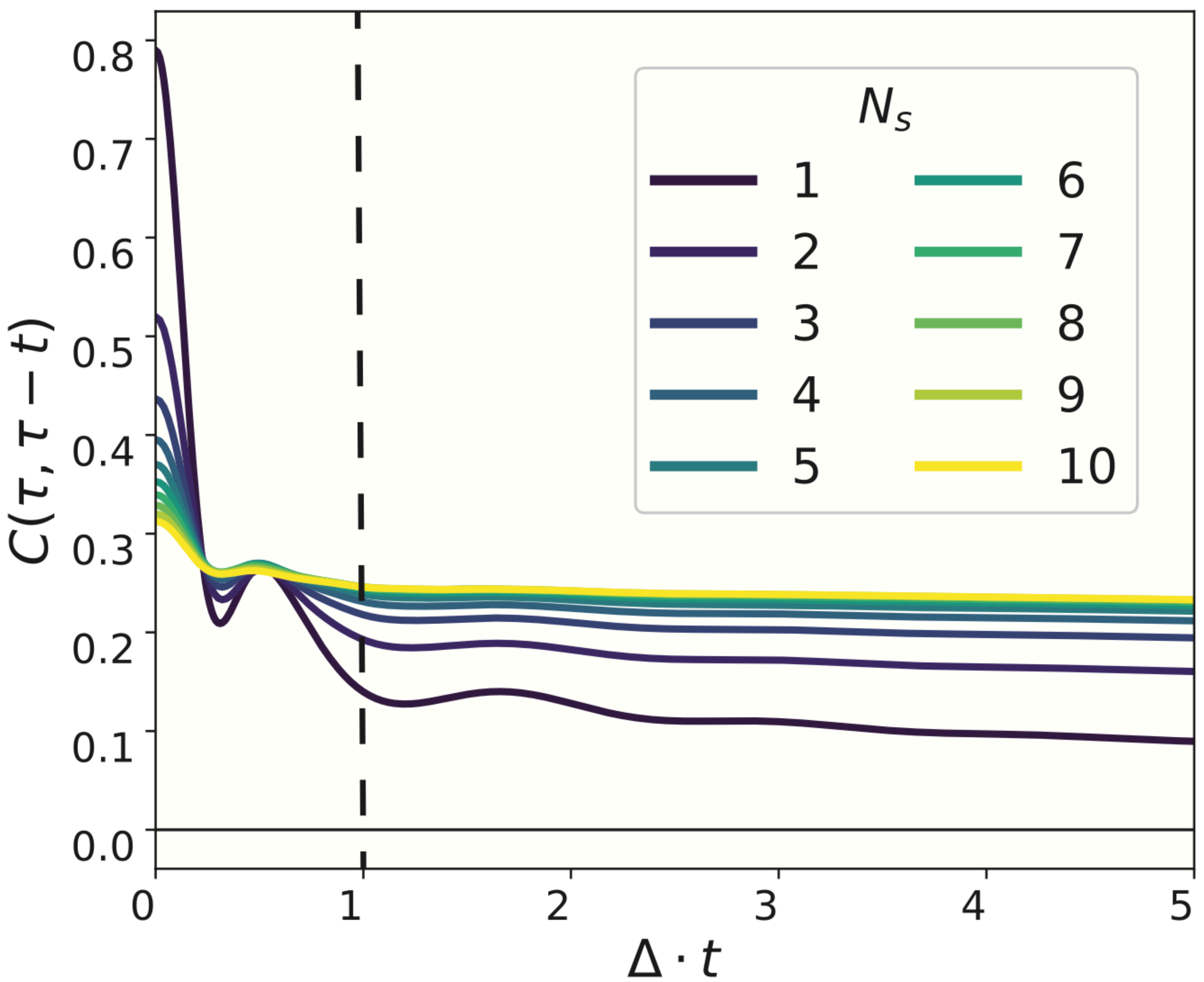
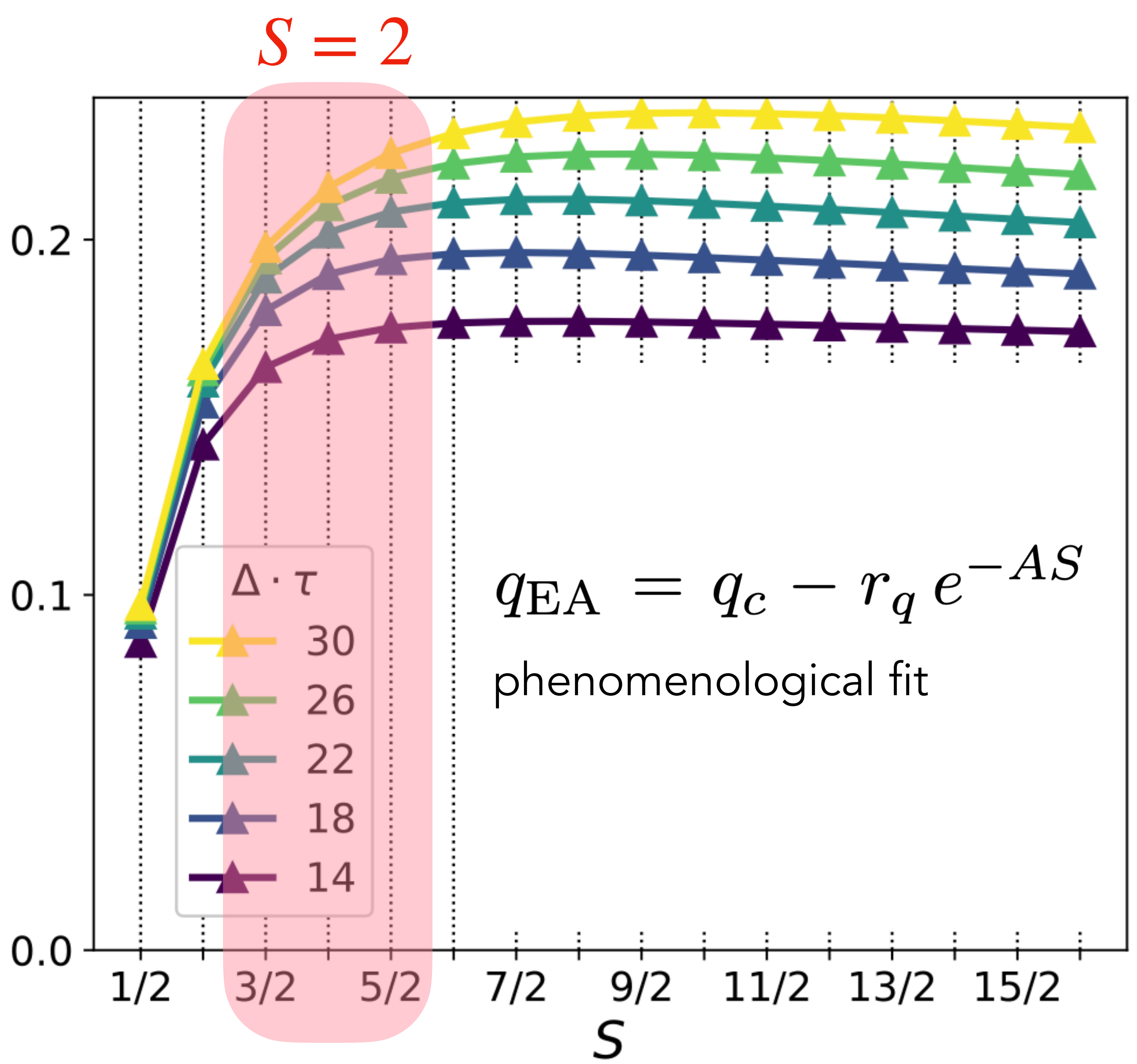


