Ground-state coherence vs orientation: competing mechanisms for light-induced magnetic self-organization in cold atoms

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Abstract

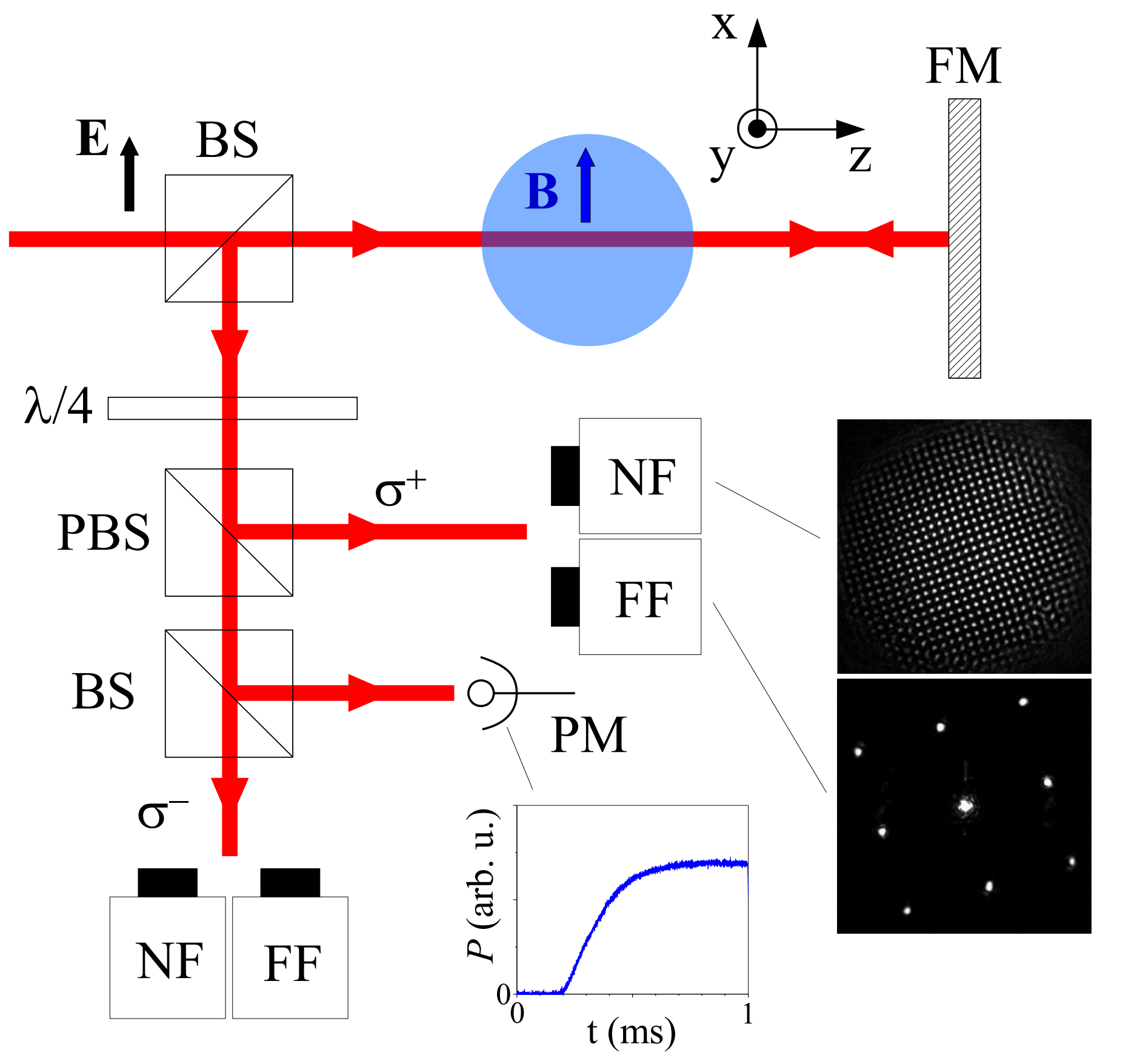
We investigated the interplay between two mechanisms for magnetic self-organization in a cloud of cold atoms subjected to a retro-reflected laser beam. The transition between two different phases, one linked to a spontaneous spatial modulation of the $\Delta m = 2$ ground-state coherence and the other to that of the magnetic orientation (spin), can be induced by tuning either a weak magnetic field or the laser intensity. The experimental observations are compared to extended numerical simulations.