Quantum-to-classical crossover



Statistical correlations between similar samples

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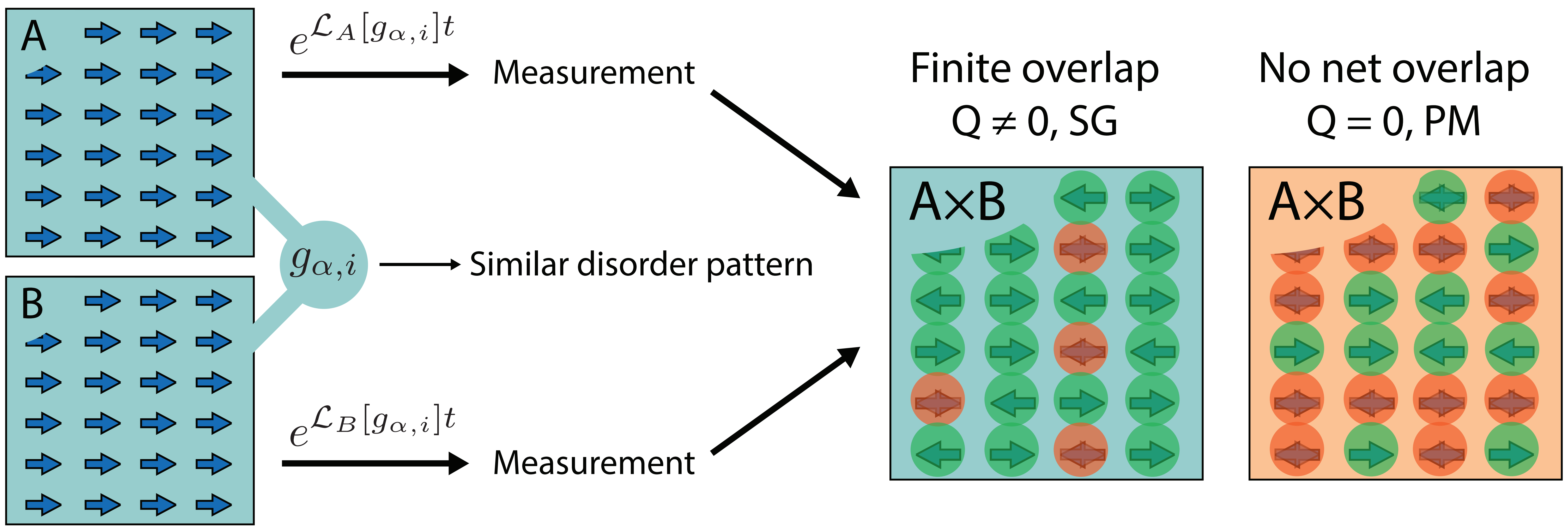
Take two copies with the same profile of disorder.