Background

Light-induced self-organization can be observed in a nonlinear medium e.g. using the single-mirror feedback scheme based on diffractive coupling [1]. Early observations employed hot atomic vapors [2, 3] and other nonlinear media [4]. Using large clouds of laser-cooled Rb atoms, we demonstrated optomechanical patterns [5], excited-state patterns [6], and various kinds of magnetic patterns [7, 8]. The present work discusses the transition between two different self-organized magnetic phases.

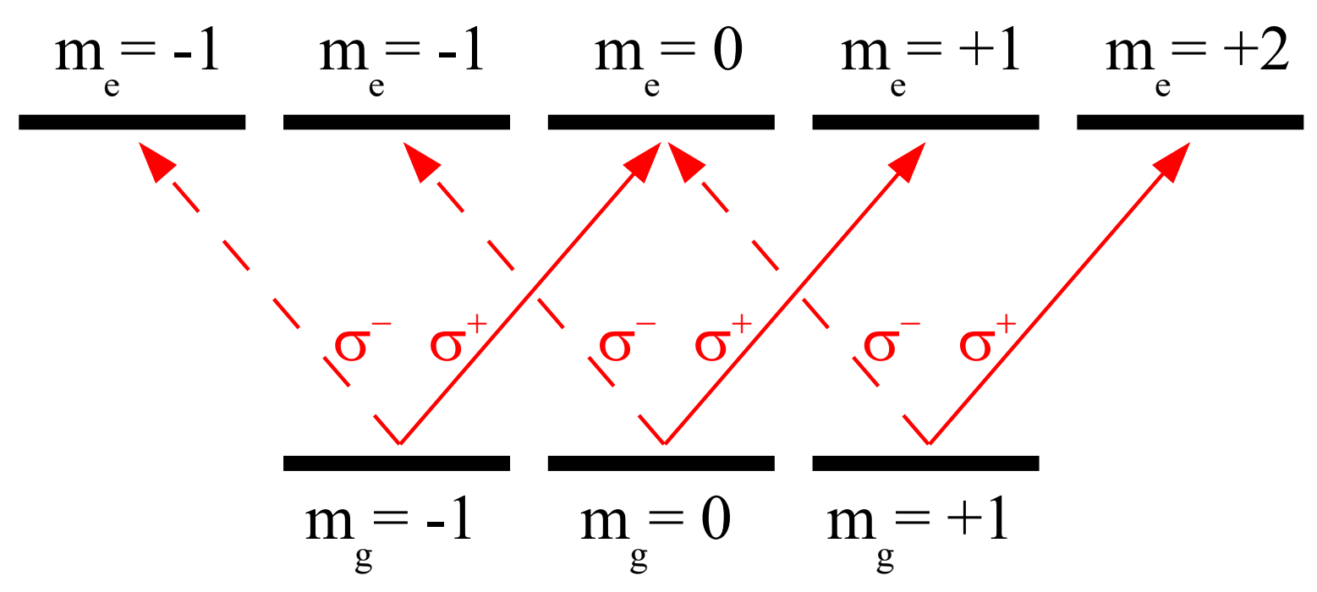
[1] Firth, J. Mod. Opt. **37**, 151 (1990). [2] Grynberg *et al*, Phys. Rev. Lett. **72**, 2379 (1994). [3] Ackemann *et al*, Phys. Rev. Lett. **75**, 3450 (1995). [4] Macdonald *et al*, Opt. Commun. **89**, 289 (1992). [5] Labeyrie *et al*, Nat. Phot. **8**, 321 (2014). [6] Camara *et al*, Phys. Rev. A **92**, 013820 (2015). [7] Labeyrie *et al*, Optica 5, 1322 (2018). [8] Kresic *et al*, Commun. Phys. **1**, 33 (2018).

Experimental Setup



A large cloud of cold ^{87}Rb atoms (diameter > 1 cm, resonant optical density ~ 100) is produced in a magneto-optical trap. A red-detuned laser beam is sent through the cloud and retro-reflected. A magnetic field is applied along the direction of incident light polarization (**x**). The light intensity distribution in the transverse plane (**x**, **y**) is recorded both in near- and far-field. The pattern formation dynamics is monitored by a photomultiplier.

Theoretical model and Numerics



magnetic moments:

- orientation: $w = \rho_{11} - \rho_{-1-1}$
- alignment: $X = \rho_{11} + \rho_{-1-1} - 2\rho_{00}$
- coherence: $\Phi = 2\rho_{-11} = u + iv$

optical properties:

$$P_{\pm} = \varepsilon_0 \,\mathrm{Re}(\chi_{\pm})\, [(1 \pm \tfrac{3}{4} w + \tfrac{1}{20} X) E_{\pm} + \tfrac{3}{20} (u \mp iv) E_{\mp}]$$

medium polarization by fields $E_{\pm}$ — linear susceptibility

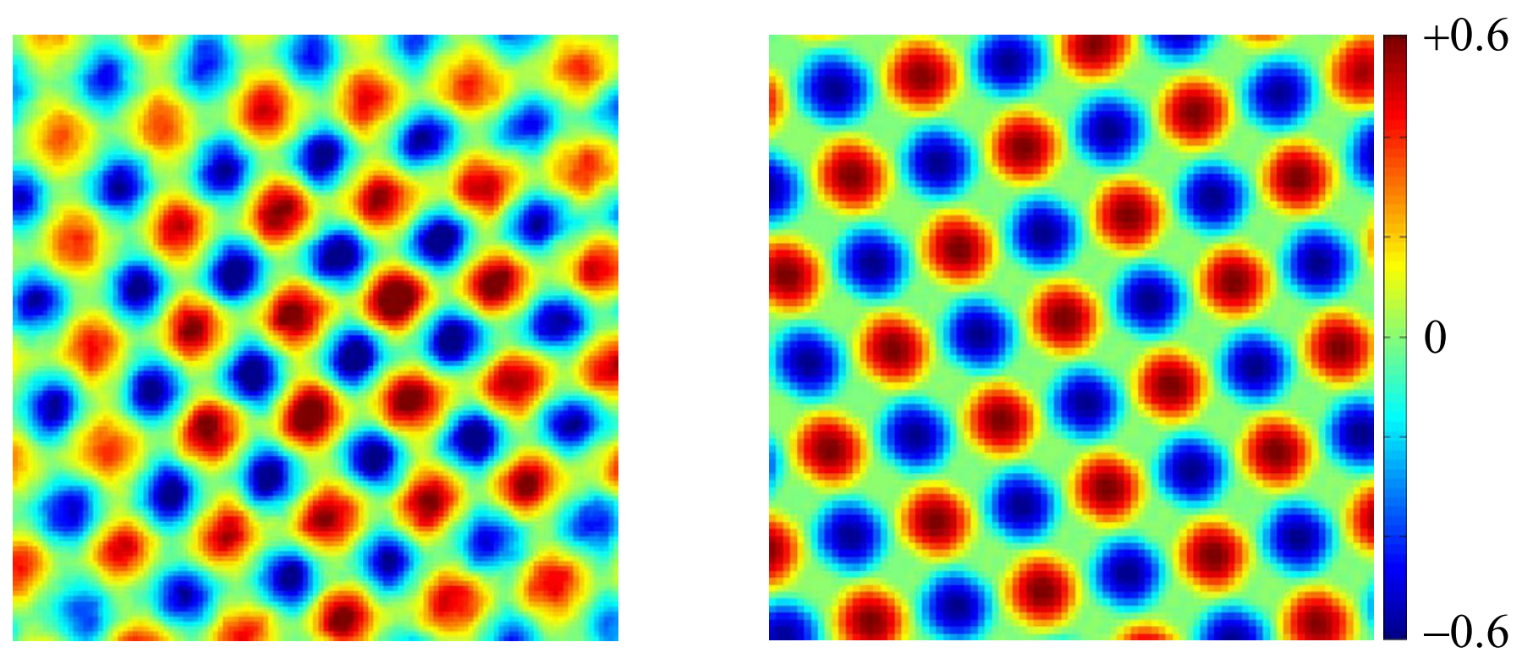
numerical simulations ⇄ light intensity distributions
distributions of atomic parameters

Two self-organized magnetic phases

$$\left.\begin{array}{l} B_x \neq 0 \\ B_y = B_z = 0 \end{array}\right\} \rightarrow \text{two different phases}$$