How much do they look similar after evolution?

$$Q(t) = \frac{1}{S^2} \overline{\langle S^x_{i,A}(t) S^x_{i,B}(t) \rangle_c}$$



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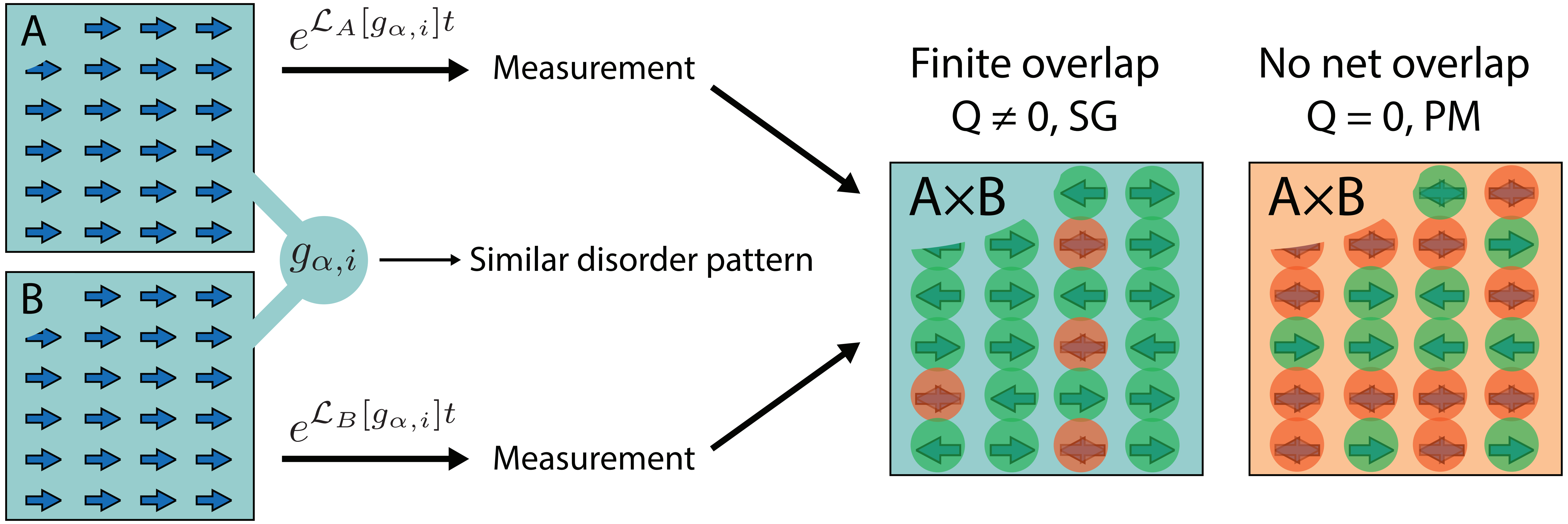