Anti-ferromagnetic (AFM) phase

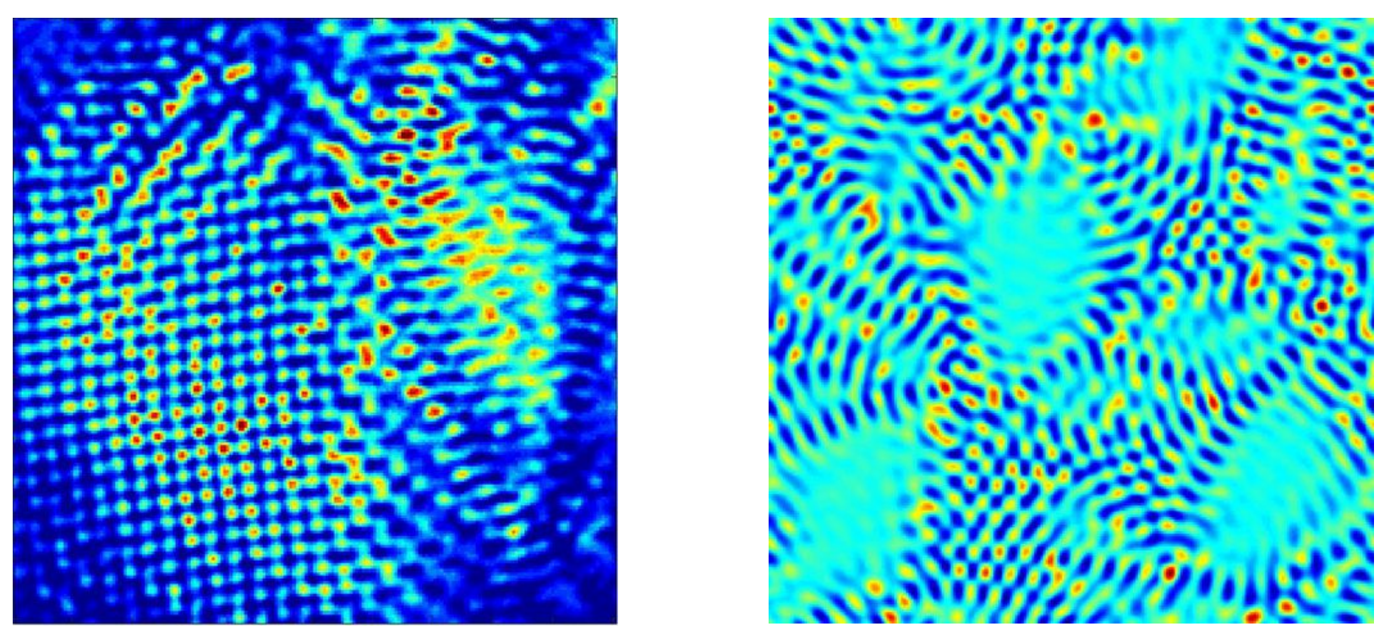
- around $B_x = 0$
- long-range order
- square symmetry
- spatial modulation of orientation



σ+ − σ− (experiment) orientation (numerics)