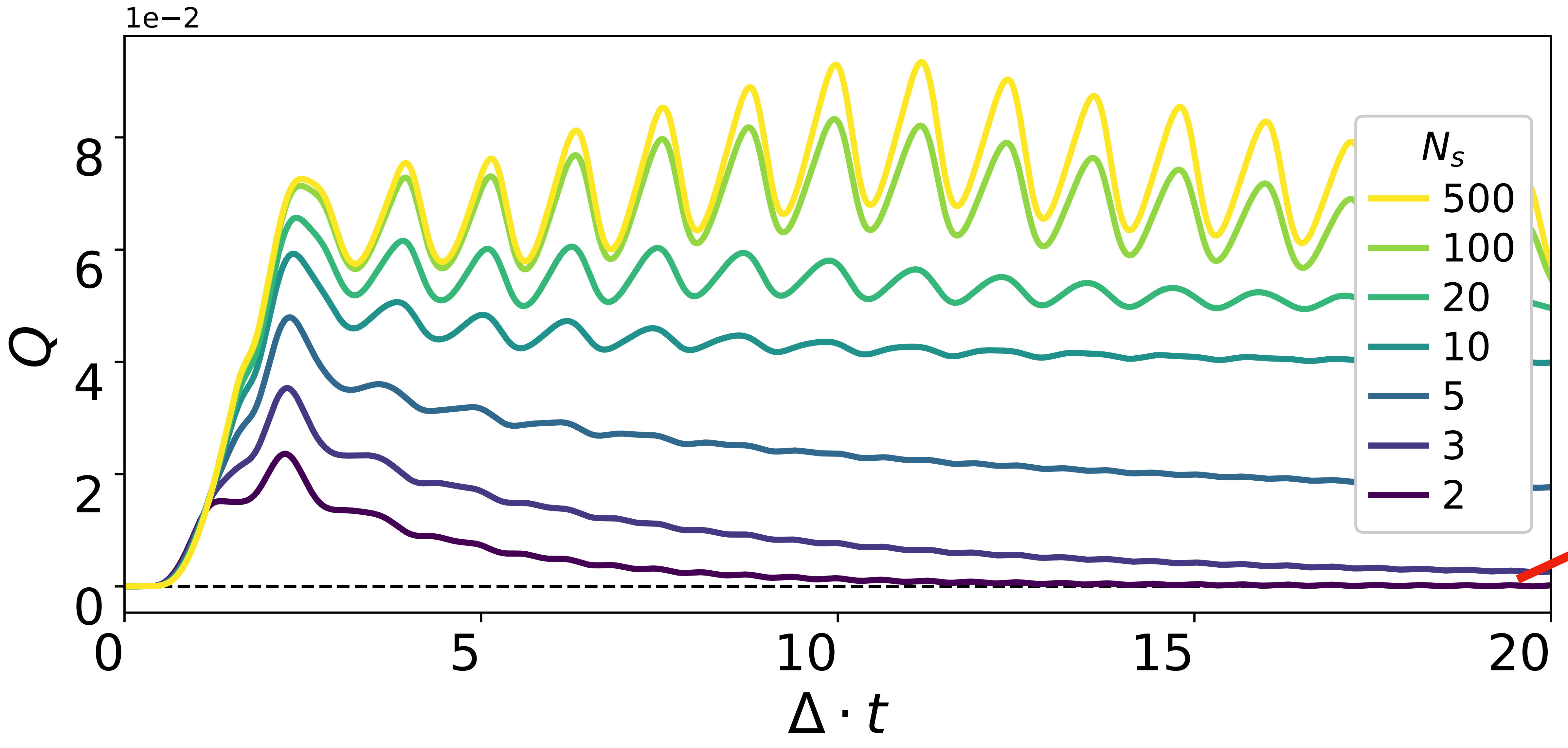

Quantum fluctuation can completely melt the spin glass **(without cavity loss)**

The cavity side of the story

Playing with the cavity frequency

Dissipation vs interactions

Both are stronger for slow photons

The cavity side of the story

Loss rate of the cavity modes $\rightarrow \kappa$

$$\left(\partial_t \rho\right)_{\text{loss}} = \kappa \sum_{\alpha} \left(2 a_\alpha \rho a_\alpha^\dagger - \{a_\alpha^\dagger a_\alpha, \rho\}\right)$$