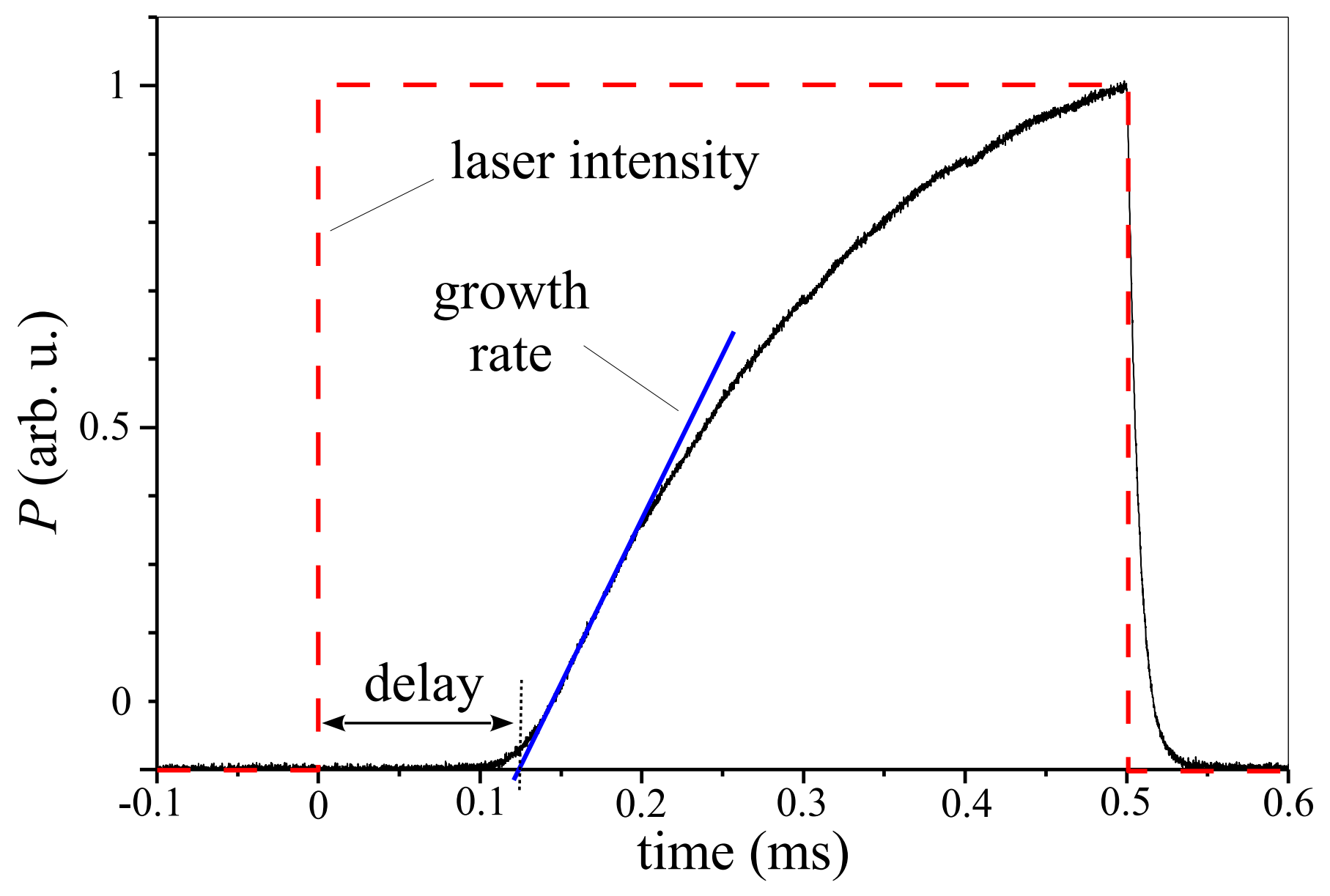
Ground-state coherence (GSC) phase

- $B_x \neq 0$
- no long-range order
- symmetry: stripes, zig-zags, checkerboards, squares
- spatial modulation of ground-state coherence

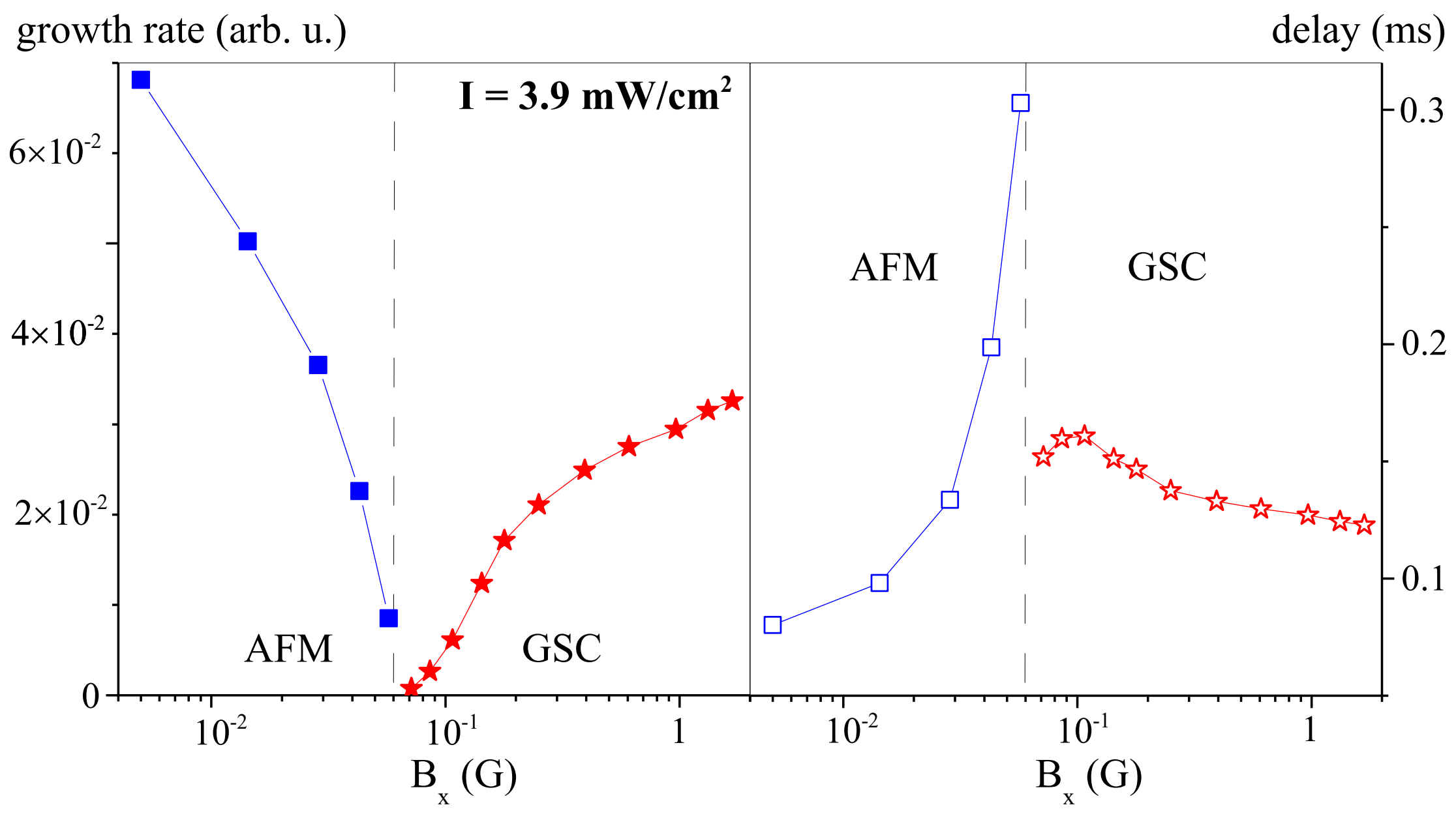


experiment numerics

Dynamics

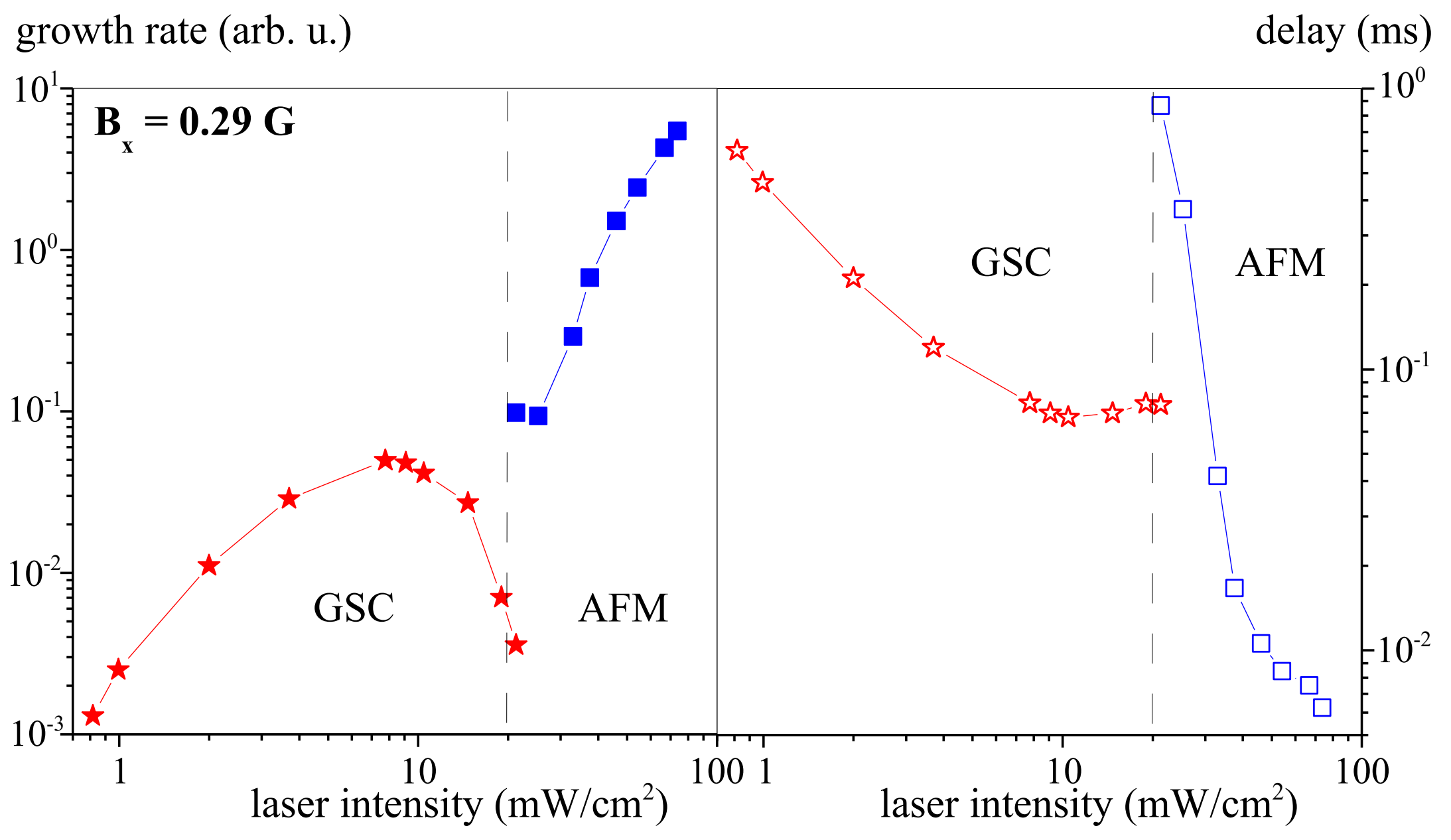


Magnetic field–induced phase transition



- AFM (orientation) destroyed by B_x
- critical slowing down of AFM near transition
- GSC threshold ≈ independent of B_x