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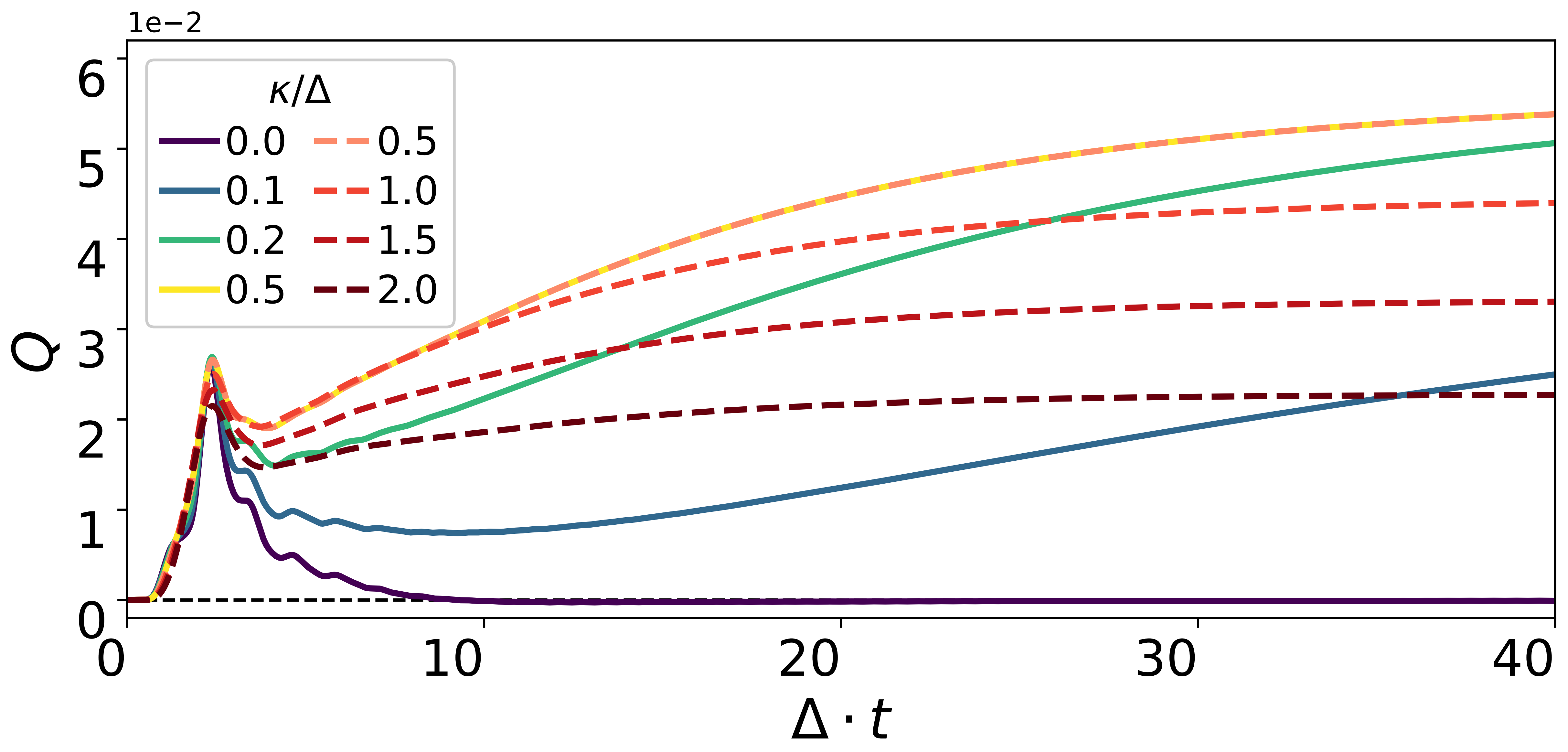

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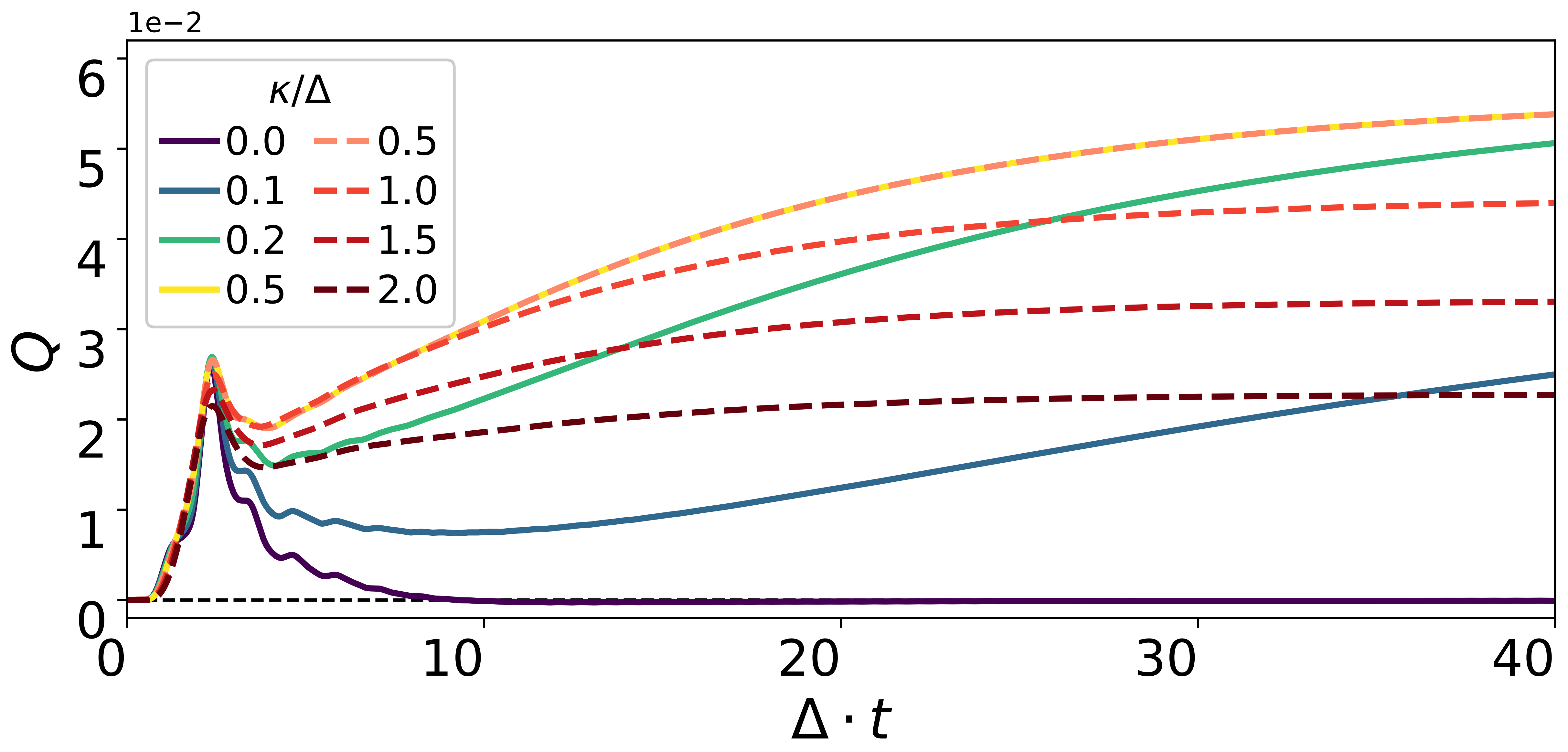