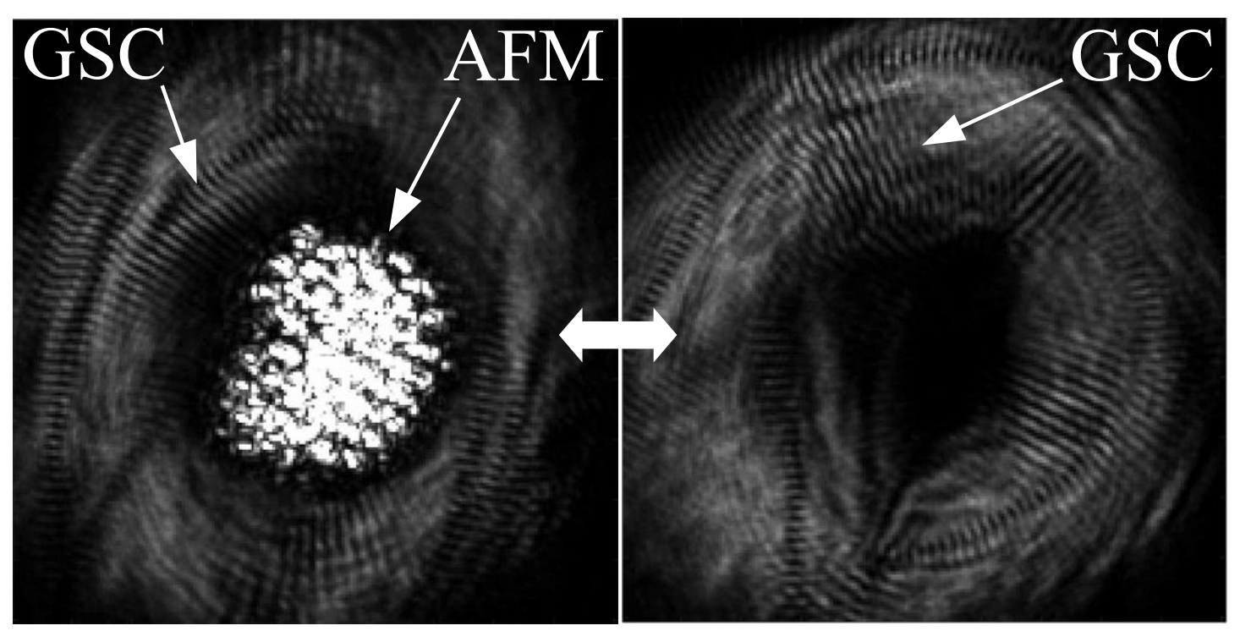
Intensity–induced phase transition

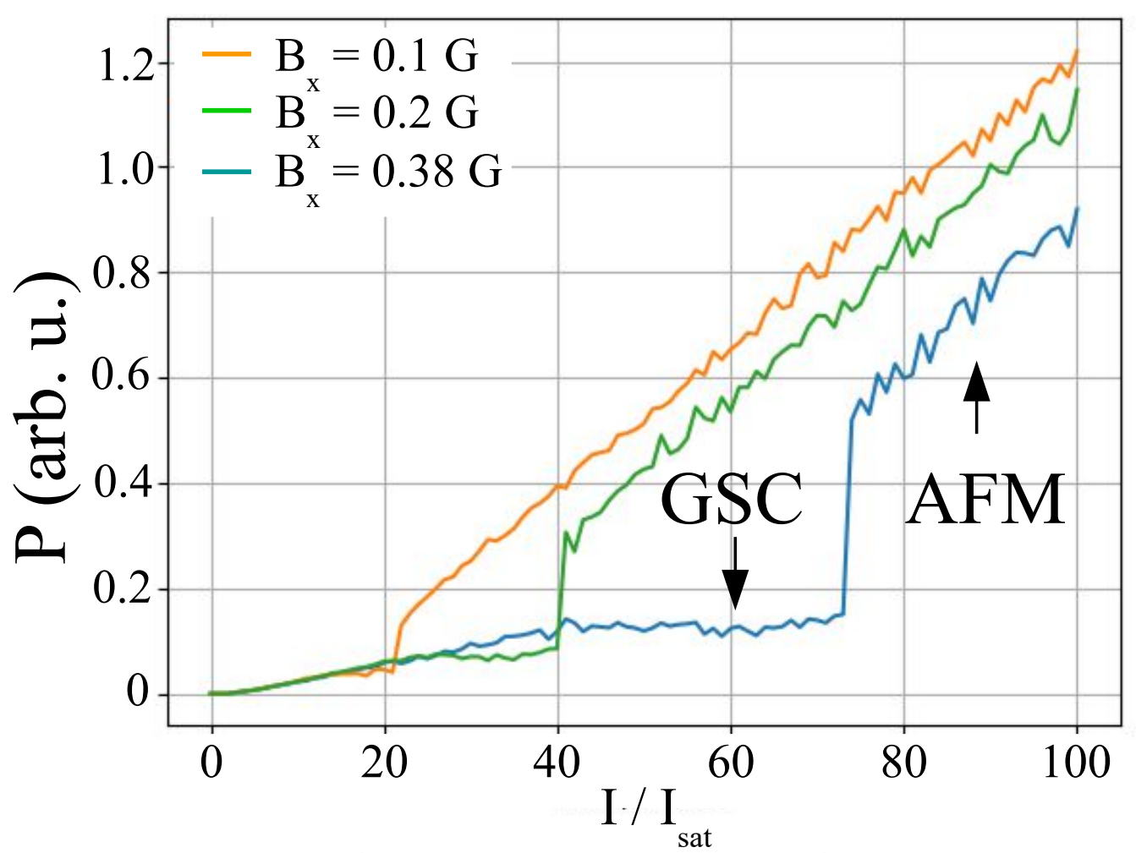


- vanishing of GSC before transition
- critical slowing down of GSC near threshold
- critical slowing down of AFM near transition

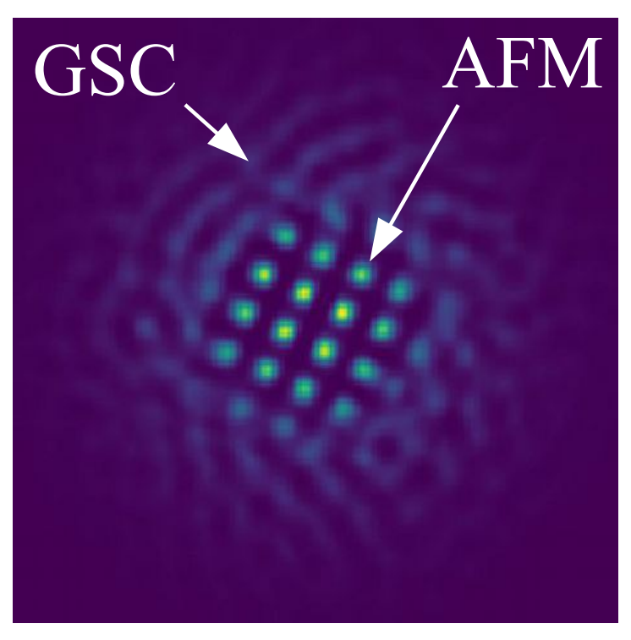
First order transition ?

Intermittent behavior of AFM near transition





plane wave simulation



Gaussian beam simulation

Outlook

- understand the nature of different transitions
- optically-controllable localized magnetic structures
- interplay between magnetic and optomechanical self-organization