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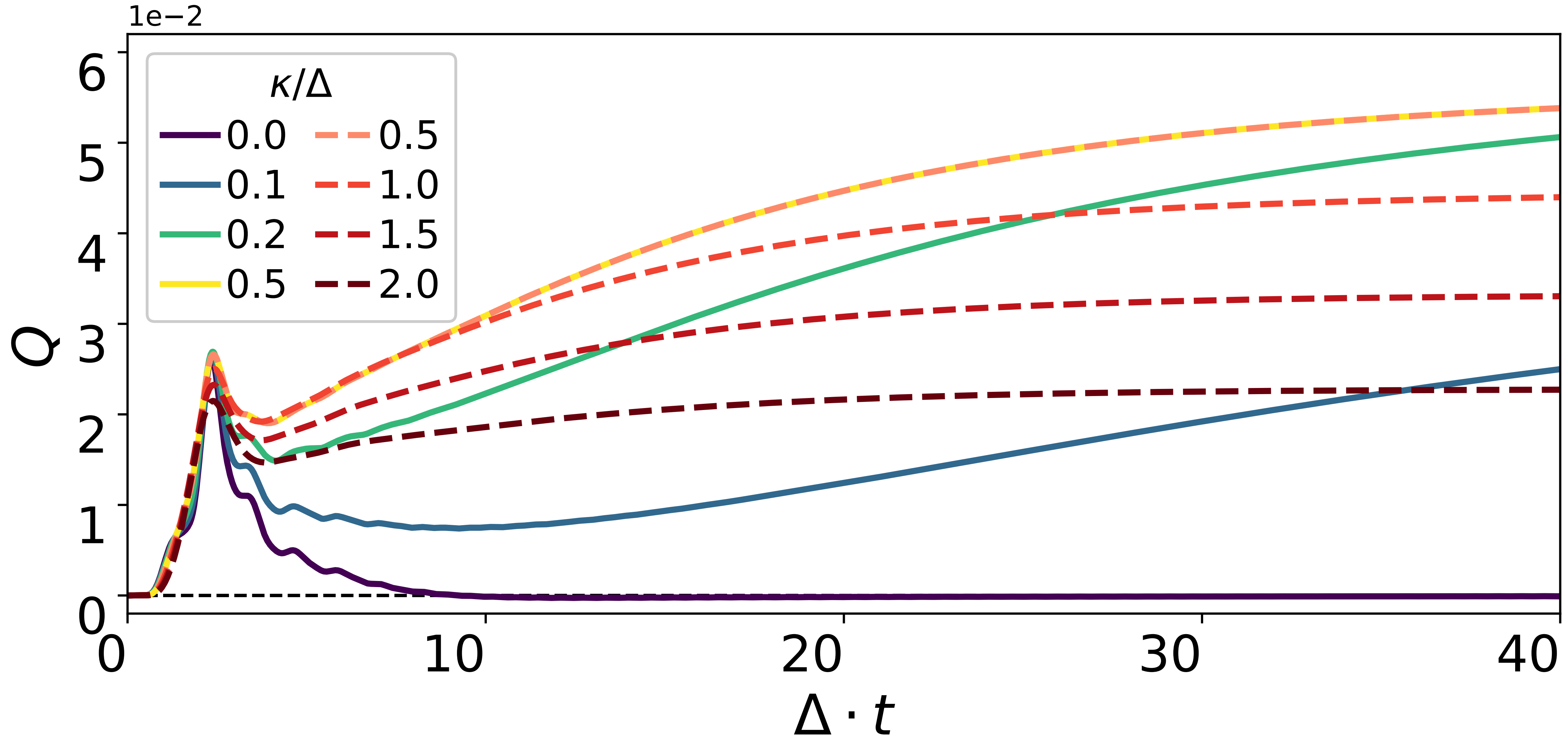

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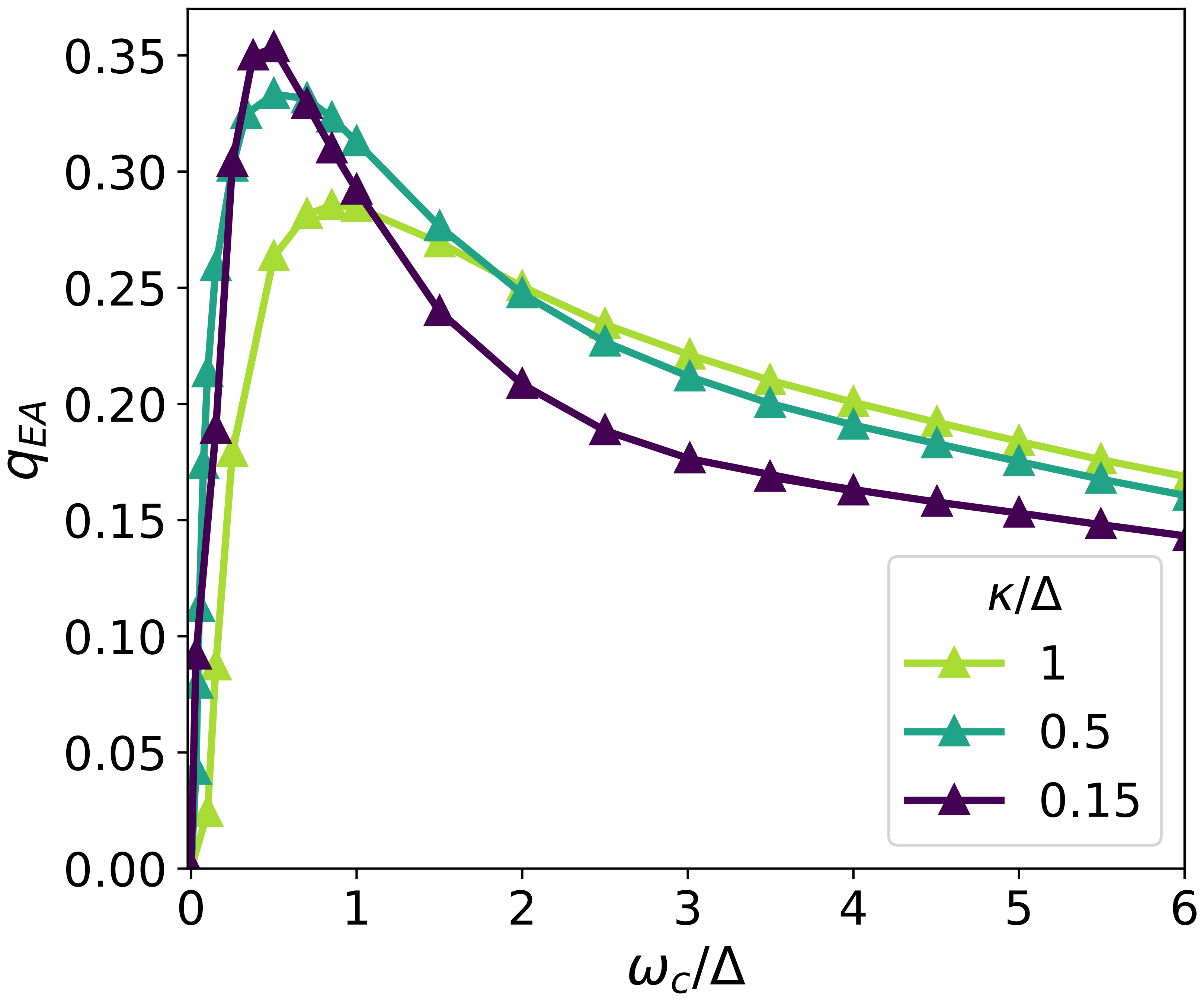
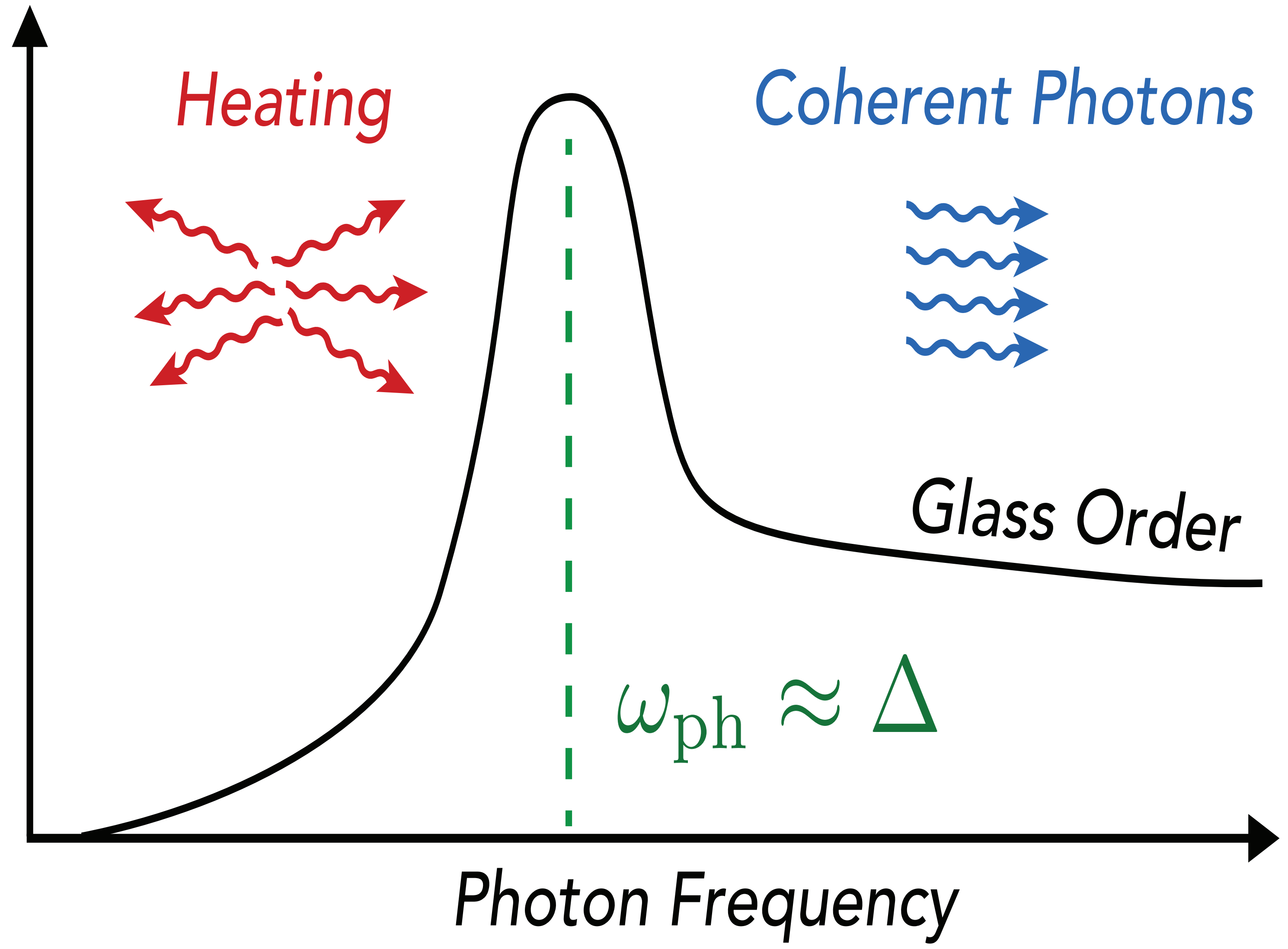
Resonant enhancement of spin glass order





Summary

- clean/controlled dynamics of SG vs solid state experiments
  (access to certain macroscopic quantities only/short range interactions - RKKY)
- possibility to engineer tunable range interactions (from long to short)
  (open problems in theory of spin glasses)
- role of (controlled) dissipation
  (moderate cavity loss helps SG formation)
- tunable quantum fluctuations at the network nodes
  (un-thinkable in solid state)
- quantum-to-classical crossover in a many body system
  (in general: intractable/very few examples/ purely phenomenological)
- <u>broad applicability</u>: programmable interactions & dissipation in c-QED with tweezers, correlated emission in atomic arrays, Rydbergs in cavities.